Prospects for Higgs Boson Measurements at the HL-LHC with CMS

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on behalf of the CMS Collaboration

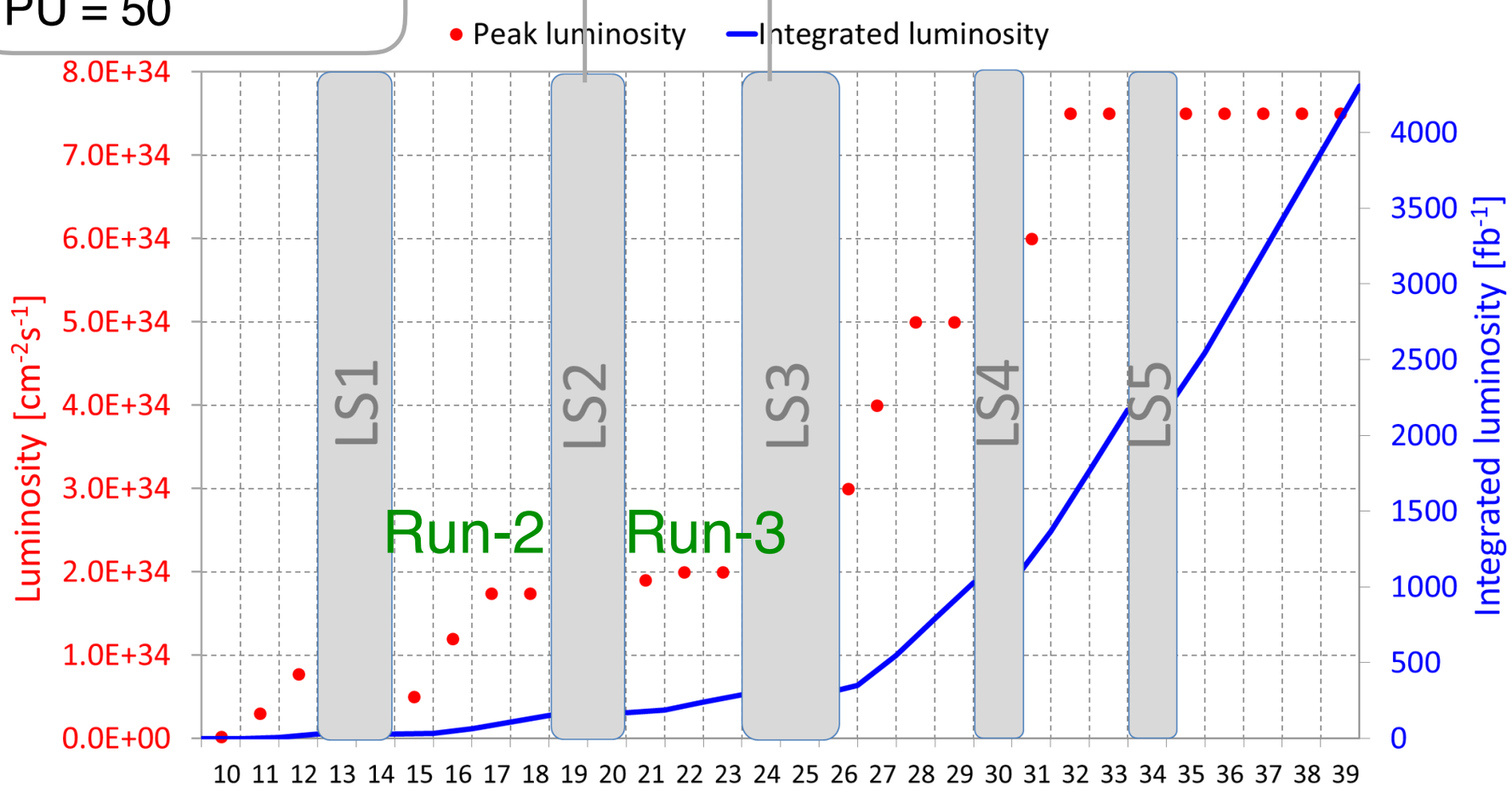
LHC → HL-LHC

- To extend the sensitivity for new physics searches → 2023-2025: **LHC major upgrade**

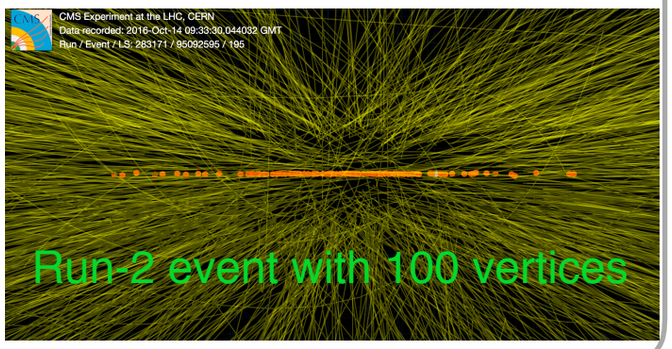
LS2 → Run3
$L = 2 \cdot 10^{34}\ cm^{-2}\ s^{-1}$
$\sqrt{s}$ = 14 TeV
PU = 50

HL-LHC or Phase 2

LS3 → HL-LHC
$L = 5\ (7.5) \cdot 10^{34}\ cm^{-2}\ s^{-1}$
$\sqrt{s}$ = 14 TeV
PU = 140 (200)



Pile-up [PU]: average number of proton-proton collisions per bunch crossing



2020-2023: 300 fb^{-1} per experiment

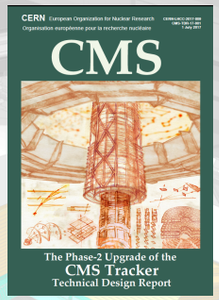
2025-2035: **~3000 fb^{-1} per experiment**

CMS Detector Upgrades

- Performance compromised by **radiation damage** and **increased pile-up**
- Detector upgrades crucial to **maximise physics potential** and **maintain a good object reconstruction** in this harsh environment → increased radiation hardness, increased forward acceptance, higher granularity …

New Tracker

- Increased radiation hardness
- Higher granularity
- Increased forward acceptance up to $\eta = 4$
- Reduced material in the tracker volume
- Tracks in hardware trigger (L1)

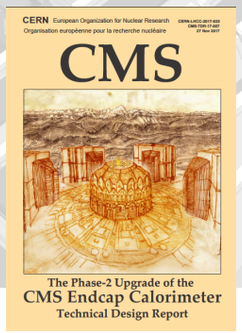


Muons

- In the forward region, improved RPC + new GEM detectors → Increased acceptance up to $\eta \sim 3$
- Front-end electronics upgrade for DT's and CSC's

New Endcap Calorimeter

- Radiation tolerant
- High granularity (HGCAL)
- Timing information



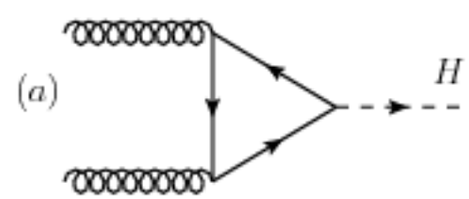
HL-LHC: a gate to Precision and New Physics

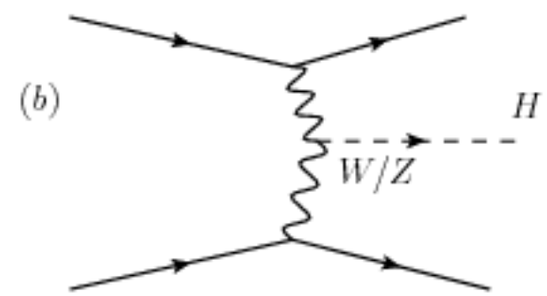
- Over **170 million Higgs** bosons in 3000 fb^{-1}
- **Unique opportunity** to thoroughly test the Higgs boson properties
  - **High precision coupling measurements** - down to a few percents
  - **Sensitivity to coupling to 2nd generation** - $H \rightarrow \mu\mu$
  - **Di-Higgs production** and **Higgs self-coupling measurement**
    See Luca Cadamuro's talk "HH production at the HL-LHC with CMS"
  - Sensitivity to **rare decays** involving new physics
- Picture of the experimental reach on Higgs boson properties measurements obtained from **projections with 3000 fb^{-1}**

  NB: 3000 fb^{-1} per experiment studied as benchmark although ultimate collider scenario with $\mathscr{L} = 7.5 \cdot 10^{34}$ cm^{-2} s^{-1} might provide up to 4000 fb^{-1}

Higgs Production Modes and Cross-sections

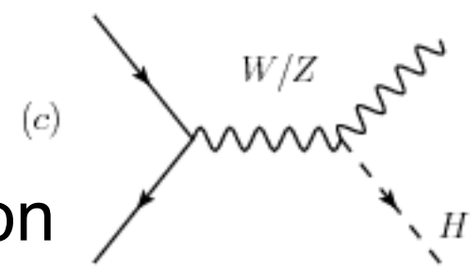
ggF
gluon-gluon Fusion

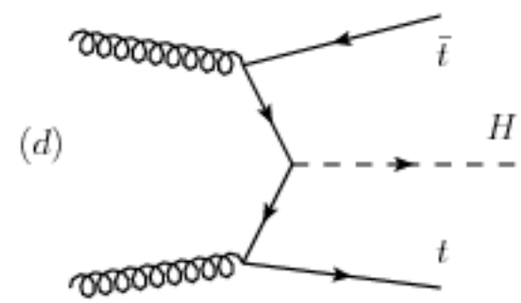




VBF
Vector Boson Fusion

VH
Vector boson
associated production





ttH
Top quark associated
production

Higgs Working Group Report
arXiv:1610.07922v2 Yellow Report 4

Cross-sections in pb for M_H = 125 GeV

√s (TeV)	ggF (a)	VBF (b)	VH (c)	ttH (d)
14	54.67	4.45	2.50	0.613

What do we measure ?

arXiv:1307.1347

- Traditional **signal strength** modifiers:
  - $\boldsymbol{\mu_i}$ for i = ggH, VBF, VH, ttH production modes
  - $\boldsymbol{\mu^f}$ for f = $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, etc decay modes

$$\mu_i = \sigma_i / \sigma_i^{SM}$$
$$\mu^f = \sigma^f / \sigma_f^{SM}$$
$$\mu_i^f = \mu_i \cdot \mu^f$$

- **"Reduced" coupling scale factors y_i**

- Deviations from the Standard Model implemented as **scale factors (κ's)** of Higgs couplings relative to their SM values

- κ_i scale factors ("**coupling modifiers**") defined in such a way that the cross-sections σ_i and the partial decay widths Γ_i associated with the SM particle *i* scale with κ_i^2 compared to the SM prediction

$$y_{V,i} = \sqrt{\kappa_{V,i}} \frac{g_{V,i}}{2\upsilon} = \sqrt{\kappa_{V,i}} \frac{m_{V,i}}{\upsilon}$$
$$(V,i = W,Z)$$

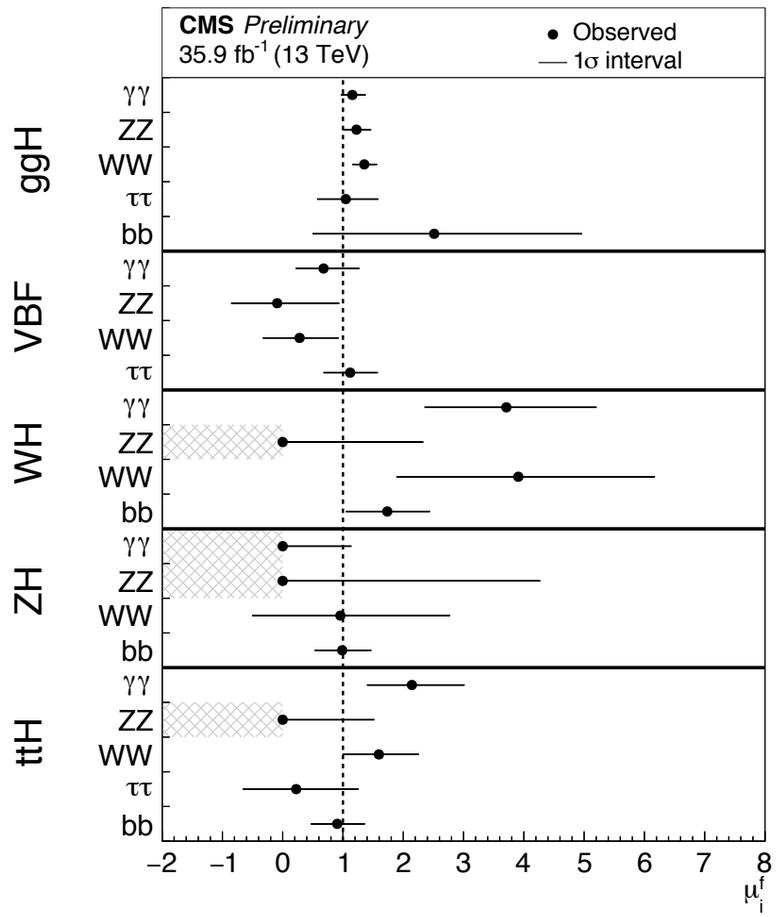
$$y_{F,i} = \kappa_{F,i} \frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i} \frac{m_{F,i}}{\upsilon}$$
$$(F,i = \mu, \tau, b, t)$$

$$\kappa_i^2 = \sigma_i / \sigma_i^{SM}$$
$$\kappa_i^2 = \Gamma_i / \Gamma_i^{SM}$$

Run-2 Measurements

CMS-PAS-HIG-17-031

- *See Nick Wardle's talk - "Measurements of the Higgs boson mass, production and decay rates and constraints on its couplings at CMS"*



Signal strengths

$$\mu_i^f = \mu_i \cdot \mu^f$$

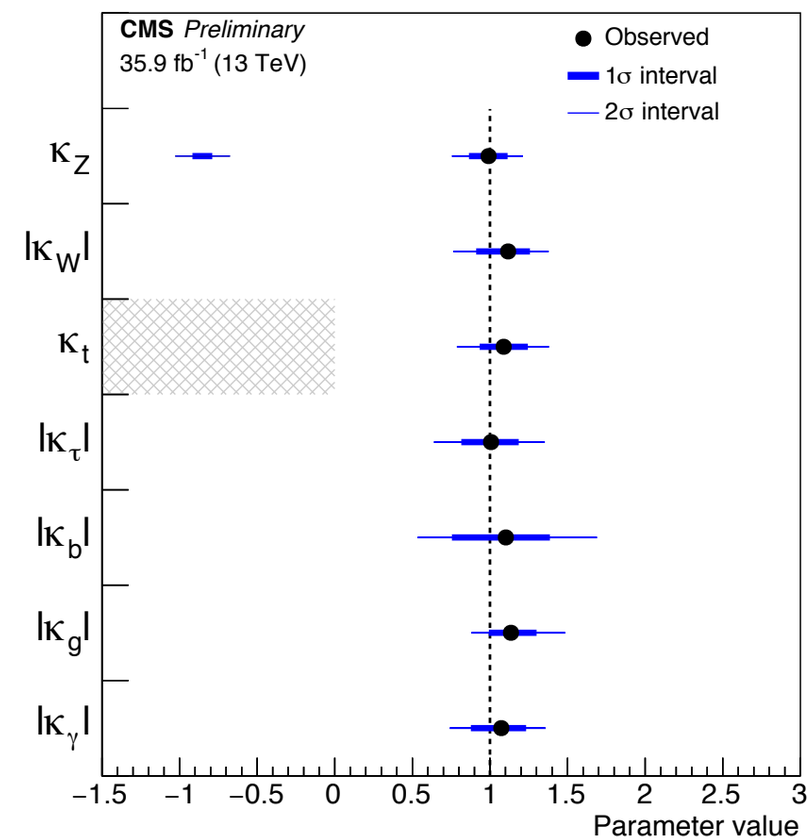
Measurements with 2016 data at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 35.9 fb^{-1}

- Start to exploit **new production-decay models**, e.g. VH and ttH with $H \rightarrow \tau\tau$ decay channel

$$\mu = 1.17^{+0.06}_{-0.06}\ (stat.)\ ^{+0.06}_{-0.05}\ (theory)\ ^{+0.06}_{-0.06}\ (syst.)$$

Fit results in the κ-framework model with $BR_{BSM} = 0$

Couplings κ_i



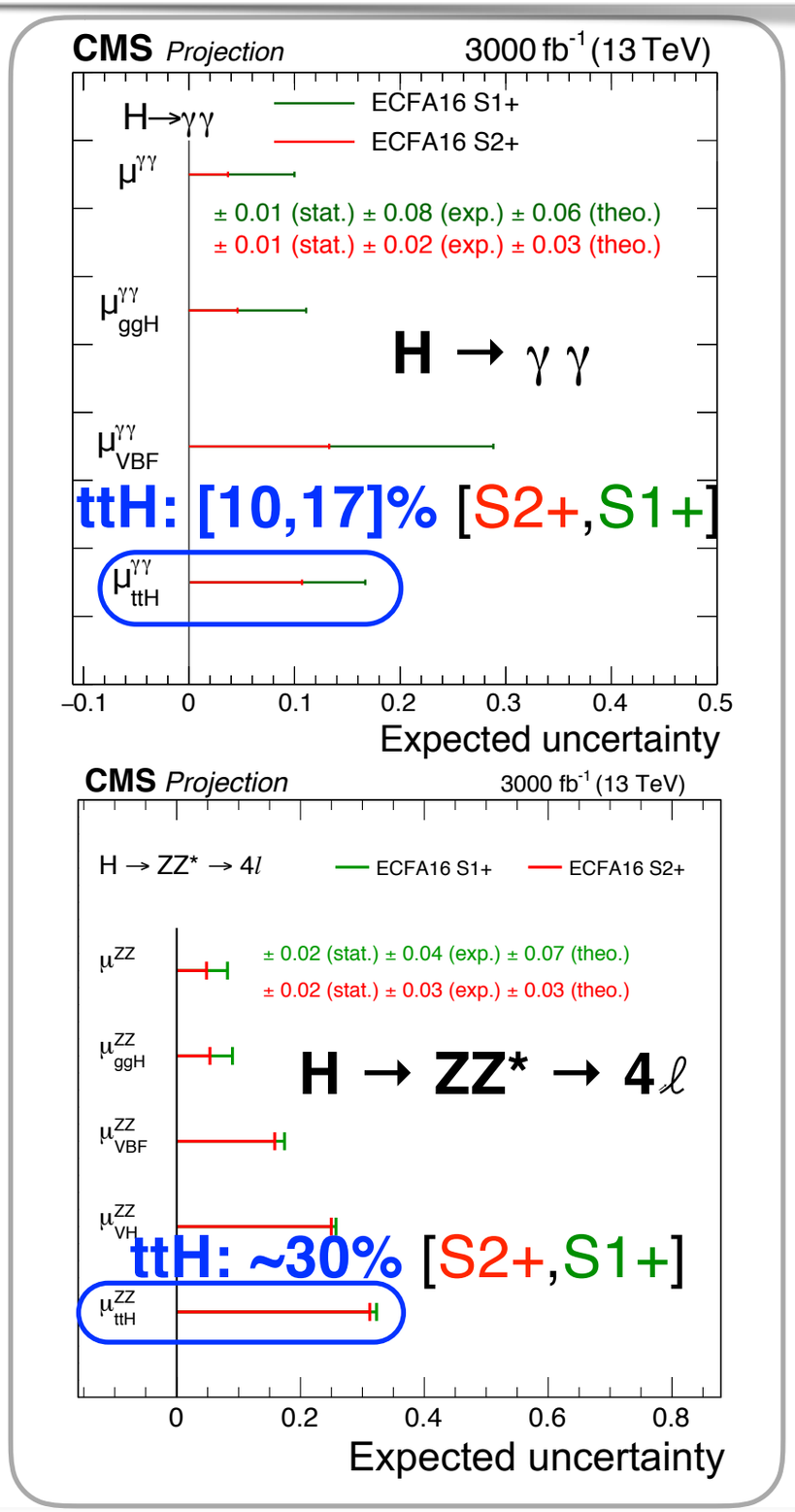
- **Uncertainties** now reaching **10-20%** level for most parameters

Existing Projections on Signal Strengths

CMS-PAS-FTR-16-002

Projections based on 2016 data at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 12.9 fb^{-1} for 3000 fb^{-1} (ECFA16)

- Two projection scenarios that include higher PU and detector upgrades effects
  - **S1+**: all systematic uncertainties constant
  - **S2+**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity (until a lower limit based on estimates of achievable accuracy with upgraded detector)
- Since then reduction in theory uncertainties (e.g. N^3LO ggF prediction) and improvement in analysis techniques
- Statistics is crucial in ttH($\rightarrow \gamma\gamma$, ZZ $\rightarrow 4\ell$) channels
- **HL-LHC can bring uncertainty on ttH down to 10% level**

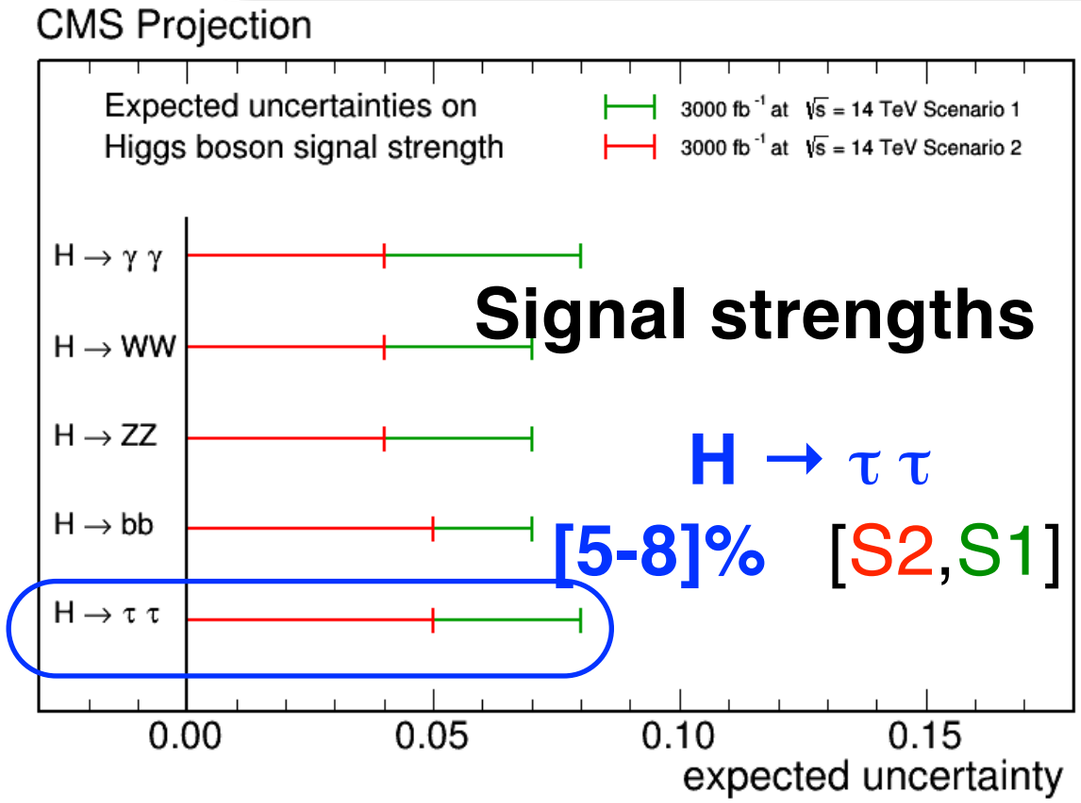


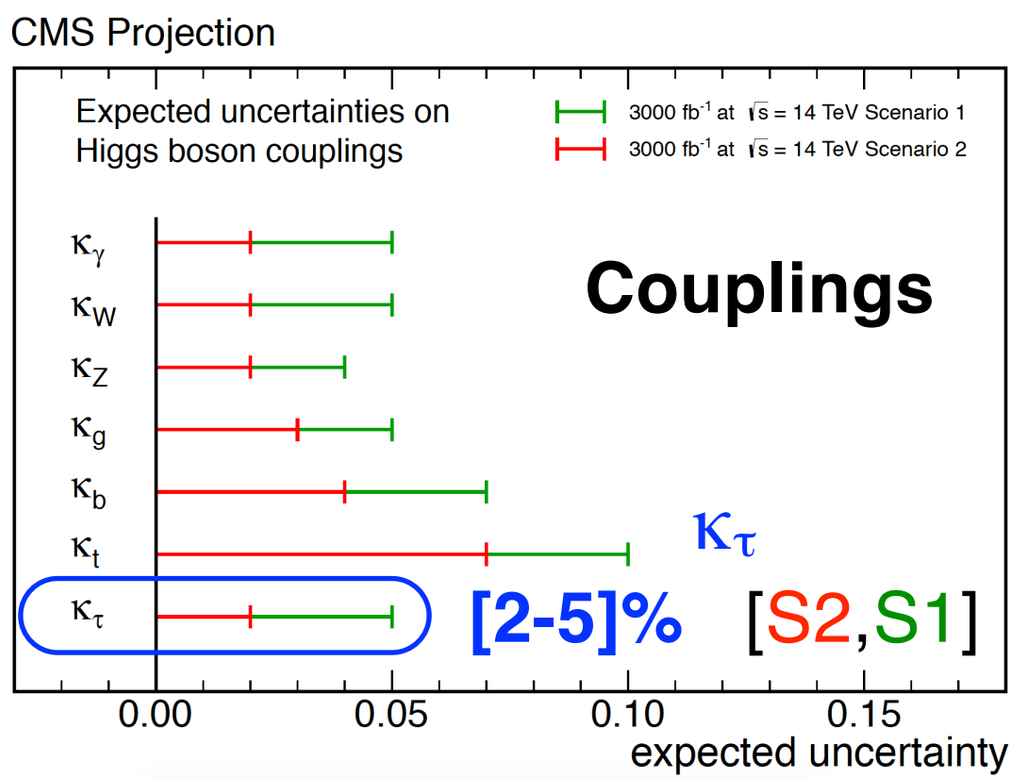
Existing Projections per Decay Mode

arXiv:1307.7135

- Projections scenarios (Snowmass report of 2013) - unchanged detector performance (no upgrade considered)
  - **S1**: systematic uncertainties constant
  - **S2**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity

Projected uncertainties per decay mode based on 5.1 fb^{-1} at $\sqrt{s}$ = 7 TeV and up to 19.6 fb^{-1} at $\sqrt{s}$ = 8 TeV



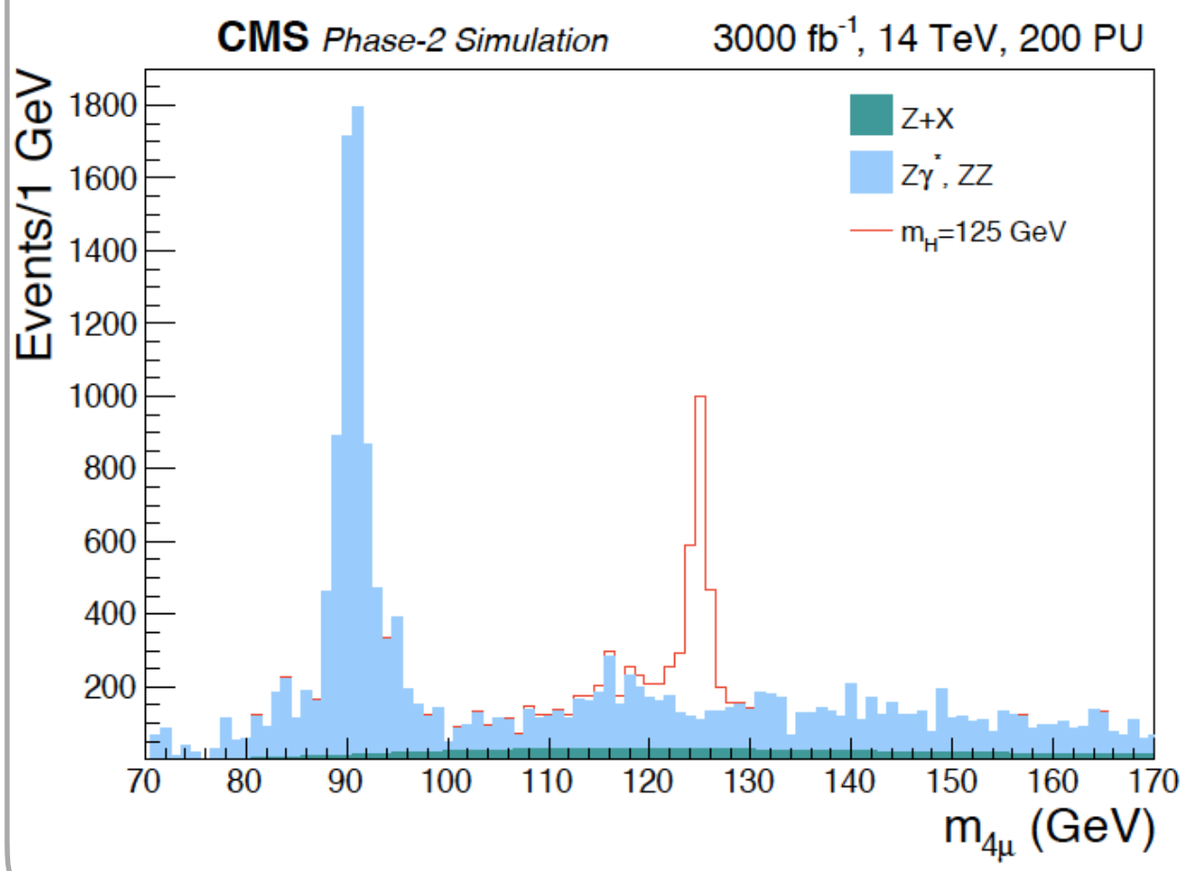


H → ZZ*

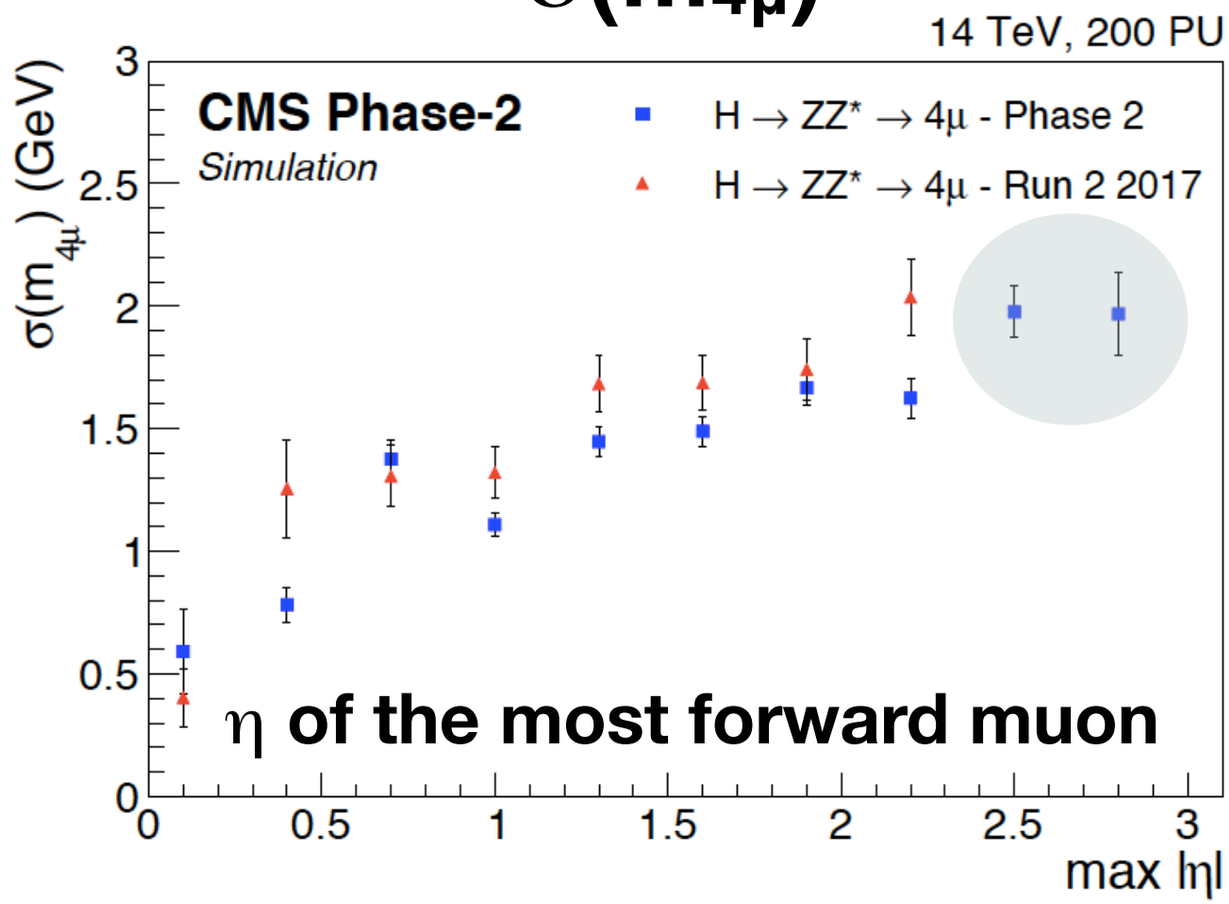
CMS TDR-017-003 *CMS TDR-017-001*

- About 20 000 ggF → H→ ZZ* → 4ℓ + another ~1550 VBF expected
- Upgraded detectors bring significant improvements
- Signal acceptance and **mass resolution** fairly **immune to pile-up conditions**

$m_{4\mu}$



$\sigma(m_{4\mu})$



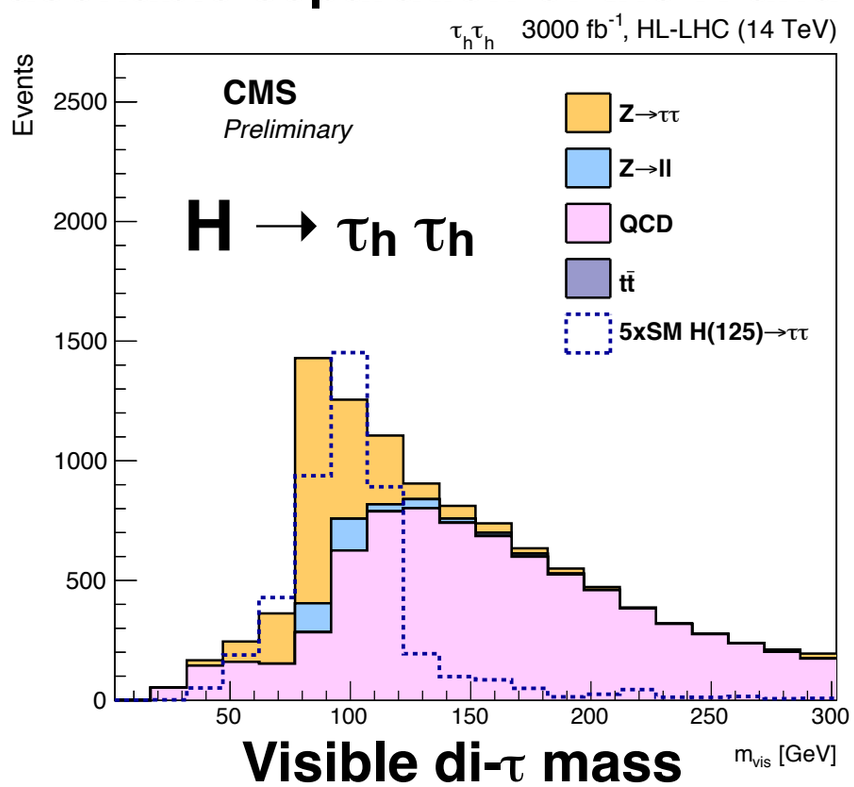
VBF H → τ τ and H → γ γ

CMS TDR-017-007

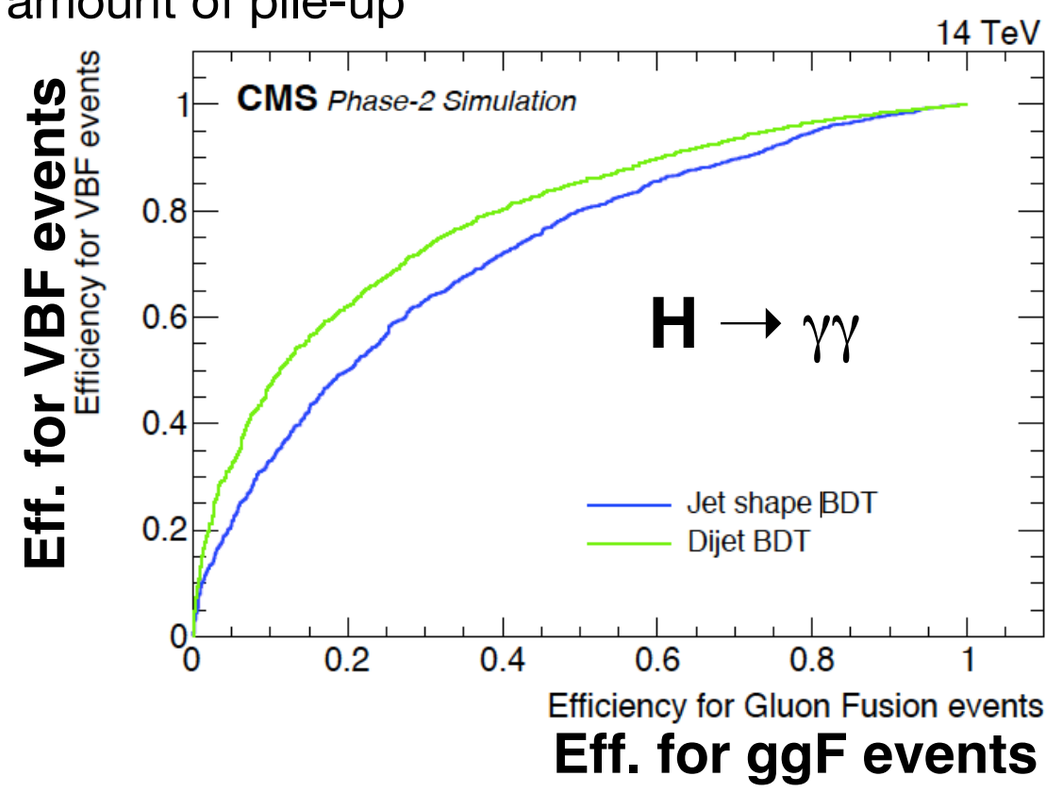
- **VBF** is of particular interest → **higher signal purity** compared to dominant ggF production mechanism
- CMS High granularity and precision timing capabilities of the High-Granularity Calorimeter (**HGCAL**)
  → **improvement in pile-up suppression**, isolation, jet shape observables and missing energy
  → **improved reconstruction** and **identification** of **forward jets** in VBF production

$\mathcal{O}$(1M) **H → ττ** events → **sensitivity to the Yukawa couplings between H and tau leptons**

→ Excellent mass resolution required to obtain **reasonable separation of the H and Z peaks**



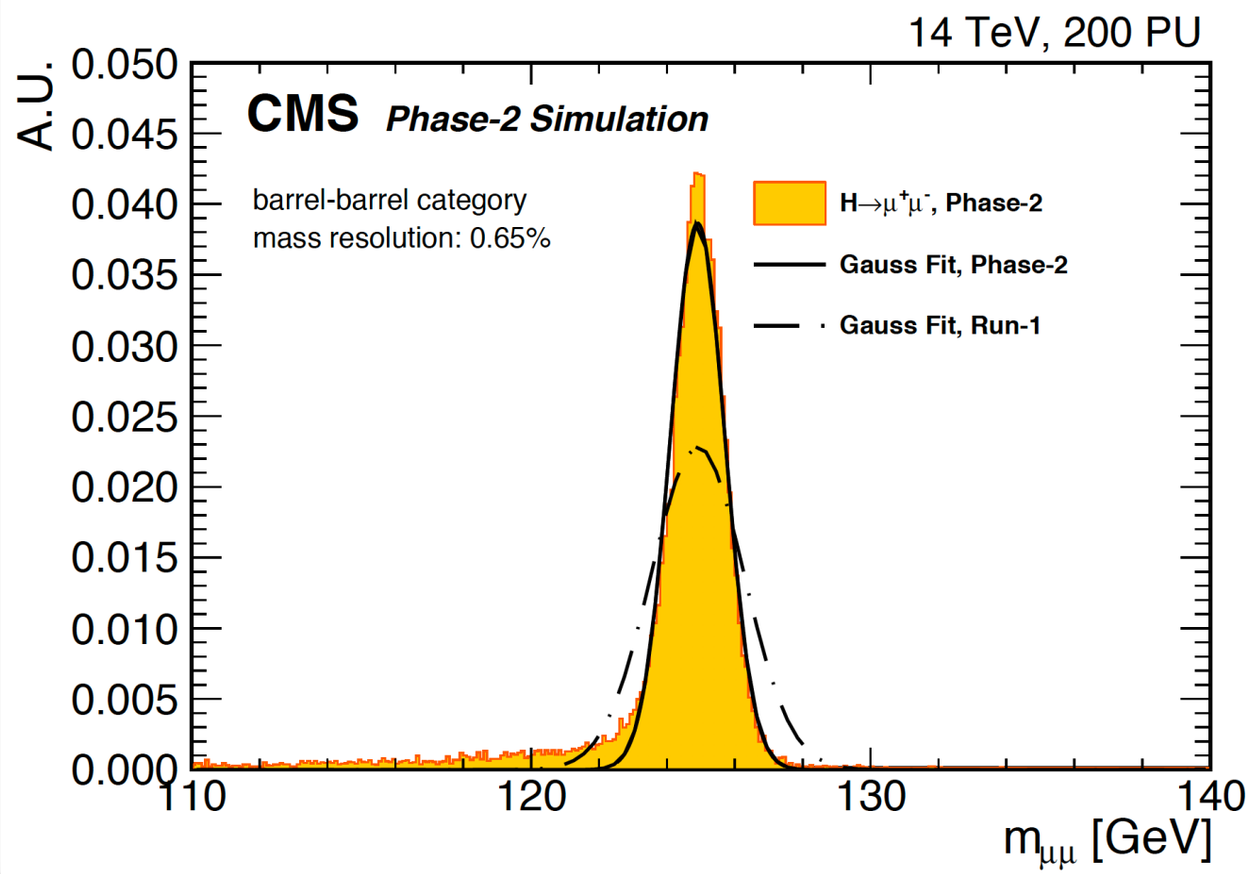
H → γγ: Analysis performed using a multivariate discriminator (**BDT**)
Discriminating power between ggF and VBF **comparable to Run-2** despite the increase in amount of pile-up



$H \rightarrow \mu\mu$

- AT HL-LHC, rare decays become accessible - BR(H→μμ)=0.022
  → Probe coupling to 2nd generation of fermions (only possible at HL-LHC)
- Upgraded tracker allows to reach a **mass resolution better than 1%**
  - Width of Gaussian fit to di-muon mass 65% lower than the Run-1 version
- Prospects for coupling measurement
  → **5% uncertainty@3000fb^{-1}**

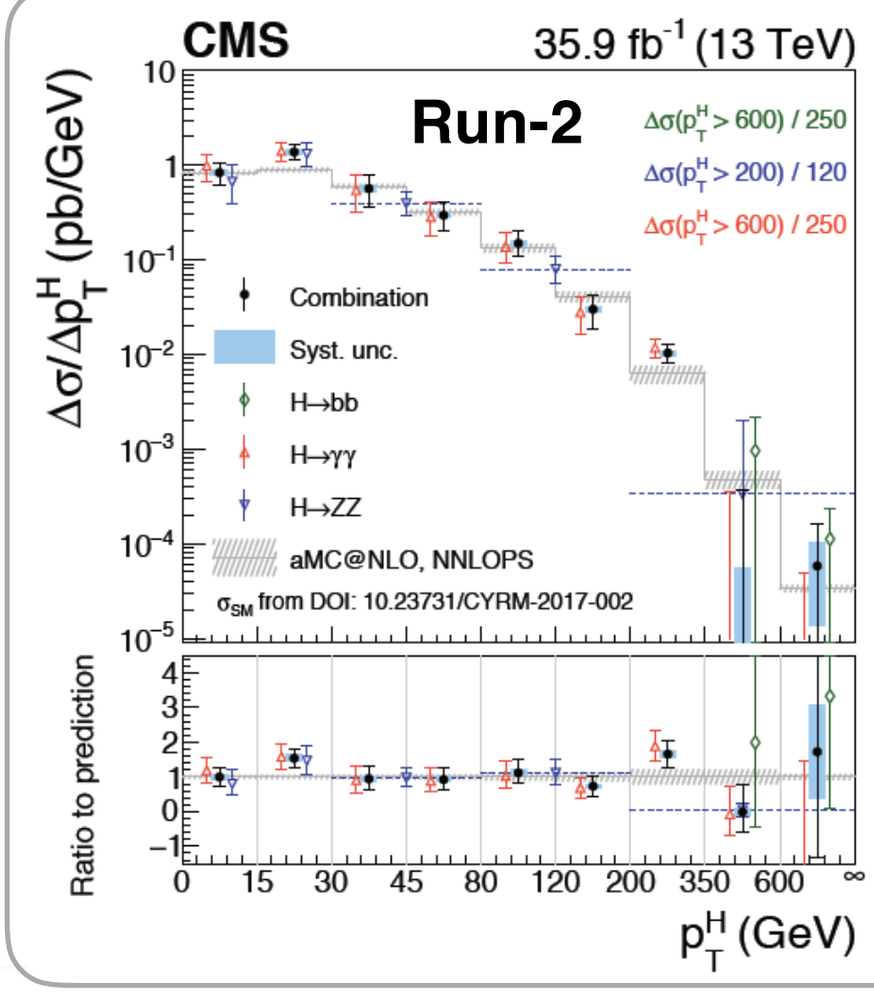
Di-muon invariant mass distribution for H→μμ decays for muons in the central region, simulated with the Phase-2 detector

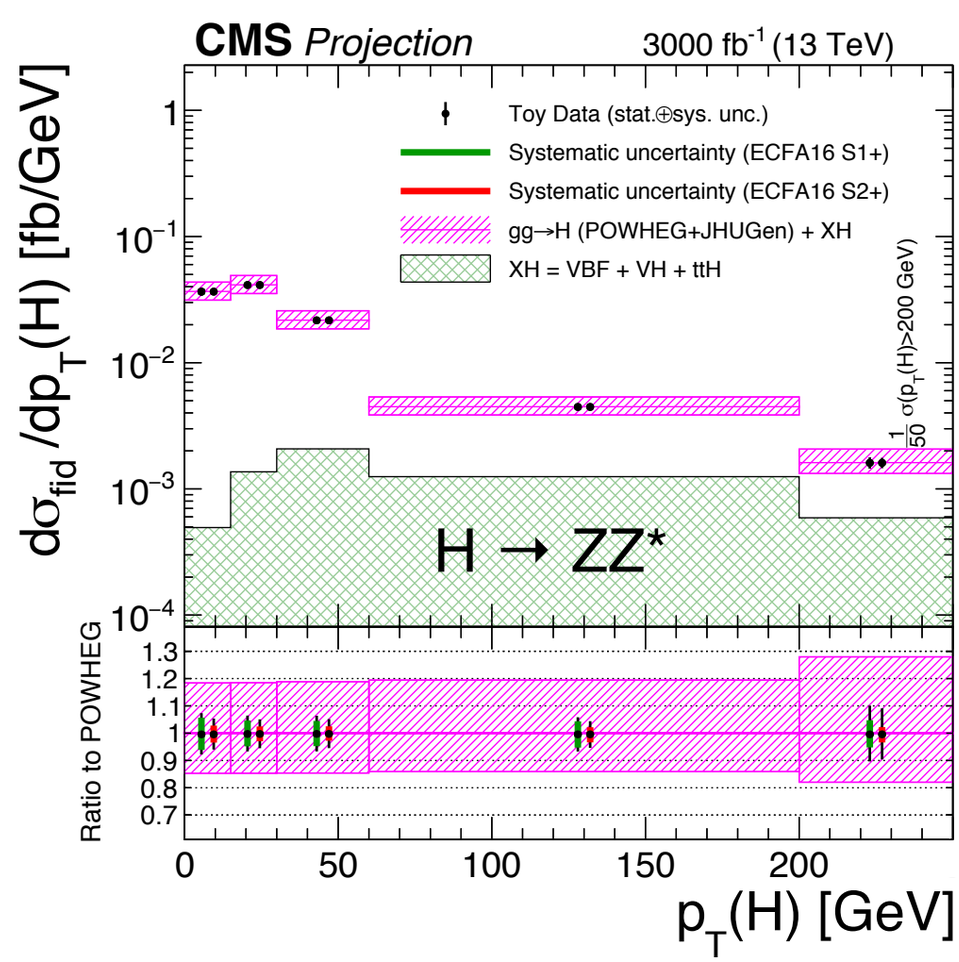


Higgs Differential Cross-Section

CMS-HIG-17-002 *CMS-PAS-FTR-16-002*

- **Higgs p_T bin uncertainty**:
  - **Run-2** (35.9 fb^{-1}) combination: **25-30%**
    See Vittorio Tavolaro's talk "Fiducial inclusive and differential Higgs boson cross sections at CMS"
  - **Projections**: **4-9%**





Projections based for H → ZZ* on 12.9 fb^{-1} 2016 data at √s = 13 TeV and for 3000 fb^{-1}

Higgs Charge-Parity Measurement

CMS-PAS-FTR-16-002

SM leading tree-level contributions

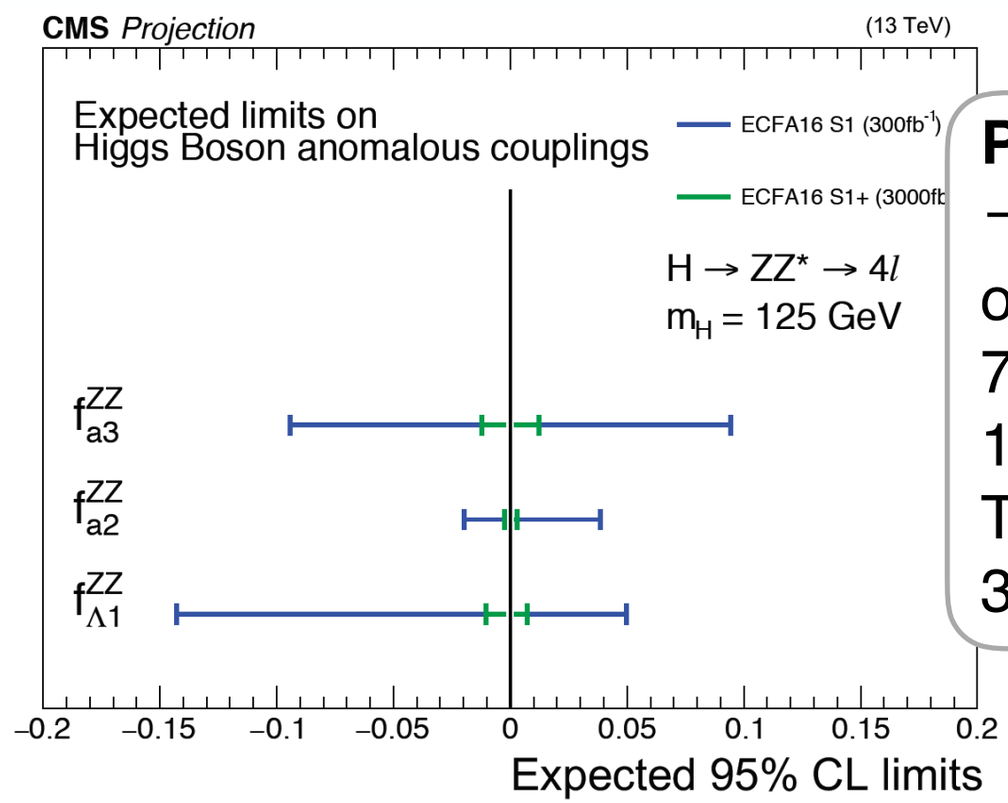
CP-odd

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{(\Lambda_1^{\mathrm{VV}})^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

higher order CP-even

- H → ZZ → 4ℓ gives sensitive test of charge-parity
- Expect to have **significant improvement (x 50 or more)** in expected limits from **new experimental techniques** introduced in Run-2
- Improvement from Run-1 to Run-2 in the 68% CL expected limit by nearly an order of magnitude comes from utilising **VH and VBF production information** (*Phys.Lett. B775 (2017) 1*)

Fraction of events for a_i operator



Projections for H → ZZ* → 4ℓ based on 5.1 fb^{-1} at √s = 7 TeV and up to 19.6 fb^{-1} at √s = 8 TeV for 300 fb^{-1} and 3000 fb^{-1}

Summary and Plans

- HL-LHC: **first Higgs factory**
- Higgs studies are central to the HL-LHC program
- Impact of new upgraded detectors under HL-LHC pile-up condition
  → Potential to reach the **percentage level in precision** on the Higgs coupling modifiers, signal strengths and differential cross-sections

- **On-going update of projections** from Run-2 results to be published in the **CERN Yellow Report** by the end of the year

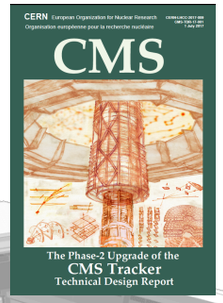
Backup

CMS Physics Program in the HL-LHC era

- Precision measurement in the (B)SM Higgs sector
  - Couplings, cross-sections, differential distributions
  - Rare & Exotic decays
  - BSM Higgs searches (extra scalars, BSM Higgs resonances, anomalous couplings)
  - Di-Higgs Production → Higgs self coupling
- Precision SM physics with High Luminosity
  - Electroweak Physics (VBF and VBS, Triboson production, Forward EW physics)
  - Strong Interactions (Photons and Jets, PDFs, Forward QCD physics)
  - Top physics (Cross section, properties, couplings, mass, FCNC)
- More exotic models become accessible thanks to the detectors upgrades at HL-LHC
  - Supersymmetry
  - Dark Matter Searches
  - Long Lived Particles, HSCP
  - Heavy Resonances, VLQ
- Flavor: Can we solve the puzzle of flavor with HL-LHC data?
  - Flavour Anomalies, CKM, Spectroscopy, …

CMS Experiment and Detector Upgrades

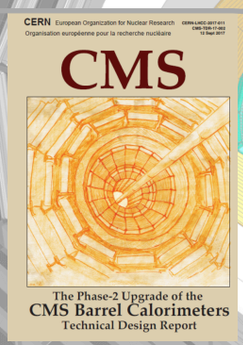
New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta < 4$



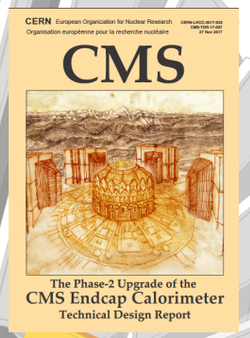
Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate muon-tagging up to $\eta \sim 3$
- CSC replace FE-Elec. for inner rings (ME 2/1, 3/1, 4/1)

Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

Barrel HCAL
- Replace HPD by SiPM
- Replace inner layers scint. tiles ?



New Endcap Calorimeter
- Radiation tolerant
- High granularity (HGCAL)



New all Al beam pipe with smaller cone angle and cyl. central pipe

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz
- New DAQ hardware

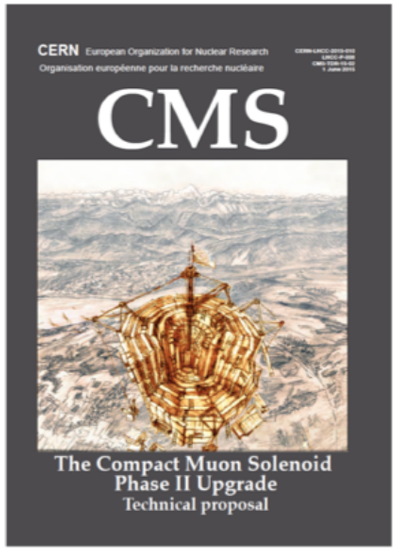
Proposal for a Timing layer
- Timing resolution ~ 10 ps
- Space resolution ~ 10's of μm

Other R&D
- Fast-timing for in-time pileup suppression

CMS Experiment and Detector Upgrades

- Series of detector upgrades needed to recover the detector performance compromised by radiation damage (especially in the endcaps) and increased pile-up
- CMS detector upgrades
  - are crucial to maximise physics potential in this harsh environment
  - will provide a wider angular coverage, timing detectors, more granular calorimeters
    → Maintain a good object reconstruction (leptons, photons, b-tagging, jets and missing E_T)
    → Pile-up mitigation is a critical element of detector designs

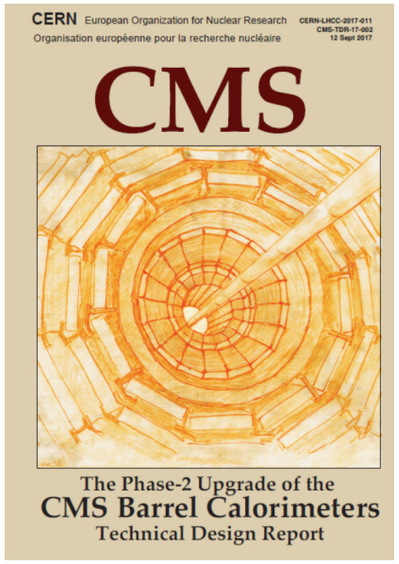
Techical proposal



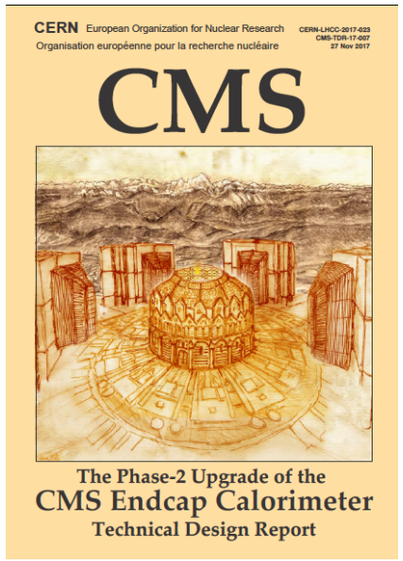
Tracker TDR

Muon TDR

Barrel Calo TDR



Endcap Calo TDR



HL-LHC … a Higgs factory

- Over 170 million Higgs bosons in 3000 fb^{-1}
- Over 1 million for each of the main production mechanisms, spread over many decay modes:
  - about 400k $H \to \gamma\gamma$
  - about 20k $H \to ZZ \to \ell\ell\ell\ell$
  - about 38k $H \to \mu\mu$
  - about 800 VBF $H \to \tau\tau$
  - about ~17k $H \to Z\gamma$

Higgs Working Group Report arXiv: 1310.8361v2o [hep-ex] 8 Jan 2014

$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

	ggF	VBF	VH	$t\bar{t}H$	Total
Cross section (pb)	49.9	4.18	2.38	0.611	57.1

→ *σ from Yellow Report 3*

Numbers of events in 3000 fb^{-1}

$H \to \gamma\gamma$	344,310	28,842	16,422	4,216	393,790
$H \to ZZ^* \to 4\ell$	17,847	1,495	851	219	20,412
$H \to WW^* \to \ell\nu\ell\nu$	1,501,647	125,789	71,622	18,387	1,717,445
$H \to \tau\tau$	9,461,040	792,528	451,248	115,846	10,820,662
$H \to b\bar{b}$	86,376,900	7,235,580	4,119,780	1,057,641	98,789,901
$H \to \mu\mu$	32,934	2,759	1,570	403	37,667
$H \to Z\gamma \to \ell\ell\gamma$	15,090	1,264	720	185	17,258
$H \to$ all	149,700,000	12,540,000	7,140,000	1,833,000	171,213,000

Strategy for projections

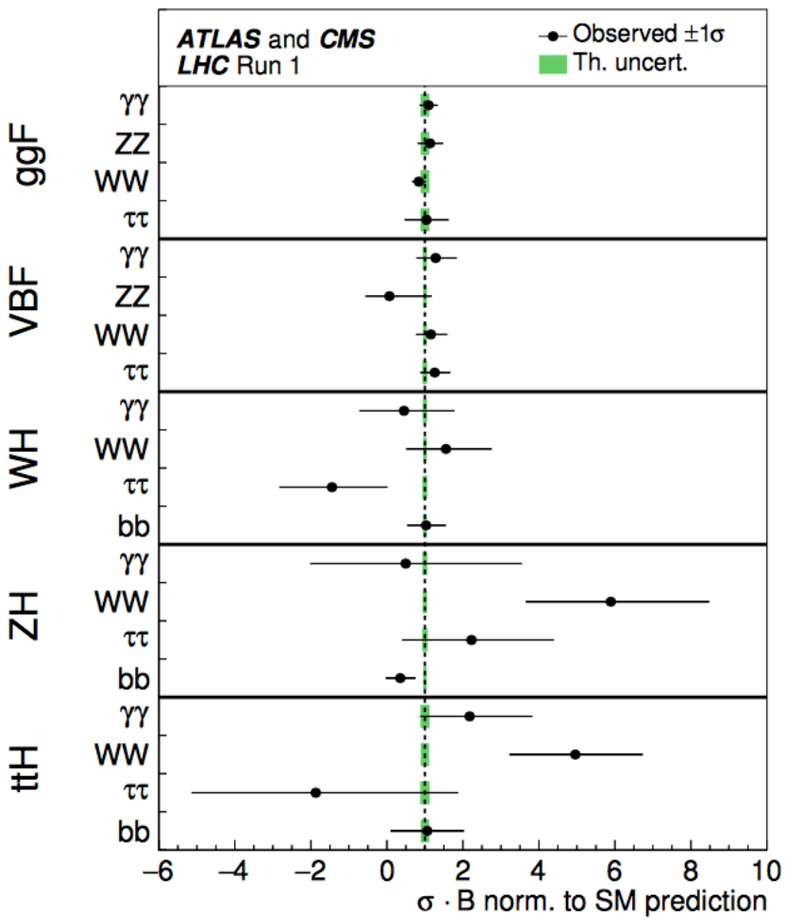
- Several scenarios assumptions made on how systematic and theoretical uncertainties will evolve and how detector upgrades will perform to compensate degradations due to high pile-up
- Several assumptions made for the estimates of systematic uncertainties at HL-LHC:
  - Pessimistic scenario [S1(+)]: Unchanged from current data analyses
    - Assume detector upgrades roughly compensate for the pile-up increase
  - Optimistic: Scaled down by $1/\sqrt{L}$
    - More data provides allows for a better control of the systematics uncertainties
- Projection Methods:
  - From Runs 1-2 at 7-13 TeV, extrapolate event yields and potentially systematic uncertainties using $\sqrt{s}$ and $1/\sqrt{L}$
  - In 14 TeV MC, smear truth particles with resolutions expected with upgraded detectors in the Phase 2 collision conditions (200 pile-up interactions per BX)

Snowmass-ECFA2016 - Extrapolation scenarios

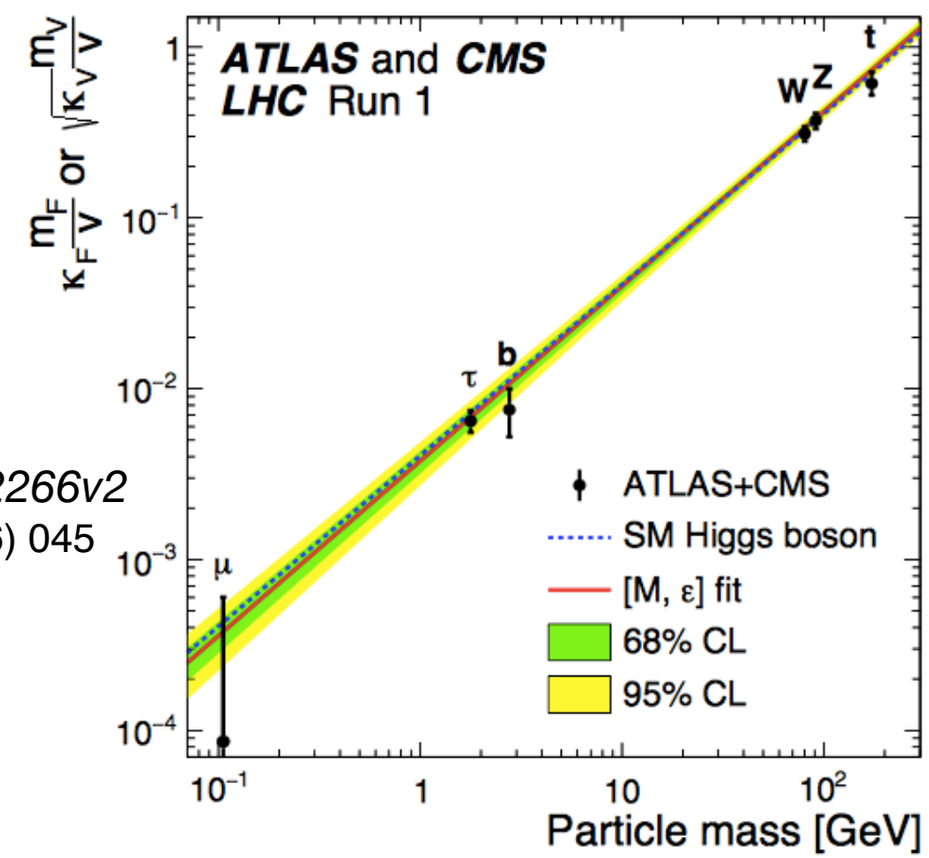
- Several assumptions made for the estimates of systematic uncertainties at HL-LHC:
  - **S1**: systematic uncertainties constant, unchanged detector performance (no upgrade considered)
  - **S1+**: includes higher PU and detector upgrades effects
  - **S2**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity (until a lower limit based on estimates of achievable accuracy with upgraded detector)
  - **S2+**: S2 +includes higher PU and detector upgrades effects

Run-1 Measurements

- Good agreement with SM expectation → SM-like Higgs boson
- No deviation with respect to SM expectation



arXiv:1606.02266v2
JHEP 08 (2016) 045



- → need to probe small deviations to narrow down New Physics
- → need higher precision measurements on signal strengths and couplings

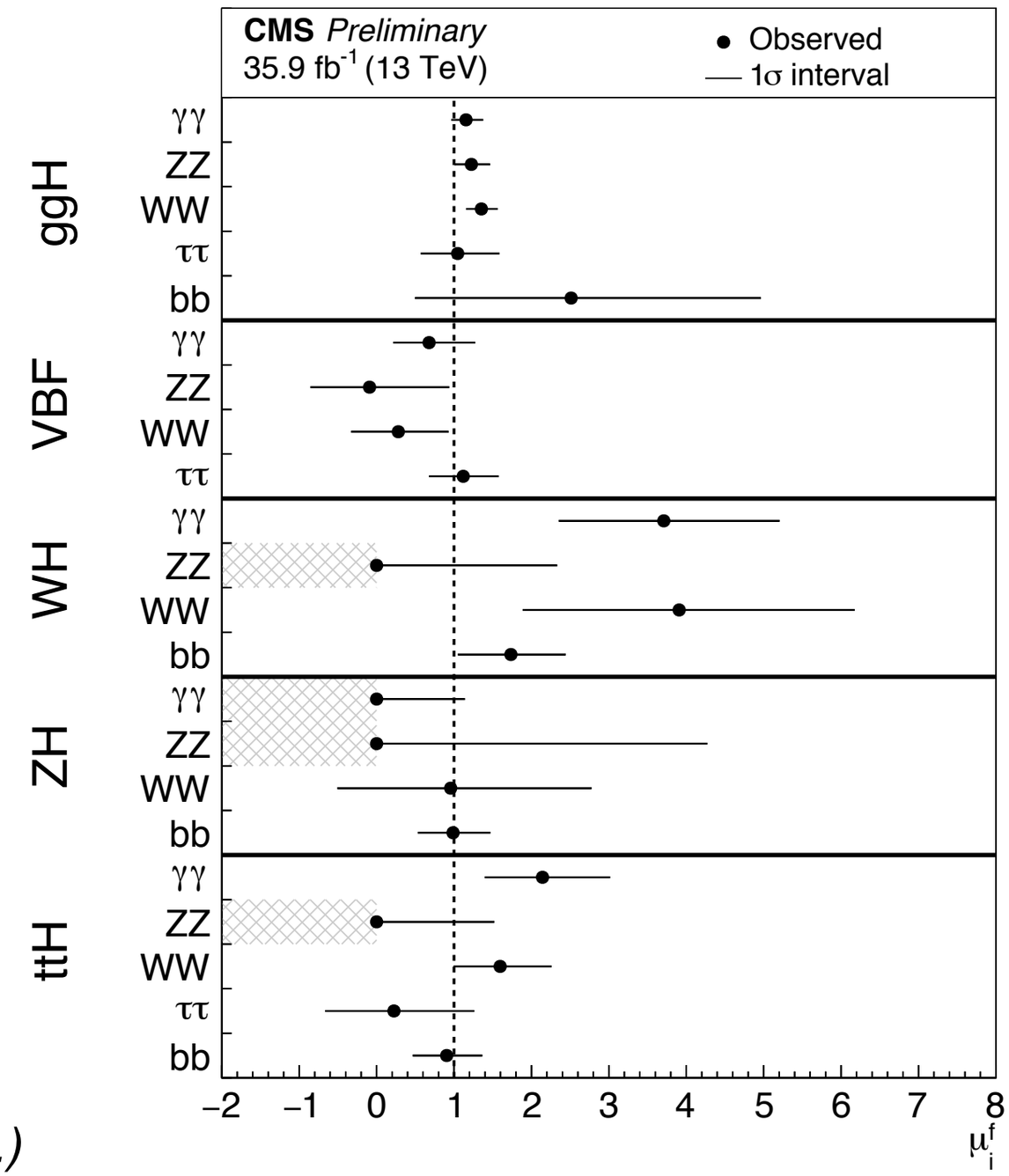
Run-2 Signal Strength Measurements

CMS-PAS-HIG-17-031

- Summary plot of the fit to the production-decay signal strengths products

$$\mu_i^f = \mu_i \cdot \mu^f$$

with 2016 data at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}



- Start to exploit new production-decay models, e.g. VH and ttH with $H \rightarrow \tau\tau$ decay channel

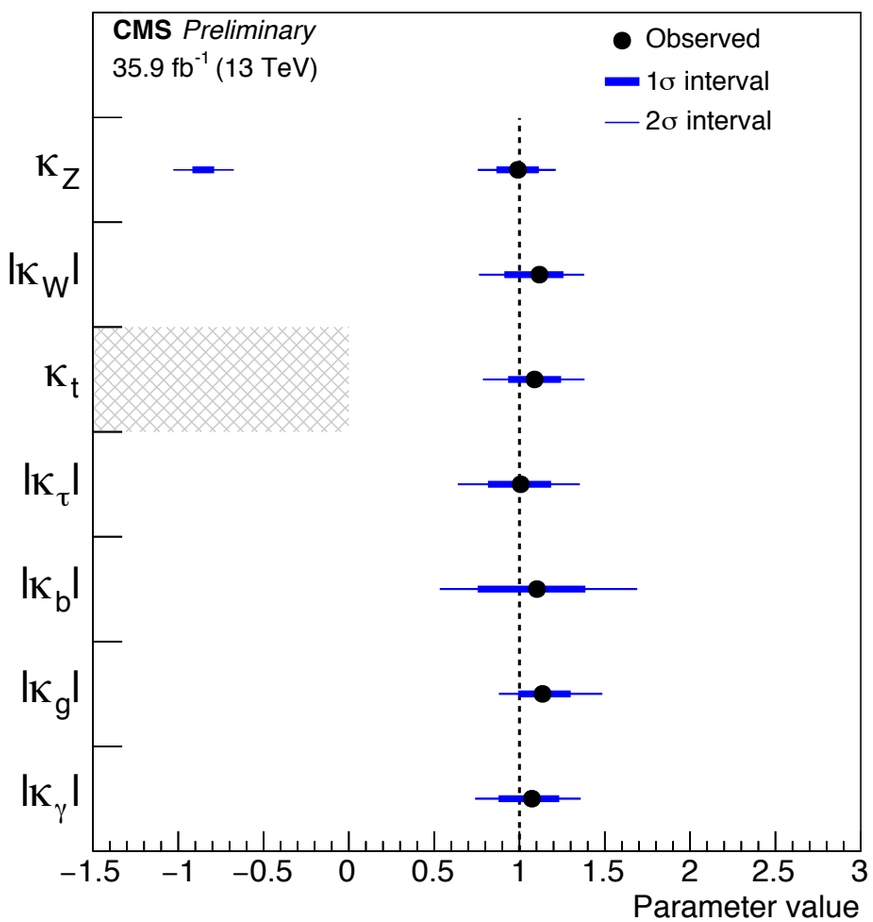
$$\mu = 1.17^{+0.06}_{-0.06}\ (stat.)\ ^{+0.06}_{-0.05}\ (theory)\ ^{+0.06}_{-0.06}\ (syst.)$$

Run-2 Coupling Modifiers Measurements

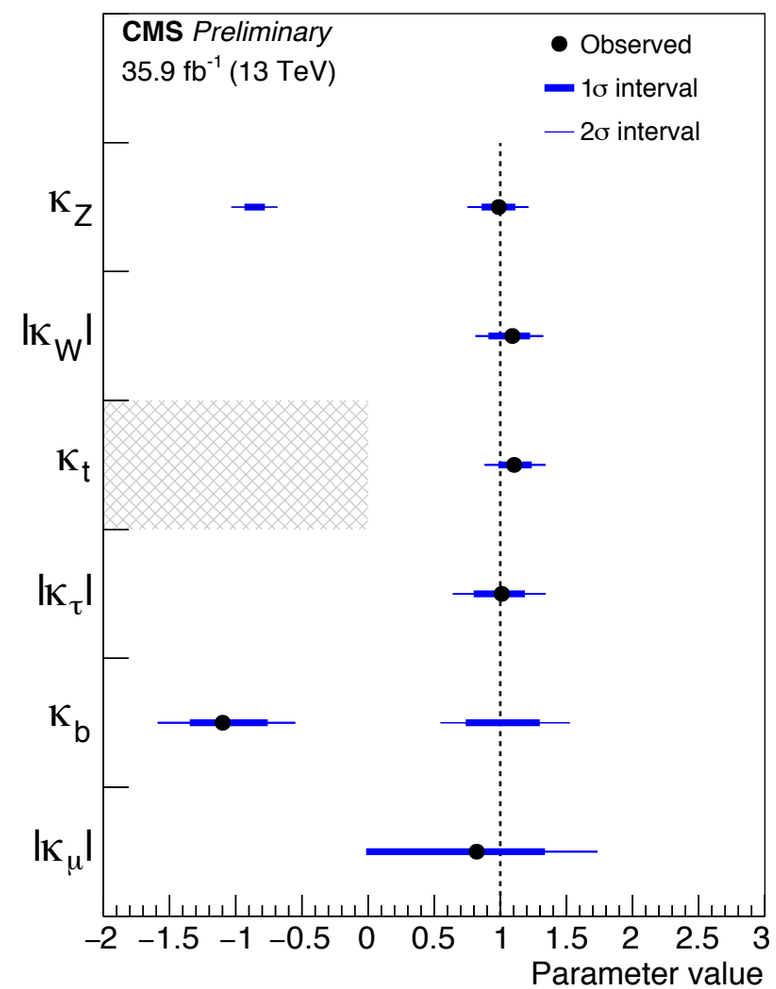
CMS-PAS-HIG-17-031

- Parameters of the κ-framework model with 2016 data at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}
- Uncertainties now reaching 10-20% level for most parameters

Fit results in the κ-framework model with $BR_{BSM} = 0$



Fit results in the κ-framework model in which the ggH and H → γγ loops are scaled with effective couplings



Run-2 Signal Strength Measurements

- Best-fit values and 1σ uncertainties for the parameters of the model with one signal strength parameter for each production and decay mode combination
- Remarkably, some of these already highly impacted by systematics
- And this is for just one year of Run-2 data, with one experiment

$$\mu_i^f = \mu_i \cdot \mu^f$$

Production process	Decay mode														
	ggH			VBF			WH			ZH			ttH		
	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.
$H \to bb$	$2.51^{+2.44}_{-2.01}$	$^{+1.96}_{-1.92}$	$^{+1.46}_{-0.59}$	–			$1.73^{+0.70}_{-0.68}$	$^{+0.53}_{-0.51}$	$^{+0.46}_{-0.44}$	$0.99^{+0.48}_{-0.45}$	$^{+0.41}_{-0.40}$	$^{+0.23}_{-0.20}$	$0.91^{+0.45}_{-0.43}$	$^{+0.24}_{-0.24}$	$^{+0.38}_{-0.36}$
	$(^{+2.06}_{-1.86})$	$(^{+1.86}_{-1.83})$	$(^{+0.89}_{-0.33})$	–				$(^{+0.69}_{-0.67})$	$(^{+0.53}_{-0.51})$	$(^{+0.45}_{-0.44})$	$(^{+0.46}_{-0.44})$	$(^{+0.40}_{-0.39})$	$(^{+0.23}_{-0.20})$	$(^{+0.44}_{-0.42})$	$(^{+0.24}_{-0.23})$	$(^{+0.37}_{-0.35})$
$H \to \tau\tau$	$1.05^{+0.53}_{-0.47}$	$^{+0.25}_{-0.25}$	$^{+0.47}_{-0.40}$	$1.12^{+0.45}_{-0.43}$	$^{+0.37}_{-0.35}$	$^{+0.25}_{-0.25}$	–			–			$0.22^{+1.03}_{-0.88}$	$^{+0.80}_{-0.71}$	$^{+0.65}_{-0.52}$
	$(^{+0.45}_{-0.41})$	$(^{+0.23}_{-0.23})$	$(^{+0.38}_{-0.34})$	$(^{+0.45}_{-0.43})$	$(^{+0.37}_{-0.35})$	$(^{+0.25}_{-0.24})$	–			–			$(^{+0.98}_{-0.87})$	$(^{+0.80}_{-0.73})$	$(^{+0.56}_{-0.47})$
$H \to WW$	$1.35^{+0.20}_{-0.19}$	$^{+0.12}_{-0.12}$	$^{+0.17}_{-0.15}$	$0.28^{+0.64}_{-0.60}$	$^{+0.58}_{-0.53}$	$^{+0.28}_{-0.28}$	$3.91^{+2.26}_{-2.01}$	$^{+1.89}_{-1.72}$	$^{+1.24}_{-1.05}$	$0.96^{+1.81}_{-1.46}$	$^{+1.74}_{-1.44}$	$^{+0.51}_{-0.22}$	$1.60^{+0.66}_{-0.59}$	$^{+0.40}_{-0.39}$	$^{+0.52}_{-0.45}$
	$(^{+0.17}_{-0.16})$	$(^{+0.10}_{-0.10})$	$(^{+0.13}_{-0.12})$	$(^{+0.63}_{-0.58})$	$(^{+0.57}_{-0.53})$	$(^{+0.26}_{-0.25})$	$(^{+1.47}_{-1.19})$	$(^{+1.32}_{-1.06})$	$(^{+0.64}_{-0.54})$	$(^{+1.67}_{-1.37})$	$(^{+1.61}_{-1.35})$	$(^{+0.45}_{-0.20})$	$(^{+0.56}_{-0.53})$	$(^{+0.38}_{-0.38})$	$(^{+0.41}_{-0.38})$
$H \to ZZ$	$1.22^{+0.24}_{-0.21}$	$^{+0.20}_{-0.19}$	$^{+0.12}_{-0.10}$	$-0.09^{+1.02}_{-0.76}$	$^{+1.00}_{-0.72}$	$^{+0.21}_{-0.22}$	$0.00^{+2.32}_{+0.00}$	$^{+2.31}_{-0.00}$	$^{+0.28}_{-0.00}$	$0.00^{+4.26}_{+0.00}$	$^{+4.19}_{-0.00}$	$^{+0.81}_{-0.00}$	$0.00^{+1.51}_{+0.00}$	$^{+1.48}_{-0.00}$	$^{+0.31}_{-0.00}$
	$(^{+0.22}_{-0.20})$	$(^{+0.20}_{-0.19})$	$(^{+0.10}_{-0.07})$	$(^{+1.27}_{-0.99})$	$(^{+1.25}_{-0.97})$	$(^{+0.24}_{-0.21})$	$(^{+4.45}_{-0.99})$	$(^{+4.41}_{-0.99})$	$(^{+0.57}_{-0.00})$	$(^{+7.58}_{-0.99})$	$(^{+7.46}_{-0.99})$	$(^{+1.33}_{-0.00})$	$(^{+2.95}_{-0.99})$	$(^{+2.89}_{-0.99})$	$(^{+0.59}_{-0.00})$
$H \to \gamma\gamma$	$1.15^{+0.21}_{-0.18}$	$^{+0.17}_{-0.15}$	$^{+0.13}_{-0.10}$	$0.68^{+0.59}_{-0.45}$	$^{+0.49}_{-0.42}$	$^{+0.32}_{-0.18}$	$3.71^{+1.49}_{-1.35}$	$^{+1.45}_{-1.33}$	$^{+0.35}_{-0.23}$	$0.00^{+1.13}_{+0.00}$	$^{+1.13}_{-0.00}$	$^{+0.09}_{-0.00}$	$2.14^{+0.87}_{-0.74}$	$^{+0.81}_{-0.72}$	$^{+0.31}_{-0.14}$
	$(^{+0.17}_{-0.16})$	$(^{+0.14}_{-0.14})$	$(^{+0.11}_{-0.08})$	$(^{+0.59}_{-0.48})$	$(^{+0.48}_{-0.43})$	$(^{+0.34}_{-0.21})$	$(^{+1.29}_{-1.16})$	$(^{+1.28}_{-1.16})$	$(^{+0.13}_{-0.06})$	$(^{+2.52}_{-1.04})$	$(^{+2.50}_{-1.04})$	$(^{+0.24}_{-0.00})$	$(^{+0.72}_{-0.62})$	$(^{+0.71}_{-0.62})$	$(^{+0.15}_{-0.06})$

Run-2 Signal Strengths

$$\mu_i^f = \mu_i \cdot \mu^f$$

Production process	Decay mode																	
	ggH			VBF			WH			ZH			ttH		
	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.	Best fit value	Uncertainty Stat.	Uncertainty Syst.
$H \to bb$	2.51 $^{+}_{-}$										$^{+0.41}_{-0.40}$	$^{+0.23}_{-0.20}$	0.91	$^{+0.45}_{-0.43}$	$^{+0.24}_{-0.24}$ $^{+0.38}_{-0.36}$
	$(^{+}_{-}$										$(^{+0.40}_{-0.39})$	$(^{+0.23}_{-0.20})$		$(^{+0.44}_{-0.42})$	$(^{+0.24}_{-0.23})$ $(^{+0.37}_{-0.35})$
$H \to \tau\tau$	1.05 $^{+}_{-}$										–		0.22	$^{+1.03}_{-0.88}$	$^{+0.80}_{-0.71}$ $^{+0.65}_{-0.52}$
	$(^{+}_{-}$										–			$(^{+0.98}_{-0.87})$	$(^{+0.80}_{-0.73})$ $(^{+0.56}_{-0.47})$
$H \to WW$	1.35 $^{+}_{-}$										$^{+1.74}_{-1.44}$	$^{+0.51}_{-0.22}$	1.60	$^{+0.66}_{-0.59}$	$^{+0.40}_{-0.39}$ $^{+0.52}_{-0.45}$
	$(^{+}_{-}$										$(^{+1.61}_{-1.35})$	$(^{+0.45}_{-0.20})$		$(^{+0.56}_{-0.53})$	$(^{+0.38}_{-0.38})$ $(^{+0.41}_{-0.38})$
$H \to ZZ$	1.22 $^{+}_{-}$										$^{+4.19}_{-0.00}$	$^{+0.81}_{-0.00}$	0.00	$^{+1.51}_{+0.00}$	$^{+1.48}_{-0.00}$ $^{+0.31}_{-0.00}$
	$(^{+0.22}_{-0.20})$	$(^{+0.20}_{-0.19})$	$(^{+0.10}_{-0.07})$	$(^{+1.27}_{-0.99})$	$(^{+1.25}_{-0.97})$	$(^{+0.24}_{-0.21})$	$(^{+4.45}_{-0.99})$	$(^{+4.41}_{-0.99})$	$(^{+0.57}_{-0.00})$	$(^{+7.58}_{-0.99})$	$(^{+7.46}_{-0.99})$	$(^{+1.33}_{-0.00})$		$(^{+2.95}_{-0.99})$	$(^{+2.89}_{-0.99})$ $(^{+0.59}_{-0.00})$
$H \to \gamma\gamma$	1.15	$^{+0.21}_{-0.18}$	$^{+0.17}_{-0.15}$ $^{+0.13}_{-0.10}$	0.68	$^{+0.59}_{-0.45}$	$^{+0.49}_{-0.42}$ $^{+0.32}_{-0.18}$	3.71	$^{+1.49}_{-1.35}$	$^{+1.45}_{-1.33}$ $^{+0.35}_{-0.23}$	0.00	$^{+1.13}_{+0.00}$	$^{+1.13}_{-0.00}$ $^{+0.09}_{-0.00}$	2.14	$^{+0.87}_{-0.74}$	$^{+0.81}_{-0.72}$ $^{+0.31}_{-0.14}$
		$(^{+0.17}_{-0.16})$	$(^{+0.14}_{-0.14})$ $(^{+0.11}_{-0.08})$		$(^{+0.59}_{-0.48})$	$(^{+0.48}_{-0.43})$ $(^{+0.34}_{-0.21})$		$(^{+1.29}_{-1.16})$	$(^{+1.28}_{-1.16})$ $(^{+0.13}_{-0.06})$		$(^{+2.52}_{-1.04})$	$(^{+2.50}_{-1.04})$ $(^{+0.24}_{-0.00})$		$(^{+0.72}_{-0.62})$	$(^{+0.71}_{-0.62})$ $(^{+0.15}_{-0.06})$

	ttH		
	Best fit value	Uncertainty Stat.	Uncertainty Syst.
$H \to bb$	0.91	+ 0.45 - 0.43	+ 0.24 - 0.24 + 0.38 - 0.36

Run-2 κ Model Couplings Modifiers

- Best-fit values and 1σ uncertainties for the κ model parameters in which the loop processes are resolved

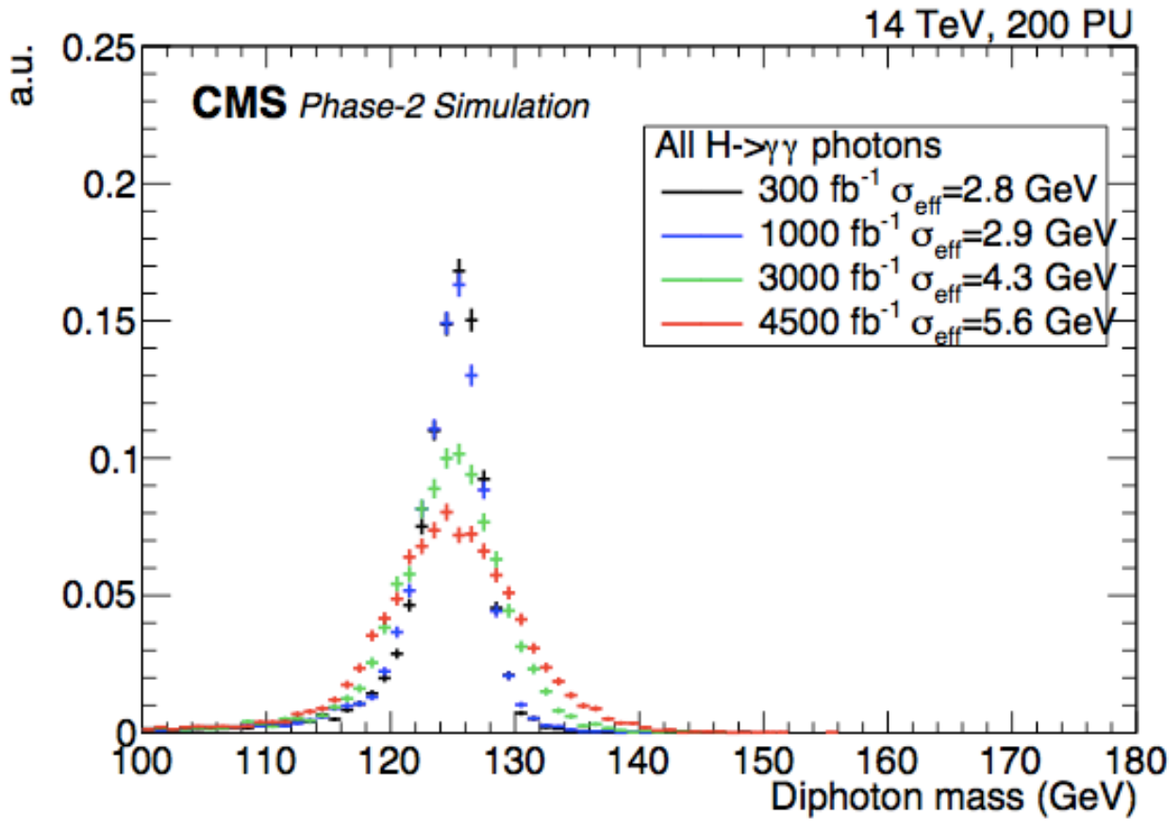
Parameter																							
κ_W				κ_Z				κ_t				κ_b				κ_τ				κ_μ			
Best fit value	Uncertainty Stat.		Uncertainty Syst.	Best fit value	Uncertainty Stat.		Uncertainty Syst.	Best fit value	Uncertainty Stat.		Uncertainty Syst.	Best fit value	Uncertainty Stat.		Uncertainty Syst.	Best fit value	Uncertainty Stat.		Uncertainty Syst.	Best fit value	Uncertainty Stat.		Uncertainty Syst.
1.09	$^{+0.12}_{-0.17}$	$^{+0.08}_{-0.16}$	$^{+0.09}_{-0.04}$	0.99	$^{+0.11}_{-0.12}$	$^{+0.09}_{-0.10}$	$^{+0.07}_{-0.07}$	1.11	$^{+0.12}_{-0.11}$	$^{+0.08}_{-0.07}$	$^{+0.09}_{-0.08}$	−1.10	$^{+0.33}_{-0.24}$	$^{+0.29}_{-0.16}$	$^{+0.15}_{-0.17}$	1.01	$^{+0.16}_{-0.20}$	$^{+0.11}_{-0.17}$	$^{+0.12}_{-0.10}$	0.82	$^{+0.50}_{-0.82}$	$^{+0.49}_{-0.82}$	$^{+0.11}_{-0.00}$
	$(^{+0.11}_{-0.10})$	$(^{+0.08}_{-0.08})$	$(^{+0.06}_{-0.06})$		$(^{+0.11}_{-0.11})$	$(^{+0.09}_{-0.09})$	$(^{+0.06}_{-0.06})$		$(^{+0.11}_{-0.12})$	$(^{+0.07}_{-0.08})$	$(^{+0.09}_{-0.09})$		$(^{+0.23}_{-0.22})$	$(^{+0.16}_{-0.15})$	$(^{+0.16}_{-0.16})$		$(^{+0.17}_{-0.15})$	$(^{+0.12}_{-0.10})$	$(^{+0.12}_{-0.11})$		$(^{+0.45}_{-1.01})$	$(^{+0.44}_{-1.00})$	$(^{+0.07}_{-0.11})$

H → γγ

CMS TDR-017-002

- With an increasing number of pile-up events, the di-photon mass resolution is mostly driven by photon energy and vertexing resolutions

- CMS: The di-Photon mass is shown for a pile-up of 200 and for different radiation ageing scenarios of the barrel calorimeter

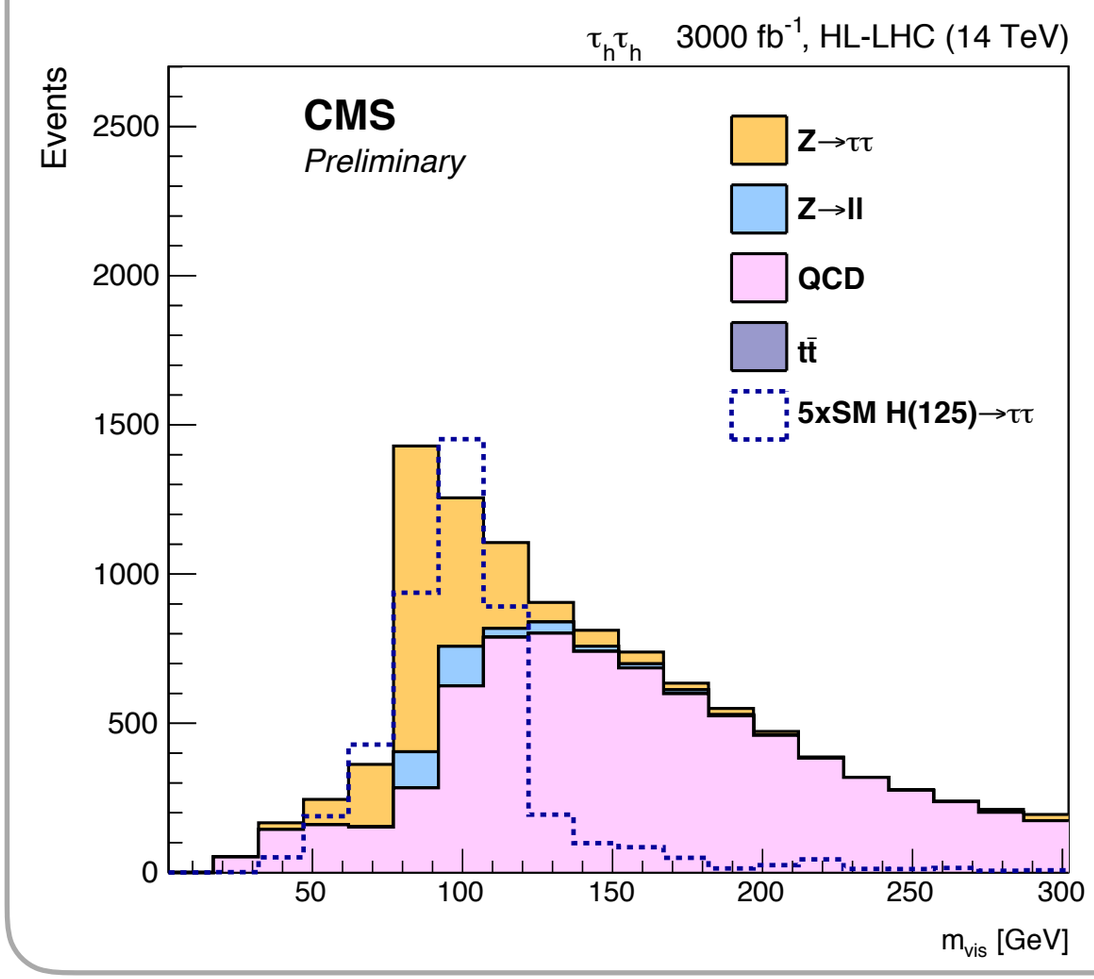


VBF H → ττ

CMS TDR-017-007

- VBF production mode is of particular interest → **higher signal purity** compared to dominant ggF production mechanism
- $\mathcal{O}$(1M) H → ττ events produced → **sensitivity to the Yukawa couplings between the Higgs boson and the tau leptons**
- → Excellent mass resolution required to obtain reasonable separation of the H and Z peaks
- **Mass resolution at HL-LHC almost the same as in Run-2**

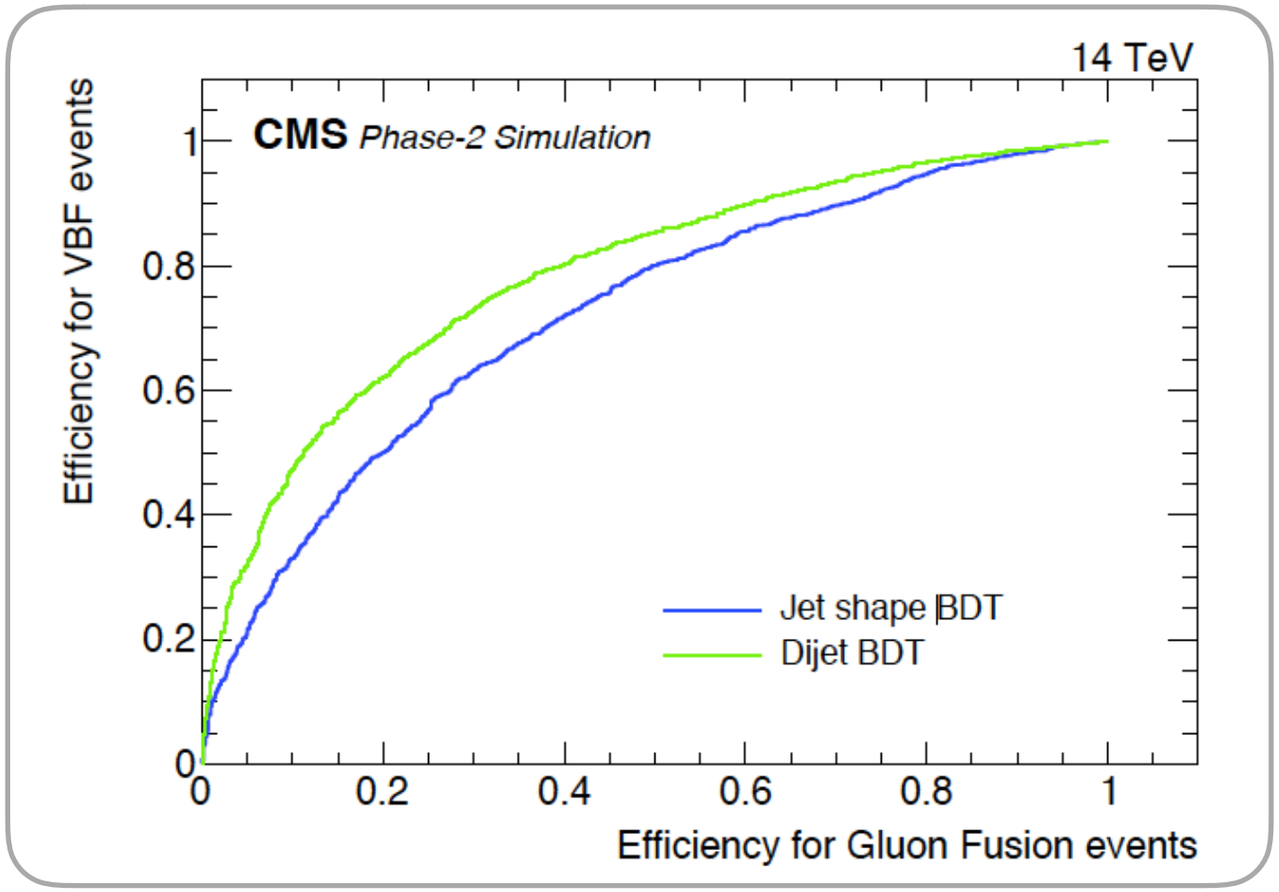
Visible di-τ mass in the fully hadronic channel after requiring a large opening angle in η between the two jets Δη(jet1, jet2) > 4.5



VBF H → γ γ

CMS TDR-017-007

- CMS High granularity and precision timing capabilities of the High-Granularity Calorimeter (**HGCAL**)
  → **improvement in pile-up suppression**, isolation, jet shape observables and missing energy
  → **improved reconstruction** and **identification** of f**orward jets** in VBF production



- Analysis performed using a multivariate discriminator (BDT)
- **Discriminating power** between ggH and VBF **comparable to Run-2** despite the increase in amount of pile-up

Higgs Differential Cross-Section

- Differential cross sections provide an interesting portal to a number of physical observables
  - The shape can be tested vs SM expectation: Small variation of the couplings can lead to significant shape distortions
- Higgs transverse momentum p_T: Sensitivity to modifications of effective Higgs Yukawa couplings at low p_T and to finite top mass effects at high p_T
- Jet multiplicity and first jet p_T → New physics in the loop, sensitivity at high p_T
- Higgs Rapidity $|\eta|$: Theory distribution mostly determined by the gluon PDF - possible test