Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

CMS Recap

Kevin Burkett

DOE Institutional Review

February 12, 2015

CMS: University Involvement

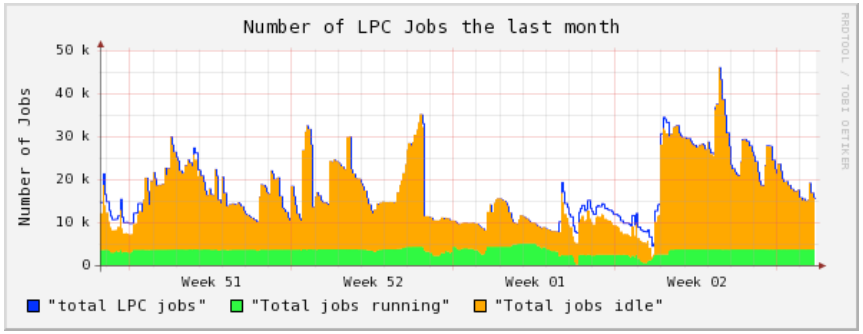
- LHC Physics Center (LPC):
  - 150 resident users
  - 700 remote users
- Vibrant community for CMS physicists based in the US
  - Training
  - Engagement in physics
  - Growing participation in upgrades
- Managed together with the USCMS university community

CMS: University Involvement

- Host of Remote Ops Center:
  - official CMS shifts, facilitating university participation in operations at lower cost than traveling to CERN
- Host of USCMS Ops Program Upgrade Project Offices
  - Management in collaboration with universities
  - Extensive use of unique FNAL facilities in assembly and R&D for Phase 1&2 upgrades

CMS: Computing

- FNAL is involved in all aspects of maintaining, evolving the computing and software infrastructure for Run 2 and beyond:
- Core software
  - Leaders and at the heart of the development team
  - Multithreaded framework mode recently implemented to process multiple events simultaneously on several cores
- Simulation
  - leaders of Phase 2 simulation software infrastructure development
  - Pythia expertise
- Computing Infrastructure Software
- Support for CMS Tier-1 Site and LPC Analysis cluster
  - Most reliably available T1, used by CMS for most difficult tasks
  - Interactive cluster for users, plus ~5000 core analysis cluster

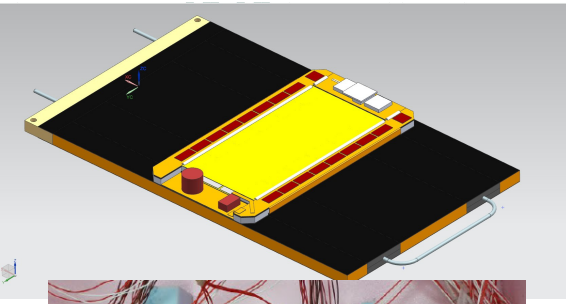


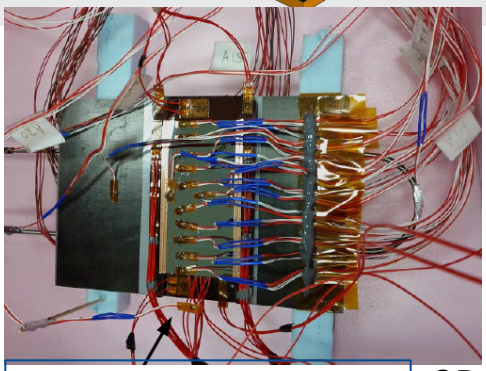
Fermilab

CMS: Theory

- Fermilab theory group making vital contributions to LHC program
  - Novel analysis techniques: Higgs width constraint, CPV in Higgs decays
  - Search strategies: mono-X searches for Dark Matter
  - Interpretation: complementarity of precision data and non-standard Higgs searches
  - Key tools: MCFM
- Strong connection with Fermilab CMS group
  - H→ZZ and H→WW
  - Pair produced resonances decaying to dijets
  - Color octet scalars
- Strong connection to USCMS community through LPC
  - Analysis collaboration
    - Benchmark scenarios for additional Higgs searches
    - Search for heavy resonances decaying to bb or bg
  - Informal exchange of ideas through Physics Forum, TOTW

CMS: Detector R&D

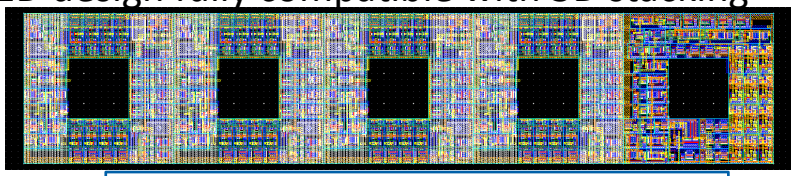




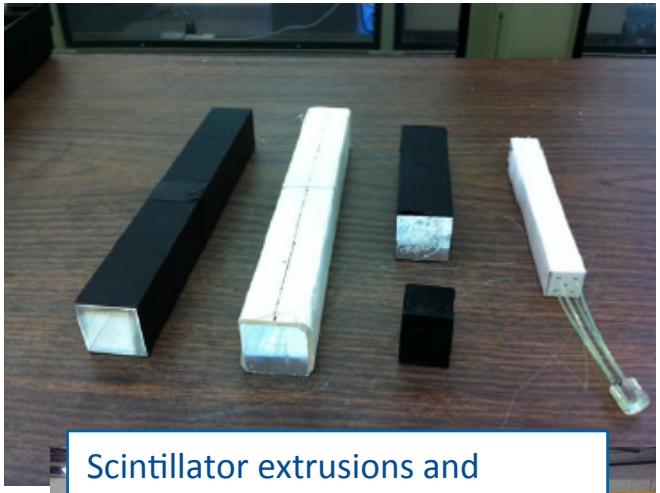
CMS PS module drawing
And thermal prototype

High Granularity Calorimeter
Thermal tests

2D design fully compatible with 3D stacking



VIPRAM associative memory IC design



Scintillator extrusions and chemistry

Scintillator extrusions facility

Three leaders of US CMS Phase 2 tasks are members of the Detector Advisory Panel

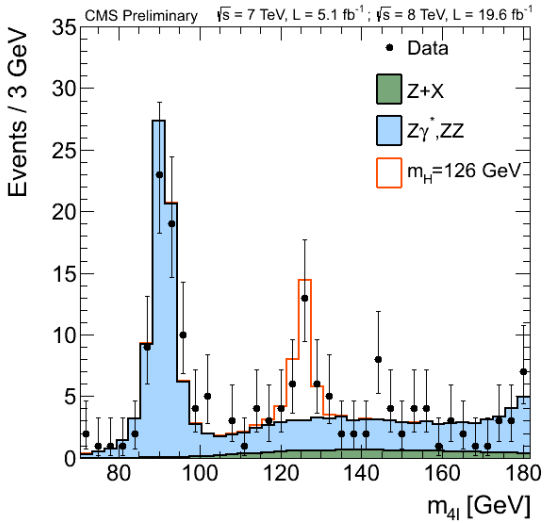
Charge Questions

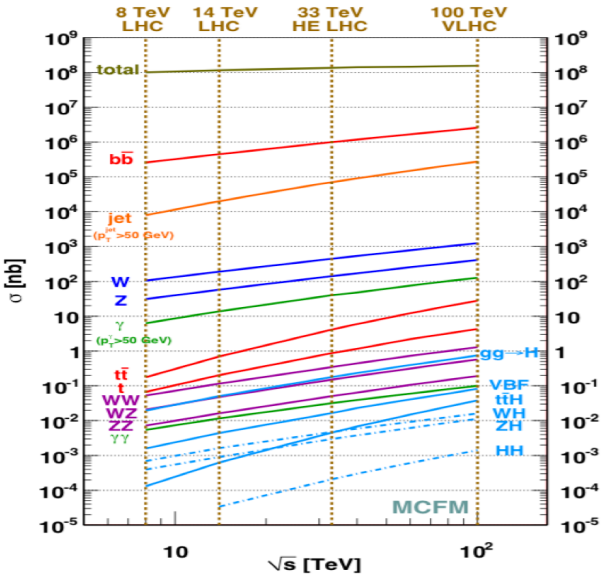
Question 1

- The quality and significance of the lab's recent scientific and technical accomplishments
- The merit, feasibility, and projected impact of the future planned physics program
- P5 alignment

Quality and Significance of Recent Accomplishments

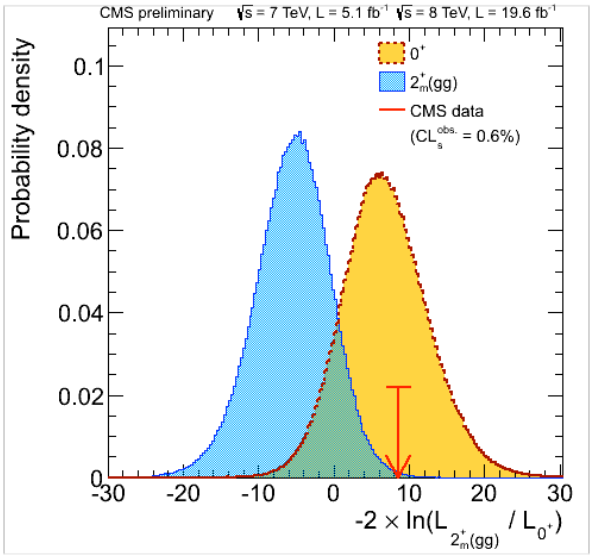
- Run 1 Physics Analysis
  - Higgs:
    - **H→ZZ→4l: Implementation of gg ME from MCFM in JHUGEN for kinematic discriminant to separate signal from ZZ background**
    - H→WW→2l2v: Development of spin/parity analysis to test non-SM Higgs
    - H→WW→lvjj: Sensitive to high mass Higgs
  - SUSY
    - Hadronic and leptonic searches
  - Standard Model Physics





Quality and Significance of Recent Accomplishments

- Run 1 Physics Analysis
  - Higgs:
    - H→ZZ→4l: Implementation of gg ME from MCFM in JHUGEN for kinematic discriminant to separate signal from ZZ background
    - **H→WW→2l2v: Development of spin/parity analysis to test non-SM Higgs**
    - H→WW→lvjj: Sensitive to high mass Higgs
  - SUSY
    - Hadronic and leptonic searches
  - Standard Model Physics

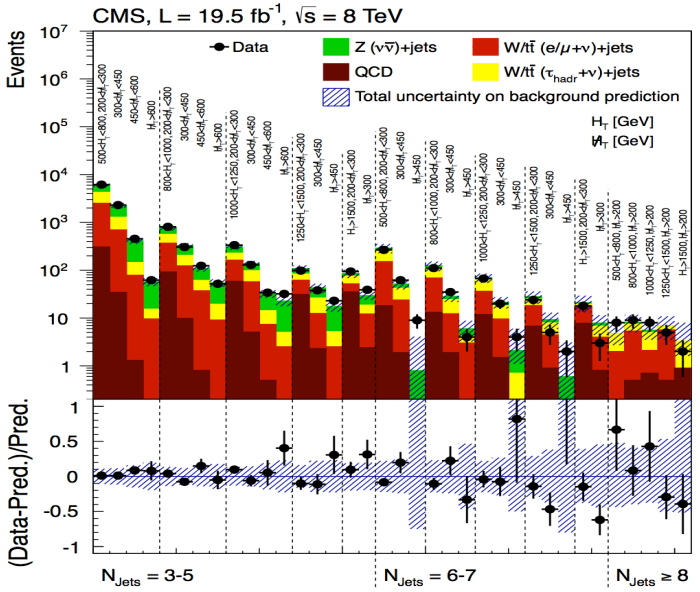


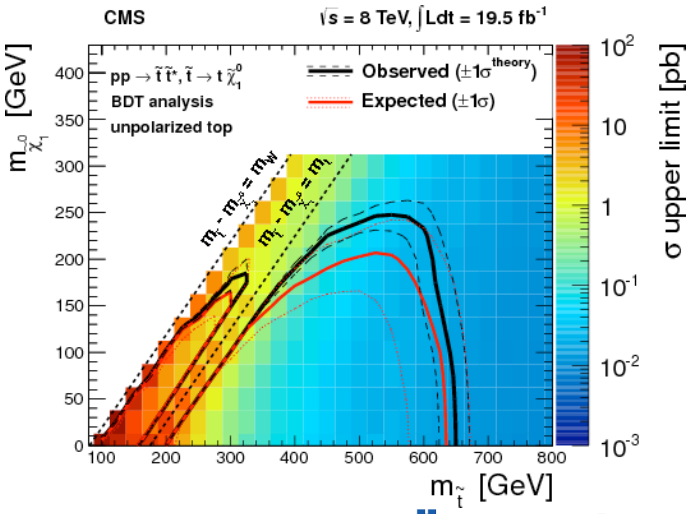
2013 – Yanyan Gao

The 2013 Alvin Tollestrup award for Outstanding Postdoctoral Research is awarded to Yanyan Gao of Fermilab for her contributions to the Higgs boson discovery with CMS, specifically in the ZZ and WW decay channels and extraction of spin and parity information for the new boson.

Quality and Significance of Recent Accomplishments

- Run 1 Physics Analysis
  - Higgs:
    - H→ZZ→4l: Implementation of gg ME from MCFM in JHUGEN for kinematic discriminant to separate signal from ZZ background
    - H→WW→2l2v: Development of spin/parity analysis to test non-SM Higgs
    - H→WW→lvjj: Sensitive to high mass Higgs
  - SUSY
    - **Hadronic and leptonic searches**
  - Standard Model Physics

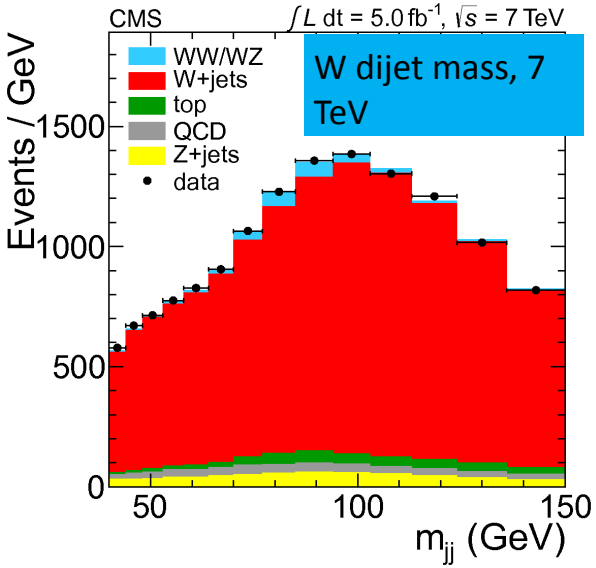


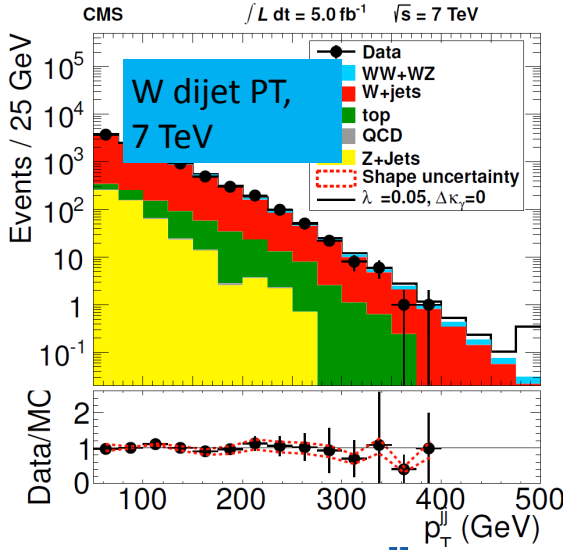


Fermilab

Quality and Significance of Recent Accomplishments

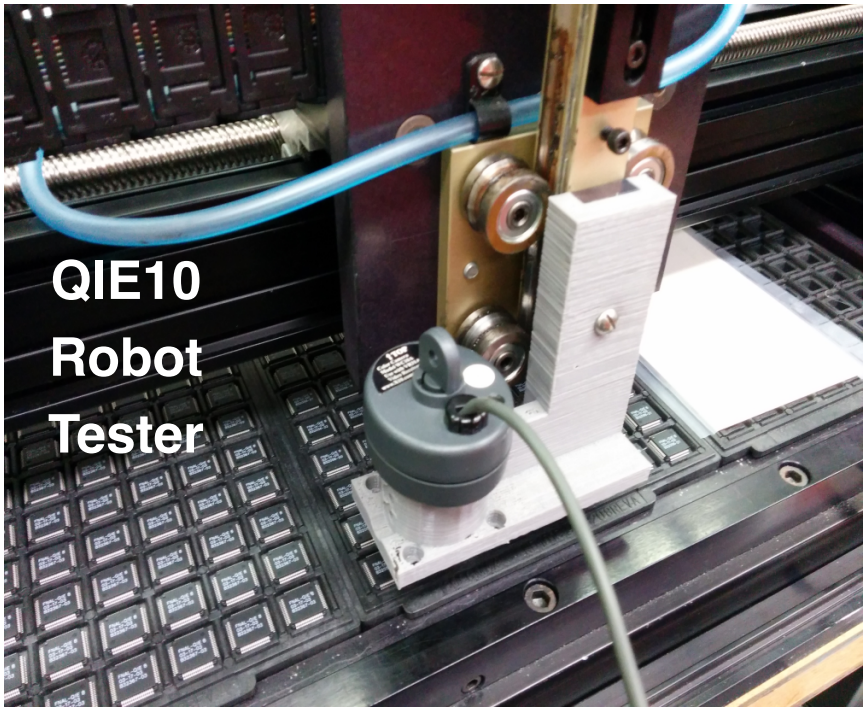
- Run 1 Physics Analysis
  - Higgs:
    - H→ZZ→4l: Implementation of gg ME from MCFM in JHUGEN for kinematic discriminant to separate signal from ZZ background
    - H→WW→2l2v: Development of spin/parity analysis to test non-SM Higgs
    - H→WW→lvjj: Sensitive to high mass Higgs
  - SUSY
    - Hadronic and leptonic searches
  - Standard Model Physics
    - **Semileptonic WW/WZ**

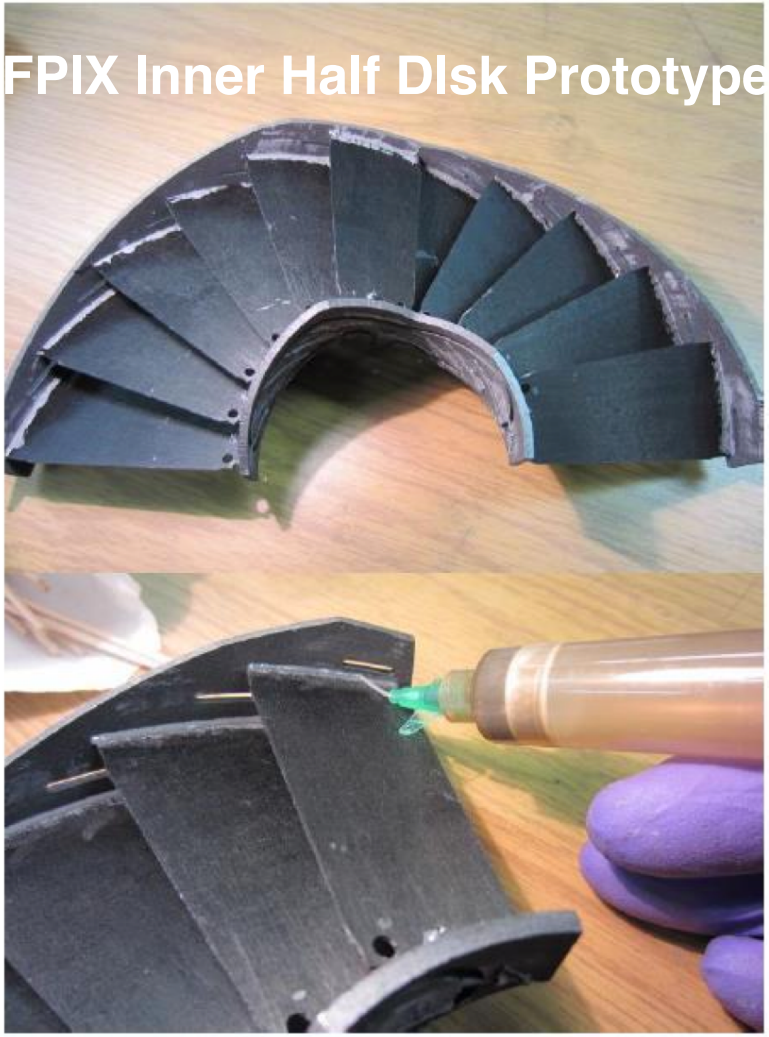




Fermilab

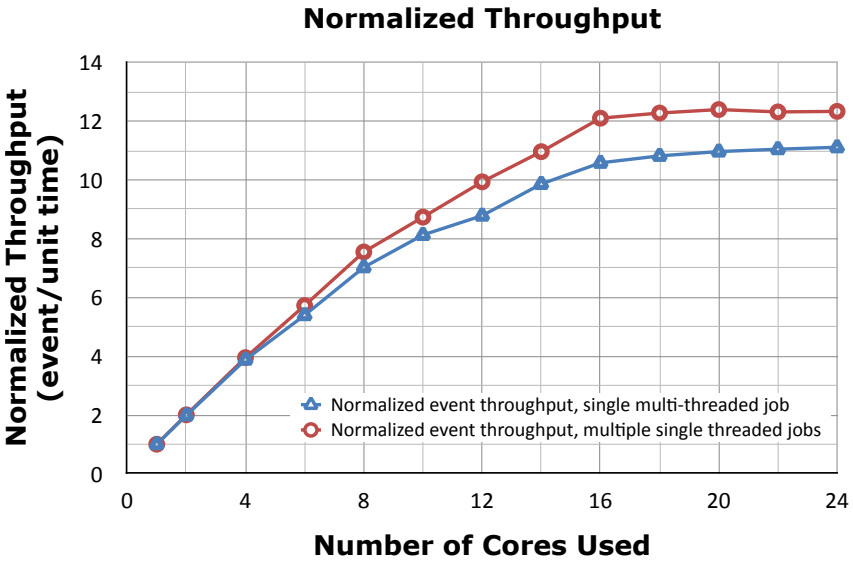
Quality and Significance of Recent Accomplishments



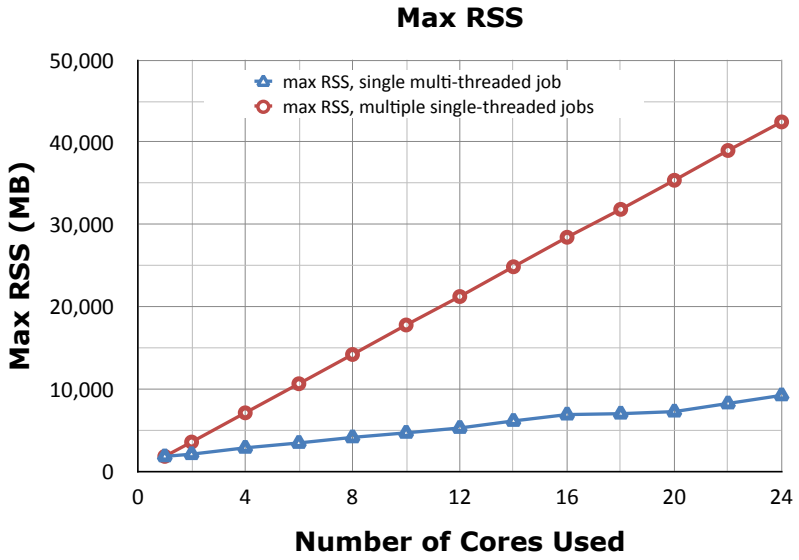


Quality and Significance of Recent Accomplishments

- Significant milestone reached in 2014 enabling the framework to run in multithreaded mode using several CPU cores concurrently to process multiple events simultaneously.

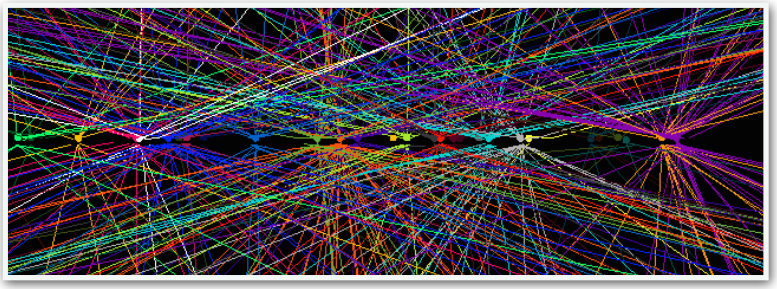


95% efficiency compared to single-threaded jobs at significant memory savings



Future Planned Physics Program

- Building off past success in analysis for Run 2
  - Inclusive SUSY search in multijets
  - Search for direct stop production
  - Vector Boson Physics
- Developing new tools
  - jet substructure, pileup
- Phase 1 and Phase 2 Upgrades



Pileup Per Particle Identification

Daniele Bertolini,[a] Philip Harris,[b] Matthew Low,[c] and Nhan Tran[d]

[a] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[b] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[c] *Enrico Fermi Institute and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[d] *Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA*

E-mail: danbert@mit.edu, philip.coleman.harris@cern.ch, mattlow@uchicago.edu, ntran@fnal.gov

Abstract: We propose a new method for pileup mitigation by implementing "pileup per particle identification" (PUPPI). For each particle we first define a local shape α which probes the collinear versus soft diffuse structure in the neighborhood of the particle. The former is indicative of particles originating from the hard scatter and the latter of particles originating from pileup interactions. The distribution of α for charged pileup, assumed as a proxy for all pileup, is used on an event-by-event basis to calculate a weight for each particle. The weights describe the degree to which particles are pileup-like and are used to rescale their four-momenta, superseding the need for jet-based corrections. Furthermore, the algorithm flexibly allows combination with other, possibly experimental, probabilistic information associated with particles such as vertexing and timing performance. We demonstrate the algorithm improves over existing methods by looking at jet p_T and jet mass. We also find an improvement on non-jet quantities like missing transverse energy.

Alignment with P5

- Science Drivers:
  - ✓ Use the Higgs boson as a new tool for discovery
    Pursue the physics associated with neutrino mass
  - ✓ Identify the new physics of dark matter
    Understand cosmic acceleration: dark energy and inflation
  - ✓ Explore the unknown: new particles, interactions, and physical principles

Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.

Question 2

- The effectiveness and efficiency of facility operations and the planning for future facilities to support the research program, including appropriateness of proposed performance metrics in terms of being realistic and maximizing the scientific productivity of the facility

Use of Facilities

- Phase 1 and Phase 2 upgrade projects are making extensive use of the unique facilities at FNAL, esp. SiDet and Testbeam
  - **SiDet**
    - Organizing FPIX assembly
    - Key for prototyping, testing modules for FPIX, Tracker
    - Significant potential for module production for Phase 2
  - **Test Beam Facility**
    - Qualification of electronics for HCAL, FPIX
    - Scintillator R&D for HCAL
    - High rate tests of new sensors, chips for FPIX, Tracker
- At SiDet, the lab has already made targeted hires to strengthen the team, with an eye to the future
  - Additional investments in infrastructure

Computing

- Computing facilities tailored to the needs of CMS
- Agreed upon performance metrics are tracked by CMS and USCMS
  - Availability
  - Reliability

Question 3

- The effectiveness of the lab management in
  - Strategic planning
  - Core competencies
  - Implementing prioritized and optimized plan
- Promoting and implementing a safe work environment

Upgrade Strategy

- Overall strategy is to build on core competencies, choose projects that are important to USCMS, and partner with USCMS colleagues to increase the impact of their contributions
- Core competencies:
  - HCAL (QIE, Scintillators), Tracker/FPIX (silicon detector assembly and operation), Trigger
  - Software (simulation, reconstruction)
  - Computing infrastructure software and facility operation
  - Project management
- Use unique facilities and resident expertise
- Invest in strategic hiring and needed infrastructure to retain strength in core competencies

Safety

LHC CMS Detector Upgrade Project

ESH&Q Policies

- Safety is achieved through standard Lab/Institute practices
  - No construction, accelerator operation, or exotic fabrication
  - No imminent peril situations or unusual hazards
  - Items comply with local safety standards in site of fabrication and operation
  - Site Safety officers at Institutes identified in the SOW
- Documents
  - NEPA exclusion, Integrated Safety Management Plan, (prelim) Hazard Analysis Report, Quality Assurance Plan

ISM

CMS Upgrade Project Integrated Safety Management Plan

Fermi National Accelerator Laboratory
CMS-doc-11587

Fermilab

8/22/13
Steven C. Nahn date
LHC CMS Detector Upgrade Project Manager

8/26/2013
Aaron Dominguez date
LHC CMS Det. Upgrade Deputy Project Manager

Martha Michels 8.21.13
Martha Michels date
Head of the Fermilab ESH&Q Section

8.21.13
Eric McHugh date
PPD Senior Safety Officer

Department of Energy

8/23/13
Stephen L. Webster date
DOE LHC CMS Det. Upgrade Project Director

pHAR

CMS Upgrade Project Preliminary Hazard Analysis Report

Fermi National Accelerator Laboratory
CMS-doc-11816

Fermilab

8/12/2013
Steven C Nahn date
LHC CMS Upgrade Project Manager

S. Grünendahl 2013-8-22
Stefan Grünendahl date
LHC CMS Upgrade ESH&Q Coordinator

Martha Michels 8.21.13
Martha Michels date
Acting Head of ESH&Q Section

8.21.13
Eric McHugh date
PPD Senior Safety Officer

Department of Energy

8/23/2013
Stephen L Webster date
DOE LHC CMS Upgrade Project Director

QAP

LHC CMS Detector Upgrade Project Quality Assurance Program

Fermi National Accelerator Laboratory
CMS-doc-11584

LHC CMS DETECTOR UPGRADE PROJECT
QUALITY ASSURANCE PROGRAM APPROVALS

Fermilab

8/14/2013
Steven C Nahn date
LHC CMS Upgrade Project Manager

8/14/2013
T J Sarlina date
Fermilab Quality Assurance Manager

S. Grünendahl
Stefan Grünendahl date
LHC CMS Upgrade ESH&Q Coordinator

Department of Energy

8/14/2013
Stephen L Webster date
DOE LHC CMS Upgrade Project Director

Fermilab

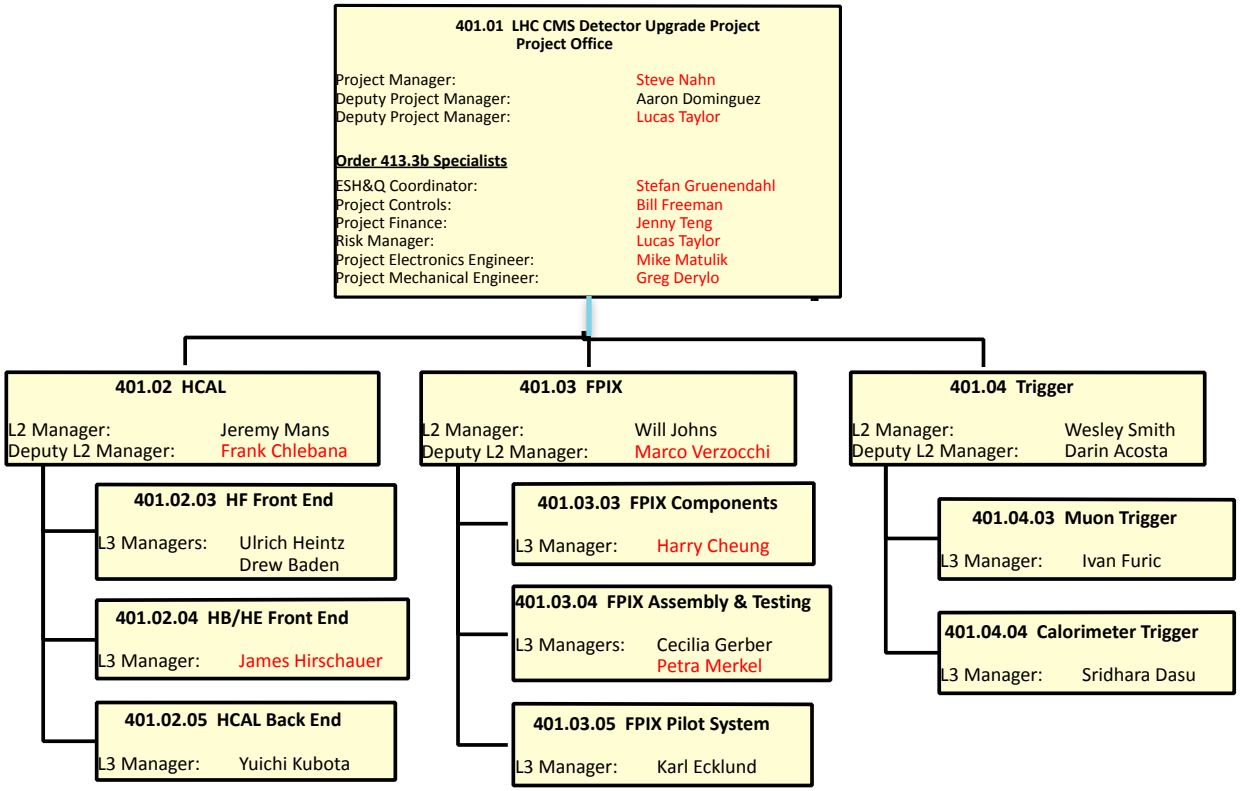
Question 4

- The effectiveness of the development and oversight of projects
- Integration of universities and other national labs in projects

Project Management

- Phase 1 Upgrades CD-3 Approved
- Phase 2 Upgrades Technical Proposal this Fall
- Lab hosts USCMS Operations Program and Upgrade Projects with close collaboration of universities

Example: USCMS Phase 1 Upgrade Project



Question 5

- The leadership, creativity, and productivity of the lab's scientific and technical staff

Leadership, Creativity, and Productivity of Lab Staff

Fermilab Physics Conveners 2009-2015

- **SUSY (Five Subgroup Conveners)**
  - Ben Hooberman (SUSY in lepton channel, 2012-13)
  - Dave Mason (SUSY in photon channel, 2012-13)
  - Rick Cavanaugh (SUSY in 3rd Generation, 2012-13)
  - Daniel Elvira (SUSY in Hadronic channel, 2009-10)
  - Seema Sharma (SUSY in Hadronic channel, 2014-15)
- **Standard Model (Three Physics Analysis Group and three subgroup conveners)**
  - Vivian O'Dell (QCD Convener, 2009-10)
  - Kostas Kousouris (QCD and Standard Model Convener, 2011-12)
  - Jeff Berryhill (Standard Model Convener, 2012-13)
  - Vasu Chetluru (QCD Photon Subgroup, 2009-10)
  - Slawek Tkaczyk (SMP Boson subgroup, 2012-13)
  - Jacob Linacre (Top Properties subgroup, 2013-14)
- **Exotica (Four Subgroup Conveners)**
  - Jim Hirschauer (Exotica Lepton+Jets, 2012-13)
  - Keti Kaadze (Exotica Lepton + Jets, 2014-15)
  - Robert Harris (Exotica Multijets, 2012-13)
  - Steve Mrenna (Monte Carlo Interpretations, 2014-15)
- **Objects (Four group and five subgroup conveners)**
  - Kevin Burkett (Tracking Convener, 2008-10)
  - Daniel Elvira (JetMET Convener, 2008-09)
  - Robert Harris (JetMET Convener, 2010-11)
  - Lindsey Gray (Electron/Photon Convener, 2014-15)
  - Robert Harris (JetMET Jet Energy Correction Subgroup, 2008-09)
  - Kostas Kousouris (JetMET, Jet Energy Correction Subgroup, 2010)
  - Niki Saoulidou (JetMET, Jet Algorithms Subgroup, 2011-12)
  - Lindsey Gray (Photon Subgroup, 2013)
  - Nhan Tran (JetMET Algorithms and Reconstruction Subgroup, 2013-14)

Leadership, Creativity, and Productivity of Lab Staff

Fermilab Leadership in CMS Management 2009-2015

- **Software and Computing**
  - Ian Fisk (L1 Computing coordinator 2010-2013)
  - Patty McBride (Deputy L1 Computing coord. 2010-11)
  - Liz Sexton-Kennedy (L1 Offline coordinator 2010-13)
  - Lothar Bauerdick (US S&C Mgr 2001-14)
  - Oliver Gutsche (L2 coordinator Computing Operations 2009-14)
- **HCAL**
  - Jeff Spalding (Project manager 2009-11)
  - Frank Chlebana (DPG convener 2009-11)
  - Slawek Tkaczyk (Installation and Commissioning Leader, 2013-14)
  - Jim Hirschauer (Operations Coordinator 2011-12)
  - Jim Freeman (Inst. Board Chair 2013-2015)
- **Tracker**
  - Lenny Spiegel (Tracker Inst. Board Rep 2009-15)
  - Simon Kwan (FPIX Phase 1 project manager (2010-14)
- **Trigger**
  - Jeff Berryhill (Stage 1 Level 1 Calorimeter Trigger Project Manager 2014-15)
  - Ted Liu (Phase 2 Level 1 Track Trigger Coordinator, 2014-15)
  - Vivian O'Dell (TriDAS Inst. Board Rep 2003-15)
- **CMS**
  - Dan Green (Collaboration Board Chair 2009-11)
  - Joel Butler (Deputy Upgrade coordinator 2009-11)
  - Jeff Spalding (Upgrade Proj. Manager 2012-14)
  - Boaz Klima (Deputy Chair Conf. Comm. 2009-11)
  - Vivian O'Dell (Deputy Chair Conf. Comm. 2009-11)
  - Pushpa Bhat (Machine Interface Group convener 2010-2011)
- **USCMS**
  - Joel Butler (Ops Program Manager 2009-13)
  - Patty McBride (Ops Program Manager 2013-14)
  - Lothar Bauerdick (Ops Program Manager 2015-)
  - Steve Nahn (Phase 1 Upgrade Project Manager 2013-15)
  - Cathy Newman Holmes (Detector Operations Program Head 2010-13)
  - Vivian O'Dell (Detector Operations Program Head 2014-15)

Question 6

- The quality and appropriateness of the lab's interactions with, and nurturing of its scientific community

LPC and the Scientific Community

- Many LPC activities are focused around the broader scientific community
  - Topic of the Week seminar, Physics Forum bring together CMS and non-CMS scientists
- Management of LPC is shared between FNAL and universities
  - Includes management board (nearly all non-FNAL) and individual LPC organizing committees
- Distinguished researcher program brings some of the best young people to the LPC, provides travel funding, and gives them a recognized honor that helps distinguish them when looking for their next position
- Hosting of training helps new members of CMS get started or rapidly develop new expertise

Concerns

- We are now entering a challenging period where we must balance a successful launch of Run 2 (both in operations and in physics), complete the Phase 1 upgrades, and launch the Phase 2 project

- For USCMS and Fermilab to succeed in the upgrades, we must maintain the needed technical expertise and facilities, shifting or growing to match the needed skills

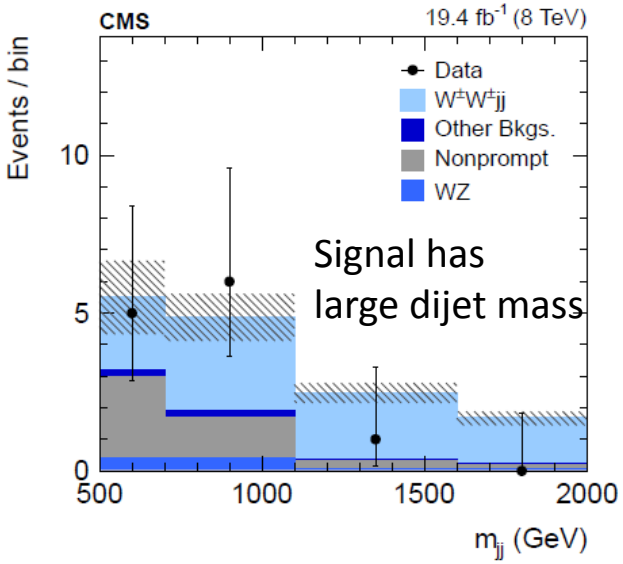
Summary

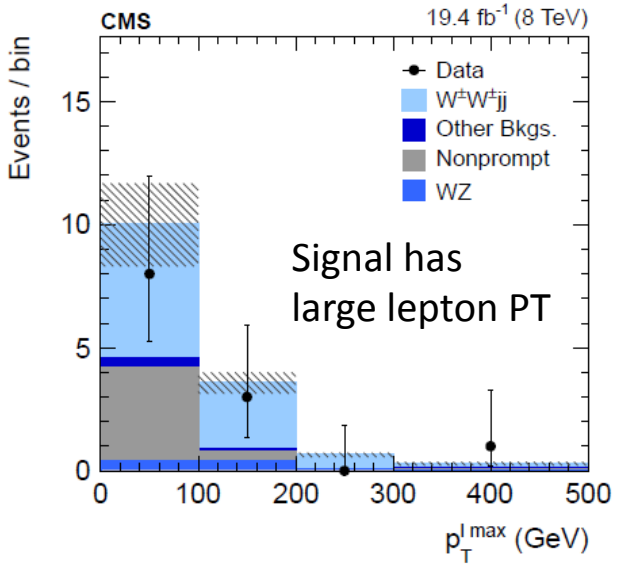
- CMS at Fermilab continues to make vital contributions to the LHC program, technically and scientifically
- We have demonstrated leadership in project management, guiding the Phase 1 upgrade project through CD-3 approval, and now preparing to launch Phase 2
- Through the hosting of the LPC and the ROC, Fermilab has created a hub of activity within the US, increasing the impact of USCMS physicists, and creating a tight connection with the theory group and wider theory community
- Our analysis activity, upgrade work, and hosting of these facilities are all well-aligned with the priorities from P5

BACKUP MATERIAL

Quality and Significance of Recent Accomplishments

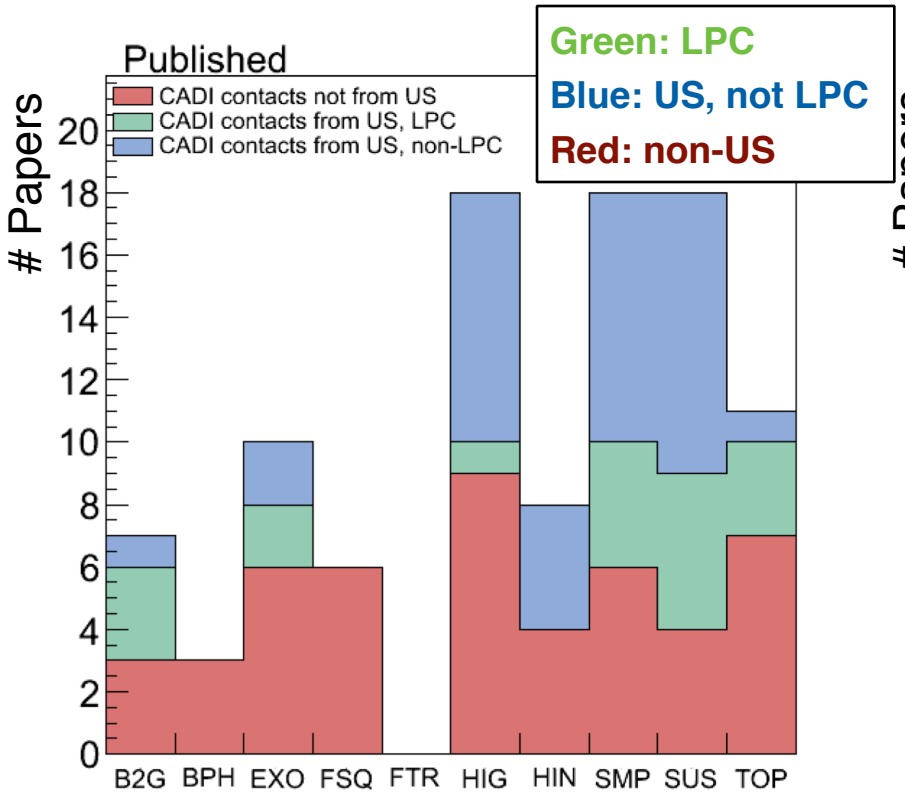
- Run 1 Physics Analysis
  - Higgs:
    - H→ZZ→4l: Implementation of gg ME from MCFM in JHUGEN for kinematic discriminant to separate signal from ZZ background
    - H→WW→2l2v: Development of spin/parity analysis to test non-SM Higgs
    - H→WW→lvjj: Sensitive to high mass Higgs
  - SUSY
    - Hadronic and leptonic searches
  - Standard Model Physics
    - **Same-sign WW Scattering**



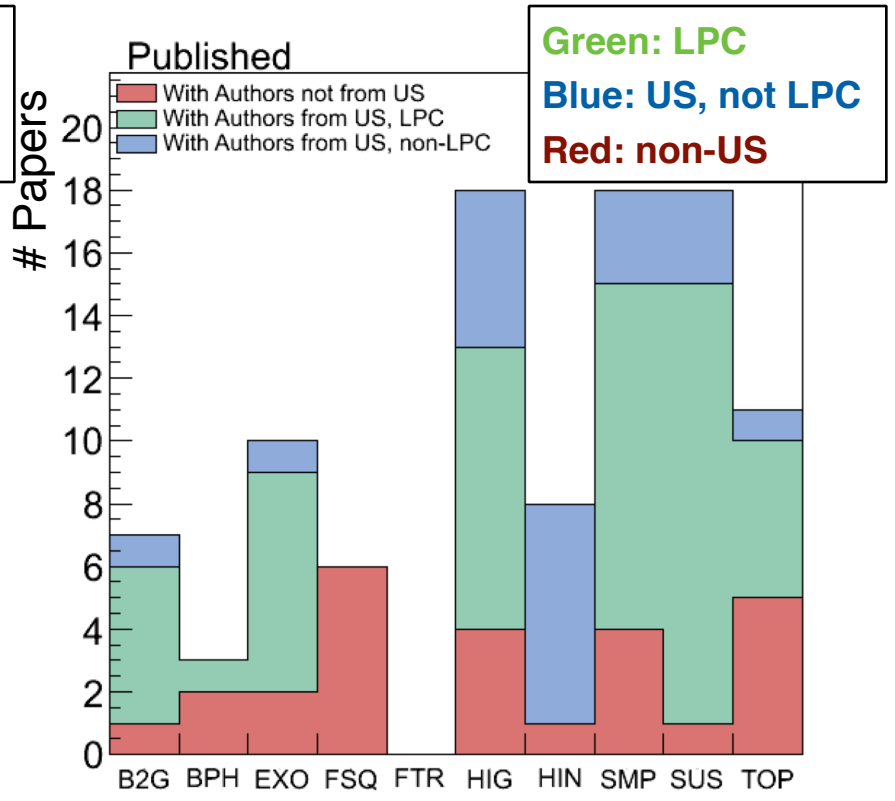


Response to 2013 S&T Review

- Development of LPC Performance metrics



Contact in 18% of pubs



Contributing to 52% of pubs

Current Positions of Past FNAL Postdocs

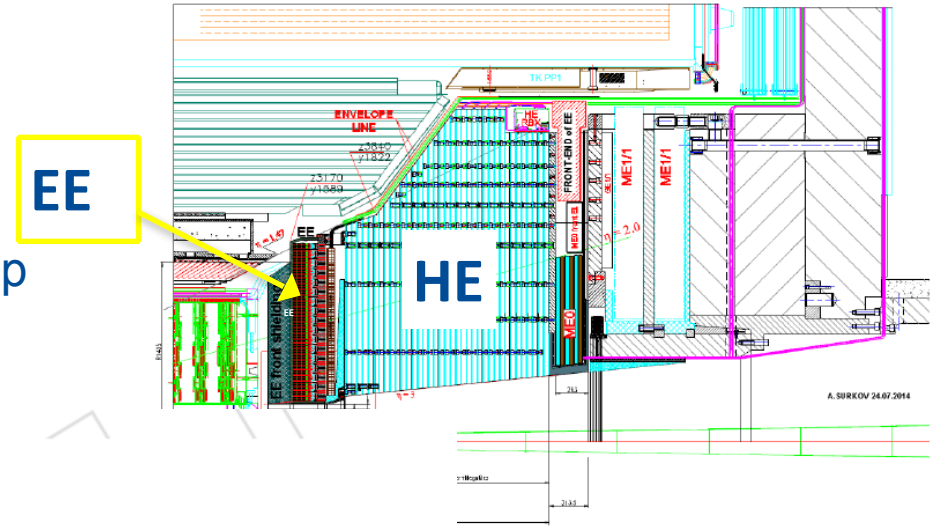
Jake Anderson	*Data Scientist, Pearson Education Software*
Ingo Bloch	*DESY Staff*
Vasundhara Chetluru	*Data Scientist, Jump Trading*
Yanyan Gao	*Postdoc, U. of Edinburgh*
Oliver Gutsche	*Scientist, SCD, Fermilab*
Jim Hirschauer	*Wilson Fellow, PPD, Fermilab*
Benjamin Hooberman	*Asst. Professor, UIUC*
Ketino Kaadze	*Asst. Professor, Kansas State*
Konstantinos Kousouris	*CERN Staff*
Verena Martinez Outschoorn	*Asst. Professor, UIUC*
Dave Mason	*Applications Physicist, SCD, Fermilab*
Kalanand Mishra	*Data Scientist, Vectra Networks*
Carsten Noeding	*System & Flight Safety Engineer, Northrop Grumman*
Seema Sharma	*Asst. Professor, IISER Pune India*
Ping Tan	*Postdoc, University of Iowa*
Lorenzo Uplegger	*Applications Physicist, SCD, Fermilab*
Fan Yang	*Trader, Quantitative Analyst, White Bay PT LLC, NY*
Francisco Yumiceva	*Asst. Professor, Florida Institute of Technology*

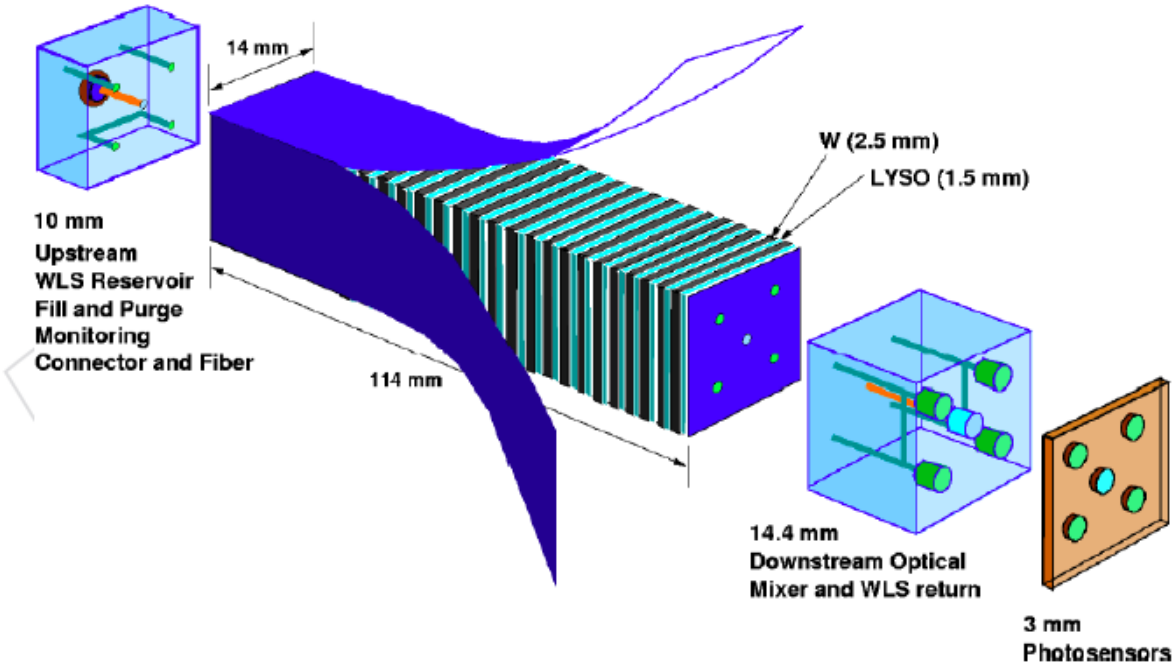
Endcap Calorimeter Options

- Maintain current geometry (Shashlik)
  - Replace ECAL endcap, refurbish HCAL endcap with radiation hard technologies
- High Granularity Calorimeter (HGCal)
  - Finely segmented calorimeter
    - Contains both electromagnetic and hadronic sections
      - 600 m2 silicon pads in W/Cu structure
      - Readout as much information as possible
        - Nicely complements the CMS emphasis on particle flow
      - + Rebuild HCAL endcap with reduced depth

Endcap Calorimeter: Shashlik option

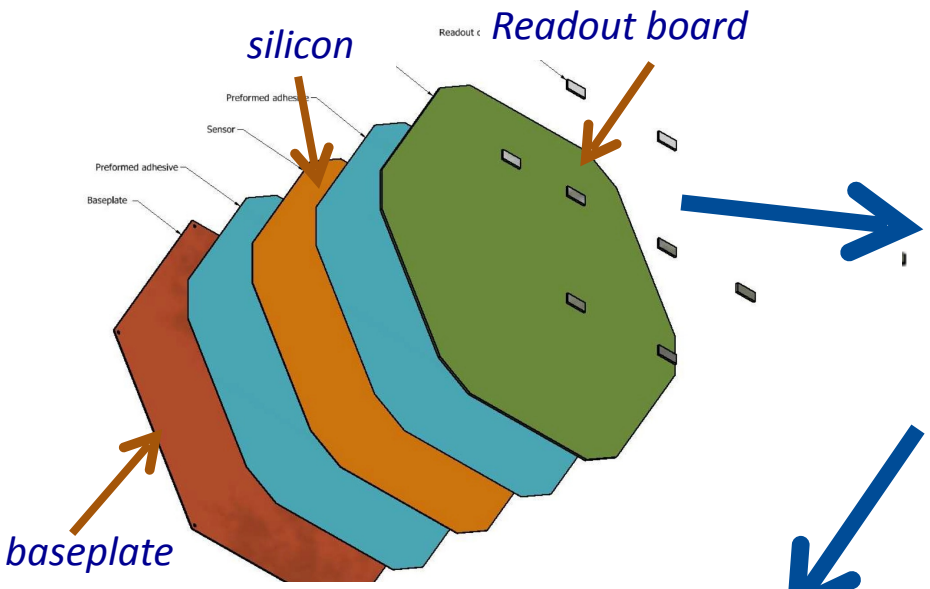
- W-absorber, LYSO scintillator
  - CeF_3 is an alternative
- Compact (~ 11cm long)
- Small Moliere radius (14mm)
- fine granularity ($14m^2$) to mitigate pileup
- High light yield for good e/γ energy resolution ~10%/sqrt(E) + 1%

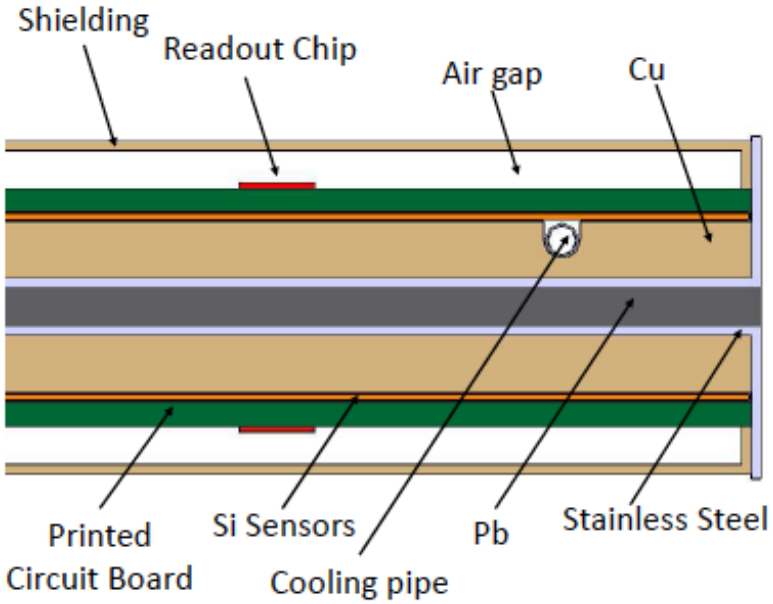




- Readout with WLS capillaries (CeF_3)
- No depth segmentation – but investigating extraction of signal near shower max with precise timing

Endcap Calorimeter: HGCal option





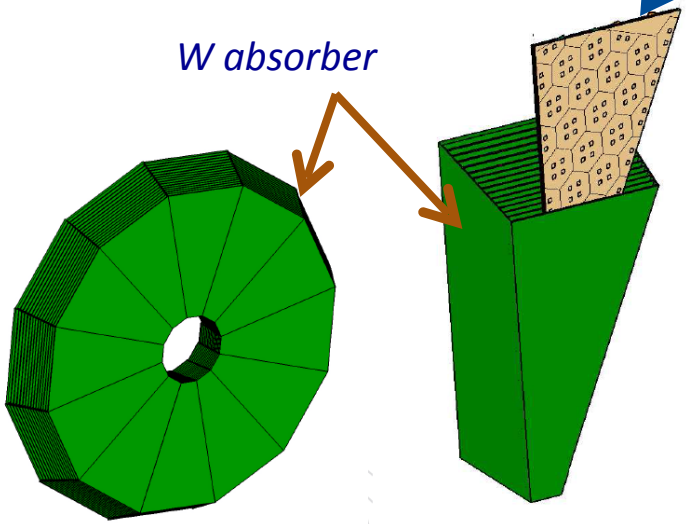
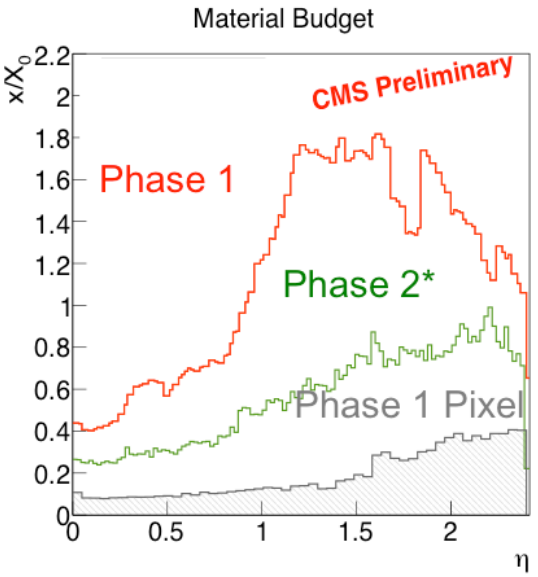


Table 3.4: Parameters of the E-HG and H-HG.

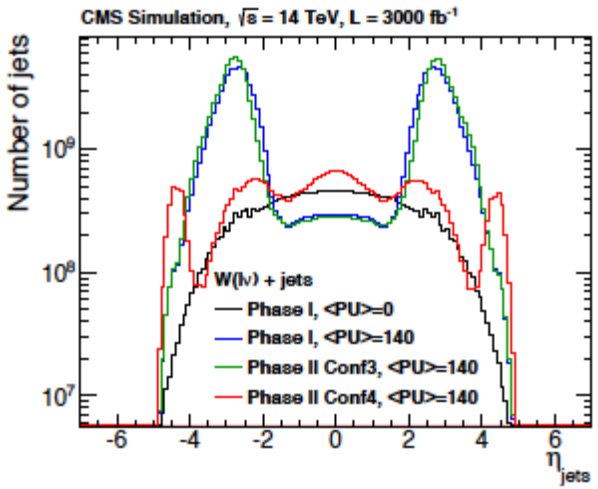
	E-HG	H-HG	Total
Area of silicon (m^2)	420	241	661
Channels	6.0M	2.7M	8.7M
Detector modules	18.2k	10.5k	28.7k
Weight (one endcap) (tonnes)	18	81	99
Number of Si planes	30	12	42

HL-LHC Tracker replacement



Requirements

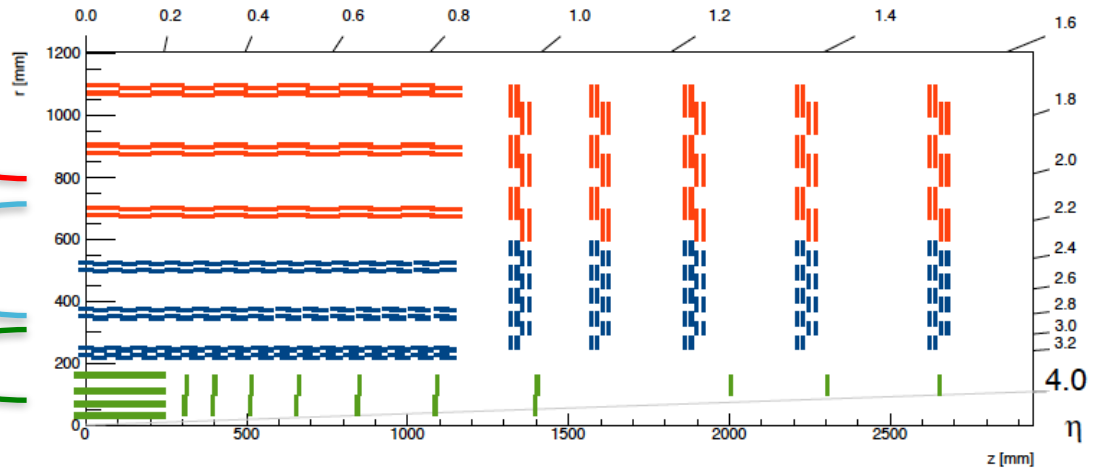
Radiation tolerance
Increased granularity
Improved 2-track separation
Reduced material
Robust pattern recognition
Support for L1 trigger upgrade
Extended tracking acceptance



Strip/Strip modules SS (pairs of strip sensors)

Strip/Pixel modules PS

Pixel modules



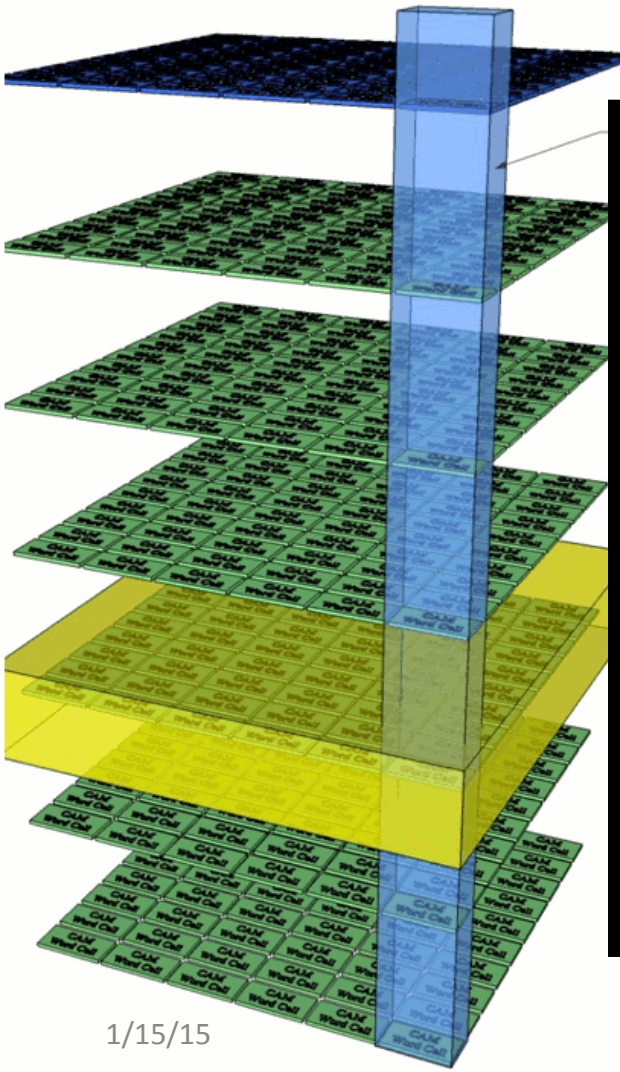
Fermilab

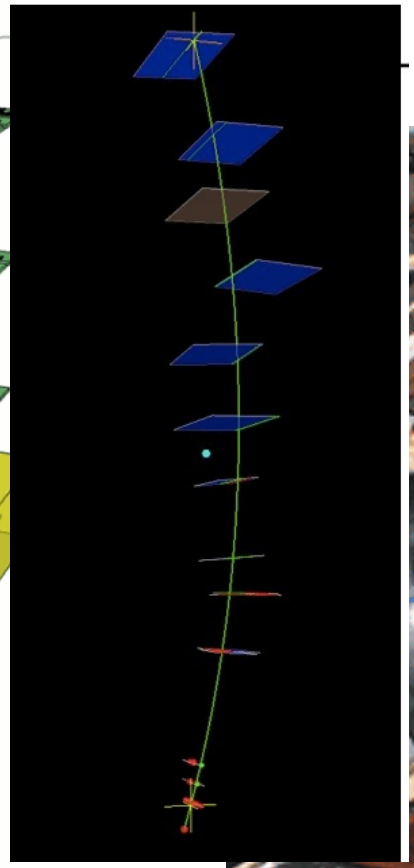
"A New Concept of Vertically Integrated Pattern Recognition Associative Memory"

TIPP 2011 Proceedings

http://www.sciencedirect.com/science/article/pii/S1875389212019165

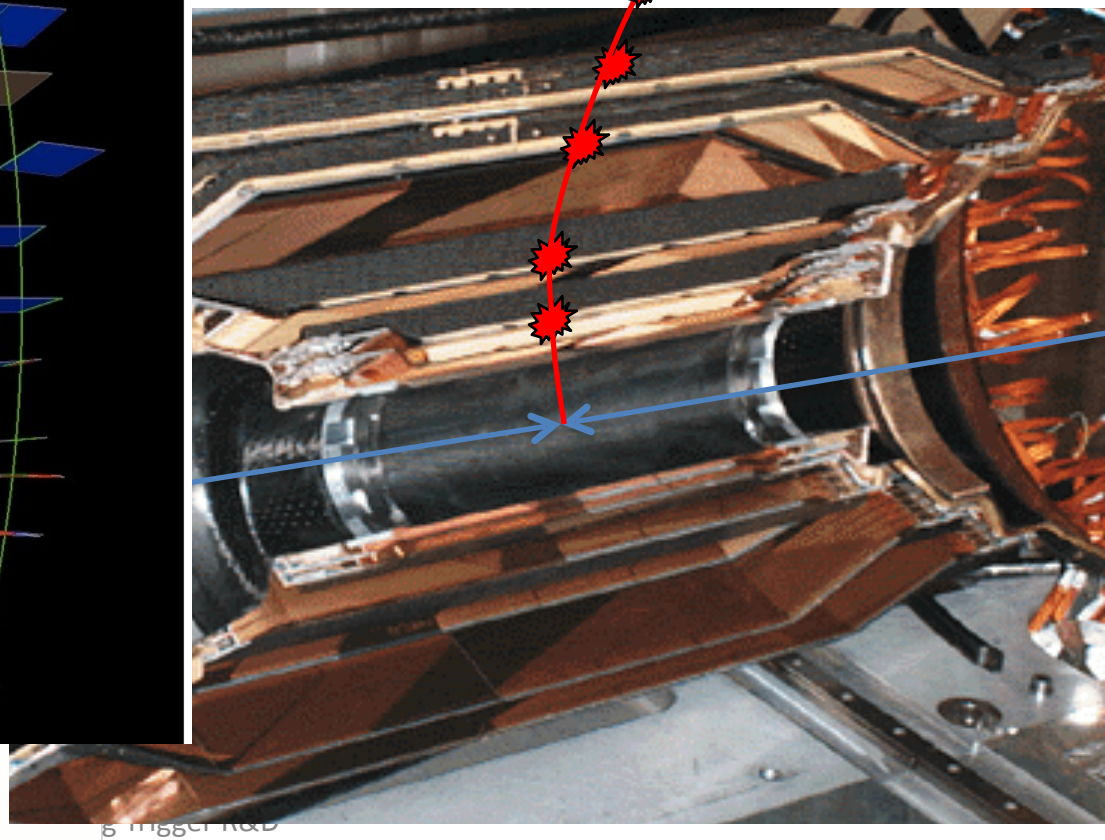
fired road





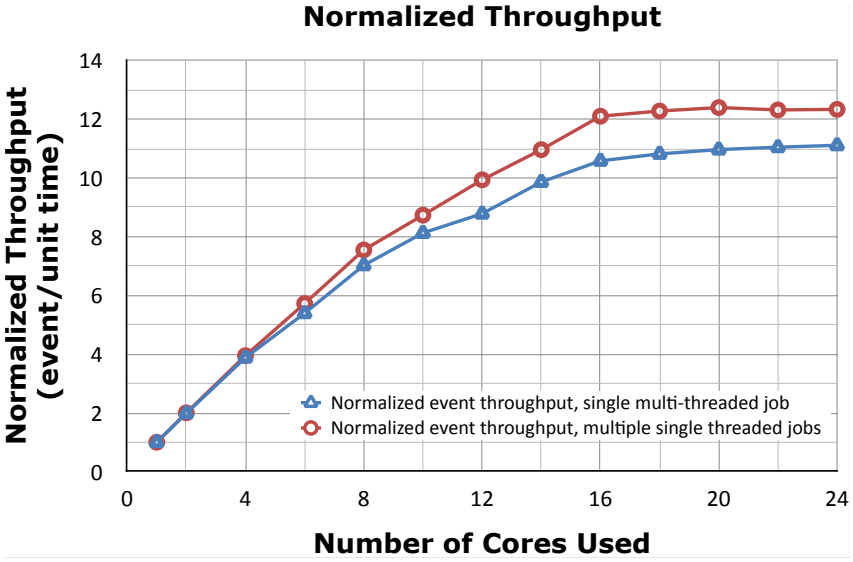
Pattern recognition for tracking is naturally a task in 3D

track

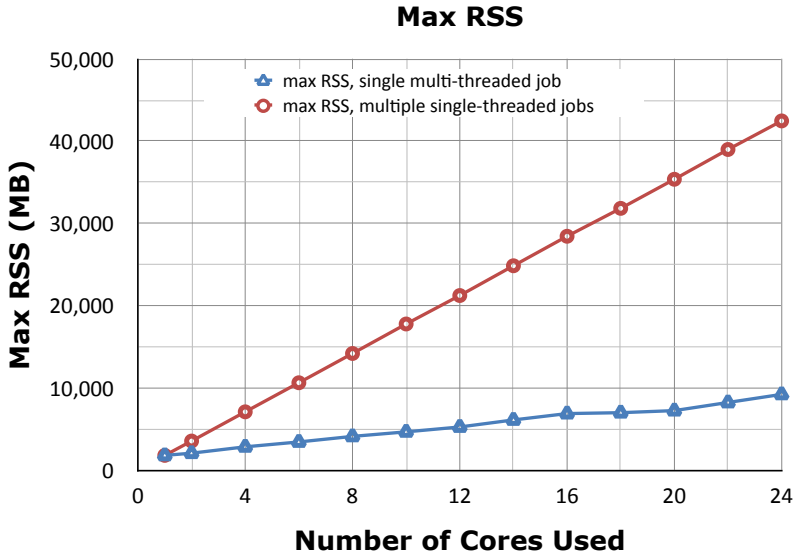


Software & Computing: Core Software

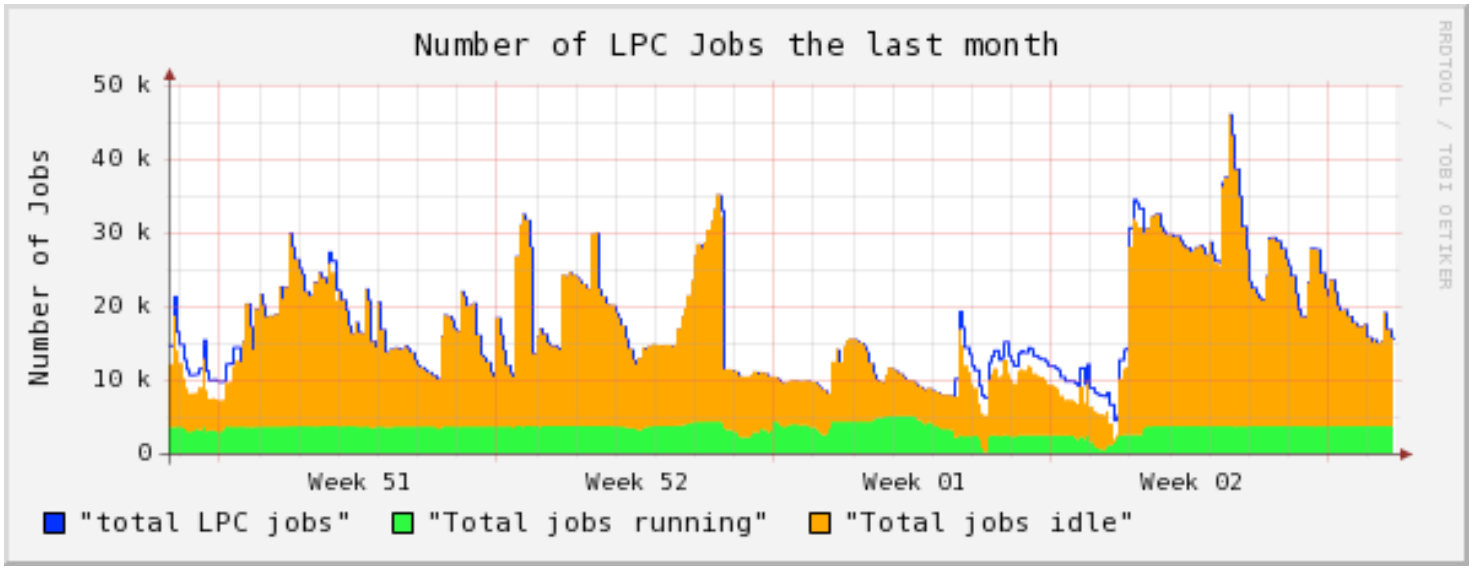
- FNAL is involved in all aspects of maintaining, evolving the software and computing infrastructure for Run 2 and beyond.
- Software framework is basis of all data and MC production, processing, and analysis.
- Fermilab software experts lead and are at the heart of the development team.
- Significant milestone reached in 2014 enabling the framework to run in multithreaded mode using several CPU cores concurrently to process multiple events simultaneously.



95% efficiency compared to single-threaded jobs at significant memory savings

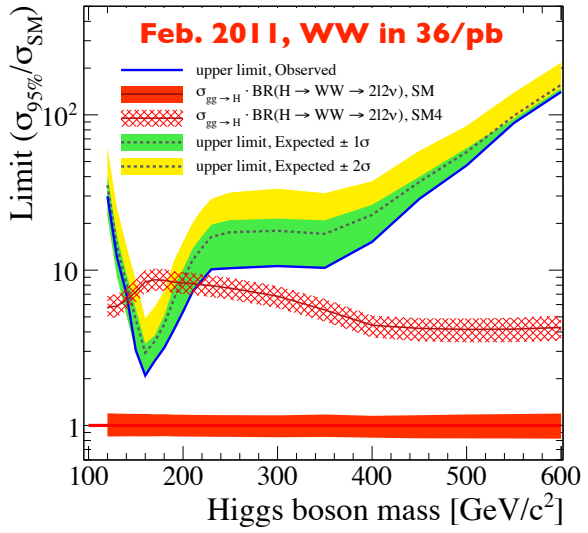


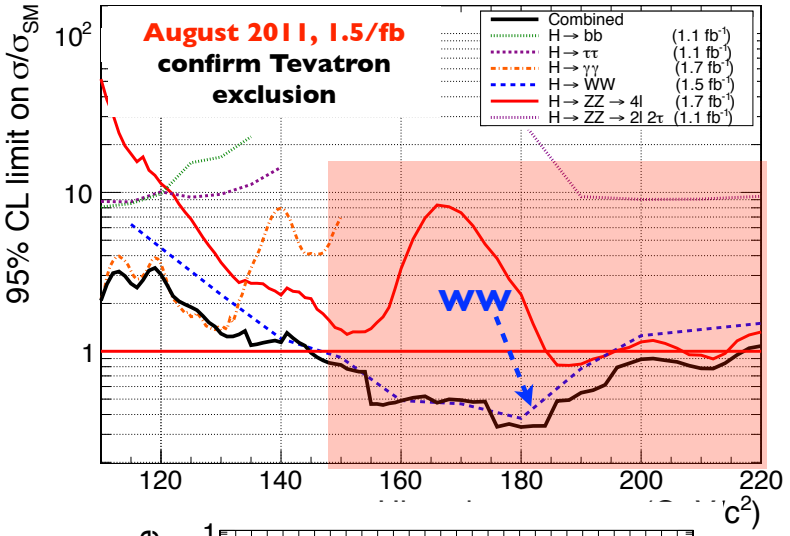
- CMS was the first HEP experiment to have a multi-threaded application
- Reconstruction enabled for multithreading, simulation and HLT trigger to follow soon
- Beyond LHC Run 2, extend parallelism to process a single event on multiple cores

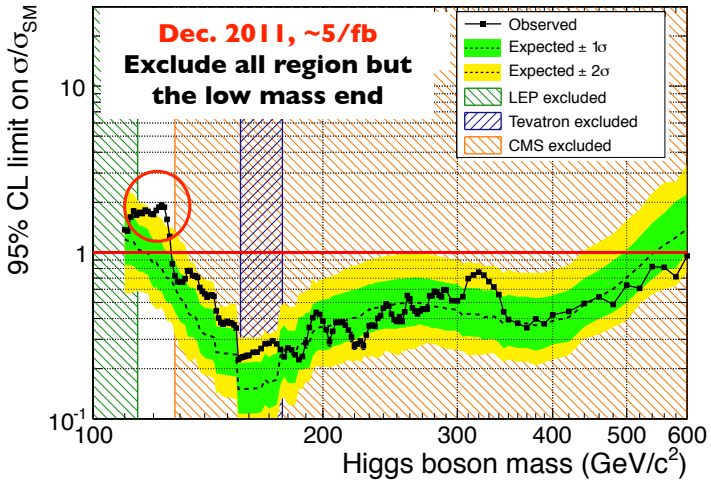


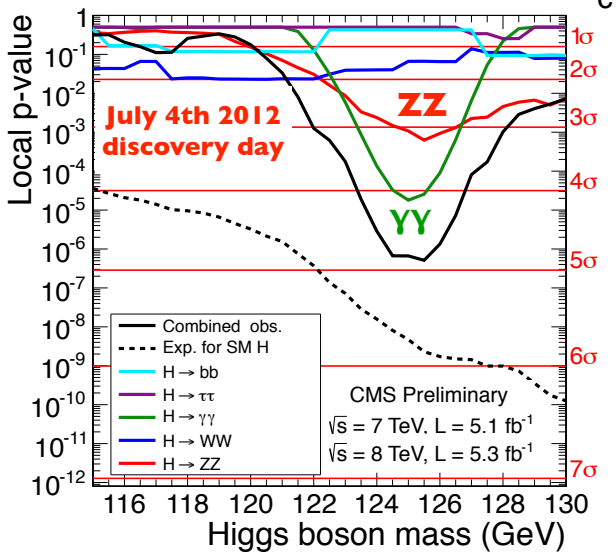
Occupancy of LPC farm this past month — preparing for the run (and CMSDAS likely) — idle jobs reaching the 30k-40k level and green running job slots completely full

Fermilab Contributions to H→WW→2l2v









10

Fermilab Contributions to H→WW→2l2ν

Following Higgs Discovery, analysis reoptimized to study spin/parity

Available on CMS information server

CMS AN -2012/453

The Compact Muon Solenoid Experiment

Analysis Note

The content of this note is intended for CMS internal use and distribution only

29 November 2012 (v4, 29 October 2013)

The Spin of a Single Produced Resonance in the Fully Leptonic W^+W^- Final State

L. Bauerdick, K. Burkett, I. Fisk, Y. Gao, O. Gutsche, B. Hooberman, S. Jindariani, J. Linacre, V. Martinez Outschoorn, S. Tkaczyk

Fermilab National Accelerator Laboratory, Batavia, USA

A. Apyan, G. Bauer, J. Bendavid, E. Butz, M. Chan, V. Dutta, G. Gómez-Ceballos, M. Goncharov, K. Hahn, P. Harris, M. Klute, A. Levin, S. Nahn, C. Paus, D. Ralph, F. Stoeckli, K. Sumorok, K. Sung, R. Wolf, S. Xie, M. Yang, M. Zanetti

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, USA

D. Barge, C. Campagnari, D. Kovalskyi, V. Krutelyov

University of California, Santa Barbara, Santa Barbara, USA

W. Andrews, G. Cerati, D. Evans, F. Golf, I. MacNeill, S. Padhi, Y. Tu, F. Würthwein, A. Yagil, J. Yoo

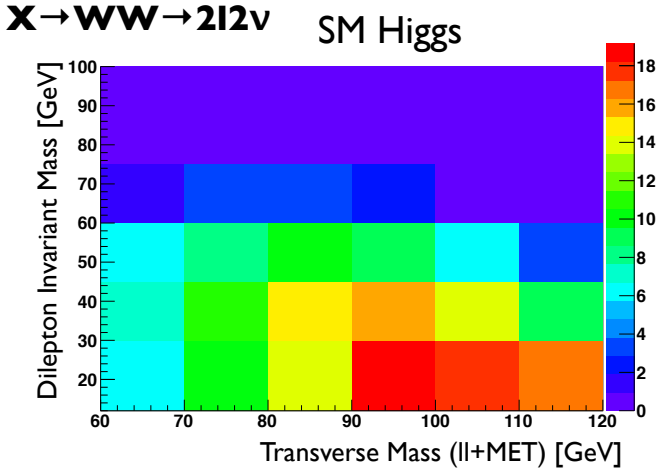
University of California, San Diego, San Diego, USA

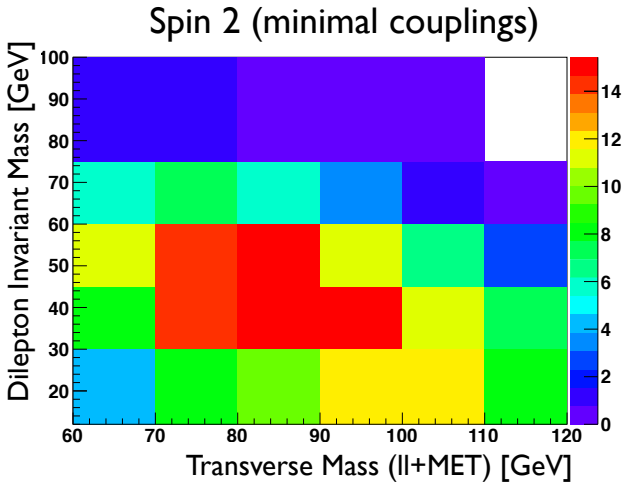
I. Kravchenko

University of Nebraska-Lincoln, USA

Abstract

This note describes a study of the spin and parity of a singly produced resonance in the $W^+W^- \to 2\ell 2\nu$ final state of pp collision data at $\sqrt{s} = 7$ TeV and 8 TeV. The study is based on the $e\mu$ final states with zero and one reconstructed jets.

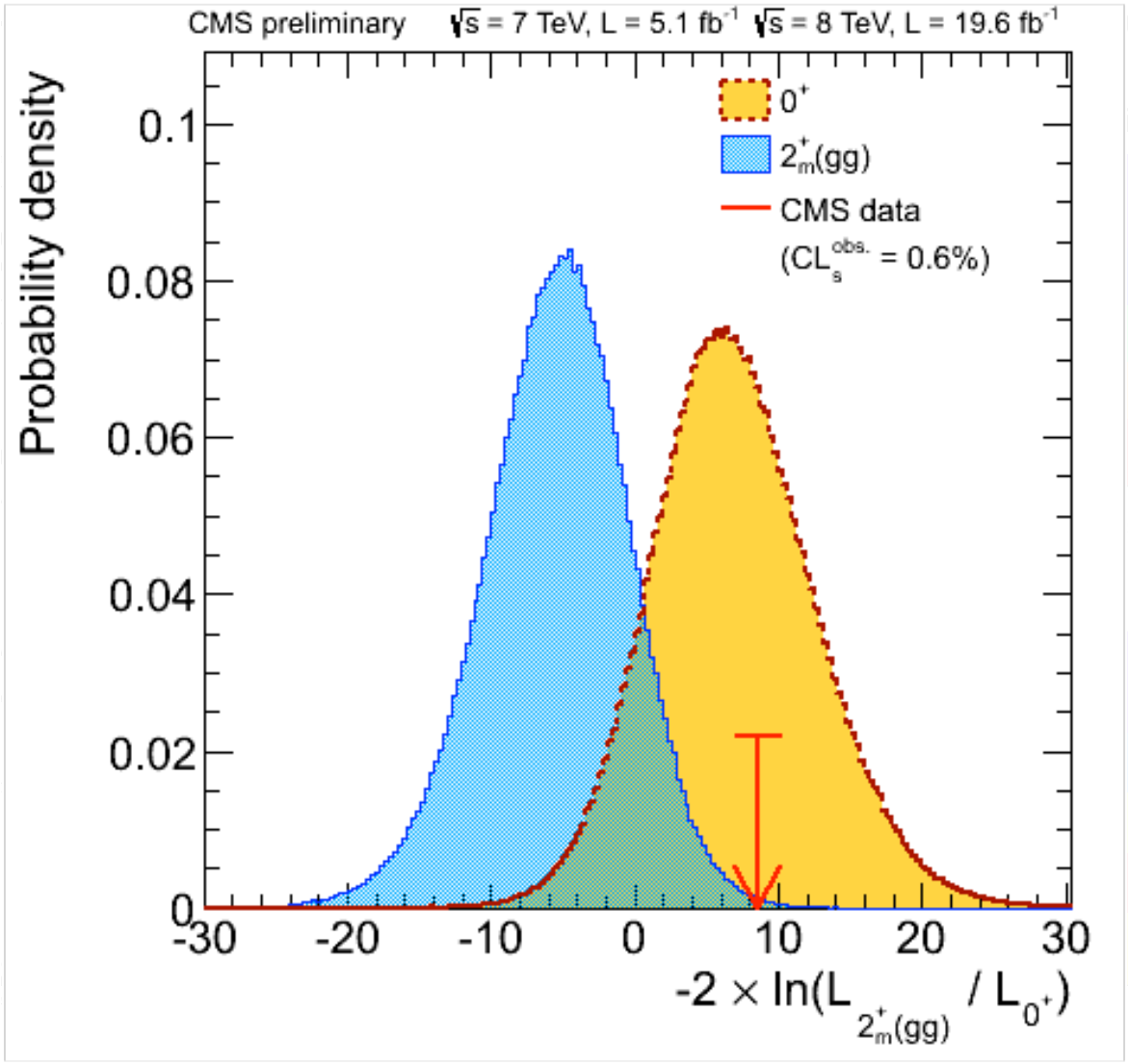


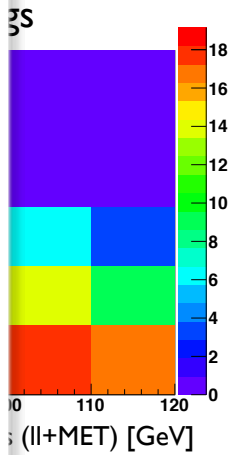


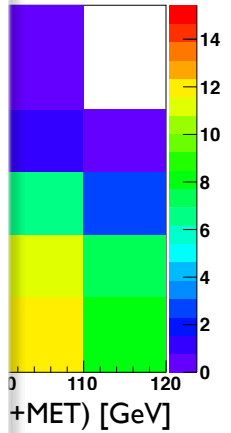
Fermilab Contributions to H→WW→2l2ν

Following

spin/parity





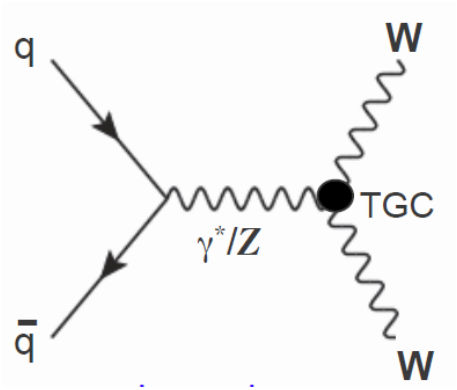


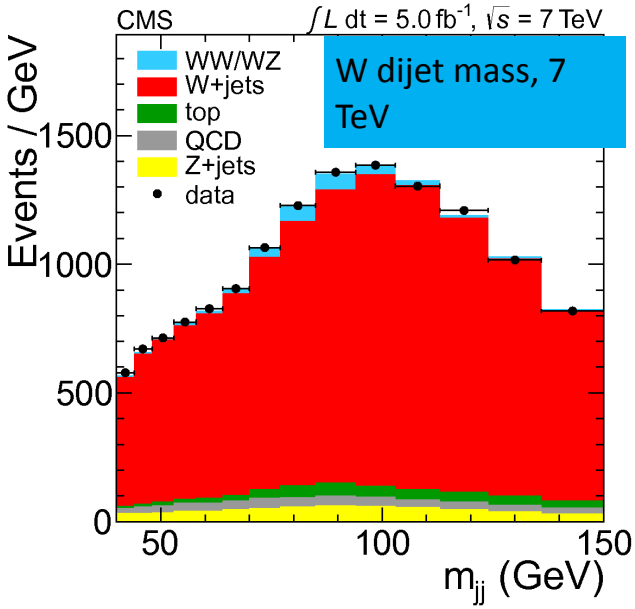
Fermilab

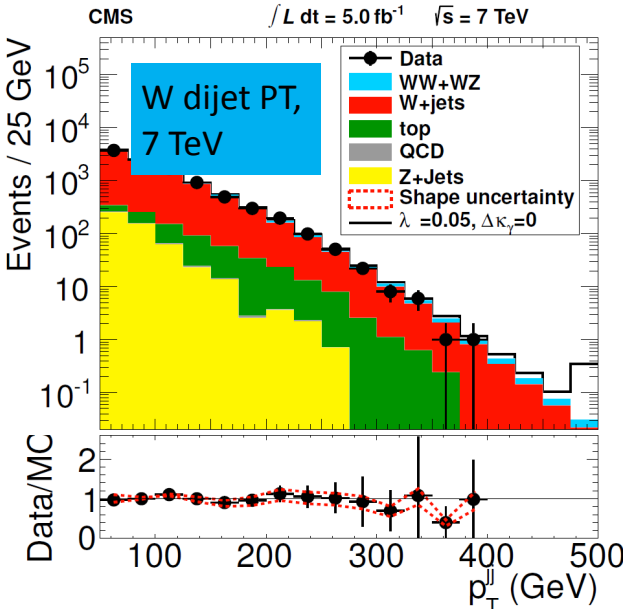
WW/WZ in the semileptonic channel

EPJC 73 (2013) 2283
K. Mishra, J. Anderson
N. Tran, J. Berryhill, F. Yang

- High branching fraction and good S/B at high PT make this an attractive mode to search for **anomalous triple gauge couplings**
- Select W+ 2 jet events and **reconstruct W or Z hadronically**
- **4.3** σ significant signal observed, **first such evidence at LHC**





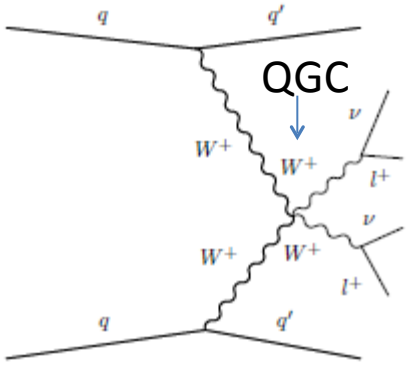


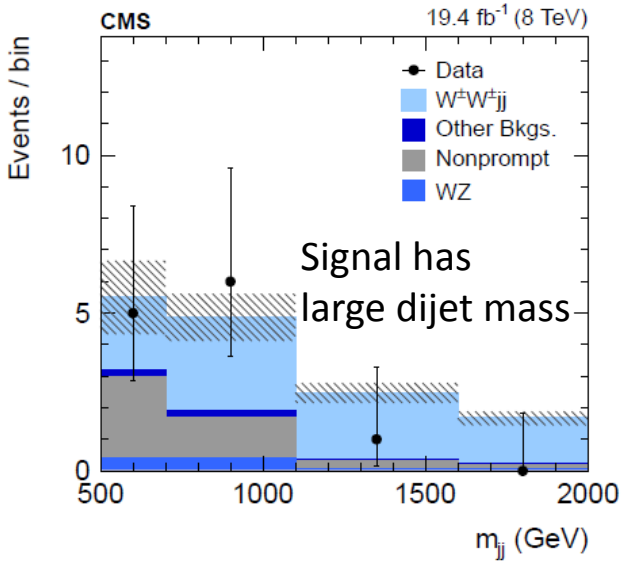
- **Cross section 69** $\pm 14\ pb$ consistent with SM (66 pb)
- Dijet PT distribution is single most powerful experimental constraint on TGCs to date

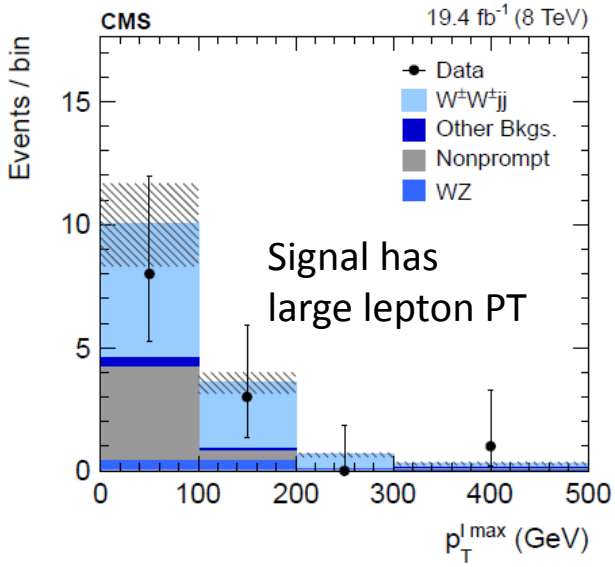
Same-sign $W^{\pm}W^{\pm}$ scattering

PRL 114 (2015) 051801
R. De Sa, S. Jindariani

- SM electroweak symmetry breaking with Higgs essential to preserve **vector boson scattering (VBS) cross section unitarity**
- **Same-sign WW vector boson scattering** production provides attractive S/B at LHC
- Anomalous differential cross sections would indicate **extended Higgs sector** (e.g. George-Machacek H++)**, new particles,** or **(giant) anomalous QGCs**







- **2.0 σ significant signal for VBS** (3.1 σ expected); first VBS search at CMS!
- First step in a comprehensive, long term LHC program to study vector boson scattering