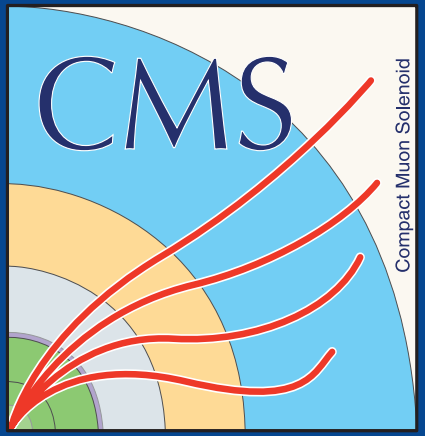
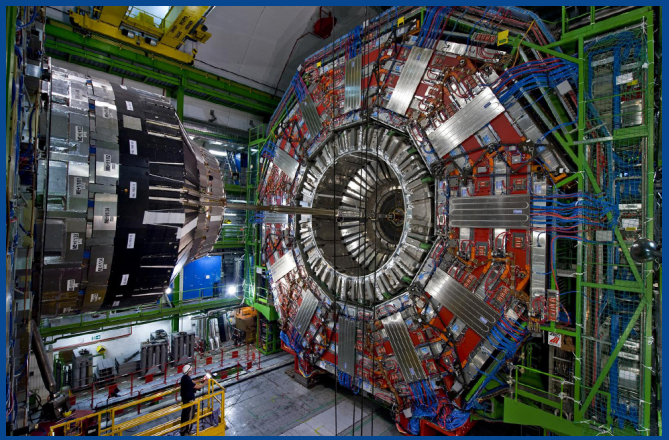
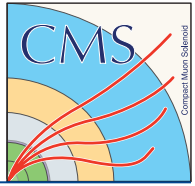
Fermilab in CMS, Opportunities for the Next Decade



Talk Presented to
Fermilab Program
Advisory Committee
Joel Butler
Nov. 16, 2017



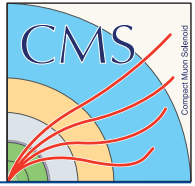
Outline



- Introduction and CERN plan
- LHC Run2 Physics results so far
- How will we accomplish all this
- CMS HL-LHC upgrades
- Summary and outlook

Introduction

Opportunities/Challenges through 2023

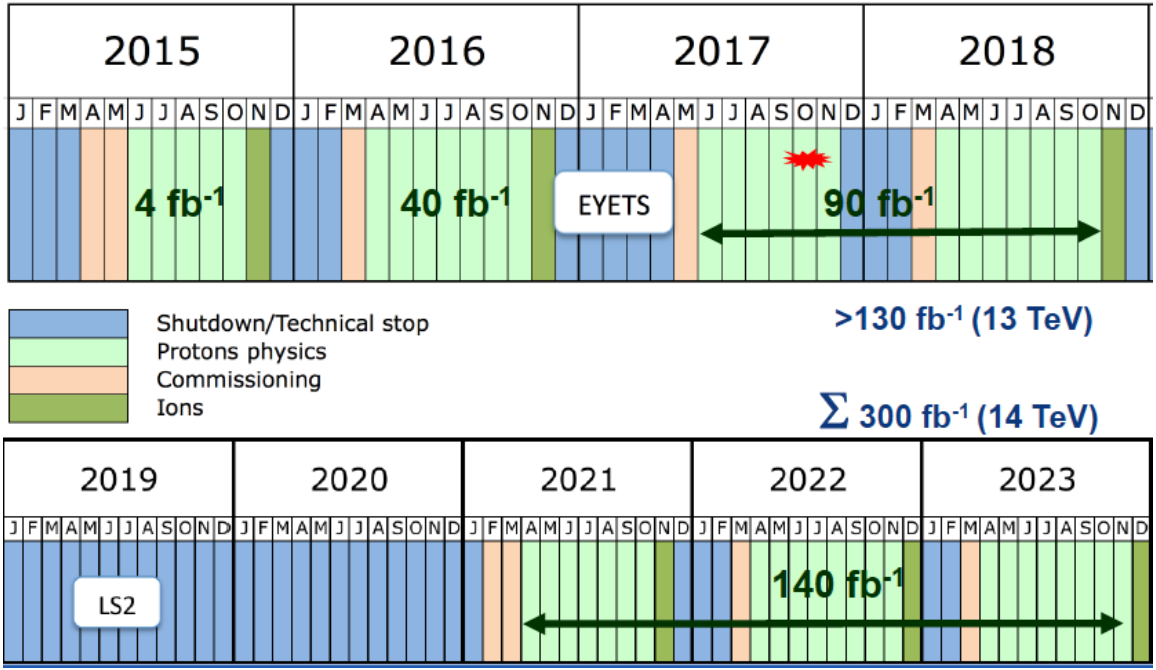


- Produce extensive physics results on the full, larger than expected, 2016 and 2017 data set
- Do FOUR Phase 2 Upgrade TDRs (Tracker, Barrel Calorimeter, Muon detectors, Endcap Calorimeter) and TWO Interim design documents (Trigger, DAQ/HLT)
- Take high quality data in 2017 and 2018 **with rising luminosity** and analyze it quickly and efficiently
- Build and install the remainder of Phase I Upgrade in 2019 and 2020
- Run until the end of 2023

We are now well along in this program, have generally met the challenges with some bumps, and look forward to the opportunities presented by an amazing harvest of data

The Plan for Collisions through 2023

Run 2 and Run 3

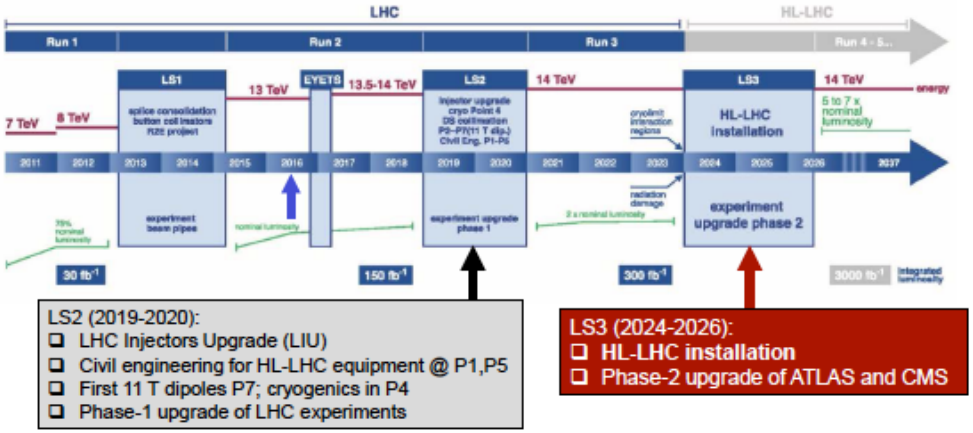


The Plan for the Luminosity Evolution of the LHC through 2040

LHC and HL-LHC

- LHC
  - 300 fb^{-1} by 2023
    - 30 fb^{-1} Run 1
    - ~40 fb^{-1}(2015/16)
    - …
- HL-LHC
  - ~3000 fb^{-1} by ~2035
  - levelled luminosity

The stretch goal is 4000 fb^{-1}.

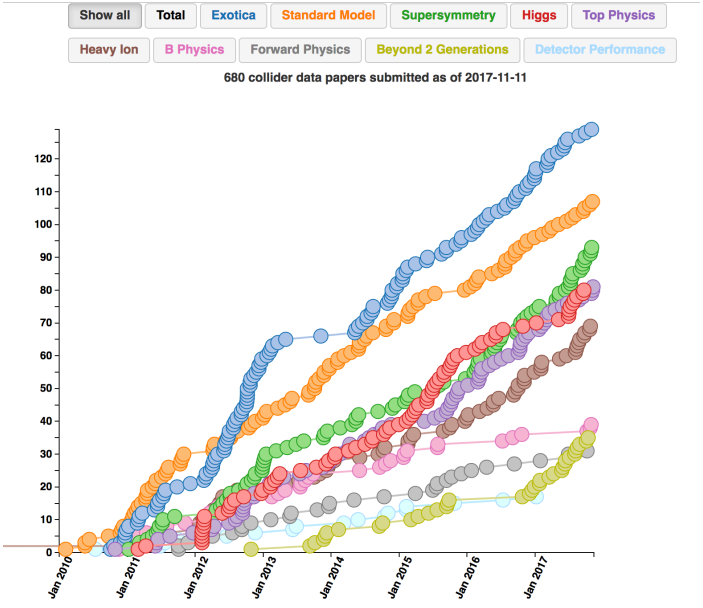


But to achieve this, the CMS detector must be upgraded to cope with the high collision rate, pileup, and radiation levels of the HL-LHC

Run 2 Physics Results

Publication Status

680 physics papers submitted
- ~20 ready for submission
- Many approaching approval

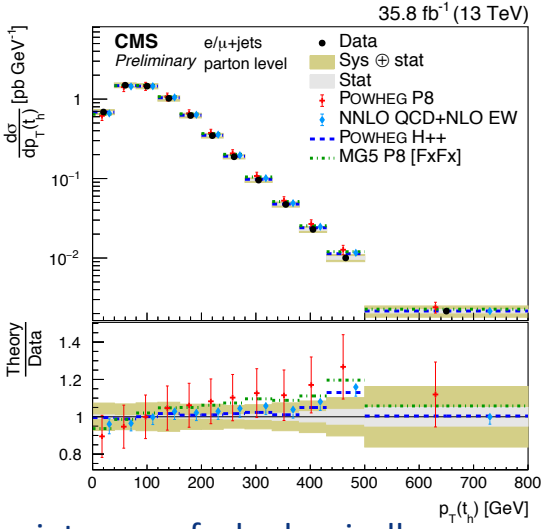


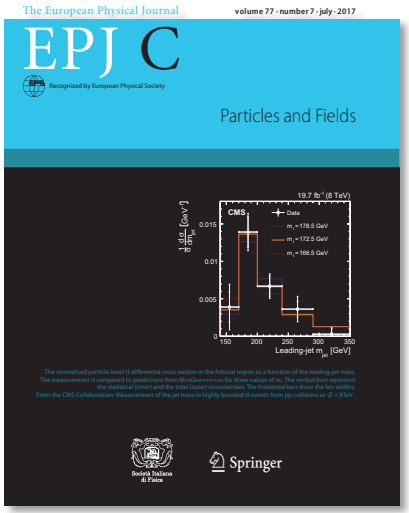
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

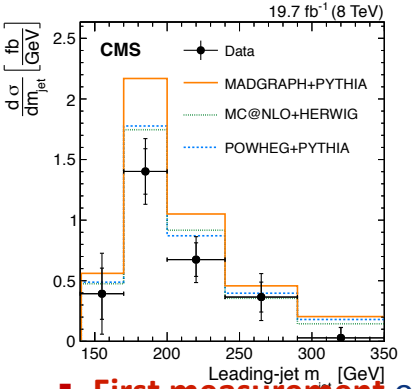
Top quark production

- Recent example from the rich harvesting of top-quark events
- Precise measurements of differential cross sections, as functions of many kinematic observables
- Comparisons to modern MC generators

CMS-PAS-TOP-17-00

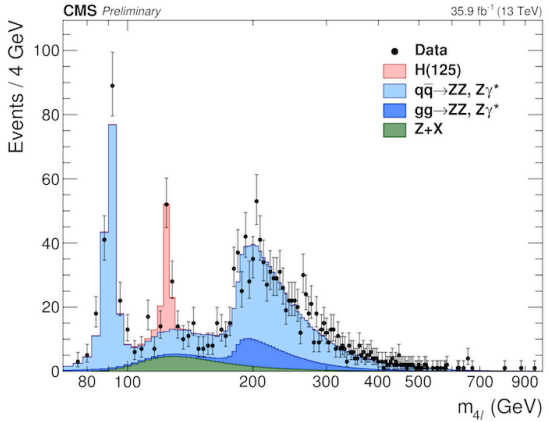






- **First measurement** of the jet mass of a hadronically decaying top quark in boosted regime (p_T > 400 GeV) !
  - Sensitivity to top quark mass
- Results consistently show **softer top production** than predicted by MC generators

Higgs Properties from ZZ* (4 leptons) and γγ



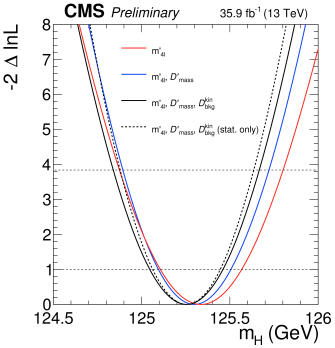
ATLAS, CMS Run 1 Combined:

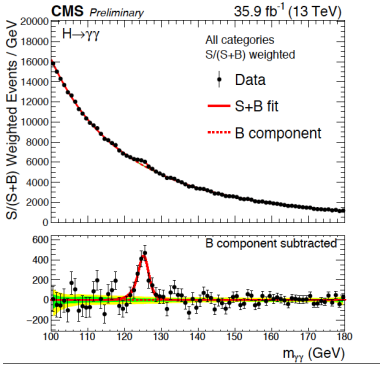
$M_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\ GeV$

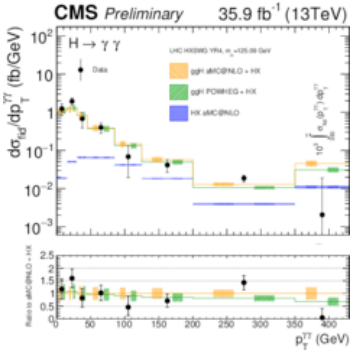
CMS 2016, 4 lepton:

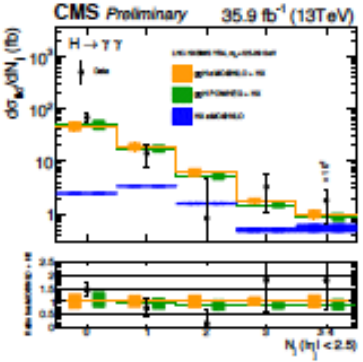
$M_H = 125.26 \pm 0.20(stat) \pm 0.08(syst)\ GeV$

HIG-16-041, Submitted to JHEP

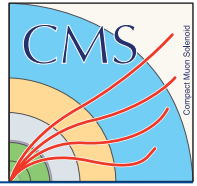








Observation of H → $\tau^+\tau^-$



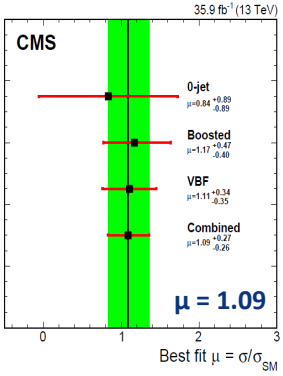
arXiv:1708.00373

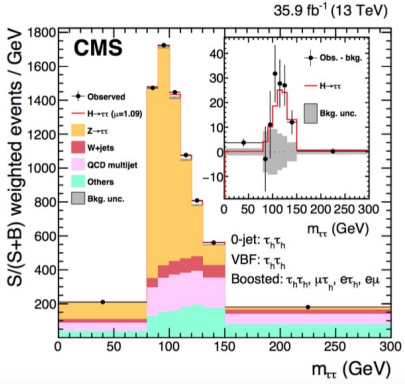
- Branching ratio = 6.3%, best channel to establish coupling of Higgs boson to fermions
- Final states: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$ → Significance of 4.9σ observed (4.7σ expected) using 13 TeV data
- Combination with 7 and 8 TeV data: **5.9σ obs. (5.9σ exp.)** and **μ = 0.98 $\pm$ 0.18**

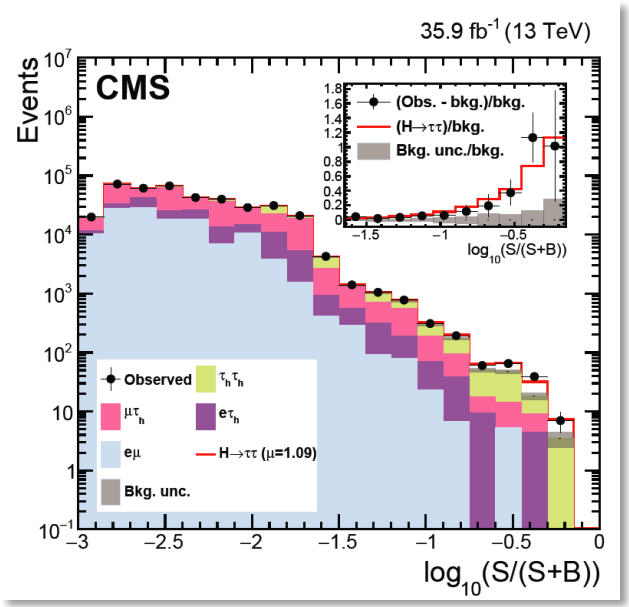
First direct observation by a single experiment of H coupling to fermions!

- Observed before in CMS+ATLAS combination

First direct observation of H coupling to leptons and to fermions of the 3rd generation!

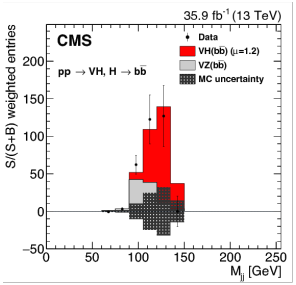


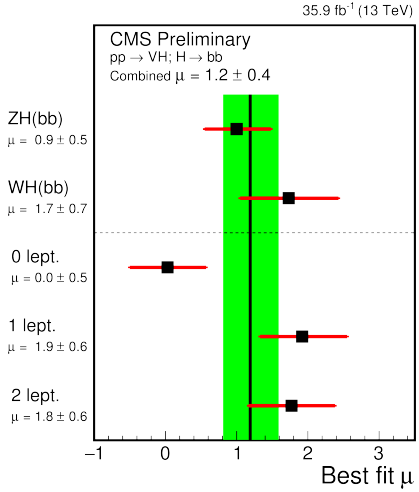


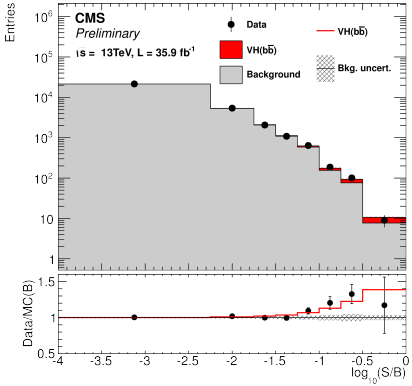


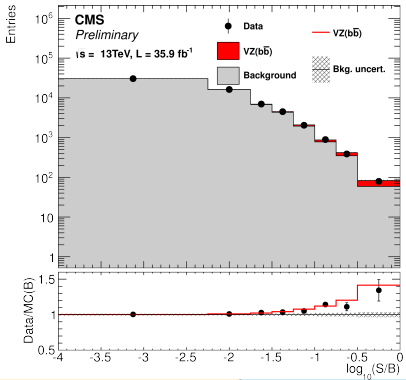
Evidence for Higgs →VH(bb)

- Br of Higgs to bb ~58%(expected)
  - Huge QCD backgrounds
- Most sensitive channel is associated production with W or Z, H→bb
  - 0L: Z(νν)
  - 1L: W(μ ν) W(e ν),
  - 2L : Z(μ μ), Z(ee)
- Mass resolution of M_{bb} is ~10%
- Based in several BDTs **Validated using di-boson production VZ(bb)**







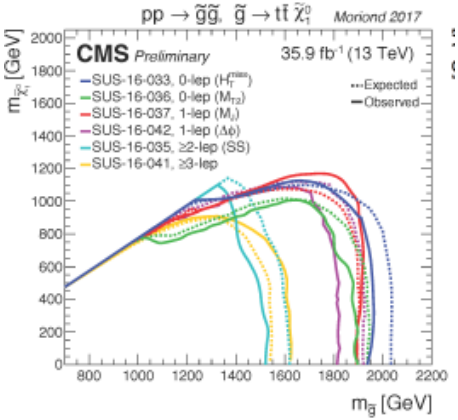


SUSY Searches

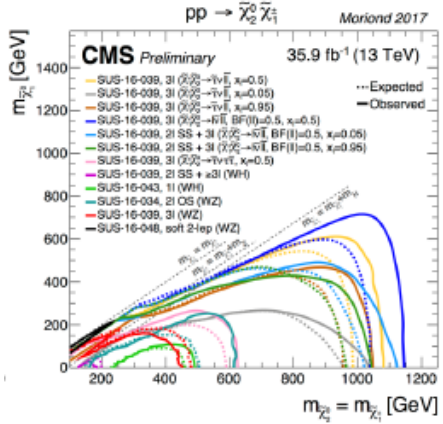
Broad program: 19 searches completed with full 2016 CMS dataset, with several already submitted to journals

- Probing different models (inclusive production, strong and electroweak production, and 3rd generation sparticles (stops)
- Different final states (with leptons, photons, jets) and analysis techniques
- Sergo's talk will describe US and FNAL efforts in some detail

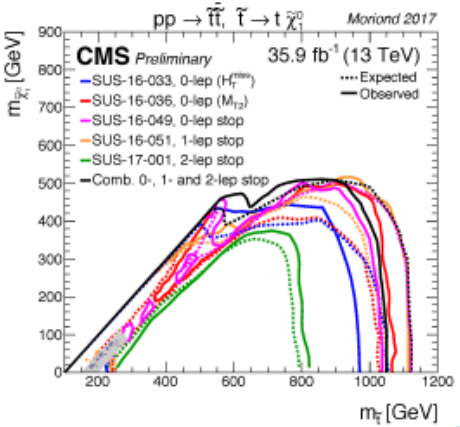
gluinos (inclusive)



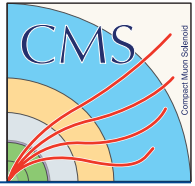
electroweakinos



stops (3rd gen)



Why are we so enthusiastic to continue?



- The Higgs was discovered more than 5 years ago but the SM model still does not explain many of the phenomena of our physical universe
- There are still very strong reasons some of the missing pieces should appear at the TeV scale, accessible at the LHC
- We have two basic tools for exploring this large, as yet largely uncharted territory
  - Looking for deviations from the precise predictions of the SM
  - Searching directly for new particles
- Both strategies require more statistics, for which CERN has a plan

Who will accomplish all this?

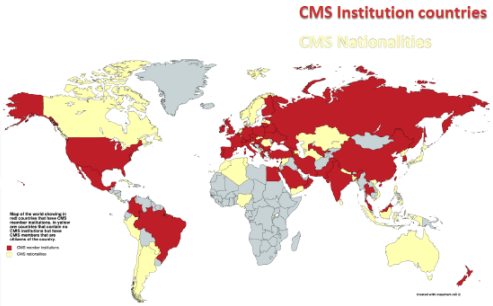
The CMS collaboration

Excellent performance of the CMS Detector is due to the ingenuity, expertise and hard work of the CMS collaboration

Collaboration of institutes

47 countries	207 institutes
1850 PhD physicists	928 PhD students
1021 undergrads	930 engineers

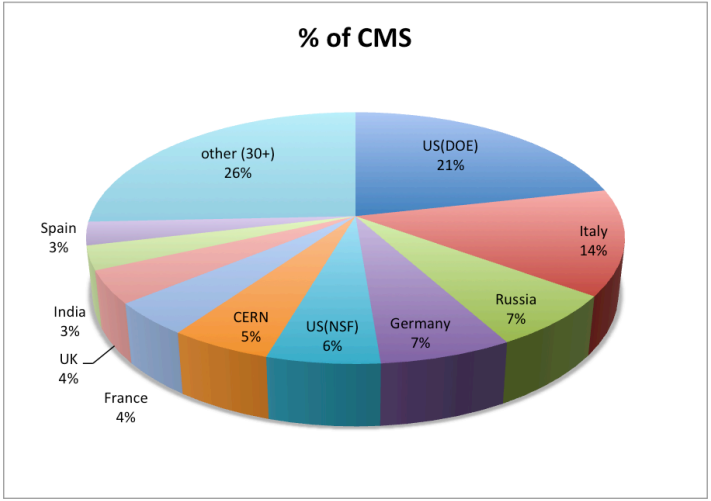
(~ 81% male, ~ 19% female)



https://cms-users.web.cern.ch/cms-users/cms/Management/Stats/stats.html

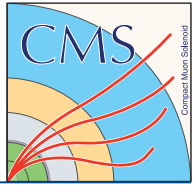
The US in CMS

- The US is by far the biggest nation in CMS
  - DOE and NSF HEP taken together are 27.26%
  - DOE NP adds 1.93%
- The US also has infrastructure and experience that give it even greater weight
- There is no way that CMS could continue as is if the US were to significantly reduce its level of activity



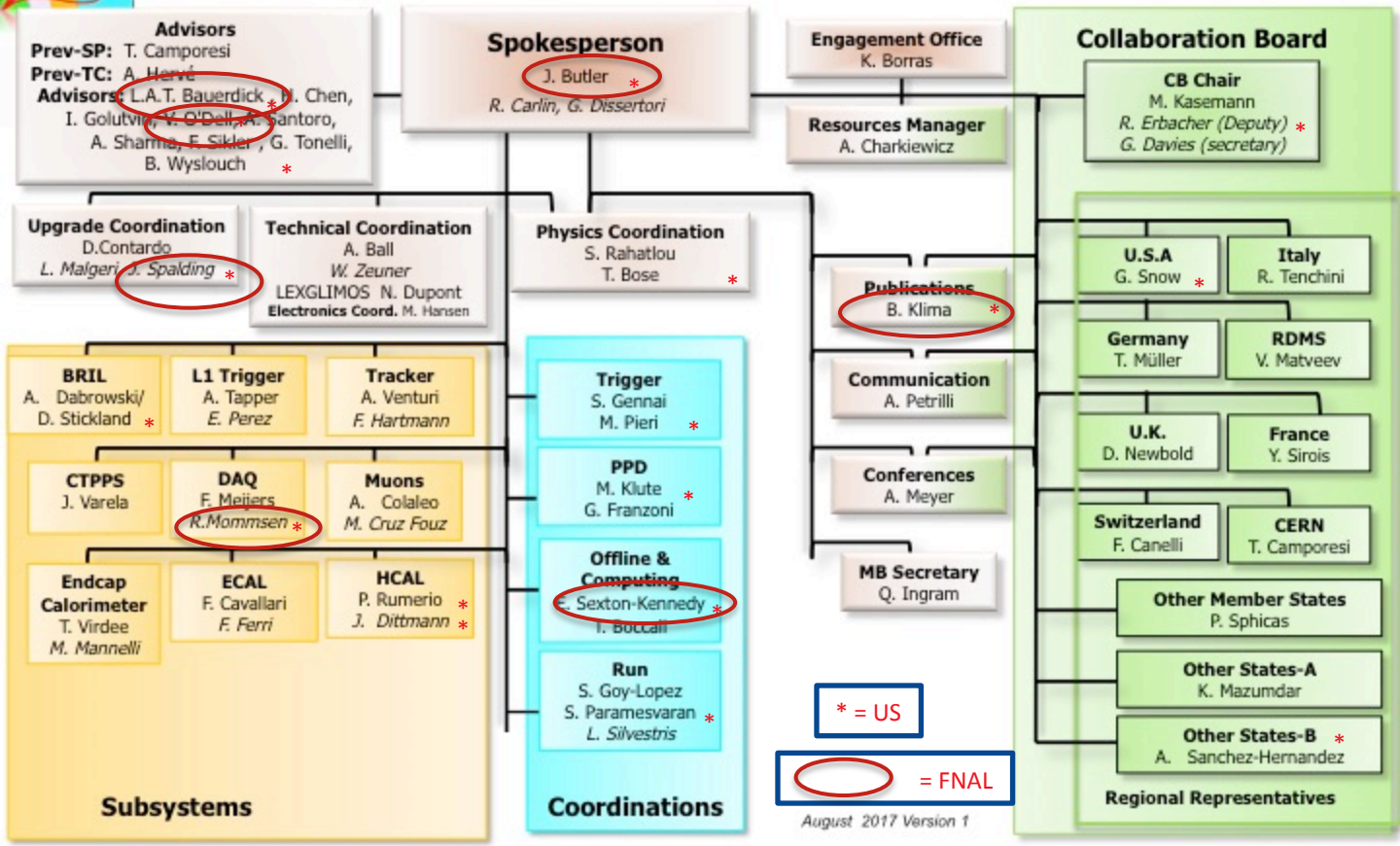
DOE and NSF are separated. NSF is the 5th biggest collaborator, bigger than CERN, France, UK, and Spain.

Fermilab in CMS

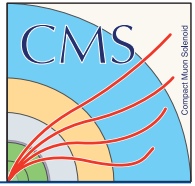


- Fermilab is just about 5% of CMS
- If considered as a "nation", it would be the 7th biggest in CMS
  - Bigger than France, UK, and Spain, large CERN member states
- With its excellent technical and engineering base, it makes contributions that go even beyond these raw numbers

CMS Management Board-Sept. 1, 2017

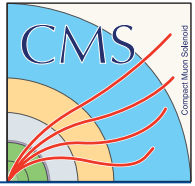


Fermilab Experience and Infrastructure



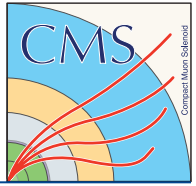
- Technical Facilities and Engineering
  - SiDet (Silicon Detector Facility)
  - Thin Film and Scintillator Extrusion Facility
  - Test Beam Facility
  - Electrical/Mechanical Engineering (ASIC engineering)
- Computing
  - Fermilab hosts the U.S. Tier-1 Center for CMS
  - the LPCCAF
  - Fermilab is home to many of the CMS software and computing experts
- Project Management Expertise and tools
- Expertise in Systems Integration
- LHC Physics Center (location: Wilson Hall 10/11)
- Remote Operations Center (location: Wilson Hall Atrium)
- Fermilab Theory Group
- Detector R&D program
- Conference/workshop support
- Communications/Outreach support

Fermilab's contributions to the CMS detector



- Construction Project: Major contributions to
  - Hadron calorimetry
  - Cathode Strip chambers for forward muons
  - Tracker Outer Barrel (TOB)
  - Forward Pixel Detector
- Phase I Upgrade
  - Forward Pixel Detector
  - Cathode Planes for Cathode Strip chambers
  - Electronics for Hadron Calorimeter
  - Stage 1 of the Calorimeter Trigger

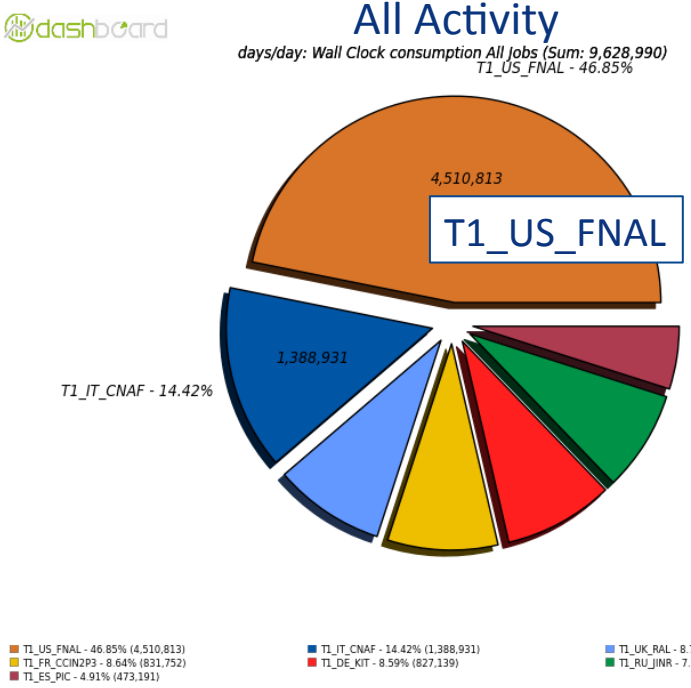
CMS Computing and Fermilab

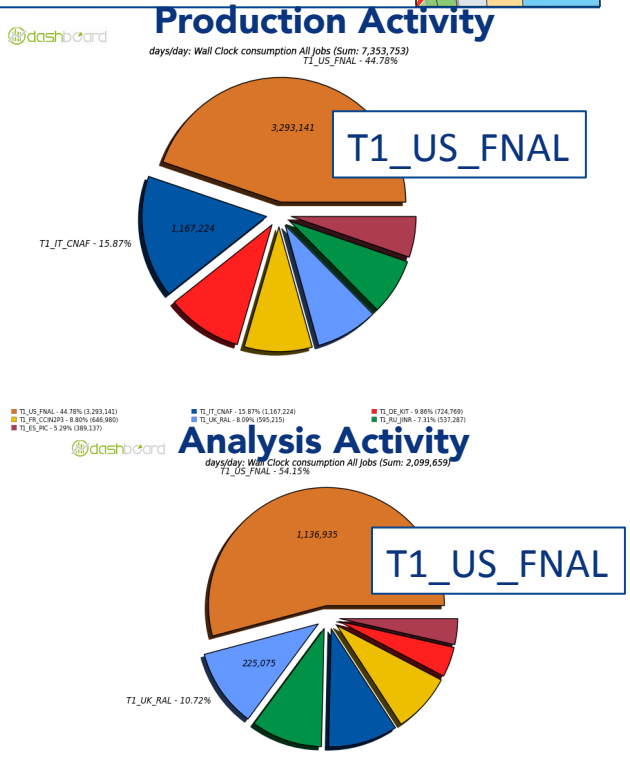


- CMS physics requires large production and processing to handle all the data and to react to changes in data taking conditions and new developments
  - Billions of MC events, fast turn-around data re-reconstruction passes
- Sufficient resources for CMS are only available through complicated and diverse computing infrastructure with more than 70 sites
  - Fermilab is the biggest Tier-1 site, the biggest resource outside CERN, and a beacon of stability
- Elasticity is and will be a key ingredient to success
  - Using elastically commercial clouds, supercomputing centers and OSG will be important for the future
  - HEPCloud will enable us to give CMS new capabilities and possibilities
- New software methodologies will help on many levels
  - Machine learning could revolutionize object reconstruction, physics analysis, data quality monitoring, control systems

FNAL is a leader here too

T1 level: cpu consumption since 07/01/2017

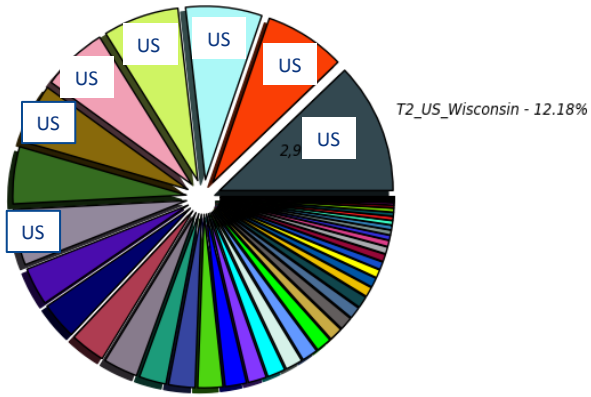




T2 level: cpu consumption since 07/01/2017

All Activity

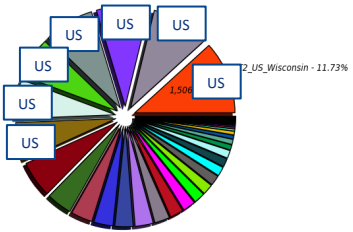
days/day: Wall Clock consumption All Jobs (Sum: 24,381,441)



T2_US_Wisconsin - 12.18% (2,970,160)
T2_US_Purdue - 7.07% (1,724,222)
T2_DE_DESY - 5.31% (1,294,491)
T2_DE_RWTH - 3.44% (838,334)
T2_IT_Pisa - 2.51% (612,824)
T2_ES_CIEMAT - 1.98% (483,038)
T2_UK_London_Brunel - 1.60% (390,080)
T2_FR_IPHC - 1.25% (303,549)
T2_FR_GRIF_LLR - 1.09% (264,656)
T2_ES_IFCA - 0.75% (182,946)
T2_US_Nebraska - 7.54% (1,837,643)
T2_US_UCSD - 6.11% (1,490,420)
T2_US_Caltech - 5.20% (1,267,058)
T2_BE_IIHE - 3.26% (794,835)
T2_IT_Bari - 2.46% (599,901)
T2_UK_SGrid_RALPP - 1.70% (414,848)
T2_CH_CSCS - 1.48% (360,694)
T2_EE_Estonia - 1.22% (296,378)
T2_BE_UCL - 0.91% (222,394)
T2_RU_JINR - 0.71% (172,255)
T2_US_MIT - 7.11% (1,733,233)
T2_US_Florida - 5.50% (1,340,238)
T2_US_Vanderbilt - 3.52% (857,930)
T2_IT_Legnaro - 3.20% (780,896)
T2_UK_London_IC - 2.32% (566,497)
T2_FR_GRIF_IRFU - 1.67% (406,025)
T2_FR_CCIN2P3 - 1.43% (349,819)
T2_IT_Rome - 1.10% (268,577)
T2_BR_SPRACE - 0.87% (212,875)
plus 23 more

Production Activity

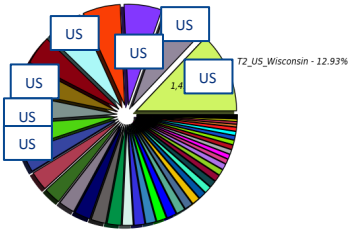
days/day: Wall Clock consumption All Jobs (Sum: 12,843,049)



T2_US_Wisconsin - 11.73% (1,506,932)
T2_US_MIT - 8.13% (1,044,102)
T2_US_UCSD - 6.13% (787,631)
T2_BE_IIHE - 3.48% (446,311)
T2_UK_London_IC - 2.94% (377,421)
T2_FR_CCIN2P3 - 2.04% (262,349)
T2_ES_CIEMAT - 1.62% (207,923)
T2_US_Vanderbilt - 1.26% (161,516)
T2_BR_SPRACE - 0.61% (77,966)
T2_US_Purdue - 9.46% (1,214,460)
T2_US_Florida - 6.55% (840,702)
T2_DE_DESY - 5.91% (758,444)
T2_IT_Bari - 3.10% (397,911)
T2_IT_Pisa - 2.44% (313,499)
T2_FR_GRIF_IRFU - 1.77% (226,922)
T2_FR_GRIF_LLR - 1.48% (189,510)
T2_CH_CSCS - 0.84% (108,158)
T2_BE_UCL - 0.57% (72,747)
T2_US_Nebraska - 8.46% (1,087,101)
T2_US_Caltech - 6.28% (806,287)
T2_DE_RWTH - 4.09% (525,812)
T2_IT_Legnaro - 2.94% (378,124)
T2_UK_London_Brunel - 2.16% (277,861)
T2_UK_SGrid_RALPP - 1.70% (217,804)
T2_FR_IPHC - 1.37% (175,601)
T2_IT_Rome - 0.81% (103,692)
T2_RU_JINR - 0.33% (42,887)

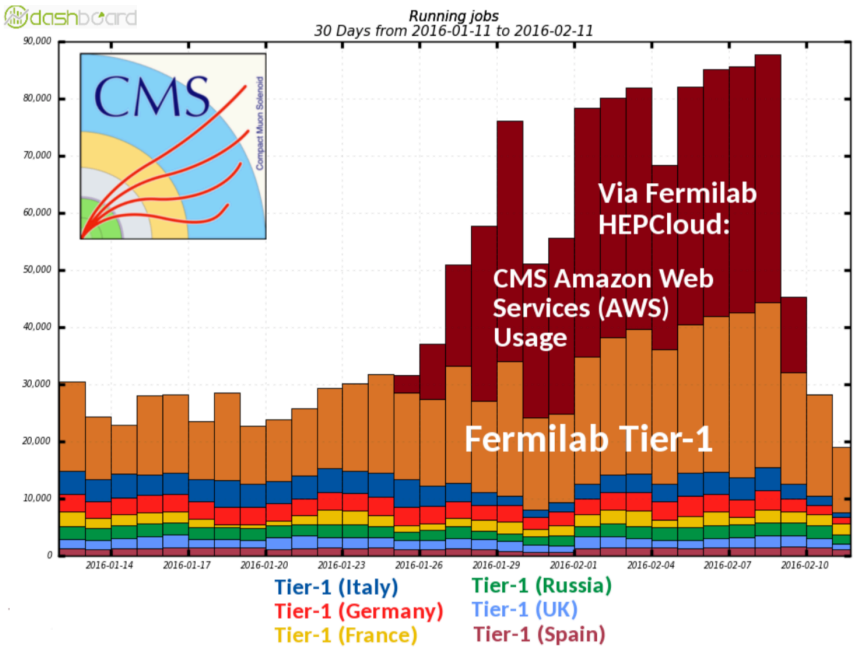
Analysis Activity

days/day: Wall Clock consumption All Jobs (Sum: 10,979,786)



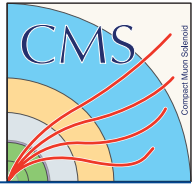
T2_US_Wisconsin - 12.93% (1,419,938)
T2_US_Vanderbilt - 6.06% (665,531)
T2_US_Purdue - 4.39% (482,182)
T2_IT_Legnaro - 3.55% (389,768)
T2_IT_Pisa - 2.60% (285,317)
T2_CH_CSCS - 2.25% (247,324)
T2_UK_London_IC - 1.63% (178,663)
T2_IT_Rome - 1.39% (152,368)
T2_BR_SPRACE - 1.16% (127,868)
T2_US_Nebraska - 6.67% (732,631)
T2_US_UCSD - 5.97% (655,714)
T2_US_Florida - 4.33% (475,239)
T2_BE_IIHE - 3.09% (339,745)
T2_EE_Estonia - 2.56% (280,743)
T2_UK_SGrid_RALPP - 1.72% (188,934)
T2_FR_GRIF_IRFU - 1.58% (172,936)
T2_KR_KNU - 1.32% (144,807)
T2_RU_JINR - 1.11% (121,670)
T2_US_MIT - 6.10% (669,911)
T2_DE_DESY - 4.65% (510,312)
T2_US_Caltech - 4.02% (441,450)
T2_DE_RWTH - 2.71% (297,488)
T2_ES_CIEMAT - 2.36% (259,228)
T2_IT_Bari - 1.70% (186,946)
T2_ES_IFCA - 1.54% (168,868)
T2_BE_UCL - 1.27% (139,419)
T2_FR_IPHC - 1.09% (119,521)

Fermilab HEPCloud AWS test compared to global CMS Tier-1



Additional efforts include other HPCs, e.g. NERSC

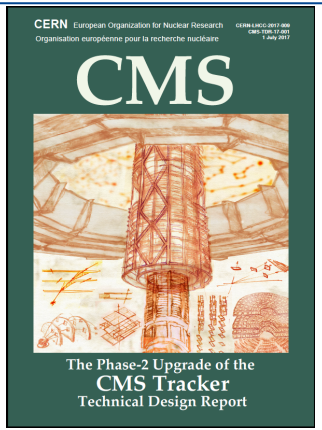
Analysis Impact

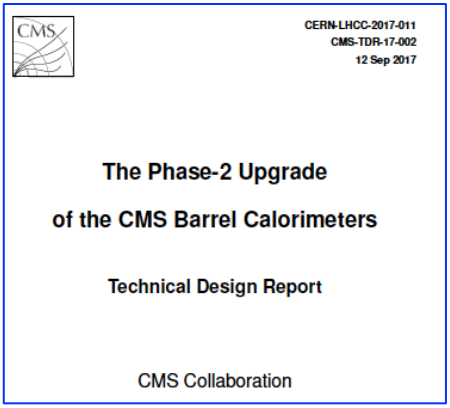


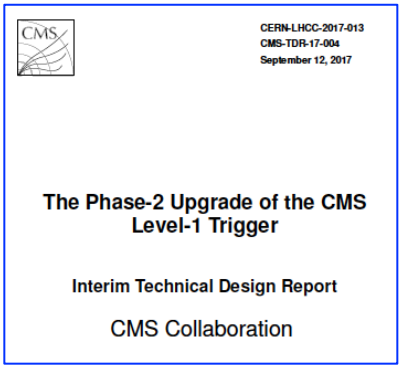
- The LPC is a key contributor to many aspects of CMS, especially data analysis
- A critical mass of expertise for physics objects, methods, software advice and training
  - CMSDAS created at LPC and widely emulated in CMS
  - Many seminars, tutorials, chats, and informal communication
- Excellent computing facilities and proximity to data at the LPC/CAF have benefitted many US and LPC analysis efforts and their collaborators
- Actual physics analysis work of LPC will be described in a later talk

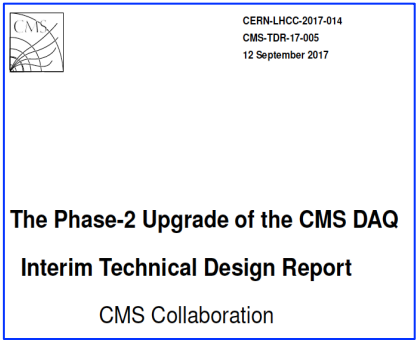
CMS HL-LHC upgrades

HL-LHC TDRs and ITDRs submitted so far



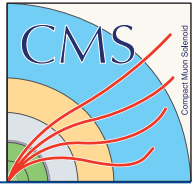






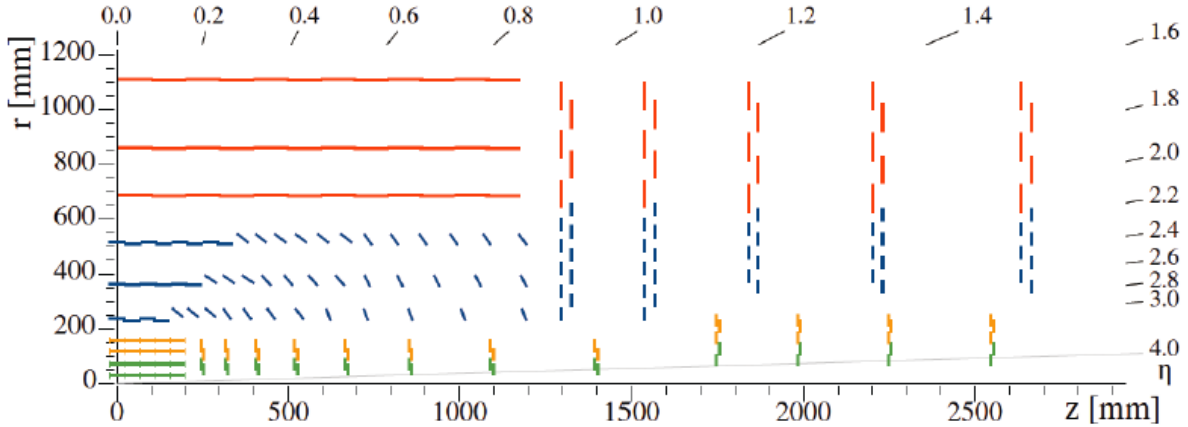
Endcap Calorimeter TDR and MIP Timing Detector Technical Proposal will be submitted to the LHCC at the end of November.

An Exciting and Robust Solution to the HL-LHC Challenge



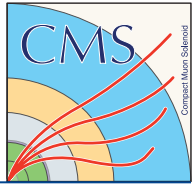
- We have to be prepared to run at pileup of 200 or more
  - LHC may produce luminosity with more pileup(fewer bunches) than advertised, as in 2011, 2012, and 2017, to address machine issues
- Three elements will allow CMS to handle whatever the machine will deliver to us
  - High granularity tracker with technology to enable track trigger at Level 1, extending to $\eta=4$
  - High granularity endcap calorimeter
    - To use 3-D shower development to disentangle pileup
  - Precision (30 ps) timing of minimum ionizing particles to separate collisions within a single bunch crossing

Tracker Layout



- Acceptance up to η=4
- Inner Tracker
  - 4.9m^2, 2 x 10^9 pixels, two types of hybrid pixel modules: 1x2 chips and 2x2 chips
- **Outer Tracker** with two types of modules: **s**trip **s**trip (2S) and **s**trip macro-**p**ixel (PS)
  - 192m^2, 42M strips, 170M macro-pixels (25m^2)
  - provides track reconstruction in <4 μs for all tracks with P_T>2GeV/c for L 1 Trigger
    - Enables advanced algorithms, particle flow, mass calculations

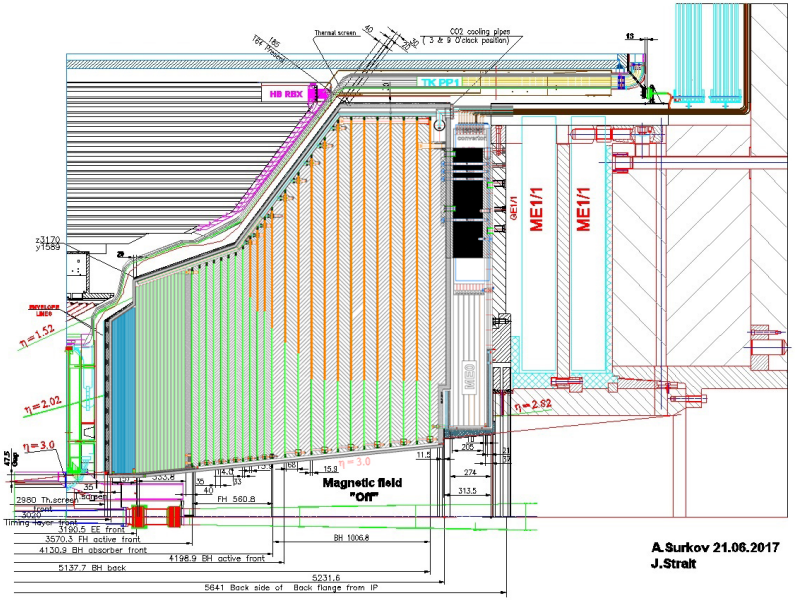
Tracker HL-LHC Upgrade



- "In summary, **the Tracker Upgrade Project pushes tracker designs into a new paradigm** with a scope that is justified in terms of technical realization as well as physics performance. The design is bold, but no technical showstoppers have been identified. It is critical that the remaining R&D be supported as strongly as possible and that appropriate funding for the R&D efforts be provided. Strong oversight is required to keep the schedule. Based on the technical and scientific review, approval is given for the project to proceed with the UCG review."

HGCAL by the Numbers

All the calorimeter is maintained at – 30°C



Construction:

- *Hexagonal Si-sensors built into modules with a W/Cu backing plate and PCB readout board*
- *SiPM on tile scintillator assemblies, built into modules with a PCB readout board*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes integrated into absorber structures*

Key parameters:

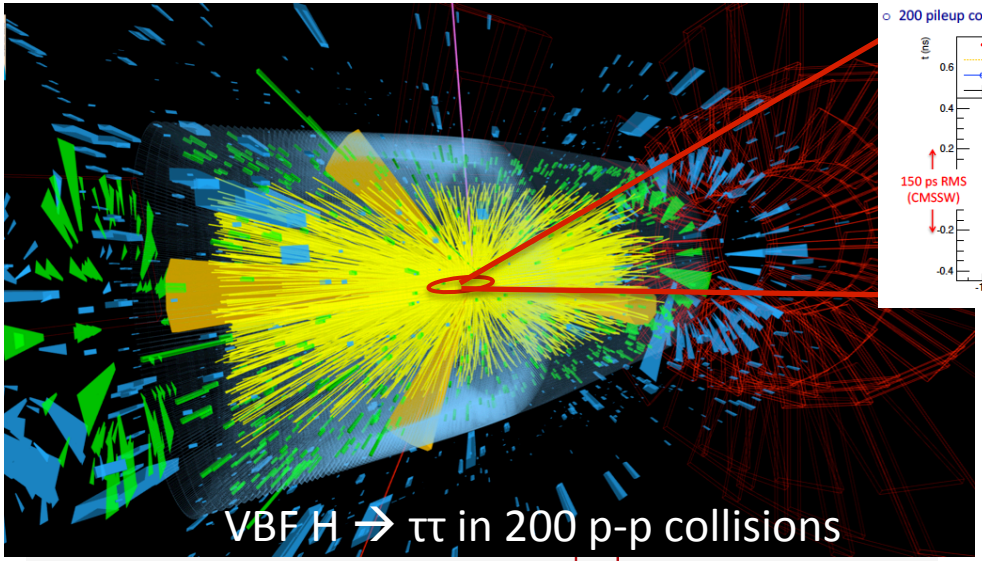
- *600 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *25'000 modules (8" sensors)*
- *520m^2 of SiPM on tile plastic scintillator*
- *~400k ch, 2x2cm^2 -> 5x5cm^2 tiles*
- *Total power at end of life 160~180 kW @-30C*

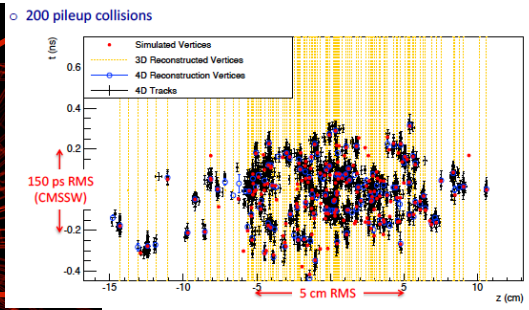
System Divided into three separate parts:

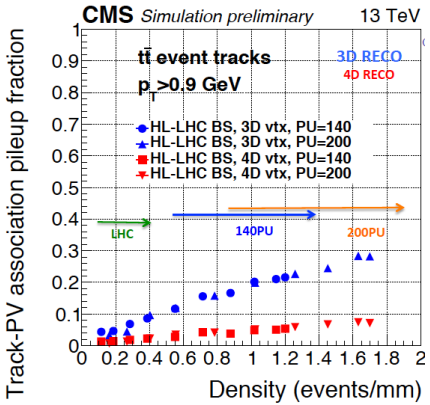
EE – Silicon with Cu-W/Pb absorber – 28 sampling layers – 25 X_0 + ~1.7 λ

FH, BH – planes of Silicon OR silicon and SiPM on tile plastic scintillator, sandwiched between SS absorber plates – 24 sampling layers – 10 λ

MIP Precision Timing Detector







Time of flight precision ≃ 30 ps, $|\eta| < 3$, $p_T > 0.7$ GeV

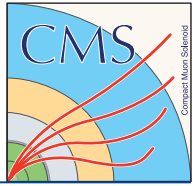
"Provide a factor 4-5 effective pile-up reduction"

- ~ 15% merged vertices reduce to ≃ 1.5%
- Low pileup track purity of vertices recovered

- **All showers timed to 30-50 ps in calorimeters**

Summary

Fermilab and the Opportunities Ahead

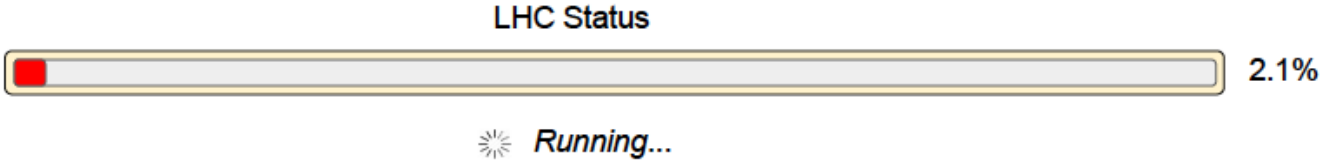


- US and Fermilab have played a leadership role in CMS
- Fermilab can be an innovator in the exciting new detector projects that will be decisive in exploiting the upgrade
  - Tracker and trigger
  - High granularity calorimeter
  - Precision timing
- Management and integration capabilities are really only available at large laboratories that do multiple projects and these are desperately needed for this complex project
- New software approaches, such as Machine Learning, hardware technologies and new collaborations for e.g. cloud computing, are areas where Fermilab can excel.
- LPC shows that Fermilab can be a help and support to university groups
- Fermilab can continue to be a leader in producing a new generation of highly trained scientists

What to do

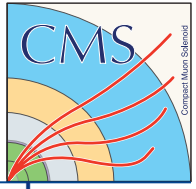
HAVE PATIENCE!

"But we hold several threads in our hands, and the odds are that one or other of them guides us to the truth. We may waste time following the wrong one, but sooner or later, we must come upon the right."
From The Hound of the Baskervilles



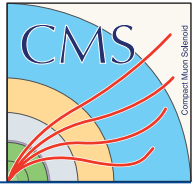
"… there is an end to our investigation. But we are bound to exhaust all other hypotheses before falling back upon this one."

Physics Outlook



- More discoveries may come in a few months or in several years
- They might start with a striking signal in a single channel or as several smaller signals emerging slowly with initially low significance from a multiplicity of hiding places.
- They may appear in scenarios we have long been exploring, e.g. SUSY or Extra Dimensions, **or may surprise us with signatures that we are not even looking for today**
- They may appear in subtle deviations from SM predictions
- As investigators/ researchers into the unknown we need to step back and survey the big picture and look for new, untried approaches or unexplored corners of our data
- **Today we have <3% of the ultimate LHC data in hand**
- **It is our mission to explore and make discoveries in this huge new expanse of scientific territory!!**

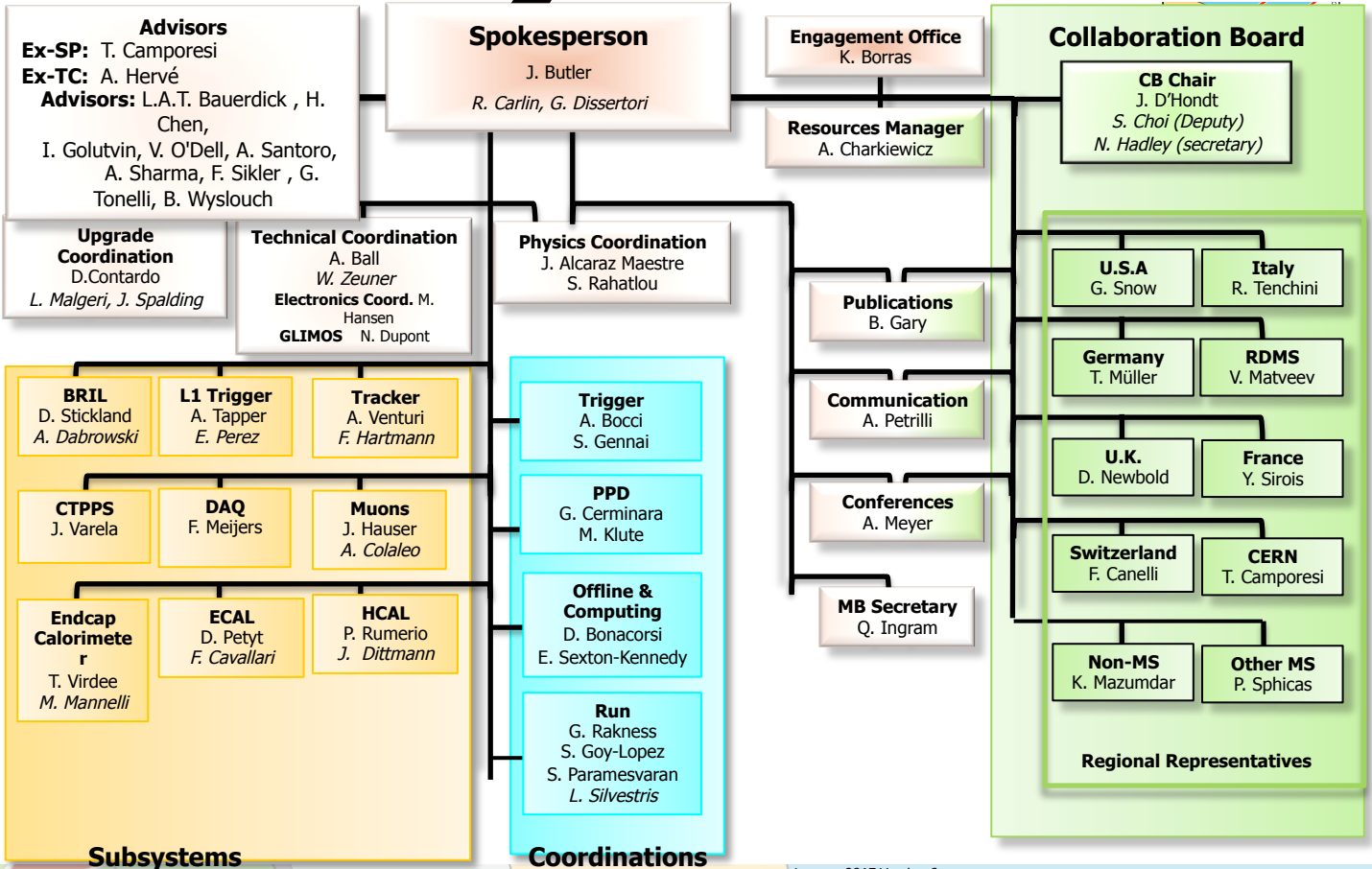
To achieve this, CMS needs a strong US energized by a strong, vibrant Fermilab!!



Thank you for your attention

Backup

CMS Management Board 2017



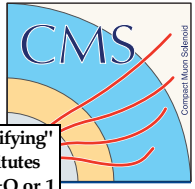
Present Regions

		Country	M&O A PhD #	CMS Institutes	"Qualifying" Institutes (3 M&O or 1 per state)
Other CERN Member State Countries	1	Austria	16	1	1
	2	Belgium	41	6	5
	3	Bulgaria	8	2	2
	4	Finland	9	3	1
	5	Greece	13	4	3
	6	Hungary	10	4	1
	7	Poland	14	2	2
	8	Portugal	8	1	1
	9	Spain	38	4	3
and Associated Member State Countries	10	Cyprus	7	1	1
	11	India	44	10	7
	12	Pakistan	3	1	1
	13	Serbia	4	1	1
	14	Turkey	12	4	4
	15	Ukraine	2	3	1
Total	**15**		**229**	**47**	**34**

		Country	M&O A PhD #	CMS Institutes	"Qualifying" Institutes (3 M&O or 1 per state)
Other Non-CERN Member State Countries or Regions	1	Brazil	27	3	3
	2	China	21	4	2
	3	Colombia	3	2	1
	4	Croatia	10	3	2
	5	Ecuador	2	2	1
	6	Egypt	3	1	1
	7	Estonia	3	1	1
	8	Iran	6	1	1
	9	Korea	32	16	5
	10	Malaysia	5	1	1
	11	Mexico	12	4	3
	12	New Zealand	2	2	1
	13	Ireland	1	1	1
	14	Lithuania	2	2	1
	15	Taipei	17	2	2
	16	Thailand	4	1	1
Total	**16**		**150**	**46**	**27**

Two large, heterogeneous Regions

Proposal



		Country	M&O A PhD #	CMS Institutes	"Qualifying" Institutes (3 M&O or 1 per state)
Other CERN Member State Countries	1	Austria	16	1	1
	2	Belgium	41	6	5
	3	Bulgaria	8	2	2
	4	Finland	9	3	1
	5	Greece	13	4	3
	6	Hungary	10	4	1
	7	Poland	14	2	2
	8	Portugal	8	1	1
	9	Spain	38	4	3
Total	**9**		**157**	**27**	**19**

		Country	M&O A PhD #	CMS Institutes	"Qualifying" Institutes (3 M&O or 1 per state)
Asian Non-CERN Member State Countries or Regions	1	China	21	4	2
	2	India	44	10	7
	3	Iran	6	1	1
	4	Korea	32	16	5
	5	Malaysia	5	1	1
	6	New Zealand	2	2	1
	7	Pakistan	3	1	1
	8	Taipei	17	2	2
	9	Thailand	4	1	1
Total	**9**		**134**	**38**	**21**

		Country	M&O A PhD #	CMS Institutes	"Qualifying" Institutes (3 M&O or 1 per state)
Other Non-CERN Member State Countries or Regions	1	Croatia	10	3	2
	2	Cyprus	7	1	1
	3	Egypt	3	1	1
	4	Estonia	3	1	1
	5	Ireland	1	1	1
	6	Lithuania	2	2	1
	7	Serbia	4	1	1
	8	Turkey	12	4	4
	9	Ukraine	2	3	1
	10	Brazil	27	3	3
	11	Colombia	3	2	1
	12	Ecuador	2	2	1
	13	Mexico	12	4	3
Total	**13**		**88**	**28**	**21**

Add (?):

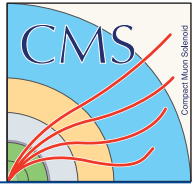
Montenegro + Lebanon

Latin America

This Region 3 could be split into two later.

MB suggested review after 2 years

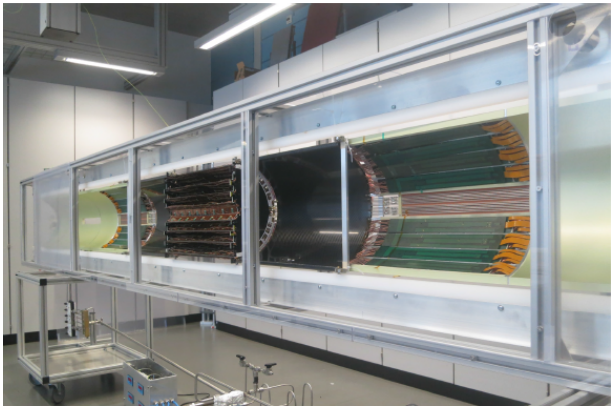
Three kinds of membership in CMS

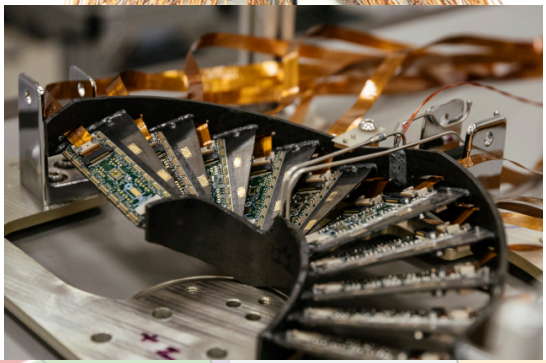


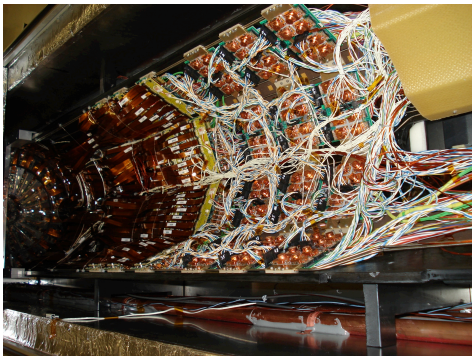
- Full participation
- Cooperating - preparing for full membership in less than 5 years
- Associate – collaboration on technical issues

Pixels

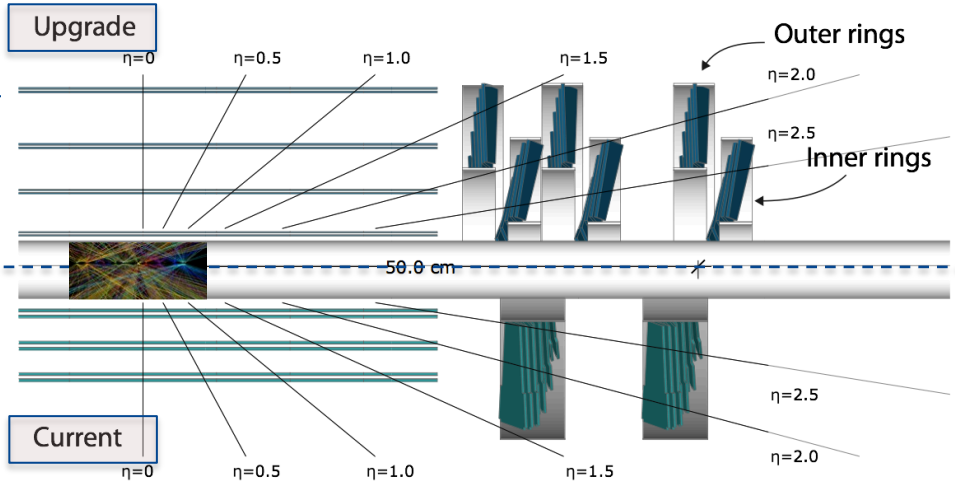
BPIX (outer): L1, L2, L3 & L4 merged







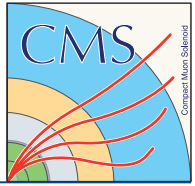
Phase 1 Pixel Detector



Pixel Upgrade: **(To be installed in EYETS)**

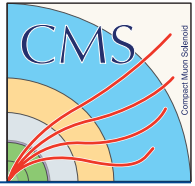
- Baseline L = $2x10^{34}$ $cm^{-2}sec^{-1}$ with 25ns BX → 50 pileup **(50PU) with very small efficiency loss**
- Tolerate L = $2x10^{34}$ $cm^{-2}sec^{-1}$ with **50ns** BX → 100 pileup **(100PU) with reduced performance**
- **Survive Integrated Luminosity of 500 fb^{-1}**
- **Same detector concept**: higher rate readout, data link and DAQ w/ less material forward
- **More Robust tracking** : 4 hit coverage; **3 layers/2 disks to 4 layers / 3 disks** (can compensate point losses in strips)
- Inner layer closer to beam → Better primary and secondary vertex resolution

HF: Forward Hadron Calorimeter



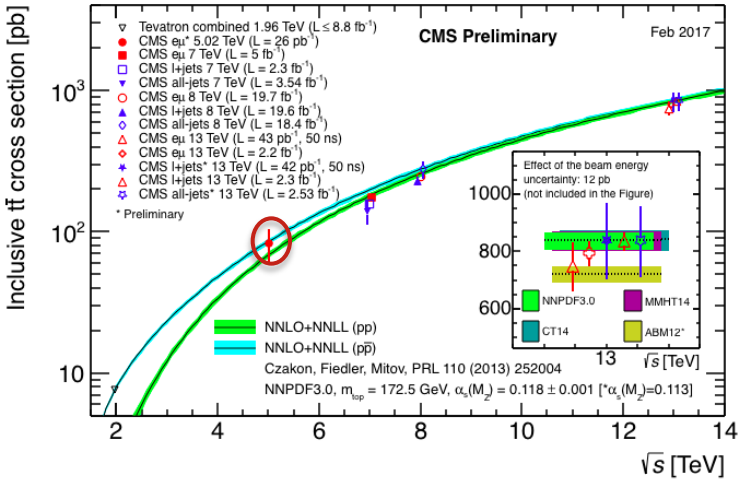
- New thin-windowed, metal envelope Multi-anode PMTs were installed in LS1
  - Less glass eliminated sources of Cerenkov light that were causing large pulses ➔ Fake MET
  - Multianode feature is the next step in this process since true signals are symmetric and false ones are not
    - Anodes currently ganged in "adapter board"
  - Timing is also different and a TDC is part of the new readout, implemented in the new QIE board
- Status (Led by University of Iowa)
  - PMT box rework started – December 7th 2016
  - PMT box rework completed – February 10th 2017
  - All PMT boxes installed – February 16th 2017 (three weeks ahead of schedule!)

Summary of the Status of Phase I Upgrade



- **Most work is now complete**
  - Muon and Infrastructure Upgrades were done in LS1
    - E.g. YB4 (beam halo shield), CO2 cooling, beampipe
  - We used the upgraded Level 1 Trigger starting in 2016
    - Trigger was installed in 2015 and operated parasitically
  - HF was started in LS1 and completed now in EYETS
  - Pixels are now installed
  - **HE** construction is finished
    - All equipment is at CERN , tested and ready to install
    - Installation will likely be in 2017/2018 YETS
  - **HB will be done in LS2 as planned**
    - Very similar to HE
    - Should be at CERN well in advance of LS2 and installed and checked out well before resumption of running

Top Pair Cross Sections



Factory	Quark	Cross Section (nb)	Luminosity ($cm^{-2}s^{-1}$)
B (KEKb)	Bottom	1.15 (Y(4S))	2.11×10^{34}
LHC	Top	0.82 (incl t-t)	1.51×10^{34}

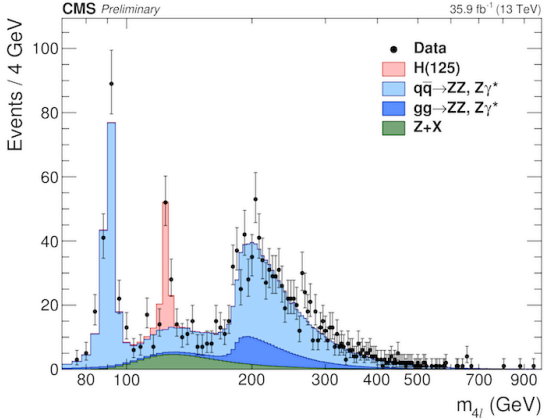
CMS: 835 ± 33 pb
Theory: 816 ± 42 pb

Top pair rate is > 10 Hz, enabling us to address much more precise questions

- Single and double differential cross sections
- Rare (FCNC) decays
- CP violation (a beginning)
- Width and more complex methods for measuring the mass

Top pair production at 13 TeV CM energy is mainly (80%) produced by gluons, providing important information on the gluon distribution at relatively high x_F, up to ~0.25

Higgs Properties from ZZ* (4 leptons)

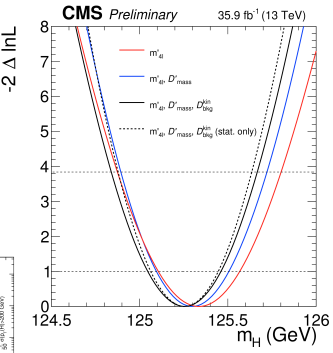


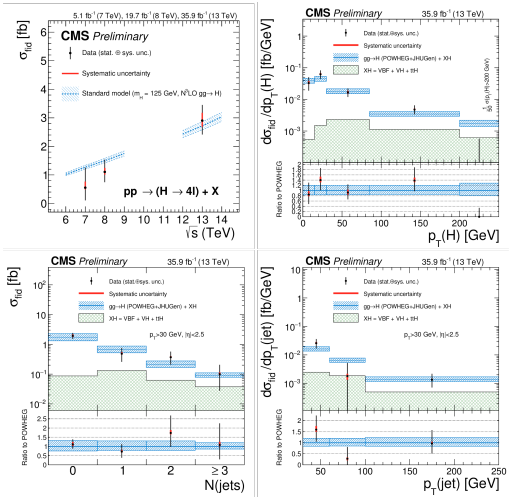
ATLAS, CMS Run 1 Combined:

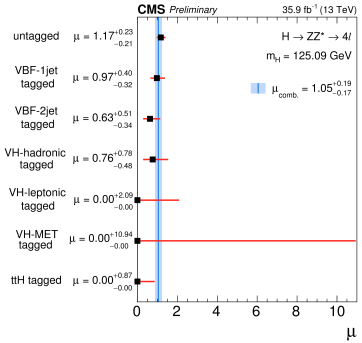
$M_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\ GeV$

CMS 2016, 4 lepton:

$M_H = 125.26 \pm 0.20(stat) \pm 0.08(syst)\ GeV$



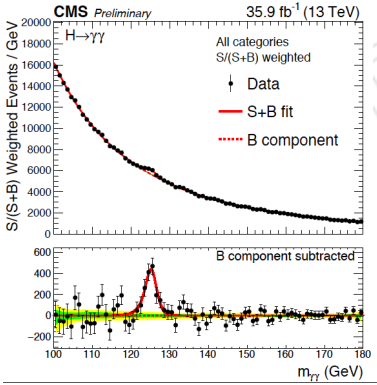


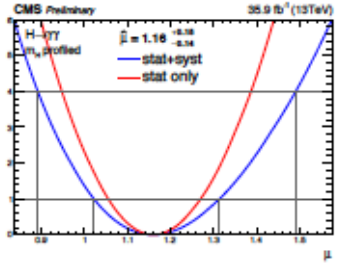


HIG-16-041, Submitted to JHEP

Cross sections

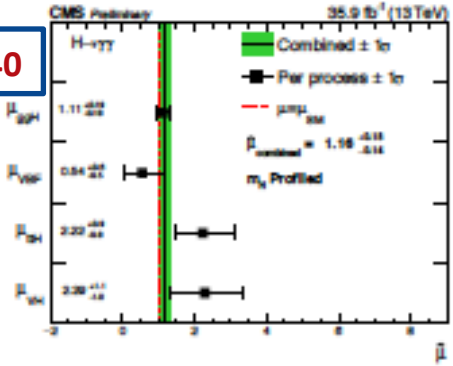
Higgs → γγ



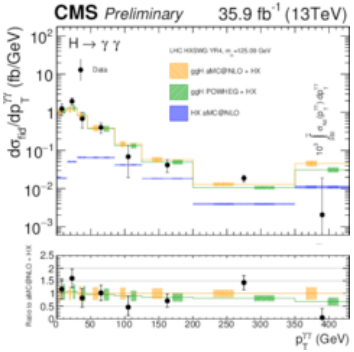


Likelihood scan for signal strength

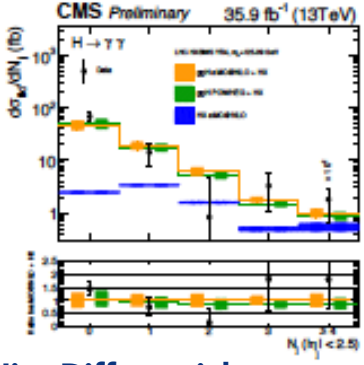
HIG-16-040



Signal strength modifiers



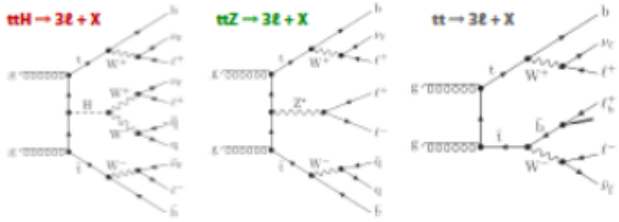
Differential cross section



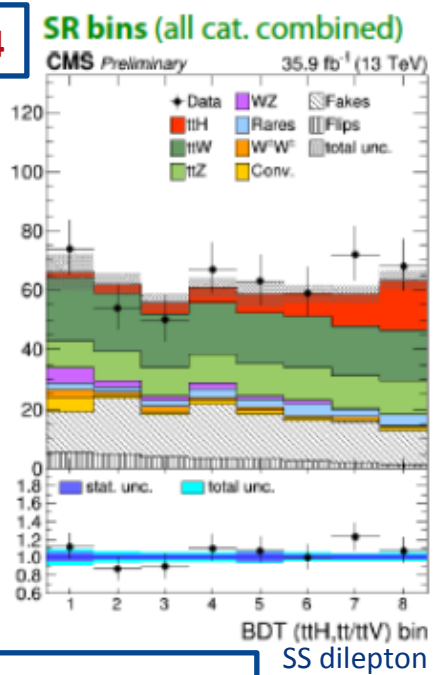
Njet Differential cross section

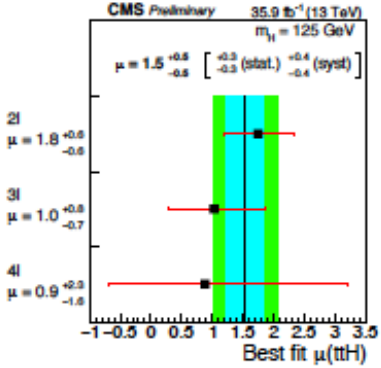
HIG-17-015

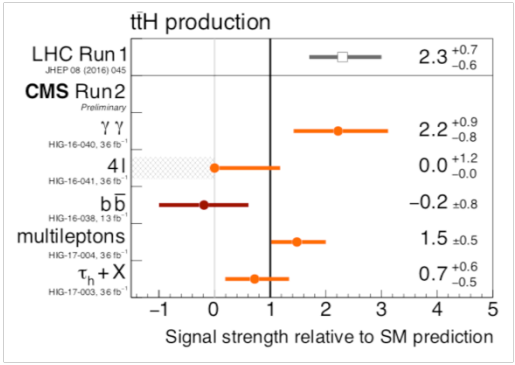
Higgs Coupling to Top Quarks



HIG-17-004







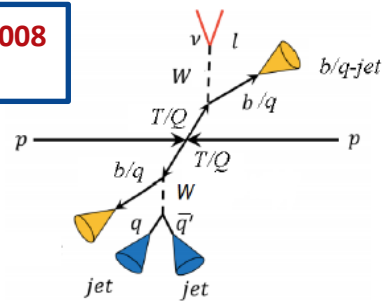
3σ evidence for tt-H in multi-lepton final states
3.3 σ (2.5 expected) when combined with 2015 result

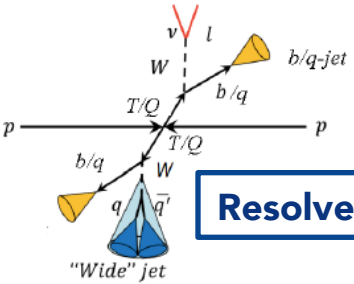
Boosted Objects, e.g., Vector Like Quarks

B2G-17-003

$$T\bar{T} \rightarrow bW^{+}\bar{b}W^{-} \rightarrow b\ell\nu\bar{b}q\bar{q}' \text{ ,Q=2/3}$$

See B2G-17-008 For Q=5/3

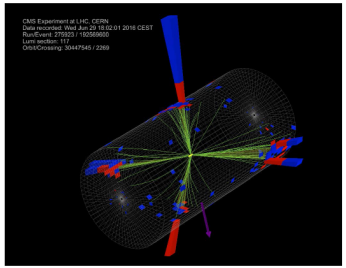




Resolve into two subjets

High mass event

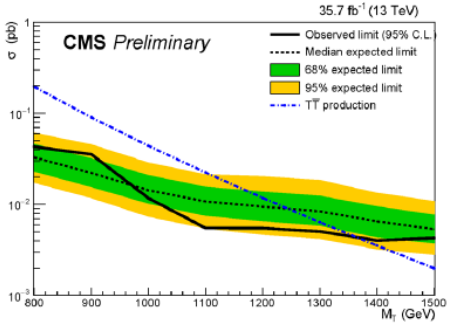
For approval



4 May 2017 B2G-17-003 approval 48

AK8 jets

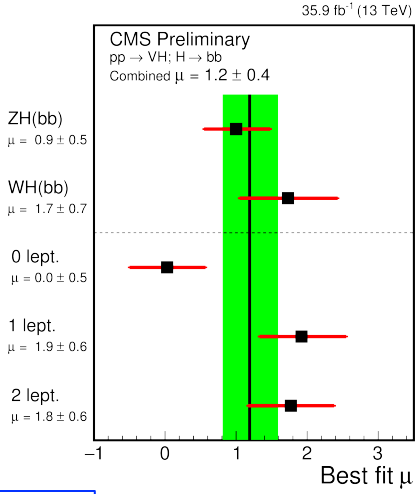
Limit:
Expected: 1245 GeV
Observed: 1365 GeV

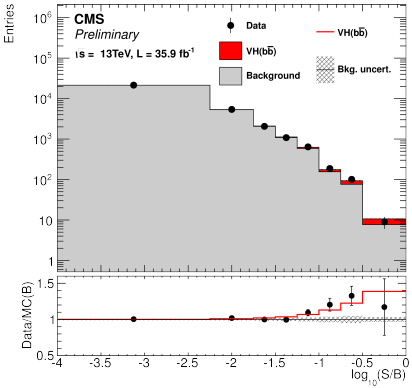


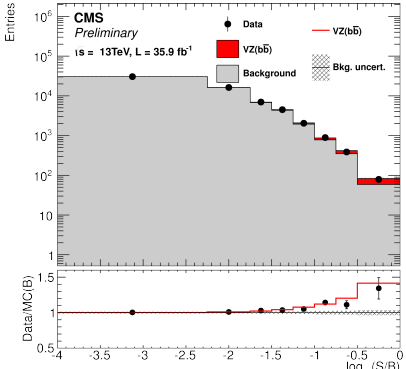
Evidence for Higgs →VH(bb)

- Br of Higgs to bb ~58%(expected)
  - Huge QCD backgrounds
- Most sensitive channel is associated production with W or Z, H→bb
  - 0L: Z(νν)
  - 1L: W(μ ν) W(e ν),
  - 2L : Z(μ μ), Z(ee)
- Mass resolution of M_{bb} is ~10%
- Based in several BDTs **Validated using di-boson production VZ(bb)**

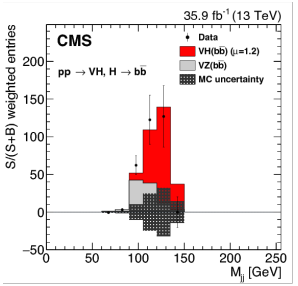
HIG-16-044, submitted to PLB





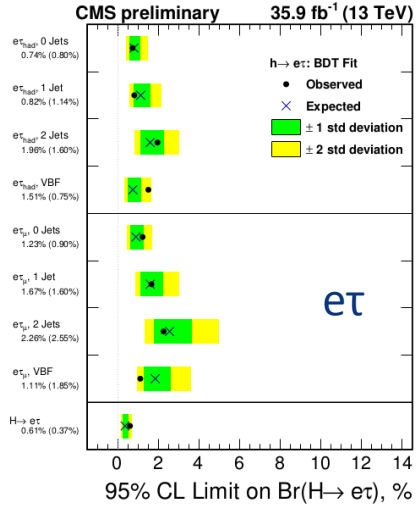


- $m_{VH,SM} = \sigma/\sigma_{SM} = 1.19\ ^{+.21}_{-.20}(stat)^{+.34}_{-.32}$ (syst) **(2016 data)**
- Significance 3.2 (2.8) σ measured(expected)
- $\mu_{VH,SM} = \sigma/\sigma_{SM} = 1.06\ ^{+.31}_{-.29}$ **(2016+Run 1)**
  Significance 3.79 (3.75) σ measured (expected)
- $\mu_{VZ,SM} = \sigma/\sigma_{SM} = 1.02\ ^{+.22}_{-.23}$ (5.0 σ)

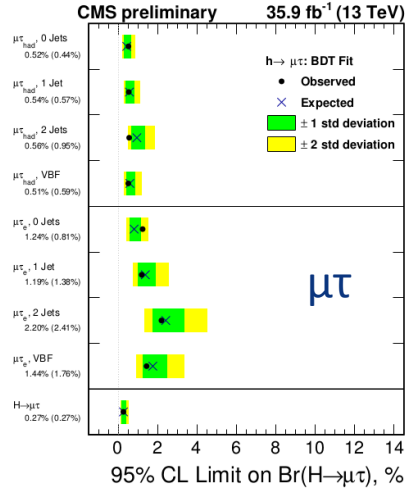


Rare Decay Highlight

- **Search for lepton flavour violating decays of the Higgs boson to eτ and μτ in proton-proton collisions at 13 TeV with full 2016 statistics.**
  - Previous 2.4σ hint in H→μτ in Run1 data (*Phys. Lett. B* **749** (2015) 337) not confirmed
  - stringent limits set on branching fractions, in few per cent range



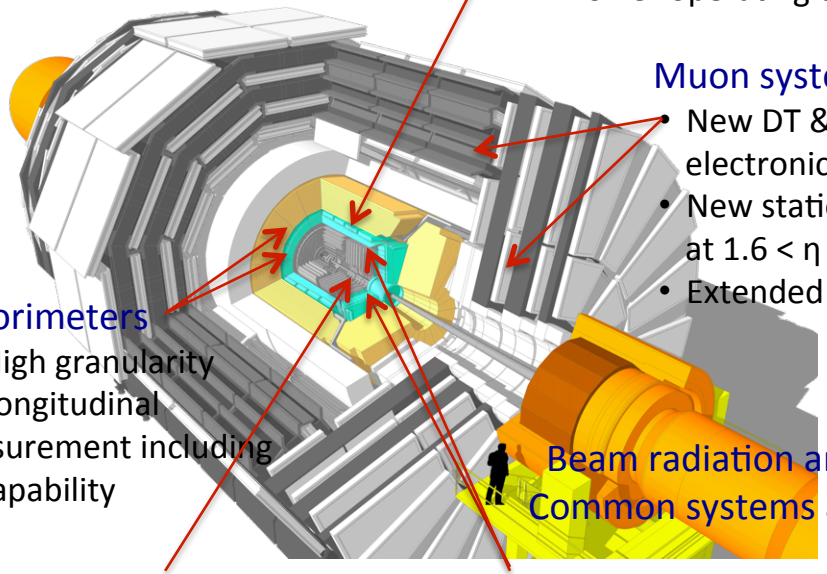
HIG-17-001



HL-LHC: CMS Phase-2 upgrades

Trigger/HLT/DAQ
- Track information in trigger at 40 MHz
- 12.5 μs latency
- HLT input/output 750/7.5 kHz

Barrel EM calorimeter
- New FE/BE electronics for full granularity readout at 40 MHz - with improved time resolution
- Lower operating temperature (8◦)



Muon systems
- New DT & CSC FE/BE electronics
- New station to complete CSC at $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

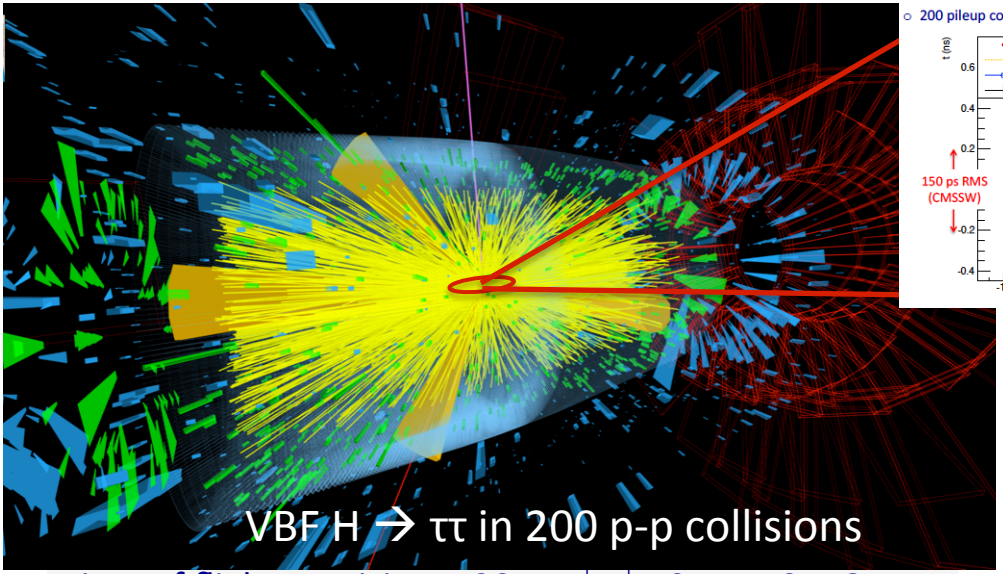
New Endcap Calorimeters
- Rad. tolerant - High granularity transverse and longitudinal
- 4D shower measurement including precise timing capability

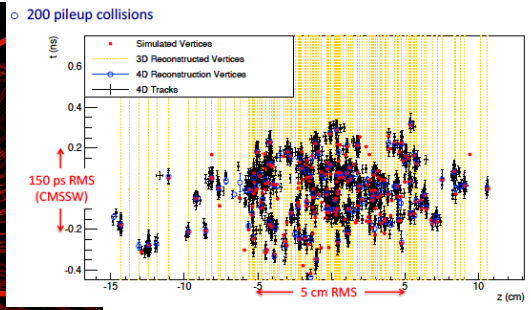
Beam radiation and luminosity
Common systems and infrastructure

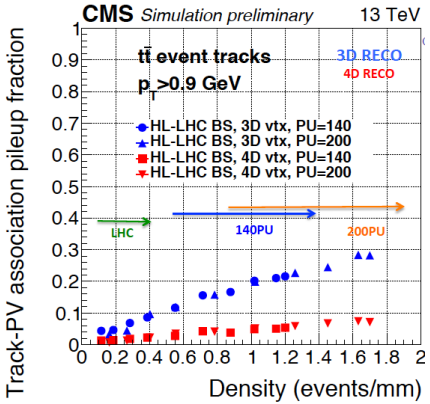
New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout (strips) for Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP precision Timing Detector
- Barrel layer: Crystal + SiPM
- Endcap layer: Low Gain Avalanche Diodes

MIP Precision Timing Detector Advantages





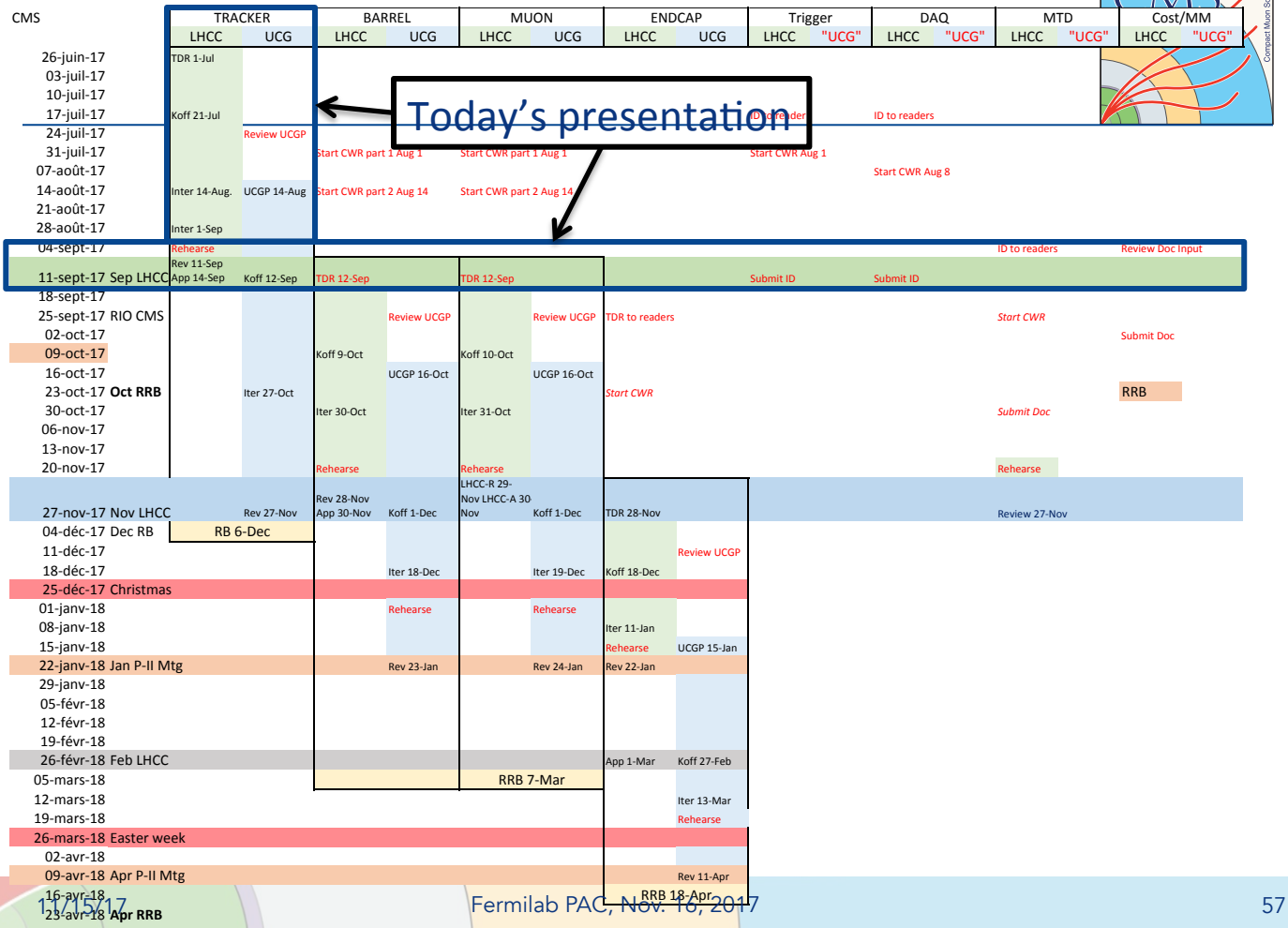


Time of flight precision ≃ 30 ps, $|\eta| < 3$, $p_T > 0.7$ GeV

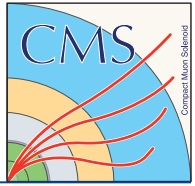
"Provide a factor 4-5 effective pile-up reduction"

- ≃ 15% merged vertices reduce to ≃ 1.5%
- Low pileup track purity of vertices recovered

Reminder of overall LHCC/UCG review process timeline



TDR and Interim Document Approval Process Timeline



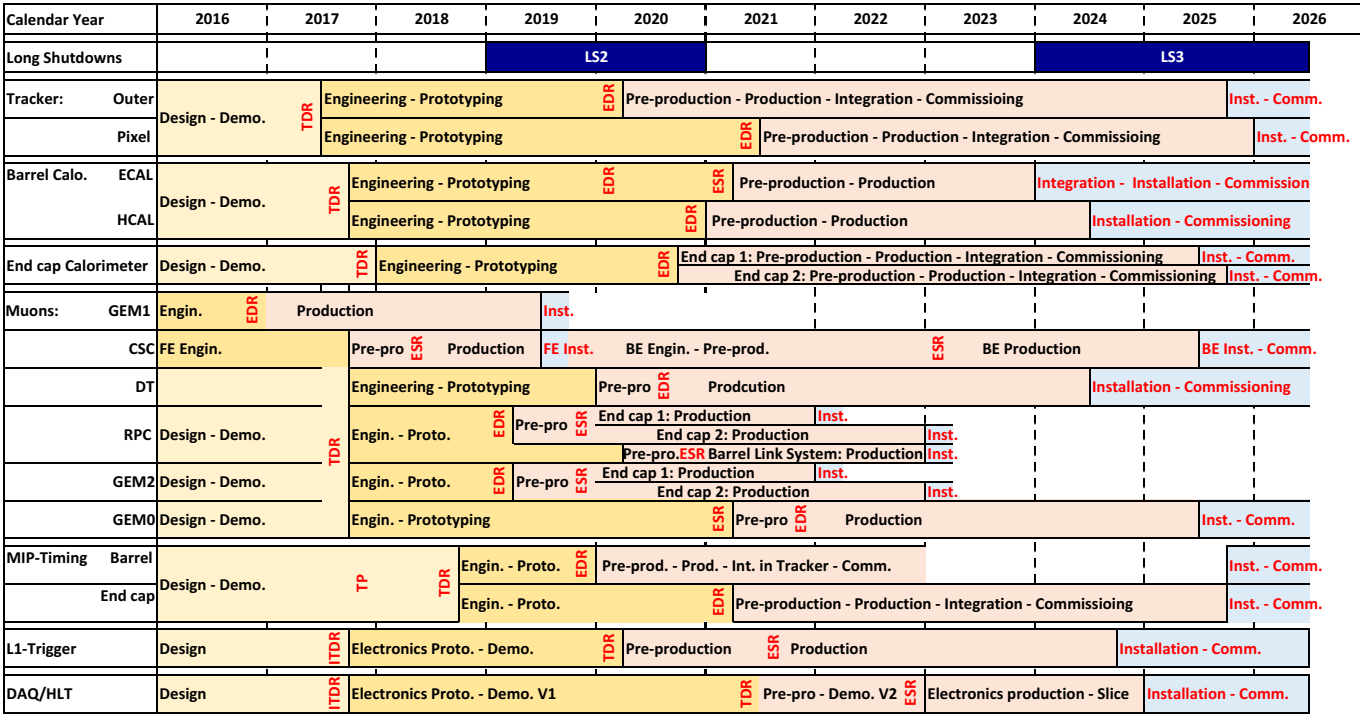
- Tracker TDR
  - Submission to LHCC 1st of July and UCG package Aug 15
  - **LHCC/UCG Sep.: Scientific approval and publication, UCG package review start**
- Muons TDR
  - Submission to LHCC Sep12 and UCG package Oct 15
  - **LHCC/UCG Nov. 2017: Scientific approval and publication, UCG package review start**
- Barrel Calorimeters TDR
  - Submission to LHCC Sept. 12 and UCG package Dec. 15
  - **LHCC/UCG Feb. 2018: Scientific approval and publication, UCG package review start**
- Endcap Calorimeter TDR
  - **Submission to LHCC Nov. 28 and UCG package Feb. 15**
  - **LHCC/UCG May. 2018: Scientific approval and publication, UCG package review start**
- L1 Trigger, DAQ/HLT and Common Infrastructure and Logistics of Works Interim Documents, Sep 2017
- Probably a MIP Timing Layer Interim Document in Sep 2017

CMS goal is to be ready for full approval by Fall 2018 RRB

Updated Overall Timeline for Phase 2 Upgrade

Based on TDRs and other documents for LHCC reviews

- For overview talks and discussions or reviews at FAs



Status of LHCC/UCG Reviews - III

- Update of cost and funding situation was provided to CERN RD, LHCC/ UCG chairs
  - New cost - with explanation of major changes since TP

CMS Phase-2 cost (kCHF)	EC-CALO	ECAL Barrel	HCAL Barrel	Muons	Tracker	BRIL	Trigger	DAQ/HLT	Common Fund	TP scope	MIP-TD	TP scope + MIP-TD
TP cost (2014 rates)	63 600	9 950	1 500	24 400	112 300	4 000	7 300	17 000	25 000	265 050	-	
Current cost (2016 rates)	66 000	12 600	2 500	24 900	111 900	2 600	5 900	12 600	25 000	264 000	14 900	278 900

Status of LHCC/UCG Reviews - IV

- Confidential MM - with level of discussion at FAs
- Discussion of options to address over-budget (1.2%) and of preparation mitigation plans in case of funding shortfall
- Balance of cost and funding of projects

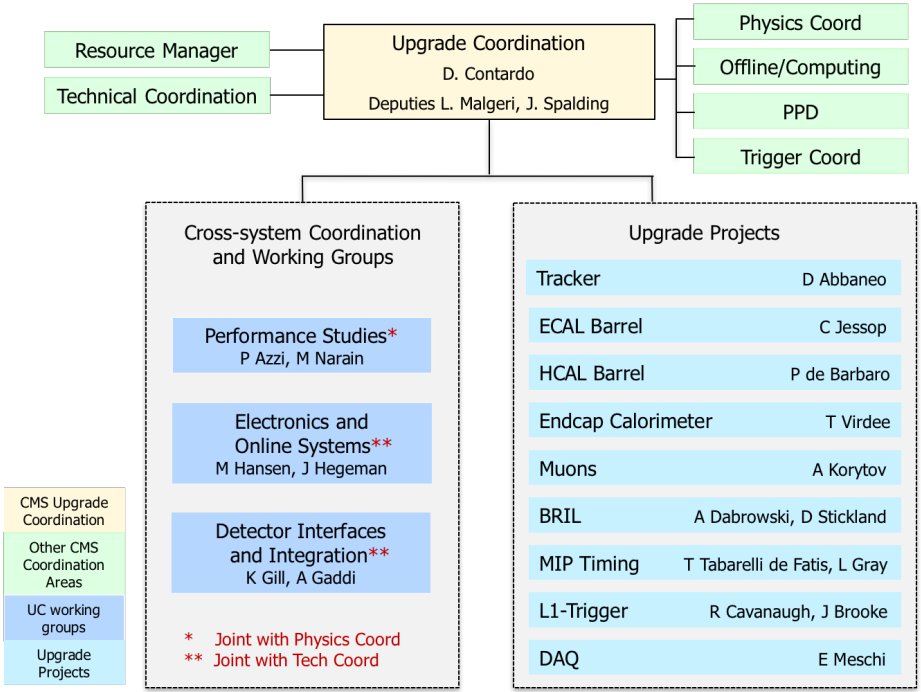
CMS Member country	EC-CALO	ECAL Barrel	HCAL Barrel	Muons	Tracker	MIP-TD	BRIL	Trigger	DAQ/HLT	Common Fund	Total
Current cost	66000	12600	2500	24900	111900	14900	2600	5900	12600	25000	278 900
Funding	65 964	12 040	2 500	24 926	115 416	9500	1 495	7 272	12 678	23 791	275 582
Funding-cost	-36	-560	0	26	3516	-5400	-1105	1372	78	-1209	-3318
(Funding-cost)/cost	-0,05%	-4,44%	0,00%	0,10%	3,14%	-36,24%	-42,50%	23,25%	0,62%	-4,84%	-1,19%
(Funding-cost)/total cost	-0,01%	-0,20%	0,00%	0,01%	1,26%	-1,94%	-0,40%	0,49%	0,03%	-0,43%	-1,19%

➢ We are expecting feedback from LHCC/UCG chair before the Oct. RRB

Update of Current Organization for Phase 2 Upgrade

For discussions or reviews at FAs

New convener names/MIP-Timing Detector a project (previously a WG)

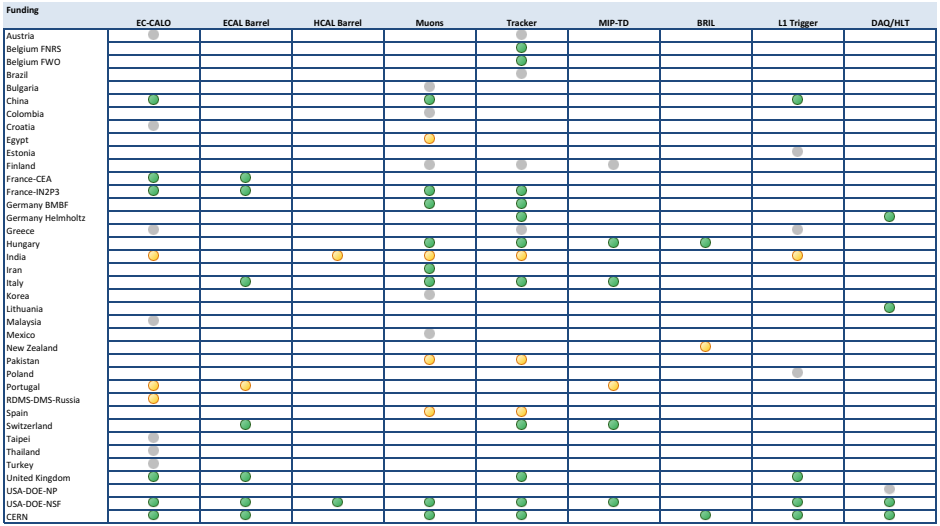


A Snapshot of the CMS Phase 2 Upgrade Cost - II

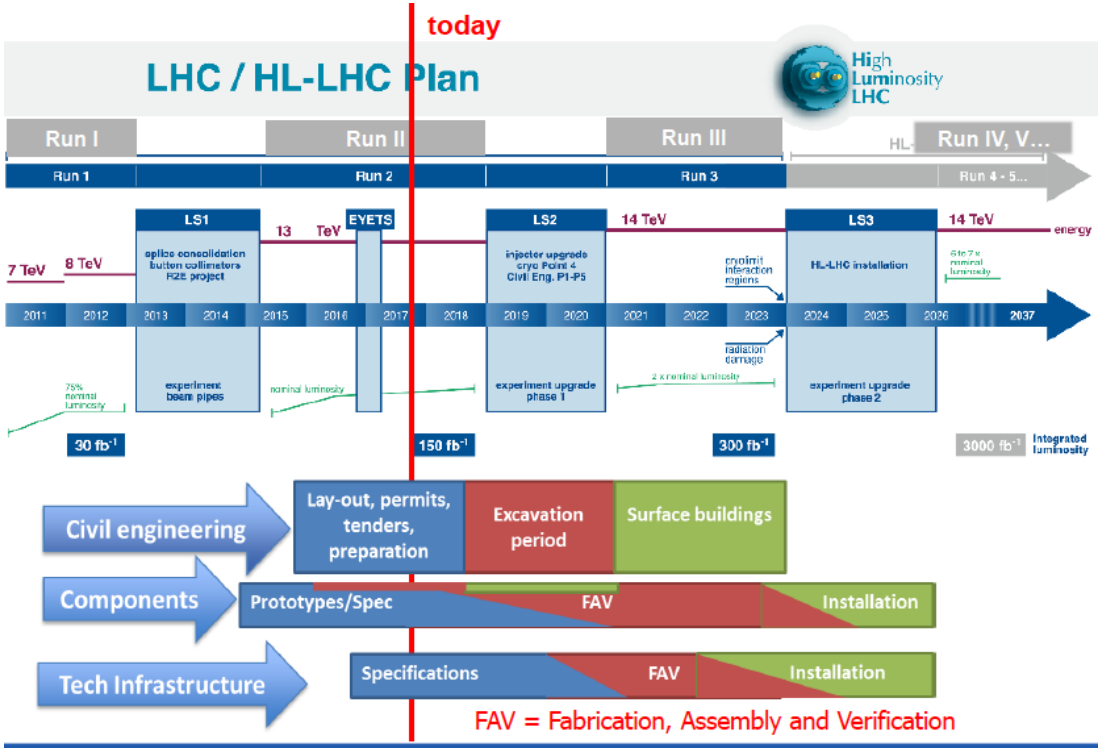
The CMS Phase-2 upgrade expected funding is established at 275.6 MCHF

Assuming similar level of discussion as ATLAS:

- ≃ 12% of the funding is at the level of requests to Funding Agencies (FA) (grey)
- ≃ 9.7% is being processed by FAs as a target (yellow)
- ≃ 78.3% is agreed by FAs (green)

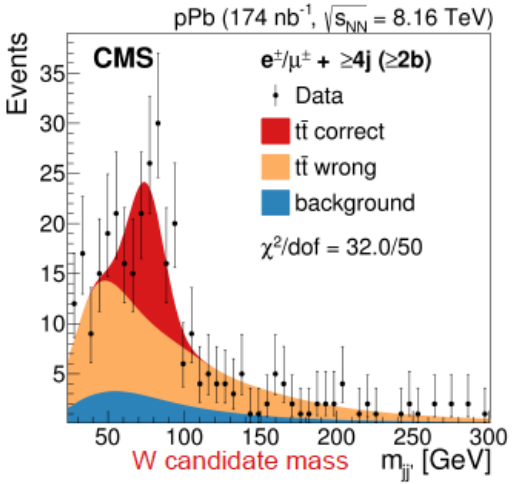


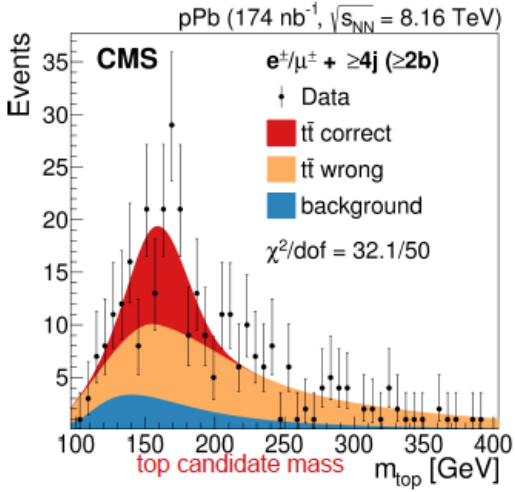
Beyond LS3


today
LHC / HL-LHC Plan
High Luminosity LHC
Run I
Run II
Run III
HL-
Run IV, V…
Run 1
Run 2
Run 3
Run 4 - 5…
LS1
splice consolidation
button collimators
R2E project
13 TeV
EYETS
LS2
injector upgrade
cryo Point 4
Civil Eng. P1-P5
14 TeV
LS3
HL-LHC installation
14 TeV
energy
7 TeV
8 TeV
6to7 x nominal luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
experiment beam pipes
experiment upgrade phase 1
experiment upgrade phase 2
radiation damage
2 x nominal luminosity
75% nominal luminosity
nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
Integrated luminosity
Civil engineering
Lay-out, permits, tenders, preparation
Excavation period
Surface buildings
Components
Prototypes/Spec
FAV
Installation
Tech Infrastructure
Specifications
FAV
Installation
FAV = Fabrication, Assembly and Verification

Top in Heavy Ions

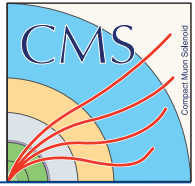
- First observation of top quark production in proton-lead collisions!
  - showcased at TOP 2017 conference and paper submit at time of presentation





arxiv:1709.07411

Status of LHCC/UCG Reviews



- Tracker Phase-2 TDR-17-001scientific review is completed report at: https://cms-docdb.cern.ch/cgi-bin/DocDB/ShowDocument?docid=13409
  Answering questions on UCG package (cost…)
- Review of Muon and Barrel Calorimeters TDRs by LHCC started two weeks ago
- Review of Trigger and DAQ ITDR (interim Technical Design Report), made of off-the-shelf components started. Answers to questions being prepared
  - Costs can be defined by current non-optimal technology and roadmaps of key companies
- Calorimeter Endcap TDR
  - Collaboration-Wide Review (CWR) will start Oct 30, for delivery to LHCC end of Nov. with object performance
  - Update with final Physics studies early Dec. for submission to LHCC before Christmas
- MIP Timing Detector Technical Proposal
  - New condensed version at request of the committee is available
    - Follow-up review of changes since March and critical reading ongoing with Mar. review panel
  - CWR planned for Oct. 30 and submission to LHCC Nov. 27
  - LHCC review includes a common meeting with ATLAS at LHCC session Dec. 1