Apr. 8th, 2021

Trigger limited hadronic Higgs measurements: bb, ττ, cc

PITT PAC

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Overview

Trigger Overview

Triggering on the Discovery Channels

Hadronic Higgs Analyses
  bb, ττ, cc

Trigger Strategies per Final State

Looking Forwards

Proton-proton Collisions at the LHC

At L = 1-2x10^{34}cm^{-2}s^{-1}

- 25-50 events/crossing
  - ~ 1 GHz pp collision rate
  - Events contain 25-50 pileup events
- **EWK rate:** 1 kHz W&Z
- **Top Rate:** 10 Hz
- **Higgs:** ~0.1 Hz, H4l: 0.1 mHz

~Output 1 MB/event → it would also be impossible to store all events

Process and Select Events in Stages

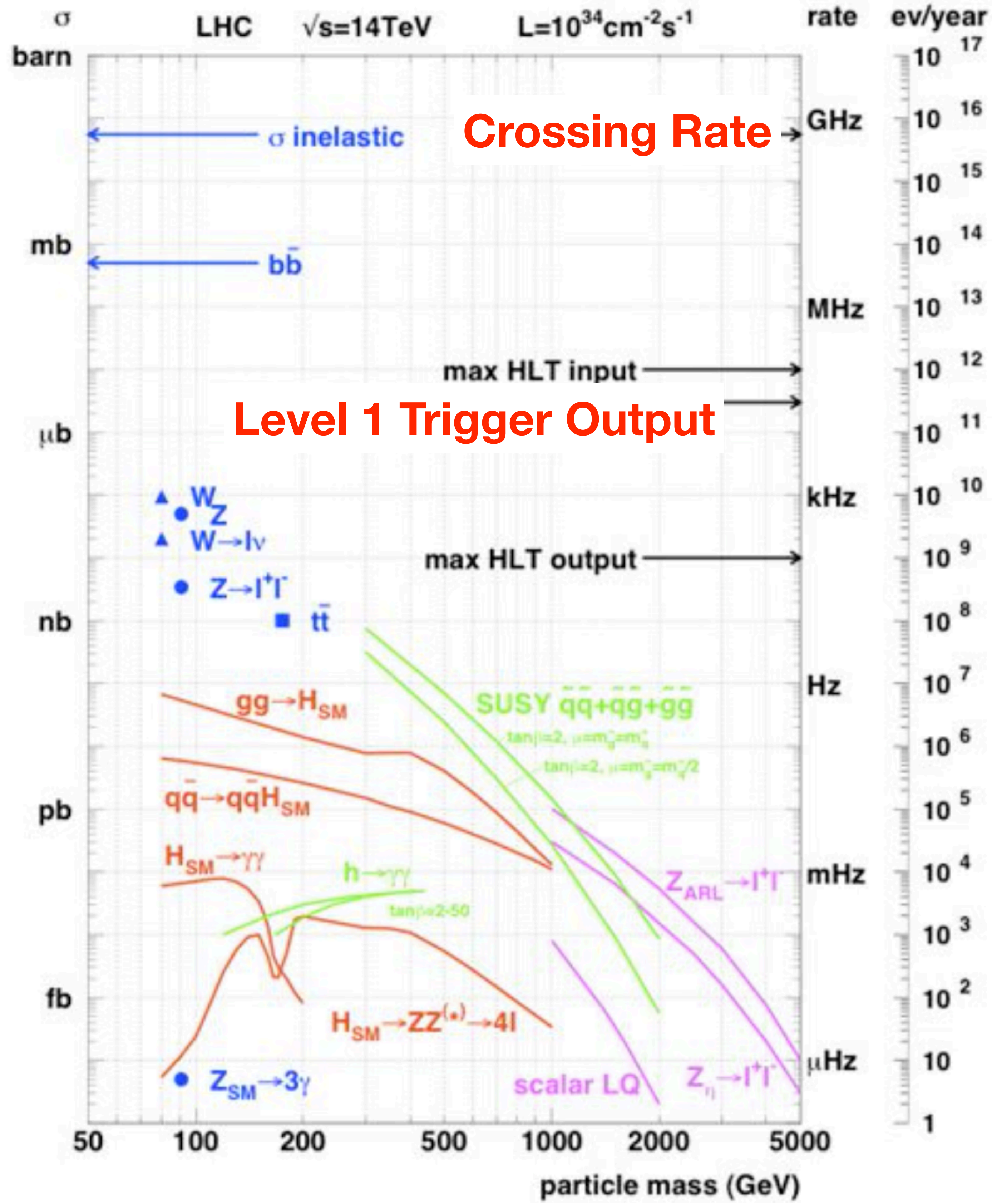
Level-1 Triggers

- reduce 1 GHz to 100kHz

High Level Triggers

- reduce 100kHz to 100's Hz

- Run I/II CMS detector buffers hold each event for ~120BX while the decision to trigger is being made using the Level 1 Trigger System



LHC Trigger Challenges

What Physics Signatures is the trigger designed for?

Electroweak Symmetry Breaking Scale ← ~40 GeV γ, e, μ

- **Higgs discovery** and **higgs sector characterization**
- **Quark**, **Lepton Yukawa couplings to higgs** ← Low P_T b-jets, τ

New physics at TeV scale to stabilize higgs sector ← Multiple low P_T objects

- **Spectroscopy** of **new resonances** (SUSY or otherwise)
- **Dark Matter** candidate ← ME_T

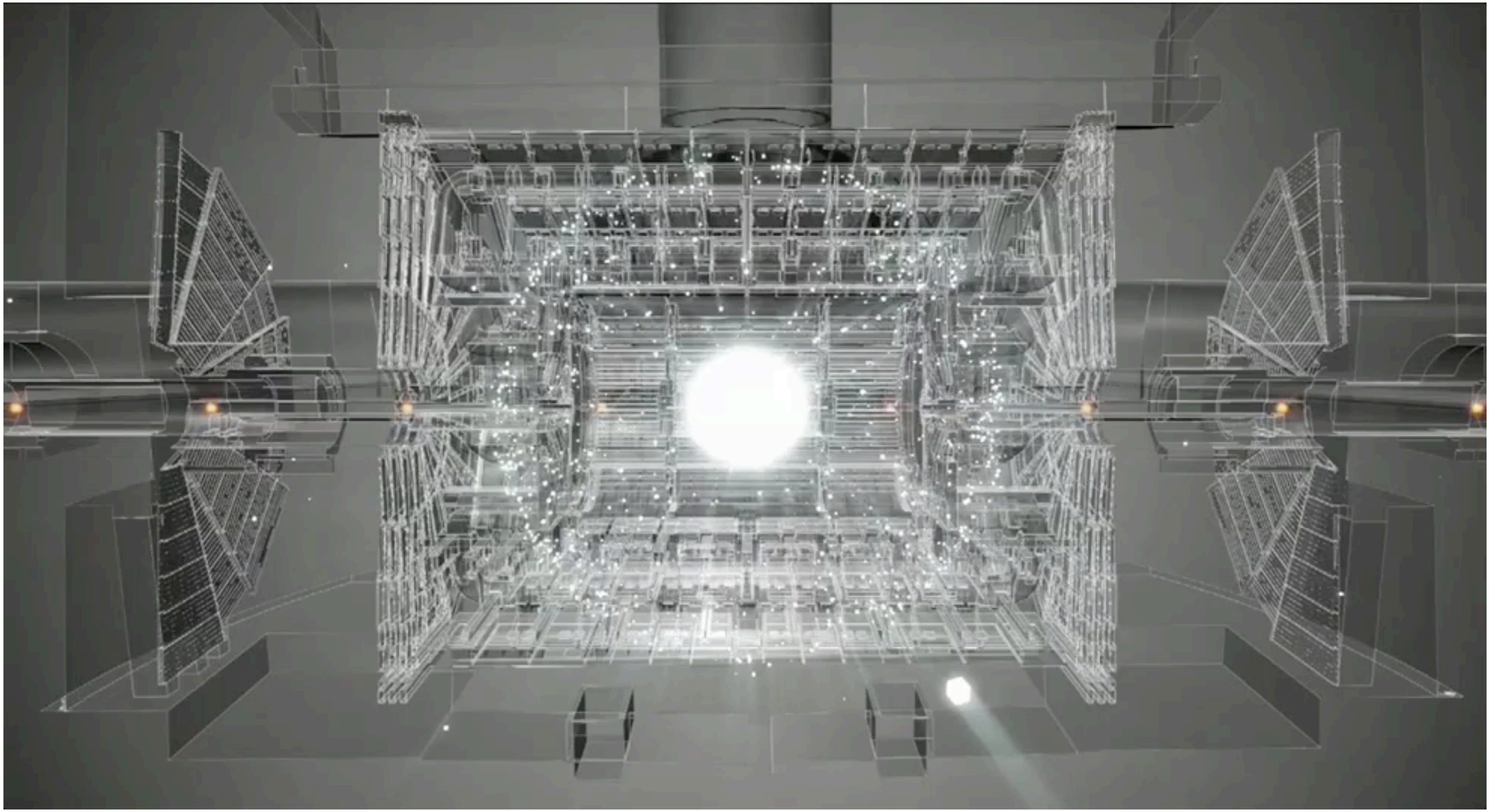
Multi-TeV scale physics (loop effects)

- **Indirect effects on flavor physics** (mixing, FCNC, etc.)
- Bs mixing and rare B decays
- Lepton flavor violation ← Dedicated Triggers
- **Rare Z** and **higgs decays**

Planck scale physics

- **Large extra dimensions** to bring it closer to experiment
- **New heavy bosons** ← High P_T leptons and photons, Multi particle and jet events
- **Blackhole production**

c = 30 cm/ns → in 25 ns, s = 7.5 m



- New Event arrives **every 25ns**
- **Many channels**, **high occupancy**, searching for only a few **special events**, with a **limited latency**
  - Develop systems which suit both the computing and latency requirements

CMS Level 1 Trigger Data Flow

CMS

Digitization of Detector Signals
+
Trigger Primitive Generation

↓

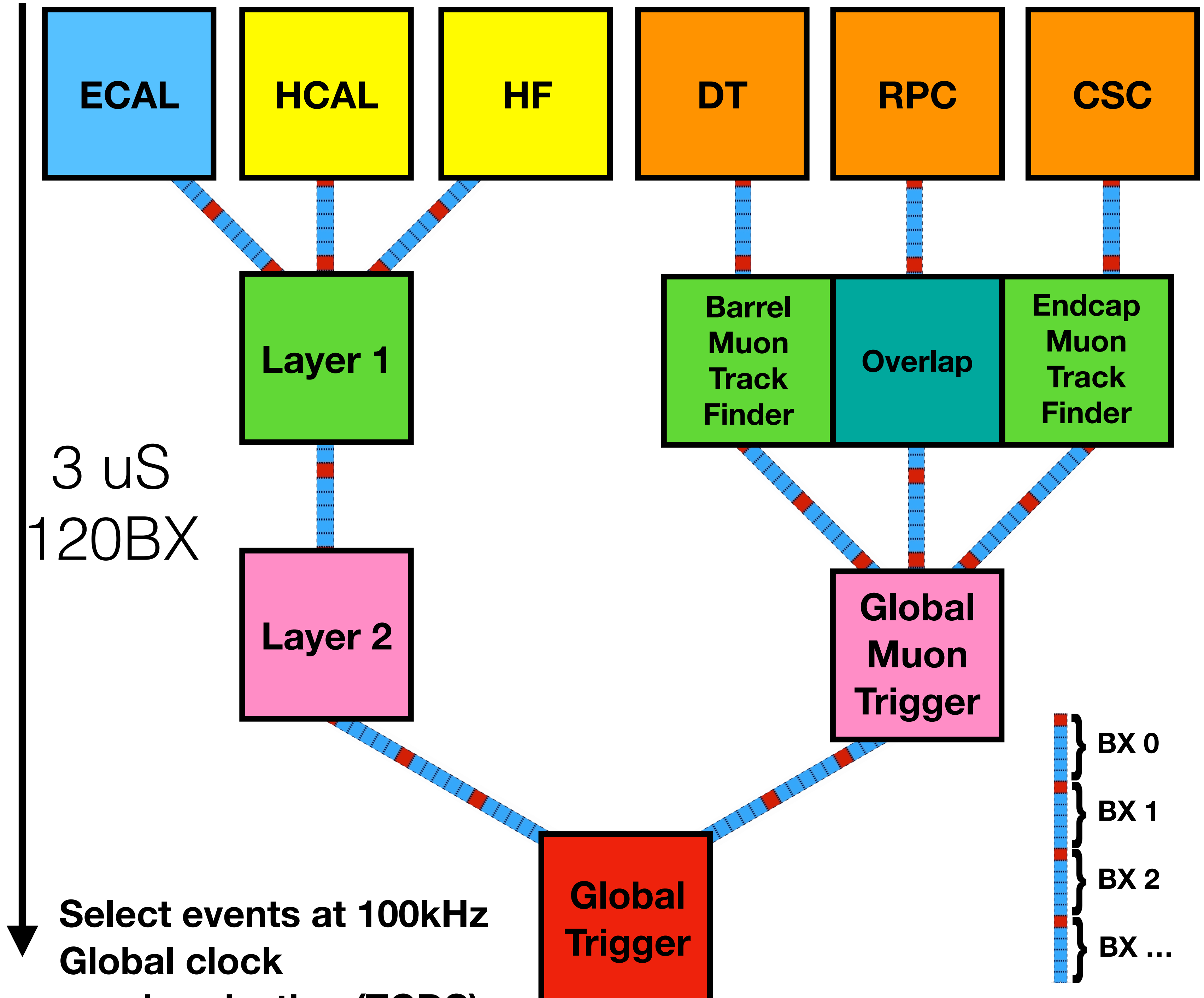
Regional Triggers

↓

Sub-detector Trigger

↓

Global Trigger

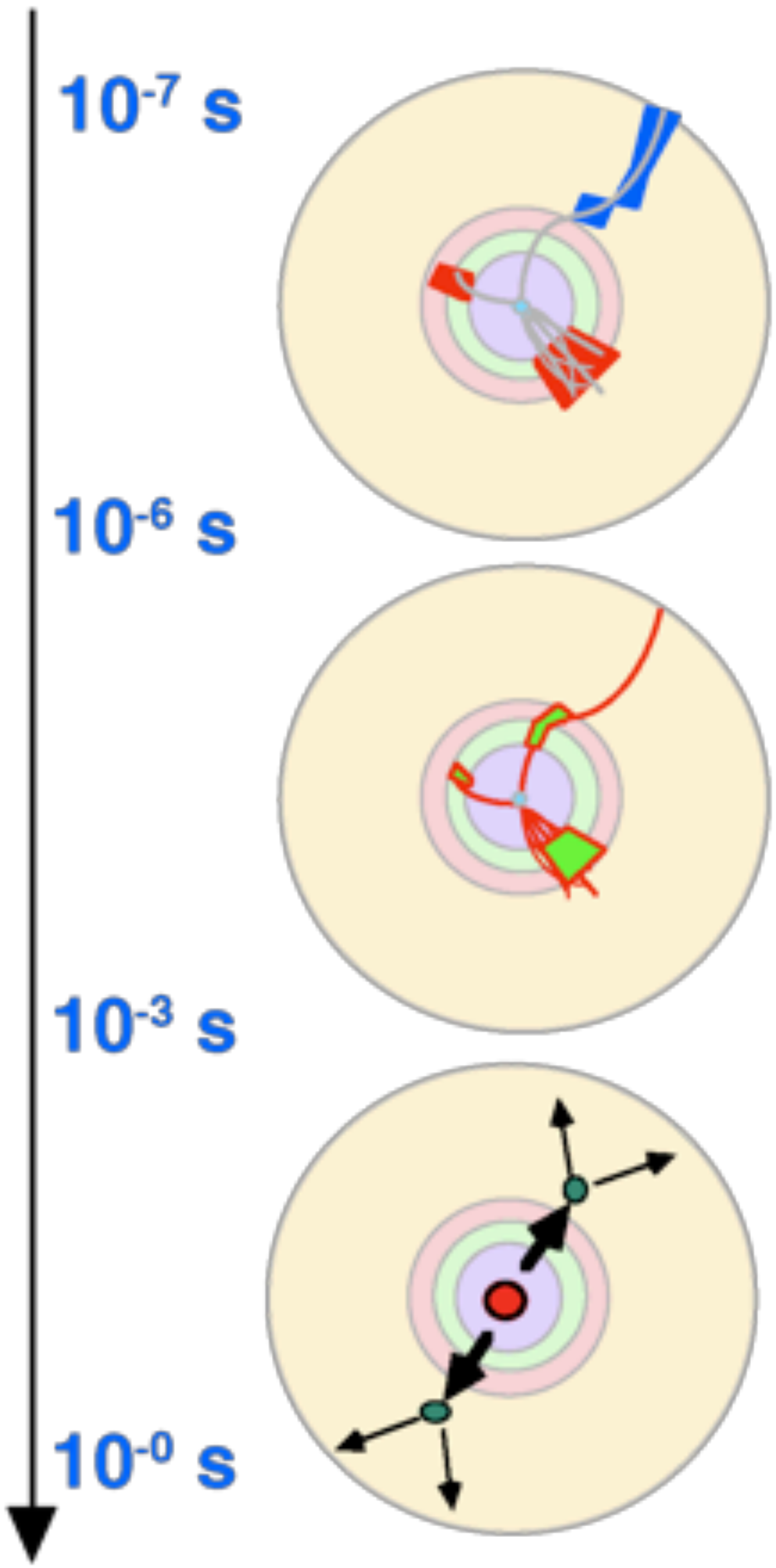


Select events at 100kHz
Global clock synchronization (TCDS)

Pipeline System
Frequency 40MHz
Feed-Forward Algorithms
- (no backwards loops)
Highly Distributed
Full Event Processed at the GT

Designed on custom built electronics employing high speed links (I/O) and (ASICs +) FPGAs

LHC Real Time Data Processing



Collision rate 10^9 Hz

Channel data sampling at 40 MHz

Level-1 selected events

Particle identification (High p_T e, μ, jets, missing E_T)
- Local pattern recognition
- Energy evaluation on prompt macro-granular information

HLT selected events

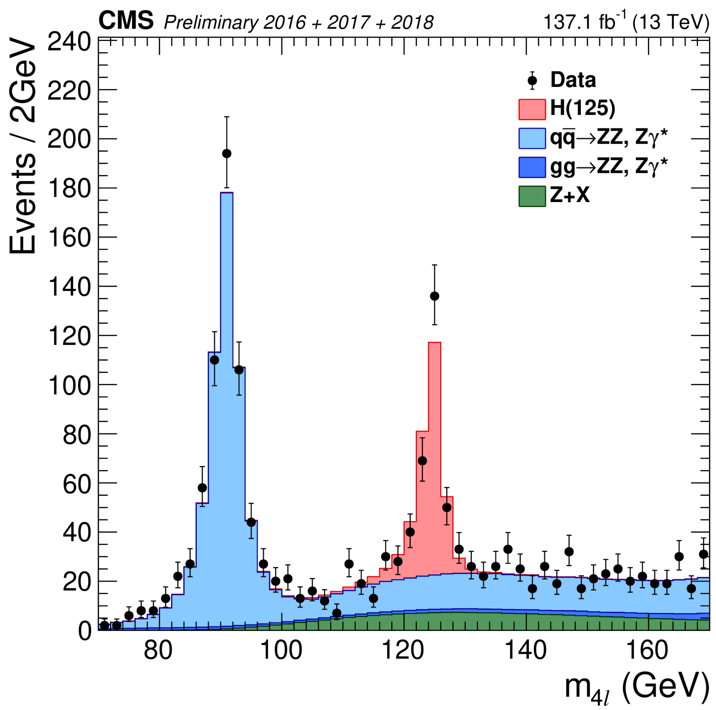
Clean particle signature (Z, W, ..)
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

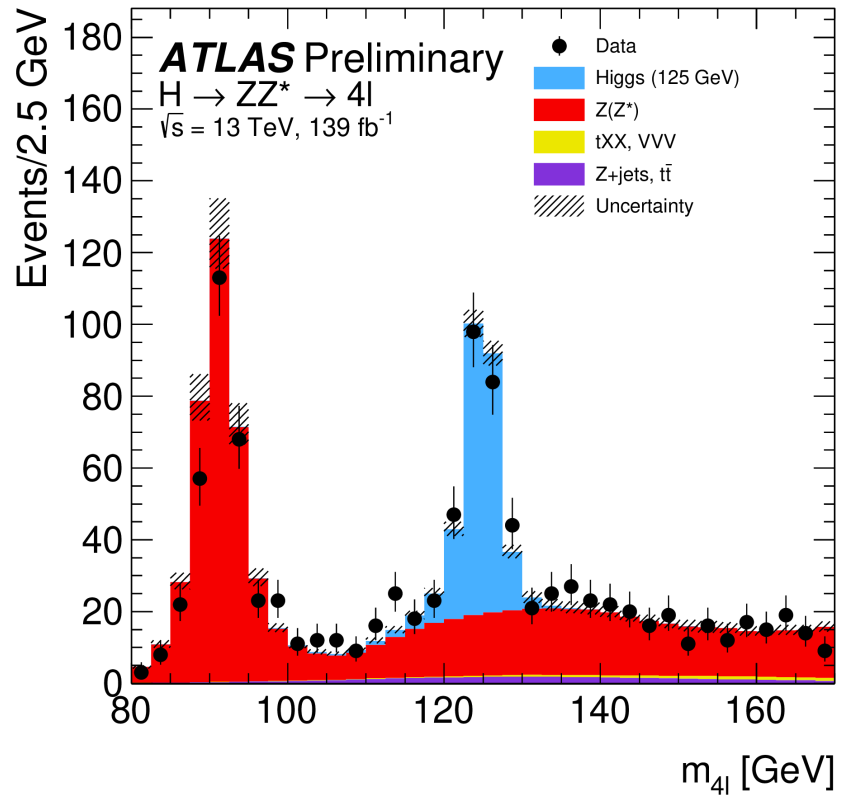
Level-3 events to tape 10..100 Hz

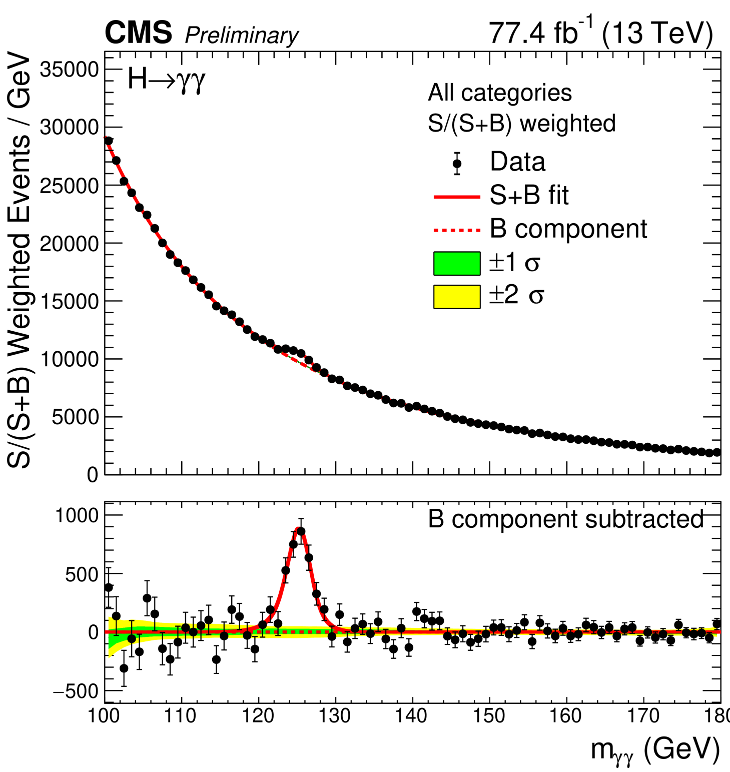
Physics process identification
- Event reconstruction and analysis

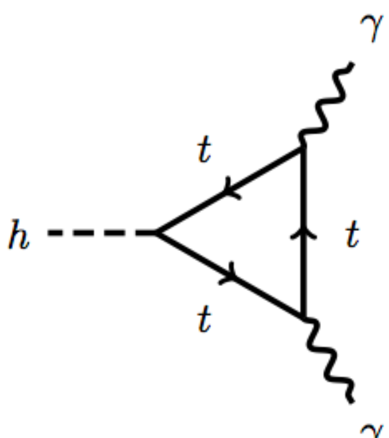
Continuous Filtering

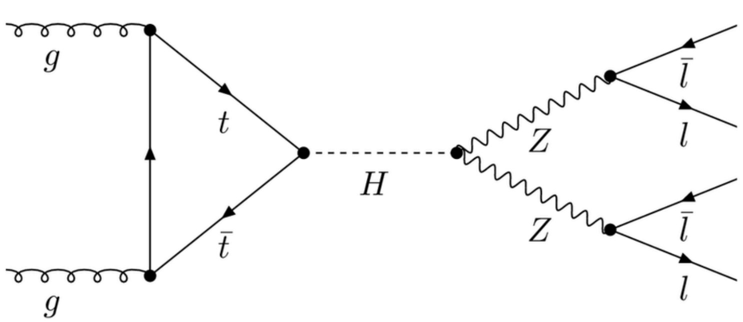
Higgs Discovery

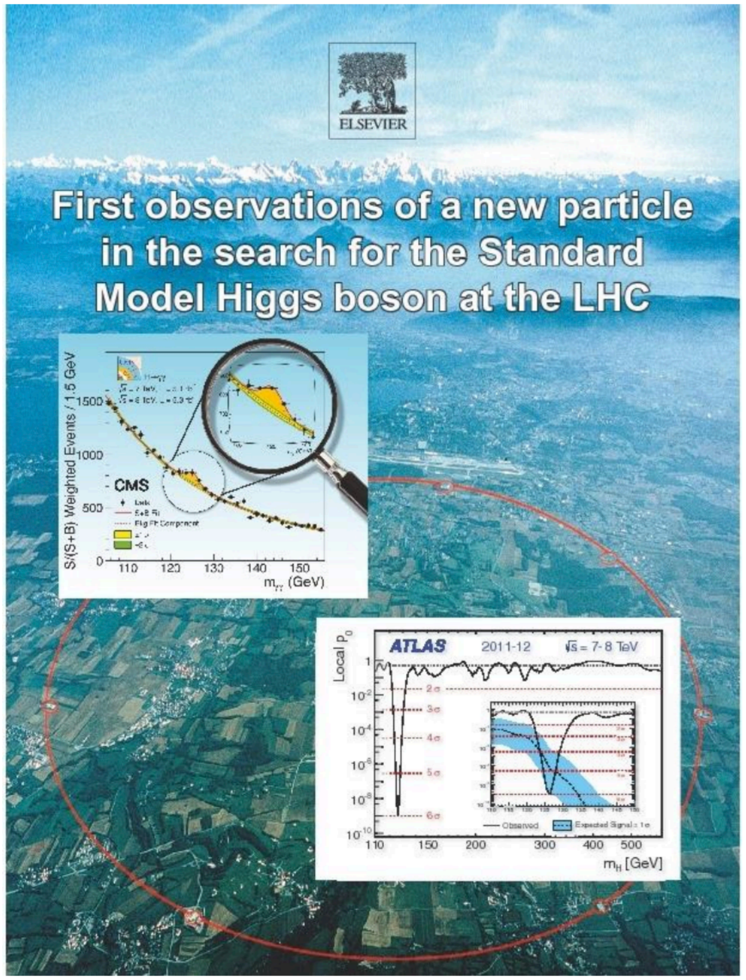








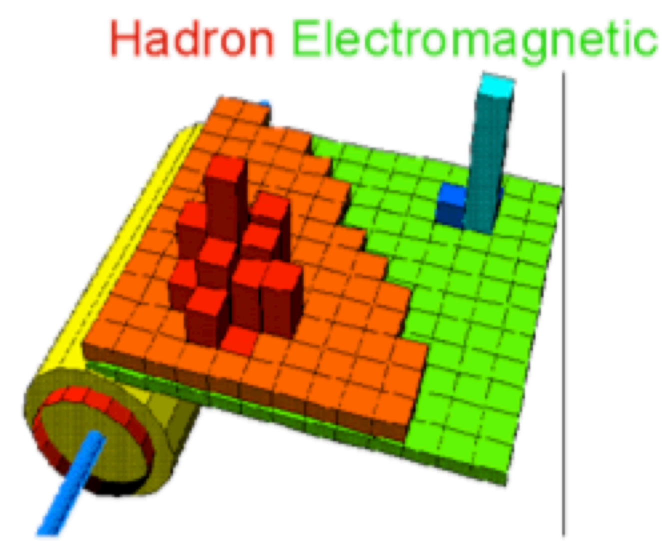


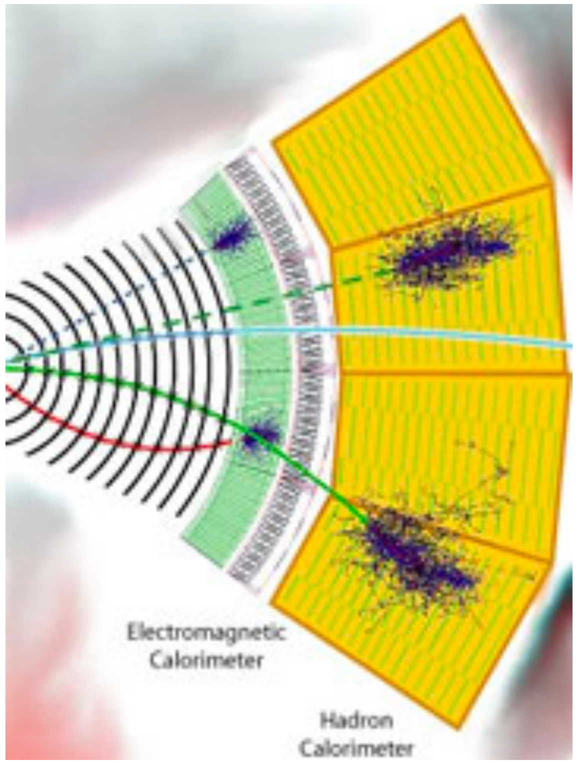


I.Ojalvo Triggering Hadronic Higgs Apr 8, 2021

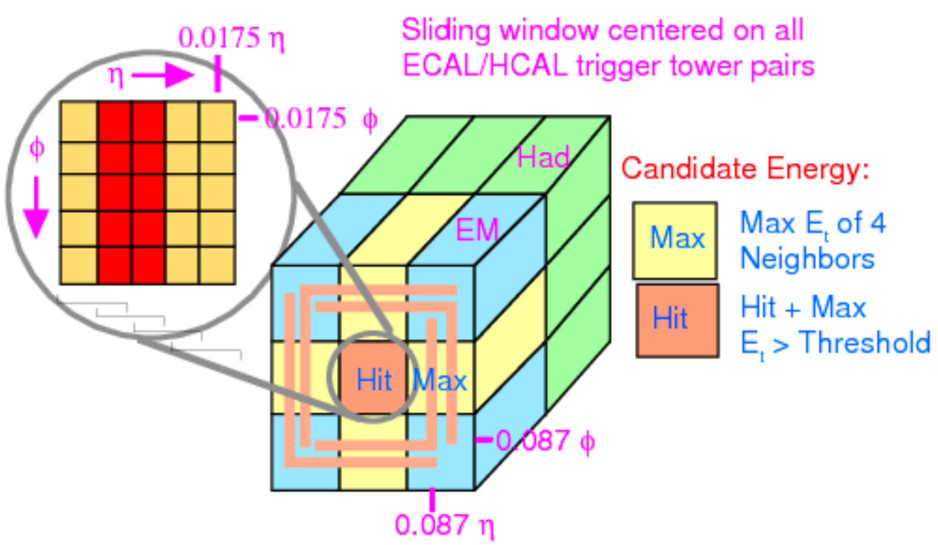
Trigger Strategy: Electrons/Photons

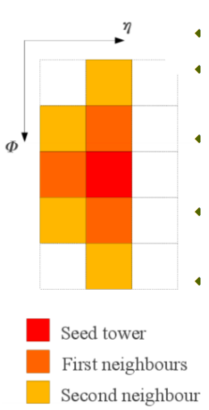
Calorimeter Data input to Level 1 as spatially fixed "Trigger Towers"



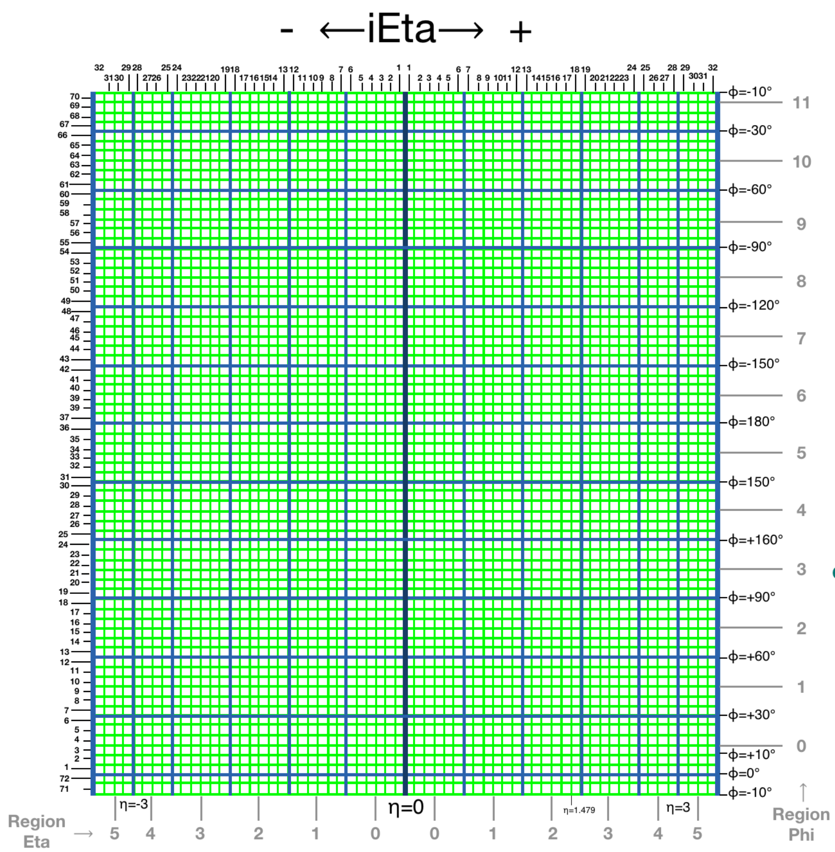


Electrons/Photons





- **Clustering around seed tower with local energy maximum (> 2 GeV)**
- **Neighboring energy deposits clustered (>1 GeV)**
- **E/H and Isolation**



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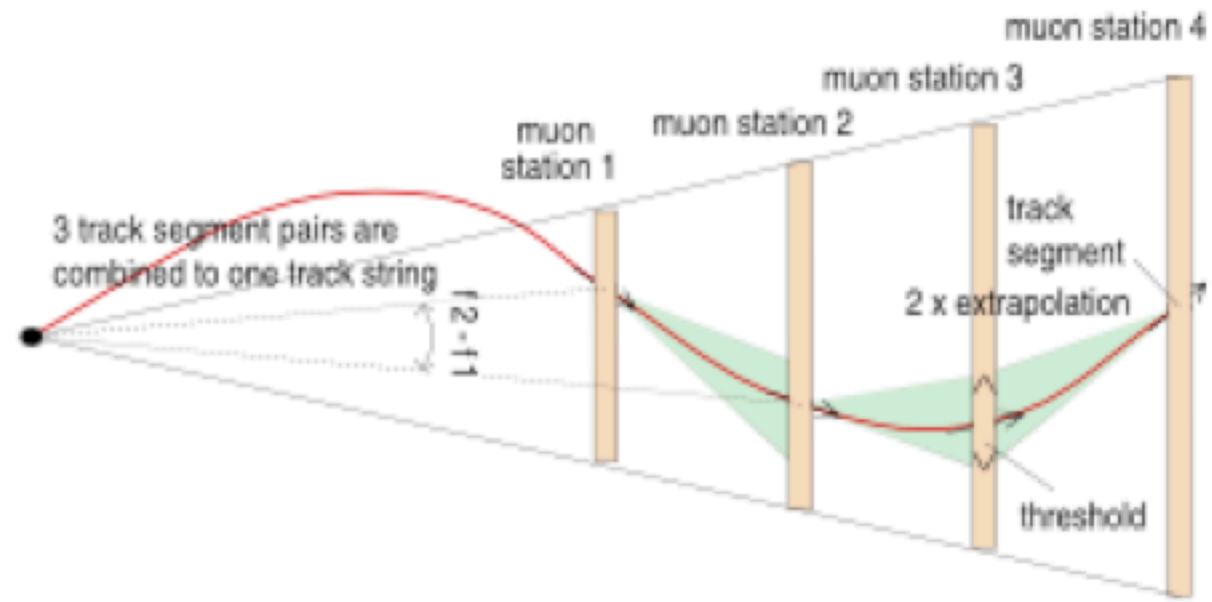
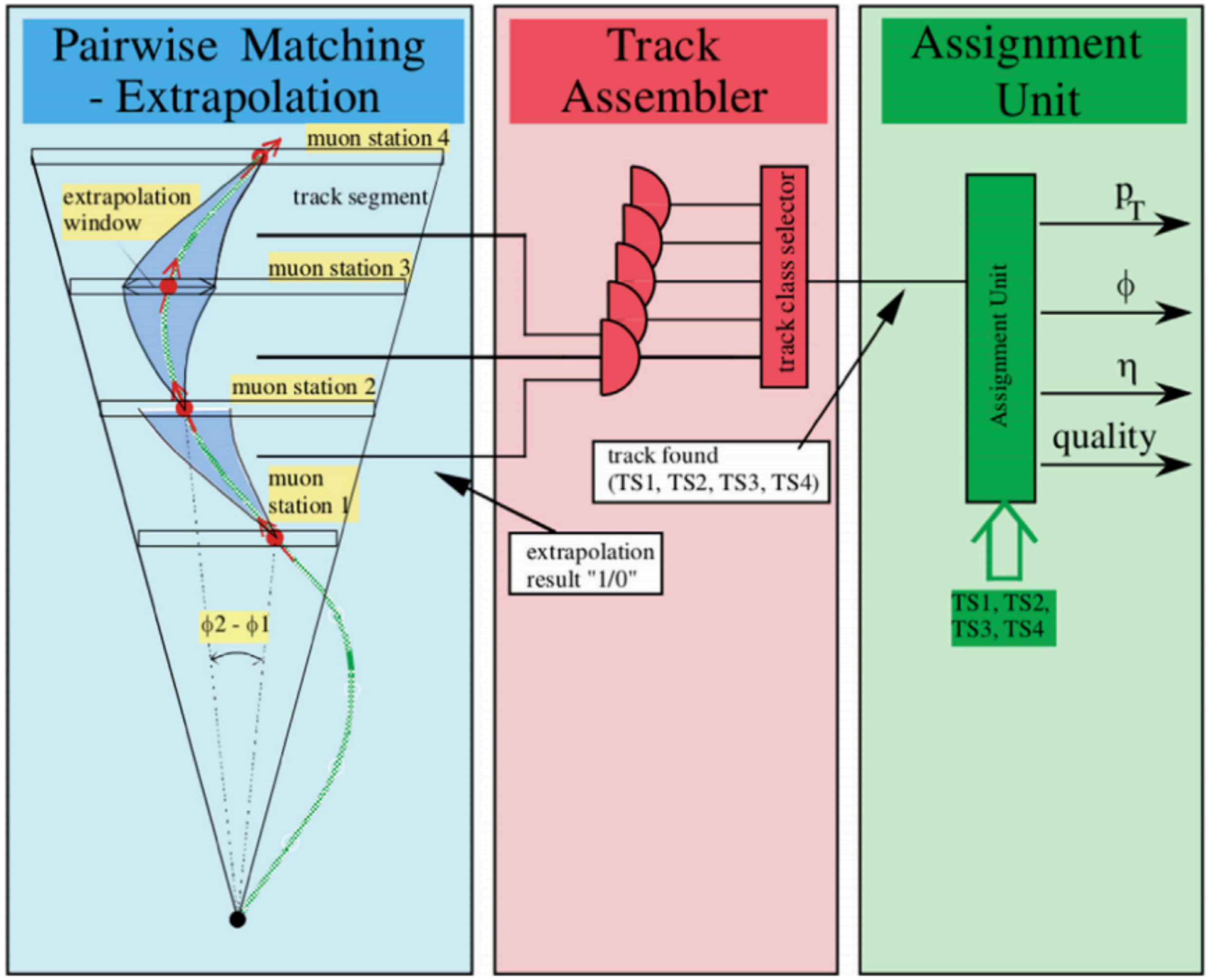


Muon Hits must be matched station by station and is dependent upon Muon Momentum

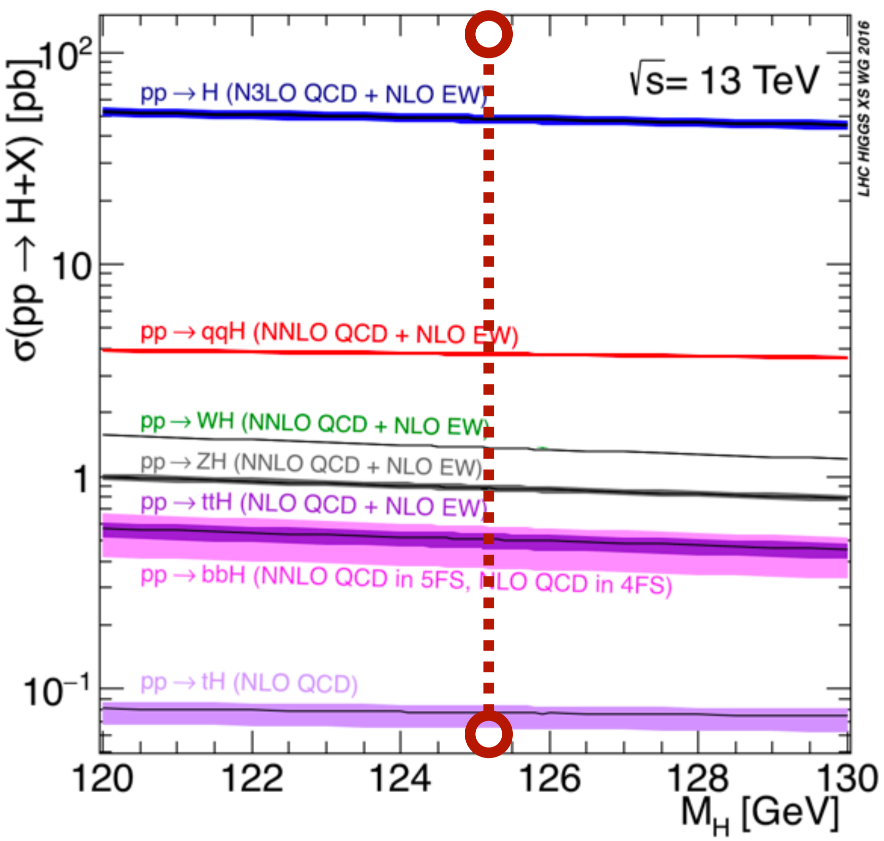
New for Run 3: Kalman Filter and NN

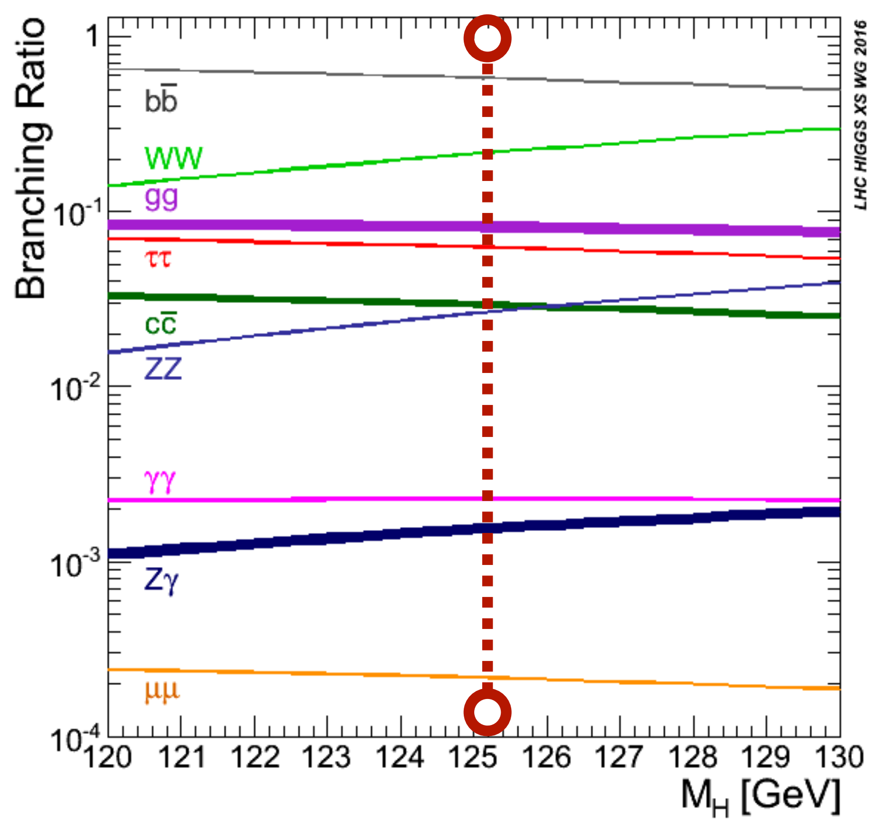
- **Input segments from Muon Chambers** forwarded to Barrel, Endcap, Overlap Muon track finders
- **Search** for track segments in adjacent modules
- **Track is assembled**
- **Kinematic assignment** based on Look Up Tables



Requires Memory to Store Patterns
Fast Logic for Matching Segments
- FPGAs are Ideal

Hadronic Higgs Decays





Higgs Hadronic Decays

- **H→bb** 58%
- **H→ττ** 6.3% → 87.6% involve hadronic
- **H→cc** 2.8%

~65% of Higgs decays at the LHC involve Hadronic Decay Modes

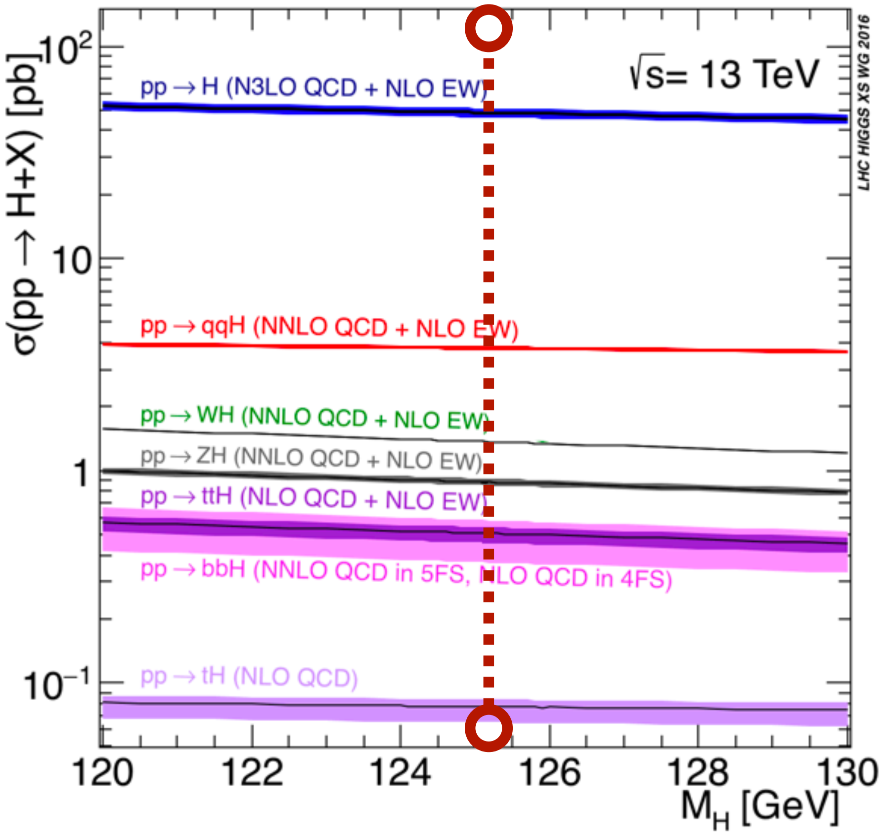
Higgs Production

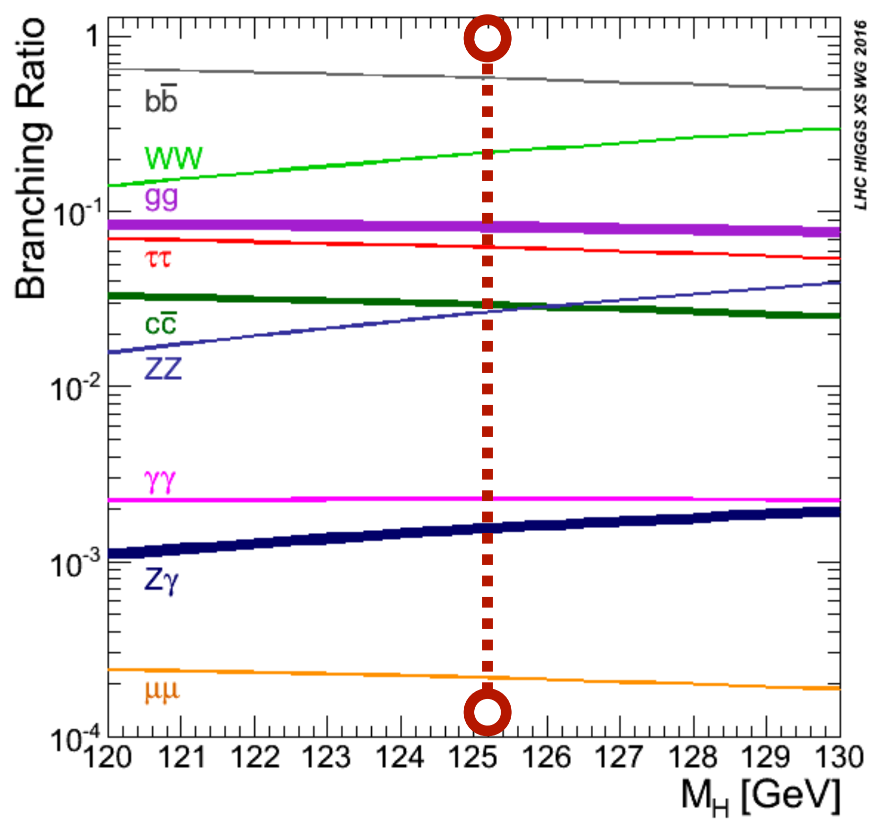
- **ggH** 90%
- **VBF** 7%
- **VH** 2.5%

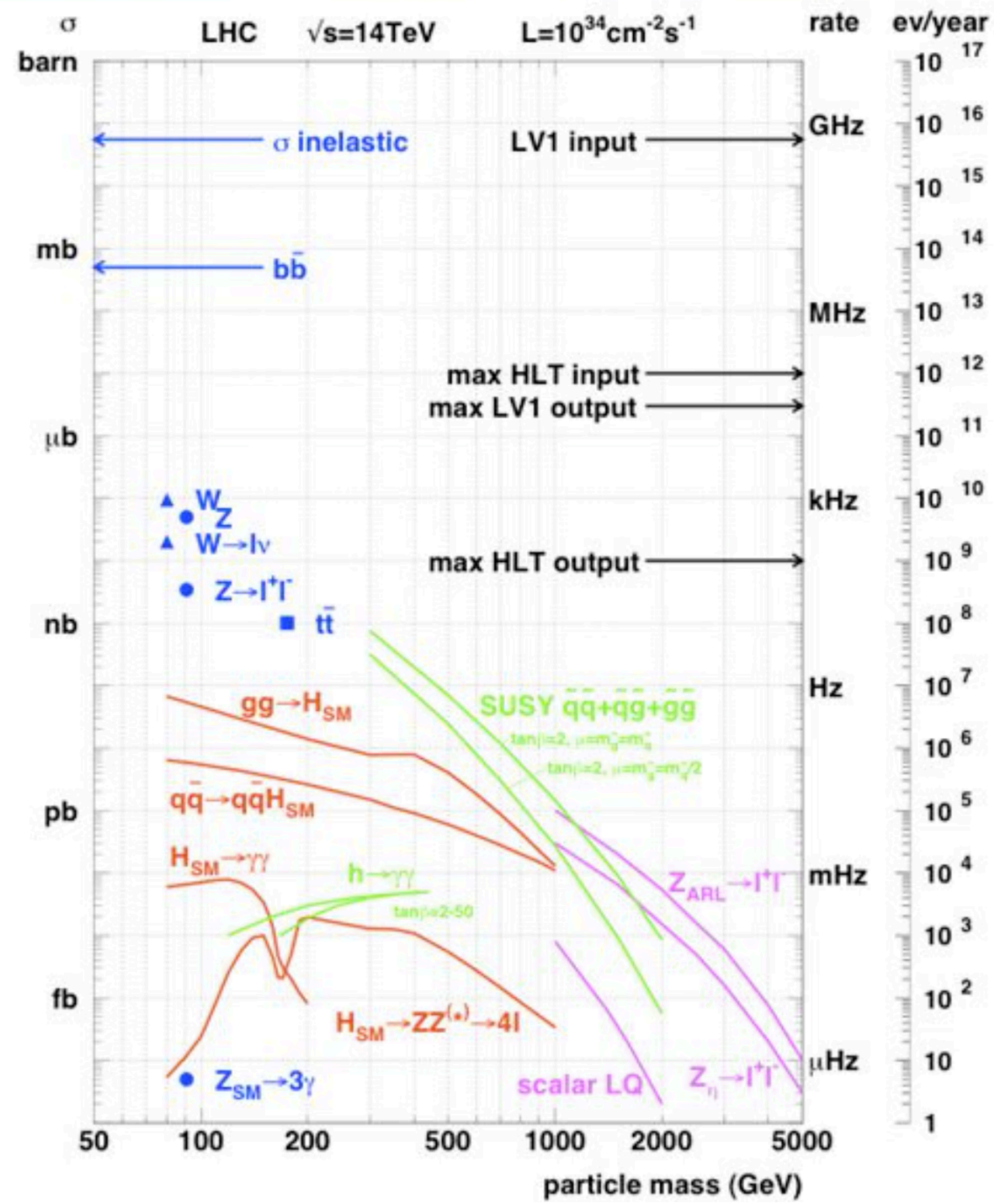
More than half of Higgs events at the LHC are produced via ggH and decay via hadronic modes

Hadronic Higgs Decays

LHC X-Section Working Group







Triggering on **Hadronic Higgs** decays at a **Hadron Collider** requires some creativity

Hadronic Higgs Analyses

Higgs to bb Observation Analysis Strategy

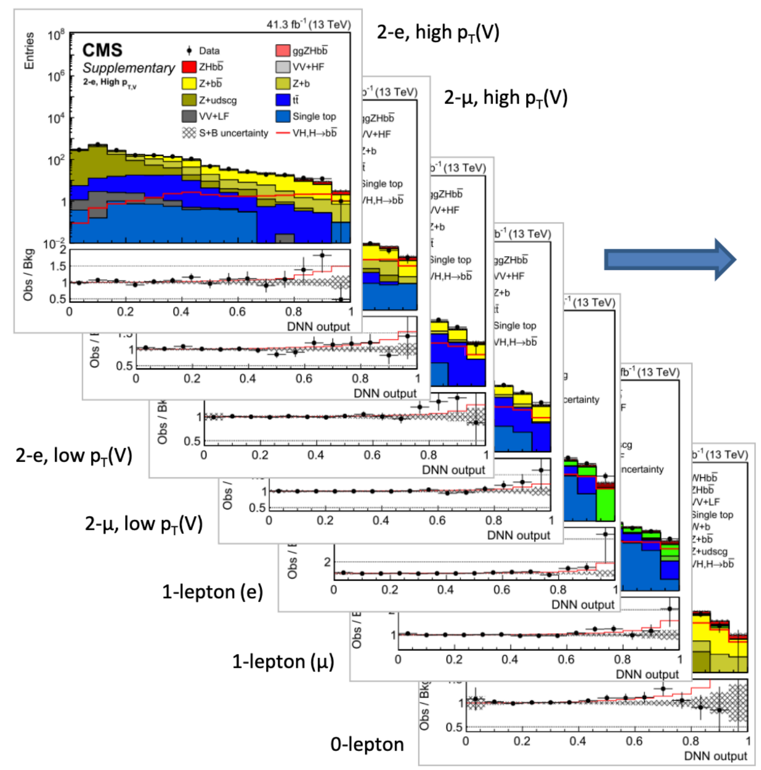
The Good:

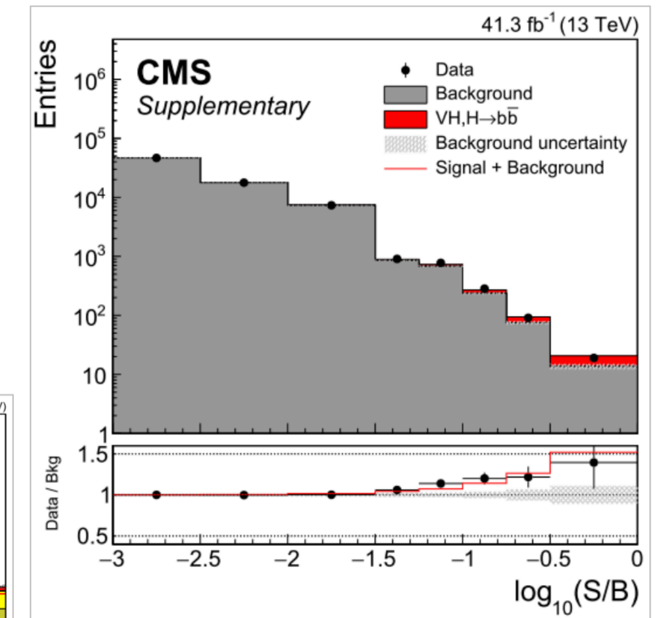
- **H→bb** 58% branching fraction

The Bad:

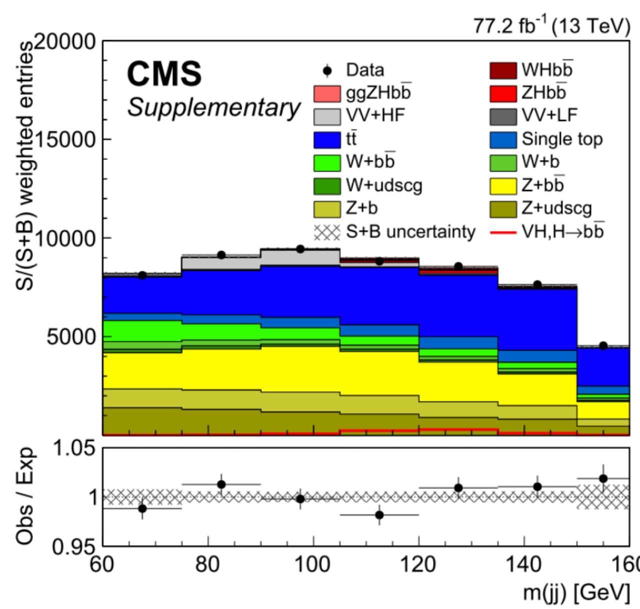
- Poor Mass Resolution
- Poor S/B ~0.05
- Triggered using Higgstrahlung! (VH)

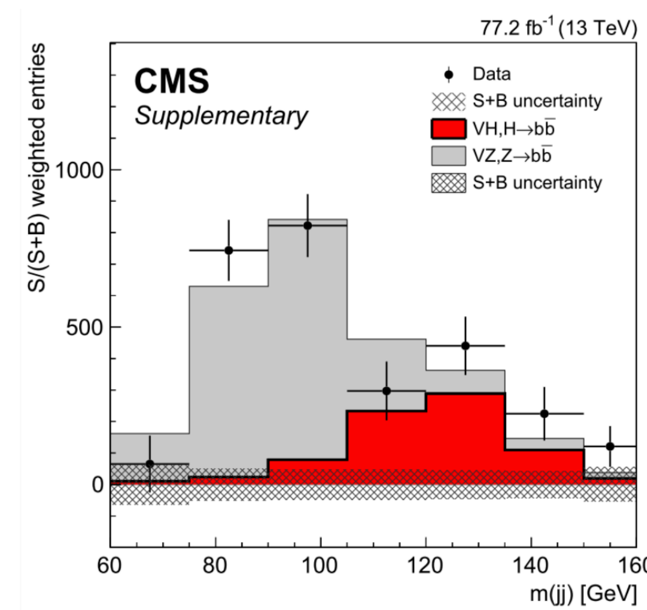
- 3 channels with 0, 1, and 2 leptons
- Large boost for vector boson
- Multivariate analysis exploiting the most discriminating variables (m(bb̄) , ΔR(bb̄) , b-tag)
- Control regions to validate backgrounds and control/constrain normalizations





Data set	Significance (σ) Expected	Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2 (2016+2017)	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23



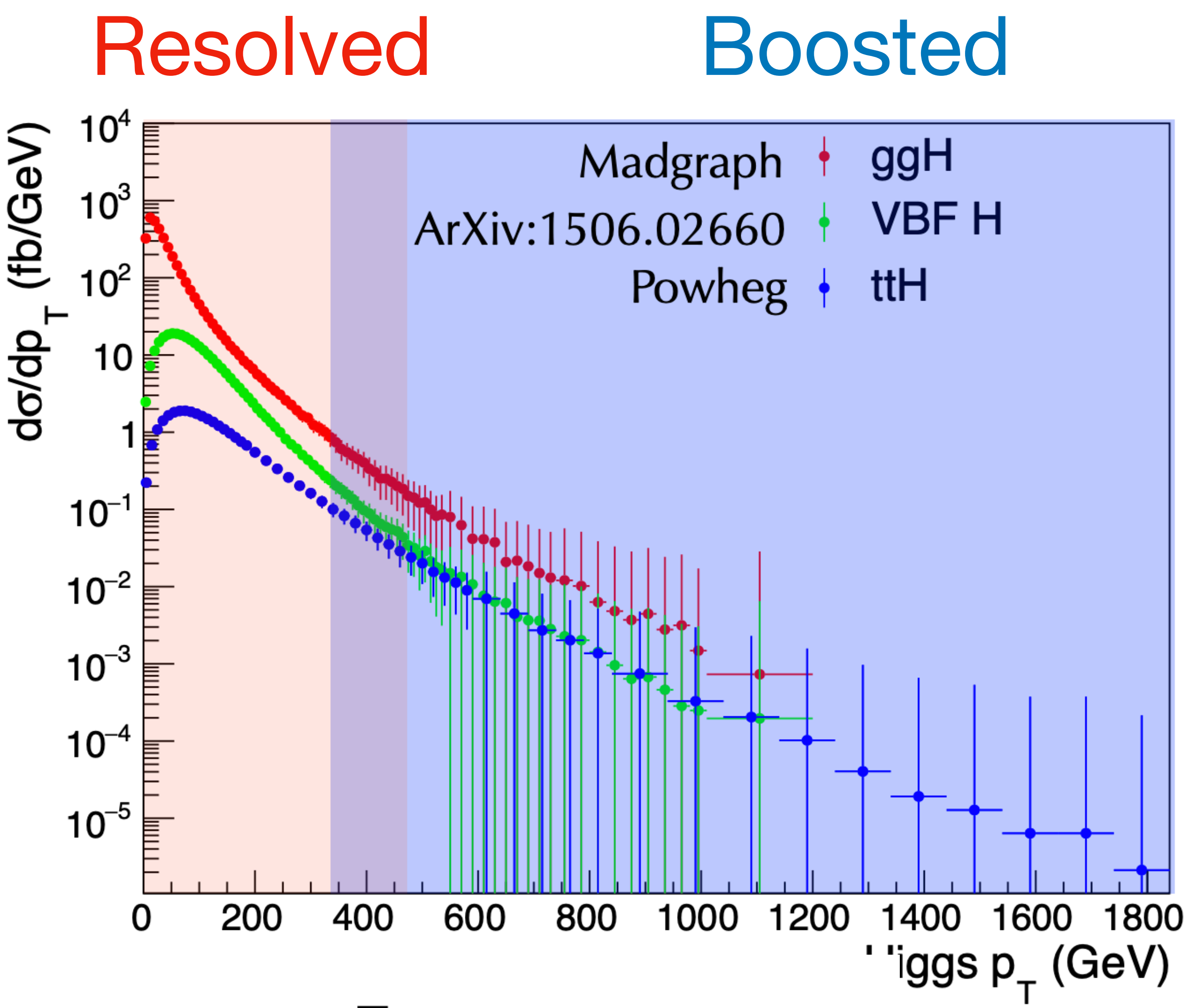


Boosted Higgs to bb

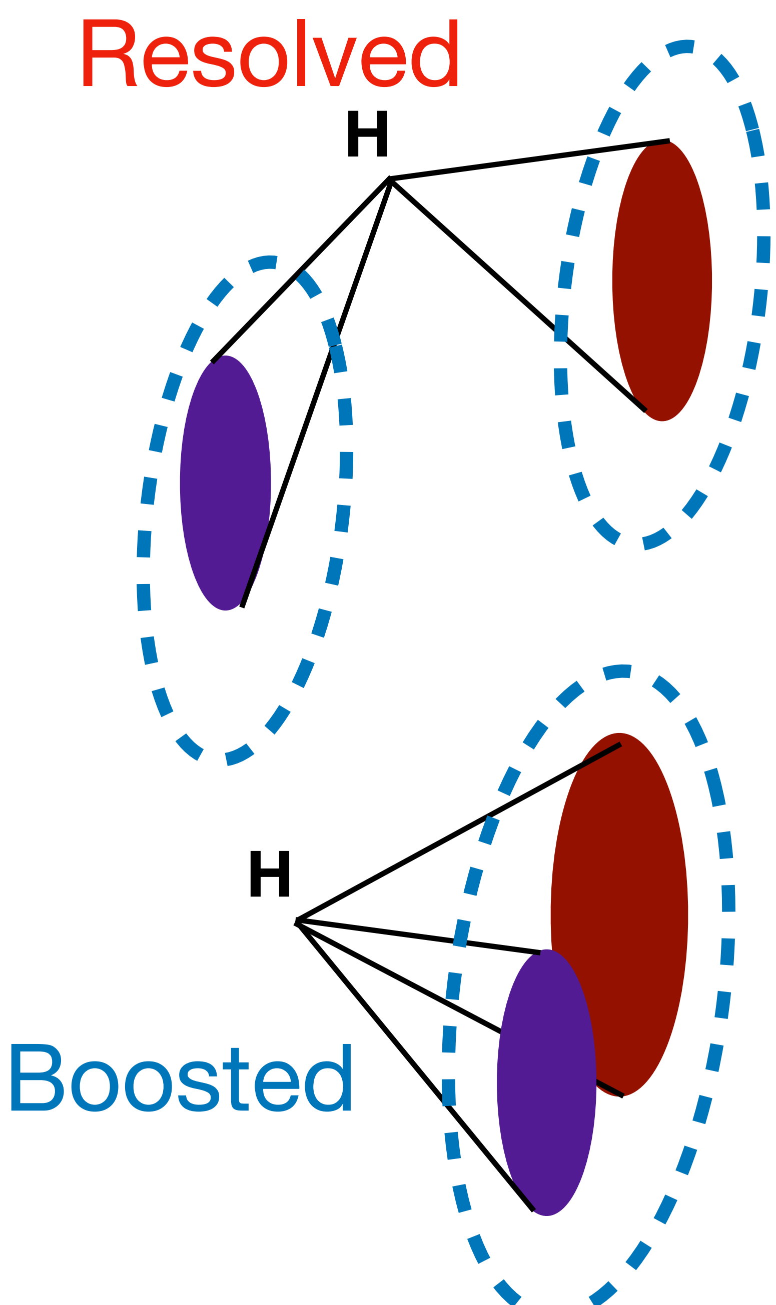
CMS: PRL 121 (2018) 12180, PAS-HIG-18-027

Search for ggH to bb in BOOSTED topologies

- Use **jet substructure** to separate QCD from boosted bb in AK8 Jets
- new strategy to search for Higgs boson to $b\bar{b}$
- but also change to probe unexplored new physics contributions to the Higgs at very high p T



$$dR(b\bar{b}) \sim 2m_H/p_T$$



Higgs to bb Boosted

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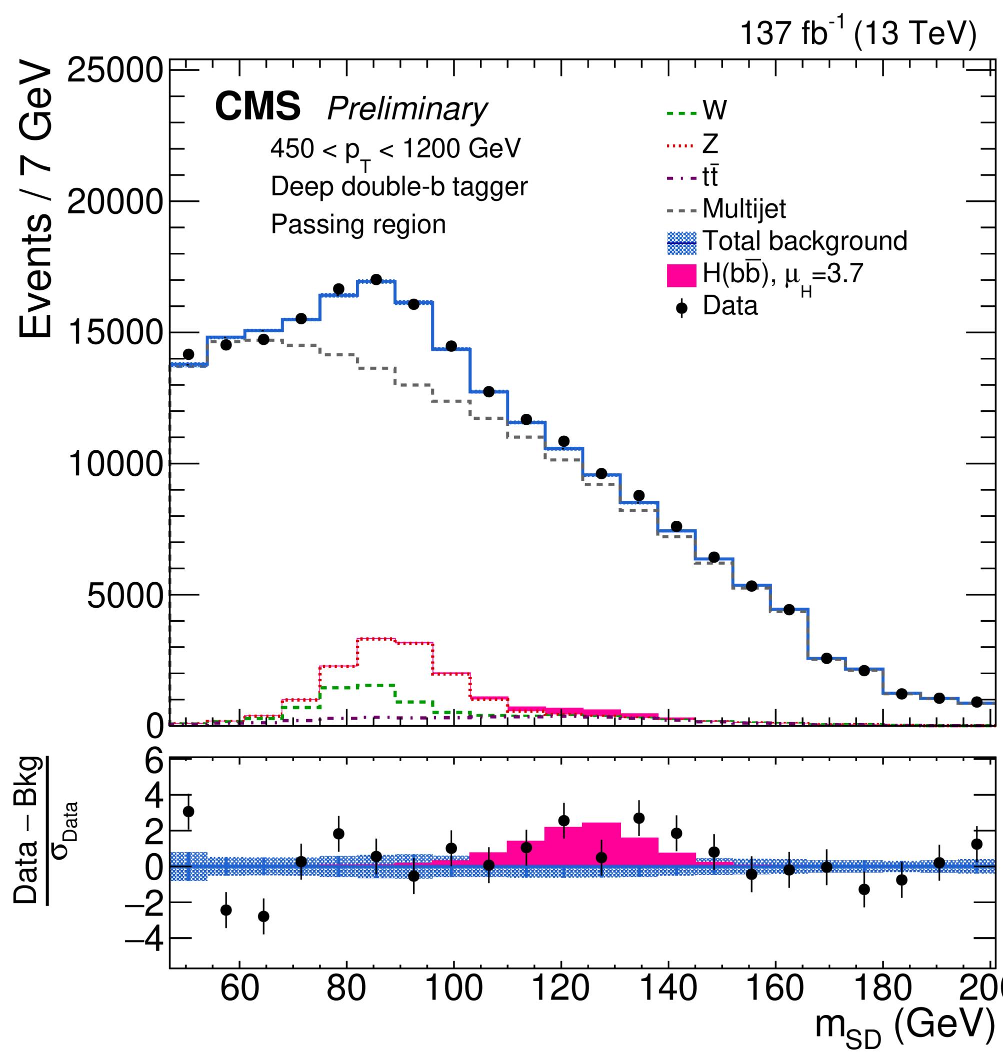
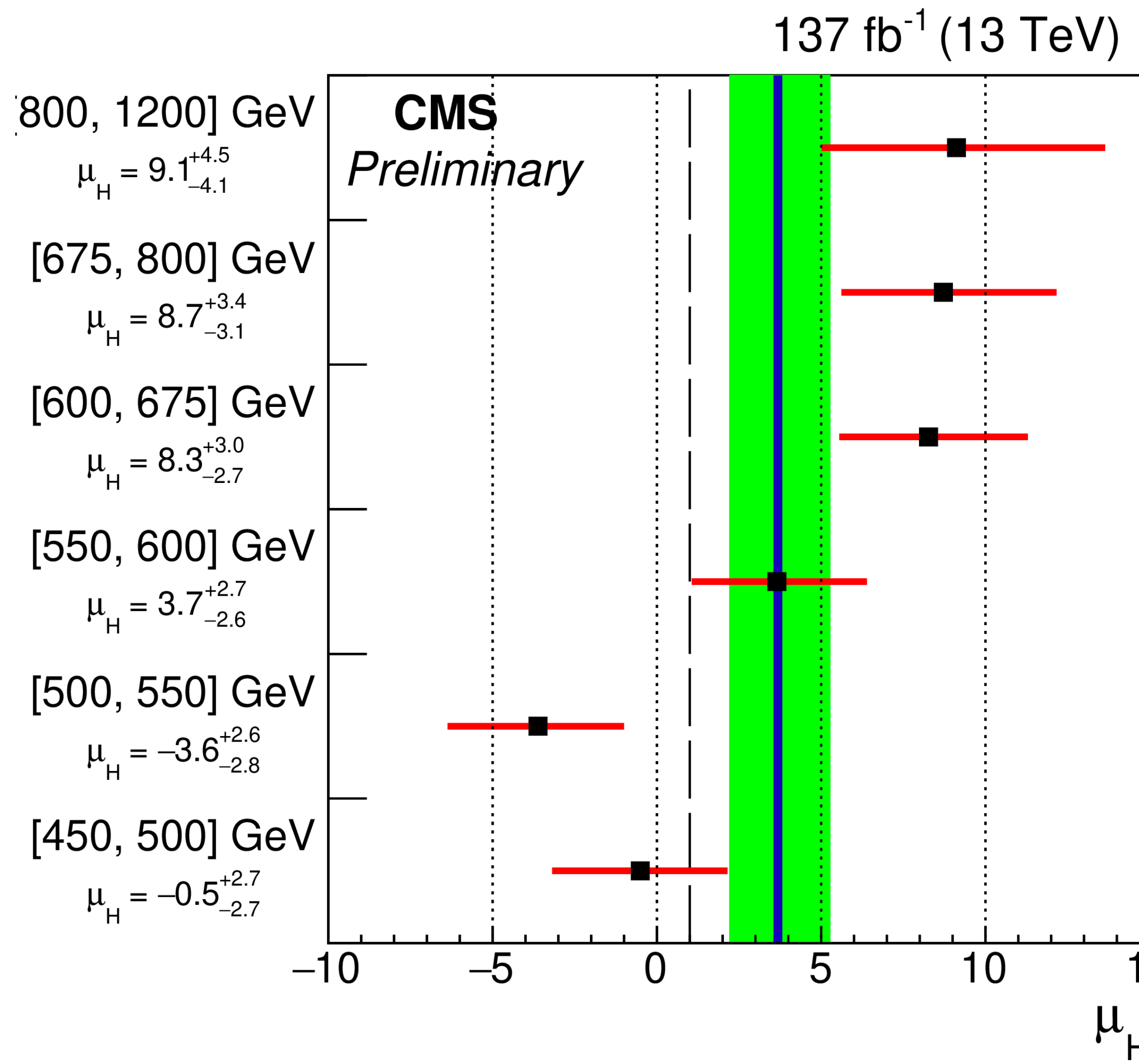




- Analysis uses b-tagging, and jet substructure to identify and reconstruct each leg
- First observation of Z→bb reconstructed in the one-jet topology 5.1σ (5.8 σ expected)

Trigger Strategy

QCD bb is produced 7 orders of magnitude more often than ggH

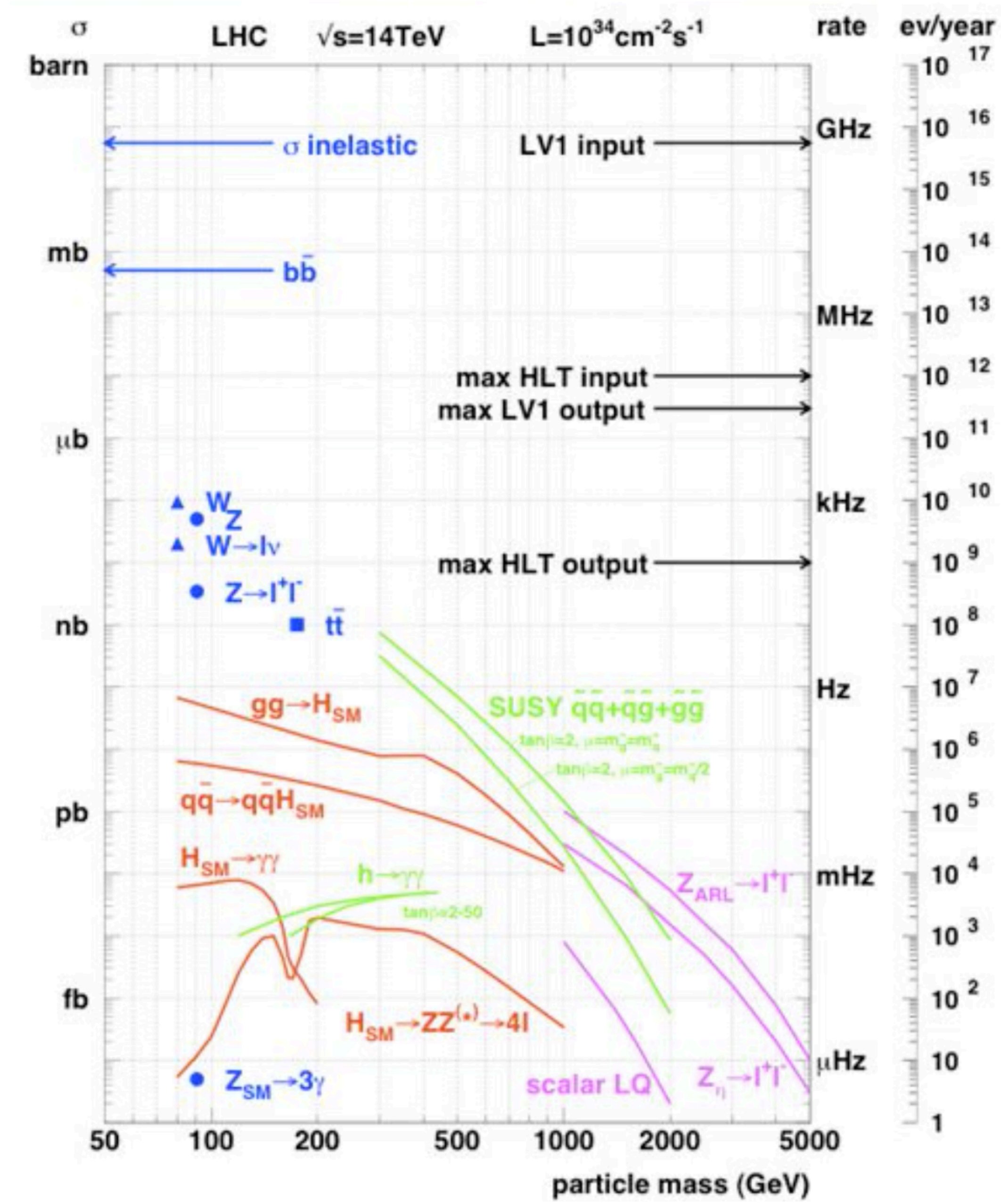
VH→bb Observation

- **Higgs-strahlung production**
- **Not triggered on directly**
  - **Z→νν, Z→ll, W→lν**

Boosted H→bb

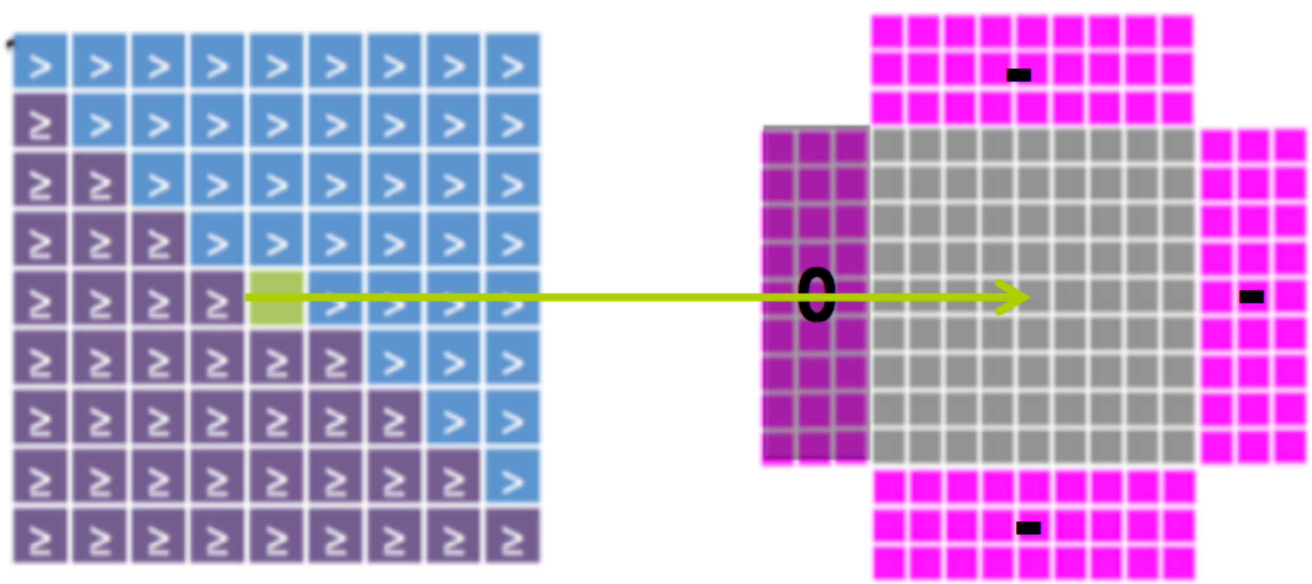
- Single CaloJet with a high pT (offline 450 GeV)
- HTT (Summed CaloJets)
- MET

Ideal for local shape finding at Level-1 and b-tagging at HLT



Level 1 Trigger Object Identification: Jet/MET/Sums

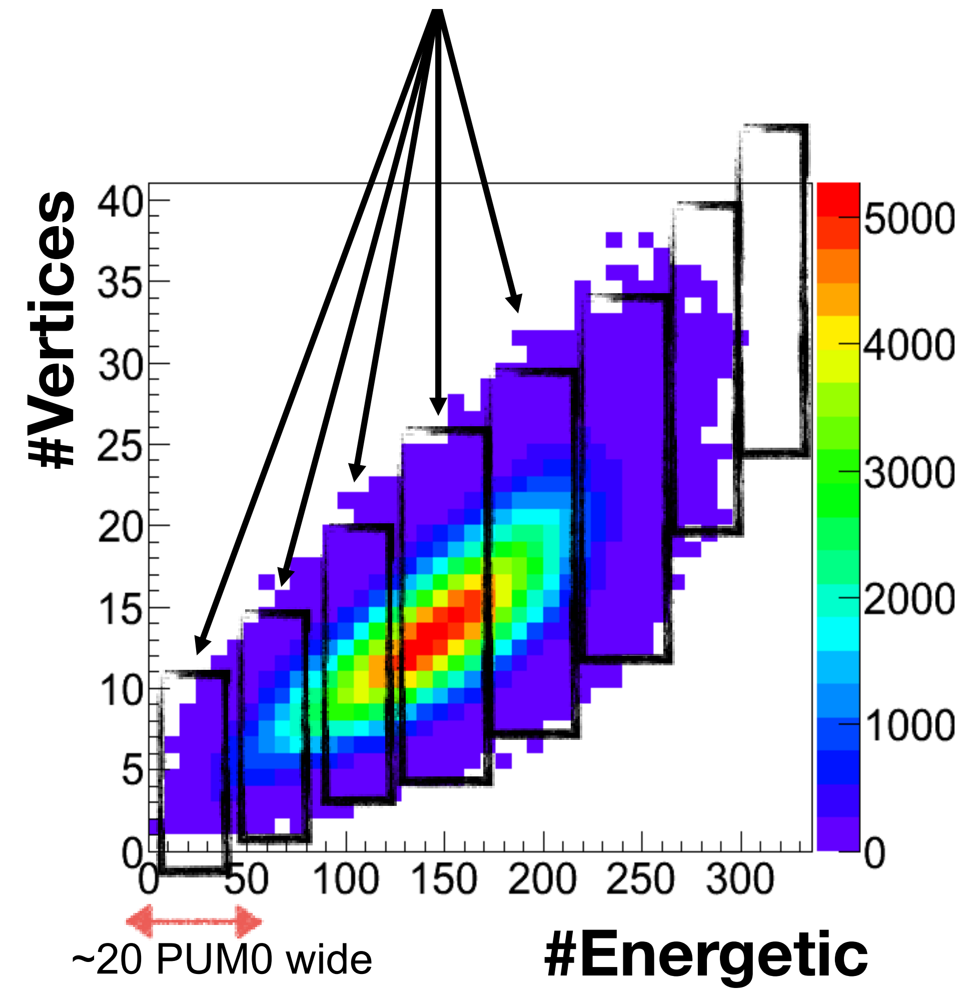
Jets and Sums Require Regional Information



Pileup subtraction

"Chunky-Donut"

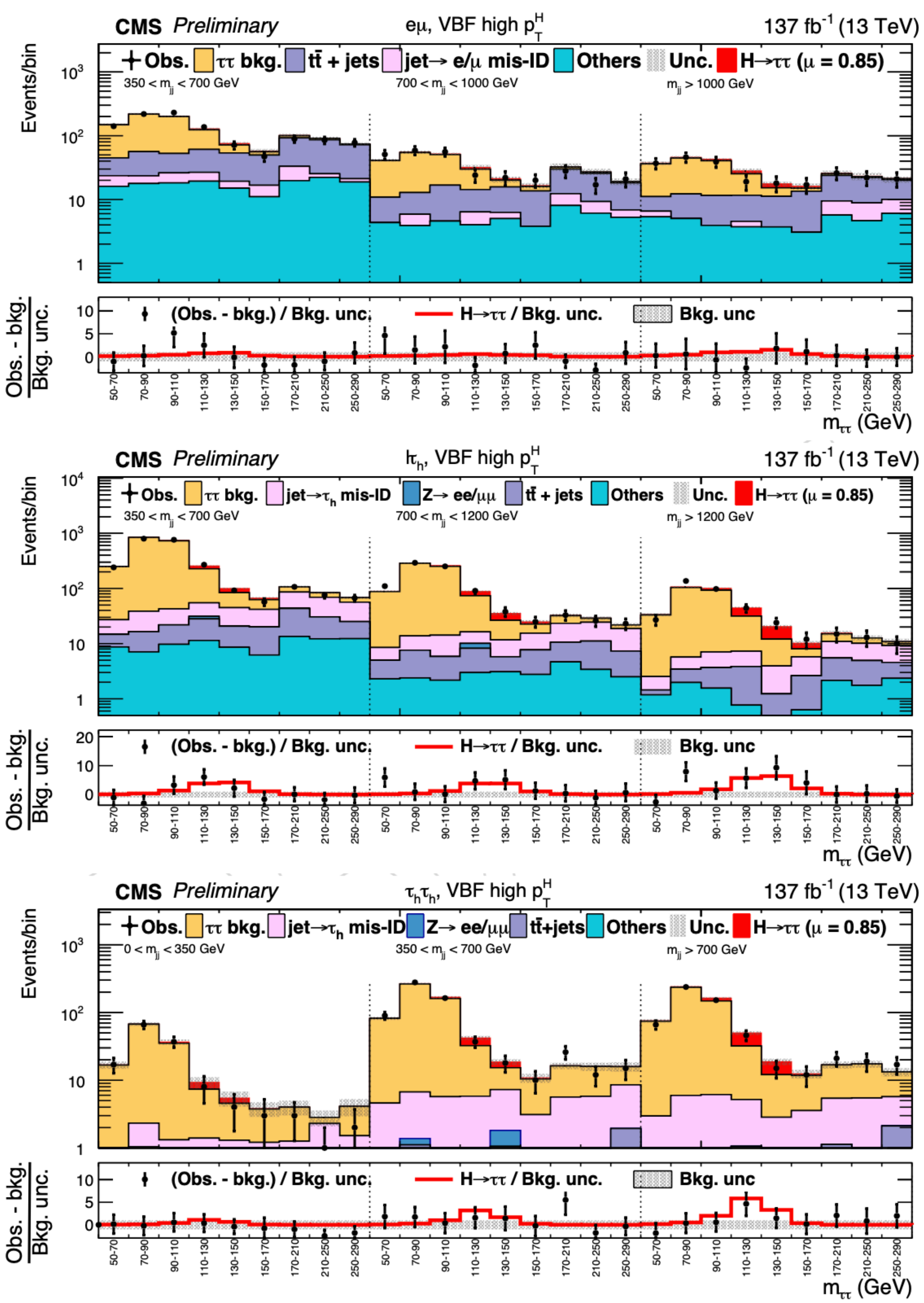
Strong Correlation



#Energetic Calo-Towers

- **Pileup Algorithms attempt to identify the number of p-p collisions per event and correct for the extra "noise"**
- **MET/Sums constructed from Summed Jets/Calo-Towers**

H ττ

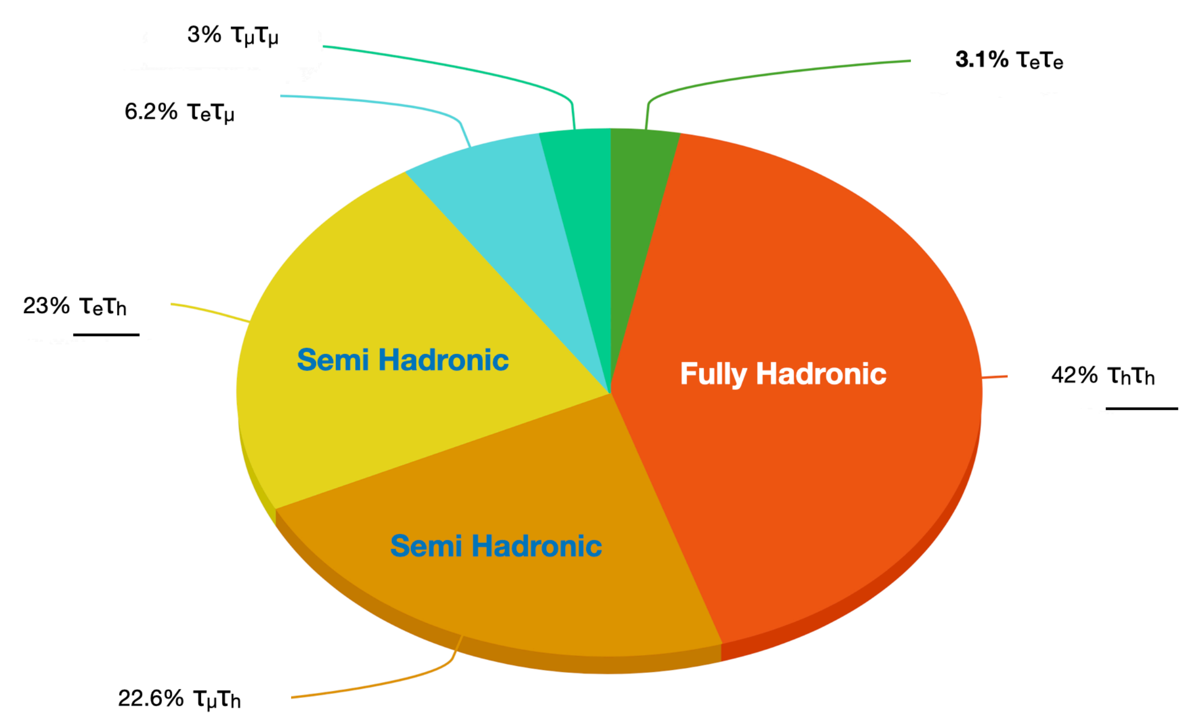


The Good:

- H→ ττ 6.3% branching fraction
- Relatively clean decay
- **Final state triggered directly**
  - Single Muon, Single Electron, Di-Tau

The Bad:

- Poor Mass Resolution
- Many backgrounds



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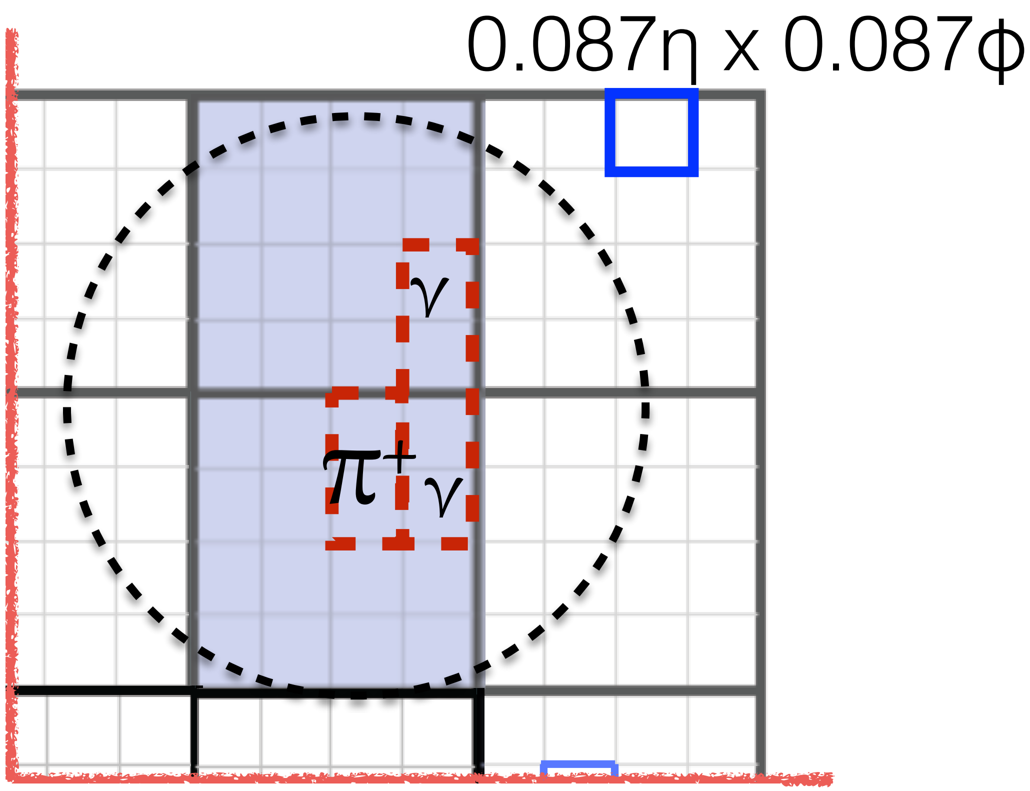
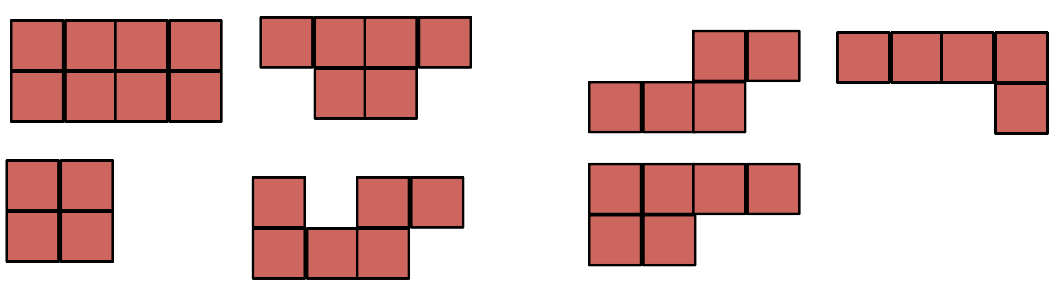
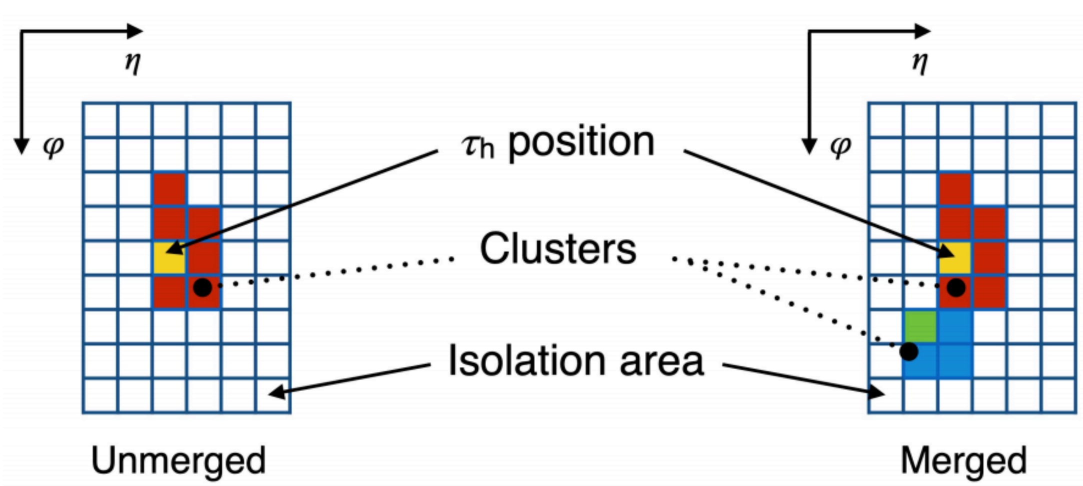






Cluster Finding:
Taus are stitched together using neighboring trigger towers

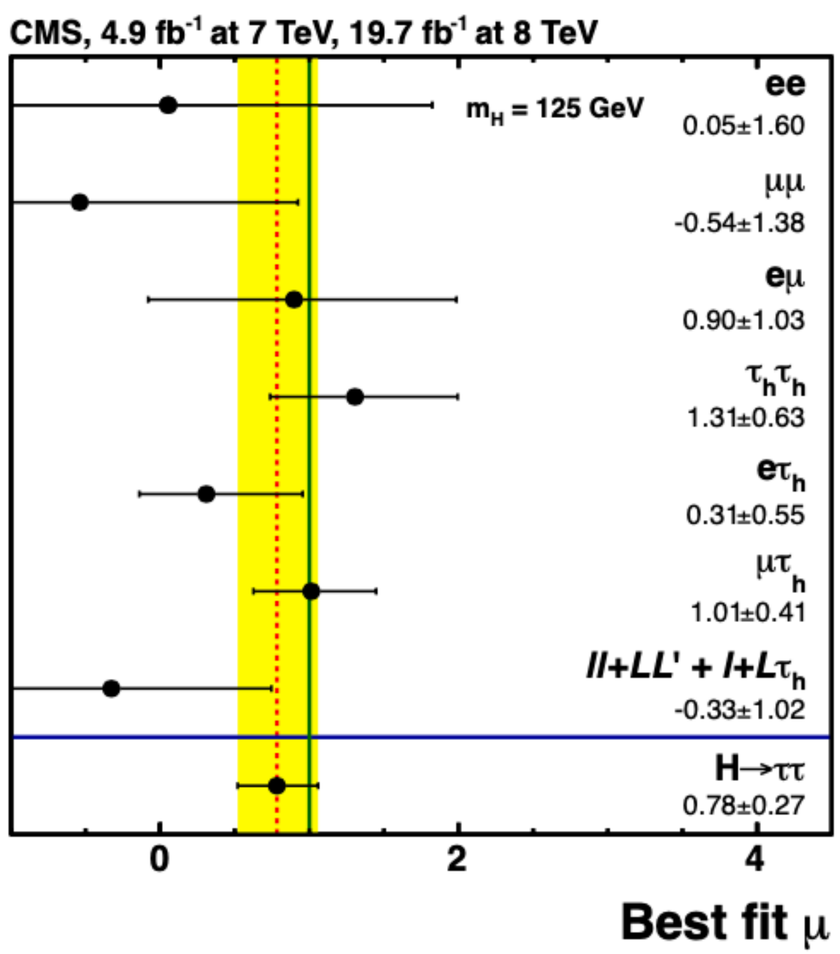
Shape Finding:
Require energy above **threshold** to be found in **specified patterns**

Isolation:
Candidate P_T/Surrounding P_T< Threshold

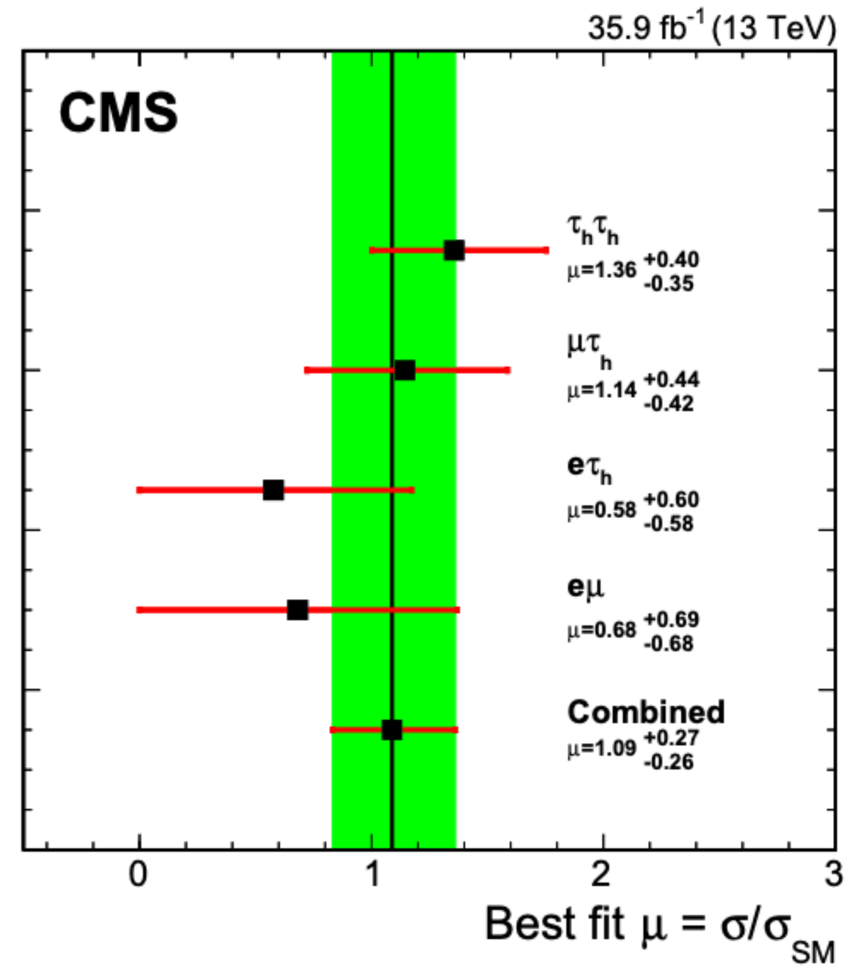
Iterative algorithms ("for loops" that need to process the same objects many times) are not optimal for Level-1 trigger design

Local shape finding "easy" to implement in low latency algorithms

Hadronic τ Trigger Improvement- Results



Run 1

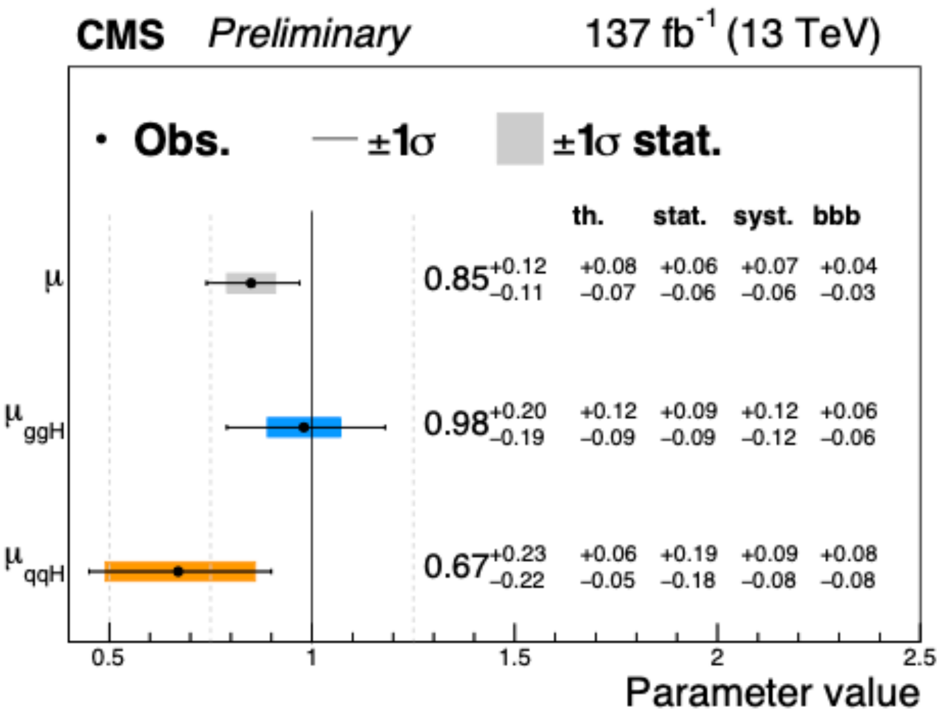


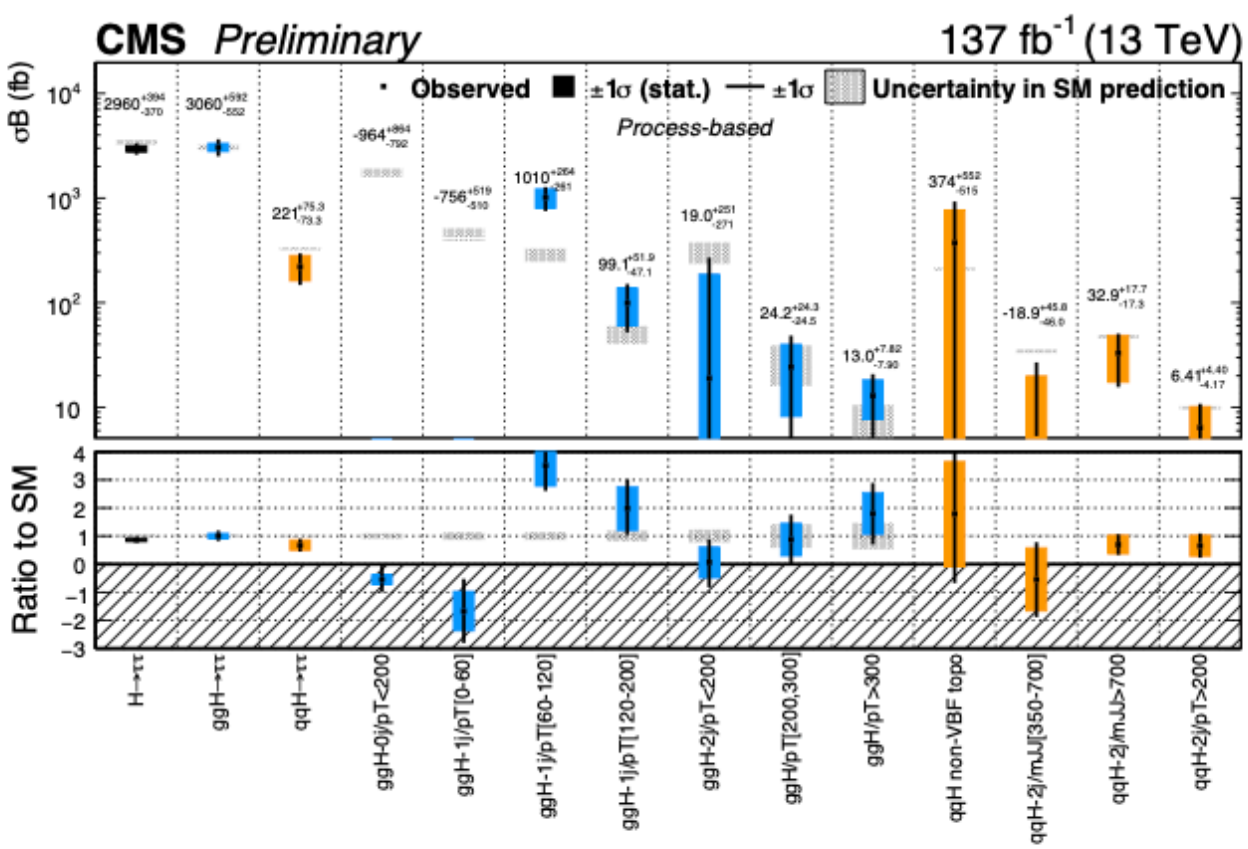
Run 2

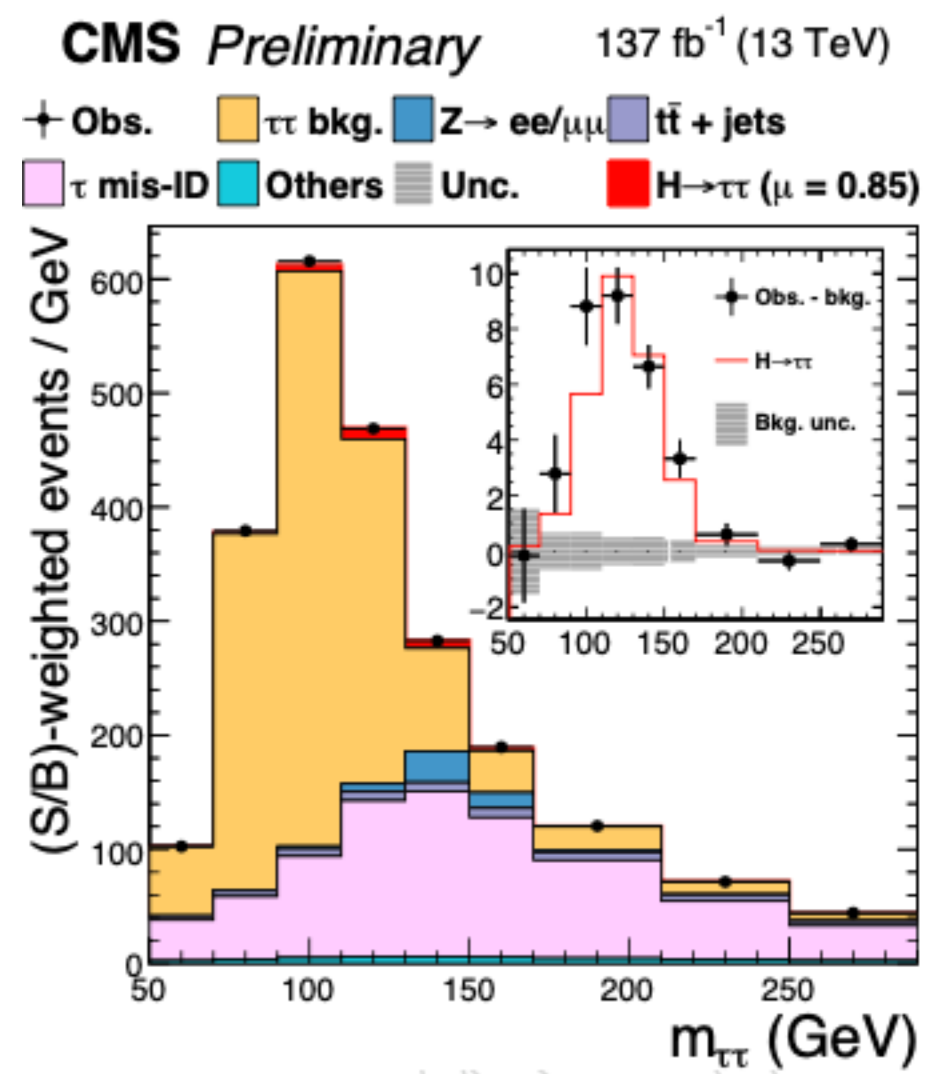
Level-1 Trigger upgrades between Run 1 and Run 2

Large improvement in double hadronic channel

Hττ Run 3- Results

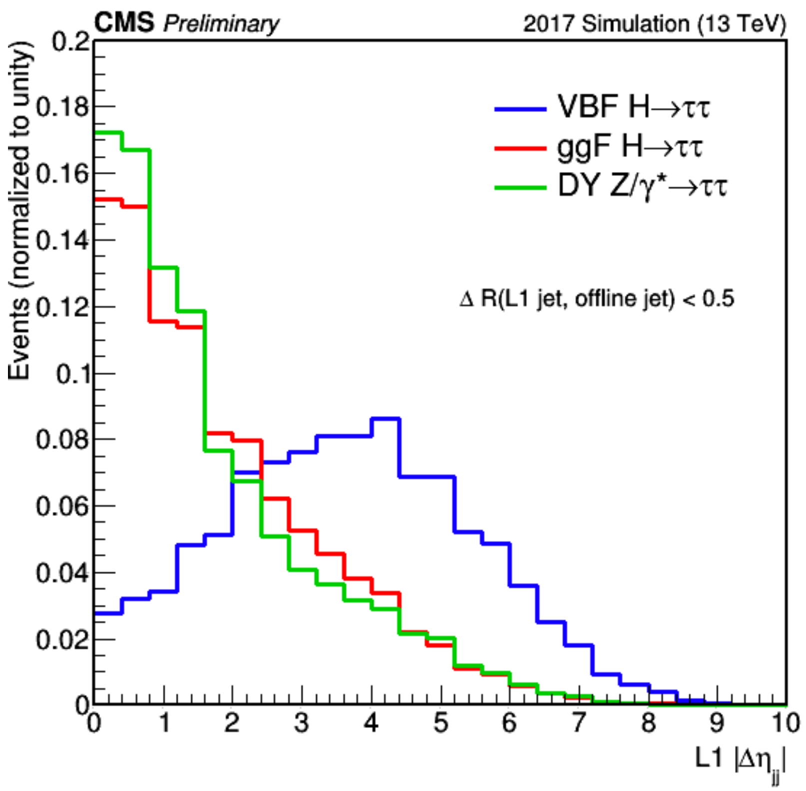


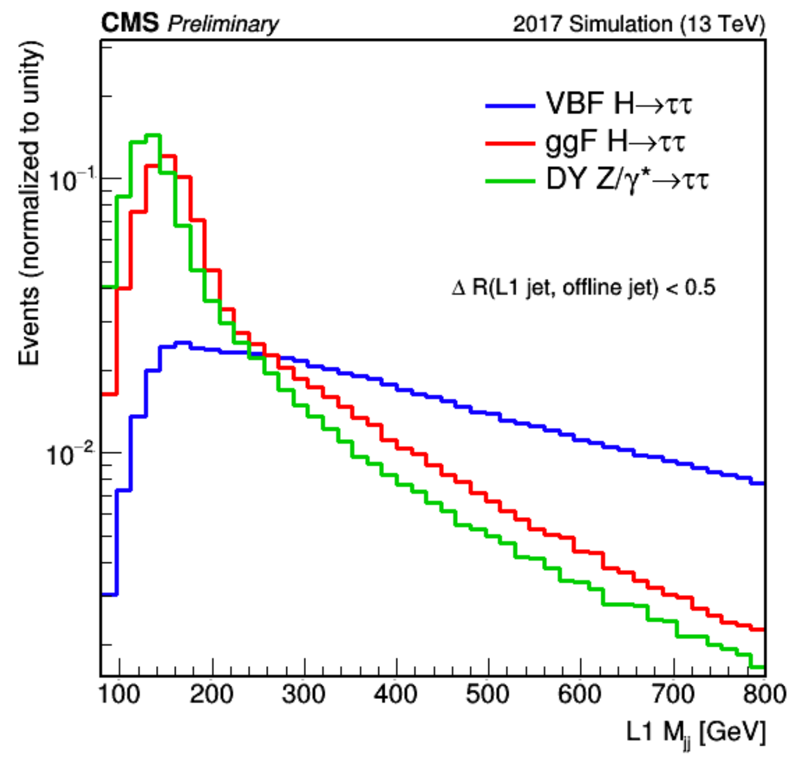


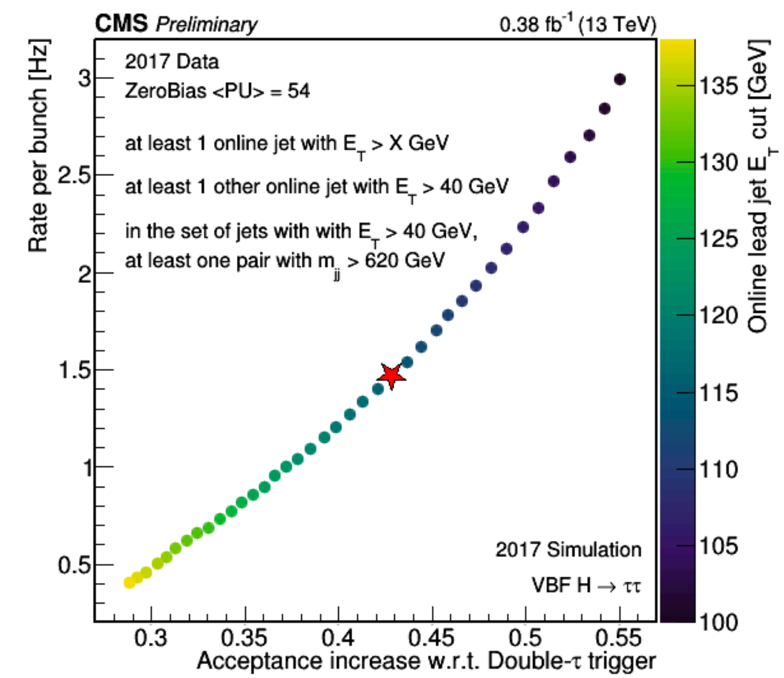


CMS-HIG-19-010

VBF Hττ Trigger Strategy



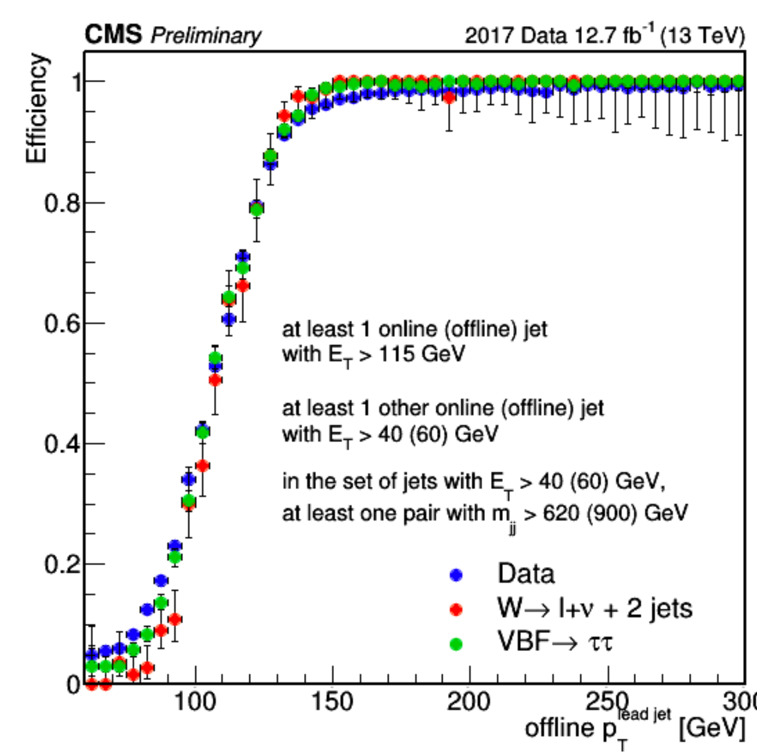




Available for Run-2

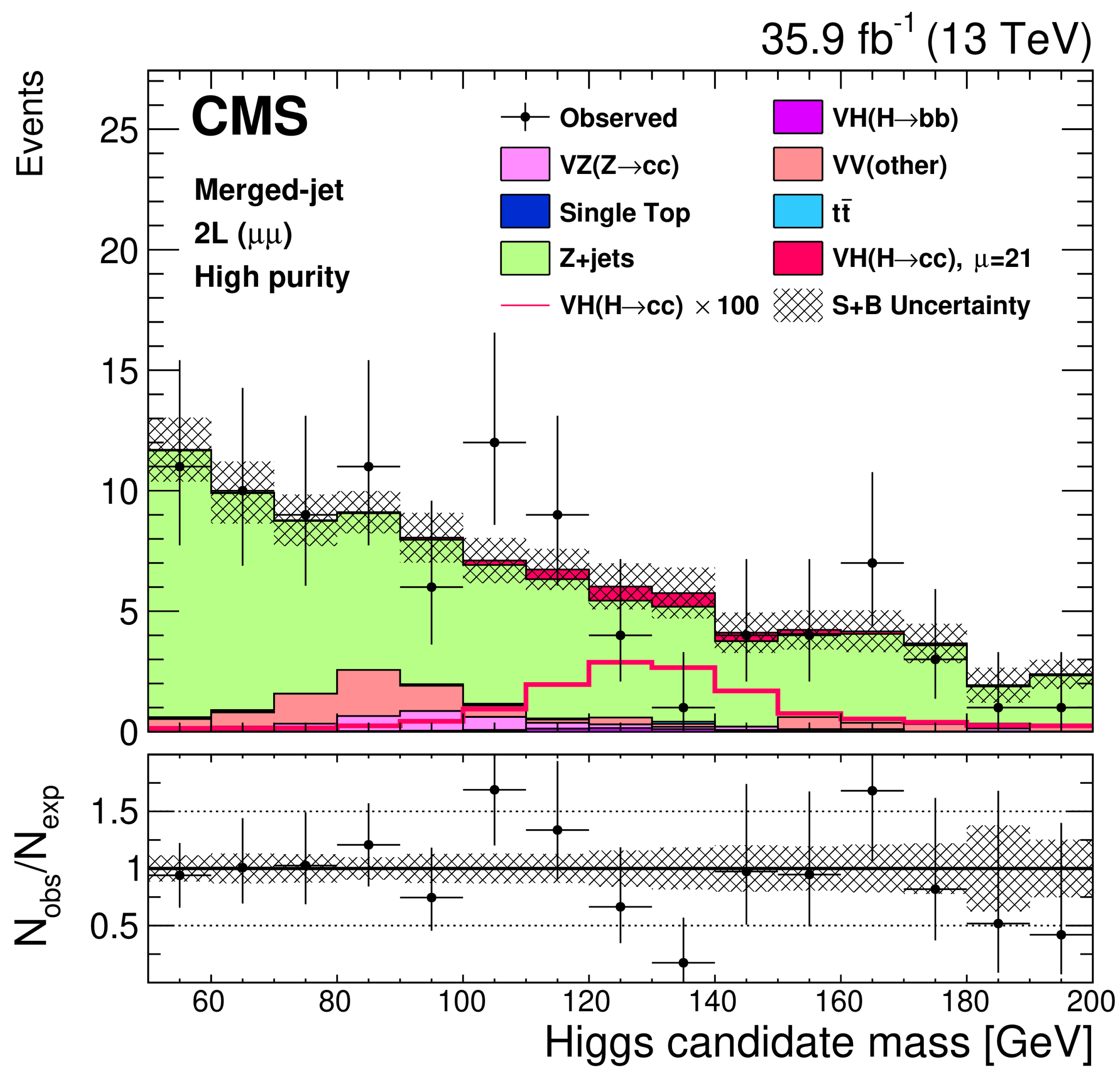
But, the Standard Model analysis used only the Single Muon, Single Electron, Double Hadronic Triggers

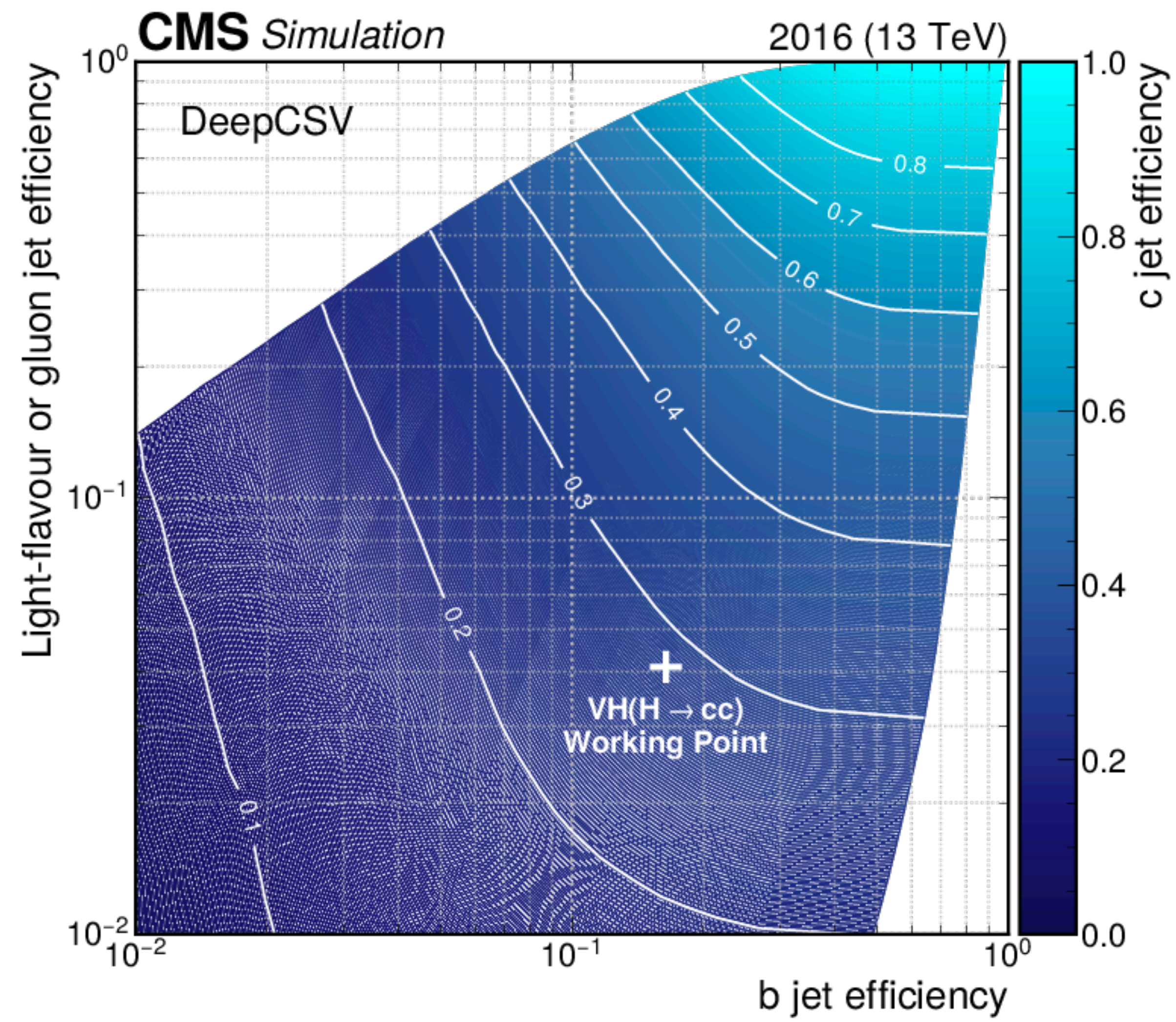
Under consideration again for Run 3



[Link](#)

2nd-Generation Fermion Coupling: H→cc





	obs(exp) UL
ATLAS (36/fb Run 2) Z→ ll + H → cc	110 (150)
CMS (36/fb Run2)	70 (37)
HL-LHC Prospects	UL < 6.3 (using ATLAS Run 2)

Direct H→cc searches targets ZH/WH production

Similar trigger strategy to VH bb

Looking Forward

New opportunities going forward

- **(More) Powerful FPGAs (primary processors)**
  - Flexibility in current trigger system, new hardware being developed
- **Better understanding of Standard Model Physics**
  - Better understanding of Hadronic Decays (τ-leptons)
  - Jet Substructure Techniques
  - Machine Learning Algorithms

High Level Synthesis: Automated design process
- Interprets algorithm specification (often written in C++ or Python) and creates RTL code
- Relatively easy to use!

New techniques under development
- Bringing more ML techniques online
- Event Level Analysis of High-level
- Data Scouting

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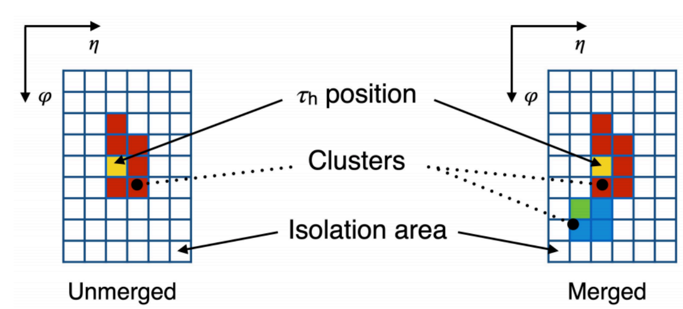
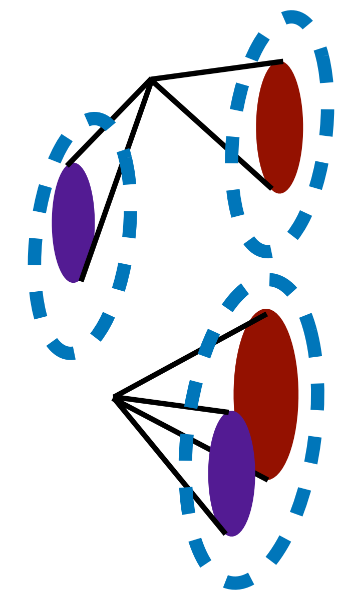
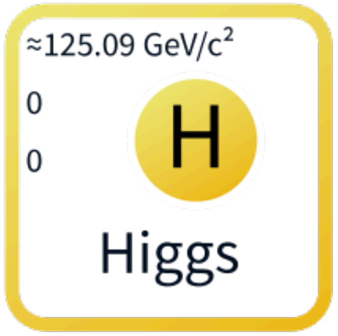




What do we need?
Algorithms that exploit local topologies
Transformation of complex offline algorithms to simple online algorithms

Exciting times for Hadronic Higgs



Fundamental New Discovery

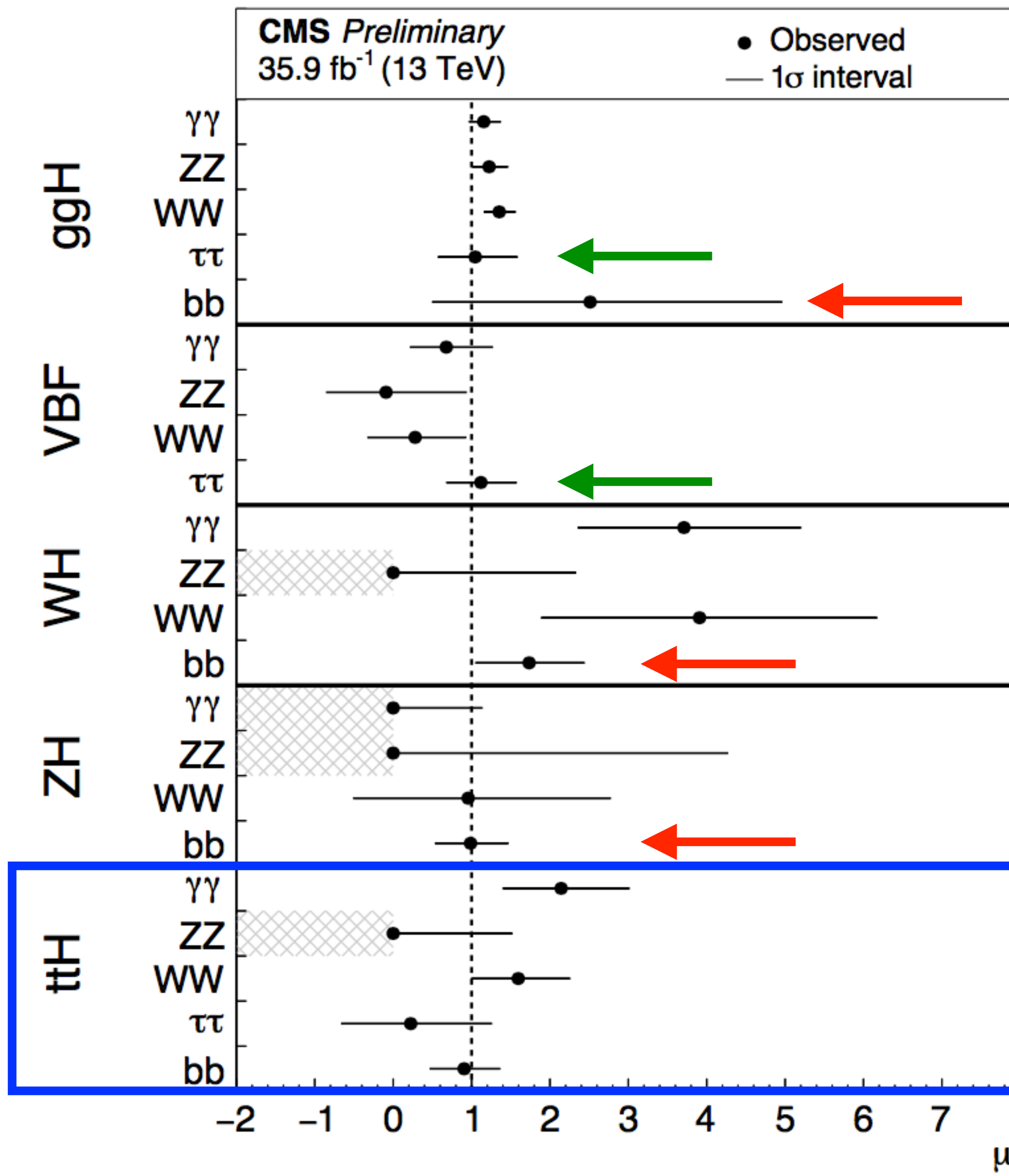
→ *Represents a Window to the Unknown*

Using **Run I + Run II Data** we have **measured well the Higgs properties** using **H→ZZ** and **H→γγ**

Discovered H→bb

Discovered ttH production

Discovered H→ττ



Remains important to study carefully this particle
But Also, Measure/Search for more Couplings (Production and Decay), Self Coupling, Rare Decays, Exotic Decays

Performance studies are used to motivate upgrade efforts!!

Questions/Comments/Discussion