The role of the CMS trigger in Higgs sector observations and searches for new resonances in Run II

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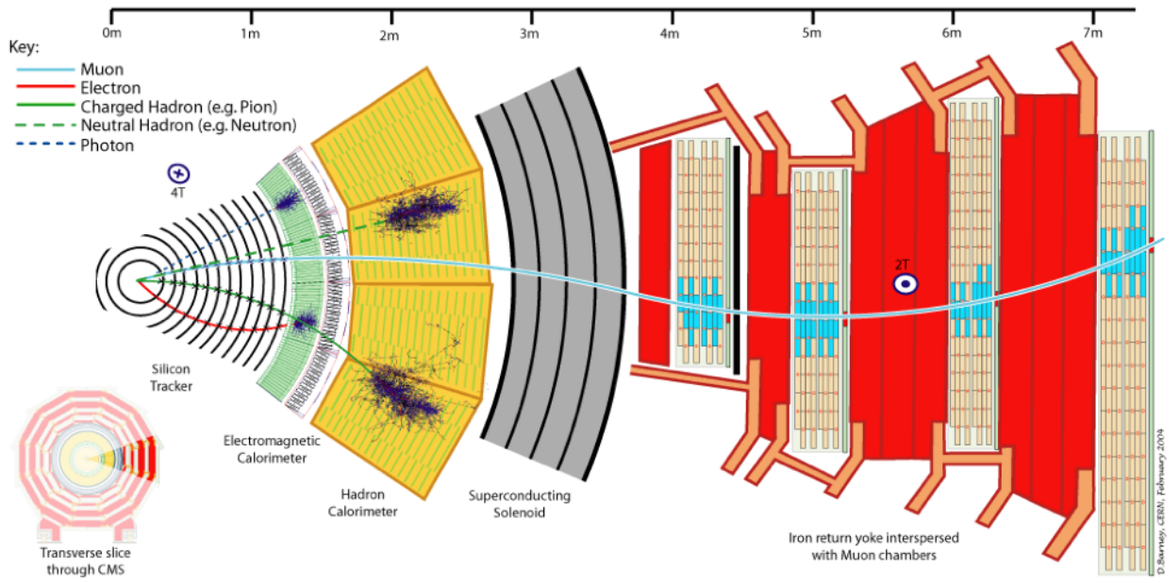
Alberta, Canada

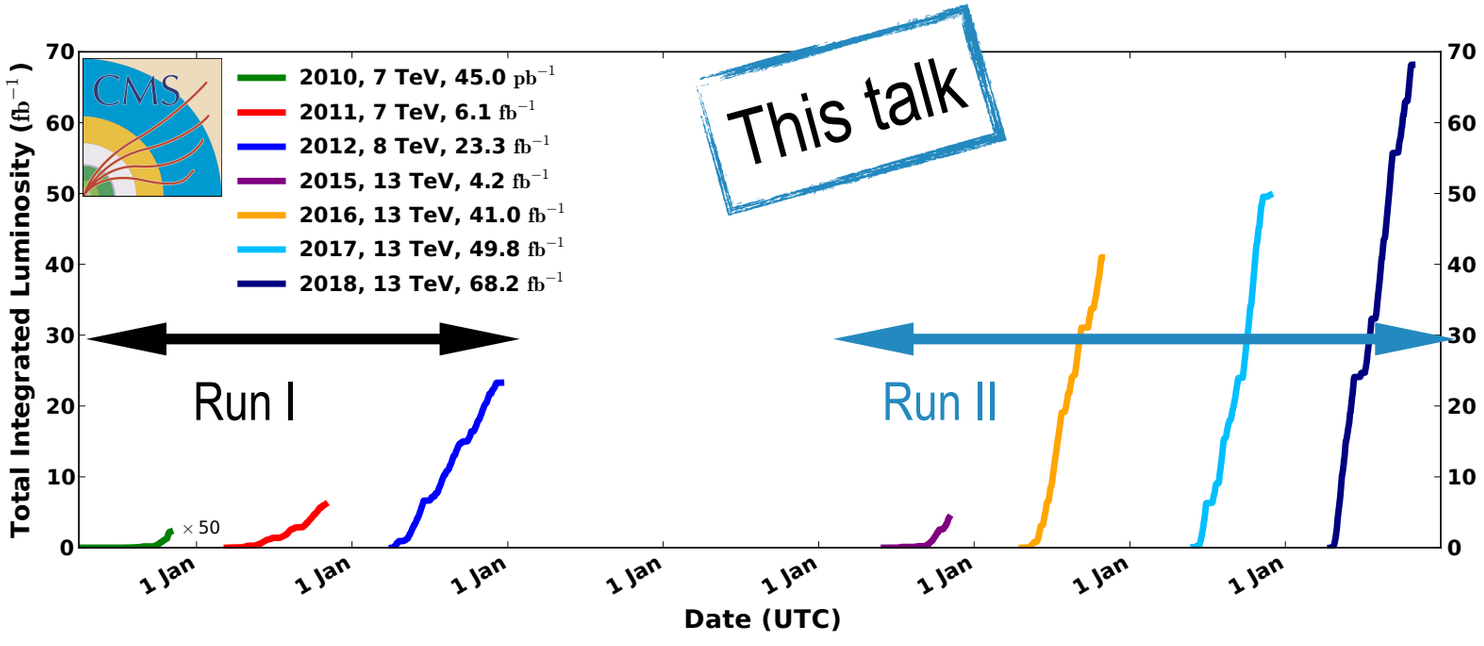
The CMS detector

- **Multipurpose** experiment at the LHC, CERN.
- **Broad physics program**: Higgs Physics, SM precision measurements, BSM searches…



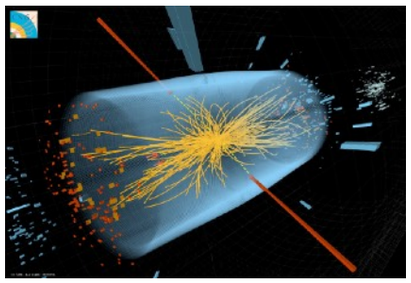
- Outstanding performance in the harsh experimental conditions of **Run II**:
  - Peak lumi 2.1×10^{34} cm^{-2}s^{-1}
  - Pileup up to 80!
- **163 fb^{-1}** of p-p collision data during Run II.

	Run I (2010-12)	Run II (2015-18)
Energy	7-8 TeV	13 TeV
Inst. Lumi.	7×10^{33} cm^{-2}s^{-1}	2×10^{34} cm^{-2}s^{-1}
PU	25	50



The CMS trigger system

- LHC bunch crossing rate: **~40 MHz** → data storage unsustainable.
- Trigger system: **fast** selection of interesting events based on kinematic cuts.
- Successive steps: rate reduction, increased granularity and complexity.



~40 MHz

Level-1 Trigger

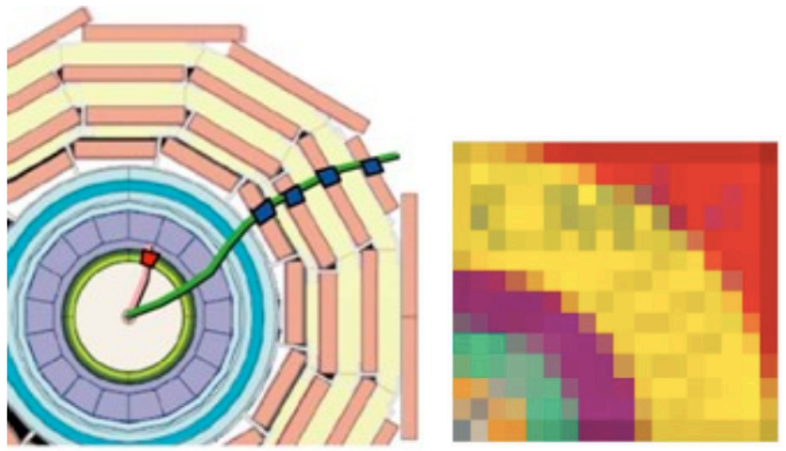
~100 kHz

High Level Trigger

~1 kHz

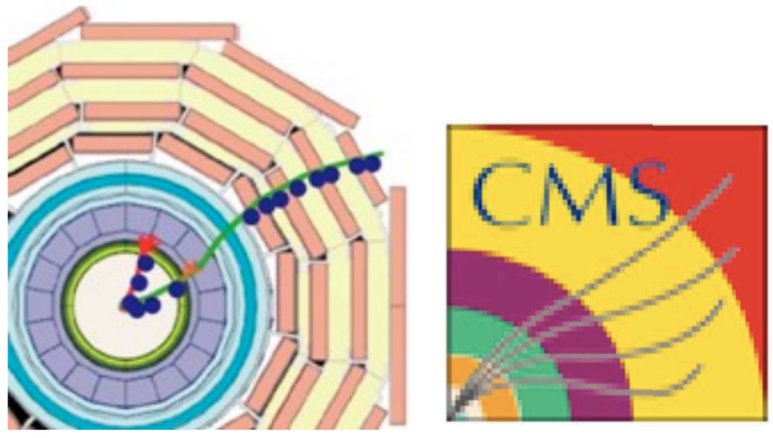
Data storage and full reconstruction

This talk



Level-1 Trigger (L1)

- Hardware
- Calorimeters and muon detectors
- ~3.8 μs



High-Level Trigger (HLT)

- Software
- Full-detector information
- ~300 ms

↔ **10^5** rate reduction!

The CMS trigger upgrade in Run II

The experimental challenges of Run II lead to the **upgrade** of the L1 trigger HW and strategy (2016):

Calorimetric trigger (e, γ, τ_h, jet, sums)

- Improved **granularity**: better E_T/position resolution
- Improved object **isolation**: better particle ID
- Implementation of **PU estimation**/subtraction: resilience to LHC conditions

+

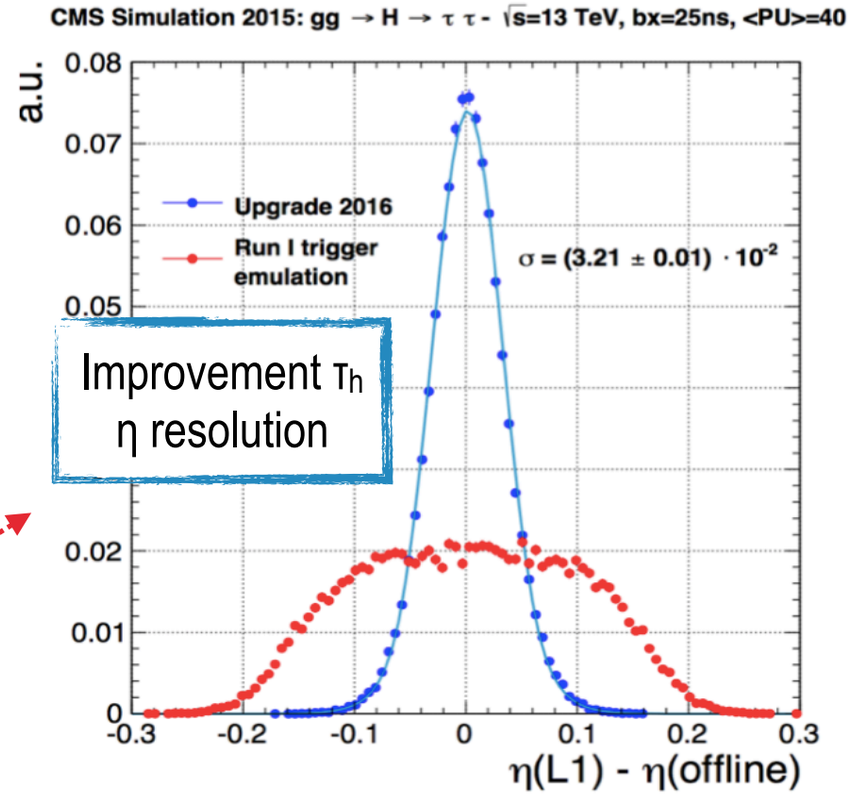
Muon trigger (μ)

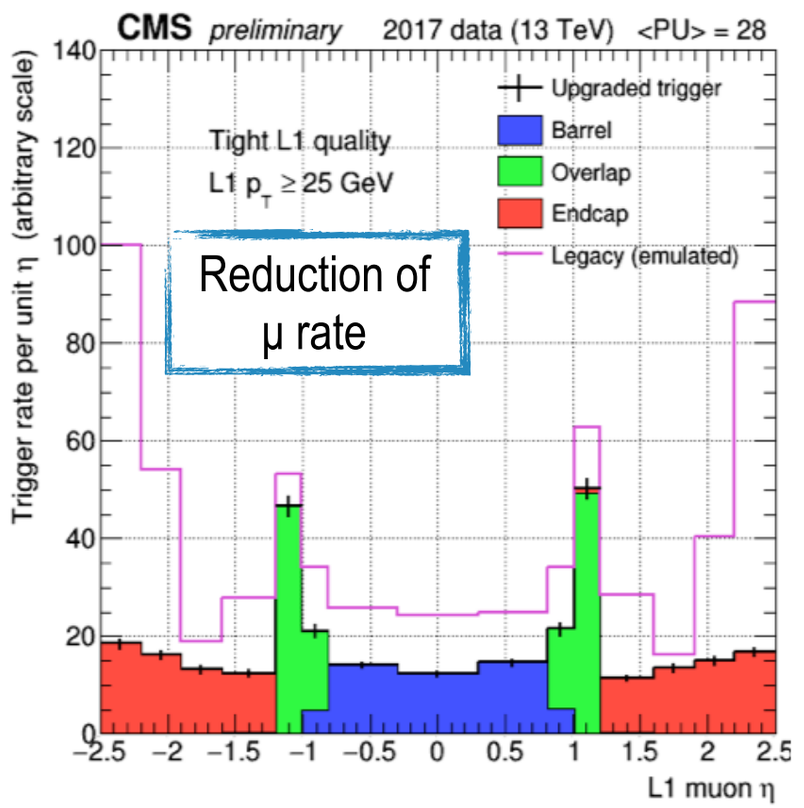
- From detector-oriented to **geometry**-oriented: no redundancy, higher efficiency, lower rate

↓

Global trigger (Trigger menu)

- More **sophisticated** object candidates, more **algorithms**, with more complex **correlations**

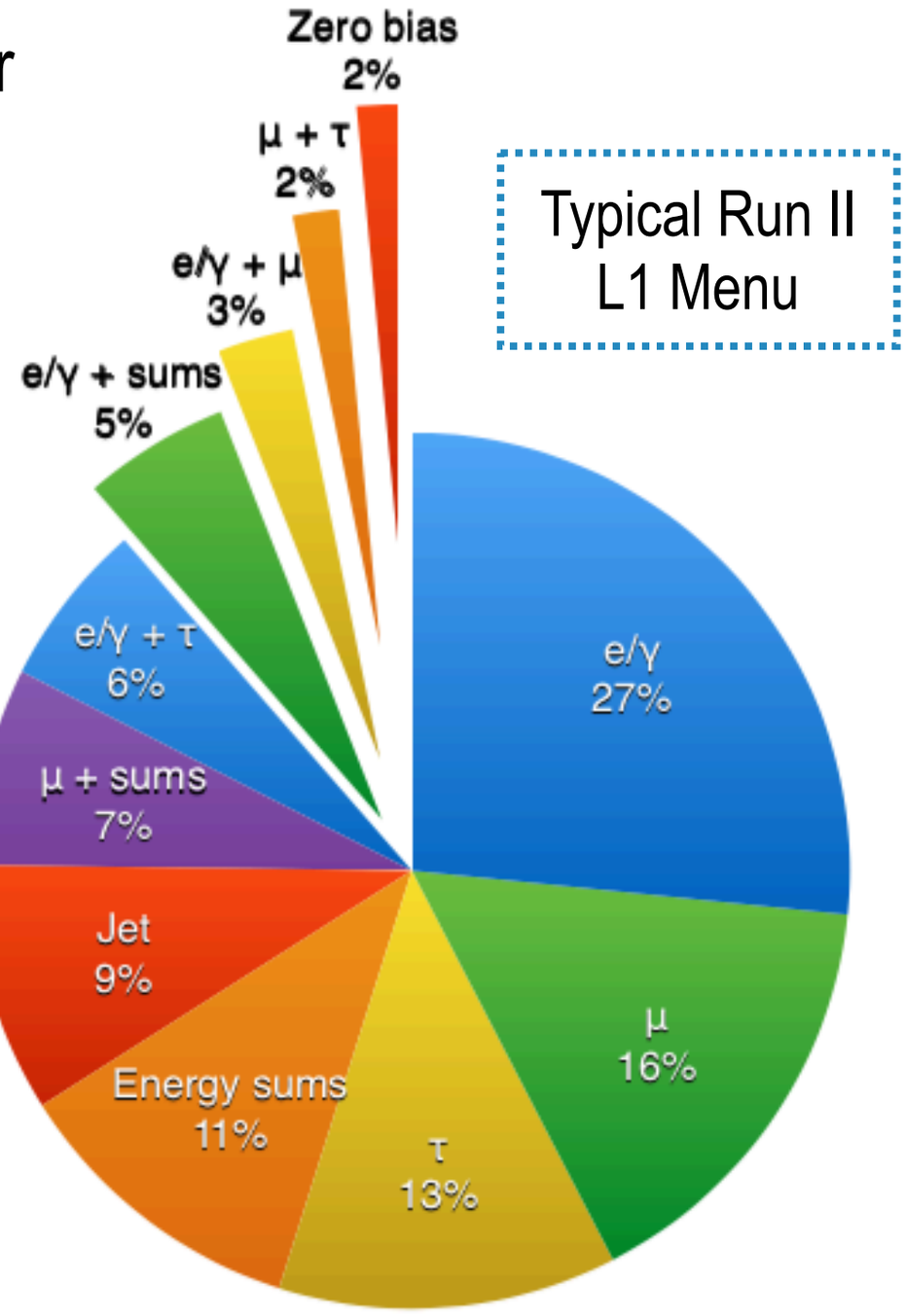




Trigger Upgrade TDR

The CMS trigger menu

- Extensive **list of algorithms** in the Global Trigger designed to select potentially interesting events.
- Starting point of the CMS **physics program**: maximize physics acceptance and background rejection.
- Flexible and scalable: **evolve** with CMS physics interests and **adapt** to the changes of LHC parameters.
- Up to 512 **algorithms** with:
  - Single/multiple objects (single-μ, dijet…)
  - Cross-object triggers (τ+e…)
  - Kinematic cuts (E_T, η, φ)
  - Topological correlations (Δη, Δφ, ΔR)
  - Invariant mass (W, Z, VBF)

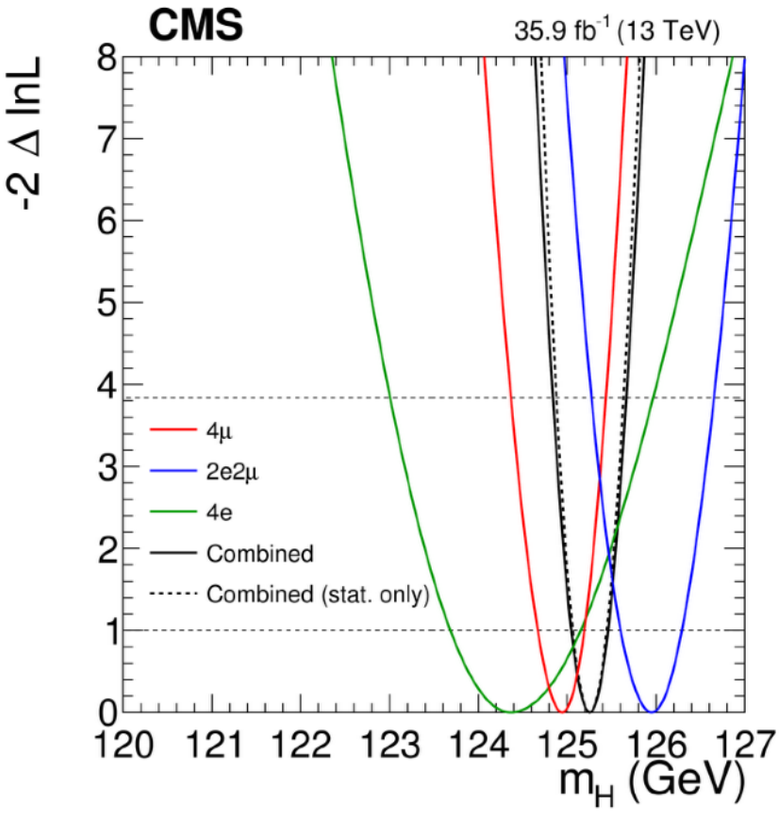


The CMS Higgs physics program

(1) PLB 779 (2018) 283
(2) PRL 121 (2018) 121801
(3) PRL 120 (2018) 231801

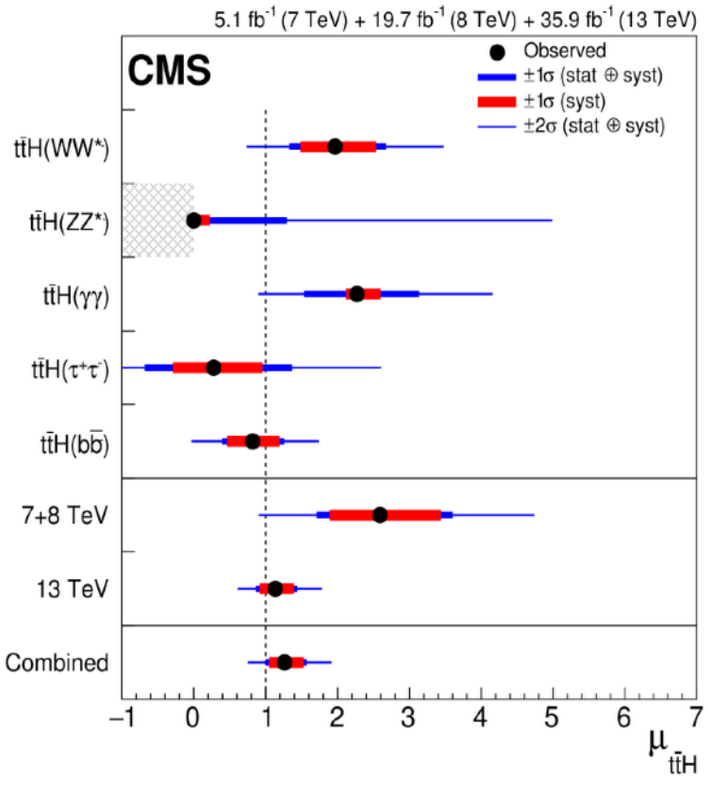
Precision measurements

- Mass/width, anomalous couplings, diff. x-sections.
- High-resolution channels: **H→γγ**,**H→ZZ→4l**
- μ, e, γ trigger selection and resolution essential.



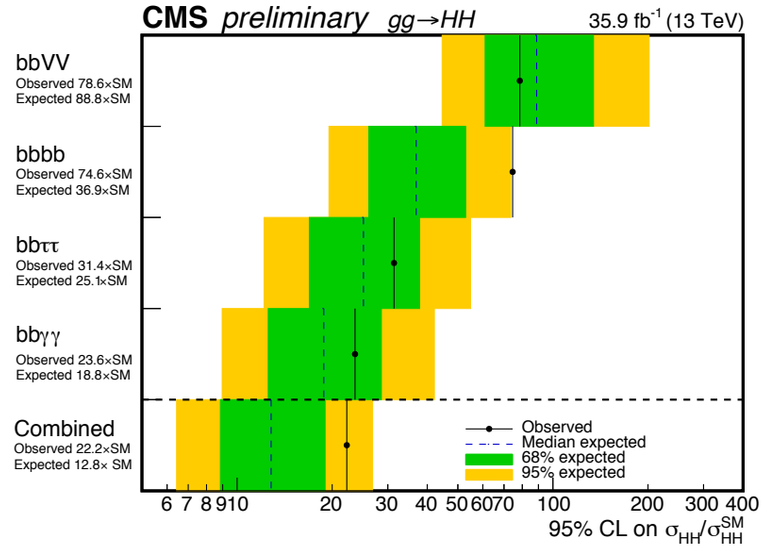
Couplings to fermions

- Recent **observations**:
  - **H→ττ**(1), **H→bb**(2)
  - **ttH**(3) process
- Efficiently triggered in Run II and accumulated large statistics.



Rare processes

- **H→μμ, HH**…
- Trigger optimisation enhanced sensitivity.

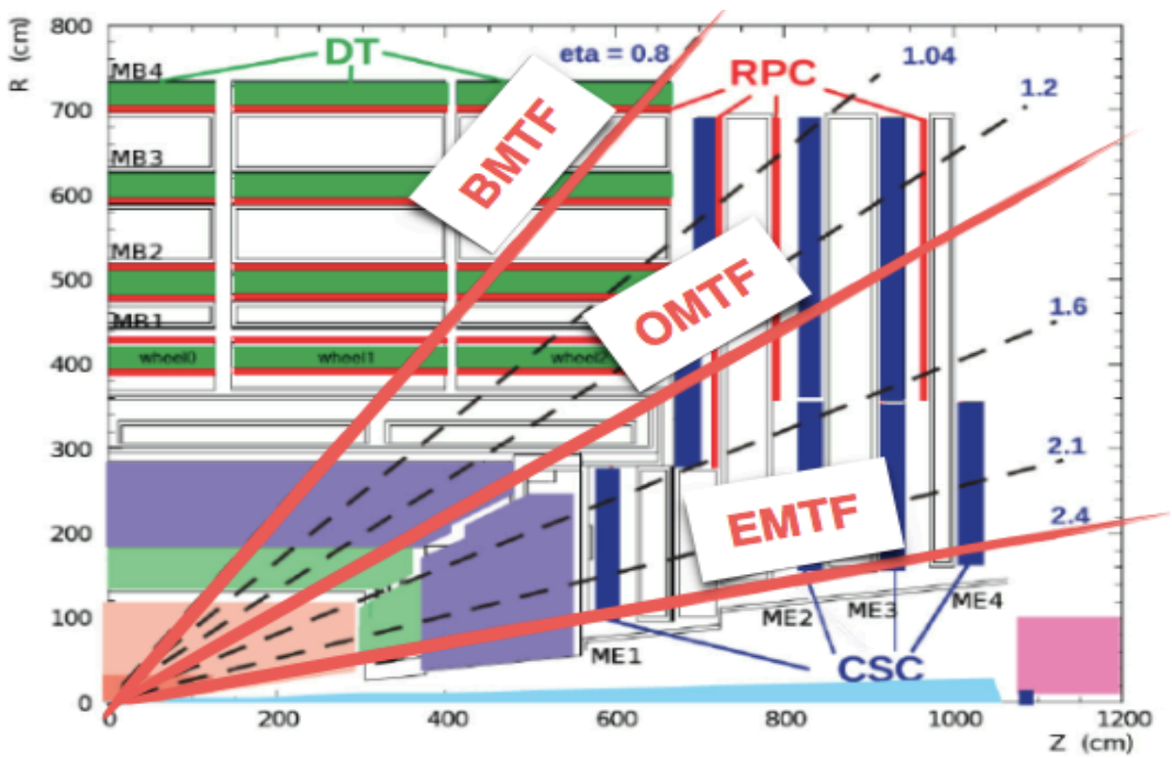


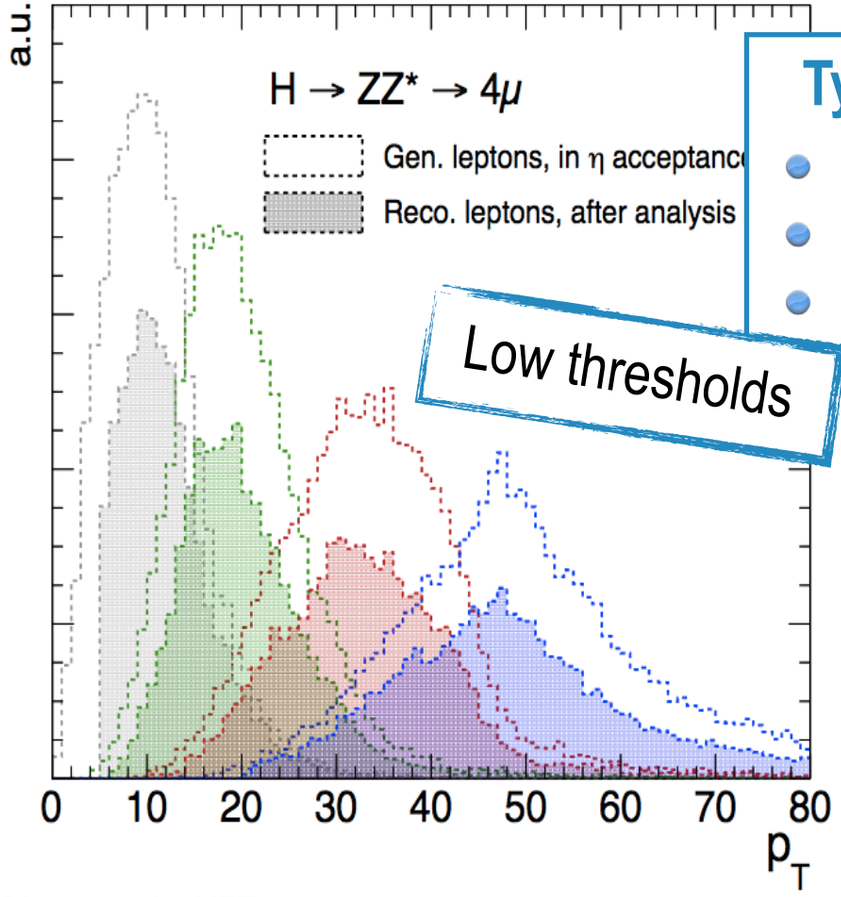
BSM searches

- Additional Higgs scalars, **H→invisible…**
- Relied on energy imbalance triggers.

The CMS Level-1 μ trigger

- From detector- to **geometry-oriented**: simultaneous information from the three overlapping detectors (DT, RPC, CSC).
- Combined **track finders** (BMTF/OMTF/EMTF) assign p_T, position and **quality** criteria to each candidate.



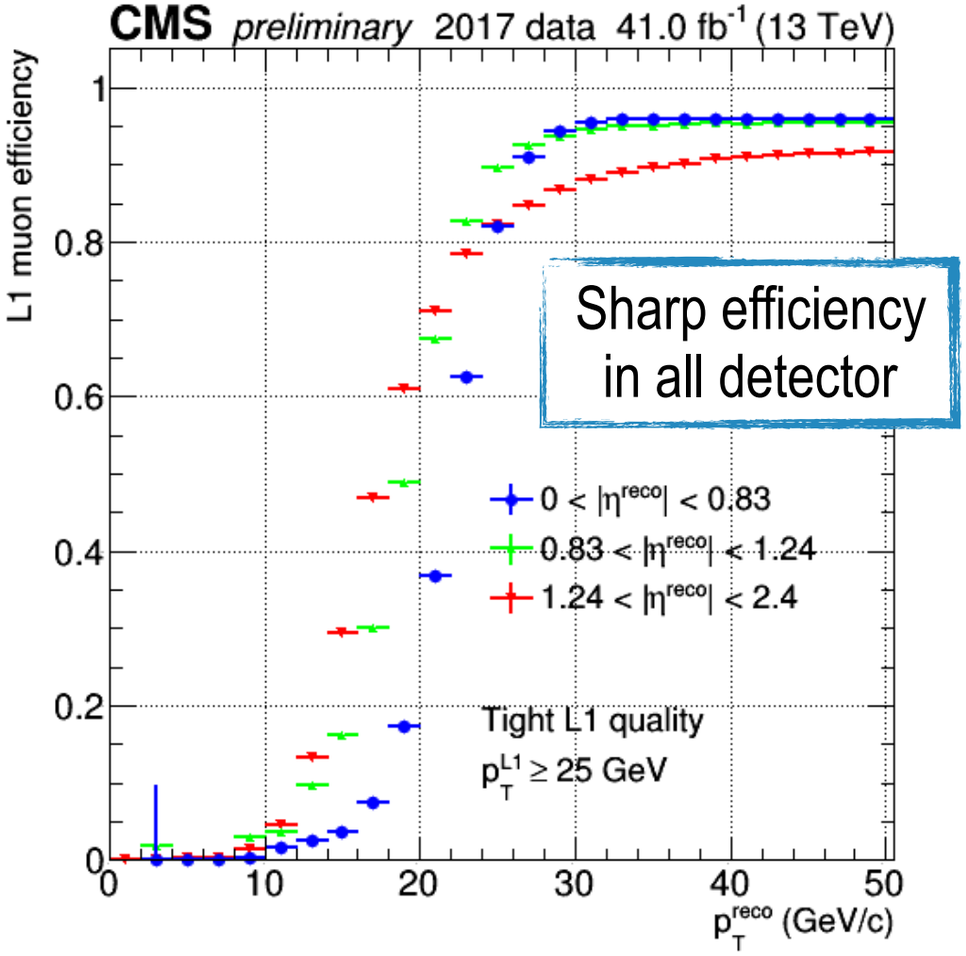


Typical L1 thresholds

- Single-μ > 22 GeV
- Double-μ > 15,7 GeV
- Triple-μ > 5,3,3 GeV

Low thresholds

Great handle for **H→ZZ*→4μ** **precision** measurements



More results HZZ

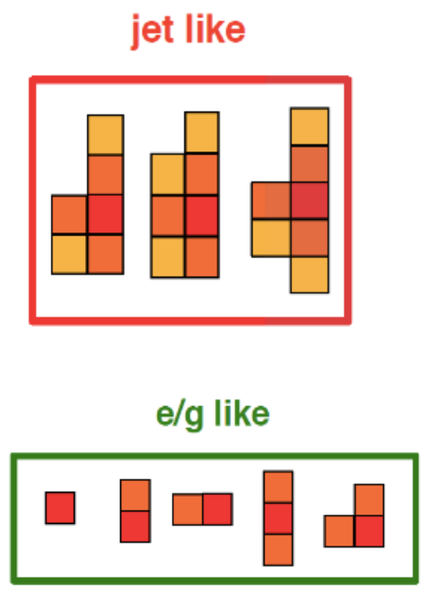
The CMS Level-1 e/γ trigger

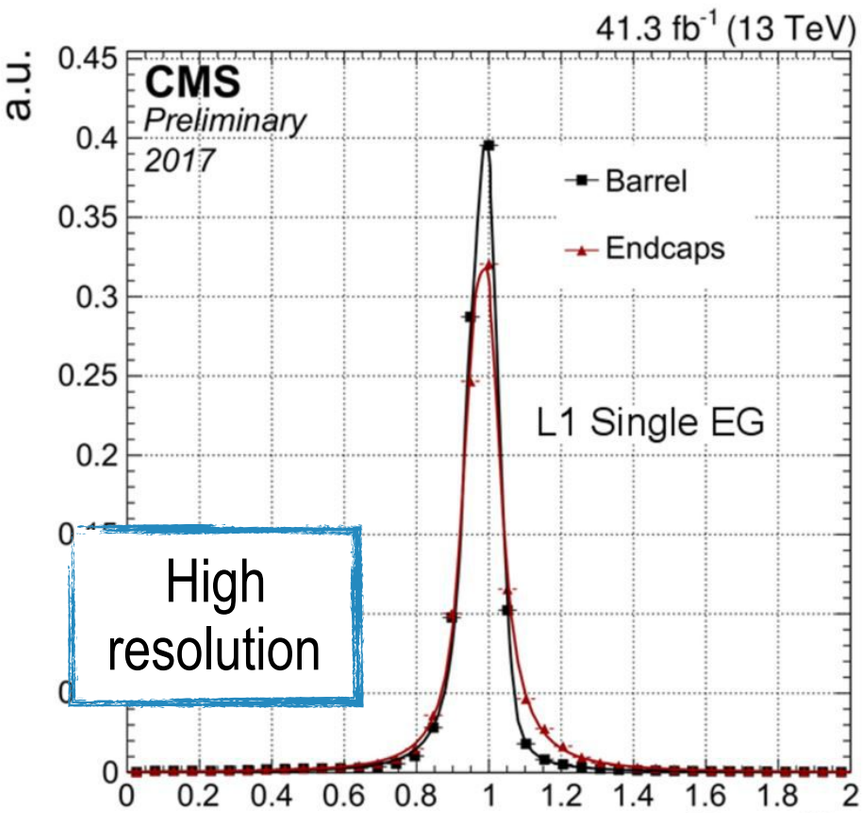
- Identification of **e/γ** candidates through shape and ECAL/HCAL deposits.
- **Pileup estimation** based on energy deposit in center of detector.
- **Isolation** requirements (vs. jets) dependent on pileup and position, relaxed with p_T for maximal efficiency.

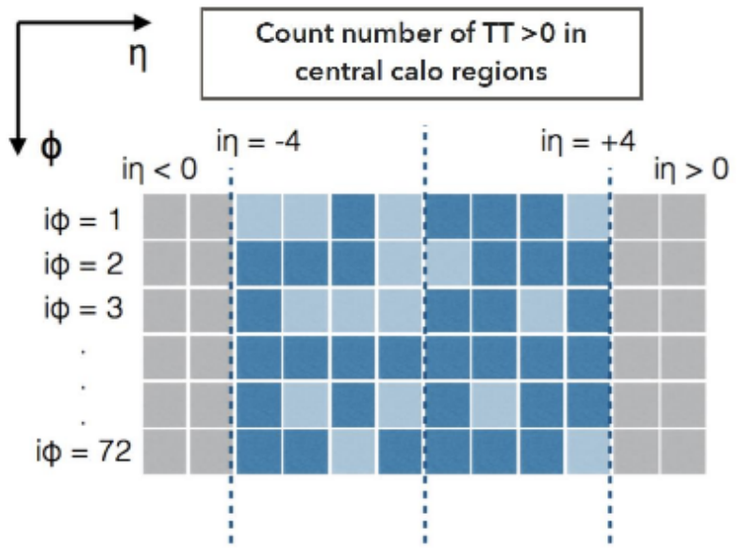
Low thresholds

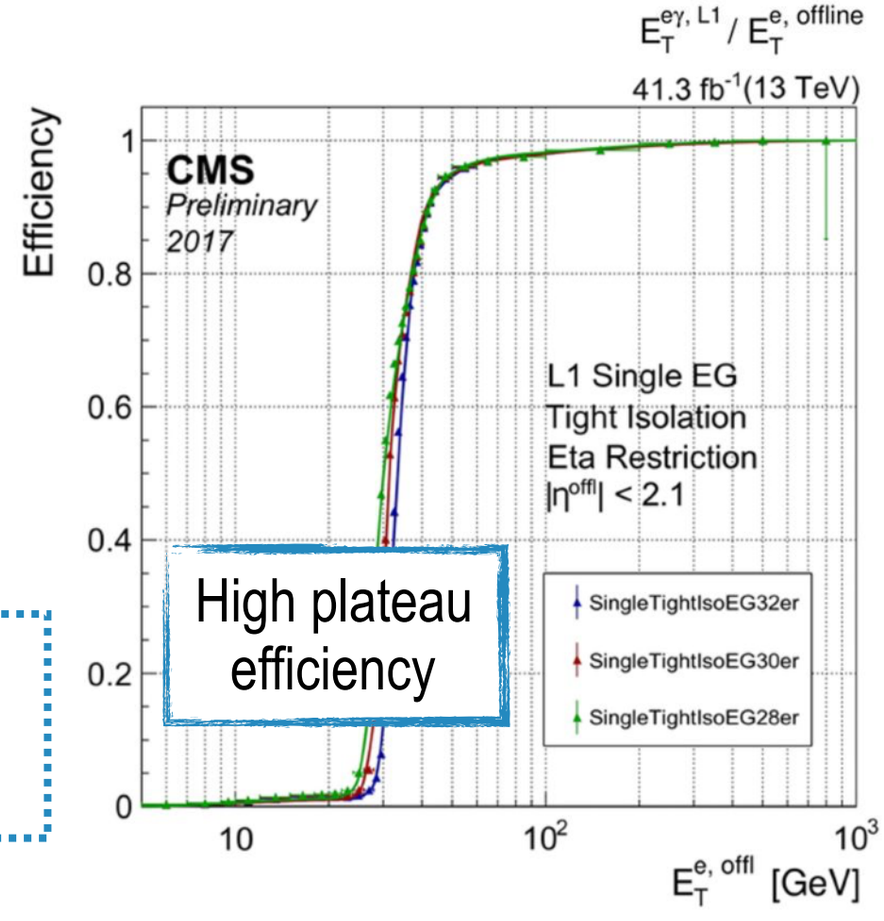
Typical L1 thresholds

- Single-eγ > 30 GeV
- Double-eγ > 25,14 GeV
- Triple-eγ > 18,17,8 GeV







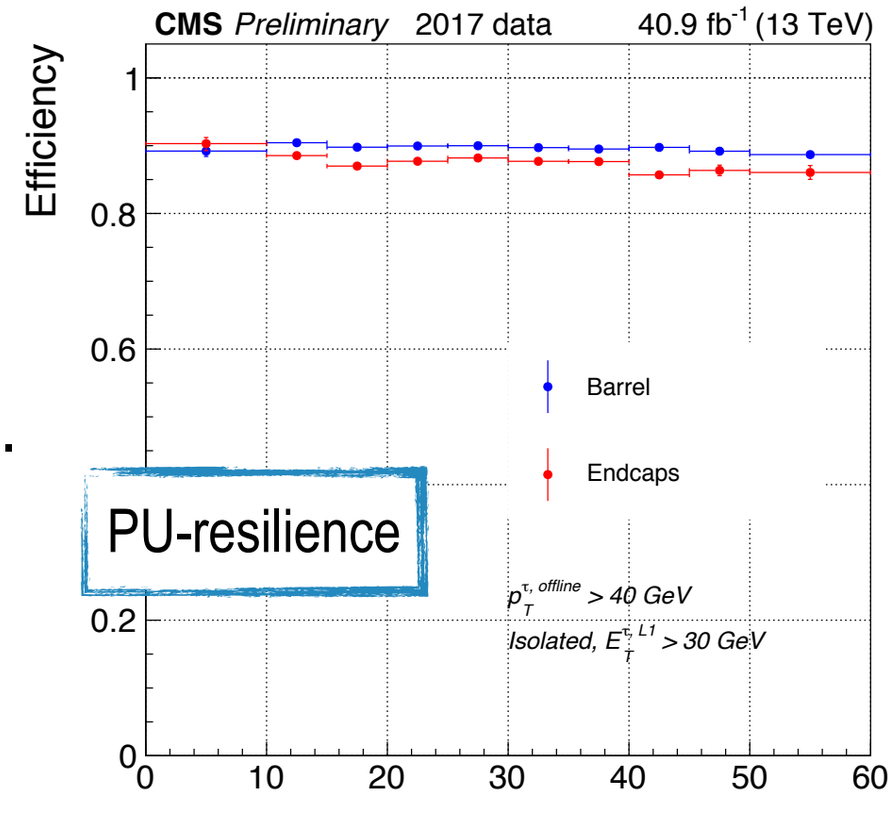


- **Electrons** are used in many analysis (H→ZZ/WW, H→ττ)
- **Photon** selection essential in H→γγ, most sensitive channel

More results: HGG, HWW

The CMS Level-1 τ_h trigger

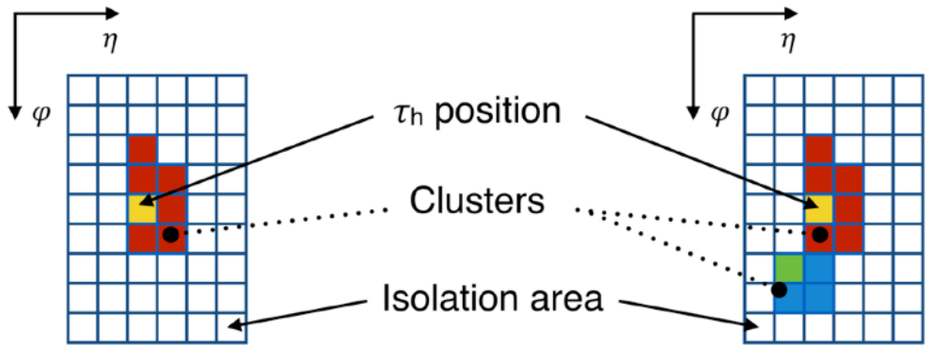
- **Dedicated hadronic τ** algorithm implemented at HW-level for the first time for Run II.
- **Merging** hadronic decay products into single candidate.
- **Pileup estimation** based on energy deposit in center of detector.
- **Isolation** (against **jets**) dependent on position, energy and pileup, and relaxed with p_T for maximal efficiency.



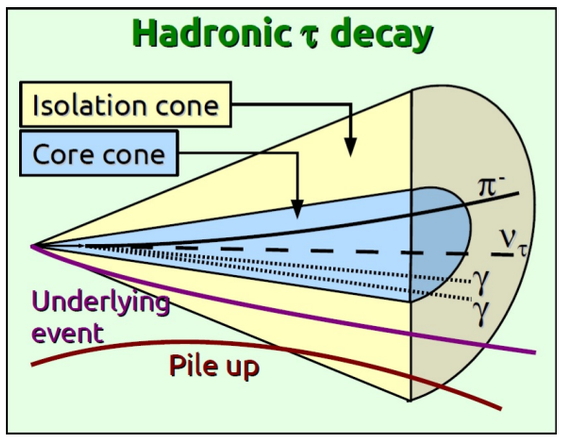
Low thresholds

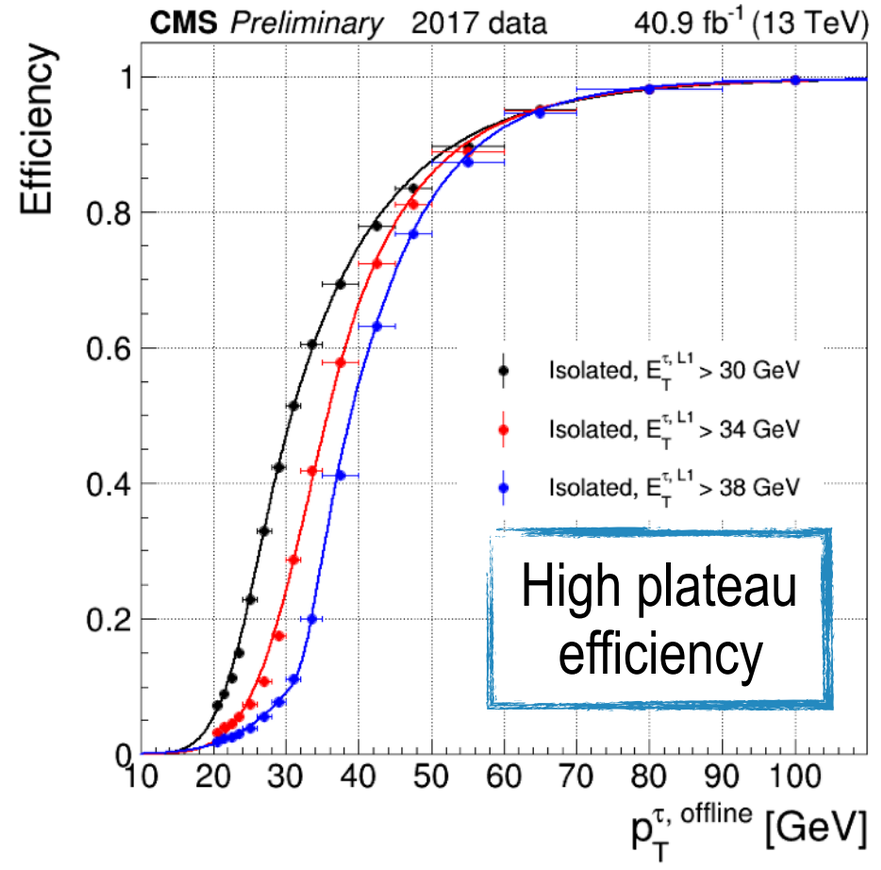
Typical L1 thresholds

- Single-τ > 120 GeV
- Double-τ > 34,34 GeV
- τ-eγ > 22,26 GeV



H→ττ observed in 2017 thanks to a dedicated τ_h algorithm



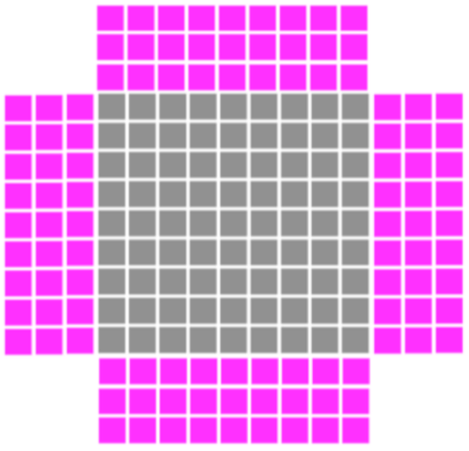


More results: HTT

The CMS Level-1 jet / sums triggers

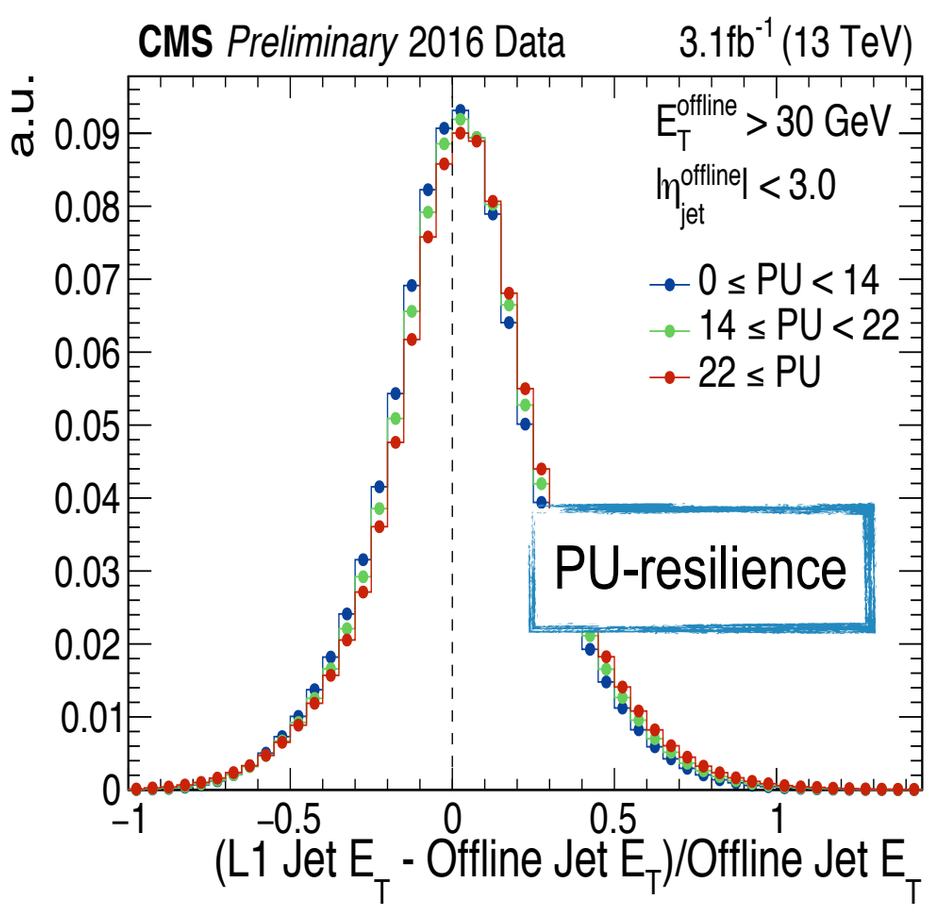
- **Dynamic** clustering and **overlap removal**.
- **Pileup energy** computed based on deposit around jet candidate and subtracted from jet energy.
- Computation of global **energy sums**: scalar transverse jet energy (**HT**) and missing transverse energy (**MET**).

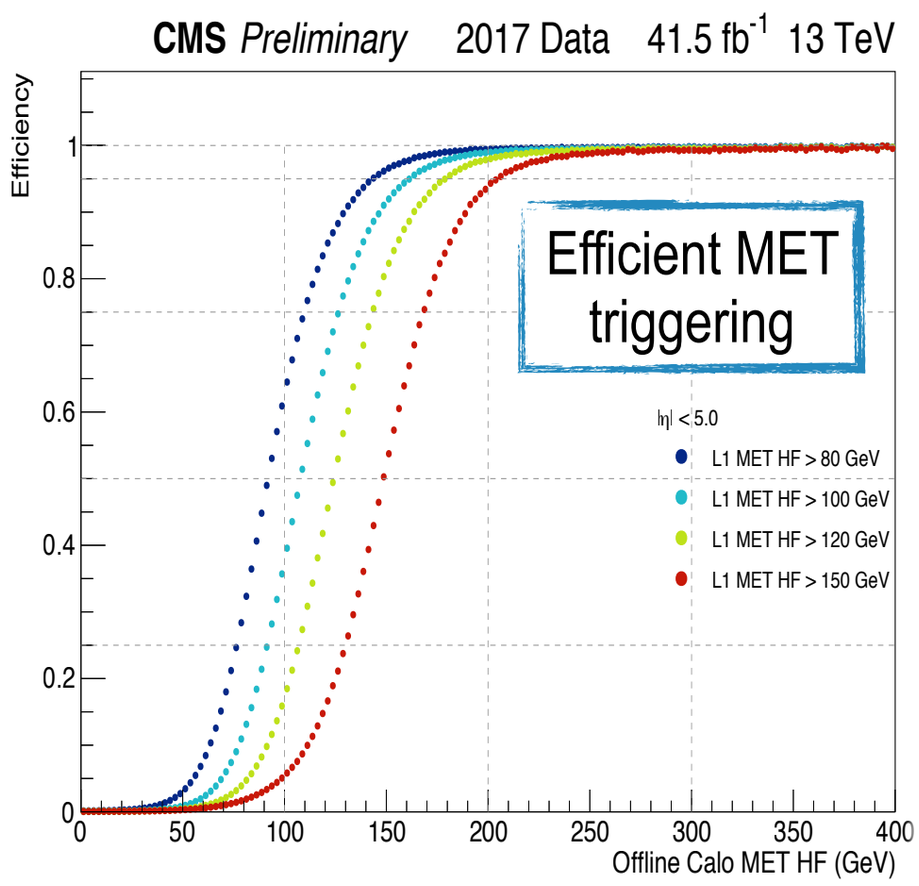
- The L1 jet trigger played a crucial role in the H→bb and ttH (fully hadronic) **observations**.
- The L1 sums trigger is the starting point of H→inv. searches.



Typical L1 thresholds

- MET > 110 GeV
- HT > 300 GeV

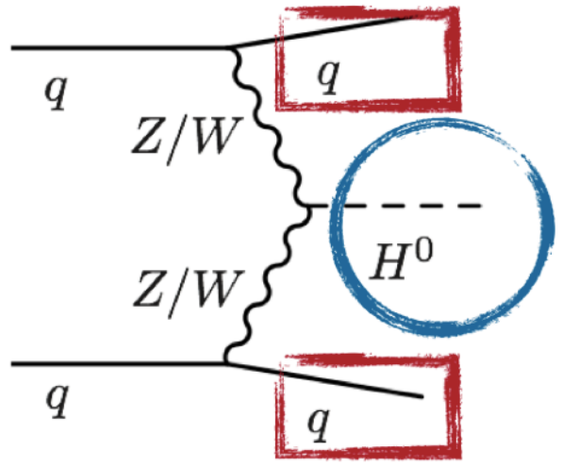




More results: Hbb, ttH, Hinv

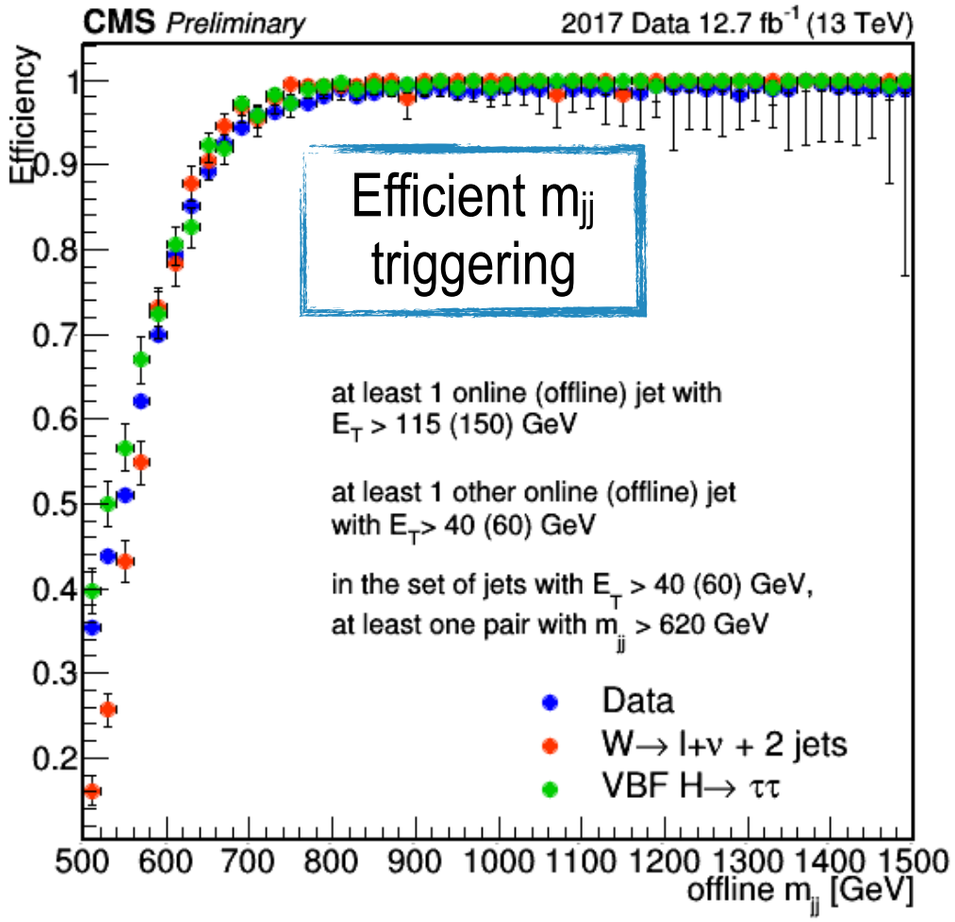
The CMS Level-1 VBF trigger

- Introduced after the trigger upgrade, it is the first trigger targeting a Higgs **production mode,** not a decay mode.
- **Characteristic** signature:
  - **VBF jets** with high invariant mass and angular separation
  - **Higgs boson** decay products in central part of the detector



- at least one jet with **E_T > 115 GeV**
- at least two jets with **E_T > 40 GeV** and **m_{jj} > 620 GeV**

- Complement to classic triggers: expansion of the **phase space** and improvement of **sensitivity**.



- VBF contributes as **~10%** to the Higgs production and is the most **sensitive** channel in H→ττ analysis.
- The VBF trigger provided in 2017 **~40% additional VBF** H→ττ events with respect to the Double-τ trigger alone.

More results: VBF

Conclusions

- The CMS trigger menu is the **starting point of many physics analysis** and it **evolves** with the collaboration interests and accelerator parameters.

- The CMS L1 trigger was **upgraded** for the challenging conditions of Run II:
  - More **sophisticated object** algorithms (isolation, PU resilence)
  - Complex **correlations** among objects (invariant masses)
  - **Analysis-targeted** algorithms (VBF)

- The Run II L1 trigger upgrade showed **extremely good performance**, being able to maintain the nominal thresholds and excellent efficiencies in spite of the LHC high pileup and instantaneous luminosities.

- This enabled an exhaustive and complete coverage of CMS **Higgs physics program** during Run II, where the trigger played a key role in the **H→ττ**, **H→bb** and **ttH** observations.

Thank you for your attention

Further reading:

- Trigger upgrade TDR
- Run-I trigger
- Level-1 trigger performance

Back-up

The CMS Level-1 trigger

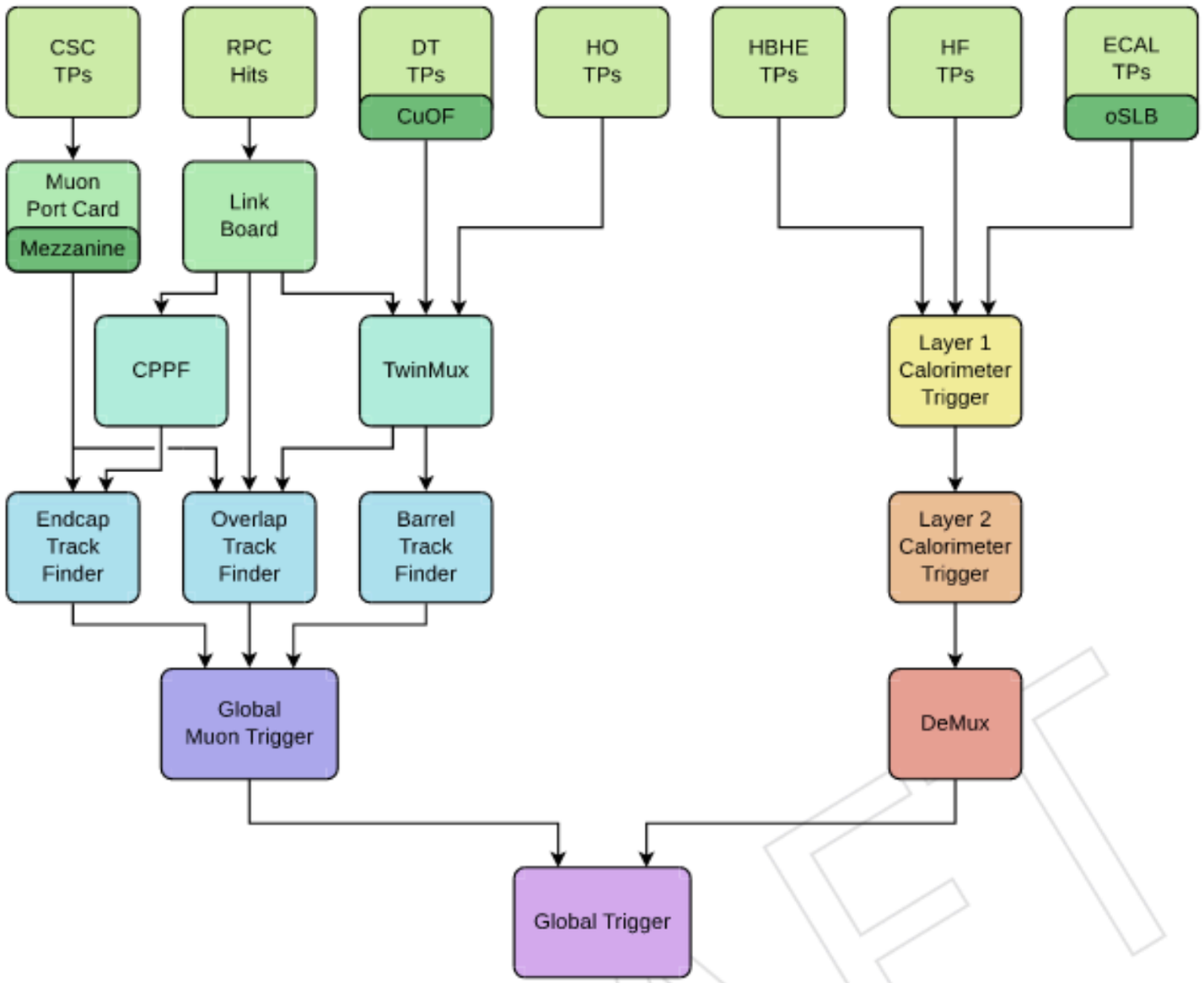
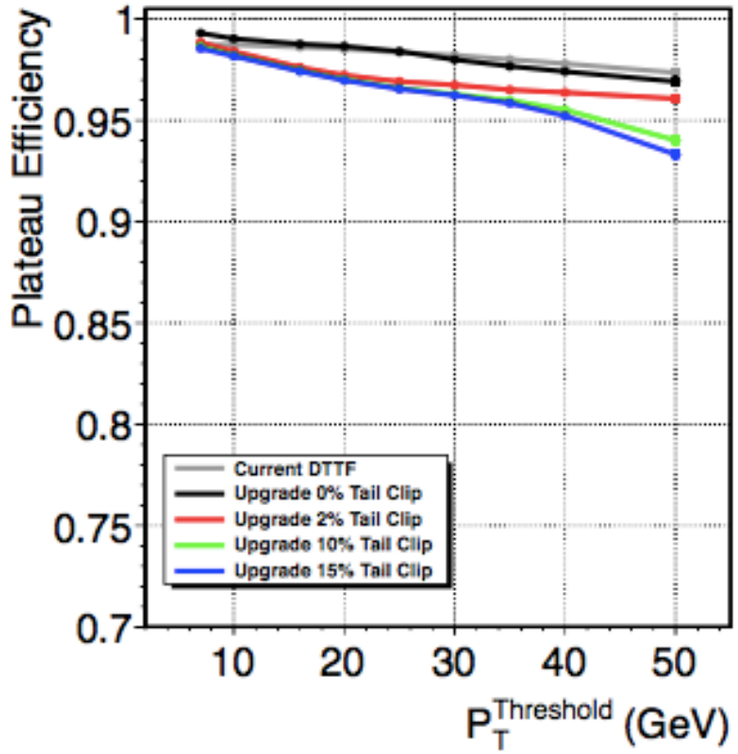
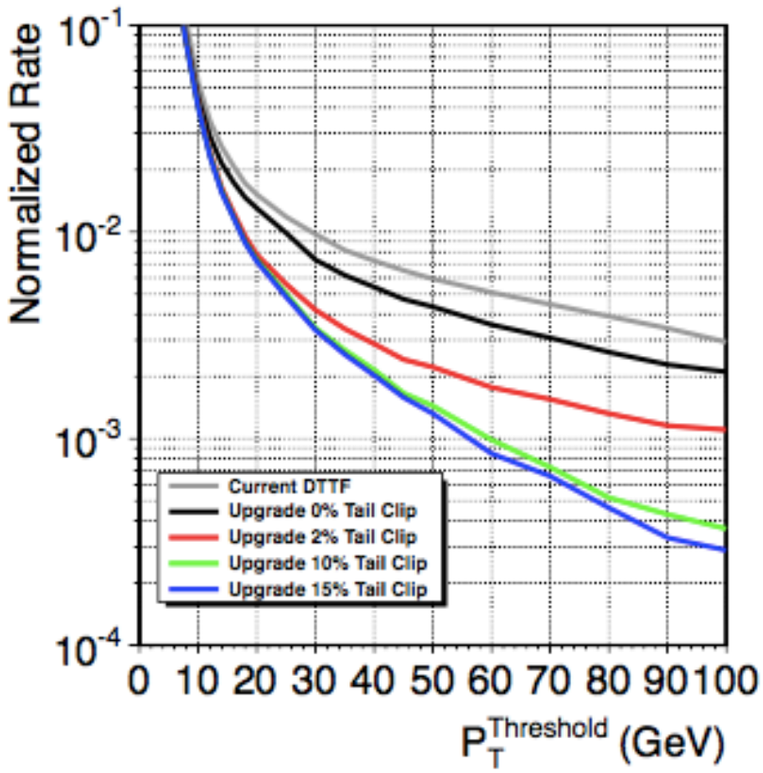
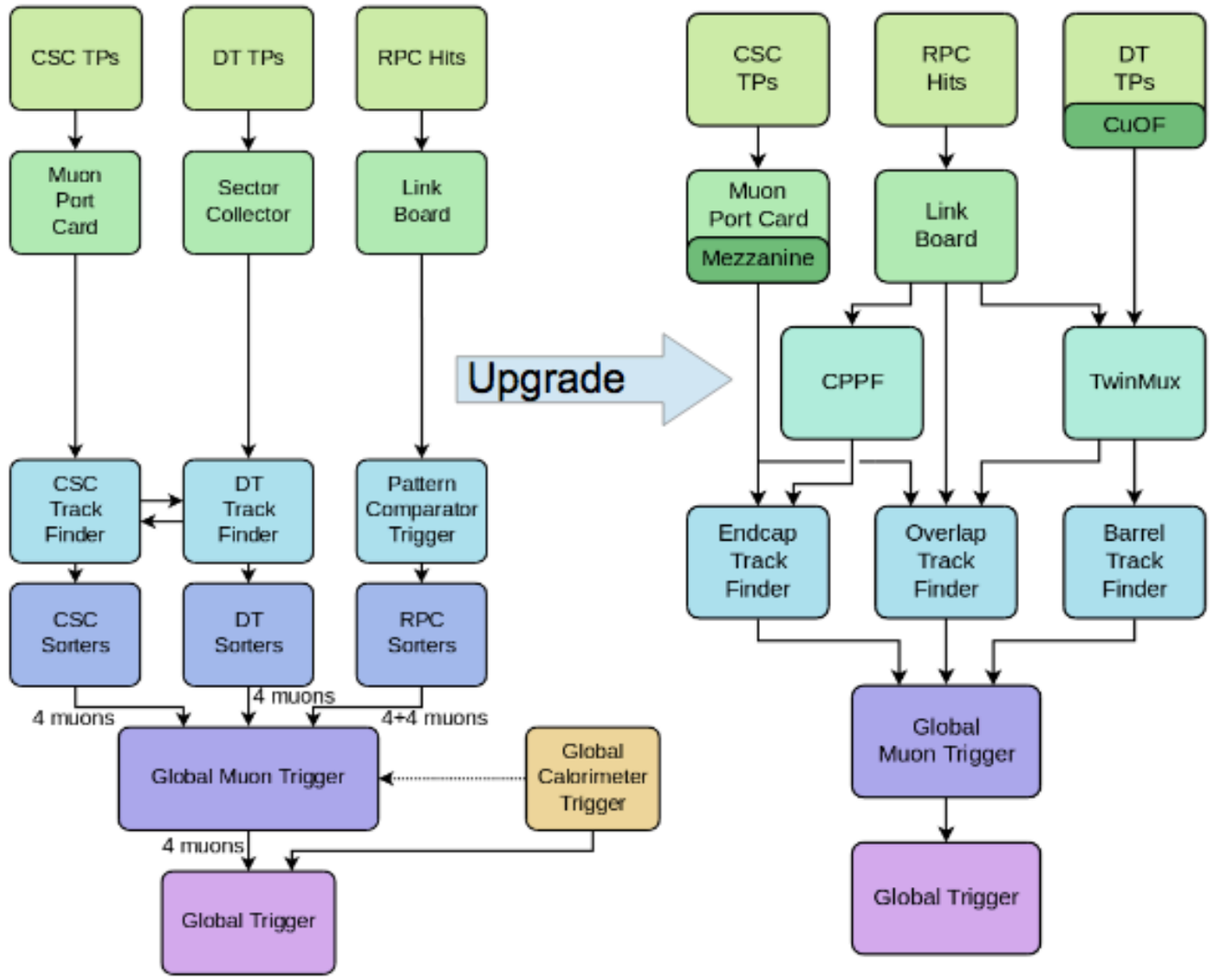


Figure 2: Diagram of the Level-1 trigger systems during Run-2.

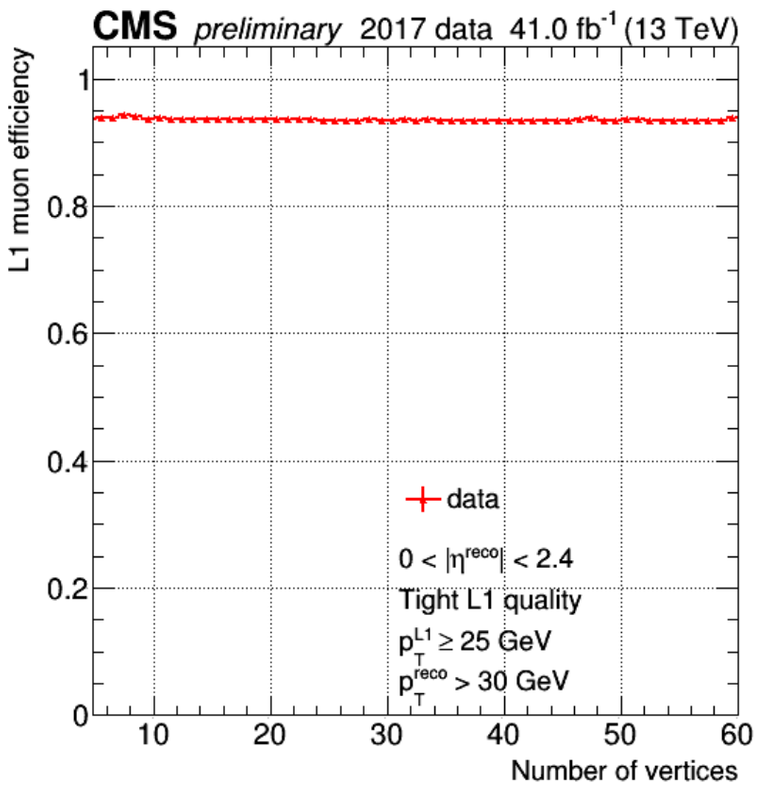
The CMS Level-1 μ trigger

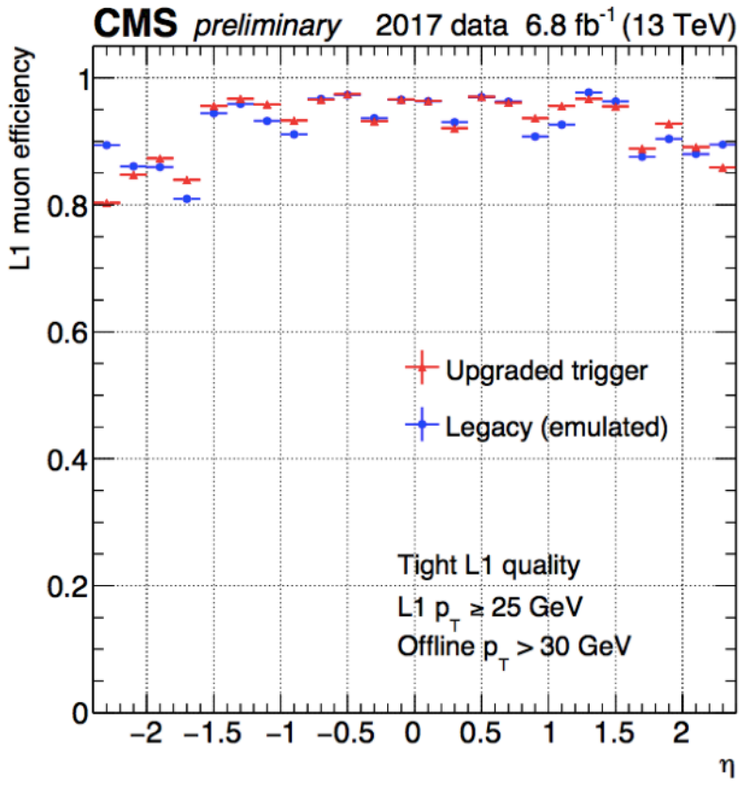


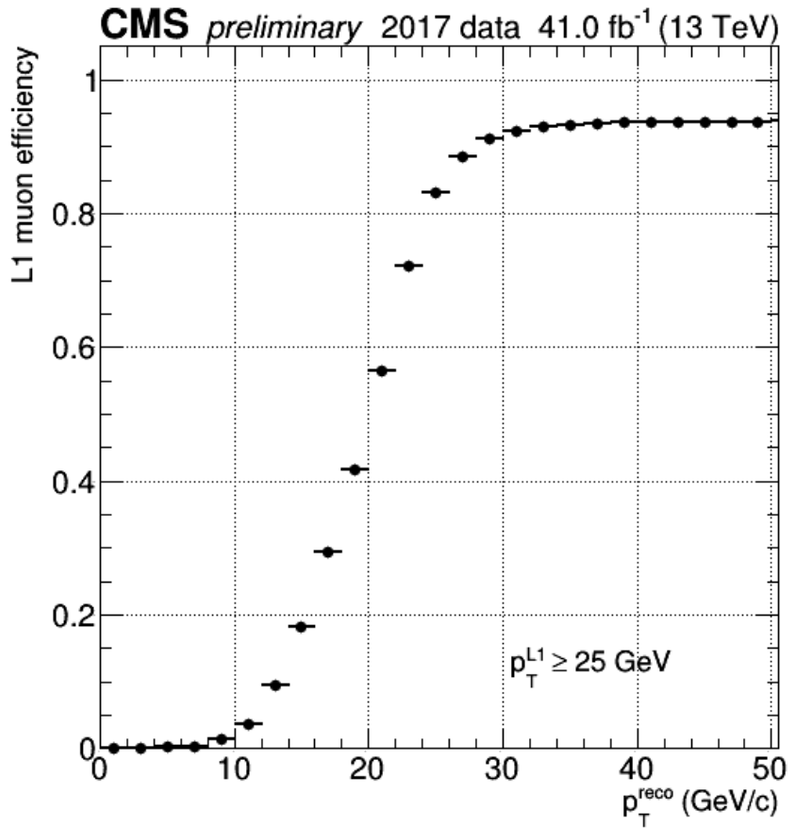


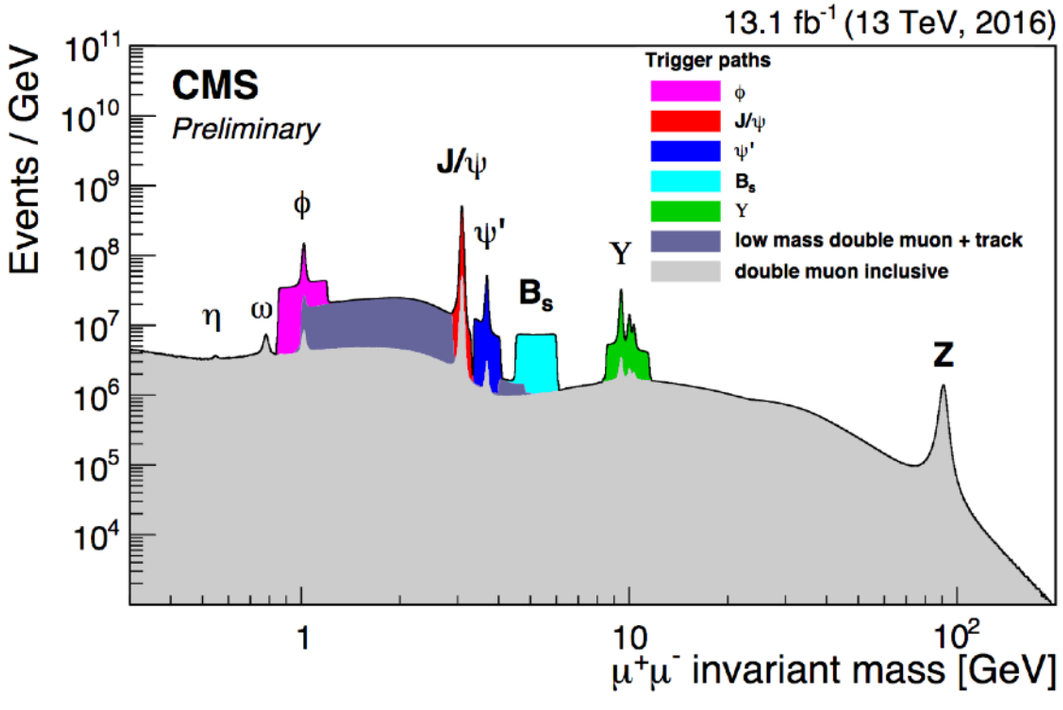


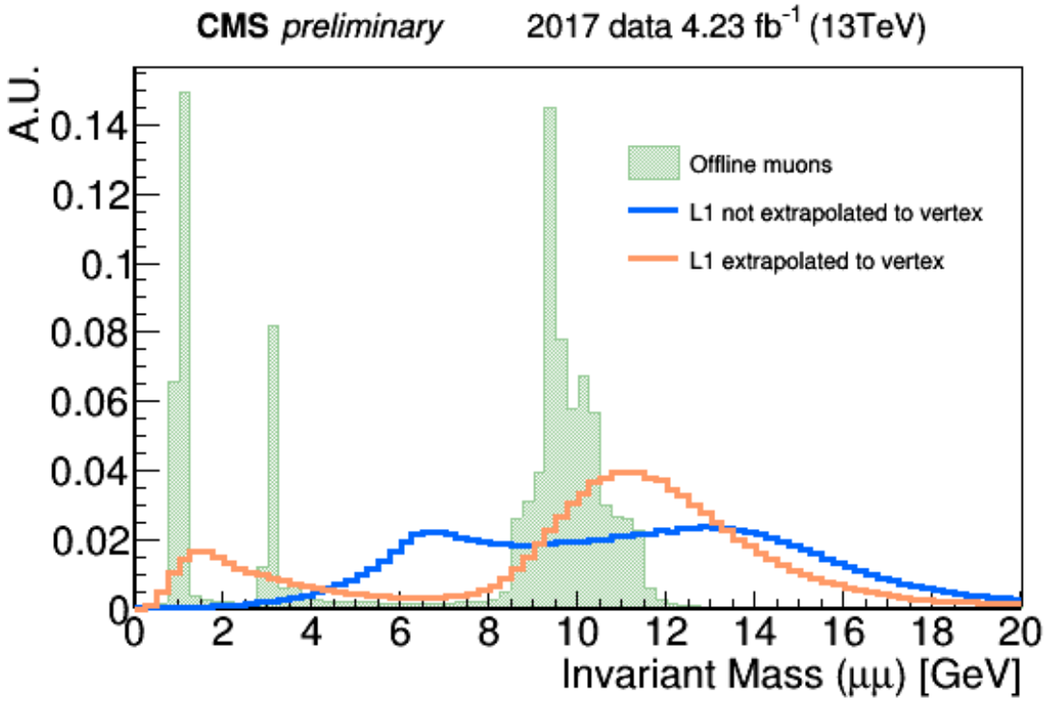
The CMS Level-1 μ trigger



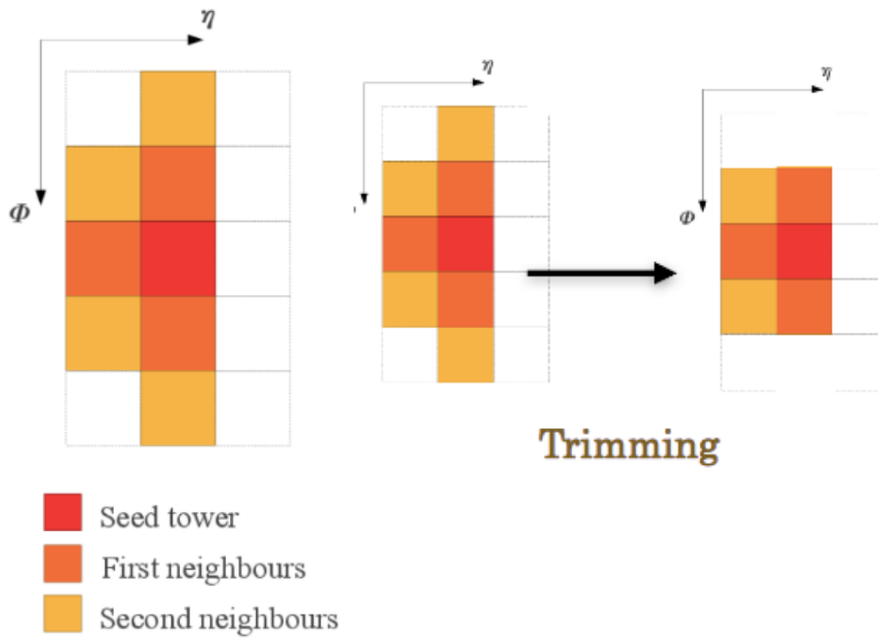




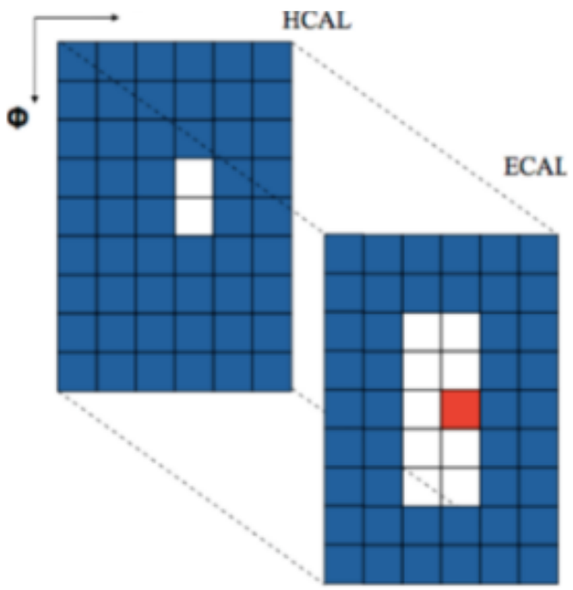


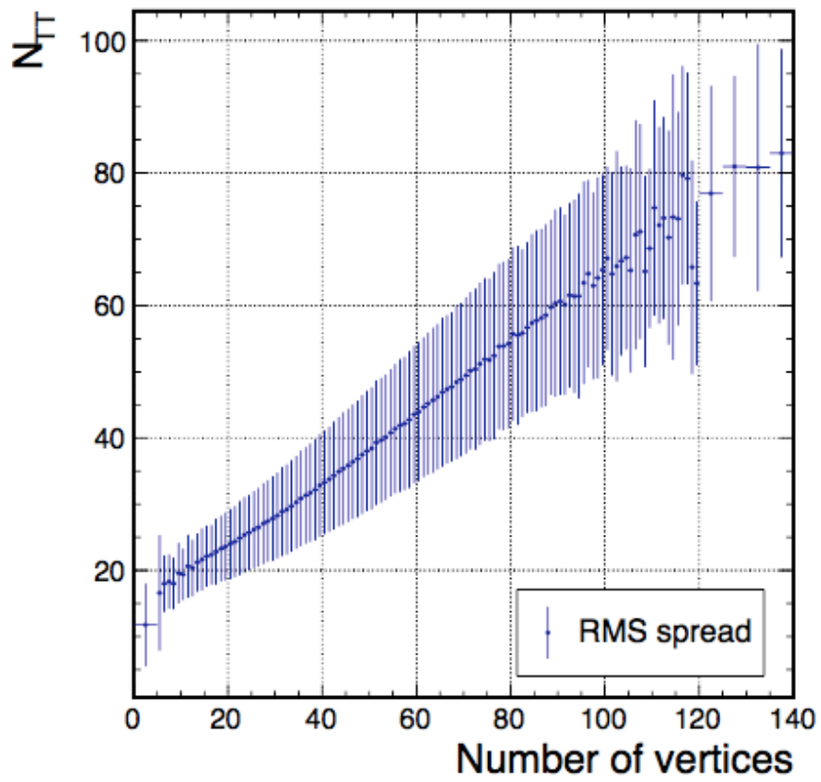


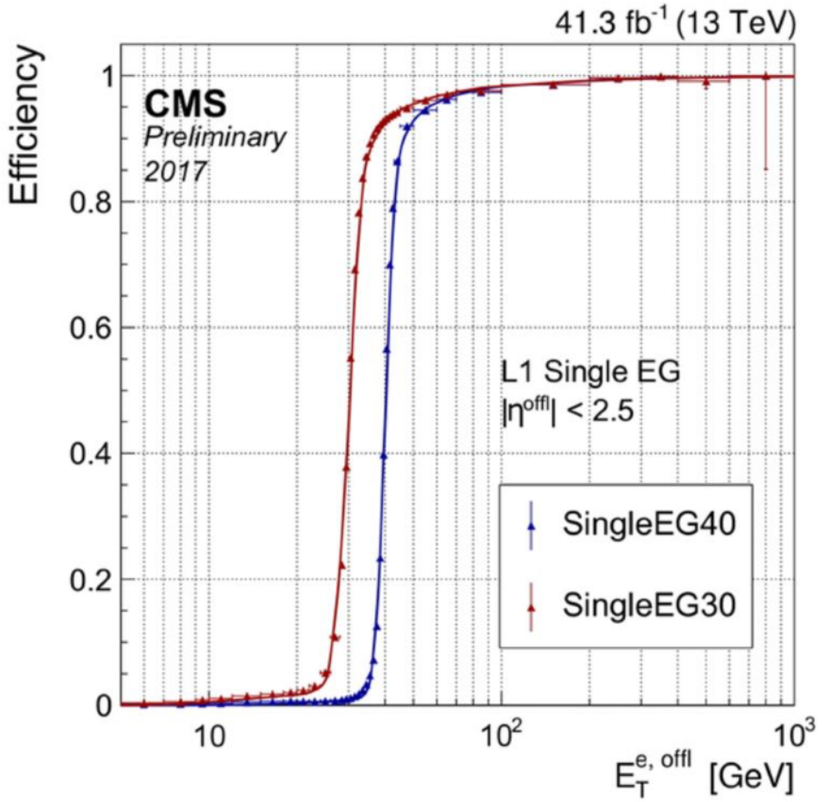
The CMS Level-1 e/γ trigger

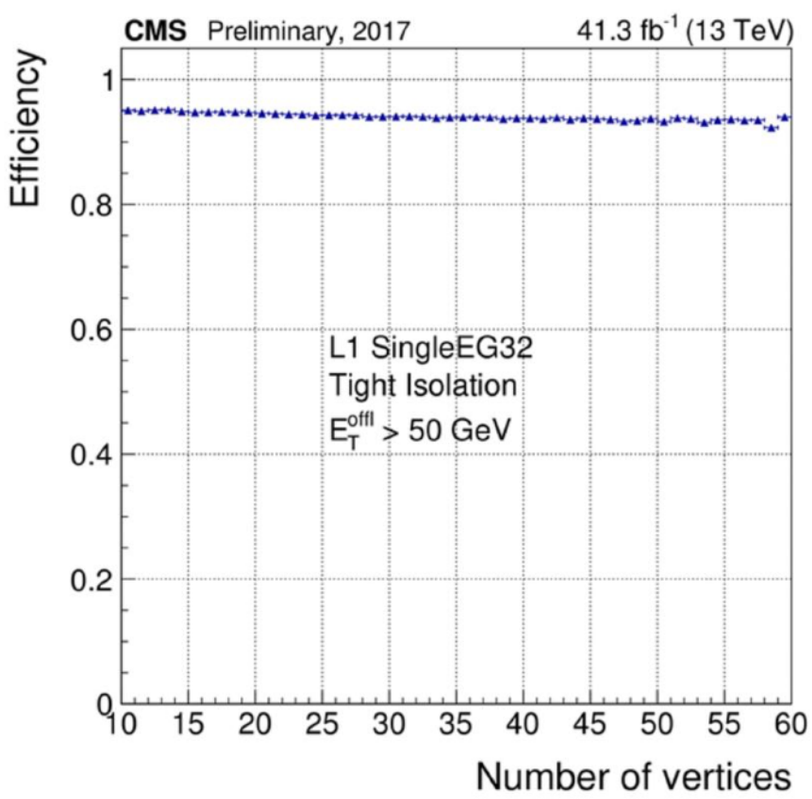


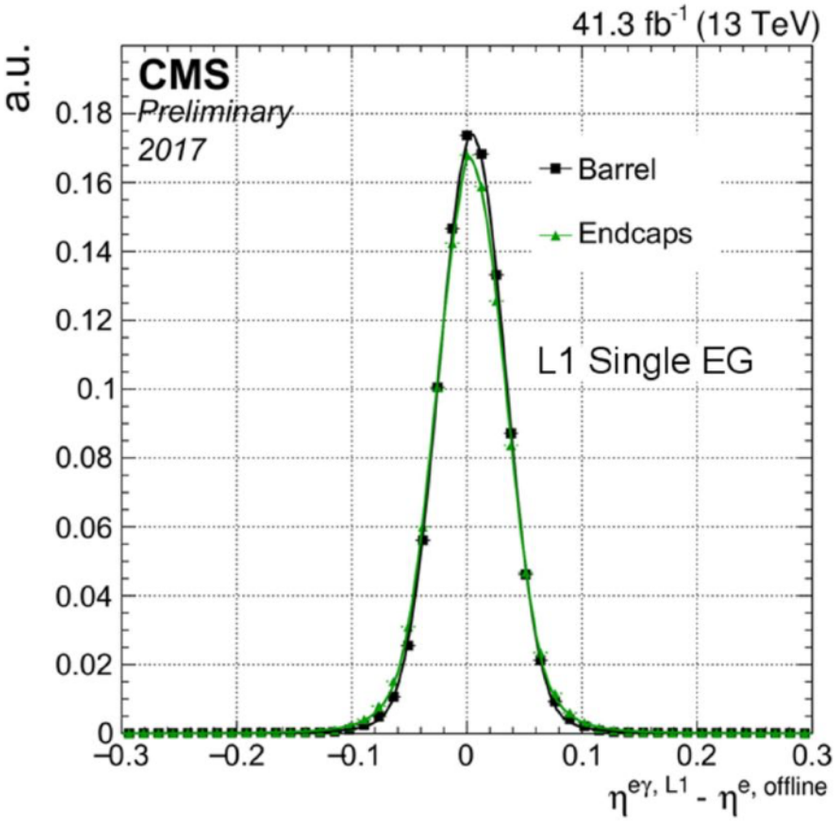
$E+H_{6x9}-E_{2x5}-H_{1x2}<\text{isolation cut}$



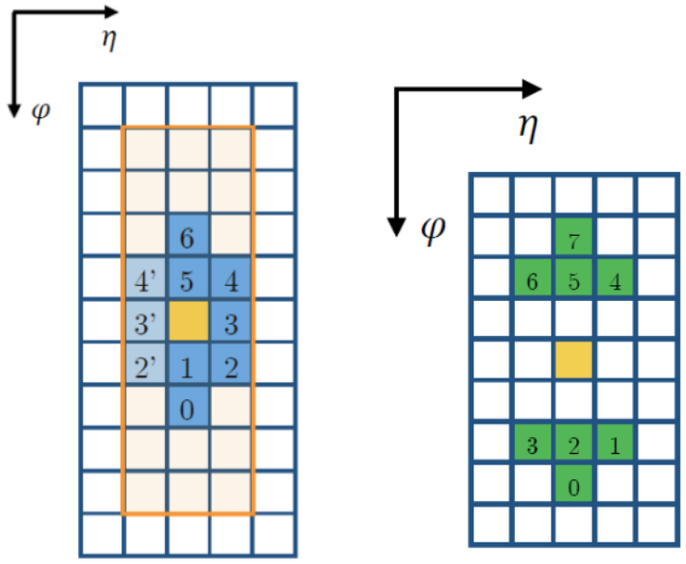




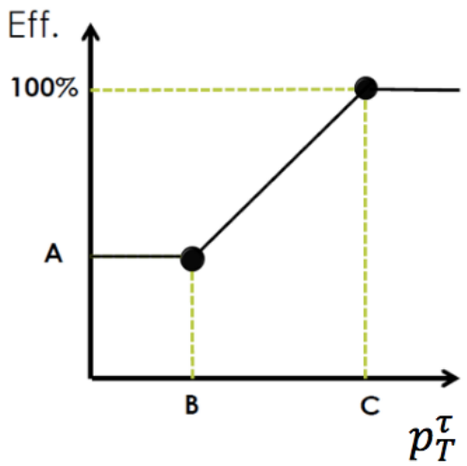




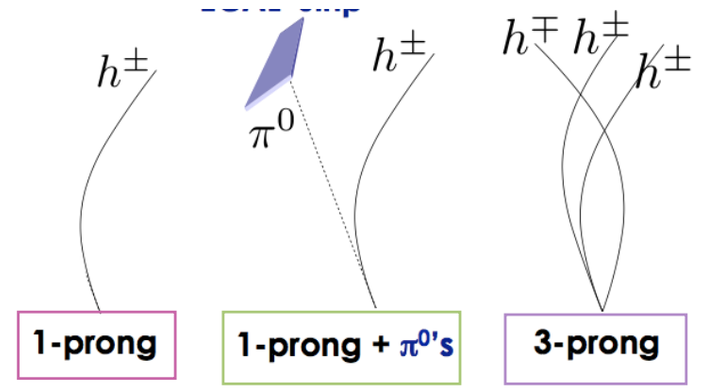
The CMS Level-1 τ_h trigger

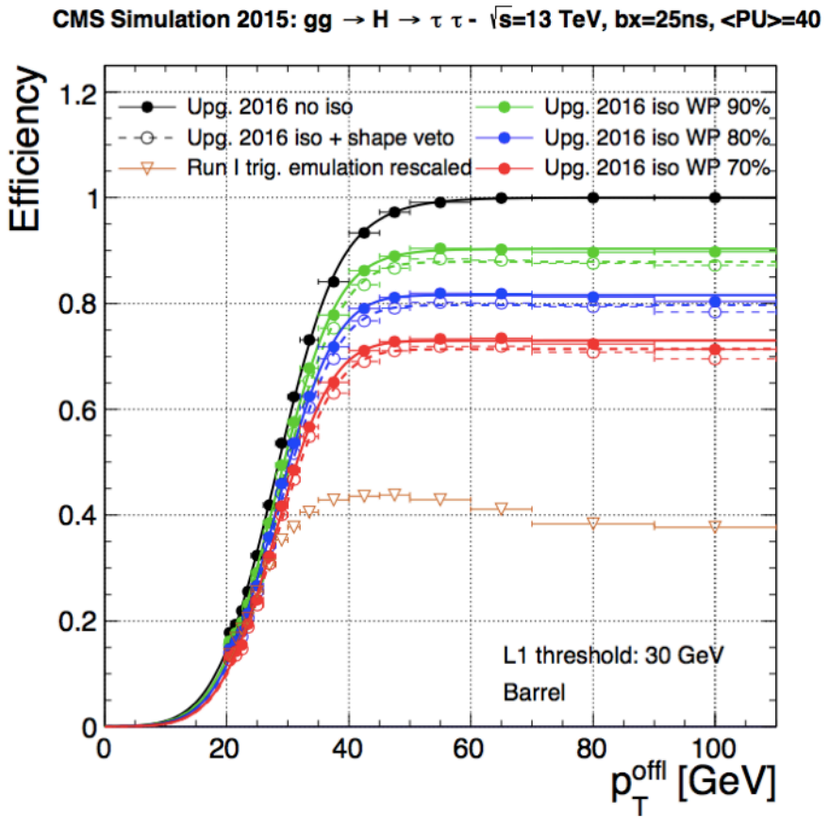


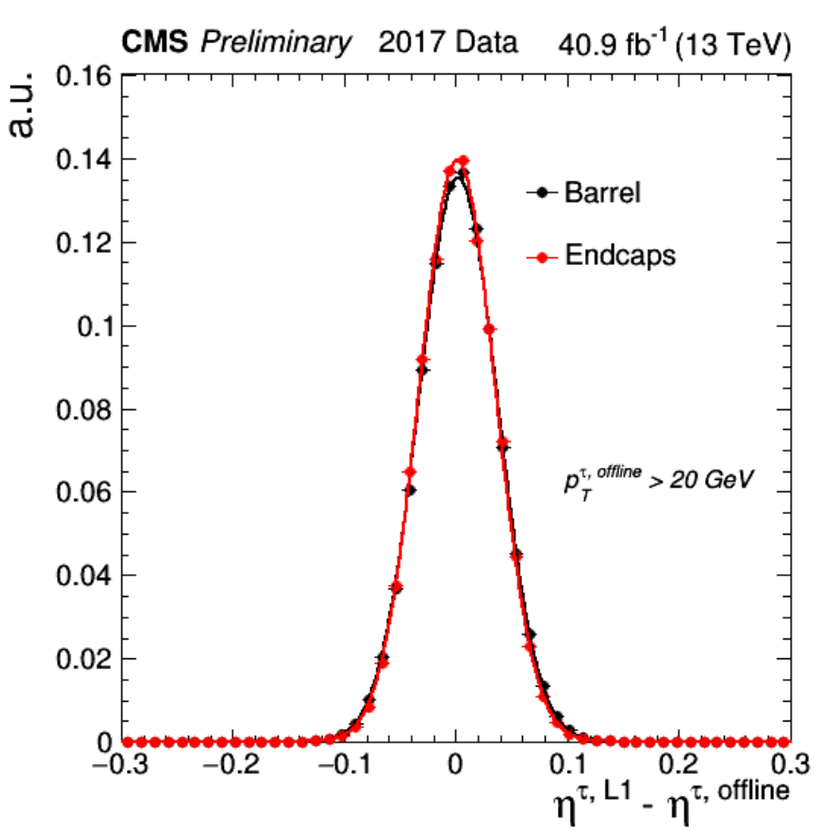
$$E^{\tau}_{T,iso} = E^{6x9}_{T} - E^{\tau}_{T,raw}$$

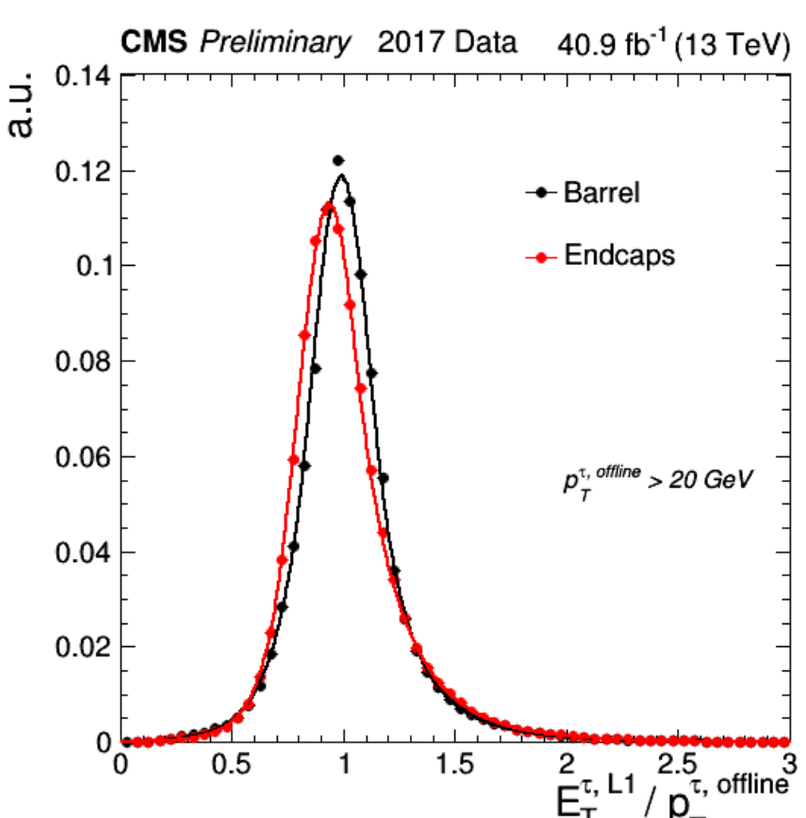


Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8



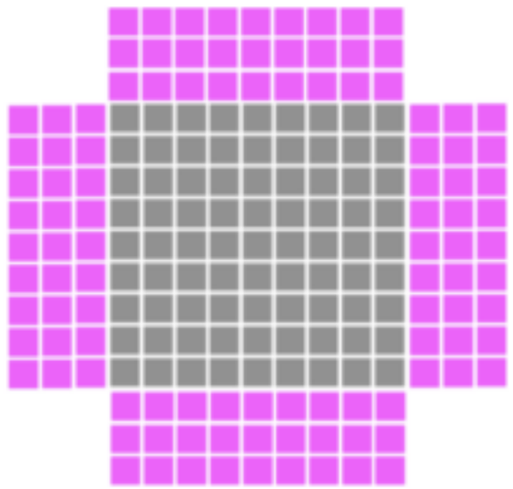




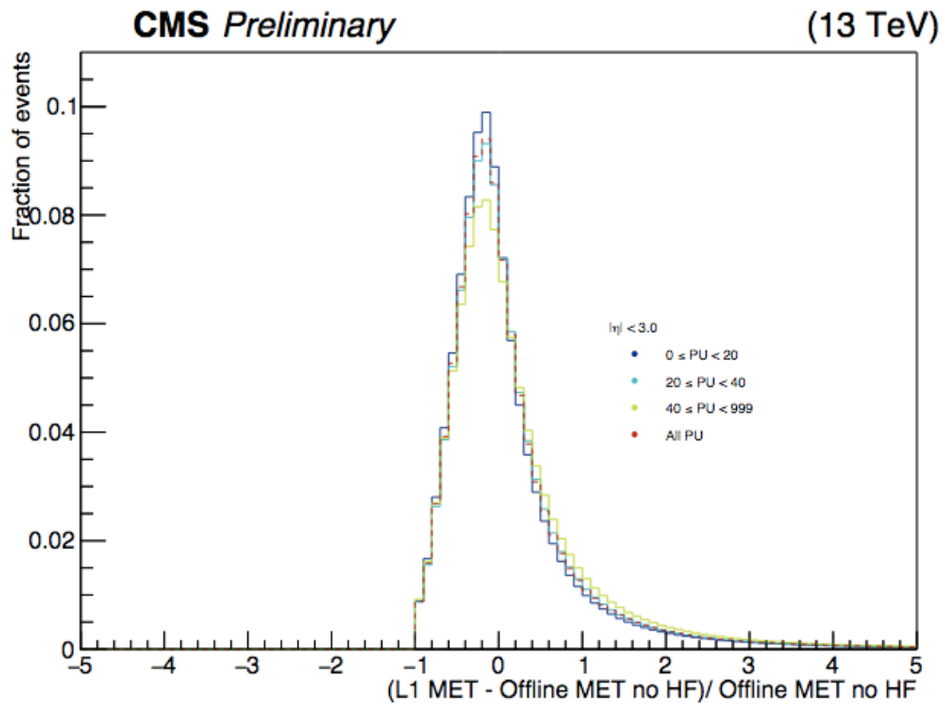


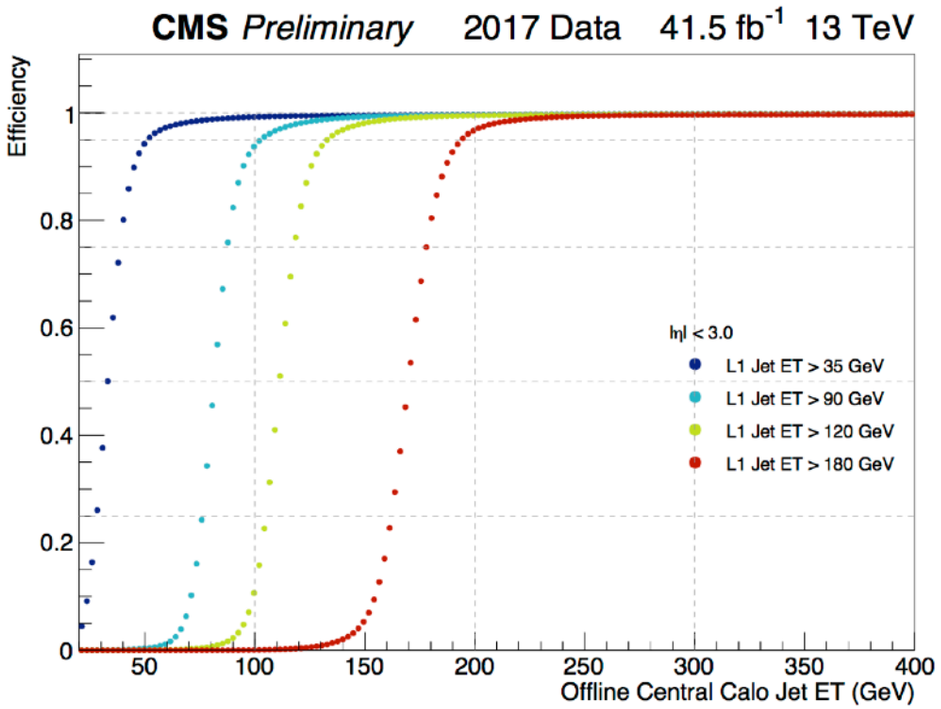
The CMS Level-1 jets and sums trigger

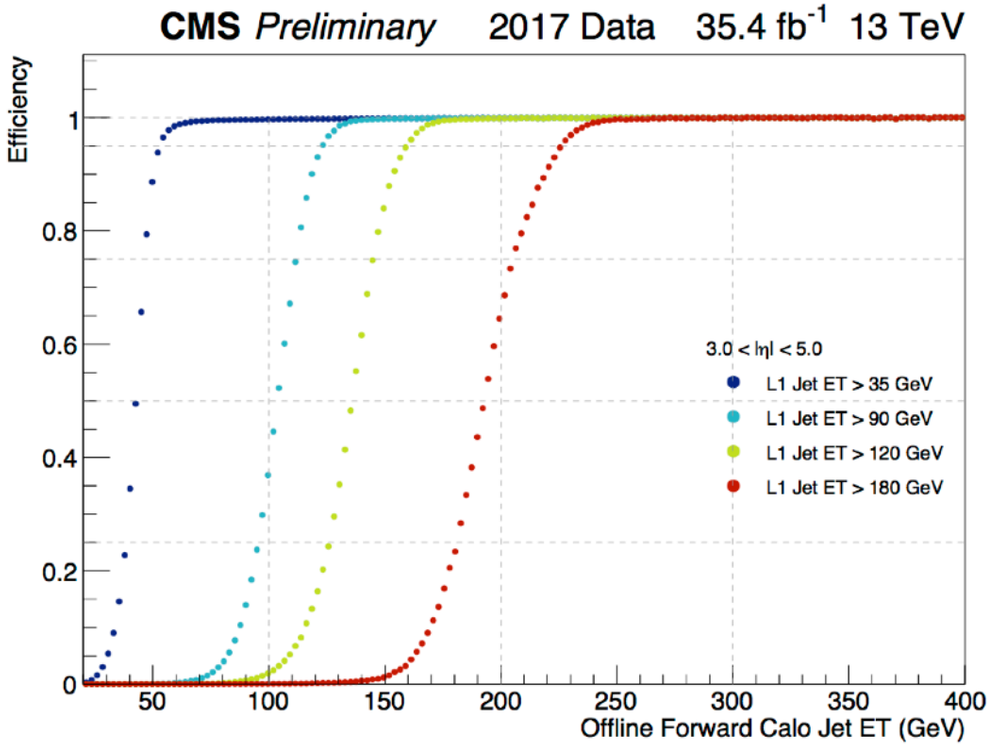
(a)



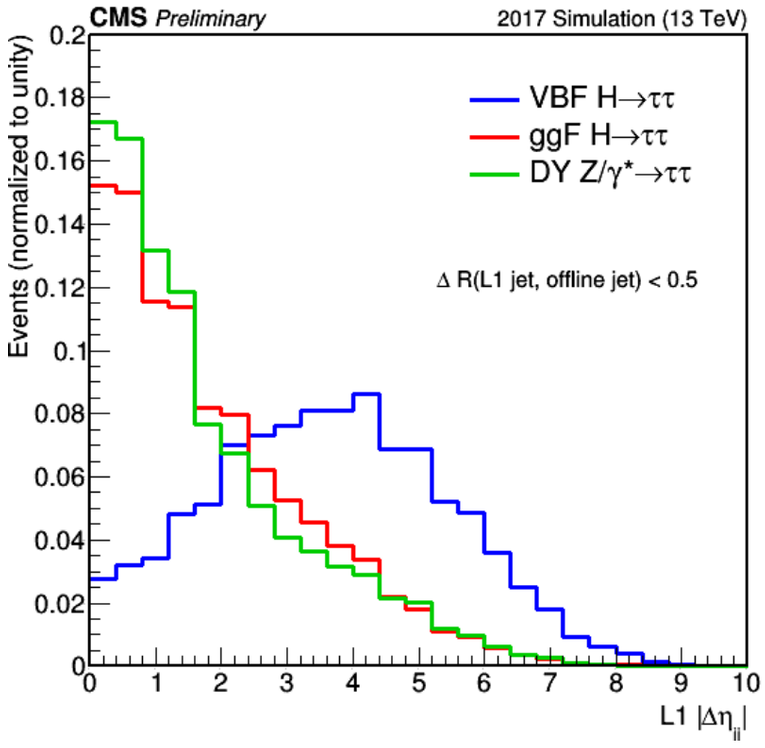
(b)

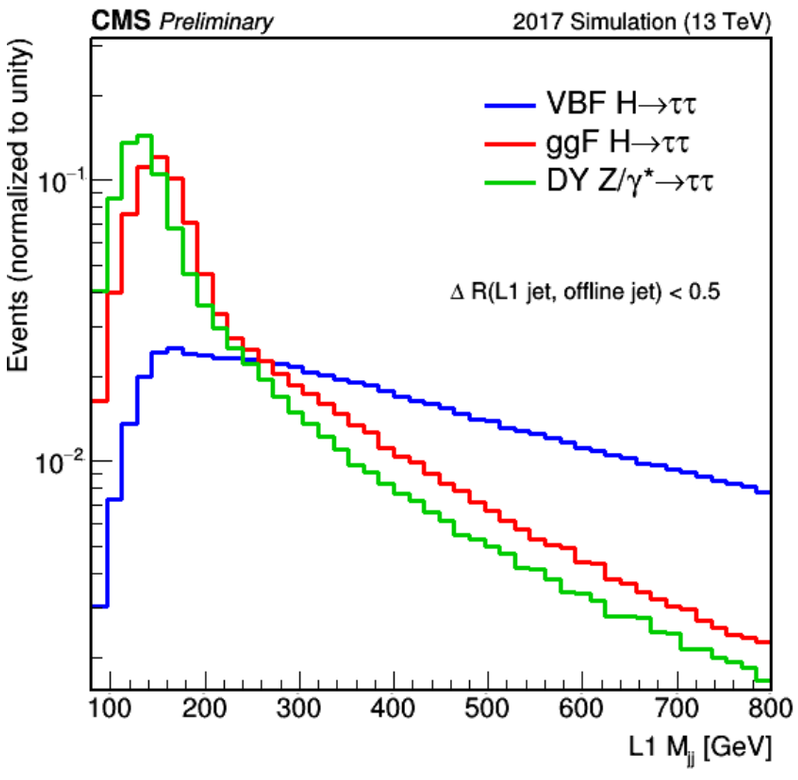


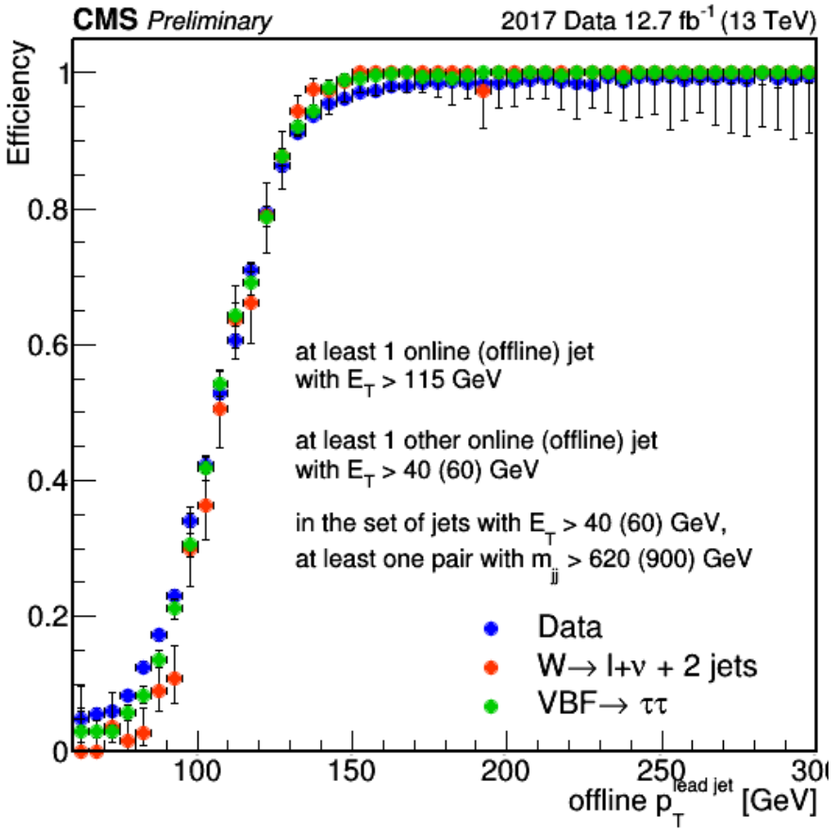


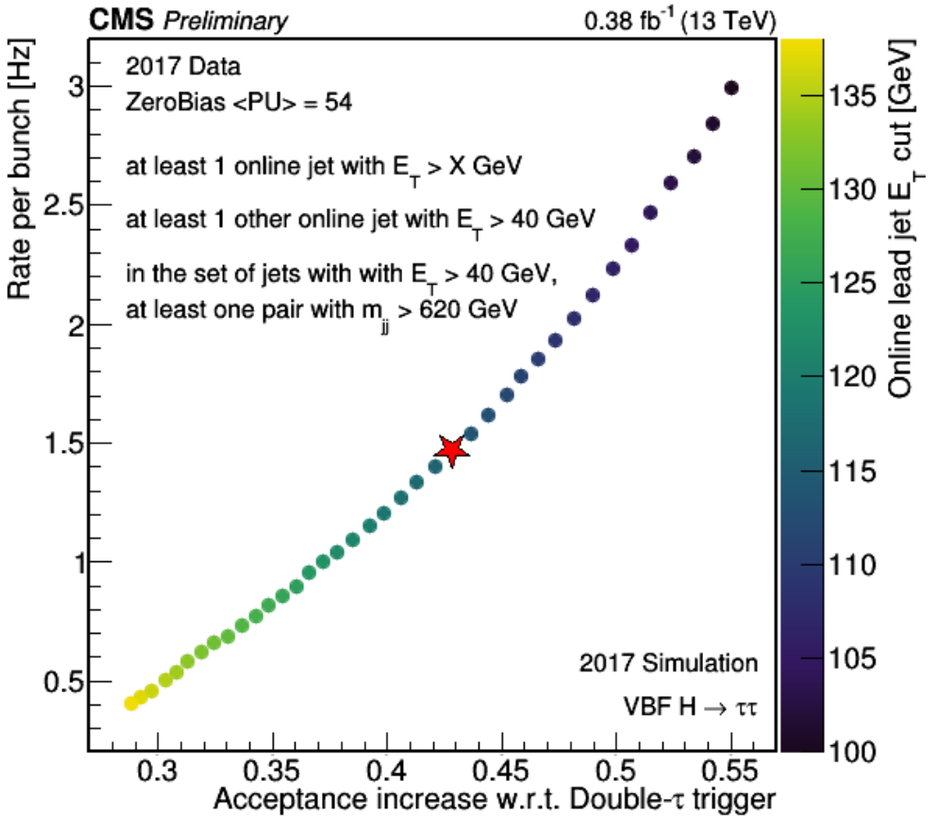


The CMS Level-1 VBF trigger

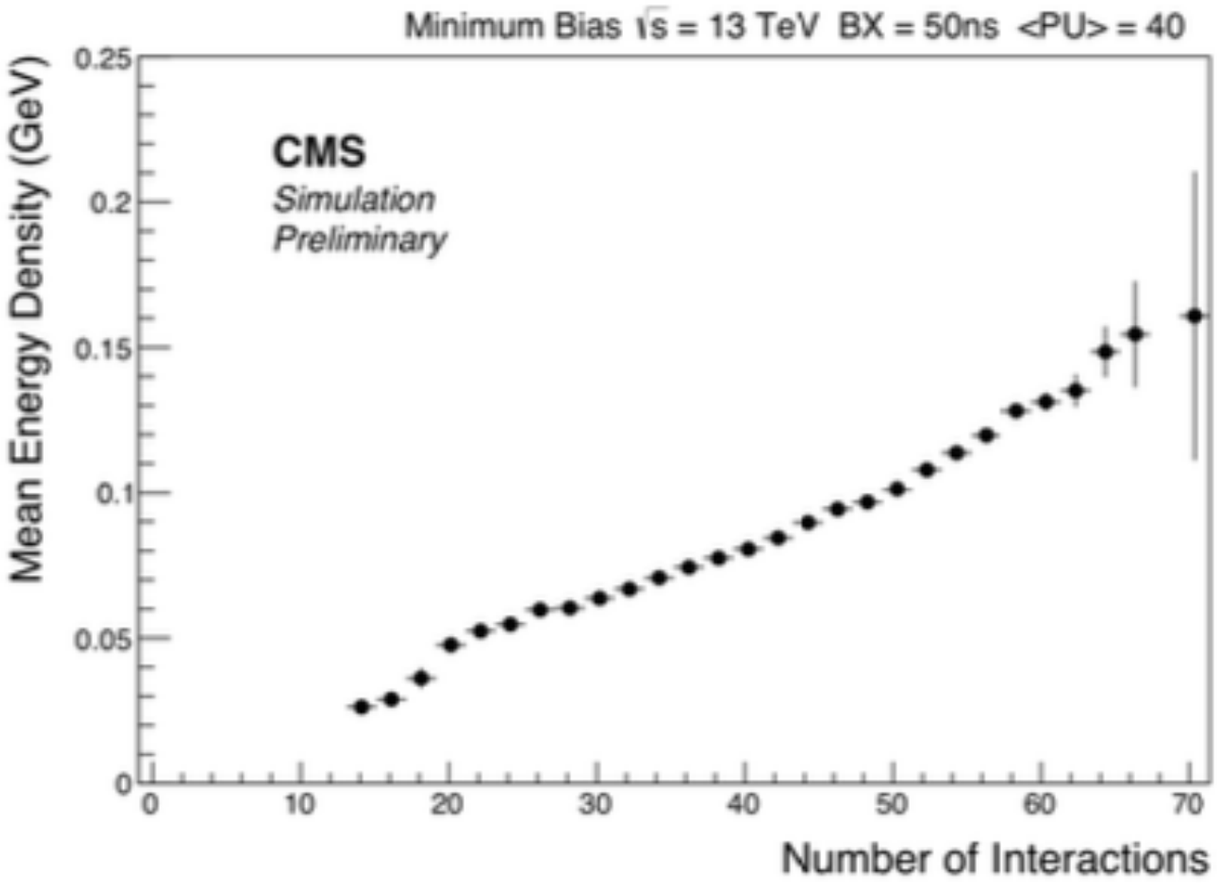


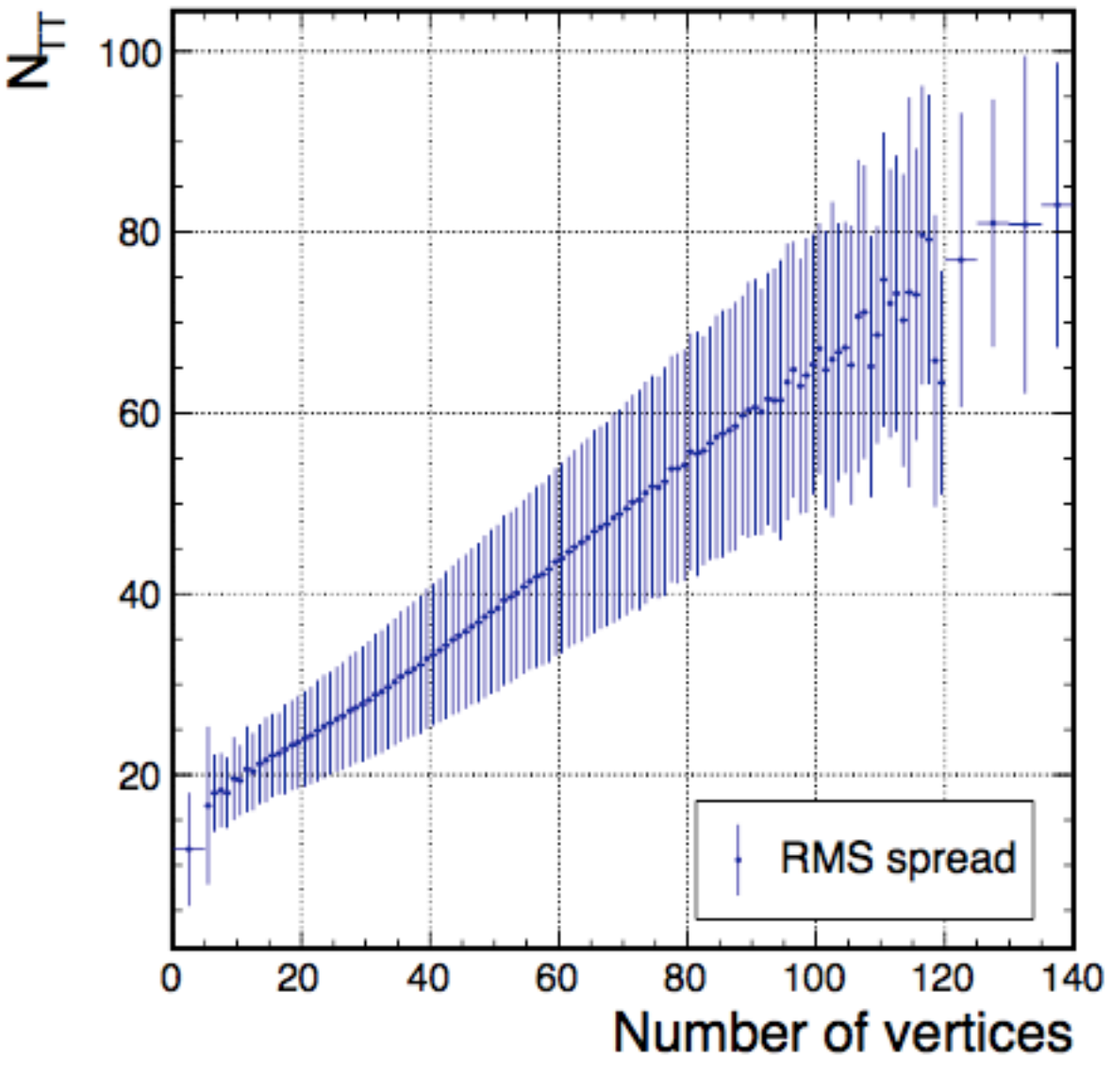






Pileup


Minimum Bias √s = 13 TeV BX = 50ns <PU> = 40
CMS
Simulation
Preliminary
Mean Energy Density (GeV)
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
Number of Interactions


N_{PT}
100
80
60
40
20
0
20
40
60
80
100
120
140
RMS spread
Number of vertices

Menu

	#Instances	Width [bits]	Quantities
Muon	8	64	ϕ, η, p_T, quality, charge, and charge valid
Jet	12	32	ϕ, η, E_T, quality
e/γ	12	32	ϕ, η, E_T, isolation, quality
Tau	12	32	ϕ, η, E_T, isolation, quality
HF min. bias	4	4	One instance per detector side, two thresholds.
Tower count	1	13	E_T
E_T, E_{TTEM}	1	12	E_T
H_T	1	12	E_T
$E_{T,miss}$	1	20	ϕ, E_T
$H_{T,miss}$	1	20	ϕ, E_T
$E_{T,HF,miss}$	1	20	ϕ, E_T
$H_{T,HF,miss}$	1	20	ϕ, E_T

Higgs Physics