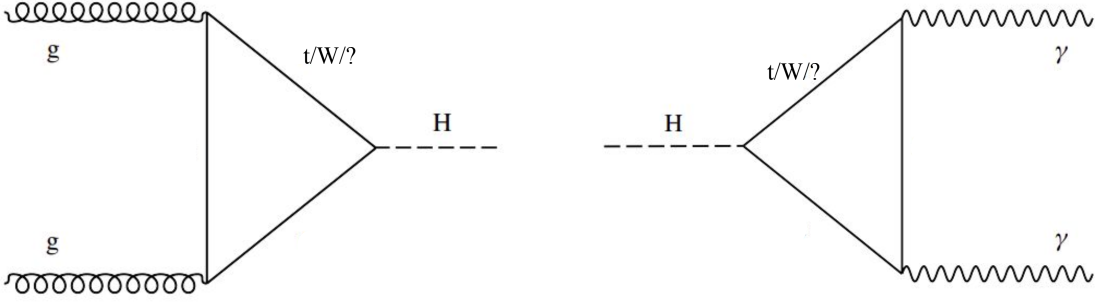
Studies of the top-Higgs interaction with the CMS experiment and the upgrade of DAQ electronics of the CMS endcap muon system

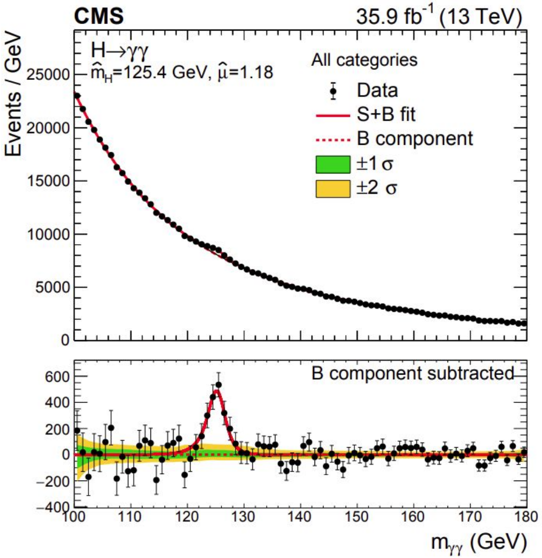
梅华林
University of California, Santa Barbara

Top-Higgs Yukawa Interaction

- Yukawa interaction a **fundamental interaction** of the Standard Model (SM)
- In the SM, the Yukawa coupling between the Higgs boson and the fermion is proportional to the mass of the fermion
- Top-Higgs Yukawa coupling (Htt) being the largest



Indirect access to top-Higgs Yukawa coupling



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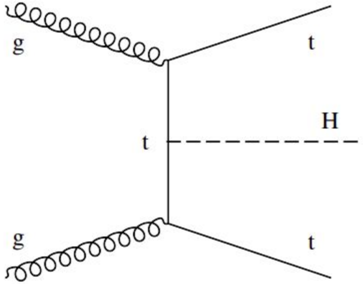
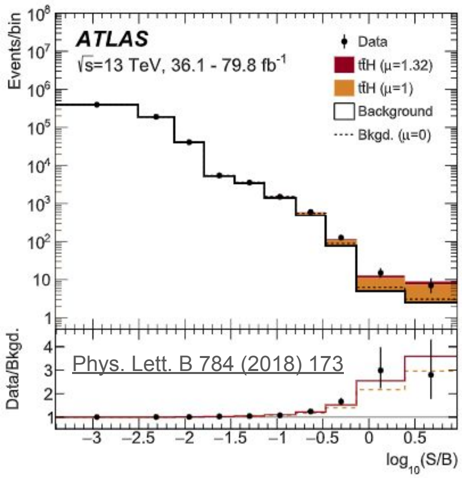
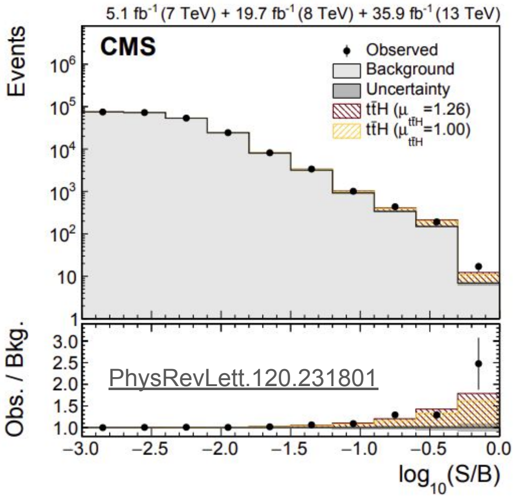
Direct probe of the top-Higgs Yukawa interaction



- Using ttH production is the most direct way to probe the top-Higgs Yukawa interaction
- Production cross section for ttH at the 13 TeV LHC is ~0.5 pb, corresponding to ~1% of the total Higgs bosons produced

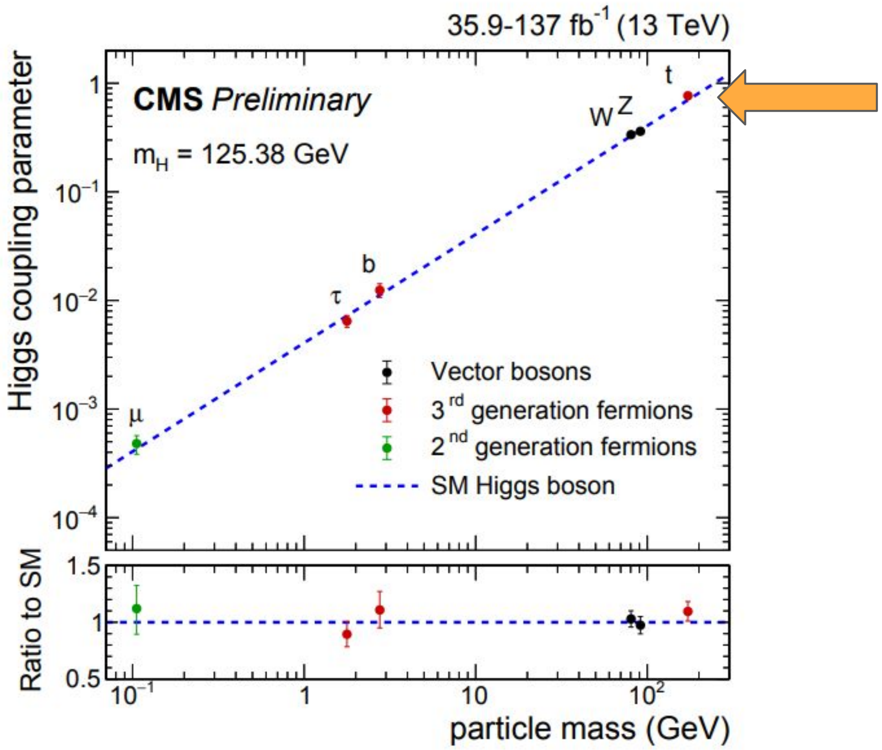




Both the CMS and ATLAS collaborations observed the ttH production with **a combination of Run 1 and partial Run 2 dataset in 2017**

Why studying top-Higgs interaction

- A basic test of the Standard Model



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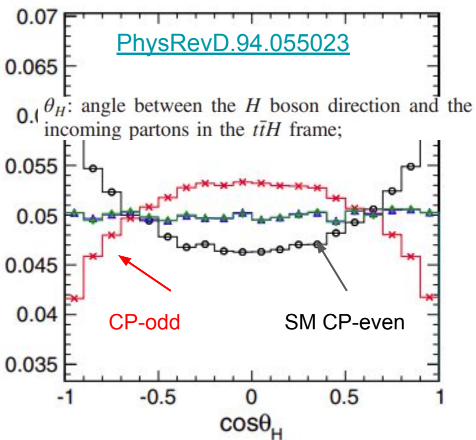
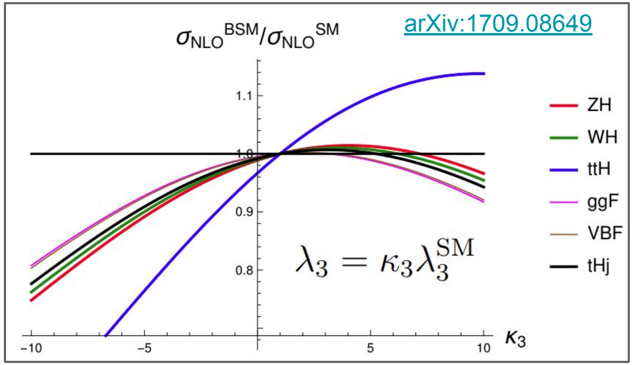
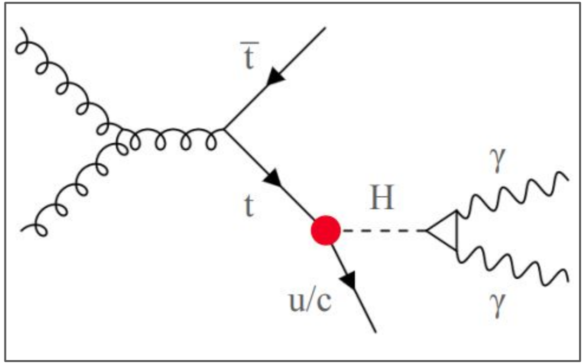
Why studying top-Higgs interaction

- A basic test of the Standard Model
- Opens up new opportunities to probe BSM physics, a few examples:

1. Measure the t-H Yukawa properties, test if there is small deviation from the SM
2. Use ttH production as a handle to better constrain the H trilinear self-coupling
3. Direct search of BSM t-H interactions







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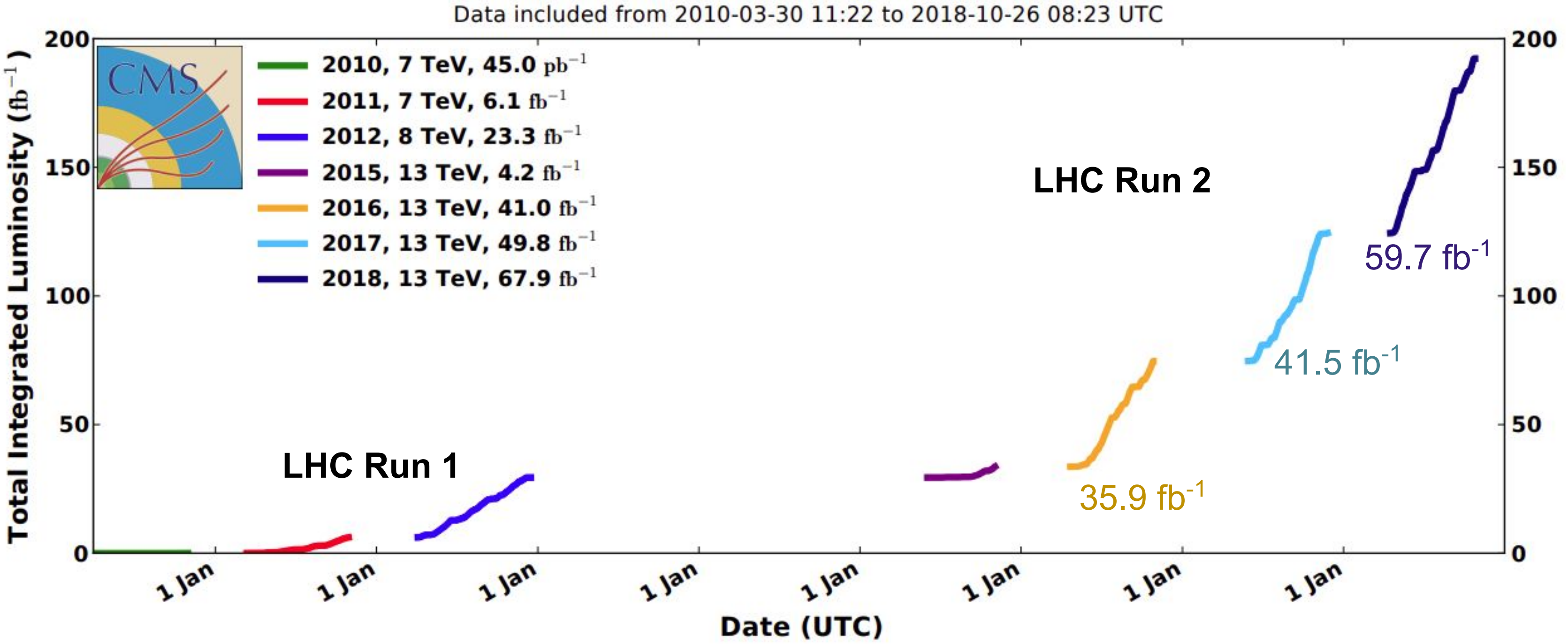
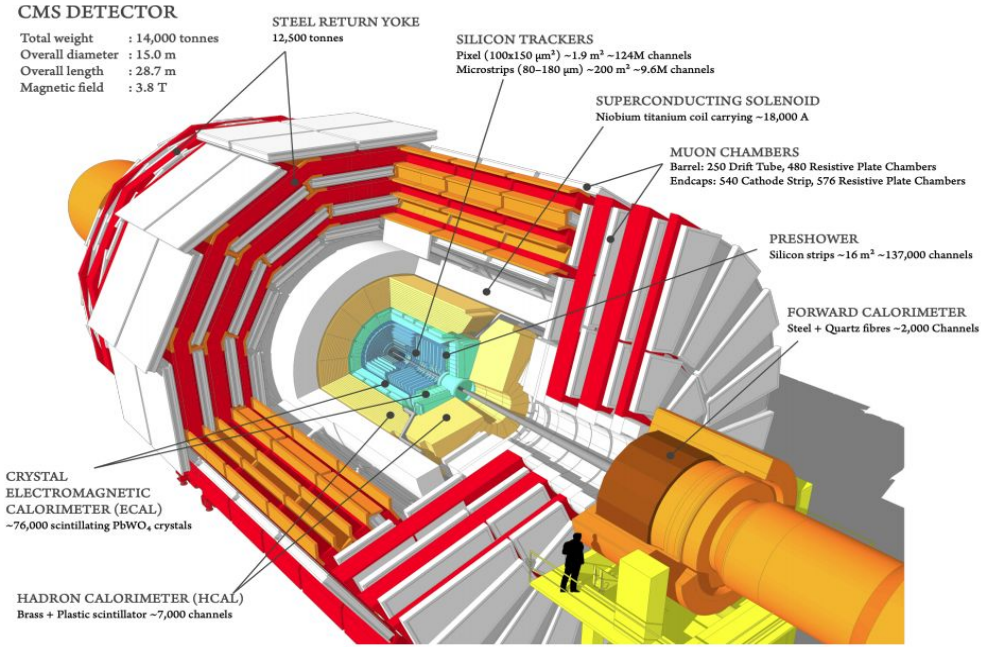
In this talk, I will discuss recent Run 2 results from the CMS experiment featuring the studies of top-Higgs interaction using the Higgs to diphoton decay channel

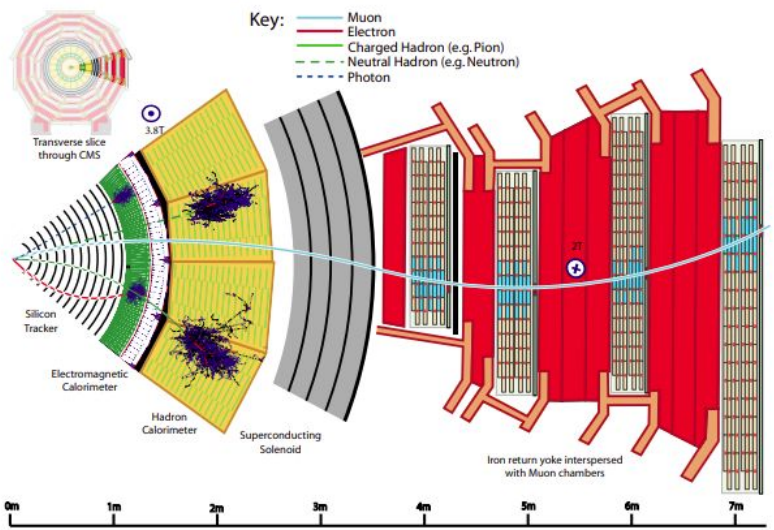
The LHC kept high performance during Run 2



Results presented later are based on 137fb^{-1} of data that CMS collected during Run 2

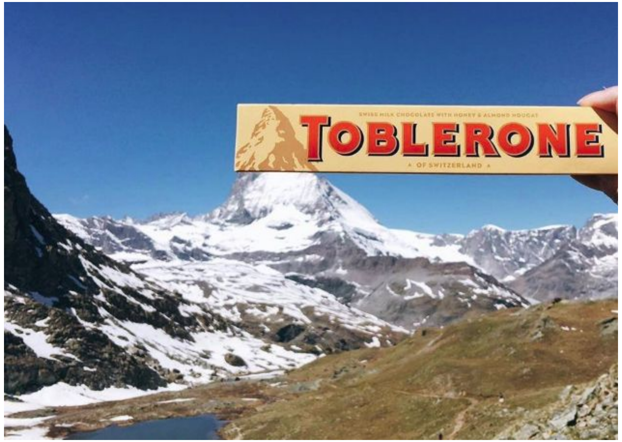
The CMS detector



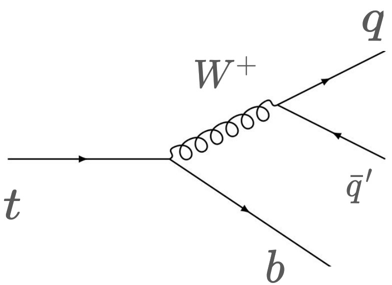


ttH(H→γγ) analysis: a brief introduction

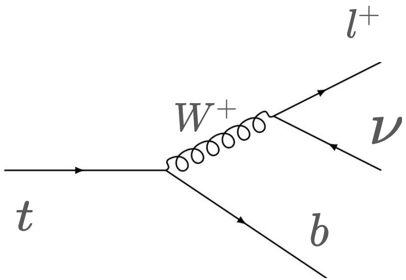
- Fit diphoton invariant mass distribution to extract parameters of interest
  - e.g., cross section, CP structure
- Utilize signatures from ttbar decay to improve S/B
  - Jet/lepton multiplicity
  - Jet triplet consistent with top quark decay
  - Event kinematics and flavour tagging information that are sensitive to differences between signal and background



Hadronic top decay:
no isolated lepton



Leptonic top decay:
1 isolated lepton

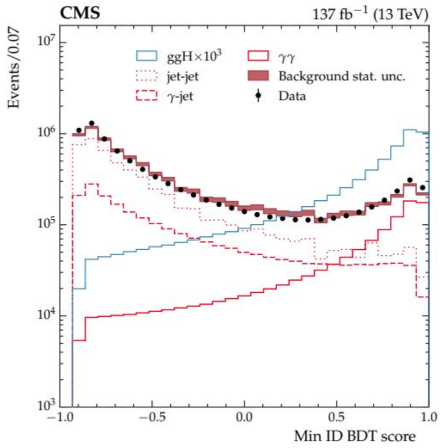


Main backgrounds

Leptonic

- ttbar + diphoton
- ttbar + 1/0 photon

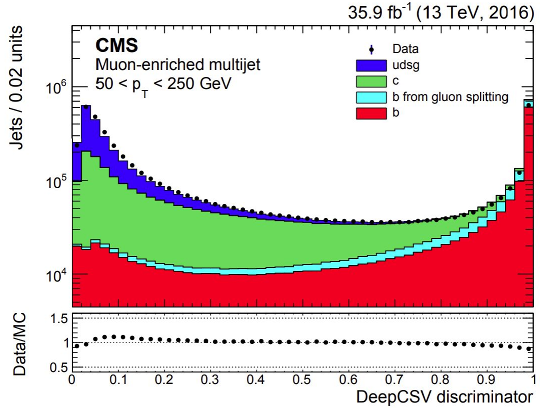
Use photon ID BDT score to suppress background with fake photons



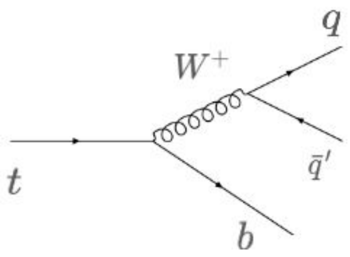
Hadronic

- Multi-jet + diphoton
- Multi-jet + 1/0 photon
- ttbar + diphoton
- ttbar + 1/0 photon

Use jet multiplicity and b-tagging score of individual jet to suppress non-ttbar background



Extra handles



Top-quark tagger (BDT)

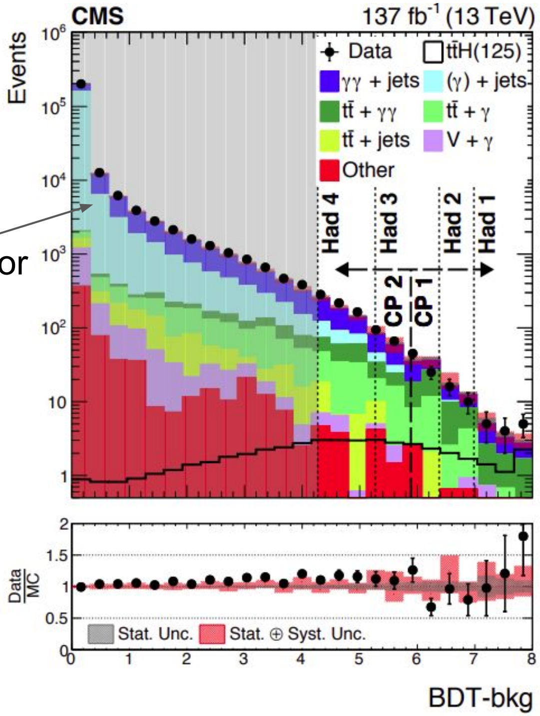
- To further reduce multi-jet background
- Retrained version based on the one used in JHEP10 (2017) 005
- Trained on ttbar MC simulation, exploits properties of three-jet candidate
  - Kinematic properties of the constituents, quark-gluon discrimination metrics, flavour tagging

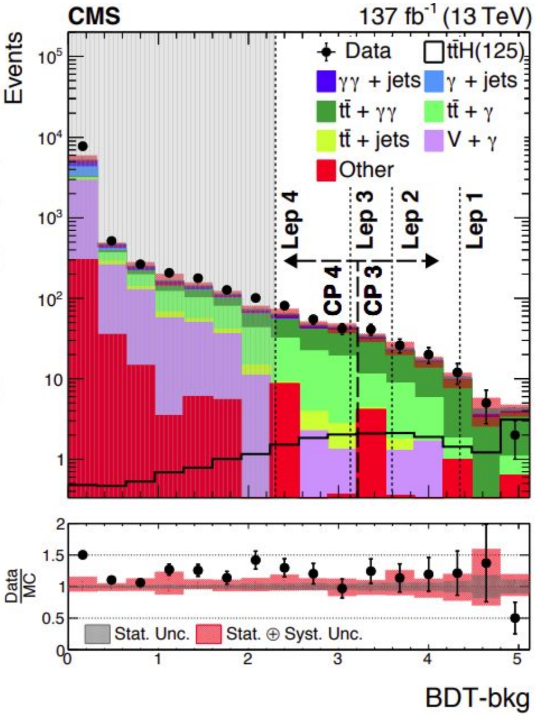
Dedicated Deep Neural Networks (DNNs)

- To fight against the ttbar + diphoton and multi-jets + diphoton
- Train a dedicated DNN for each with signal and background MC simulation
  - Utilize low level information such as full four-vector of leading jets/leptons, flavour tagging information and other event level kinematic properties

BDT-bkg performance

Data driven for γ+jets



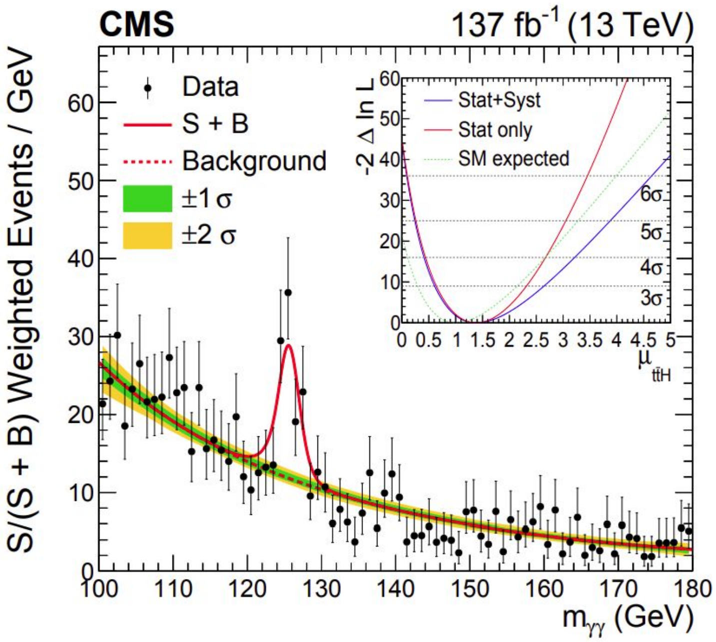


100 < $m_{\gamma\gamma}$ < 120 GeV or 130 < $m_{\gamma\gamma}$ < 180 GeV

- Events are either rejected or further divided into subcategories to maximize sensitivity
- The BDT-bkg score has good separation between signal and background
- Good data-MC agreement in the signal regions

PhysRevLett.125.061801

Cross section measurement



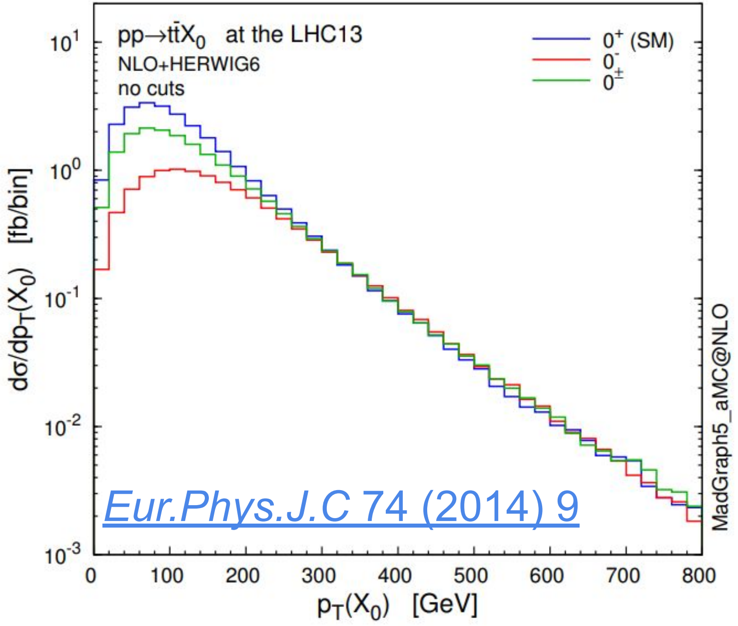
- σ_{ttH}*$BR_{\gamma\gamma}$ = $1.56^{+0.34}_{-0.32}$ fb

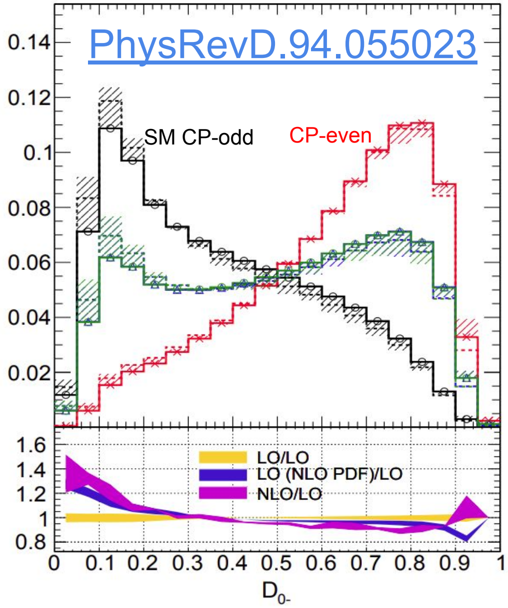
  $1.56^{+0.33}_{-0.30}(\text{stat})^{+0.09}_{-0.08}(\text{syst})$ fb
- $(\sigma_{ttH}$*$BR_{\gamma\gamma})_{SM}$ = $1.13^{+0.08}_{-0.11}$ fb
- μ_{ttH} = $1.38^{+0.36}_{-0.29}$ = $1.38^{+0.29}_{-0.27}(\text{stat})^{+0.21}_{-0.11}(\text{syst})$
- Observed (expected) significance: 6.6σ (4.7σ)
- **First observation of the ttH production in a single Higgs decay channel**

What is new in this result

- In 2018, CMS released a ttH($H \rightarrow \gamma\gamma$) measurement with partial Run 2 dataset ($77fb^{-1}/137fb^{-1}$), **exp/obs significance: 2.7σ/4.1σ** (CMS PAS HIG-18-018)
- If considering only statistical effect (with ~2 times more data), naively one would get **3.6σ expected significance** with full Run 2 dataset
- In the end, we got **4.7σ expected**, that is **30% improvement in sensitivity**
  - Better control background estimation when training the BDT, especially using data-driven γ+jets to improve training statistics in hadronic channel
  - Better utilization of modern machine learning techniques: both the analysis level BDTs and introduced various useful input features (hadronic top-tagging BDT, dedicated DNNs for difficult backgrounds)

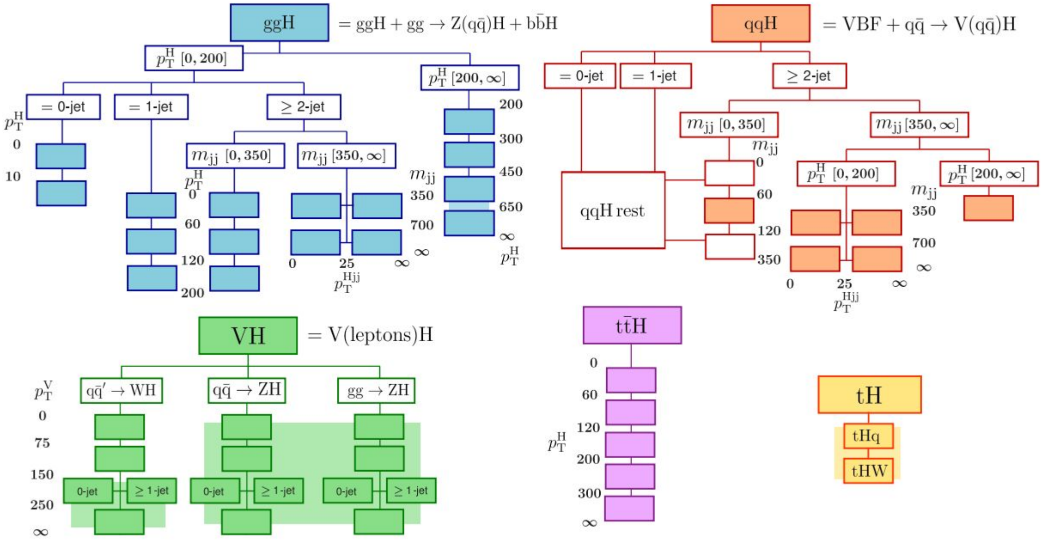
What else can we learn from these ttH events

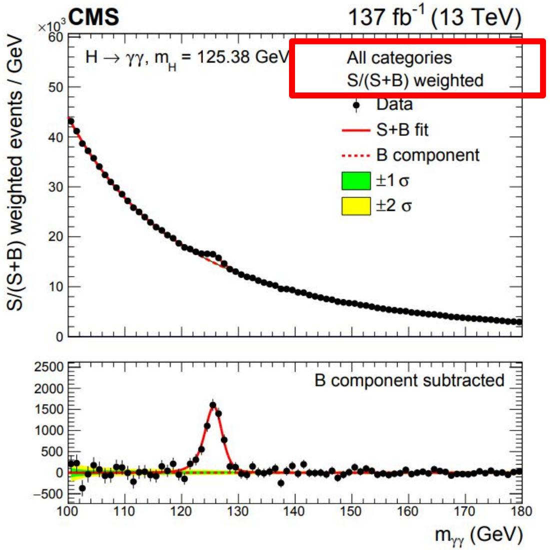




- Probe the CP nature of top-Higgs interaction, can either use extra information from the events (e.g. Higgs pT spectrum) or build dedicated discriminant to distinguish different CP hypotheses

CMS H→ γγ Run 2 legacy result





- Under the simplified template cross section (STXS) framework, produced a comprehensive measurement of the Higgs boson properties with H → γγ channel (signal strength, STXS stage 1.2, coupling modifier) with the full Run 2 dataset (2016 + 2017 + 2018)

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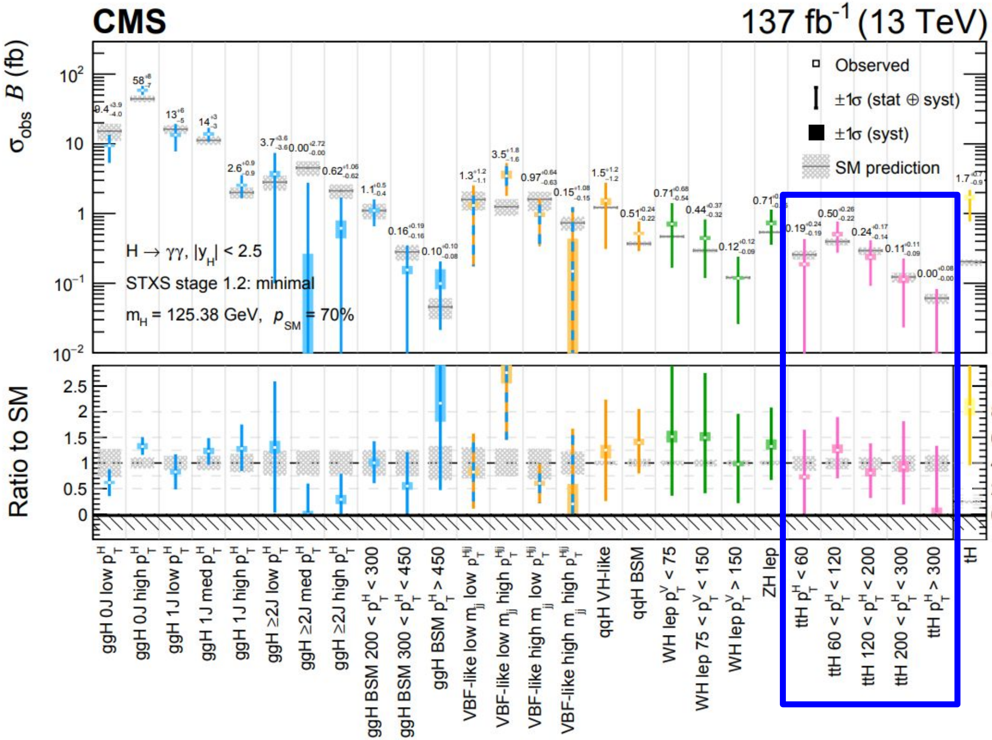
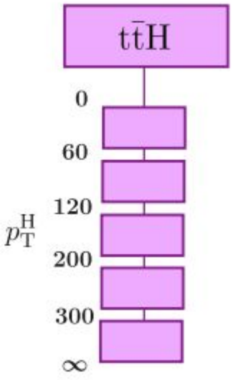
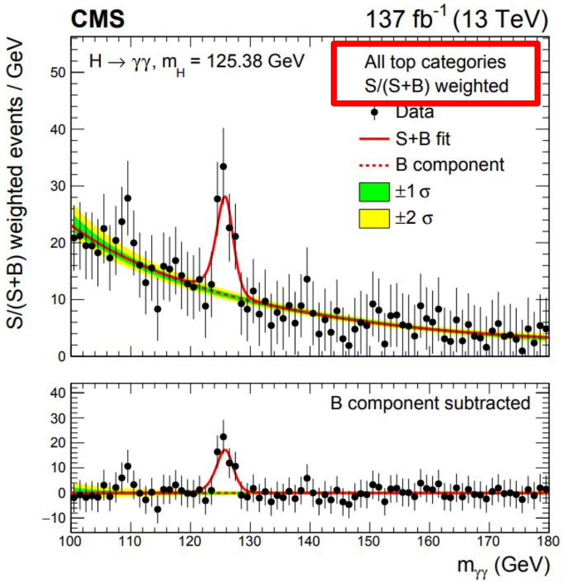
ttH production under STXS stage 1.2



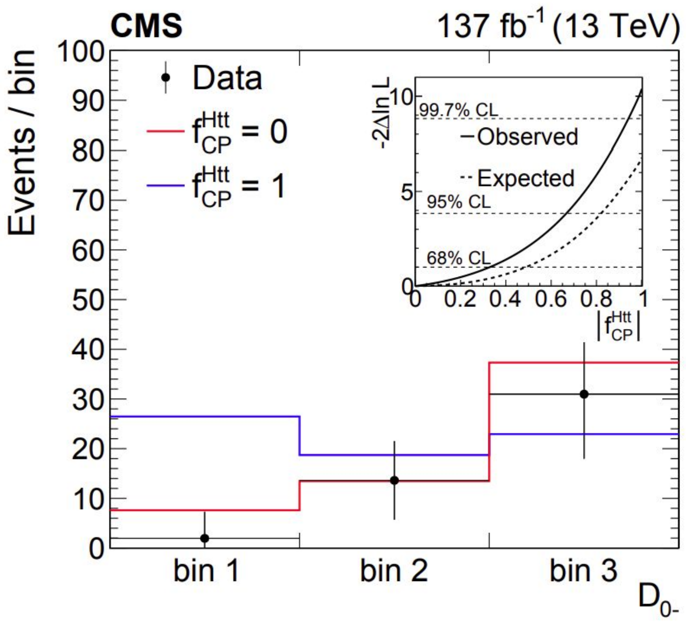




Extend sensitivity to BSM physics

First measurement of ttH production cross section in 5 regions of the Higgs boson p_T, so far everything consistent with SM

CP measurement result



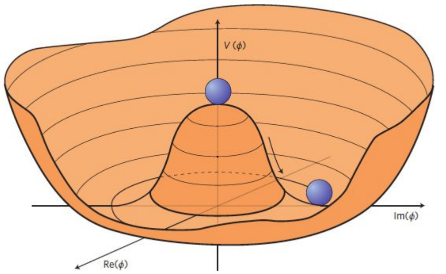
D0- represents the CP BDT output

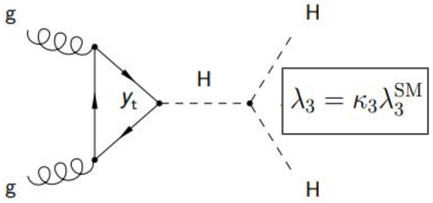
- Possible fractional CP-odd contribution

$$f_{CP}^{Htt} = 0.00 \pm 0.33$$

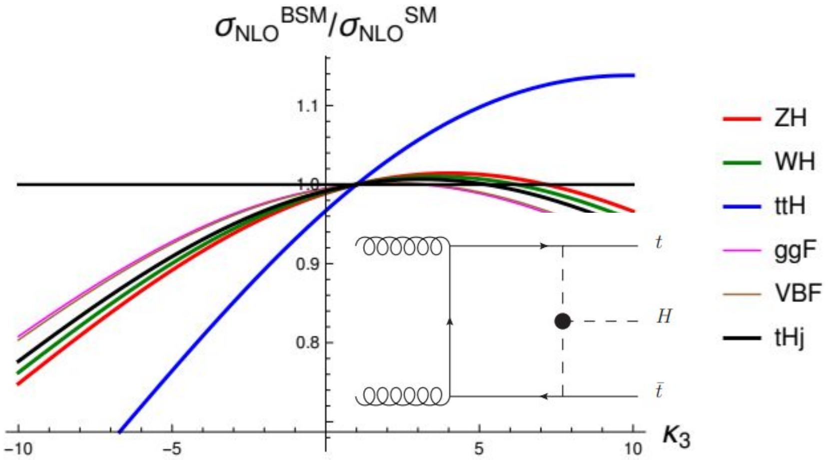
- $|f_{CP}^{Htt}|$ is constrained to be smaller than 0.67 at 95% confidence level (CL)
- Observed (expected) significance for the exclusion of pure CP-odd hypothesis: 3.2σ (2.6 σ)
- **First test of CP structure of the Htt coupling**

Use ttH process to probe the H self-coupling



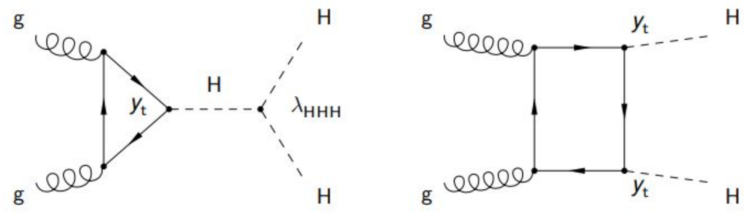


$$V = \frac{m_h^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

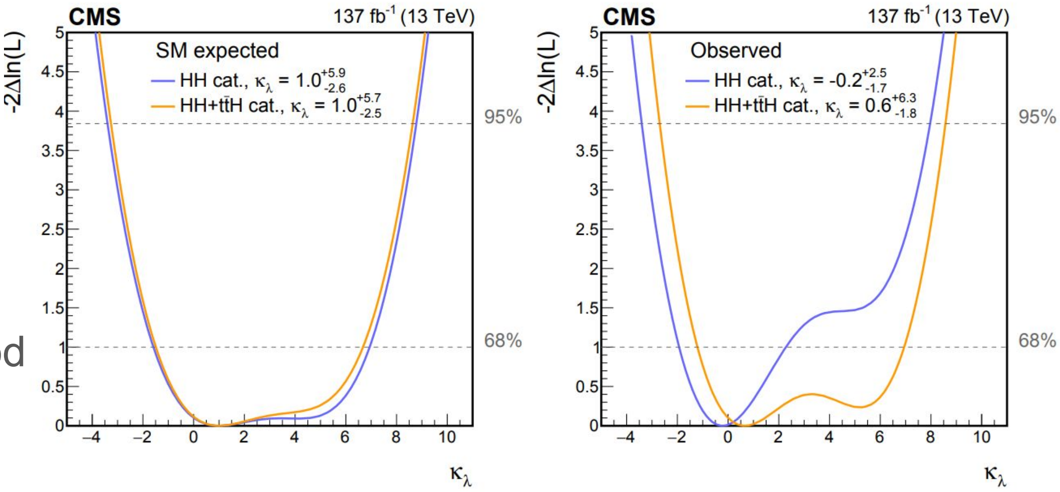


- Understanding the shape of the Higgs potential is one of the most important goals of the HL-LHC physics program
- Both the HH and H production cross section depends on κ_λ
- In the case of anomalous values of κ_λ, which are signs of new physics, the single H process with the largest modification of the cross section is ttH

Application in CMS Run 2 HH→bbγγ result

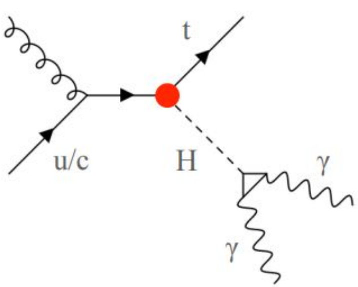


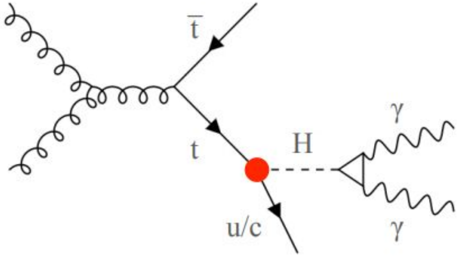
One of the most sensitive channels to HH production due to large Br(H→bb) and good mass resolution of the H → γγ channel



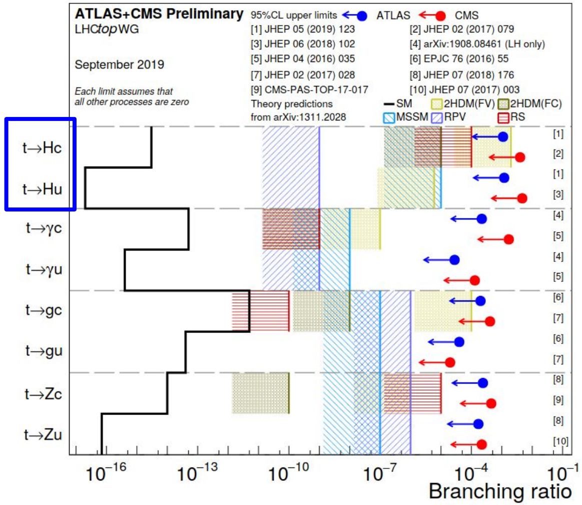
- Additional orthogonal categories targeting the ttH process are included
- ttH leptonic and hadronic categories are developed and optimized for the measurement of the ttH production cross section
- **The sensitivity of constraining κ_λ increases by 5% when fitting the HH and ttH categories simultaneously**

Direct search of BSM t-H interactions (e.g. FCNC)



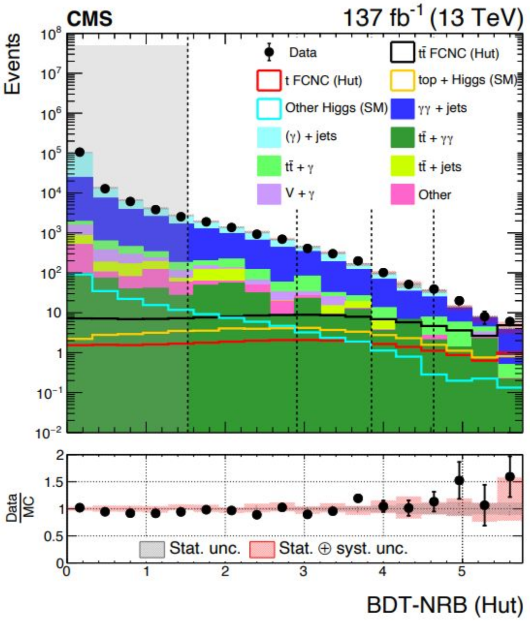


Status of top FCNC results as in 2019

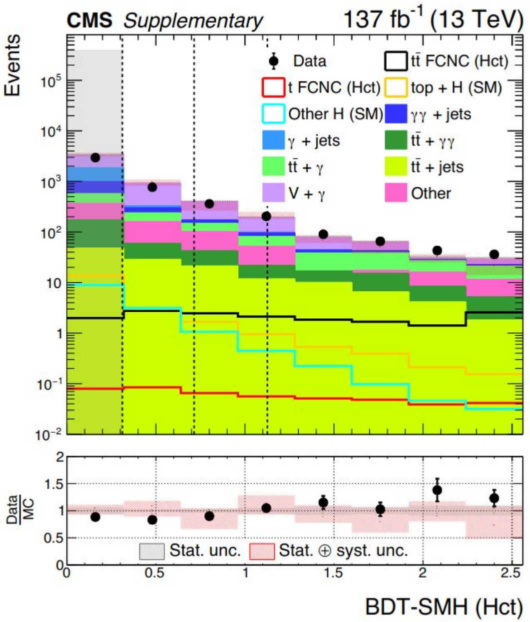


- $t \rightarrow H + u/c$ through a Flavour Changing Neutral Current (FCNC) is forbidden at tree level and suppressed through the GIM mechanism (BR < $O(10^{15})$)
- In many scenarios of BSM model, the $t \rightarrow Hq$ branching fractions are enhanced by many orders of magnitude w.r.t SM values, thus motivates the search for top-Higgs FCNC process

Search strategy



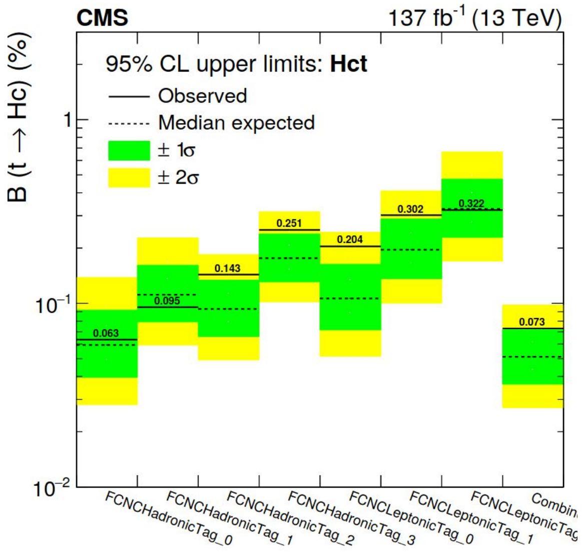
BDT targets non-resonant bkg

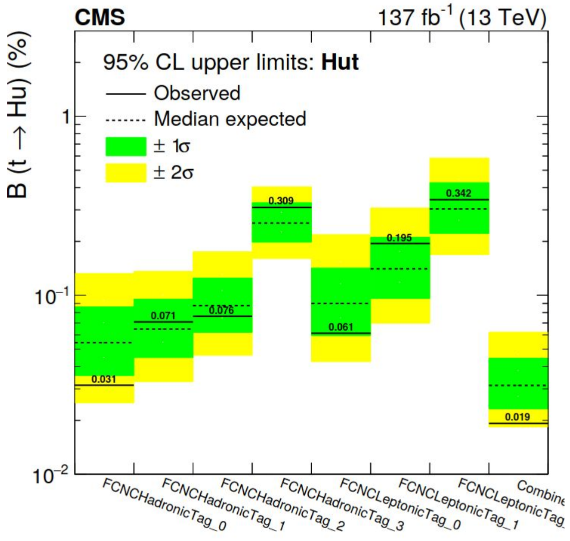


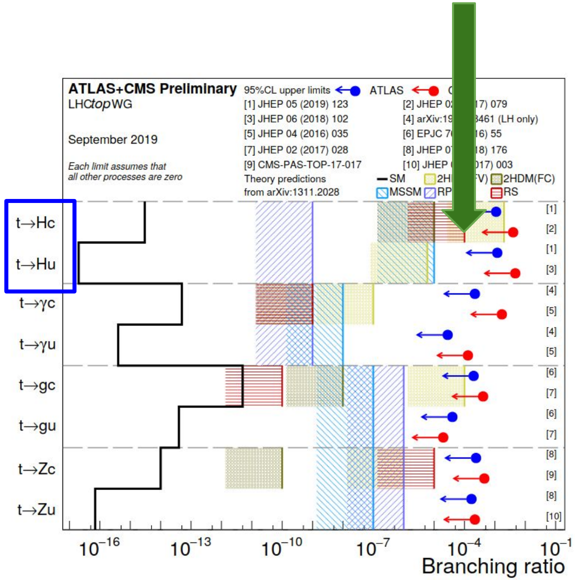
BDT targets SM Higgs bkg

- In a recent search of t-H FCNC based on H→γγ, the strategy is largely based on previous SM ttH(H→γγ) measurement
- Utilize multiple methods (MVA+kinematic fit) trying to reconstruct the top candidate
- Use two dedicated BDTs targeting both non-resonant background (ttbar, GJets etc) and SM Higgs backgrounds (ttH)

New CMS limit with using Run 2 dataset



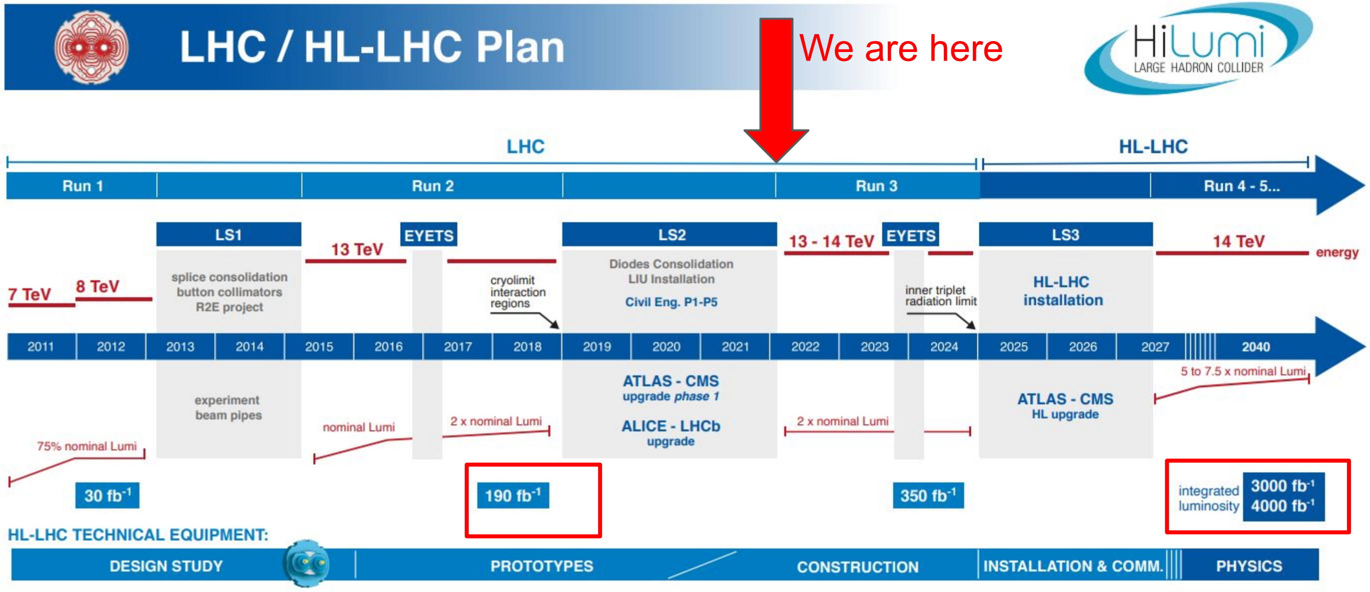




- The observed (expected) upper limits on B(t → Hu) and B(t → Hc) are 1.9×10^{-4} (3.1×10^{-4}) and 7.3×10^{-4} (5.1×10^{-4}), respectively
- **Current world's best limits**, almost an order of magnitude better than previous results with partial (2016) Run 2 data combination (H→γγ + H→bb + H→leptons)

The upgrade of DAQ electronics of CMS endcap muon system

The HL-LHC upgrade



Higgs coupling to 2nd generation fermions?

Higgs self-coupling?

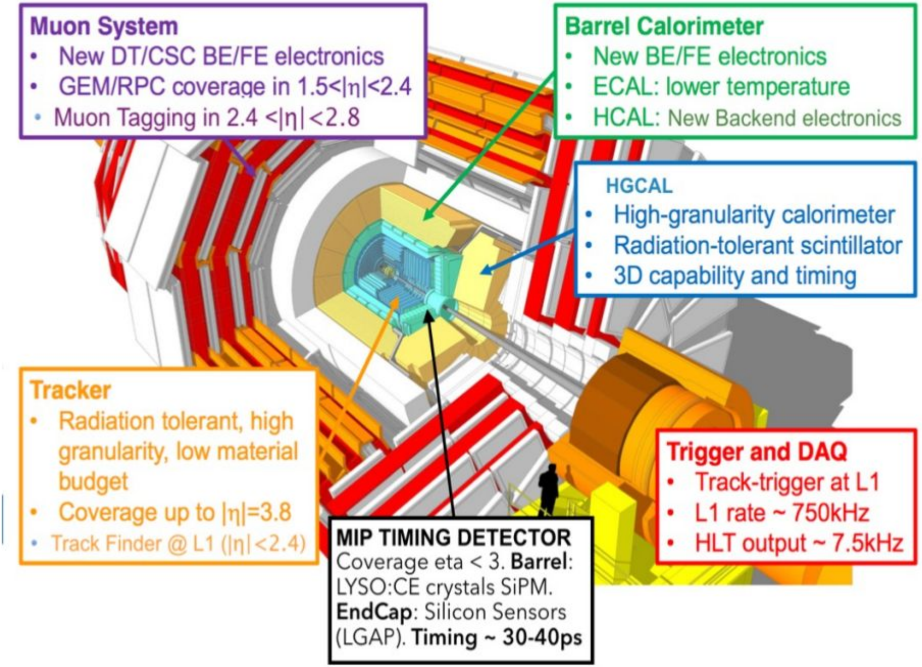
Any BSM?

…

Expect a factor of 20 more data at the end of HL-LHC

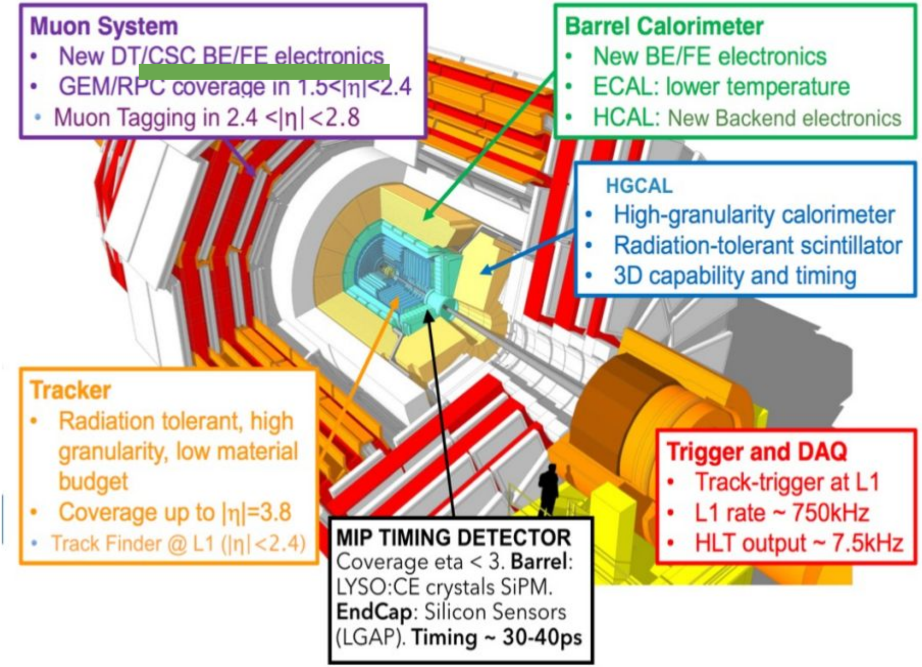
- Despite the success of LHC Run 1 and Run 2, there are still fundamental physics questions unanswered, many of these searches are limited by statistics, their sensitivity increases in proportion to the integrated luminosity

The CMS phase II upgrade



- Key parameters that drive many of the CMS phase II upgrade
  - L1A rate: 100 kHz → 750 kHz
  - L1A latency: 3.2 μs → 12.5 μs
  - Higher pileup interactions: ~200
- The implications on the upgrade are:
  - Higher granularity of detecting module
  - Precise timing resolution
  - Increased TDAQ bandwidth
- Radiation hardness of the sensors and front-/back-end electronics are also important factor to consider due to high radiation at the HL-LHC condition

The CMS phase II upgrade



Next will discuss the upgrade of CSC readout electronics for phase II that I am working on

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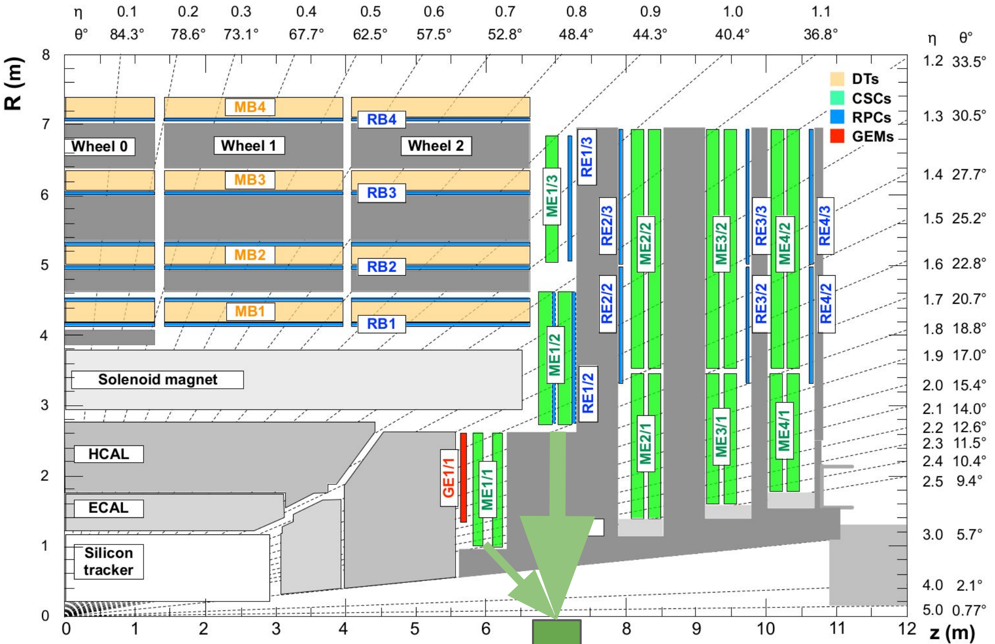
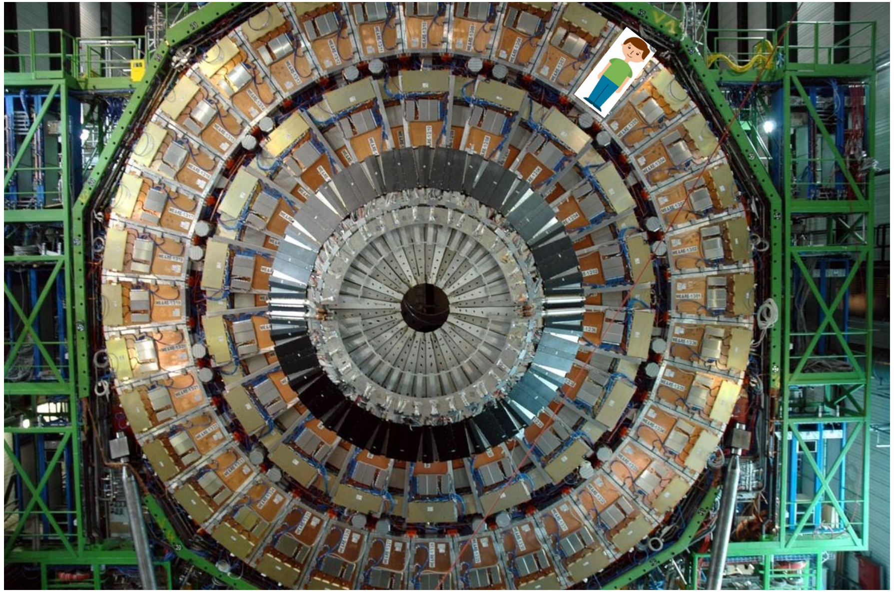
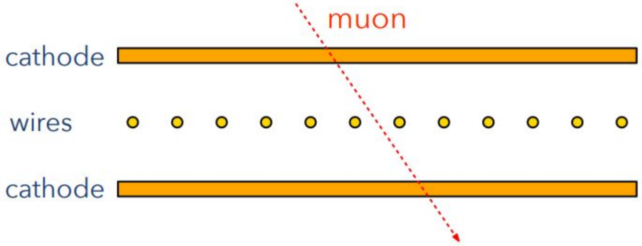
A brief introduction of the CSC system



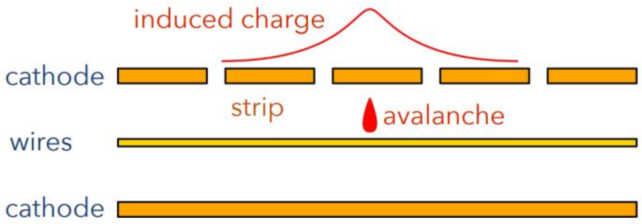


A brief introduction of the CSC system

- CSC stands for: **Cathode Strip Chamber**, based on multi-wire proportional chambers
- 540 in total installed on both endcaps of CMS
- Crucial for muon triggering and identification at high $|\eta|$ region ($0.9 < |\eta| < 2.4$)
  - Time resolution ~3.4 ns; position resolution ~50-145 μm
- Finely segmented cathode strips for measuring muon position in the bending plane
- Anode wires run azimuthally and provide a coarse measurement in the radial direction

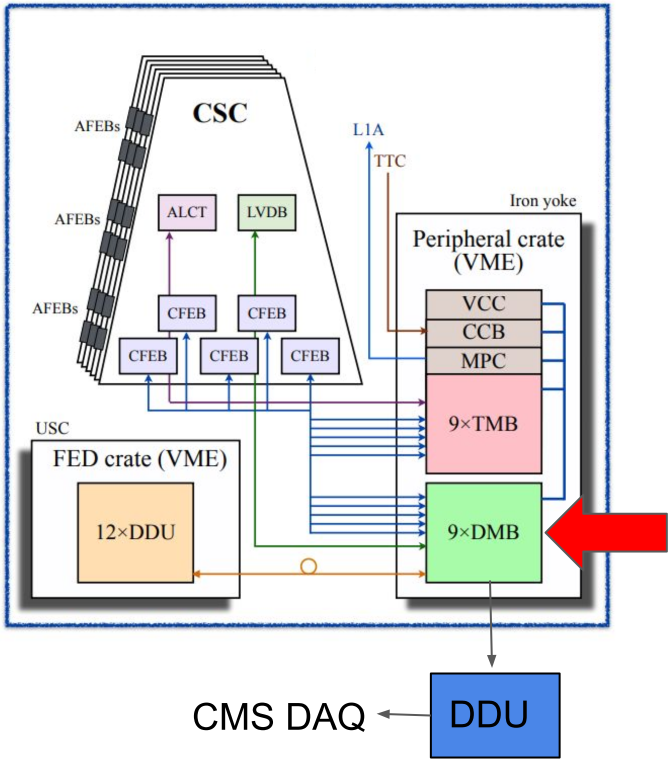


6 such layers per CSC



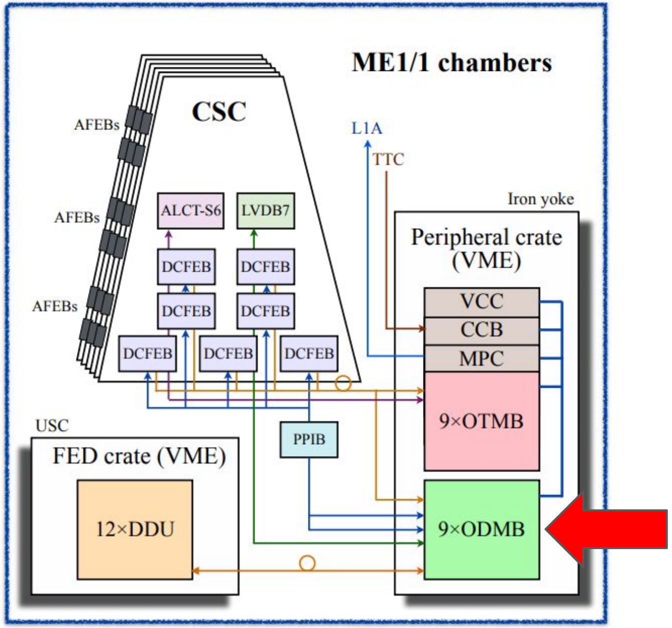
Working gas: 40% Ar + 50% CO_2 + 10% CF_4
Nominal HV: 3600V/2900V

The DAQ boards for CSC



- During Run 1, each CSC sends DAQ data to a Data acquisition MotherBoard (**DMB**), which then passes the data to next stage of DAQ
- DMB is also responsible for slow control of front-end electronics, rely trigger signals, LV control of the CSC system

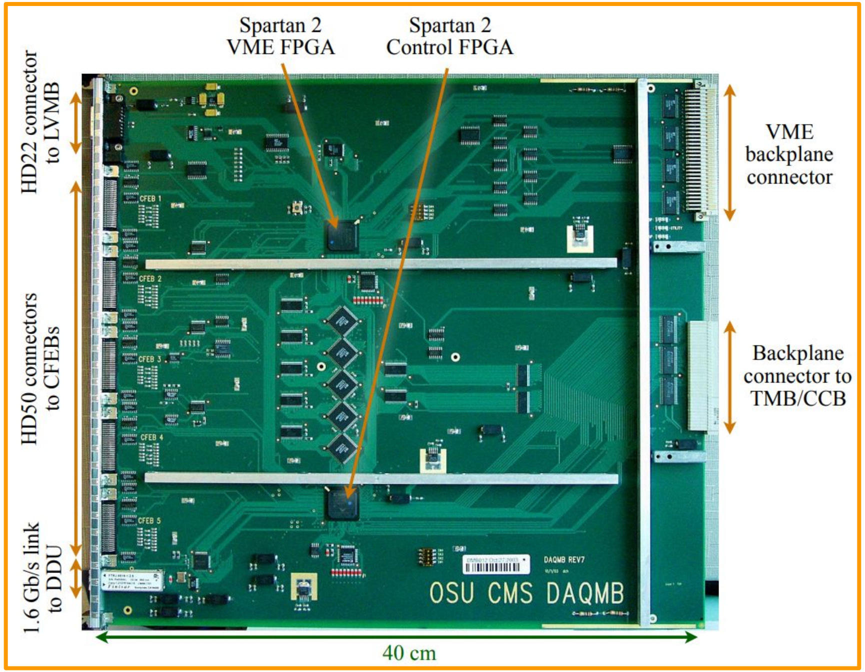
The DAQ boards for CSC

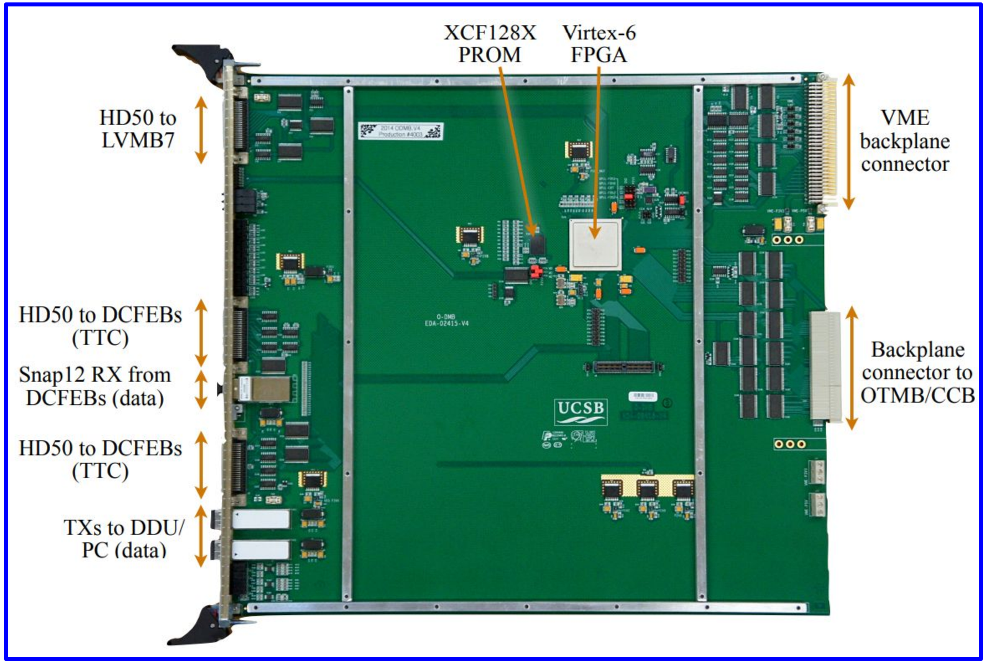


* DCFEB has a larger internal buffer thanks to a more advanced FPGA, thus reduce the risk of data loss due to high instantaneous luminosity, it also sends DAQ data via optical fibers instead of copper cable as in CFEB

- During Run 1, each CSC sends DAQ data to a Data acquisition MotherBoard (**DMB**), which then passes the data to next stage of DAQ
- DMB is also responsible for slow control of front-end electronics, rely trigger signals, LV control of the CSC system
- In LS1, as a consequence of the Cathode Front-End Board (**CFEB**) being upgraded to the Digital CFEB (**DCFEB**) *, the DMB was upgraded to Optical DMB (**ODMB**) for CSCs closest to the interaction point

Examples of DMB and ODMB





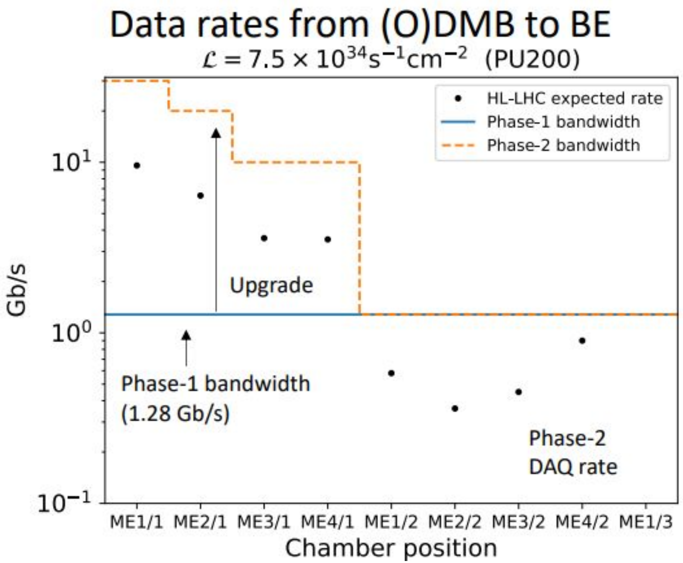
DMB (468 in total)

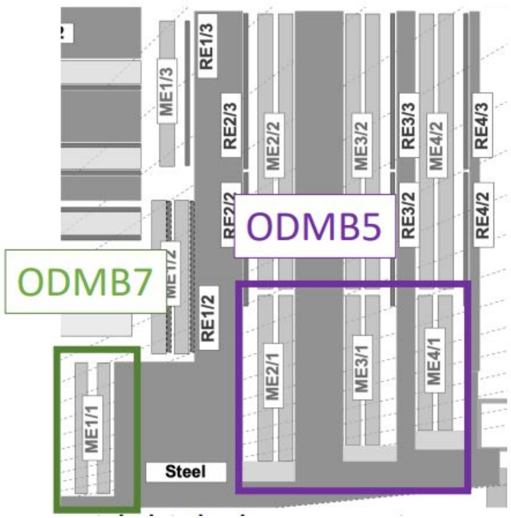
ODMB-2013 (72 in total)

Motivation for the new ODMB (ODMB7/5)

The DAQ data rate of CSC is driven by the event size and L1A*local trigger rate

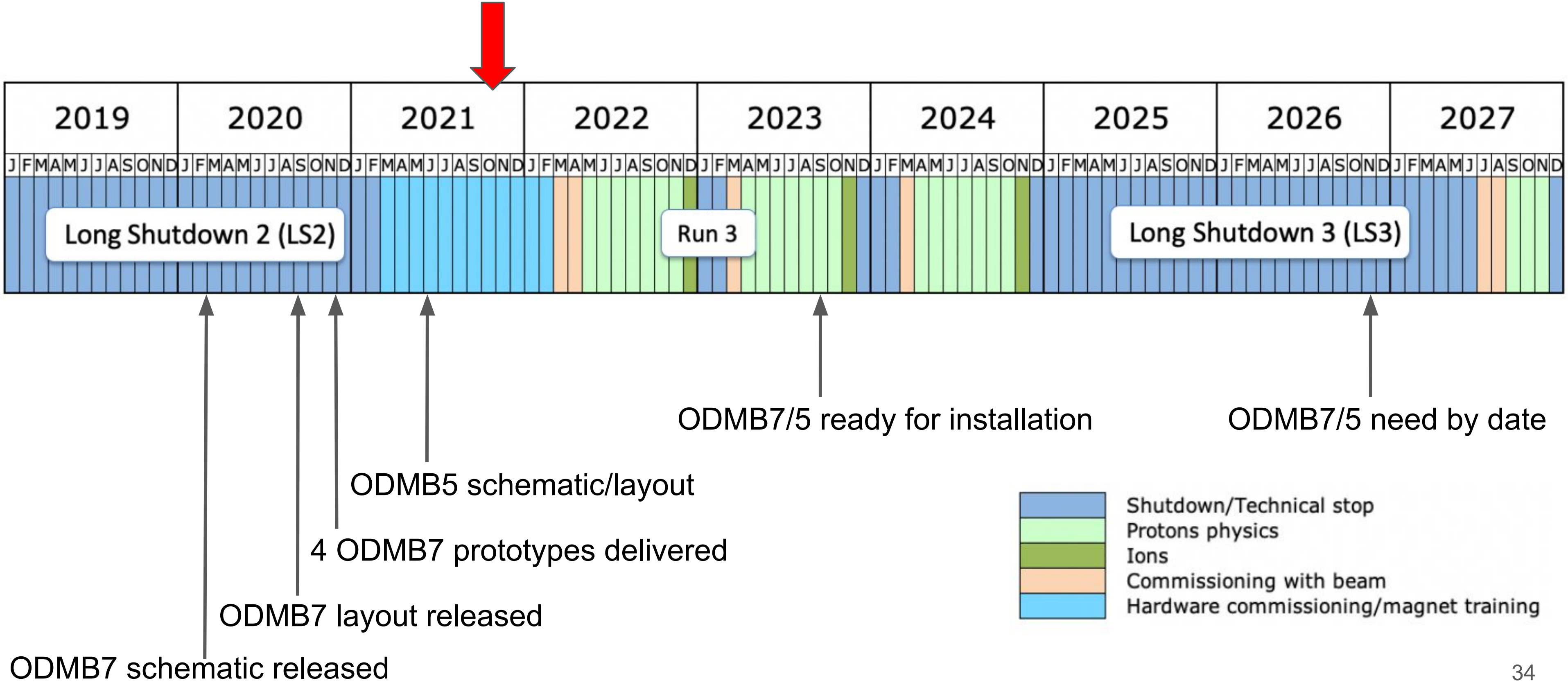
At the HL-LHC condition, not only the L1A rate increases, the local trigger rate also increases due to higher background rate in the CMS cavern





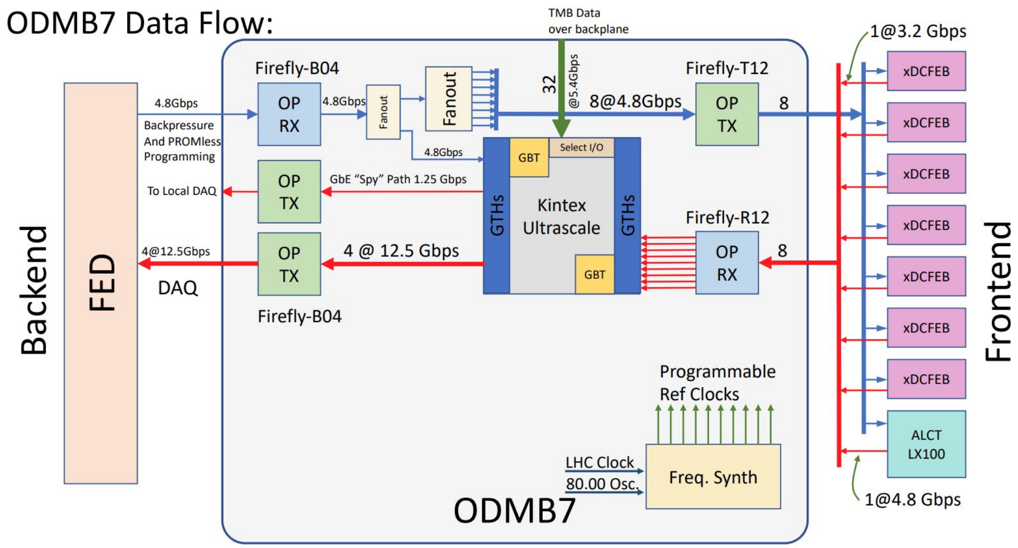
- Due to the increased data rate at HL-LHC, the (O)DMBs serving CSCs closest to the beam pipe will be upgraded to the new ODMB7/5 => **increase bandwidth**
- In addition, the new ODMB7/5 also provides promless programing option for the front-end boards, in case their EPROMs stops working due to high radiation

Major milestones of the ODMB7/5 project



Highlights of the new ODMB7 design

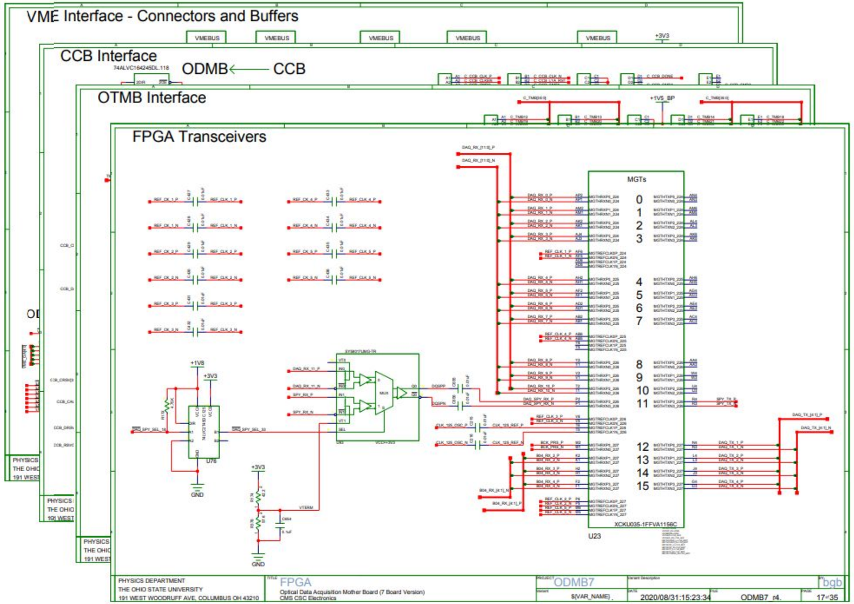
- New Kintex ultrascale FPGA
- New firefly optical transceivers
- Allows promless-programing of front-end boards
- Use a frequency synthesizer to provide reference clocks for optica transceivers

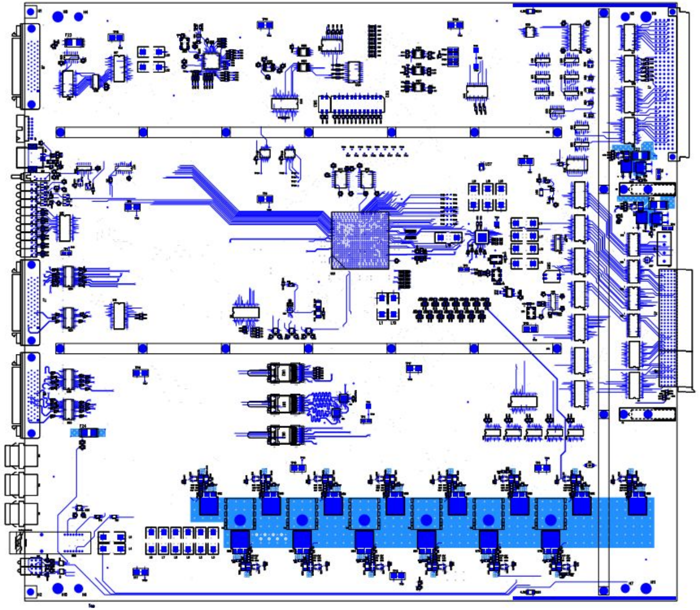


The design is very different from current ODMB, with many new features

ODMB7 schematics and layout

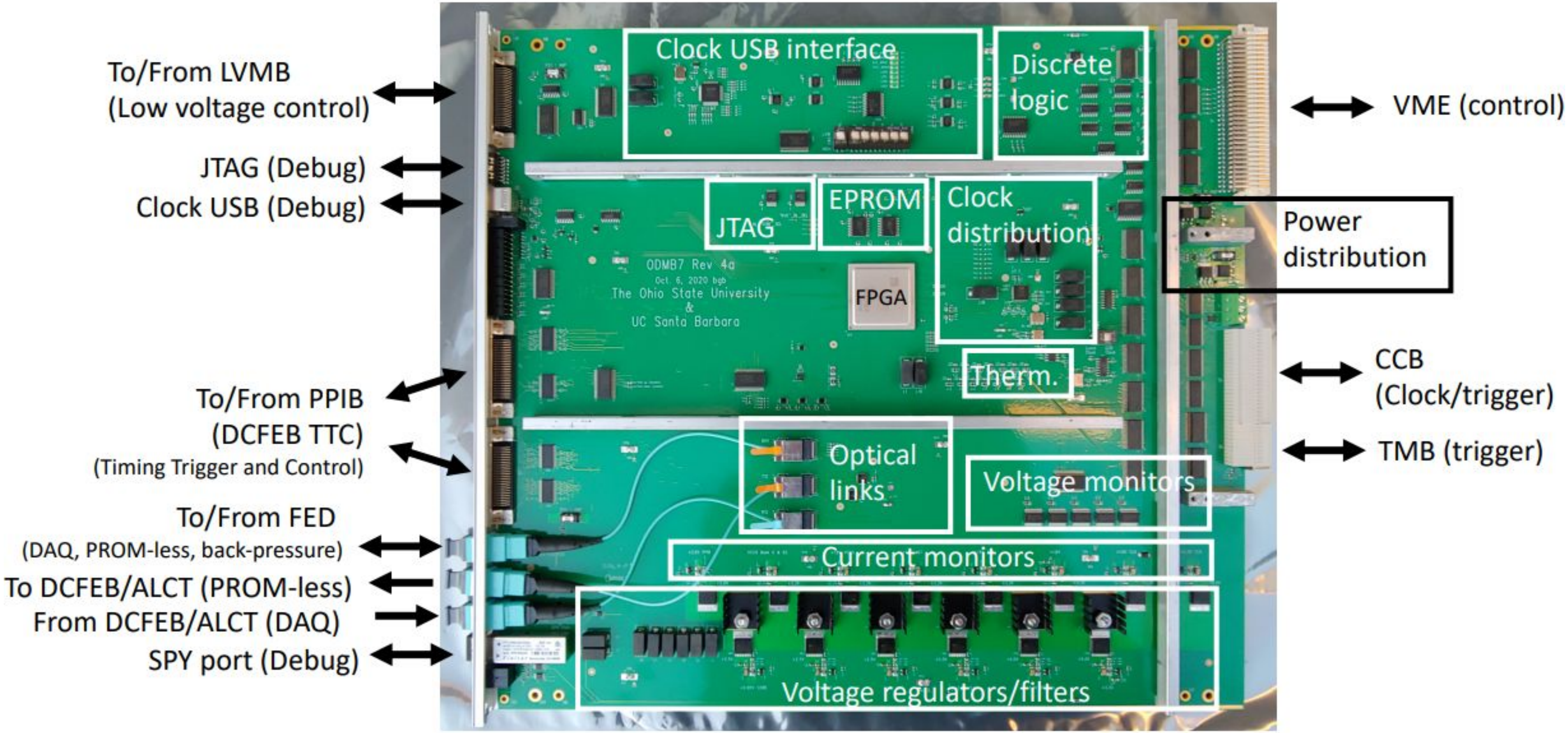
16 layers



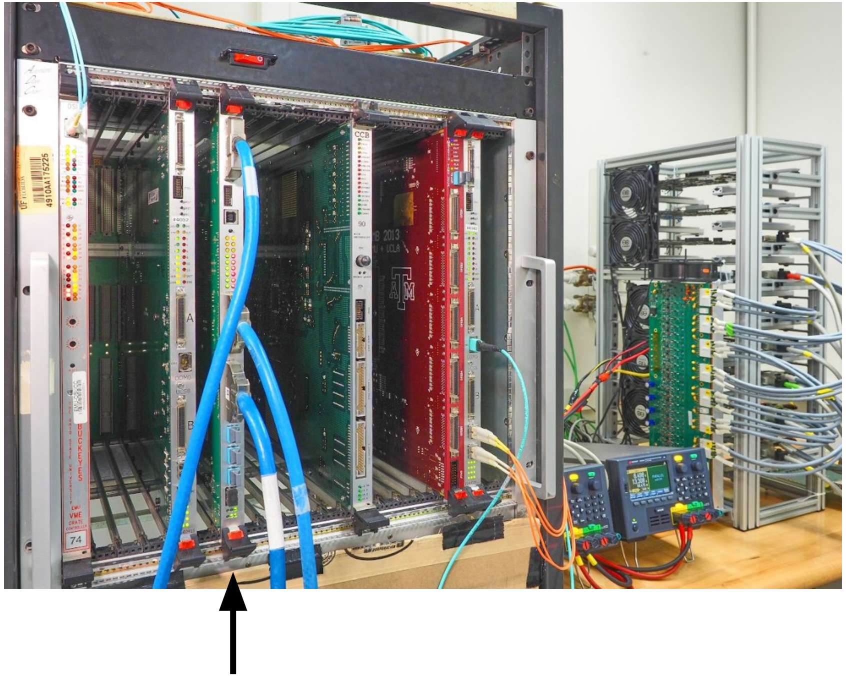


- The schematics and layout were designed by engineers and reviewed by other project members (postdocs, PhD students)

ODMB7 prototype

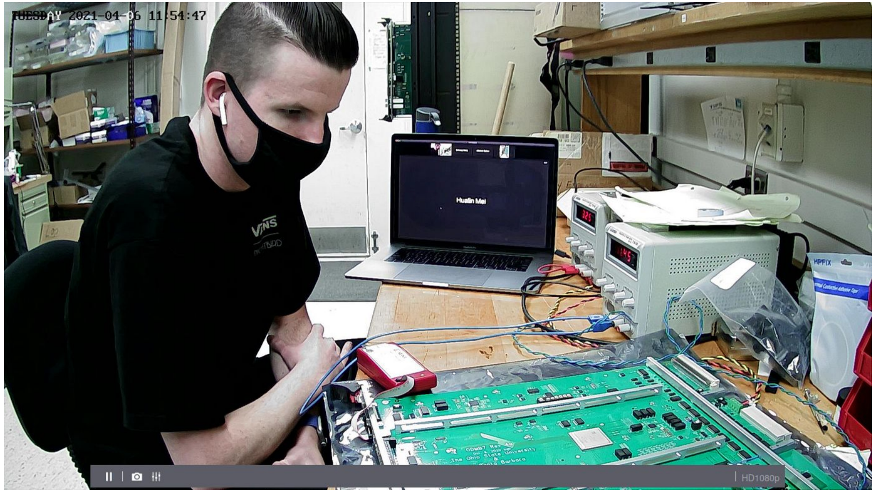


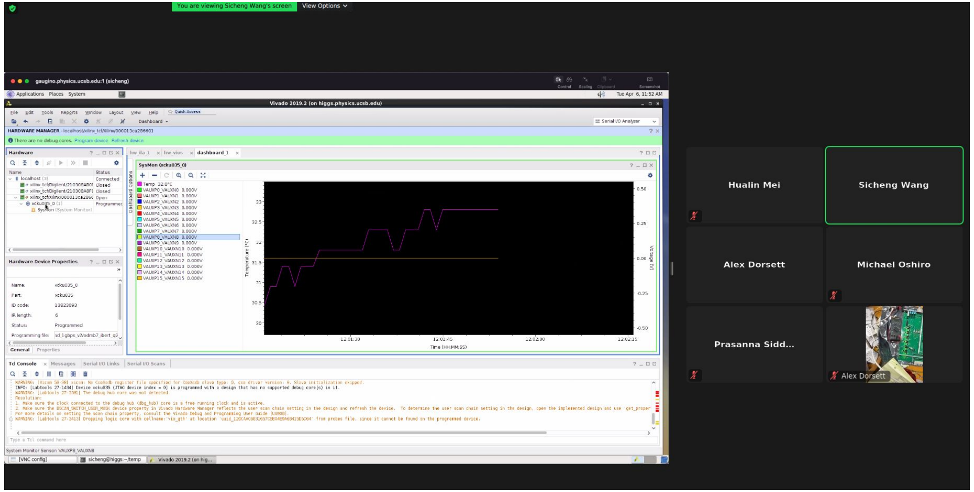
Setup at UCSB lab



ODMB7 prototype

Operation mode during covid

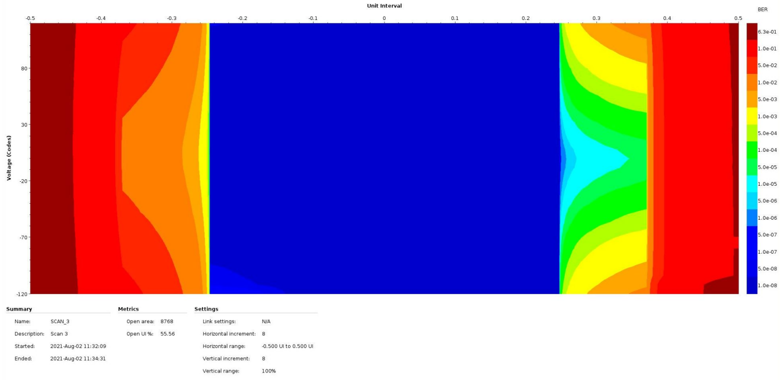




- After the prototypes were delivered to UCSB, project members from 4 different time zones (California, Ohio, CERN, South Korea) held extensive debugging sessions via zoom
- A number of small issues were identified, temporary fixes were made on the boards and will be fixed for the pre-production

Firmware development (interfaces)

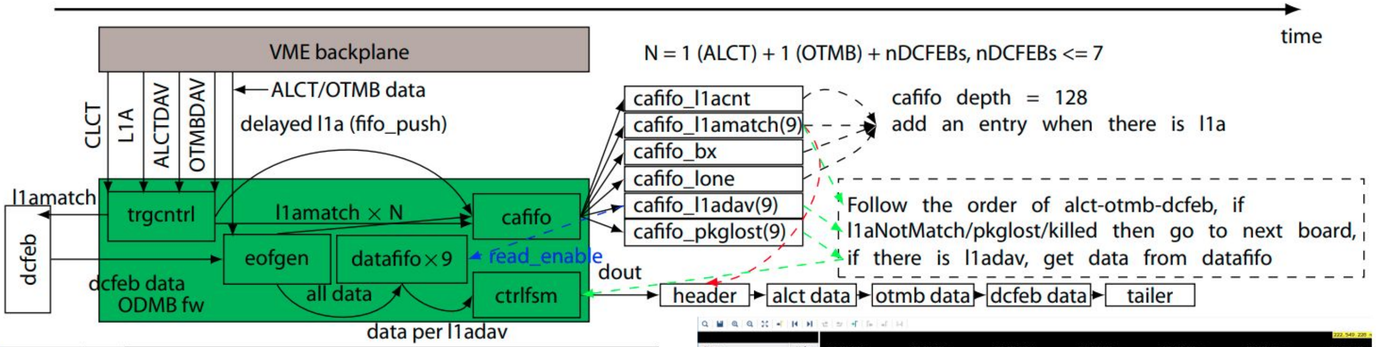
- Started with developing firmware for major interfaces that ODMB7 use to interact with and other boards

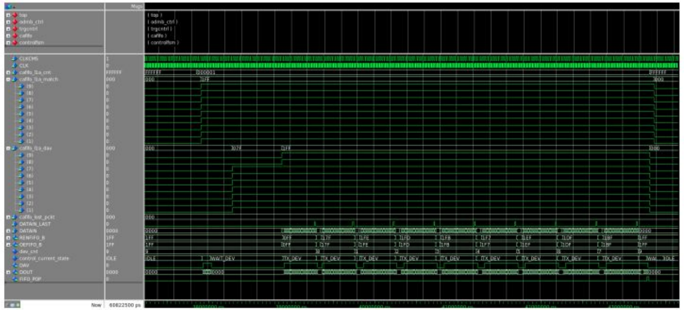


Board to board optical communication at 12.5Gb/s

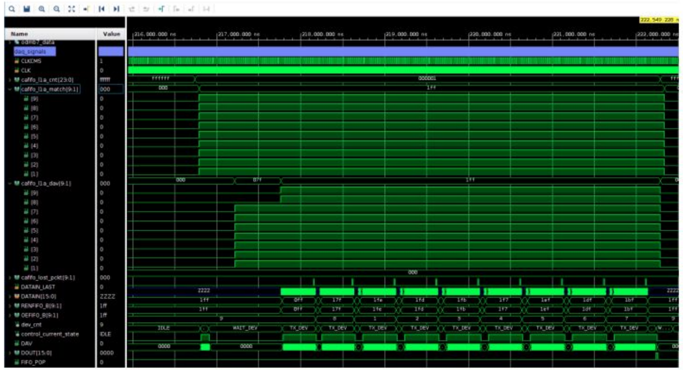
```
****** ODMB Vitals:QPLL UNLOCKED ******
R   4100          FFF0      Unique ID
R   4200          D3B7      FW version. Date 10/07/2020
R   4300          D3B7      FW build

********** DCFEB JTAG Control **********                                       PASSED
DCFEB 1: read UserCode. Firmware version 6.2E
DCFEB 2: read UserCode. Firmware version 6.2E
DCFEB 3: read UserCode. Firmware version 6.2E
DCFEB 4: read UserCode. Firmware version 6.2E
DCFEB 5: read UserCode. Firmware version 6.2E
DCFEB 6: read UserCode. Firmware version 6.2E
DCFEB 7: read UserCode. Firmware version 6.2E

********** DCFEB Pulses **********                                             PASSED
DCFEB 1: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.
DCFEB 2: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.
DCFEB 3: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.
DCFEB 4: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.
DCFEB 5: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.
DCFEB 6: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.
DCFEB 7: INJPLS 5/5, EXTPLS: 5/5, BC0: 5/5, L1A_MATCH: 5/5.

********** LVMB **********                                                     PASSED
Power on/off test on 7/7.Read 200 voltages per device. Voltage reading: 4200/4200.

********** OTMB PRBS Test **********                                           PASSED
Number of PRBS sequences: 100 (10,000 bits each)
PRBS sequences matched: 99 (expected 99)
PRBS bit errors: 100 (expected 100)

********** CCB registers tests **********                                      PASSED
Repeated test 100 times. No BAAD reads or bit flips in 10 signals and registers.
```

Firmware development (DAQ)





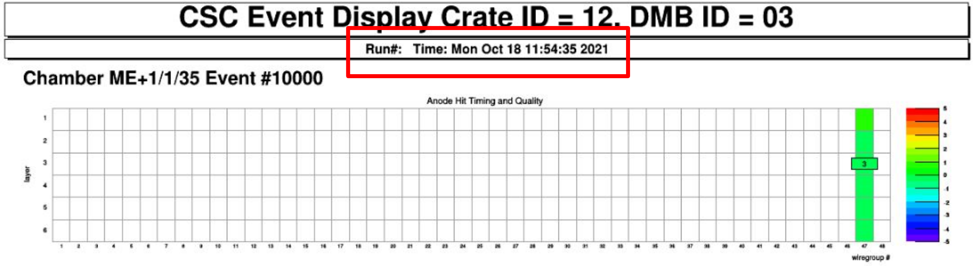
ODMB simulation



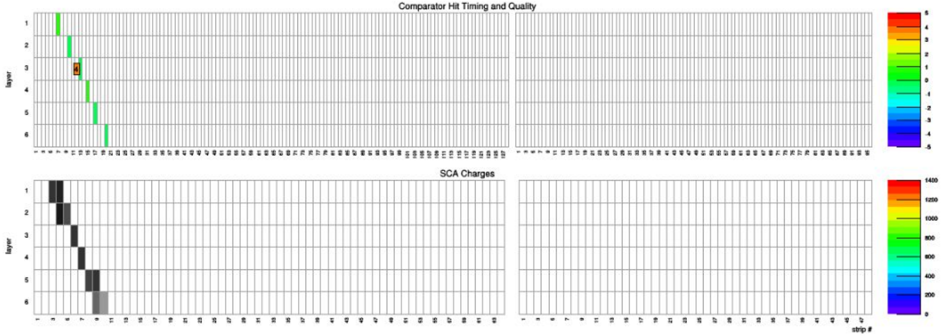
ODMB7 simulation

- Recently developed the basic DAQ logic for ODMB7
- Check behavior in simulation by comparing signals against current ODMB simulation
- The ODMB7 DAQ firmware works in simulation

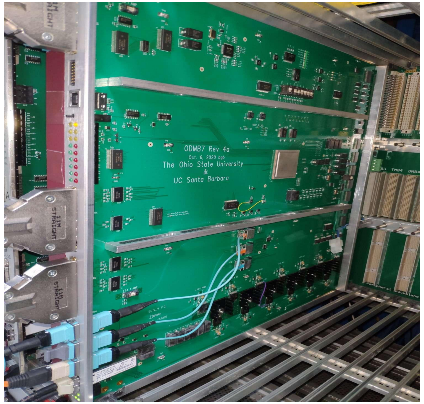
First time DAQ with new ODMB7



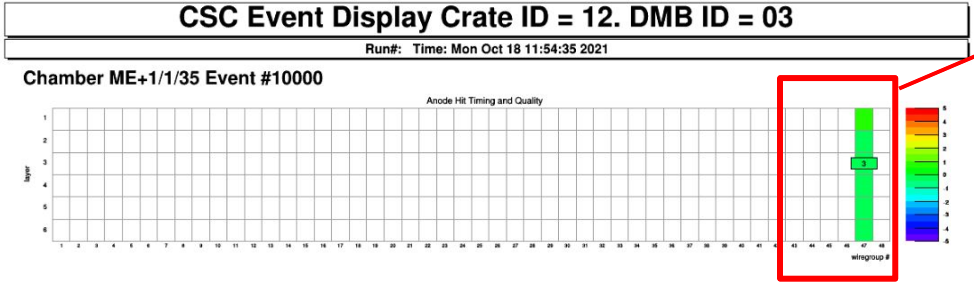
One event display



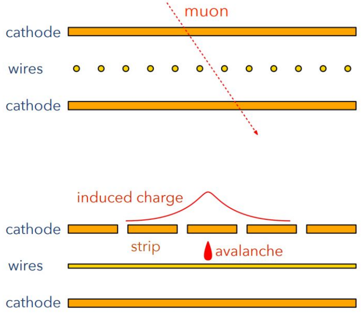
- Earlier this month, with a real CSC chamber at CERN testing site, we are able to take cosmic data with the new ODMB7 for the first time!



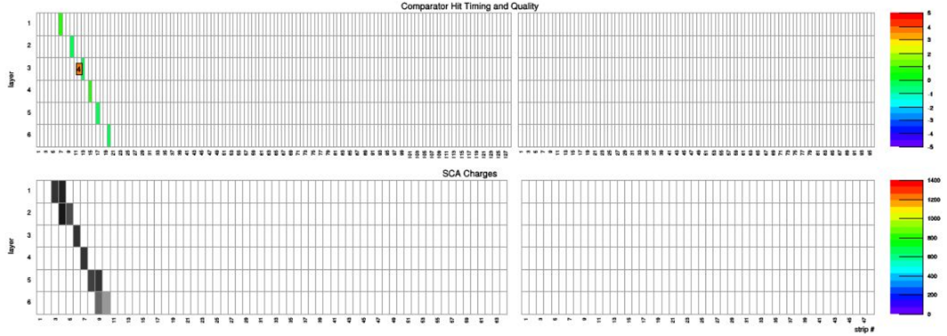
First time DAQ with new ODMB7

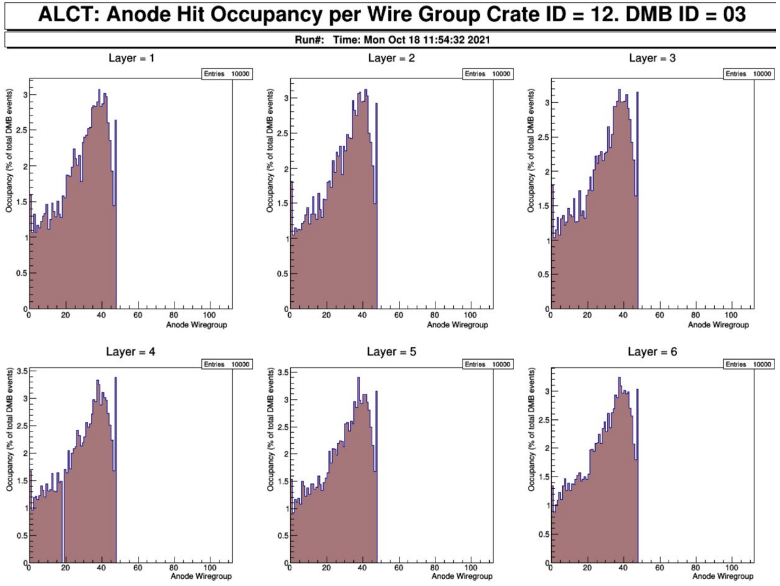


Anode data, for trigger and DAQ

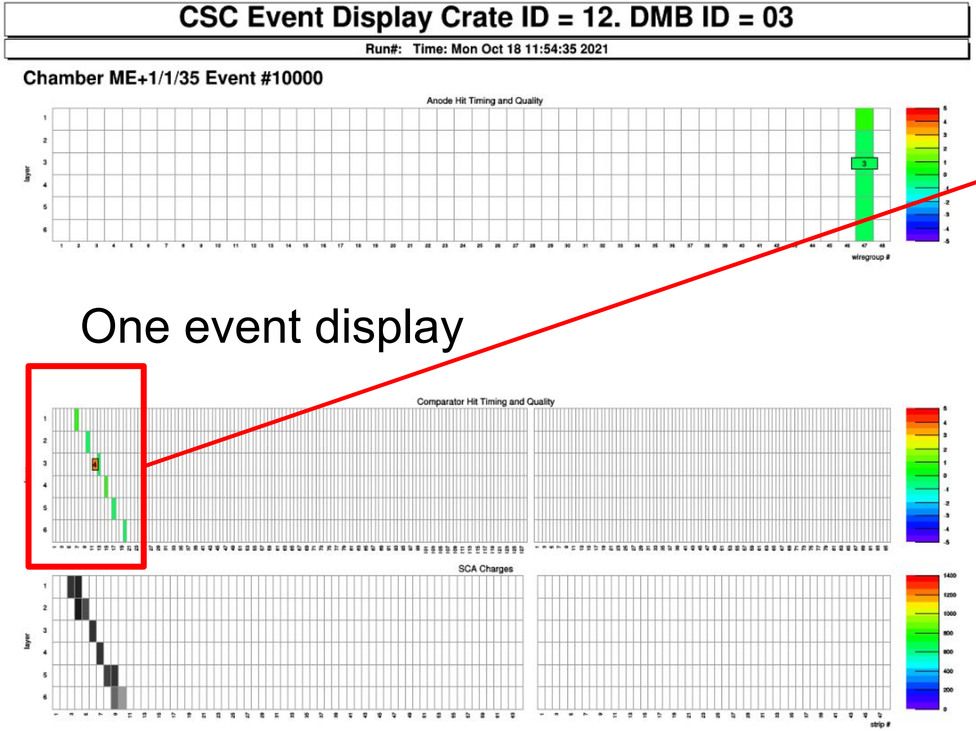


One event display



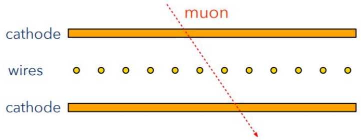


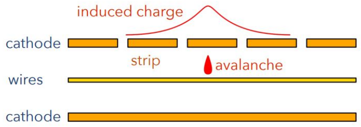
First time DAQ with new ODMB7

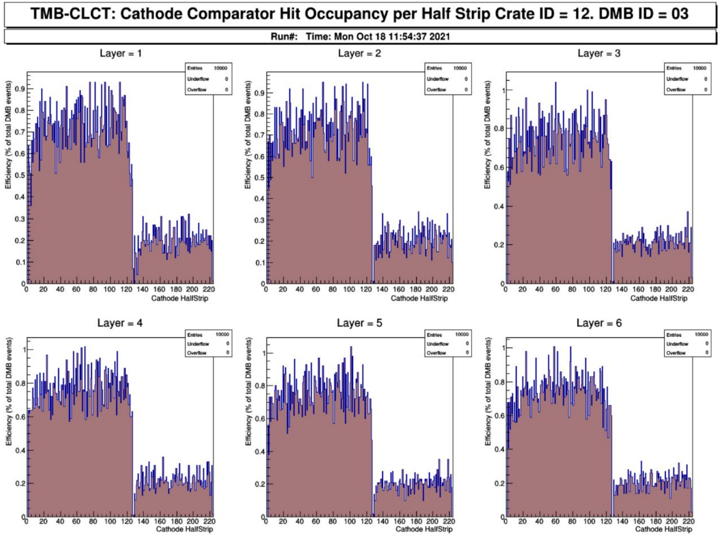


One event display

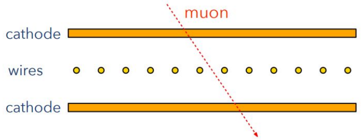
Cathode data, for trigger

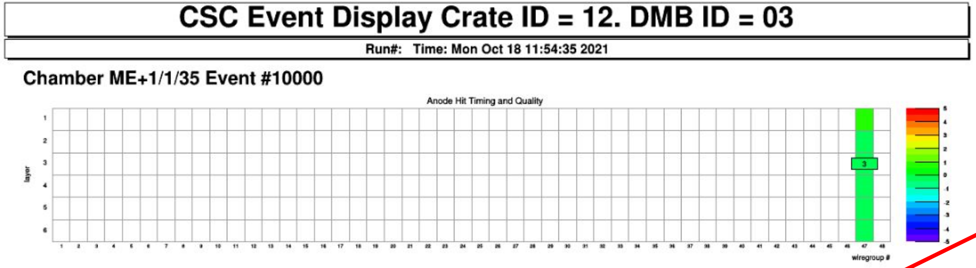




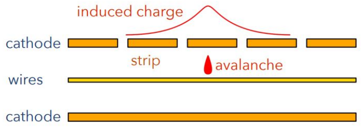


First time DAQ with new ODMB7

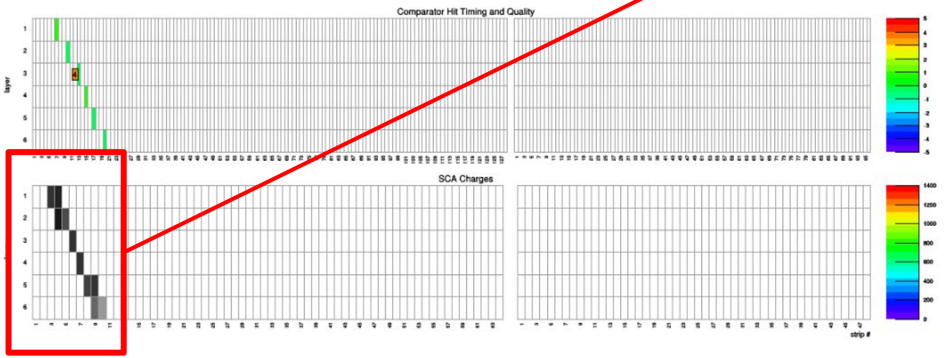


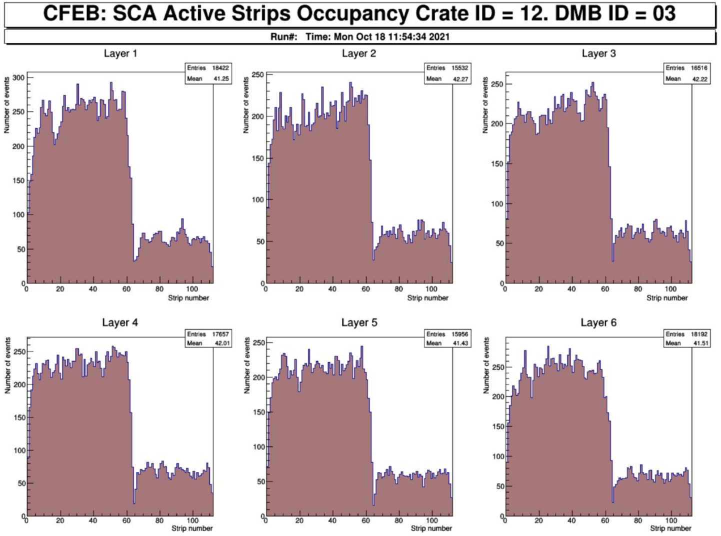


Cathode data, for DAQ



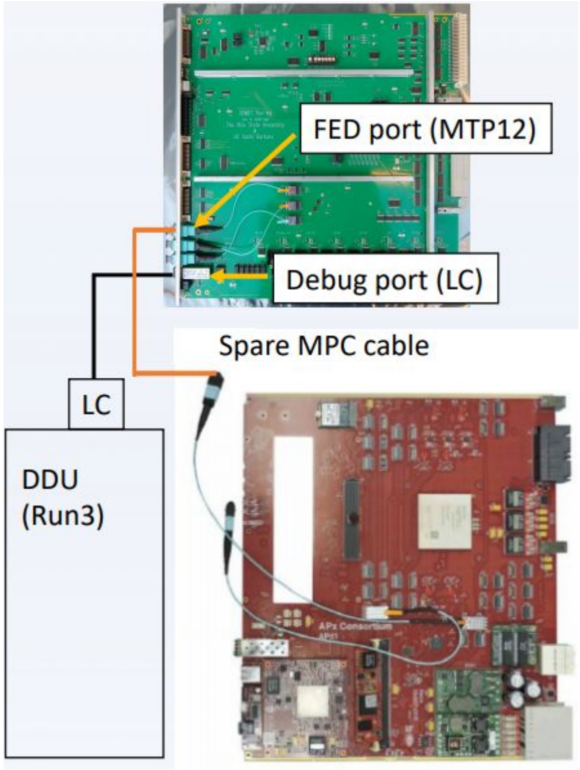
One event display





The future of the ODMB7/5 project

- Currently we are finalizing the development of ODMB7 firmware
- The ODMB5 prototypes are expected to arrive late 2021/early 2022
- Prepare software for production test
- Expect to put one ODMB7 prototype as a demonstrator in CMS at one Year End Technical Stop
- In the end, will produce 72 + 108 + spares = 180+ new boards for the phase II CMS detector



ATCA FED

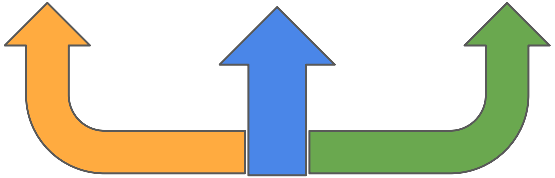
Summary

- Since of observation of ttH production in 2018, studying the top-Higgs interaction has become one of the most important physics topics at the LHC
- Other than examining the nature of top-Higgs interaction, this talk has also summarized 3 examples to explore potential BSM physics

Study CP nature of Htt Yukawa coupling

Better constrain HH trilinear self-coupling

Search for top-Higgs FCNC process



- The DAQ electronics of the CMS endcap muon system needs to be upgraded for HL-LHC, the development of new ODMB7/5 has been a success so far, more exciting time is ahead of us

Backup

CP structure of the Htt coupling

- By probing the interaction between the Higgs boson and vector bosons, CMS and ATLAS have determined that the H quantum numbers are consistent with J^{PC} = 0++
- However, the CP structure of H couplings to fermions has never been tested
- The CP structure of the Htt amplitude can be parameterized as:

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_\mathrm{t}}{v}\overline{\psi}_\mathrm{t}\left(\kappa_\mathrm{t} + \mathrm{i}\tilde{\kappa}_\mathrm{t}\gamma_5\right)\psi_\mathrm{t}$$

CP even yukawa coupling   CP odd yukawa coupling

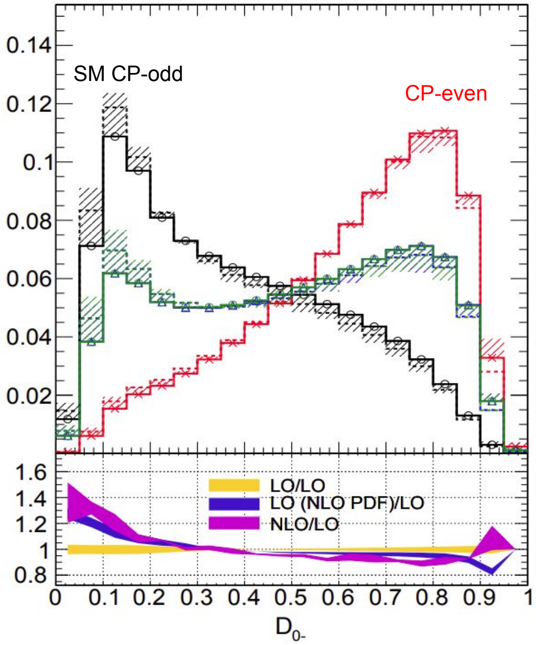
$* \text{ In SM, } \kappa_\mathrm{t} = 1 \text{ and } \tilde{\kappa}_\mathrm{t} = 0$

- Experimentally, we can test the CP structure by measuring

$$f_\mathrm{CP}^\mathrm{Htt} = \frac{|\tilde{\kappa}_\mathrm{t}|^2}{|\kappa_\mathrm{t}|^2 + |\tilde{\kappa}_\mathrm{t}|^2}\,\mathrm{sign}(\tilde{\kappa}_\mathrm{t}/\kappa_\mathrm{t})$$

CP measurement strategy

- In principle, one can use matrix element based technique to distinguish CP-even from CP-odd hypothesis
- This may not be practical for studying ttH, given the final state particles can be either mis-tagged or not reconstructable
- In practice, two BDTs were used in both Hadronic and Leptonic channels to separate CP-even from CP-odd
    - Utilize kinematic properties of jets/diphoton, b-tagging information and lepton multiplicity as input variables



PhysRevD.94.055023

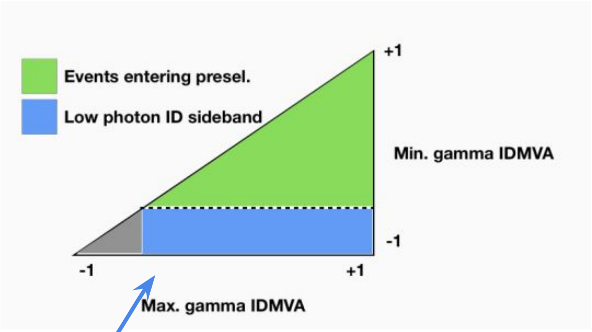
On the other side of the ring

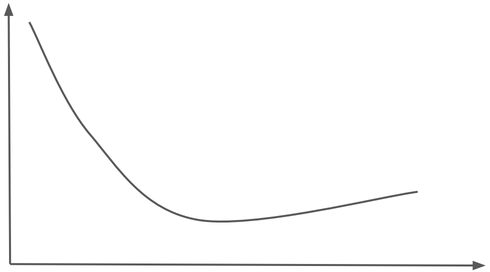
- ATLAS submitted a similar paper about ttH ($H \rightarrow \gamma\gamma$) and its CP study two weeks later, with very similar strategy and results

	CMS (arXiv:2003.10866)	ATLAS (arXiv:2004.04545)
σ_{ttH} * $BR_{\gamma\gamma}$	$1.56^{+0.34}_{-0.32}$ fb	NA
μ_{ttH}	$1.38^{+0.29}_{-0.27}(\mathrm{stat})^{+0.21}_{-0.11}(\mathrm{syst})$	$1.4 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})$
Obs (exp) significance	6.6 σ (4.7 σ)	5.2 σ (4.4 σ)
$\lvert f_{CP}^{Htt} \rvert$ exclusion at 95% CL	0.67	0.47
Pure CP-odd exclusion, obs (exp)	3.2 σ (2.6 σ)	3.9 σ (2.5 σ)

Data-driven estimation of multijet + photon

- One of the main backgrounds in hadronic channel: multijet + photon
  - Poorly modeled by MC simulation
  - Suffer from low statistics for BDT-bkg training
- Model this background with a data sample
  - One photon candidate failing photon ID BDT requirement
  - Almost exclusively jet faking a photon
- Replace the failing ID value in each event
  - Use a value drawn from a MC distribution





* JINST 10 P04015

ttH cross section extraction

- Signal models are built from ttH MC simulation
  - Use independent MC simulation from those used for BDT-bkg training/optimization
- Background models are extracted from $m_{\gamma\gamma}$ distribution in data (*)
- Perform simultaneous binned maximum likelihood fit to the $m_{\gamma\gamma}$ distributions in the eight categories to extract (σ_{ttH}* $BR_{\gamma\gamma}$) and the signal strength (μ)