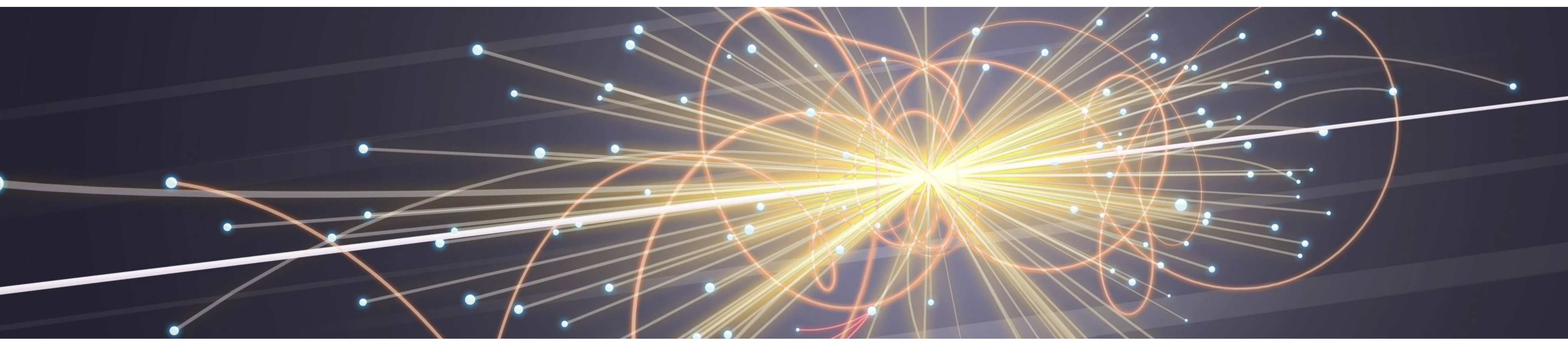
Higgs production at Run 2 and projections for the HL-LHC with the CMS phase-2 detector

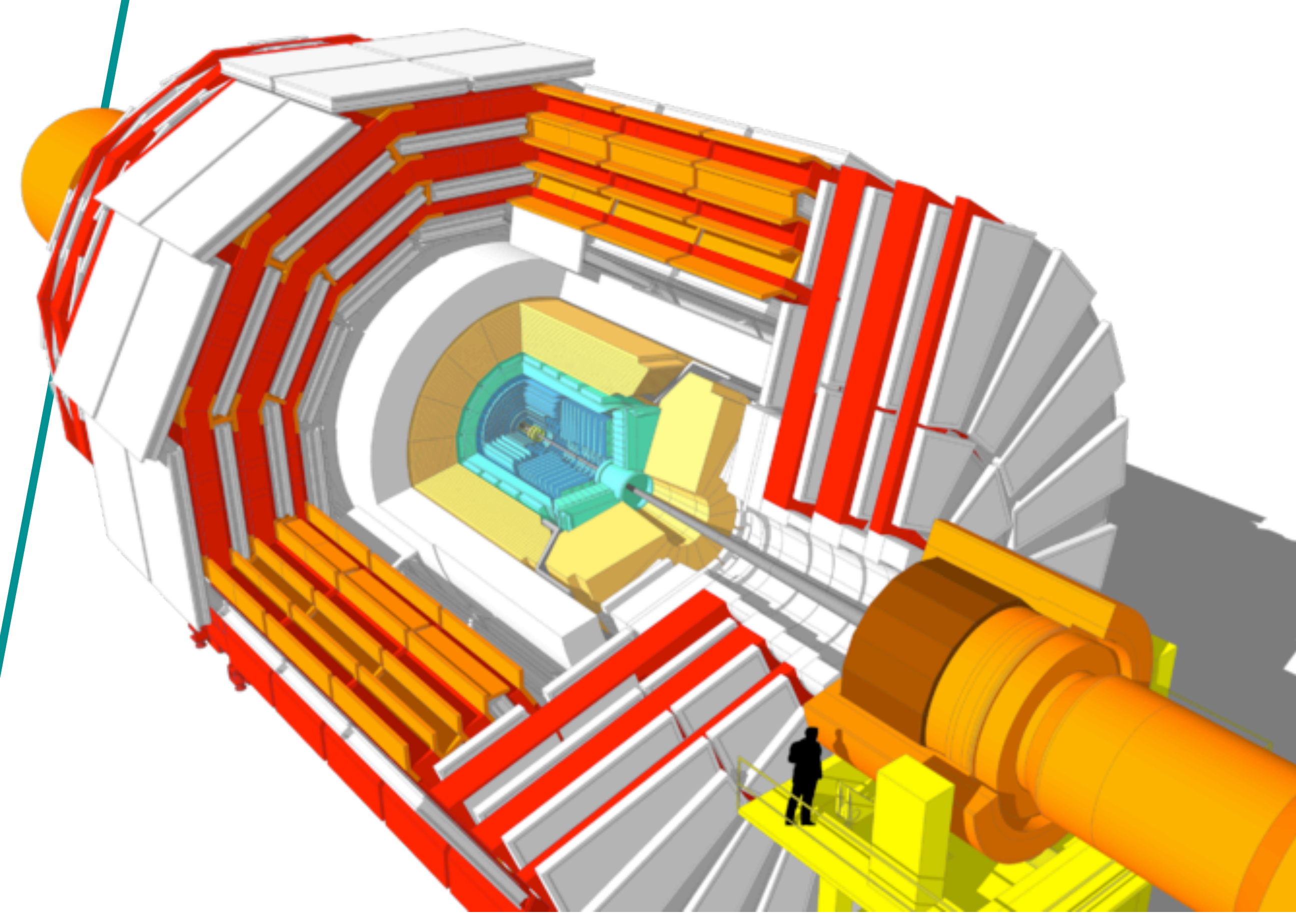


Alessandro Da Rold, on behalf of the CMS Collaboration

Interpreting the LHC Run 2 data and Beyond   Trieste, 27 - 31 May 2019

Overview

- **Run 2**
  - H → $\tau\tau$ @ 13 TeV
  - HH → bb$\gamma\gamma$ @ 13 TeV
- **HL-LHC**
  - ECAL @ HL-LHC
  - H → $\gamma\gamma$
  - H → $\tau\tau$, HH → bb$\gamma\gamma$



- **Not in this talk**
  - ECAL @ Run 2
  - H → $\gamma\gamma$ @ 13 TeV
  - H → ZZ @ 13 TeV

Details in Federico's talk!

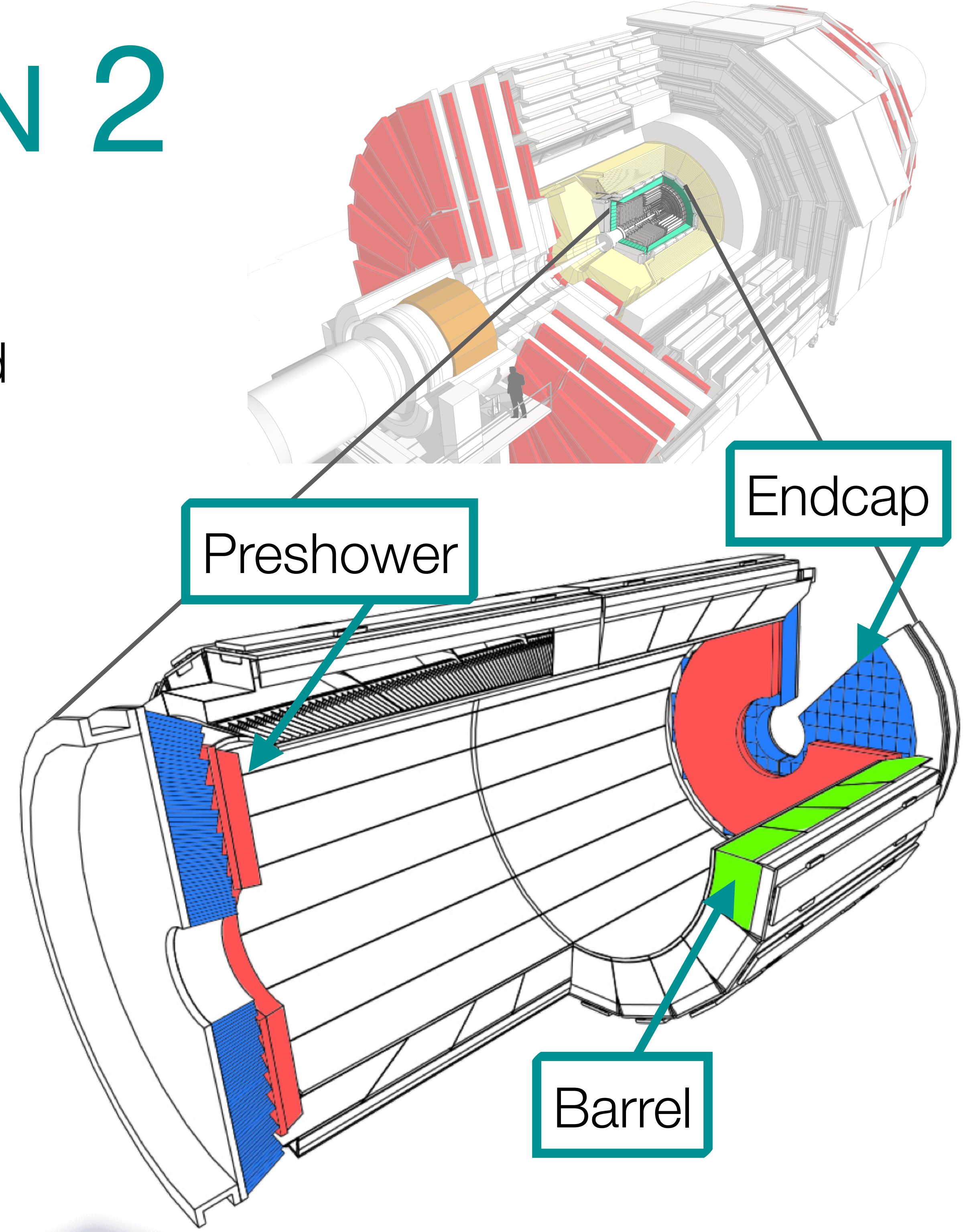
ECAL during Run 2

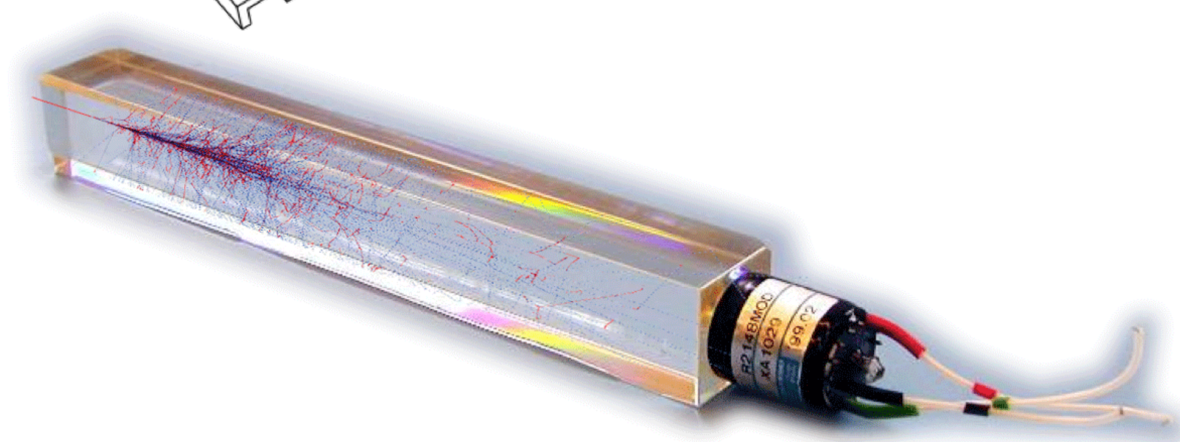
- **Hermetic, homogenous calorimeter** placed inside solenoid magnet → Barrel and endcaps configuration

- 75 000 lead tungstate (**$PbWO_4$**) crystals: fast scintillation, radiation resistant, short radiation length

- Purposes:
  - Precise measurement of electron and photon **energies**
  - Precise time measurement (background rejection, **particle identification**)

- Energy resolution and particle identification fundamental in the discovery and characterisation of the **Higgs boson**





- **Selection**
  - $\mu\tau_h$, $e\tau_h$, $e\mu$, $\tau_h\tau_h$
  - Leptons must have opposite charge
  - High p_T^{miss} and small M_T^W, b-tag
- **Categories**
  - 0-jet: H from gluon fusion
  - **VBF:** most sensitive channel
  - Boosted: associate jet production
- **Systematics**
  - Data driven background estimations ~10%
  - τ identification 5% and trigger 10%
  - Lepton scale factors 2-3%

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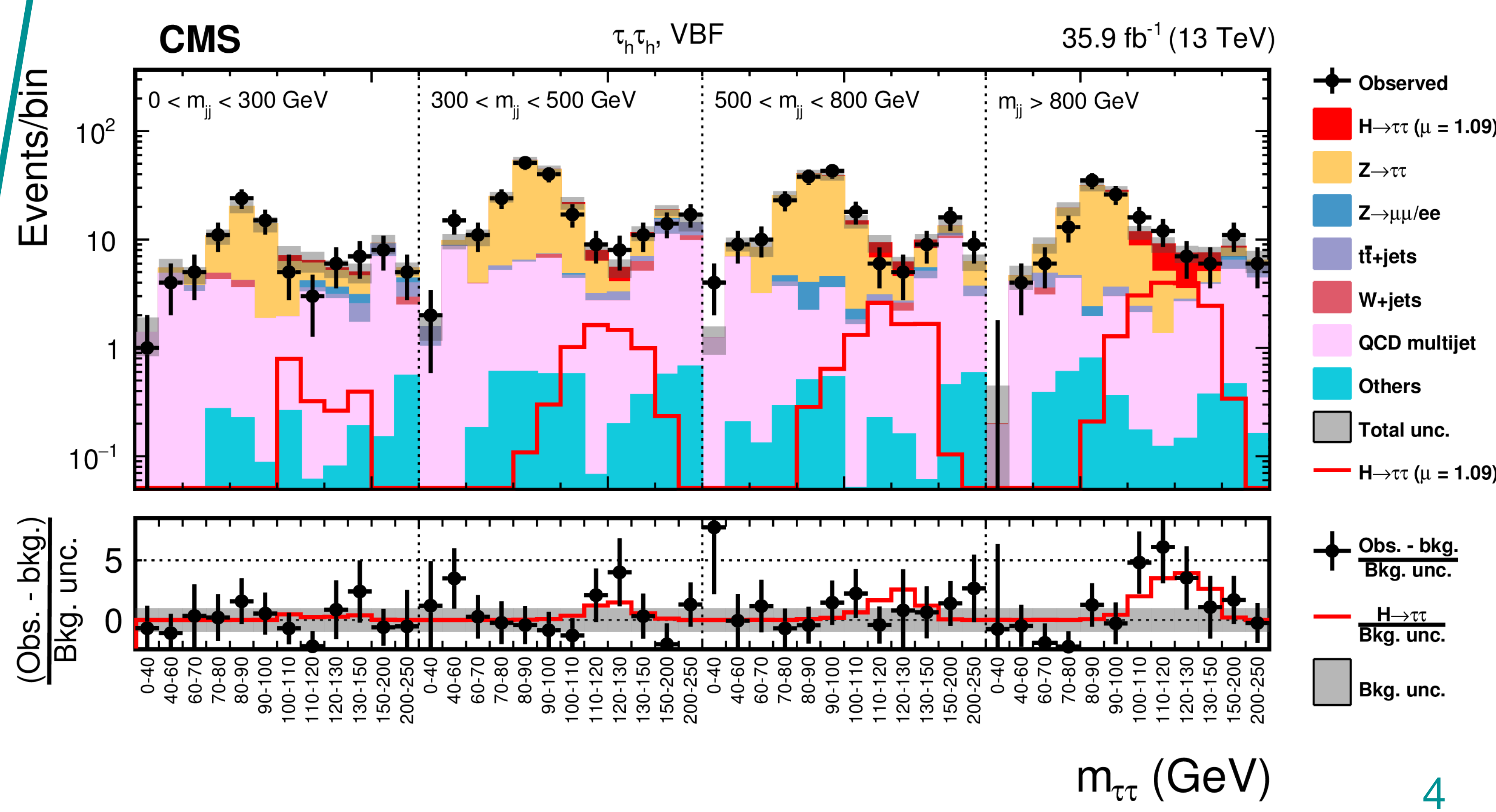
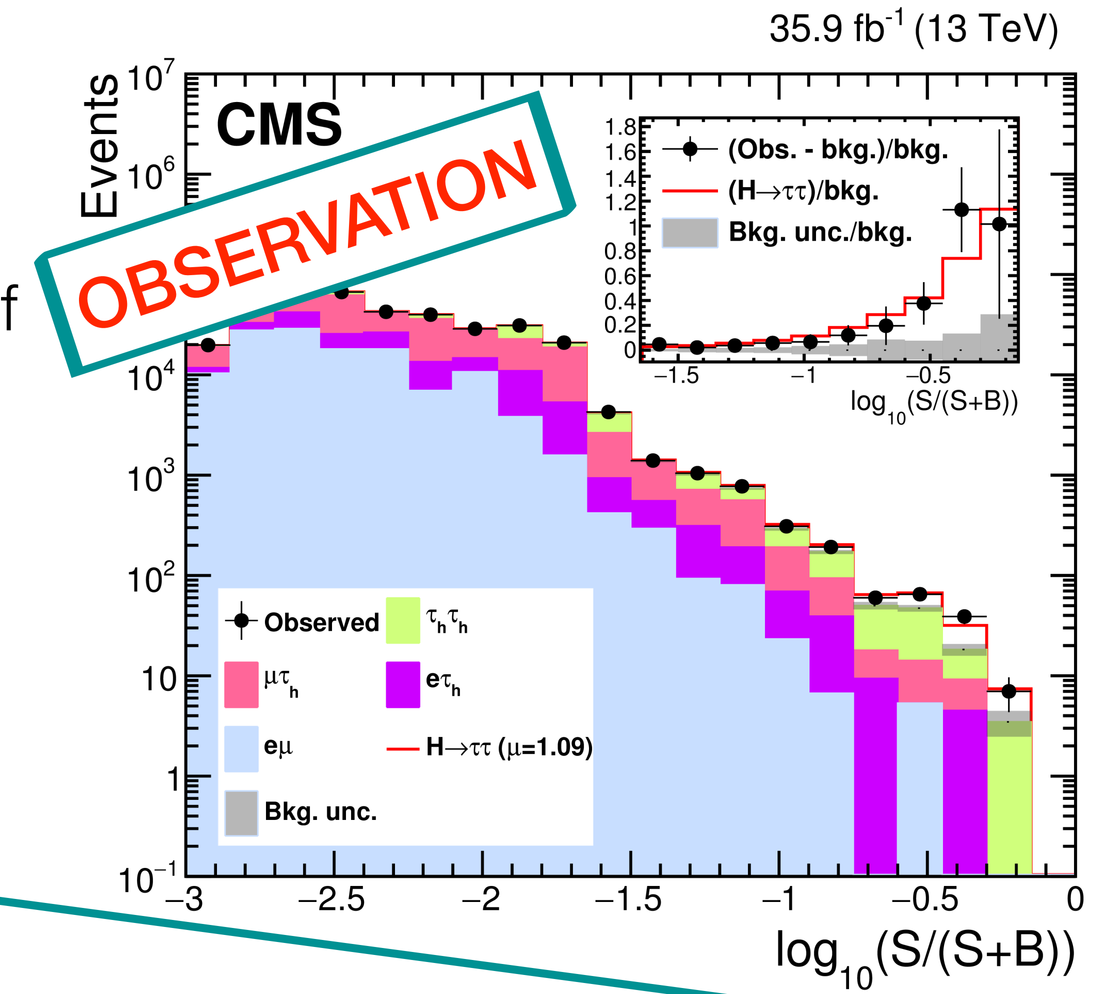
$H \rightarrow \tau\tau$

- Fundamental to establish **fermion masses generation** mechanism
- All decays studied exploiting ECAL information on number of deposits (1-prong, 1-prong + π^0(s), 3-prongs)
- **Main backgrounds:** $Z \rightarrow \tau\tau$, W+jets, QCD (control sample), $t\bar{t}$ (simulation)

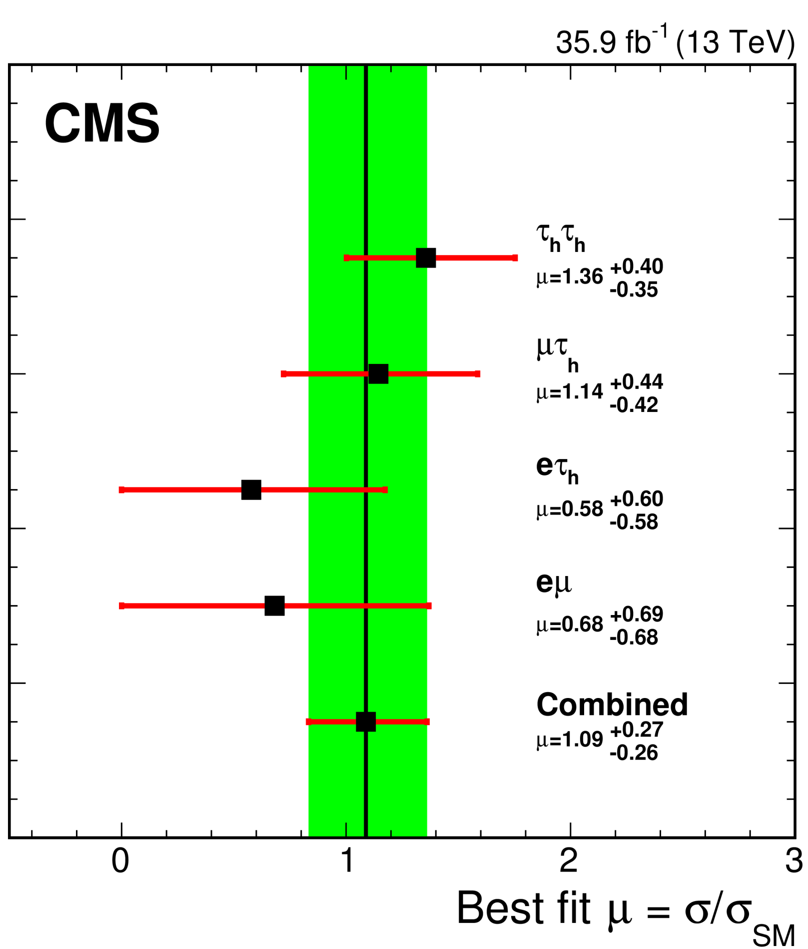


H → ττ

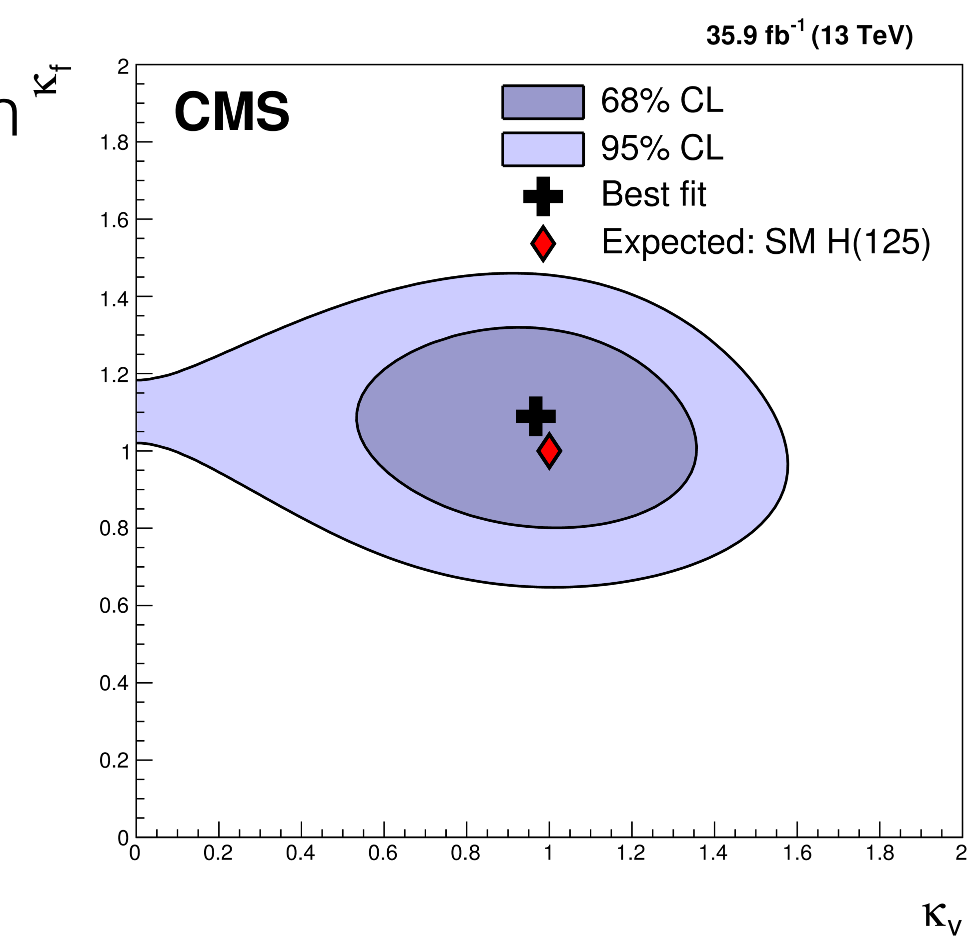
- Combine results for all channels as a function of **$\log_{10}(S/(S+B))$**
- Excess corresponding to 125 GeV particle
  → Significance 4.9 σ (**5.9 σ** with 7 and 8 TeV measurement)



- **Signal strength of $1.09^{+0.27}_{-0.26}$**
  → Compatible with SM



- Likelihood scan assuming M_H=125.09 for **k_V** and **k_f**
- Contours compatible with SM hypothesis



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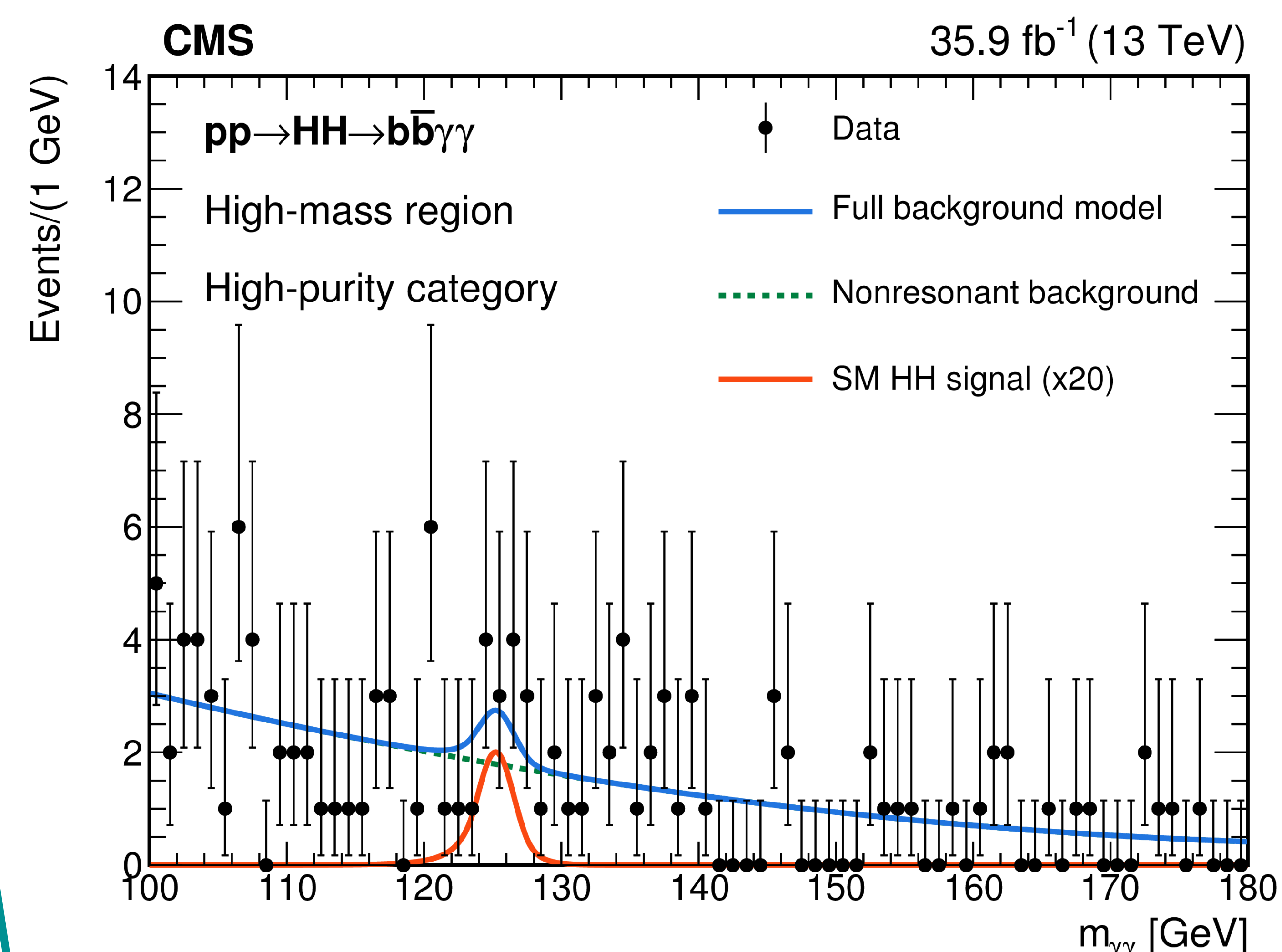
HH → bb$\gamma\gamma$

- **Selection**
  - $\gamma\gamma$ trigger
  - Jet and γ relative isolation
  - H($\gamma\gamma$) and H(bb) in mass window
- **Categories**
  - Sensitivity to non resonant searches
  - MVA discrimination between H and nγ+jets
- Signal model: double Crystal-Ball
- Background model: nγ+jets (polynomials) and single H distributions

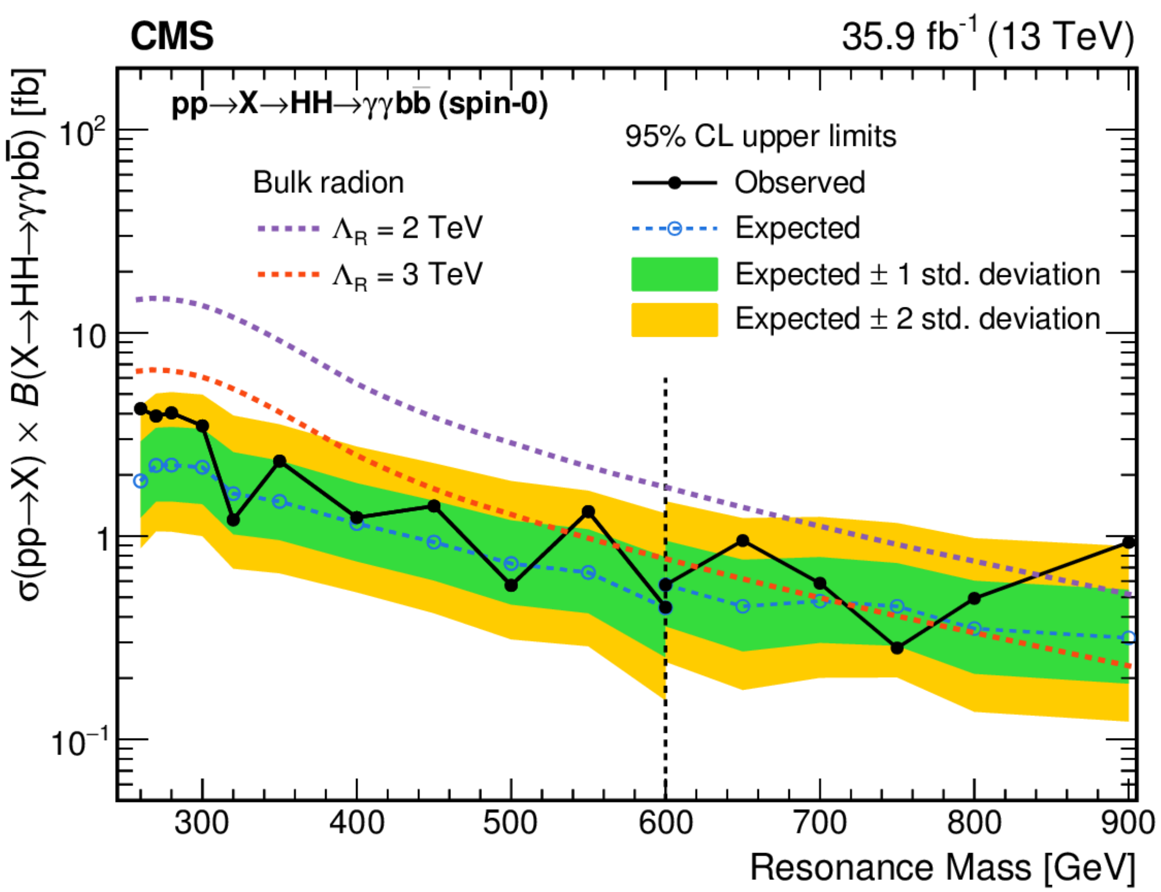
- BSM theories foresee particles that couple to H pairs
- **Final state fully reconstructed**, “big” branching ratio
- Both **resonant** and **non-resonant** searches
- Main background: nγ+jets

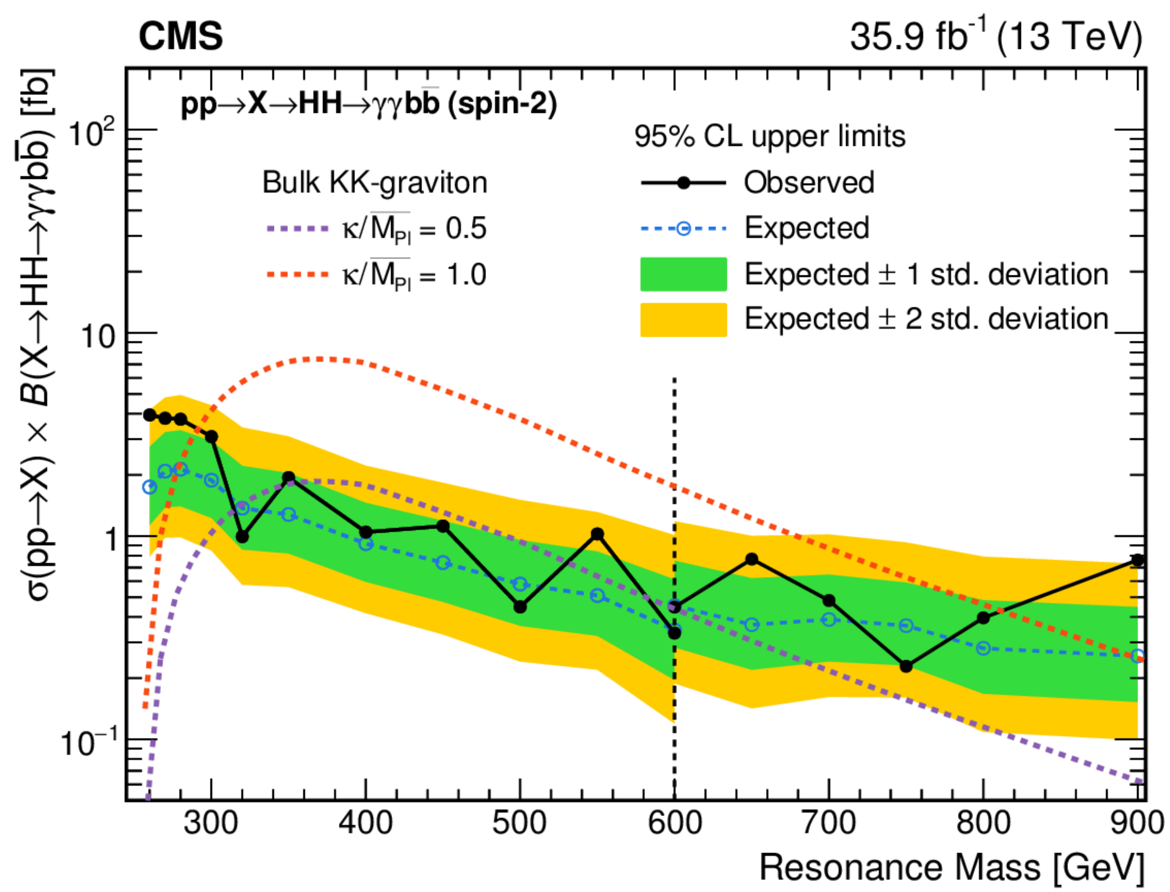


HH → bb$\gamma\gamma$

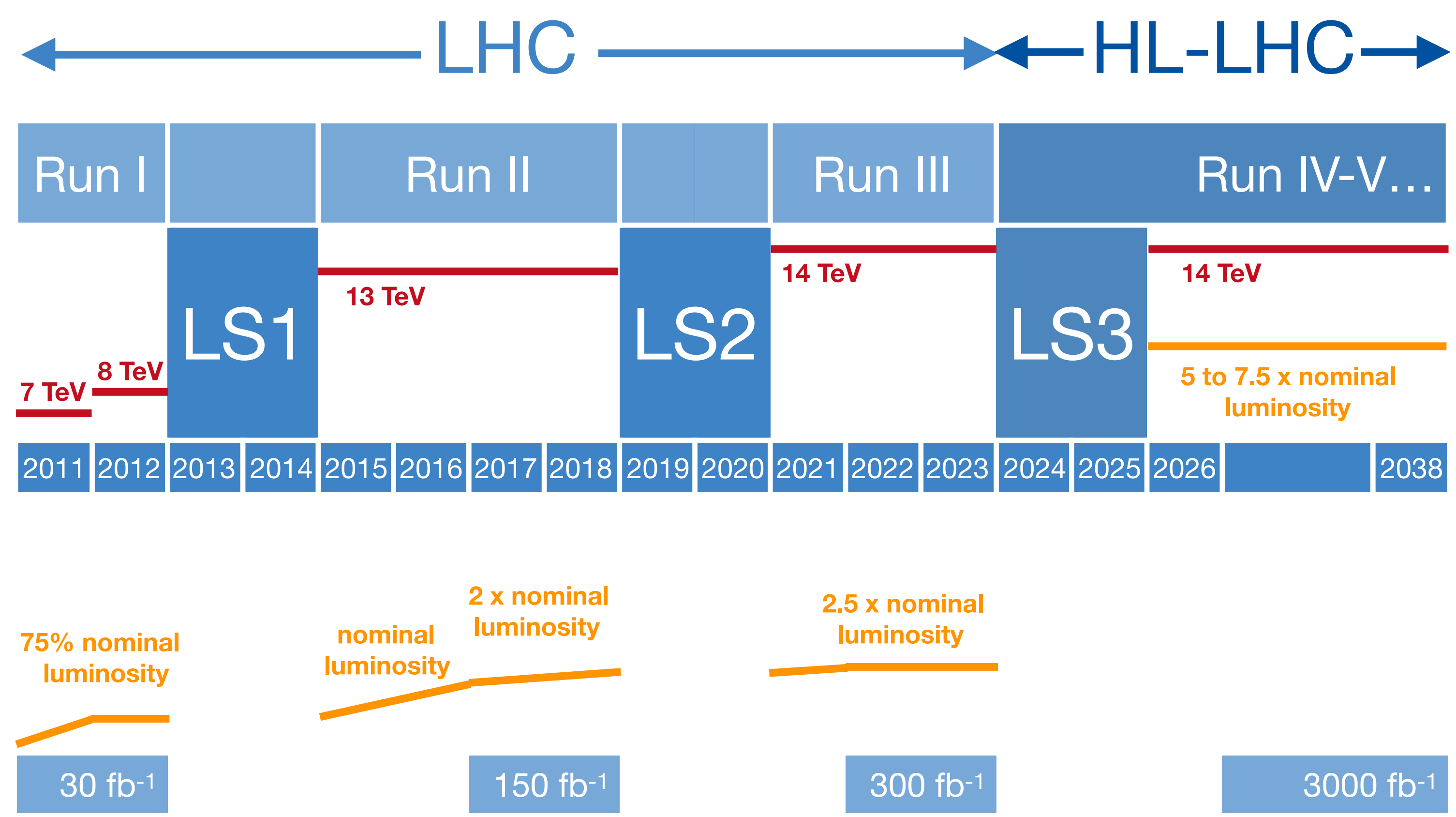
- **No evidence** of SM HH production ➞ **Limits** on cross section and branching ratio
- **Exclusion** of possible spin-0 and spin-2 particles
- Upper limit on $\mu_{HH} < 24$
- Limits on anomalous HHH coupling $-11 < k_\lambda < 17$

- **Systematics**
  - Photon energy resolution 5%
  - Jet energy resolution and scale 5%
  - Theoretical uncertainties 3-5%



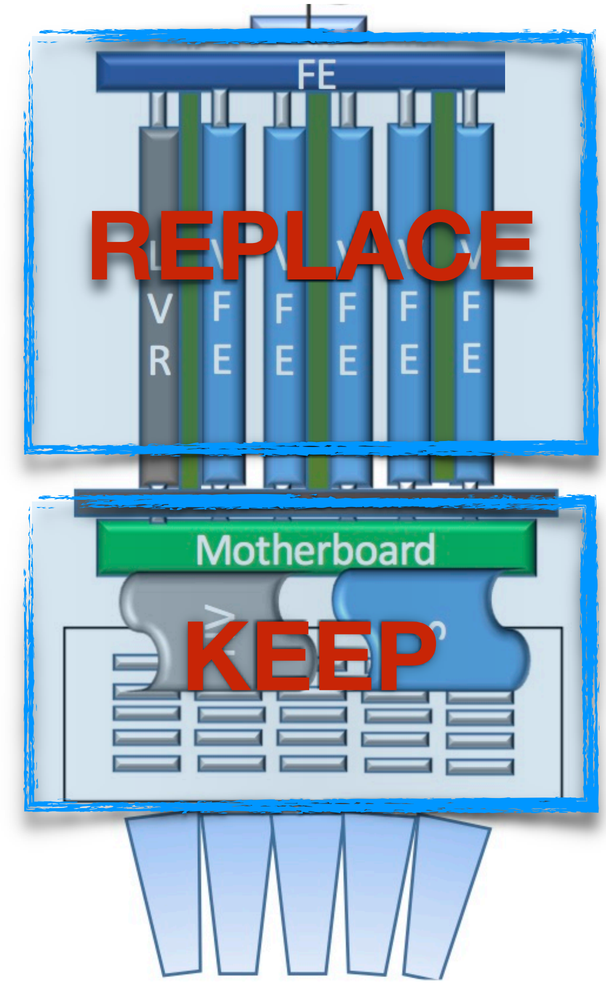


From LHC to High-Luminosity LHC



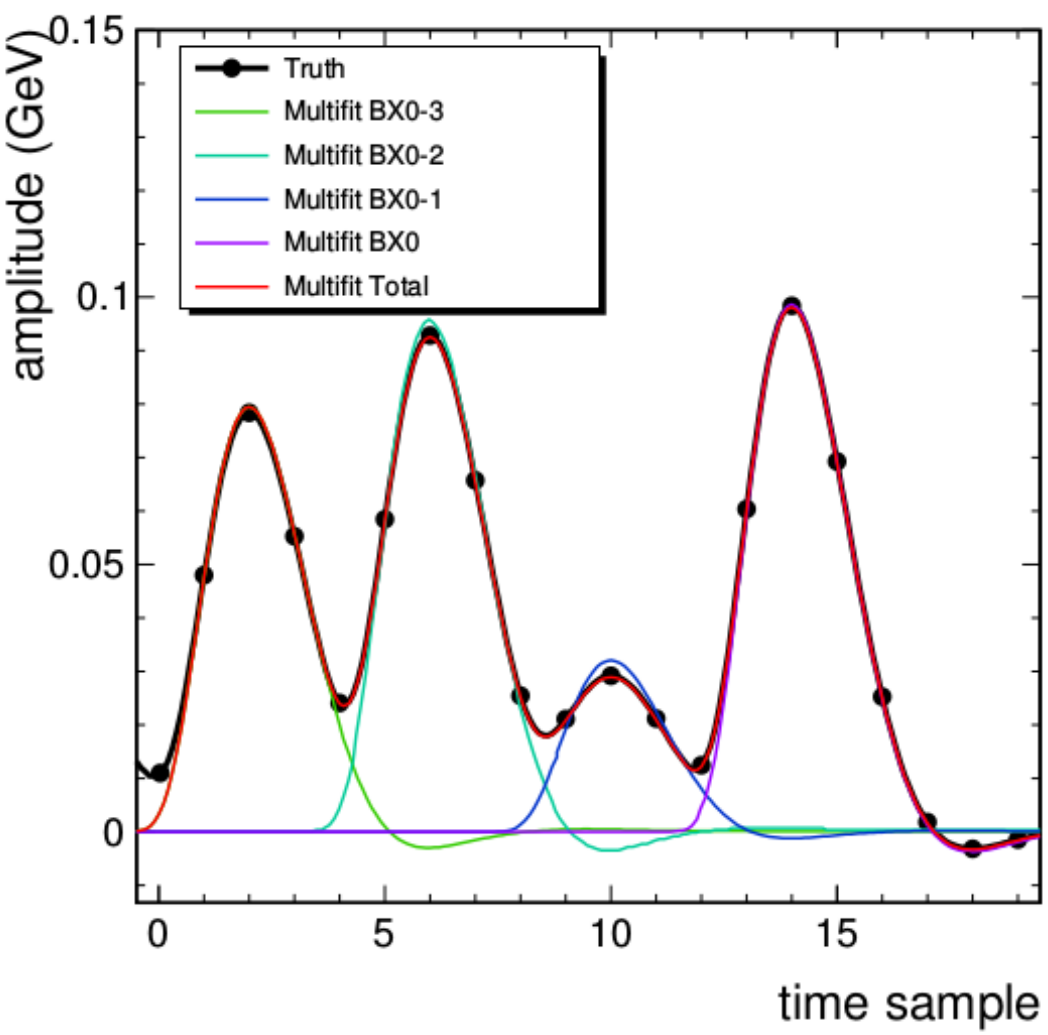
- Performances:
  - Centre of mass energy 14 TeV
  - Instantaneous luminosity from 1.7×10^{34} to 7.5×10^{34} $cm^{-2}s^{-1}$
  - Goal: 3000 fb^{-1} integrated luminosity → **Huge statistics**
- Consequences:
  - **Huge crystal irradiation** → Loss of ~50% of barrel crystals' transparency and small reduction of energy resolution (endcap crystals replaced by HGCAL)
  - Substantial **increase in pileup** rate: from ~60 to 140-200 events/collision
- In order to maintain Phase-1 performances, need to:
  - Reduce noise in photo detectors (Avalanche Photo-Diodes) due to LHC irradiation → **Cooling** and new front-end pre-amplifier with shorter shaping time
  - Perform **precision time measurements** to identify primary vertexes and reduce pileup contamination

ECAL UPGRADE



- Energy and time determination: sampling of shaped signal from photodetectors → Upgrade of the very front-end, **reduction of the shaping time**

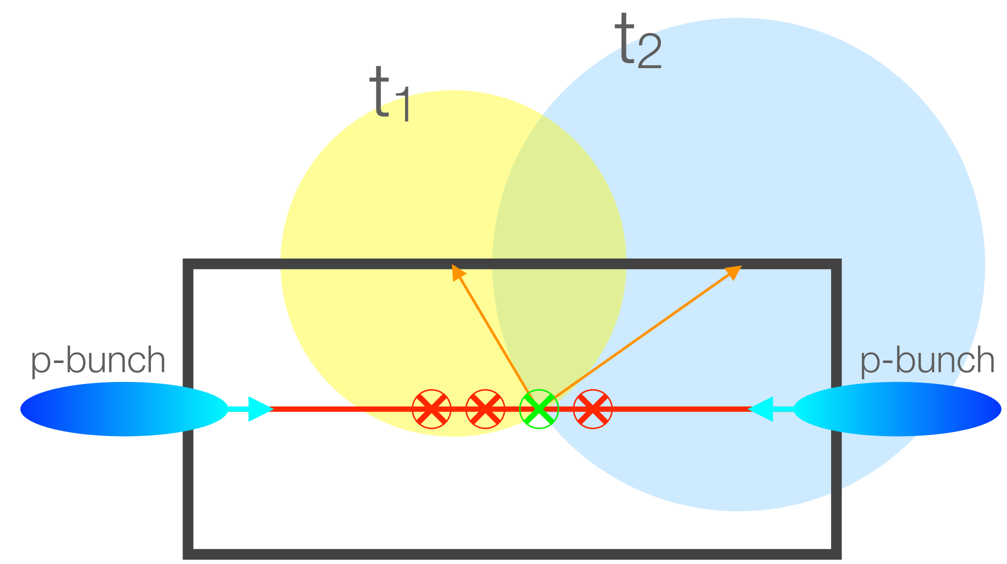
- Cooling system to reduce APDs dark current: from 18°C to 9°C

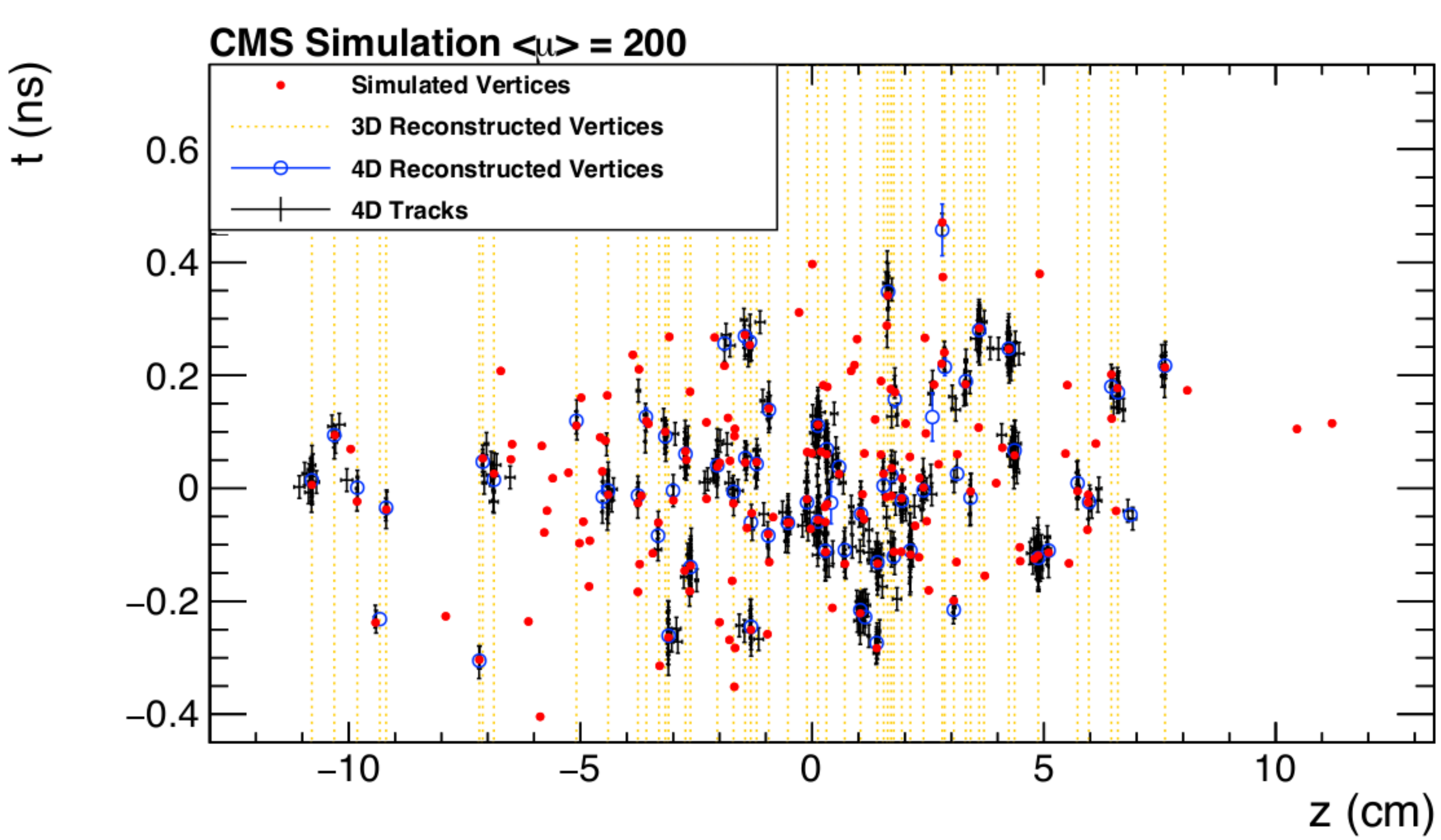


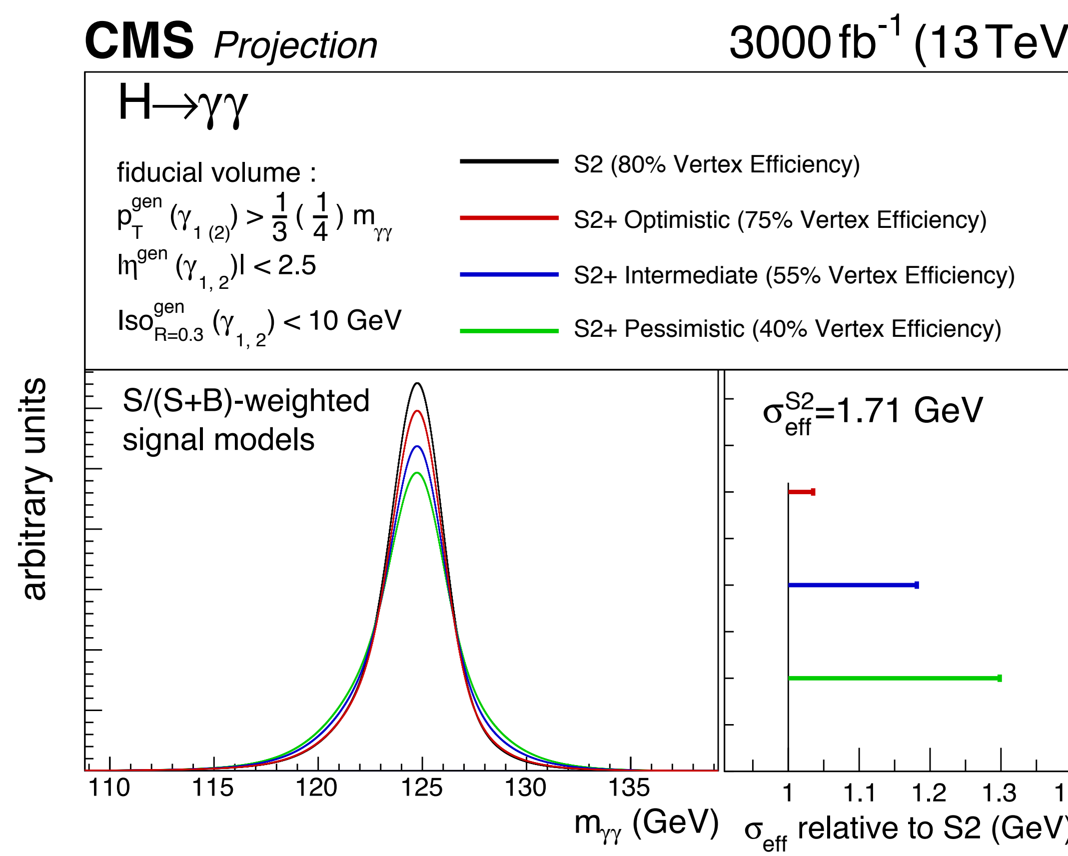
- Model the signal as a sum of one in-time pulse and a series of out-of-time pulses
  - Remove out of time pileup
  - Obtain **time of arrival from template fit** of pulse shape
- Test beam results: **30 ps resolution achievable** for 25 GeV photons

$H \rightarrow \gamma\gamma$ @ HL-LHC

- **Photon energy resolution**
  - Exploit 3x3 crystal information to reduce pileup and noise contribution
- **Vertex position**
  - Dominant with the increase of pileup
  - 140 pileup ➞ 40% vertex reconstruction efficiency
  - Solution: **O(30 ps) time resolution** allows better than 1 cm primary vertex determination ➞ Pileup contributions back to Run 2 levels







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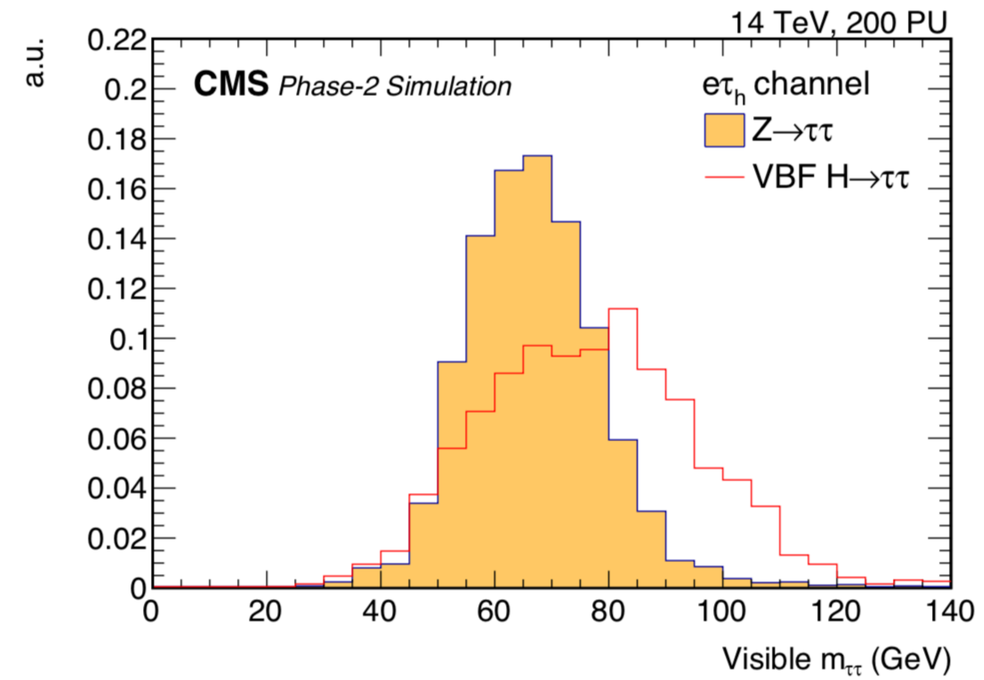
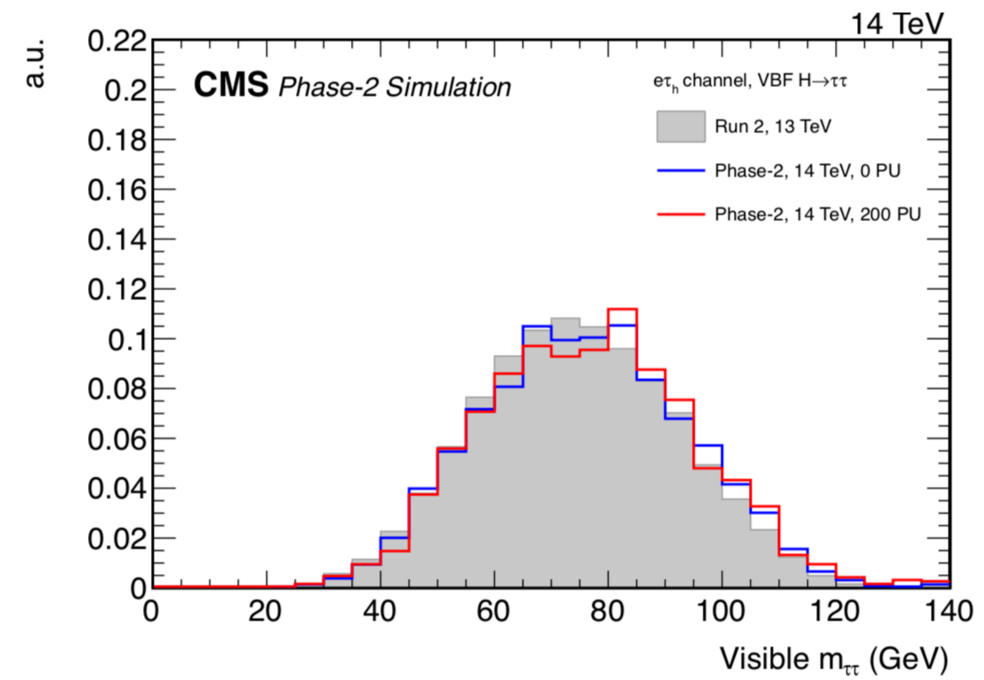
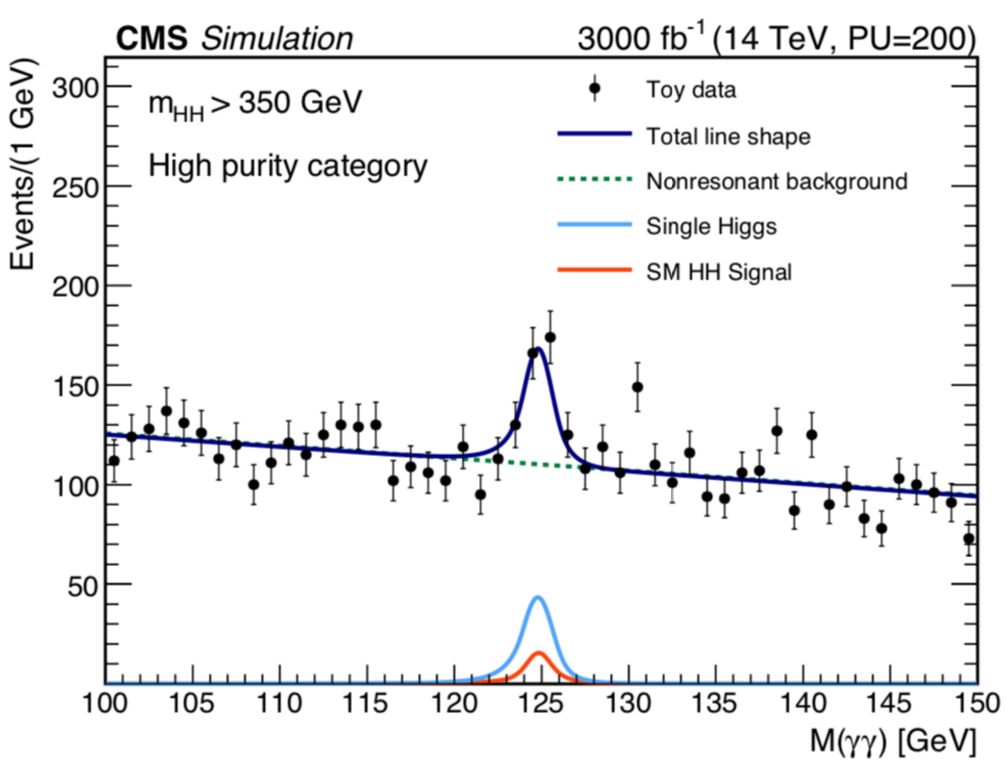
H → $\tau\tau$ @ HL-LHC

- Fundamental Z → $\tau\tau$ background rejection
  → Excellent **mass resolution required**
- Same conditions of Run 2 achievable with upgrade
- Expected sensitivity on coupling modifier of **2-5%** (30% in Run 2)





HH → bb$\gamma\gamma$ @ HL-LHC



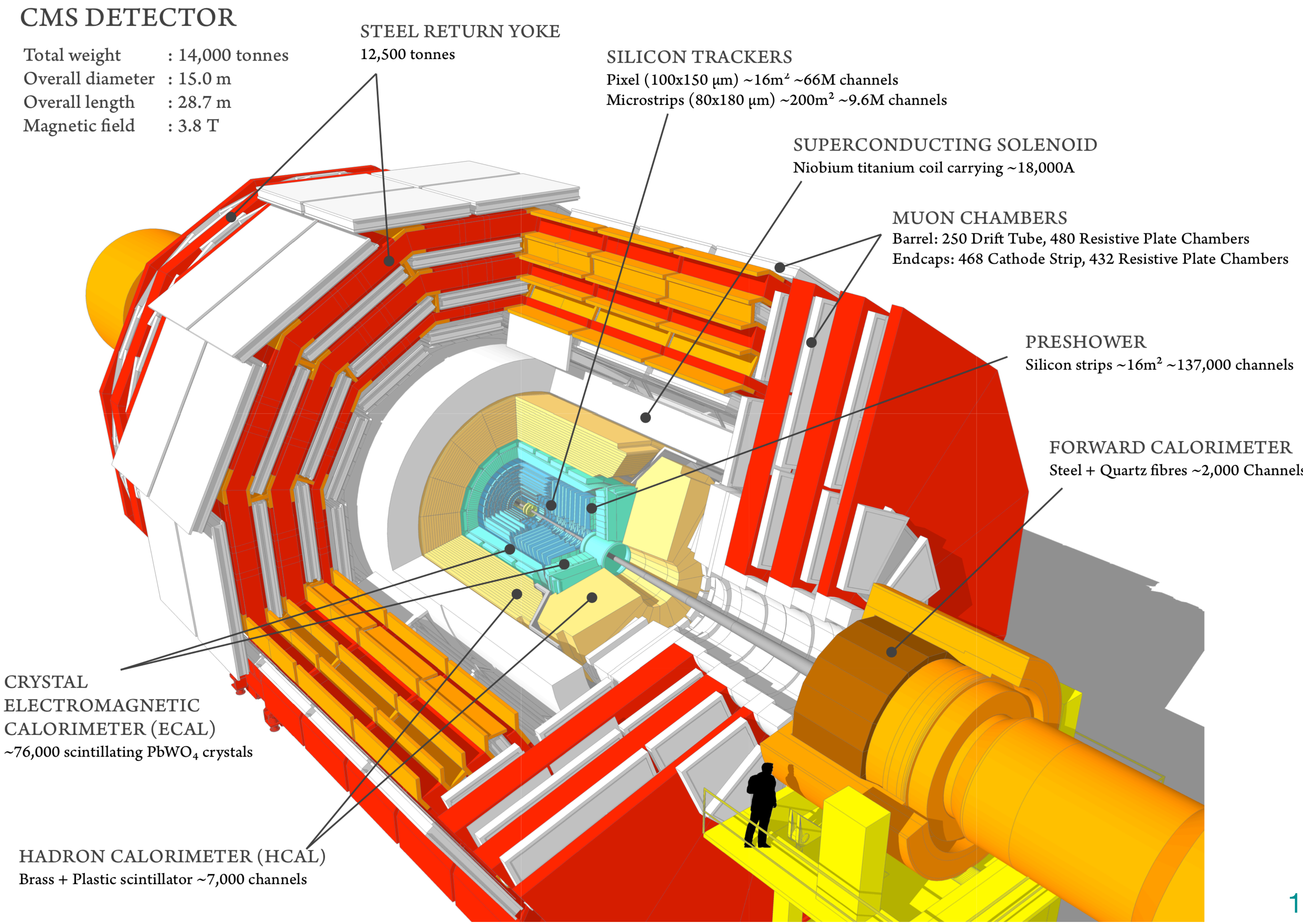
- Expected significance **1.9 σ** with 1000 fb^{-1}
- Improvements considering also γ **background rejection** with new ECAL timing performances
- M($\gamma\gamma$) allows separation between signal and non-resonant background, no H - HH discrimination

Summary

- Excellent results in Higgs searches in Run 2 (see also H → bb and coupling studies in general)
- **Huge statistics** needed to study rare processes such as HH production → High-Luminosity LHC
- HL-LHC is a very **challenging environment** due to pileup and radiation condition → Need an **upgraded detector**
- **Precise timing** and new **electronics** guarantee similar performances as those of Run 2
- More precise analysis of single Higgs processes and study of rare multi-Higgs production are expected from simulations

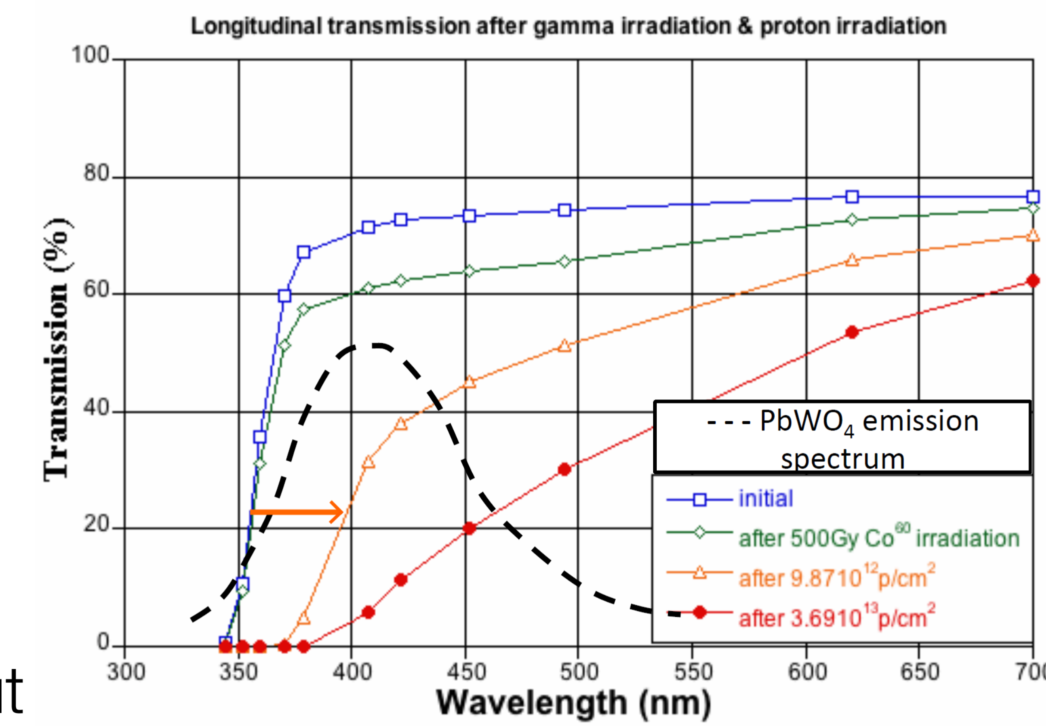
BACKUP

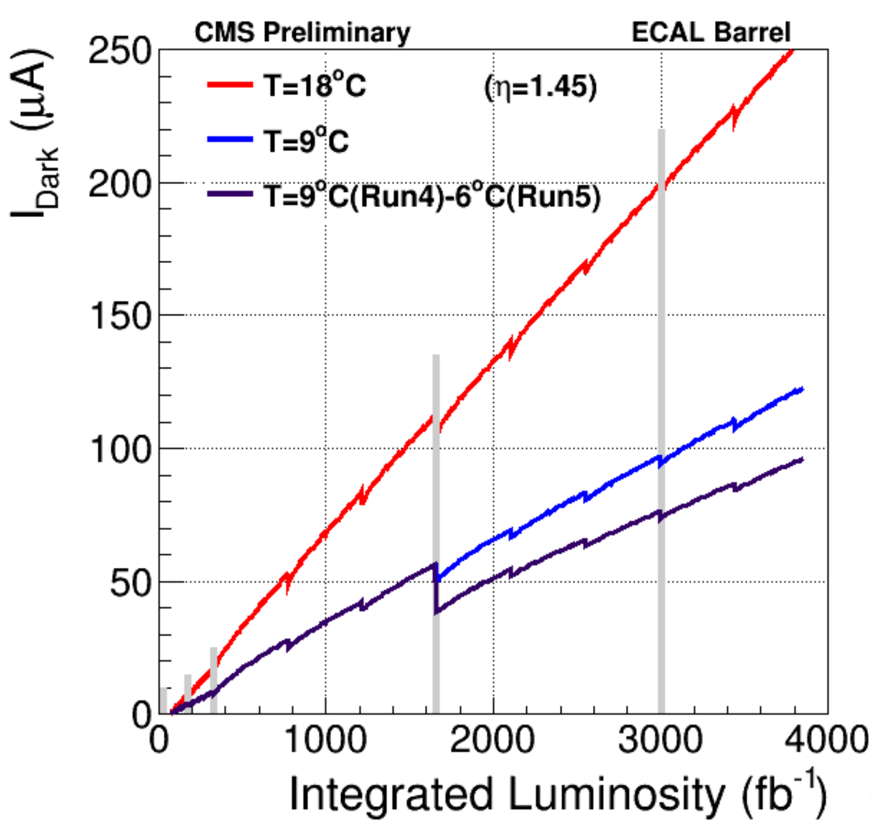
THE CMS EXPERIMENT

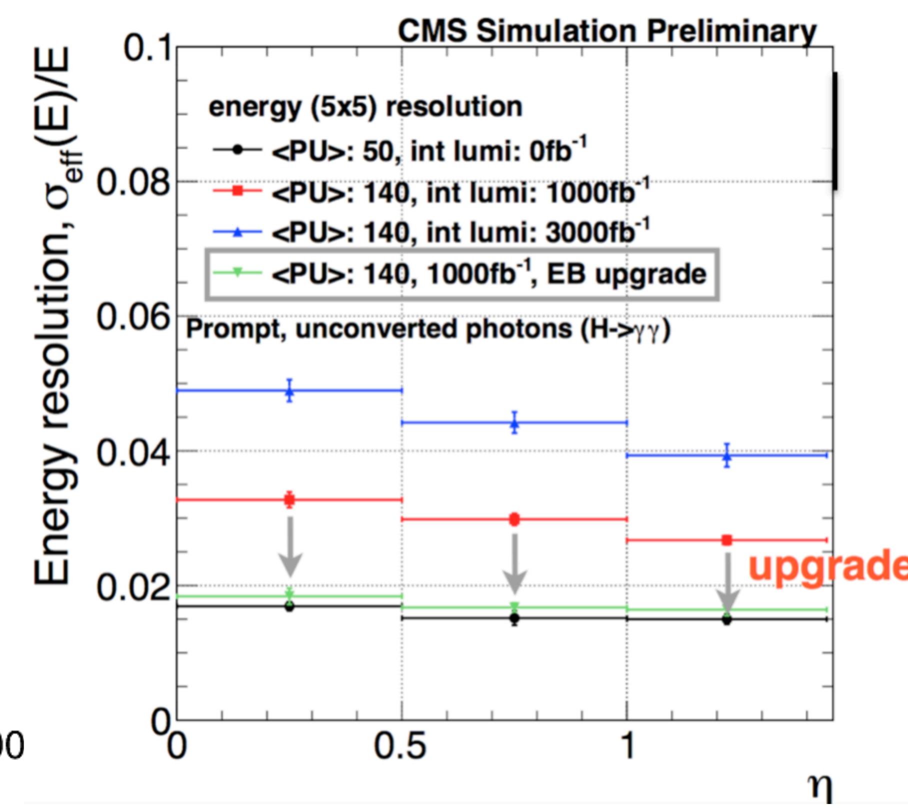


AGEING PERSPECTIVES

- $PbWO_4$ crystals
  - **Transparency loss:** γ radiation damages can be cured (annealing), hadron interactions produce permanent defects (shift in wavelength)
  - Lower temperature operations (9°C vs 18°C) limit the annealing but increase the light output







Avalanche Photo-Diodes

- Experience **high dark current** due to high level of LHC irradiation → Worse energy resolution
- Lower operations' temperature (9°C vs 18°C) strongly reduces dark current