Detector limits

Beniamino Di Girolamo - CERN

Outline

- Limits from radiation damage and ageing (detectors)
- Limits from pile-up
- Limits from ageing (infrastructure)
- Limits, corrective measures, upgrades

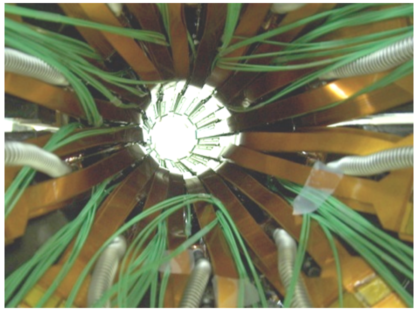
I am greatly indebted to the ECFA workshop speakers

Petra Riedler

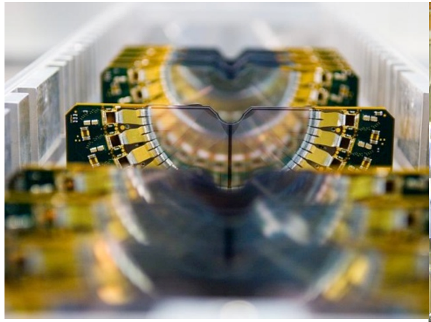
Present LHC Tracking Sensors

Silicon tracking detectors are used in all LHC experiments:

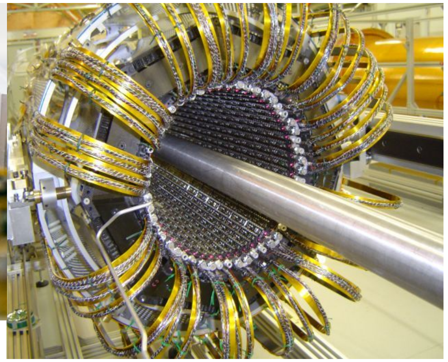
Different sensor technologies, designs, operating conditions,….



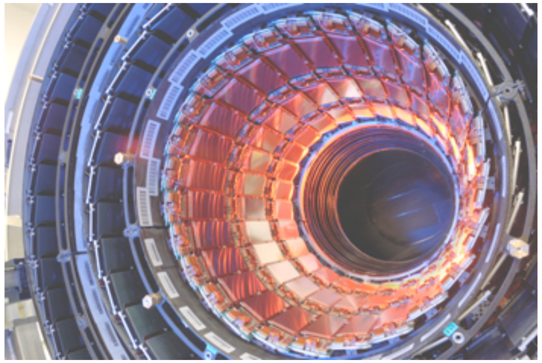
ALICE Pixel Detector



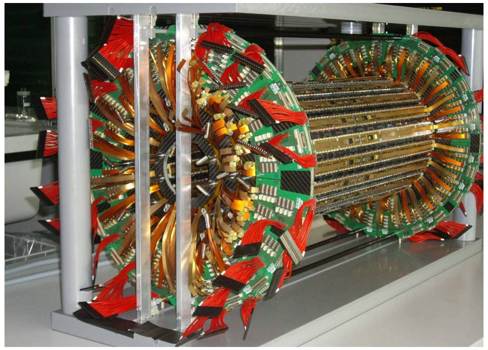
LHCb VELO



ATLAS Pixel Detector



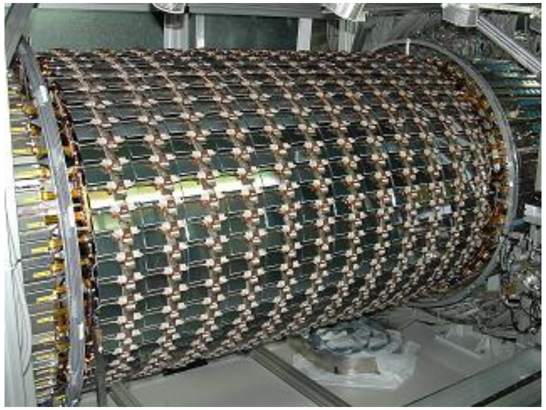
CMS Strip Tracker IB



CMS Pixel Detector

ALICE Drift Detector

ALICE Strip Detector

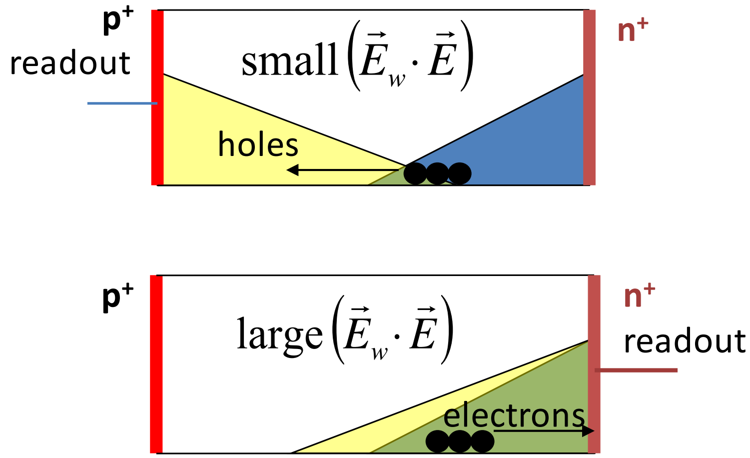


ATLAS SCT Barrel

Petra Riedler

Sensor Technology in Present Experiments

- p-in-n, n-in-p (**single sided process**)
- n-in-n (**double sided process**)
- Choice of sensor technology mainly driven by the **radiation environment**



G. Kramberger, Vertex 2012

	Fluence 1MeV n_{eq} [cm^{-2}]	**Sensor type**
ATLAS Pixel*	1×10^{15}	n-in-n
ATLAS Strips	2×10^{14}	p-in-n
CMS Pixels	3×10^{15}	n-in-n
CMS Strips	1.6×10^{14}	p-in-n
LHCb VELO	1.3×10^{14}**	n-in-n, n-in-p
ALICE Pixel	1×10^{13}	p-in-n
ALICE Drift	1.5×10^{12}	p-in-n
ALICE Strips	1.5×10^{12}	p-in-n

n-side readout (n-in-n, n-in-p):
- Depletion from segmented side (under-depleted operation possible)
- Electron collection
- Favorable combination of weighting field and
- Natural for p-type material

* 5×10^{15} for IBL; ** per year

Petra Riedler

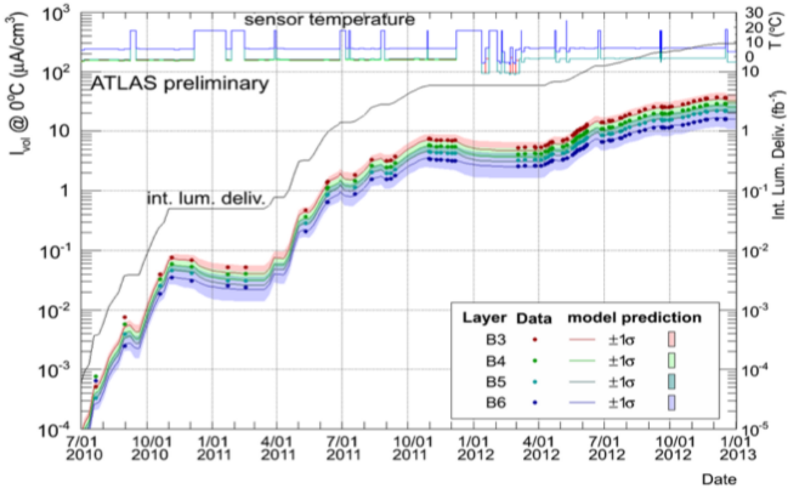
Radiation Damage Effects in Sensors

- Effects observed in ATLAS, CMS and LHCb (lower luminosity in ALICE)
- **Main challenge for the sensors is an increase in leakage current:**
  - Risk of thermal runaway -detector becomes inoperable
    - Operate sensors at low temperatures (see talk by B. Verlaat)
  - Increase in shot noise - degraded performance
- Leakage current increases with integrated luminosity in agreement with the predictions

- **Further effects:**
  - Sensor depletion voltage changes with radiation damage
  - Loss of signal due to radiation induced damage

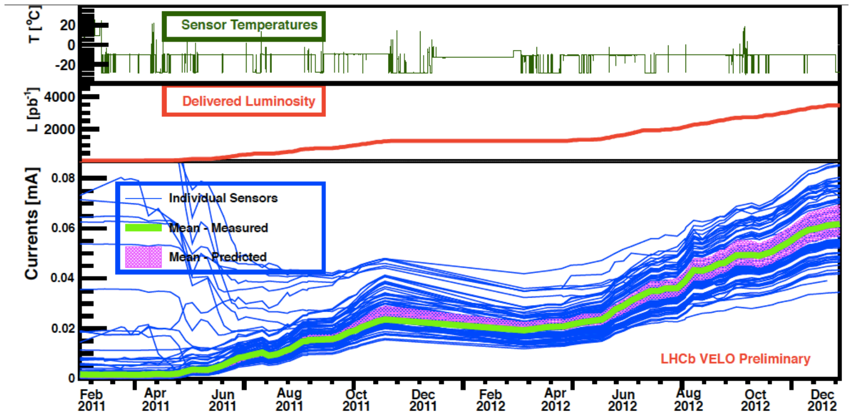
Effects will increase for HL-LHC

Leakage current vs. integrated luminosity (examples)



Excellent agreement over 4 orders of magnitude, need a good knowledge of inputs (**L,flux,T**).

ATLAS SCT Barrel
H. Pernegger, LHCP 2013



LHCb VELO
H. Snoek, Hiroshima 2013

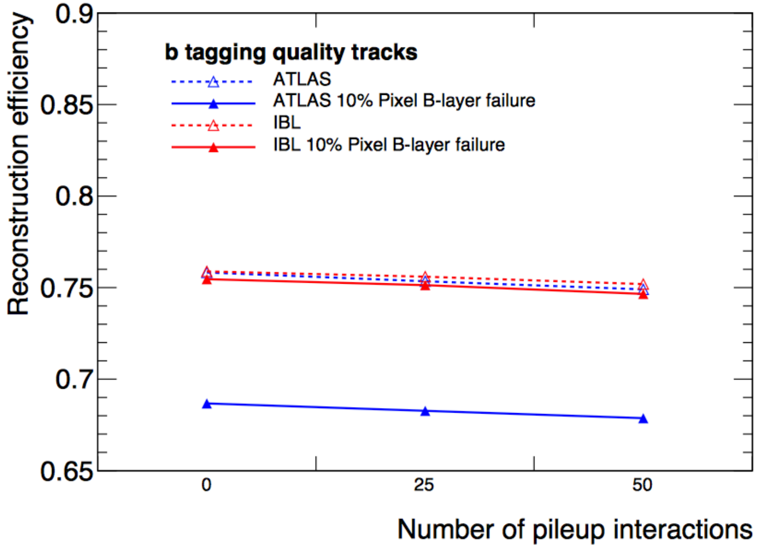
Radiation damage: silicon detectors

- The Run 1 experience gives us a lot of confidence in the models and calculations
  - The agreement is good, within 10-30%, that is remarkable given all the safety factors used at the time of the comstruction
- The models can be used to make predictions and to extrapolate the life time expectations
  - I could predict the type-inversion of two of the three ATLAS pixel layers within 1 fb^{-1} (the third did not yet go through enough radiation)

Radiation damage: silicon detectors

- Summarizing the effects scale as $\sim 1/r^2$, in ATLAS and CMS we have silicon layers at radii r going from ~ 3-4 cm to ~ 120 cm
- Just to get a ball park number (very rough, forgive me):
  - $\phi(r) \sim (0.6 \cdot A \cdot r^{-2}) \cdot 10^{14}$ 1 MeV n_{eq} cm^{-2} $/fb^{-1}$ (r in cm)
    - Provided that they are kept cold! A is the "cooling tax". If the detector is not cold enough then A < 1.
    - For example a layer at 5 cm that can stand up to a fluence of 10^{15} 1 MeV n_{eq} cm^{-2} would reach that level after ~400 fb^{-1} (ATLAS current innermost layer, A=1)
    - Example a layer at 4.4 cm that can stand up to three times the 10^{15} fluence would reach it at ~500 fb^{-1} if A =0.6 (CMS current innermost layer).

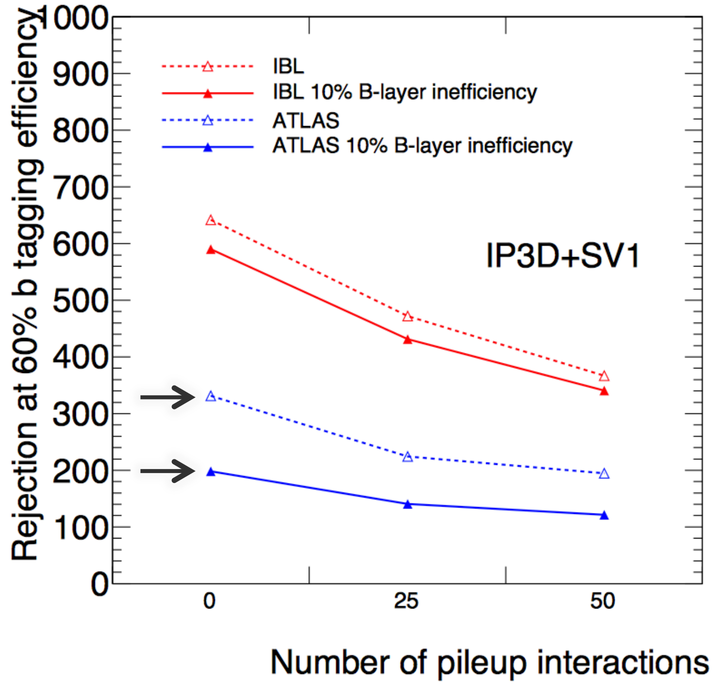
What happens if a layer is inefficient



Detector ageing

Almost 1:1 10% inefficiency reflects to 10% worsening of performance in reconstruction

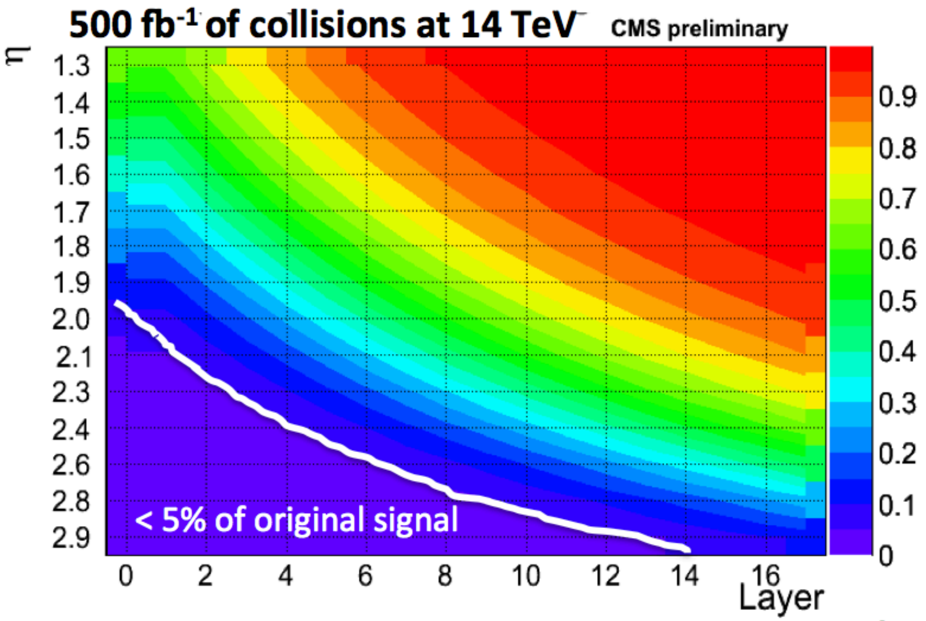
…but it becomes a factor ~ 1.5 on more complicated quantities like the light jet rejection vs. the b-tagging efficiency

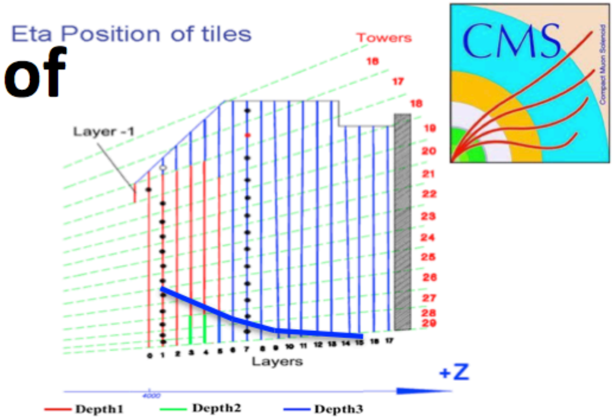


The loss of a complete layer is catastrophic

Radiation damage: calorimetry

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

Radiation damage: calorimetry

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

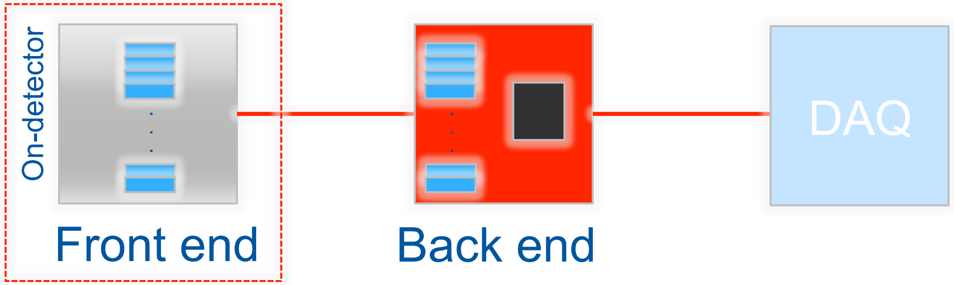
10/2/13 Pawel de Barbaro, University of Rochester: Calorimetry/Detectors for HL-LHC 43

Radiation damage: summary

- The silicon detectors will hit limits at ~400-500 fb^{-1}
  - The outer layers will follow with the rough scaling mentioned earlier
    - A missing layer has catastrophic effects: the detector needs to be upgraded
- The calorimetry is also affected and at the same threshold of ~ 500 fb^{-1}

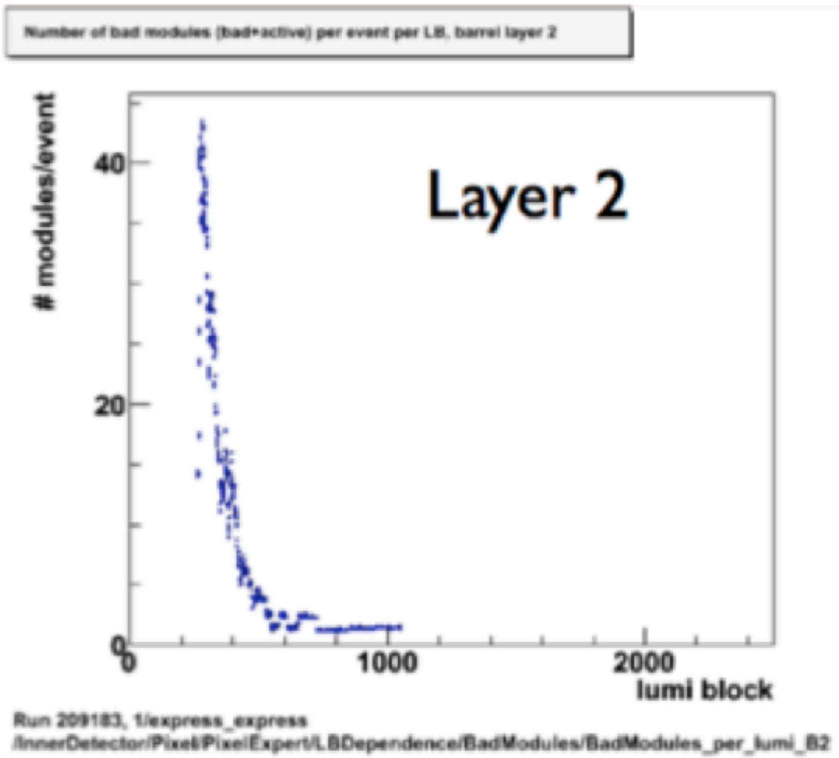
Pile-up

- The effects of pile-up can be visible on:
  - Memory buffers on front-end chips
  - Links between the front-end and the back-end electronics
  - Limitations in processing power in back-end electronics
  - Links between the back-end electronics and the rest of the data acquisition



Effects of pile-up: simplified

Link occupancy at 100 kHz L1 Trigger					
	μ	B-Layer	Layer 1	Layer 2	Disks
50 ns	37	51%	45%	69%	40%
25 ns; 13 TeV	25	47%	42%	65%	37%
	51	71%	67%	88%	52%
	76	95%	97%	148%	75%



Example of link saturation

Example of processing power limitations

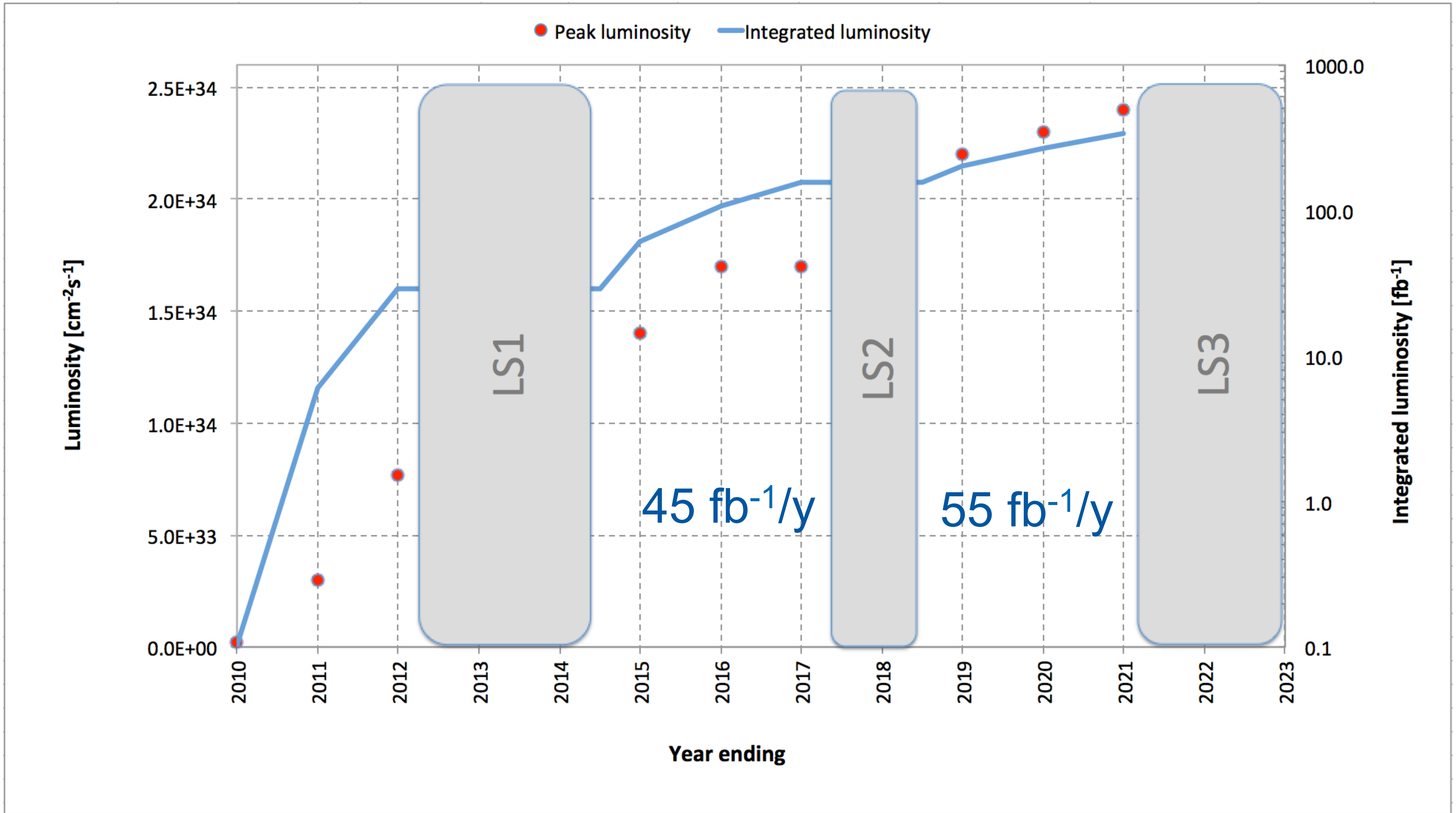
Summary of pile-up limitations

- The current detectors have been designed for a pile-up of 25 events
  - We surprisingly managed to manage last year with ~ 37 pile-up events
  - We equip ourselves to be able to survive up to ~ 50 pile-up events (not all detectors)
  - We won't be able to stand 140 pile-up events without a substantial upgrade

Expected upgrades

- Essential upgrades
- “Nice to have” upgrades
- What are the PICs and CONs for the experiments

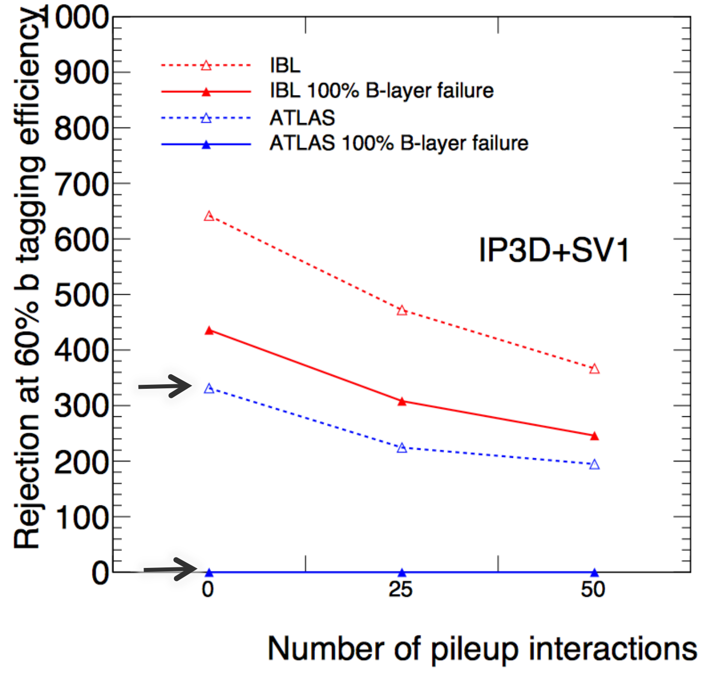
LHC Performance Projections



After the LS3: 5.10^{34} $cm^{-2}s^{-1}$ and 300 fb^{-1}/y

Essential upgrades

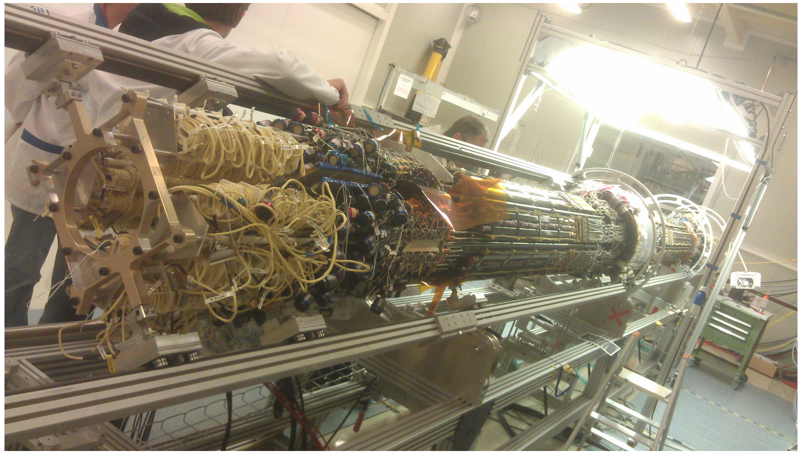
- It is difficult to distinguish between essential and “nice to have” upgrades for the inner detectors
  - The effects of both link saturations and ageing/ complete damage are very big



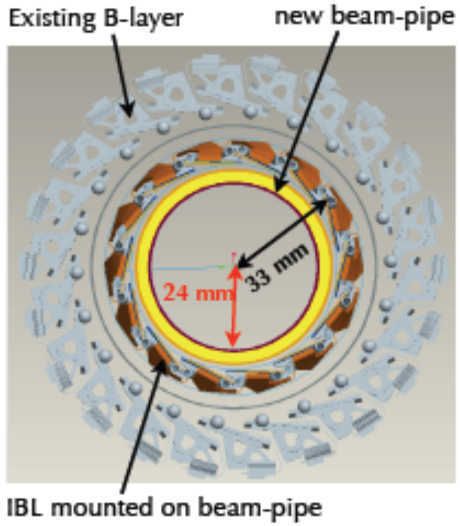
ATLAS and CMS PICs

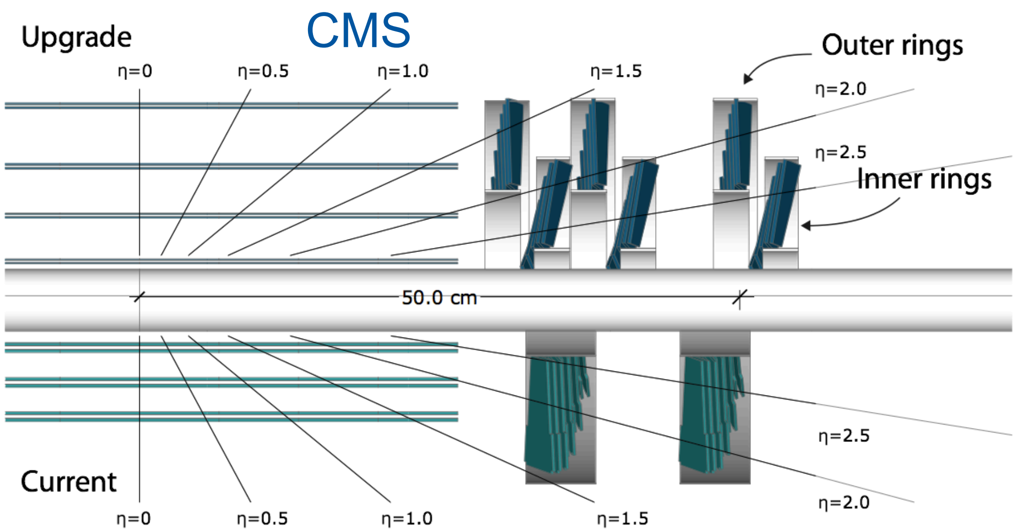
- Both PICs are concentrated before LS3 (even before LS2)
- ATLAS Pixel and Strips act on the back-end electronics to avoid link saturations and processing performance bottlenecks
- ATLAS Pixel did a PIC on services to restore the detector to 99% and to cure link saturations
- CMS Pixel did a PIC to eliminate some bottlenecks
- ATLAS is installing a 4th layer (IBL) to fight against the ageing of the actual innermost layer
- CMS will install a new Pixel detector to fight against the ageing and the pile-up increase

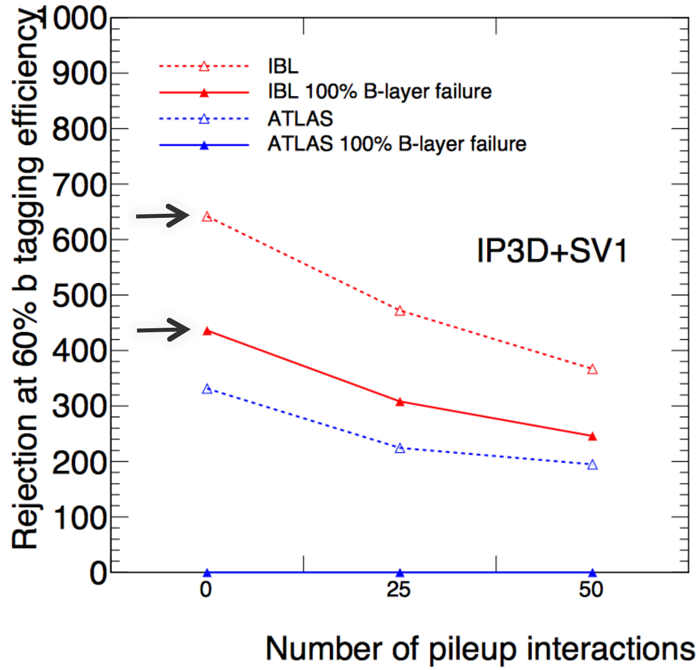
ATLAS and CMS PICs



ATLAS







The PICs and why no PIC beyond PIC?

- We are forced to act on our Pixel and Strip detectors
  - Higher instantaneous luminosity than design, up to a factor 2.5-3 and tout de suite
    - I still remember in our TDRs: “LHC will start at a lower lumi, we will do a lot of b-physics for 3 years, then…”
- By the time we will be at the LS3 threshold the inner detectors start to reach the 400-500 fb^{-1} limit
  - They will be dead soon after LS3
  - It takes long time to change them
  - a year stop is not enough: ATLAS has 100 M channels, 92 M are from the Pixel detector: imagine the services

Infrastructure improvements and ageing effects

- Many examples given at Aix-les-Bains workshop, few are reported here
- The back-end electronics is today based on VME standards. It will get old, obsolete, difficult to maintain
  - New trends in telecommunications and higher-speed needs pushing towards different standards (xTCA) and/or commodity PCs
  - More speed = more power needed = more cooling needed
  - The current infrastructure needs upgrades

Infrastructure improvements and ageing effects

- At the same time the cooling infrastructure is getting old
  - Old pipes showing weakness
- Higher luminosity = higher activation
  - Air circulation and possible activation may become a problem
  - The current infrastructure needs to be improved
- Elevators and crane ageing
  - Age and non rad-hard components (cabling, controls)

Limits, corrective measures, upgrades

- Here touched just the most important detector limits
- For some of them corrective actions can be made
  - Replacement of cabling, electronics, pipes
  - Additional links to overcome saturations
- For some other we really need upgrades
  - Detector layers will simply become non operational with catastrophic effects on the physics already between 400 and 700 fb^{-1}

Conclusion

- Tried to keep it simple
  - The radiation damage effects would deserve a lot more information (different effects at different radii, etc), but a ball park number is sufficient
  - The ageing of both detectors and infrastructure plays a role on top of the radiation and activation effects
- The bottom line is that to go beyond 500-700 fb^{-1} upgrades of detectors and infrastructure are needed (Didier will present what and when)