LHC Upgrade Physics in CMS (Higgs Sector)

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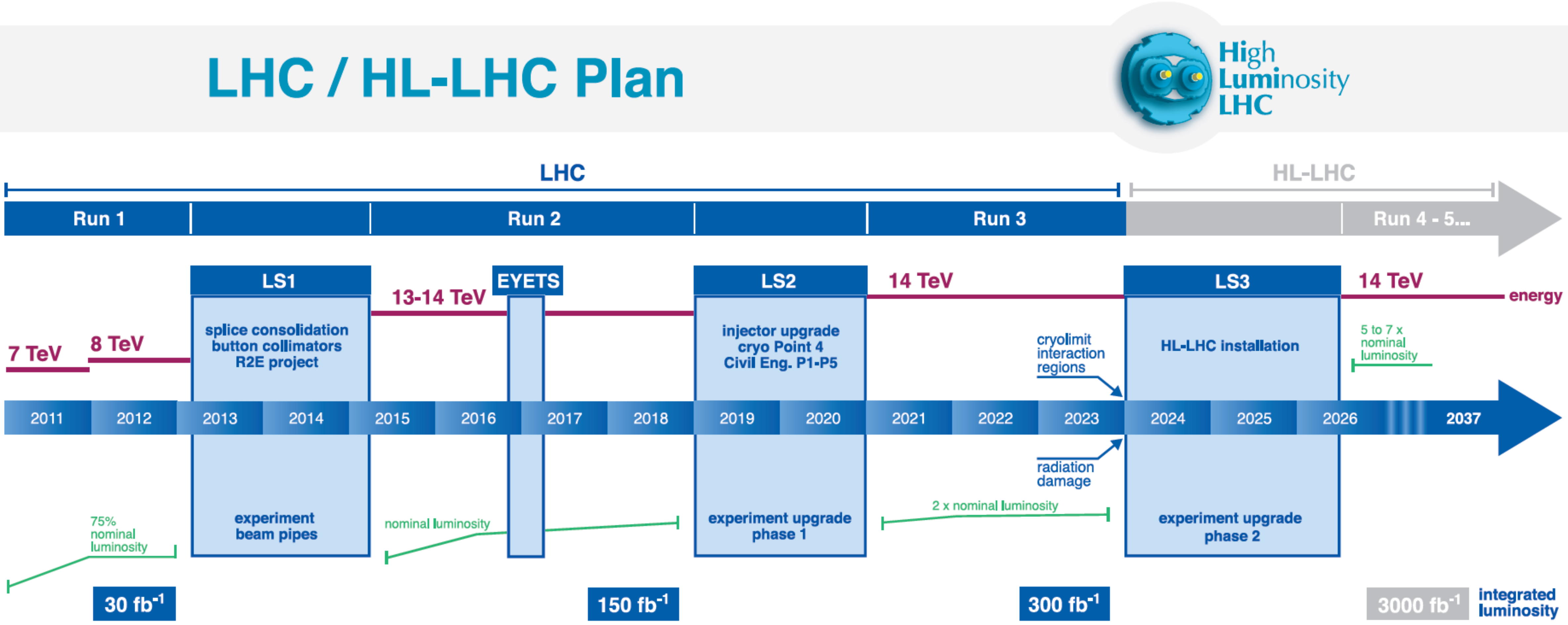
for the CMS Collaboration

LHC / HL-LHC Plan



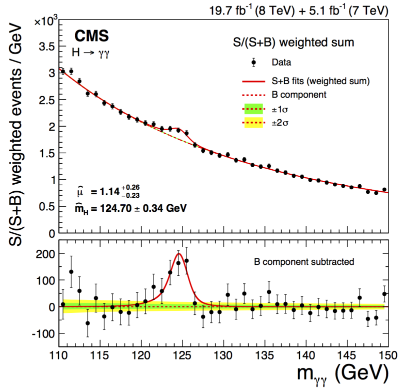
PU 140 (200) @ 25(50) ns bunch crossing

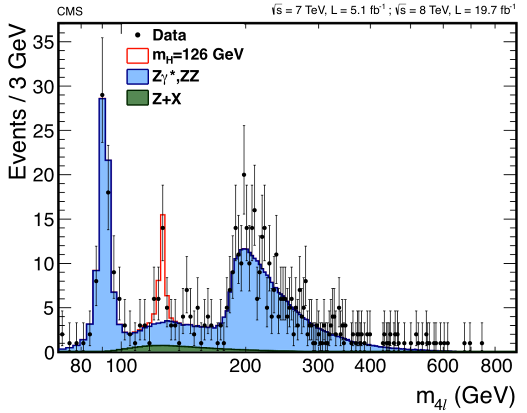
Detector and trigger challenges

ATLAS and CMS were designed to cope with L= 1-2 x10^{34} $cm^{-2}s^{-1}$

- Need detectors and trigger with high performances from low to high energy scales
  - 125 GeV SM-like boson measurements
  - Multi-TeV new physics searches
- Phase 1 Upgrade: twice LHC design luminosity
  - Event pileup reaches ~50 collisions per beam crossing (@ 25 ns)
  - Factor 5 increase in trigger rates relative to 2012 run
- Phase 2 Upgrade: 5x LHC design luminosity
  - Event pileup reaches ~140 collisions per beam crossing (@ 25 ns)
  - Need solutions to cope with very high rates (10-15 x 2012), radiation and pileup
- CMS Documentation:
  - Phase I & II Upgrade Technical Proposal (CERN-LHCC-2011-006, 2015-010)
  - Phase II Upgrade Scope Document" (CERN-LHCC-2015-019)

Physics program priorities





The discovery of a SM-like scalar boson at m_H~125 GeV defines the physics priorities

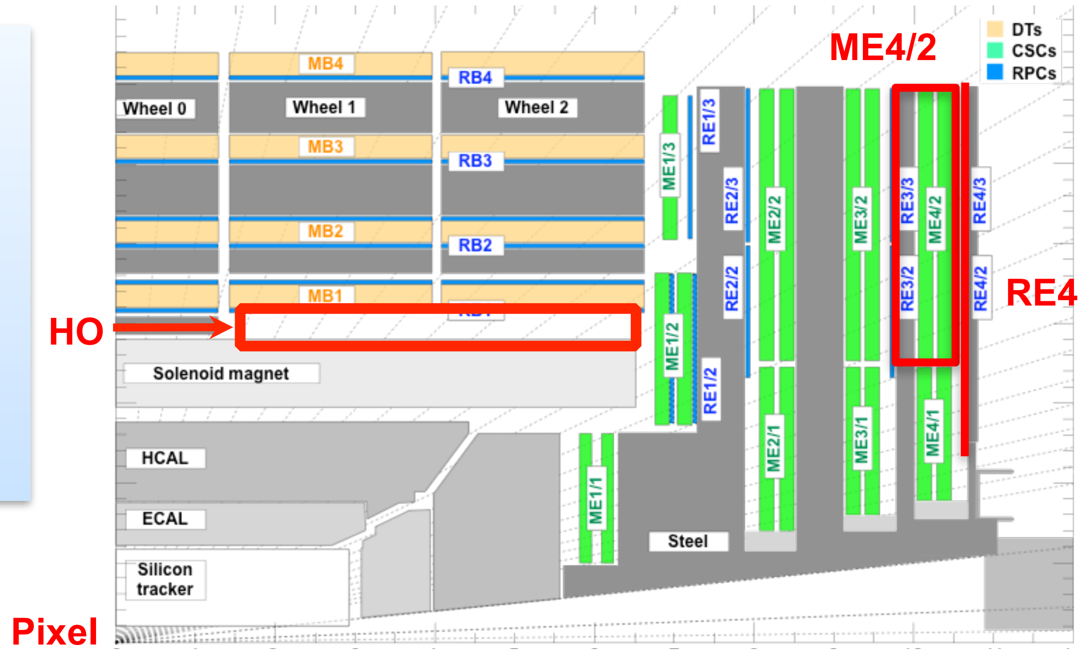
- With LHC 13/14 TeV data until ~2022 (~300 fb^{-1})
  - Measure SM-like scalar boson properties
    - mass, J^{PC}
    - individual couplings with 5-15% precision
  - Search for new physics at a higher scale (new energy region)
    - SUSY
    - Exotics
- With HL-LHC 14 TeV data until ~2032 (~3000 fb^{-1})
  - High Precision SM scalar boson measurements
  - Study Higgs boson rare decays and self-coupling
  - Study VV scattering
  - Characterize any New Physics discovered during Phase 1 at 14 TeV
  - Search for new physics in very rare processes

Higgs Physics at HL-LHC

- The High-Luminosity LHC has been identified as the **highest priority program in High Energy Physics** by both the European Strategy Group and the US Particle Physics Project Prioritization
- What can we do at HL-LHC in the Higgs sector?
  - Measure existing decay channels with the highest precision
  - Observe rare Higgs decays
    - $H \to \mu\mu$
    - $H \to Z\gamma$
    - $H \to cc$ (?)
  - Double Higgs production (Higgs self-coupling)
  - Vector boson scattering
  - Look for small deviations from SM predictions

CMS upgrade program

LS1 Projects
- Complete Muon coverage (ME,RE4)
- Improve muon operation, DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD→SiPMs)
- DAQ1→DAQ2
- L1 Trigger upgade



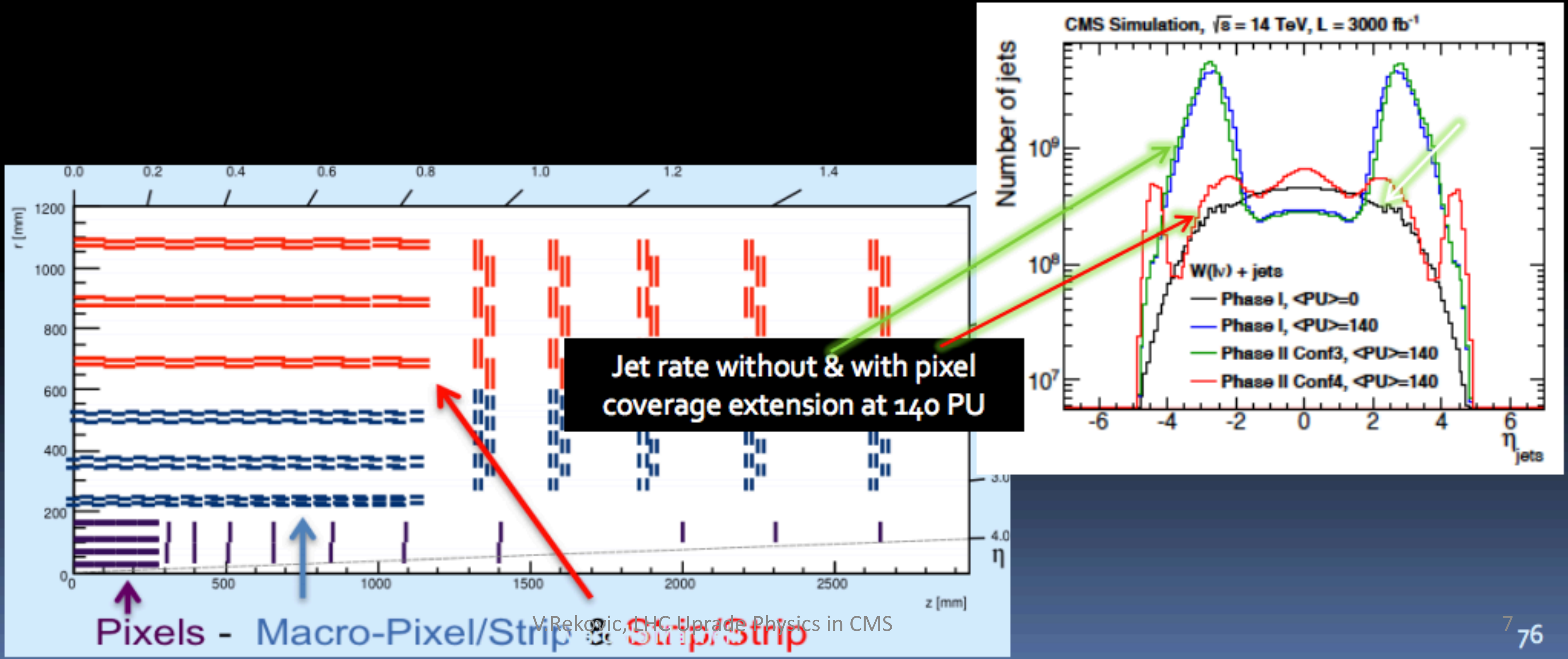
LS1 LS2 (2018) LS3 (~2023)

Phase 1 Upgrades
- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- GEMs for forward muon detector

Phase 2 Upgrades:

Tracker replacement, L1 Track-Trigger
- Forward: calorimetry, muons and tracking
- High precision timing for PU mitigation
- Further Trigger upgrade (higher granularity)
- Further DAQ upgrade

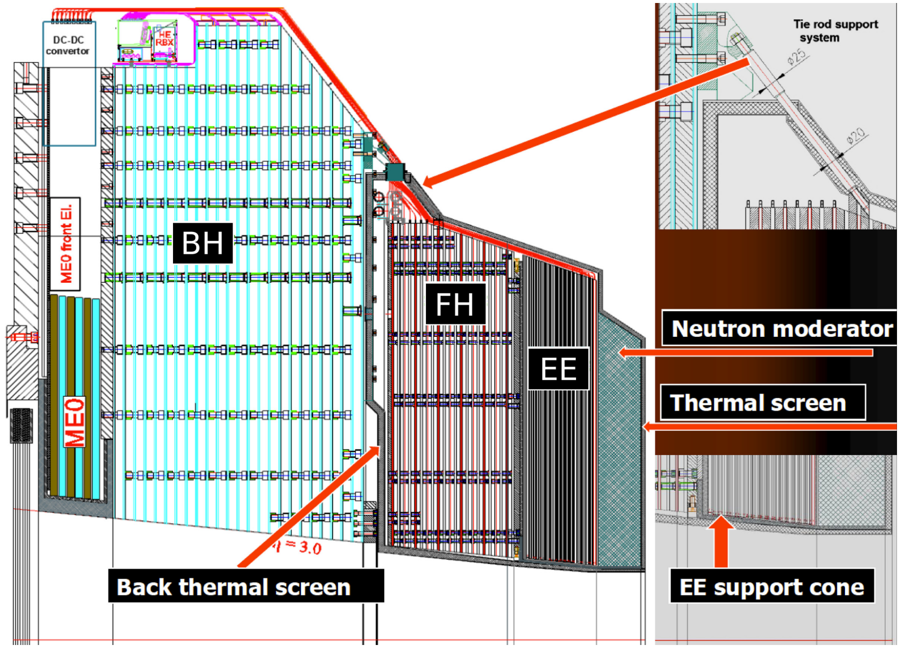
- Extension of Pixel coverage up to |η|~ 4
  - Reduce rate of fake jets due to PU for VBF/VBS physics
  - Associate jets to tracks - vertex to mitigate pile-up effect
  - Expect significant improvements for all VBF processes: Higgs - BSM dark matter & for VBS



CMS Phase II – HGCal – Silicon-based Calorimetry

- In HL-LHC Pile-up will become ever more severe, making the identification of electromagnetic objects more challenging and swamping the relatively-isolated VBF and VBS jets with increasing QCD multijet background.

- New Calorimetry in the forward region high-granularity sampling calorimeter.
  - silicon/tungsten electromagnetic section
  - two hadronic sections, both using brass as the primary absorber material.
- Provide precision and radiation hardness

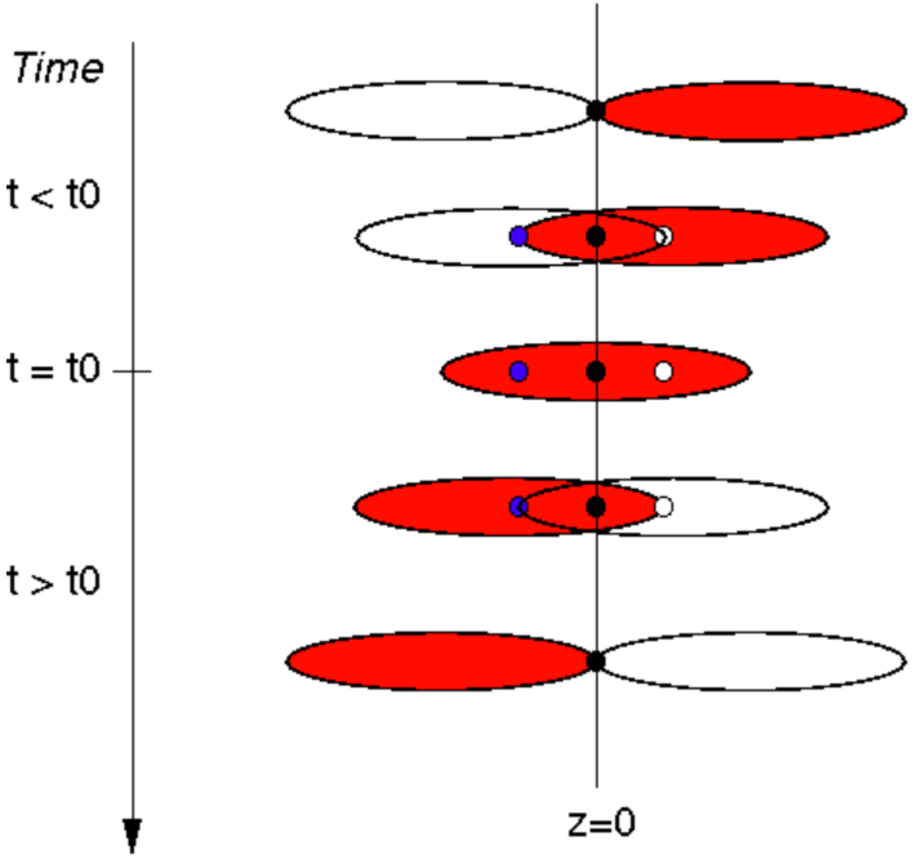


Calorimeter Pile-Up Mitigation

- Collisions are distributed over several cm in Z, and a few 100 ps in time.

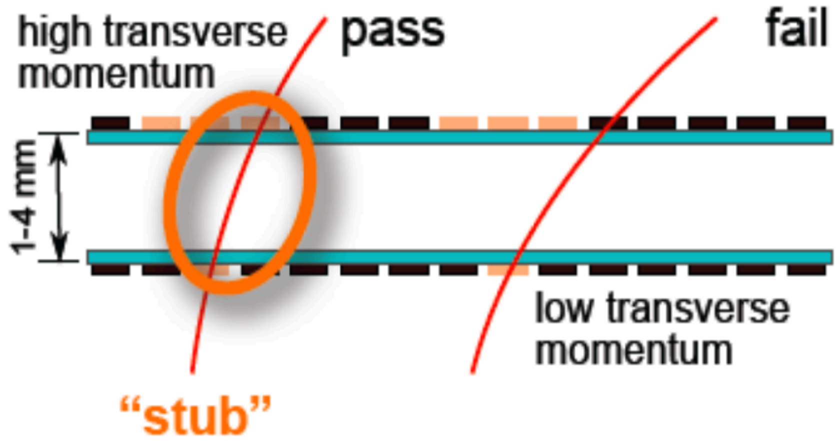
- Consider 10ps~20ps TOF calorimeter resolution for MIP's and γ, together with Tracker coverage:
  - Tracking identifies location Z0 of interesting collision vertex
  - TOF of charged particles from that collision identifies time t0 of interesting collision
  - Use Z location and time to select calorimeter clusters associated to Z0 & t0 of interesting collision
  - For H -> γγ use timing of γ's to produce reduced list of possibly compatible vertices, then select best match with similar criteria as for present analysis

- Ongoing discussion for TOF detectors in front of Barrel and EndCap Calorimeter



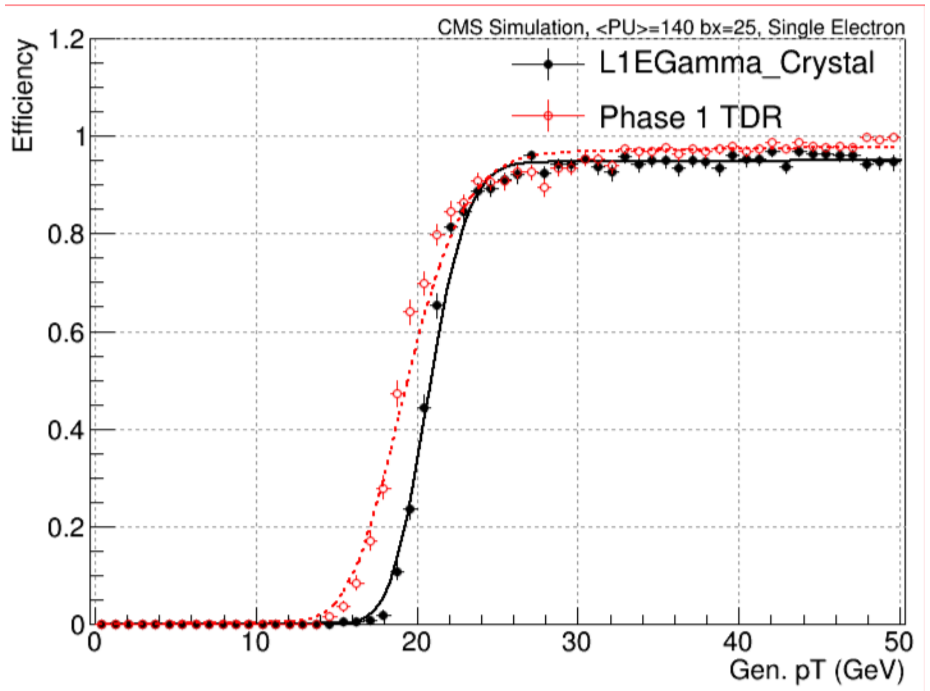
CMS Phase II Tracking Trigger

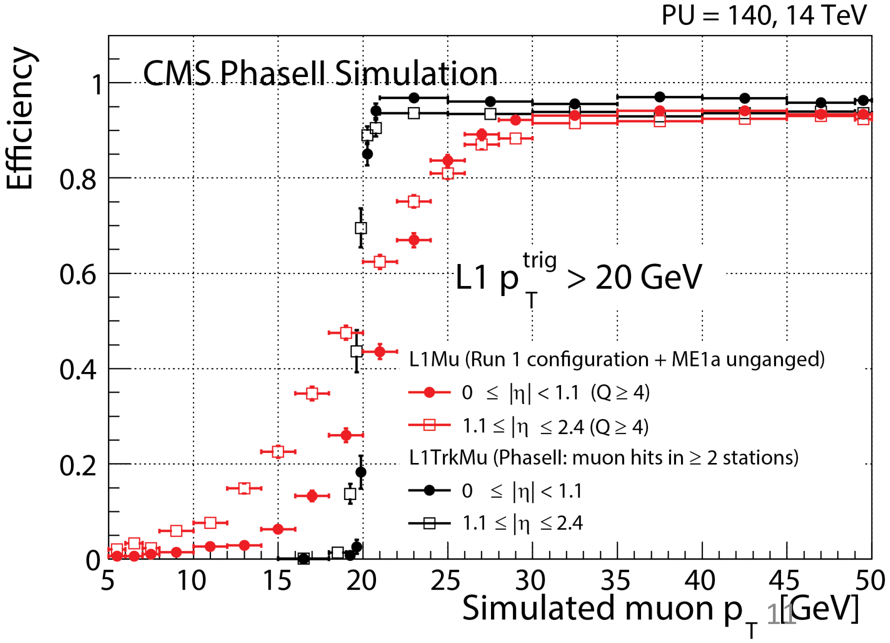
- Design modules with pT discrimination
  - Correlate hits in two closely-spaced sensors to provide vector (stub) in transverse plane: angle is a measure of pt
  - Exploit the strong magnetic field of CMS
- Level-1 “stubs” are processed in the back-end
  - Form Level-1 tracks, pT above 2~2.5 GeV
  - Use to improve different trigger channels (rate reduction x 5-10 for lepton triggers)



CMS Phase II Trigger

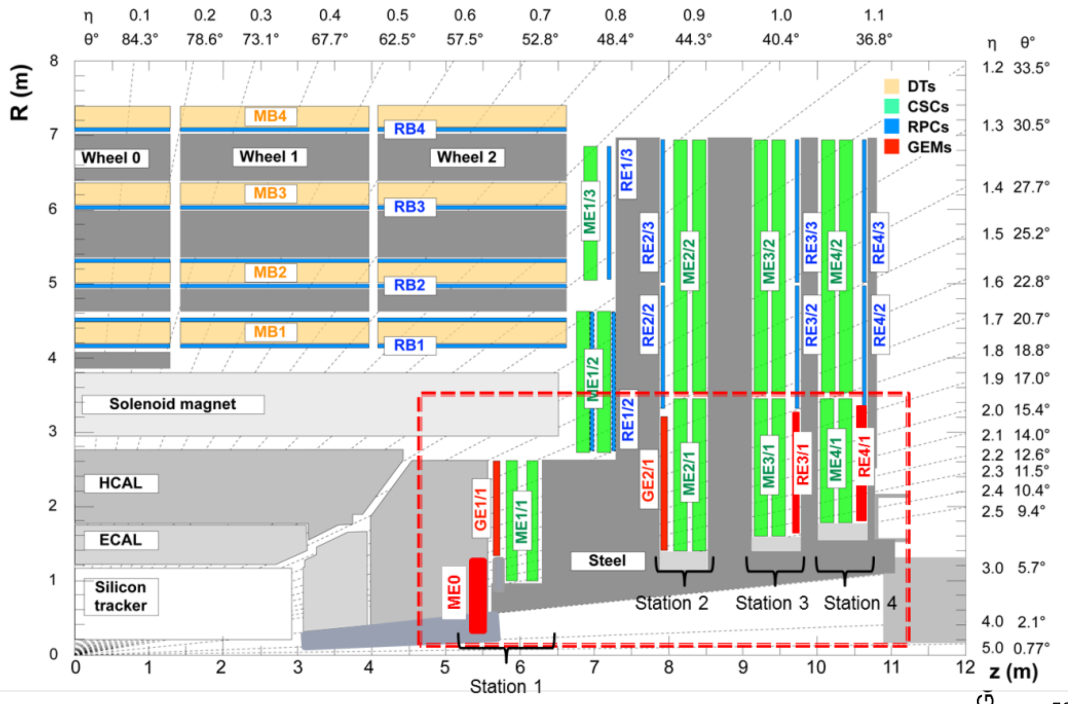
- Replace Ecal Barrel and Endcap Front End electronics
  - Latency 12 μsec
  - Provide individual crystal level (not 5x5 sums) trigger information
- L1 Accept rate ~750 kHz
  - More acceptance lower threshold
- Tracking trigger
  - Leptons: Pt cut & isolation. Jets: vertex
- New L1 Trigger (Calorimeter, Muon, Global) take advantage of Track Trigger and correlations b/w objects
- HLT output rate increase x 10, to 10 kHz

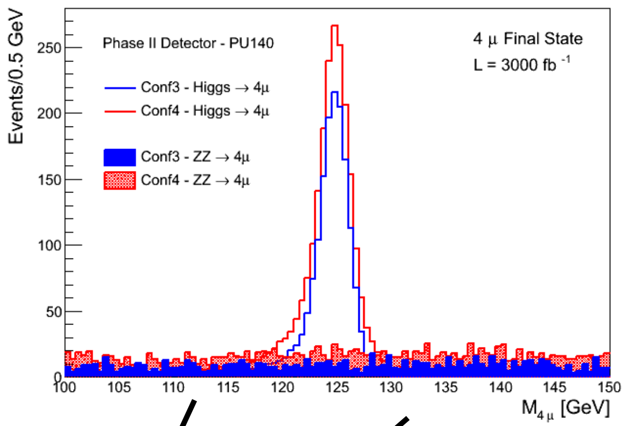


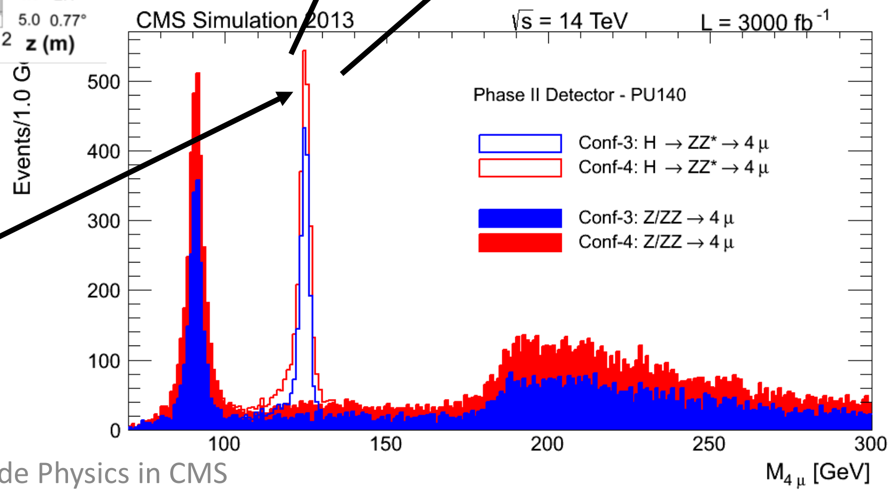


CMS Phase II Muon detector

Increase det. acceptance up to |η|=4.0







>40% more H→4μ events

CMS Higgs boson projections

- CMS reported the expected sensitivity of various Higgs boson analyses at the HL-LHC in, based on projections of 8 TeV measurements using 2012 CMS data, and DELPHES simulation studies incorporating the Phase-II detector upgrades.
  (CMS Phase II Technical Proposal)

- The studies presented here repeat and complement the previous public results at 300 fb^{-1} and 3000 fb^{-1}, updating the corresponding analyses techniques to their current status.

Higgs boson projections after LS1

Approaches adopted for physics projections

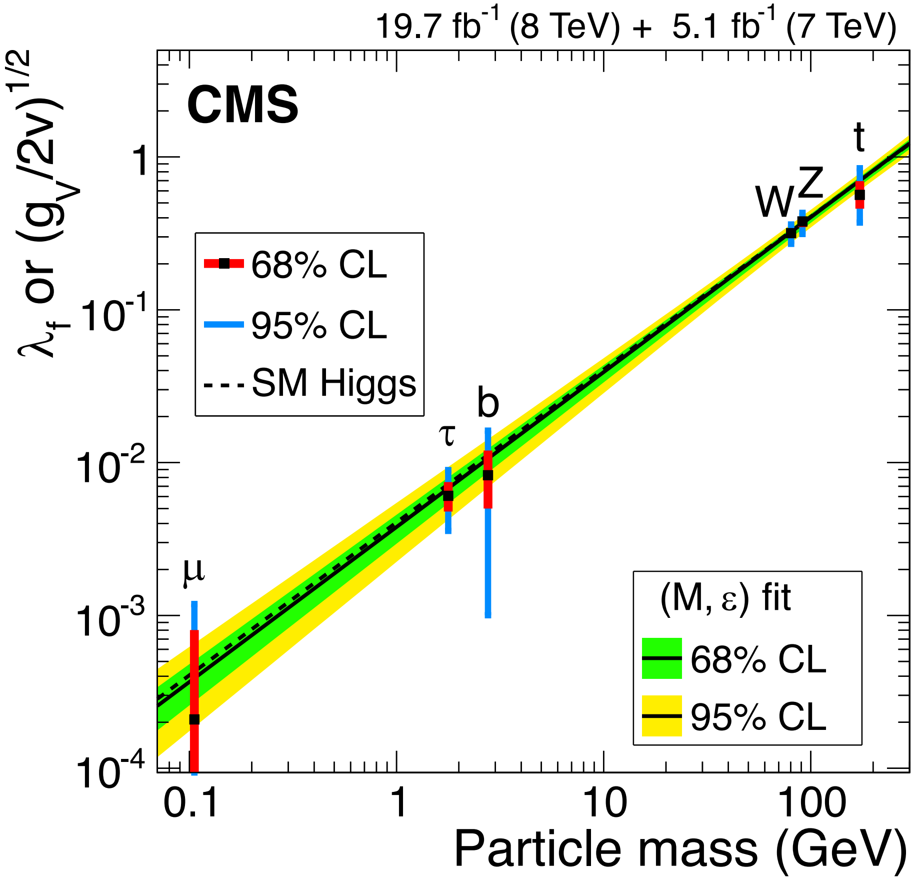
- **CMS**: projections are presented under four different scenarios assumed for the size of systematic uncertainties:

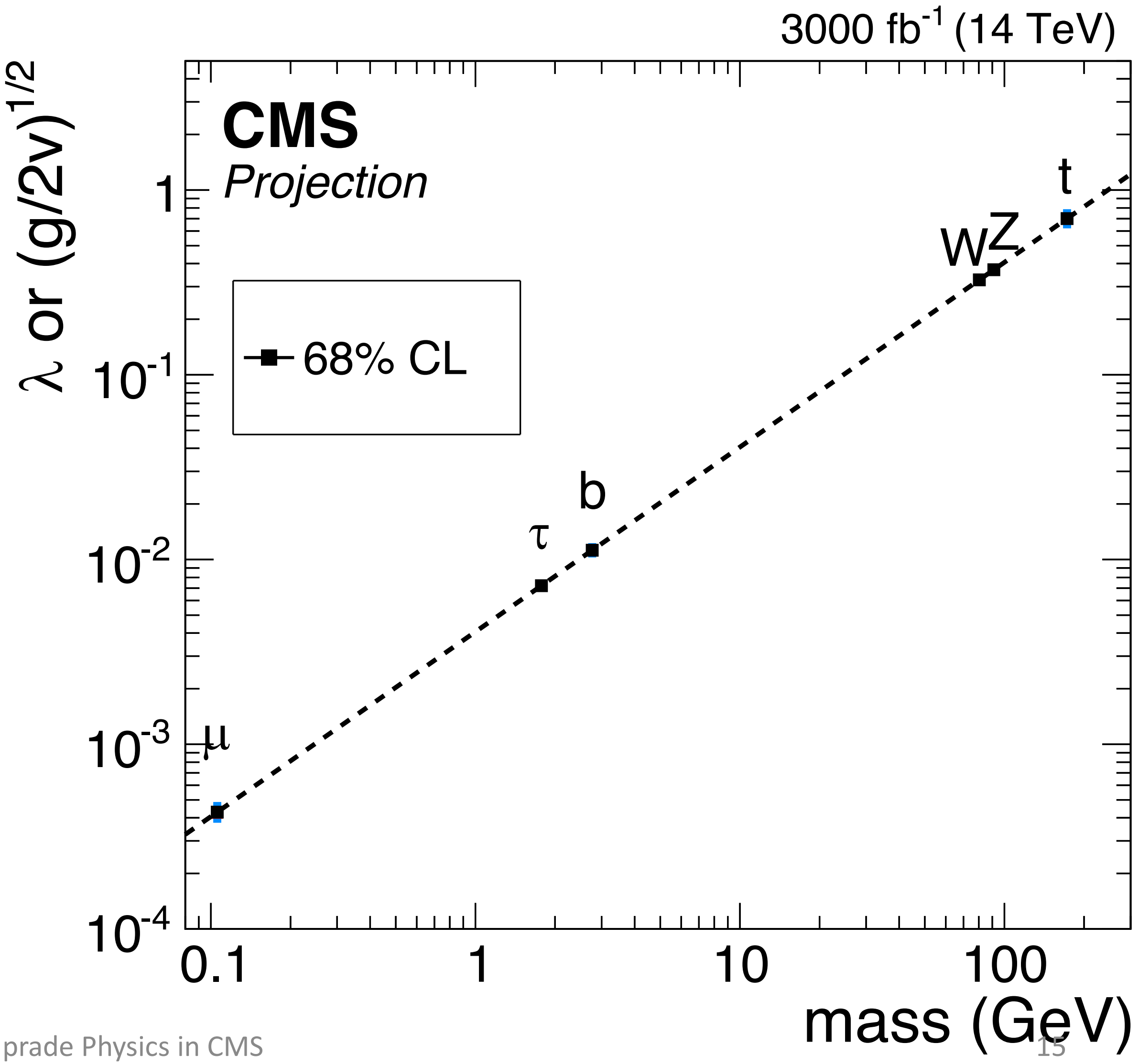
  - S1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
  - S1+ : S1 + effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account

  - S2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by $1/\sqrt{L}$ (till lower limit from estimates of achievable accuracy with upgrade detectors)
  - S2+: S2 + effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account

Higgs coupling ratios vs. mass

Mass-scaled coupling ratios vs. particle mass

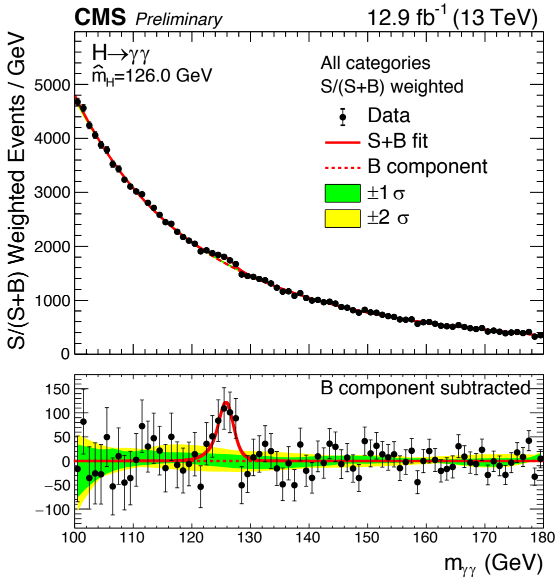


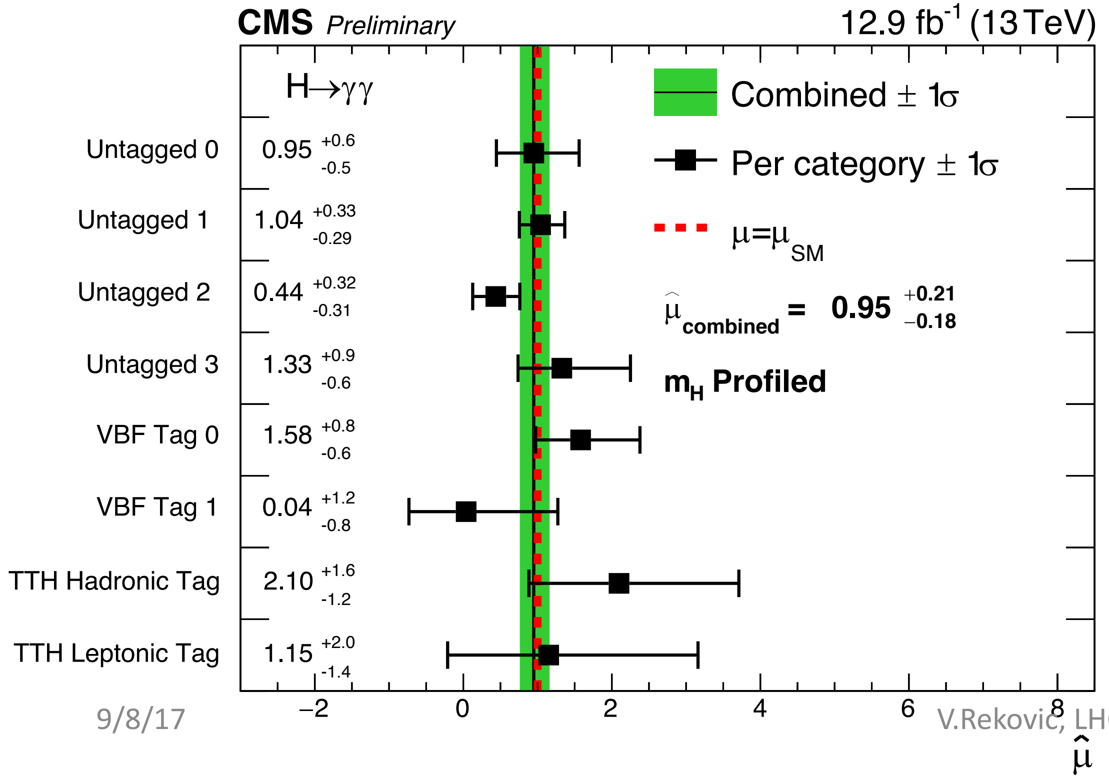


$H \to \gamma\gamma$

CMS-PAS-HIG-16-020

Reconstruct M(***γγ***)
Must know E(***γ***) and vertex.

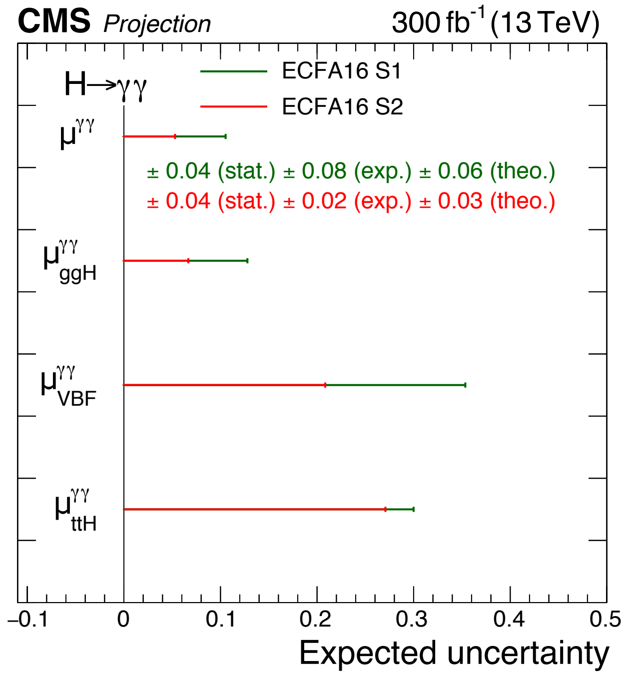


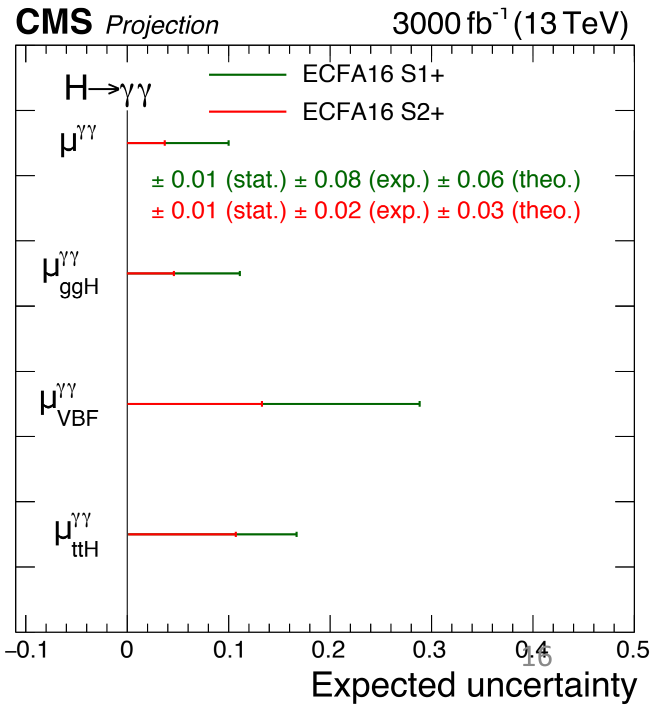


CMS-PAS-HIG-16-033

Project to 3000 fb^{-1}

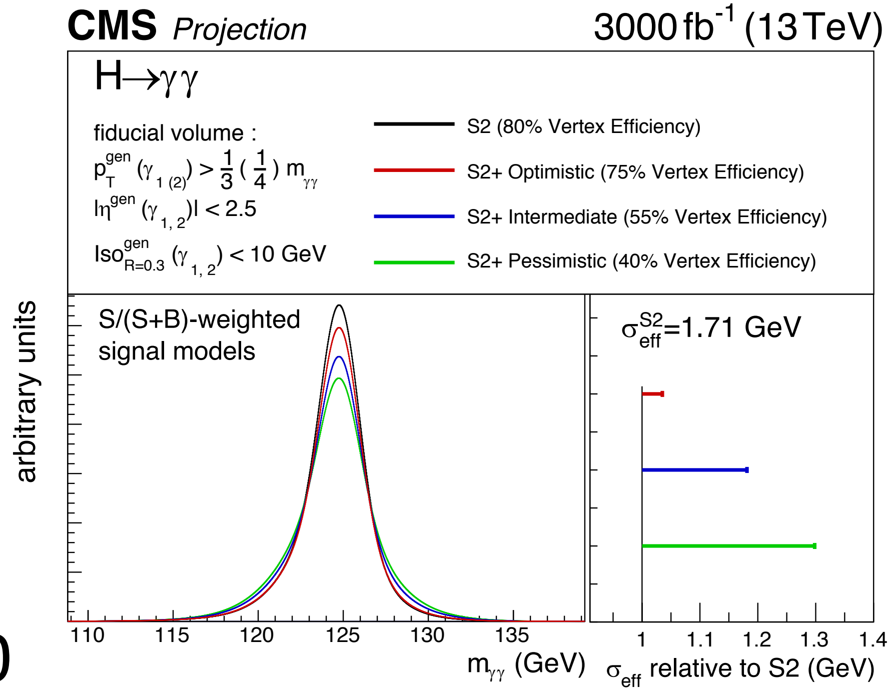
Leading experimental uncert
- Luminosity (reduced~1.5%)
- JES

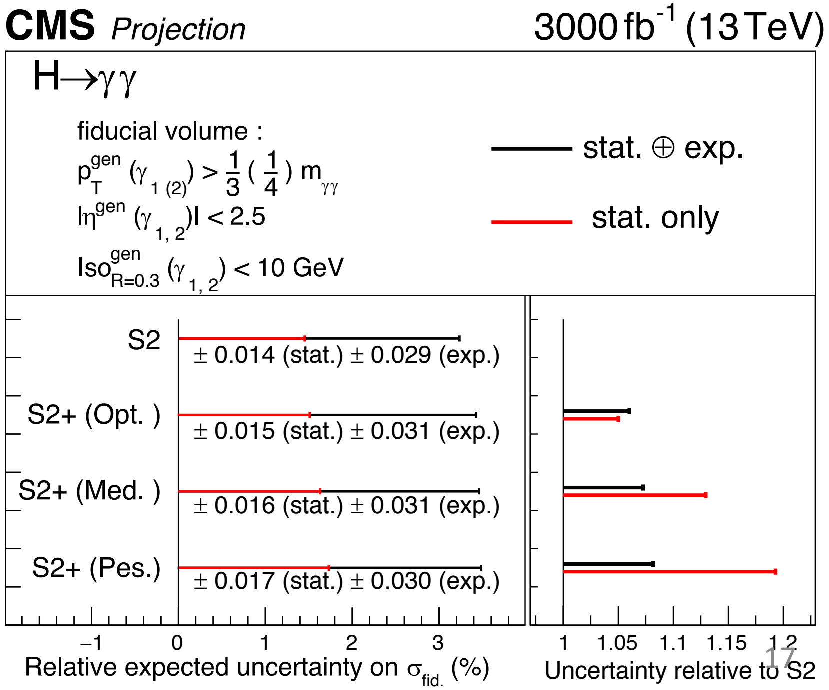




H→γγ *and Timing*

Vertex identification scenarios
S2 – 80% vtx id, no degradation due to PU
S2 pessimistic – 40% vtx id, 5% drop γ eff PU140
S2 intemediate – 55% vtx id (from timing for ***γ***)
S2 optimistic – 75% vtx id (from timing for ***γ*** and charged ptcls)



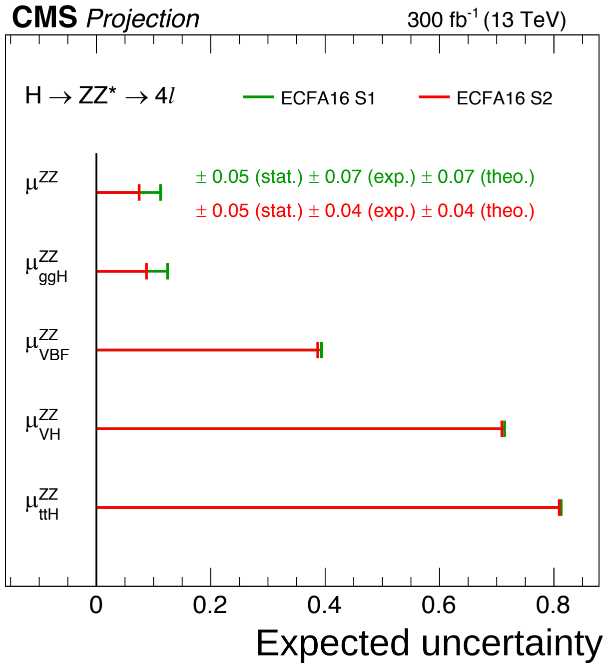


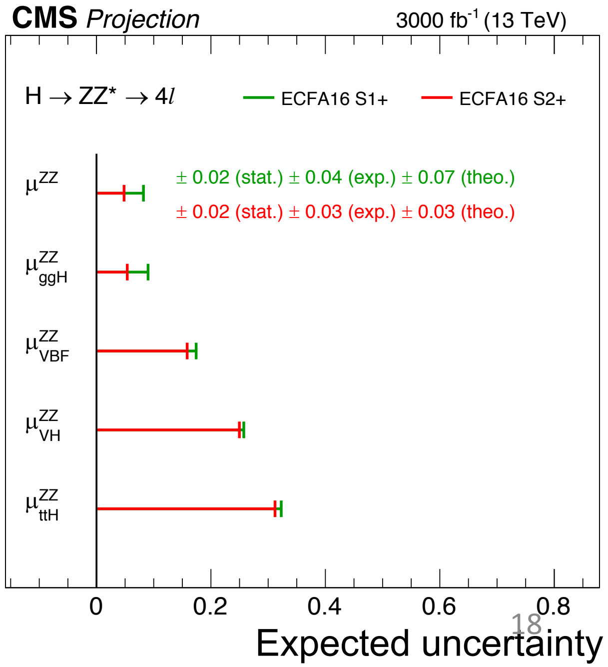
H→ZZ

Project from 2016 analysis with 12.9 fb^{-1} CMS-PAS-HIG-16-033

Uncertainties: integrated L (1.5%), lepton ID (1%)

Projections:
- Theory plays important role in ggH
- For the subleading production modes, the uncertainties are dominated by the statistical component
- At 3000 fb−1, the experimental systematics uncertainties (dominated by luminosity, JES, and lepton efficiencies) are slightly constrained, due to nature of the fit.



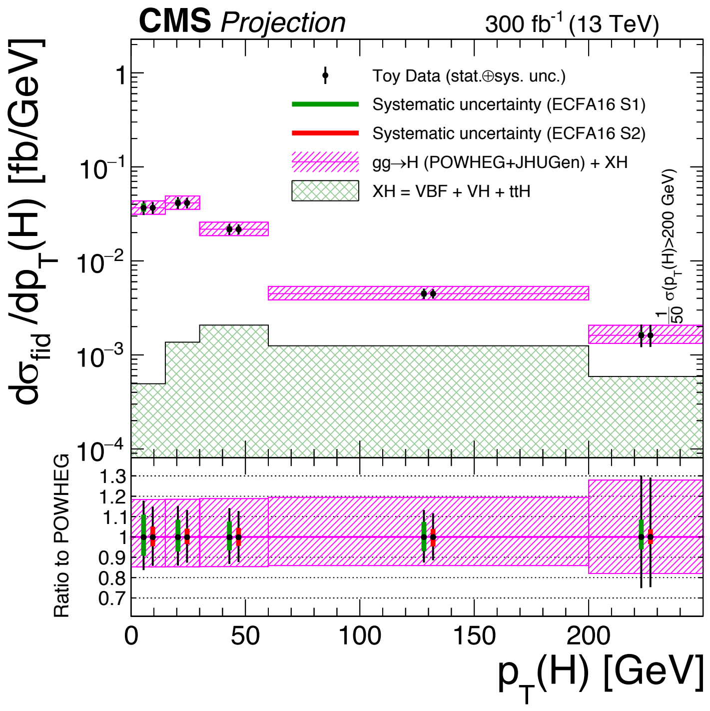


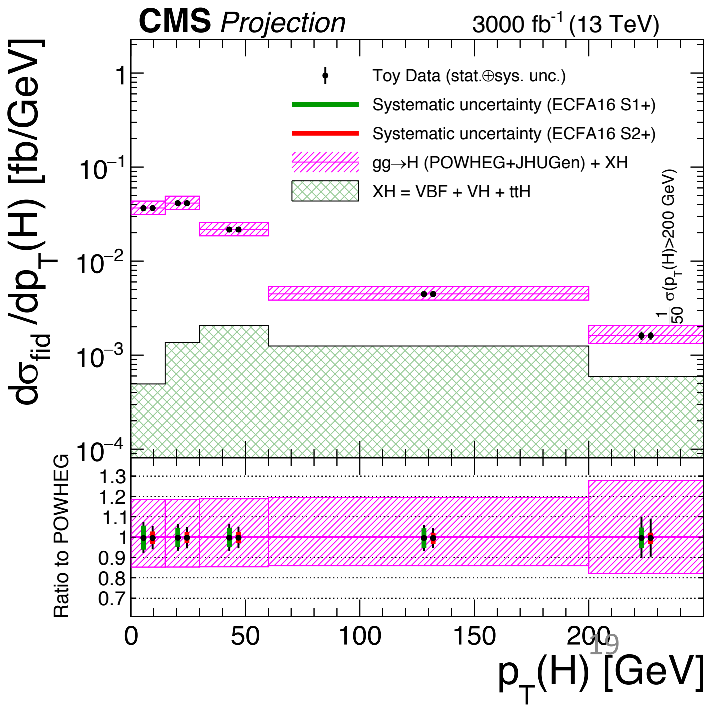
$d\sigma(H \rightarrow ZZ)/dp_T$

In this measurement, the theoretical un- certainties in the total signal cross section are not relevant and the cross section is measured in a fiducial phase space closely matching the experimental acceptance

Results of projections:

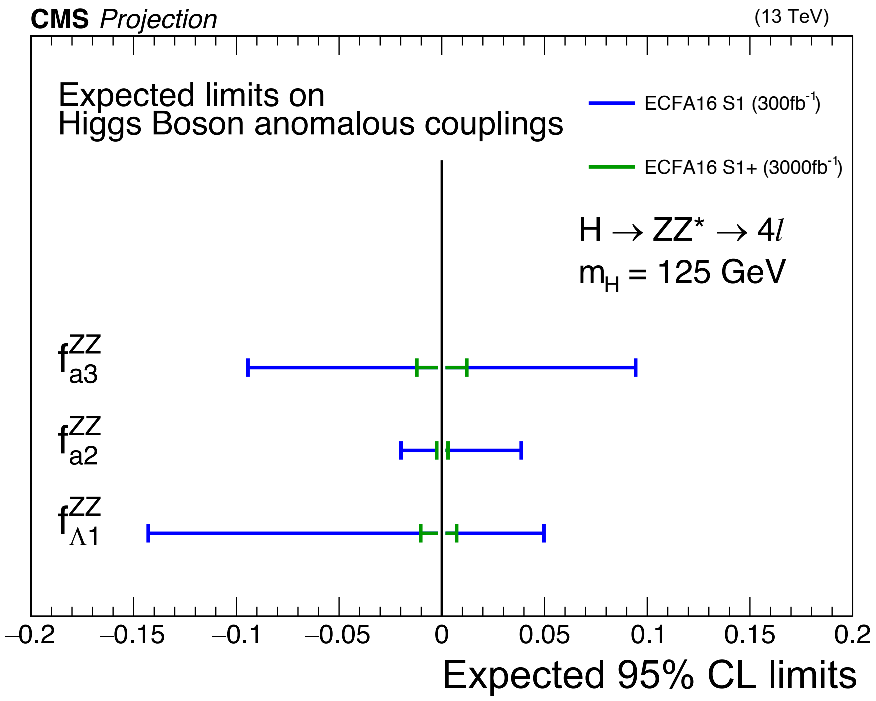
high p_T region (p_T > 200 GeV) is still dominated by the statistical uncertainty at 3000 fb−1.
- 10 to 29% (4 to 9%) for 300 (3000) fb−1.





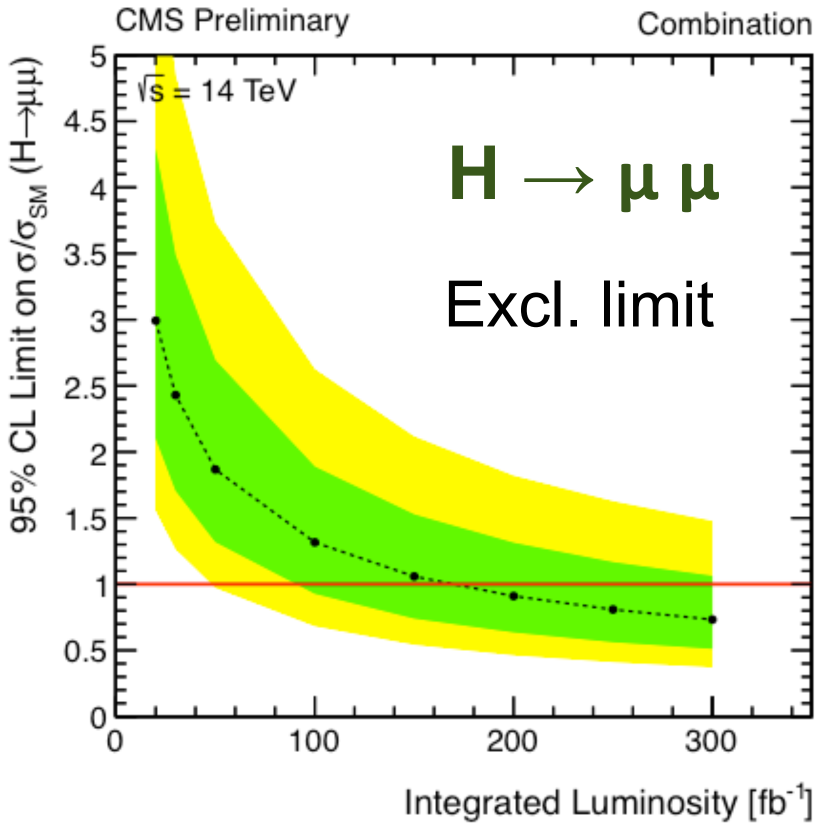
H→ZZ *anomalous coupling*

- Anomalous contributions in the spin-0 tensor structure of HZZ interactions can be characterized by coefficients a_2, a_3, Λ_1, and Λ_Q (**arXiv:1411.3441**)
- Only tensor structures proportional to *a*2, *a*3 and Λ1 are observable using on-shell H boson decay.
- Since the measurement is statistically limited, only scenarios S1 and S1+, where the systematic uncertainties are unchanged with respect to the reference analysis, are shown.

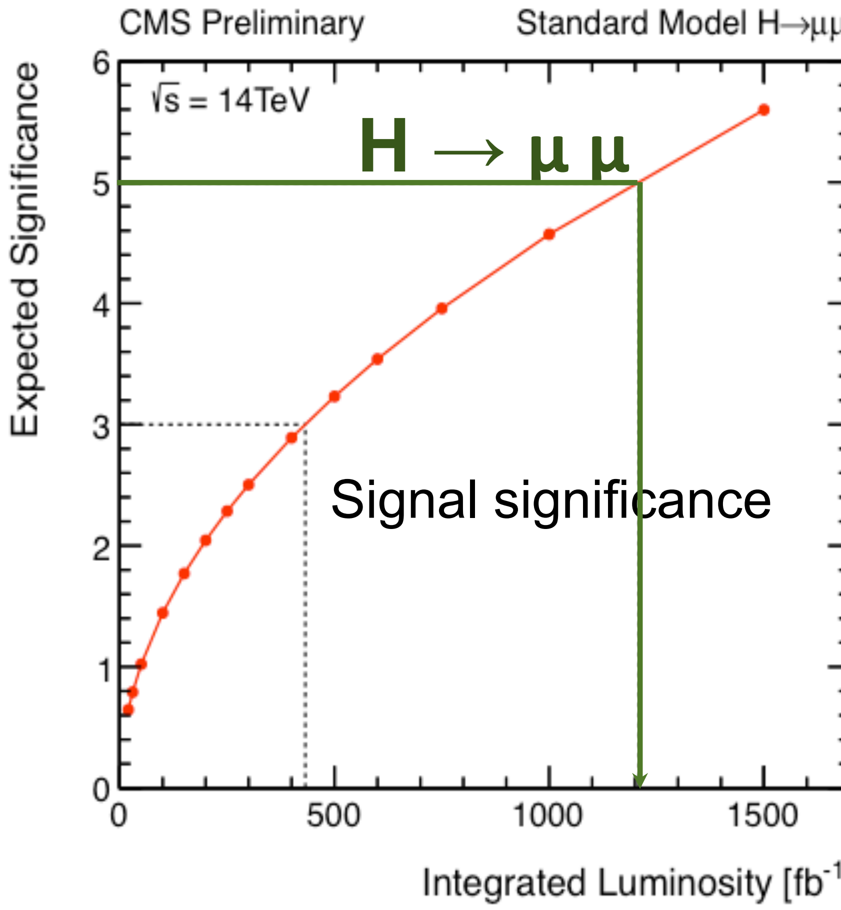


H→μμ

- Ongoing analysis with Run II data



- The decay H→μμ can be observed with a significance of 5 sigma
  - measurement of the Hμμ coupling with a precision of ~10%



H→cc

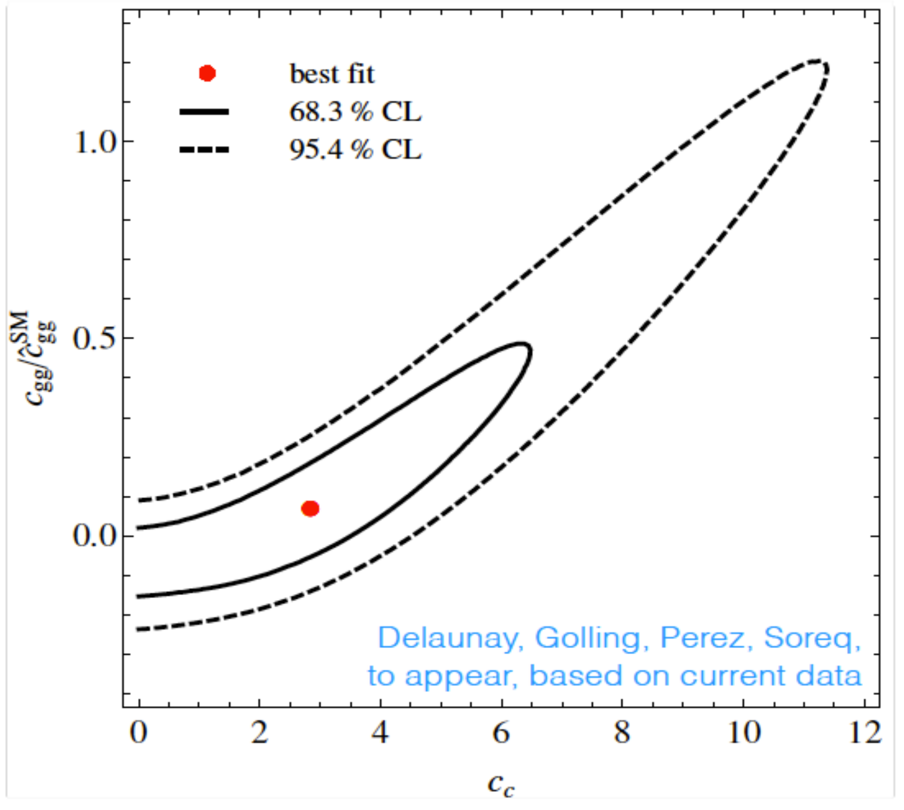
- Hcc coupling can still be 4-8 x SM

$$\mathcal{L} = c_c\, h\, \frac{m_c}{v} \bar{c}c + \ldots$$

- In composite Higgs

$$c_c \simeq 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(\epsilon_c^2 \frac{g_\psi^2 v^2}{m_\psi^2}\right)$$

large for composite charm and light charm partners



Measuring it?

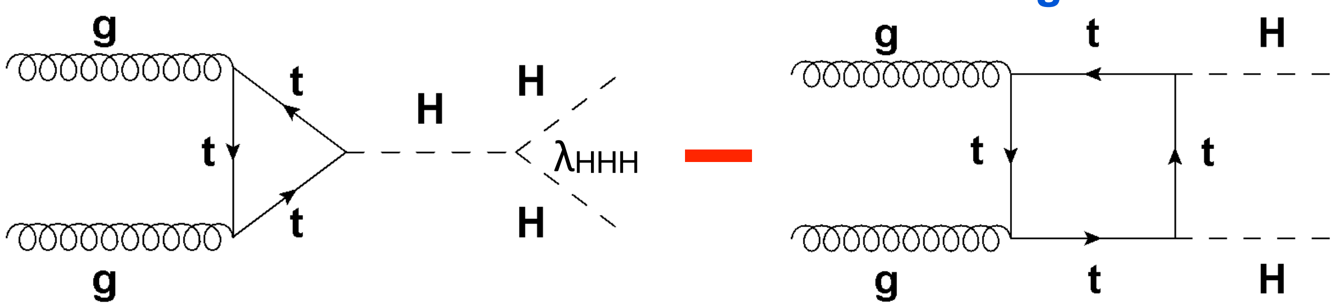
Like H→bb, but with charm tagging?

Or via H→ J/ψ γ ? 1306.5770

G. Salam, A. Weiler

SM Higgs boson pair-production

Destructive interference between the two diagrams



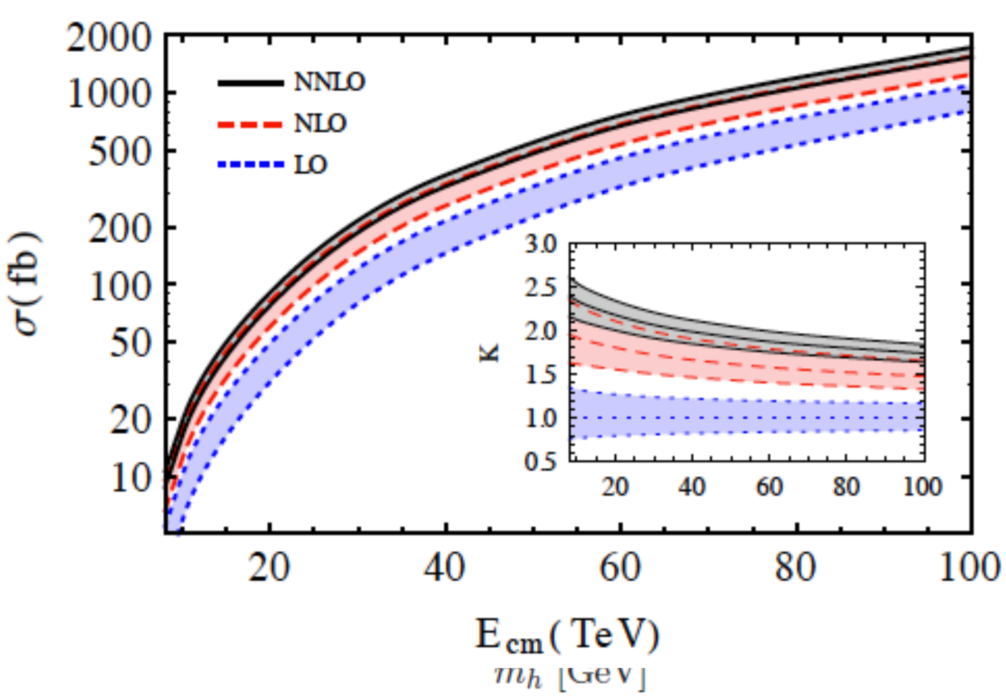
Many channels to investigate
Most promising ones:

$b\bar{b}W^+W^-$ (large BR but large bkg.)

$b\bar{b}\gamma\gamma$ (clean but small BR)

$b\bar{b}\tau^+\tau^-$
$b\bar{b}\mu^+\mu^-$ also being considered
$b\bar{b}b\bar{b}$
$b\bar{b}2l2\nu$

Taken from **"Higgs self-coupling measurements at the LHC"** by M. J.



NNLO cross-section at m_H=125 GeV:
σ = 40 ± 3 fb

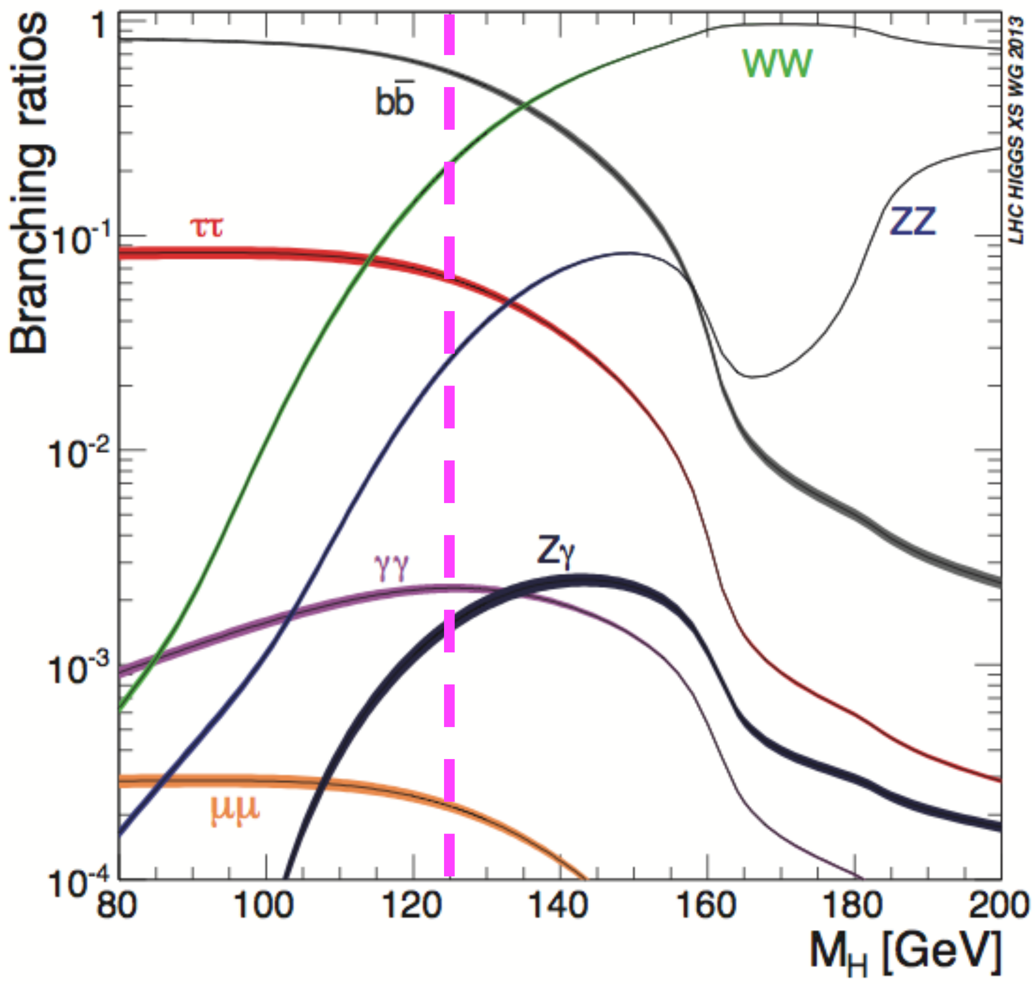
G. de Florian, J. Mazzitelli, 1309.6594

di-Higgs production with 3000 fb^{-1}

At HL-LHC with L=3000 fb^{-1} we will produce ~120000 HH events

However we pay a big price in BR's …

bƃW+W-	~14000 evt
bƃγγ	~ 150 evt
bƃ$\tau^+\tau^-$	~ 4300 evt
bƃ2l2ν	~ 730 evt

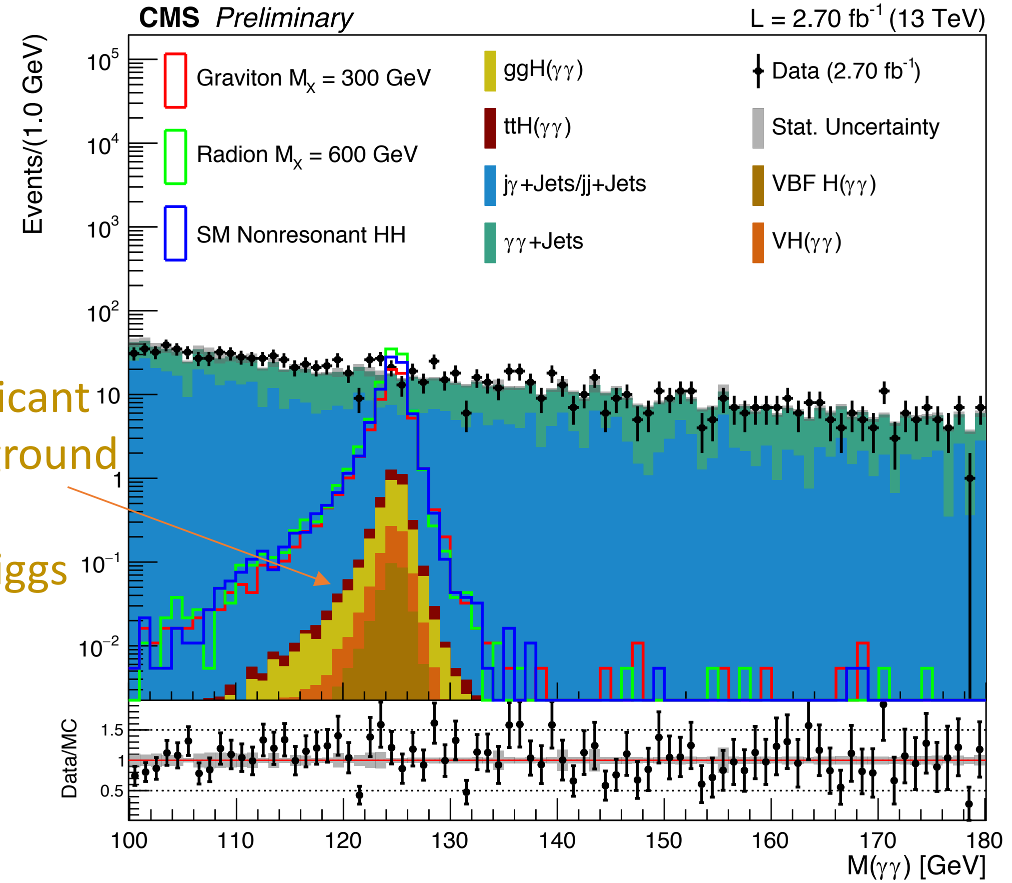


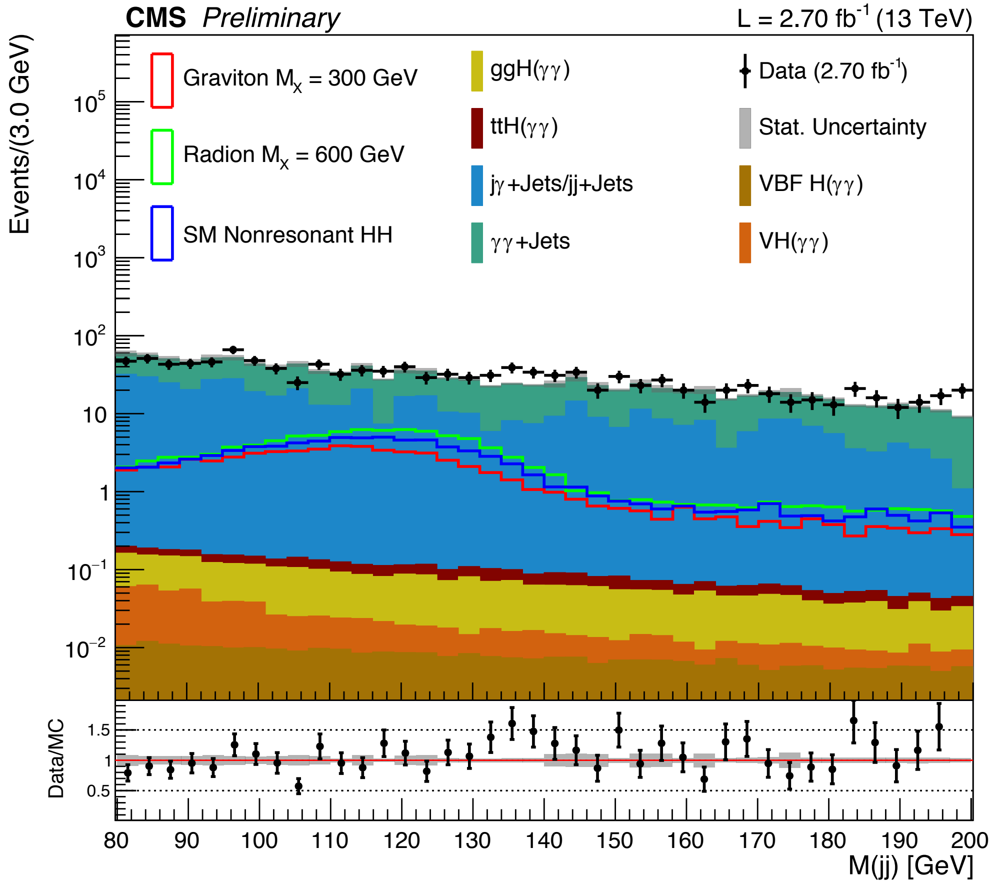
di-Higgs production @13 TeV with 2.7 fb^{-1}

Example: HH→bƃγγ: CMS-PAS-HIG-16-032

2D fit M(γγ) x M(bb)

Significant background from SM Higgs





project from Run II (2015 data 2.3 to 2.7 fb^{-1})

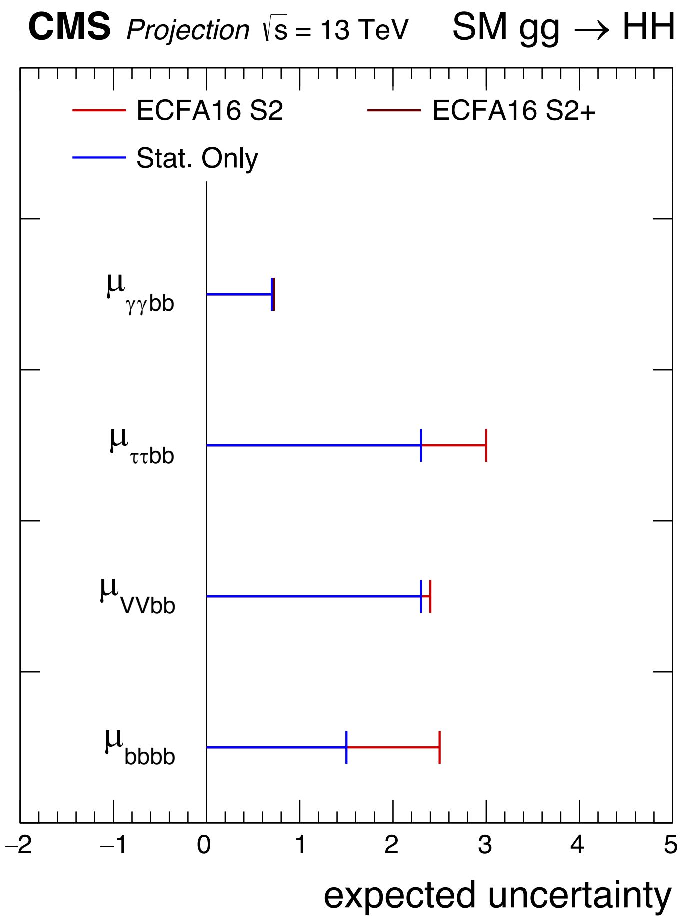
SM H→HH projections

$b\bar{b}\gamma\gamma$

γ efficiencies and uncertainties are treated in the same way as for the H → γγ. 90% of the photons coming from HH decays are central, neglect degradation of photon efficiency in the forward region

$b\bar{b}\tau^+\tau^-$

- current uncertainty of **tt shape** prediction is scaled down by a factor three to match the the estimated fraction of jets faking *τ* leptons at the HL-LHC.
- **QCD multijet** (subdominant background) obtained from data and therefore the statistical uncertainty is assumed to be negligible.
- ***μ*, e and *τ*$_h$** uncertainties are assumed to be that of 2015 analysis.



$b\bar{b}W^+W^-$

Main backgrounds, **tt** and **Drell-Yan** processes, are expected to be estimated from data and therefore their uncertainties are considered

$b\bar{b}b\bar{b}$

Main background, **QCD multijet** production, is estimated from data. and its uncertainty is scaled down with the integrated luminosity in the projection. The uncertainties in the predictions of the other backgrounds are assumed to be unchanged with respect to the 2015 analysis.

SM X→HH

Consider radion for 3 different masses, measure expected limits on cross section, and derive mass scale Λ_R (the ultraviolet cutoff of the model) at which the radion is excluded.

Table 6: Projection of the sensitivity to gg $\rightarrow X \rightarrow$ HH $\rightarrow$ bbbb production at 3000 fb^{-1} expected to be collected during the HL-LHC program. The 95% CL expected limits are provided for spin-0 resonance hypothesis with different mass assumptions.

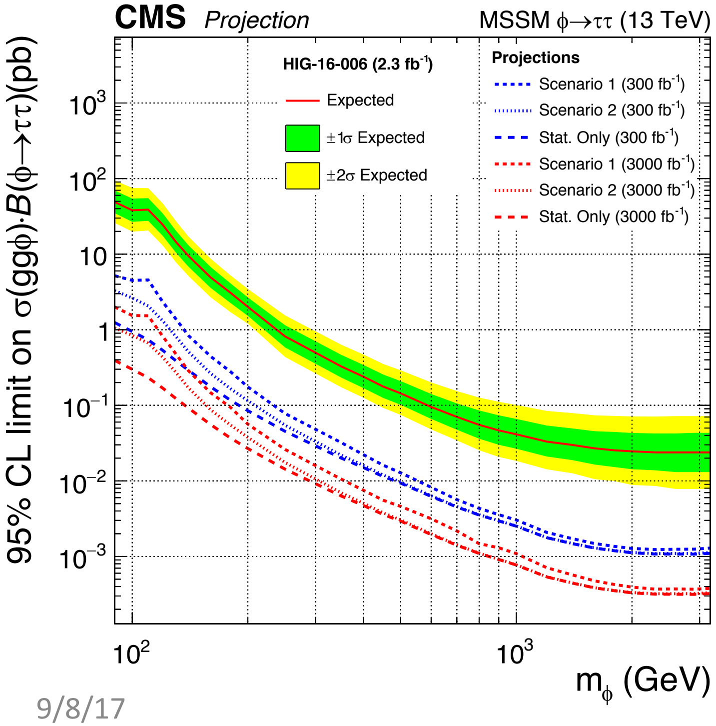
m_X (TeV)	Median expected limits on σ (fb) ECFA16 S2	Median expected limits on σ (fb) Stat. Only	$\sigma_R^{NLO}(\Lambda_R = 1\,\text{TeV})$ (fb)	Λ_R (TeV) excluded ECFA16 S2
0.3	46	41	7130	13
0.7	7.3	3.4	584	8.9
1.0	4.4	2.4	190	6.6

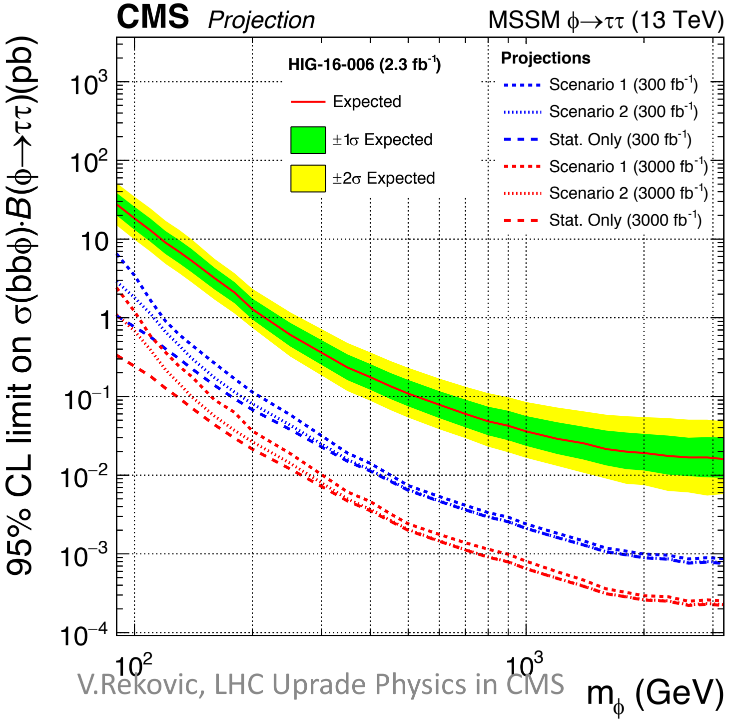
MSSM $\varphi \to \tau\tau$

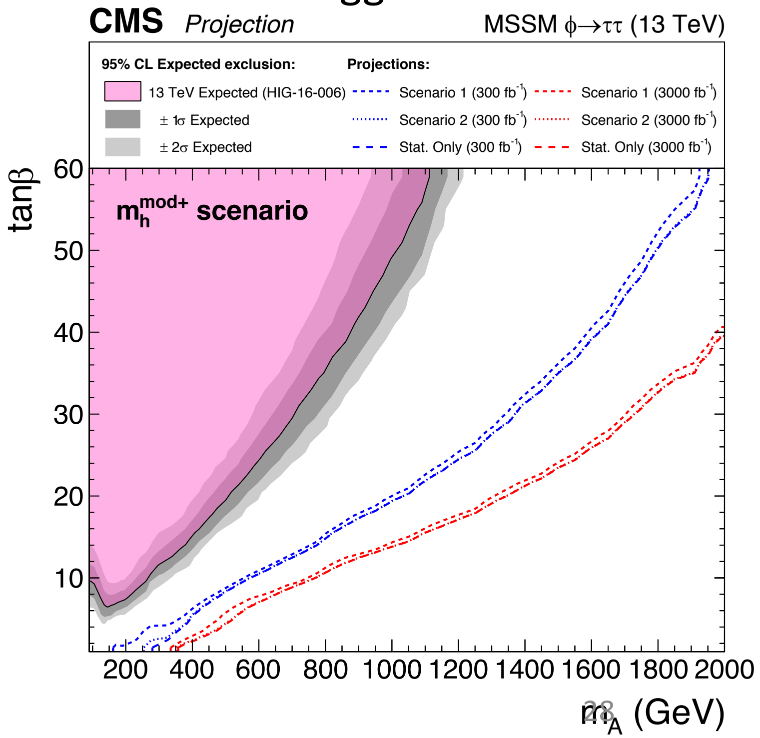
Final states of the two τ leptons: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ and $e\mu$.
Background: Drell-Yan (dominant) with a decay to τ lepton pairs, W+jets, tt, and QCD multijet

"model-independent": search for single resonance signal for a Higgs boson M[90 GeV, 3.2 TeV,] and decaying into τ leptons

"model-dependent" limit is set as a function of m_A and tan β in a particular MSSM benchmark scenario, combining the prediction from both production modes and all three neutral Higgs bosons







Conclusions

- The experience gained and on-track upgrades program suggest that CMS experiment will meet the physics expectation at HL-LHC with 3000 fb-1, @ √s=14 TeV and instantaneous luminosities of 5x1034 cm^{-2} s^{-1}
- Very rich Higgs program available with the upgraded CMS detector for the next 20 years despite very harsh conditions (high radiation, high pile-up)
  - Higgs boson couplings can be measured with few percent precision
    - 1-4 % statistical, experimental
    - 3-7 % theory - would be great if can improve to 1% level (call for help from theory community)
  - rare Higgs boson decays can be probed
  - Higgs self-coupling studies possible

Backup

- Extension of Pixel coverage up to |η|~ 4
  - Reduce rate of fake jets due to PU for VBF/VBS physics
  - Associate jets to tracks - vertex to mitigate pile-up effect
  - Expect significant improvements for all VBF processes: Higgs - BSM dark matter & for VBS