Challenges for the CMS detector at the HL-LHC for Higgs physics

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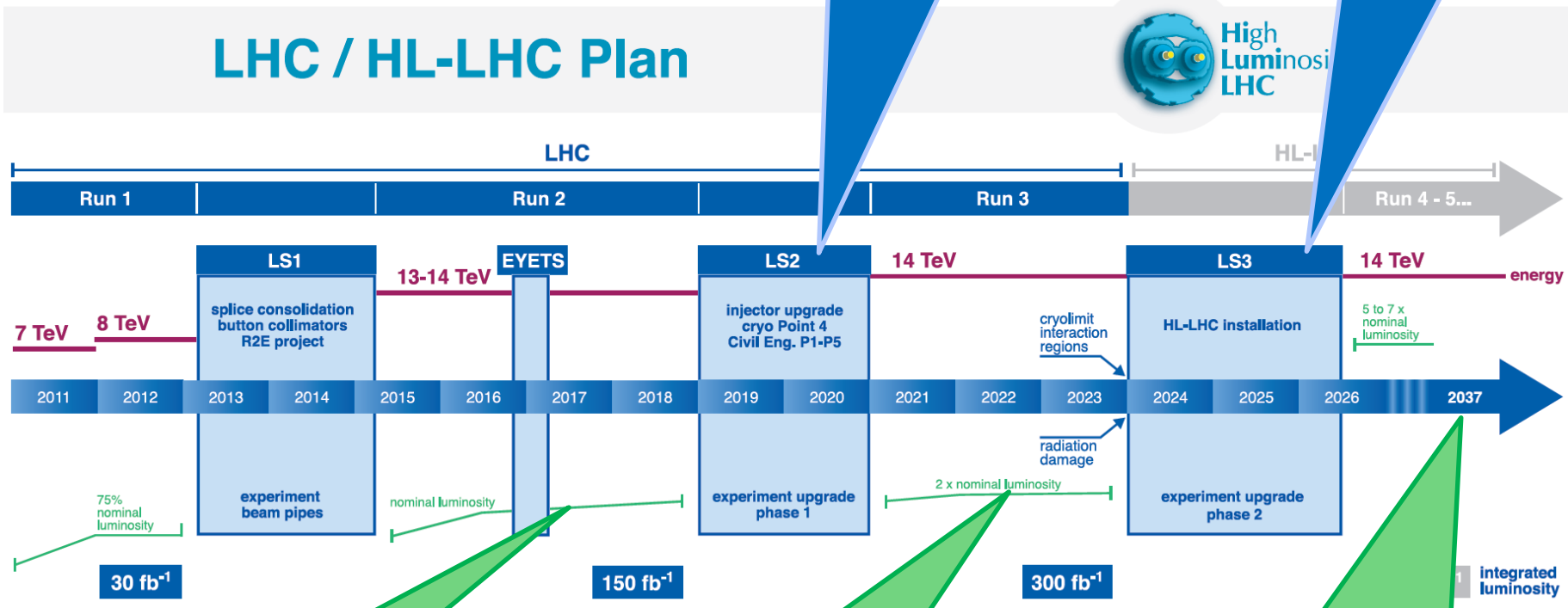
Outline

- LHC schedule
- Higgs Physics program at LHC
  - What do we want to measure?
- Summary of CMS HL-LHC Upgrades
- Main challenges
  - How does detector performance affect measurements?
  - What limits the measurements?
- Summary

LHC schedule

upgrade of injector chain to deliver brighter bunches

new quad triplets to focus beam at ATLAS and CMS decrease β^* to 10-15 cm



Run 2:
Design $\mathcal{L} = 10^{34}/\mathrm{cm}^2/s$

Run 3:
$\mathcal{L} = 2 \times 10^{34}/\mathrm{cm}^2/s$ for 300/fb

HL-LHC:
Peak $\mathcal{L} = 2 \times 10^{35}/\mathrm{cm}^2/s$ level luminosity to $\mathcal{L} = 5 \times 10^{34}/\mathrm{cm}^2/s$ for 3000/fb or $7.5 \times 10^{34}/\mathrm{cm}^2/s$ for 4000/fb

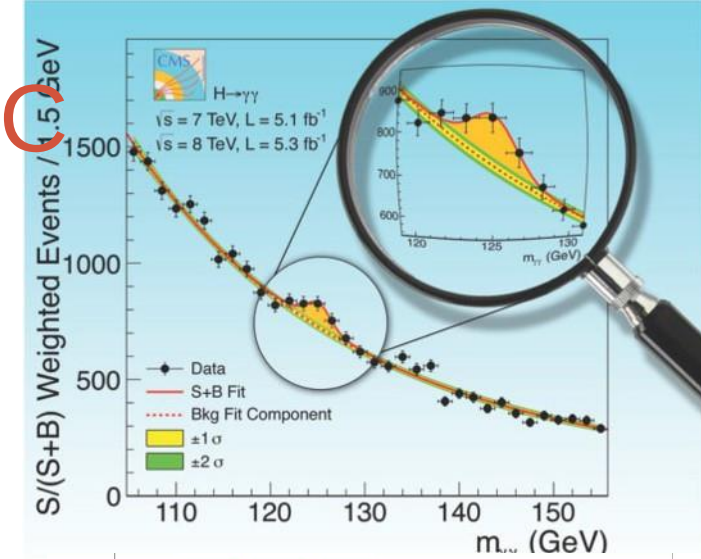
Higgs physics program at LHC

- ATLAS and CMS
  - Higgs boson discovery

    ATLAS Collaboration, Phys. Lett. B716 (2012) 1–29

    CMS Collaboration, Phys. Lett. B 716 (2012) 30–61
  - $m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\mathrm{GeV}$

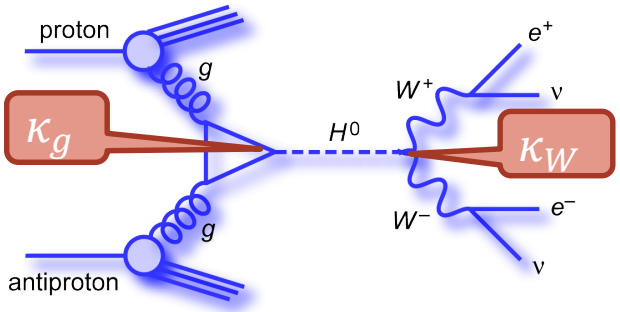
    ATLAS and CMS Collaborations Phys. Rev. Lett. 114 (2015) 191803



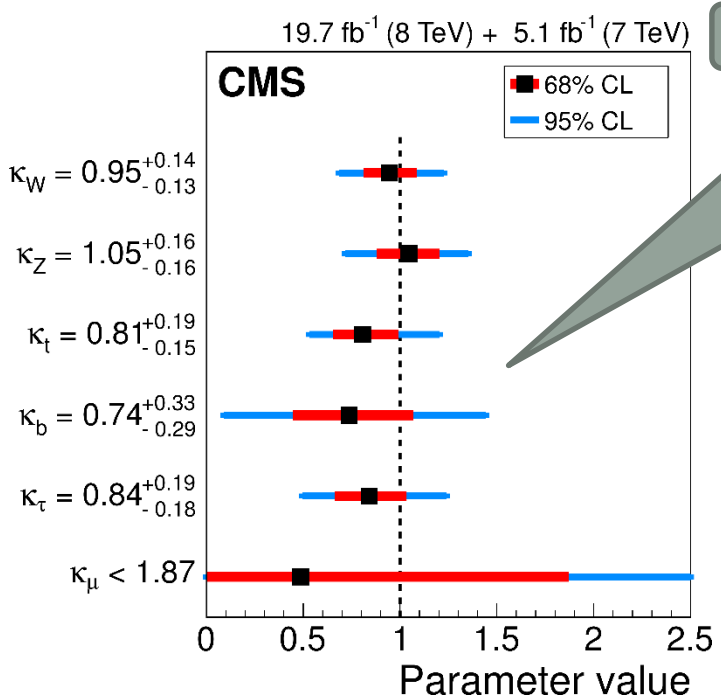
- SM predicts all properties of the Higgs boson without any free parameters
- Any deviations are evidence for new physics
- LHC is the place to study the Higgs boson in the next decade
- Measure the properties of the Higgs particle as precisely as possible to discriminate between new physics scenarios.

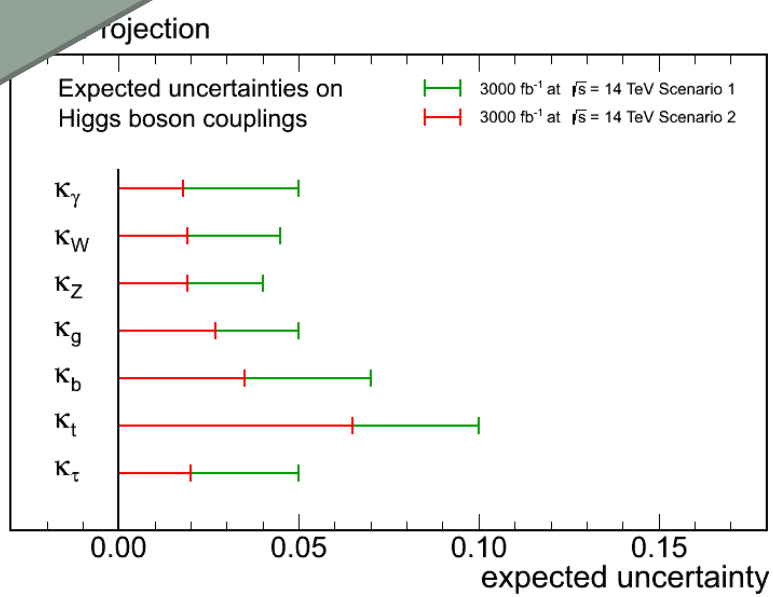
Coupling measurements

- The rate of a given process depends on several couplings
  - Example H→gg→WW: $\sigma B \propto \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$
  - The κ's multiply the SM couplings
  - κ_g is a function of κ_t and κ_b
  - κ_H multiplies the Higgs width and depends on all couplings



κ's are typically measured to ≈20%

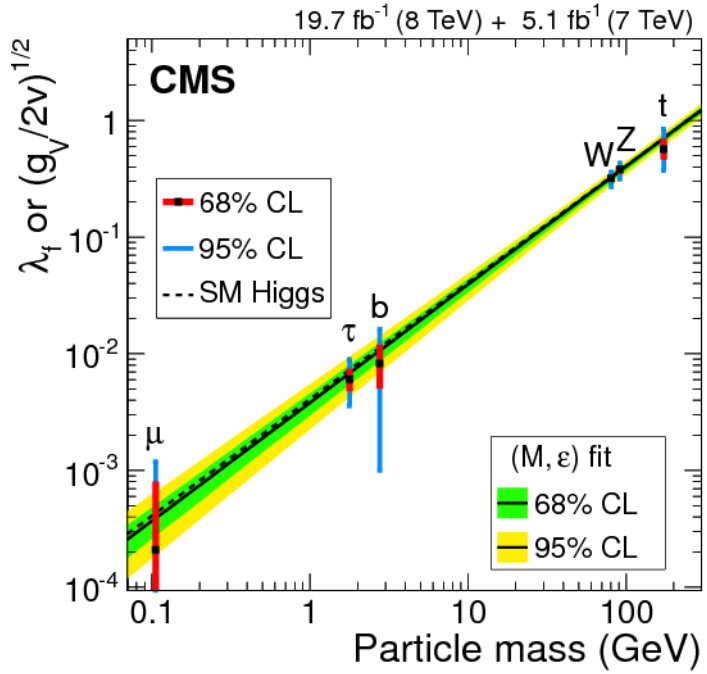


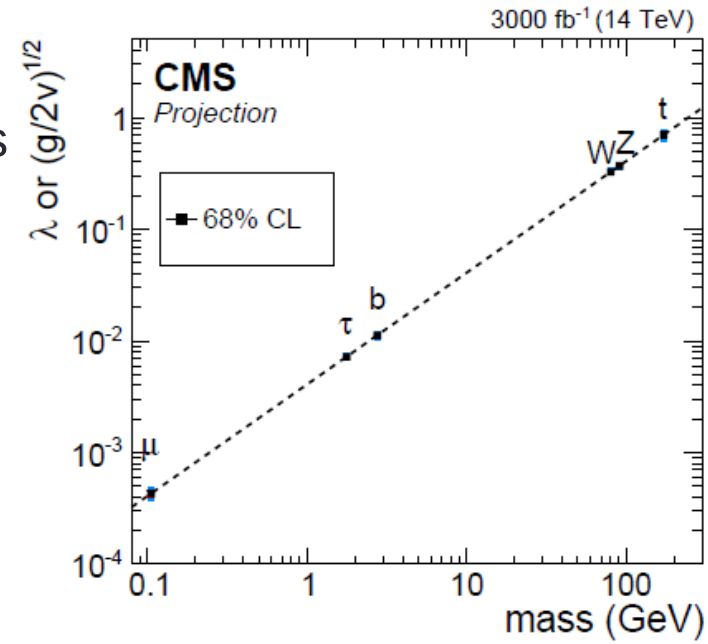


Is it "the Higgs boson"?

- In the SM the Higgs couplings depend on particle masses
  - Fermion couplings ∝ mass
    - $\mathcal{L} = \frac{\lambda_f v}{\sqrt{2}}(\bar{f}_L f_R + hc)$ with $m_f = \frac{\lambda_f v}{\sqrt{2}}$
  - Gauge boson couplings ∝ mass^2
    - $\mathcal{L} = \frac{1}{2}\left(\frac{gv}{2}\right)^2 W_\mu^t W^\mu + \frac{1}{2\cos^2\theta_w}\left(\frac{gv}{2}\right)^2 Z_\mu Z^\mu$
    - with $m_W = \frac{gv}{2}$ and $m_z = \frac{m_W}{\cos\theta_w}$
  - Measurements consistent with SM predictions
- Expected deviations from SM predictions

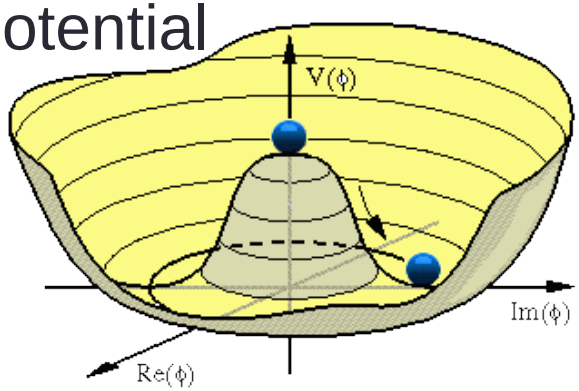
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

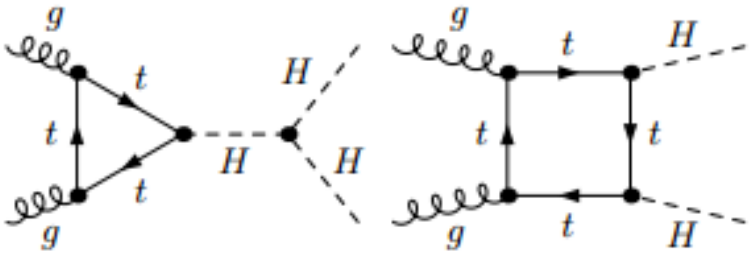




Higgs pair production and self coupling

- The Higgs self-coupling probes the Higgs potential
  - $V = -\mu^2 \Phi^t \Phi + \lambda (\Phi^t \Phi)^2$
  - with $v = \sqrt{\frac{\mu^2}{\lambda}} = 246\ \mathrm{GeV}^2$; $m_H = \sqrt{2\lambda} v = 125\ \mathrm{GeV}$
  - In the SM $g_{HHH} = 6\lambda v = \frac{3m_H^2}{v}$
  - Production gg → Top box or triangle
    - maximal destructive interference for SM

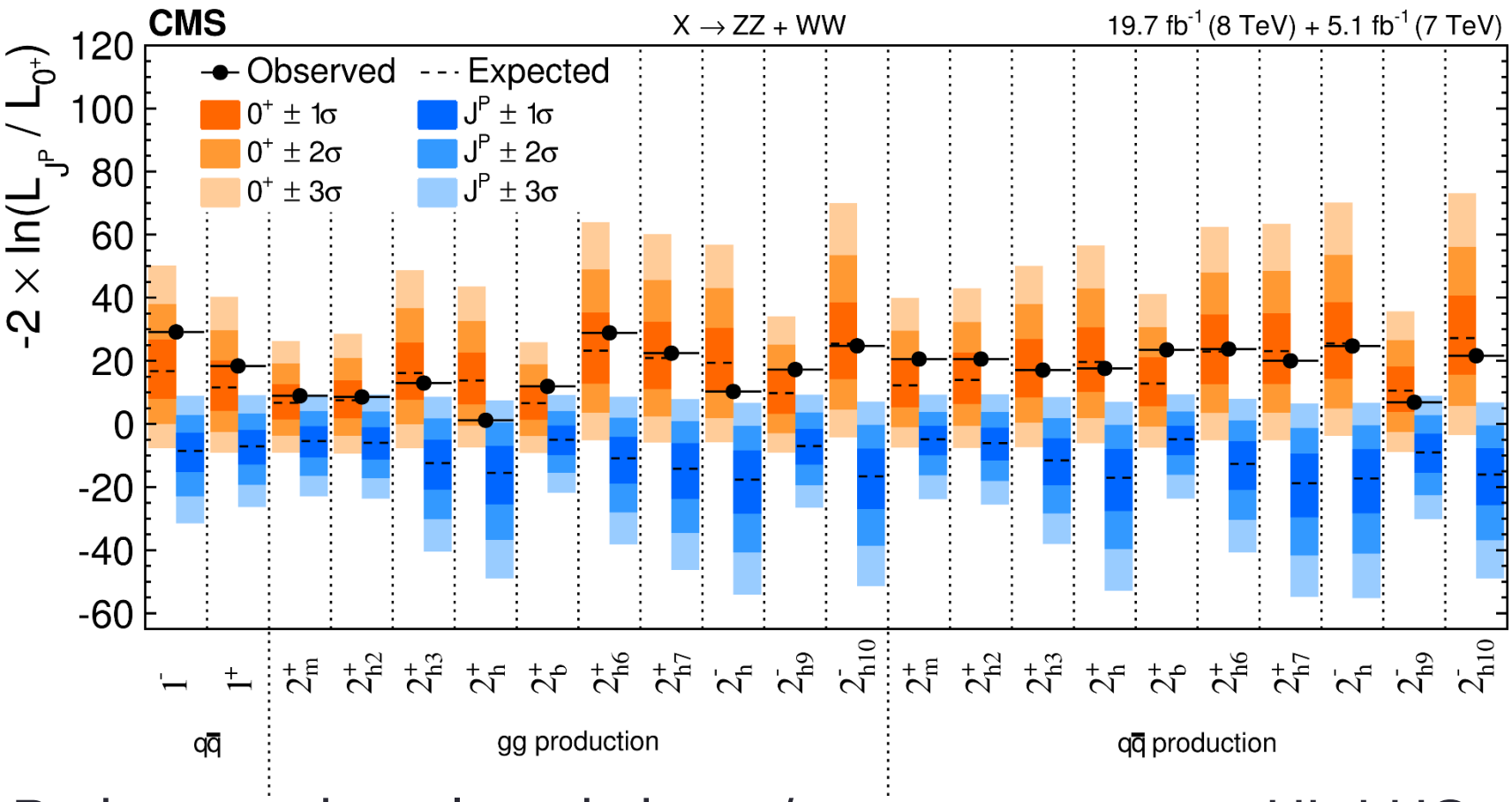




- Probe with Higgs pair production
  - SM $\sigma = 34\ \mathrm{fb}$ in 14 TeV pp collisions
  - Models with an extended Higgs sector modify g_{HHH} by typically 20%
  - HH resonances can also modify the HH production rate
  - Promising final states are bb$\gamma\gamma$, bbWW, and bb$\tau\tau$
  - Expected precision is 50%

CP structure and spin

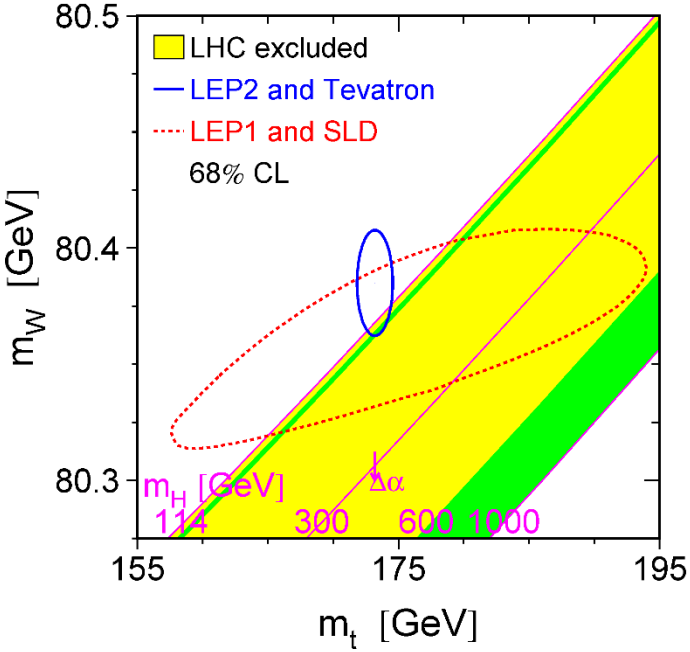
- Spin 0^-, 1, and 2 are excluded with high confidence

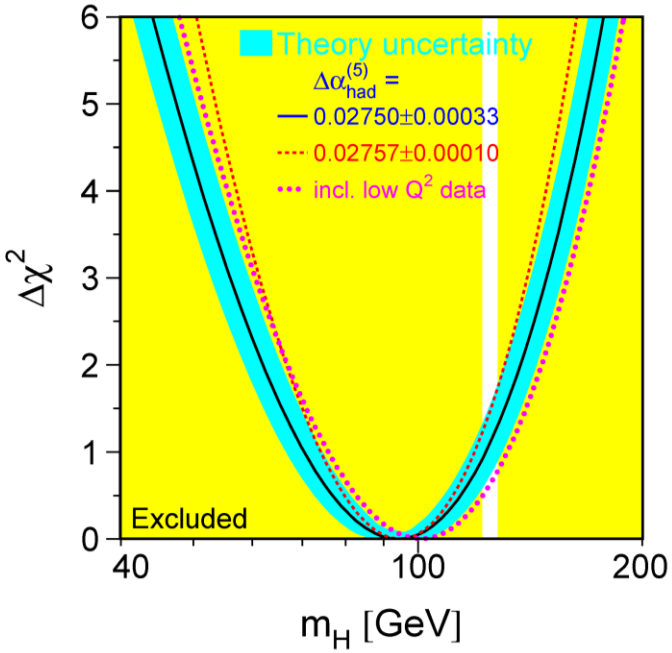


- Probe pseudoscalar admixture/tensor structure at HL-LHC

Higgs boson mass

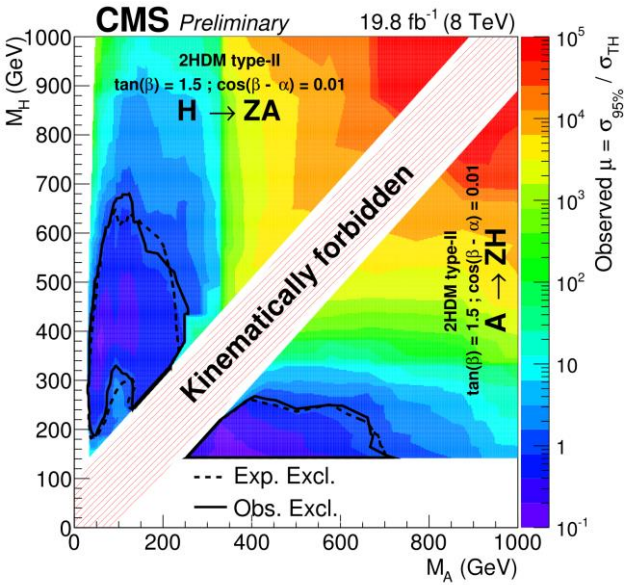
- Self-consistency test of the Standard Model
  - Radiative corrections involving the Higgs boson contribute to the SM prediction for the W mass.
  - electroweak fit $m_H = 94^{+29}_{-24}$ GeV
  - A discrepancy with the directly measured mass indicates new physics.
- Current precision of m_H is sufficient to make this test.
- The Higgs mass affects its branching fractions
  - $\delta m_H \approx 100$ MeV ➔ 0.5% uncertainty in $\frac{\kappa_b}{\kappa_W}$
- BSM theories (e.g. MSSM)
  - predict the Higgs mass in terms of M_Z, $\tan\beta$, M_A
  - radiative corrections from top loops
  - $\delta m_t \approx 100$ MeV ➔ $\delta m_H \approx 100$ MeV
- Expected precision for m_H from HL LHC is 50 MeV





Extended Higgs sector

- An extended Higgs sector with two Higgs doublets is motivated by many BSM theories, eg MSSM
- Additional degrees of freedom: $h^0, H^0, A^0, H^\pm$
- Generic 2HDM has two parameters
  - $\tan\beta = \frac{v_2}{v_1}$ - ratio of vev's, subject to $v_1^2 + v_2^2 = v_{SM}^2 = 246\ \mathrm{GeV}$
  - $\alpha - h^0 - H^0$ mixing angle
- Alignment limit ($\cos\beta - \gamma \ll 1$) ➔ h^0 becomes SM like
- Direct searches for massive scalars H^0, A^0 are complementary to precision measurements
- Production
  - H^0 and A^0 through gg and $b\bar{b}$ fusion
  - Electroweak pair production $pp \to A^0 H^\pm, H^+ H^-$
- Interesting decays
  - $H \to ZZ, WW, hh$
  - $A \to Zh, b\bar{b}, \tau\tau$
  - $H^\pm \to \tau\nu$



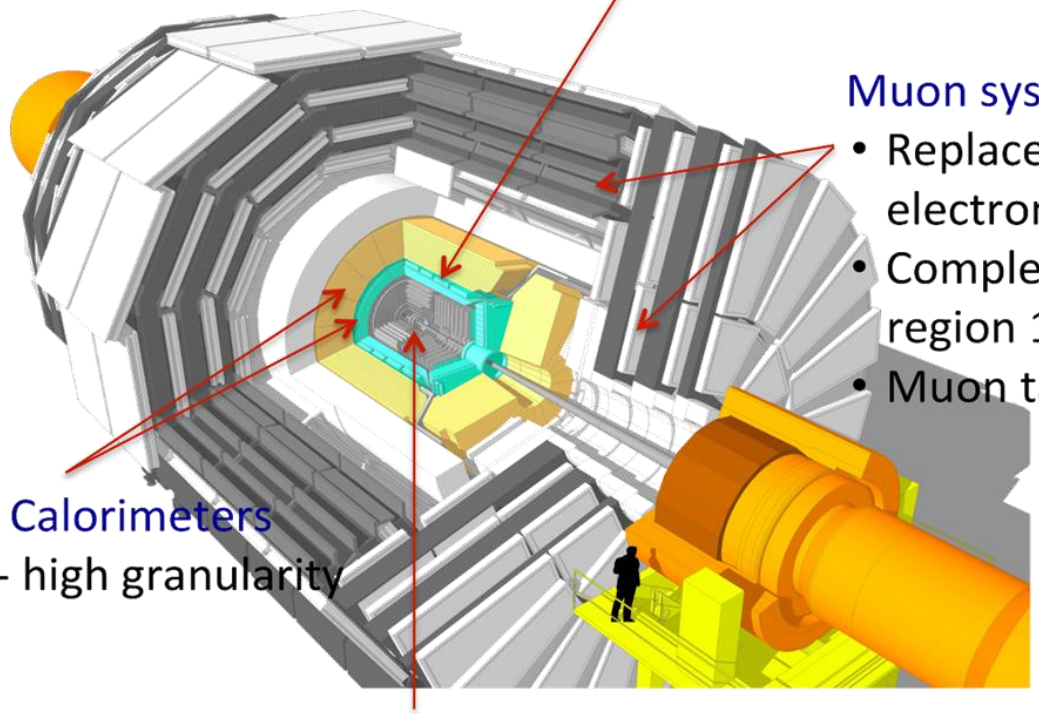
Detector requirements

- Low thresholds in the trigger
- Reconstruct all the standard physics analysis objects with high efficiency, low fake rate, and high resolution.
- Higgs → $\gamma\gamma$, ZZ, WW, $\mu\mu$
  - ➔ Excellent electron, photon, and muon reconstruction
- Higgs → bb
  - ➔ b-quark tagging and precision reconstruction of primary and secondary vertices.
- Higgs → $\tau\tau$
  - ➔ tracking of charged hadrons, measurement of electromagnetic energy, muon and electron reconstruction.
- Vector Boson Fusion (VBF)
  - ➔ high η
- tt +Higgs
  - ➔ jet reconstruction and b-quark tagging.

Summary of CMS HL-LHC Upgrades

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≈7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8◦)



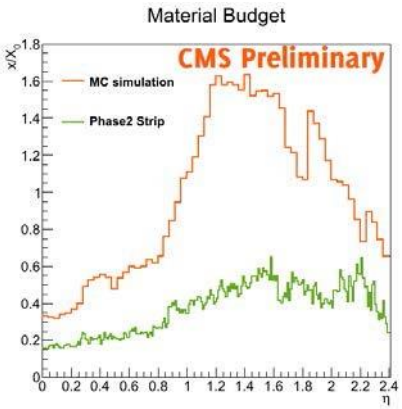
Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

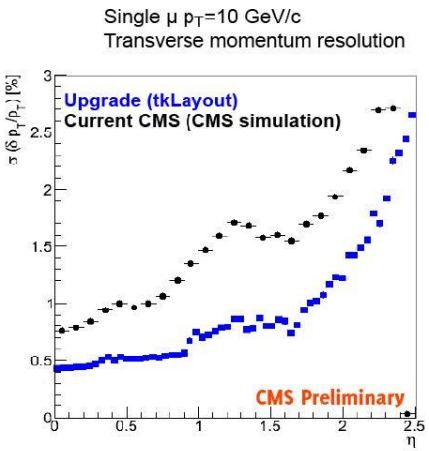
Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

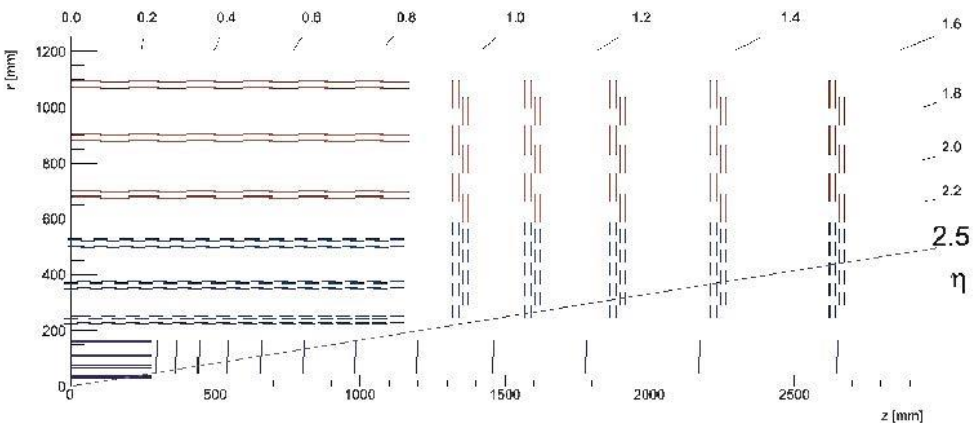
Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

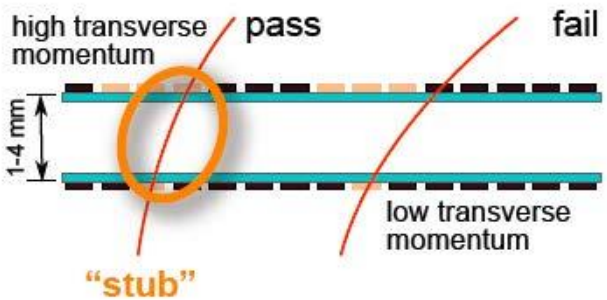
CMS phase 2 tracker

- Outer tracker
  - High granularity, efficient track reconstruction to >140 PU
  - Two-layer p_T-modules to provide level 1 trigger at 40 MHz
  - Improved material budget
- Pixel detector
  - Extended coverage with disks to |η|<4
  - Thin sensors 100 μm; smaller pixels 30x100 μm
  - New ROC
- Level 1 track-trigger
  - find tracks with pT≥2 GeV



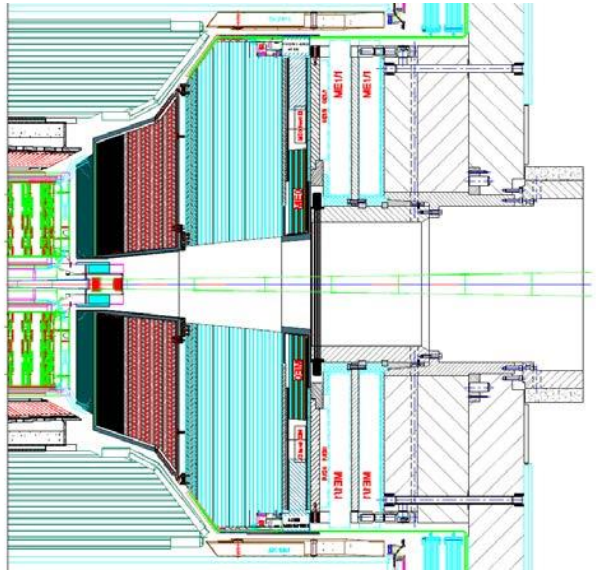


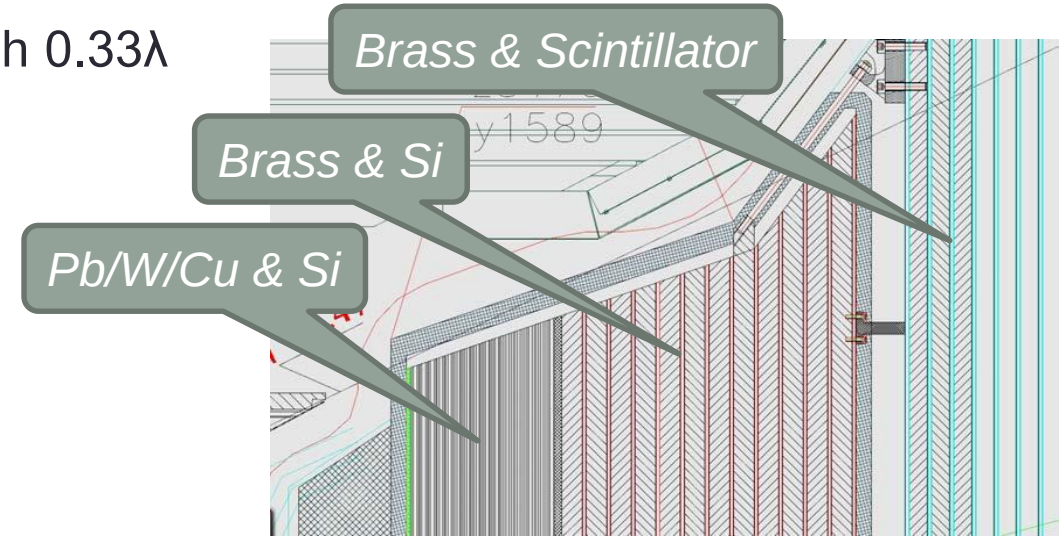




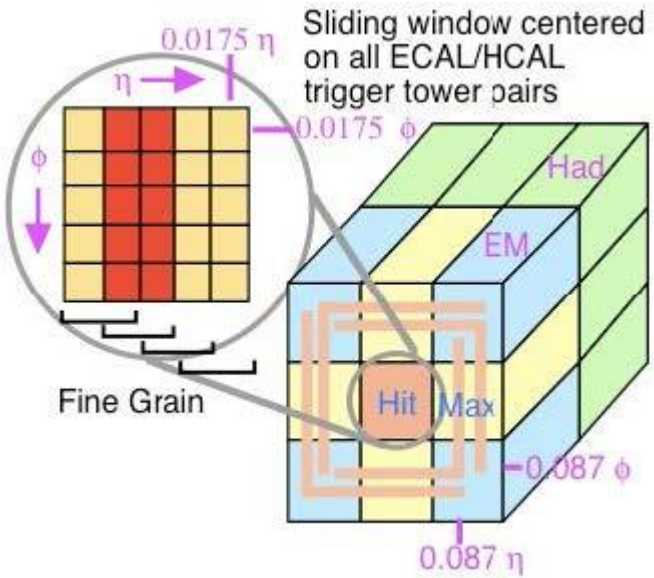
CMS phase 2 endcap calorimeter

- Electromagnetic Calorimeter:
  - 30 samplings of W/Pb/Cu total of 25 Xo
  - 11 layers of 0.5 Xo, pad size 0.9 cm^2
  - 10 layers of 0.8 Xo , pad size 0.9 cm^2
  - 10 planes of 1.2 Xo, pad size 1.8 cm^2
  - 420 m^2 of silicon pad detectors
  - 7M channels
- Front Hadronic Calorimeter
  - 4 interaction lengths
  - 12 layers of brass/silicon each 0.33λ
  - Pad size 1.8 cm^2
  - 3M channels
- Backing calorimeter
  - Five interaction lengths
    (e.g. sampling of 0.5λ).
  - Radiation levels lower
    ➔ can use plastic scintillator





CMS phase 2 trigger



- Replace ECAL frontend electronics
  - Allows L1 latency of 10-20 μs
  - Provides individual crystal level information
    - not 5x5 sums
- L1 track trigger
  - Lepton p_T & isolation, jets, vertex
- New L1 Trigger (Calorimeter, Muon, Global) to Incorporate
  - track trigger
  - Finer calorimeter cluster information
  - Additional muon coverage for |η|>1.5
  - muon & calorimeter seeds for track match
- L1 accept rate of 750 kHz
  - Larger acceptance and lower thresholds
- HLT output rate of 10 kHz
  - Limited by downstream computing

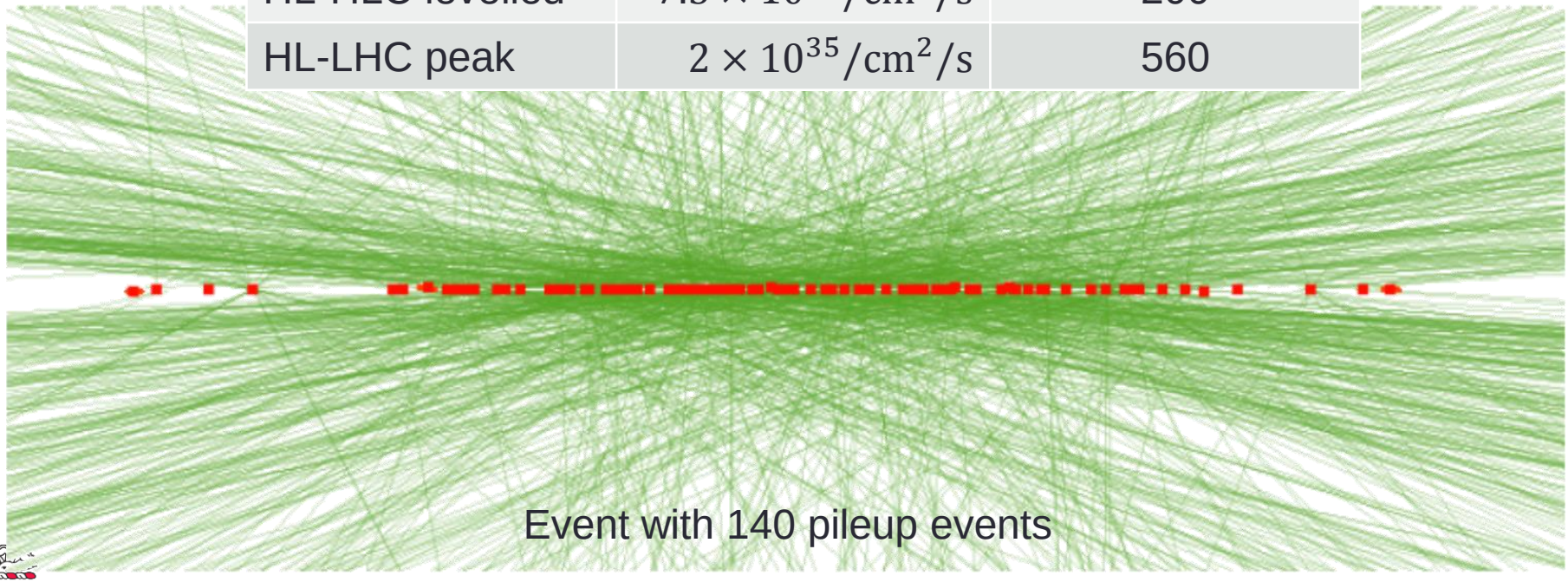
Main challenges

- Pileup
  - Largest source of hits in the tracking system
  - Increases the combinatorial complexity of the track reconstruction
  - Increases the rate of fake tracks
  - Adds extra energy to calorimeter measurements, such as jet energies
  - Increases the amount of data that has to be read out in each BX
  - Increases execution time for the reconstruction of events in the High Level Trigger and the offline analysis
- Trigger
  - Rates increase with increasing luminosity
  - Thresholds must stay low to preserve acceptance for Higgs production
- Radiation damage
  - Detector elements and electronics are exposed to high radiation dose
  - Degrades signal, requires continuous calibration
  - Limits life time of detectors

Pile-up

- With 25 ns bunch spacing

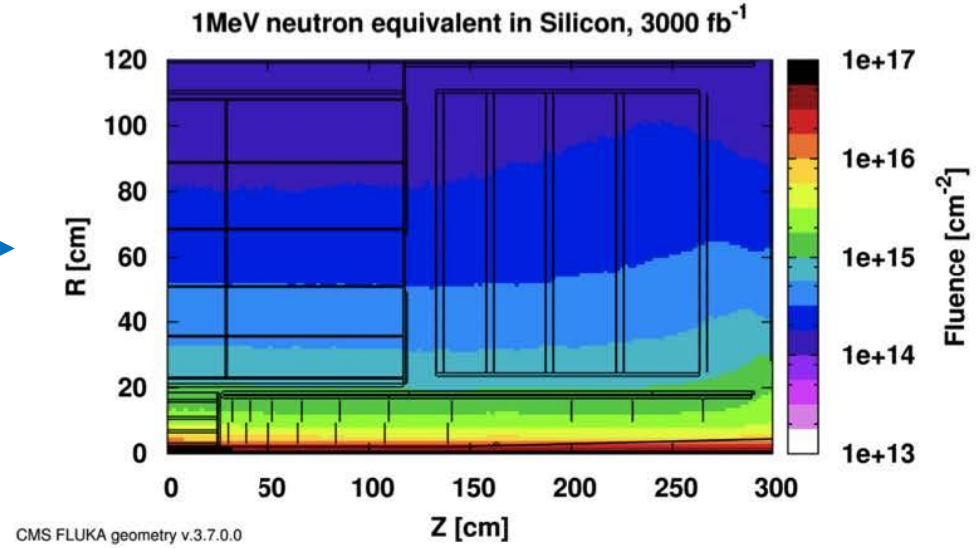
period	$\mathcal{L}$	$\langle n \rangle$
Design/Run 2	$10^{34}/\mathrm{cm}^2/\mathrm{s}$	25
Run 3	$2 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$	50
HL-HLC levelled	$5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$	140
HL-HLC levelled	$7.5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$	200
HL-LHC peak	$2 \times 10^{35}/\mathrm{cm}^2/\mathrm{s}$	560



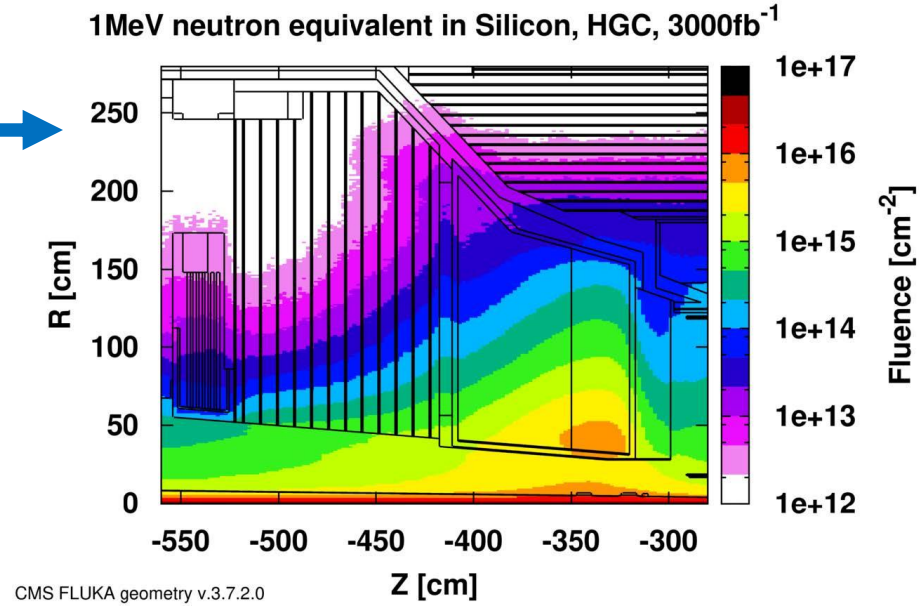
Event with 140 pileup events

Particle fluences

- 3000/fb in 1 MeV n_{eq}/cm^2
  - in tracker volume

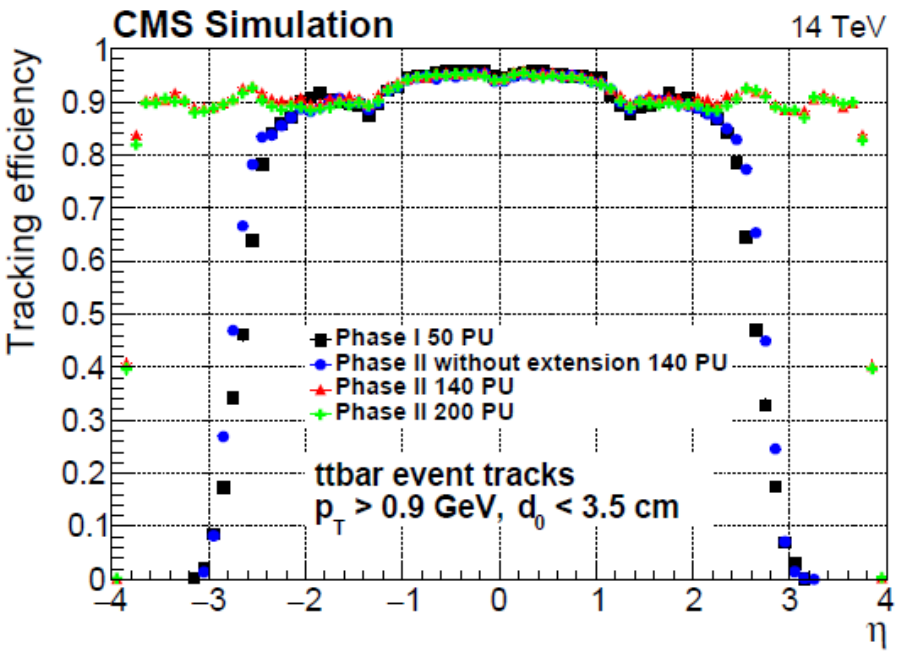


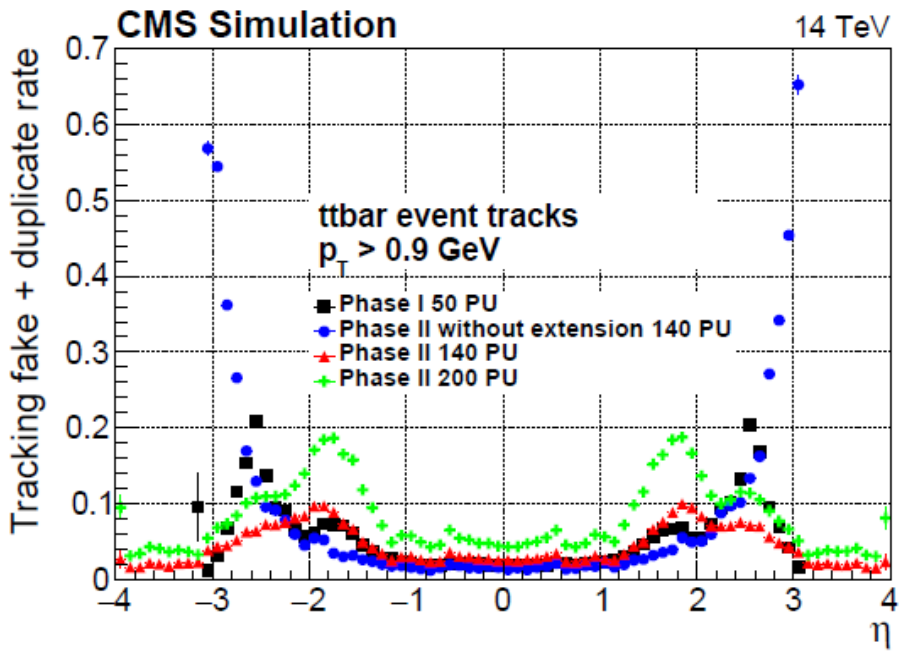
  - In endcap calorimeter



Effect of pileup on track efficiency

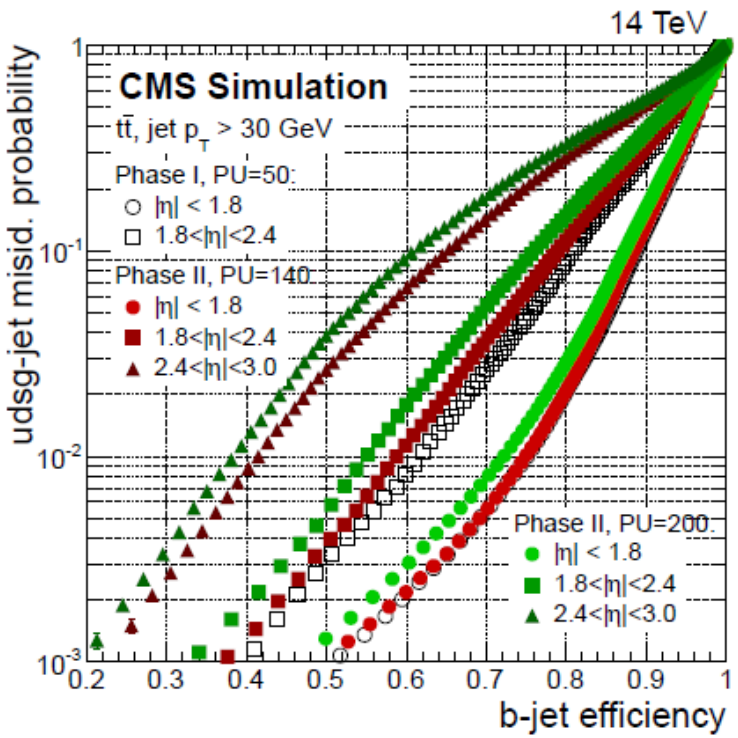
- $t\bar{t}$ events with 140 PU (●) and 200 PU (●)

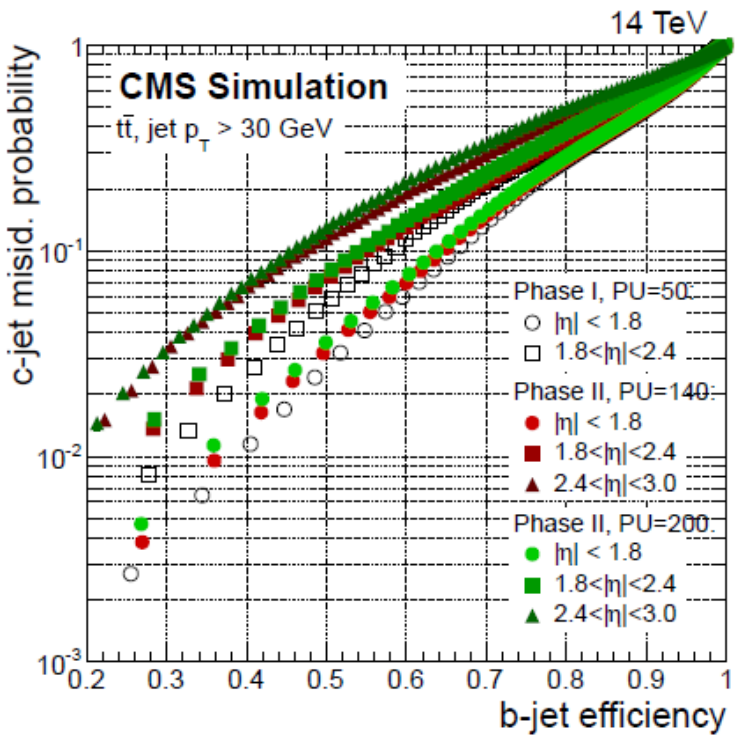




Effect of pileup on b-tagging

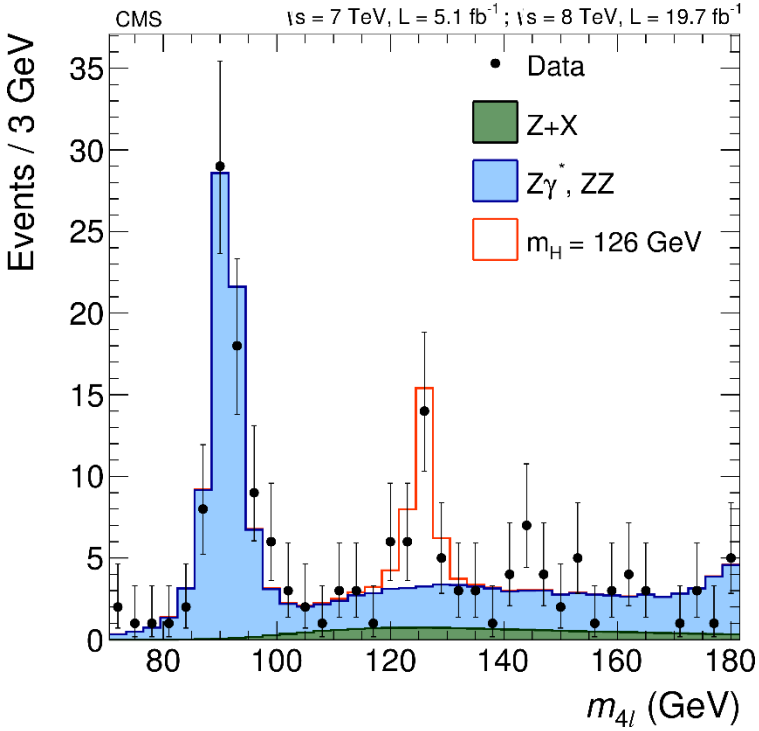
- Important for H→bb, HH, and ttH production
- $t\bar{t}$ events with 140 PU (●■▲) and 200 PU (●■▲)

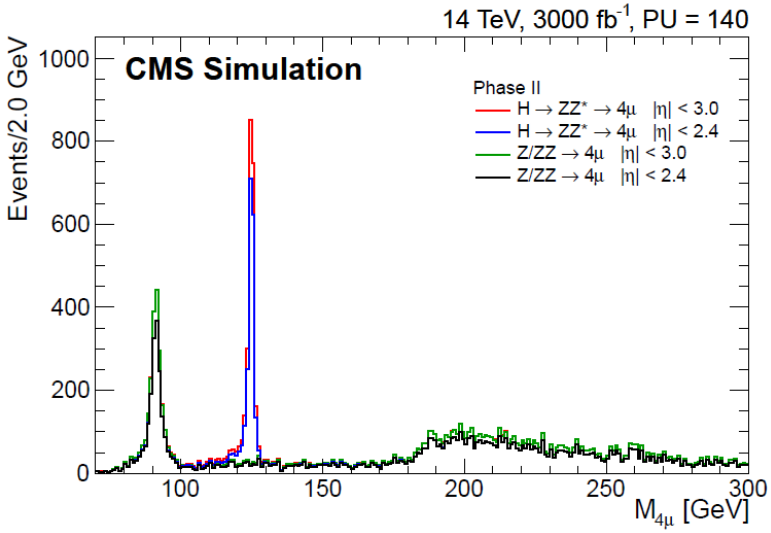




$H \rightarrow ZZ^* \rightarrow 4\ell$

- The golden channel
  - Complete reconstruction of Higgs decay
  - Coupling measurements
  - Mass measurement
  - Spin/Parity tests
- Run 1 trigger
  - $p_T < 7$ GeV (e) and $p_T < 5$ GeV (μ)
- HL LHC will produce
  - 16k events from gg fusion
  - 1.4k event from VBF
- Key parameters
  - Acceptance → η coverage, low trigger thresholds
  - Mass resolution → pileup mitigation



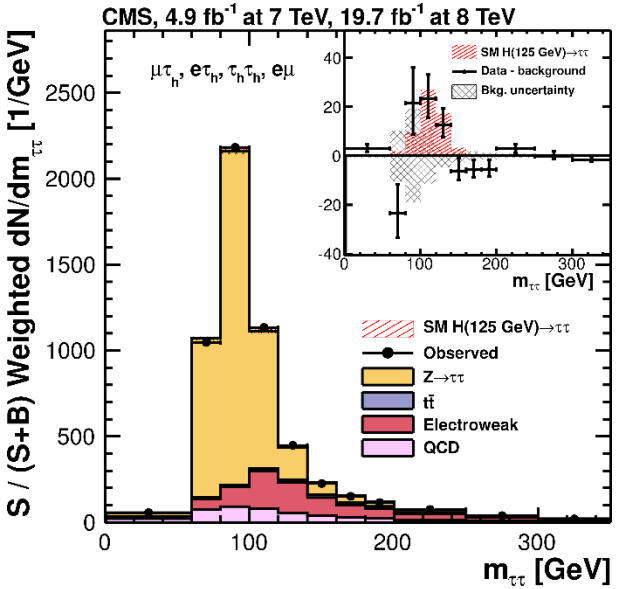


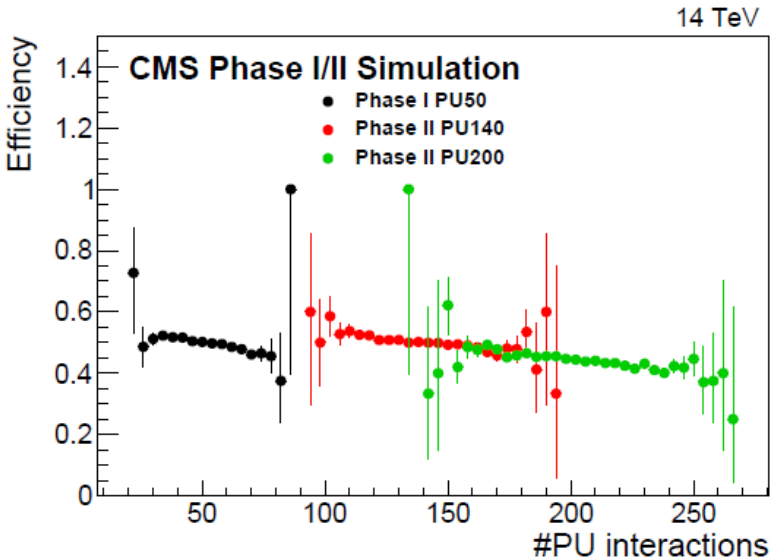
H → ττ

- Only observed decay of Higgs bosons to fermions
  - $\mu_\tau = 0.78 \pm 0.27$, >3σ local significance
- Decay products have p_T of 20-50 GeV
  - → low trigger thresholds
- Track trigger is needed for had decays
  - Run-I p_T threshold was 45 GeV
  - L1 trigger menu for HL-LHC:

Trigger	Threshold w/o track trigger	Threshold with track trigger
τ	140 GeV	88 GeV
ττ	90 GeV	56 GeV

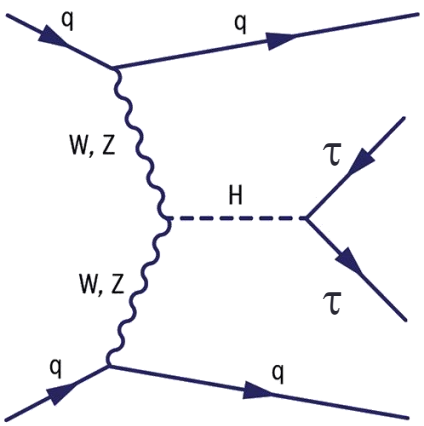
  - Track trigger increases acceptance by factor 5.5
- Expect 2-5% precision



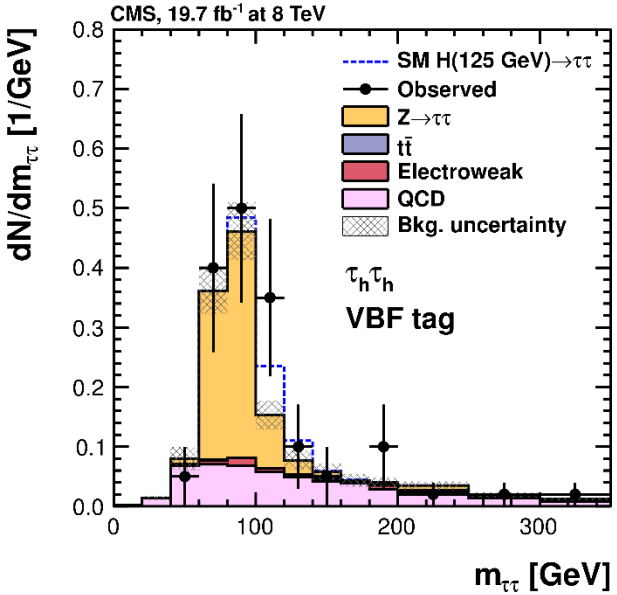


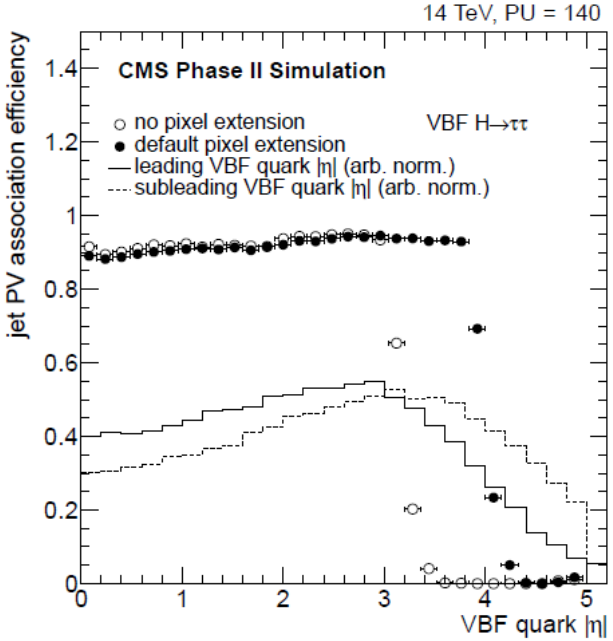
H → ττ - VBF tag

- Vector boson fusion



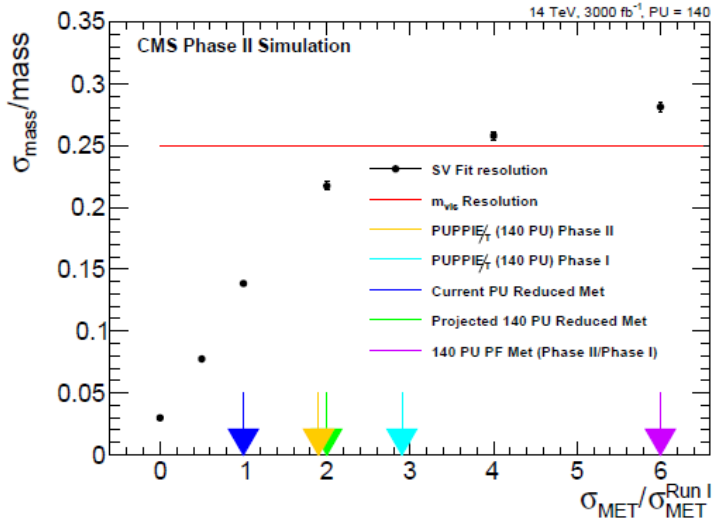
  - Suppresses $Z \to \tau\tau$ background
  - Jets at high $|\eta|$
- Acceptance of tracker in η is key



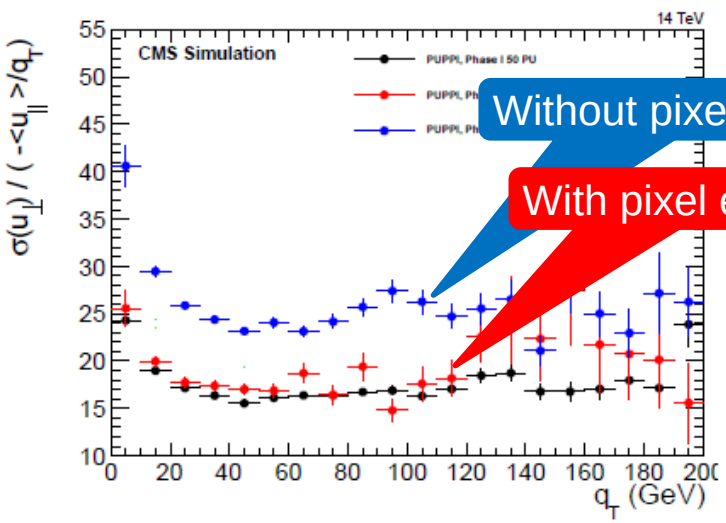


H → ττ - missing p_T resolution

- $m_{\tau\tau}$ resolution depends on missing p_T
- Missing p_T resolution
  - Extended tracker coverage in η
  - Pileup mitigation

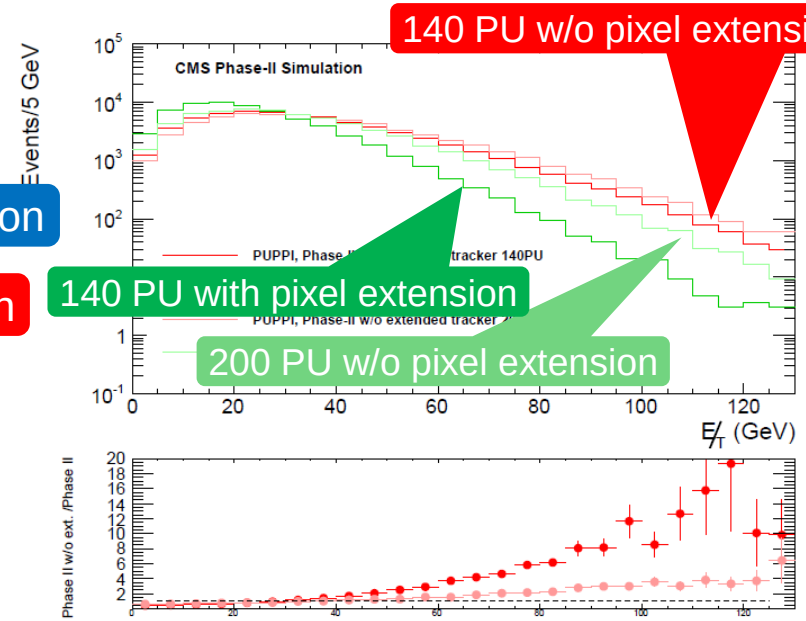


Perpendicular recoil of Z bosons



Without pixel extension

With pixel extension



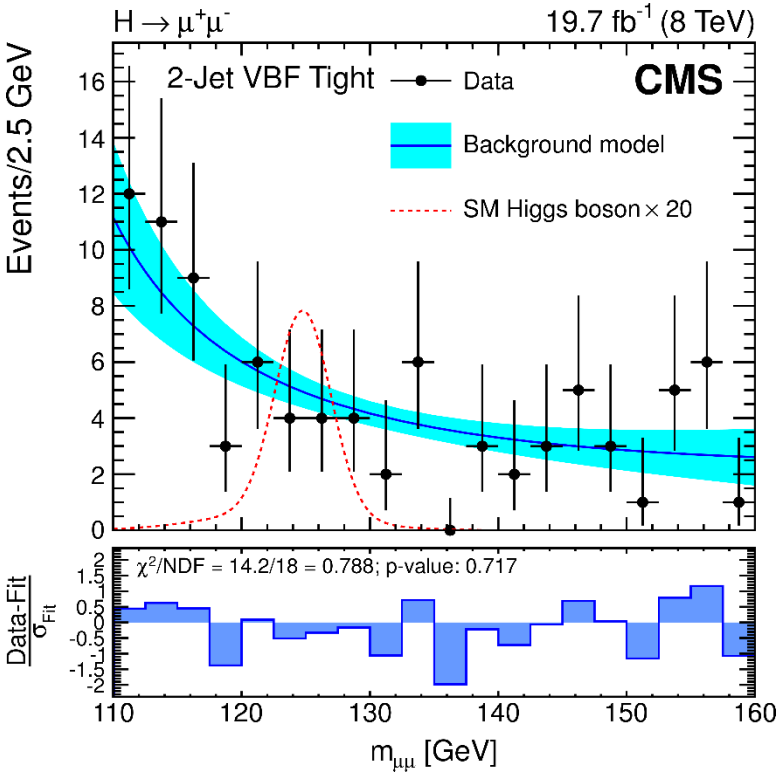
140 PU w/o pixel extension

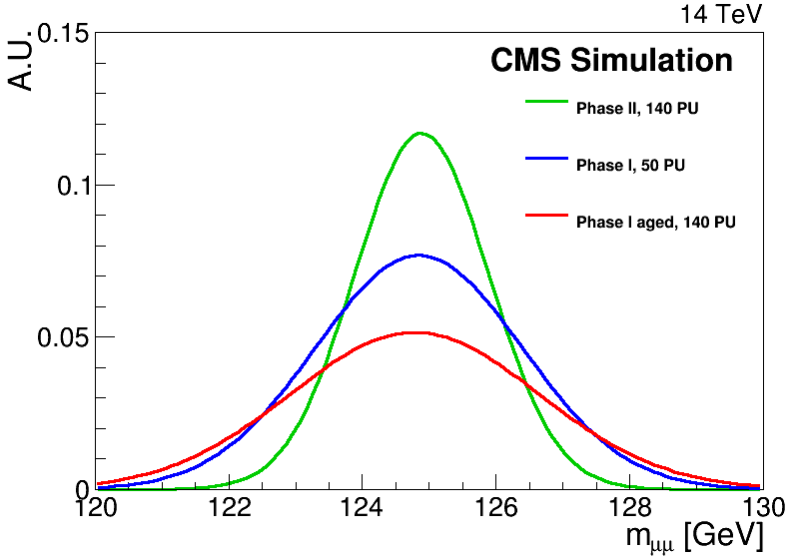
140 PU with pixel extension

200 PU w/o pixel extension

$H \to \mu\mu$

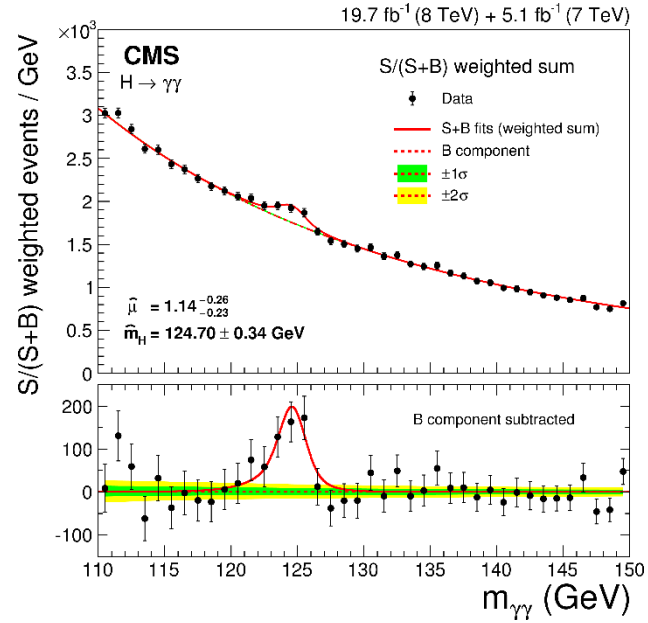
- Best channel to measure Higgs couplings to 2nd fermion generation
- SM $B = 2.2 \times 10^{-4}$
- Run 1 result:
  - $\sigma < 7.4\ \sigma_{SM}$ @ 95% CL
  - $B(H \to \mu\mu) < 0.0016$
- HL-LHC expectations
  - Expect 5% precision with 3000/fb
  - $\mu\mu$ mass resolution is key
  - Depends on improvement of
    - Mass resolution
      - less mass in tracker
      - Pileup mitigation
    - Acceptance in $|\eta|$

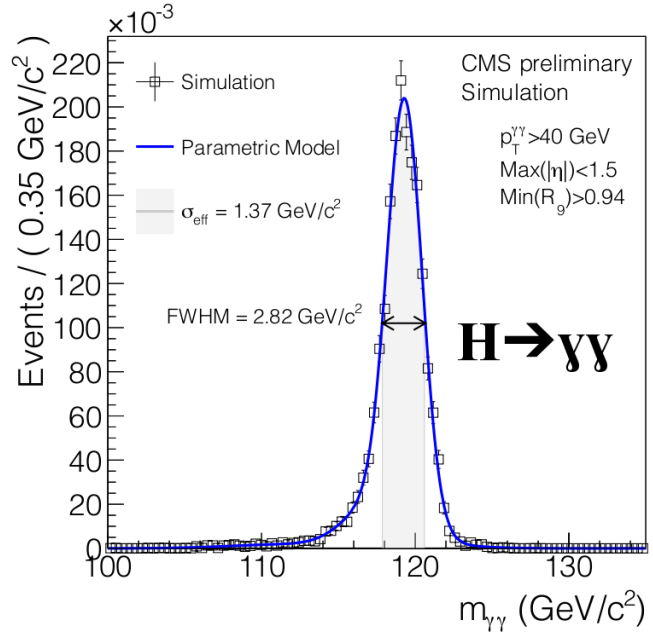




$H \rightarrow \gamma\gamma$

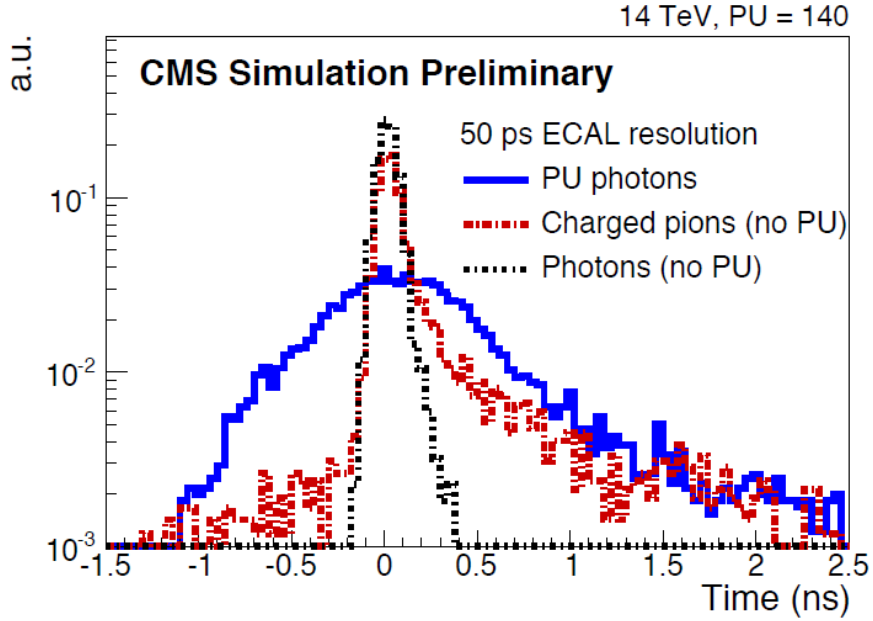
- Complete reconstruction of Higgs decay
- Coupling measurements
- Mass measurement
- Spin tests
- Key parameter: $m_{\gamma\gamma}$ resolution
  - identify $\gamma\gamma$ vertex in presence of pileup
  - largest contribution to $m_{\gamma\gamma}$ resolution
- Pileup mitigation
  - Shower direction
    - Resolution of 2 mrad at $|\eta| = 1.7$ possible
    - Allows determination of vertex to 2 cm
    - Better than 5 cm width of luminous region
  - Shower timing
    - Resolution of 10-20 ps maybe possible
    - Help localize vertex



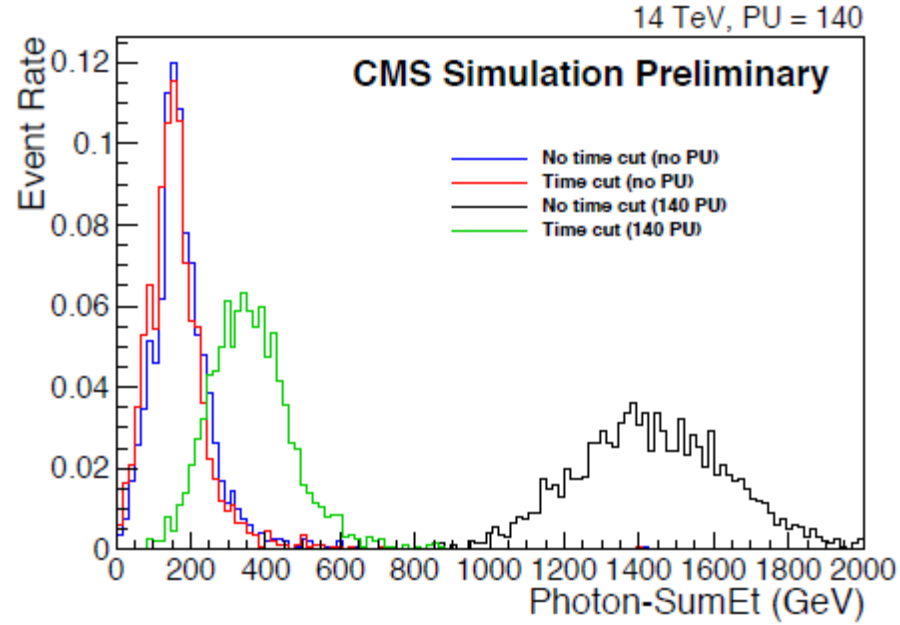


$H \rightarrow \gamma\gamma$ - shower timing

- Reconstructed time for
  - Photons from events with 140 PU
  - Single charged pions (no PU)
  - Single photons (no PU)

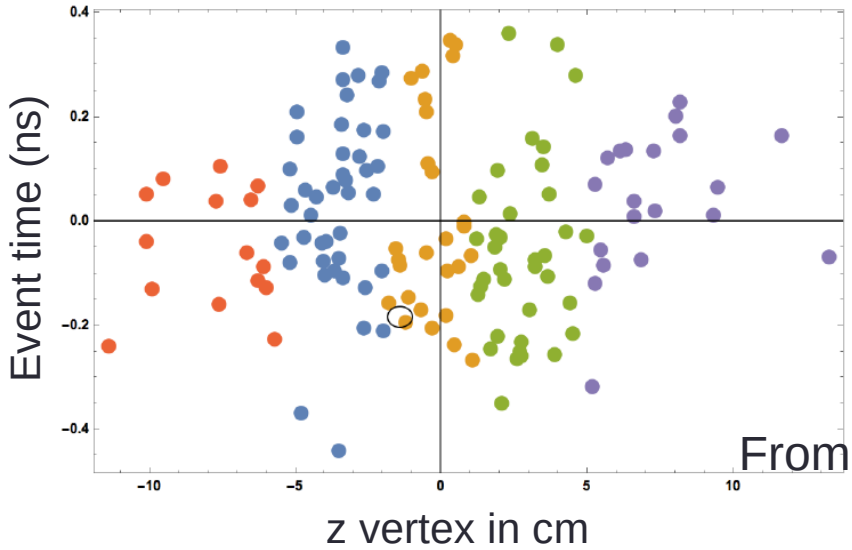


- $\sum E_T$ of all photons from VBF $H \rightarrow \gamma\gamma$ sample
  - Without PU timing has no effect
  - With 140 PU no timing cut
  - With 140 PU with timing cut



Pileup mitigation with timing information

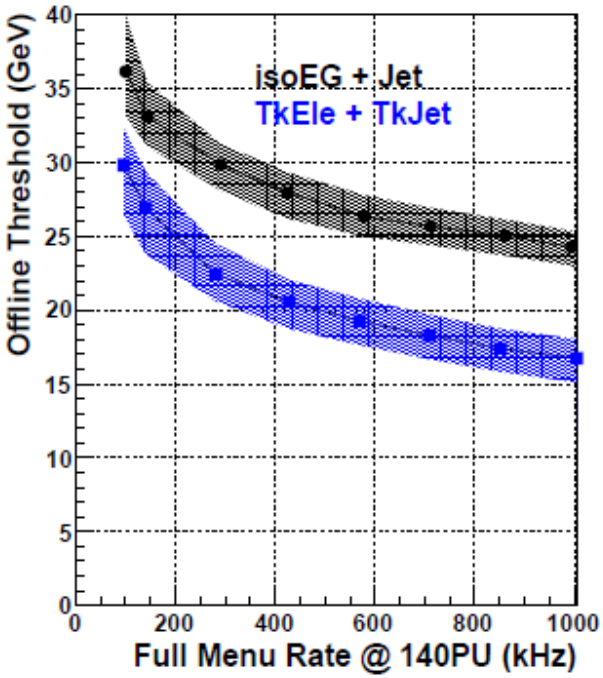
- Pileup interaction vertices are distributed in z
  - Rms ≈ 5 cm
  - Restricting the region along the z-axis around the hard interaction vertex from which tracks emanate reduces the contribution of pileup interactions
- Pileup interactions are also distributed in time
  - Rms ≈ 170 ps
  - If tracks and calorimeter signals had a time stamp with 10-20 ps resolution one could restrict the time interval around the time of the hard interaction to reduce the contributions of pileup interactions



From S. White, arXiv:1409.1165

Trigger system

- Higgs bosons decays products have low p_T
  - Low trigger thresholds are essential to maintain acceptance
- Level 1 trigger bandwidth required
  - At 140 PU with track trigger: 260 kHz
  - At 200 PU with track trigger: 500 kHz
  - At 140 PU w/o track trigger: 1500 kHz
  - At 200 PU w/o track trigger: 4 MHz



- Trigger acceptance for H→ττ

Trigger condition	Acceptance for H→ττ
τ > 88 GeV or ττ > 56 GeV	20%
τ > 94 GeV or ττ > 59 GeV	16%
τ > 136 GeV or ττ > 66 GeV	6%

Summary

- In the coming 15 years the LHC will continue to increase its luminosity
  - Goal is to accumulate an integrated luminosity of 3000/fb
  - Peak $\mathcal{L} = 2 \times 10^{35}/\mathrm{cm}^2/\mathrm{s}$ levelled to $\mathcal{L} = 5 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
  - 140-200 pileup interactions/crossing
- There is a compelling program of measurements to study the Higgs boson
  - Precision measurements (couplings, mass, spin)
  - Searches (extended Higgs sector – and of course new physics)
  - Require low trigger thresholds, excellent mass resolution and maximal acceptance
- The main challenge of the environment will be large number of pileup interactions
- Pileup mitigation
  - Trigger – more bandwidth, new capabilities (eg track trigger)
  - Increased detector granularity and acceptance in η
  - Photon pointing and timing measurements
  - Timing could add an additional dimension to pileup rejection

References

- CMS Collaboration, “Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid”, Technical Report CERN-LHCC-2015-010, LHCC-P-008, 2015.
- CMS scope document LHCC-G-165, 2015.
- Higgs Working Group Report of the Snowmass 2013 Community Planning Study, arXiv:1310.8361 [hep-ex]