Review of CMS results and upgrade plans

University of Birmingham Particle Physics seminar

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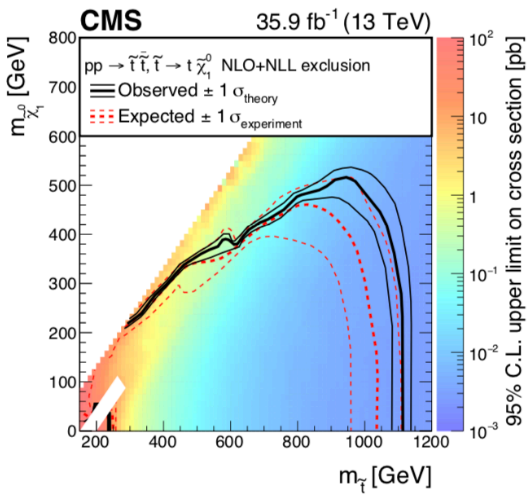
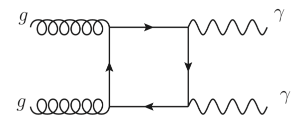
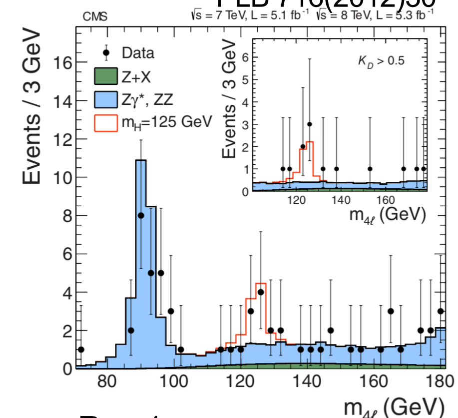
Broadly classify LHC analyses into:







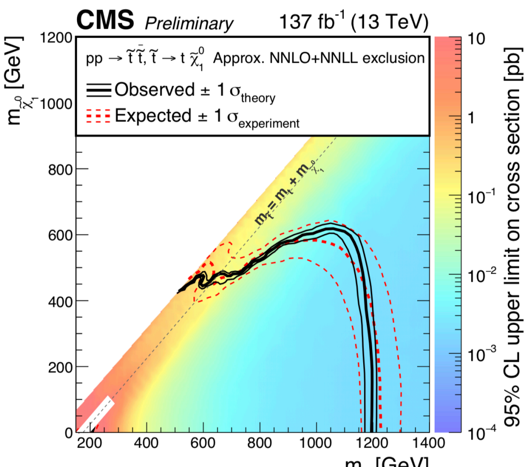
PLB 716(2012)30

Run 1

Searches

Precision measurements

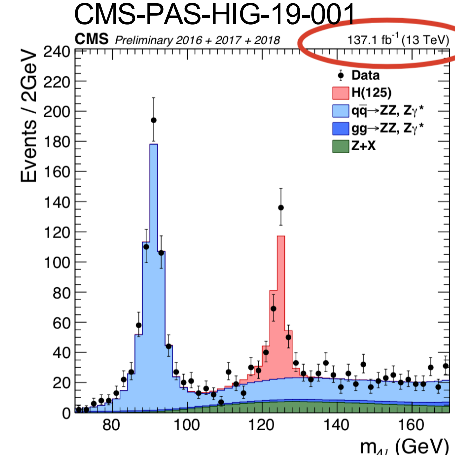
Measurements of SM control regions within search analysis



Full Run 2

CMS PAS SUS-19-009

CMS-PAS-HIG-19-001



Full Run 2

Improve with:

More events (higher luminosity)
Larger cross-section (higher energy)

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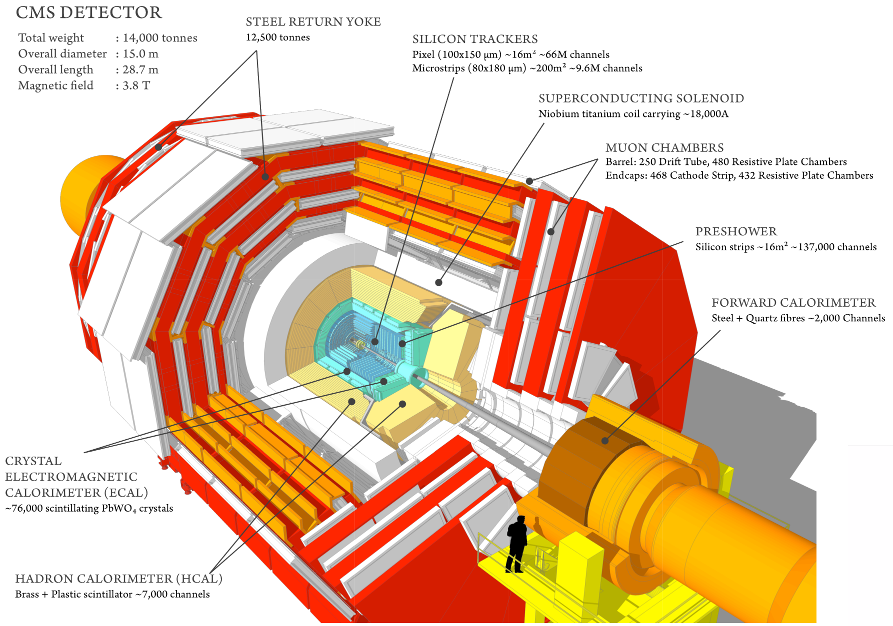
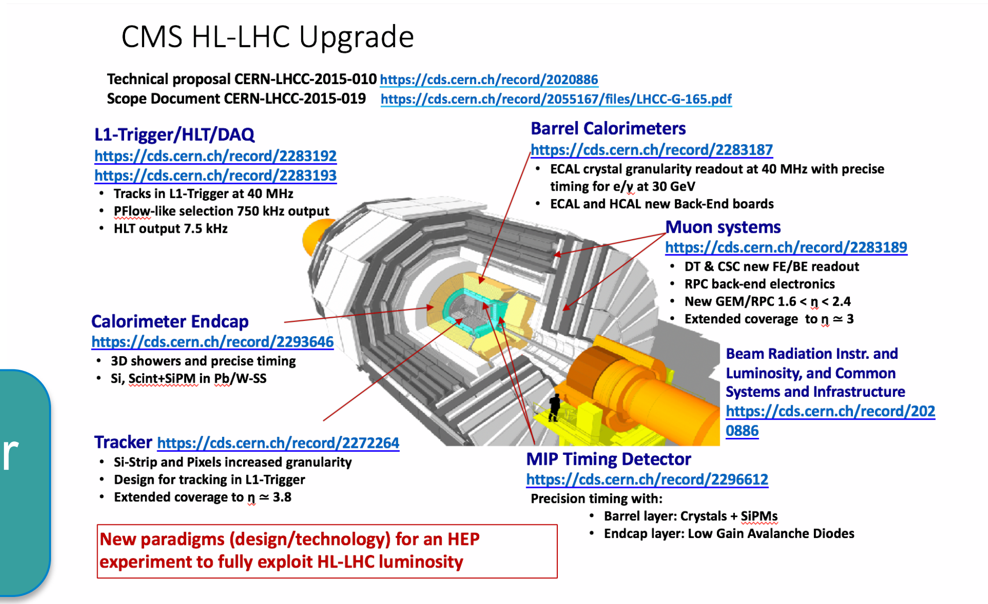


Current Detector



Proposed upgrades for High-luminosity LHC

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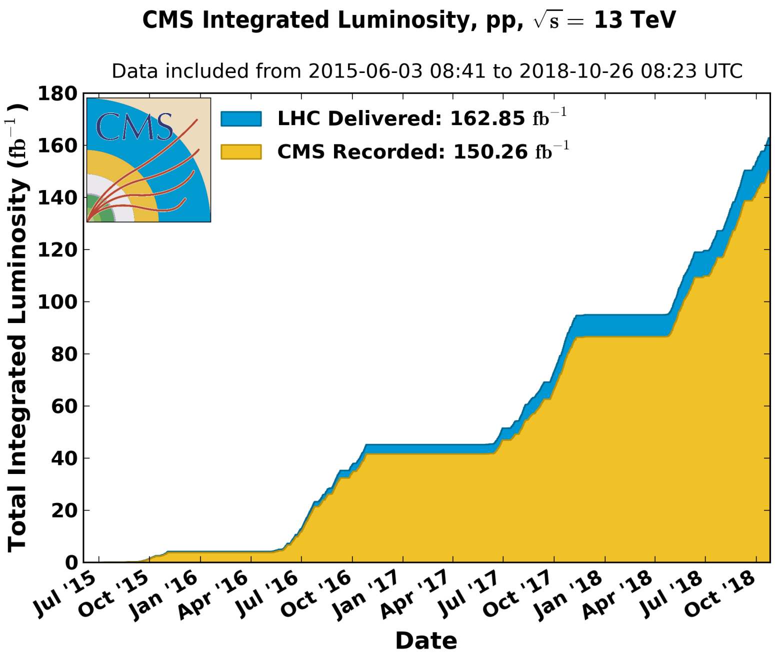
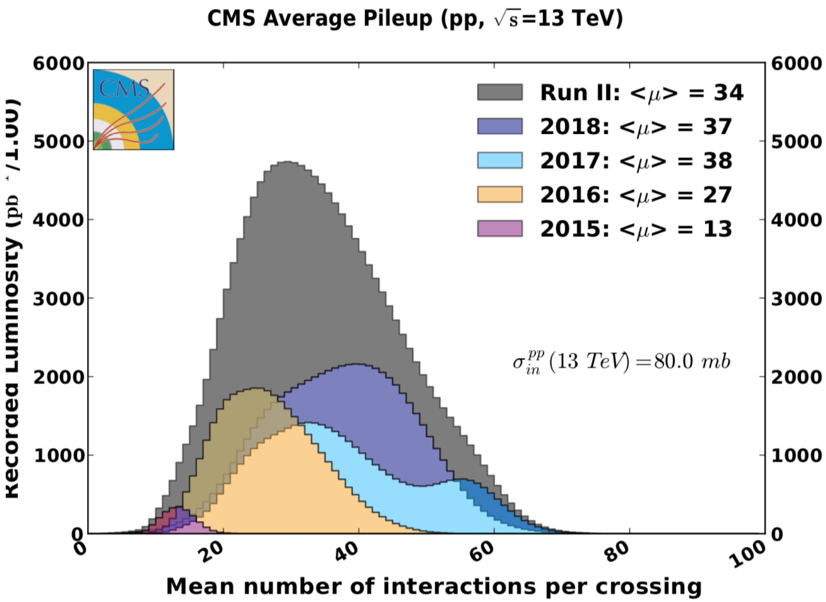
Run 2 Outline

- 2015-2018
- Proton-Proton centre of mass energy 13 TeV (7/8 TeV in run 1)
- Higher instantaneous and integrated luminosity





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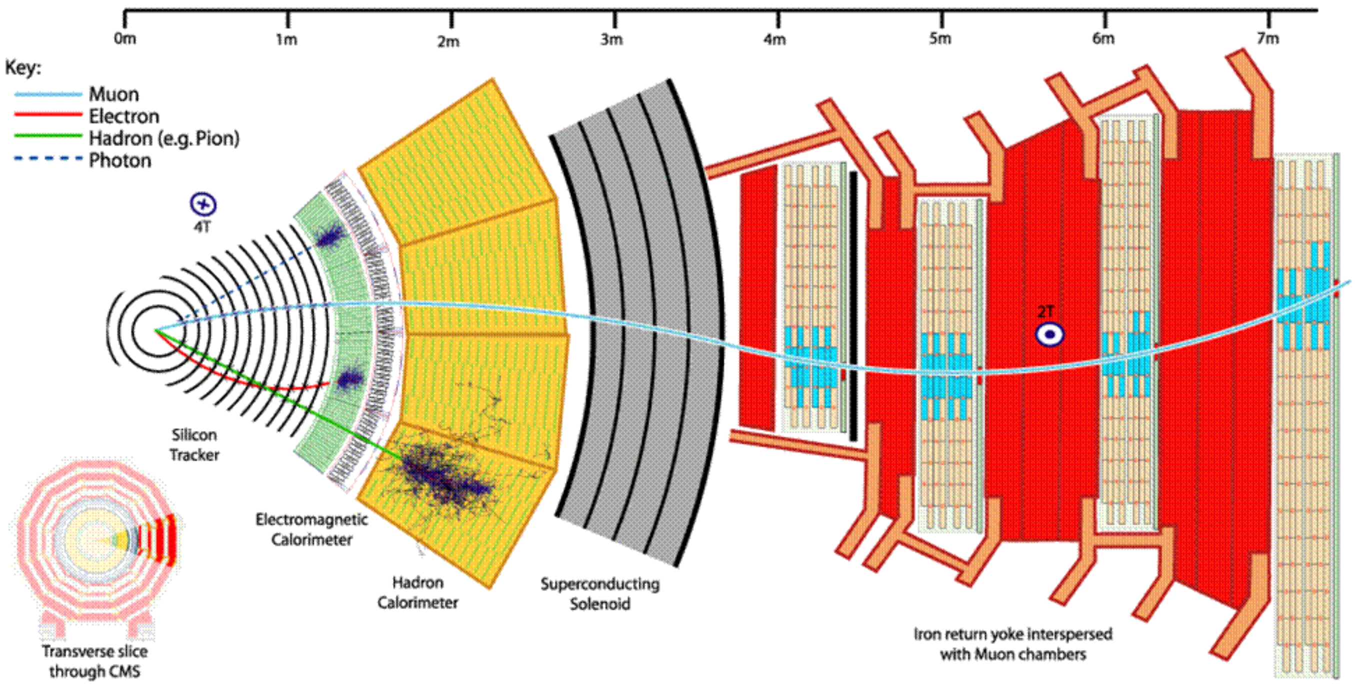
Physics outline



- Focus on 4 or 5 recent analyses performed with run 2 data at CMS
- Description quite high-level, with focus on motivation and conclusions

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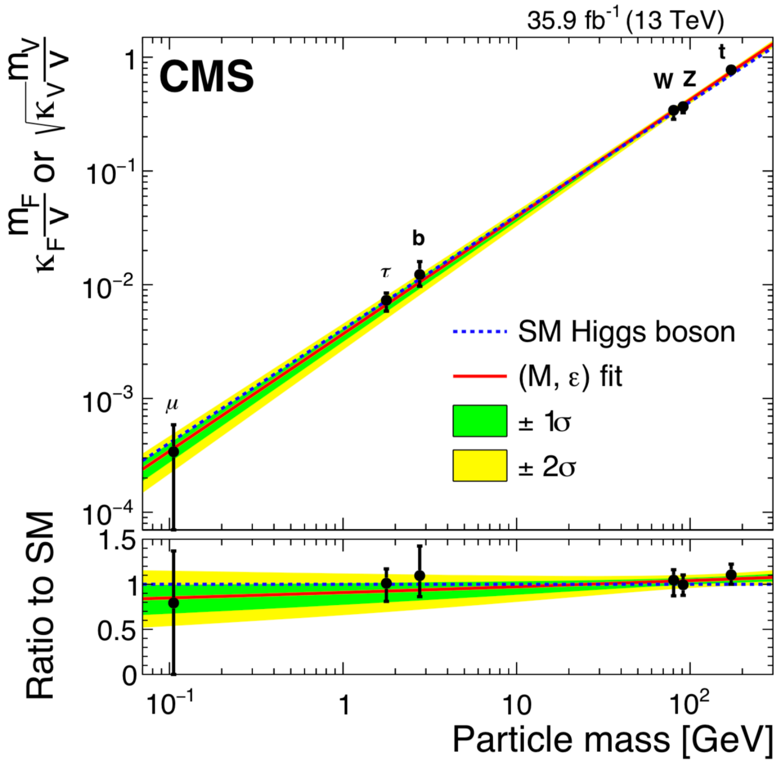
Higgs physics

- Run 1: Discovery of Higgs boson, using decays to bosons
  - H → WW
  - H → Z Z
  - (H → γ γ)

  } Coupling proportional to square of mass
- Run 2: Establish couplings to 3rd generation fermions
  - H → τ τ
  - H → b $\bar{b}$

  } Coupling directly proportional to mass
- And initial results on couplings to 2nd generation fermions
  - H → c $\bar{c}$
- High-Lumi LHC
  - Higgs self-coupling

1809.10733



W. Adam, EPS conference

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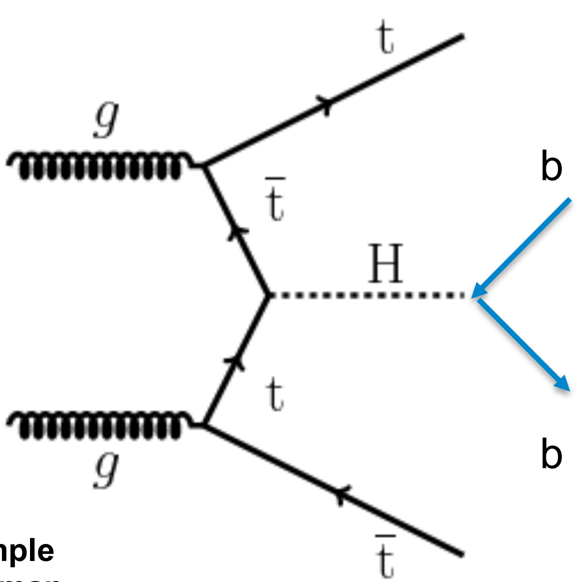
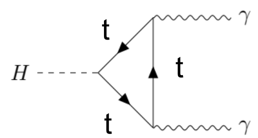
$t\bar{t}H$ ($H \rightarrow b\bar{b}$)



Example Feynman diagram

- Associated production of Higgs boson with tt pair
- Higgs Coupling strength proportional to fermion mass, "Yukawa coupling"
  - Top heaviest known Fermion
  - Direct access to coupling strength
  - Unlike indirect measurements e.g:



- $t\bar{t}H$ observed last year (multiple Higgs decay modes): *PRL 120 (2018) 231801*
- $H \rightarrow b\bar{b}$ observed last year (multiple production modes): PRL 121 (2018) 121801

https://cds.cern.ch/record/2675023

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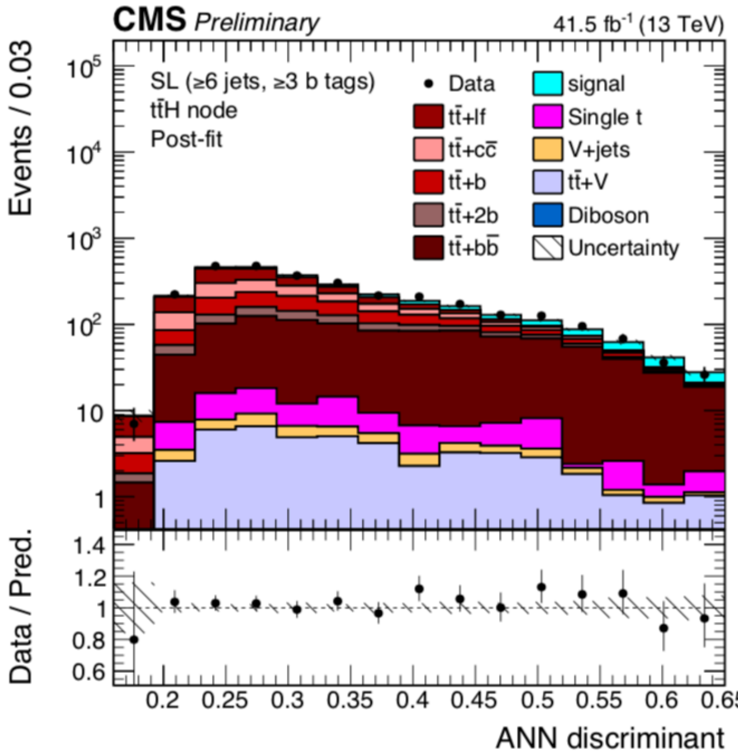
$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

Classify events based on W decays to maximise sensitivity

- Both W decay to hadrons
  - Largest background: Multijet
- 1 W decays to hadrons, 1 to leptons
  - Largest background: $t\bar{t}$ + jets
- Both W decay to leptons
  - Largest background: $t\bar{t}$ + jets

Further classify by number of jets and b-jets



Several multivariate techniques are used to discriminate signal + background, e.g:

- Artificial Neural Network (ANN)
- Boosted Decision Tree

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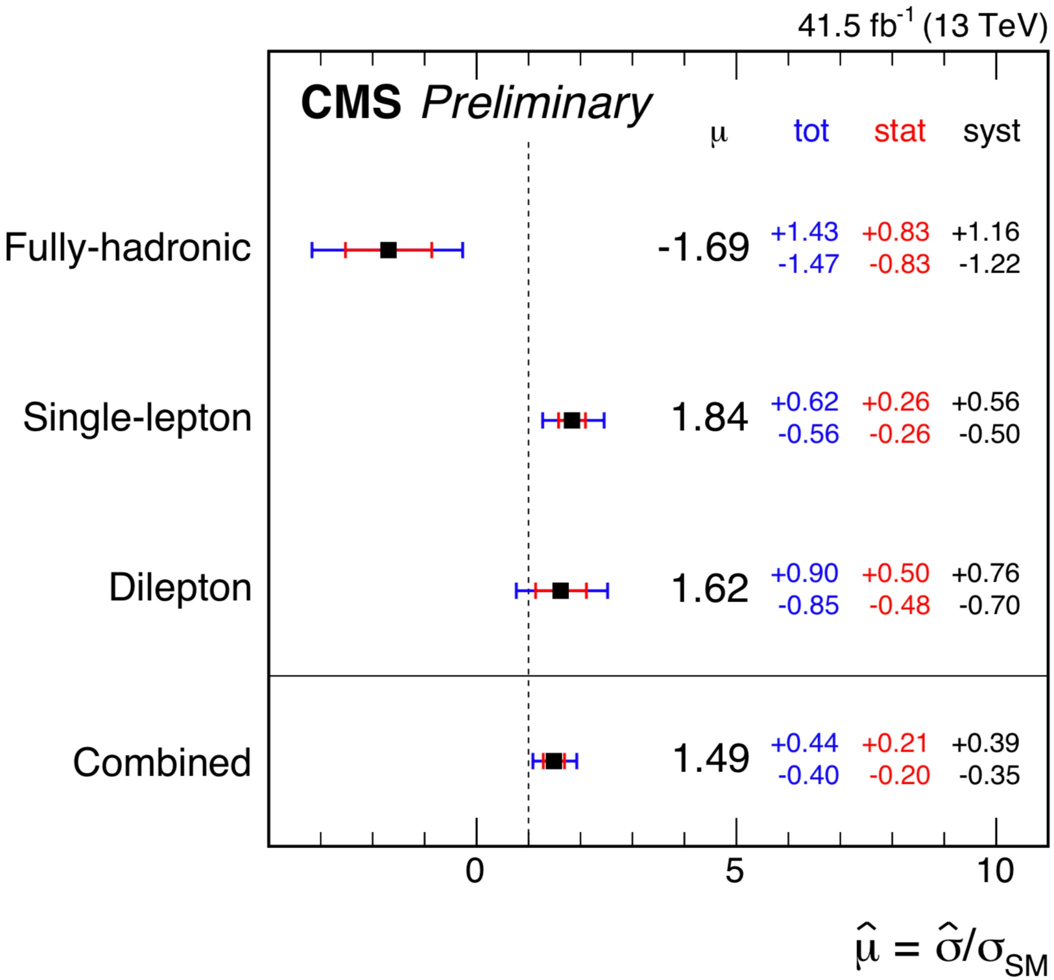
$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

Largest uncertainties:

- uncertainty in the signal $t\bar{t}H$, and background $tt+b\bar{b}$, $tt+c\bar{c}$ cross-sections
- b-tagging scale factors



Plot shows the signal-strength, i.e. ratio of the observed signal to the standard model expectation

Observed significance of **3.7σ** above background-only hypothesis, (3.9 when combined with 2016 data)

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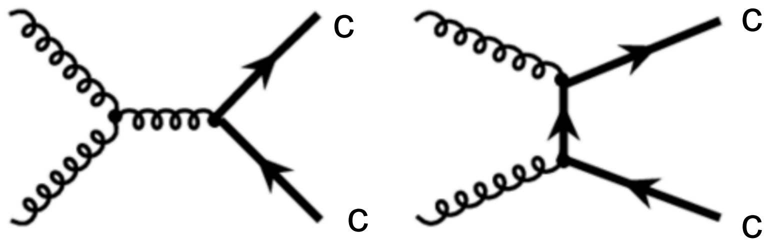
VH (H→cc̄)

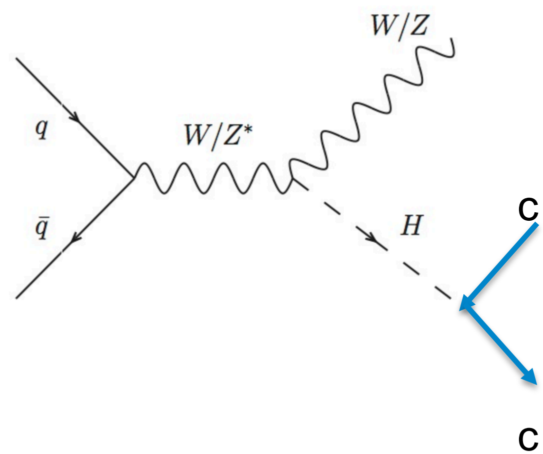
- Probe Higgs decay to second-generation fermions
  - H → cc̄ branching ratio 20x smaller than H → bb̄
  - Could be significantly modified by new physics
- Associated production with W/Z boson
  - W→ℓν, Z→νν, Z→ℓℓ



Large multi-jet background

↓

Require associated production with W/Z boson



https://cds.cern.ch/record/2682638

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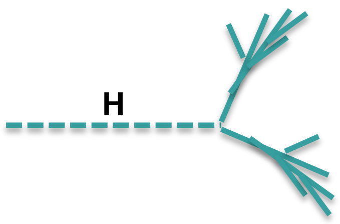
VH (H→c$\bar{c}$)

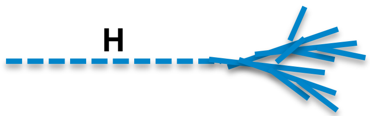
- Two separate searches, then combined
  - Resolved jets
    - Low p_T Higgs
  - Merged jets
    - High p_T Higgs
- Jet identification crucial feature in each case
  - Multiclassifier DeepCSV to identify charm jets
    - Harder than b-jet identification (lighter)
  - Soft drop substructure technique: Remove soft wide angle radiation
- Backgrounds
  - V+jets, t$\bar{t}$

Resolved jets



- Higgs reconstructed from two distinct charm-quark jets

Merged jets



- Reconstructed as single jet
- Make use of jet-substructure techniques

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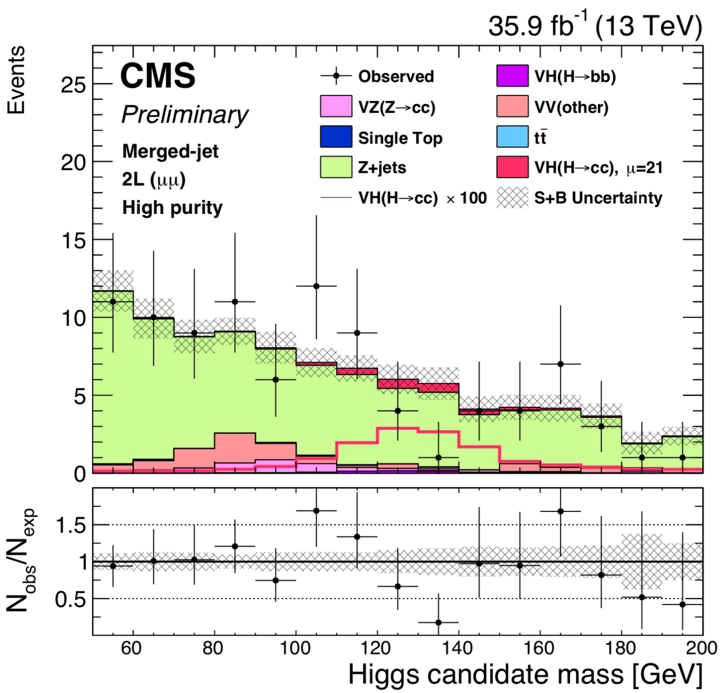
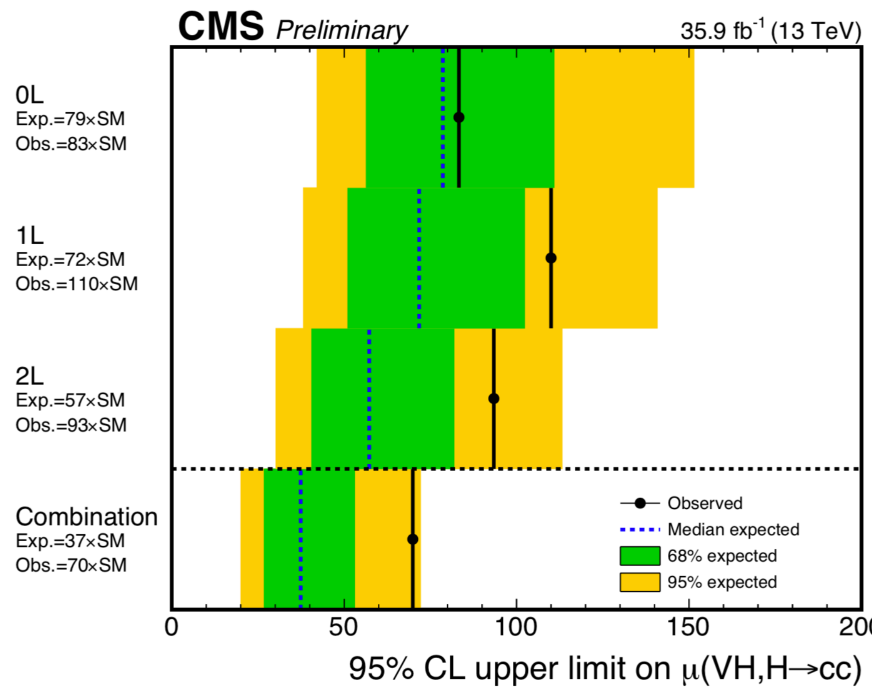
VH (H→c$\bar{c}$)





2μ channel, merged-jet

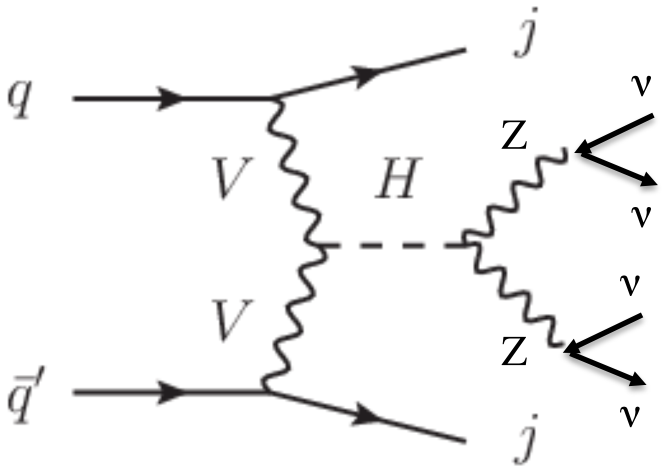
Signal curve x 100

Limit combining all channels:

< 70 x SM prediction (37 expected, slight excess in resolved category)

Limit H→μμ
2.9 x SM

H → Invisible



Standard Model process: branching ratio only 0.001

PLB 793, 520-551

- Search for invisible decays of Higgs Boson
- Small decay to invisible (neutrinos) in the SM
  - New physics scenarios predict enhancements
    - Axions, light Higgs, extra dimensions ...
  - Interplay between measurement and search
- Vector Boson Fusion (VBF) topology most sensitive
  - Suppresses most SM backgrounds

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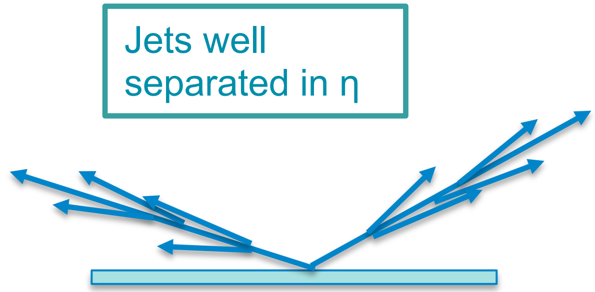
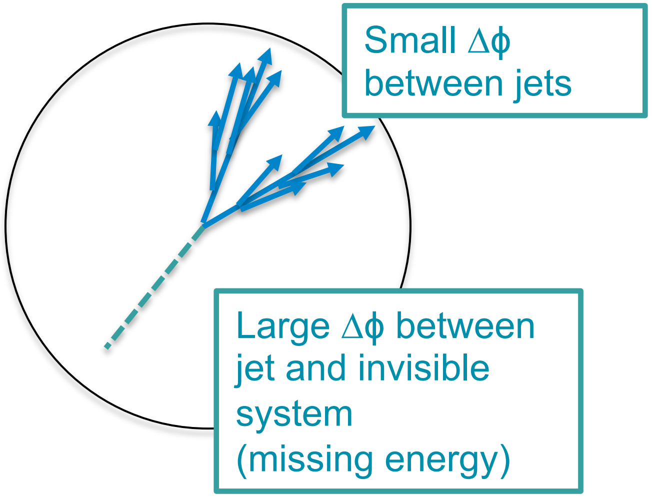
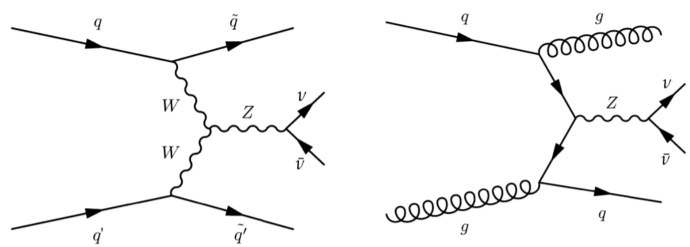
H → Invisible





- Exploit topology of VBF events to greatly reduce background
- Largest residual backgrounds from
  - Z→νν and W→ℓν
    - Both VBF and ‘QCD’ processes contribute



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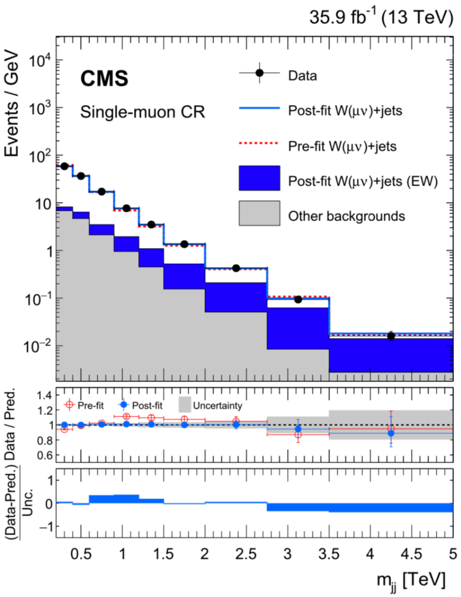
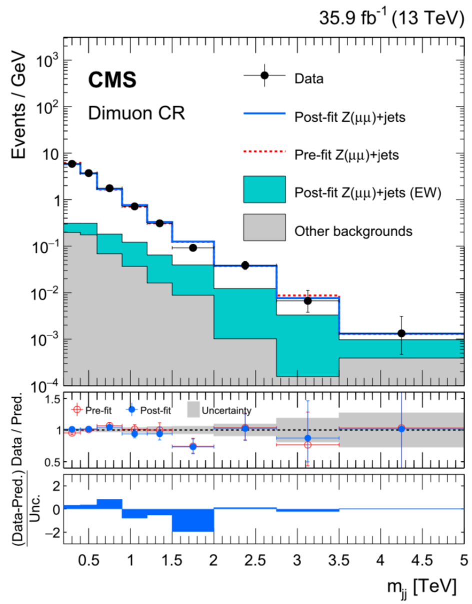
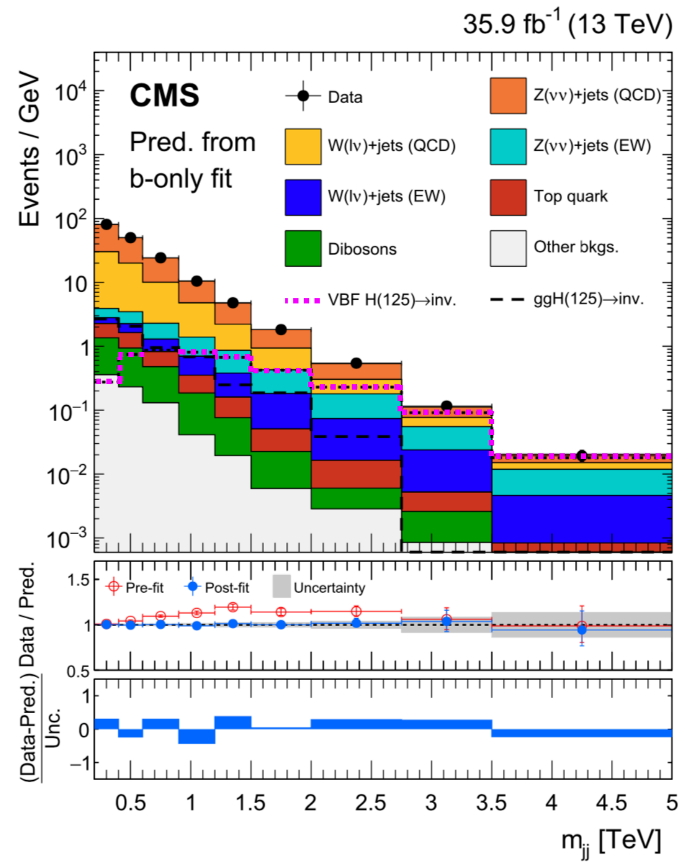
H → Invisible







W and Z backgrounds constrained using single and di-lepton control regions

Di-jet mass most sensitive variable – signal peaks at high di-jet mass

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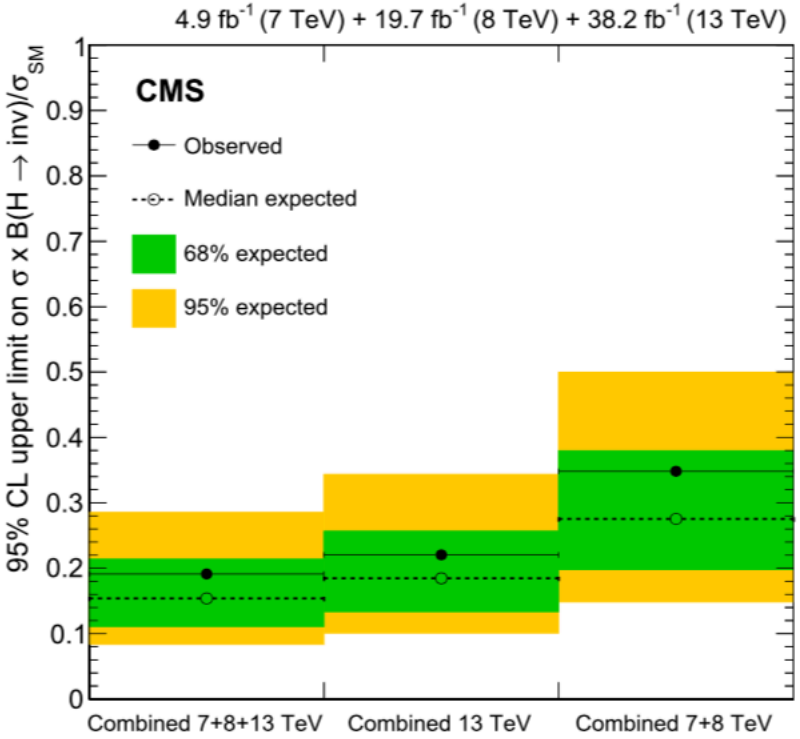
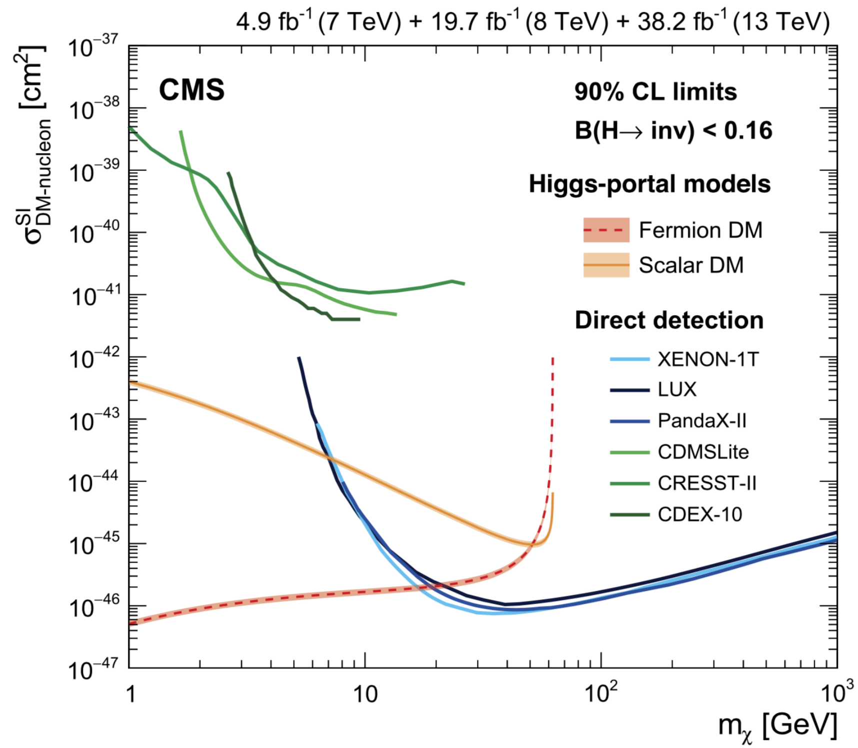
H → Invisible



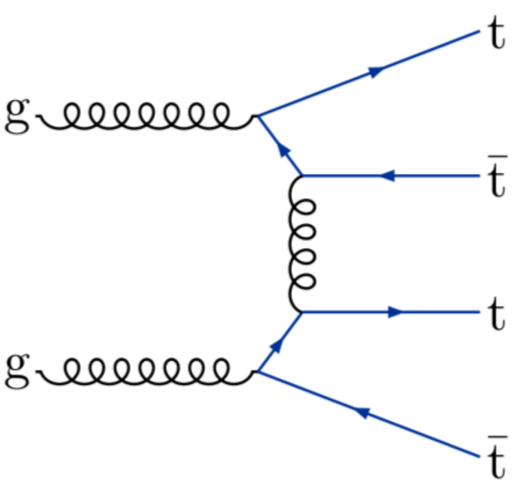


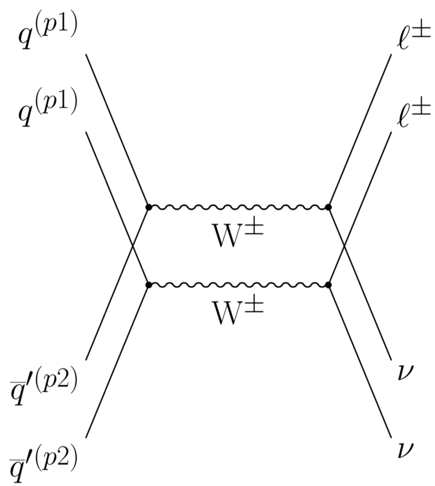
95% CL Upper limit on branching ratio of 0.33 → 0.19 when combined with other existing data

Strong constraints on 'Higgs-portal' models (stable dark matter particle couples to SM Higgs boson)

Rare Standard Model processes

- Even with the large Run 2 data set, certain Standard Model processes are still very rare
- Two analyses interesting to look at:





'4 top' production: 1908.06463

WW production from double parton scattering: 1909.06265

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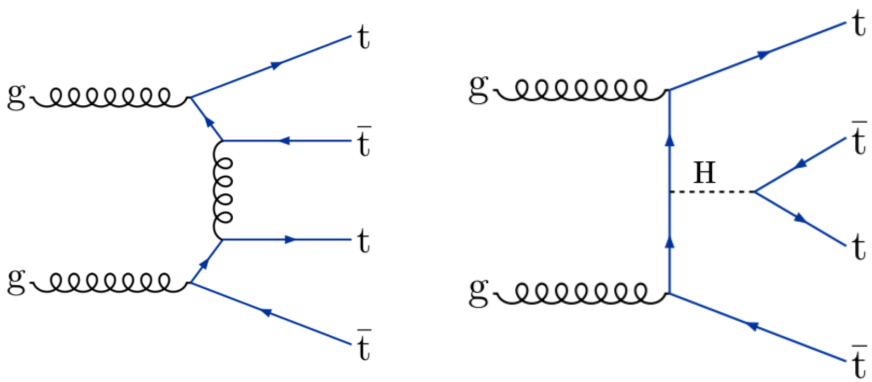
4 top production

137 fb^{-1}

Measurement/search is sensitive to the Higgs-top Yukawa coupling (set limits) and also to new heavy scalar and pseudoscalar bosons

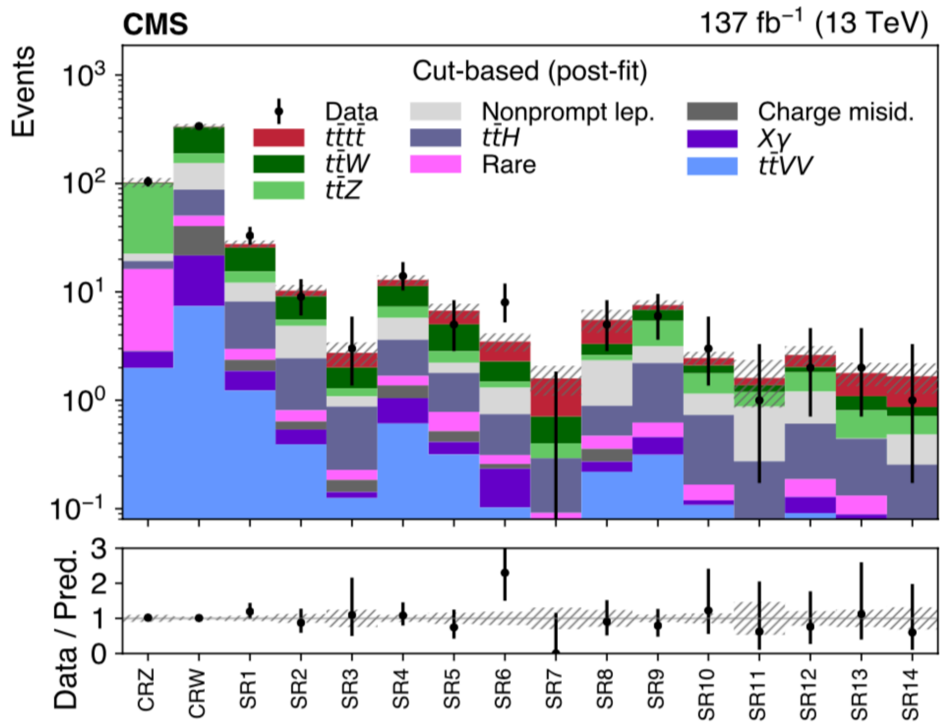


- Measurement of a rare Standard Model process
  - Search for deviations which might show hints of new physics
- Generally decays to 4 b-quark jets, + 4 W (further decay to leptons/light jets)
- Main backgrounds
  - $t\bar{t}$ + W, $t\bar{t}$ + Z, $t\bar{t}$ + γ, $t\bar{t}$ + H(WW)
- Cut-based analysis
  - Events classified according to: N_{jet}, N_{bjet}, N_{lepton}
- BDT classifier
  - Additional variables such as missing energy and scalar sum of jet energy

1908.06463

4 top production

- Largest uncertainties from
  - Limited number of data events (low background analysis)
  - Normalisation of backgrounds
    - Additional scaling to correct from mismodelling in MC
  - Jet energy scale / resolution
  - Identification of b-jets



Excess over background prediction
- Measured signal with significance of **2.6σ**
- Cross-section measurement $\mathbf{12.6^{+5.8}_{-5.2}}$ **fb**
  - SM prediction $12.0^{+2.2}_{-2.5}$ fb

- Observed yields in each of the signal regions (defined by cuts on number of jets/b-jets/leptons)
- Signal in red

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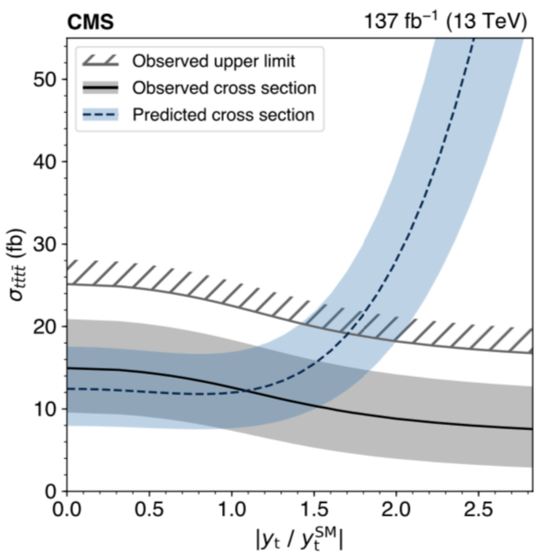
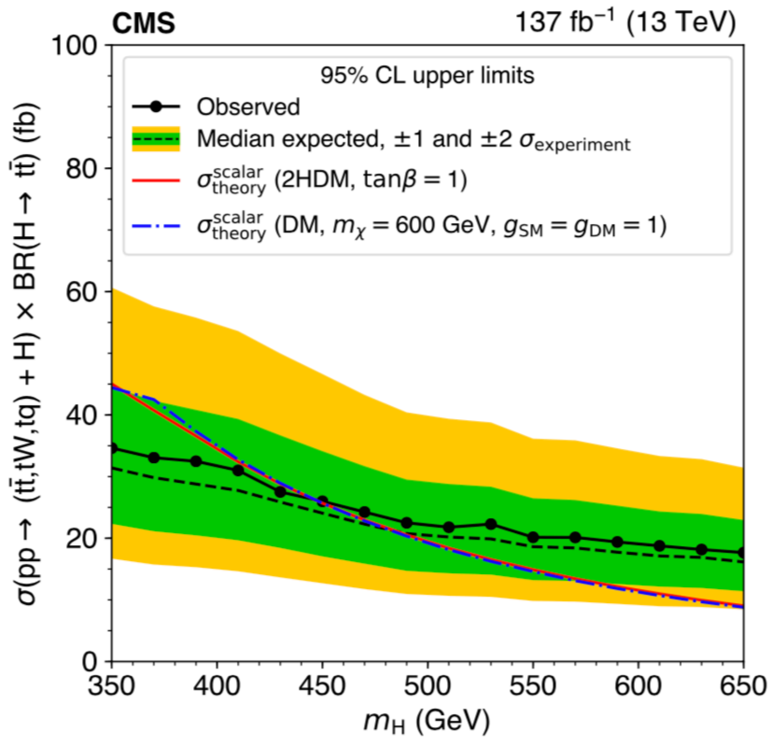
4 top production



Limit on Higgs-top Yukawa couplings

- On shell (assuming off-shell is SM)
    - From scaling $t\bar{t}$+H background **< 1.7 x SM** (shown on plot)
- Off shell (assuming on-shell is SM)
    - From virtual Higgs diagram **< 1.8 x SM**



Limits set on new heavy Higgs boson

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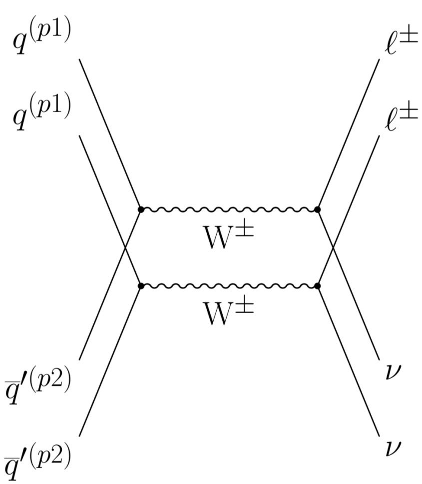
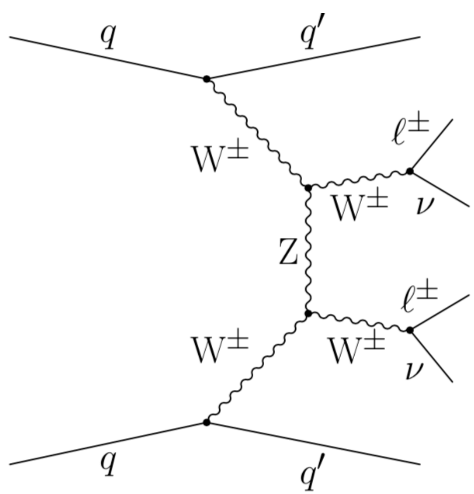
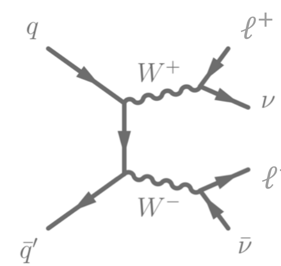
Double parton scattering (DPS)

- Two hard scatters of partons within proton-proton collision
  - Test of dynamics of partons with the proton
  - Important background in searches for new physics





Cross-section from **opposite sign** SPS WW production is much larger



Same sign WW production promising process to study DPS

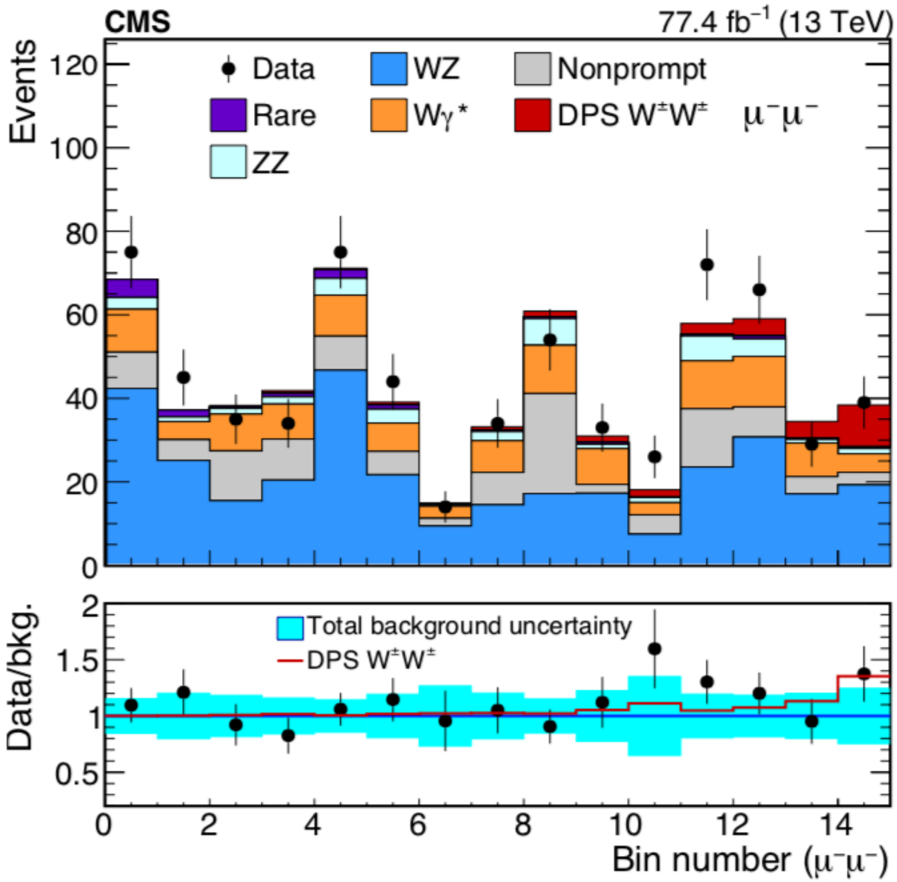
At leading order same-sign Single Parton Scattering (SPS) has **two additional jets**

1909.06265

Double parton scattering (DPS)

- Absence of additional jets reduces the SPS background
- Largest residual backgrounds from
  - WZ production, decaying to leptons – genuine same-sign leptons
    - One lepton from Z is emitted outside of the acceptance
  - Non prompt leptons (e.g. QCD multi-jet, W+jets)

Two separate multivariate classifiers used to discriminate between these types of background

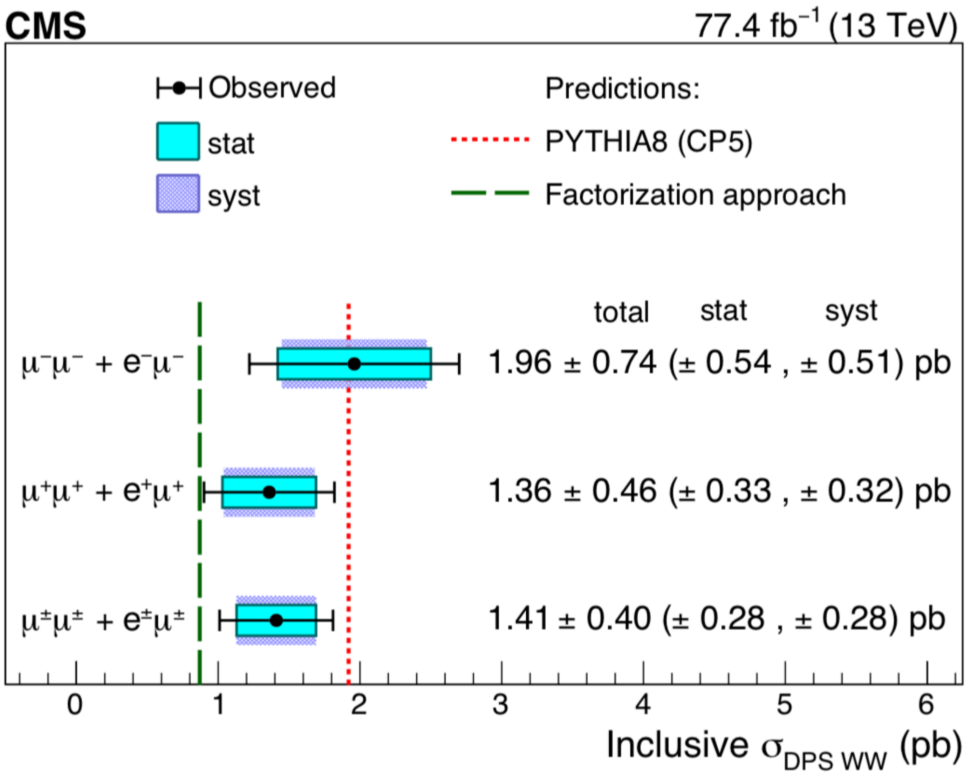


Double parton scattering (DPS)

Observed significance of **3.9σ**

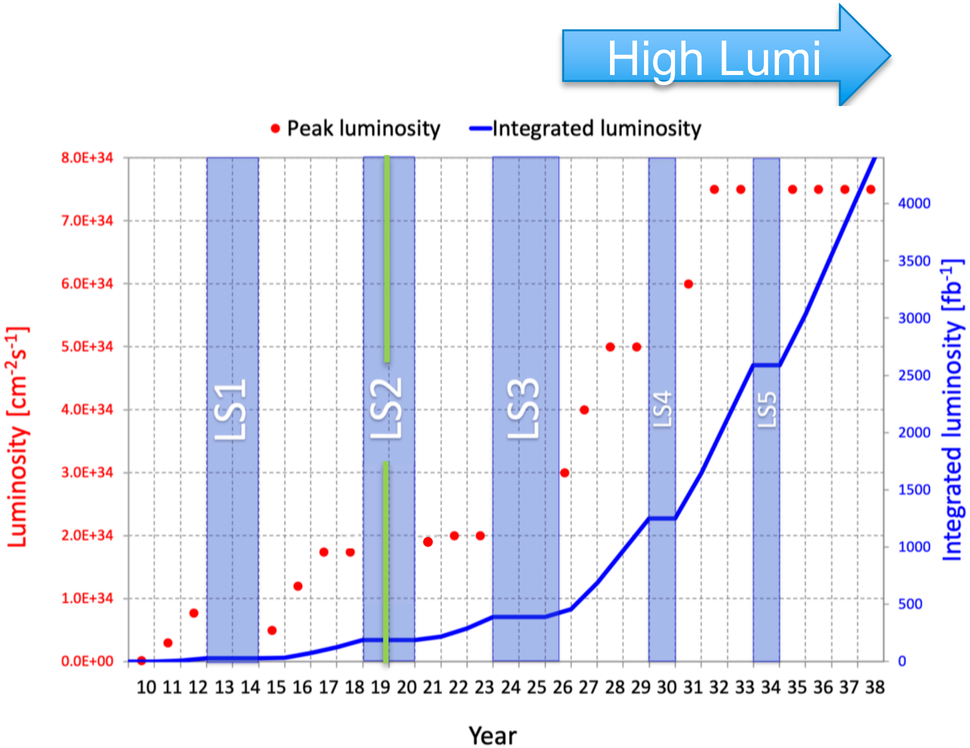
First measurement of DPS WW cross-section

- **1.41 ± 0.28 (stat) ± 0.28 (syst) pb**
    - Largest systematic uncertainty from estimation of non-prompt lepton contributions



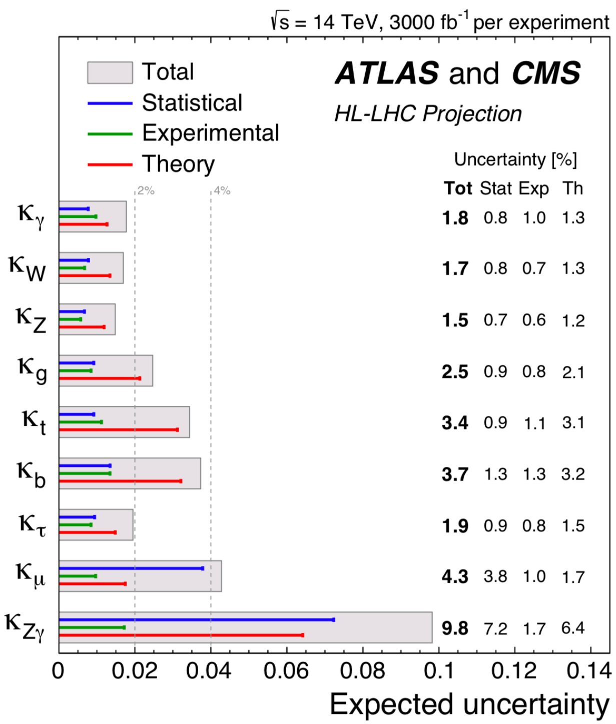
High-luminosity LHC

- Planned upgrade to LHC:
  - Increased luminosity – typically 140-200 proton-proton interactions per bunch crossing
  - Up to 250 fb^{-1} per year yielding ~3000 fb^{-1} by end of run
  - Starting ~2026



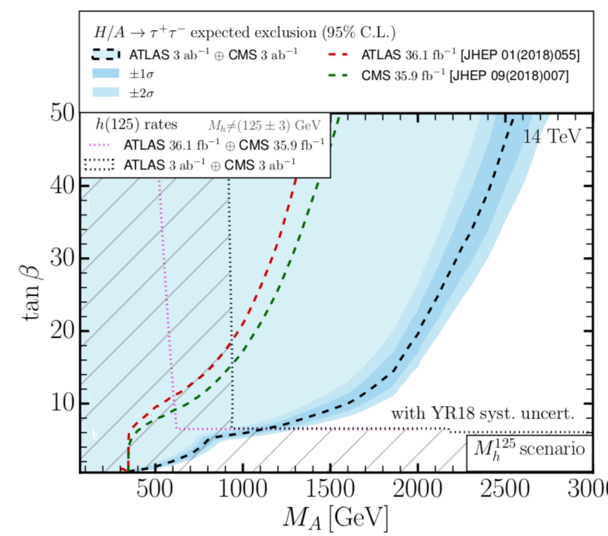
Thanks to Sudan Paramesvaran for input to following slides

Motivation – Higgs physics



- Higgs SM couplings will be measured to the percent level
- Large statistics will particularly help with complex final states
- Assuming SM couplings 4σ evidence for HH (ATLAS+CMS)

- Large statistics will improve sensitivity to new Higgs bosons.
- One example decaying to $\tau\tau$ will have reach up to 2.5 TeV for tan β > 50.



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

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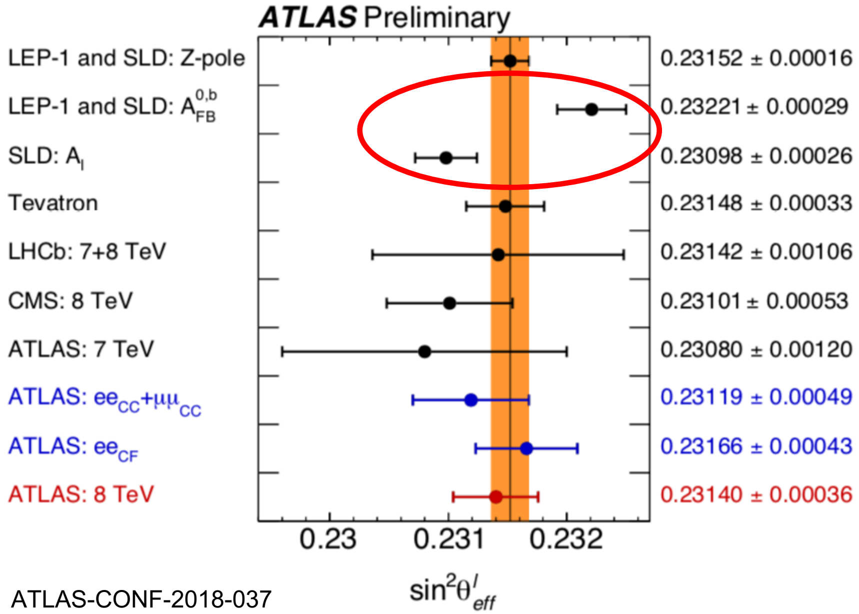
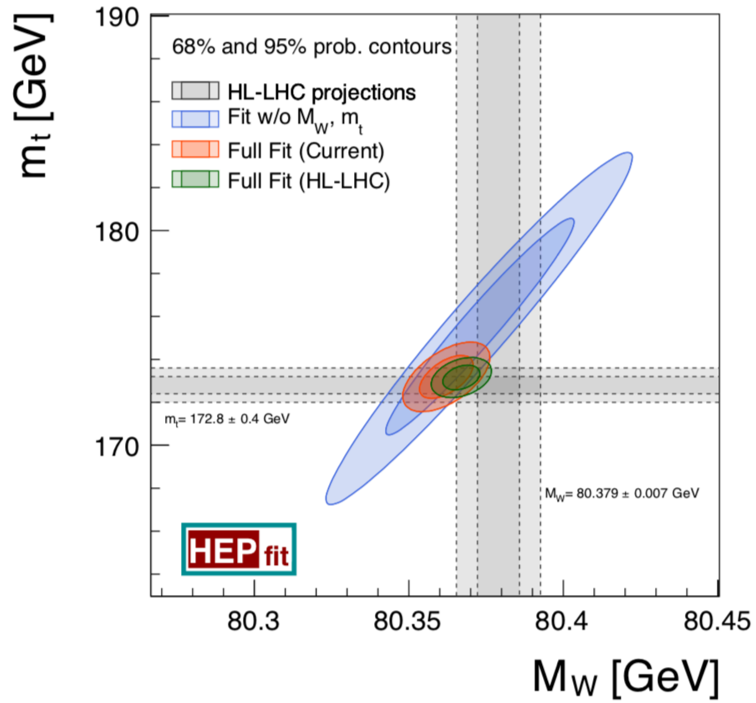
Motivation – SM physics



ATLAS-CONF-2018-037



- Precise measurement of weak mixing angle can help resolve discrepancy between LEP and SLD results
- Single measurement as good as current world average (PDF uncertainty still dominates)

- W boson mass uncertainty of 7 MeV (current world average 12 MeV)
- Higher statistics
- Increased constraint of PDFs (extended leptonic coverage)

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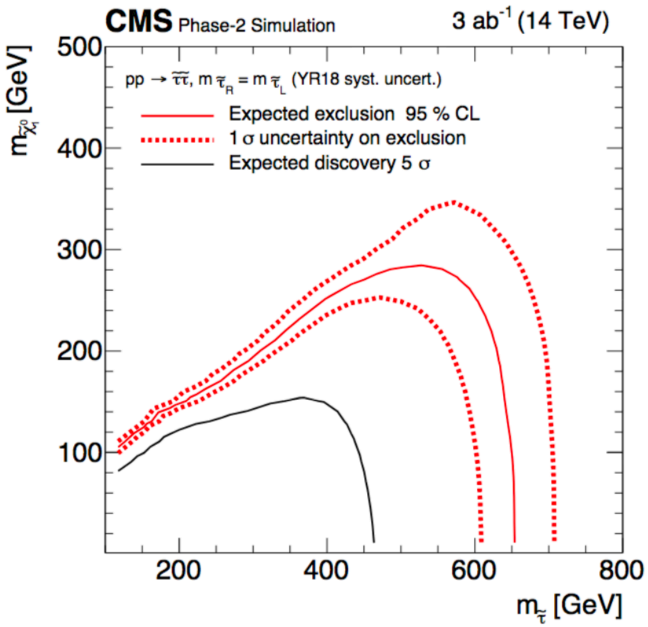
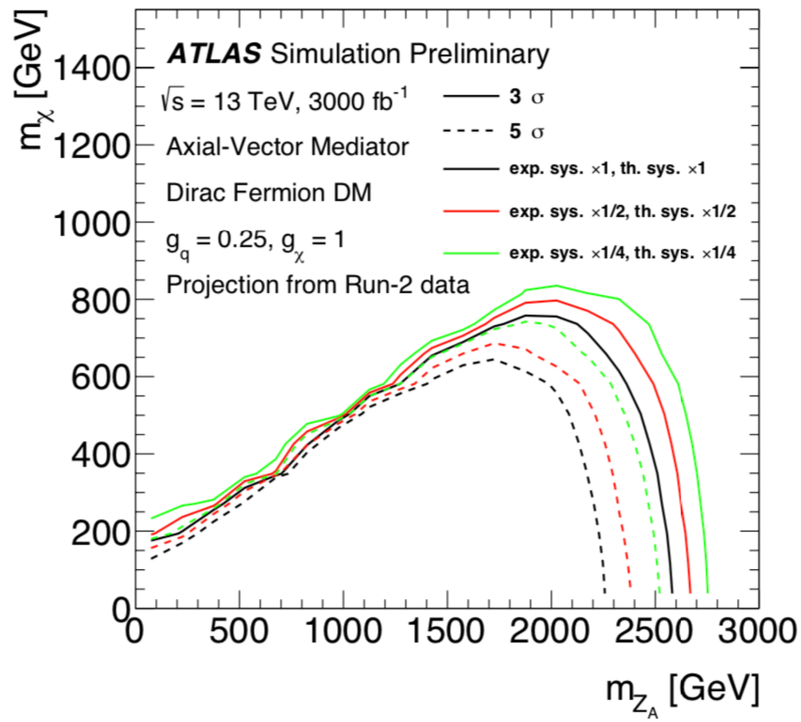
Motivation – Beyond the SM





- Large increase in sensitivity to Super-Symmetry signatures
- E.g. di-stau production
  - Only excluding ~100 GeV currently
  - Will be able to reach ~500 GeV for discovery

- Searches for Dark Matter will have a much improved discovery reach - on the order of a TeV when using the monojet + missing energy signature

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System should cope with higher radiation and more collisions per bunch crossing

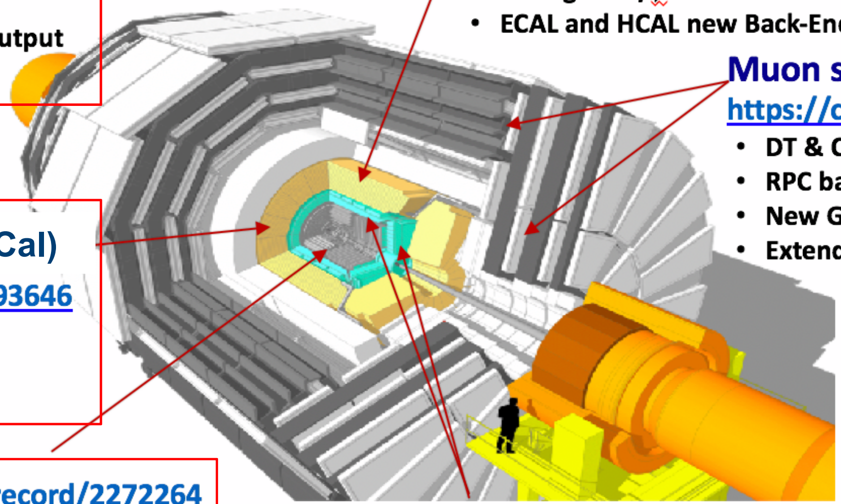
CMS HL-LHC upgrades

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



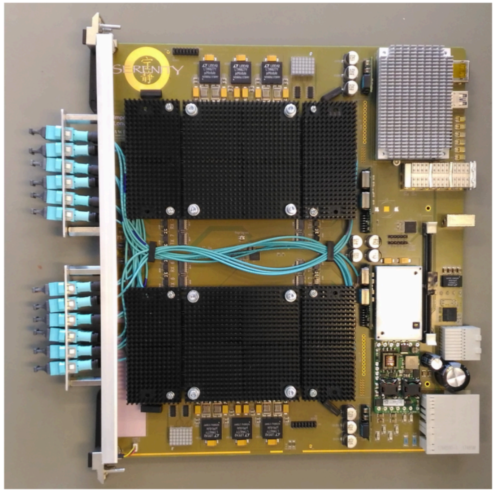
Endcap Calorimeter (HGCal)
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

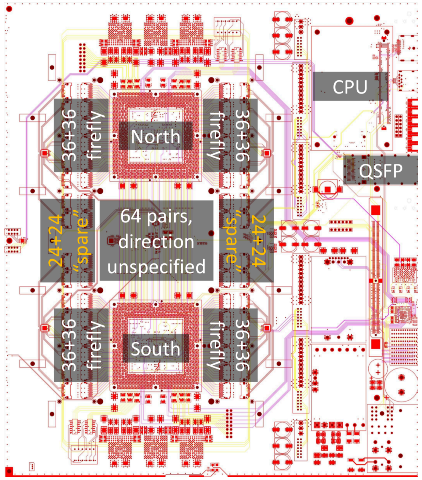
Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Common Off-detector Electronics Technology -



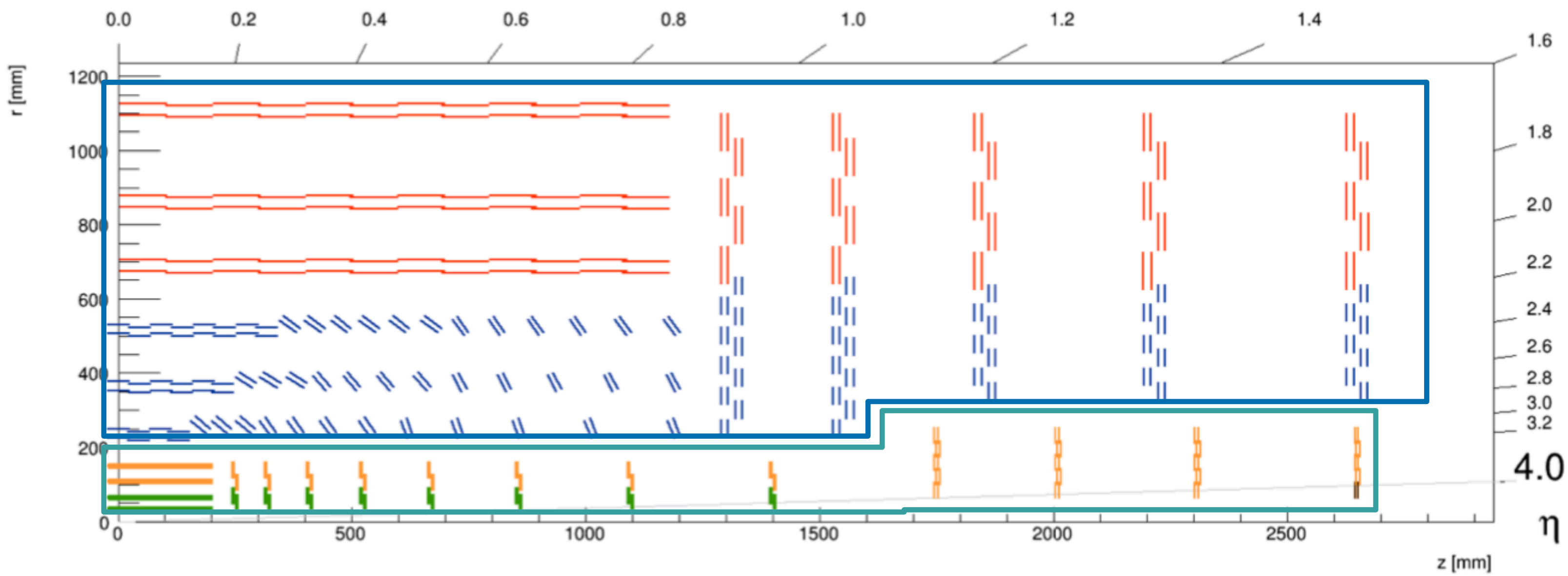
- Prototype ATCA card (Advanced Telecommunications Computing Architecture) to provide back-end electronic services for CMS: Serenity
  - Flexible, dual FPGA card
  - Flexible, pluggable FPGA units
  - Generic, open processing platform



- Originated out of the UK CMS collaboration
- Backend electronics for:
  - HGCal trigger and DAQ
  - Outer-tracker readout,
  - L1 trigger

7Tb/s: 288 fibres @ 25Gb/s

Tracker upgrade



Inner Tracker

- Tracking up to η=4
- 2×10^9 pixels
  - Thin, radiation hard

Outer Tracker

- 13200 “Pt modules” (providing L1 Trigger primitives):
  - Coverage up to |η| ~ 2.5
- Occupancy < 1%

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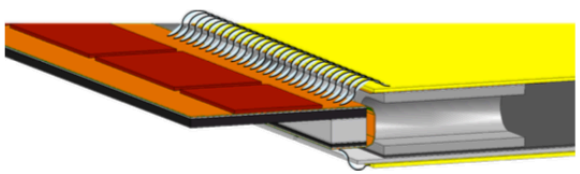
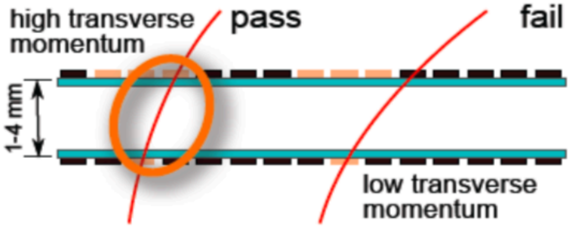
Tracking in the Level-1 trigger

- Better trigger selectivity needed to exploit high luminosity
  - Better p_T resolution, e-γ discrimination
- Inclusion of data from the Outer Tracker at L1

FPGA based track-finder

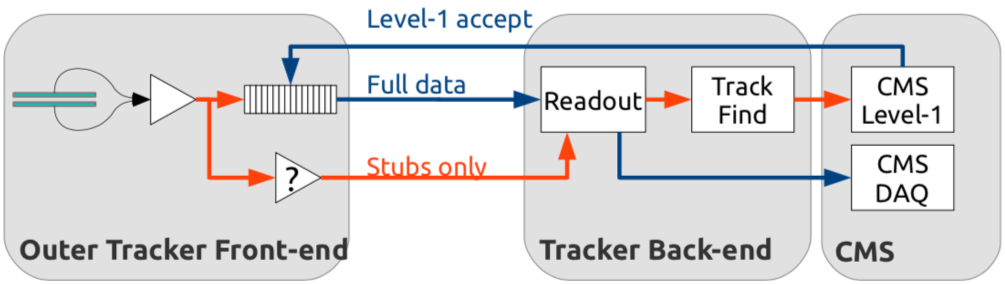
- Two silicon sensors with small spacing in a module
- One ASIC correlates data from both sensors selecting tracker "stubs"





The "stubs" are sent to the track finder backend, and used to create L1 track primitives with p_T > 2GeV @ 40MHz

The vast majority of tracks have low p_T and can be discarded from L1



C. Caillol, S. Paoletti

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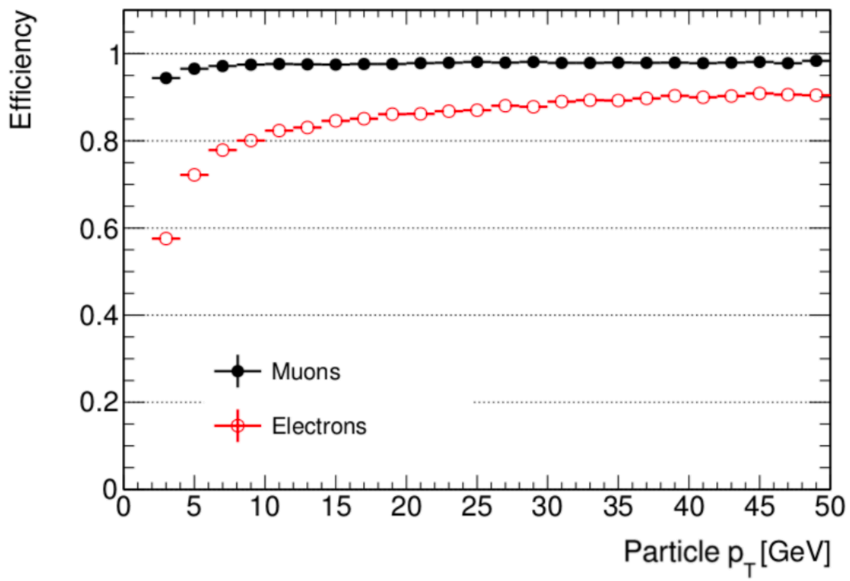
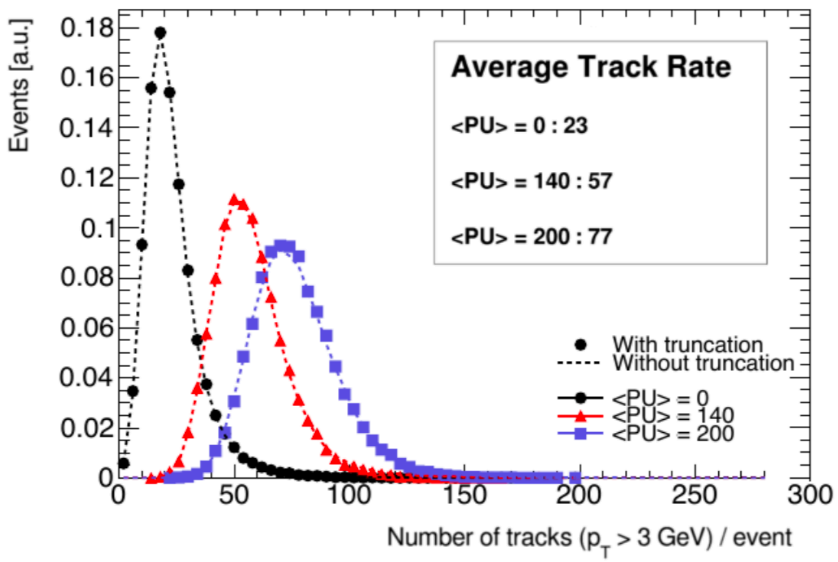
Tracking in the Level-1 trigger





- L1 tracking efficiency vs p_T
- Muon turn-on around 3 GeV (stub threshold)

- Total L1 track rate for $t\bar{t}$ events
- The total rate for 200 pileup events is easily accommodated by the downstream L1 trigger

CMS-TDR-014

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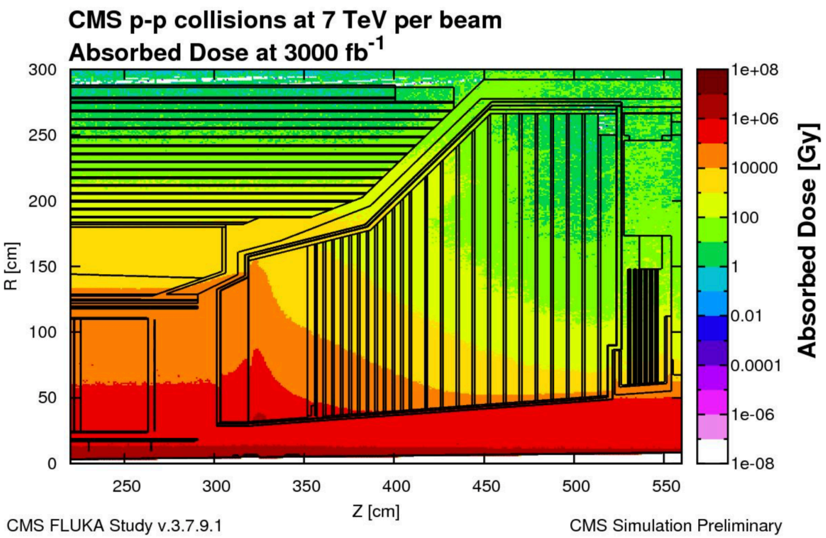
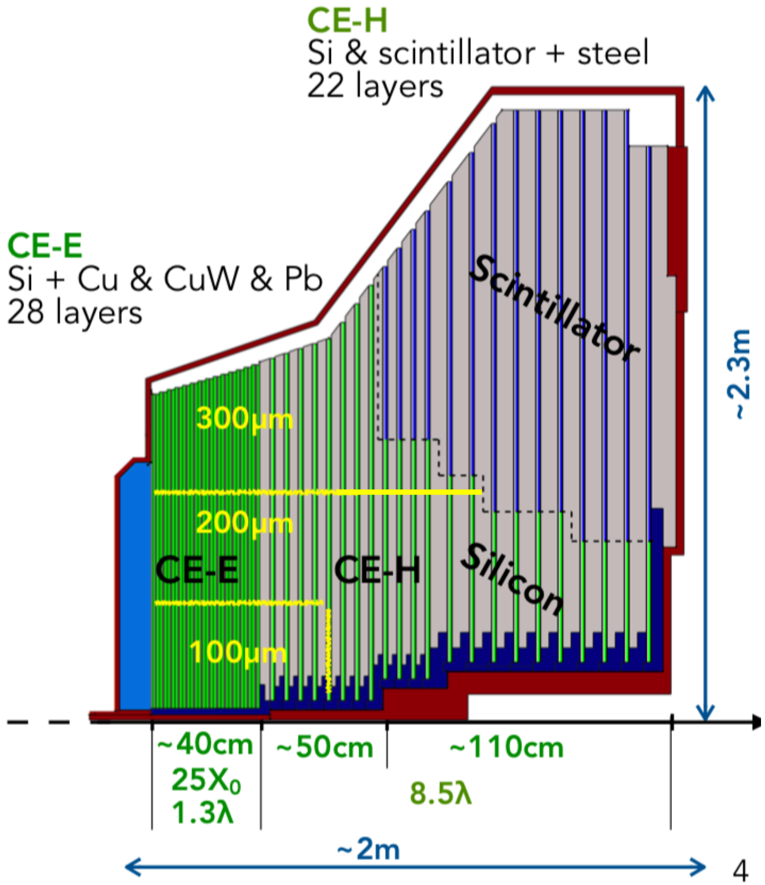
High-granularity end-cap calorimeter (HGCal)

Machine requirements

- Very high fluence and absorbed dose in forward region
  - Silicon sensors for the bulk of the calorimeter
  - Plastic scintillator tiles at the rear





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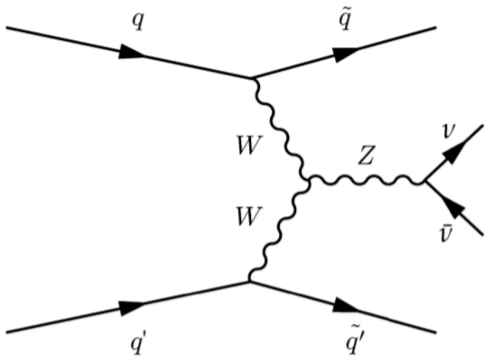
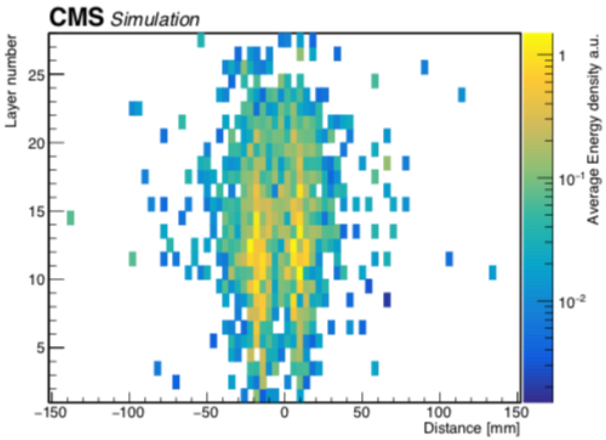
High-granularity end-cap calorimeter (HGCal)

Physics motivation

- Boosted topologies become more relevant
  - Need for high-granularity
  - Fine longitudinal readout segmentation
  - Good performance at high η (complements tracker upgrade)
- Exploit VBF production





14 GeV p_T photons at η=2.4 with 3 cm separation

A. Martelli, CMS-TDR-17-007

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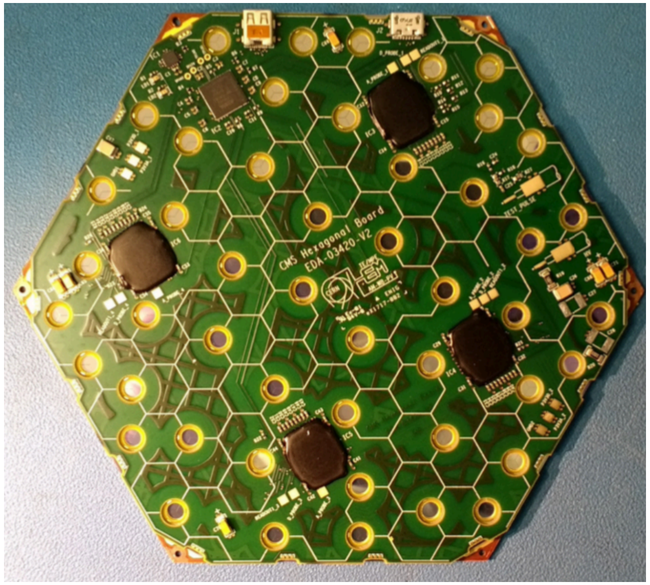
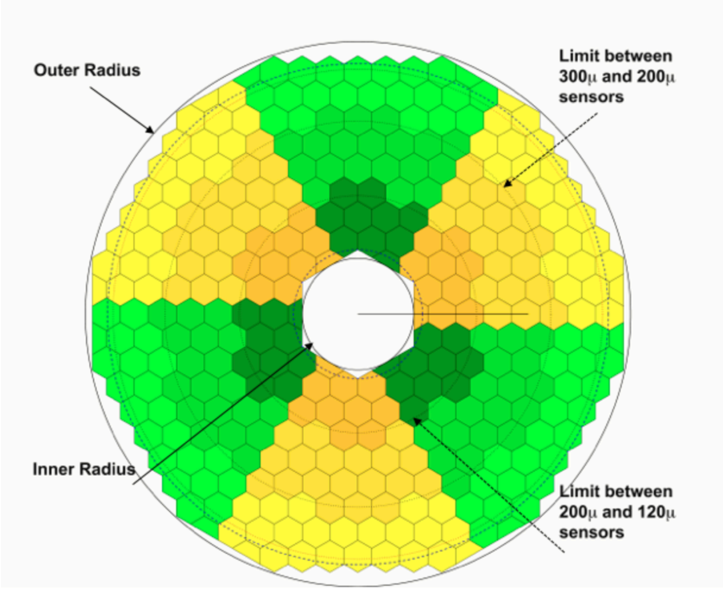
High-granularity end-cap calorimeter (HGCal)

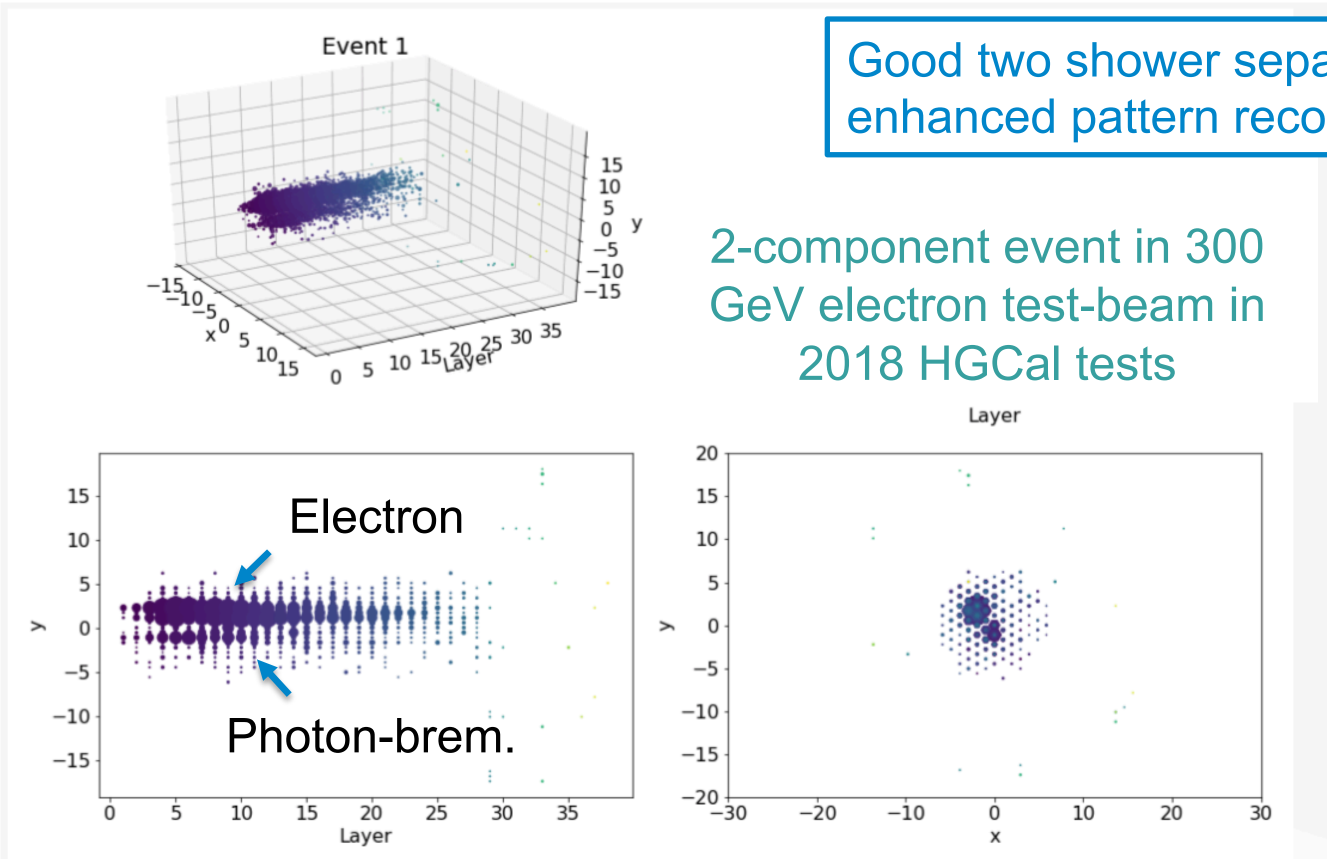
Hexagonal silicon cells, to make most efficient use of circular silicon wafers





A. Martelli, CMS-TDR-17-007

Advantages of high granularity

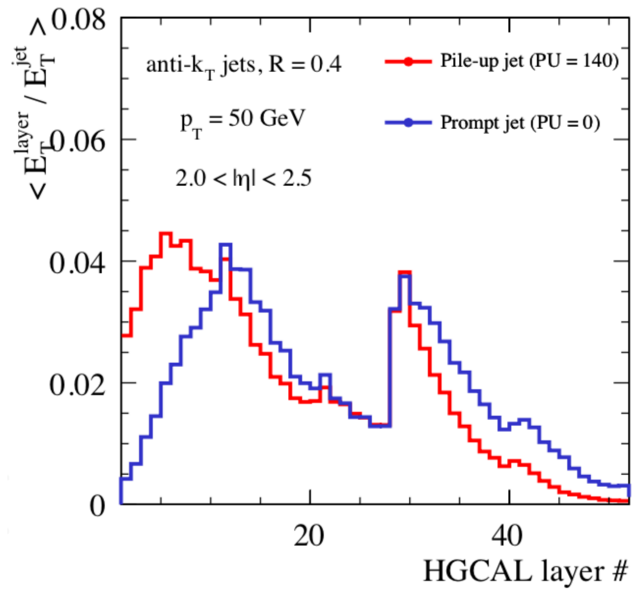


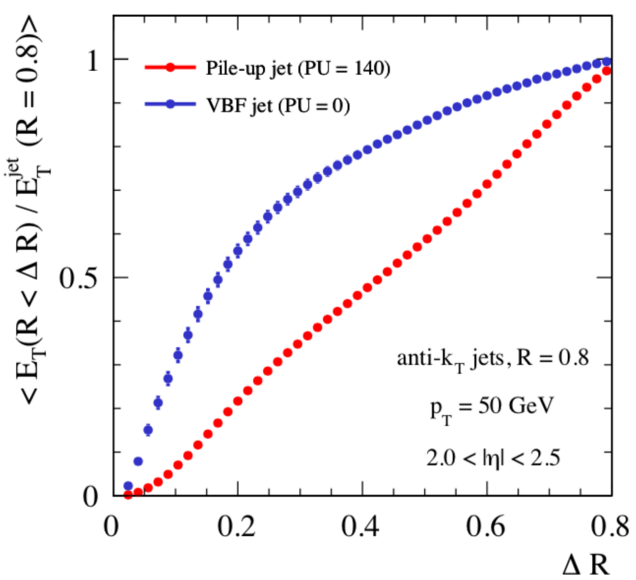
Good two shower separation with enhanced pattern recognition

2-component event in 300 GeV electron test-beam in 2018 HGCal tests

Advantages of high granularity - jets

Longitudinal and lateral energy profiles





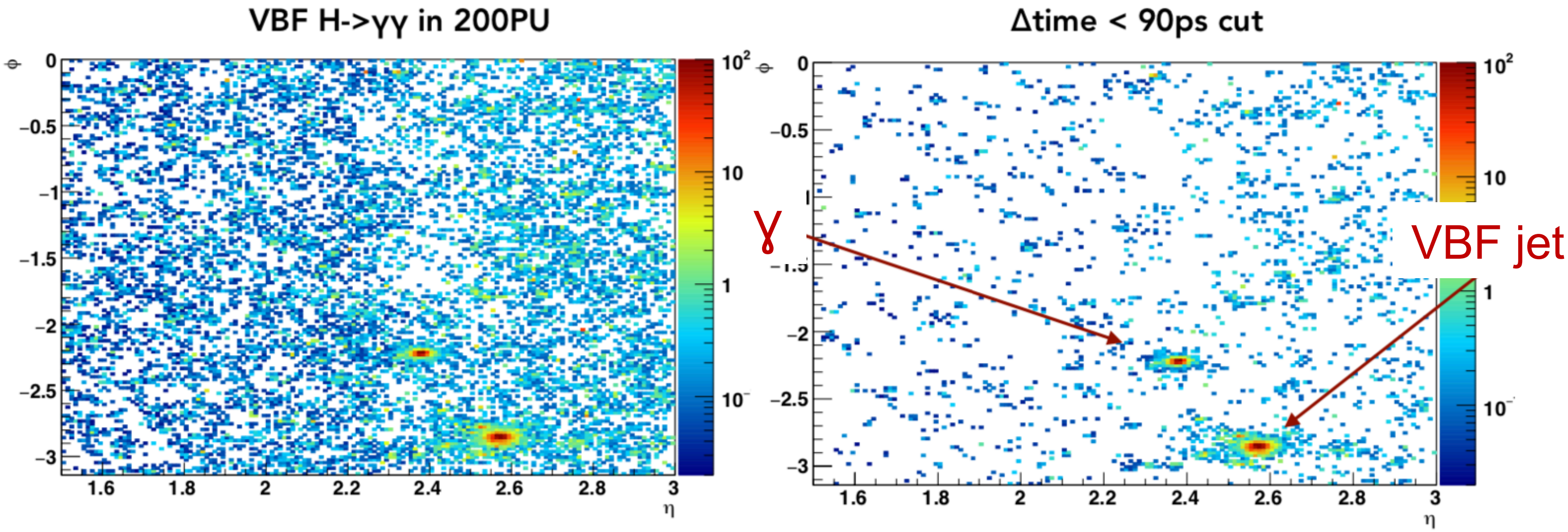
High granularity gives potential for separation of PU jets (mostly soft gluon jets) from interesting quark jets (e.g. from VBF)

→ Useful for resolving boosted topologies, top-, VBF- and tau-tagging

A. Martelli, A. Lobanov

Using precise timing information

- Potential for 5D reconstruction (x,y,z, energy + time)



Powerful way to mitigate pileup
- allows reduced PU effect on jet reconstruction and energy estimate

→

Improve track → vertex association, better b-tagging and lepton isolation

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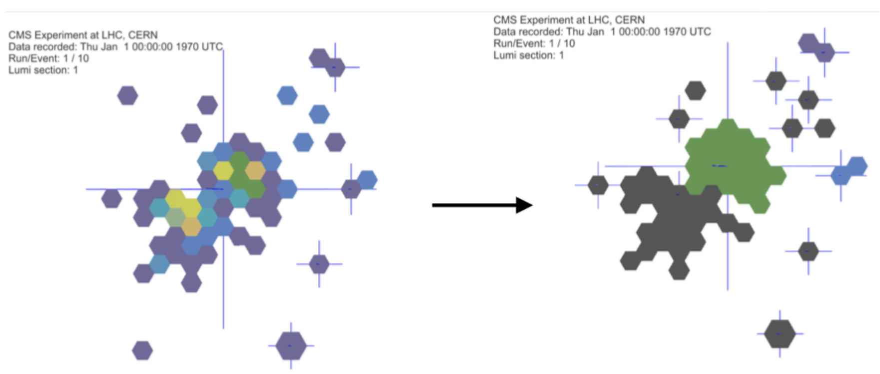
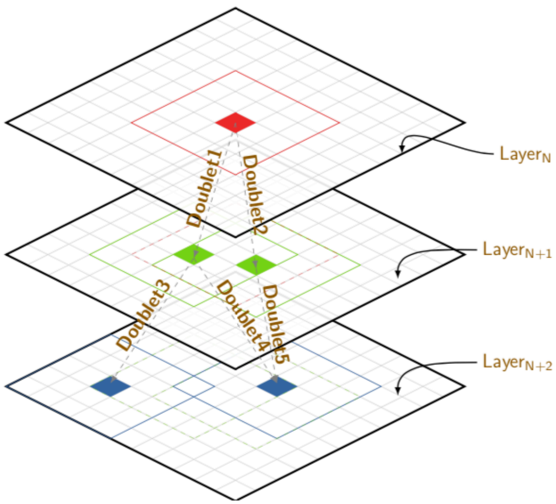
Particle reconstruction and identification

- Developing new **TICL** framework:
  - The **I**terative **Cl**ustering
  - Combining clustering and pattern recognition iteratively





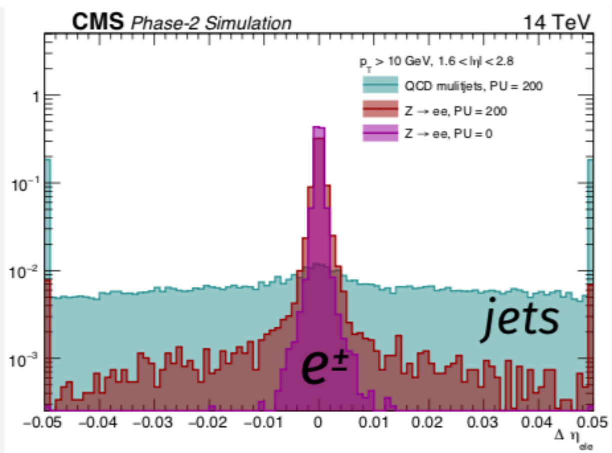
1. Build layer images (2D clusters)

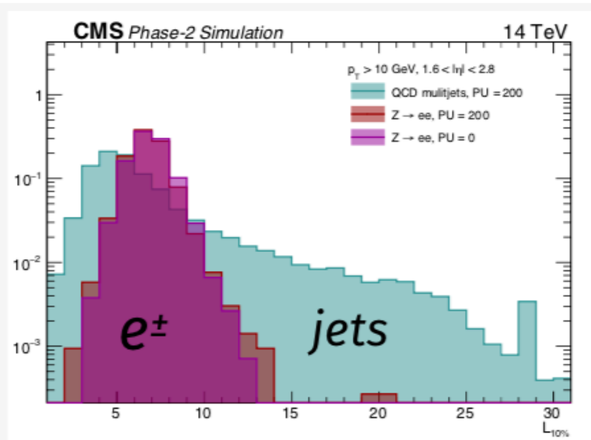
2. Associate the 2D clusters to reconstruct 3D showers

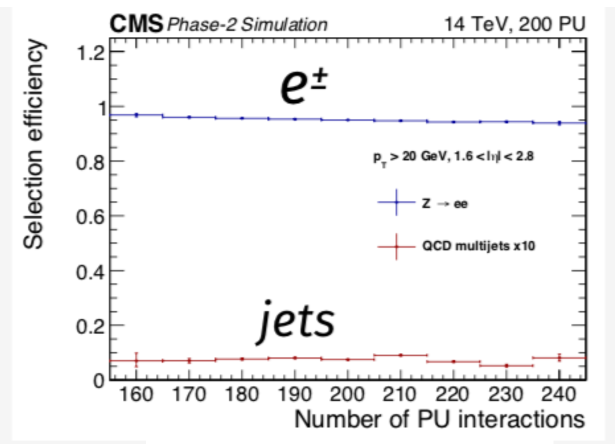
A. Martelli, A. Lobanov

Electron identification

- Electron are a standard candle for particle flow
  - Compact, of known shape and associated to a track
  - Axis pointing improves rejection of PU photons with respect to bremsstrahlung







Electron shower shapes shown to be independent of pileup

Efficiency vs number of PU interactions

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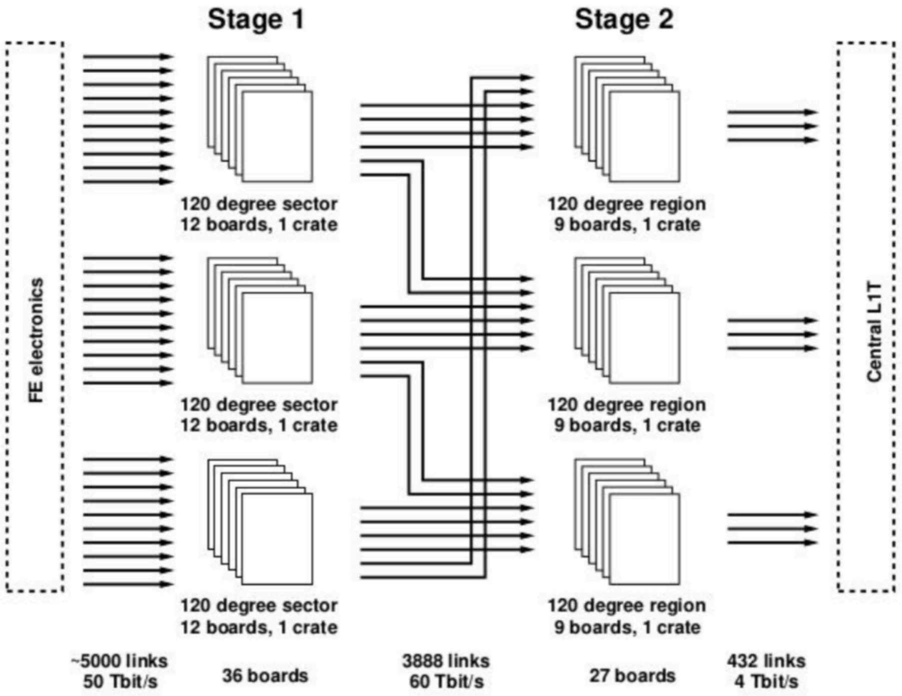
HGCal trigger system

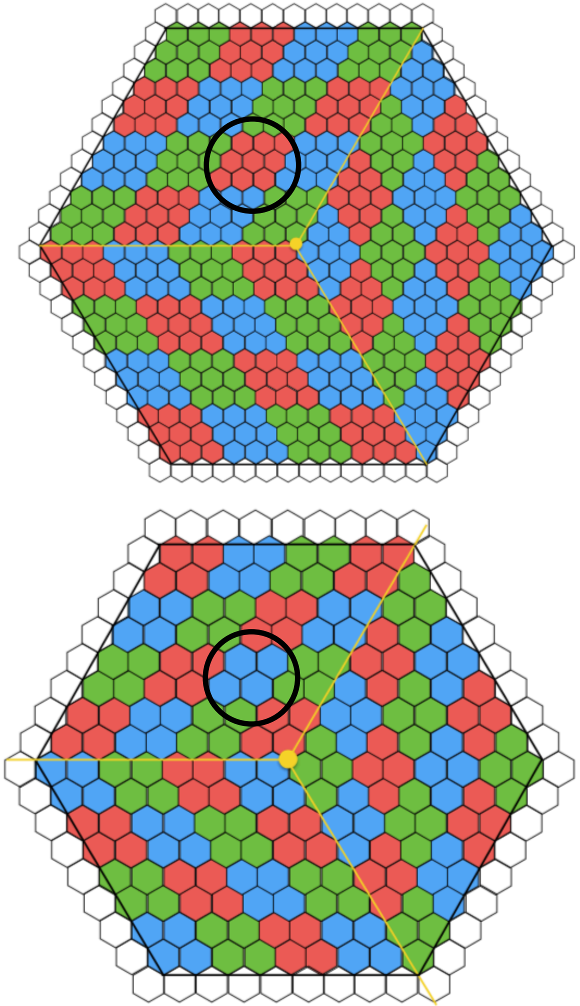
- Trigger capabilities in the forward region are key feature of the CMS upgrade
- HGCal will generate ‘trigger primitives’ (3D energy clusters) to pass to the L1 trigger
- Two-stage backend design
  - Stage 1: data handling and calibration
  - Stage 2: trigger primitive generation



One end-cap

HGCal trigger system

- Reducing expensive bandwidth is a challenging element of the system
  - O(10000) links @10Gpbs from the front end to the trigger primitive generator
- Form basic “trigger cells” from the sensor cells in the front end
  - Combine either 4 or 9 depending on position in detector
- Cells are passed to the backend electronic after some selection
  - Simplest: threshold cut on energy



V. Palladino

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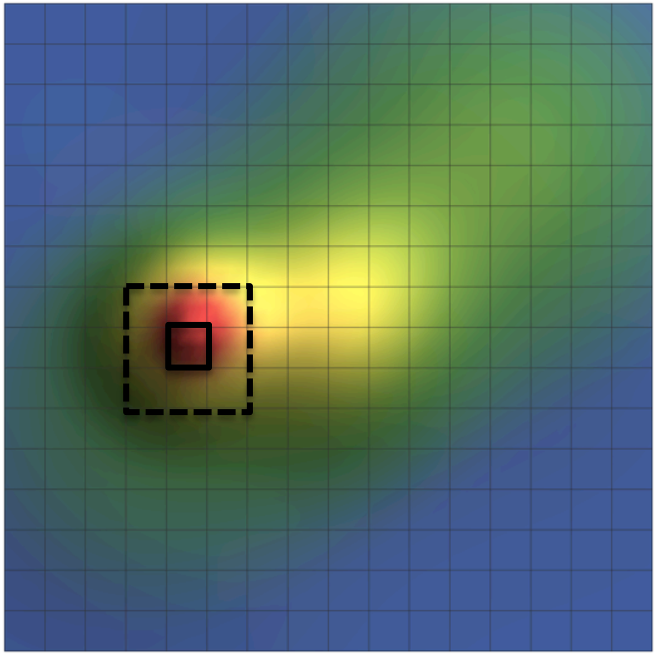
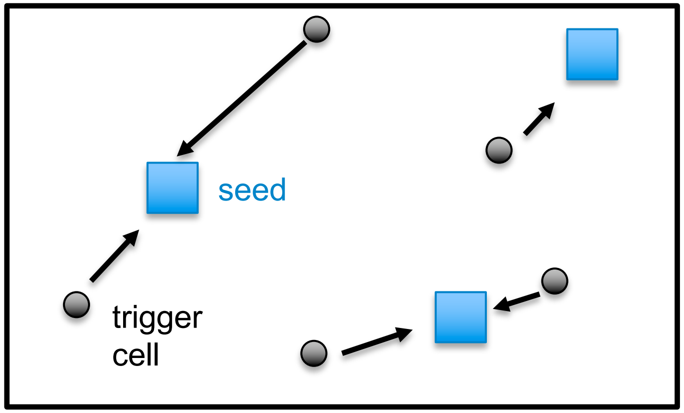
Backend stage 2



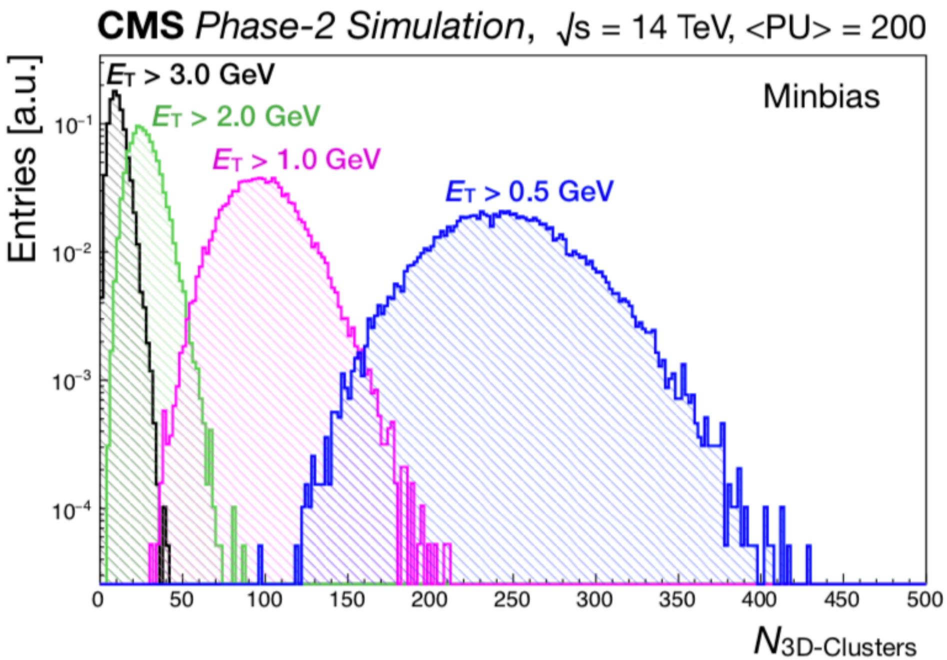
Fill 2D histogram with trigger cells - Seed finding



- Nearby TCs are associated to seeds in 3 dimensions forming 3D clusters
  - Passed to L1 trigger (after some selection)

HGCal trigger system

- The 3D clusters are then combined with the tracking information at L1
  - Particle flow at trigger level
- The firmware for stages 1 and 2 is currently being implemented



Number of 3D clusters per end-cap in tt events with 200 PU

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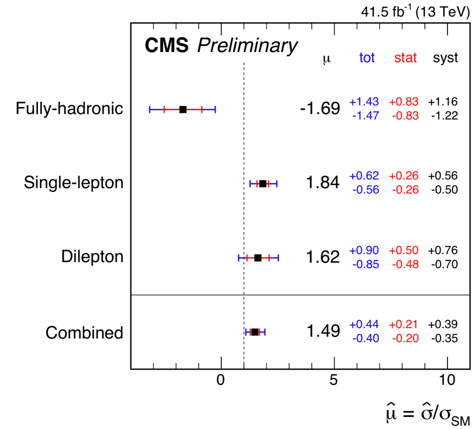
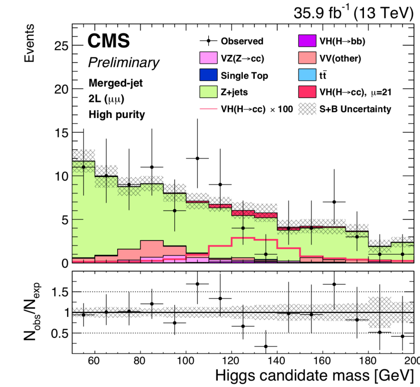
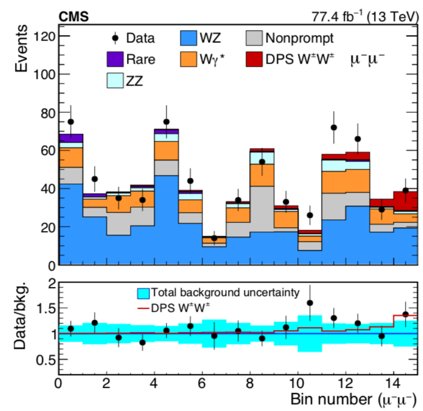
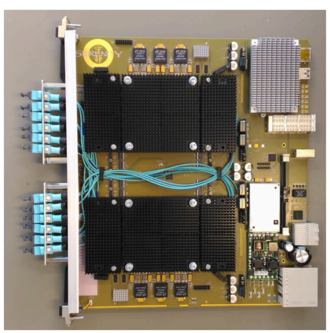
Summary

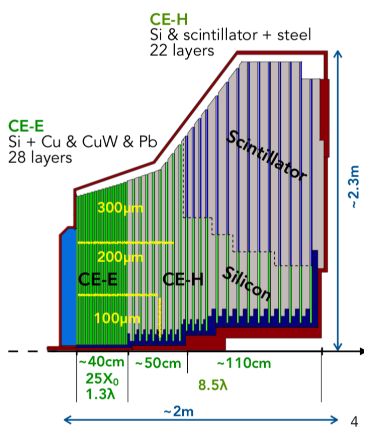
- Important and interesting physics results are taking advantage of the large data set from the LHC run 2
    - Higgs, top, standard model, and new physics searches











Many of the CMS HL-LHC upgrade projects are entering a crucial period with data taking around 6-7 years away