CMS Outlook for Higgs Physics in Run 2 and Beyond

Higgs Hunting 2016
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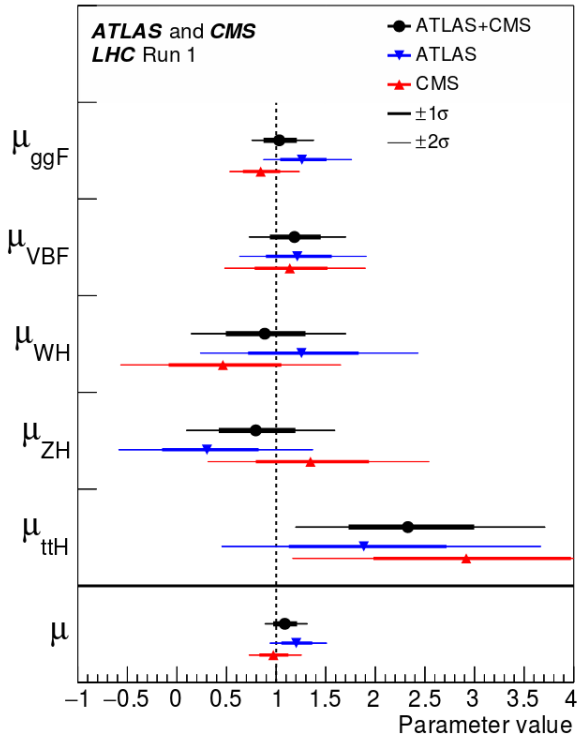
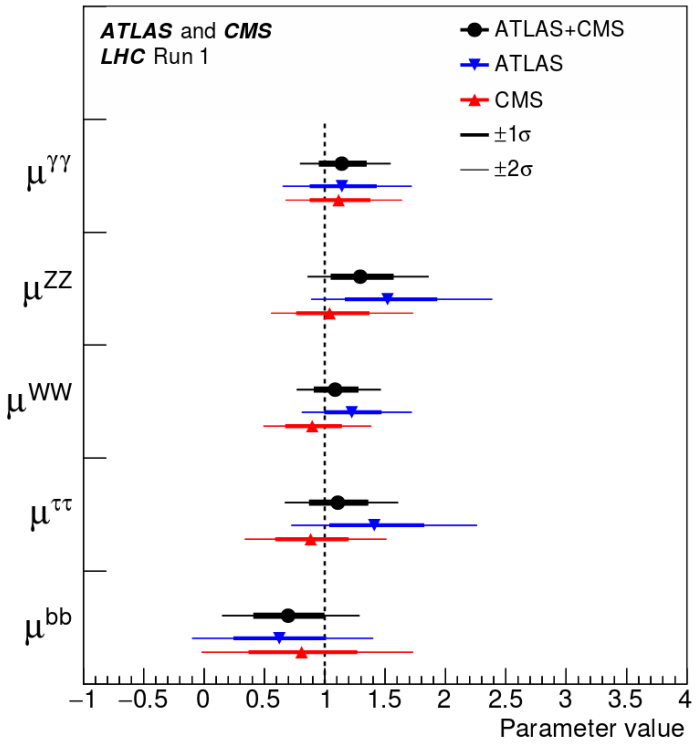
On Behalf of the CMS Collaboration

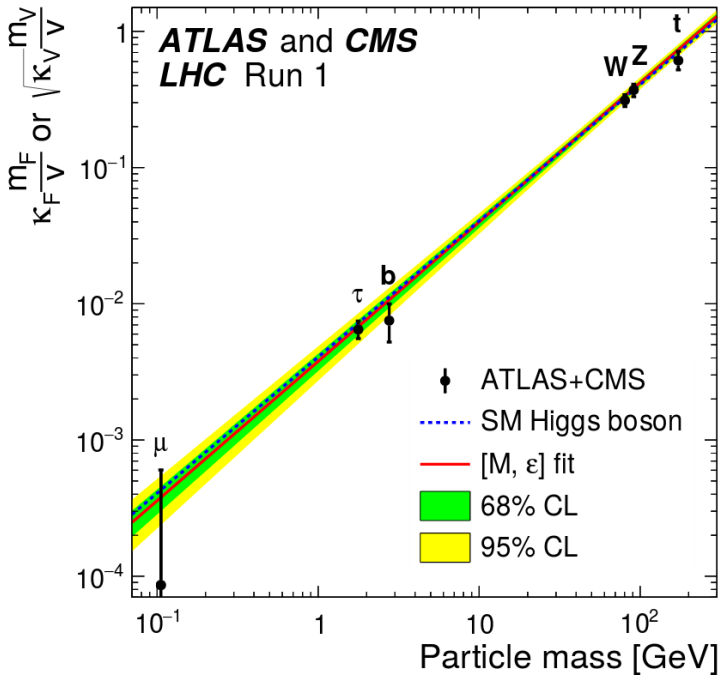
Introduction:

What's next for Higgs Physics?

- The 125 GeV Higgs boson has been discovered (7+8) TeV) and rediscovered (13 TeV)
- There are some deviations, but well within the current uncertainties
  - ➔ No *striking* discrepancies from the SM have been observed so far



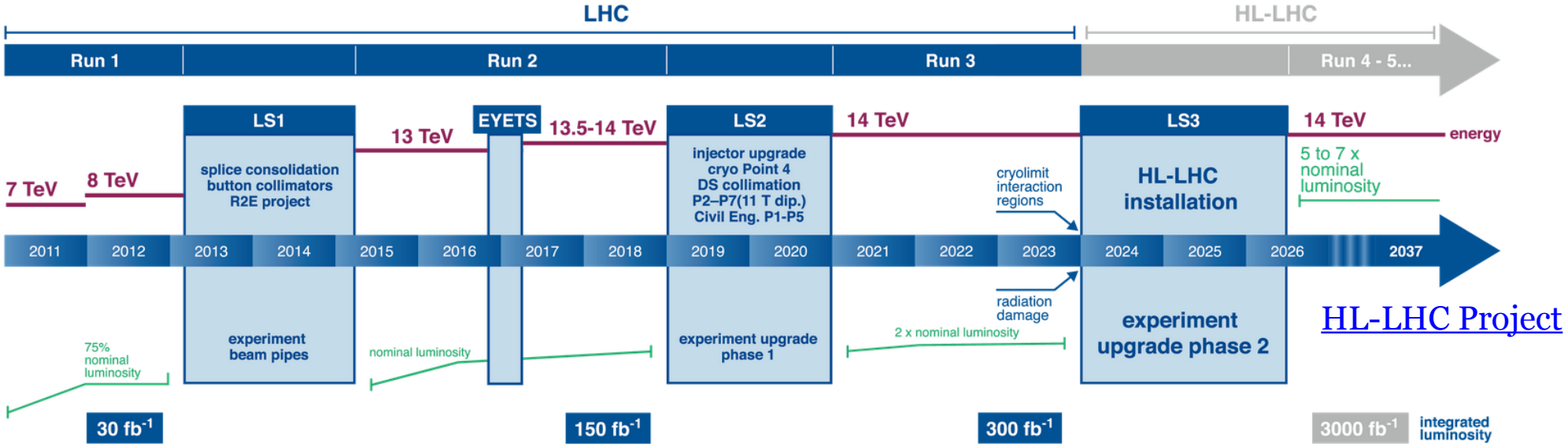


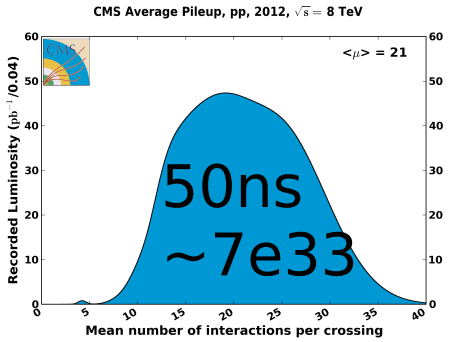


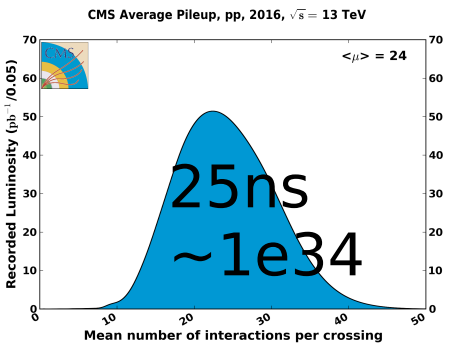
- The LHC experiments must continue to test the SM predictions for the Higgs sector
  - ➔ Increase the precision of the measurements
  - ➔ Search for rare and BSM signatures

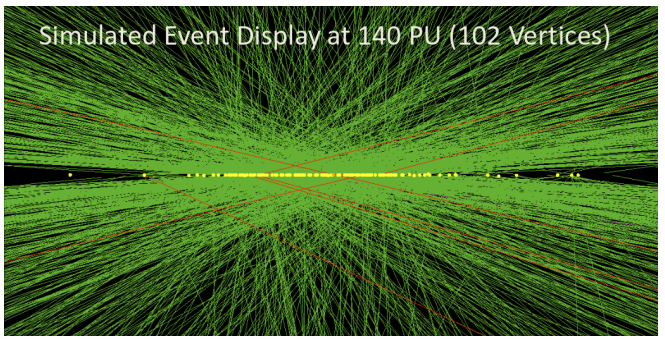
LHC Plans and Schedule

- In order to advance the Higgs program, we need more collision data
- Experiments need to evolve and be ready for the harsher conditions
  - ➔ Phase-1 upgrades: completed or ongoing to last until the end of Run 3
    - Maintain or improve Run 1 performance at L=1.4e34 and higher pileup
  - ➔ Phase-2 upgrades: concluding R&D, finalizing project details for HL-LHC
    - Replace detectors due to radiation damage, handle higher pileup



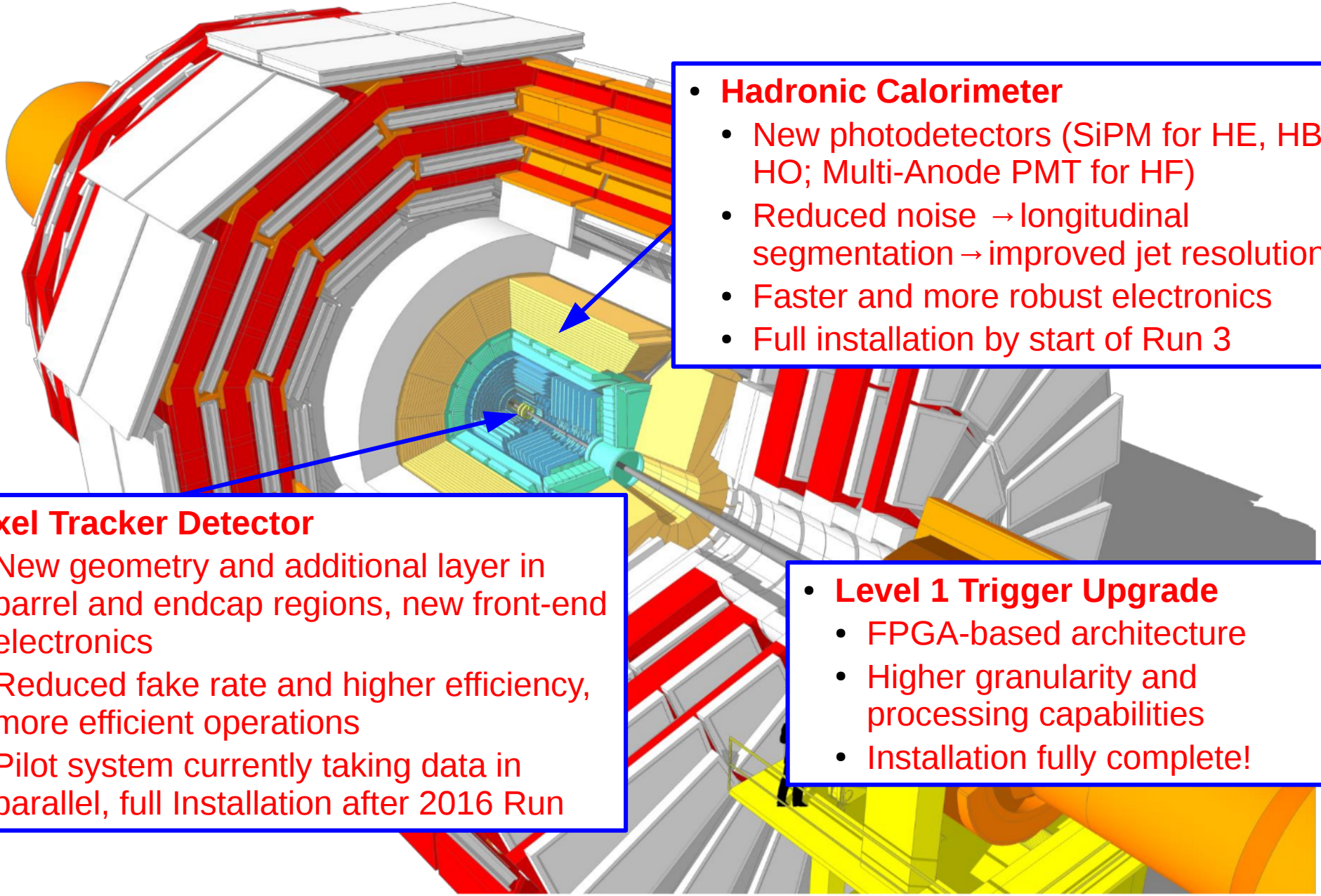






CMS Upgrades for Run 2

CMS-UG-TP-1



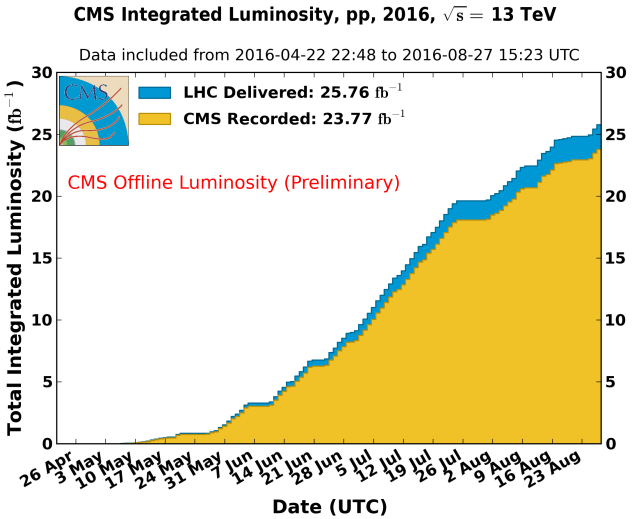
- **Hadronic Calorimeter**
  - New photodetectors (SiPM for HE, HB, HO; Multi-Anode PMT for HF)
  - Reduced noise →longitudinal segmentation→improved jet resolution
  - Faster and more robust electronics
  - Full installation by start of Run 3

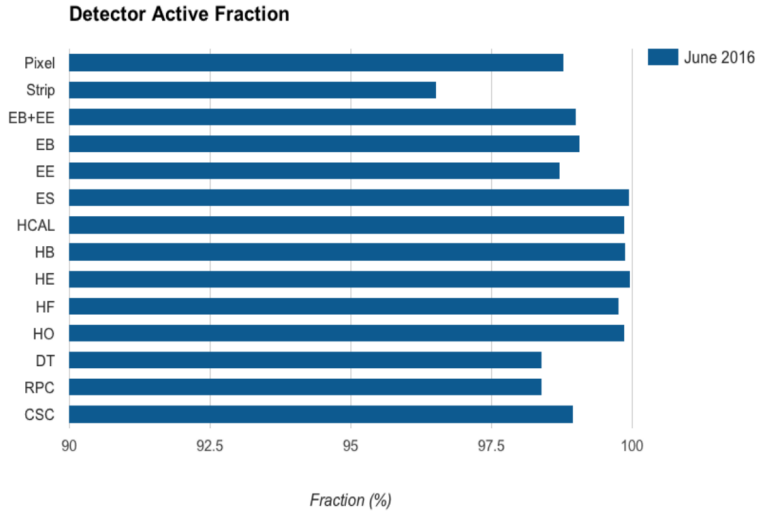
- **Pixel Tracker Detector**
  - New geometry and additional layer in barrel and endcap regions, new front-end electronics
  - Reduced fake rate and higher efficiency, more efficient operations
  - Pilot system currently taking data in parallel, full Installation after 2016 Run

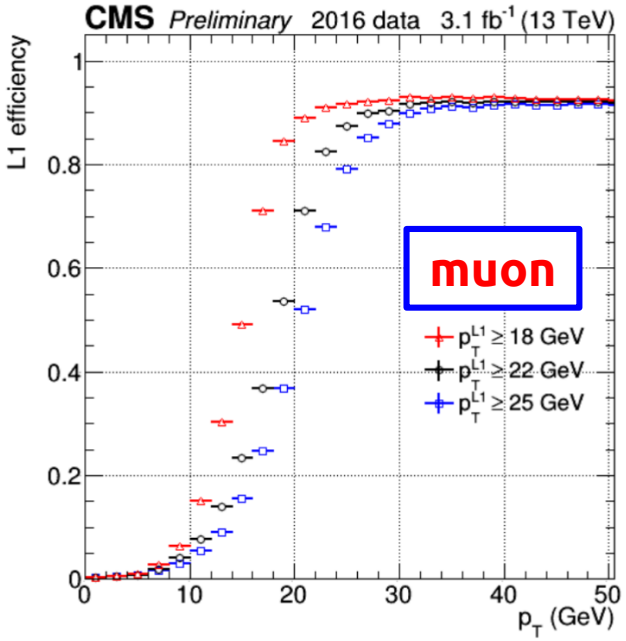
- **Level 1 Trigger Upgrade**
  - FPGA-based architecture
  - Higher granularity and processing capabilities
  - Installation fully complete!

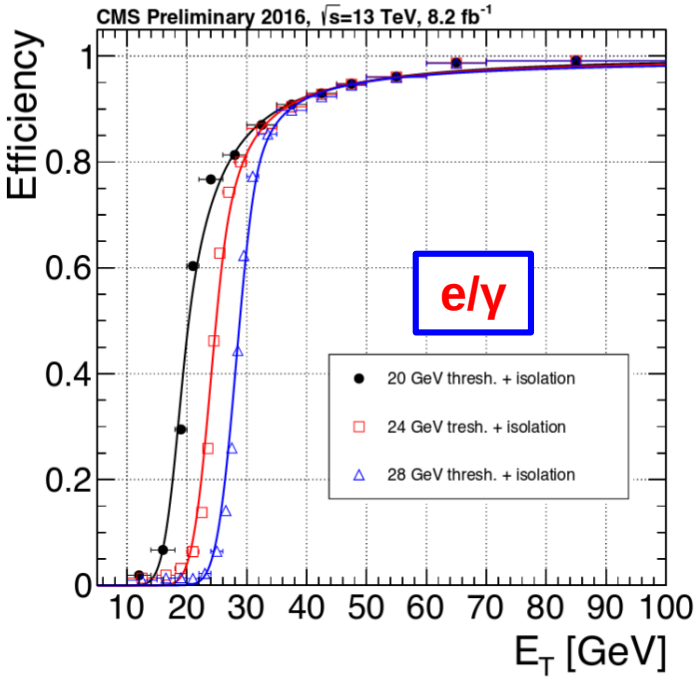
Online Performance in Run 2

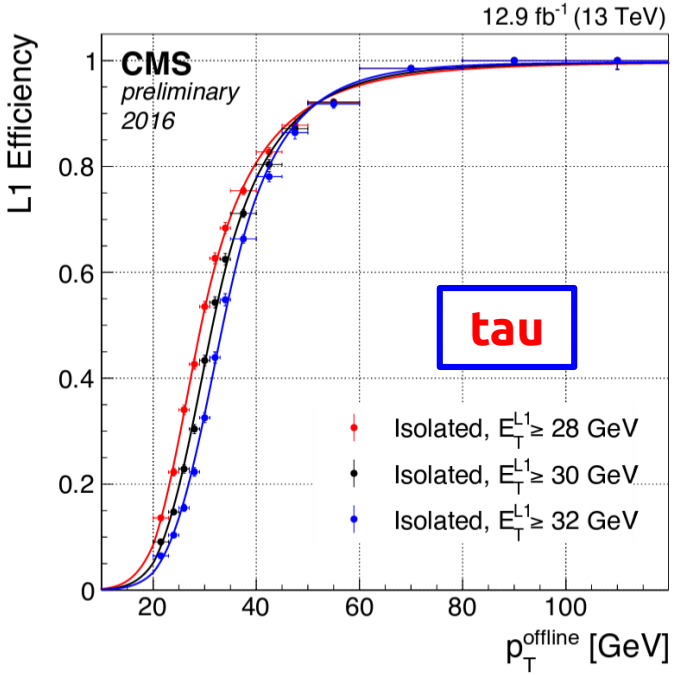
- CMS operating in 2016 with high efficiency
  - ➔ ~96% detector active
  - ➔ ~92% data taking eff.
- L1 Trigger upgrade is performing very well
  - ➔ Fully commissioned and highly efficient



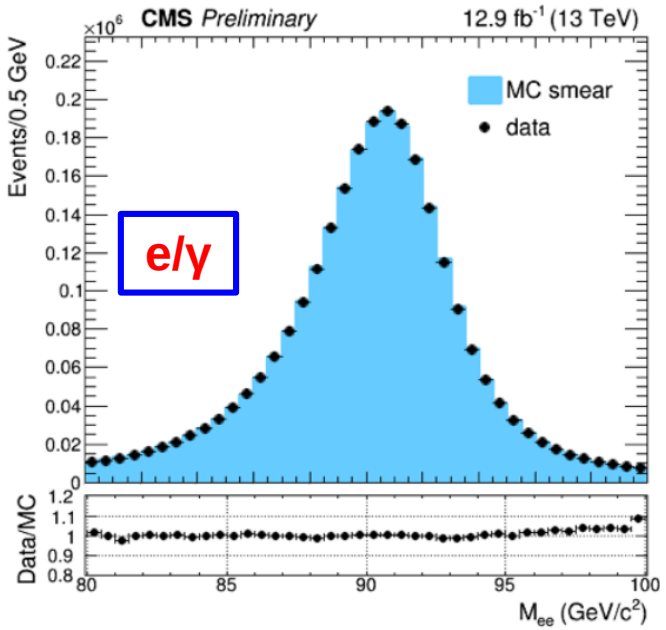


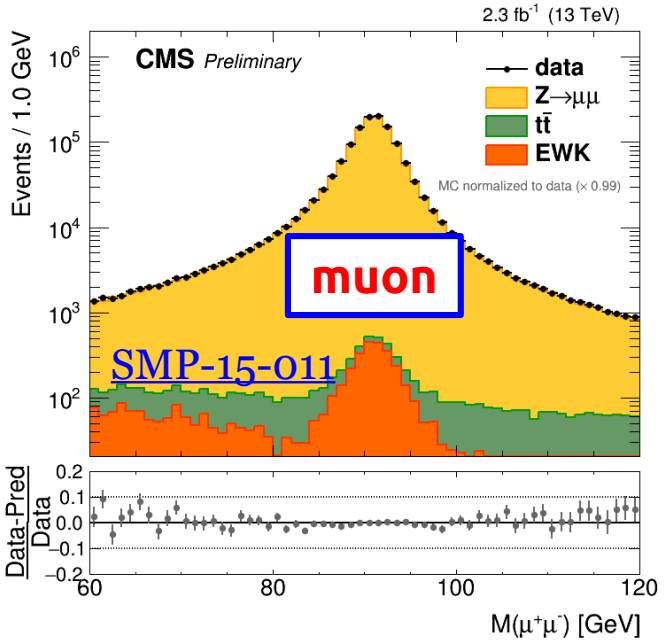


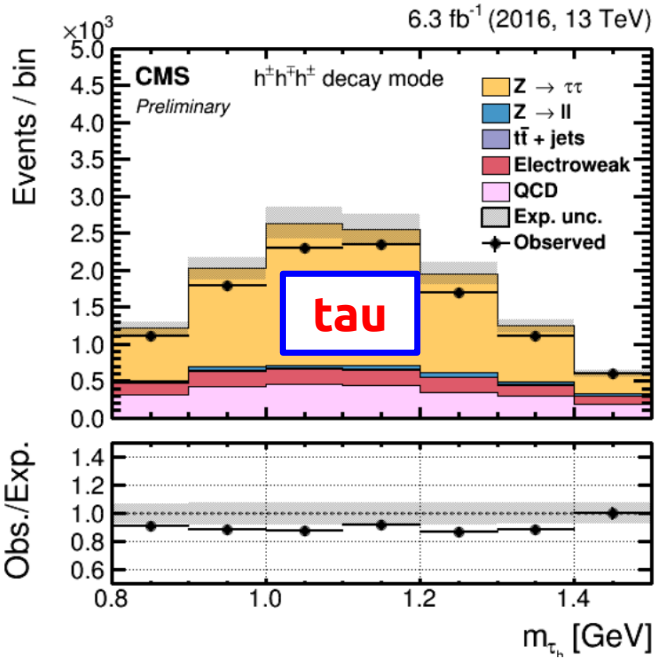


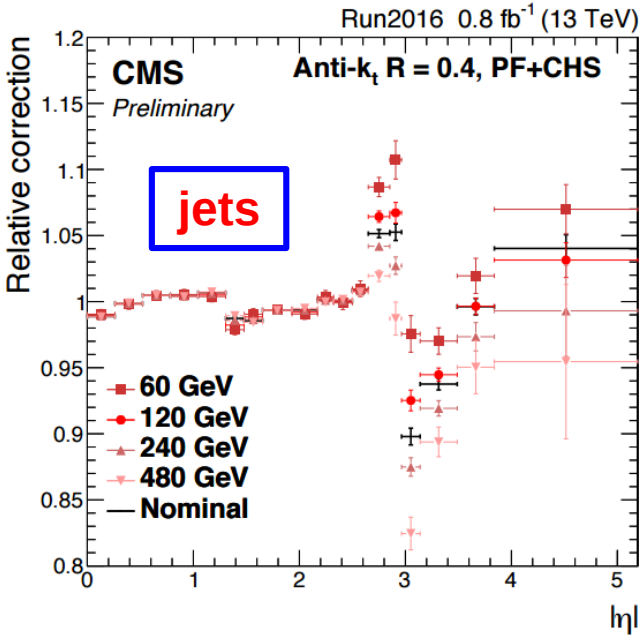


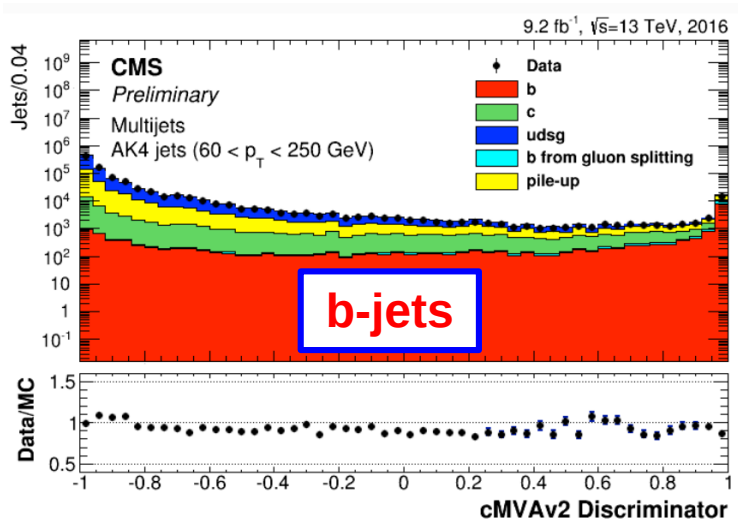
Object Reconstruction in Run 2

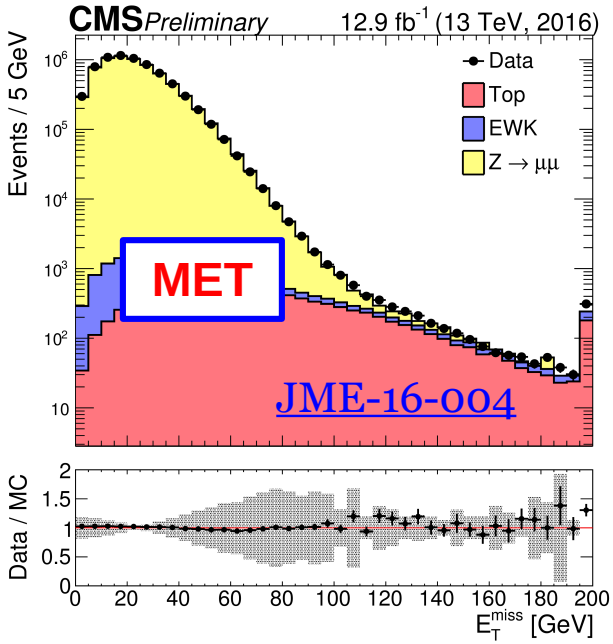






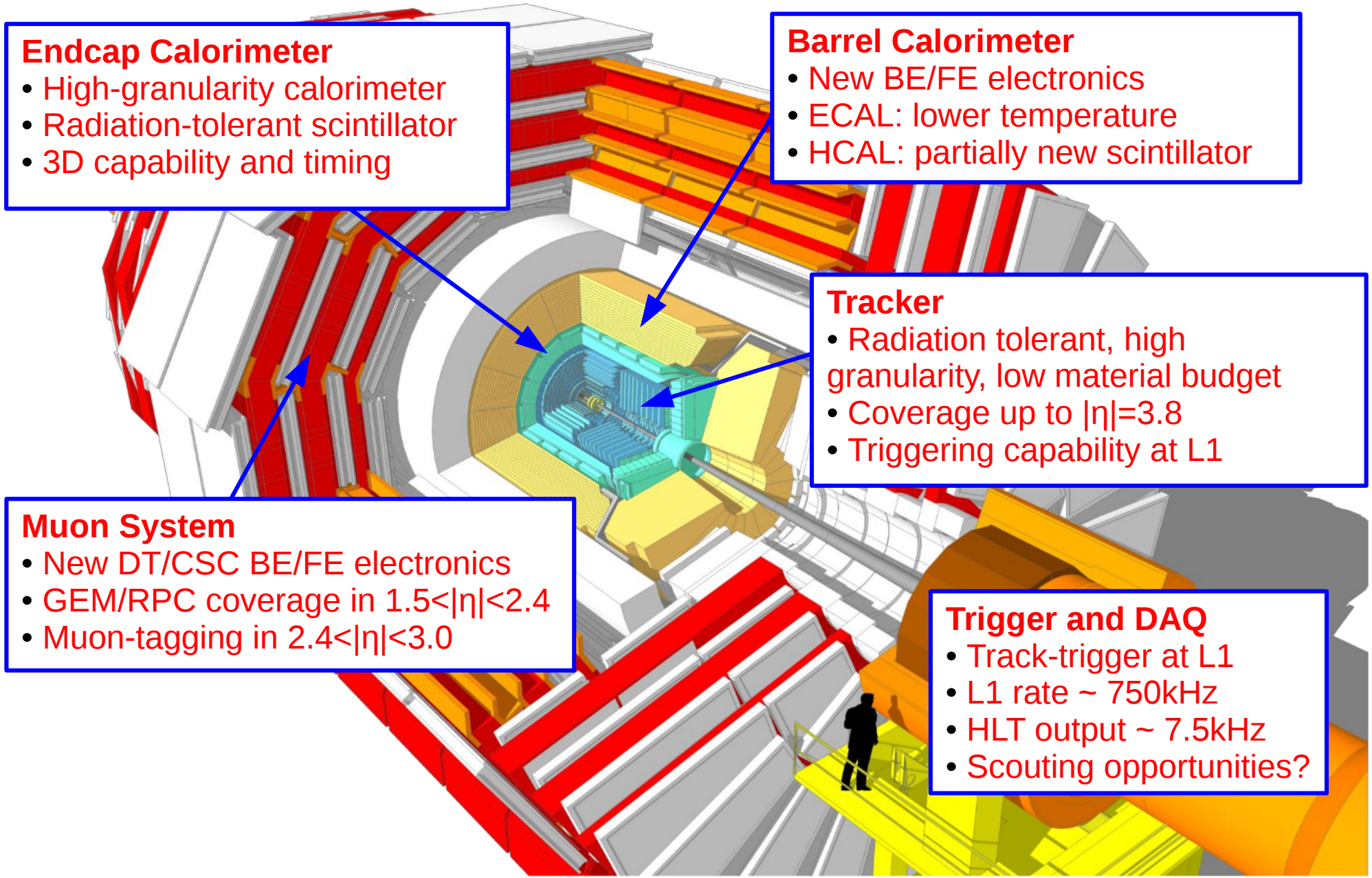






CMS Upgrades Beyond Run 2

TDR-15-002



Endcap Calorimeter
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Triggering capability at L1

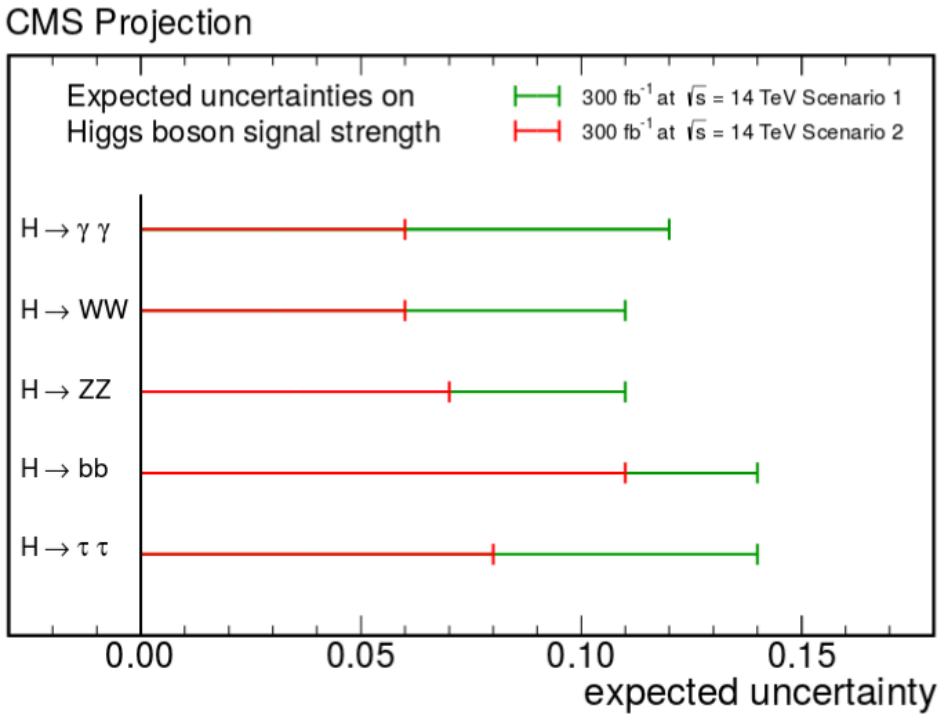
Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

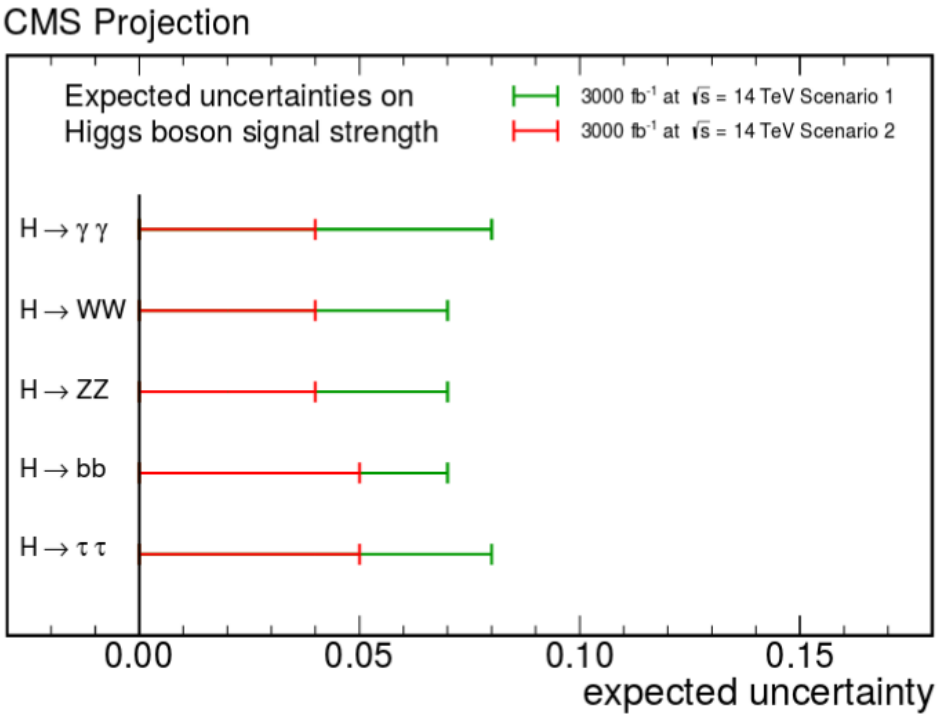
Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz
- Scouting opportunities?

CMS-NOTE-2013-002

Higgs Boson Signal Strength

- Projections have been obtained by scaling event yields to 300(0) fb^{-1} at $\sqrt{s}$ = 14 TeV
- Use Run 1 Legacy results (7+8 TeV) and assume performance unchanged
- Two scenarios for systematic uncertainties were considered:
  - ➔ Scenario 1: systematic unc. unchanged
  - ➔ Scenario 2: theoretical unc. scaled by 1/2, experimental unc. scaled by $1/\sqrt{\int \mathcal{L}}$





End of Run 3 (300 fb^{-1}): 6-14% uncertainty on signal strengths
HL-LHC (3000 fb^{-1}): 4-8% uncertainty on signal strengths

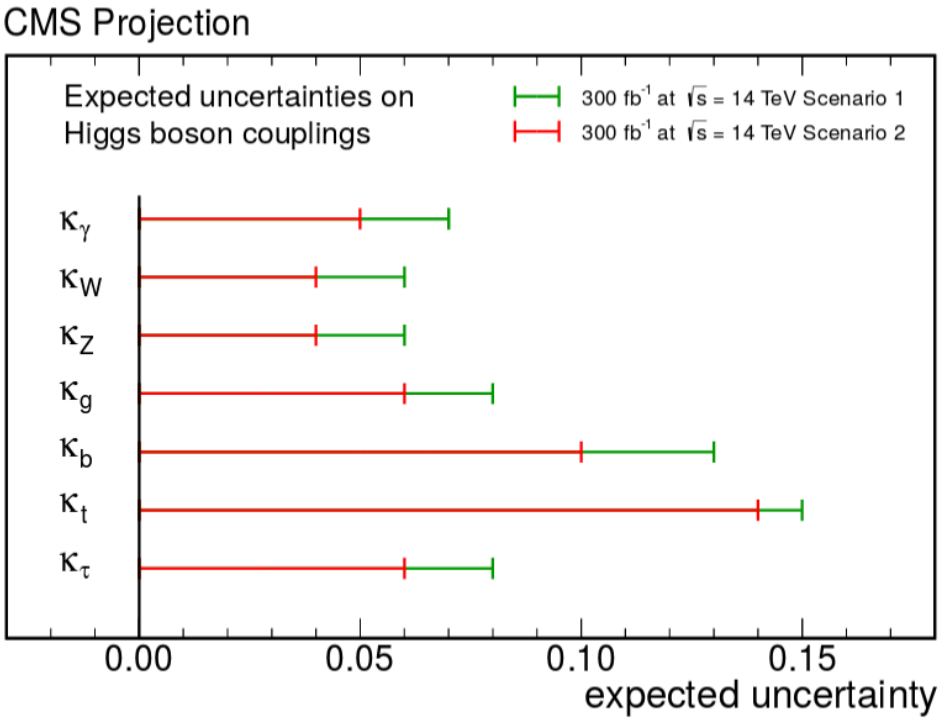
Higgs Boson Couplings

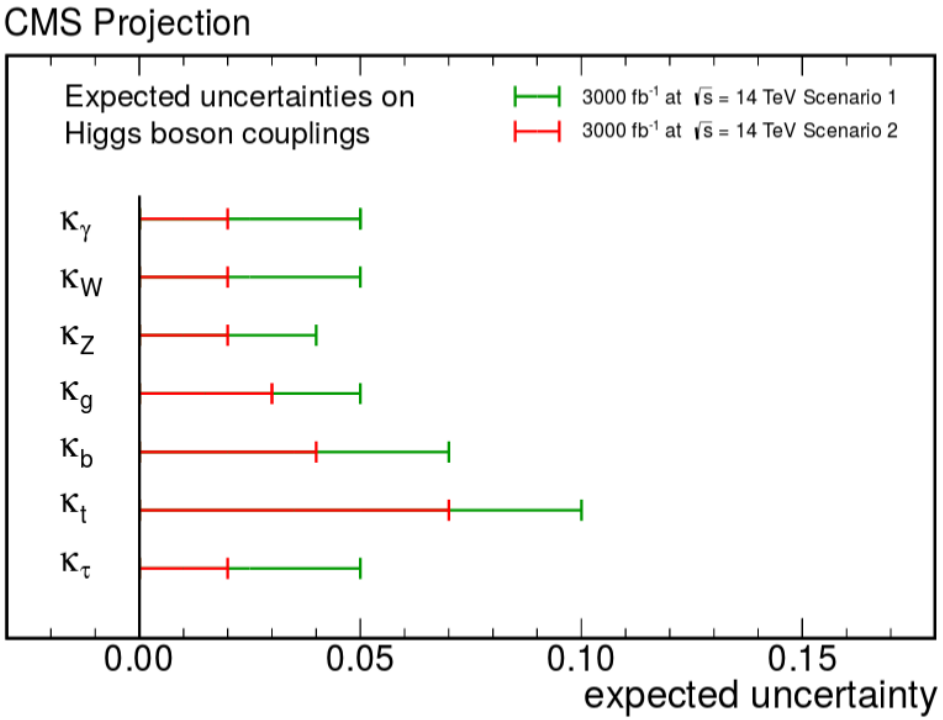
CMS-NOTE-2013-002

- Projected couplings have been obtained using the kappa framework

$$\sigma \cdot \mathrm{BR}(xx \to \mathrm{H} \to ff) = \sigma_{\mathrm{SM}}(xx \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to ff) \cdot \frac{\kappa_x^2 \cdot \kappa_f^2}{\kappa_{\mathrm{H}}^2}$$

- Theoretical uncertainties have been dominant in the projections
  - ➔ In the last year N^{3}LO gg→H predictions have been produced (unc. almost halved)





End of Run 3 (300 fb^{-1}): 5-15% uncertainty on couplings
HL-LHC (3000 fb^{-1}): 2-10% uncertainty on couplings

Anomalous Couplings

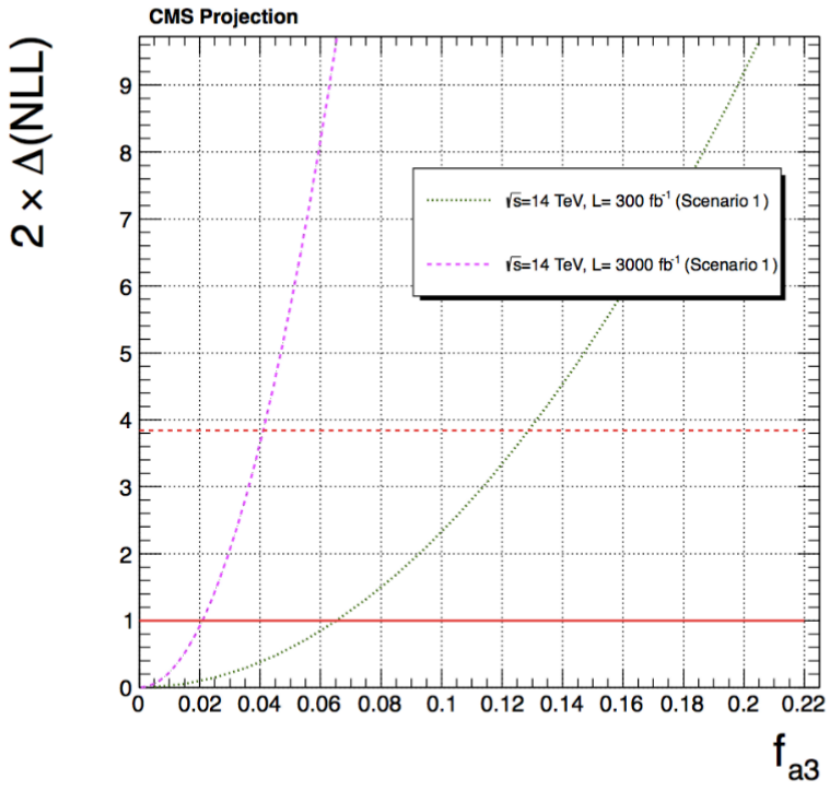
CMS-NOTE-2013-002

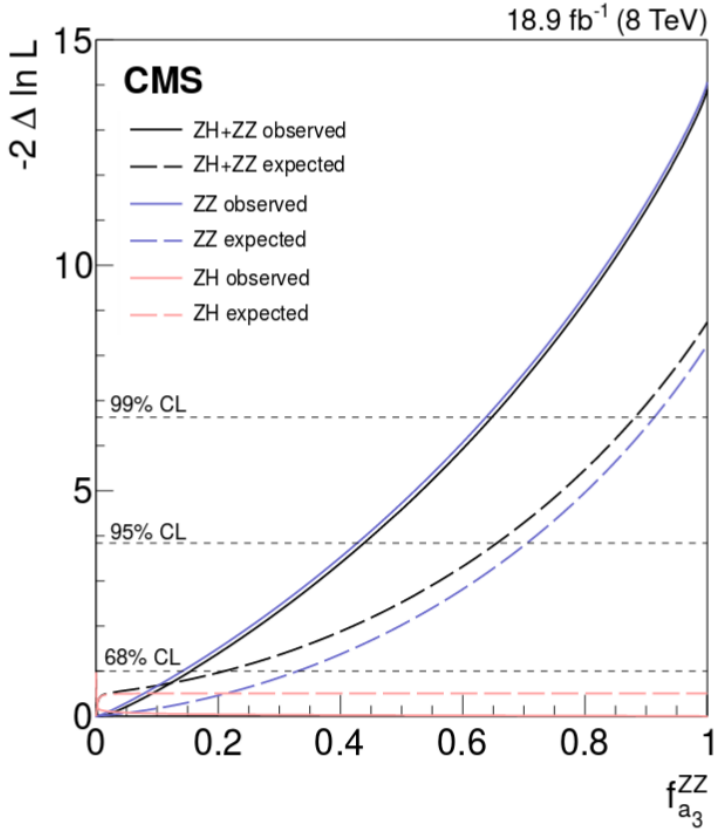
HIG-14-035

- Important to determine spin and quantum numbers of the particle accurately
- Generic amplitude of H→ZZ for spin-0 particle can be written as:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{HVV}} + \frac{\kappa_1^{\mathrm{HVV}} q^2_{\mathrm{V}_1} + \kappa_2^{\mathrm{HVV}} q^2_{\mathrm{V}_2}}{\left(\Lambda_1^{\mathrm{HVV}}\right)^2}\right] m^2_{\mathrm{V}_1} \epsilon^*_{\mathrm{V}_1} \epsilon^*_{\mathrm{V}_2} + a_2^{\mathrm{HVV}} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{\mathrm{HVV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu}$$

- Can test for anomalous CP-odd coupling a_3
  - ➔ Expect to constrain fraction $f_{a3} < 0.13$ (0.04) 95% CL with 300 fb^{-1} (3000 fb^{-1})
- Even tighter constraints combining with VH channels, which has now been done

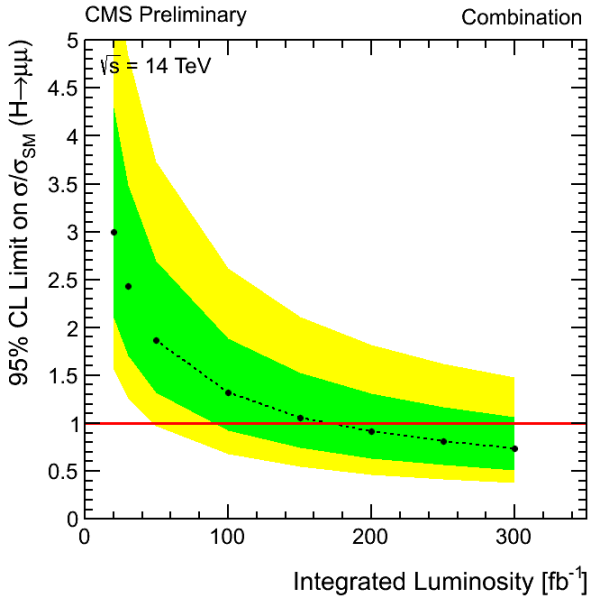


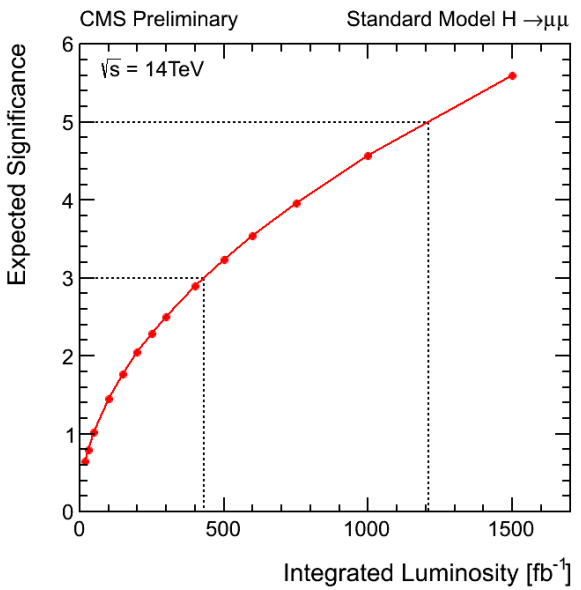


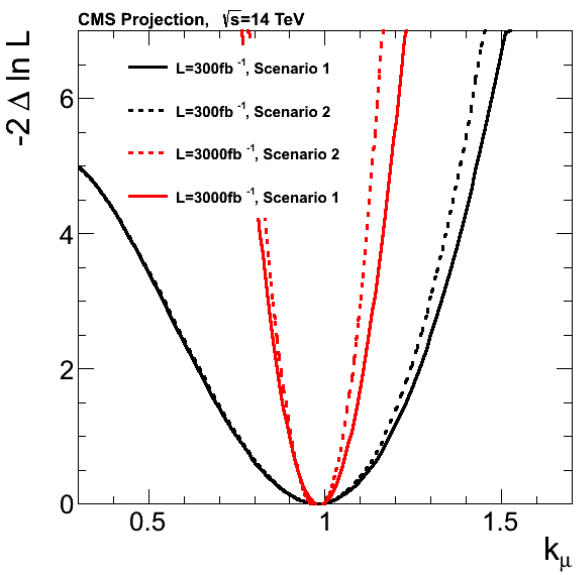
Rare Decays: H→μμ, H→J/ψ γ

HIG-13-007
HIG-14-003

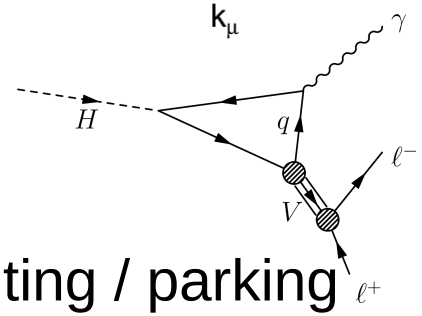
- H→μμ decay allows for a test of second generation leptonic coupling
  - ➔ Challenging experimentally due to large Drell-Yan background
- Very mild excess observed in the Run 1 search
  - ➔ 3σ (5σ) evidence (observation) expected with ~450 fb^{-1} (~1200 fb^{-1})





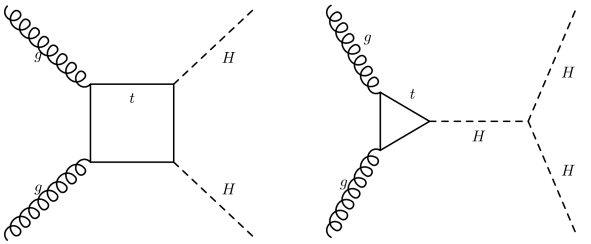


- 2nd generation coupling in quark sector even more challenging
  - ➔ BR(H → J/Ψ γ) tiny in the SM (~3×10^{-6}), current limit 1.5×10^{-3}
  - ➔ May require non-standard analysis techniques like data scouting / parking
  - ➔ OR new ideas (many good ones in this conference!)



Double Higgs Production

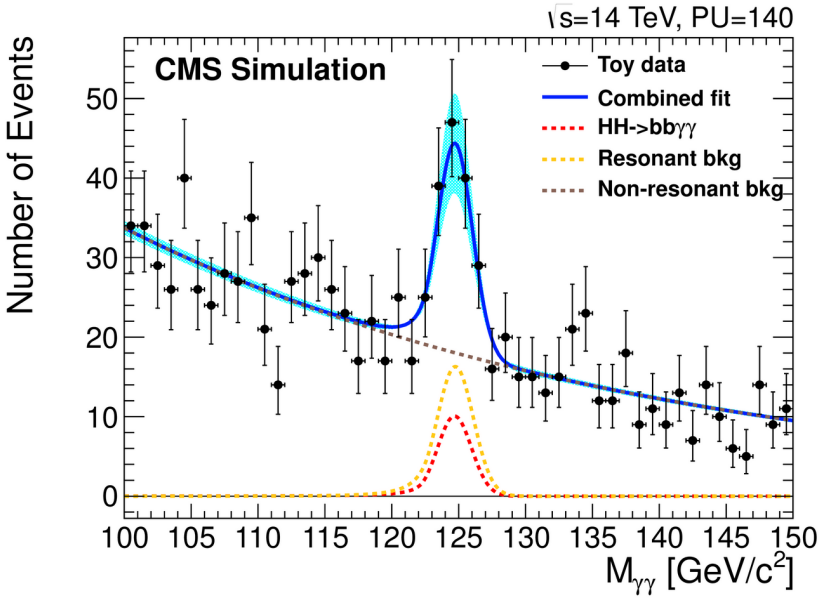
FTR-15-002

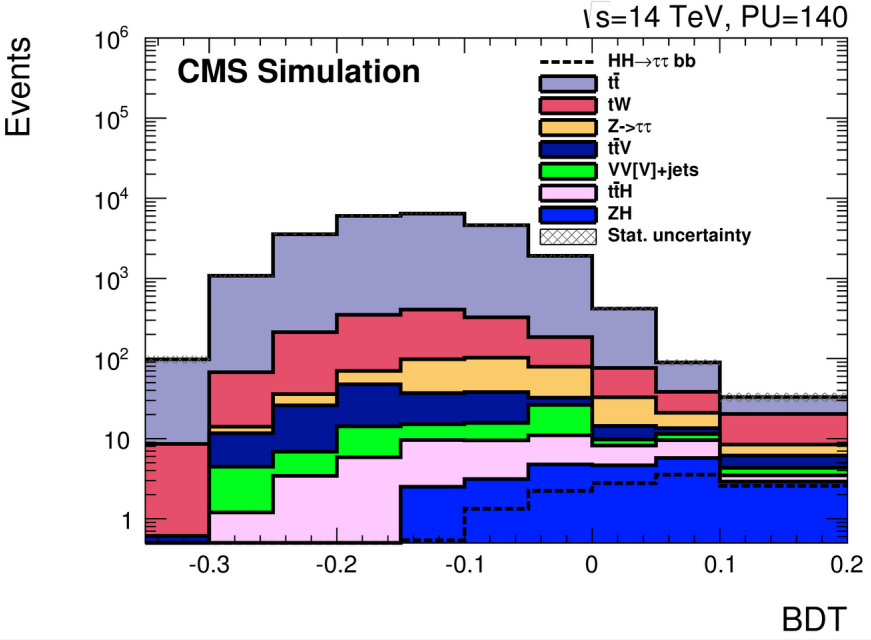


- Studies of trilinear coupling directly probes the Higgs potential
  - ➔ Also sensitive to potential new physics effects

$$V(\mathrm{H}) = \tfrac{1}{2}m_{\mathrm{H}}^2\mathrm{H}^2 + \lambda v\mathrm{H}^3 + \tfrac{1}{4}\tilde{\lambda}\mathrm{H}^4;\ \lambda_{\mathrm{SM}} = \lambda = \tilde{\lambda} = \frac{m_{\mathrm{H}}^2}{2v^2}$$

- Projections carried out using dedicated simulation of upgraded CMS detector
  - ➔ Combination of bbγγ and bbττ channels





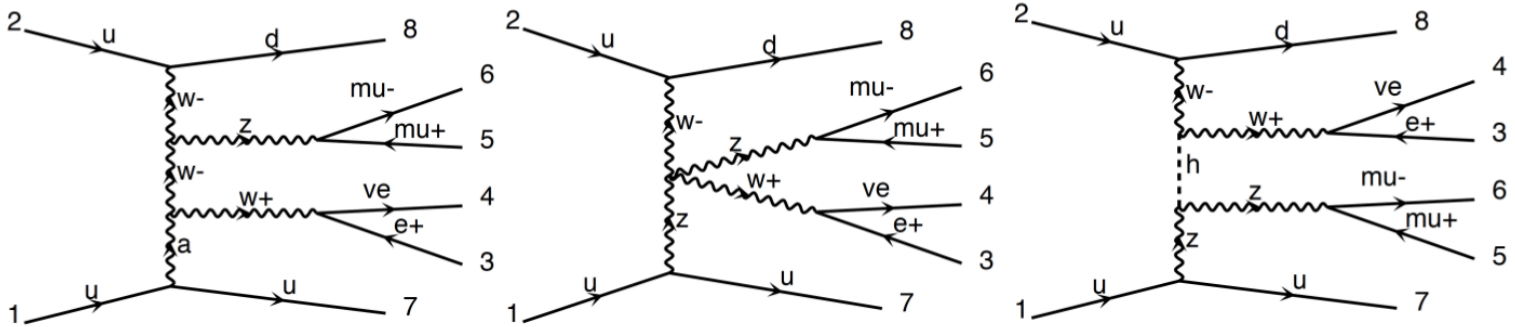
HL-LHC (3000 fb^{-1}): ~2σ significance, ~54% unc. on cross section

- Many other channels available, hopefully can have 3σ evidence in CMS alone

VV Scattering

FTR-13-006

- Can test whether VV scattering unitarity is restored as predicted in the SM
  - ➔ An important role of the Higgs boson
- New physics in the EWK Symmetry Breaking sector can alter the cross section



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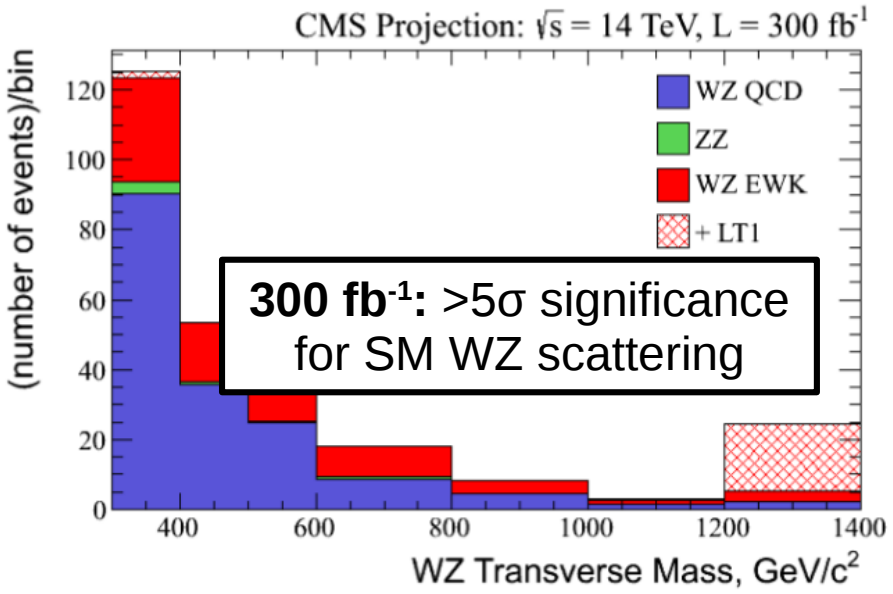
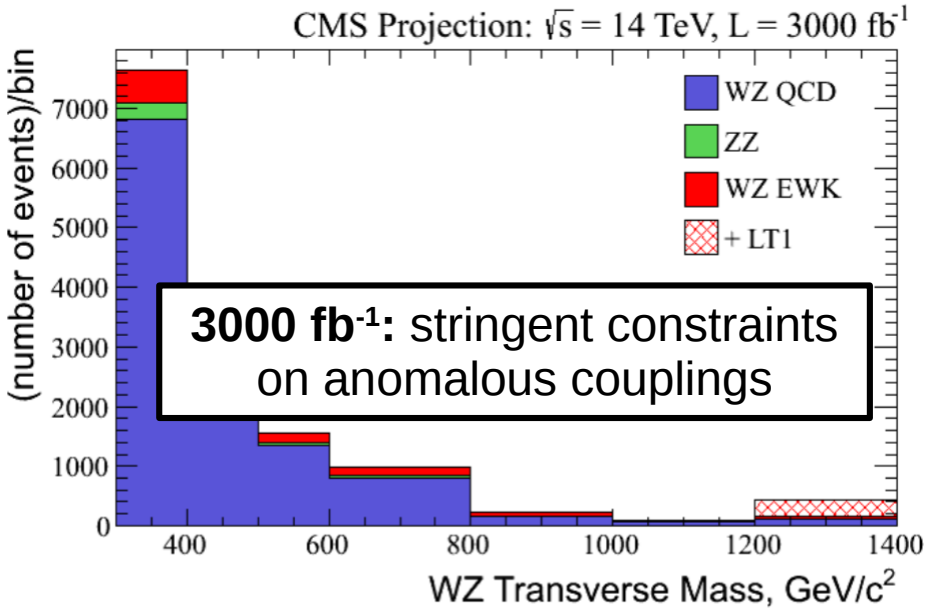




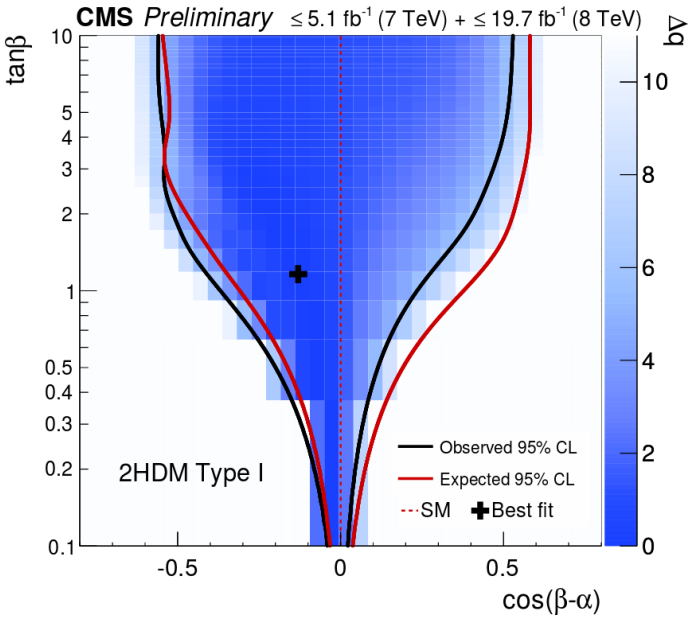
Extended Higgs Sector

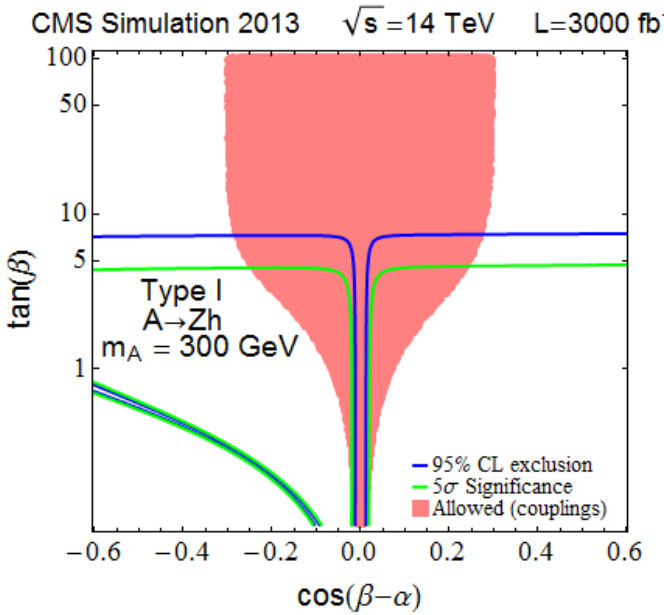
HIG-16-007
FTR-13-024

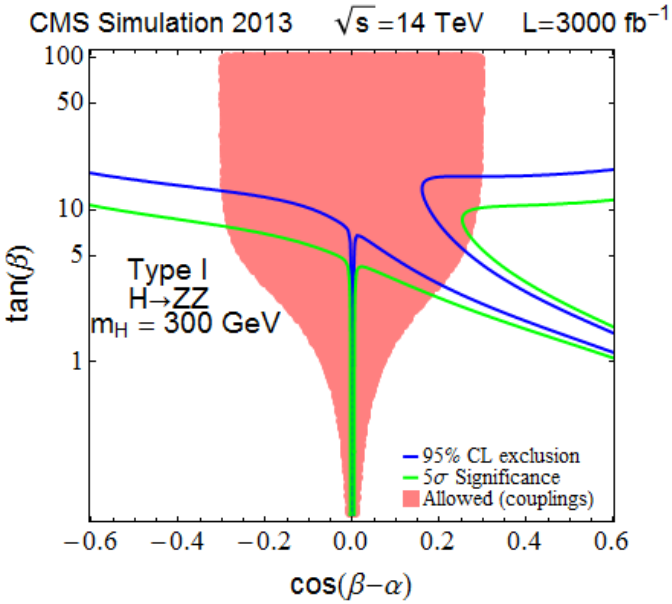
- Many models of new physics (e.g. SUSY) predict an extended Higgs sector
- 2HDM parameters are constrained by Higgs couplings measurements
  - ➔ Recent result from CMS using combined Run 1 couplings measurements

	2HDM	
	type I	type II/MSSM
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

- Complemented by direct searches for additional Higgses
- Projection with dedicated simulation of CMS upgrades
- Large parameter space available for a discovery
  - ➔ Or else, stringent limits on the model parameters



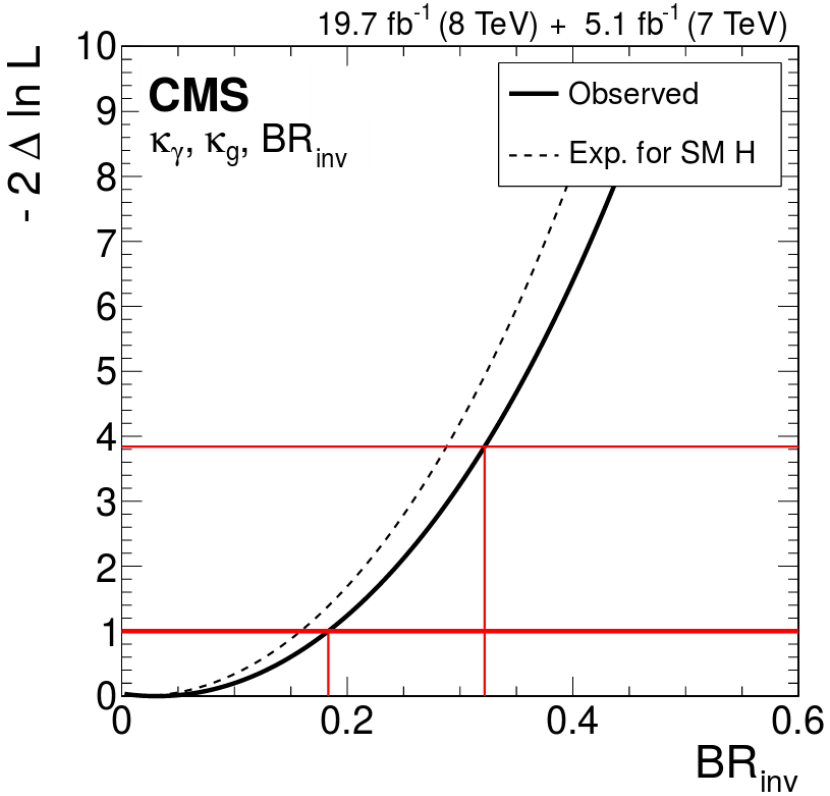


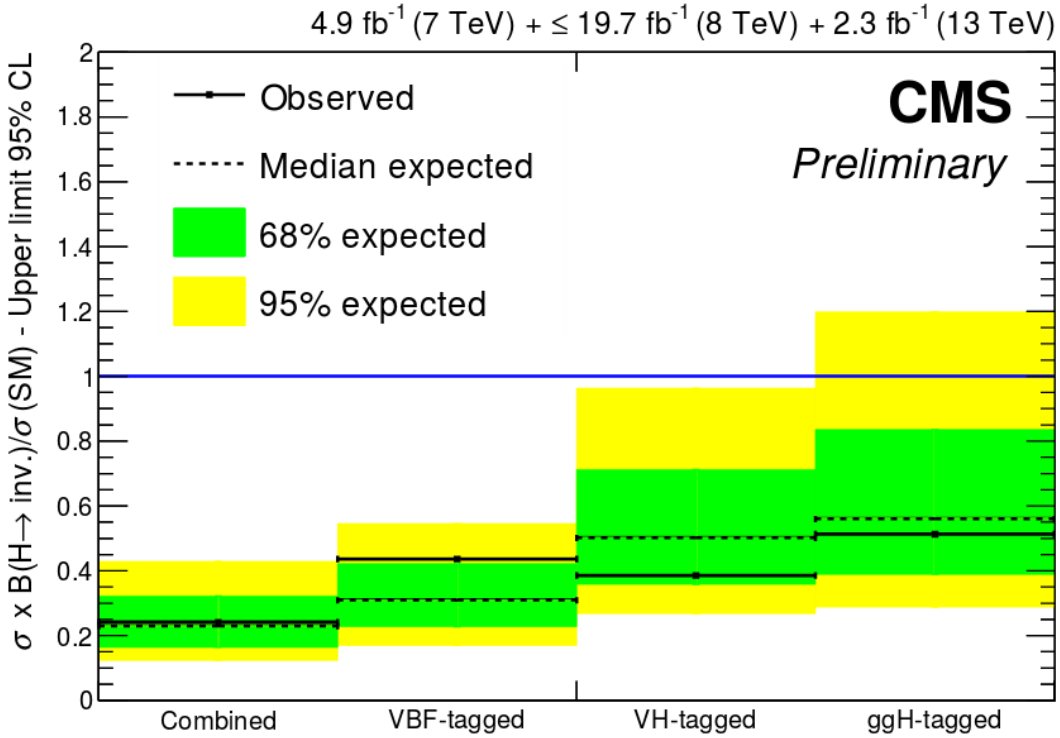


Invisible Decays

CMS-NOTE-2013-002
HIG-16-016

- Since the Higgs couples to all massive particles, it may be a portal to Dark Sector
  - Also, the BR_{BSM} is an important parameter in couplings measurements
- Projections assuming 2012 performance for 300, 3000 fb^{-1}
  - Using Higgs coupling combination and ZH-tagged direct search





End of Run 3 (300 fb^{-1}): BR_{BSM}<0.17-0.28
HL-LHC (3000 fb^{-1}): BR_{BSM}<0.06-0.017

- Limits improved by including VBF channel
  - Already at conservative end of 300 fb^{-1} projection!

Conclusions

- **CMS Higgs Physics program for Run 2 is well under way, and outlook is good for the future**
- **Experiment upgrades underway to cope with challenging data taking conditions**
- **Projections for the future have been shown**
  - Keep in mind analysis methods always improving
  - Projections don’t take into account novel ideas!
- **Higgs physics program will remain an important aspect of the LHC experiments**
  - Unprecedented precision and sensitivity are waiting!!!

Additional References

L1 muon trigger performance - ICHEP16 dataset

CMS L1 Calorimeter Trigger performance in 2016 data

Performance of b-Tagging Algorithms in Proton Collisions at 13 TeV using the 2016 Data

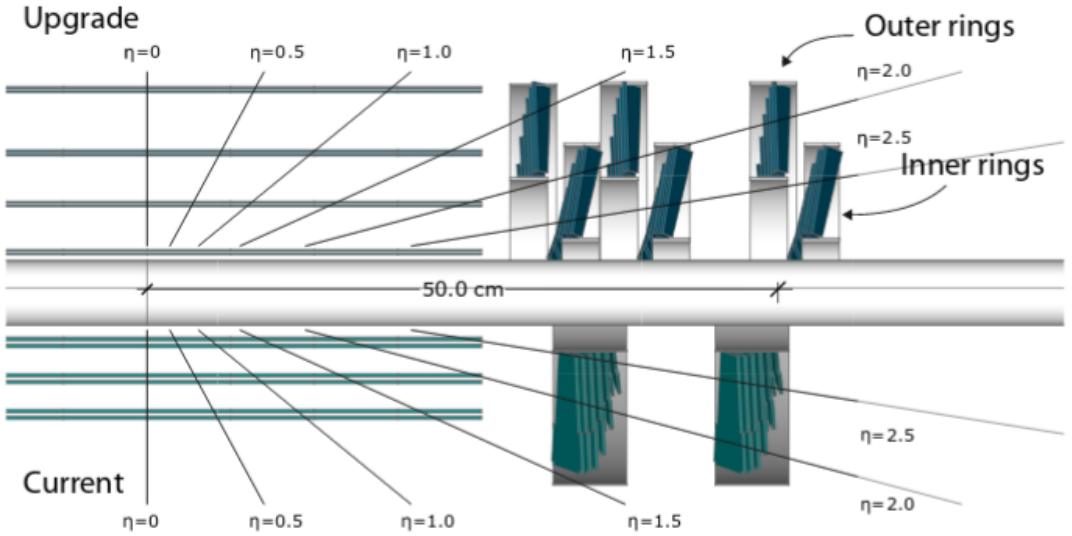
Tau energy scale and μ → τ misidentification rate estimated with early 2016 data using Z events

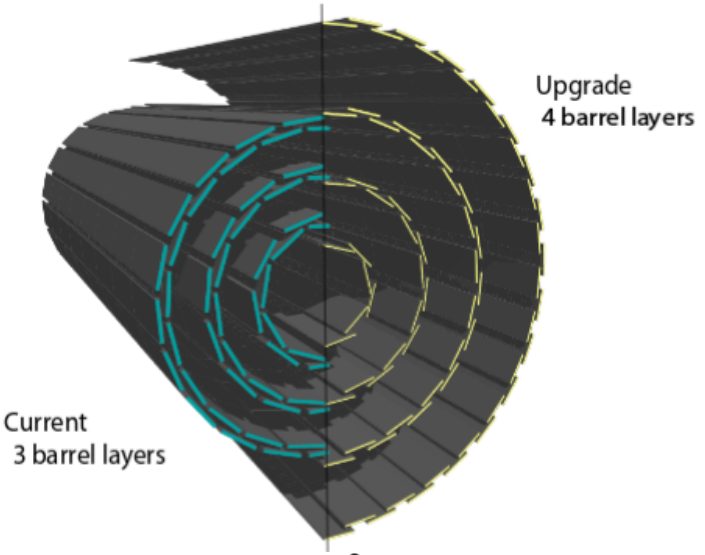
Electron and photon performance in CMS with first 12.9/fb of 2016 data

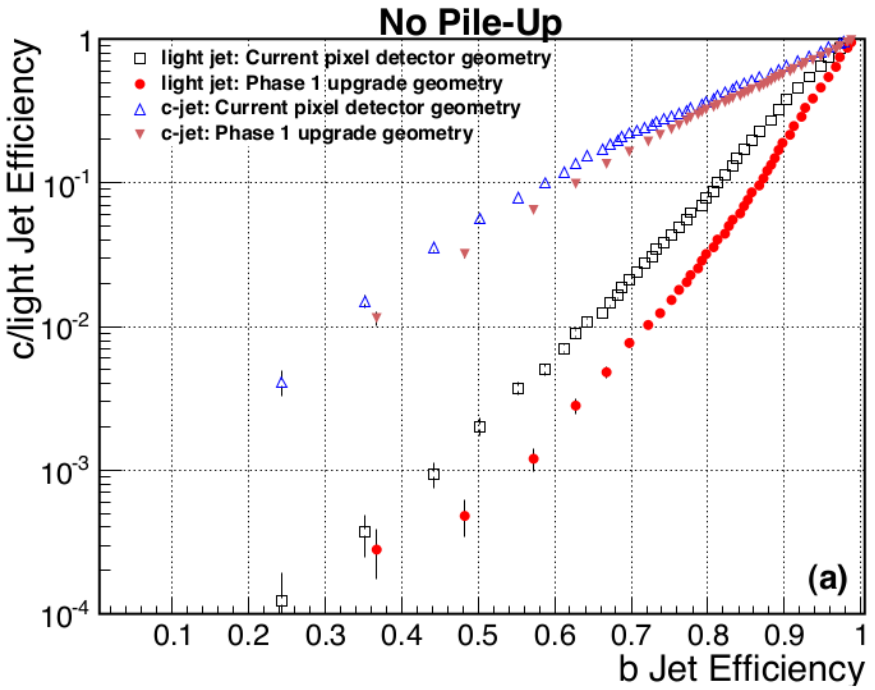
Backup

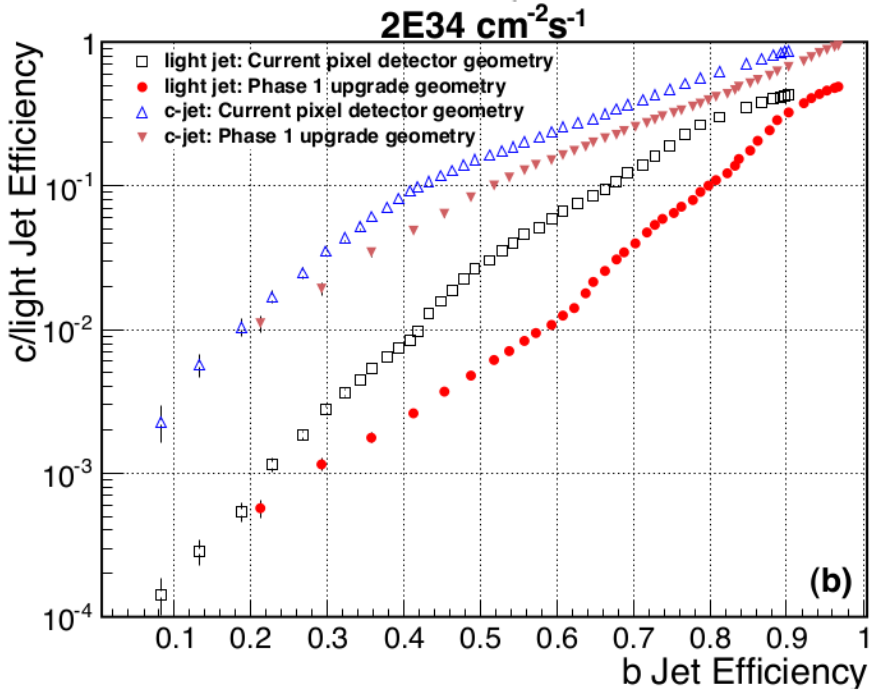
Phase 1 Pixel Detector Upgrade

CMS-UG-TP-1

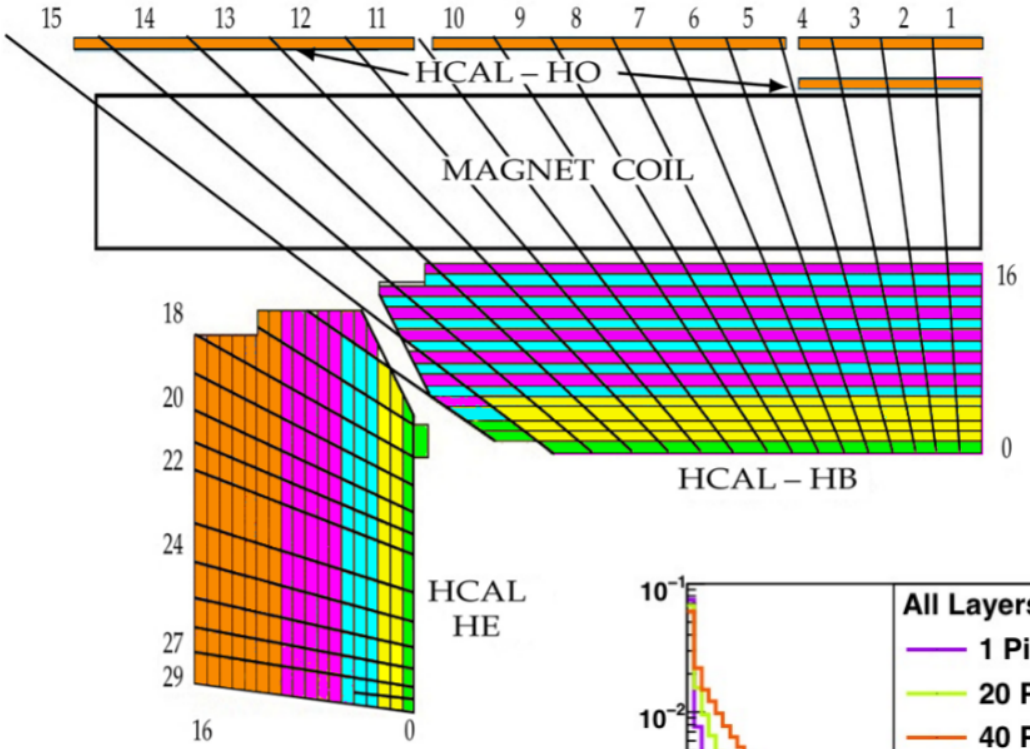


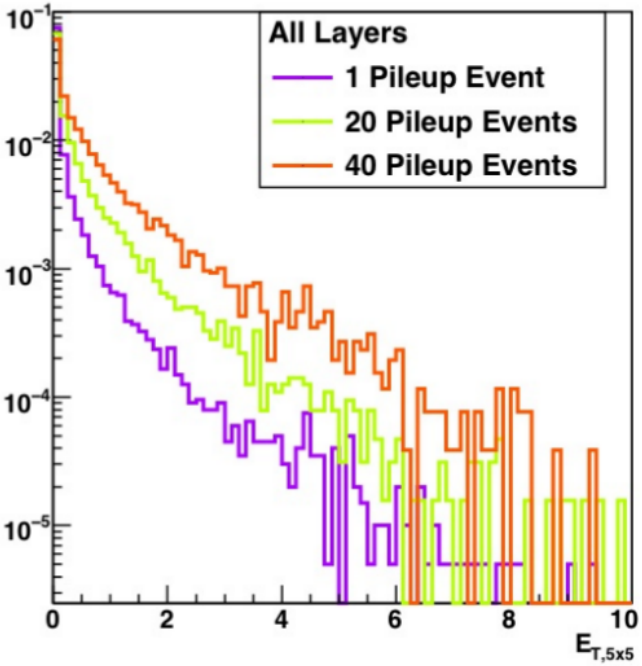


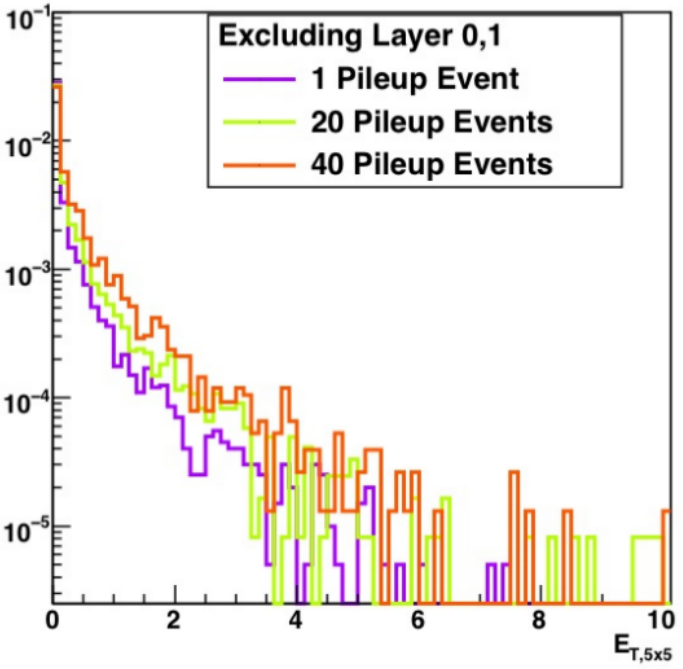




Phase 1 HCAL Upgrade







Phase 1 L1 Trigger Upgrade

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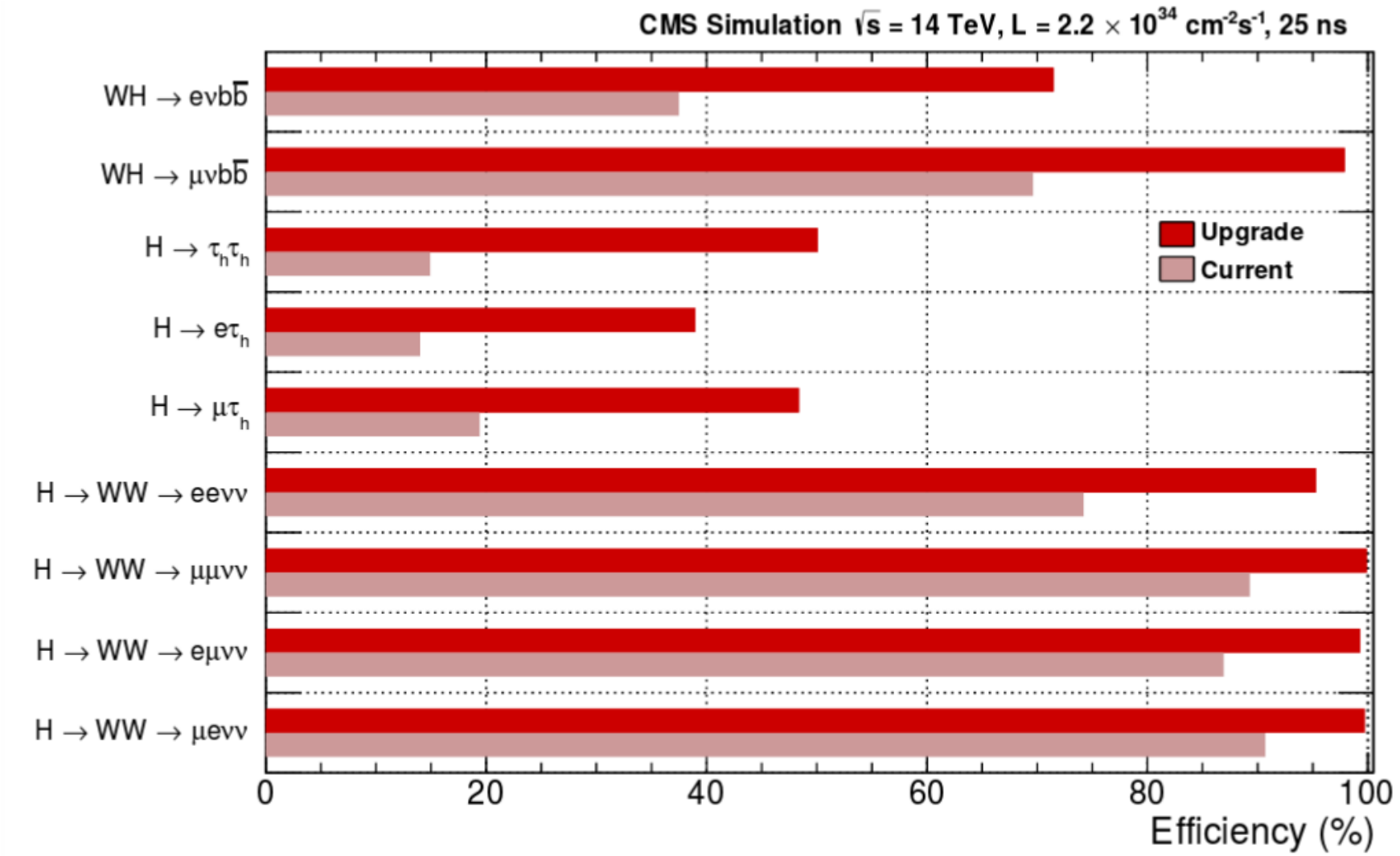
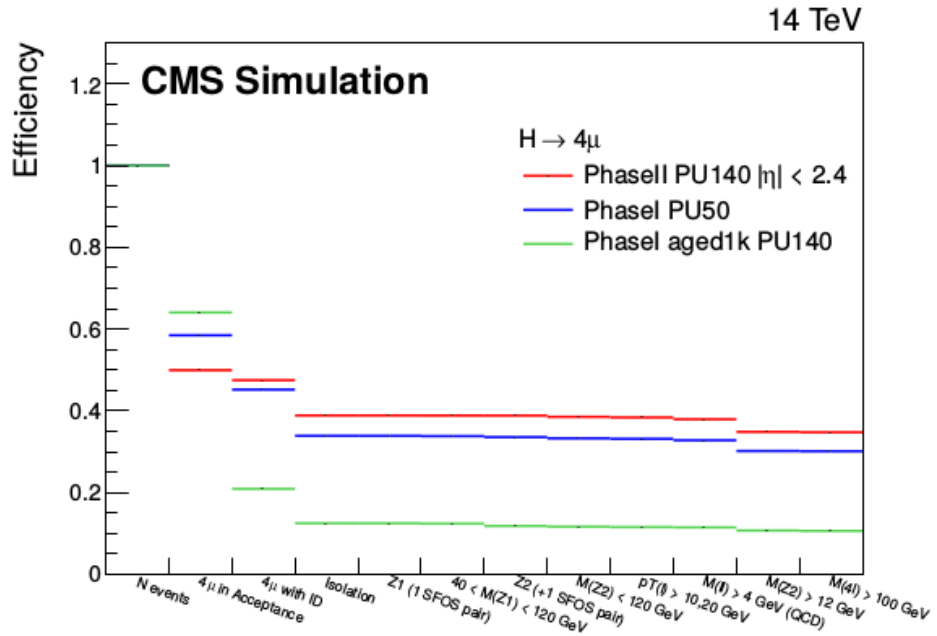
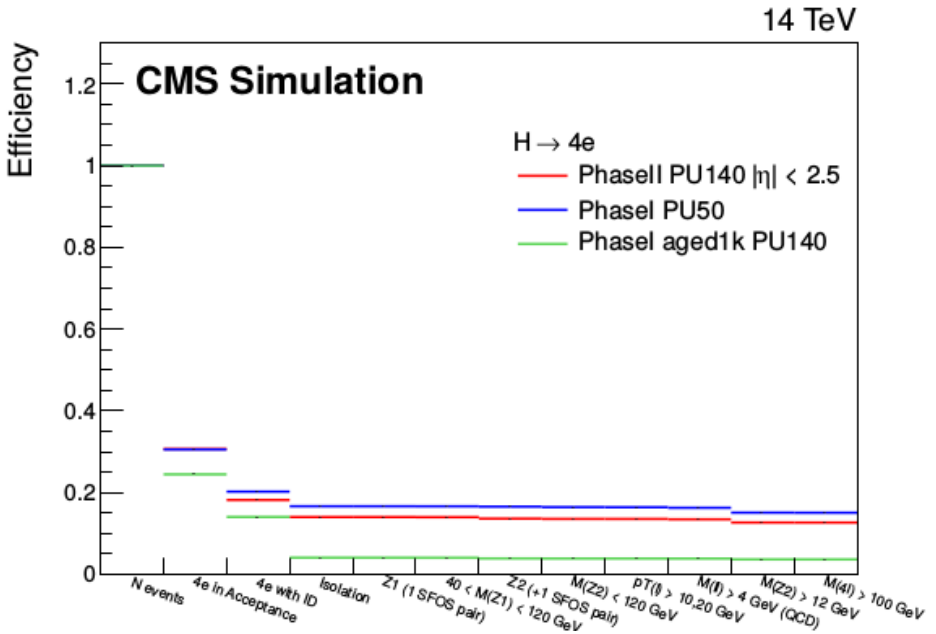
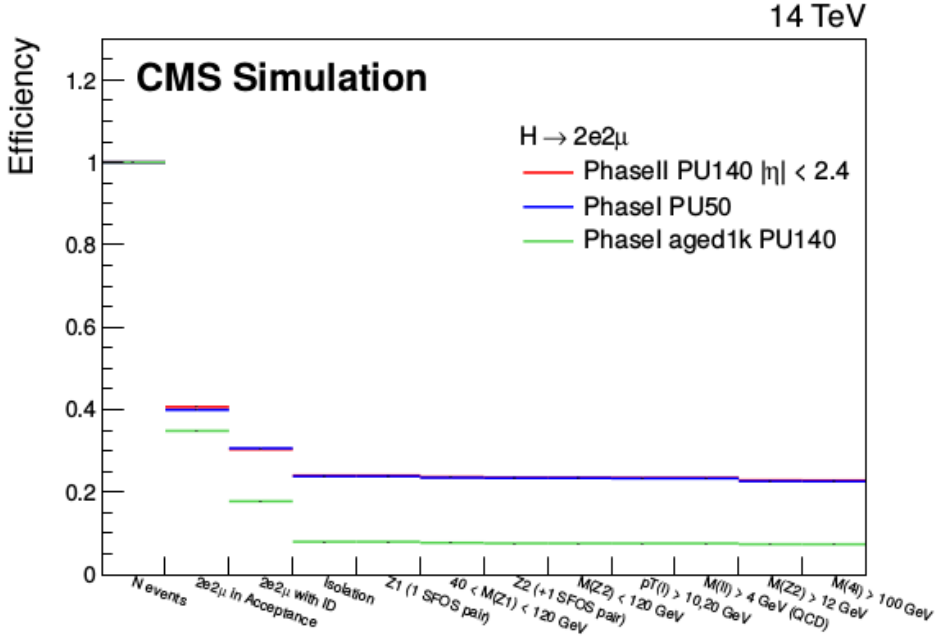


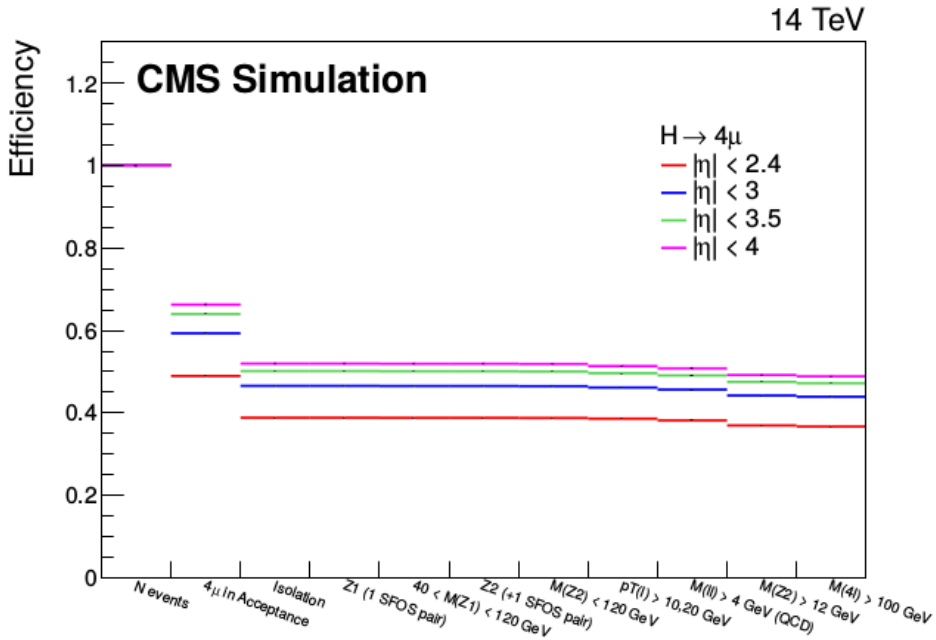
Phase 2 Upgrades: H→ZZ

TDR-15-002



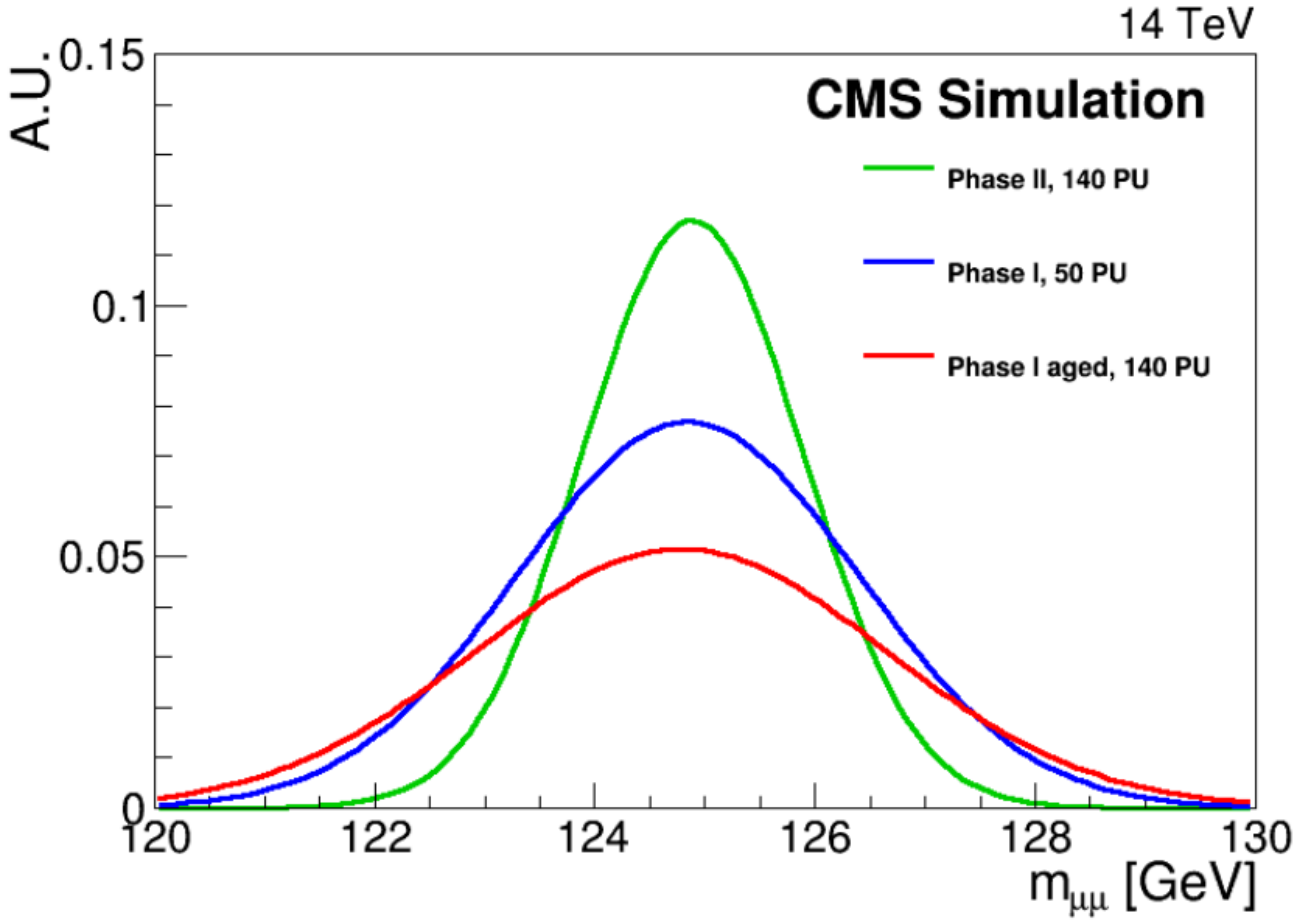






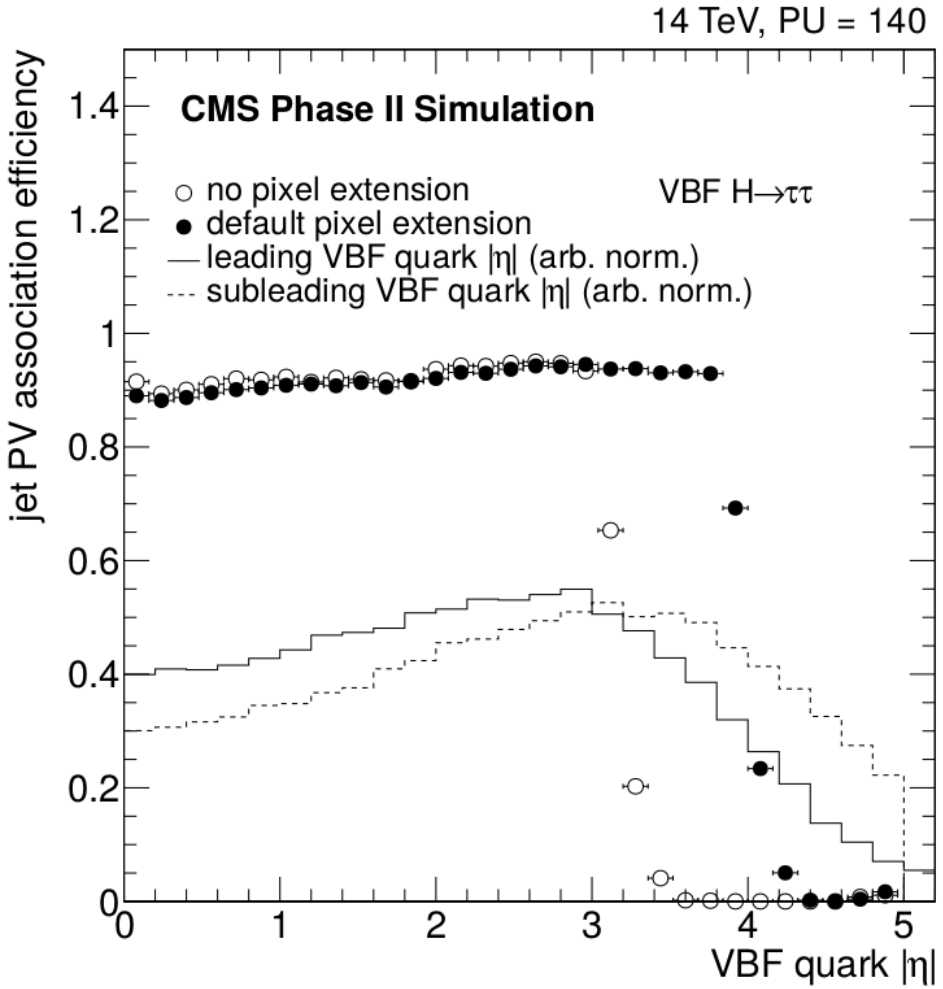
Phase 2 Upgrades: H→μμ

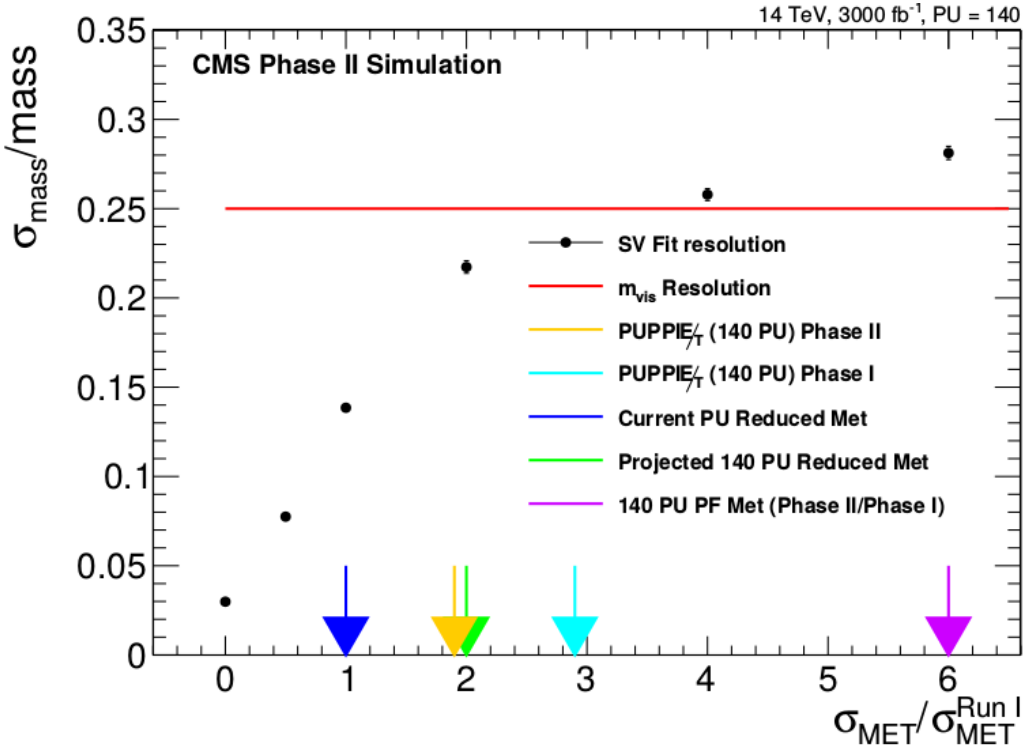
TDR-15-002



Phase 2 Upgrades: H→ττ

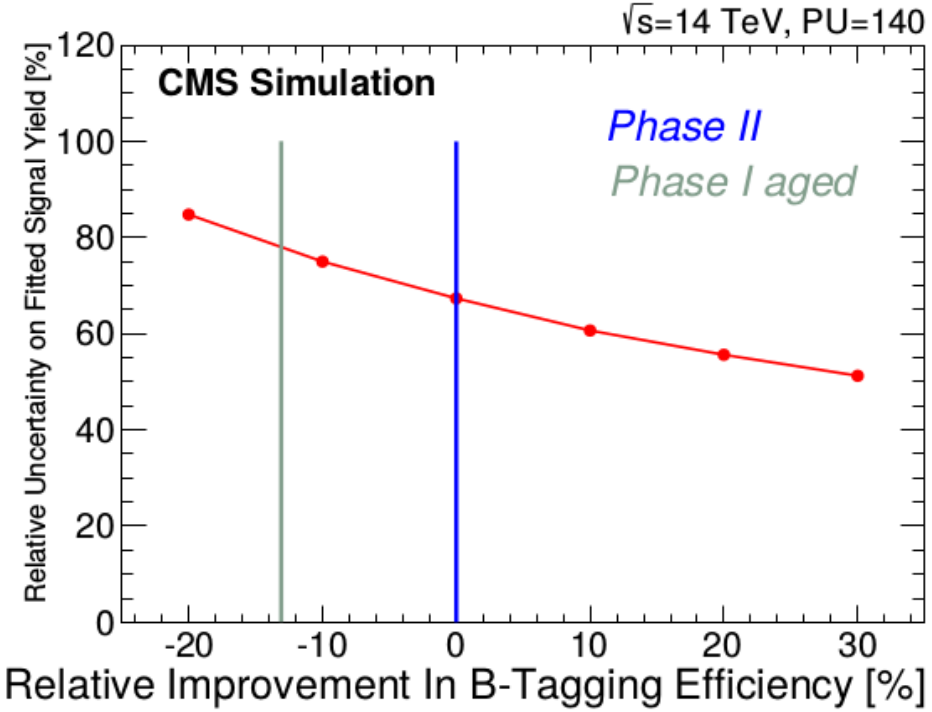
TDR-15-002

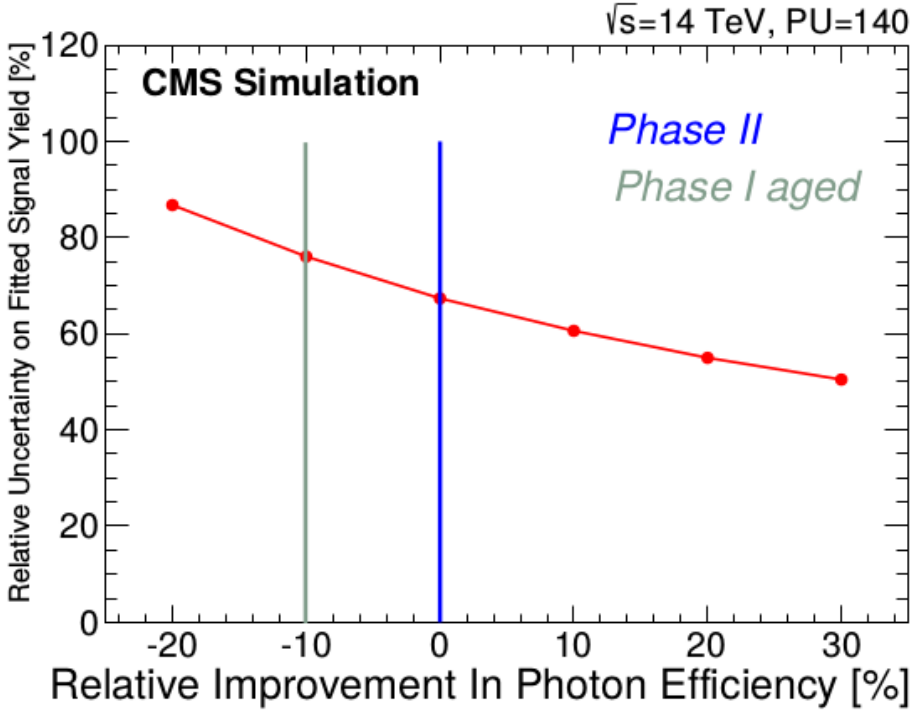




Phase 2 Upgrades: HH

TDR-15-002





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Extrapolated Coupling Precision

H decay	prod. tag	exclusive final states	cat.	res.	ref.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%	[6]
	VBF-tag	$\gamma\gamma + (jj)_{\mathrm{VBF}}$	2	<1.5%	
	VH-tag	$\gamma\gamma + (\mathrm{e}, \mu, \mathrm{MET})$	3	<1.5%	
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%	[23]
$\mathrm{ZZ} \to 4\ell$	$N_{\mathrm{jet}} < 2$	4e, 4μ, 2e2μ	3	1-2%	[7]
	$N_{\mathrm{jet}} \geq 2$		3		
$\mathrm{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%	[8]
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\mathrm{VBF}}$ (DF or SF dileptons)	2	20%	[24]
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2		[25]
$\tau\tau$	0/1-jet	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu) \times$ (low or high p_T^τ)	16	15%	[10]
	1-jet	$\tau_h\tau_h$	1		
	VBF-tag	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\mathrm{VBF}}$	5		
	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\tau_h\tau_h, \mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu)$	8		[26]
	WH-tag	$\tau_h\mu\mu, \tau_h\mathrm{e}\mu, \mathrm{e}\tau_h\tau_h, \mu\tau_h\tau_h$	4		
bb	VH-tag	$(\nu\nu, \mathrm{ee}, \mu\mu, \mathrm{e}\nu, \mu\nu$ with 2 b-jets$) \times$x	13	10%	[27]
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6		[28]
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3		
$\mathrm{Z}\gamma$	inclusive	$(\mathrm{ee}, \mu\mu) \times (\gamma)$	2		[29]
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%	[30–32]
	VBF-tag	$\mu\mu + (jj)_{\mathrm{VBF}}$	3		
invisible	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\mathrm{MET})$	2		[21]

Extrapolated Coupling Precision

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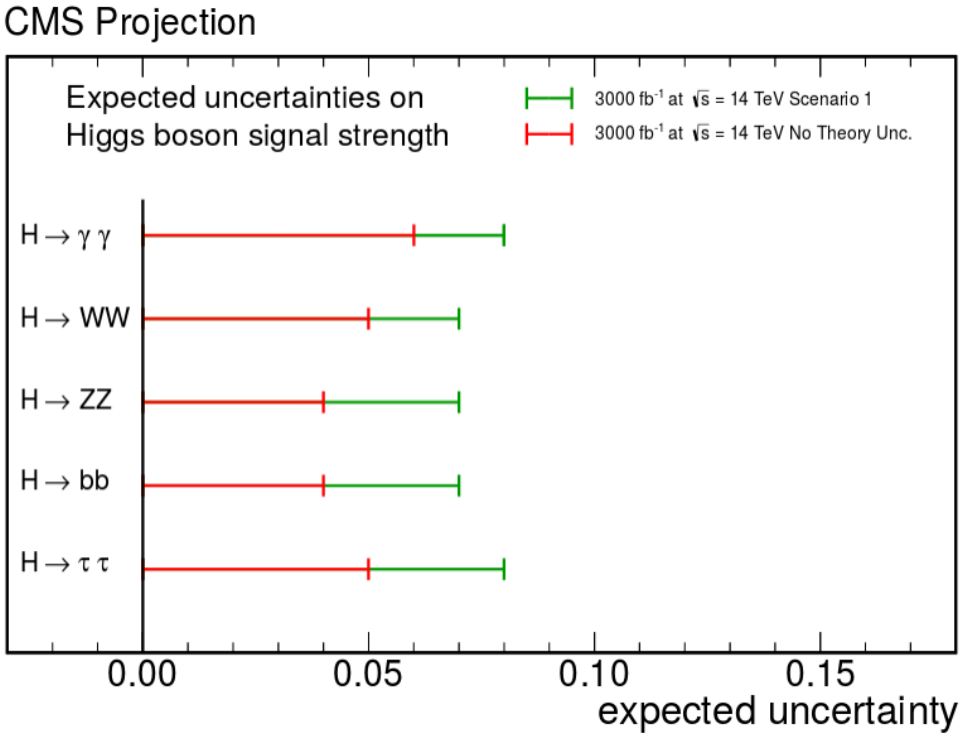
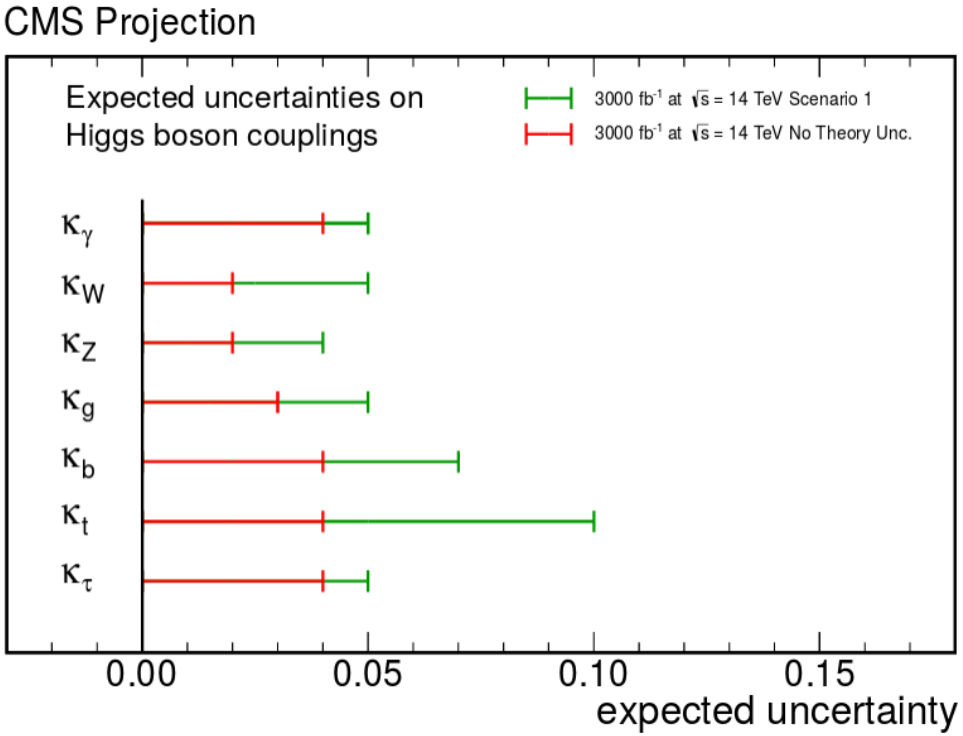
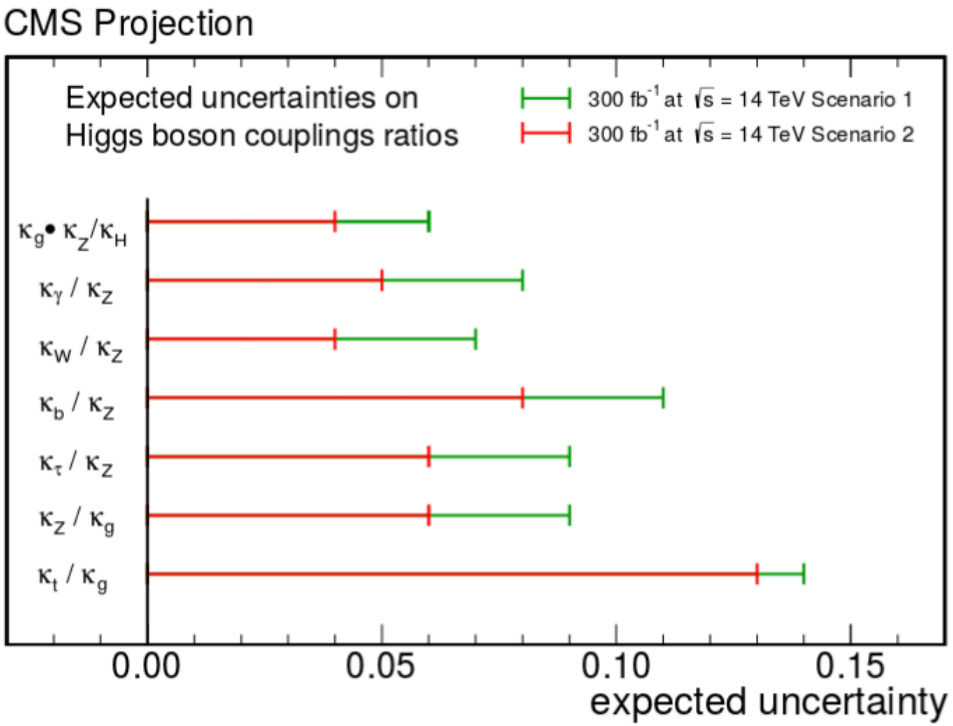
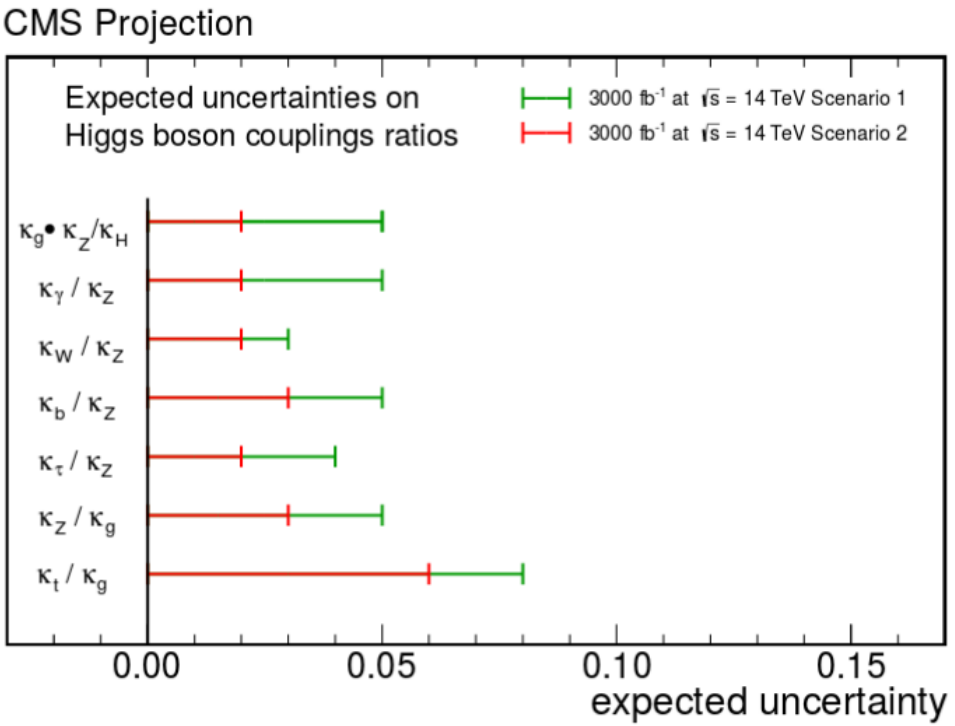




Extrapolated Coupling Precision

CMS-NOTE-2013-002





Rare Decays: H→J/ψ γ

HIG-14-003