Triggering Discoveries at CMS

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Overview

Calorimeter Trigger at CMS

Brief word on Operations

- More to come later!

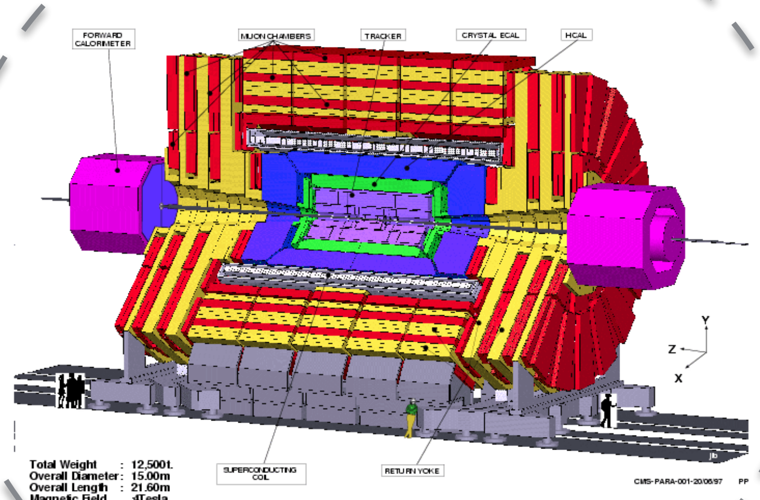
Standard Model Measurements

Higgs Discoveries

Beyond the Standard Model Searches

Trigger Overview

Data is selected for offline analysis with the 2-tiered **trigger system**



40MHz Collision Rate
~1 MB/event

Level 1 Trigger

Coarse Calorimeter Readout
No Tracking Input! **Very Fast!**

L1A 100kHz

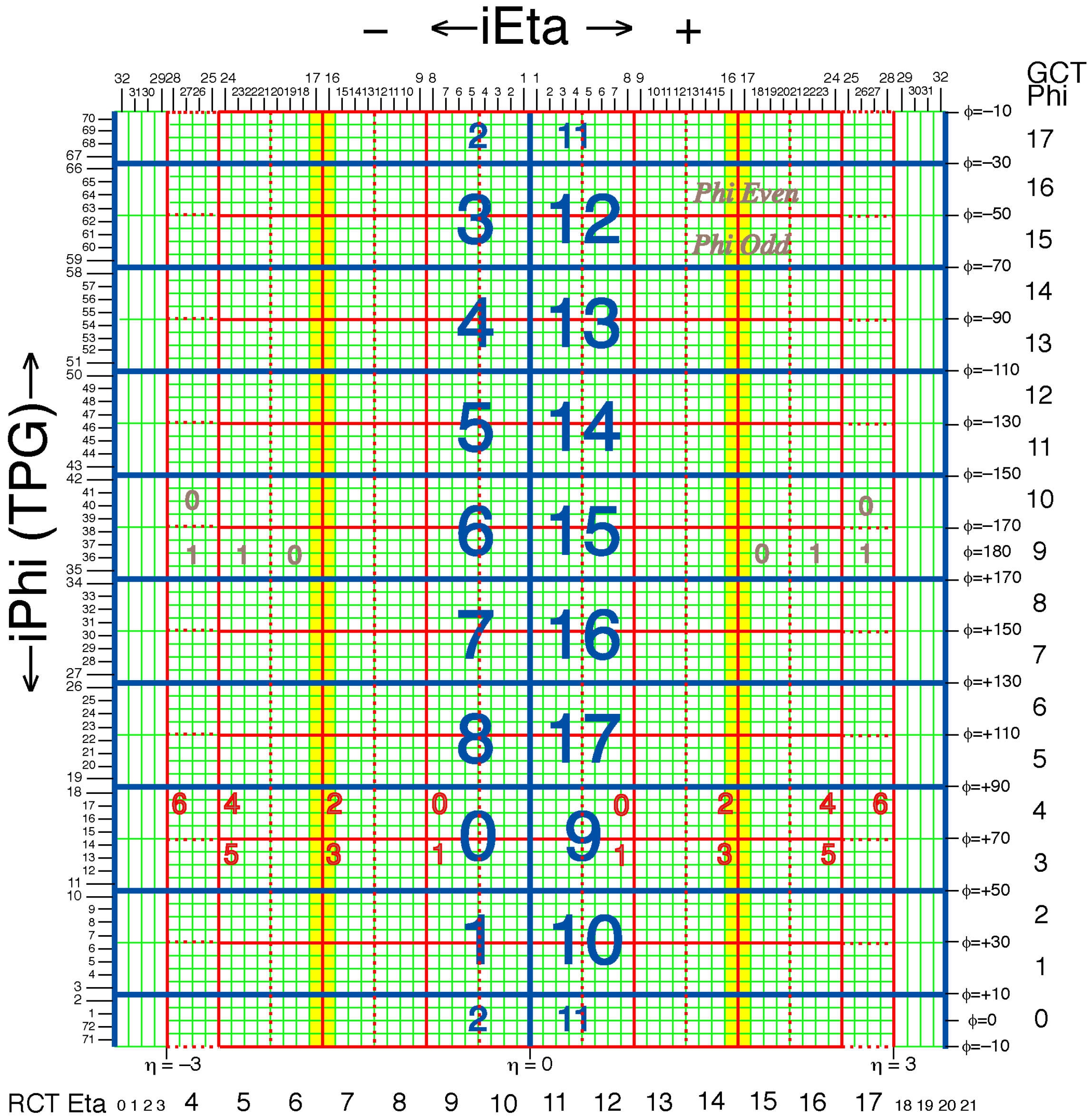
High Level Trigger

Full Detector Information
Available -> trade off: Fast Algos

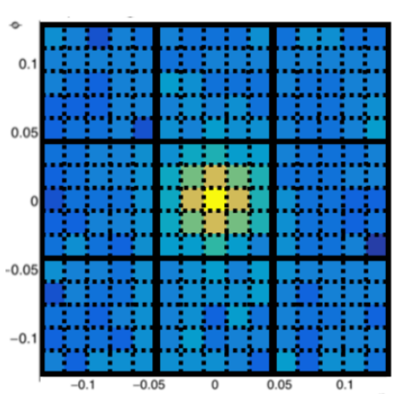
Final Decision ~1 kHz

Full Detector Readout for RECO and Offline Analysis

Regional Calorimeter Trigger



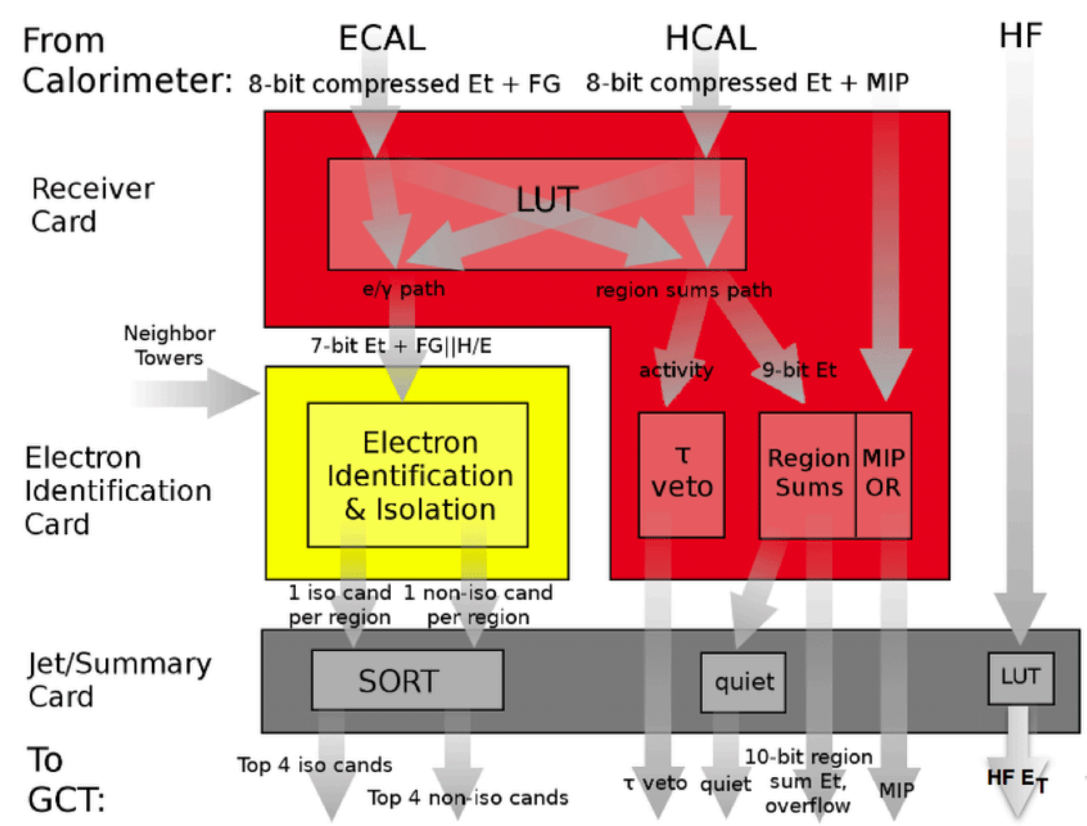
Blue is crate boundary/number
Red is card boundary/number (dash - region split)
Gray is region number
Green line is tower boundary
Yellow is barrel/endcap overlap region



System Designed for Fast Pattern Recognition!

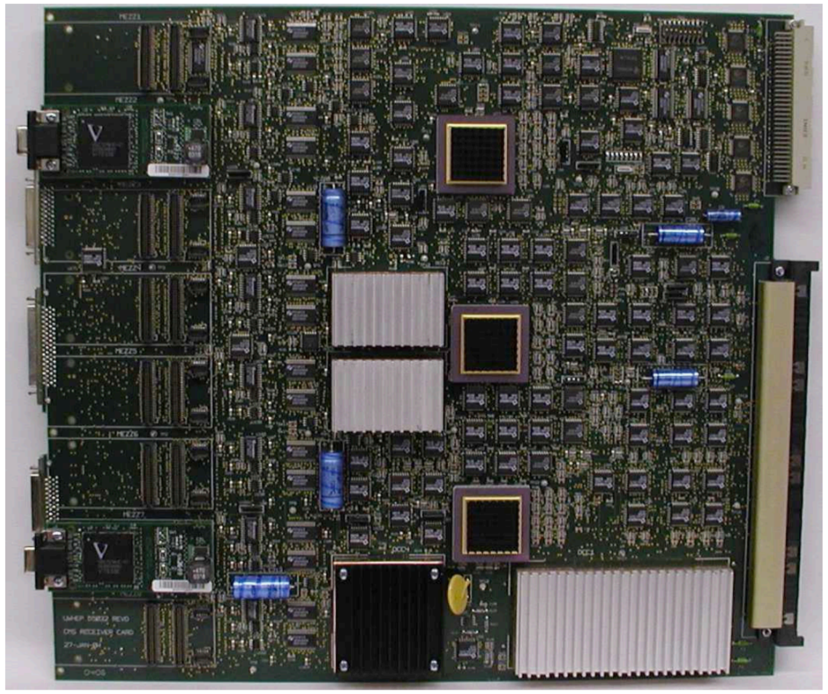
Completely installed since 2007
RCT divided into 18 Crates
- 2 crates in eta x 9 crates in phi

Each crate's data processing is handled by:
- 7 Receiver Cards
- 7 Electron Identification Cards
- 1 Jet/Summary Card

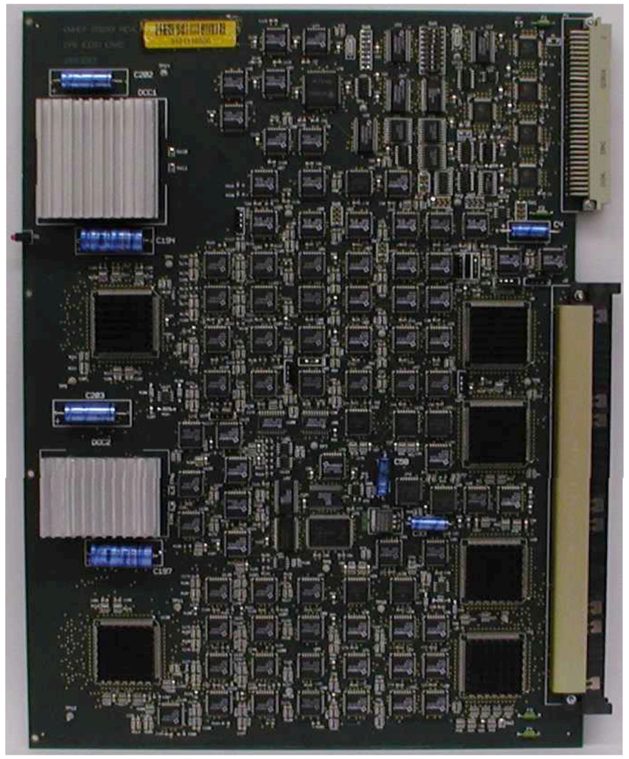


Regional Calorimeter Trigger

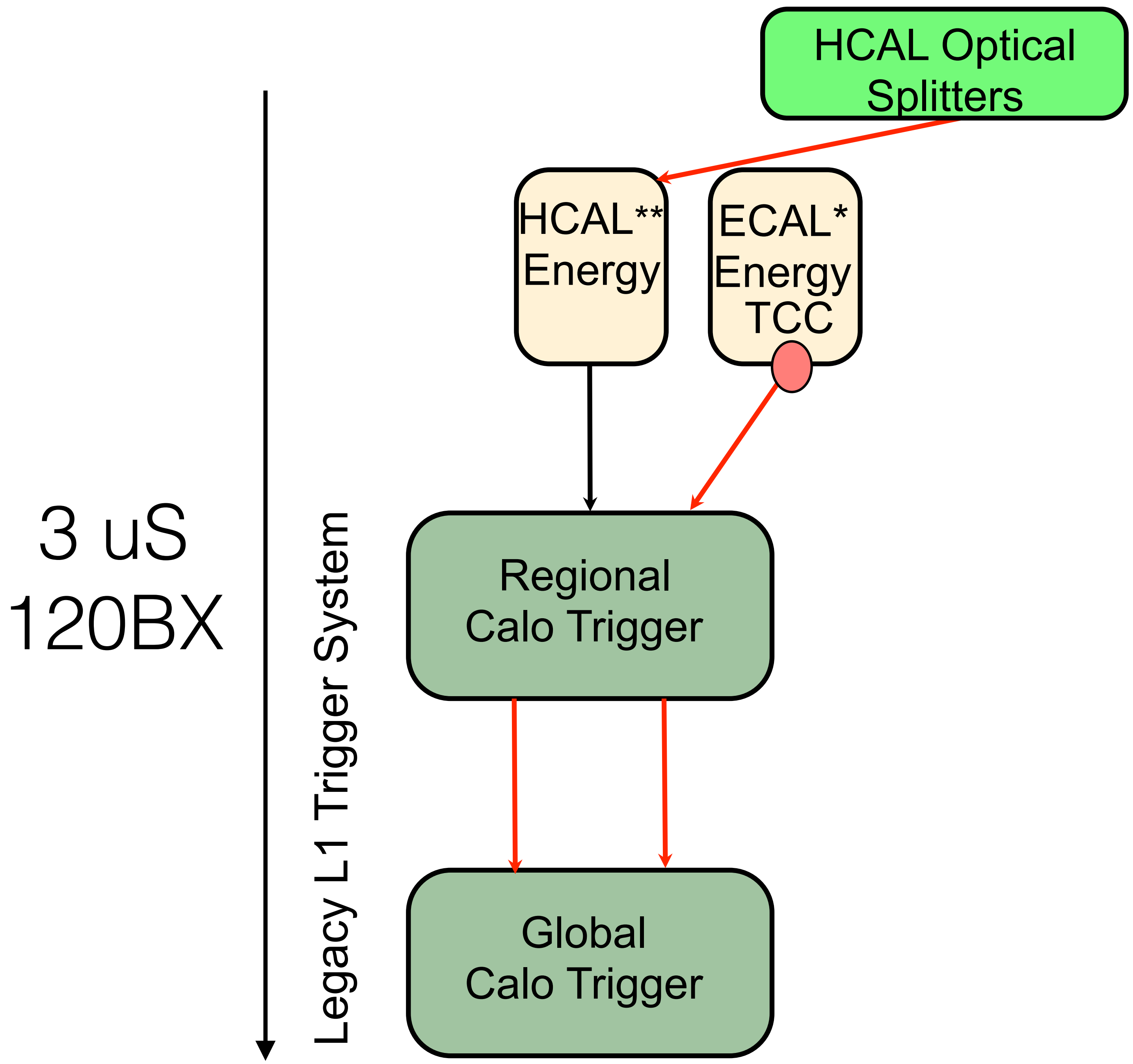
Receiver Card



Electron Identification Card

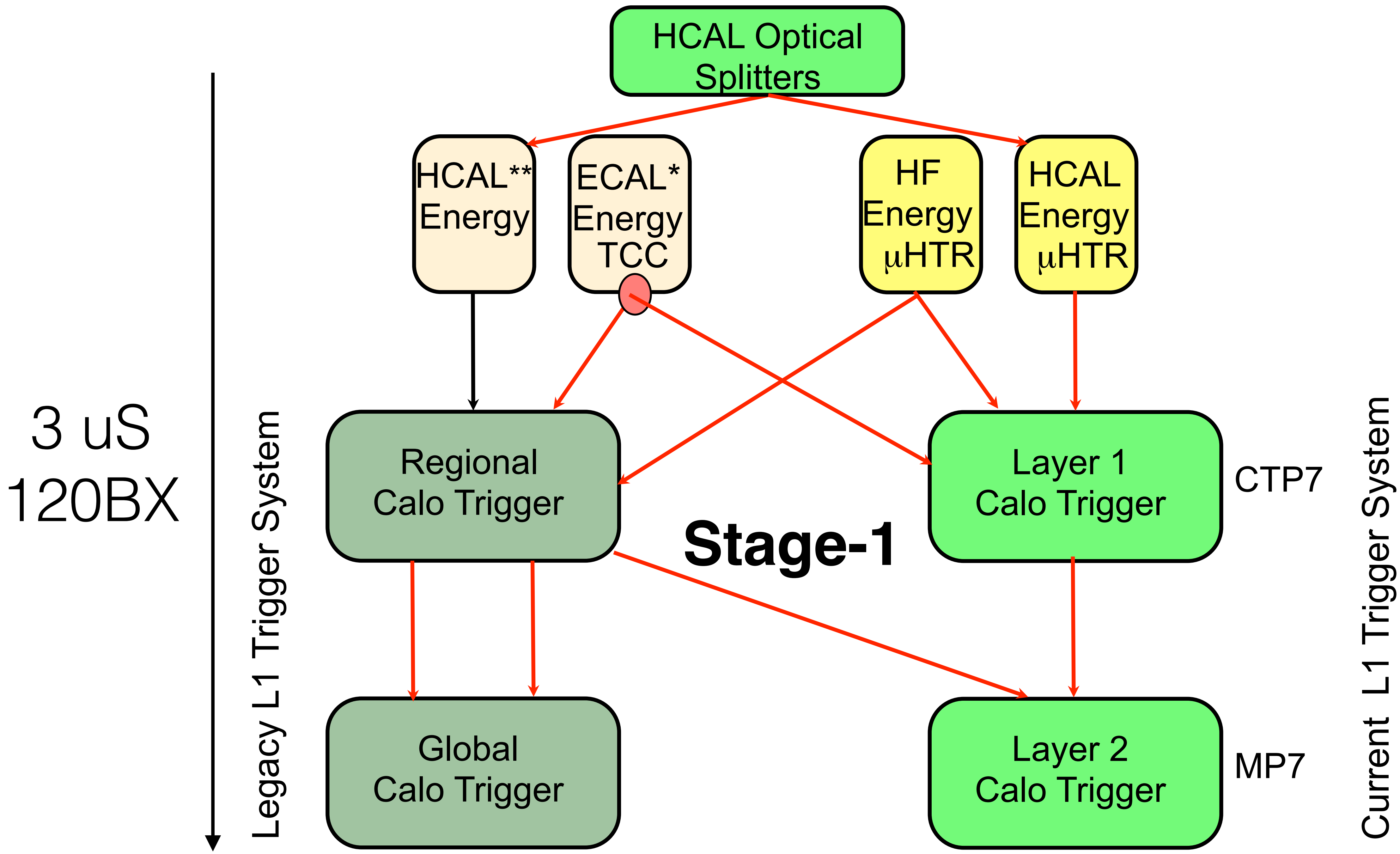


Calorimeter Trigger Design Run I System



- Coarse inputs from the Calorimeters
- Generate a trigger within 3 uS at a max rate of 100kHz

Calorimeter Trigger Design Current (Run II) System



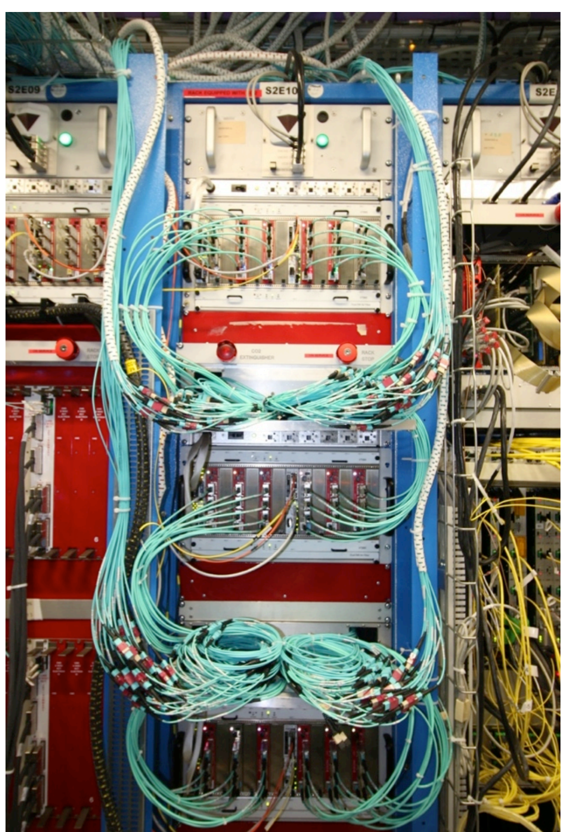
After running successfully during LHC Run 1 the Calorimeter Trigger underwent a series of upgrades

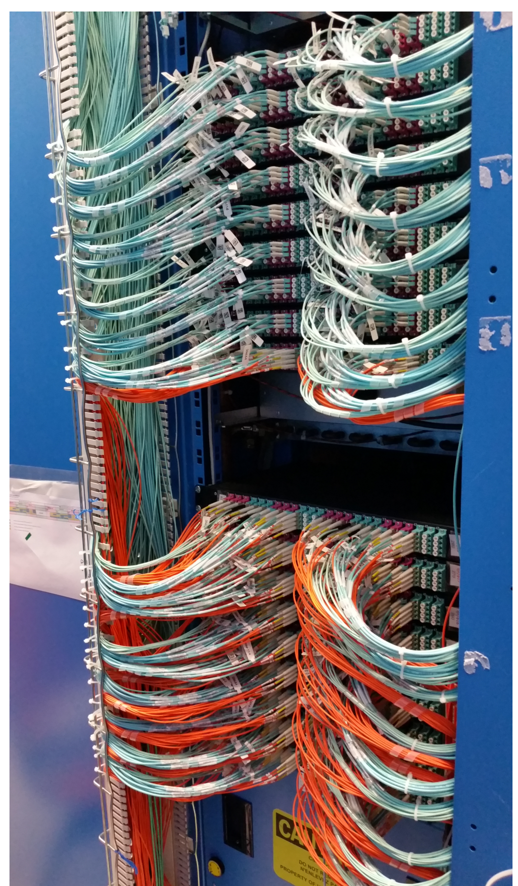
Calorimeter Trigger in Run 2

oRSC - Optical Regional Source Card allowed us to redesign algorithms and make use of Phase-1 technology before full Phase-1 installation

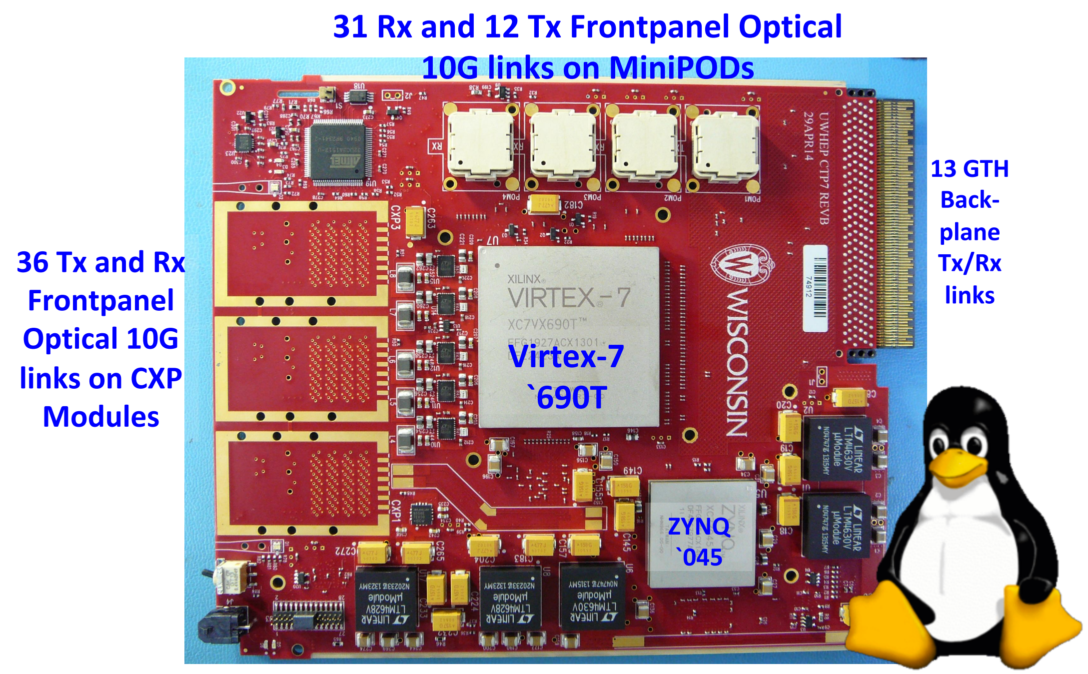
2015

Layer-1





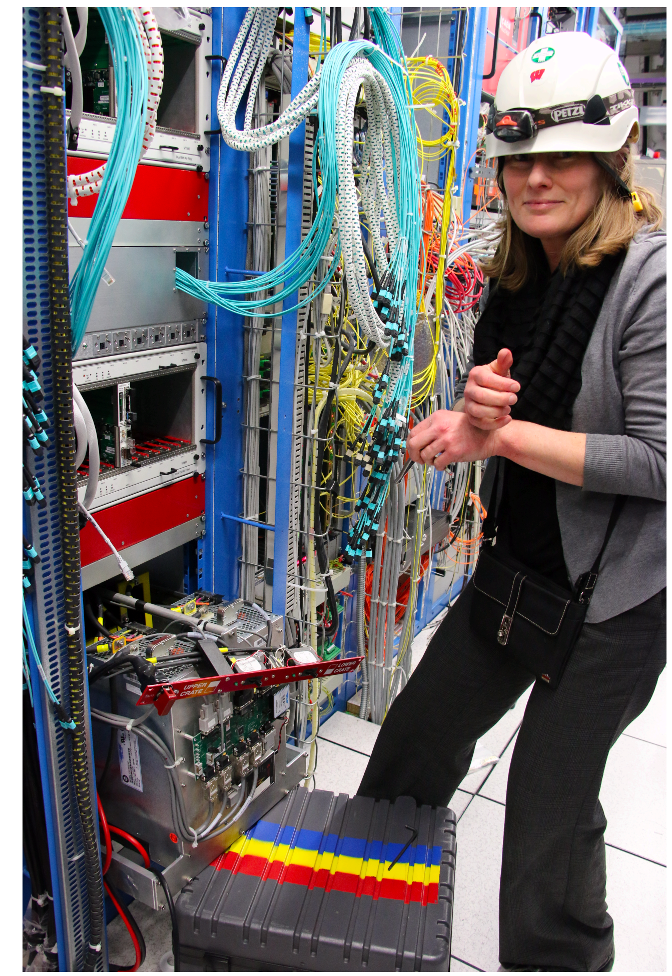
2016-2018



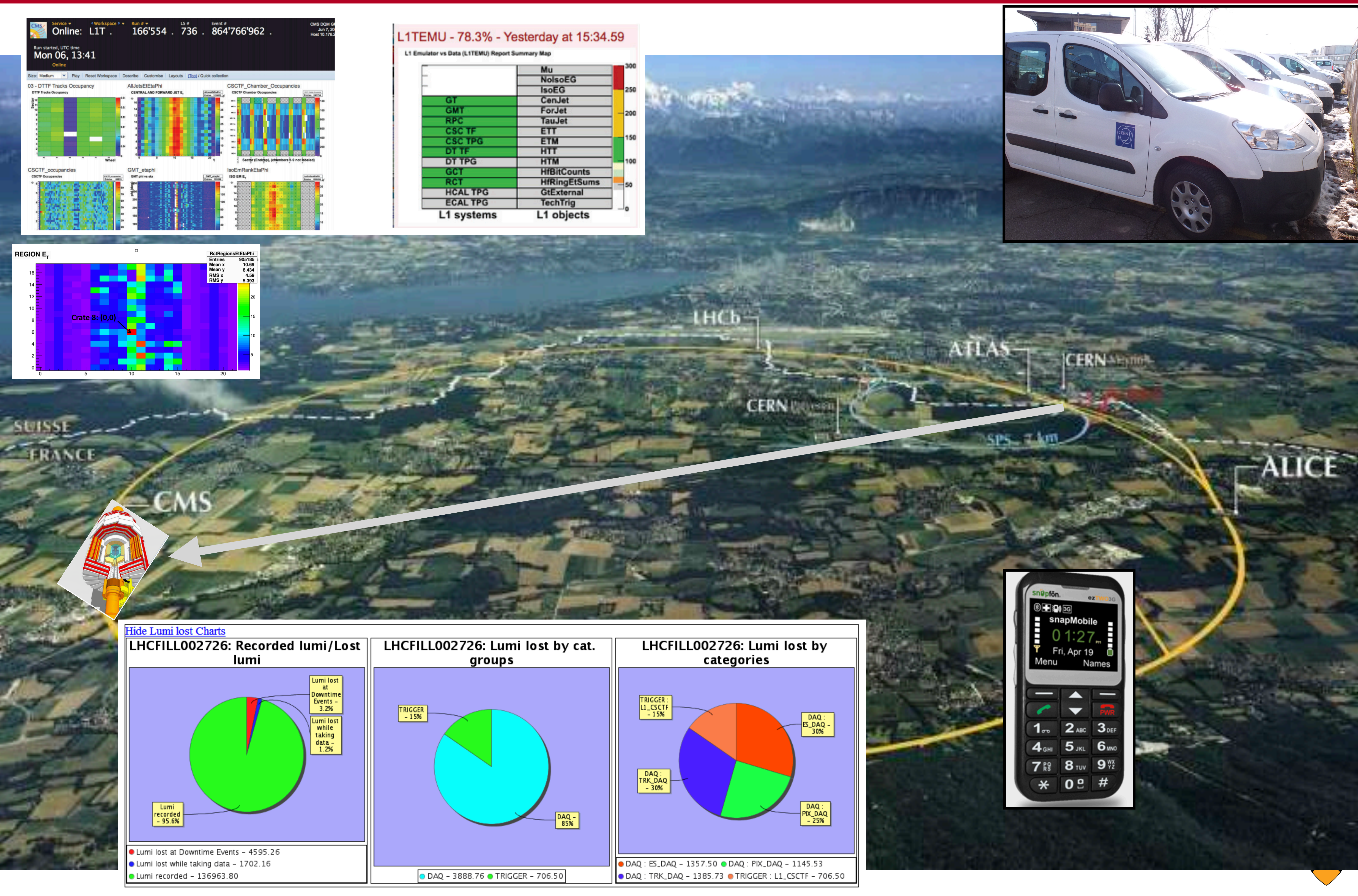
Calorimeter Trigger Processor-7 (CTP7) designed and built by UW engineering was the first card to run onboard Linux at CMS!

Trigger work as a Post-Doc for Wesley

- Please see Pam’s talk for more about Operations!



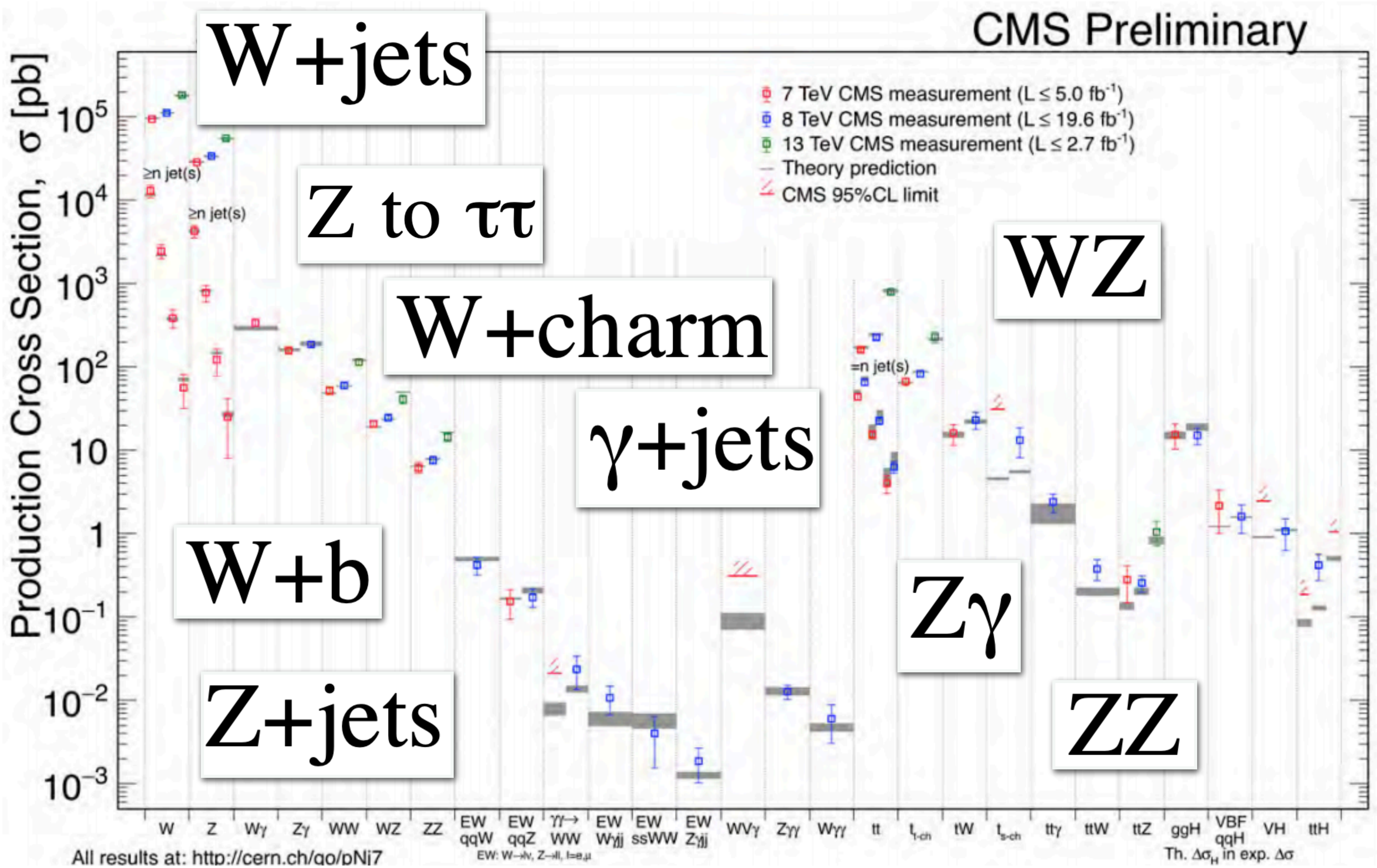
Students' Role in the Trigger System



Wesley's Students' Analysis Work

All students on CMS (in my era) were required to perform one ***Standard Model Measurement*** *and one* ***Beyond the Standard Model Search***

Standard Model Measurements

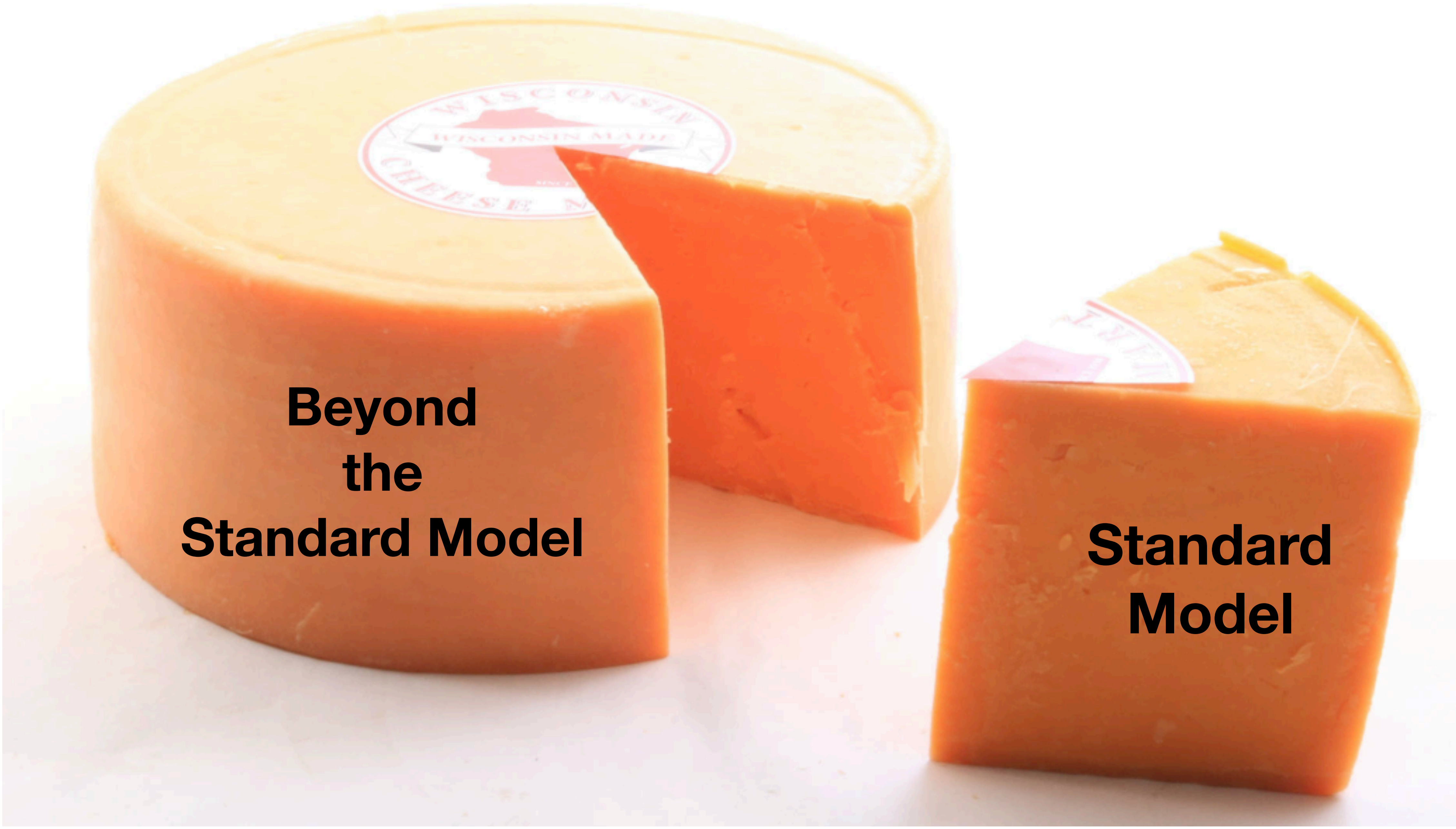


These measurements have led to new physics searches for additional
Higgs bosons and dark matter


WISCONSIN
WISCONSIN MADE

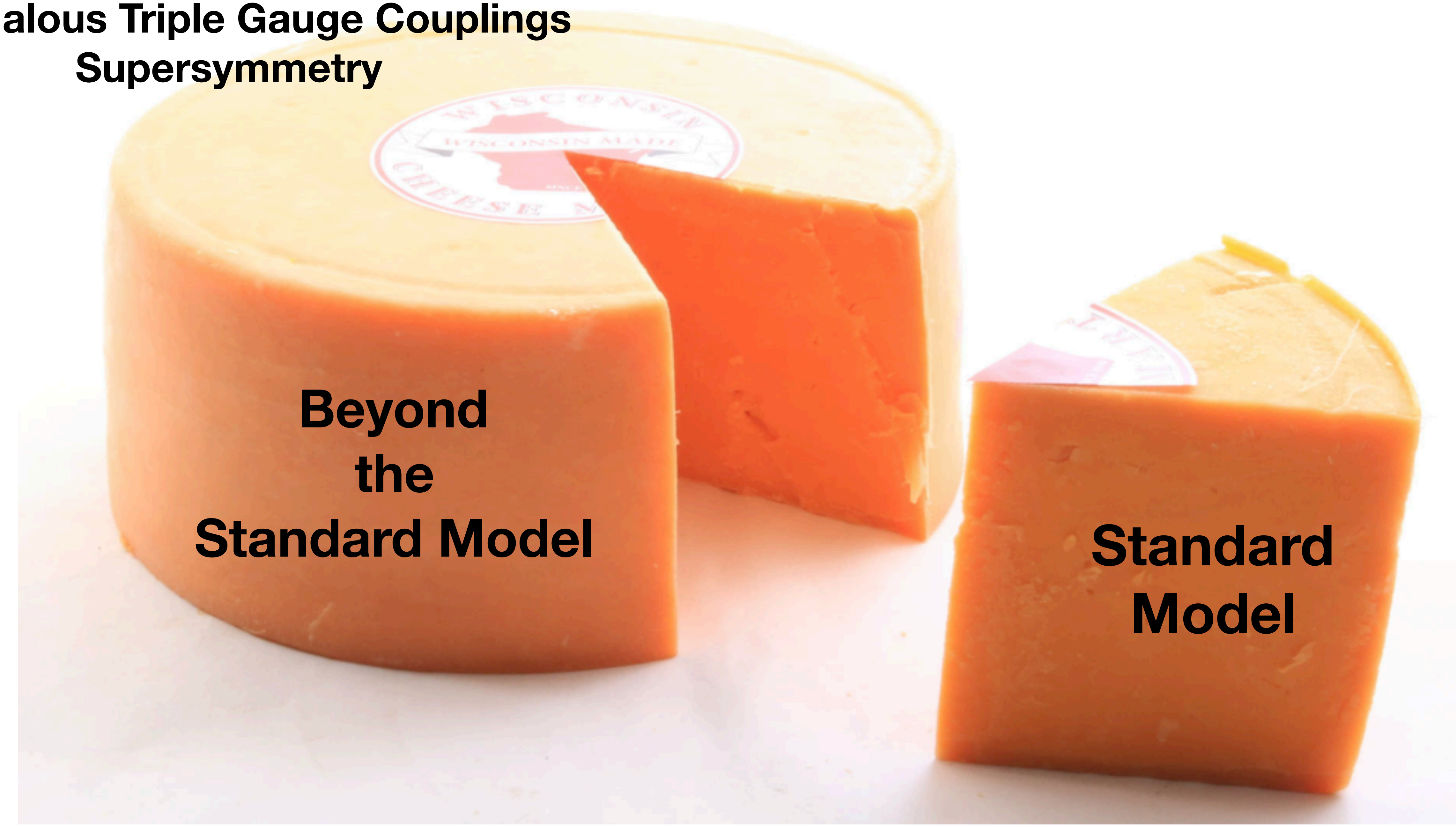
Beyond the Standard Model Searches

Beyond the Standard Model Searches



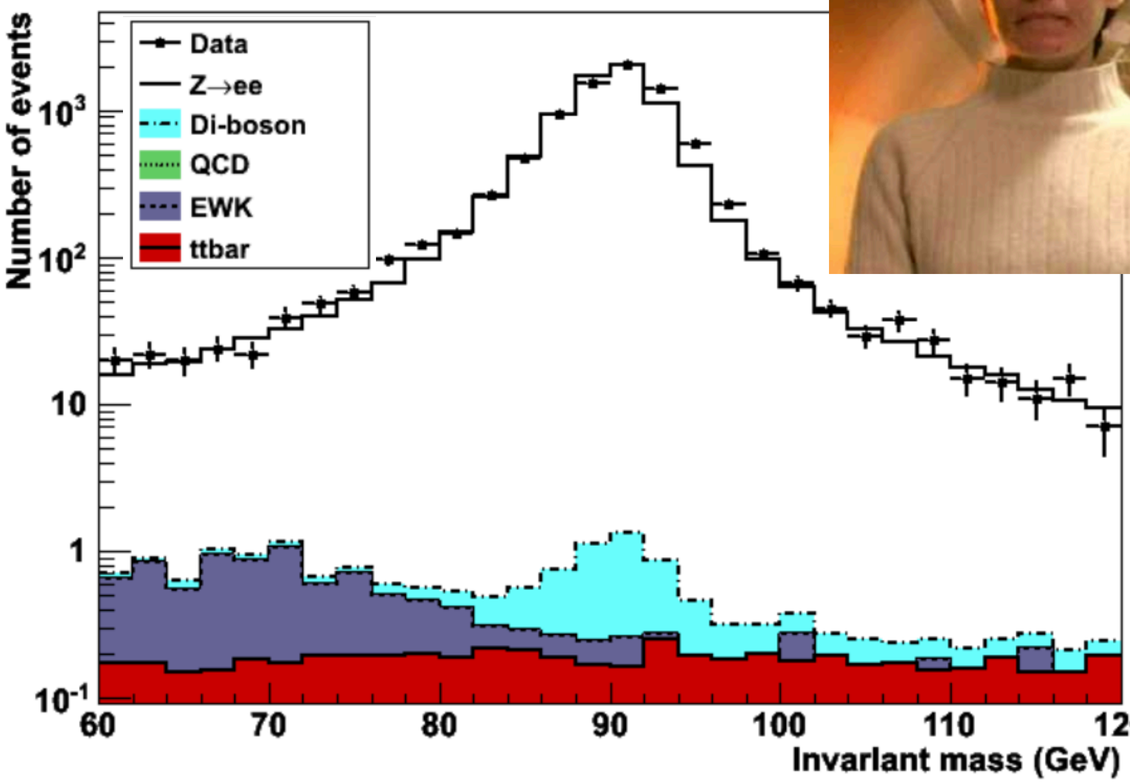
Beyond the Standard Model Searches

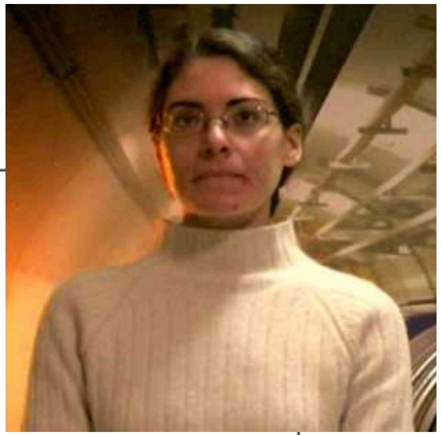
Searches for Dark Matter,
Anomalous Triple Gauge Couplings
Supersymmetry



Precision Tests
Understand QCD, Electroweak
Measure EWSB

First Measurements of Z→ee
- An important milestone for the experiment and for the LHC!





The agreement of these results bodes well for CMS:

The detector is well calibrated and can produce a solid measurement of standard model physics. This points toward a future of successful new measurements and exciting physics.

Quantity	Value
Luminosity $\mathcal{L}$	36.1 pb^{-1}
n_{total}	8453
$n_{background}$	19
Efficiency ϵ	0.610
Acceptance A	0.387

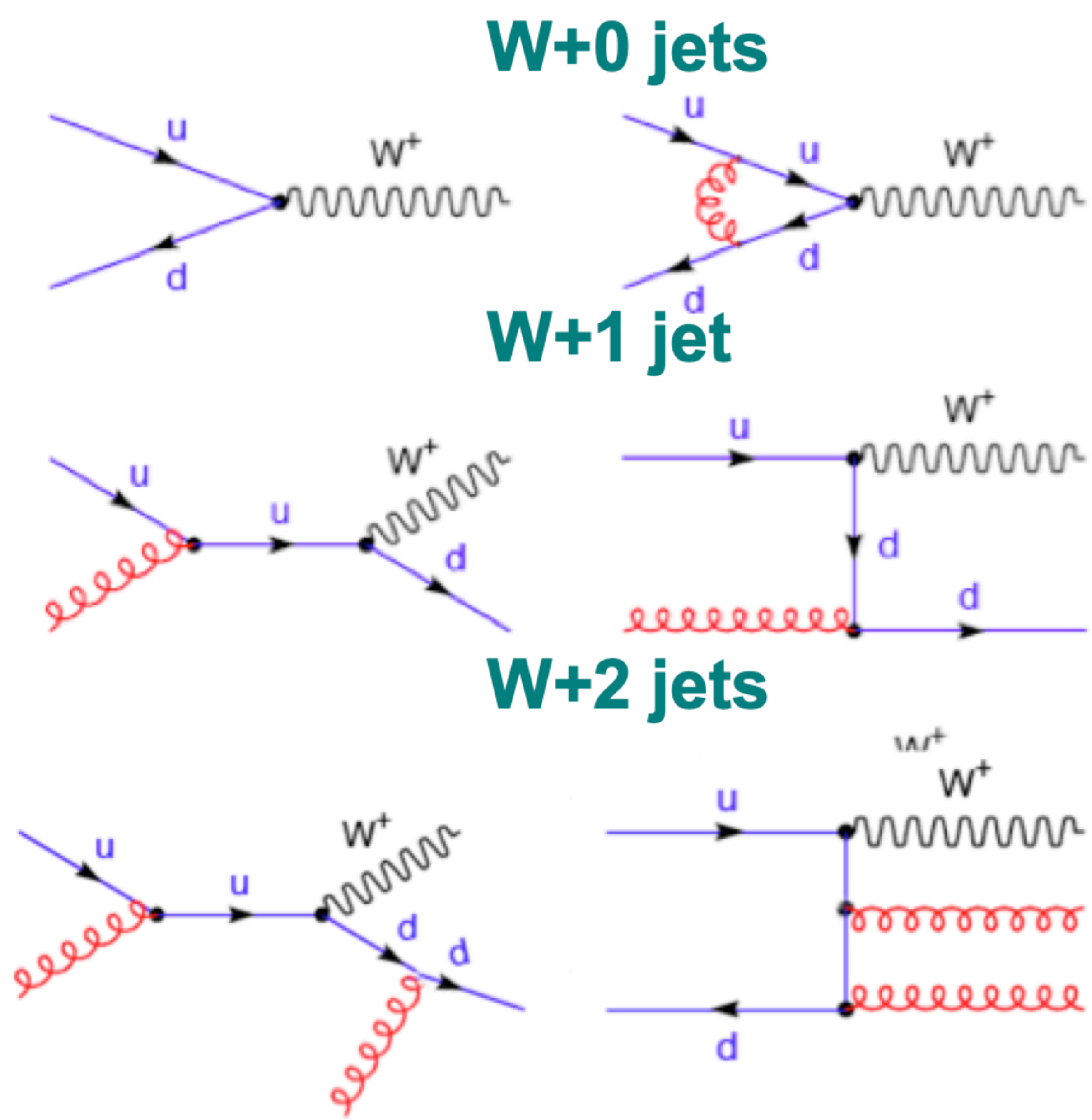
Goal: measure the rate of events with jets and a W boson decaying to an electron and a neutrino

- Inclusive rate of n jets (i.e., ≥ n jet), not corrected for acceptance
- Starting with ratio measurements where systematics uncertainties partially cancel

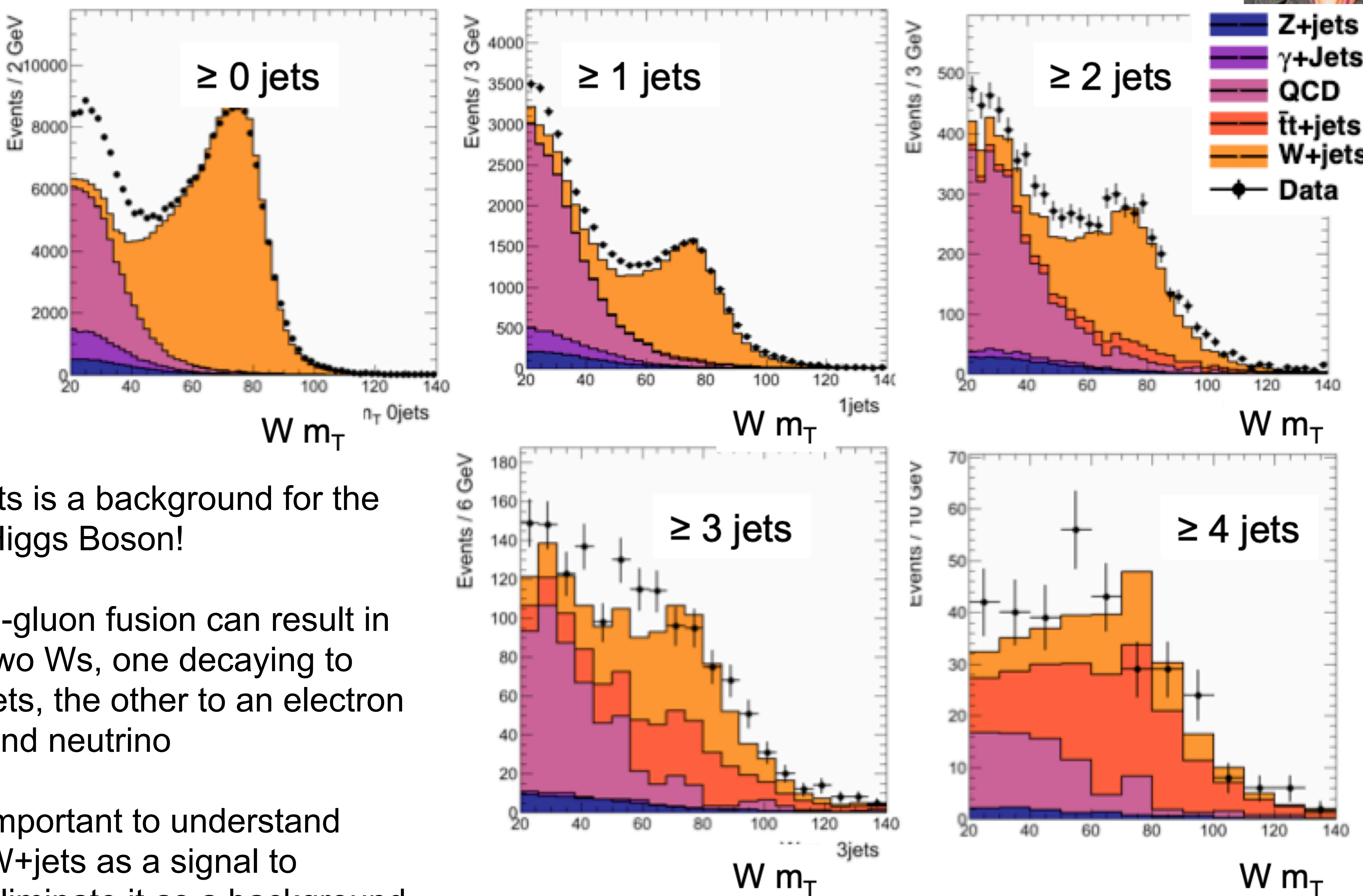
First Measurement of Electroweak Interaction at much higher energies

Test of perturbative QCD calculations

- Verification of theoretical cross-section and parton distribution functions (PDFs)



First Measurements of W+Jets at CMS - Kira Grogg

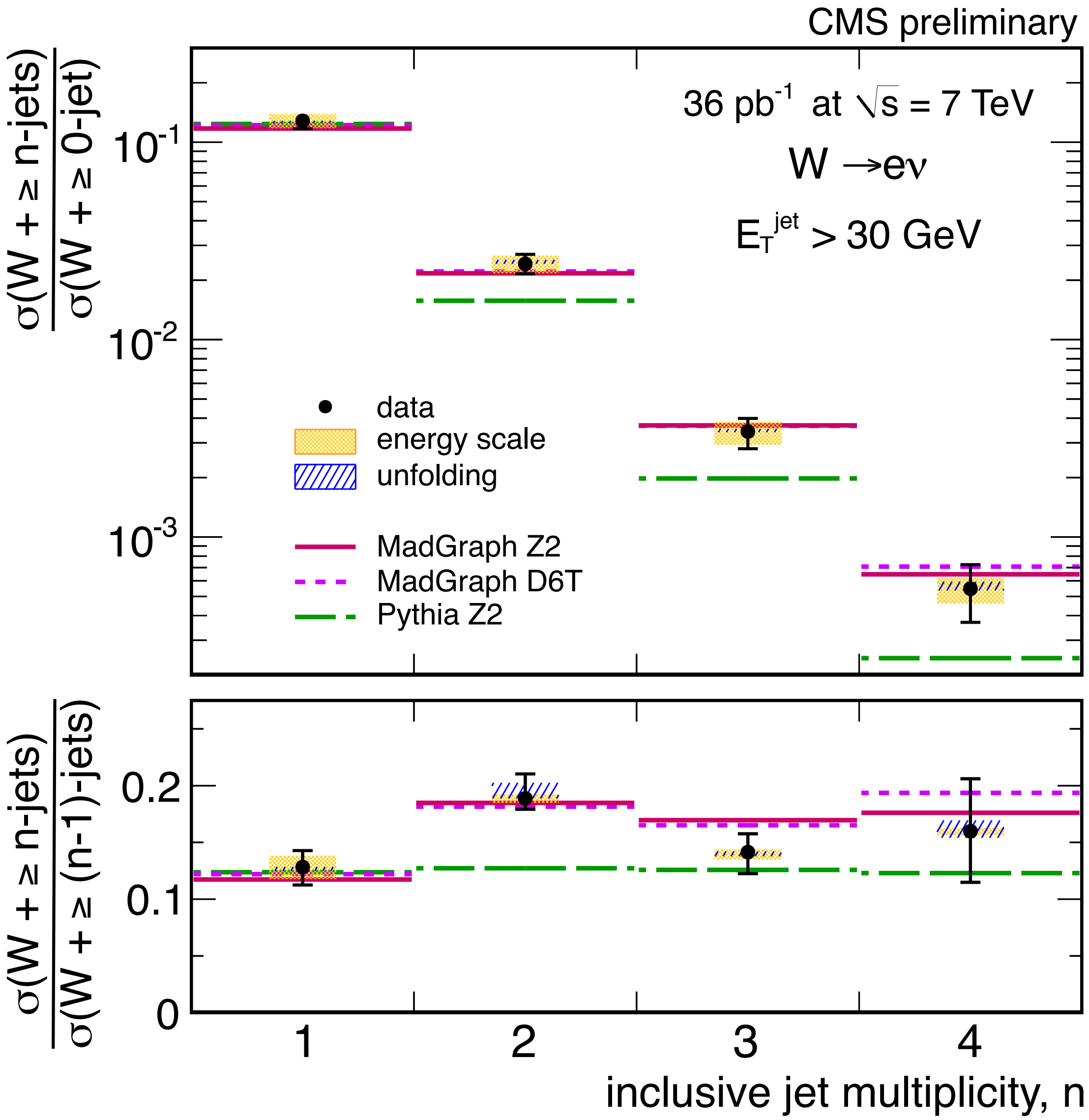


W+jets is a background for the Higgs Boson!

gluon-gluon fusion can result in two Ws, one decaying to jets, the other to an electron and neutrino

It is important to understand W+jets as a signal to eliminate it as a background

First Measurements of W+Jets at CMS - Kira Grogg



Signal extraction, efficiency corrections and unfolding are performed on exclusive n-jet bins (i.e., n=0, n=1, n=2, n=3, n≥4)

- Statistical + uncorrelated systematics are black error bars
  - Lepton efficiency, fit
- Central values shifted by correlated systematics, orange band
  - Jet counting
- Unfold with different methods, blue band
  - Different tune (Z2 vs D6T), generator (MadGraph vs Pythia), or algorithm (SVD vs Bayes)

Good agreement between data and MadGraph MC

σ(W+njets) / σ(W)

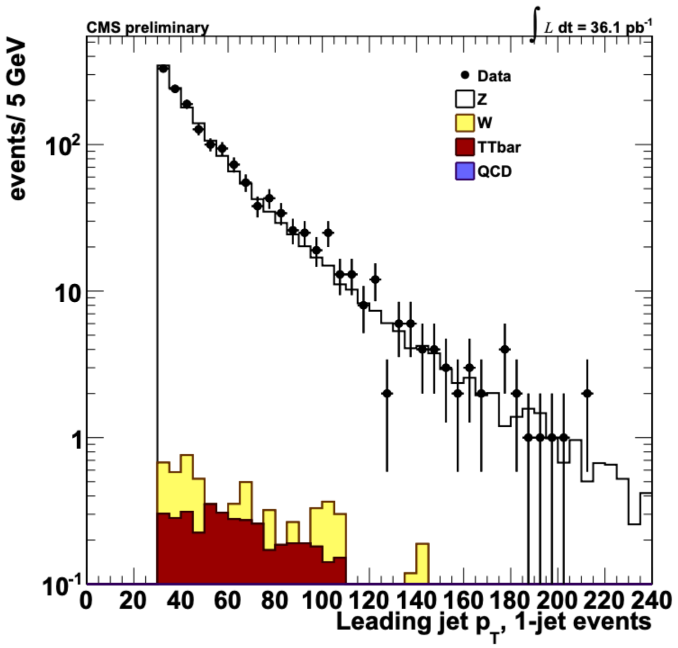
- No uncertainty in luminosity
- Reduces event selection uncertainty

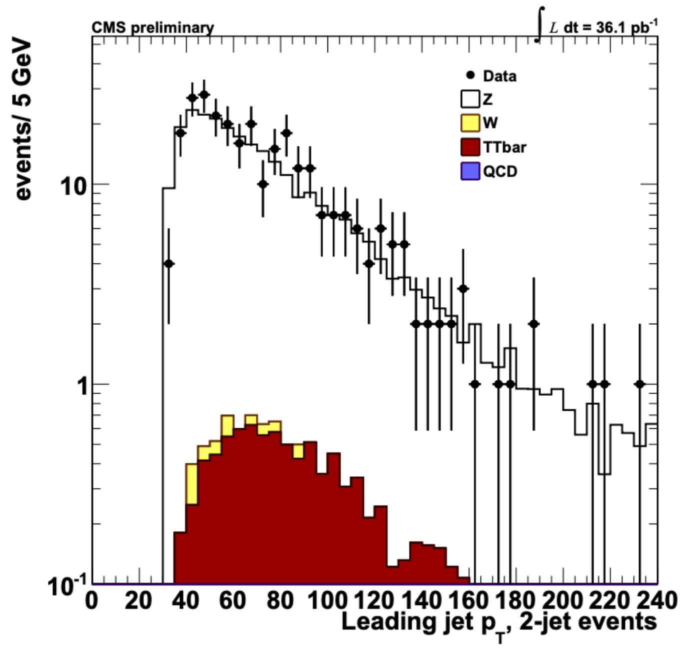
σ(W+njets) / σ(W+(n-1)) jets

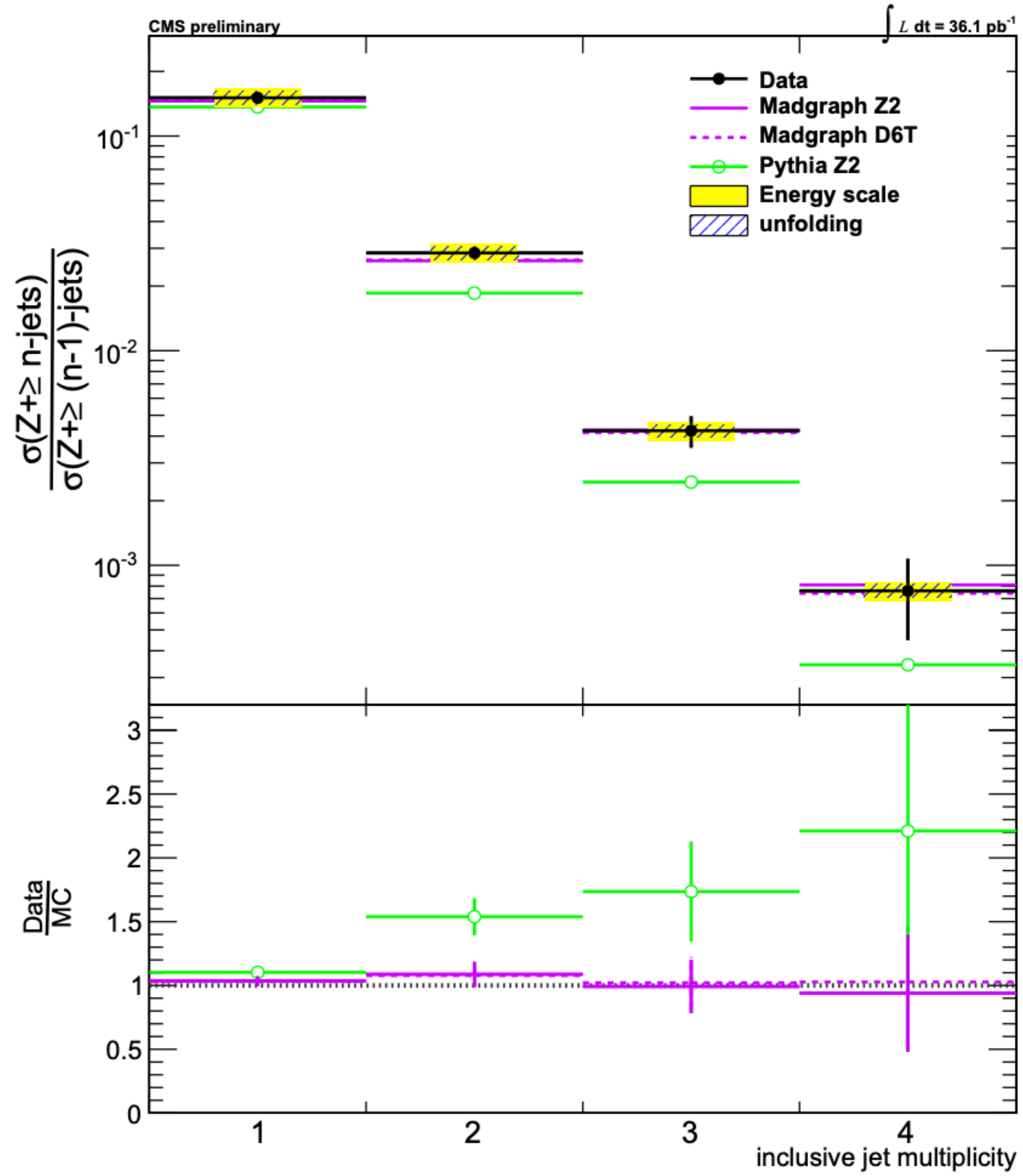
- Reduces JES uncertainty

Z+Jets differential cross-section

- Another important milestone for the experiment and for the LHC!







An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer.

Scientific Autobiography and Other Papers
MAX PLANCK

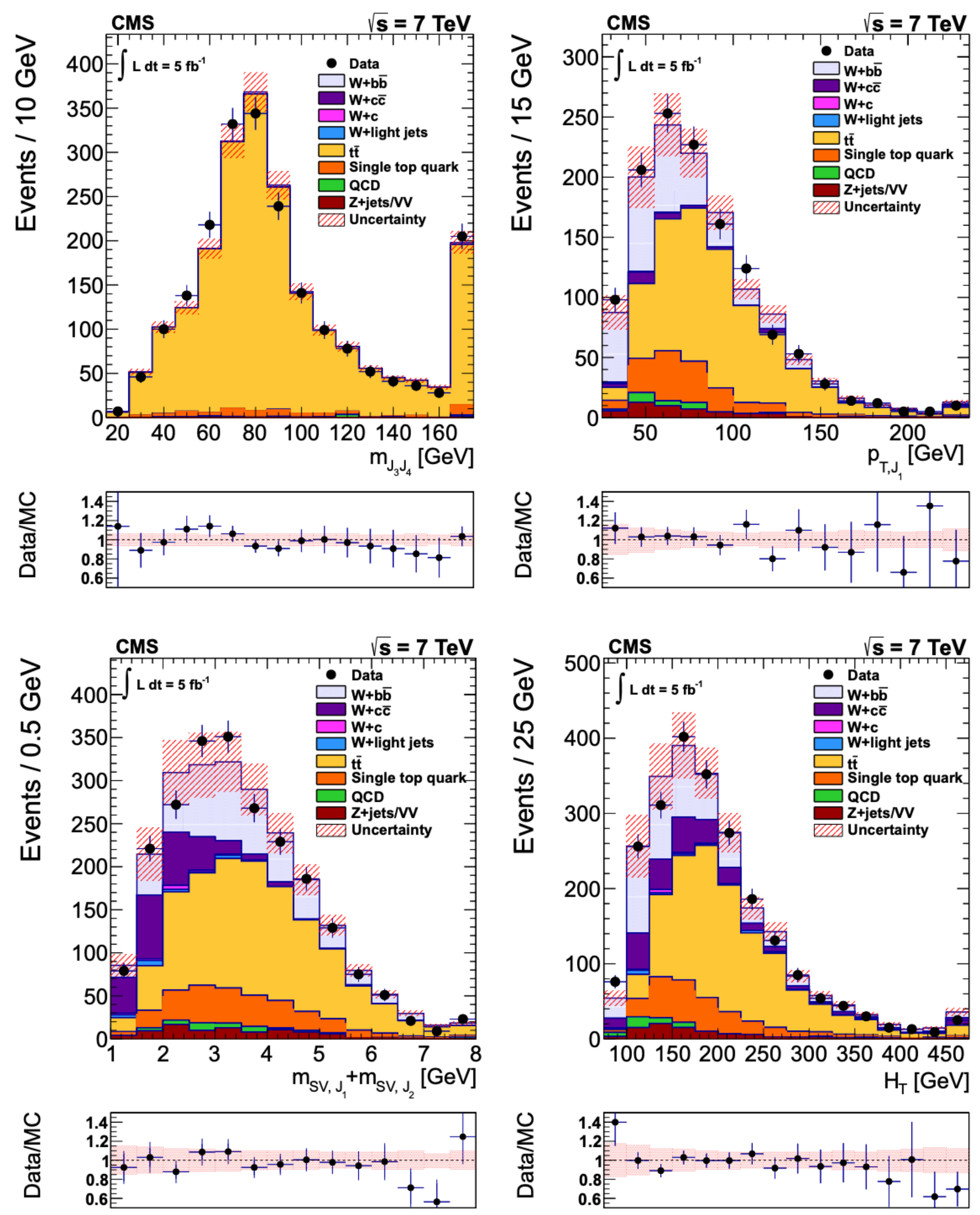
W+bb Cross Section Measurement at 7 TeV

W+bb is an irreducible background in the search of Higgs to bb

In previous measurements…

- W>=1 b-jet had shown between 1.5 to 2x disagreement prediction and measurement
- W+2b jet agreed well with SM expectation (~0.55 pb)

This analysis is a test of collinear splitting of heavy flavored QCD

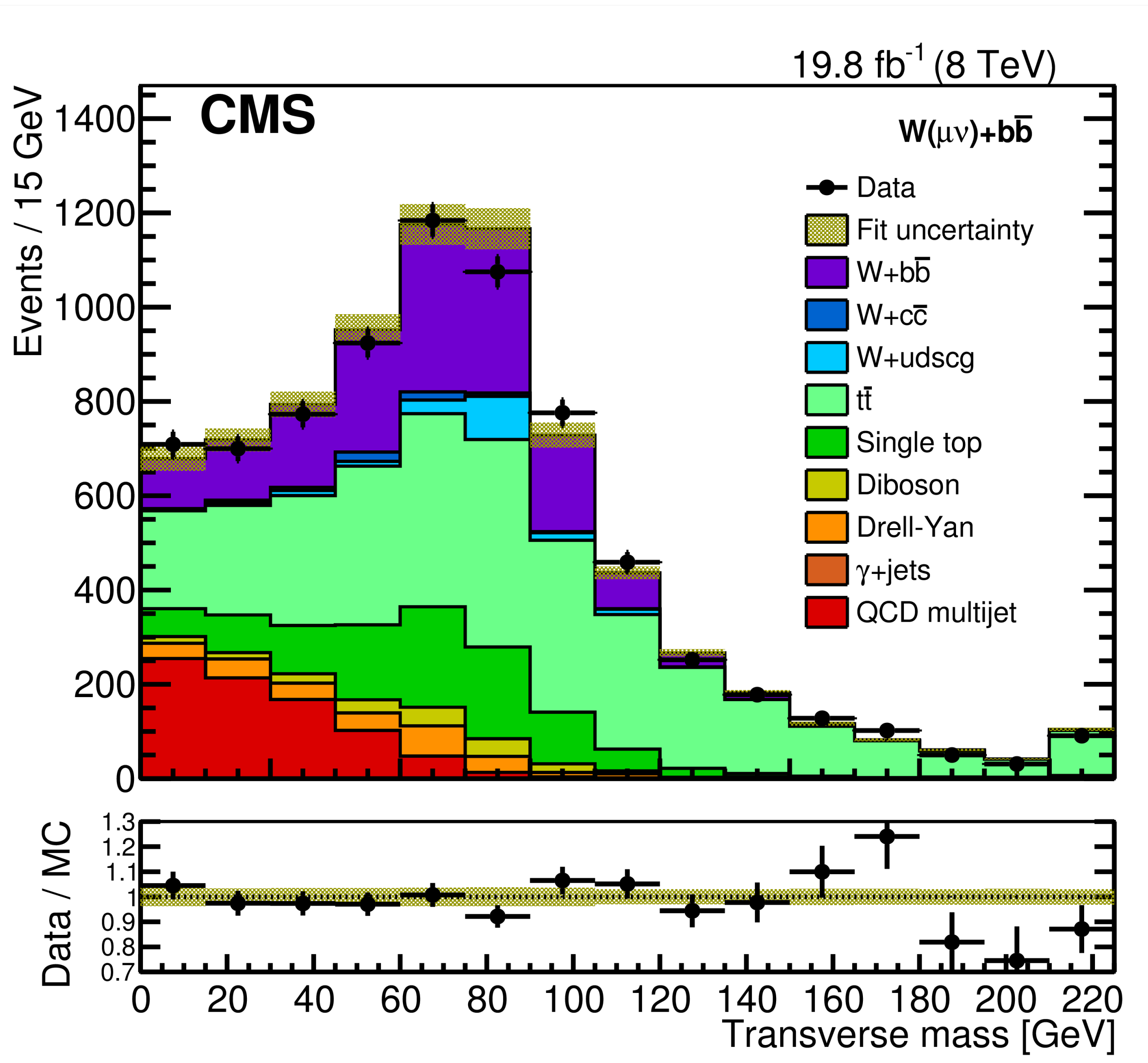


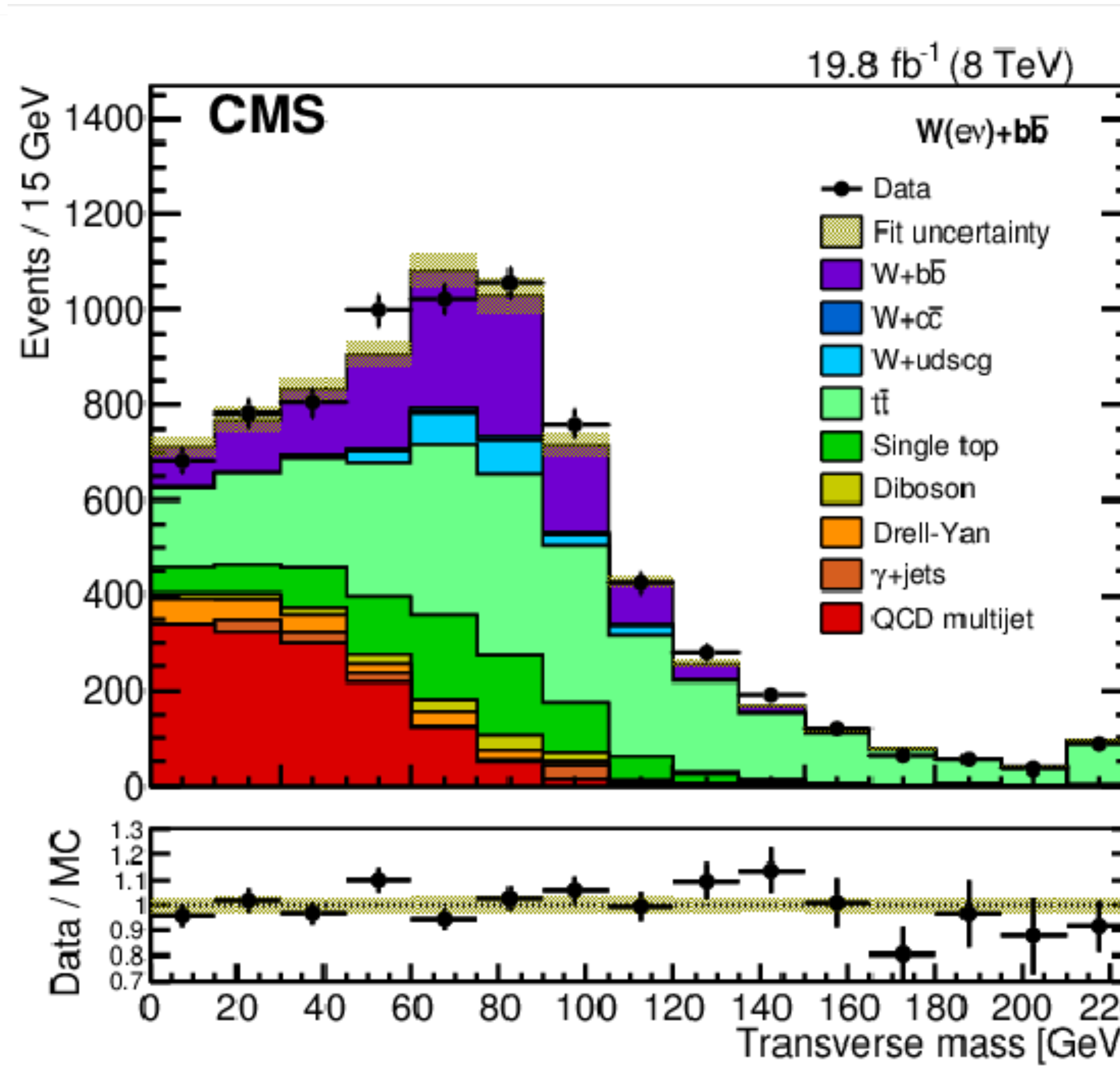
The signal significance of this measurement was on the order of 3 sigma… but it lead to the CMS H->bb group using 2 control regions to estimate W+b and W+bb

Arxiv: 1312.6608

W+bb at 8 TeV - Tom Perry

Measured with 20 fb^{-1} at 8 TeV
Included Muon and Electron Channels



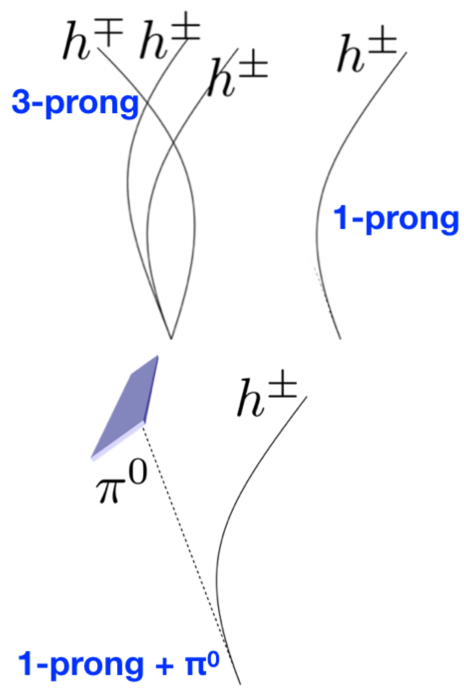


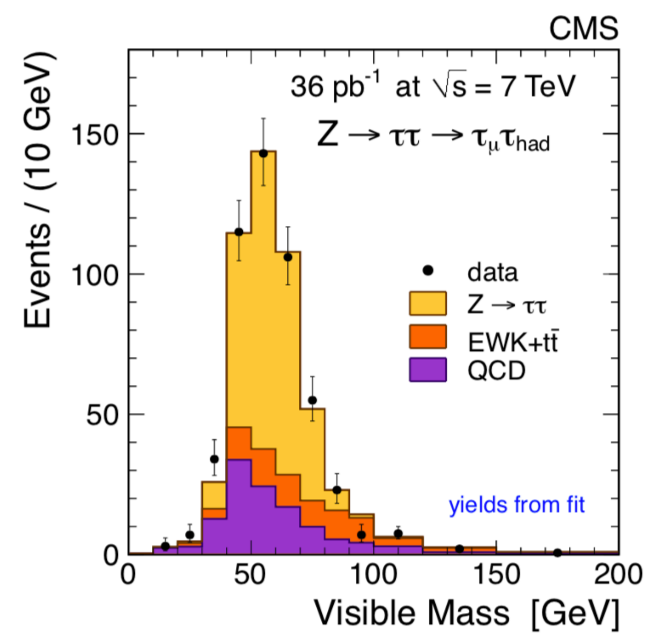
Tau Analyses

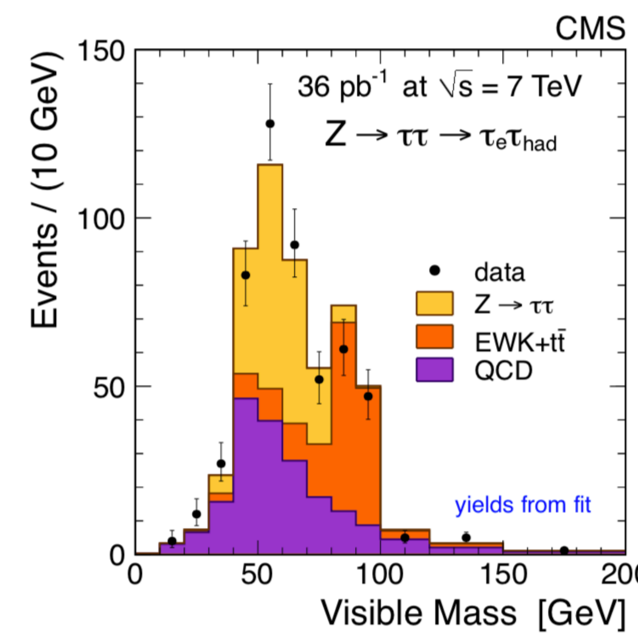
Physics with Tau Leptons (published in 2001) by Achim Stahl
- It is unclear whether or not one can study Tau decays at the LHC!

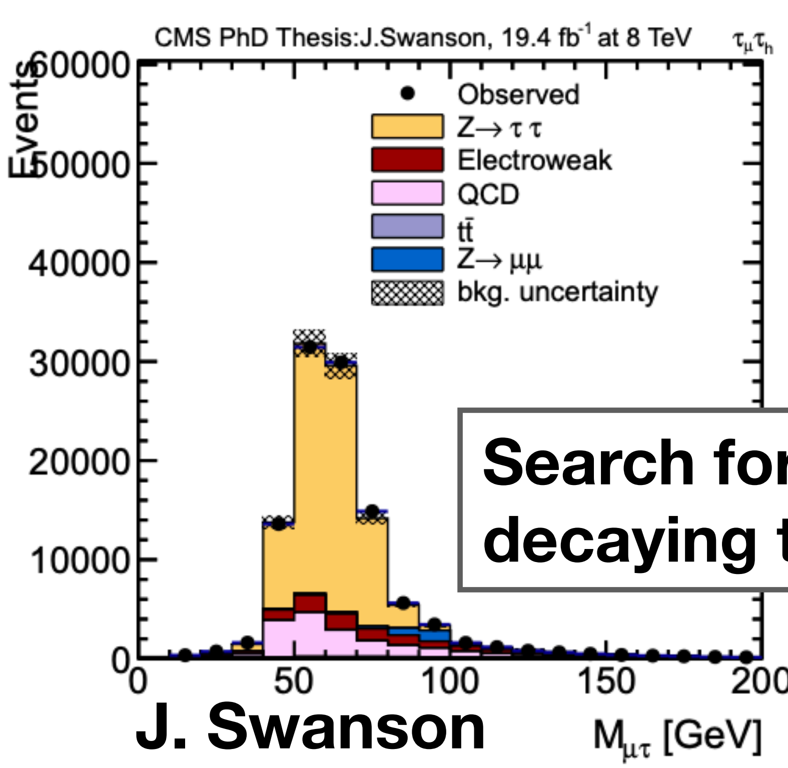
Development of HPS Algorithm
- Used for all of Run-1 and Run-2

M. Bachtis



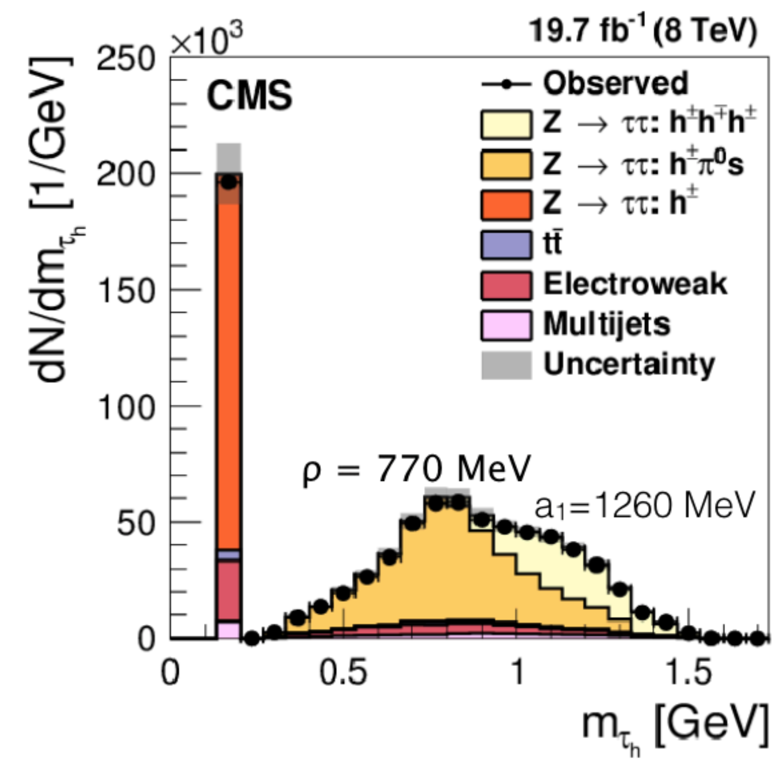






J. Swanson

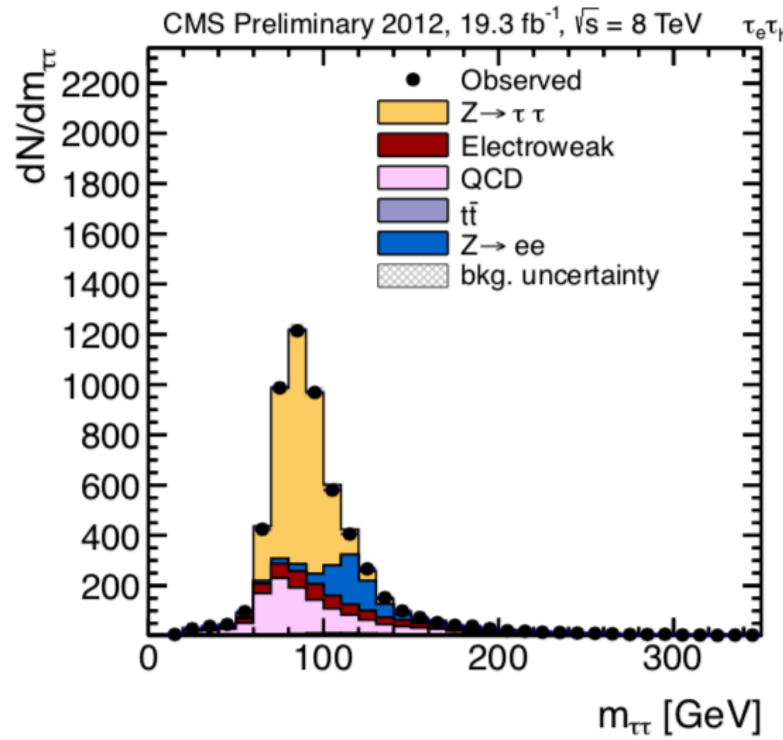
Search for Higgs decaying to Taus

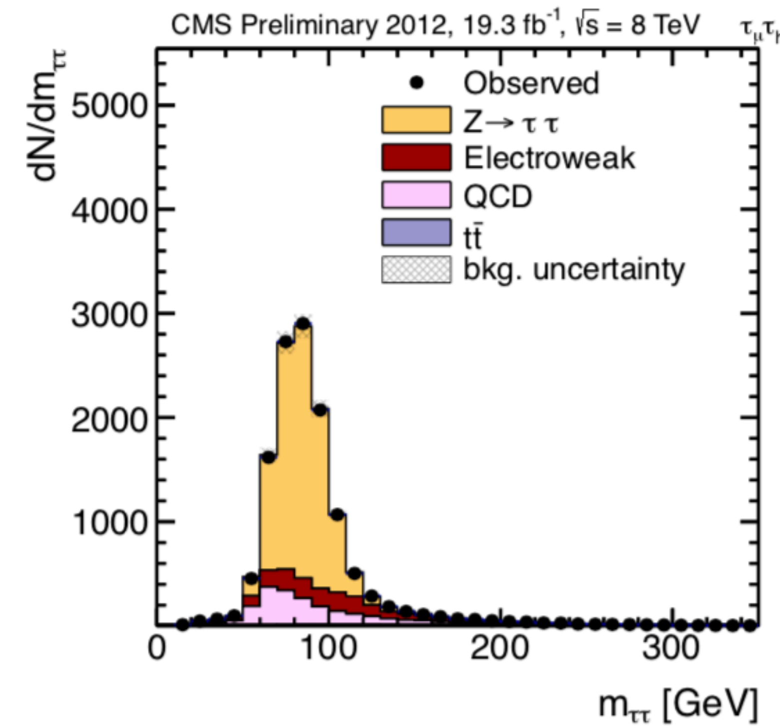


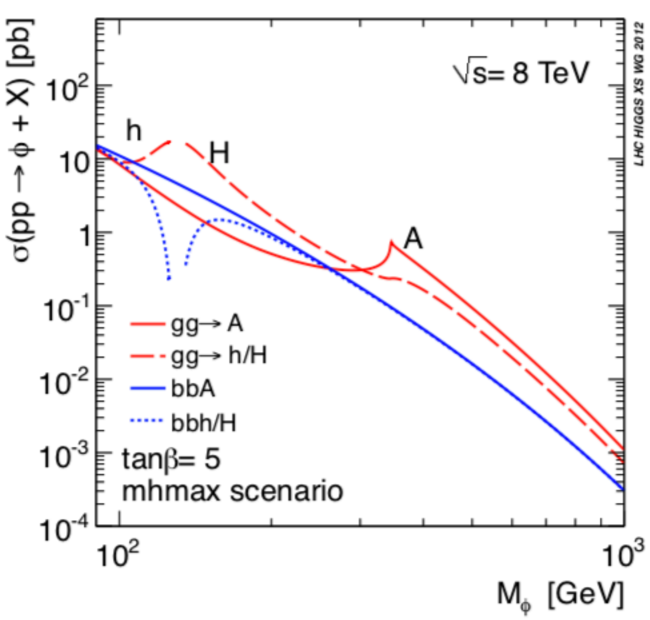
A Search for Neutral MSSM Higgs decay to ττ

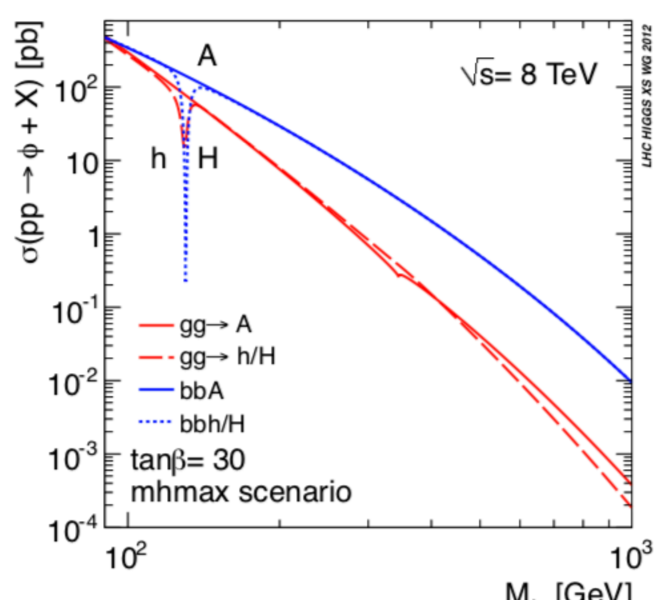
τ's **have a very short lifetime** and decay quickly to lighter leptons or hadrons

- Showing the channel where **one** τ **decays** to an **electron** (**muon**) and the other decays to **hadrons**







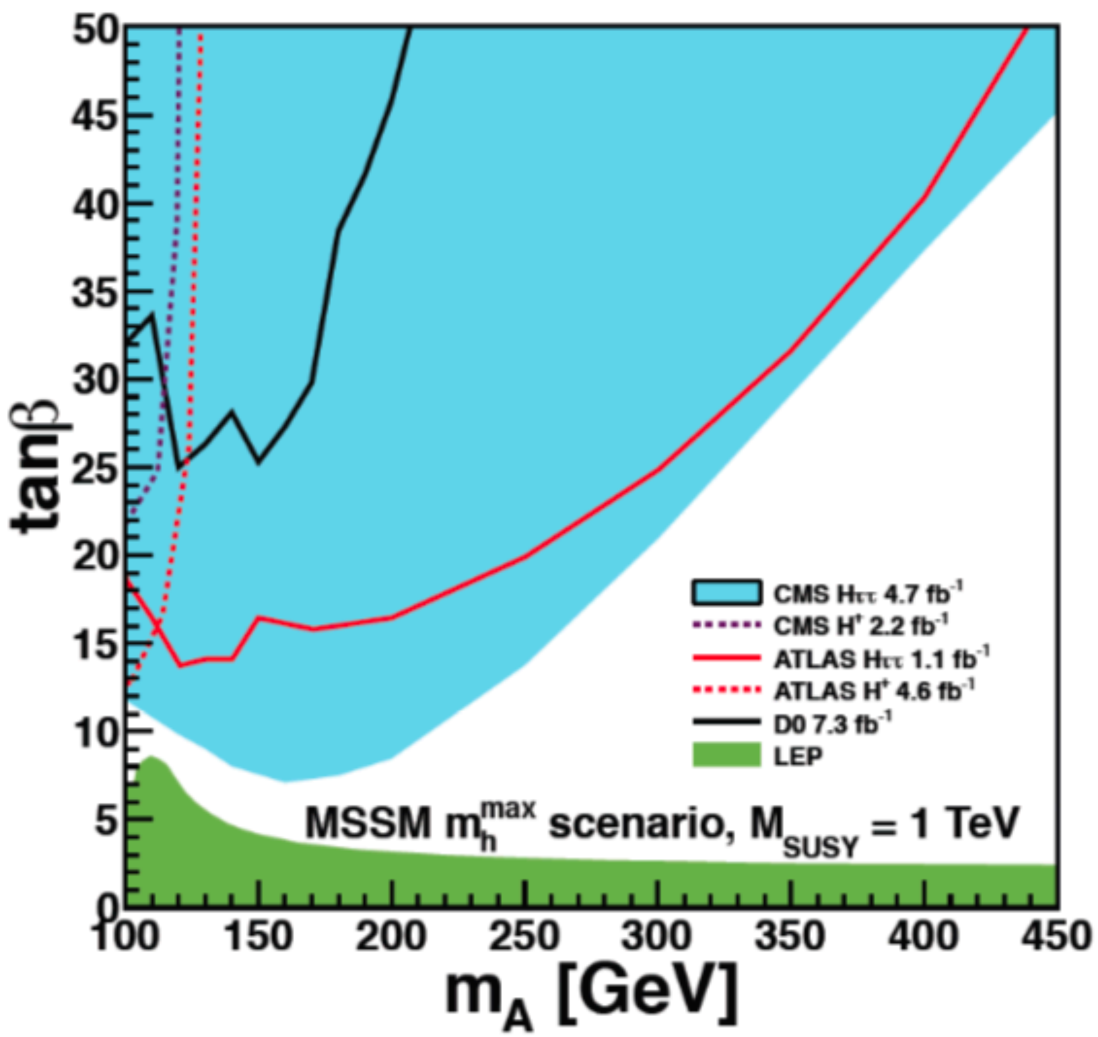


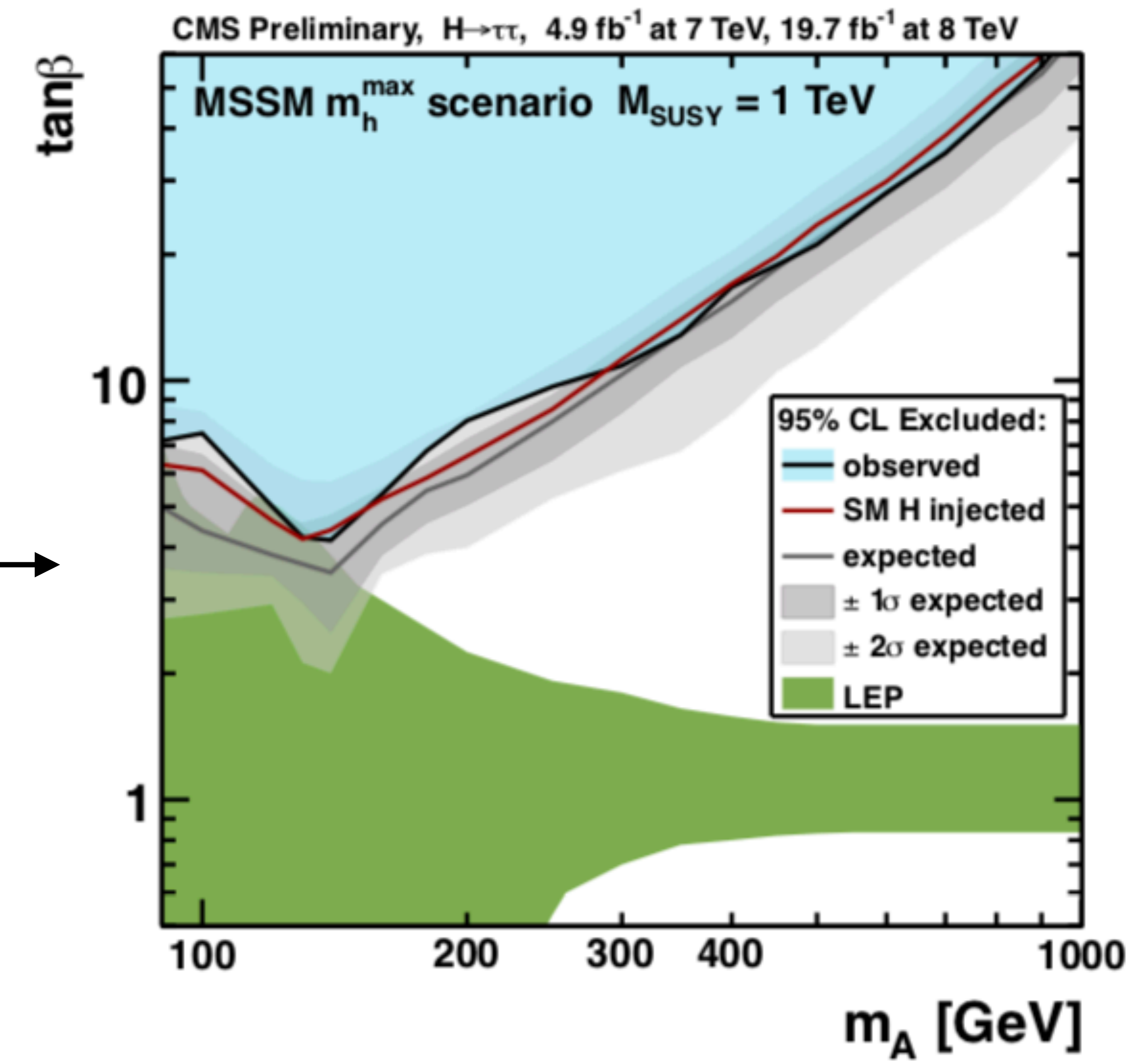
Excellent probe for the MSSM

At large tan β the b-Associated production becomes the dominant contribution to the overall cross-section

[Arxiv: 1312.6608](https://arxiv.org/abs/1312.6608)

MSSM H→ττ Results

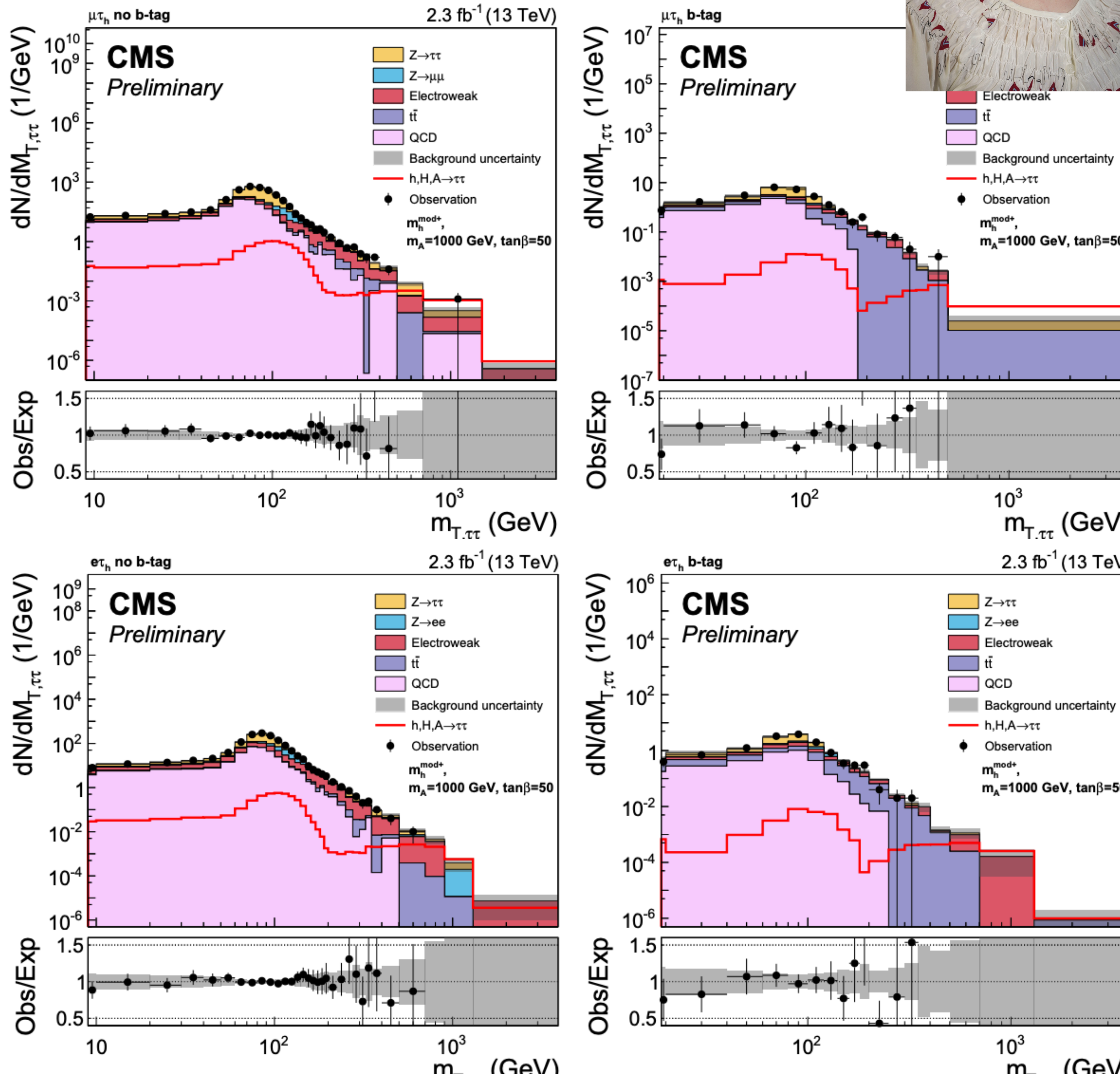




MSSM Higgs to TauTau - Laura Dodd

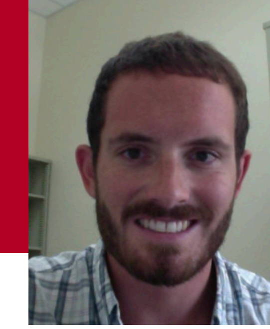
Search Continued with 13 TeV in 2015

Benefitted from improved Tau Triggers at Level-1!



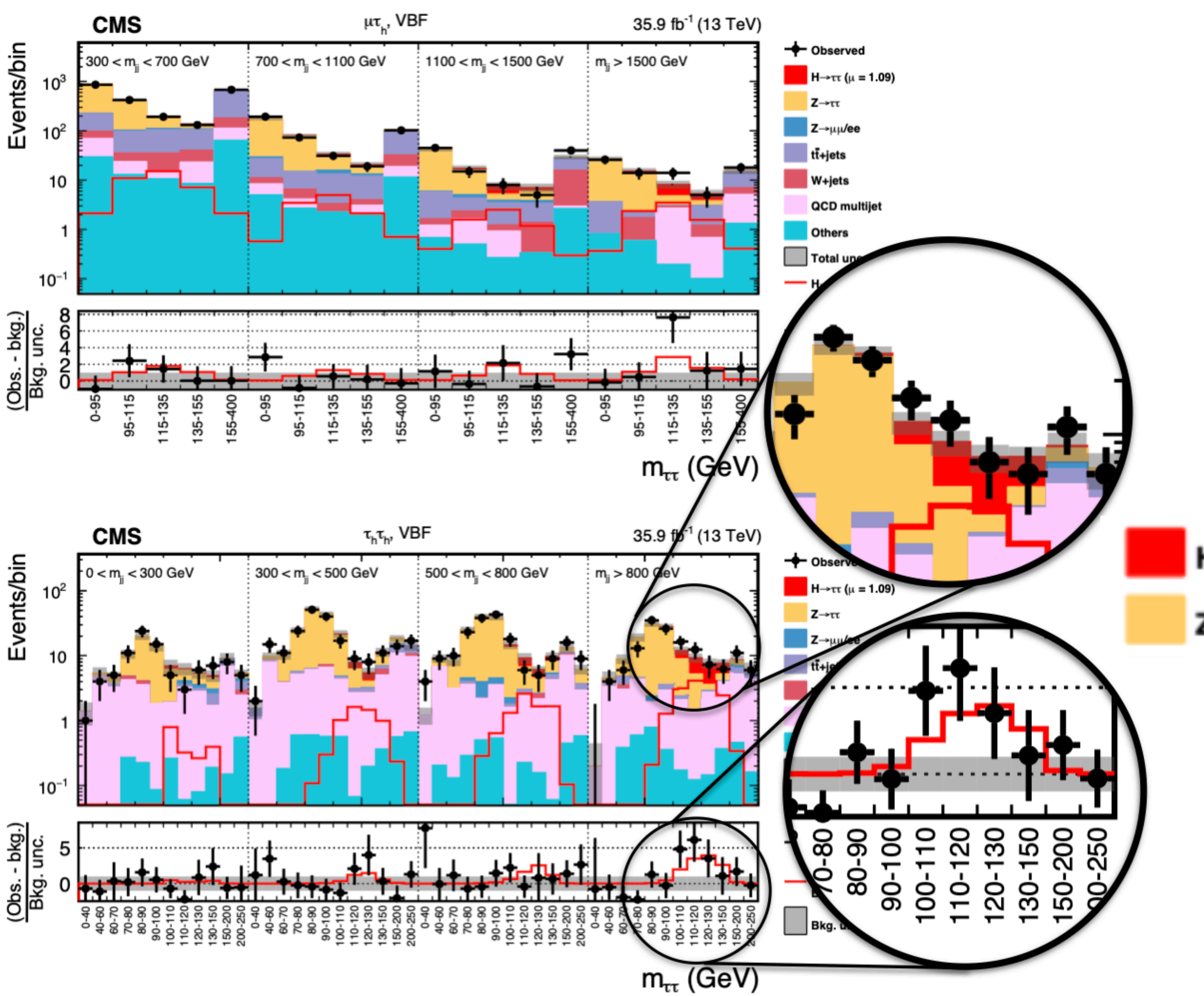
I.Ojalvo Wesley Fest 2019 Aug 30, 2019

Discovery of the H→ττ with the CMS Detector

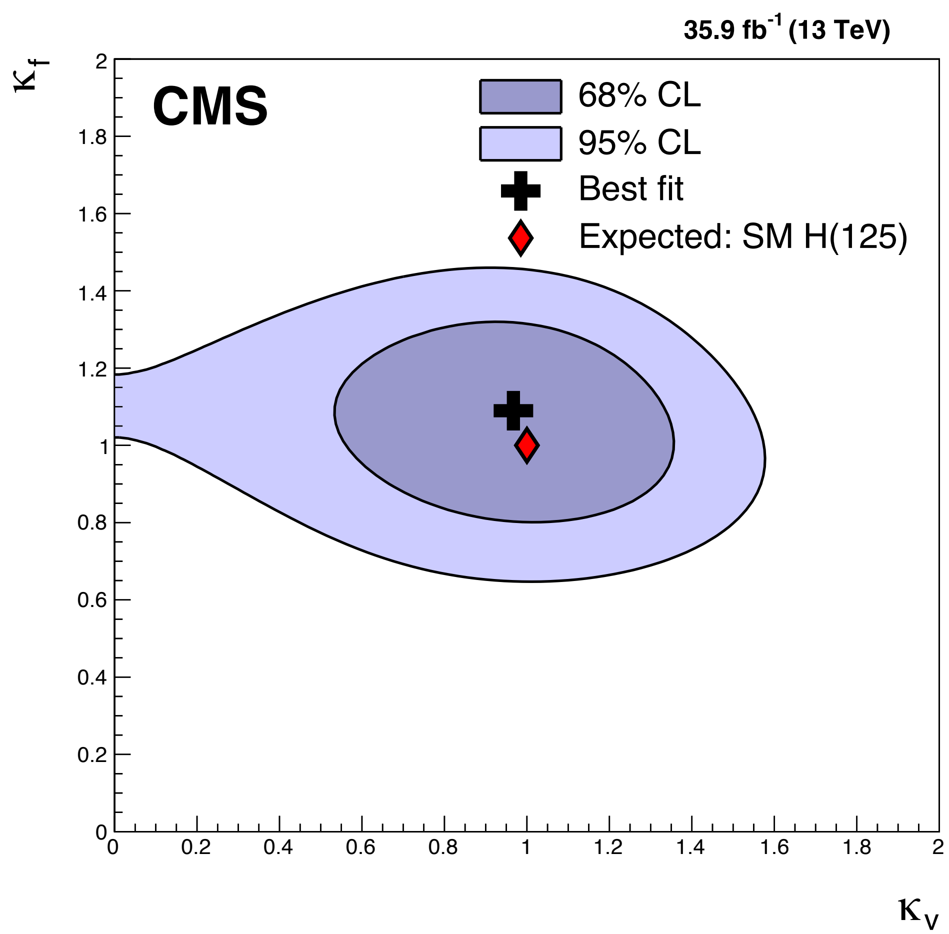


$\mu\tau_h$, VBF

$\tau_h\tau_h$, VBF



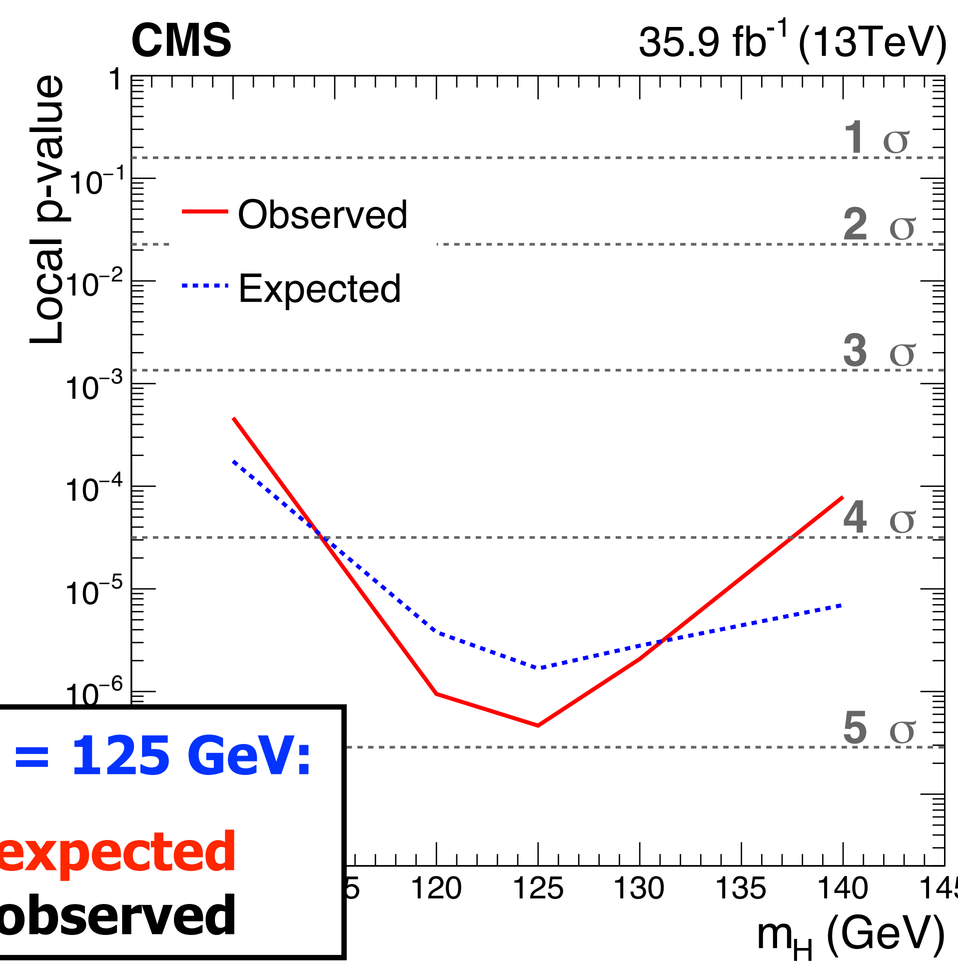
Discovery of the $H \rightarrow \tau\tau$ with the CMS Detector



5.9 σ observed significance when combined with Run I (7 and 8 TeV)

Coupling strength to Fermions vs. Bosons

Consistent with SM, where $\kappa_V=\kappa_F=1$

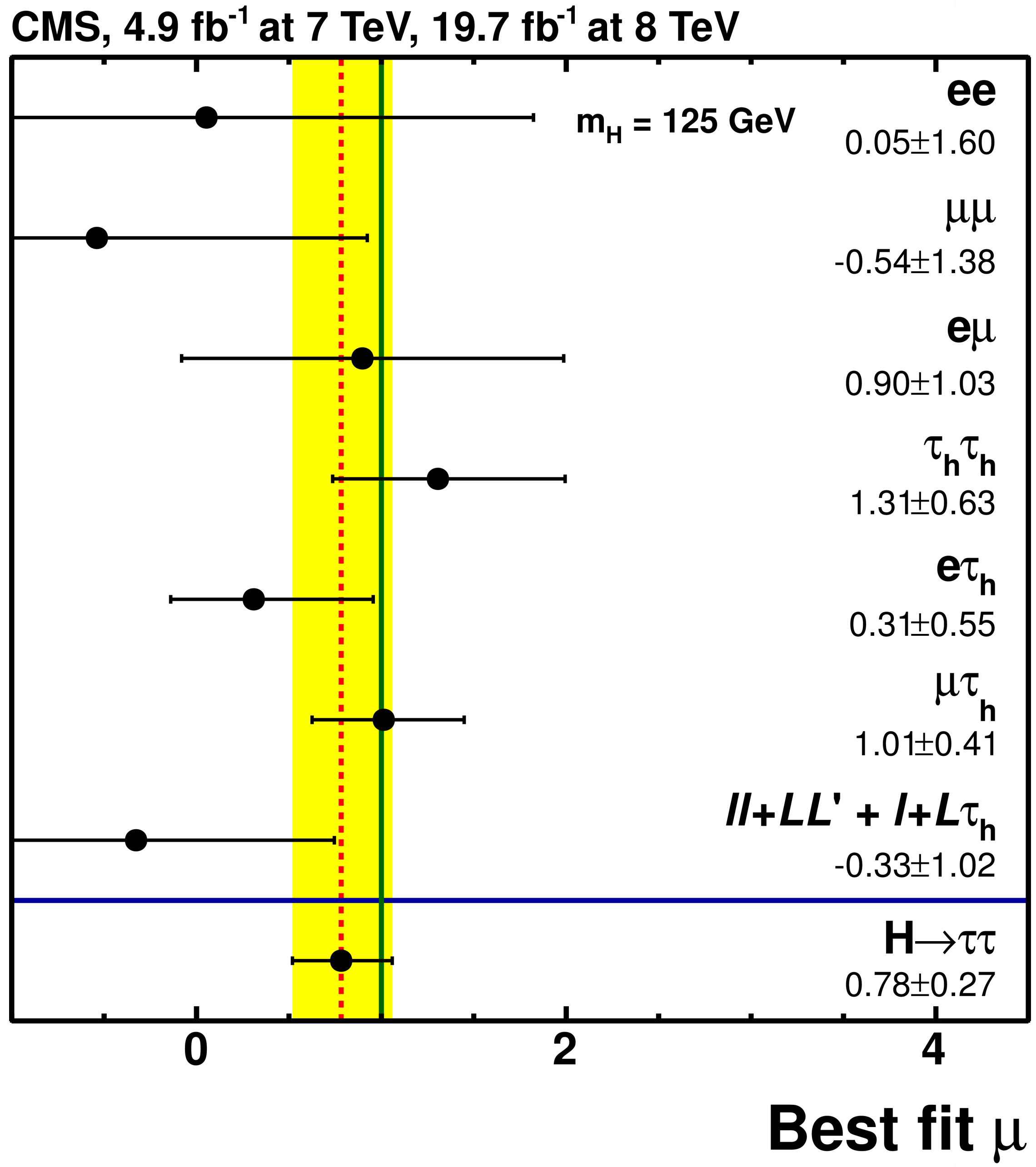


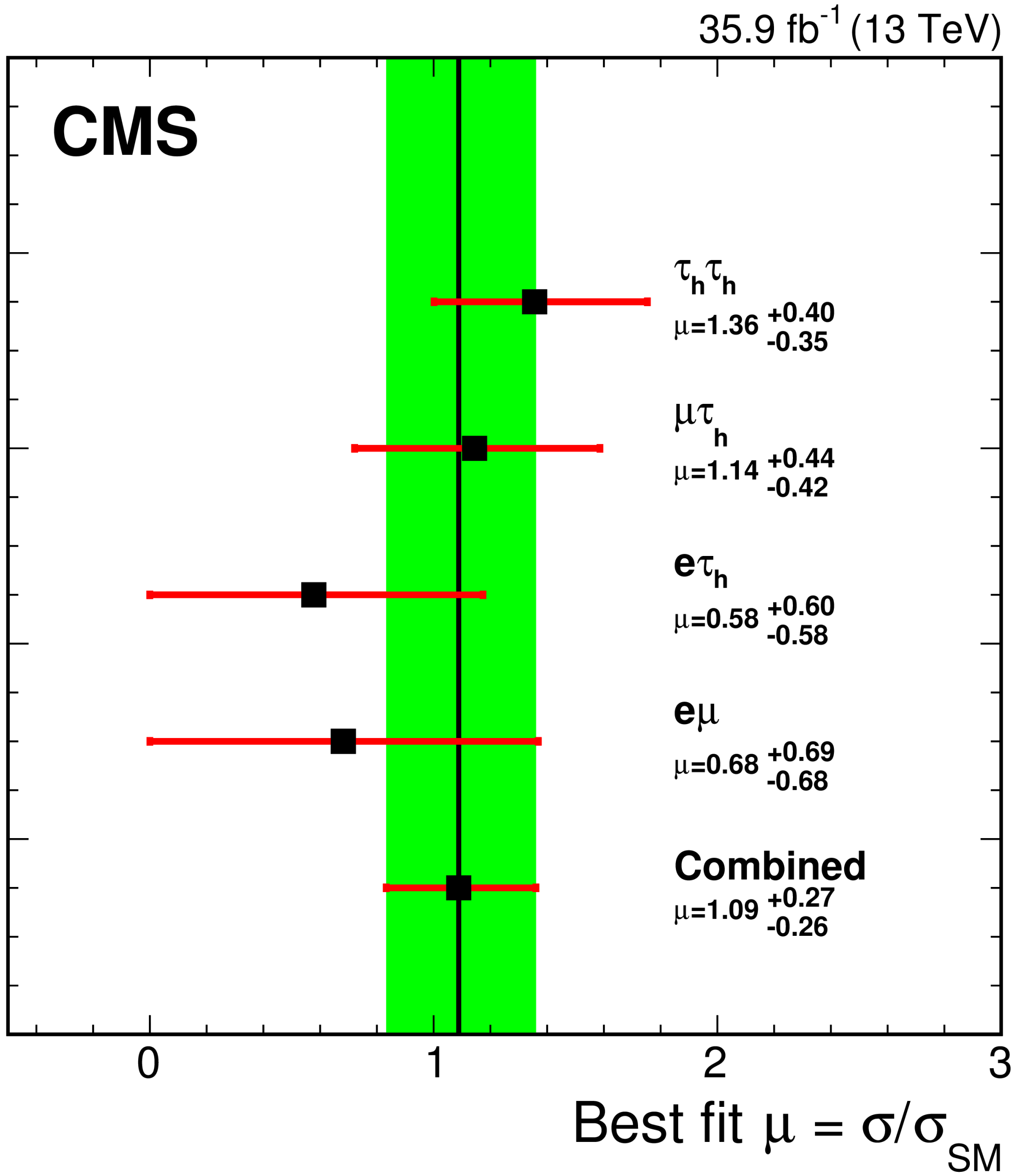
At m_H = 125 GeV:

4.7 σ expected

4.9 σ observed

Discovery of H→ττ with CMS: Run-1 vs Run-2





Largest improvement with respect to Run I seen in the $\tau_h\tau_h$ channel due to 30% signal efficiency gain in τ_h Trigger

- Despite a harsher Run II environment

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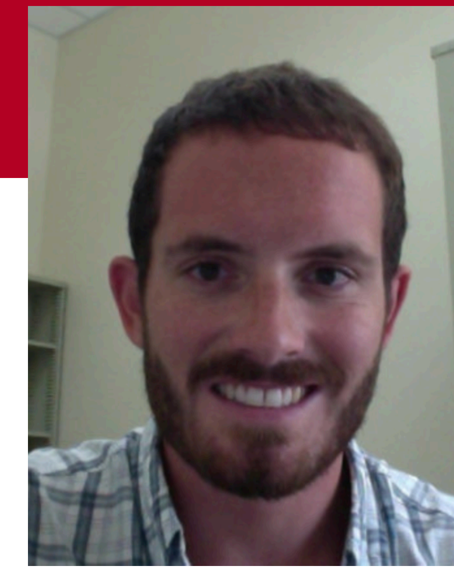
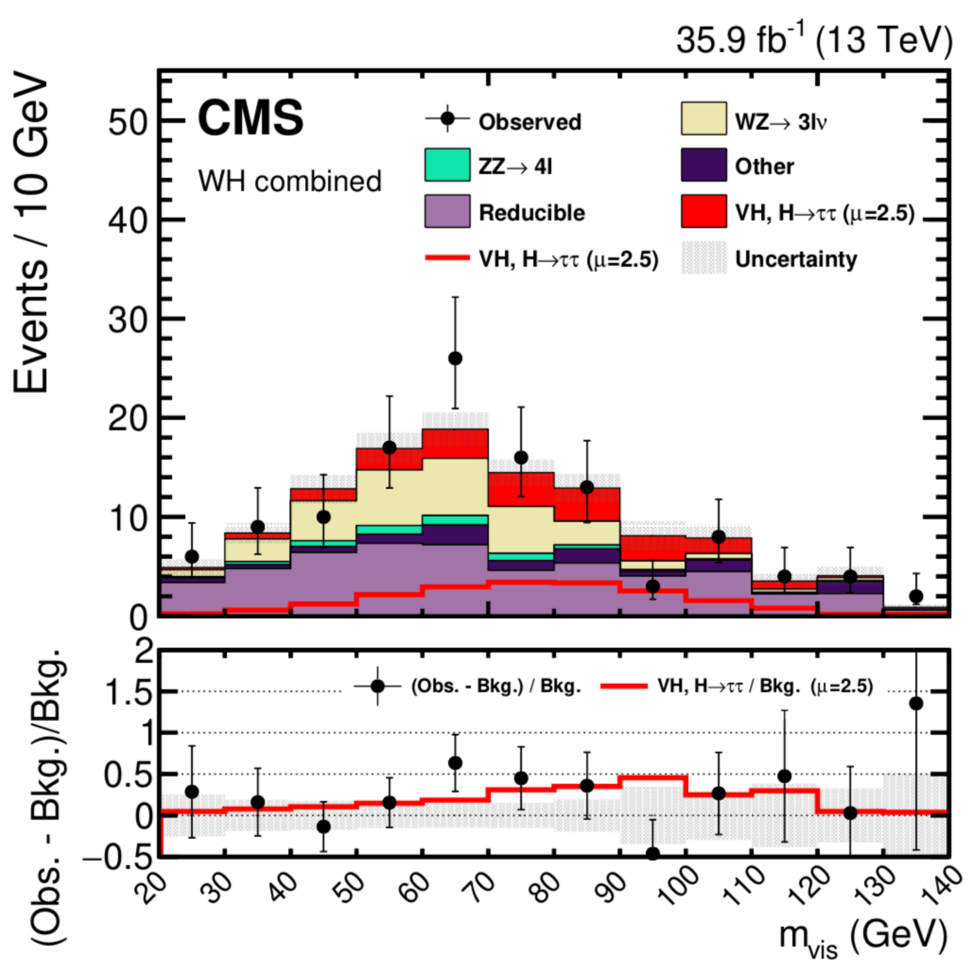
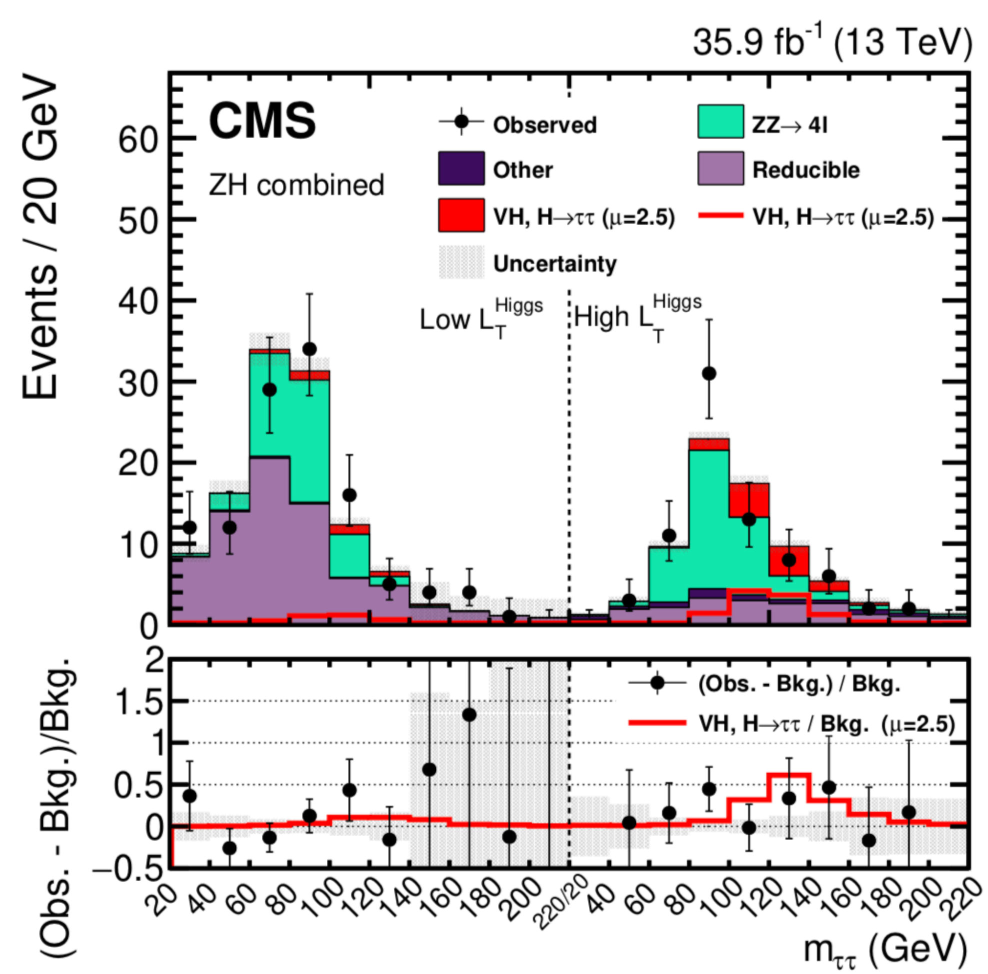
I.Ojalvo

WH/ZH - Tyler Ruggles

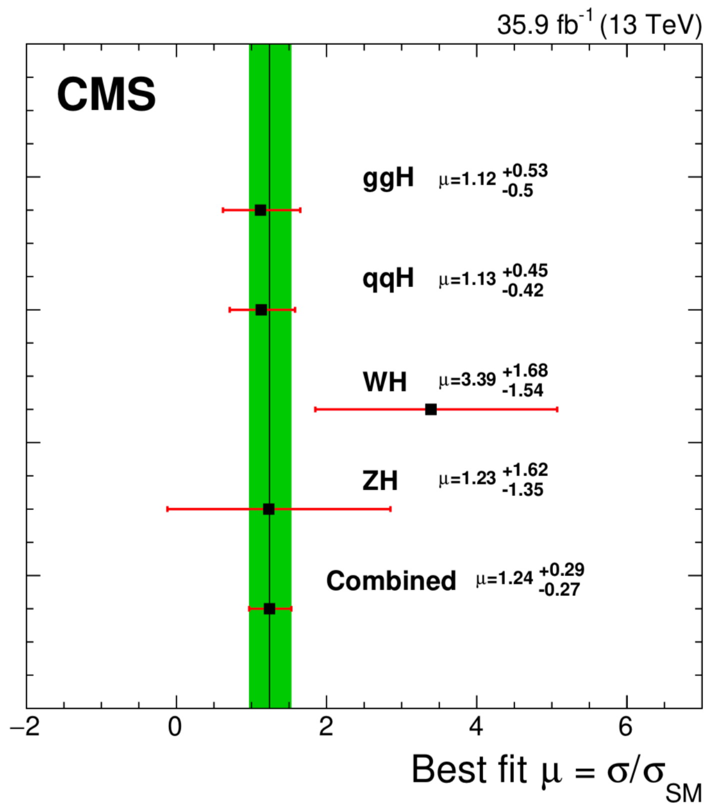
- **Search for WH and ZH where the Higgs decays to Taus**
  - **A great way to measure the Higgs coupling to Bosons and Fermions simultaneously!**

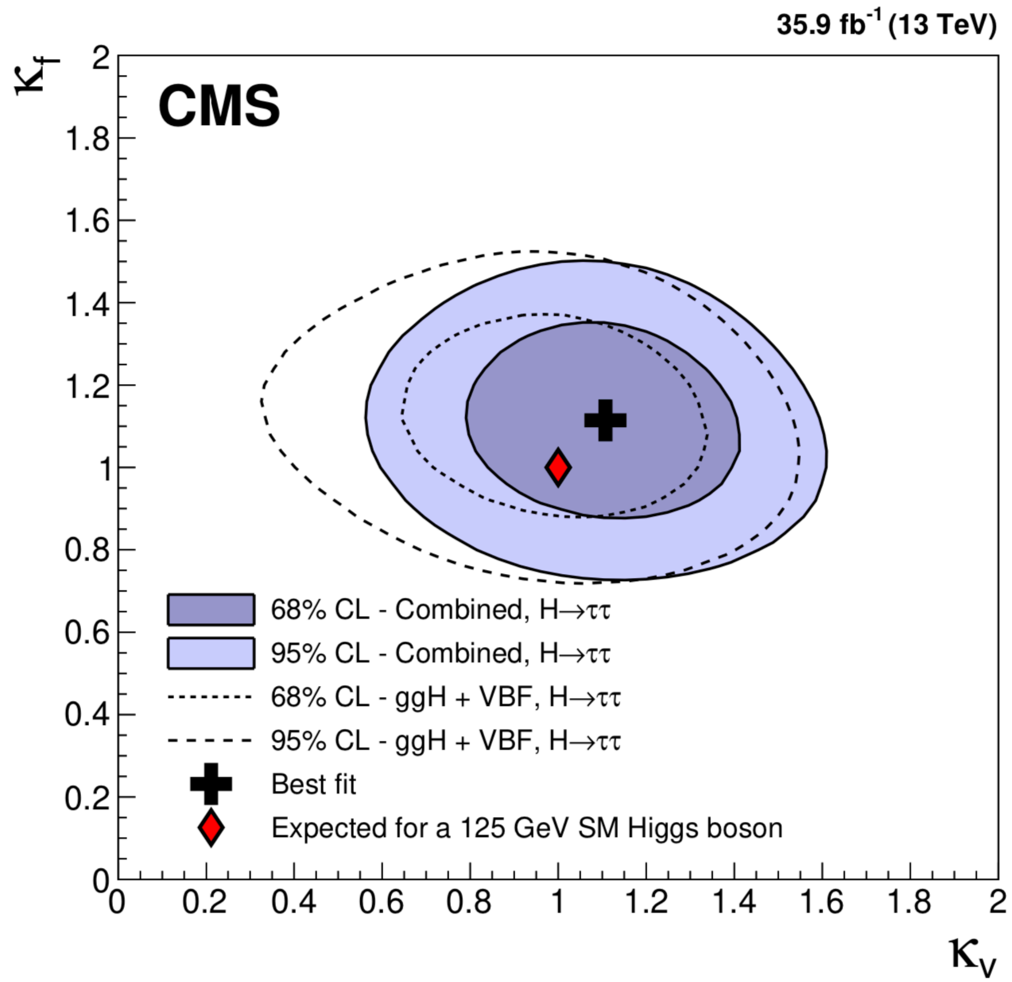


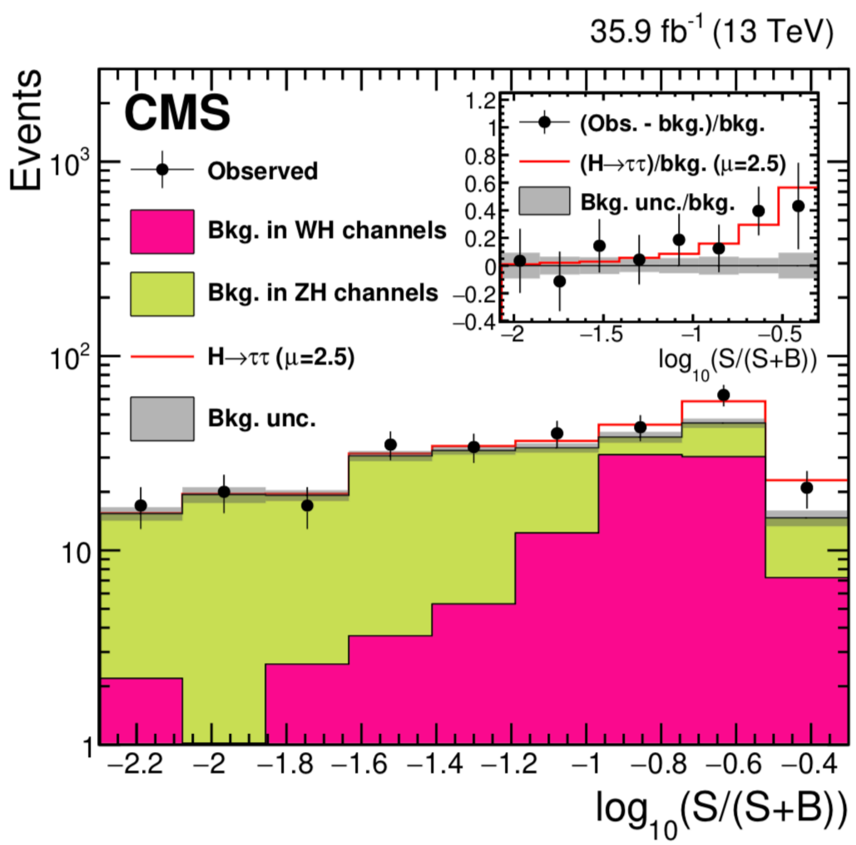




WH/ZH - Tyler Ruggles







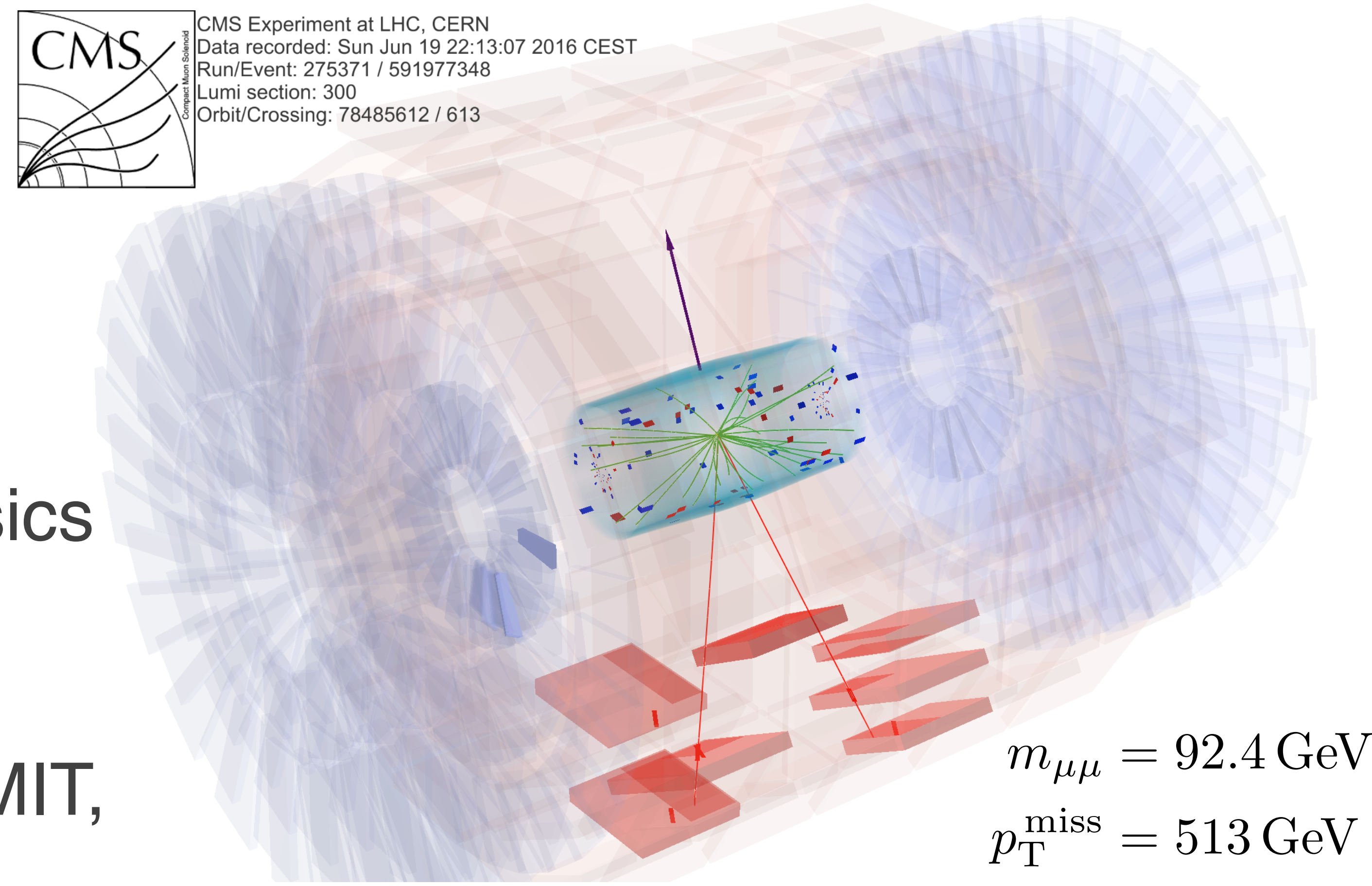
"Wesley taught me not only how to display and convey my results to others, but also how to pick them apart and ask the relevant questions needed to identify problems and develop solutions."

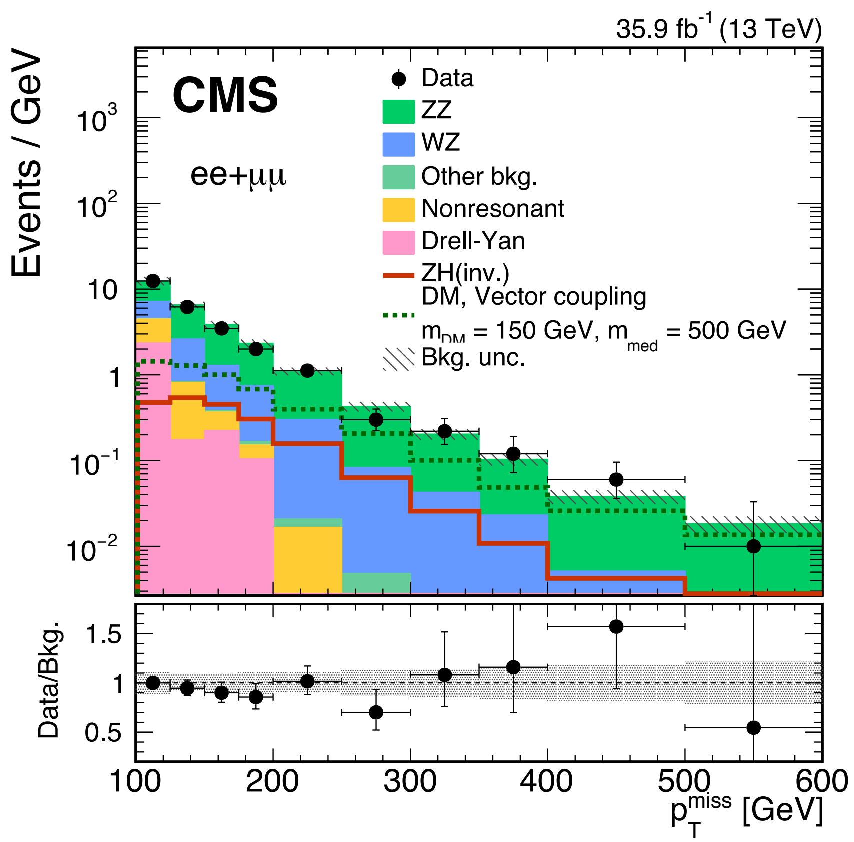
"These general skills have been invaluable while switching domains to researching renewable energy technologies and energy systems. Thank you Wesley!"

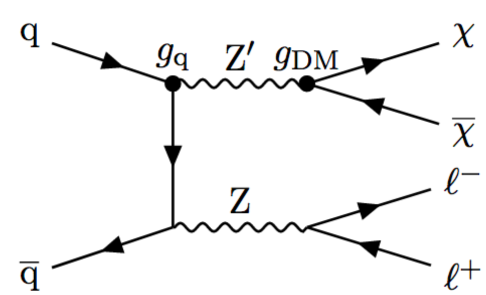
A few slides from former students

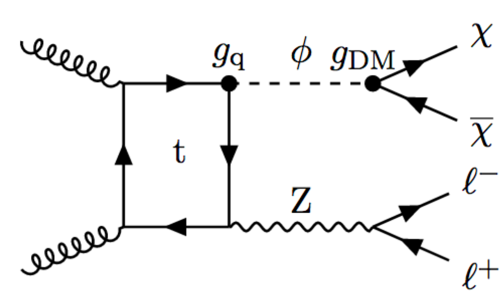
Mono-Z BSM search

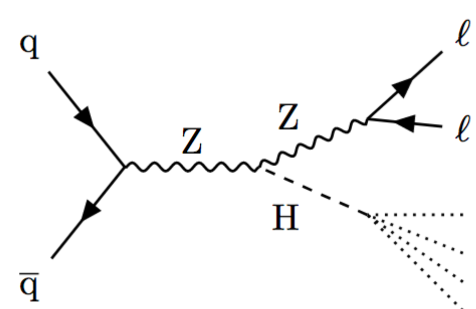
- Part of CMS MET+X group
  - EXO-16-010, EXO-16-052
- Set limits on diverse set of new physics models involving Z boson ISR or associated production
- Fun, friendly team from Wisconsin, MIT, Aachen, Northeastern

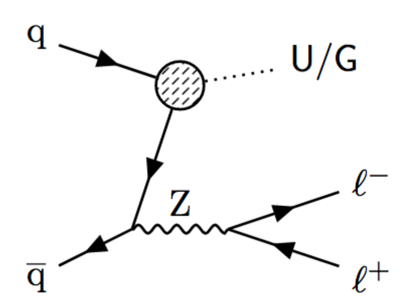






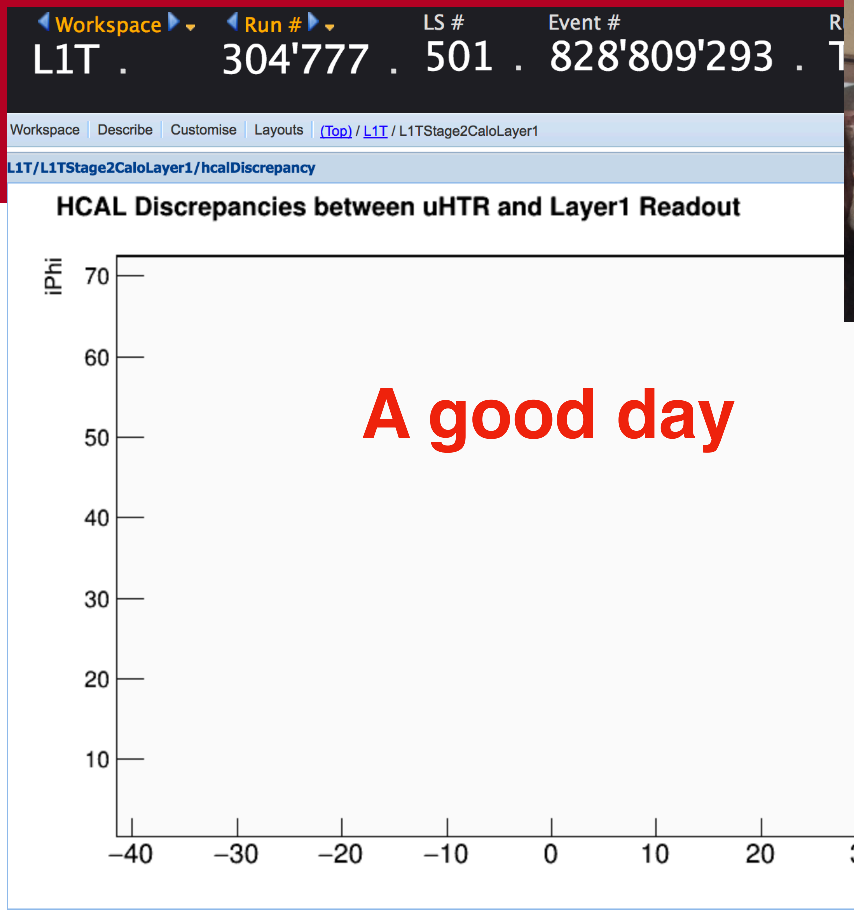


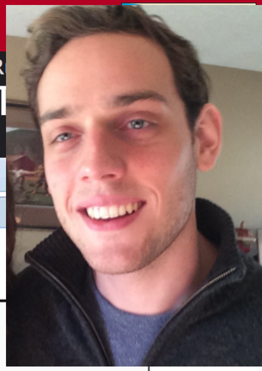


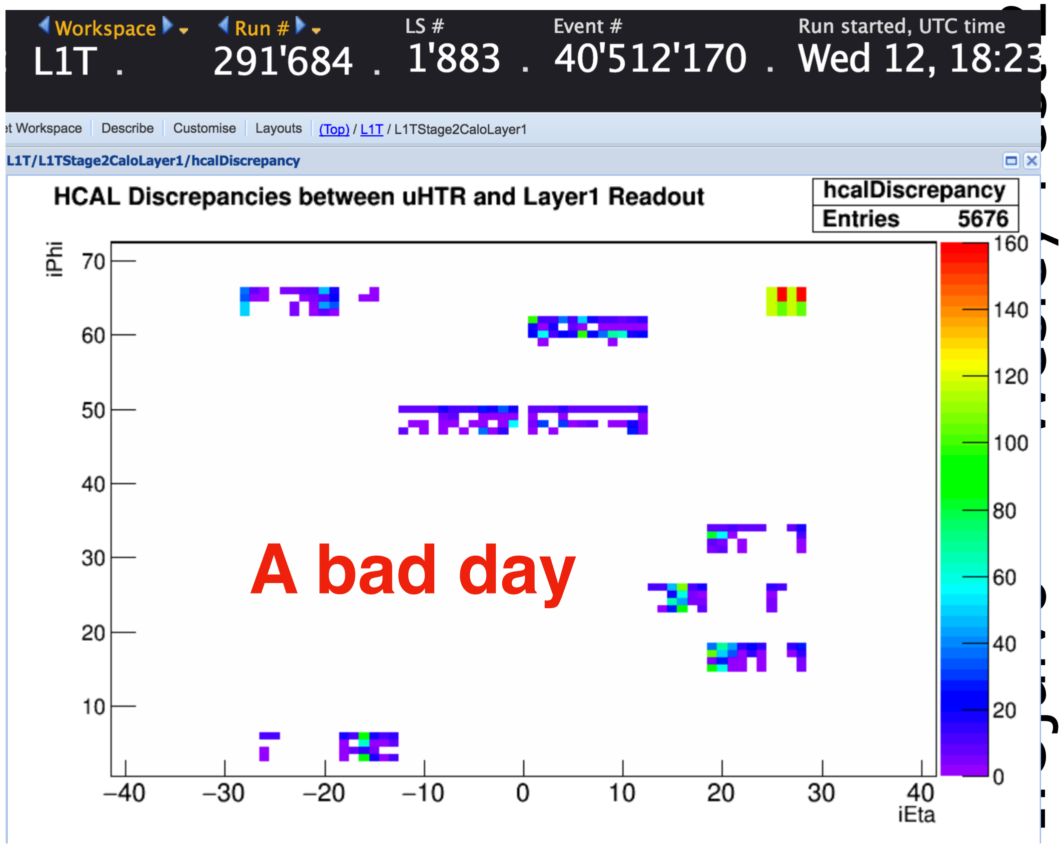


Trigger Offline and Data Quality

- I joined the group just as we started commissioning the calo trigger upgrade
  - I helped commission and operate the system
  - DQM, emulator, unpacker
  - CaloLayer1 on-call, L1 DOC
  - Plugged in some fibers, not as many as others
- Watched for issues in calo trigger 2015-18
  - Fixed some issues
  - **Badgered**™ people to fix some issues
  - Found some strange features in the data
- Our system had **very few issues in Run II**
  - **So we helped ECAL, HCAL, CaloLayer2 diagnose their issues :)**
  - I don't think this was by chance—Wesley put together a great team of engineers and made sure students had the resources they needed to ensure operations







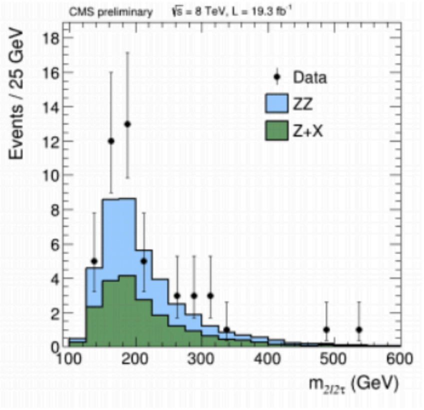
Discovery of the Higgs decay to ZZ - Ian Ross

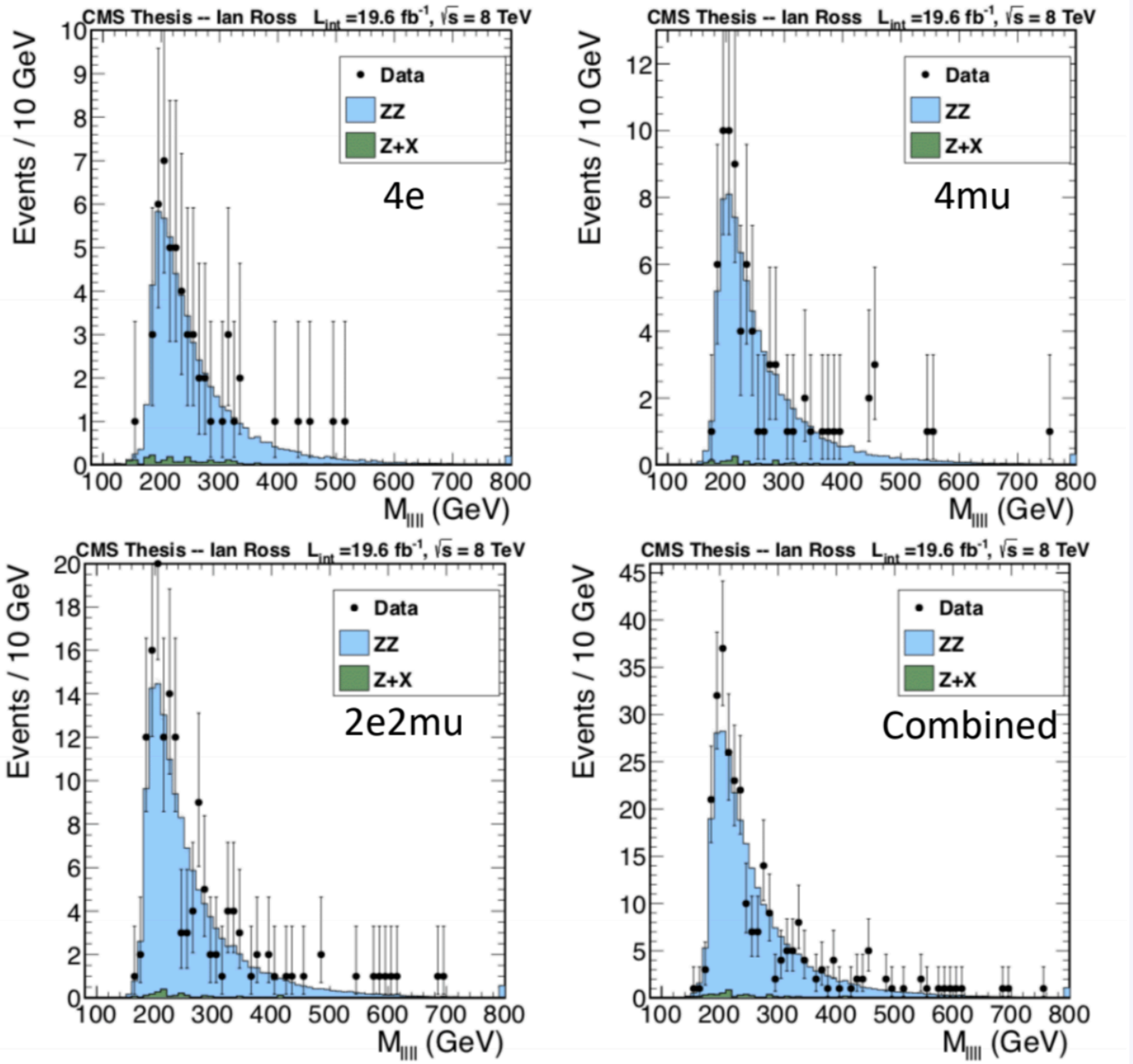
Standard Model ZZ->4l

- Signature of 4 isolated leptons in the detector
  - Low statistics, but squeaky-clean signature
  - Irreducible background to a Higgs search
- Standard model cross section measurement:

$$\sigma(pp \to ZZ) = 7.7^{+0.5}_{-0.5}(stat.)^{+0.6}_{-0.5}(\text{sys.}) \pm 0.3(\text{lumi})\text{pb}$$

- Even observed the ZZ->2l2tau final state! How novel!



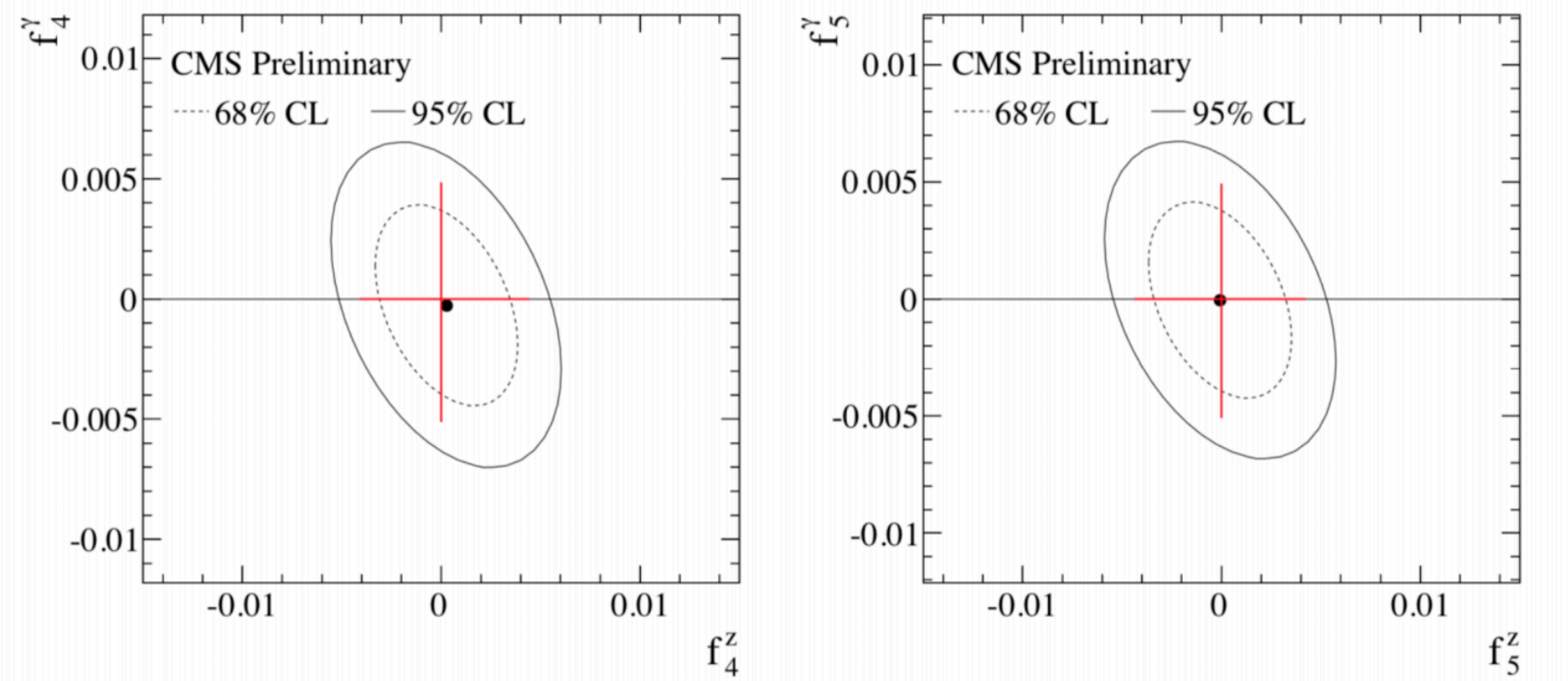


Anomalous Triple Gauge Couplings - Ian Ross

BSM: Anomalous triple gauge couplings

- Existence of anomalous neutral triple gauge couplings (f_i^Z , f_i^γ) would manifest in enhanced tail in M_{llll} distribution
- Was able to set the tightest (at the time) limits on f_i^Z , f_i^γ coupling strength

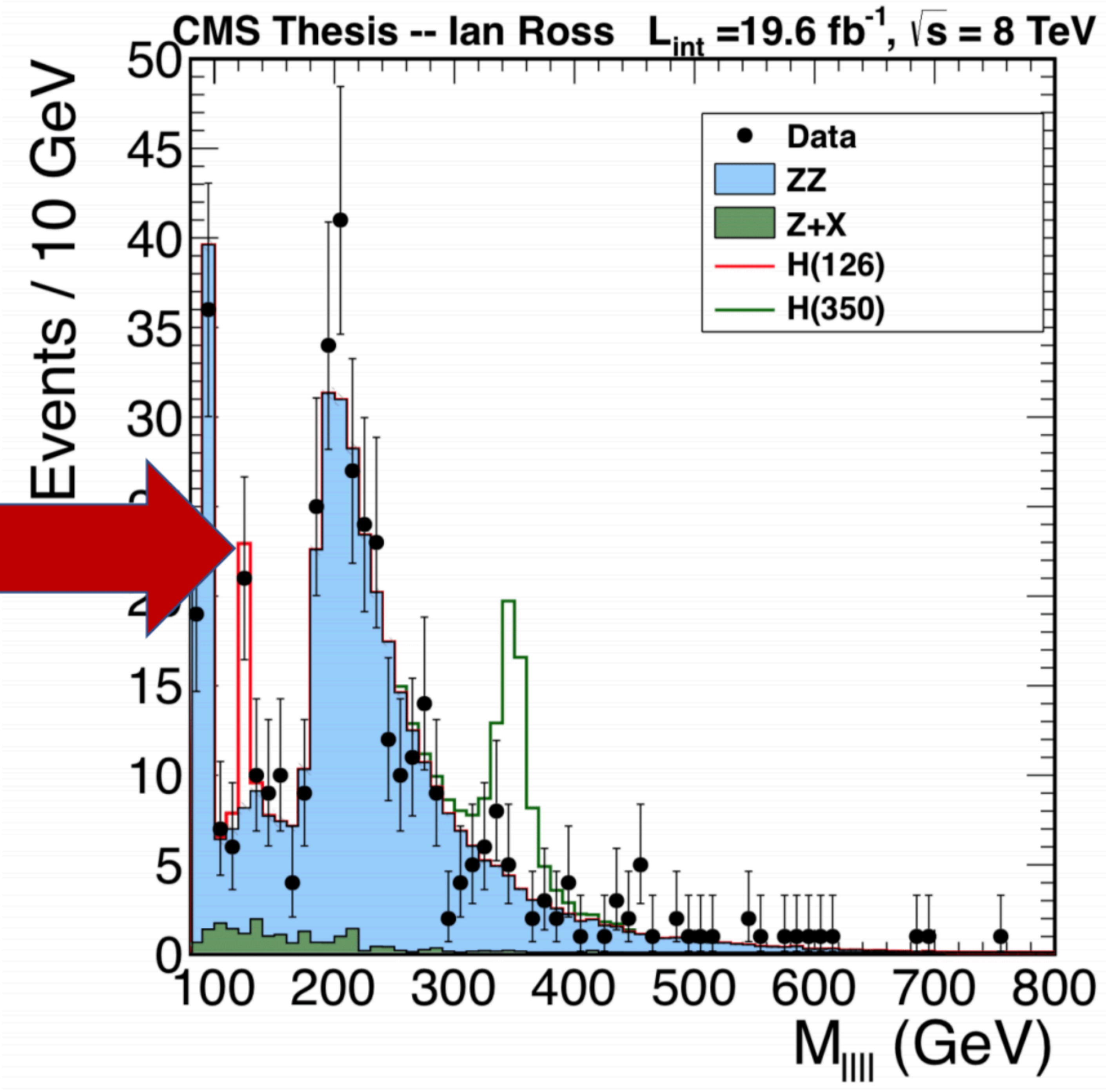
i	f_i^Z	f_i^γ
4	$-0.004 < f_4^Z < 0.004$	$-0.005 < f_4^\gamma < 0.005$
5	$-0.004 < f_5^Z < 0.004$	$-0.005 < f_5^\gamma < 0.005$



Discovery of the Higgs decay to ZZ - Ian Ross

...and also...

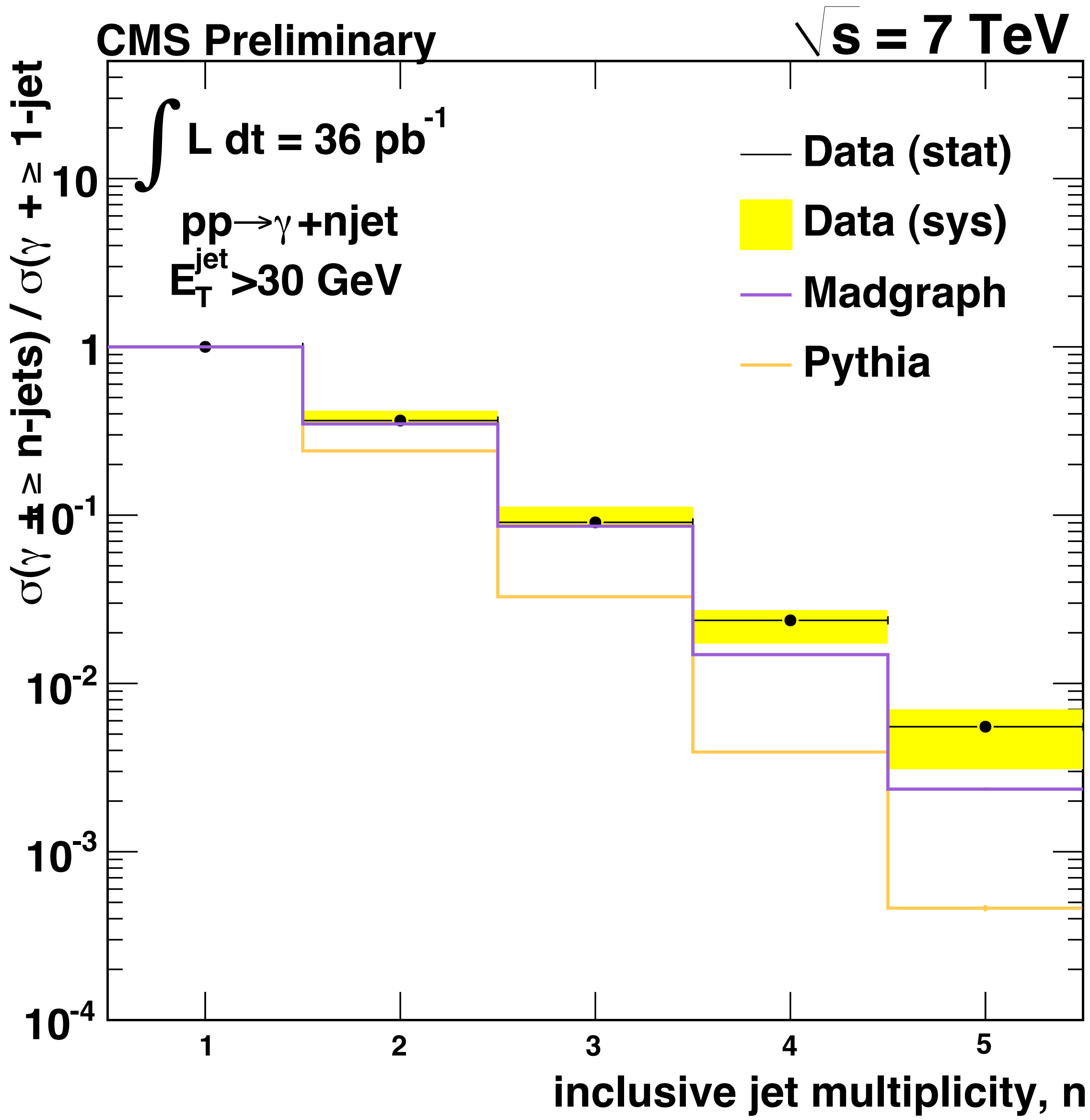
- Look at that Higgs boson!



Photon + Jet Multiplicity - Mike Anderson

Motivations:

- **Test/Validate theoretical predictions**
  - Cross section calculations are challenging # jets increases
- Explore new kinematic regions in hadron-hadron collisions
- **Background to pp->Higgs->γγ**
  - –Background for **beyond standard model** searches
- Ability to **constraining PDFs** of the proton
- Calibration of a NEW Detector!



Photon + Jet Multiplicity - Mike Anderson

First measurement of jet rate in association with a high-p_T photon

Results with $36pb^{-1}$ of data

- Loose photon isolation selection
- Jets with p_T > 30 GeV, R=0.5, using anti-k_T algorithm

Rates of jets in agreement with Madgraph simulations for ≥1 and ≥2 jets, but higher than predicted for ≥3 and ≥4

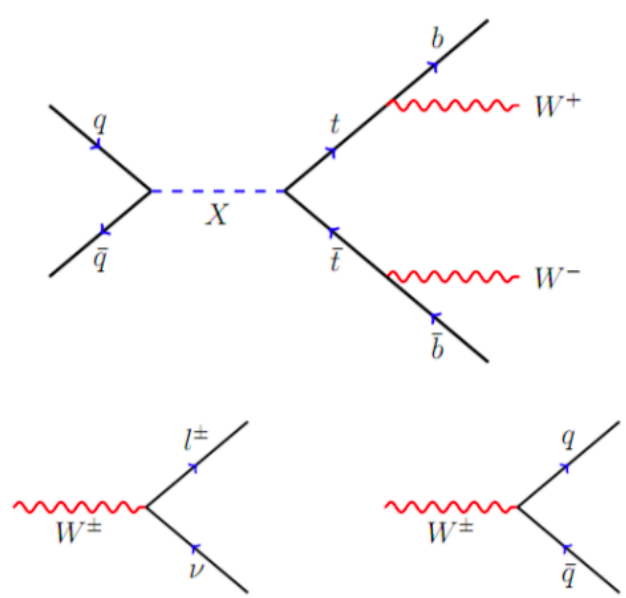
- This is expected because Madgraph sample used contains matrix elements for up to γ+3jets
- Data disagreement with Pythia is also expected because Pythia only simulates photon+1 jet, and uses showering to create more jets

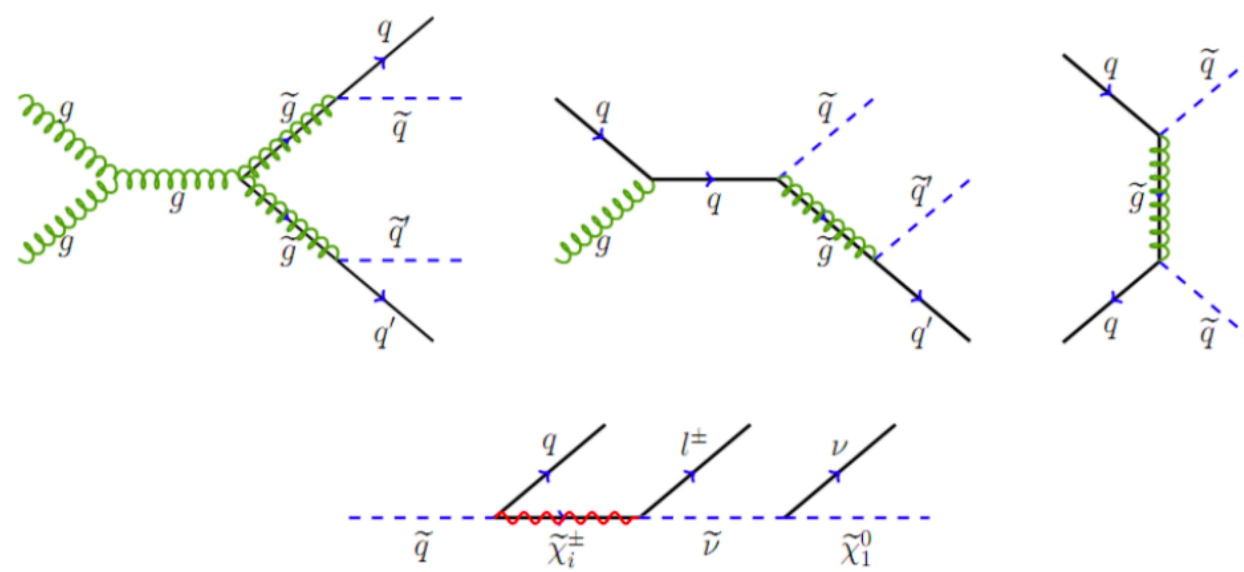
Tuned Monte Carlo event generators can be used for new physics searches. Ex:

- γ+1 jet: background to H->γγ
- γ+jets+missing E_T: a signature for super-symmetry

Search for same-sign dileptons

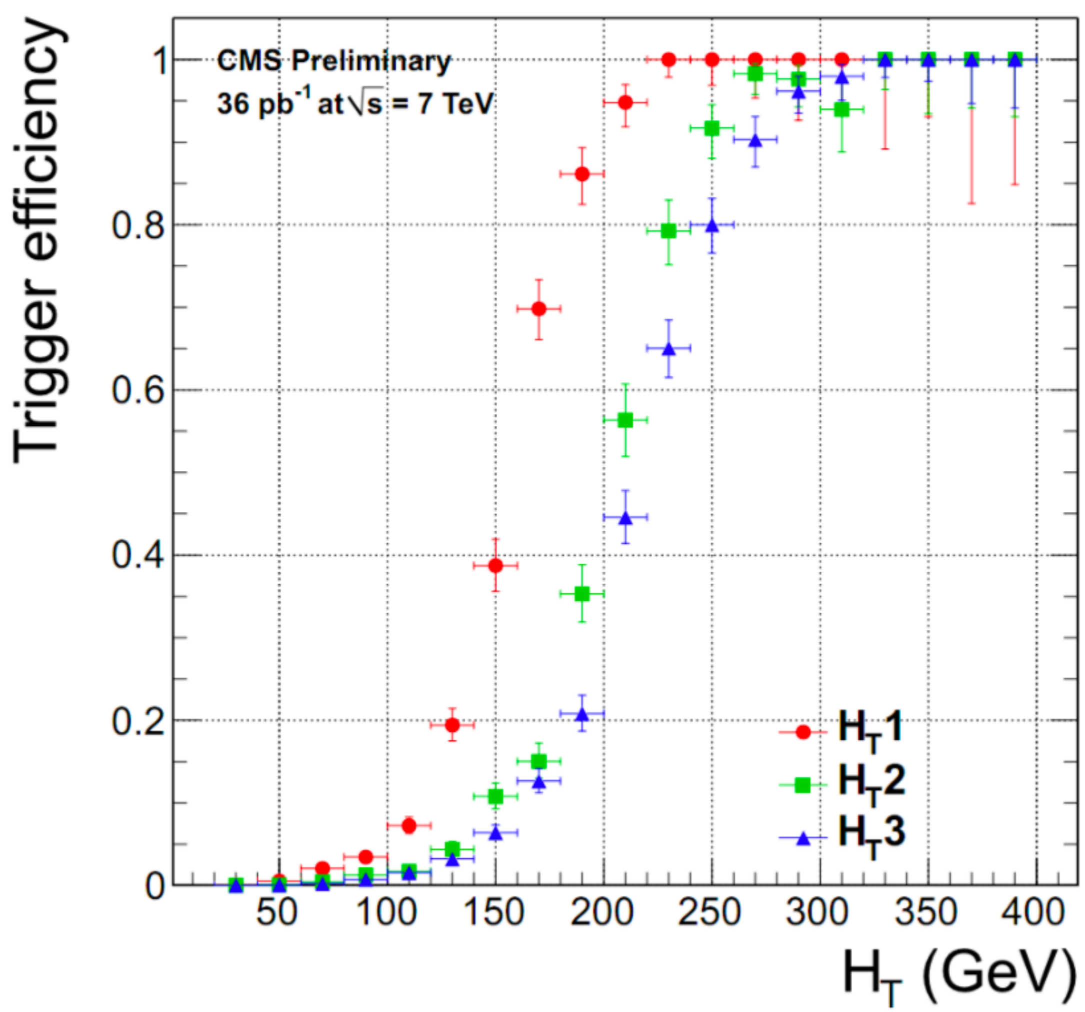
- Top quark observation major milestone
- Top quark physics major background to SUSY searches
  - Top signatures similar to many new physics models
- Isolated ss dileptons very clean BSM signature
  - SM sources vanishingly small
    - Primary background 1 iso lepton plus jet fake
  - Same-sign leptons occur naturally in SUSY models
- Looks like a strange UW analysis?
  - Not a SM measurement (unless you count the top xsec measurement tacked on)
  - Doesn't have taus in final state
  - SS dilepton search a hilariously bad idea with 36 pb^{-1} lumi





Trigger selection

- Wouldn't be a Wesley talk without a trigger slide!
- Best idea in the whole analysis: use H_T triggers, keep the lepton p_T thresholds low
- Necessary to use multiple single-lepton, H_T triggers
  - Move to higher thresholds with increasing luminosity so triggers remain unprescaled
- H_T trigger efficiency vs reconstructed H_T
  - Another cool idea: measured from data via muon triggers
    - Just need events with a good muon and lots of H_T
  - Then you can pick up the muon trigger efficiency via T&P



Same-sign dilepton yields for all analyses

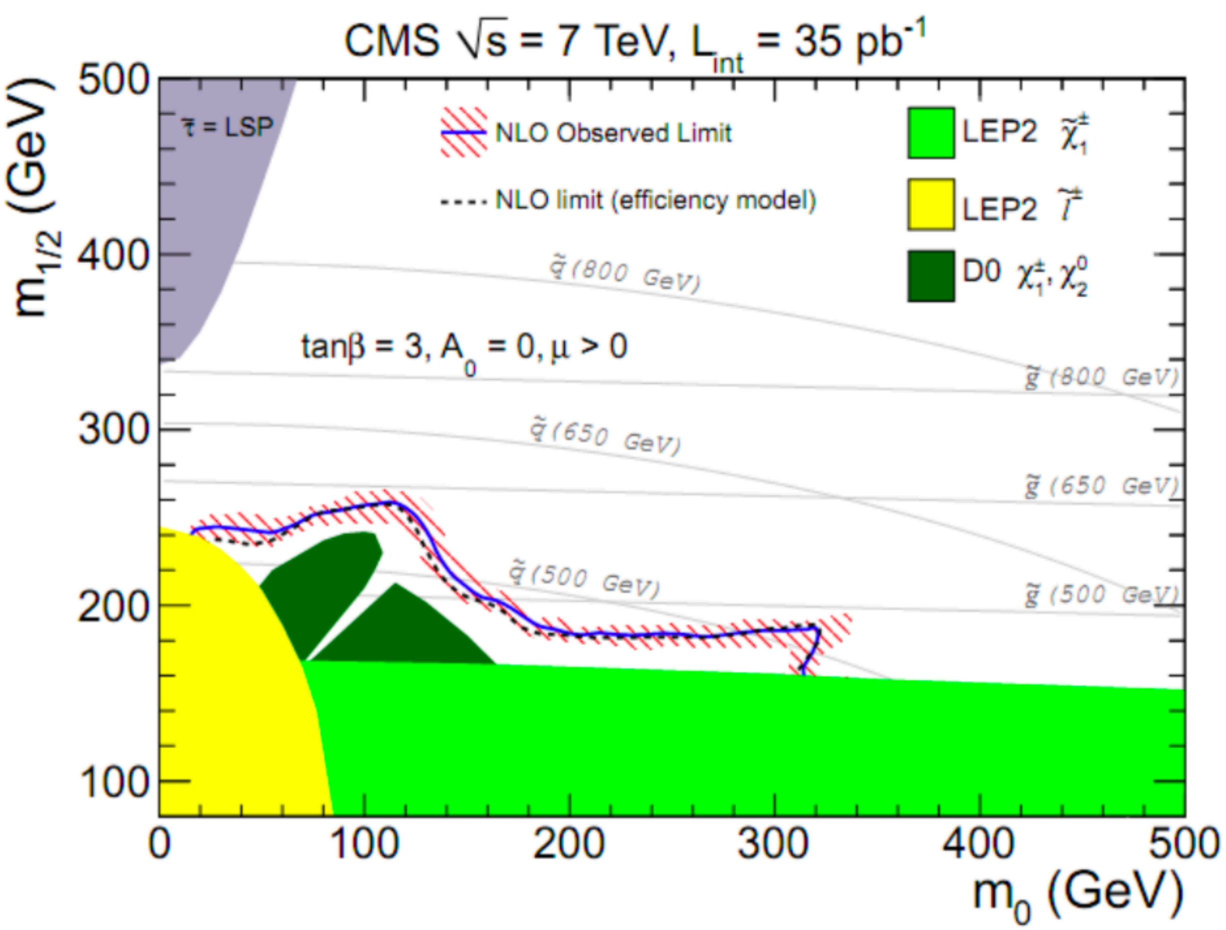
- Background predicted via fake rate method
  - Includes looser fake definitions to improve statistical uncertainty
- MC contribution predicted from fake rate method applied to simulation
  - Scale factors obtained from fit results included in calculation
  - Includes pileup + L1 offset corrections

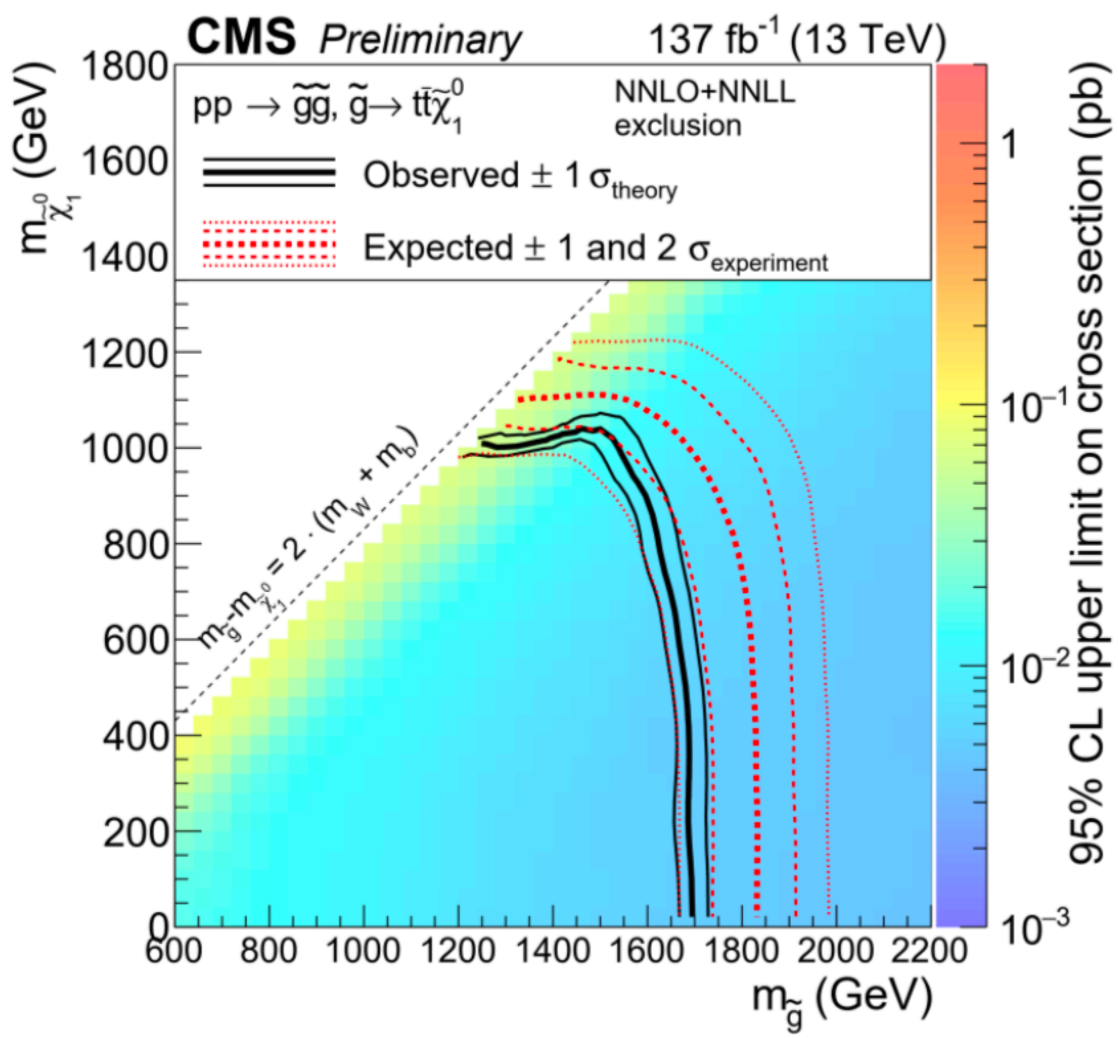
Search Region	ee	$\mu\mu$	$e\mu$	total	95% CL UL Yield
Lepton Trigger					
$E_T^{miss} > 80$ GeV					
MC	0.09	0.20	0.28	0.58	
predicted BG	0.07 ± 0.04	0.43 ± 0.22	0.64 ± 0.17	1.14 ± 0.25	
observed	1	0	0	1	4.2
$H_T > 200$ GeV					
MC	0.26	0.11	0.47	0.84	
predicted BG	0.22 ± 0.08	0.54 ± 0.19	0.79 ± 0.18	1.55 ± 0.26	
observed	1	0	1	2	5.2
H_T Trigger					
Low-p_T					
MC	0.16	0.05	0.18	0.39	
predicted BG	0.15 ± 0.02	0.05 ± 0.03	0.33 ± 0.08	0.52 ± 0.07	
observed	1	0	0	1	4.5

- The stupid ee channel was the reason I almost didn't graduate
- (But not a half-bad top production cross section!)
  - $\sigma(tt) = 159.1 \pm 12.1(\text{stat})\ ^{+33.8}/_{-28.2}(\text{syst}) \pm 6.4\ (\text{lumi})$ pb

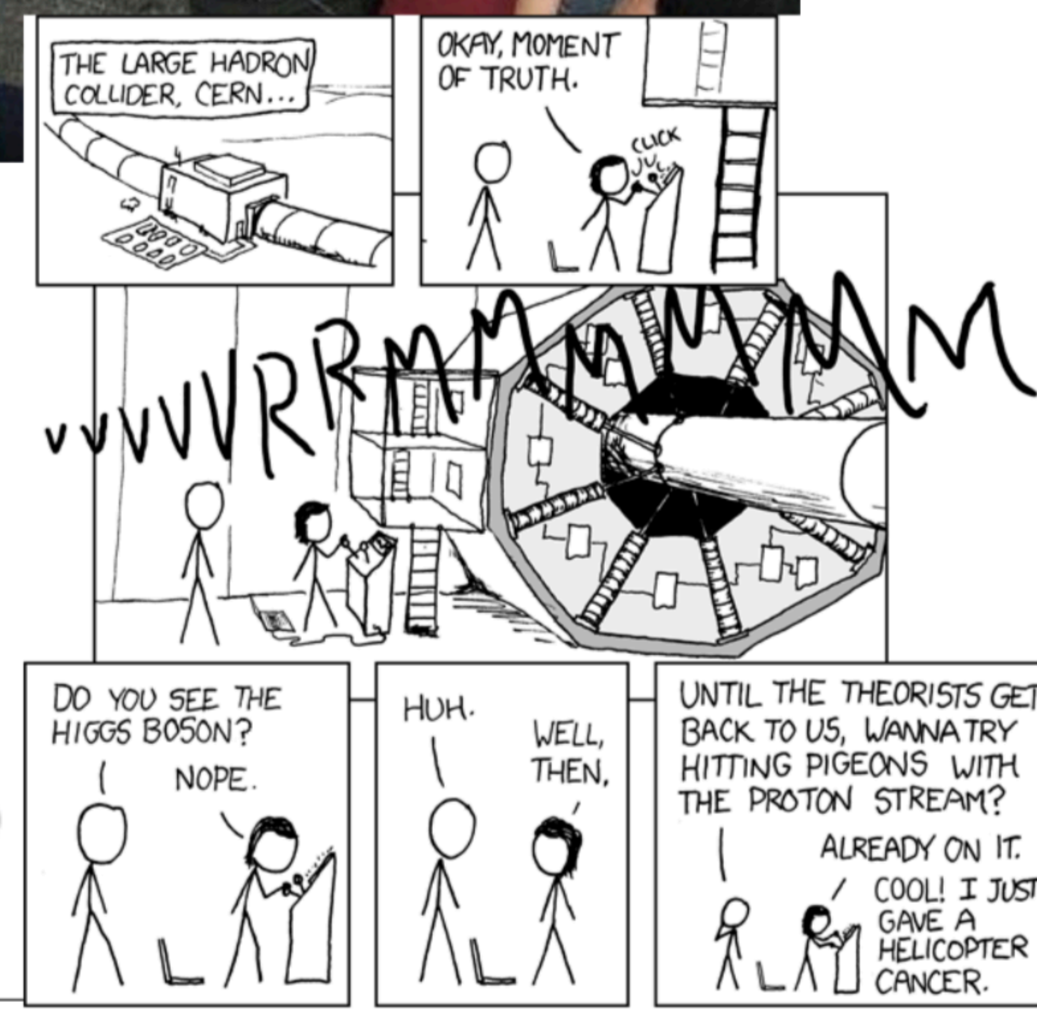
Exclusion contour in CMSSM

- **Remember when we used to compare to the LEP2 results?**
  - **But nobody had a heat map of the xsec limit…**
- **Here's how it looks when you have 2x the energy and 4000x the lumi, you search in 20x as many signal regions, and you simulate a gazillion signal points**





LHC in the news; NBD



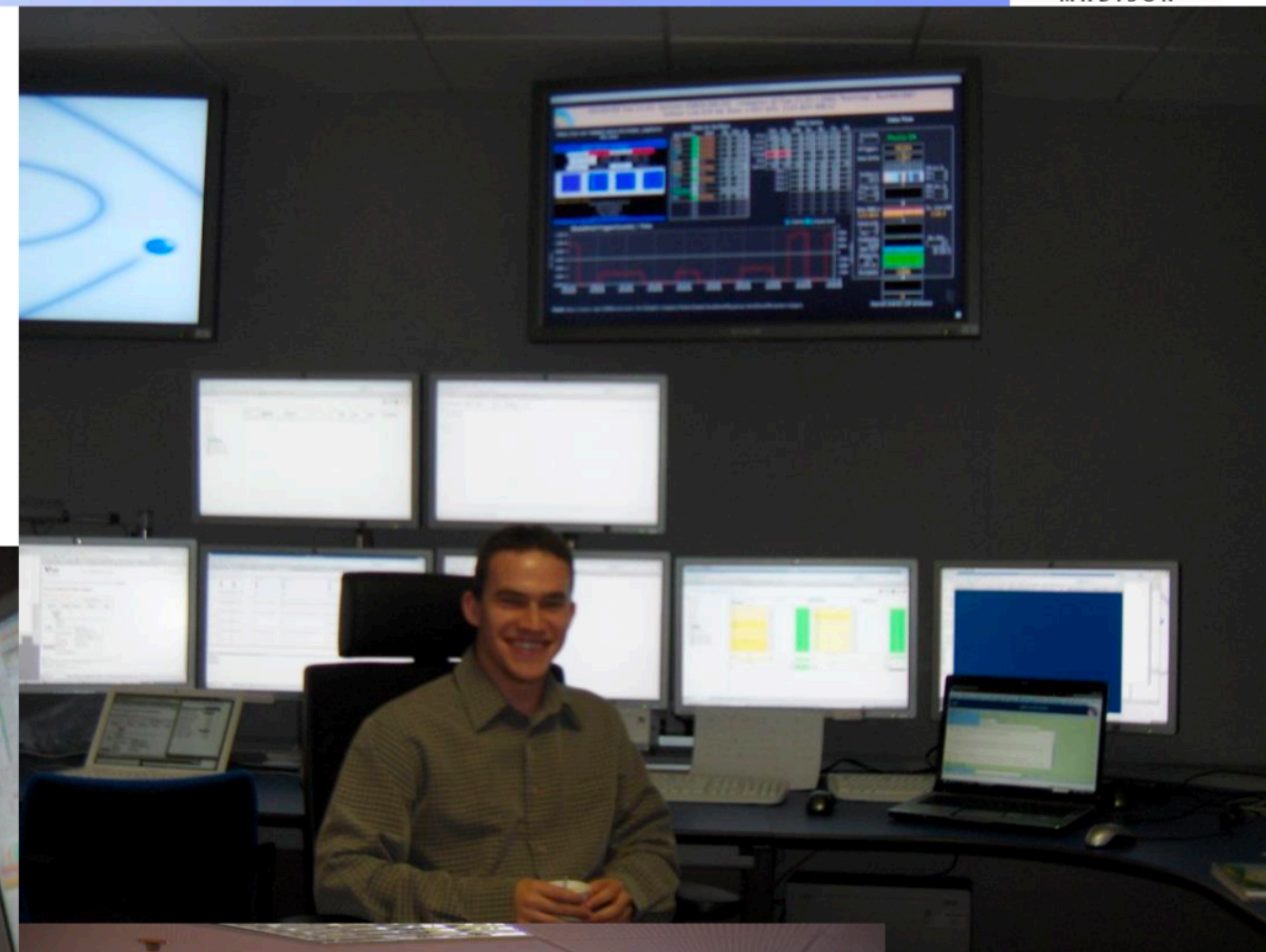
This may be the last thing you ever read: Large Hadron Collider fires up in minutes

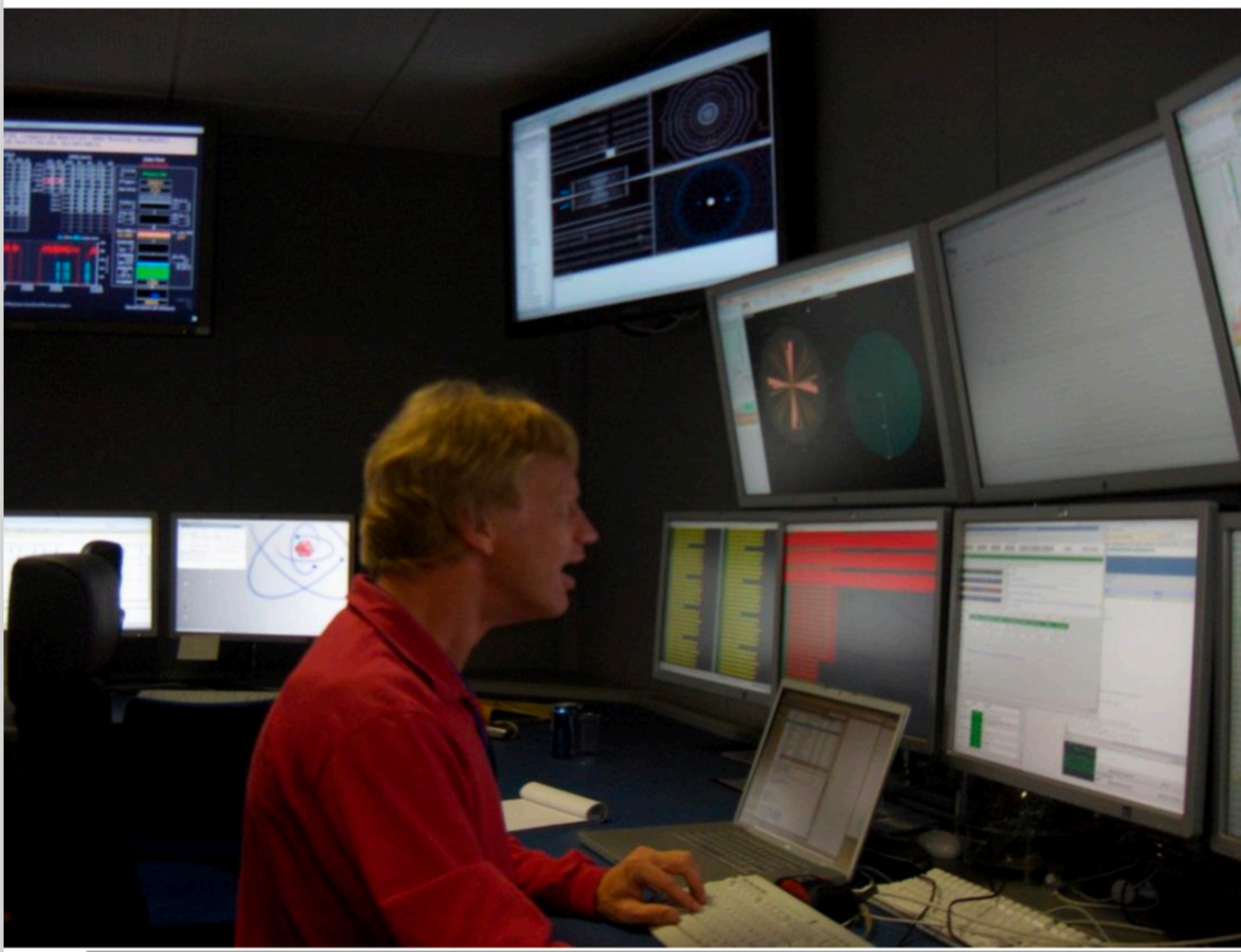
By Andrew D. Smith / Guest blogger
adsmith74@gmail.com | Bio
2:12 AM on Wed., Sep. 10, 2008 | Permalink

Babysitting the detector

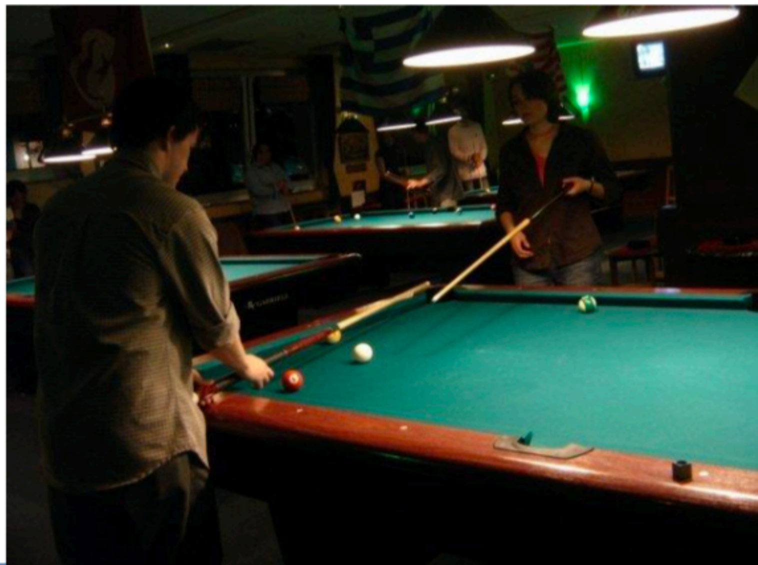
Detector systems have to be carefully monitored during run

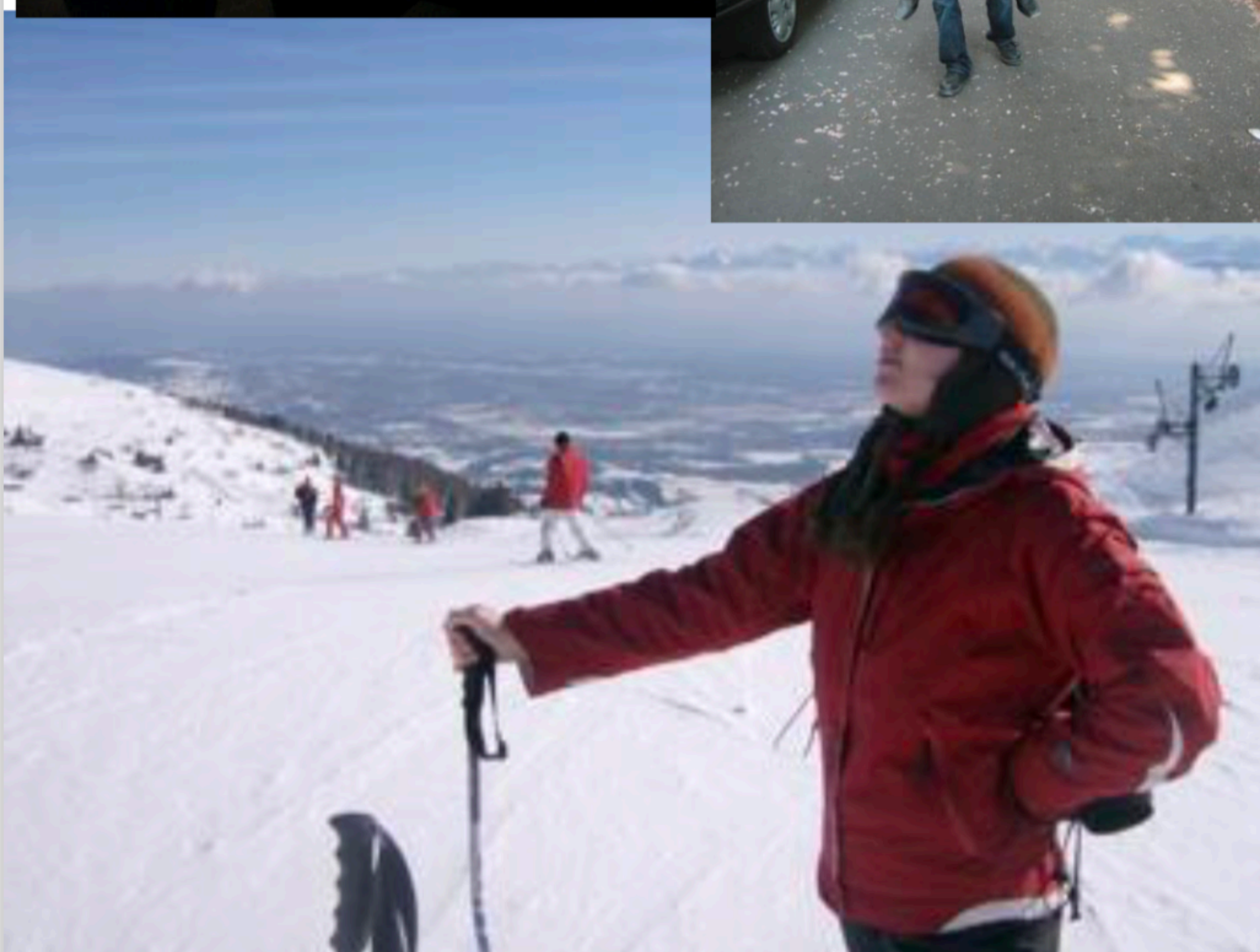
- **Most important system: Coffee machine**
- **Best part: Someone made HLT monitor sound like Wesley**

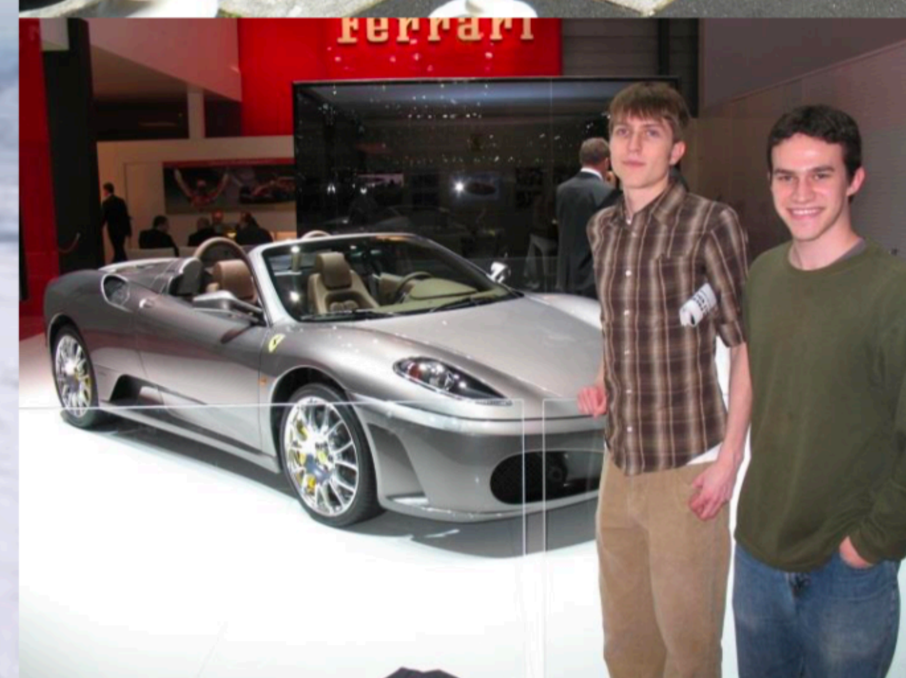




Ode to Geneva







First taus in CMS

Michalis Bachtis

Thesis topic: H → ττ in CMS

Work with Wesley and quotes

- RCT operations and early Phase I Calorimeter Trigger studies.

Wesley was really sensitive about downtime (especially wrt GCT).

However safety was first

  - *"Trigger always works. Trigger never sleeps"*
  - *" I do not care about downtime. You are NOT allowed to go in P5 by yourself in the middle of the night!! We care about your safety"*

- High Level Trigger (taus in my case)

Wesley did an excellent job at the HLT as Trigger coordinator which was proven a huge success in the beginning of CMS data taking.

  - *" The HLT should relax for high P_T objects making sure the efficiency approaches 100%"*
  - *"Better is the enemy of the good" - when I would change tau HLT every week*
  - *"Michalis, you are taking classes. You should not work so hard, or else you will burn out. If someone asks you to do something for CMS this semester send them to me!"*

- Phase I early studies

We did a lot of work in early algorithms but unfortunately I graduated before the real "fun" started.

  - My only complaint from Wesley was that he didn't let me work the last 6 months of my thesis with Tom on CTP6. But he was probably right!

Impact of Wesley in my career

Michalis Bachtis

Trigger

- If I had not gotten the trigger virus from Wesley, probably I would still be in my staff position at CERN and would not have come back to the US. I would also not work in any detector/hardware related project other than the L1

Excitement about technology

- Electronic design is super cool. Wesley always looked forward to future technologies and thought how to do physics with them. If I had not been in Wesley’s group, I would not have gone in this direction

Some things he can do and I still do not know how!

- He made every PhD thesis and every postdoc position a successful story. Everyone would do a good thesis and graduate exactly on time.
- His patience (with students, postdocs and CMS colleagues) was incredible
  - I still do not know how he could deal with some people

We are certainly already missing Wesley’s energy from CMS

Personally I miss him as a group leader at UW

- Group metings were so fun !Every single week, something would happen.

Conclusions: Thank You Wesley!

Your students, post-docs and colleagues will benefit from your passion for physics and teaching for years to come!

Wisconsin State Journal

WWW.MADISON.COM/WSJ ★★★ TUESDAY, JULY 1, 2008 MADISON, WISCONSIN

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to death in home

State Journal

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plexion and medium build.

Madison police spokesman Joel DeSpain said it appears that Hamilton was targeted. "It wasn't a random attack," DeSpain said.

"Detectives are currently trying to determine why he was targeted."

Please see **SLAYING**, Page A10

care center
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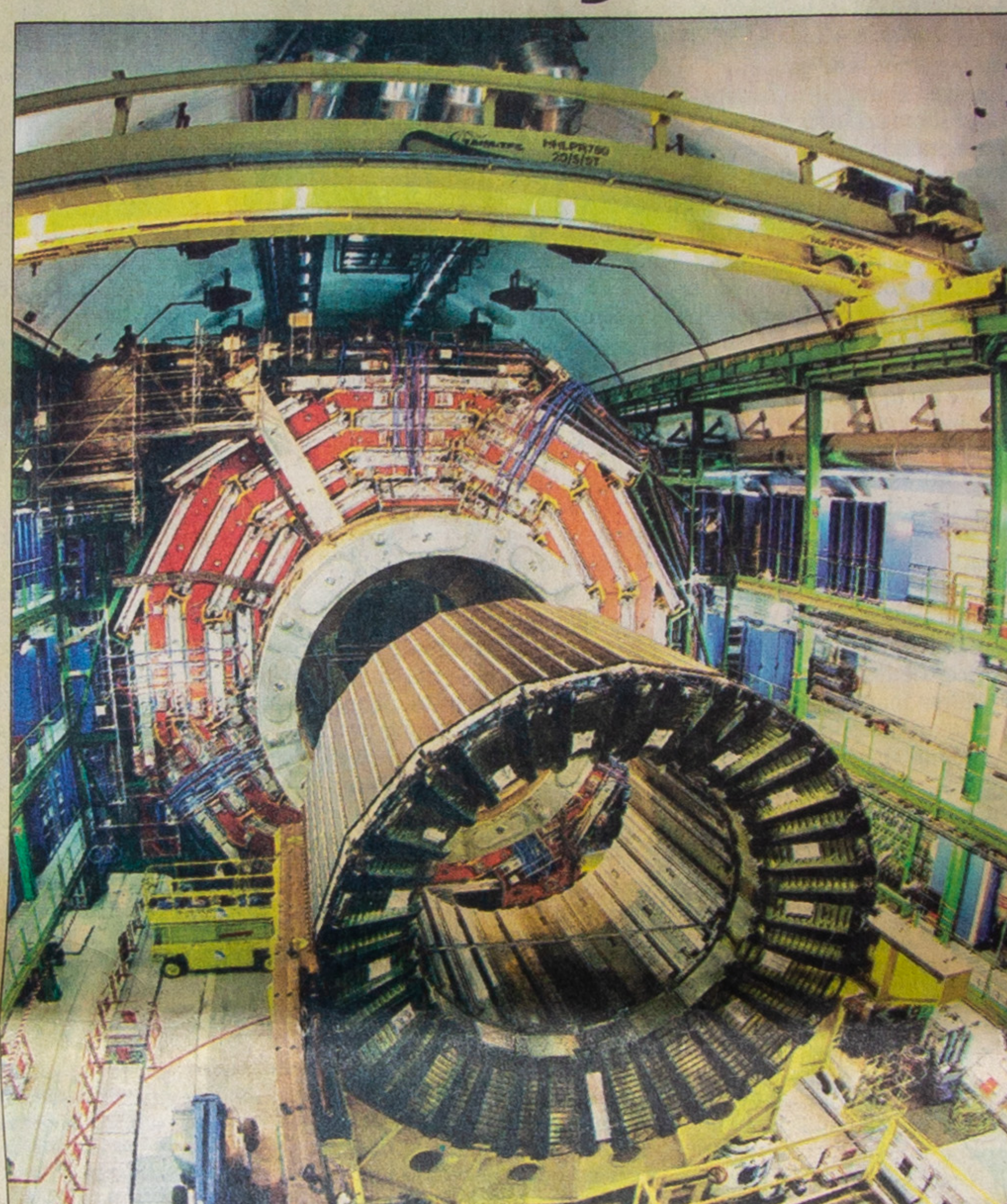
sumer advocates as an important step in helping parents find high-quality child care.

Still, the database does not offer any type of quality rating system, a fact Doyle called

READERS' CHOICE *Vote at www.madison.com/wsj*

Will collider destroy Earth?



Some fear bold project could create a black hole

By DOUGLAS BIRCH
Associated Press

MEYRIN, Switzerland — The most powerful atom-smasher ever built could make some bizarre discoveries, such as invisible matter or extra dimensions in space, after it is switched on in August.

But some critics fear the Large Hadron Collider could exceed physicists' wildest conjectures: Will it spawn a black hole that could swallow Earth? Or spit out particles that could turn the planet into a hot dead clump?

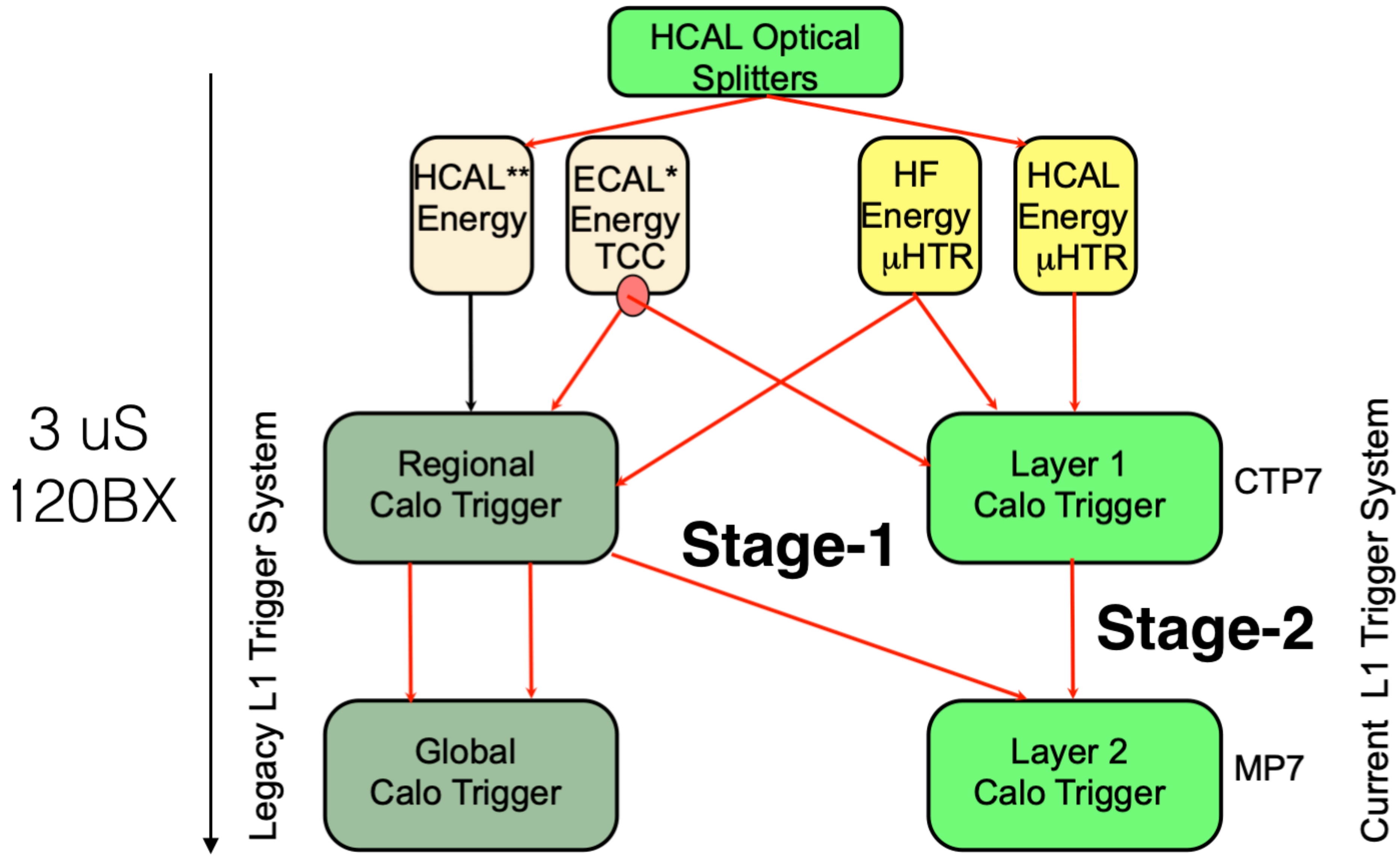
Ridiculous, say scientists at the European Organization for Nuclear Research, known by its French initials CERN — some of whom have been working for a generation on the $5.8 billion collider, or LHC.

"Obviously, the world will not end when the LHC switches on," said project leader Lyn Evans.

David Francis, a physicist on the collider's huge ATLAS particle detector, smiled when

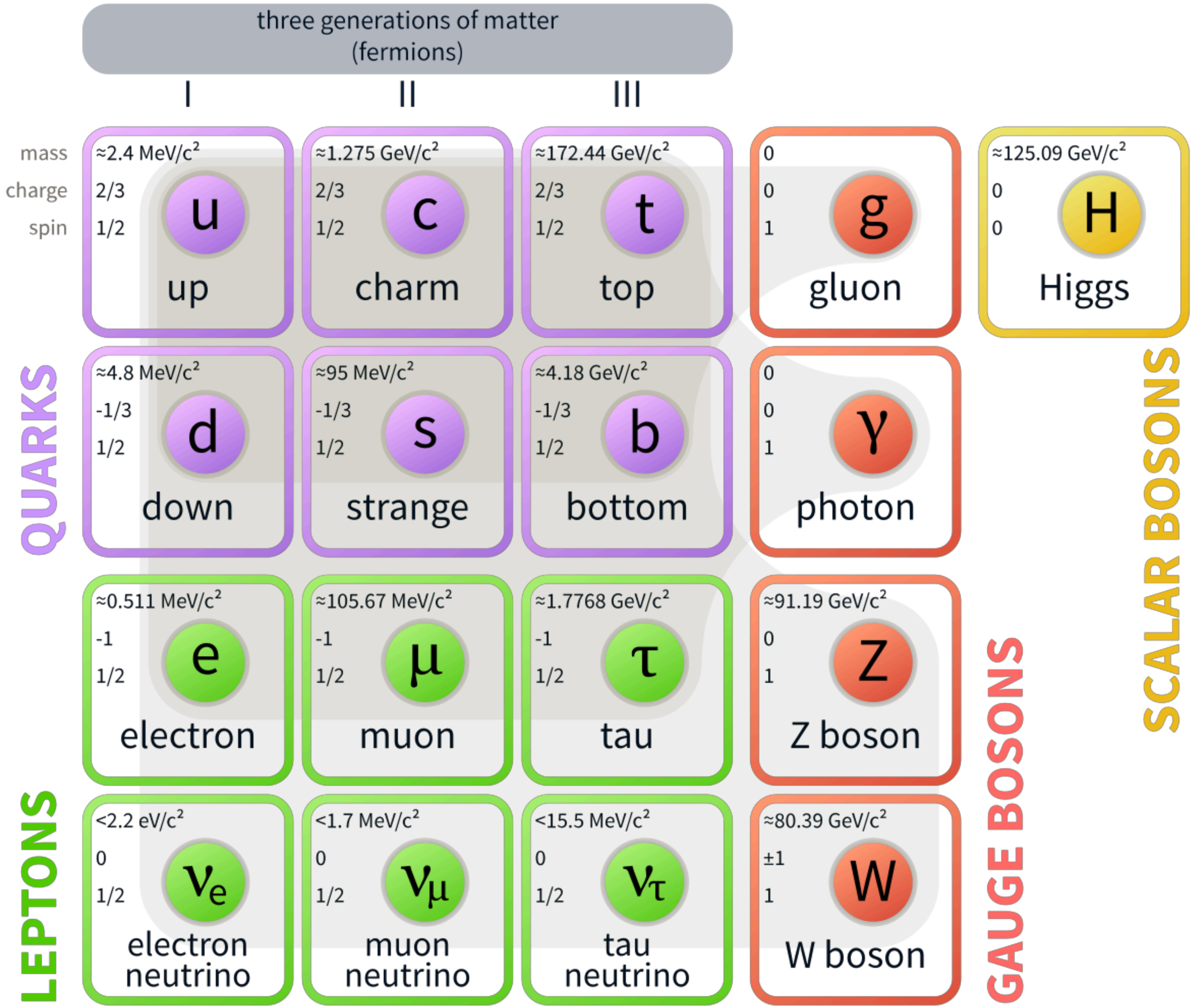
Trigger work as a Post-Doc for Wesley

- UW has designed and operated the more complex portion of the Calorimeter Trigger
  - The first layer (RCT/Layer-1) is responsible for processing all data from the calorimeters at 40 MHz

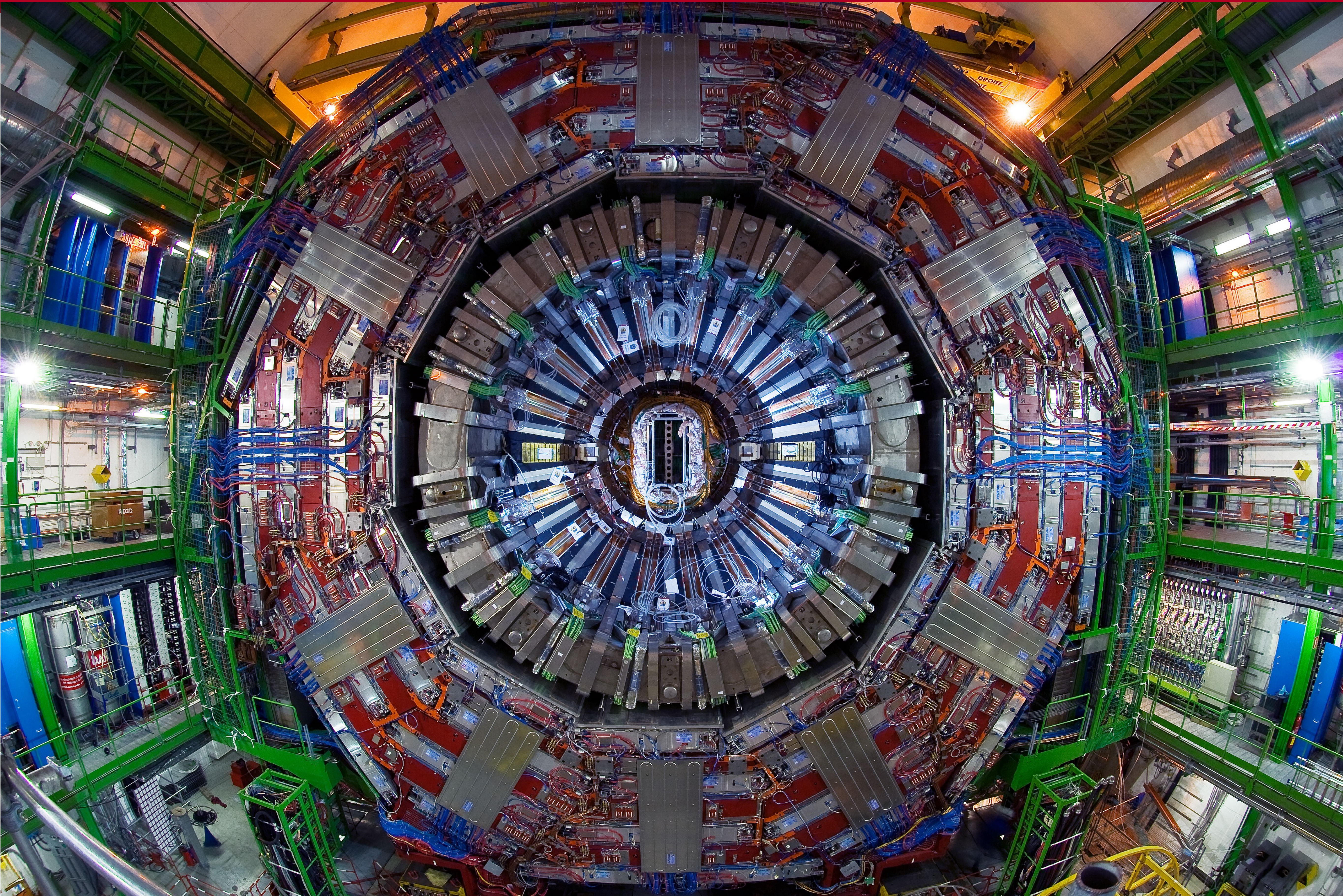


- This gave me the opportunity to work with the best engineering team at CMS
  - **OK, maybe I am a tiny bit biased ;)**
- We developed algorithms for Phase-1, with notable improvements to Hadronic Tau ID

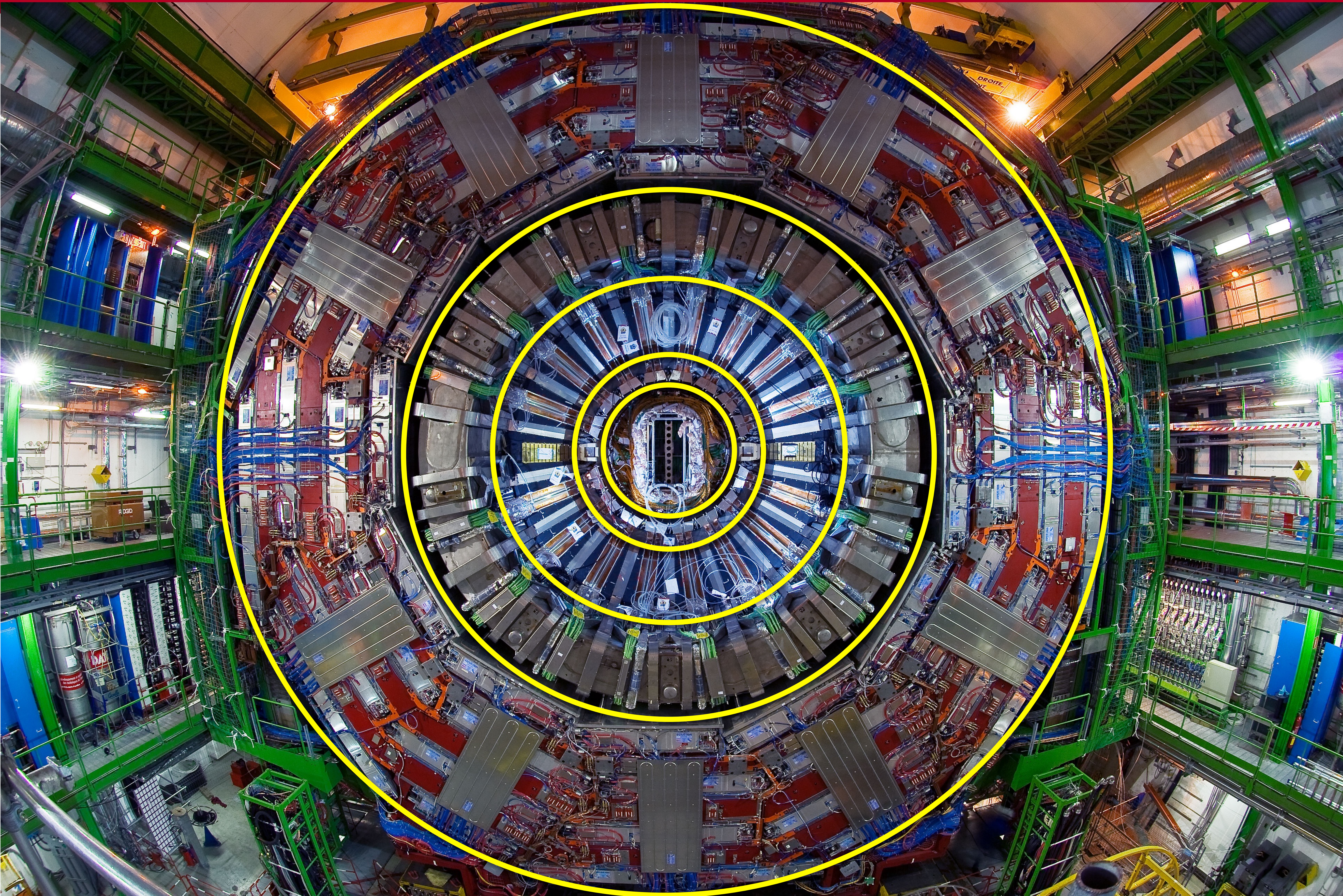
Standard Model of Particle Physics



Particle Detection at CMS



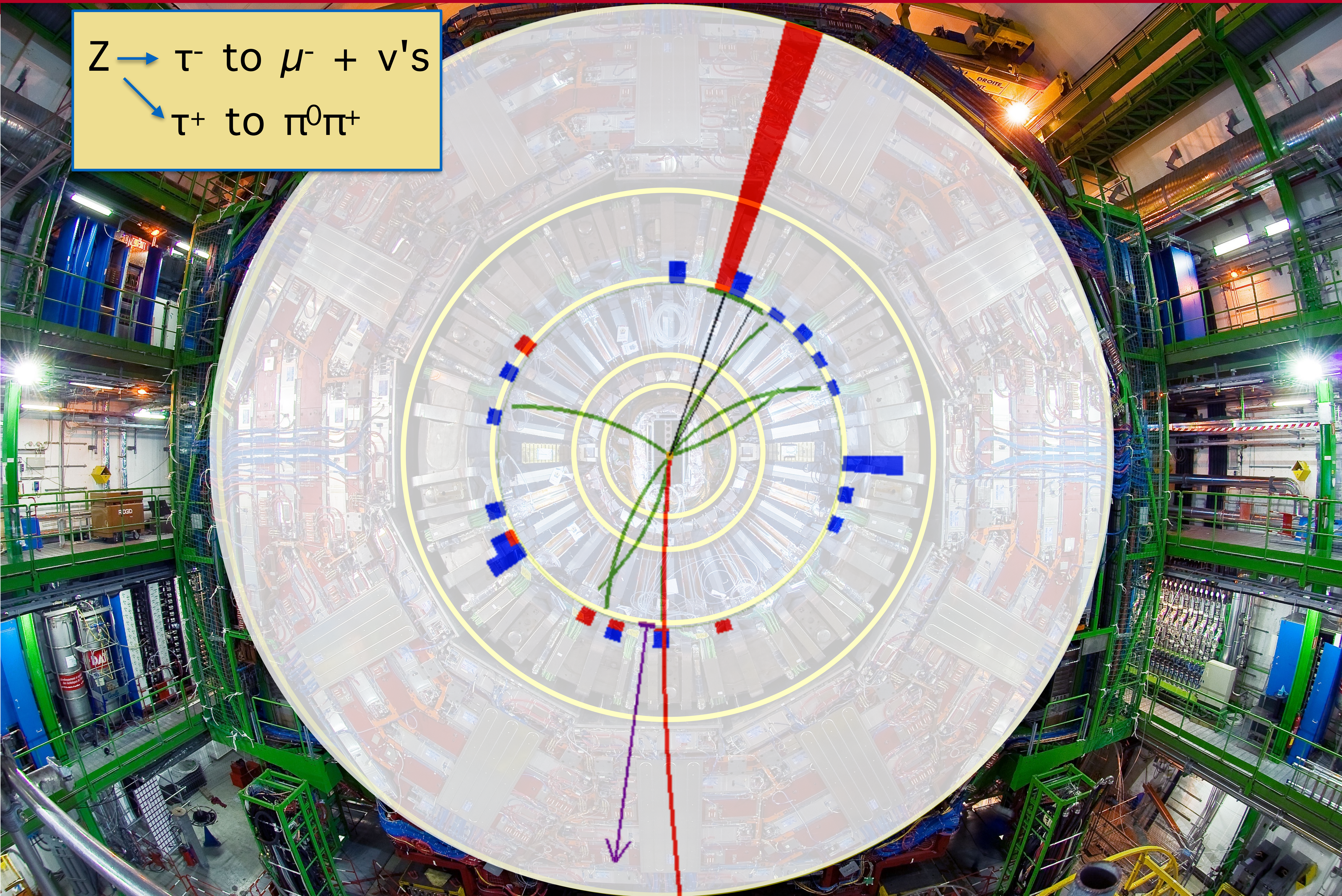
Particle Detection at CMS



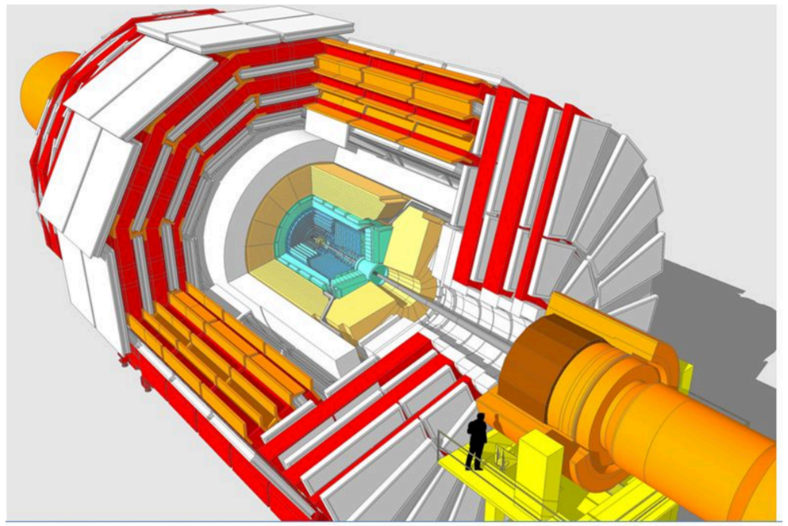
Particle Detection at CMS

$Z \rightarrow \tau^- \text{ to } \mu^- + \nu\text{'s}$

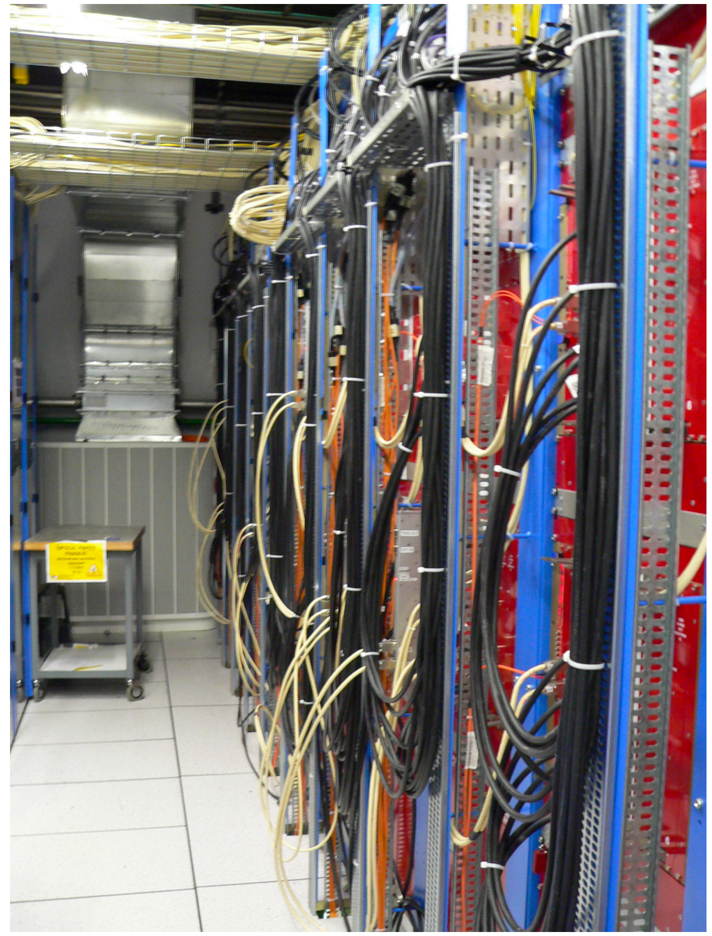
$\searrow \tau^+ \text{ to } \pi^0\pi^+$



Calorimeter Trigger System



Energy Deposits in the Calorimeters

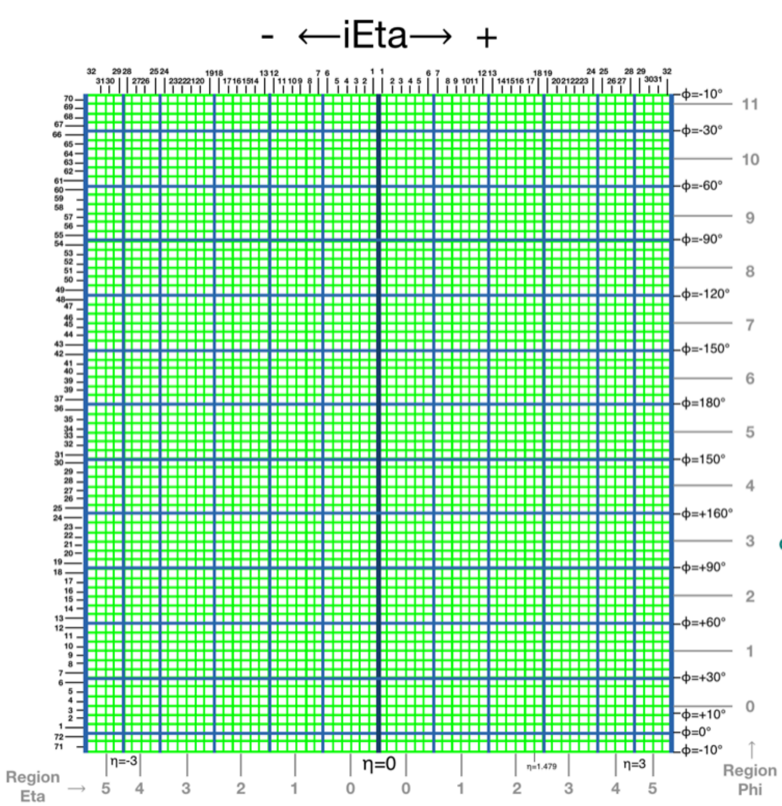


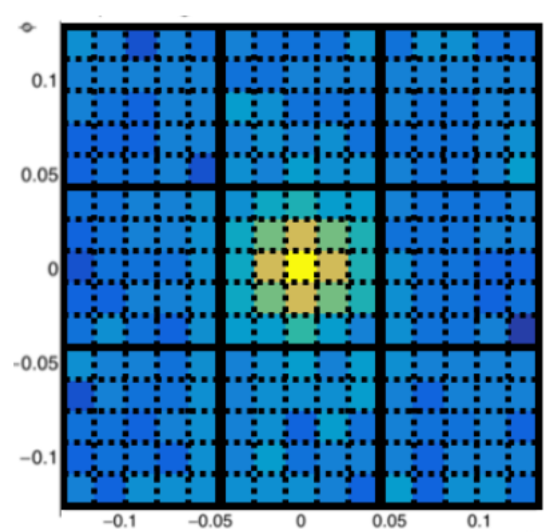
Calorimeter Calibrations

Electron Identification, Isolation

Tau finding and Regional Sums

Electron Sorting





Electron Finding and Sorting