The Notre Dame CMS Group

5 professors

2 research scientists

3 postdoctoral researchers

13 graduate students

6 undergraduate students

3 engineers

2 technicians

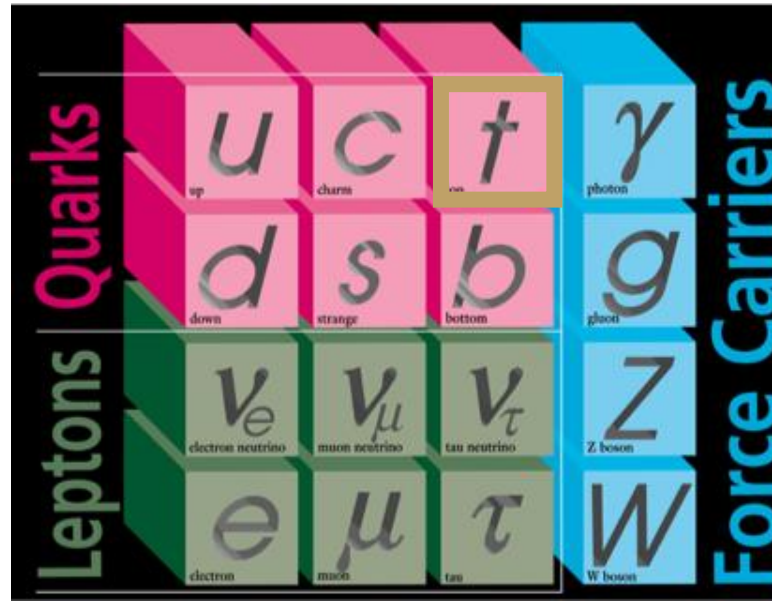
CMS Workshop at Universidad Iberoamericana, Mexico City, January 12, 2018

Kevin Lannon’s Group

Studies of the top quark, computing for HEP

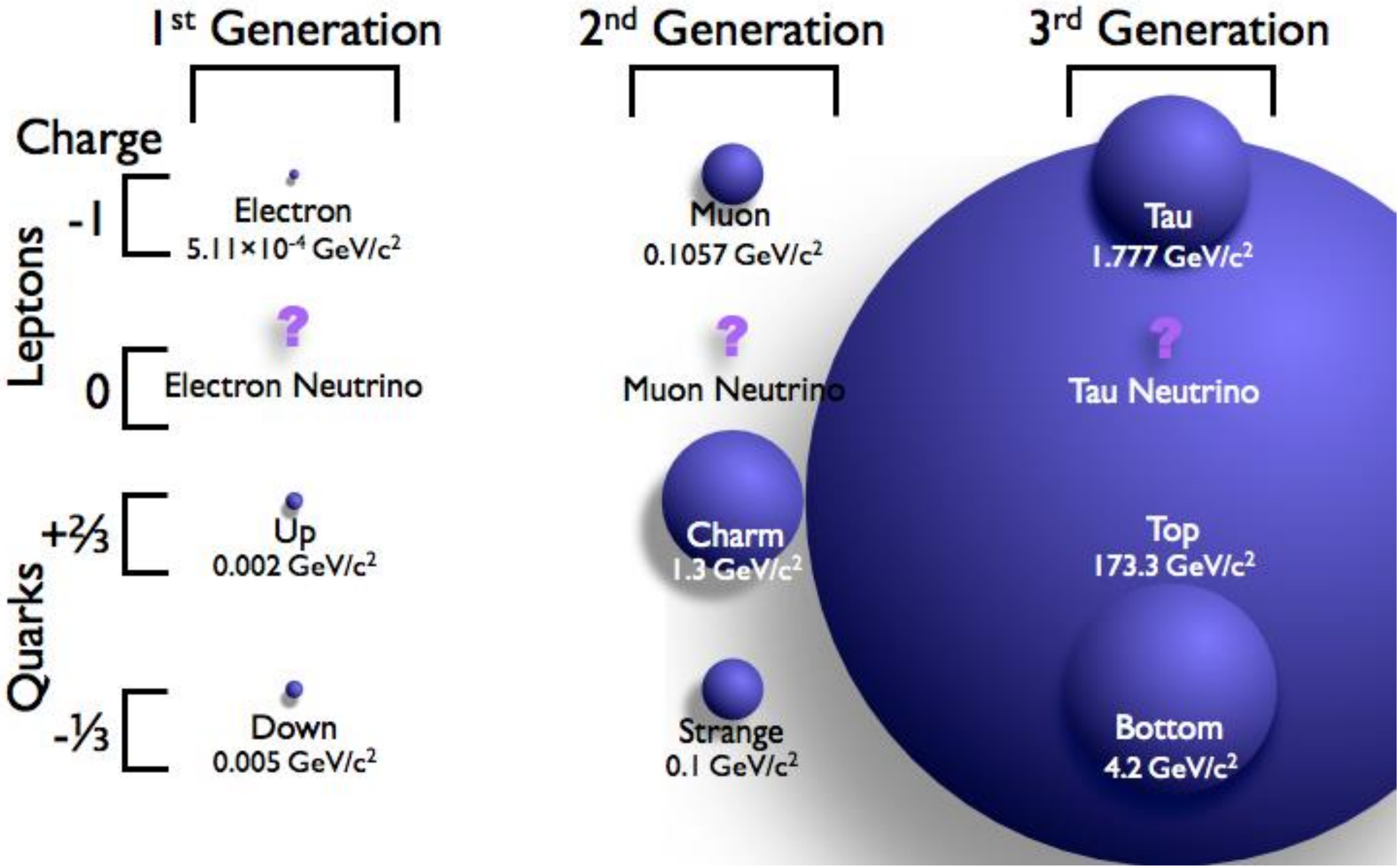
Why Study the Top Quark?

- One of most recently discovered particles in SM
- Really big mass
- Could be key to new physics
  - Limited opportunities to study = places for new physics to hide
  - Big mass = special role in EWSB?



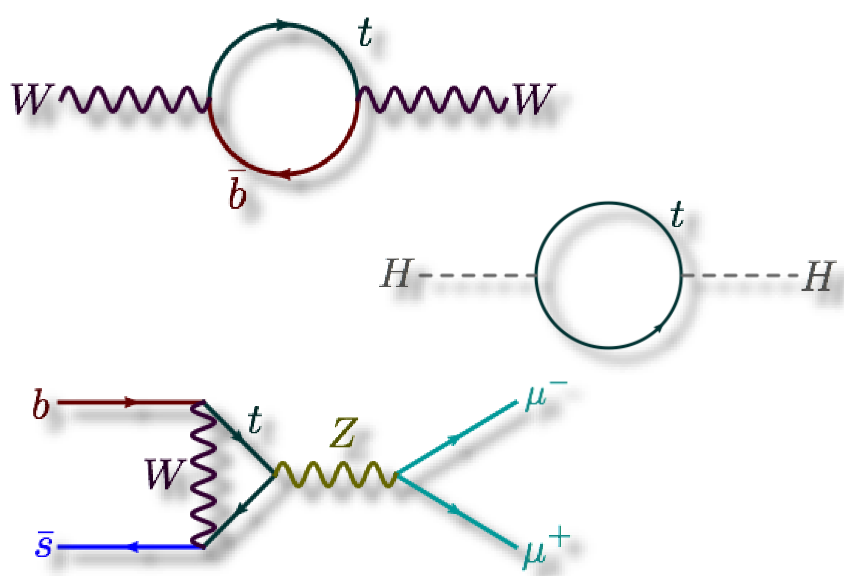
- Decays before hadronizing
  - Only chance to study "bare quark"

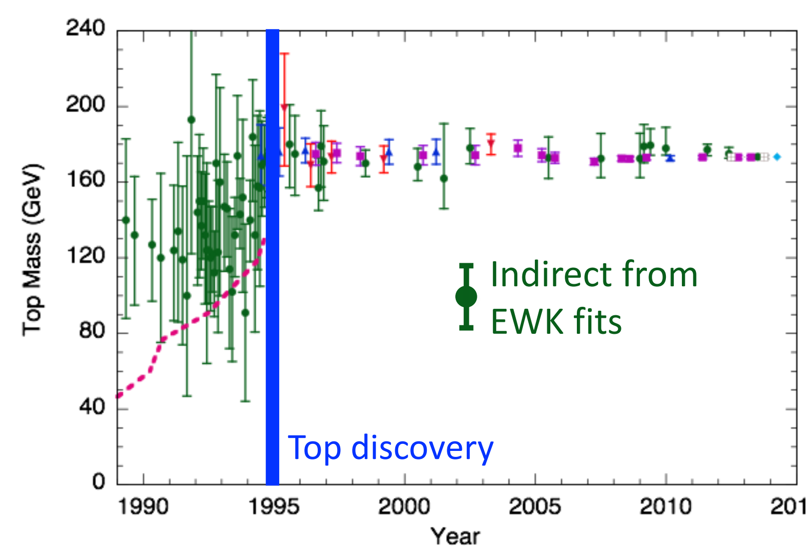
Top Quark Stands Out!



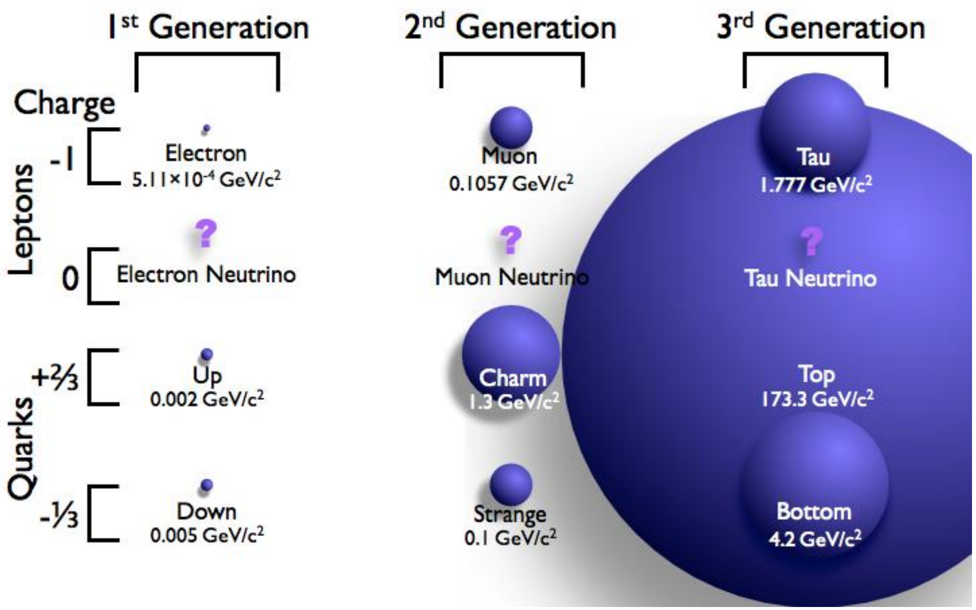
Top Fingerprints on SM

- Loop corrections to EW observables and rare decays proportional to top quark mass
  - Because top quark gives largest correction to Higgs mass, it's the focus of many attempts to address the hierarchy problem
- Even before discovery, presence (and mass) of top could be inferred





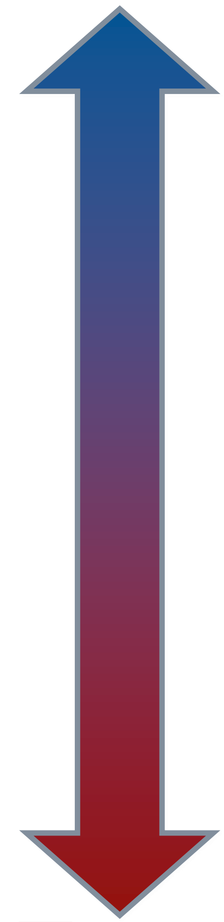
Ultimate Questions



- Why are there generations/flavors? Is the pattern of masses trying to tell us something?
- Since top quark is so different, perhaps it holds answer?

BSM with Top Quarks

Respect



Envy

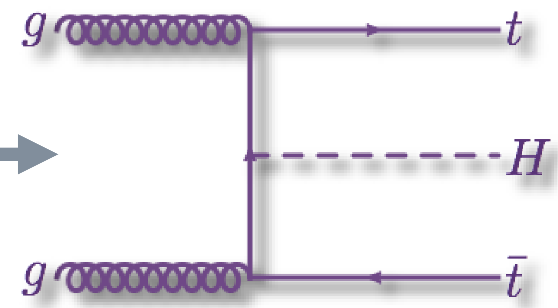
Precision studies:
- → Inclusive and differential cross sections
- → W helicity
- → spin correlations
- → AFB/charge asymmetry

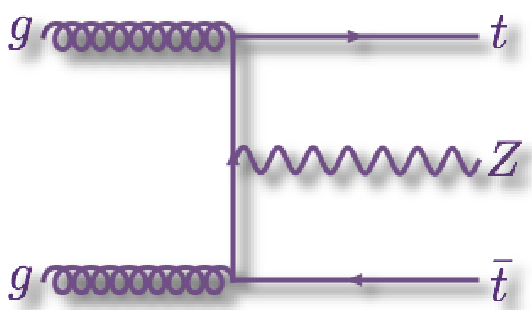
In between: Associated production! Search for rare (in SM) processes to check for deviations.

Explicit Searches for New Physics:
- → Vector-like partners
- → SUSY stop squarks
- → X->ttbar

Top Quarks + What?

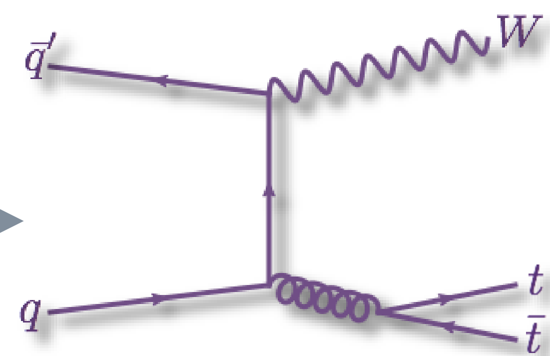
Top quarks + Higgs: Obviously! Source of mass and most massive particle. Sign me up!





Top quarks + Z boson: Also very interesting! Hard to probe t-Z coupling directly any other way.

Top quarks + W boson: We can already learn everything we need to about this coupling in SM via top quark decays (t->Wb). But if you have top quarks + extra Ws, that could certainly be a sign of new physics (i.e. X->tW).



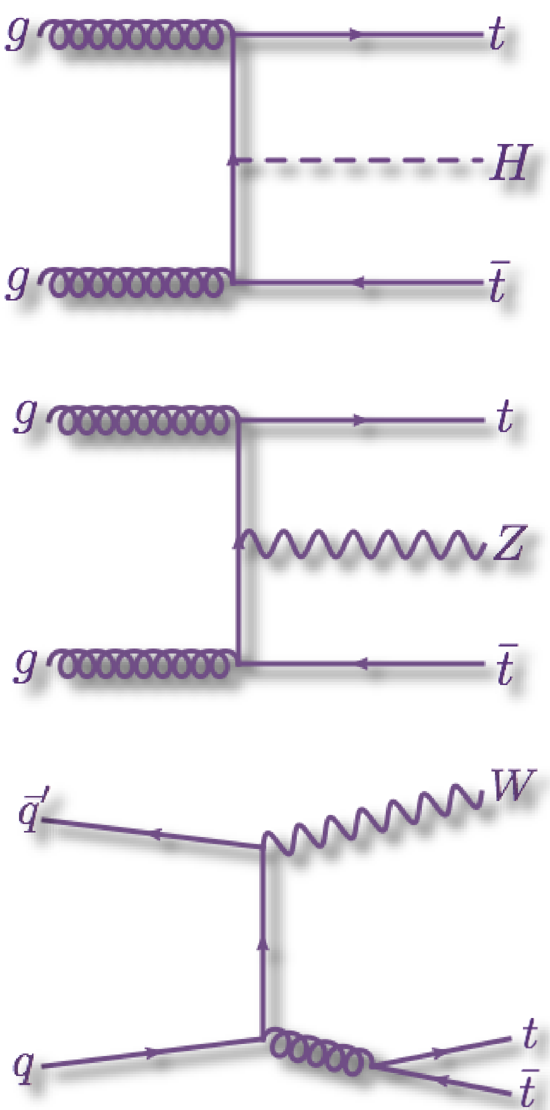
Top quarks + photons, bottom quarks, gluons/light quarks, top quarks (!): The list goes on and on. Where do you draw the line?

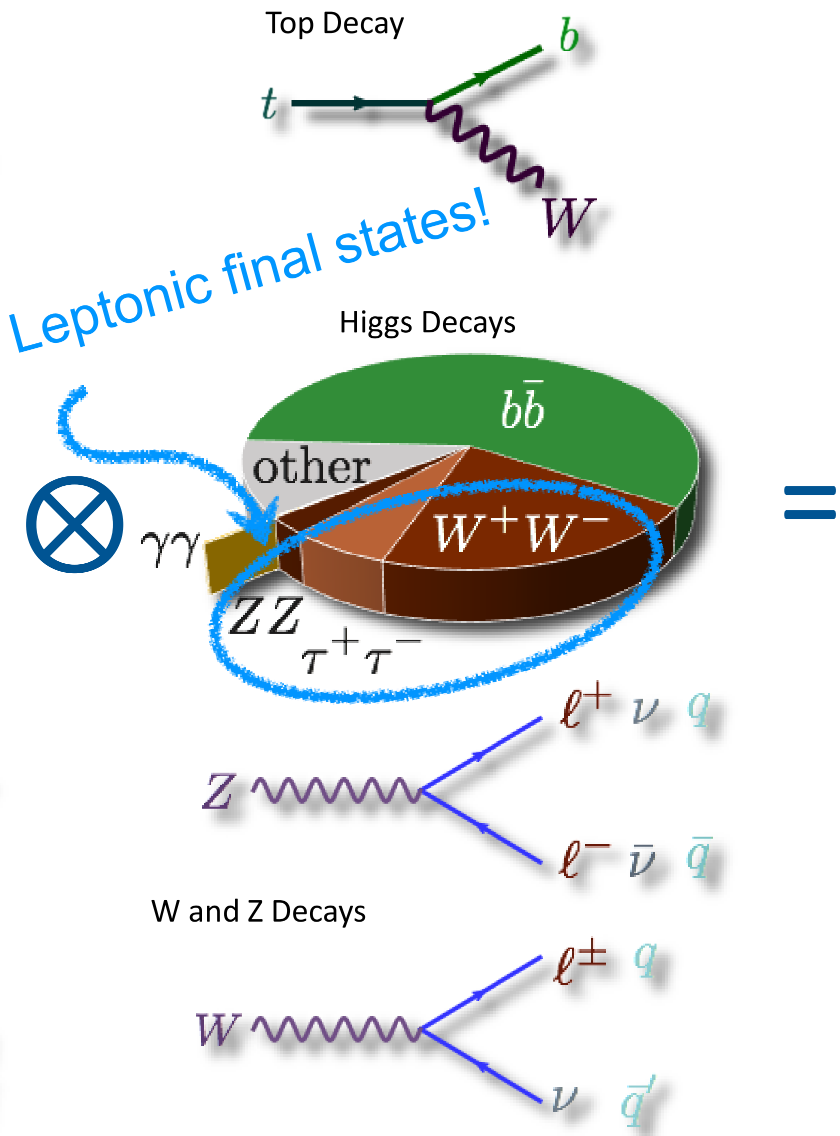
Coming of Age for Top at LHC

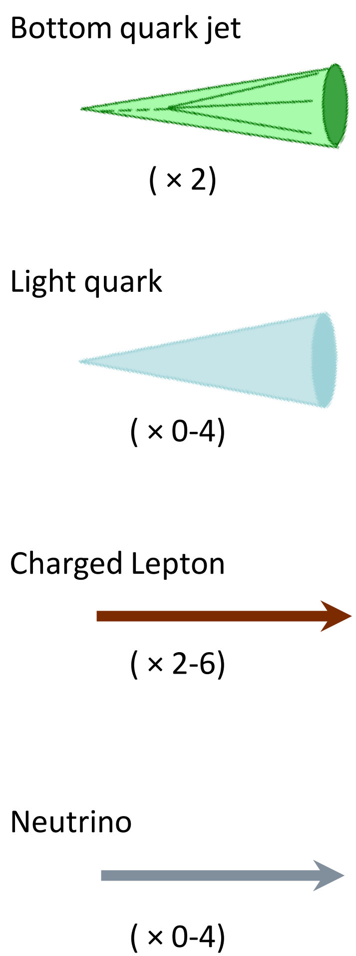
	Run	$\sqrt{s}$	Top Pair Production Per Exp. Max Rate	Top Pair Production Per Exp. Total Sample	First Observation
Tevatron	1	1.8 TeV	0.5/hr	550	Pair Production
	2	1.96 TeV	11/hr	72,000	Single Top (s+t)
LHC	1	7 TeV	2,500/hr	860,000	$t\bar{t}\gamma$
		8 TeV	6,800/hr	4,900,000	Single Top (tW), $t\bar{t}Z$, $t\bar{t}W$
	2	13 TeV	45,000/hr (curr.) 53,000/hr (full)	36,000,000 (curr.) 101,000,000 (full)	$t\bar{t}H$?, ???

Experimental Signature

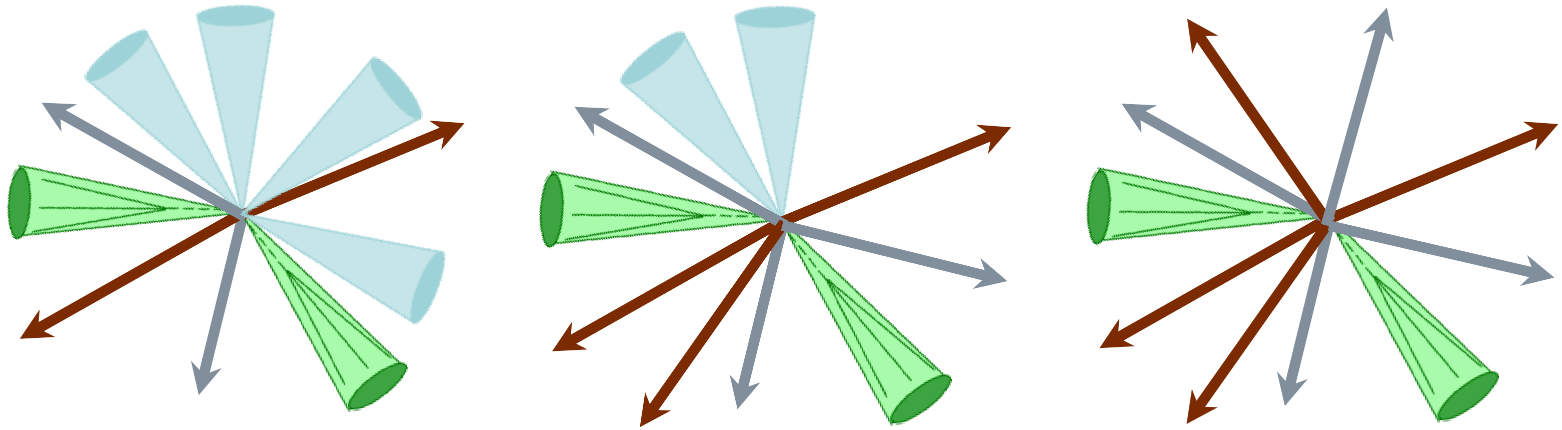
Get final states with multiple leptons from W, Z, and H decays







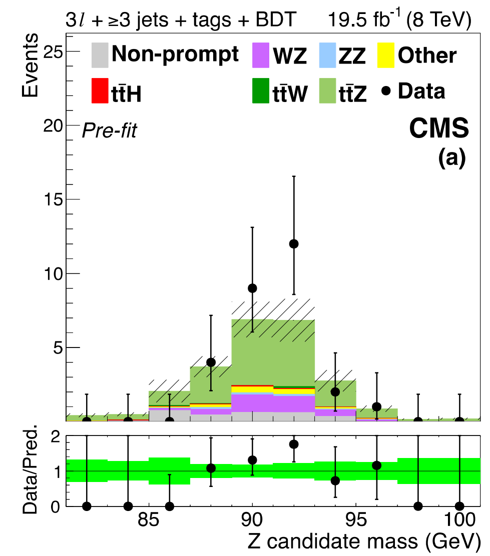
Multilepton Signatures



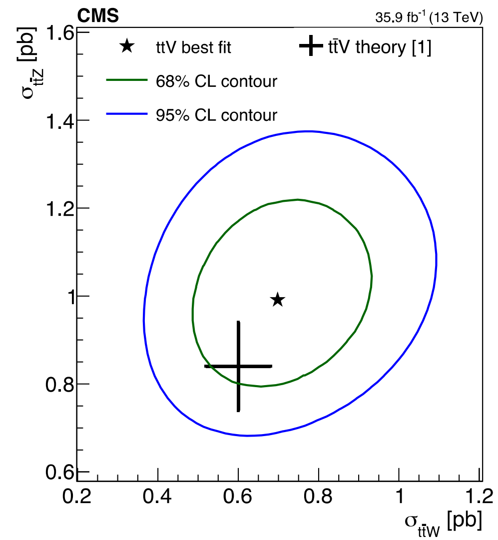
	2ℓ	3ℓ	$\geq 4\ell$
$t\bar{t}H$	Same-sign leptons 5-6 jets	3-4 jets	2 jets
$t\bar{t}W$	Same-sign leptons 4 jets	2 jets	N/A
$t\bar{t}Z$	Opposite-sign leptons 6 jets	Lepton pair in Z peak 4 jets	Lepton pair in Z peak 2 jets

Multilepton ttW, ttZ CMS Results

- ttZ
  - Observed in 8 TeV data
  - Continue to refine measurements in 13 TeV
- ttW
  - Evidence in 8 TeV data
  - Observed in 13 TeV data
- Analyzing ttZ and ttW in context of new physics (e.g. effective field theory interpretations)



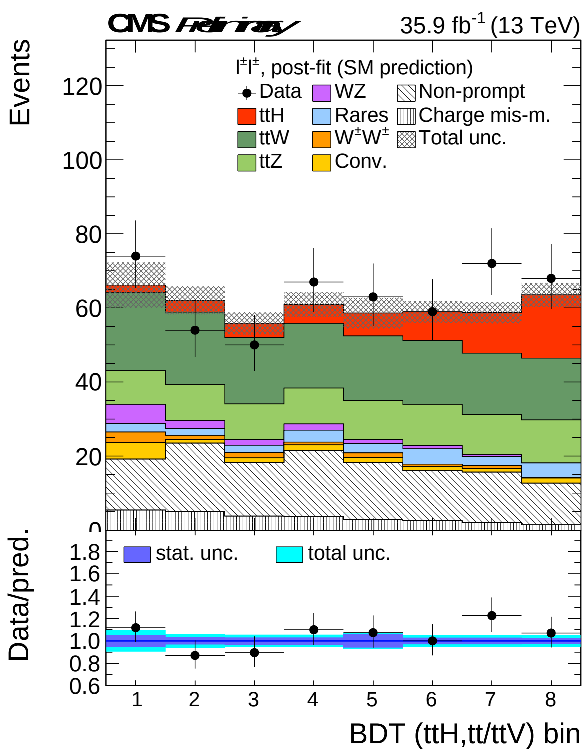
https://arxiv.org/abs/1510.01131

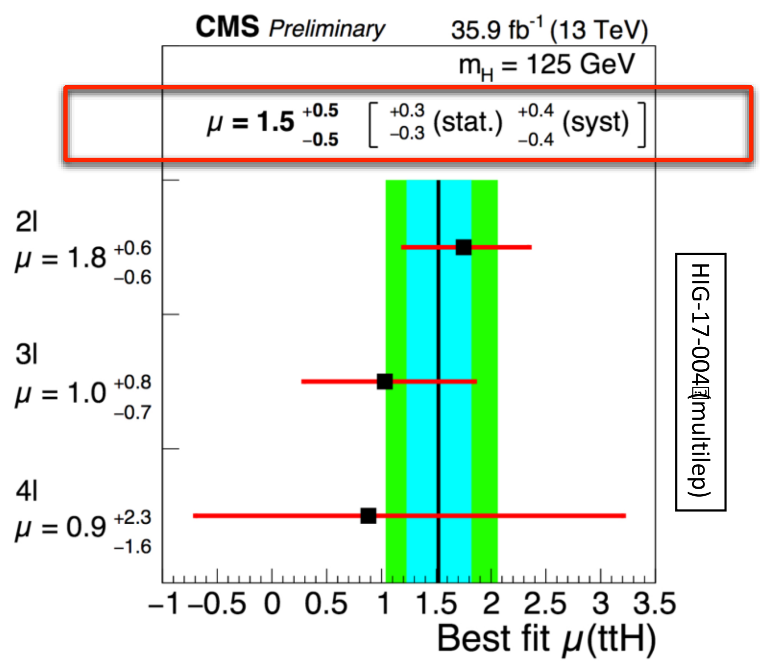


https://arxiv.org/abs/1711.02547

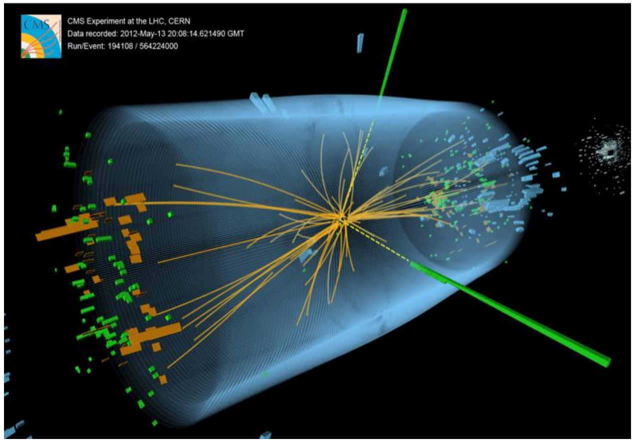
Multilepton ttH CMS Results

- Observe a 3.3σ evidence of ttH with 13 TeV data
  - See an excess of about 1.5 ± 0.5 times the SM expectation (not currently significant)
  - Saw similar excess in 8 TeV, but with less significance
- Will be interesting to see how this develops with more data!





Analyzing This Data



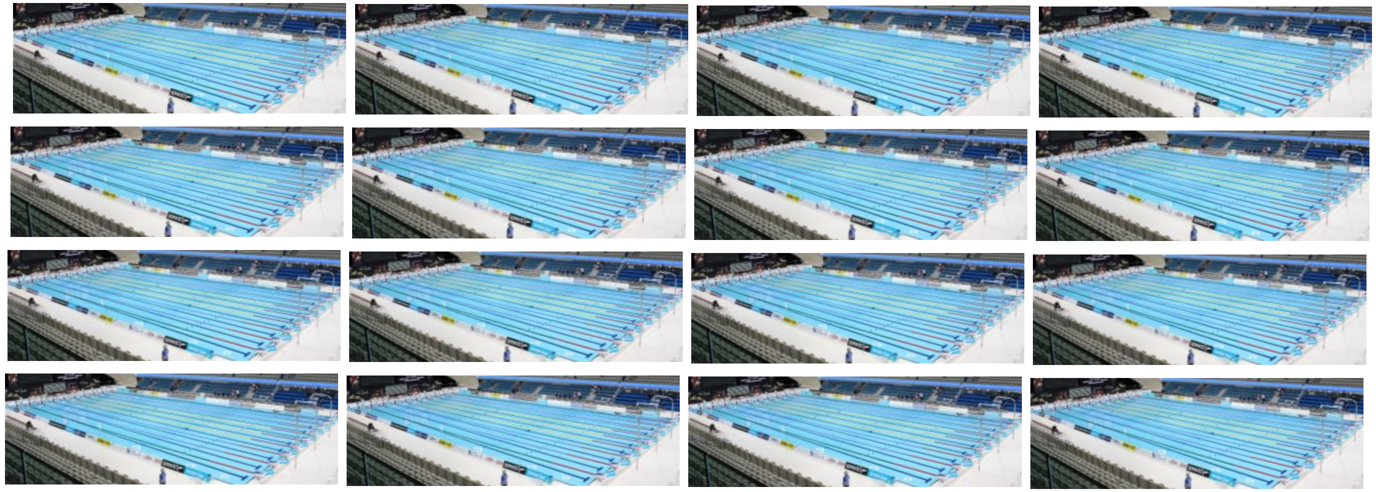
- All the information is in the picture
- Would be possible to do the analysis with the pictures, a ruler, and a calculator...
- In the past, it was done this way!

The Problem

- Collisions that produce new particles are really rare!
- Example: Higgs production is very rare
- One Higgs boson produced every 3 billion collisions
- Peak rate of 9 Higgs bosons/minute
- Total number of collisions produced to find Higgs: 690 trillion
- If each collisions were one grain of sand... 

Oceans of Data

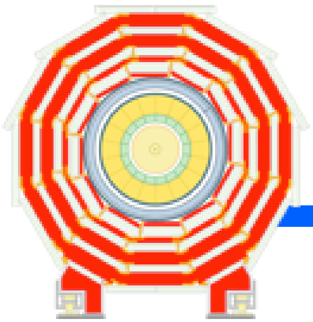
- Would fill 17 Olympic-sized swimming pools

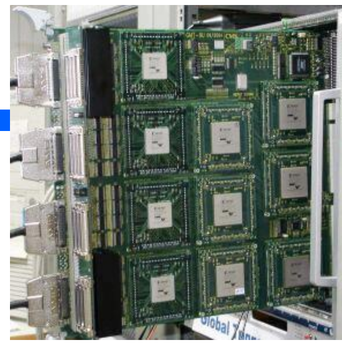


All of the Higgs collisions would fill 1/2 Tbsp 

How do we find the “1/2 Tbsp” of Higgs events?

How fast do we need to Go?





Basic facts:

➞Data from detector: 500 kilobytes / collision

➞Processing time for analysis: 5 sec (basic)

Computer farm with ~16000 CPUs

High speed network/switch

To physicists

FPGA Chips do very simple analysis
~ μs to analyze data

Simplified analysis code
~ ms to analyze data

	Proton Collisions in Detector	Level 1 Trigger	High Level Trigger
Data Rate	27 MHz	100 kHz	1 kHz
Data Collected	67 EB	250 PB	2.5 PB
Processing time	21 Million CPU years!	79 Thousand CPU years	793 CPU years

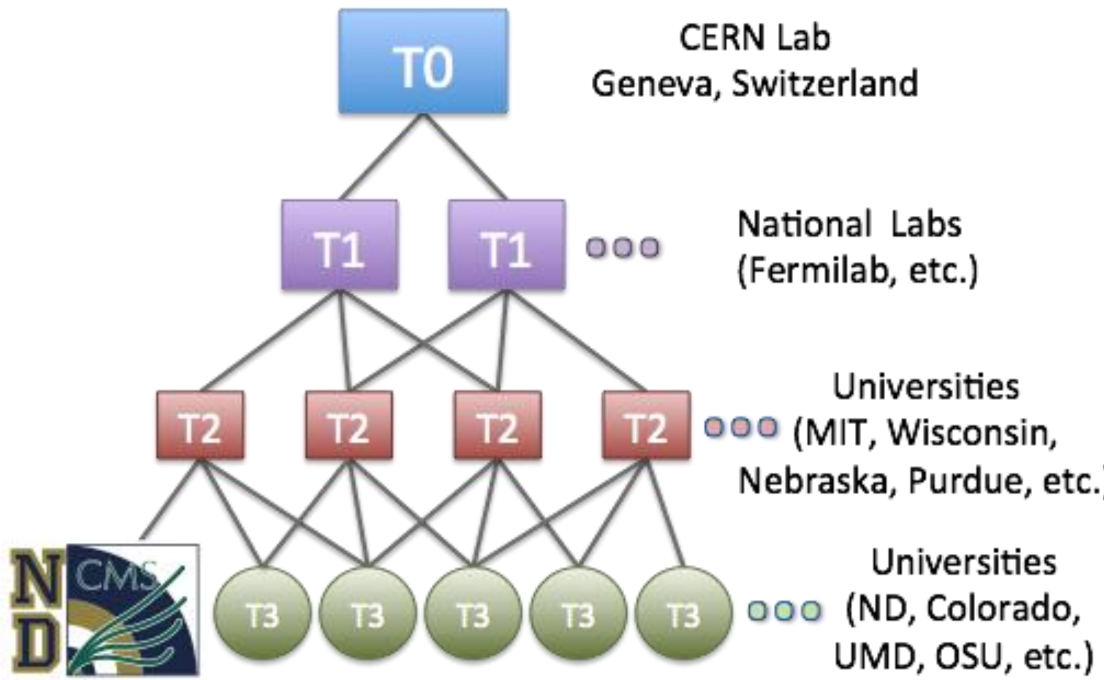
For 1 year's worth of data

Worldwide LHC Computing Grid

Shared by all four LHC experiments!

- Over >170 sites around world
- > 600k CPU cores available
- 2 million jobs submitted per day
- > 400 PB of total storage available

WLCG Organization



(~100k CPU cores)

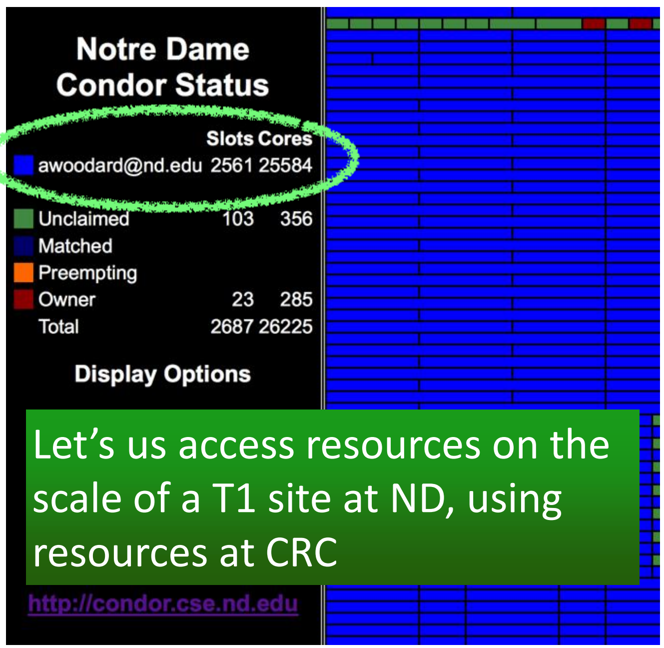
(~5k-20k CPU cores)

(~1k-10k CPU cores)

(~100-1000 CPU cores)

Opportunistic Computing

- Lobster: Allows running CMS software on non-dedicated resources
  - Started as an REU project; taken over by grad students (in collaboration with Prof. Thain’s group from CSE)



Let’s us access resources on the scale of a T1 site at ND, using resources at CRC

ND Grad Student Anna Woodard (and Matthias Wolf, not pictured) receive poster award a CHEP 2015 conference from Miss Okinawa.

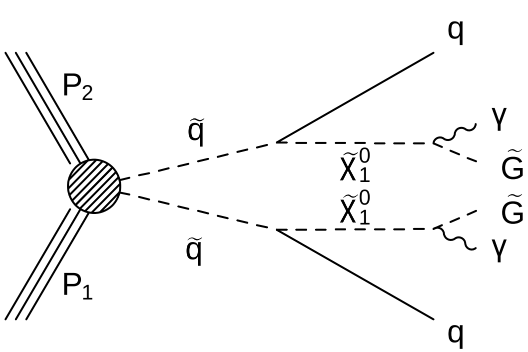
Mike Hildreth's Group

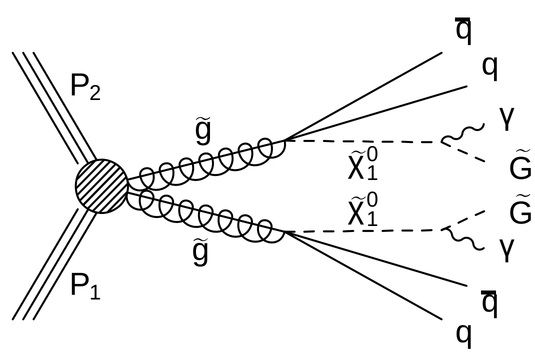
Searches for supersymmetry, computing for HEP

Physics Analysis

SUSY Searches:

- Searches for Gauge-Mediated SUSY Breaking (GMSB) signatures in events with two photons and missing energy (+ jets) (Gravitino is LSP)
- Data-driven background estimation for dominant QCD and EW backgrounds
- Results interpreted in two simplified models:
  - T5gg: gluino pair production where the NLSP neutralino decays to a gravitino and photon
  - T6gg: squark production where the squark decays to a quark and a neutralino

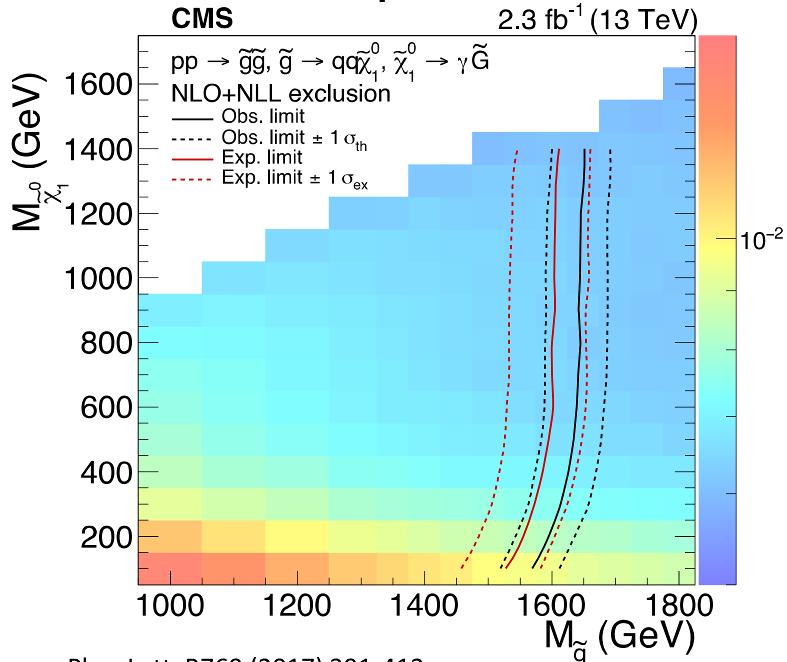




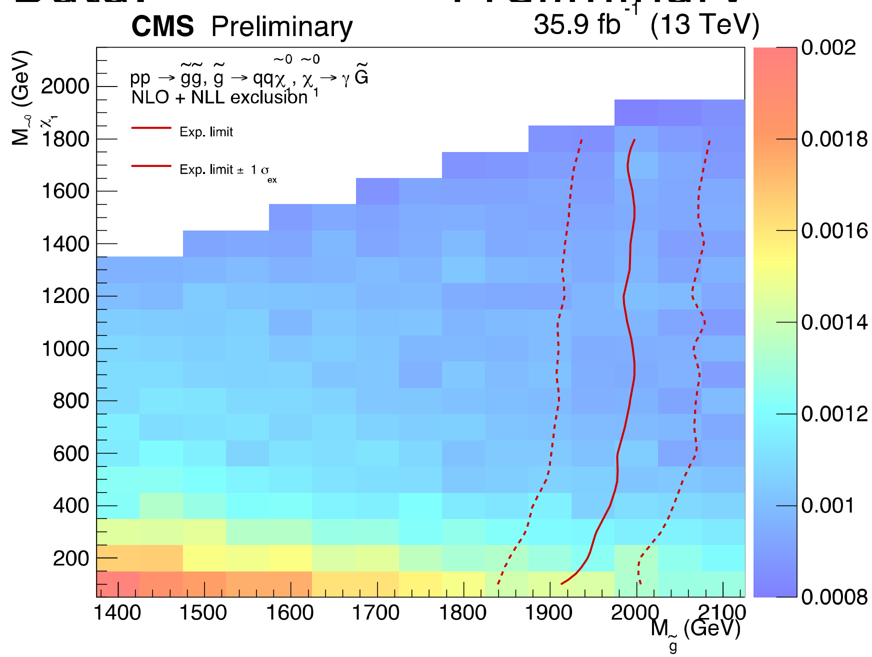
Physics Analysis

SUSY Searches:

- Results published on 2015 Data: Preliminary



Phys.Lett. B769 (2017) 391-412

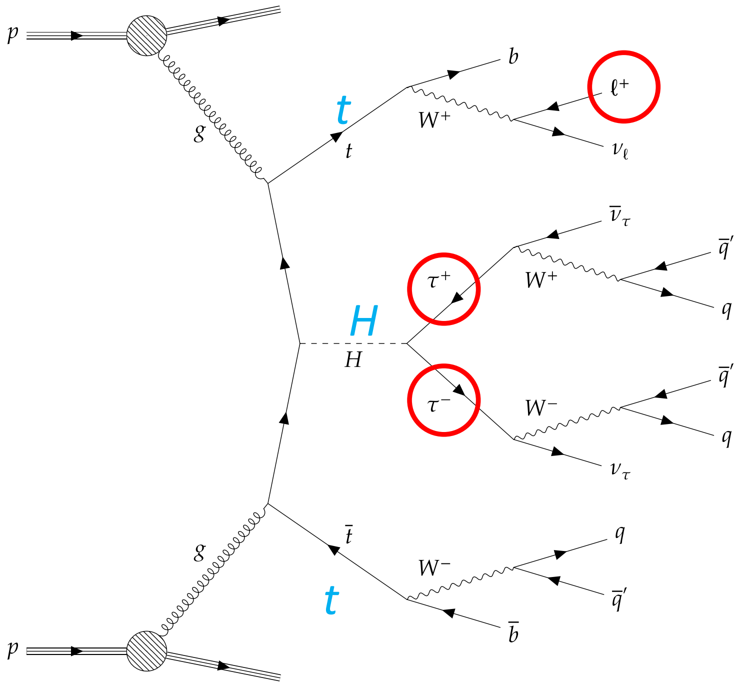


SUS-17-011

Physics Analysis

ttH search/measurements

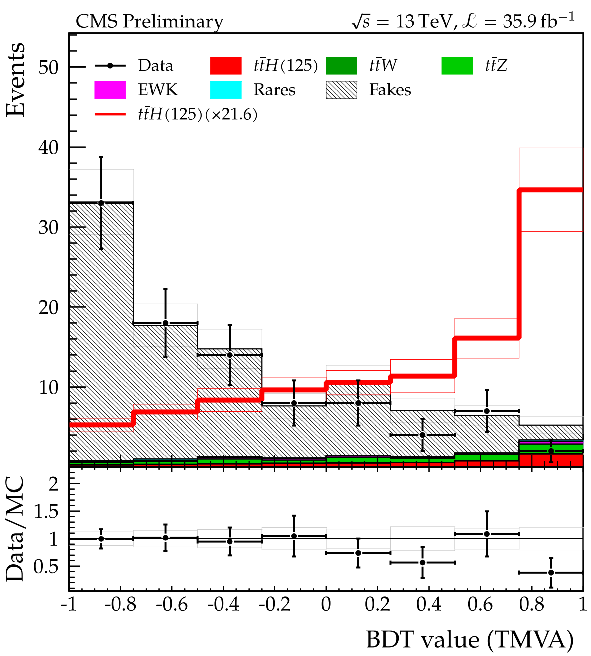
- ttH search, where $H \rightarrow \tau_h \tau_h$ (two hadronic taus)
- Selected in lepton+2-tau channel
- “modern” MVA-based tau-ID
- Cascaded set of multi-variate discriminants (BDTs) used to separate Higgs decays from huge tt+jets background
- 8 TeV (published) and 13 TeV (prelim) results



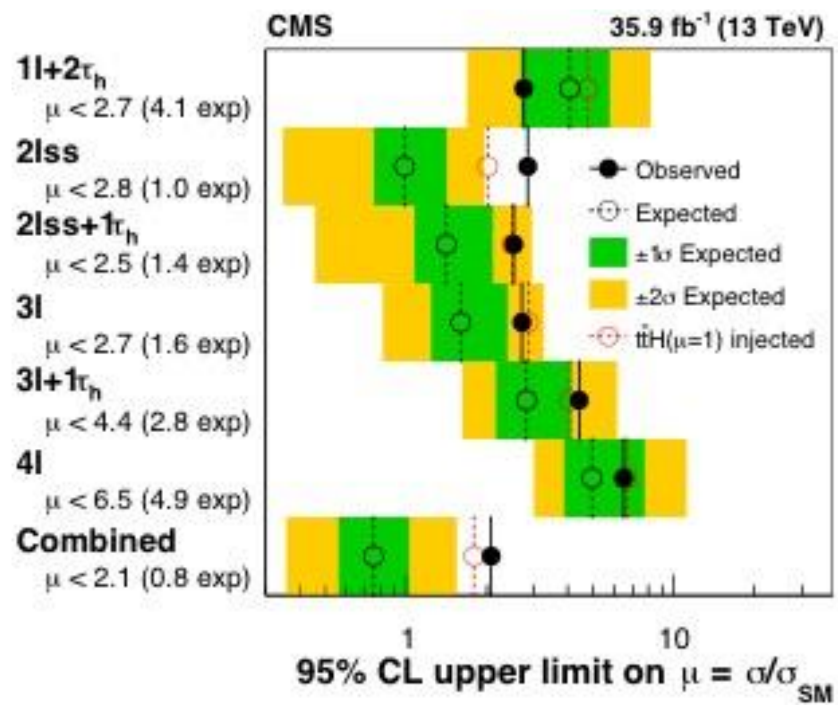
Physics Analysis

ttH search/measurements

- 13 TeV (prelim) results



HIG-17-018; post-fit seperation results



CMS Computing Infrastructure

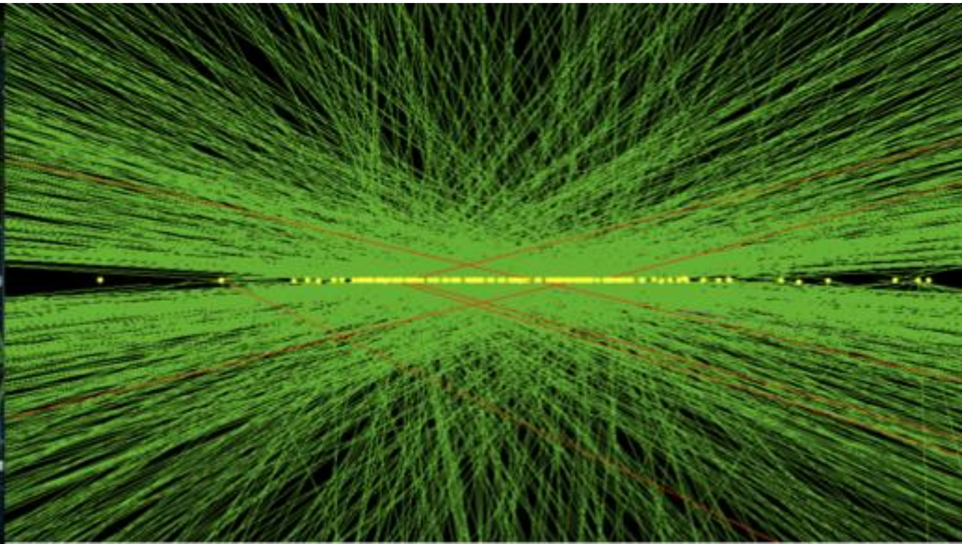
- CRAB3 Development (Matthias Wolf)
  - Incorporated some of the ideas behind LOBSTER into CMS's CRAB* infrastructure that analysts use for grid jobs
  - In particular: Automatic Job Splitting introduced
    - Pilot jobs submitted to test how long a typical event takes to analyze
    - Jobs sized in order to hit target runtime
    - Clean-up infrastructure to catch jobs that run too long, split them, and re-submit
- UNIFY [CMS Grid Production Environment] (Allison Hall)
  - Suite of software that organizes, submits, and monitors CMS production jobs
    - MC and Data
  - Introducing automation, automatic task recovery

*CMS Remote Analysis Builder

Overview of Notre Dame CMS “Jessop Group” Activities and Interests

Colin Jessop

University of Notre Dame



Colin Jessop Bio

Education: B.A/M.A Cambridge University, UK
Ph.D. Harvard University (CDF@FNAL, Calorimetry, Top &Higgs Analysis. co-discovery of top quark)

Training: Post-Doc @ SLAC: R&D on BaBar Crystal Calorimeter
CP Violation analysis in B's and Tau's.

Positions: Panofsky Fellow @SLAC
Managed *BaBar* ECAL calibration at startup of *BaBar* experiment
Managed *BaBar* EM radiative decay analysis program ($b \rightarrow s\gamma$)

Professor: University of Notre Dame
LPC electron/photon group leader (2006-2007)
US CMS ECAL Institute Board Chair (2008-2012)
US CMS L2 project manager for ECAL operations (2012-present)
CMS ECAL upgrade manager (2012-present)
US CMS L2 phase 2 ECAL/HCAL Barrel upgrade manager (2015-)
Higgs analysis ($H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$), leading group to search for lepton flavor violating decay of Higgs in run 2

Jessop CMS Group Members

Research Professor
Nancy Marinelli

Electronic engineer
Nikitas Loukas

Post-Doc
Silvia Taroni

Engineering Physicist
Sasha Singovski

Graduate Students

Nabarun Dev

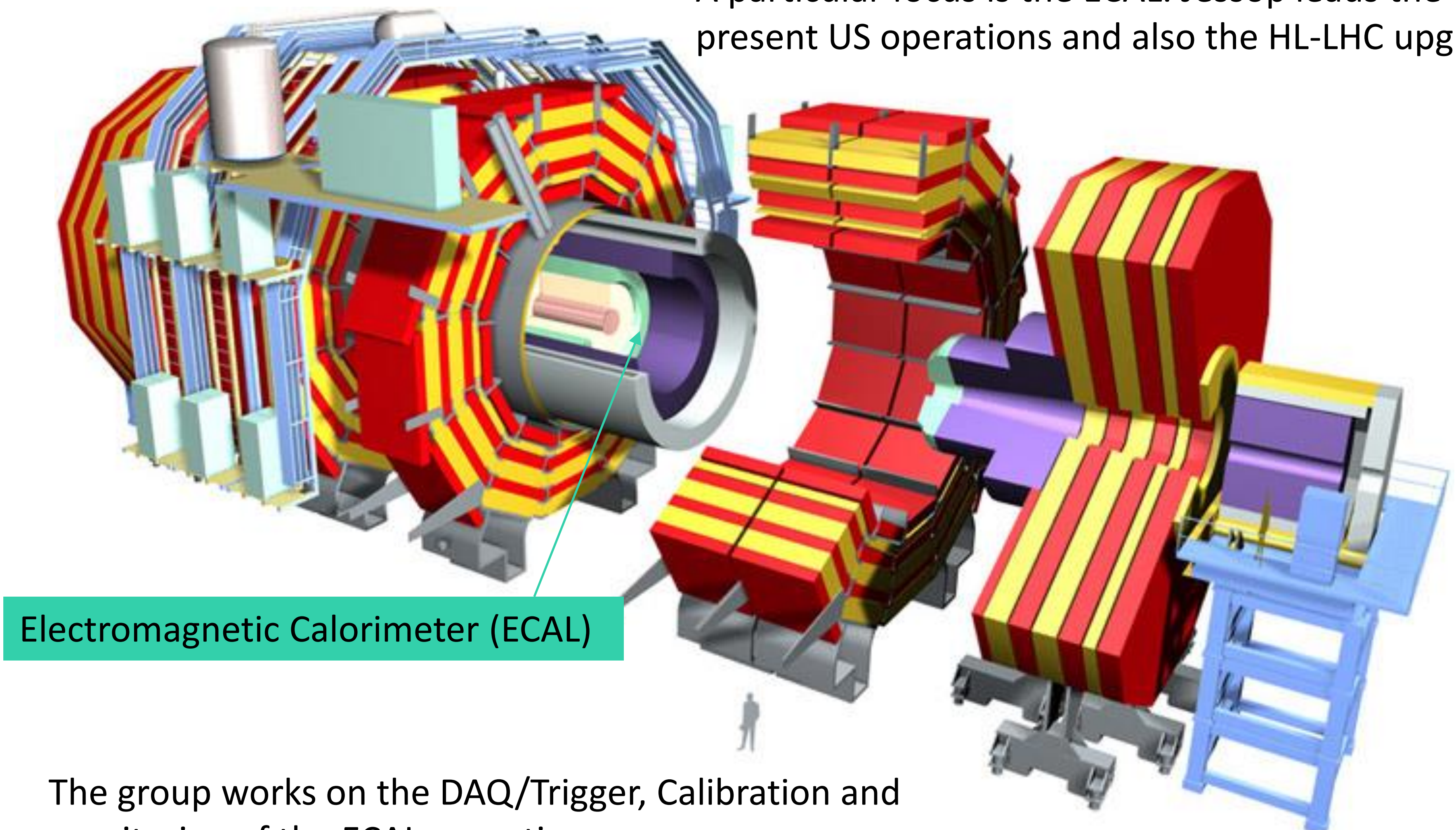
Fanbo Meng

Michael Planer

Prasanna Siddireddy

CMS Electromagnetic Calorimeter (ECAL)

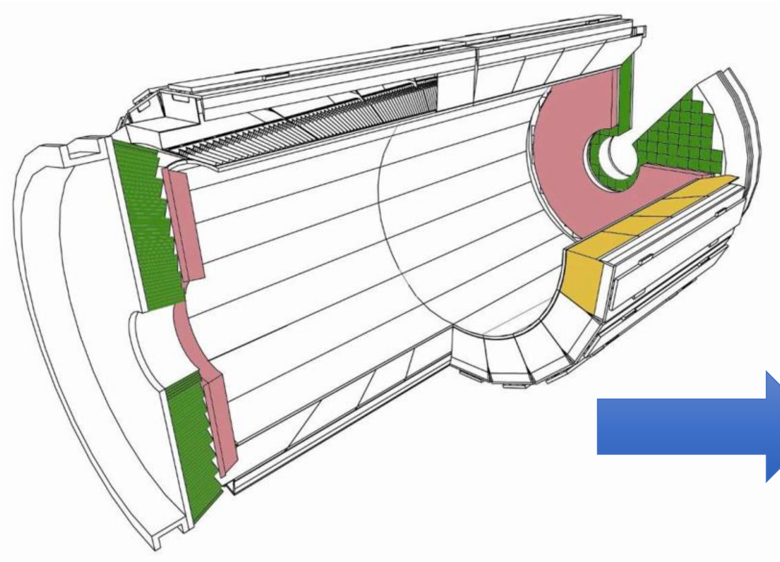
A particular focus is the ECAL. Jessop leads the present US operations and also the HL-LHC upgrade

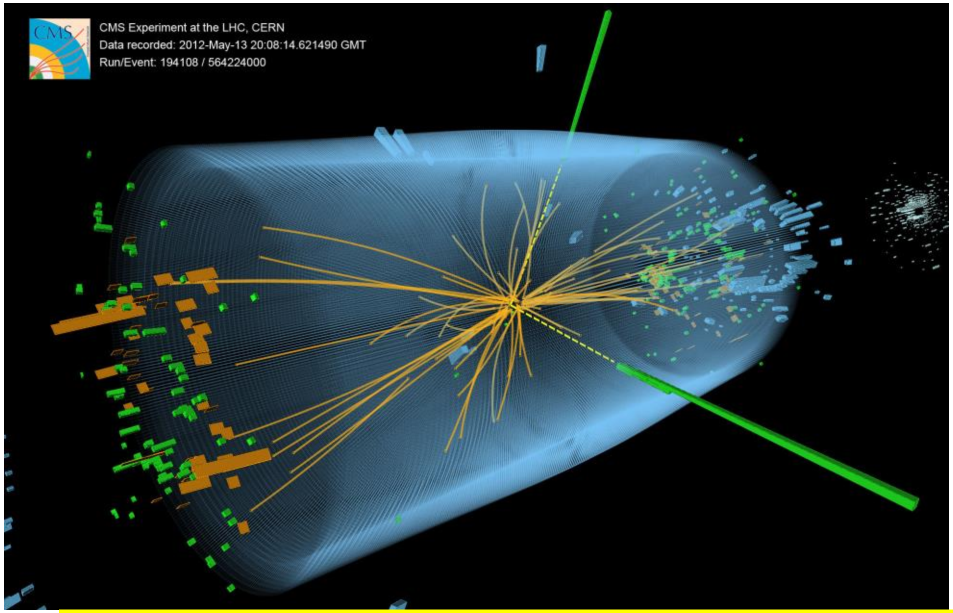


The group works on the DAQ/Trigger, Calibration and monitoring of the ECAL operations

The Study of the Higgs Boson in the H→γγ mode

CMS ECAL

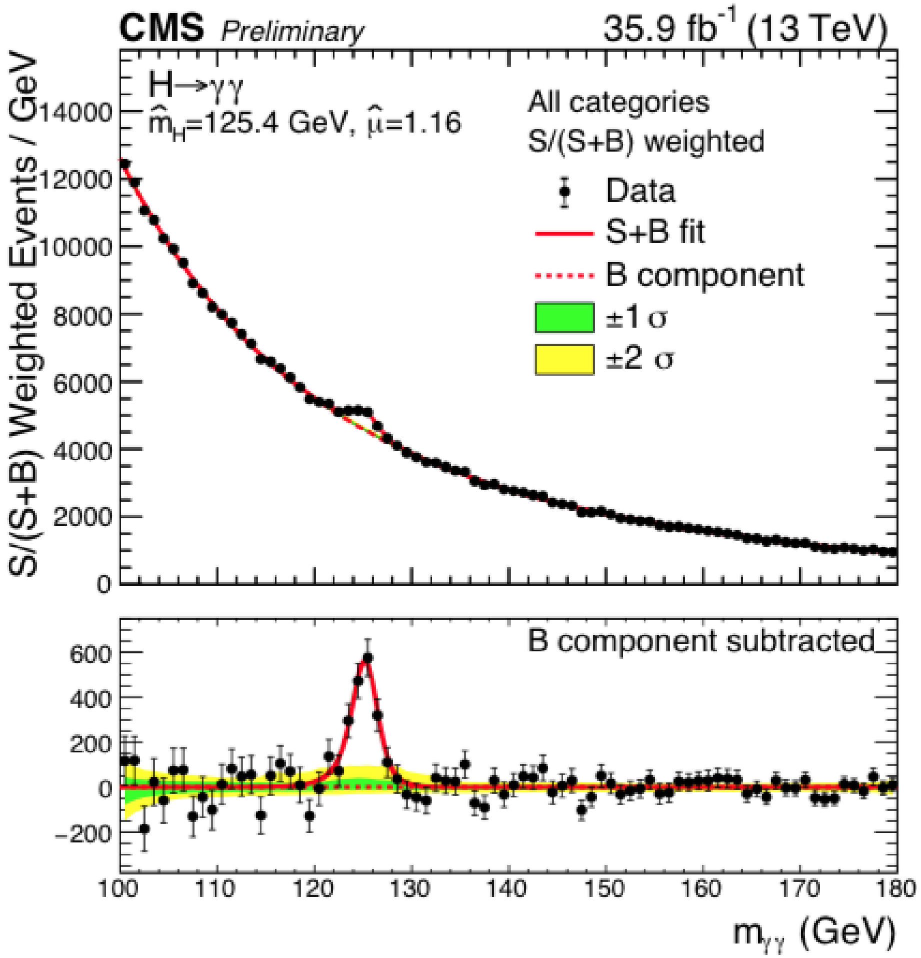




A H→γγ candidate event observed in the ECAL

The group was part of the discovery team in the H→γγ mode and continues today with precision study of this decay.

Precision Study of H→ $\gamma\gamma$

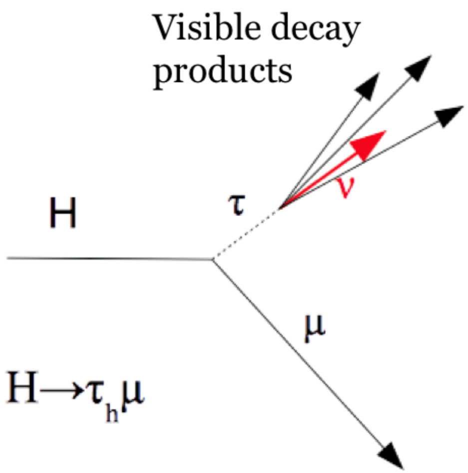


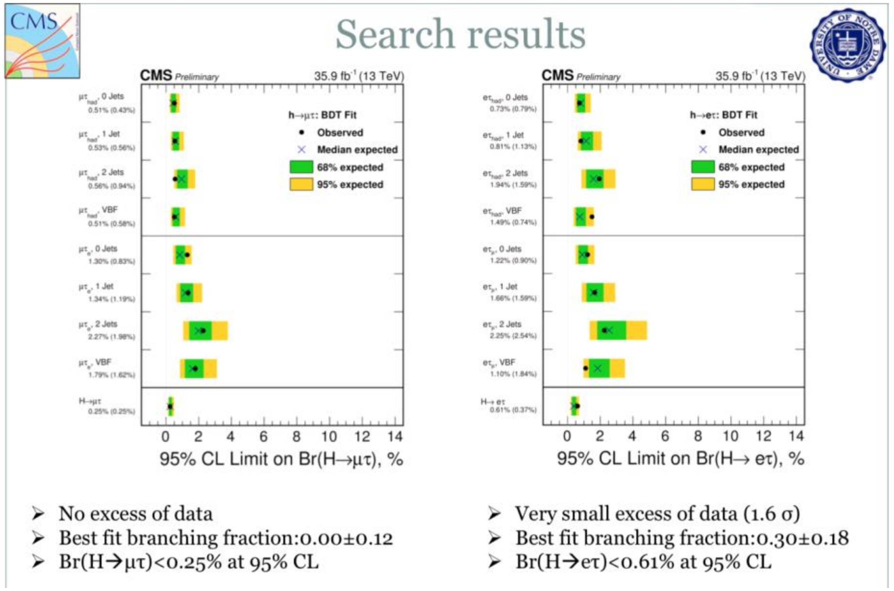
Result shown by graduate student Michael Planer at the European Physical Society Conference in Venice, Italy   July 2017

Searches for unexpected decays of the Higgs Boson

The group is also focused on searching for new and unexpected decays of the Higgs Boson such as the possible lepton flavor violating decays.

In the standard model only H→ττ,μμ or ee
NOT H→ μτ,eτ,eμ





Results presented by students Nabarun Dev and Fanbo Meng in conferences in Venice and Paris, 2017

No observation but world's best exclusion limits

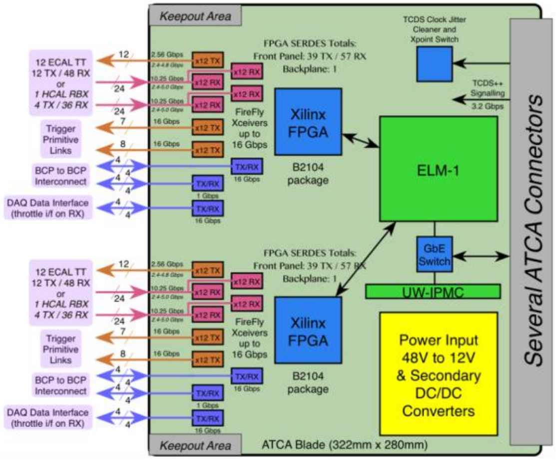
ECAL/HCAL electronics upgrade

To accommodate 10x higher intensity beams at the high luminosity LHC the group
Is designing new readout electronics to increase the spatial resolution of the detector readout by 25 times and time resolution by 5 times

Physicist Marinelli developing new algorithms for readout

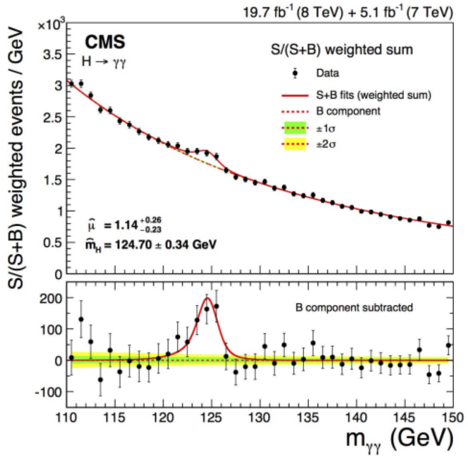
Engineers designing high speed processor board

Like a 1 Megapixel to 25 Megapixel camera upgrade

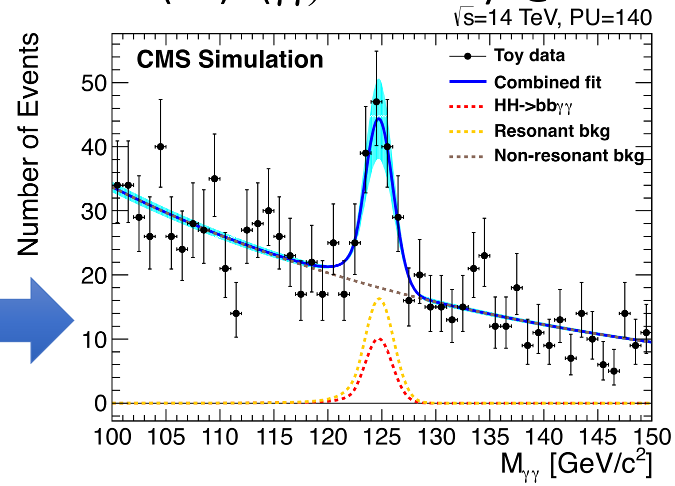


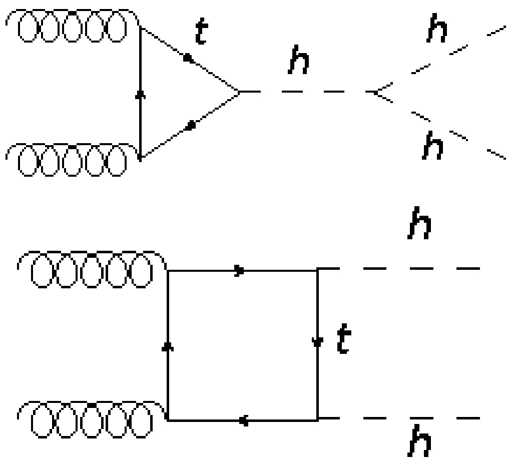
New discoveries with upgraded electronics now made possible

H→γγ discovery in Run1



H(bb)H(γγ) discovery @ HL-LHC





The upgraded ECAL should make possible the discovery of di-Higgs production
Which measures the nature of the physical vacuum

Phase I Upgrade of CMS HCAL

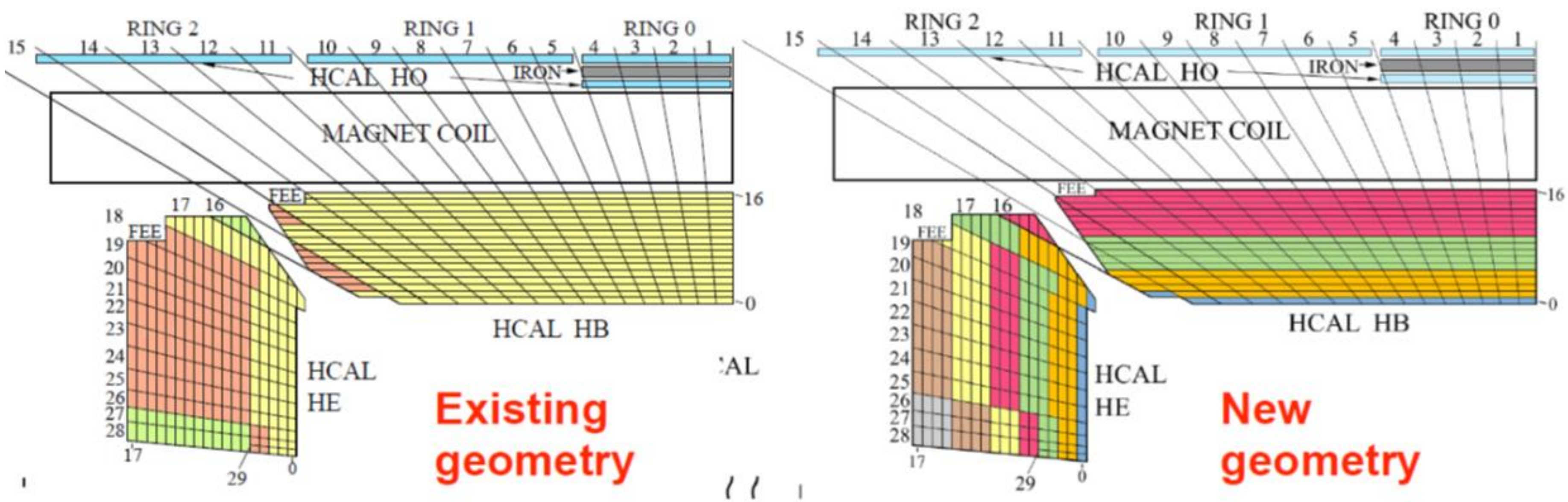
Mitch Wayne's group

Yuri Musienko and Mr. Arjan Heering at CERN

SiPM development and characterization

Dan Karmgard, Jeff Marchant, Mike McKenna, Dan Ruggiero, Mark Vigneault at Notre Dame

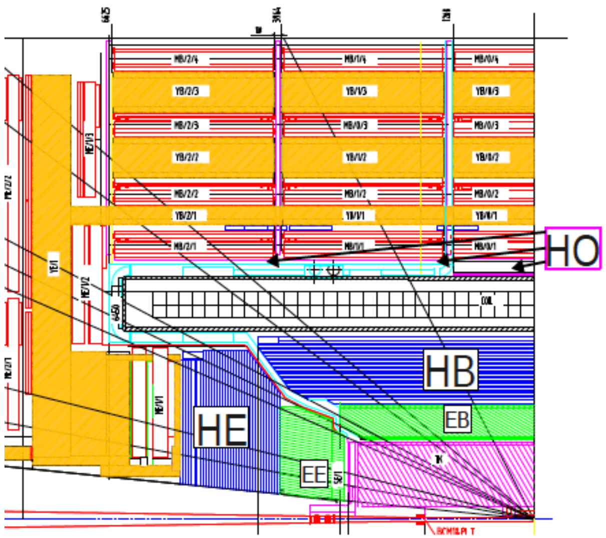
ODU development and fabrication

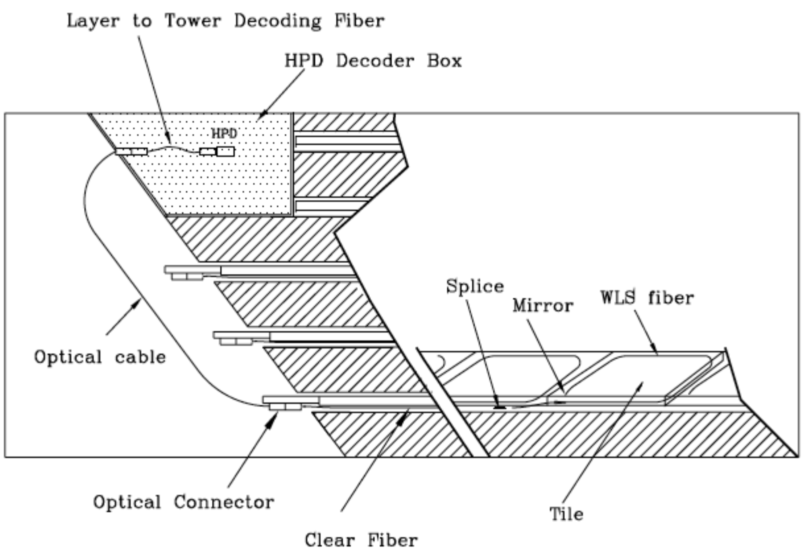


Calorimetry with SiPMs at LHC

- Ideal photodetector for calorimetry at LHC
  - Large linear dynamic range in photon count
  - Very fast – minimal impact on pulse shape at high pileup
  - High photon detection efficiency (PDE)
  - High gain (minimize impact of electronics noise)
  - No radiation sensitivity or internal noise sources
  - CMS: 4T magnetic field tolerance and compactness
- HPD was the best option in 2000
  - ☺ PDE of ~12%, gain ~2000, fast, large dynamic range, low radiation sensitivity
  - ☹ Magnetic field tolerance is marginal, internal discharge noise, gain*PDE is too small for thin layers of scintillator
  - ☹ Large device size limits the channel count (depth segmentation)

HCAL

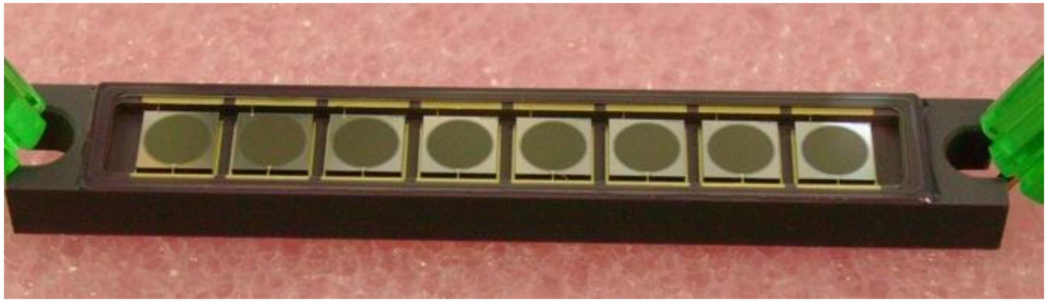


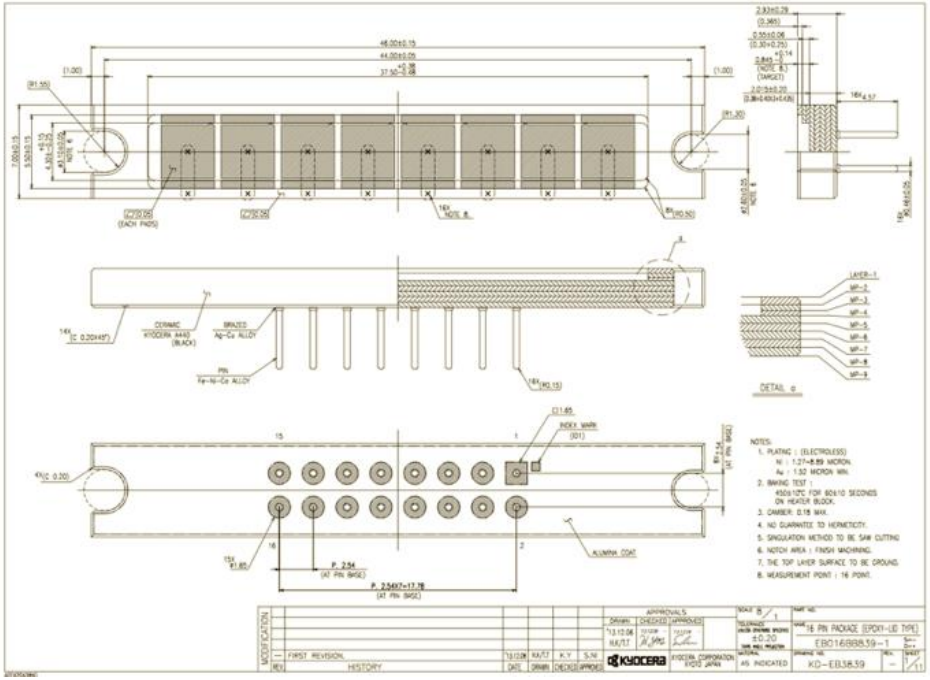


- CMS HCAL uses plastic scintillator as active material, read out with WLS fibers from individual tiles
- Optical decoder unit converts cables from per-layer to per-tower (channel)
  - For HPD, many layers must be combined to provide significant MIP signal

Packaging for SiPMs

- Protection for SiPMs important to avoid damage, humidity effects, etc
- Epoxy sealing is not acceptable due to large neutron signals induced
- Design complete, will accommodate 2.8 mm and 3.3 mm devices
- Thoroughly tested for temperature and humidity effects
- Quote from Kyocera, ready to purchase for preproduction

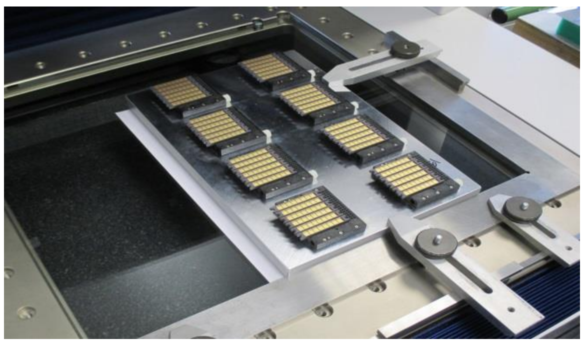




LHC CMS Detector Upgrade Project

SiPM packaging

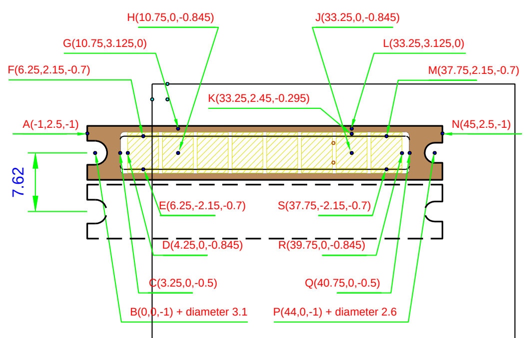
- SiPM packages are high temperature ceramic from Kyocera
- 2000 production packages measured in the CERN metrology lab
- Yield of good packages essentially 100%



Packages mounted in precisely located ZIF sockets

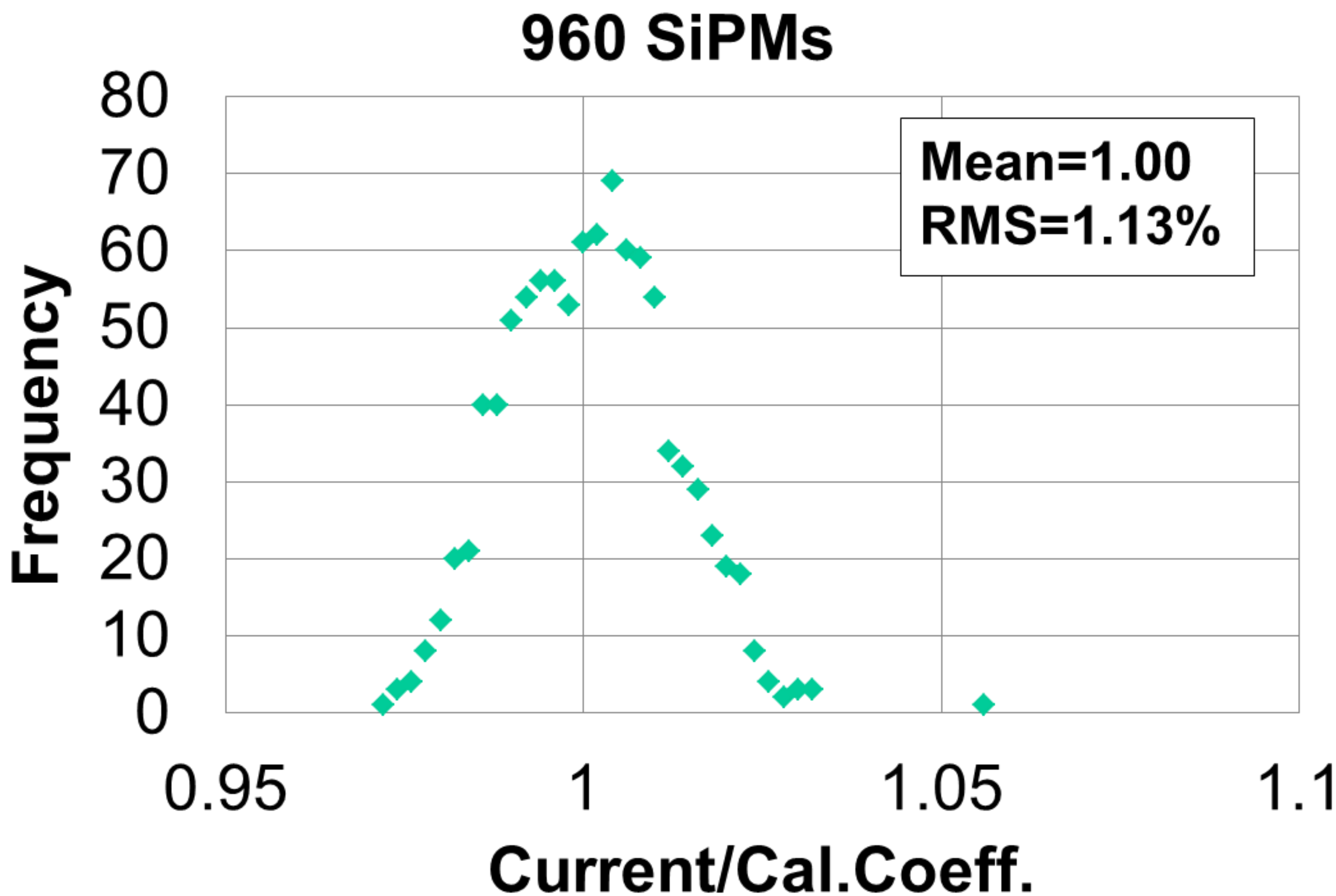
Fully loaded this setup enables the measurement of up to 48 packages at one time on the CMM

Measured points for each package



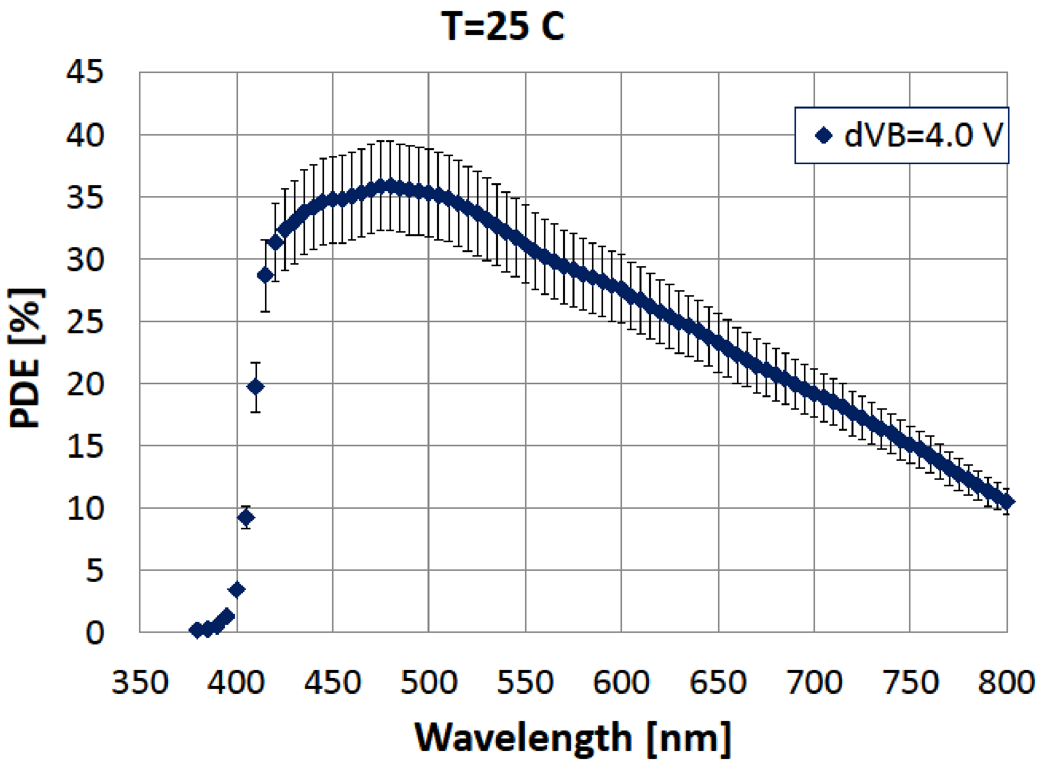
Results for Hamamatsu (HPK)

Gain x PDE uniformity for 2.8 mm devices

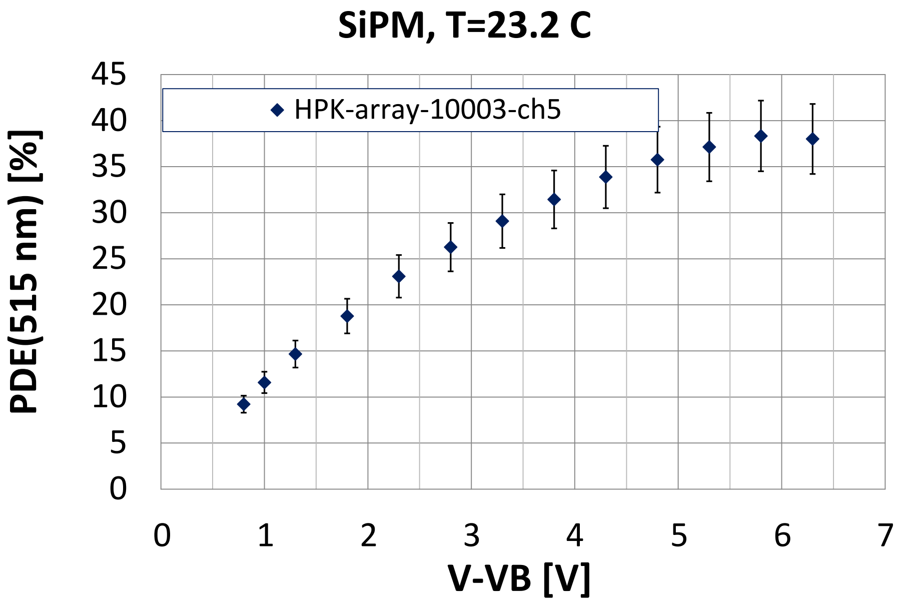


Results for Hamamatsu (HPK)

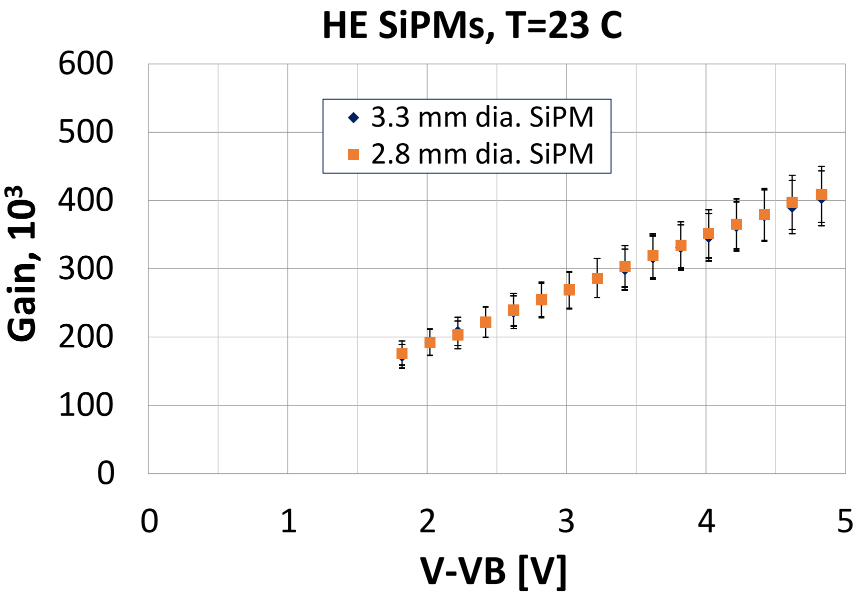
PDE – Spectral response



PDE and Gain vs V – V_B

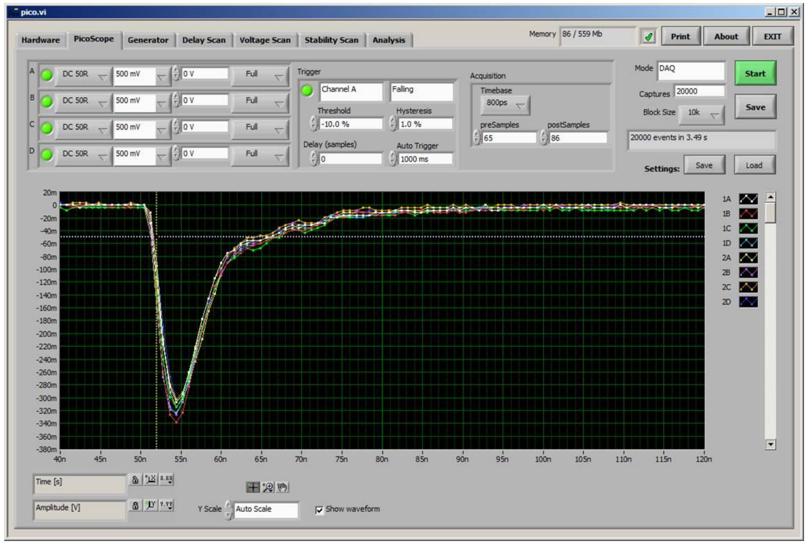


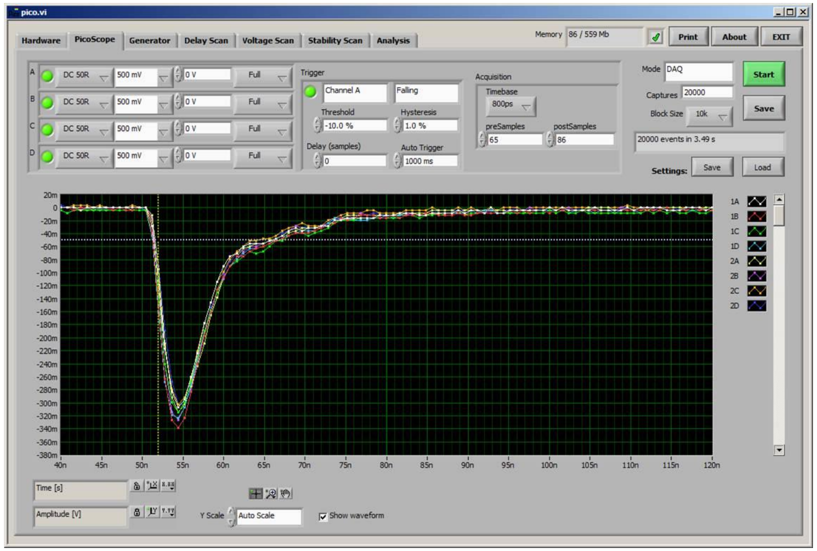
PDE



Gain

Results for Hamamatsu (HPK)





Recovery time
15 Ω load

Response to laser pulse for:
2.8 mm devices (above)
3.3 mm devices (below)

Recovery time is ~ 7-8 nsec for both, meets specification

LHC CMS Detector Upgrade Project

Summary of HE SiPM QC

Batch #	Arrays	Gain*PDE (sigma), %	Id-V	Rs	Noise	C-V	Total	Rejects ,%
1	200	1.51	5	0	12	0	17	8.5
2(mixed)	300	1.3	9	0	9	0	18	6
3	100	1.43	2	0	6	0	8	8
4	350	1.54	2	0	26	0	28	8
5	450	1.47	1	0	32	0	33	7.33
All	1400	1.45	19	0	85	0	104	7.43

Normal Arrays: 1004 good arrays

720 needed for HE + 180 for spares

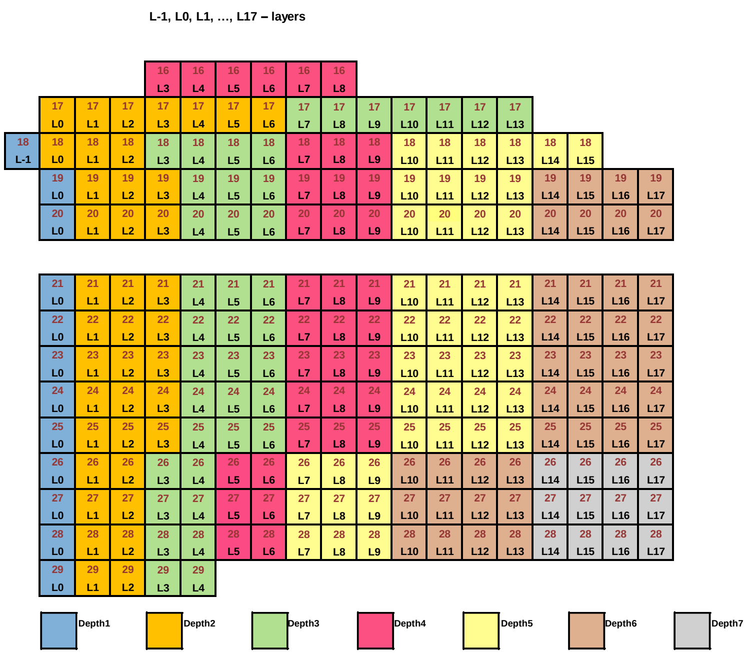
Mixed Arrays: 282 good arrays

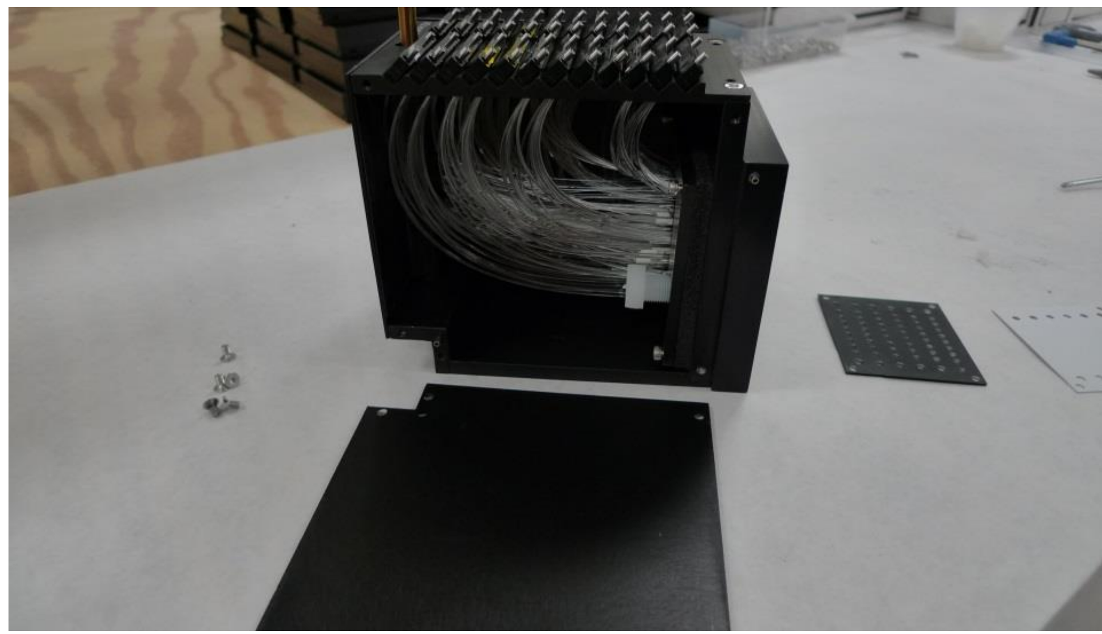
144 needed for HE + 36 for spares

HE ODU Fabrication at Notre Dame

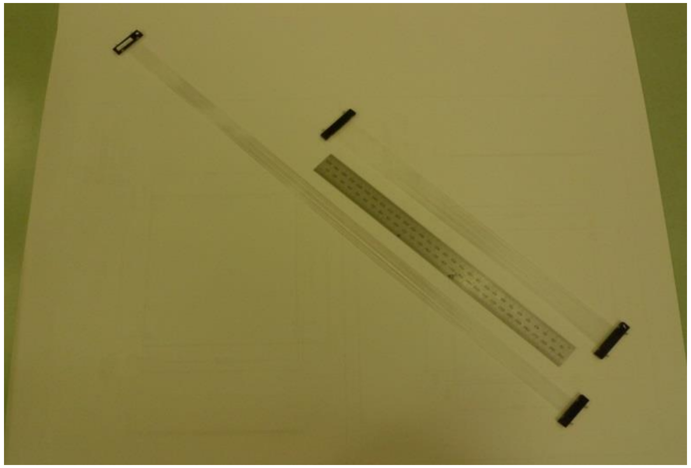
ODU: *D. Karmgard, R. Kim, J. Marchant, M. McKenna, D. Ruggiero, M. Wayne*

Notre Dame

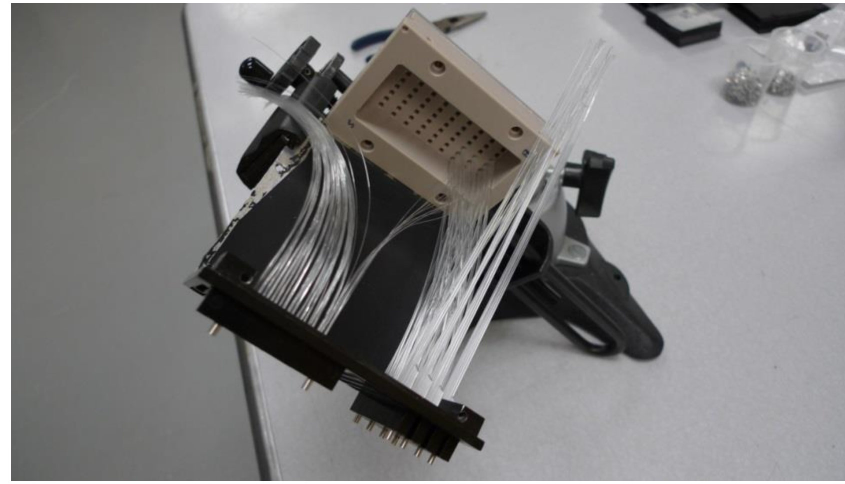




ODU Assembly

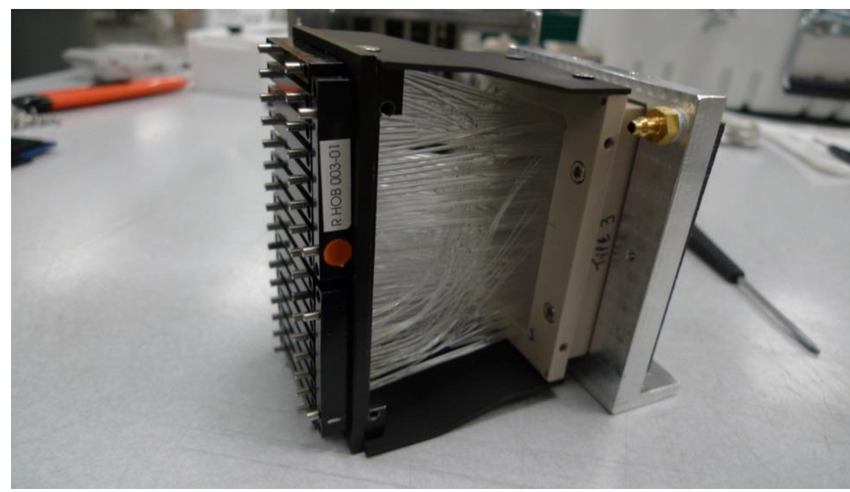


Fiber Pigtails for HE/HB



Threading the optical fibers

Optical test, glue, flycut the ends

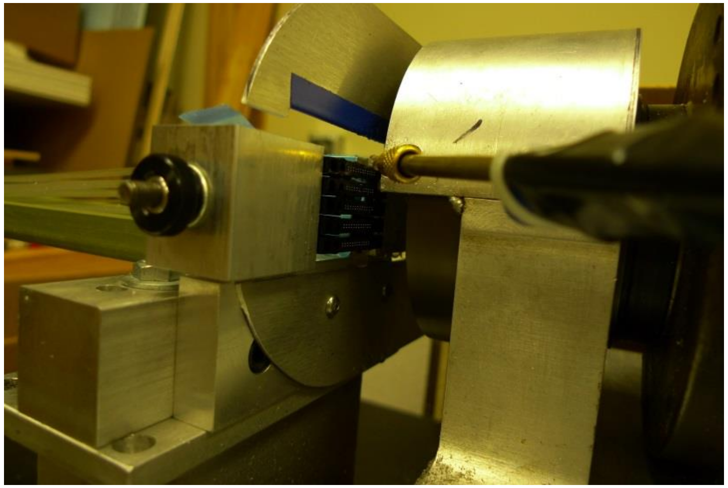


Fully assembled ODU

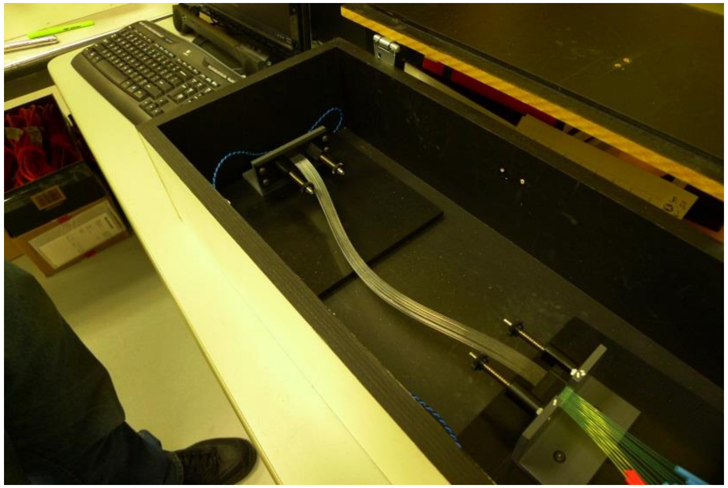
LHC CMS Detector Upgrade Project

Fiber pigtail polishing and QC

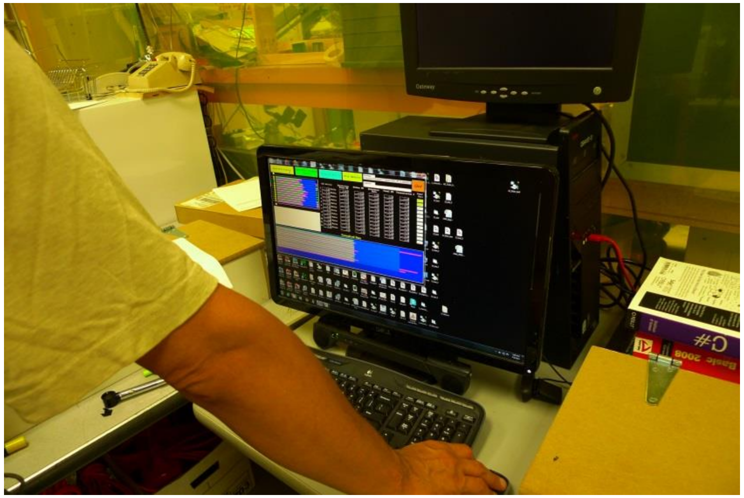
Connector finishing at ND



Diamond flycut several at once

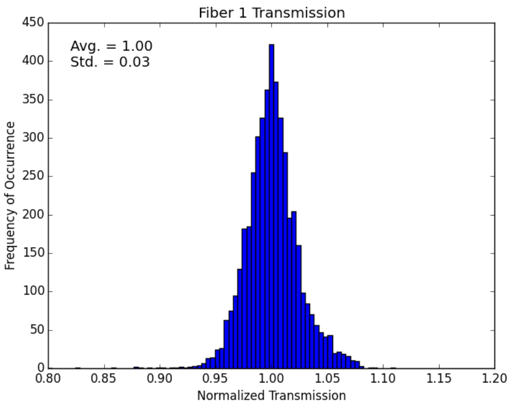


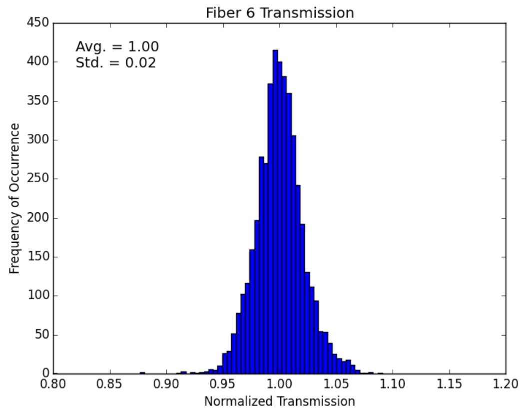
Illuminate fibers for transmission test

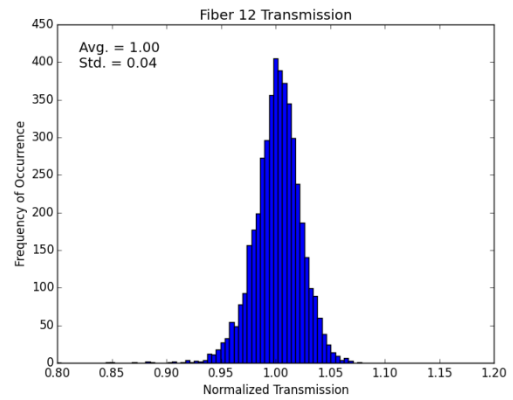


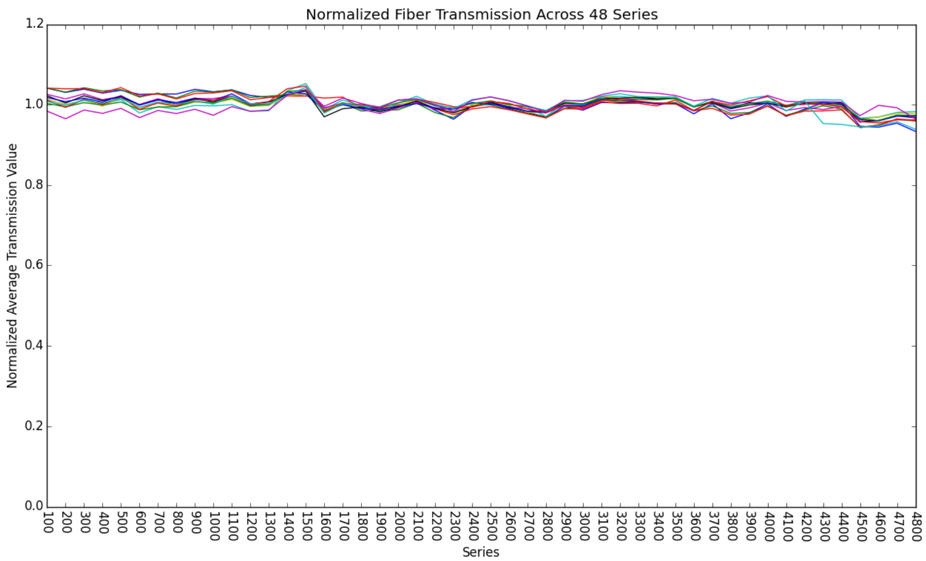
Verify transmission, store results

QC of the fiber cables/pigtails







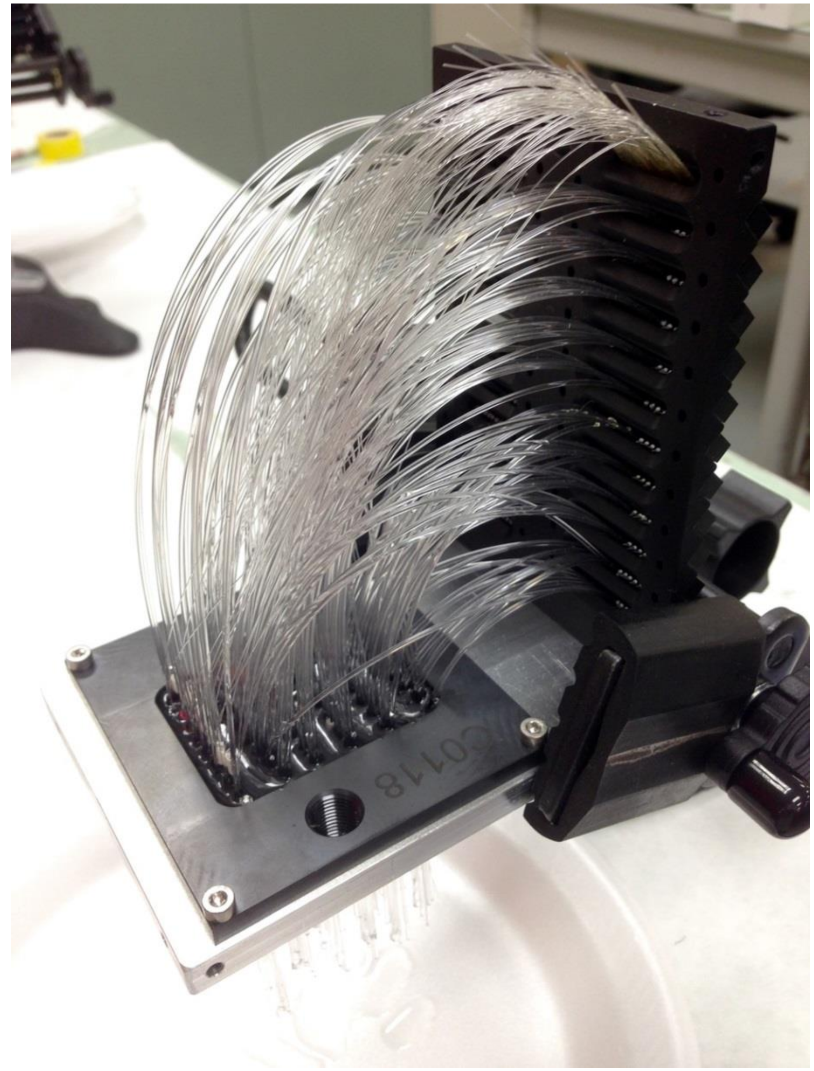


Reject fibers with transmission > 2 sigma below mean

4594 pigtails tested – 3960 "perfect" (3780 needed for 180 units)

Can still use "bad" pigtails if the bad fiber isn't used in mapping

ODU Threading and Gluing

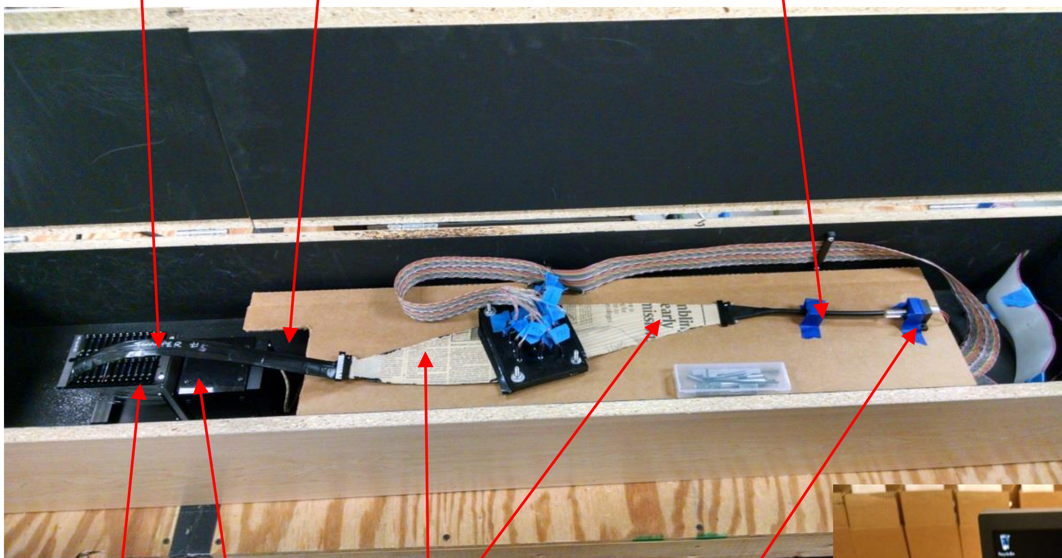


ODU Test Stand

Waveguide

Diode

Waveguide



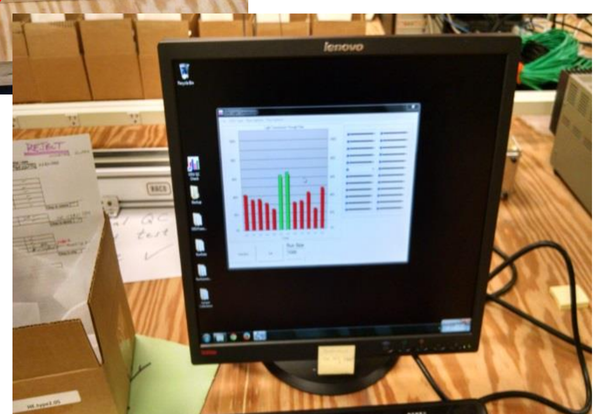
Y11

Diode

ODU

Mixer

- Computer controlled
  - Turn on blue LED
  - Illuminate Y11
  - Read 1,000 times
  - Calculate average & sigma
- Compare average light level at diodes
  - Calibrated to read the same without ODU+Mixer
  - Gives light loss in the ODU+Mixer
- Move waveguide to every connector
- Save average & sigma for each diode at each fiber



Real time computer display

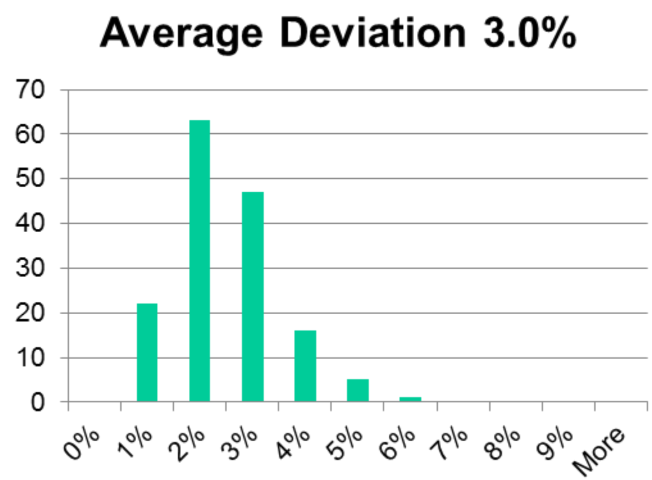
QC of the finished ODUs

LHC CMS Detector Upgrade Project

Relative light transmission for each signal and calibration fiber has been measured for 160 ODUs

Percent deviation in relative transmission for 40 Type1 Units

	HE.type1.Patch Plate Mapping (viewed outside box)																								
Cal	2.1%	2.7%	2.5%	2.3%	3.2%	4.7%	2.4%	2.5%	2.0%	3.0%	3.0%	3.0%	Cal						4.1%	4.1%					
5				2.8%	3.3%	3.8%	2.0%	1.8%	2.4%	3.9%	2.3%	2.8%	0and-1						3.7%	3.7%	4.1%	3.1%	3.8%	4.6%	4.0%
6				1.9%	3.0%	3.6%	2.2%	1.7%	2.6%	3.3%	2.7%	2.6%	0				2.5%	2.0%	4.1%	2.6%	3.0%	2.8%	4.2%	4.7%	3.5%
7				1.2%	2.6%	3.9%	2.2%	1.6%	3.1%	3.2%	1.9%	3.1%	1				1.8%	2.5%	5.2%	2.3%	2.0%	2.4%	3.5%	3.8%	3.0%
8				1.5%	2.8%	3.1%	2.5%	1.8%	2.7%	3.3%	3.0%	2.5%	2				2.2%	2.7%	4.7%	2.1%	1.8%	2.5%	3.6%	5.4%	3.5%
9					2.4%	3.9%	2.3%	1.7%	3.0%	3.4%	2.4%	2.8%	2*												
10					2.9%	4.4%	2.3%	1.4%	1.8%	4.8%	4.0%	3.1%	3			2.5%	2.1%	1.8%	4.2%	2.1%	2.1%	2.4%	3.3%	2.7%	
11					1.9%	4.0%	2.4%	1.4%	2.4%	3.9%	4.0%	3.9%	4or3			2.5%	2.4%	2.4%	3.5%	2.7%	2.5%	2.8%	3.2%	2.7%	
12					2.1%	4.9%	3.1%	1.8%	1.9%	3.1%	3.1%	3.1%	3*												
13					2.0%	4.3%	3.2%	1.6%	2.2%	4.0%	2.2%	3.4%	4*												
14						4.0%	3.7%	3.1%	2.0%	3.0%	5.0%	3.2%	16							4.0%	2.8%	2.1%	3.0%	4.7%	3.6%
15						5.5%	3.0%	2.8%	2.0%	3.7%	6.0%	3.2%	17							3.1%	2.6%	2.2%	3.9%	5.9%	4.0%



QuarkNet

55 Centers in 25 states and Puerto Rico

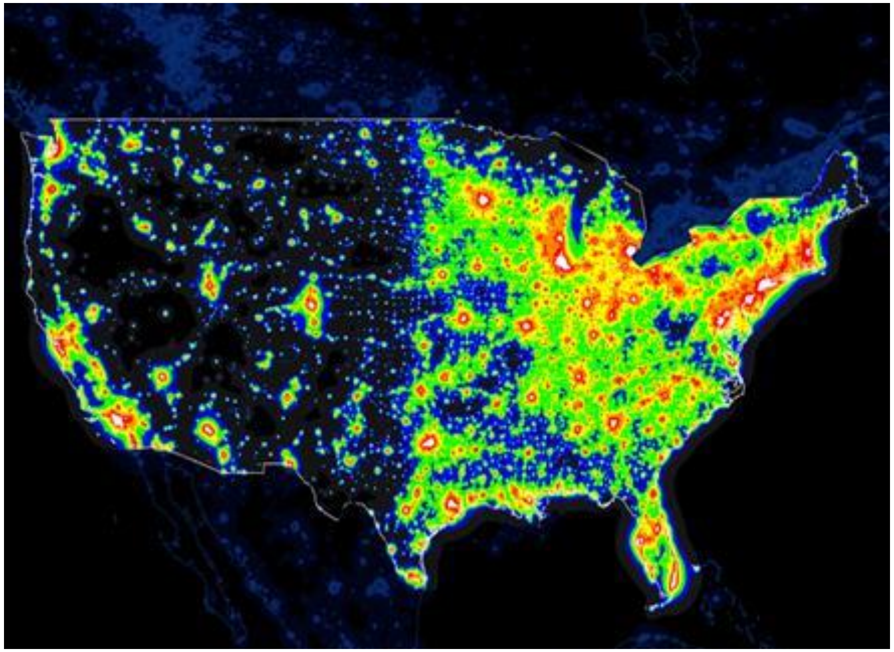
500 HS Teachers
150 Particle Physicist mentors
100 HS Students annually

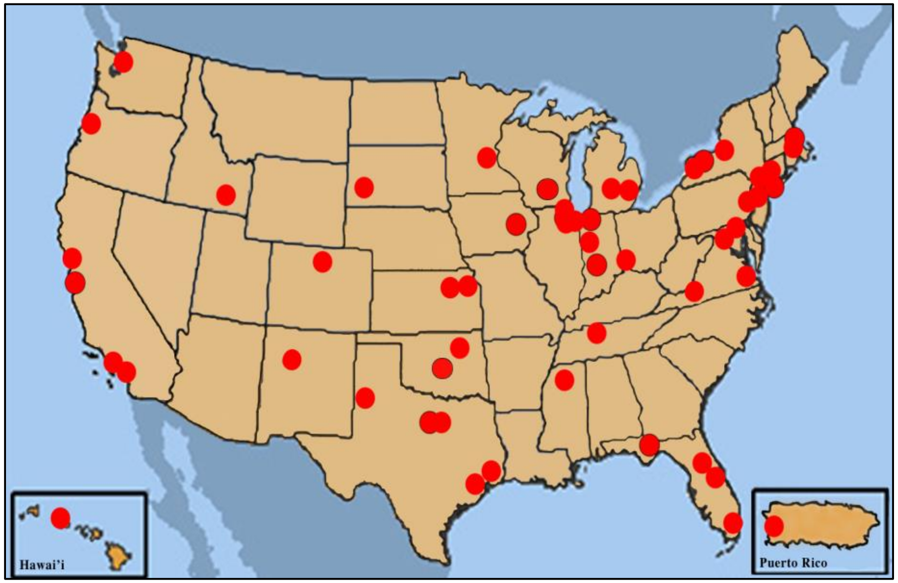
A professional development program for HS Teachers with immersive research experience for HS teachers and students.

Now in its 20th year. Supported by NSF.

PIs: M. Wayne, M. Bardeen, M. Swartz

http://quarknet.i2u2.org

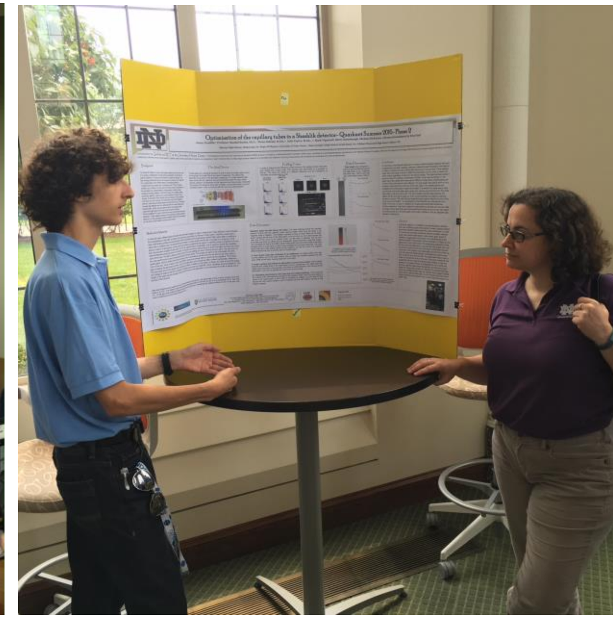




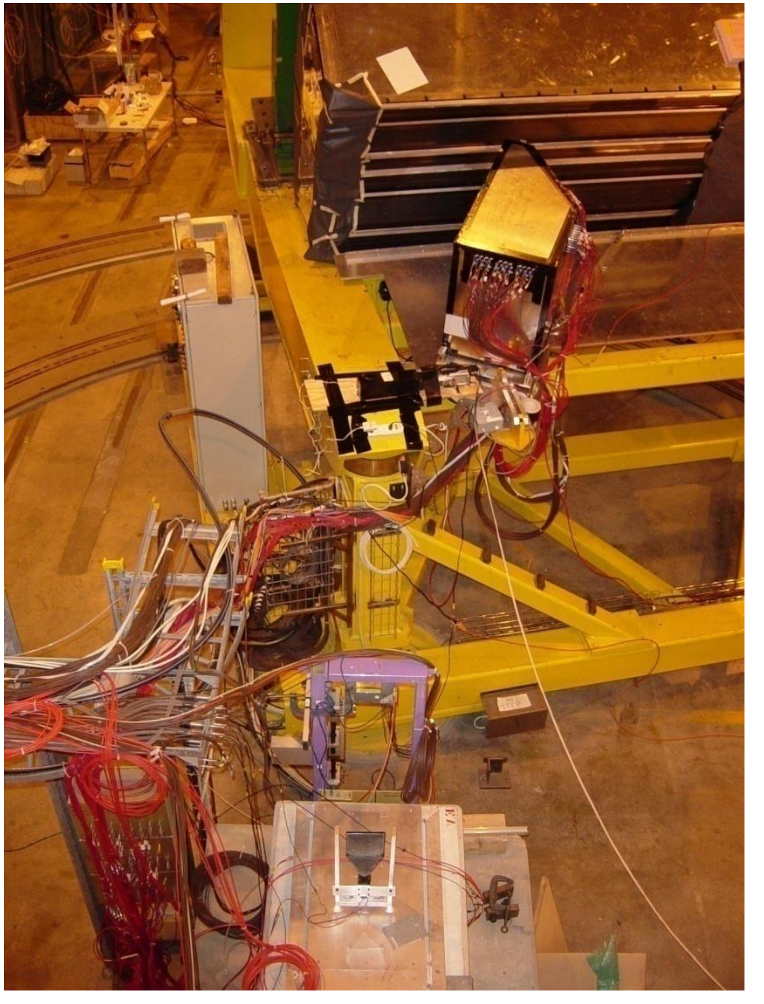
Notre Dame QuarkNet Center
Typical Summer Program

Collaboration with and Professional Development for Teachers

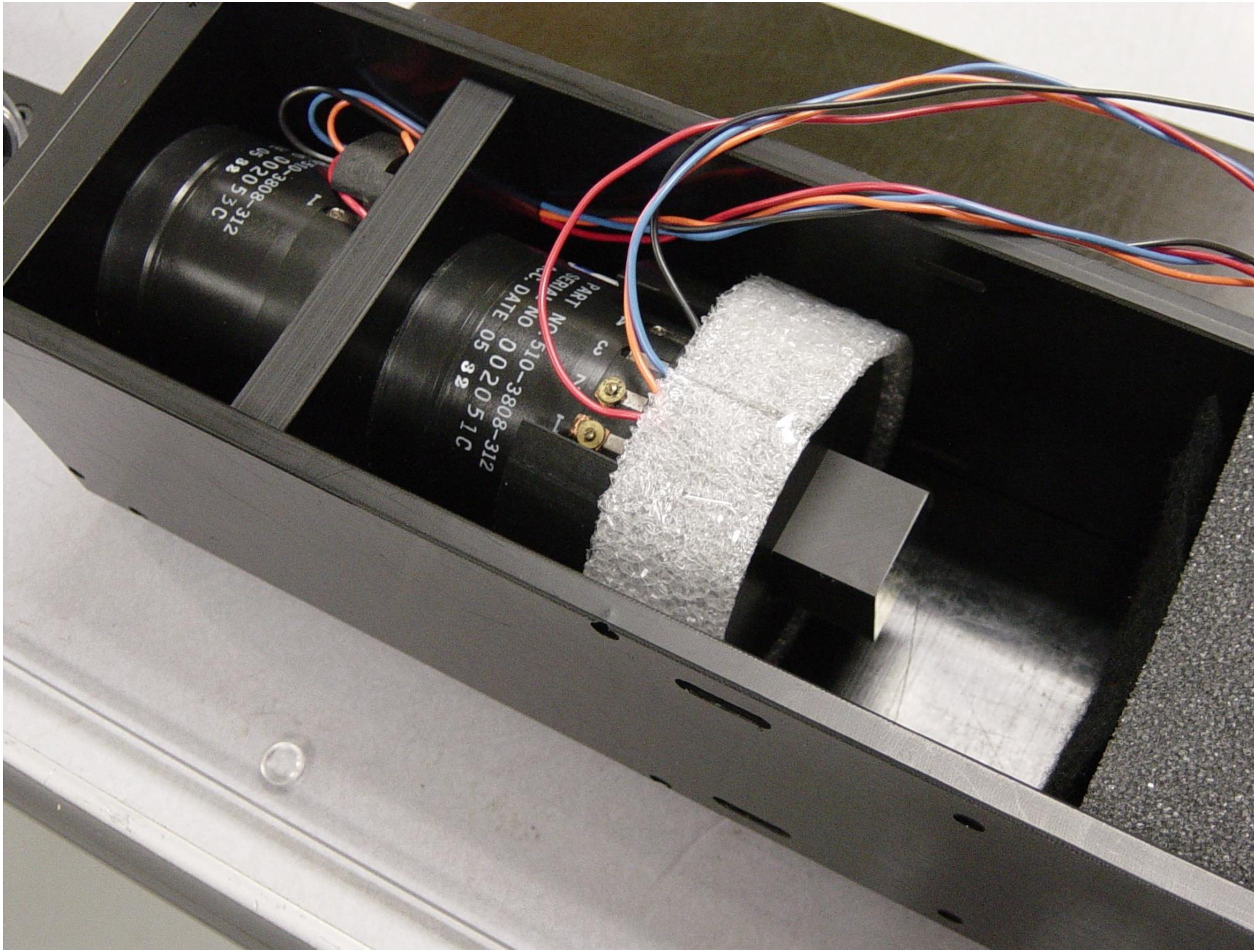
HS students present their work and data in poster sessions.



Compact Particle Detectors
built and operated by teachers and students



Assembly ↑   CERN Beam →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510-3808-312
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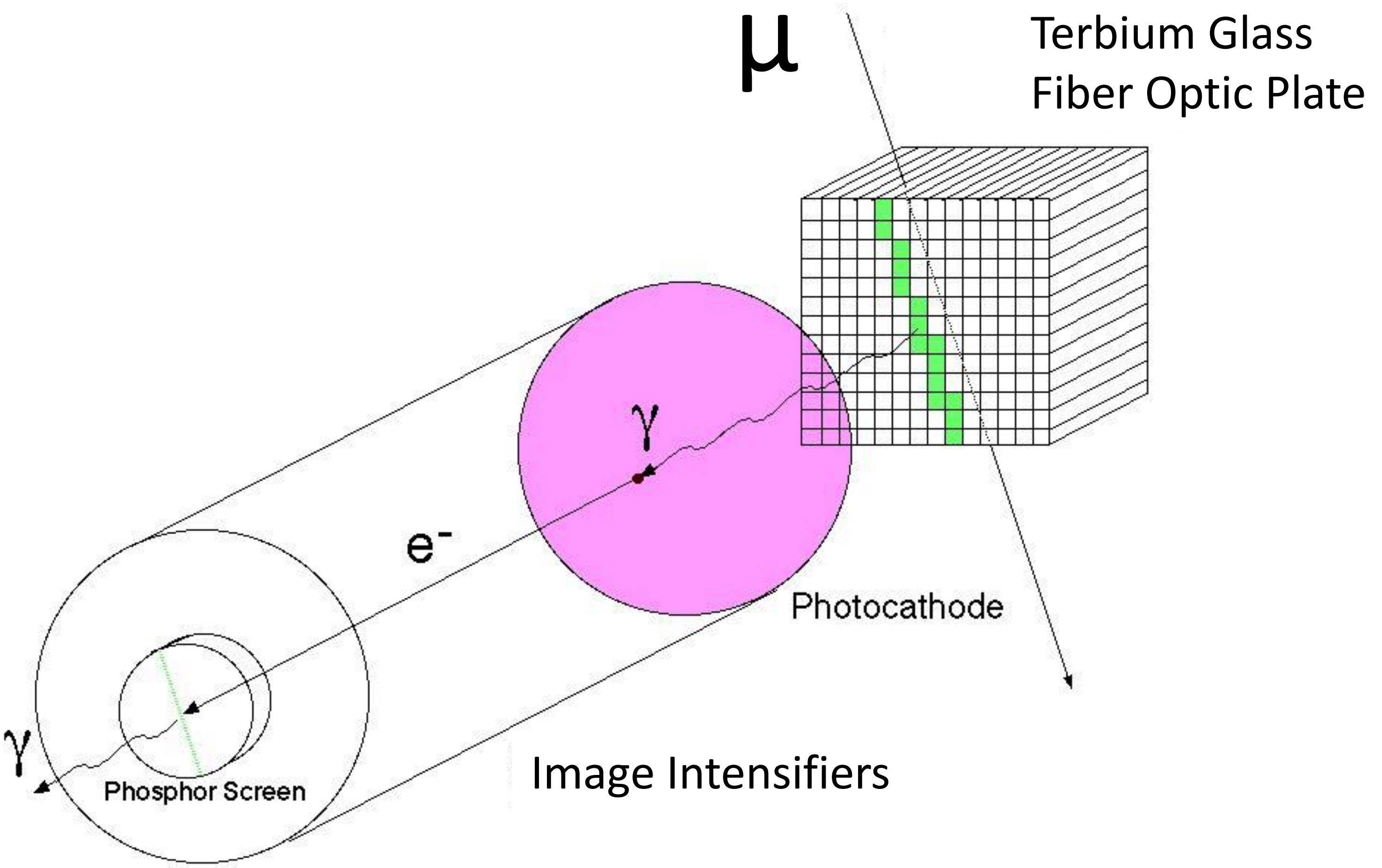
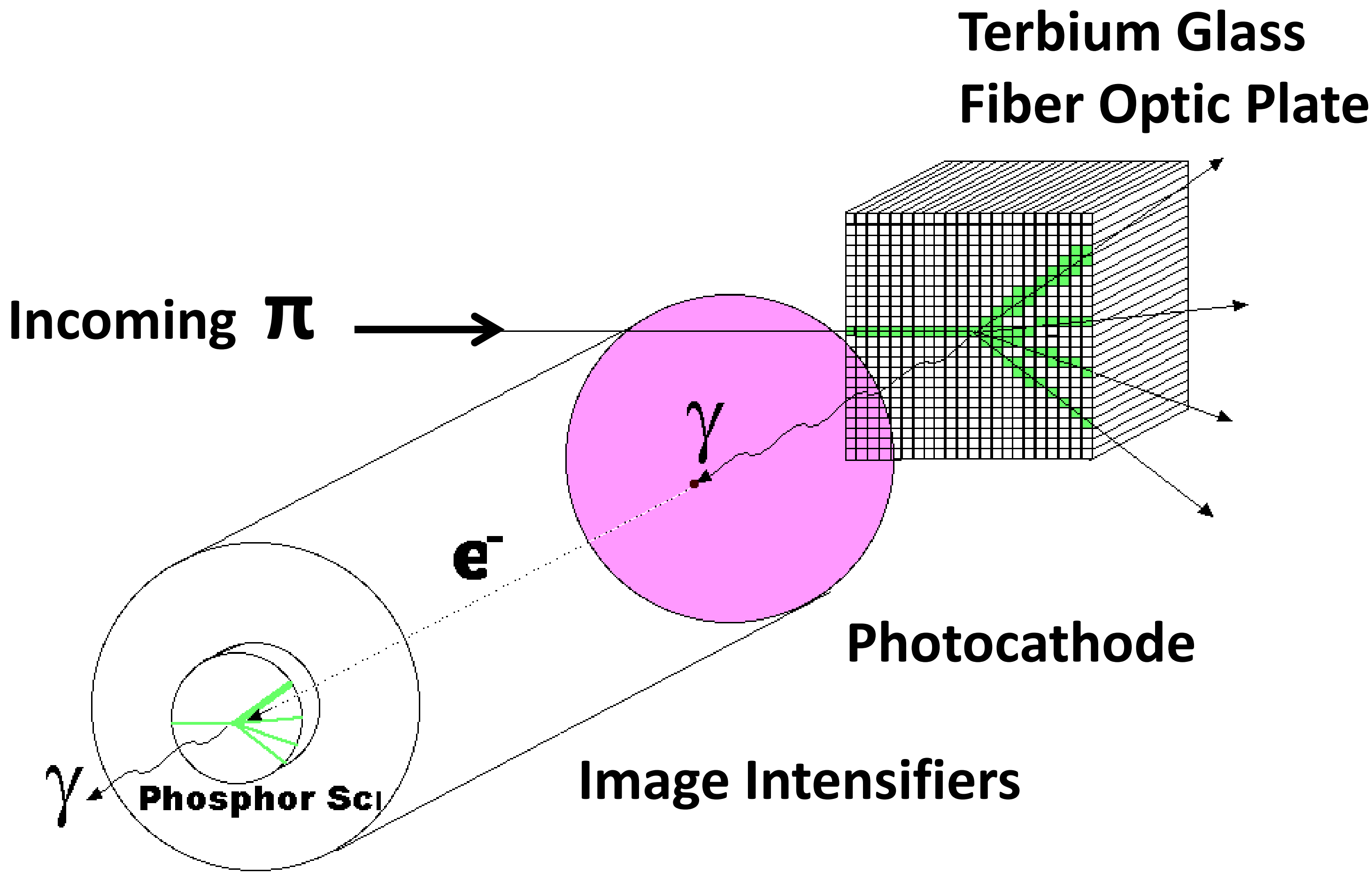
Schematic of the Apparatus



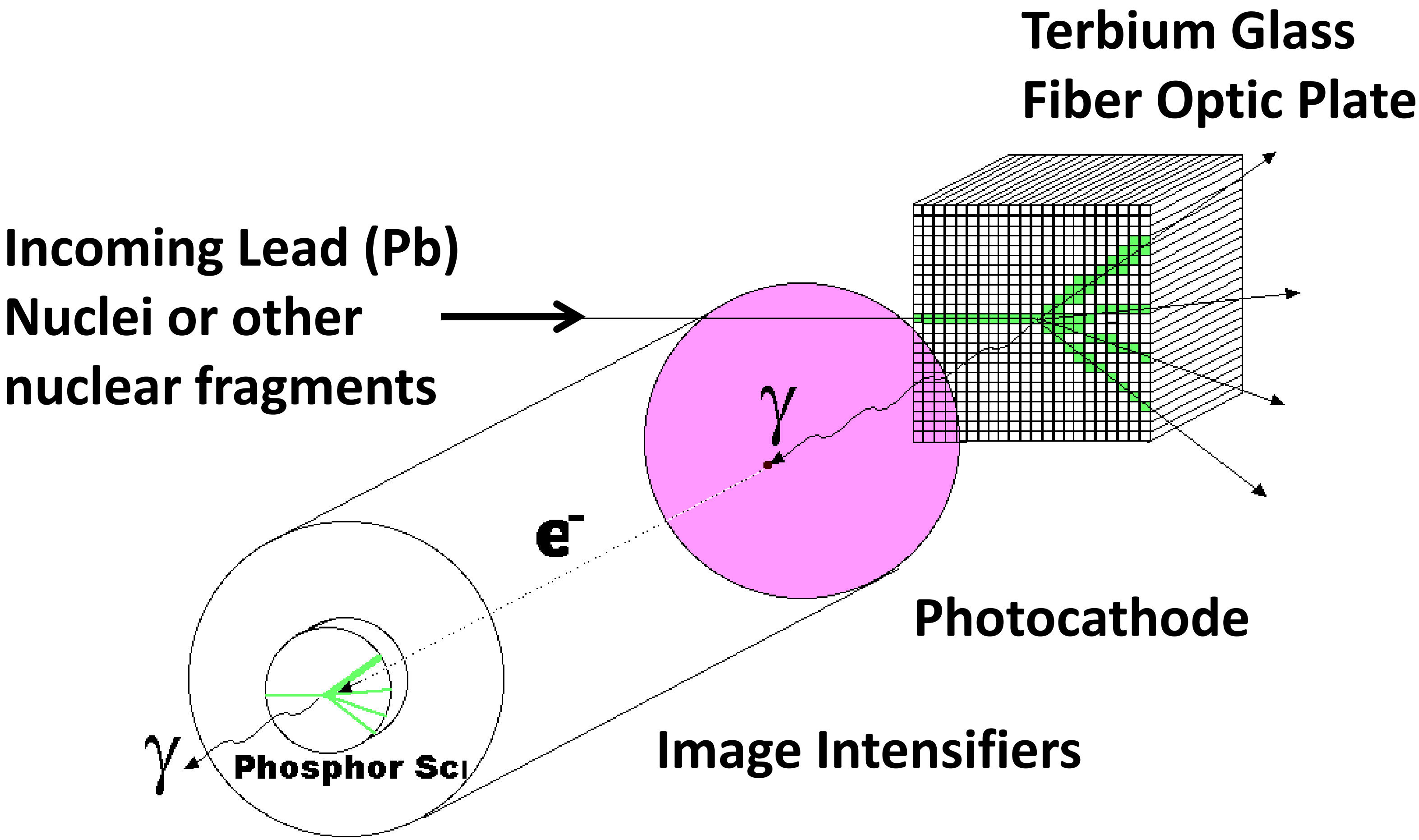
Pion (π) Interactions Observed



Pion (π) Interactions Observed

Preparing for Beam Test of a detector using Heavy Ions at CERN (H8) Fall 2016

Heavy Ion Interactions Observed



Typical Collisions of Heavy Ions