Session 1: experiments: summary

Selection of highlights and topics of discussion from the ECFA HL-LHC Experiments Workshop (1-3 Oct) which seemed (to the speaker) to be relevant to RLIUP Austin.

The “physics landscape” 30fb-1 ––>300fb-1 ––> 3000fb-1 and thus the physics potential of the HL-LHC. Fabiola.

The need to upgrade certain key detector elements of ATLAS and CMS for ANY programme beyond 300fb-1. Beniamino

The role of the upgrade changes in mitigating the high rate, high pile-up conditions of HL-LHC needed to reach the 3000fb-1 target in a reasonable timescale. Prospects for pile-up mitigation by tuning the luminous region. Didier.

Physics motivation & realisation of the LHCb upgrade, plus the forward physics and ALICE p-p programmes. Richard

Which left Mike as the victim trying to fit the disparate requirements for operation and upgrade into a workable schedule, taking into account accelerator consolidation and upgrade options

EFCA HL-LHC expts workshop: 1-3 Oct

Motivation: ESPP document adopted by Council in May

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Strategy explicitly recommends 3 ab-1 target

DG ––> we should consider this tacit approval for the HL-LHC programme and proceed.

Further evaluation of:
- physics reach
- technical feasibility for expts and machine
- timeline & cost estimates

needed for formal approval by Research Board, Council, Funding Agencies

"Do not wait to strike until the iron is hot….make it hot by striking!!!" *W.B. Yeats*

Physics landscape & further exploration

Think like a wise (wo)man but communicate in the language of the people

W.B. Yeats

Fabiola:

Three main results from LHC Run-1

We have consolidated the Standard Model
(wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \rightarrow \mu\mu$ decay)
→ it works BEAUTIFULLY …

We have completed the Standard Model: Higgs boson discovery
(almost 100 years of theoretical and experimental efforts !)

We have NO evidence of new physics

Note: the last point implies that, if New Physics exists at the TeV scale and is discovered at $\sqrt{s}$ ~ 14 TeV in 2015++, its spectrum is quite heavy → it will require a lot of luminosity (→ HL-LHC 3000 fb^{-1}) and energy to study it in detail → implications for future machines (e.g. most likely not accessible at a 0.5 TeV LC)

Physics landscape & further exploration

However: we also know that the SM is not the ultimate theory of particle physics, because of the many outstanding questions, including:

- ❑ Why is the Higgs boson so light ("naturalness" problem) ?
- ❑ What is the the nature of the dark part (96% !) of the universe ?
- ❑ What is the origin of the matter-antimatter asymmetry ?
- ❑ Why is gravity so weak ?

There are compelling reasons to believe that answers to some of the above questions lie at the TeV scale, whose exploration JUST started …

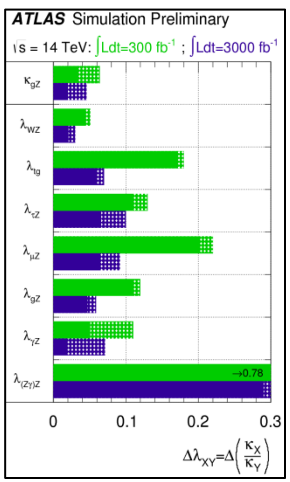
→ The STRONG physics case for the HL-LHC with 3000 fb^{-1} comes from the imperative necessity of exploring this scale as much as we can with the highest-E facility we have today (note: no other planned machine, except a 100 TeV pp collider, has a similar direct discovery potential). Likely, and perhaps more importantly, the HL-LHC will also tell us what are the right questions to ask and how to continue.

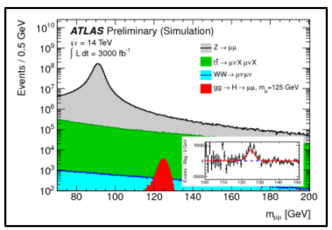
LHC —> HL-LHC: *THE* Higgs factory

today : ATLAS+CMS have 1400 Higgs events events HL-LHC (3000fb-1) > 3M/170M useful for precise measurement

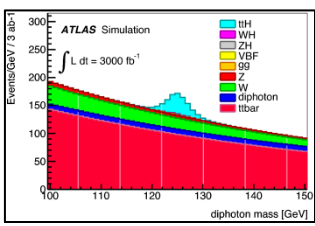
- ❑ Measure as many Higgs couplings to fermions and bosons as precisely as possible
- ❑ Measure Higgs self-couplings (give access to λ)
- ❑ Verify that the Higgs boson fixes the SM problems with W and Z scattering at high E

Couplings





ttH → γγ

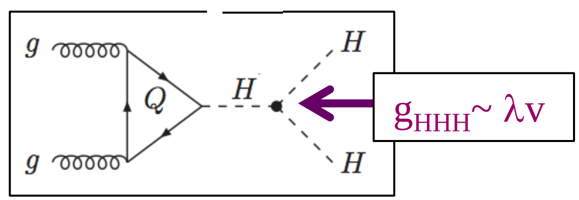


H —> μμ

x 1.5 to 2 for 300 --> 3000fb-1

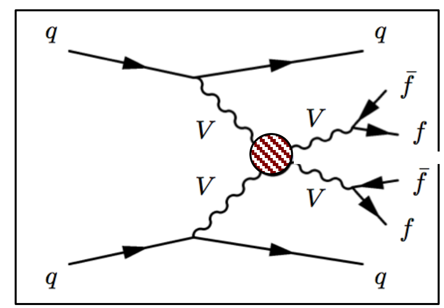
Access to rare processes

Self-coupling



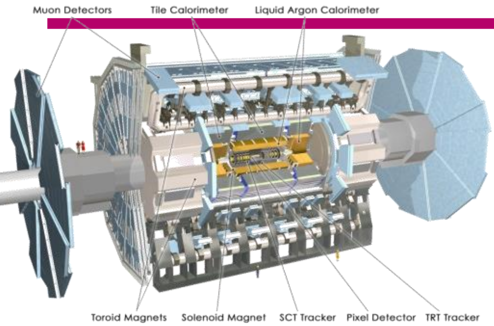
Difficult measurement precision 30% for 3000fb-1?

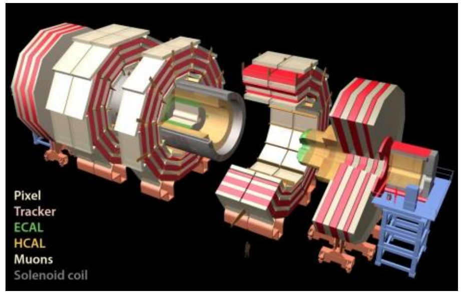
Vector boson fusion



Check if Higgs does the (whole) job of cancelling divergences

Experiment upgrades





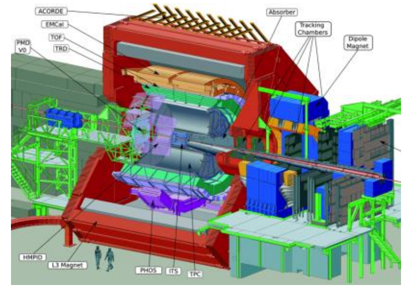
Study Standard Model in detail, including
Higgs couplings and eventually self-coupling
Continue search for Physics beyond the SM.

Requires x10 in statistics beyond design 300fb-1

Phase 0,1 upgrades in LS1, YETS and LS2
to match LHC performance over Run 2,3.

Key components of present detectors will not survive radiation beyond 500fb-1 —> Phase2

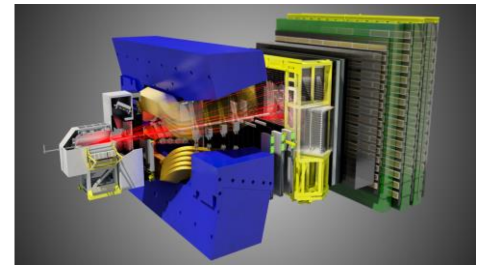
in LS3, equip for 3000fb-1 p-p over 10 years
LHC —> HL LHC : <pileup> (23 —> 140)



High statistics HI measurements using rare probe particles at low pT.

10nb-1, min bias

Single phase major upgrade to detector & readout in LS2



Record very high stats to search for effect of possible new physics on flavour structure. (complementary to ATLAS & CMS progr)
50fb-1 , 40Mz readout

Single phase major upgrade to detector & readout in LS2

Phase1 upgrades

ATLAS & CMS: some analogy to PIC's – few radical changes in technology

- Phase 1 upgrades are needed to maintain performance beyond 1×10^{34} Hz/cm^2, PU ~ 25

By run 3: pixel, new muon stations, trigger, calorimeter improvements:

- With these upgrades ATLAS and CMS will be able to operate with good performance up to PU of ~ 70 and integrated luminosity ~ 500 fb^{-1} (max) [PU will be severe limit if @ 50ns]

LHCb and ALICE:

potential of existing detectors becoming exhausted by LS2 (doubling time v. long)
major upgrades to detector & readout in LS2 ––> program extending well into HL-LHC era
operation assumes levelled luminosities for rate tolerance, efficiency and physics stability

LHCb

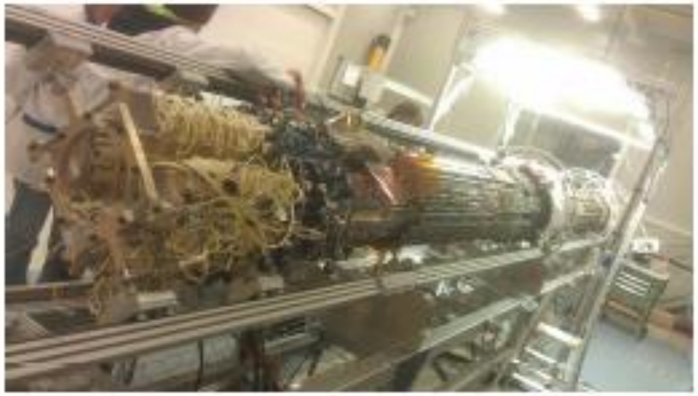
Replacement of VELO
Major upgrade of RICH optics,
Major upgrade of tracking system (technology decisions by end of this year)
Upgrade all existing detector FE electronics
1 MHz ––> 40MHz

ALICE

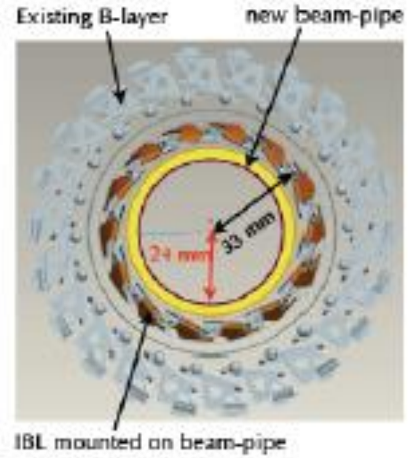
All readout :
500Hz ––> 50kHz with min bias trigger
new beampipe,
Inner tracking system
4-GEM endplates for TPC

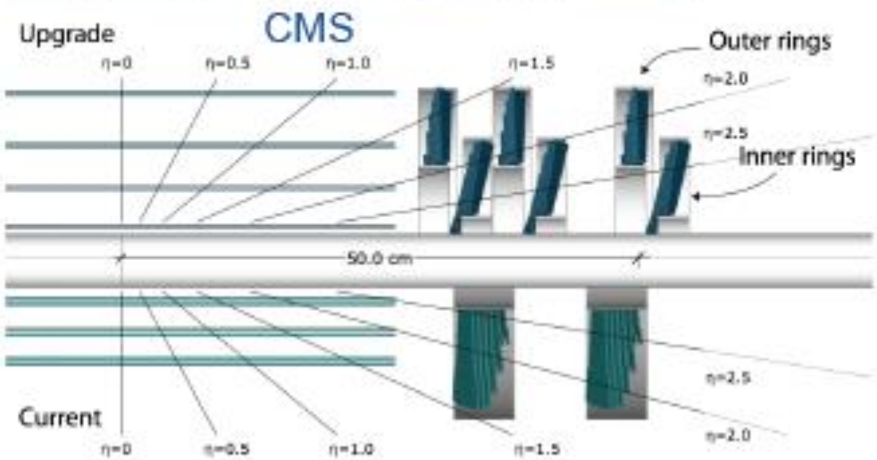
ATLAS & CMS "PICs"

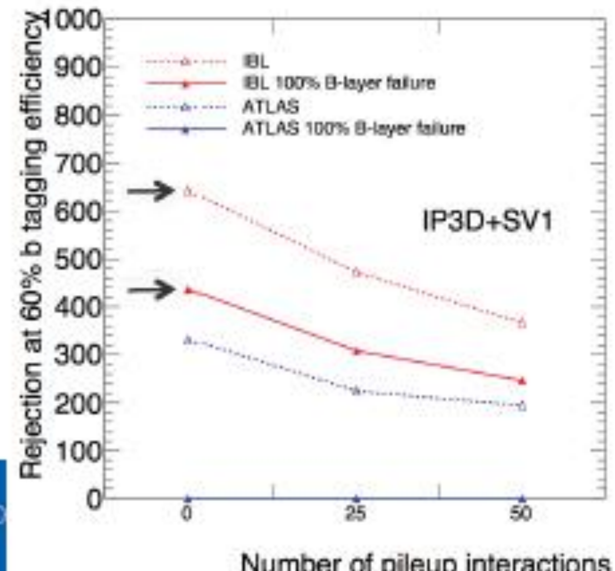
4 layer pixel trackers



ATLAS

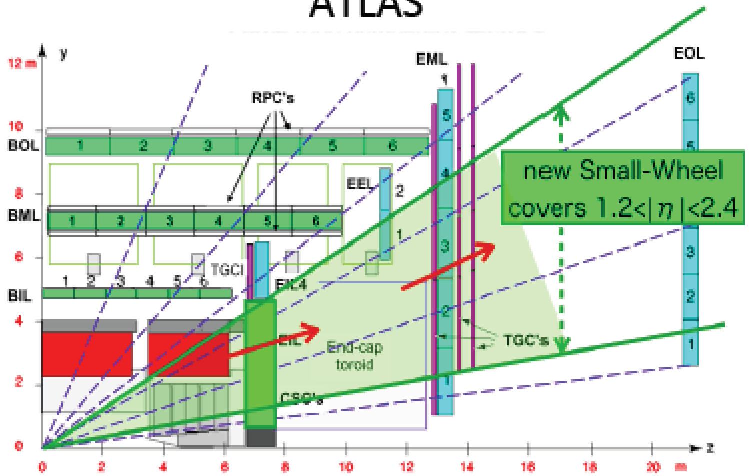




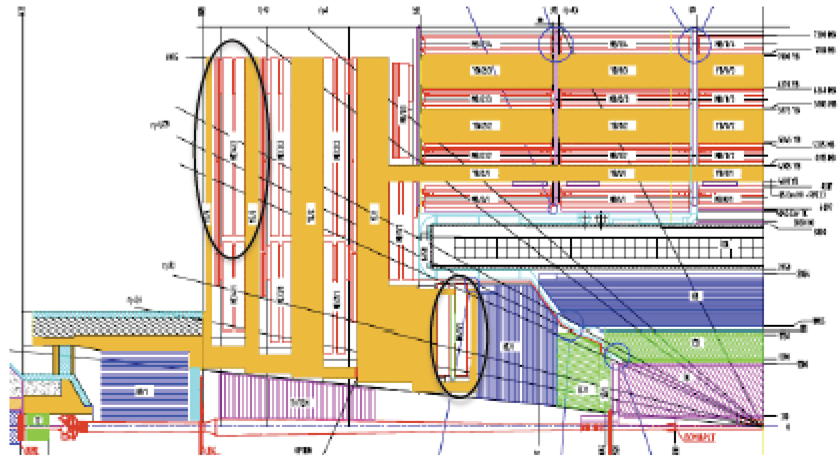


ATLAS & CMS "PIC's": muon systems

ATLAS

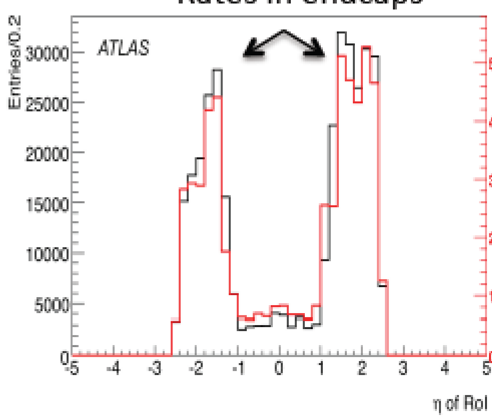


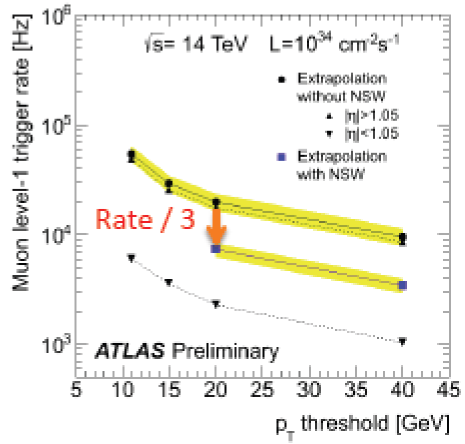
CMS

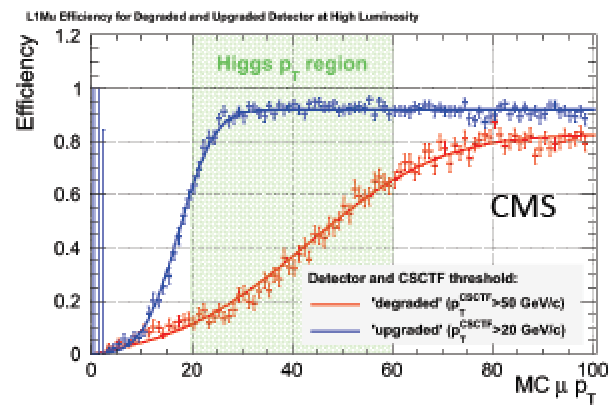


Similar issues and benefit in trigger for upgrades in ATLAS and CMS

Rates in endcaps







ATLAS & CMS: Phase 2 upgrades mandatory

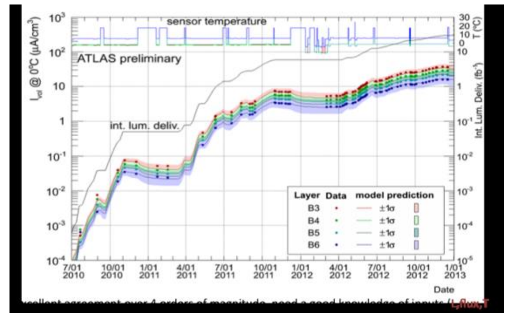
Beniamino

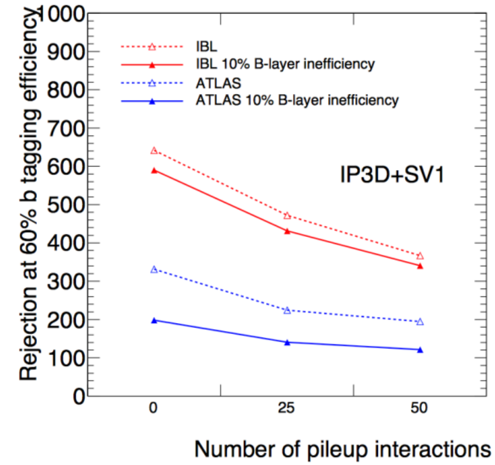
Silicon sensors: leakage current increase with radiation dose = ∫L dt.

-very well modelled

- can predict that existing detectors will be seriously compromised at ~500fb-1

-key physics quantities degrade much faster than layer inefficiency

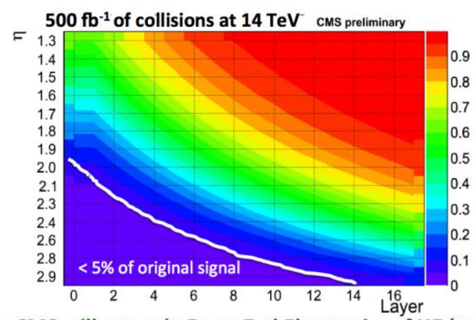


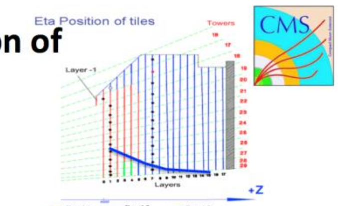


Calorimeters:

Signal (light) output reduced by radiation damage
Can prolong life with smarter readout but
at ~500fb-1, there's nothing left to work with.

Extrapolated Signal Degradation of CMS Hadron Endcap





- Extrapolated degradation based on exponential parameterizations of observed damage as a function of sampling depth (layer) and η
- At 500 fb^{-1}, in the high η region, signal drops to 5% or less of the original value.

CMS will upgrade Front End Electronics of HE (and HB) in LS2.
This upgrade will ensure performance of HE up to LS3:

- ✓ Photon Detection Efficiency (PDE) of SiPMs will be x3 higher than in present photodetectors.
- ✓ Depth segmentation will allow for re-weighing of radiation damage degradation.

CMS HCAL Endcap calorimeter will be replaced during LS3

10/2/13 Pawel de Barbaro, University of Rochester: Calorimetry/Detectors for HL-LHC 31

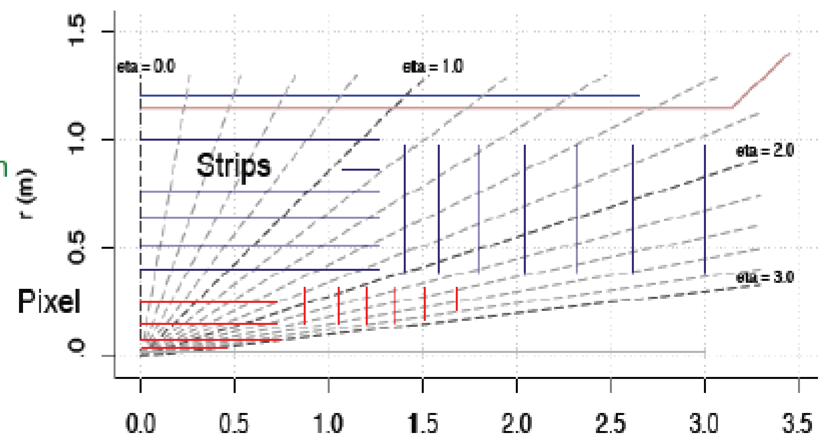
ATLAS & CMS Phase 2 trackers

Didier

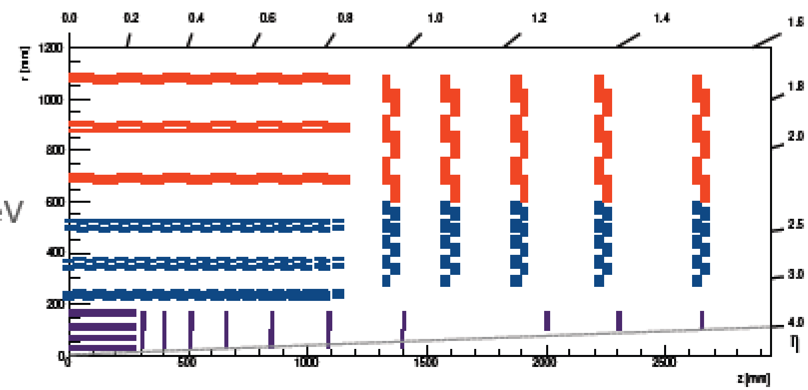
Light-weight designs using 2-phase CO2 cooling systems — Pixels will need replacement in LS's

- Common features
  - Granularity
    - Strip pitch ~ 80-90 μm & length ~ 2.5/5 cm in inner/outer layers (& macro-pixel sensors in CMS 1.5 mm long)
    - Pixel pitch ~ 25-30 μm and ~ 100 μm length
  - Sensor Technology
    - n-in-p planar technology for increased radiation hardness
    - n-in-n, 3D, diamond or other technologies for innermost layers
  - Trigger implementation
    - Custom ASIC Associative Memory chips (as developed for FTK) for pattern recognition followed by a track fit in FPGA
- Specific configurations
  - CMS trigger read-out at 40 MHz - Pt-module concept select "stubs" for tracks with Pt ≥ 2 GeV
  - ATLAS read-out region of interest at ≥ 500 kHz
- Proposal to extend coverage of Pixel detectors up to |η| ~ 4
  - Associate jets to primary vertex through track matching

ATLAS design



CMS design



Phase2: Calorimeters

Beniamino

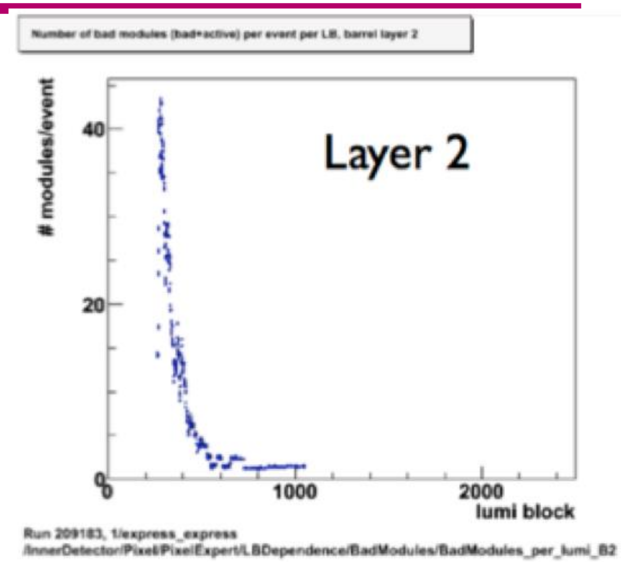
Summary table

Experi-ment	detector	technology	Critical condition	maximal value for Phase2 of LHC	Expected degradation, considered mitigation
ALICE	PHOS	PbWO4	Hadron fluence	$< 10^{9}$ h/cm ^{2}	OK
ALICE	EMCal/Dcal	Pb/Scint Shashlik	Radiation Dose	~ 0.1 kRad	OK
LHCb	ECAL	Pb/Scint Shashlik	Radiation Dose	~ 6 Mrad	will replace central cells during LS3 (spares exist)
LHCb	HCAL	TileCal	Radiation Dose	~ 1 Mrad	Not critical, accept the loss
ATLAS	ECAL Barrel	LAr	Inst. luminosity	OK up to 10^{35} cm $^{-2}$/s	OK
ATLAS	ECAL Endcap	LAr	Inst. luminosity	OK up to $5*10^{34}$ cm $^{-2}$/s	OK, re-calibrate if required
ATLAS	HCAL Endcap	LAr	Inst. luminosity	OK up to $8*10^{34}$ cm $^{-2}$/s	OK
ATLAS	HCAL Barrel	TileCal	Radiation Dose	~ 0.3 Mrad	Re-calibrate
ATLAS	Forward	LAr	Inst. luminosity	Possible degradation above $2*10^{34}$ cm $^{-2}$/s	May have to replace or add new detector during LS3
CMS	ECAL Barrel	PbWO4	Hadron fluence	$2*10^{12}$ h/cm ^{2}	Re-calibrate
CMS	HCAL Barrel	Brass/Scint	Radiation Dose	~ 0.1 Mrad	Re-calibrate
CMS	ECAL Endcap	PbWO4	Hadron fluence	~ $2*10^{14}$ h/cm ^{2}	Will be replaced during LS3
CMS	HCAL Endcap	Brass/Scint	Radiation Dose	~ 10 Mrad	Will be replaced during LS3
CMS	Forward	Steel/Quartz fibers	Radiation Dose	~ 500 Mrad	Re-calibrate

Pileup and luminous region

Pile-up effects visible throughout detector & readout chain

- Occupancy – difficulty separating event information
- Memory buffers on front-end chips
- Selectivity of trigger system working with limited info
- Links between the front-end and the back-end electronics
- Limitations in processing power in back-end electronics
- Links between the back-end & rest of DAQ
- Event reconstruction in high level trigger & offline



Both ATLAS and CMS:

- are designing Run 4 detectors to cope with a mean pile-up of 140 (<140>) (25ns, 5 x 10^{34})

"tails" up to 200 events per crossing.[Degradation not sudden, but tails have large effect]

-are very interested in methods (eg crab kissing) allowing the extent of the luminous region in time and space to be tuned, so as to reduce the pileup density in either z or t dimensions

does not open up a door to accepting 2x the inst lumi

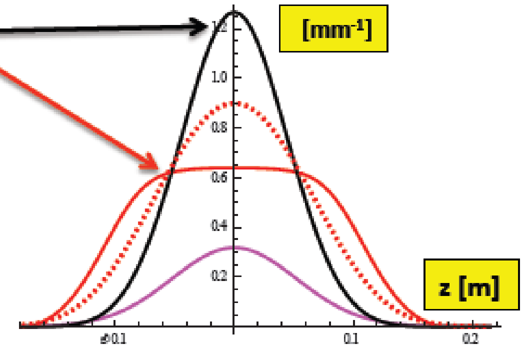
(mean pile-up also has bad effects eg neutrals in calorimeters)

The potential to exploit fast timing (σ ~10ps) to mitigate pile-up still requires substantial R & D, but there is a dedicated community pursuing this.

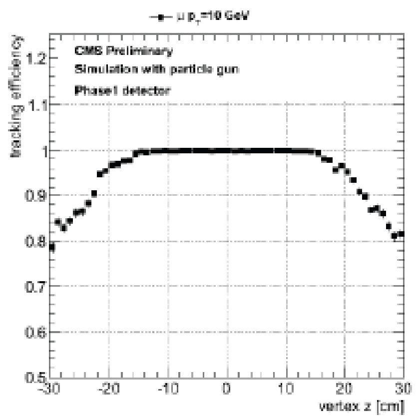
Pileup mitigation

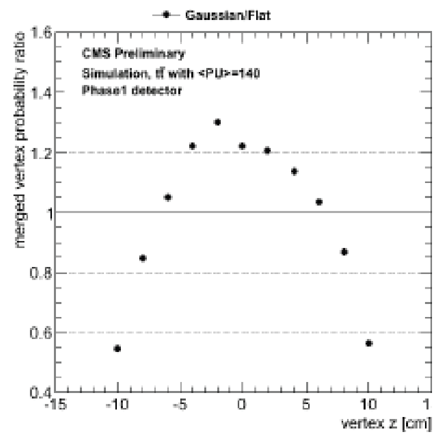
Didier

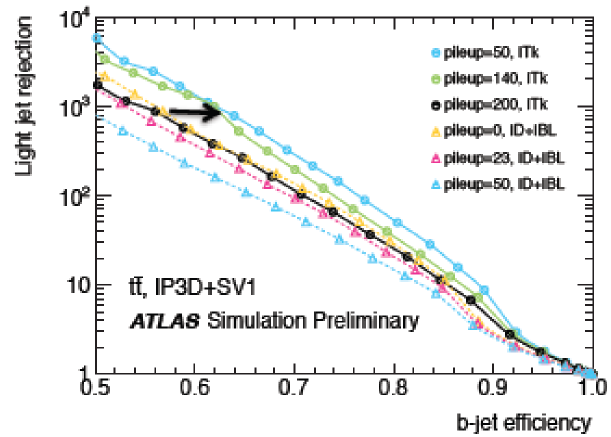
- Preliminary studies with CMS Phase 1 detector
  - Tracking acceptance covers flat luminous region
  - No significant tracking efficiency difference at 140 PU
  - Vertex finding efficiency decrease & number of merged vertices increase for Gaussian density
- Track association to primary and secondary vertices will be more efficient with flat density
  - Improved corrections to calorimeter energies
  - Improved b-tagging efficiency. Ex. a 10% gain as shown in right bottom plot will increase 2b-tagging efficiency by ~ 40 %



Scenarios of interaction density / crossing
S. Fartouk presentation at ECFA workshop







It is essential that Accelerator & Experiments investigate all opportunities to mitigate PU effects to fully profit from the LHC High Luminosity potential

Trigger systems

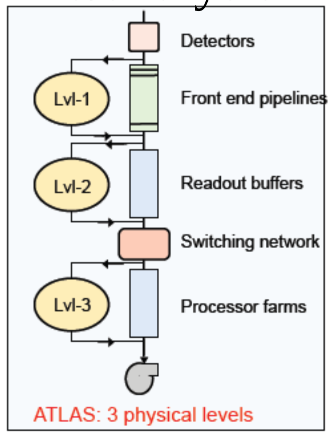
Didier

Phase 1: L1 trigger upgrades to operate at 50 PU within the limitation of 100kHz output rate: ongoing from LS1 through LS2. exploit: additional muon layers
better calorimeter granualirty
more complex event info/analysis

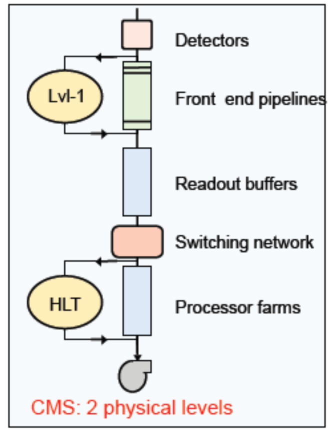
Phase 2:
Increase bandwidth
latency
HLT o/p rate
use tracker in trigger

Major changes to detector electronics required.

- ATLAS
  - Increase Level 1 bandwidth to 500 kHz in 5 μs latency
    - Readout of tracker information in Region of Interest
  - Level 2 in 20 μs latency with tracks and 200 kHz HLT input
  - Possible HLT output up to 10 kHz
  - → Requires
    - Upgrade of front-end and back-end electronics of Calorimeter and Muon detectors



- CMS
  - Readout Tracker "stubs" at 40 MHz
  - Readout crystal granularity in ECAL
  - Increase latency to 10 μs and level 1 rate up to 1 MHz
  - Possible HLT output up to 10 kHZ (present HLT rejection)
  - → Requires
    - New ECAL Barrel front-end electronics
    - Upgrade of back-end electronics
    - Increased computing power - HLT can benefit from L1-track reconstruction (as for ATLAS phase 1 FTK)



The Matrix

Mike

	Run 2	EYETS	LS2	Run 3	LS3
ALICE		Contingency	18 mo. Shift into 2018		
ATLAS	3 years	No	14 mo. Start 2018		27 (35) mo. Start 2022
CMS	EYETS plus N months	19 weeks	14 – 18 mo. Not before summer		30 – 35 mo. Start 2023
LHCb		Contingency	18 mo. End 2018		
Cryo	4 years max.	Selective maintenance			
Maintenance		Selective maintenance	16 mo.		20 mo.
LIU		9.5 months for L4 connect/or cable prep.	20.5 mo. beam to pilot		
LHC	3 years max contiguous	Opens way for year 4	18 mo.	3 years	2 years

Mike

EYETS

W.B Yeats

- EYETS (YETS + 6 weeks= YEETS?) required by CMS, buys contingency for ALICE and LHCb.
- Extending EYETS to 9.5 months for Linac4 subsequently presented as an option
  - motivation recognized
  - is problematic for the experiments.
  - note the possibility of cable cleanup and preparation for LS2 during this period
- Given EYETS:
  - continue run 2 into 2018 for at least 6 months
  - continue run 2 until end 2018
  - possible compromise 9 months into 2018
- Any of these options naturally leads to a delay of the start of LS3 from 2022 to 2023

Mike

Options presented

- Baseline
  - No EYETS
  - 2018 LS2 has to go to 18 months
  - LS3 starts in 2022
- Slipped baseline+6
  - EYETS plus continue run 2 to mid-2018
  - 3 year run 3 – LS3 starts in 2023
- Slipped baseline+12
  - EYETS plus continue run 2 to end 2018
  - Slightly shortened run 3 – LS3 starts in 2023

Planning : further comments

-Phase 1: consolidations & upgrades underway will help equip expts for cycle of 3-4 operations years including minimal ~ 13 week year end stop, followed by LS of 1-2 years.

-Phase 2 : ATLAS& CMS will need ~30 month LS3: not effective to stage

Activation (+ contamination?) serious issue from LS3 onwards .

ALARA to be built into designs & operating procedures from outset

eg Low intensity runs for cooling + Advance "hot" LS3 activities to end LS2

-Infrastructure end of lifetime replacements not yet accounted for
- in LS3 could seriously disrupt underground work ––> advance to LS2 if at all possible

LS2 timed to allow Phase 2 infra work to be advanced ––> help restrict length of LS3

-1 year shift in LS3 start (to 2023) eases funding profile for Phase 2 upgrades

-Best to minimise # sequential calendar years without any physics (continuity, headlines)

Resources: labs, test beams , RP facilities & equipment , simulations, new TAS/shielding needed well in advance ––> Joint coord. & executive structures (coord comm + PO)

Operation: special requests

Apart from usual programme of p-p and Pb-Pb at top energy

-p-p reference data: equiv energy: ALICE (6 pb-1: takes about 2 month @ 200kHz)
end of run 3 : dominant ref data requirement
ATLAS/CMS 300pb-1

-p-Pb proven to be very interesting : requested for Run 2 : 50nb-1 @ 5.1 or 8 TeV
after LS2 : ~1pb-1

p-Ar and Ar-Ar possible requests

-Luminosity calibrations needed at every energy

-Forward programmes :

TOTEM High β^* & AFP & CMS-TOTEM fwd programme at low β^* in Runs 2,3

no high β^* running anticipated after LS3

(ATLAS and CMS beampipes bore to be kept at ~45mm despite TAS at ~60mm)

forward physics at nominal lumi may continue thereafter (eg LHCb)

Experiment magnet field reversals as previously :

LHCb will need to switch dipole polarity every ~2 weeks to control systematics

ALICE will need to switch solenoid polarity occasionally

Conclusion

Following the Higgs discovery, the justification for high lumi LHC and a target p-p luminosity of 3000fb-1 is compelling.

Phase 1 consolidations to ATLAS & CMS and major upgrades to ALICE & LHCb will allow the present programme to continue effectively for Runs 2,3. (ie to initial p-p target of 300fb-1).

Thereafter, ATLAS and CMS must make major upgrades due to radiation effects which critically damage performance once ∫Ldt exceeds 300-500fb-1.

These Phase 2 upgrades are being designed to allow studies of a broad range of physics, including precision studies of the (low mass) Higgs, at the high pile-up, high radiation dose conditions expected at Hl-LHC. (3-4 years R & D + 5-6 years to build)

A realistic schedule over the next decade is essential for correct resource request/allocation. Basic gaol is to cost-effectively maximise useful integrated lumi as a function of time.

These are technically very difficult upgrades – getting the resources (including human) needs new models of support from Collaborations & much help from CERN. Support facilities and planning for infrastructure replacement are urgent issues.