Experiments Upgrade Roadmap

Geneva, October 29th, 2015

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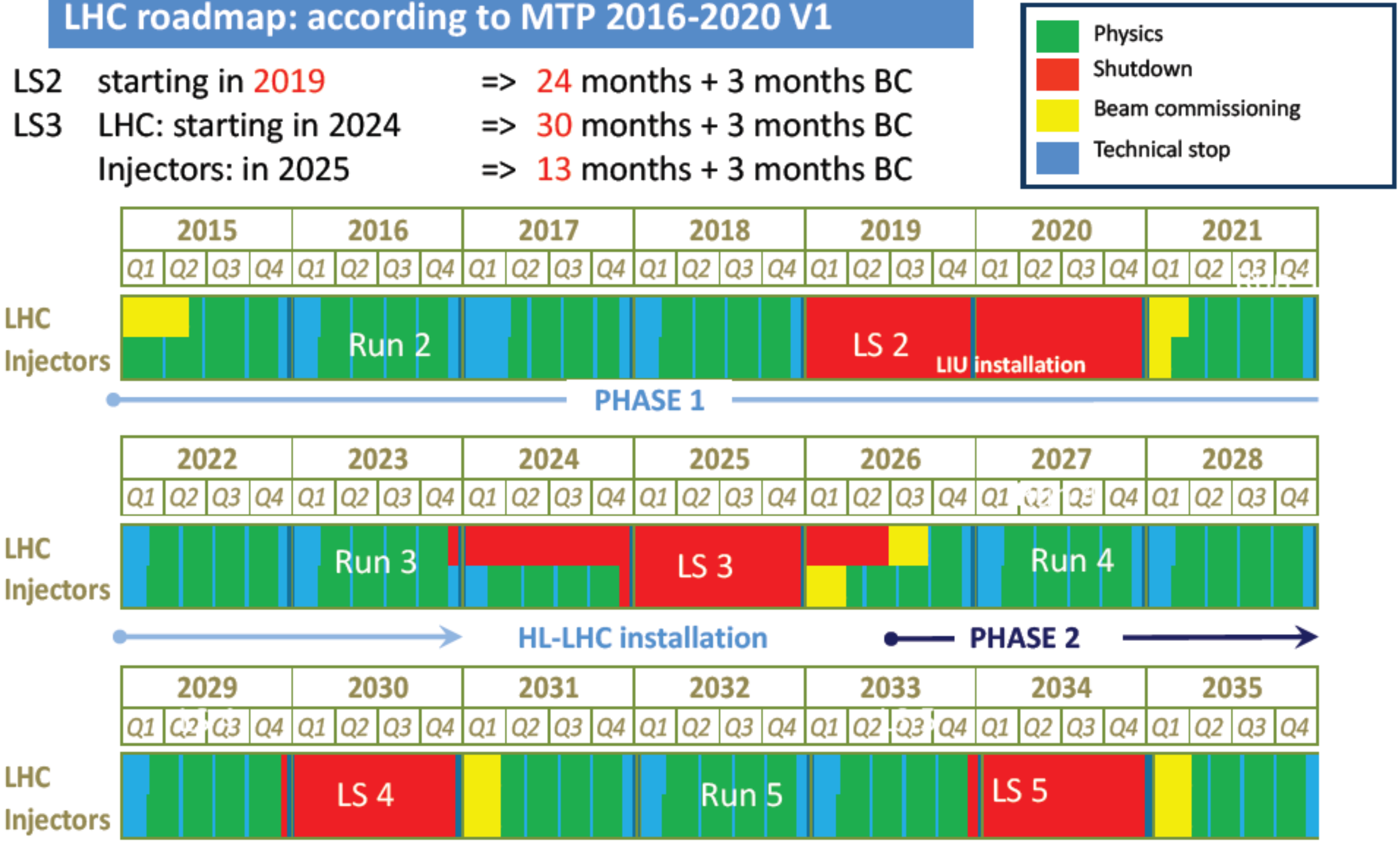
The time frame

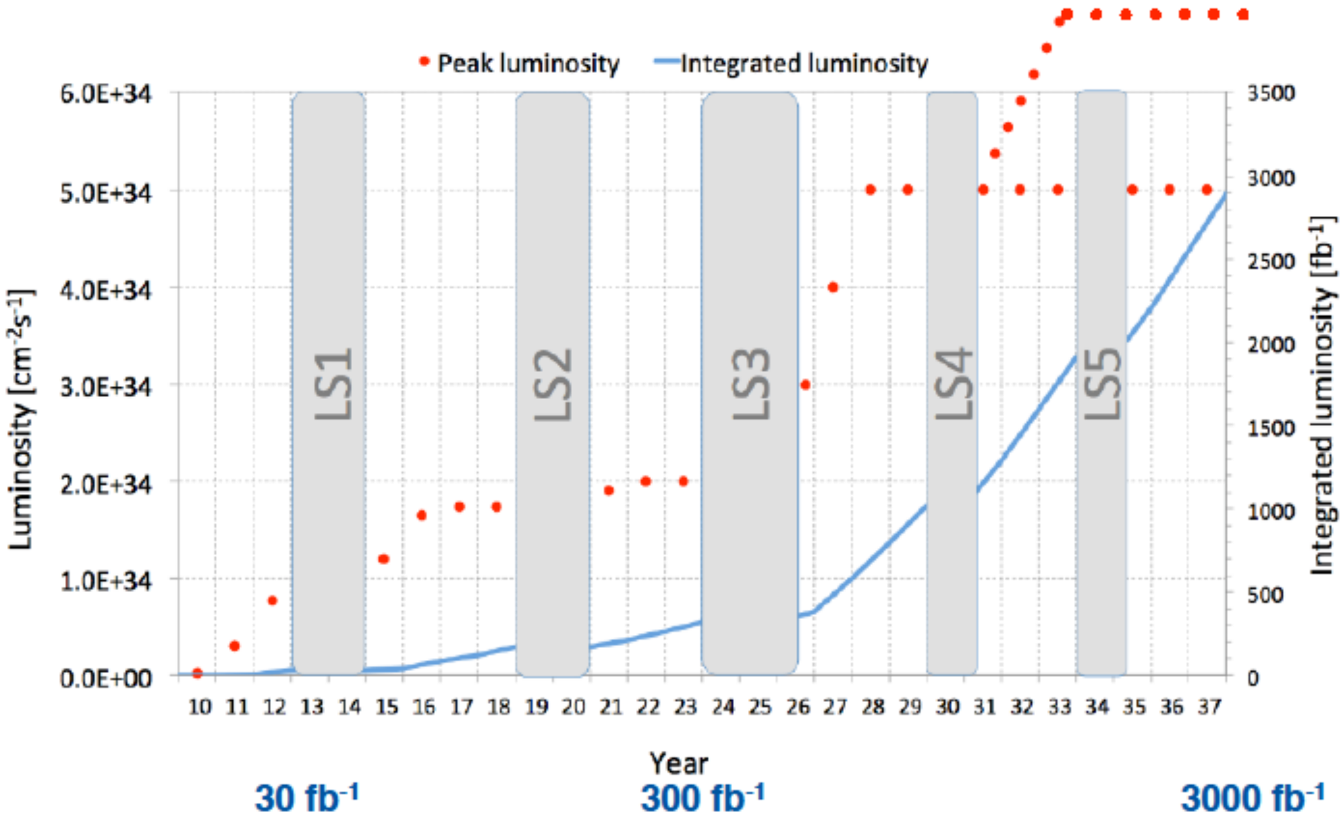
LHC roadmap: according to MTP 2016-2020 V1

LS2 starting in 2019 => 24 months + 3 months BC
LS3 LHC: starting in 2024 => 30 months + 3 months BC
Injectors: in 2025 => 13 months + 3 months BC



The assumptions

- 3000 fb-1 is the target integrated luminosity
- 5E34 —> 140 Pile-up is the nominal peak luminosity
- 7E34 —> 200 Pile-up is the ultimate peak luminosity (>LS4)



Phase II Detectors Upgrades

- **Maintain detector performance** in the presence of high radiation doses, increased pile-up, and challenging trigger rates.
  - Possibly introduce moderate performance improvements that will allow to take fully advantage of the HL-LHC physics program, e.g. extended coverage
  - Detectors must work well at nominal luminosity (140PU) and only moderately degrade at ultimate luminosity (200PU)
- Upgraded detectors will be **installed during LS3**, currently scheduled for 2.5 years starting in 2024
  - Some limited and mature elements may be installed in LS2, with some advantage in terms of schedule, early tests, and reduced material activation: CMS FWD GEM, beam pipes, …
- Many detector elements, readout electronics, data acquisition system and online computing will require significant upgrades —> part of this review
  - Also distributed offline computing will require significant redesign and improvements —> part of a separate review process

The approval process

- **Document** detailing the process prepared in consultation with DRC and the experiments
  - **Step1**: Approval of preliminary design for the complete set of Phase-II upgrades - September 2015
    - Including scoping options
  - **Step2**: Approval of baseline design, cost and schedule - TDRs starting in 2016
  - **Step3**: Approval for construction
- After several iterations with RRB and Experiments, DRC sent final version to RRB on September 29 (DRC-2015-058)
  - More direct interaction of RRB with LHCC and UCG chairs
- ATLAS and CMS Step1 documents received (in pieces) between May and September and reviewed over the summer by LHCC and UCG
  - Draft UCG reports available
  - LHCC position contained in the summary

Step 1 Elements (I)

Physics motivation and performance, with a discussion of the **optimization of cost vs. capability**. In particular it is important to produce good quantitative justification for any detector extension or improvement, for instance, in terms of solid angle coverage or other enhanced functionality.

A **detailed description** of each element of the upgrade, supported by R&D or prototyping results.

Plan and schedule for remaining R&D, prototyping, etc. needed to develop detailed designs, and to determine final cost estimates and schedule.

Plans **for selecting among alternative technical solutions**, if any.

Step 1 Elements (II)

Current estimates of approximate total **CORE project co**sts, manpower, schedule and needed funding profile, in the appropriate detail to complete this step of the review.

A preliminary **top-level project management plan** setting out the project organisation, key milestones (including project phases and review strategy), deliverables, and risk analysis

A **list of expected Technical Design Reports (TDRs)** and an overall plan with milestones and schedule for producing them.

Options for the upgrade scoping with a total cost in the approximate range 200–235–275 MCHF with an analysis of the impact on the physics performance and in particular on the agreed performance benchmarks.

Step 1 Money Matrix

The experiment will provide a separate document containing a preliminary funding plan, which takes account of inputs on the likely scale of funding from the Funding Agencies' involved, with the "**money-matrix**" expected from the various funding agencies. This document will be treated in **strict confidentiality** between the parties involved in each Experiment, and at this stage, will only represent **preliminary planning figures** from the Funding Agencies.

Step1 Review Process

- The LHCC will be responsible for a **complete review** of the projects presented by the collaborations for technical feasibility and capability to address the science, based on the documentation and on direct interactions with the project management team, while the **UCG** will specifically review the evaluation of the **cost and schedule.**

- The reviews by LHCC and UCG will include consultation with CERN Management and the Funding Agencies to clarify any potential issues or concerns and provide relevant information, so that these can be taken into account in analysing options for the detector upgrade scoping and formulating their recommendations.

Step 1 Approval Process

- The findings of the LHCC/UCG will be **submitted to the CERN Research Board (RB)**, which will issue a recommendation for the **scale of funding** for the Phase II Upgrade, upon the verification that an optimal balance between experiments requests, physics performances and funding availability has been achieved. —> **Done on Sep 30.**

- The findings of the LHCC and UCG Committees will be presented by their Chairs at a **special session of the October 2015 RRB** meeting, followed by the request by the CERN Management to endorse the RB recommendations and the associated **scale of funding** for ATLAS and CMS Phase II upgrades. CERN Management will then inform the experiments, allowing them to proceed to the next phase of the process —> OCT 26

Documentation basis

ATLAS	CMS
Lettor Of Intent: https://cds.cern.ch/record/1502664	Technical Proposal (TP) https://cds.cern.ch/record/2020886
Scoping Document: 271 - 229 - 200 MCHF	Scoping Document 265 - 242 - 208
Detailed cost estimates provided during the UCG review	Detailed cost estimates provided during the UCG review
Confidential money matrix	Confidential money vector

A big effort

- Experiments have done a lot of serious work to define the upgrade program
- Simulations are in general realistic, although in some cases various parametrizations and approximations have been used
- Costing has been presented in great detail (WBS level 4 or more), assigning a quality flag to each estimate that defines the level of uncertainty
- In sharp contrast to the original construction, the upgrades are based on years of experience with successful detectors: evolution vs going where no-one had gone before.
- Plans to produce TDRs are well defined, starting in 2016

ATLAS Upgrades

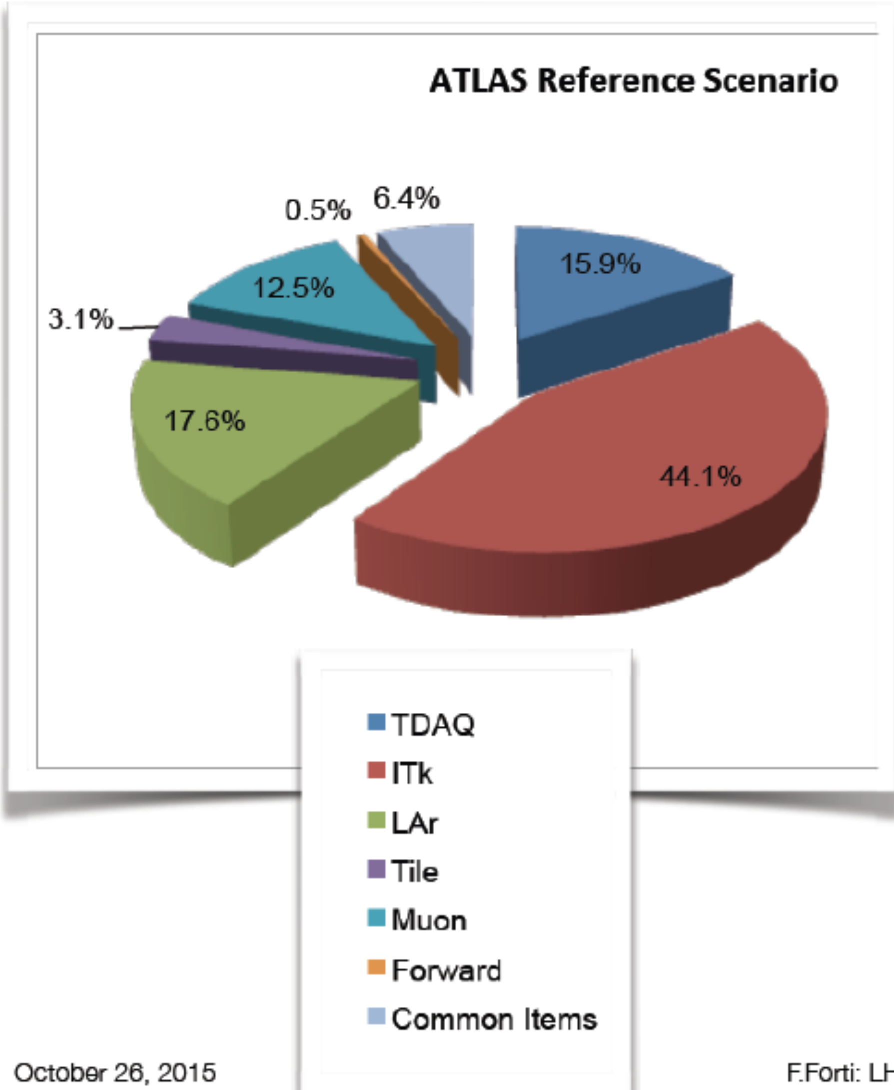
- Main upgrade elements in the Reference scenario
  - The TDAQ (Trigger and Data Acquistion): uses a 2-level hardware trigger (L0/L1) with enhanced specifications of 1 MHz/400 kHz rates and 10μs/60μs latencies, and a 10 kHz EF output rate.
  - The ITk (Inner Tracker): (outer) Strip system uses LoI layout defined in 2012, while (inner) Pixel layout starts from LoI layout and extends tracking from $\eta = 2.7 \rightarrow 4.0$.
  - The LAr: includes a full readout upgrade to 40 MHz streaming off-detector, a replacement of the current FCal with a finely segmented sFCal, and the addition of a high-precision timing detector in the η range of $2.4 \rightarrow 4.3$.
  - The Tile: includes a full readout upgrade to 40 MHz streaming off-detector, and the inclusion of the last (D) layer information in the L0 Muon trigger.
  - The Muons: include replacement of all on-chamber electronics, including the BI inner-barrel region, with replacement of MDTs with sMDT+RPC in this region, addition of an RPC-seeded L0 MDT trigger, and a muon-tagger for η of $2.6 \rightarrow 4.0$.

Physics channels

- Study the effect of scoping options on physics objects and physics channels

Detector system	Trigger–DAQ		Inner Tracker	Inner Tracker + Muon Spectrometer	Inner Tracker + Calorimeter		
Object Performance / Physics Process	Efficiency/ Thresholds $\mu^{\pm}$	$e^{\pm}$	b-tagging	$\mu^{\pm}$ Identification/ Resolution	Pile-up rejection	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$
$H \longrightarrow 4\mu$	✓			✓			
VBF $H \to ZZ^{(*)} \to \ell\ell\ell\ell$	✓	✓		✓	✓	✓	
VBF $H \to WW^{(*)} \to \ell\nu\ell\nu$	✓	✓	✓	✓	✓	✓	✓
SM VBS ssWW	✓	✓		✓	✓	✓	✓
SUSY, $\chi_1^{\pm}\chi_2^{o} \to \ell b\bar{b} + X$	✓	✓	✓	✓	✓	✓	✓
BSM $HH \to b\bar{b}b\bar{b}$			✓			✓	

Scoping options



WBS	Detector system	Reference Detector Total Cost [MCHF]	Middle Scenario Differential Cost [MHCF]	Low Scenario Differential Cost [MCHF]
	ATLAS	**271.04**	**-42.55**	**-71.16**
1.	TDAQ	43.31	-11.41	-18.19
1.1	L0 Central Trigger	1.21	-	-
1.2	L0 Calorimeter Trigger	0.70	-	-0.24
1.3	L0 End-cap Muon	2.56	-0.11	-0.11
1.4	L0 Barrel Muon	1.32	-0.14	-0.17
1.5	L1 Central Trigger	1.93	-	-
1.6	L1 Global Trigger	3.39	-	-
1.7	L1 Track	4.19	-0.67	-2.49
1.8	FTK++	13.03	-4.88	-9.56
1.9	DAQ/Event Filter	14.98	-5.62	-5.62
2.	ITk	120.36	-7.2	-23.6
2.1	Pixel	32.19	-0.9	-4.8
2.2	Strip	72.10	-6.3	-18.8
2.3	Common Items	16.08	-	-
3.	LAr	45.98	-13.60	-13.60
3.1	Read-out electronics	31.39	-	-
3.2	sFCal	10.03	-10.03	-10.03
3.3	HGTD	4.56	-4.56	-4.56
3.4	LAr MiniFCal		*+0.91*	
3.5	Si-based MiniFCal		*+3.57*	
4.	Tile	8.58	-	-
5.	Muon	34.08	-8.78	-12.79
5.1	MDT	7.69	-2.07	-3.16
5.2	RPC	7.99	-2.32	-4.79
5.3	TGC	4.44	-	-
5.4	High-Eta Tagger	3.50	-3.50	-3.50
5.5	Power System	10.47	-0.89	-1.34
6.	Forward	1.30	-	-
7.	Integration & Installation	17.42	-1.56	-2.98

Cutting into the flesh

Trigger and Data Acquisition	Reference (275 MCHF)	Scoping Scenarios Middle (235 MCHF)	Low (200 MCHF)
Level-0 Trigger System			
Central Trigger	✓	✓	✓
Calorimeter Trigger (e/γ)	$\lvert\eta\rvert < 4.0$	$\lvert\eta\rvert < 3.2$	$\lvert\eta\rvert < 2.5$
Muon Barrel Trigger	MDT everywhere RPC-BI Tile-μ	MDT (BM & BO only) Partial η coverage RPC-BI Tile-μ	MDT (BM & BO only) No RPC-BI Tile-μ
Muon End-cap Trigger	MDT everywhere	MDT (EE&EM only)	MDT (EE&EM only)
Level-1 Trigger System			
Output Rate [kHz]	400	200	200
Central Trigger	✓	✓	✓
Global Trigger	✓	✓	✓
Level-1 Track Trigger (*RoI based tracking*)	$p_T > 4$ GeV $\lvert\eta\rvert \le 4.0$	$p_T > 4$ GeV $\lvert\eta\rvert \le 3.2$	$p_T > 8$ GeV $\lvert\eta\rvert \le 2.7$
High-Level Trigger			
FTK++ (*Full tracking*)	$p_T > 1$ GeV 100 kHz	$p_T > 1$ GeV 50 kHz	$p_T > 2$ GeV 50 kHz
Event Filter	10 kHz output	5 kHz	5 kHz
DAQ			
Detector Readout	✓ [400 kHz L1 rate]	✓ [200 kHz L1 rate]	✓ [200 kHz L1 rate]
DataFlow	✓ [400 kHz L1 rate]	✓ [200 kHz L1 rate]	✓ [200 kHz L1 rate]

Detector System	Reference (275 MCHF)	Scoping Scenarios Middle (235 MCHF)	Low (200 MCHF)
Inner Tracker			
Pixel Detector	$\lvert\eta\rvert \le 4.0$	$\lvert\eta\rvert \le 3.2$	$\lvert\eta\rvert \le 2.7$
Barrel Strip Detector	✓	✓ [No stub layer]	✓ [No stereo in layers #2,#4] [Remove layer #3] [No stub layer]
Endcap Strip Detector	✓	✓ [Remove 1 disk/side]	✓ [Remove 1 disk/side]
Calorimeters			
LAr Calorimeter Electronics	✓	✓	✓
Tile Calorimeter Electronics	✓	✓	✓
Forward Calorimeter	✓	✗	✗
High Granularity Precision Timing Detector	✓	✗	✗

Muon Spectrometer	Reference (275 MCHF)	Scoping Scenarios Middle (235 MCHF)	Low (200 MCHF)
Barrel Detectors and Electronics			
RPC Trigger Electronics	✓	✓	✓
MDT Front-End and readout electronics (BI+BM+BO)	✓	✓ [BM+BO only]	✓ [BM+BO only]
RPC Inner layer in the whole layer	✓	✓ [in half layer only]	✗
Barrel Inner sMDT Detectors in the whole layer	✓	✓ [in half layer only]	✗
MDT L0 Trigger Electronics (BI +BM+BO)	✓	✓ [BI +BM only]	✓ [BI +BM only]
End-cap and Forward Muon Detectors and Electronics			
TGC Trigger Electronics	✓	✓	✓
MDT L0 Trigger and Front-End read-out electronics (EE+EM+EO)	✓	✓ [EE +EM only]	✓ [EE +EM only]
sTGC Detectors in Big Wheel Inner Ring	✓	✓	✓
Very-forward Muon tagger	✓	✗	✗

Physics reach effects

SM physics: H —> ZZ —> 4mu

Scenario	$H \to 4\mu$	$ZZ^{(*)} \to 4\mu$	$\Delta\mu/\mu$
Reference	2551 ± 51	741 ± 27	0.022
Middle	2104 ± 46	351 ± 19	0.024
Low	2014 ± 45	336 ± 18	0.024

EWSB @ TeV Scale: Vector-Boson Fusion/Scattering

Scenario	VBF $H \to WW^{(*)}$	VBF $H \to ZZ^{(*)}$	VBS ss$W^\pm W^\pm$
Reference	0.14	0.134	0.088
Middle	0.20	0.137	0.165
Low	0.30	0.142	0.199

Equivalent luminosity, or equivalent mass reach for new fenomena

chargino + neutralino / resonant hh —> 4b

Scenario	SUSY $\chi_1^\pm \chi_2^0 \to \ell b\bar{b} + X$		BSM $HH \to b\bar{b}b\bar{b}(M_{G^*_{KK}}$=2.0 TeV)	
	Mass (GeV)	$\mathcal{L}^{\text{int}}_{\text{equiv.}}$ [fb^{-1}]	Significance	$\mathcal{L}^{\text{int}}_{\text{equiv.}}$ [fb^{-1}]
Reference	850	3000	4.4	3000
Middle	770	6000	4.5	
Low	675	12000	3.1	7200

For some physics the middle and low scenario correspond to x2/x4 equivalent luminosity

Run1 - Run2 - Phase I - Phase II

ATLAS LHCC Summary

- The ATLAS Reference Scenario (271 MCHF) provides a fully performant detector capable of addressing the physics at the HL-LHC.
- The Reference Scenario provides manageable performance degradation between 140 interactions per crossing, which is the baseline HL-LHC luminosity, and 200 interactions per crossing, which is currently considered as the ultimate HL-LHC luminosity.
- The limitations of the Low Scenario (200 MCHF) are very apparent, especially in terms of the reduced tracking/muon coverage and its consequences on the physics, offering significantly worse detector capabilities.
- The Middle Scenario (229 MCHF) is generally less performant than the Reference Scenario, reducing redundancy and robustness of the apparatus and it is noticeably worse in the detector's physics capabilities especially in the presence of even a small fraction of detector inefficiency.
- In some physics cases, the reduced detector capability is equivalent to requiring a factor two (Scenario 2) or a factor four (Scenario 1) in additional luminosity (and thus running time) to compensate for the reduced performance.

ATLAS UCG Summary

- The ATLAS reference detector cost estimate is CHF 271 M. The cost estimates are very well developed for this stage, and provide a firm basis for our reports to the RB and RRB. Risk analysis and mitigation strategies are underway.
- In particular the forward LAr and the Muon system have major technical choices ahead, with possible significant implications on cost and schedule.
- We are encouraged to see ATLAS actively exploring opportunities to combine procurements with other experiments for "big ticket" items like silicon, power supplies, etc.
- The funding outlook is guardedly optimistic, with substantive, relatively encouraging interactions in progress with the FA's, in much greater detail than at this stage of original construction. Large uncertainties remain, and it will take a lot of time to secure commitments. Fortunately there appears to be an almost complete alignment of interests with needs.

- **We conclude that the ATLAS Phase II upgrade project is ready to proceed to detailed detector design, and to establish a baseline cost and schedule for construction.**

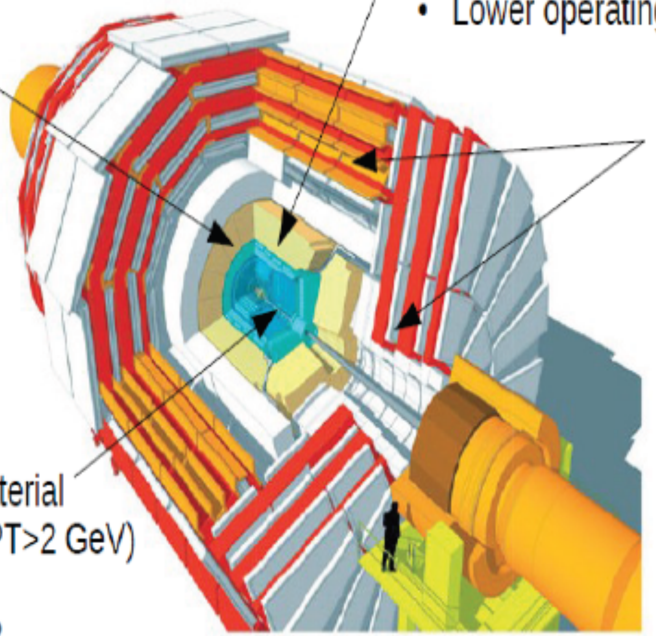
Recommendation

CMS Upgrade

- Main upgrade elements in the reference scenario

New Endcap Calorimeter
- Radiation Tolerant
- High Granularity
- 3D capability

Barrel Calorimeter
- Replace FE/BE electronics
- Lower operating temperature(8°)



Muon system
- Replace DT/CSC FE/BE electronics
- Complete RPC coverage In region $1.5<\eta<2.4$
- Muon tagging with GEMs for $2.4<\eta<3.0$

New Tracker
- Radiation tolerant – less material
- 40 MHz selective readout (PT>2 GeV) for track trigger
- Extend to coverage of $\eta\sim3.8$

Trigger/HLT/DAQ
- L1 Track Trigger
- L1 Trigger: 12.5 μs latency, 750 kHz output
- HLT output of 7.5 kHz

CMS Upgrade Reference Scenario

CORE cost estimate	MCHF (2014)
Pixel Detector	23
Outer tracker	89
Tracking System	**112**
EB electronics	10
HB scintillators	1
Endcap HGC+BHE	64
Calorimeters	**75**
DT and CSC electronics	10
Muon stations:GE11,GE21, RE31 and RE41	10
Muon extension ME0	5
Muon Systems	**25**
Beam Monitors and Luminosity	**4**
Hardware trigger	7
HLT	11
DAQ	6
Trigger and DAQ	**24**
Infrastructure, Systems and Support, Installation	**25**
Total	**265**

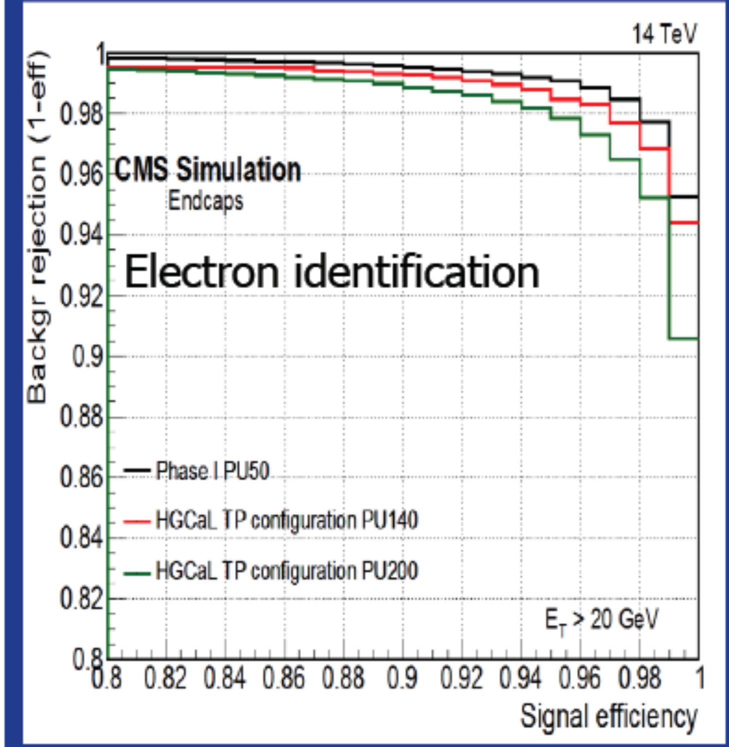
CMS Scoping

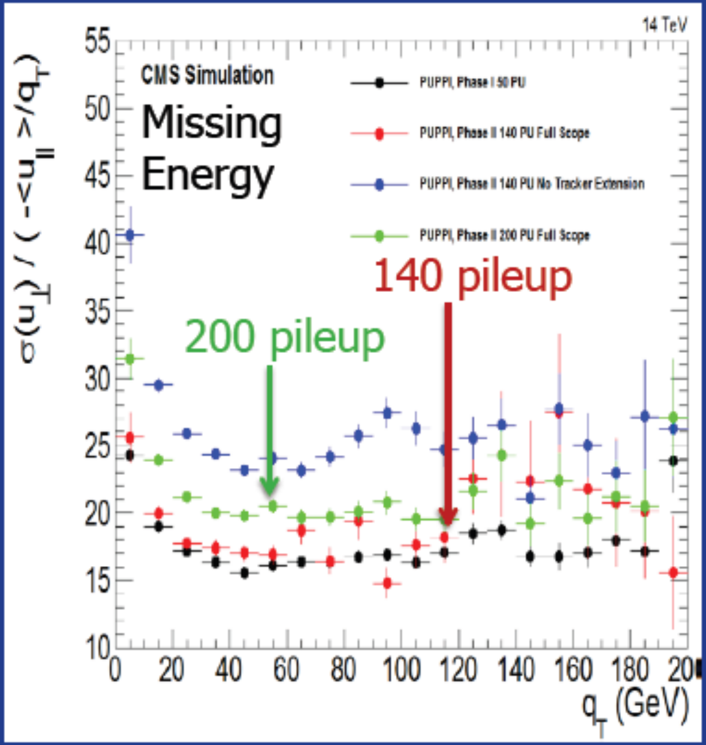
Upgrade configuration of $\simeq$ 242 MCHF cost			
De-scoped item	**Operation and performance impact**	**Cost reduction (MCHF)**	**Recoverability**
Tilted modules in the outer tracker	Track-trigger resolution	3.9	No
No Muon endcap stations 3 and 4	Redundancy, efficiency and resolution	2.0	Yes
No replacement of CSC stations 3 and 4 readout	Efficiency at trigger rate $\geq$ 500 kHz	2.5	Yes
HLT/DAQ power	Trigger rate $\leq$ 300 kHz	8.0	Yes
HGC 24-11 layers	Energy resolution, pileup mitigation, shower pointing, timing	7.0	No
TOTAL cost reduction		**23.4**	

Upgrade configuration of $\simeq$ 208 MCHF cost			
De-scoped item	**Operation and performance impact**	**Cost reduction (MCHF)**	**recoverability**
Tilted modules in the outer tracker	Track-trigger resolution	3.9	No
No Muon endcap stations 3 and 4	Redundancy, efficiency and resolution	2.0	Yes
No replacement of CSC stations 3 and 4 readout	Efficiency at trigger rate $\geq$ 500 kHz	2.5	Yes
HLT/DAQ power	Trigger rate $\leq$ 300 kHz	8.0	Yes
No Muon endcap stations 2	Redundancy, efficiency and resolution	4.0	Yes
No Muon extension to $\eta \simeq 3$	Muon acceptance	4.5	No
HGC 18-9 layers	Energy resolution, pileup mitigation, shower pointing, timing	13.0	No
No Pixel extension $\eta \simeq 4$	Pileup, jet tagging and Missing ET	7.7	Yes
No replacement of Muon DT minicrates	Efficiency and trigger rate $\leq$ 300 kHz	6.1	Yes
One less layer in outer tracker barrel	Track-trigger efficiency	5.0	No
TOTAL cost reduction		**56.7**	

Performance at increased pileup

- **Calorimeter based quantities are affected in the following manner**
  - **Electron identification loss is less than 5%**
  - **Missing energy resolution degrades by ~15%**
    - **And potentially can be improved using shower topology and precision timing provided by the high granularity forward calorimeter**



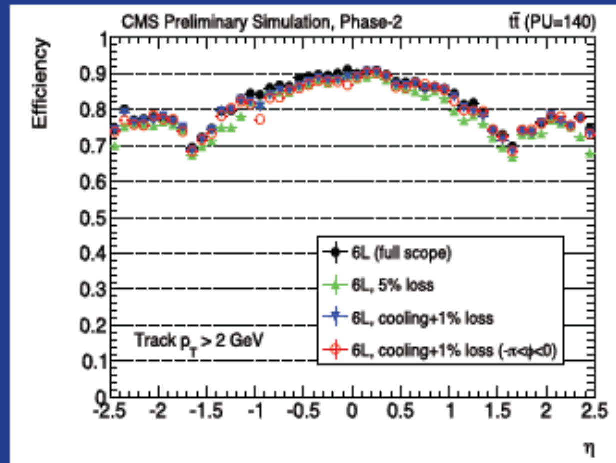


Scoping effects

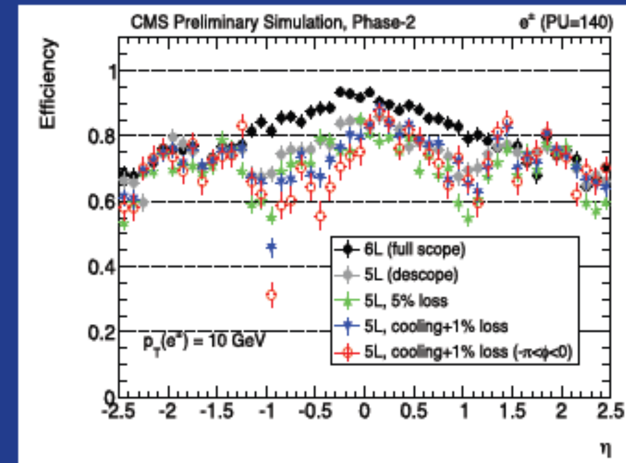
- Tracker scoping affects efficiency and redundancy: much more sensitive to module or cooling losses

- Calorimenter scoping degrades energy and angular resolution

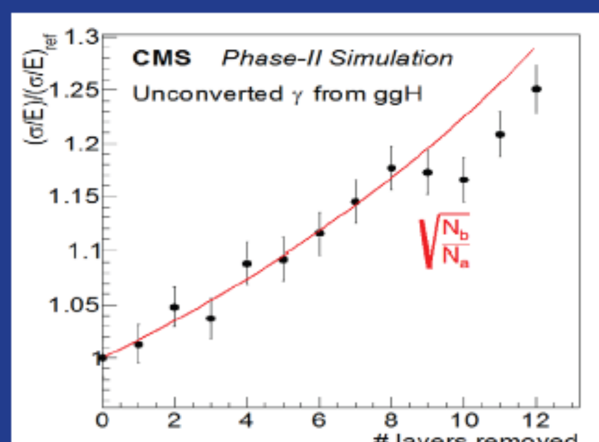
Full Scope

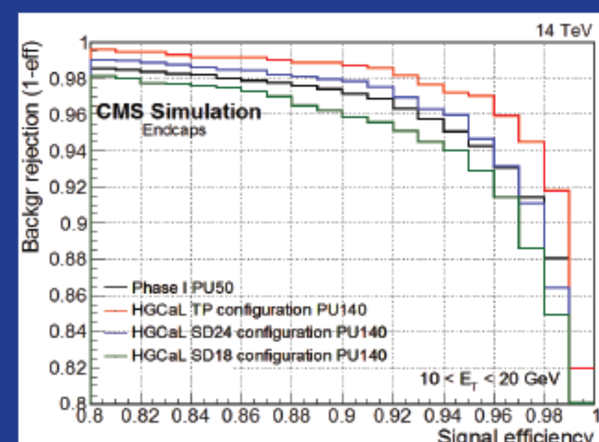


One less tracking layer



Photon energy resolution degrades by ~10(25)% in Scenario 1 (Scenario 2)
Electron fake rate increases by 60% (x2.5) in Scenario 1 (Scenario 2) at typical 90% efficiency working point





Combined effect of scoping scenarios

The effect of the combined descopes on the physics reach for selected benchmarks signals is expressed as an increase factor to the operation time that would be needed to compensate the performance degradation - studies presented are for the baseline luminosity (140 PU)

Scenario 1

Process	Descoped items	Effects considered	Impact
VBF $H \to \tau\tau$	trigger	trigger acceptance	1.25
$H \to \mu\mu$	RPC	muon id.	1.02
$H \to 4e$	HGCAL (24/11)	electron resolution, id., and acceptance	1.3

Scenario 2

Process	Descoped items	Effects considered	Impact
VBF $H \to \tau\tau$	trigger, tracker ext.	trigger acc., E_T^{miss} res., jet counting	4.2
$H \to \mu\mu$	muon system	muon id.	1.25
$H \to 4\mu$	tracker ext.	muon acceptance	1.25
$H \to 4e$	HGCAL (18/9), tracker ext.	electron res., id., and acc.	2.0
$W^{\pm}HE_T^{miss}$	tracker ext.	E_T^{miss} resolution	6.7

- **A scenario of reduced scope, to lower the upgrade cost in the range of 240 MCHF, would sustain good performance, but cannot ensure a similar performance to post Phase I upgrade period**
- **A scenario of further reduced scope, to lower the cost in the range of 200 MCHF, will have a significantly adverse effect on the HL-LHC program**

CMS LHCC Summary

- The Reference Scenario with total CORE cost of 265 MCHF is a well-developed proposal that can fully exploit the physics potential of HL-LHC, providing manageable performance degradation between 140 interactions per crossing, which is the baseline HL-LHC luminosity, and 200 interactions per crossing, which is currently considered as the ultimate HL-LHC luminosity.
- Scoping Scenario 1 (242 MCHF), while preserving the main experiment performance, significantly reduces CMS physics capabilities, especially in presence of the unavoidable detector inefficiencies.
- Scoping Scenario 2 (208 MCHF) has a significantly adverse effect on the HL-LHC physics programme with reductions in coverage and performance that for some channels would require more than a factor of four in additional luminosity, and thus running time, to obtain the same physics measurement precision.

CMS UCG Summary

- The CMS reference detector cost estimate is CHF 265 M. Cost estimates are remarkably mature, applying an appropriate level of conservatism, and provide a firm basis for our reports to the RB and RRB.
- The level of R&D and prototyping to be completed by CMS before the TDR's is relatively large. (Not part of the core costs, but critical.)
- We are therefore encouraged that CMS are assessing the uncertainty level of their cost estimates by employing industrial-like assignment of quality flags (QF 0 - 5) for unit costs and for number of required units, and have risk analyses and mitigation strategies underway. CMS is actively exploring opportunities to combine procurements with other experiments for "big ticket" items like silicon, power supplies, etc.
- The funding outlook is guardedly optimistic, with substantive, relatively encouraging interactions in progress with the FA's, in much greater detail than at this stage of original construction. Large uncertainties remain, however, and it will take a lot of time to secure commitments. Fortunately there appears to be an almost complete match of interests with needs.

- **We conclude that the CMS Phase II upgrade project is ready to proceed to detailed detector design, and to receive the funding necessary to establish a baseline cost and schedule for construction.**

Recommendation

General UCG observations

- The Collaborations have worked extremely hard and effectively to understand the scoping trade-offs, capabilities of the collaboration and the funding possibilities.
- The experiments have also made a large effort on risk analysis and mitigation strategies.
- An important role in this respect will be played by the development of common, possibly centralized, approaches to large procurements.
  - e.g. Silicon, FPGA, power supplies, ...
- The UCG recommends that a common approach is developed between the experiments and with CERN regarding the costing of the **infrastructural improvements** and of the upgrade of the **HLT farms** needed for the Phase 2 operation.

The outcome

Based on the LHCC and USG findings and their subsequent endorsement by the Cern RB, the CERN Management is the RRB agreed with the following statement:

“The RRB considers the Step1 of the approval process for the Phase II Upgrades for the ATLAS and CMS experiments **successfully completed**.

A **scale of funding between the full funding and the intermediate scenario seems to meet the performance requirements**. The CERN Management, supported by the findings of the LHCC and the UCG, considers the funding scenario realistic.

The experiments are therefore encouraged to proceed to the next step of the Phase II upgrades”

In summary

- An important step has been accomplished by the experiments
- A lot of work ahead to timely proceed to the next step.
- The interaction between machine and experiments has a key role in the final design choices
- A strong interaction with the host lab to realistically discuss the impact on the infrastructure is mandatory

Thank you!