LHC U.S. CMS Detector Upgrade Project

CMS Presentation to the HEPAP Facilities Subpanel

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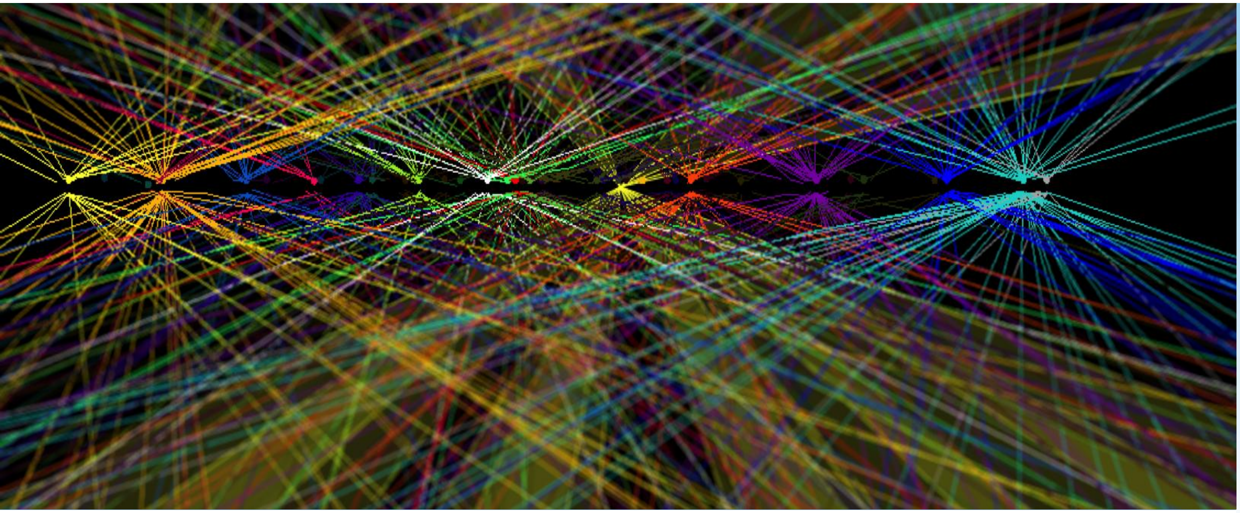
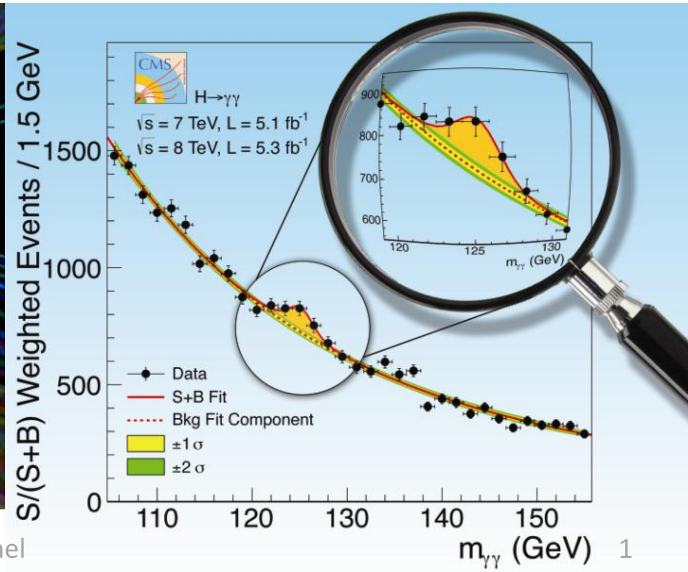
On behalf of the CMS HL-LHC Upgrade Project

13 Feb 2013





Outline

- Will the LHC achieve high luminosity?
- Do the physics opportunities justify an upgrade?
- What subsystems will need to be upgraded?
- What is the approximate cost and schedule?
- Conclusions

Prospect for High Luminosity: the HL-LHC

- The LHC has rapidly achieved high luminosity
  - 7.7×10^{33} cm^{-2} s^{-1} at 8 TeV
  - Key parameters have exceeded design goals
- The understanding of the machine, modeling, and superb instrumentation led to a clear understanding of its behavior
  - Predictions of the effectiveness of improvements have been accurate
  - Effective machine studies, facilitated by the excellent instrumentation, have been efficient and productive
- By ~2022, the peak luminosity will exceed 2 $\times 10^{34}$ cm^{-2} sec^{-1} and about 300 fb^{-1} will have been recorded

Goals of HL-LHC (after ~2022):

- Maximum of <140> interactions/crossing with leveling
  - $L = 5 \times 10^{34}$ cm^{-2} sec^{-1} for 25ns
    - $L = 2.5 \times 10^{34}$ cm^{-2} sec^{-1} for 50ns
  - 250 fb^{-1} per year
  - 3000 fb^{-1} total

	J	F	M	A	M	J	J	A	S	O	N	D
2011		1	2	3	4	5	6	7	8	9	IONS	
2012			1	2	3	4	5	6	7	8	9	
2013	IONS	IONS	LS1 - SPLICE CONSOLIDATION									
2014												
2015	RECOM	RECOM	RAMP-UP	1	2	SCRUB 25 ns	3	4	5	6	IONS	
2016		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
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2021		RAMP-UP	1	2	3	4	5	6	7	8	IONS	
2022	HL-LHC UPGRADE											

Technical stop or shutdown
Proton physics
Ion Physics
Recommissioning
Intensity ramp-up

There is more than one path to reach the goal

Challenges for CMS at High Luminosity

- High Pileup
  - Must keep reconstruction of "physics objects" pileup safe
    - Preserve resolution and calibration
      - Including global variables such as Missing E_T.
    - Correctly and efficiently tag objects such a e, μ, and γ as isolated
  - Must make sure triggers have adequate signal efficiency at necessary background rejection levels
  - Must keep data volume and reconstruction time under control
- Radiation Damage to detectors
  - Pixel detector and silicon strip tracker
  - Forward calorimetry

What we have observed so far

- After 3 years of running at 7 and 8 TeV:
  - A Higgs boson candidate exists at a mass of ~126 GeV (CMS. ATLAS)
  - BR($B_s \rightarrow \mu^+\mu^-$) has been measured (LHCb) to agree with SM
  - No new "Beyond the Standard Model" physics has emerged YET
    - Ruled out squarks with masses < 1Tev
      - But 3rd generation squarks below 1 TeV are still compatible with the data
    - Ruled out gluinos with masses < 1 TeV
    - New gauge bosons, Z' and W', with SM couplings are ruled out below 3 TeV

- The motivation for new physics at the TeV scale remains strong
  - Hierarchy problem (naturalness, stabilization of M_H)
  - Vacuum Stability

What are the physics goals for HL-LHC

- **Measure properties of the Higgs with increasing precision to test SM hypothesis**
  - **The existence of a light Higgs candidate requires all the capabilities built into the original CMS detector, which was optimized for such a particle**
- Continue to look for new physics beyond the SM
  - Employing even more sophisticated search strategies as the "easier" BSM scenarios are ruled out and more complex ones and new ones become the focus

This requires us to upgrade CMS to achieve, at the minimum, similar performance at the higher luminosities and pileup that we have achieved in the current detector. We also want to improve the detector to be even better, especially where there are indications of significant physics payoffs.

Higgs Properties

- **Measure properties of the Higgs with increasing precision to test SM hypothesis**
  - mass, J^{PC}, will probably be done determined before HL-LHC for the non-mixed case
    - But need to check that it is not an admixture of ~SM Higgs with a non-SM object
  - BR, ratios of BR to get at couplings: $\gamma\gamma$, ZZ*, WW*, bb, and $\tau^+\tau^-$

- Rare decays
  - H → $\mu^+\mu^-$
  - H → Z γ

- Difficult Production Modes
  - These also produce information on couplings and physics
    - E.g. t-tbar-Higgs
    - Vector boson fusion, studies of WW scattering and unitarization of the scattering amplitude

- Higgs Self-coupling
  - Production of two Higgs bosons
    - A parameter of the gauge potential itself

Higgs Projections for 3000 fb^{-1}

Coupling	inty (%)	
	3000 fb^{-1}	
	Scenario 1	Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

•Scenario 1:

- 2012 systematics

•Scenario 2:

- theory syst: scaled by a factor ½
- other systematics scaled by 1/√(∫Ldt)

- The decay $H \rightarrow \mu^+\mu^-$ can be observed with a significance of 5 σ s
  - measurement of the Hμμ coupling with a precision of ~10%.
- Higgs self coupling can be measured to 15-20%
- t-tbar-Higgs

SUSY and other BSM Physics

- **There are many ways that SUSY could be eluding detection**
  - Compressed spectra
  - “Diluted” spectra
    - BR into many modes
  - Stealth or RPV scenarios without MET
  - Long-lived sparticles

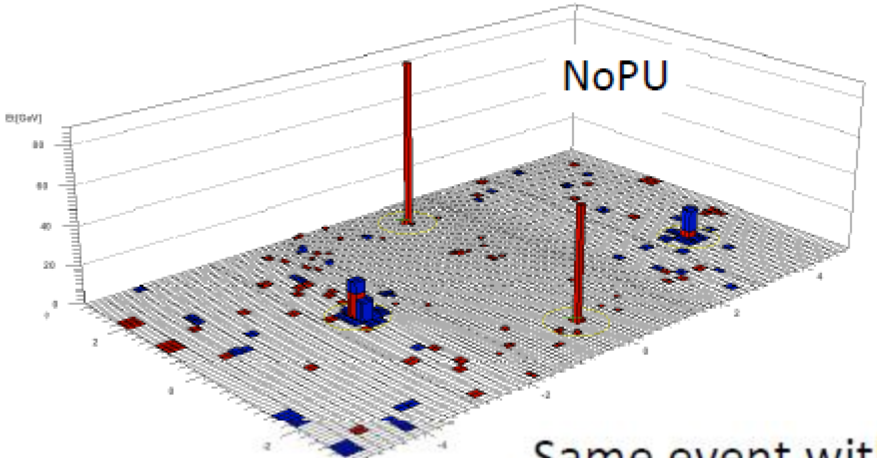
I am not dead yet
No need to go to bed
No need to call the doctor
Cause I'm not yet dead.
(Spamalot)

- SUSY can be consistent with Standard Model Higgs
  - Lightest SUSY Higgs looks like SM Higgs in decoupling limit (large M_A)

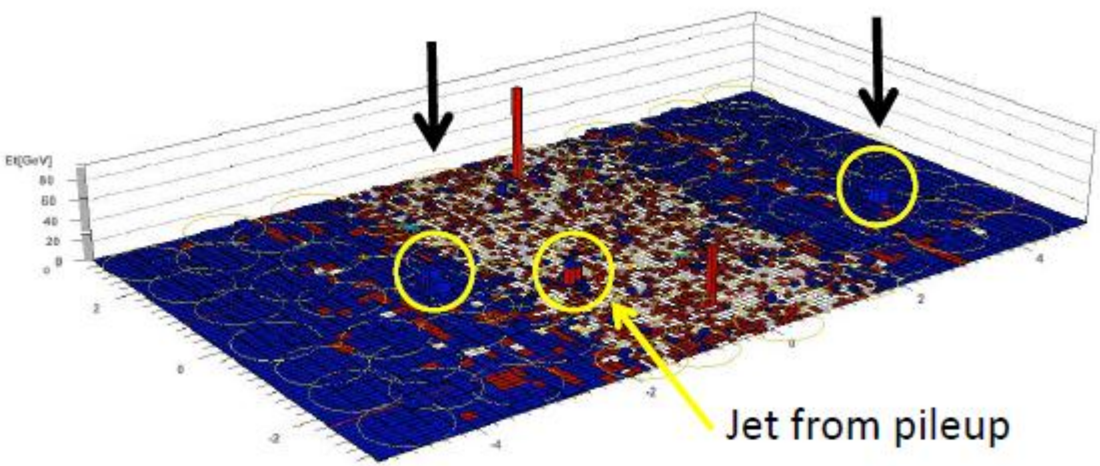
- We are closing these loopholes, and will continue to do so in second run starting in 2015
  - But **some scenarios may not be fully excluded before HL-LHC**
    - **and other scenarios will arise**

- **There are many other possibilities for new physics**
  - **Searches for new resonances, e.g. techniparticles, Z’**
  - **Departures from QCD or EW scattering predictions**
  - **Precision top studies**
  - **Precision EW studies, e.g. triple gauge couplings**
  - **Many, many more**

Challenge of High Luminosity



Same event with 140PU



78 vertices

From special data run with intense bunches

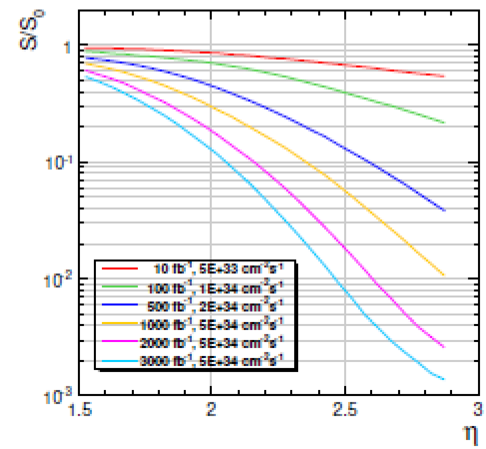


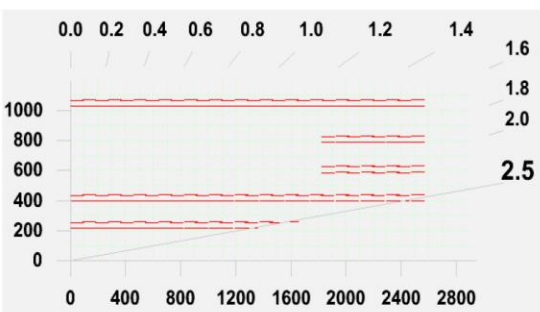
FIGURE 3. Light loss curves as a function of $|\eta|$ and for different integrated luminosity for the present $PbWO_4$ EE detector.

Need for the Upgrade

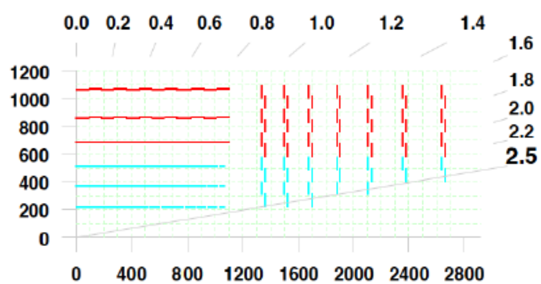
- Given these problems, the physics capability of CMS will be severely compromised
- To fully carry out the physics program, CMS is considering the following upgrades:
  - A new tracker with the capability of providing tracking in the Level 1 trigger
  - New endcap and forward calorimetry (important for VBF physics)
  - Pileup mitigation by extending tracking to the forward region
  - Pileup mitigation by adding precision timing to several detectors
  - Robust muon triggering and tracking at high η.
  - Increased bandwidth for the Level 1 trigger and the High Level Trigger

Tracking Trigger Issues

- Level 1 (L1) Trigger needs improvement
  - By end of LS2, all available granularity in calorimeters and muon system are used
- ADD TRACKING AT L1 in outer tracker (>20 cm)
  - Design a tracker that can deliver reasonably stiff tracks, P_T>2.5 GeV, at 40 MHz to track processor
  - Tracker must be designed from scratch to facilitate this
  - Two Geometries and three methods of extracting stubs satisfying P_T cut
- Pixels – radiation hardness of sensors



Long barrel
•10 layers of "stacks"
•In 5 double stacks with 4 cm separation
•100 μm x 1mm pixels

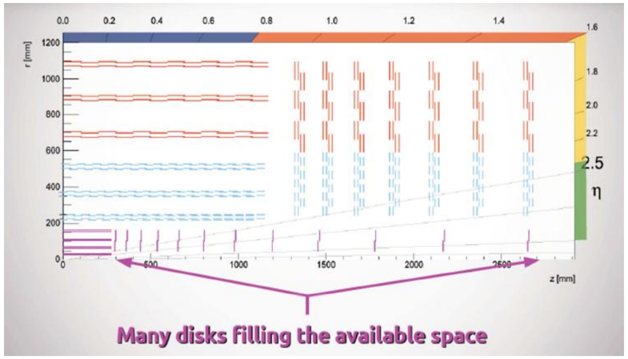


Barrel + endcap
•inner layers use pixels + strips
•Outer layers use strips

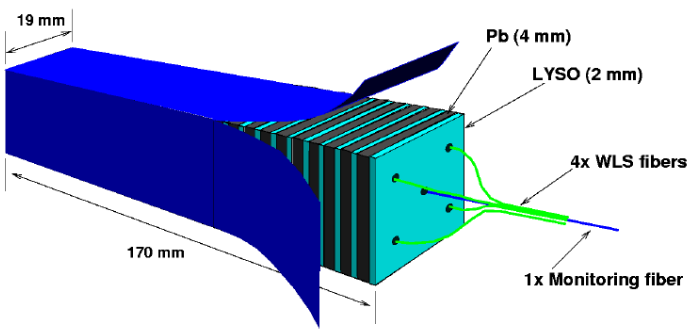
Both have many more channels than now
• Power, cooling, material budget, and cost are issues

Forward Direction

Precision timing	Identification of primary vertex Pileup mitigation
EE	Shaslik geometry Readout of multiple depths?
HE	Increased phi segmentation
HF	Rebuild HF with increased fiber packing fraction Compact HF closer to interaction point Add e/γ and muon identification capability
Tracker	Increased eta coverage across EndCap/Forward Calorimeter
Muon	Better performance in high rate environment
Trigger	Increased muon trigger efficiency in forward region



Forward disks to increase tracking to high η



Shashlik forward Calorimeter concept

Cost and Schedule

- Schedule is dictated by timing of LS3
  - This could be as early as 2022
  - Need to start construction about 5 years earlier
  - Need to freeze the conceptual design and complete most of the R&D about 2 years before that
  - To achieve this, plan to submit a "Technical Proposal" in 2014 based on simulation and R&D now underway

- Cost
  - We only have a "cost model" done some time ago based on cost of original detector and what we have learned from our R&D
    - For the US, in our metric, based on our current interest (scope), and with 40% contingency, the cost range is $200-300M
  - We are now have a well defined process for setting the cost range for the project

Conclusion

- The LHC is highly likely to achieve high peak and integrated luminosity
  - Fully 80-90% of the total luminosity at the LHC will be achieved at the HL-LHC
  - CMS can take advantage of the luminosity to
    - make precision studies of the Higgs Boson candidate
    - Look for new physics beyond the Standard Model up to masses of a few TeV
  - But the detector must be upgraded to be at least as efficient for physics as it is now by improving
    - Tracking
    - Forward calorimetry
    - Trigger and data acquisition

The LHC is likely to be the only machine on this time scale that can study the Higgs and continue the direct search for new physics at a few TeV. The US already has a big investment in the CMS program and should make sure it capitalizes on it by participating appropriately in the CMS upgrade.

Backup

Heavy Ion Physics

- The Heavy Ion community is extremely interested in continued HI running
  - Current PbPb data set is $150\mu b^{-1}$ (3kHz max collision rate)
  - Expect collision rates to gradually increase to 50kHz
  - Aiming for $10nb^{-1}$ PbPb to be collected in HL-LHC era
- LHC has provided new probes for studying the properties of Quark-Gluon Plasma
  - Precise measurements of jet modification
  - First observation of parton energy loss using γ-jet and Z^0-jet correlations
  - Measurements of b-quark vs gluon/light quark energy loss
  - Observation of sequential modification of the Y-family
- Current studies are statistics limited
  - $10nb^{-1}$ data set will allow precision studies of Z^0-jet correlations and b-jets
  - Use full power of pp analysis techniques, e.g. top quark ID and b-physics observables

10 year plan

	J	F	M	A	M	J	J	A	S	O	N	D
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LS1

PHYSICS AT 6.5/7 TeV

LS2 – Injector upgrade

"ULTIMATE" PHYSICS (~2.4e34 $cm^{-2}s^{-1}$)

LS3 – HL-LHC upgrade

- Technical stop or shutdown
- Proton physics
- Ion Physics
- Recommissioning
- Intensity ramp-up

Updates under discussion

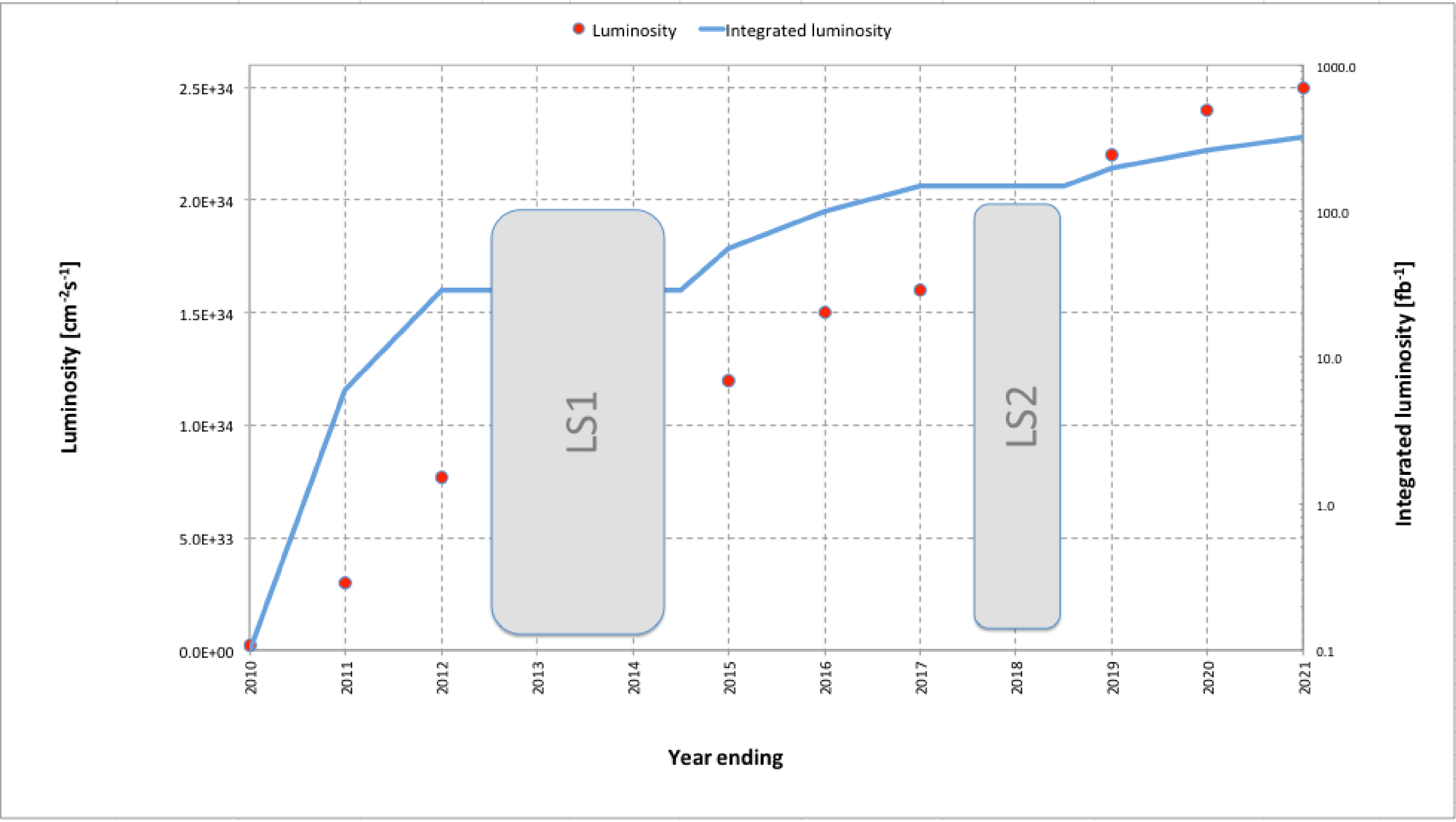
Installation Opportunities

- There are edge effects in opening and closing the CMS to get access to the detectors inside the solenoid – open/close time ~2 months
  - A Long Shutdown (LS) is ~> 1 year so the available work time is >> than the open/close time
  - A Technical Stop (TS,) is ~ 3 months (e.g. winter shutdown - YETS) so available work time <open/close time
  - An Extended Technical Stop (ETS) is ~5-6 months (e.g. an extended winter shutdown) to have time to do one installation or repair operation

- Trigger and DAQ electronics in the Underground Service Cavern (USC) can take place during running but must not impact operations

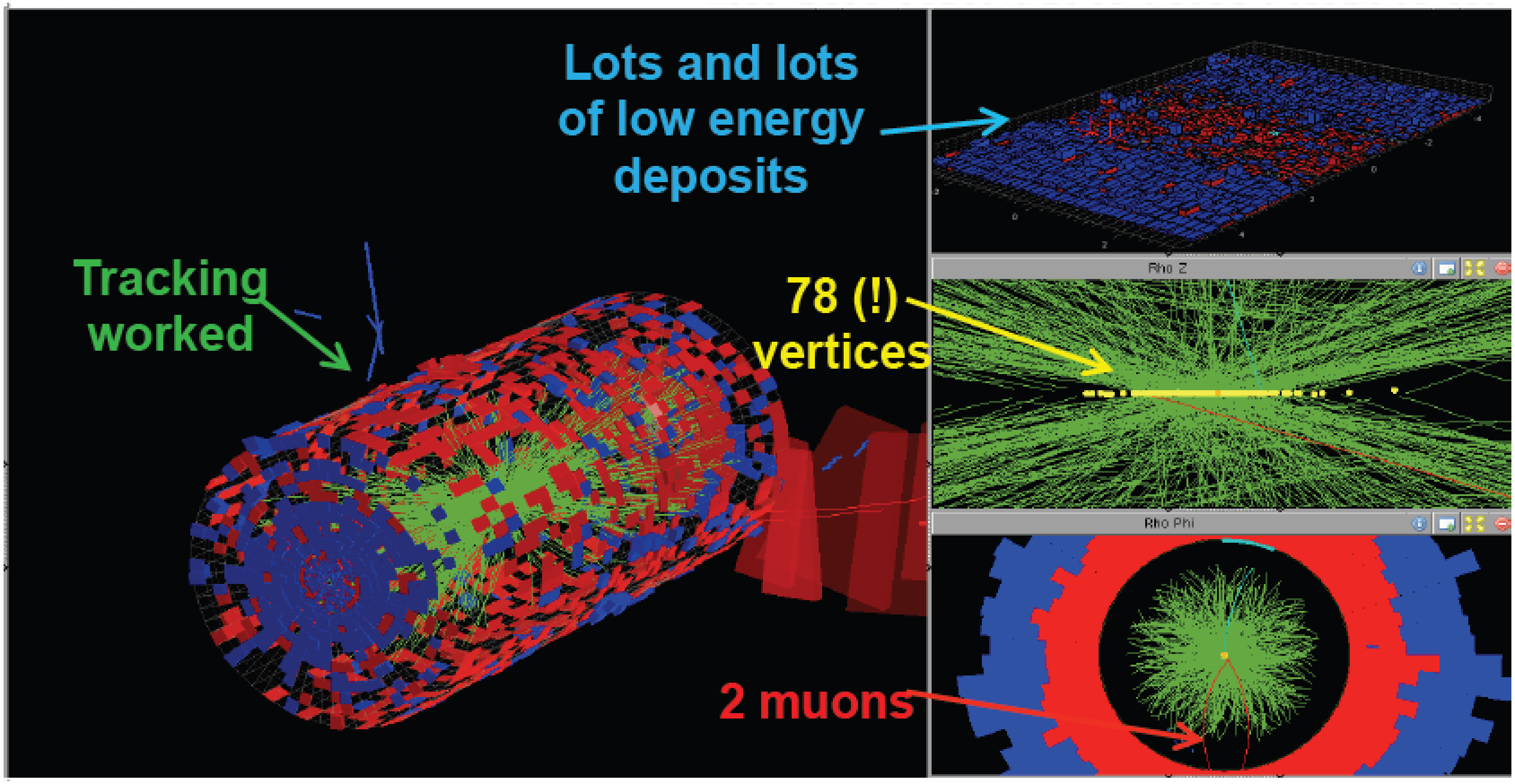
- The installation schedule for upgrades is shaped by access to the collision hall

Projected performance to LS3



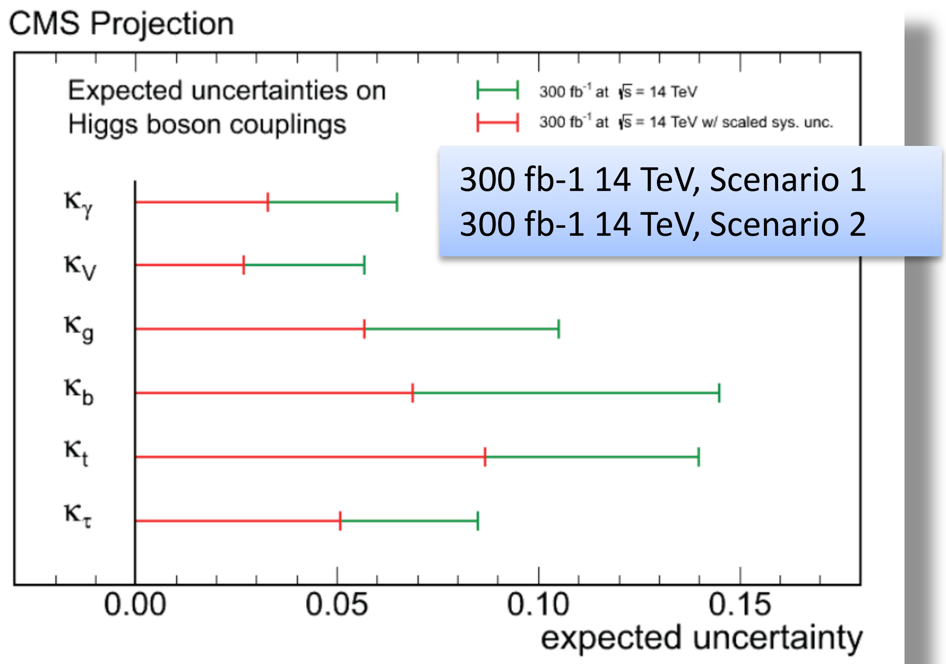
Total integrated luminosity: 300 – 400 fb^{-1}

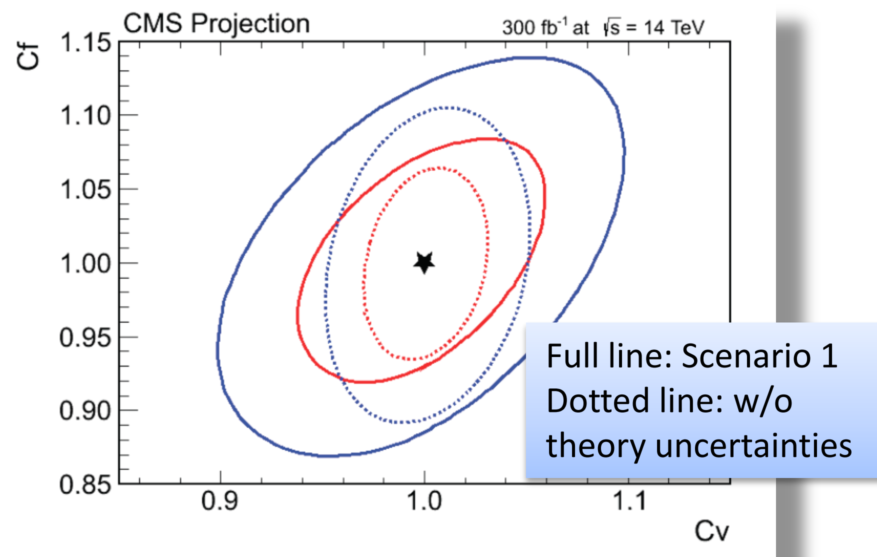
Pileup!


Lots and lots
of low energy
deposits
Tracking
worked
78 (!)
vertices
2 muons
Rho Z
Rho Phi

Projected Higgs couplings with 300 fb^{-1}

- Two scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{(\int L dt)}$





Extracting Couplings*

- are taken into account.
- The tensor structure is assumed to be SM.

=>observed state assumed to be a CP-even scalar

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

**LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle* http://arxiv.org/abs/1209.0040v1