## CMS Upgrade R & D



#### CHIPP Workshop on Detector R & D

#### Ben Kilminster

Uni. Zürich on behalf of CMS Switzerland











- See other talks in this workshop
  - Tilman Rohe, PSI: "Silicon tracking detectors"
  - Guiseppe lacobucci, Genève : "ATLAS Upgrade"
    - European strategy for High Energy colliders
    - LHC roadmap and design parameters
    - LHC High Luminosity operation (LHC-HL)
- Borrowed heavily from
  - R. Horisberger, PSI : "Technical Design Report of the Upgrade of CMS Pixel Detector", LHCC upgrade review Sept. 2012
  - R. Wallny, ETH : "Swiss contributions to CMS Upgrades", CHIPP meeting, June 2013
  - F. Nessi-Tedaldi, ETH : ECAL upgrade work







### R&D summed up in one picture



### R&D summed up in one picture



470 charged hadrons  $P_T > 0.1$  GeV per unit  $|\eta|$  at 8 TeV More at 13 TeV ! 78 reconstructed vertices Real data from special run Expect 50 – 100 pile up by 2018 100 – 200 pile up by 2022

### Challenges





### Swiss focus



# R & D efforts focused on high-occupancy interior of detector Electromagnetic calorimeter **Detector** material Precision inner tracking 100000

### Swiss focus









Spatial constraints of existing detector present added difficulties ECAL : Current space allocation based on PbWO crystals : All other materials bigger ! Tracking : Additional tracking layers must fit in existing volume Material : Require more cables, cooling

### Improvements sought



#### Goals of upgrades ECAL : Reduced damage from hadrons **Compact sampling calorimeter Tracking**: Improved light yield from WLS Additional tracking layer Higher data bandwidth Reduced hit energy threshold Radiation harder Material: Lighter cooling tubes Lighter mechanical structure Lighter coolant Maintain current cable material



### Physics gain of improvements



### CMS Construction: CH Contributions







# Phase I Upgrades < 2018

# Silicon Pixel barrel (PSI, ETHZ, UZH)



### Limitations of Current Pixel System

0.92

0

500

1000

1500

bunch train

2000



- Impact parameter resolution limited by material in forward region
- Track efficiency drops with Inst. Lumi
  - Layer 1 hit inefficiency
    - LHC design 1x10<sup>34</sup> @ 25 ns : 4%
    - LHC at 2x10<sup>34</sup> @ 50ns : 50%
  - Several bottlenecks
    - Buffer Space in ROC
    - Optical readout of modules
    - FED to event builder



h277

3000

1.11313e+07

3500

bunch

Entries

2500







### System parameters : Current & Upgrade



Parameter of Pixel System	<u>Present</u>	<u>Upgrade</u>
# layers (tracking points)	3	4
Beam pipe radius (outer)	29.8 mm	22.5 mm (LS1)
Innermost layer radius	44 mm	29.5 mm
Outermost layer radius	102 mm	160 mm
Pixel size (r-phi x z)	100µ × 150µ	100μ × 150μ
In-time pixel threshold	3400 e	1800 e
Pixel resolution (r-phi x z)	13μ x 25μ	13μ x 25μ <mark>(or better)</mark>
Cooling	C <sub>6</sub> F <sub>14</sub> (monophase)	CO <sub>2</sub> (biphase)
Material budget X/X <sub>0</sub> (η=0)	6%	5.5%
Material budget X/X <sub>0</sub> (η=1.6)	40%	20%
Pixel data readout speed	40MHz (analog coded)	400Mb/sec (digital)
1 <sup>st</sup> layer module link rate (100%)	13 M pixel/sec	52 M pixel/sec
Readout chip pixel rate cabability	~120 MHz/cm <sup>2</sup>	~580 MHz/cm <sup>2</sup> 16
control & ROC programming	TTC & 40MHz I <sup>2</sup> C	TTC & 40MHz I <sup>2</sup> C

## Readout Modifications (1): ROC



- Readout Chip (ROC) function :
  - Stores and outputs hit information for pixels exceeding set threshold within time window
    - Address, pulse height, time stamp stored
- Specifications ROC PSI46dig: Mitigation of
- Increased luminosity by LHC machine ~2x10<sup>34</sup>
- Higher pixel rates due to reduced Layer 1 radius (r<sub>L1</sub> = 30 mm)
- Higher data output rate capability due to 50ns (?) LHC operations
- Reduced sensor signals due to irradiation (L1 sensor ~250 fb<sup>-1</sup>)
- ROC changes:
- Increase DC time-stamp- / data-buffers (12 / 32  $\rightarrow$  24 / 80)
- ROC internal token passage & double buffered (64) readout
- 160 Mbit/sec digital readout for pixel addr. & pulse heights
- ROC level 8-bit ADC for pixel pulse height digitization
- Reduced pixel in-time threshold of <1600e (present 3400e)</li>
- Increase data transmission rate (factor x 4)

#### Recticle of Jan 2013 Engineering Run



ROC version	Rate [MHz/cm2]
PSI46 (ana)	~100
PSI46dig	~200
PSI46dig+ (L1)	~500





ROC : Readout Chip TBM : Token Bit Manager POH : Pixel Optohybrid FED : Front End Driver

#### Changes to pixel data readout link:

- TBM combines 2 serial ROC 160Mb/s data streams to 4b/5b encoded 400Mb/s.
- 400Mb/s / fiber → 2x present pixel readout rate
- Number of fibers per module:
  - BPIX: 1 for L4, 2 for L2 & L3, 4 for L1 !
  - FPIX: 1 for inner ring, ½ for outer ring.



Tracking efficiency for tt sample with ROC data losses.  $\rightarrow$  pions etc. (hadronic interactions)



Results in significant gain in signal reconstruction efficiency for multi-lepton final states:

$$\begin{array}{ll} H \rightarrow ZZ \rightarrow 4\mu & + 41\% \\ H \rightarrow ZZ \rightarrow 4e & + 51\% \end{array}$$



#### Transverse impact parameter resolution with 50PU



Gains in longitudinal impact parameter resolution even more pronounced !

e.g.  $\eta < 1$ , p=100GeV  $\rightarrow$  gain = 1.63 ! (transversal impact parameter gain =1.15)

### Improved B-tagging and Vertexing



#### Upgrade Pixel @ $<\mu>=50$ $\Leftrightarrow$ Current Pixel @ $<\mu>=0$ $\rightarrow$ maintain physics capability or better at large PU

Swiss CMS Detector R&D

### SUSY particle searches with $\gamma\gamma + E_T^{miss}$



- SUSY searches with  $\gamma\gamma$  +  $E_t^{miss}$  background : mis-identification of electrons and photons
- Fake rate of electrons being identified as photons depends crucially on pixel detector
- MC study of fake rate with  $Z^0$  decays into  $e^+e^-$





### Module Testing and Construction

- CH-consortium builds L1 and L2 modules (33%)
  - Provide Test Board for whole collaboration
- Extensive testing (now) :
  - Irradiations
  - Test beam campaigns
  - Electrical tests under controlled environment
  - High-rate X-ray tests









Sept 13 2013

Swiss CMS Detector R&D

### Material budget



#### From simulation of radiation lengths



## Supply Tube





### CO<sub>2</sub> Cooling Loop Engineering Model





### CO<sub>2</sub> Cooling Loop Engineering Model





### CO<sub>2</sub> Cooling Loop Engineering Model







# Phase II Upgrades 2022

# ECAL (ETHZ)





- Cumulative loss of signal expected, due to hadron damage to crystals and aging of photo sensors
  - Studies pioneered by ETHZ NIM A 545 (2005) 67, NIM A 564 (2006) 164, NIM A 622 (2008) 266, NIM A 684 (2012) 57
  - Radiation longevity of present electronics is currently being studied
- A data-validated aging model is implemented in CMS full simulation
  - Tuning of reconstruction and study of physics performance degradation (including pile-up effects)
  - => replace endcaps after 500 fb<sup>-1</sup> to keep ECAL coverage to  $\eta$ <2.6

## ECAL Phase II Upgrade Strategy



ECAL upgrade "working hypothesis" (approved by ECAL Steering Committee and ECAL Institution Board):

- Complete replacement of the ECAL endcaps (EE) and preshower detectors
- Replacement of the ECAL barrel (EB) Front end Electronics
- Cooling of EB to 8 °C (now 18 °C) to control noise

#### **ECAL endcaps**

- Full recovery of radiation damage with heating, bleaching not possible
- EE partial crystal replacement not feasible
- Allows extended η-coverage
- Allows higher granularity (less pile-up)
- Allows for ECAL/HCAL combined approach

#### ECAL barrel

- Adapt 20 μs latency and 1 MHz L1A trigger rates
- Mitigate ECAL spike problem and its impact on ECAL triggers
- Solves partially electronics wear out problem
- limit the leakage current in the APDs

Electronics replacement is driven by the trigger rate and latency requirements.



### ECAL Phase II Upgrade R&D

### "Strawman" layout:

- Sampling calorimeter
- Absorber: Pb or W
- Scintillator: crystalline or sintered, inorganic
- Readout: direct or via WLS
- Main issue: radiation hardness of all components





- LYSO, YSO, CeF<sub>3</sub>, sintered scintillators, photo-detectors
- Proof-of-principle readout tests

### Proof-of-principle





Swiss Involvement in CMS Upgrades

25 June 2013

### **ECAL Electronics**



ECAL Trigger	EB status	Phase 2 requirements
L1A rate	abs. max. (120-150) kHz	(500 to 1000) kHz
L1A latency	6.4 μs (fixed)	(10 to 20) µs
ECAL 'spikes'	False triggers	mitigate

ECAL 'spikes': signals from direct interactions in the APDs, causing false triggers)

ECAL end-caps (EE): rebuilding EE completely requires new electronics

Additional question: longevity of the electronics – this is presently studied

**Possible ETH contributions (in line with our past contributions)** 

- Participation in the system design
- Participation in the required ASICs development
- Participation in prototyping, fabrication and testing of Front-End electronics
- Adaptation and remake of the DCS components (as necessary)
- Electronics installation and testing in the electronics integration center



# Phase II Upgrades 2022

## Inner tracker (PSI, ETHZ, UZH) Diamond R&D (ETHZ)



### Tracker Longevity



- Outer strip tracker longevity strongly depends on cooling performance
  - may loose good fraction of inner modules without cooling by 500 fb<sup>-1</sup> (thermal runaway)
  - 4th pixel layer may partially compensate cooling induced strip tracker losses
- Proposal to replace Tracker during LS3



- Current **pixel sensor** radiation budget (inner layer L1) is 250 fb<sup>-1</sup> = 1.5 x 10<sup>15</sup> n<sub>eq</sub>/cm<sup>2</sup> @29.5mm
  - Pixel detector mechanical envelope expected to stay the same
  - Pixel can be accessed during any year-end technical stop / L1 exchange possible
  - L2 radiation dose is 4x less
- Explore alternative sensor material for L1:
  - Planar / 3D / Diamond (including 3D diamond)



## Diamond R&D

- Diamond sensors can be operated @300 <sup>0</sup>K
  - − Excellent thermal conductor
    → heat removal
- Low leakage current
  - good signal/noise ratio even at high radiation dose ~10<sup>15</sup> p/cm<sup>2</sup>
- Planar strip, pad, pixel and 3D structures tested
- Diamond projects:
  - ATLAS & CMS Beam Conditions Monitor

500µm

- CMS Pixel Luminosity Telescope (?)
- ATLAS Diamond Beam Monitor





Planar

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### Conclusions



#### • High inst. and integ. Luminosity present challenges for maintaining CMS physics

- Swiss upgrade efforts focus on improving :
  - Inner tracking
  - Material budget ie, cooling & supply
  - Electromagnetic calorimeter
- Phase 1 barrel pixel upgrade
  - Production readout chips being tested
  - CO<sub>2</sub> cooling plant and prototype cooling system almost ready for testing
  - Many electronics components prototyped
- Phase II upgrades being defined
  - Electromagnetic Calorimeter
    - ECAL end cap replacement
    - ECAL electronics upgrade
  - Tracking
    - Tracker replacement (including pixel)
    - Possible use of diamonds
  - Possible extension of tracking and calorimetry up to  $|\eta| \le 4$ ?
- CMS-CH intends to continue its vital role in CMS ECAL and Pixel



# Backup

### LHC Timeline





### **Upgrade Motivation**

- **CMS Design:** 10 years of  $\mathcal{L}=10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> (25 ns) with mean pile up < $\mu$ >~25 for  $\int \mathcal{L} dt \leq 500 \text{ fb}^{-1}$
- LHC is expected to outperform its design specs after LS1 •
  - 2010-2013:  $\mathcal{L} \simeq 80\%$  of design, exceeding nominal pile-up at 50ns
- Phase I (2010-2020) Upgrades: Consolidation and ٠ Performance improvements
  - Complete the phase 1 detector
  - Mitigation of beyond baseline performance of the LHC (data rate)
  - improvements for post LS2 operation at  $\mathcal{L} \leq 2...2.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$  (25ns) with  $\langle \mu \rangle \sim 70$
- **Phase II (2022-) Upgrades:** Precision Physics and Radiation Damage Mitigation •
  - Higgs sector survey, BSM searches, SM precision physics
    - Keep low trigger threshold, accept high rate
  - Deliver Phase I detector performance in much harsher environment
  - Replace detector components at end of their lifetime



25 Mean number of interactions per crossing

qd 40

Recorded Luminosity

10 19 20



### CMS Upgrades







### Pixel Phase I Upgrade





"Evolutionary" upgrade with minimal disruption of data taking:

Robust vertexing in large PU  $<\mu>\sim50$  (25ns) ٠  $\rightarrow$  increase 3 layers to 4 layers (1.6 x present detector)  $\rightarrow$  improved track seeding

Radius Faces Modules 30 mm 12 96 CH 28 224 CH 68 mm 109 mm 44 352 CERN/TW, I/SF 160 mm 64 512 D

- Shift material to high  $\eta$ , CO<sub>2</sub> cooling  $\rightarrow$  improved impact par. resolution ٠ + Fwd Disks USA  $\rightarrow$  reduced  $\gamma$  conversion
- Modify ROC for  $\mathcal{L}=2x10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> operation  $\rightarrow$  reduce data loss at r<sub>11</sub>=29.5mm •

 $\rightarrow$  decrease threshold ~x 2!

- Expected lifetime 500 fb<sup>-1</sup> (L1 2 x 250 fb<sup>-1</sup>)
- Swiss Consortium (ETHZ, PSI, UZH): ROC design, supply tube & mechanics, CO<sub>2</sub> cooling, •

2x L1 & L2 module production and testing



## Phase II Physics Program

- Precision survey of Higgs sector
  - Properties
  - − Study rare decays (eg H $\rightarrow$ µµ @ 5σ)
  - Study (self-) couplings (ie. HH  $\rightarrow$  bbyy)
  - Study VV scattering ....
- Precision SM physics
  - Top Factory
  - EWK precision studies, ...
- Search for new physics in very rare processes
  - Characterize any New Physics discovered during Phase 1 @ 14 TeV

"CMS at the High-Energy-Frontier", Input to the Update of the European Strategy for Particle Physics, CMS-Note 2012/006

		Uncertainty (%)		
Coupling	$300 \text{ fb}^{-1}$		$3000 \text{ fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
$\kappa_{\gamma}$	6.5	5.1	5.4	1.5
$\kappa_V$	5.7	2.7	4.5	1.0
$\kappa_g$	11	5.7	7.5	2.7
$\kappa_b$	15	6.9	11	2.7
$\kappa_t$	14	8.7	8.0	3.9
$\kappa_{ au}$	8.5	5.1	5.4	2.0

Scenario 1: systematics as in 2012 Scenario 2: theory syst. scaled by a factor  $\frac{1}{2}$ , other systematics scaled by  $1/\sqrt{L}$ 



"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. (...) " Whitepaper "Update of the European Strategy for Particle Physics"

### System Parameters: Present and Upgrade



#### Parameter of Pixel System

# layers (tracking points) beam pipe radius (outer) innermost layer radius outermost layer radius pixel size (r-phi x z) In-time pixel threshold pixel resolution (r-phi x z) cooling material budget  $X/X_0$  ( $\eta=0$ ) material budget X/X<sub>0</sub> ( $\eta$ =1.6) pixel data readout speed 1<sup>st</sup> layer module link rate (100%) ROC pixel rate cabability control & ROC programming Sept 13 2013

Present 3 29.8 mm 44 mm 102 mm 100u x 150u 3400 e 13µ x 25µ  $C_6F_{14}$  (monophase) 6% 40% 40MHz (analog coded) 13 M pixel/sec ~120 MHz/cm<sup>2</sup> TTC & 40MHz I<sup>2</sup>C Swiss CMS Detector R&D

#### <u>Upgrade</u>

4 22.5 mm (LS1) 29.5 mm 160 mm 100µ x 150µ 1800 e 13µ x 25µ (or better)  $CO_2$  (biphase) 5.5% 20% 400Mb/sec (digital) 52 M pixel/sec ~580 MHz/cm<sup>2</sup> TTC & 40MHz I<sup>2</sup>C

### CO<sub>2</sub> cooling plant



- Two CO<sub>2</sub> systems will be installed, one for FPIX and one for BPIX (15KW each)
- Different temperatures possible for FPIX and BPIX
- *Redundancy*: BPIX and FPIX can both be run on either one of the two cooling plants
- Copper pipes pressure certified (+20°C, 70bar)
- Operating temperature range -20°C (operations) to +15°C (commissioning)
- System cooling tests with engineering copies of BPIX & FPIX cooling loops & heat loads.
- Installation in LS1

#### **Redundant BPIX/PFIX CO<sub>2</sub> cooling circuits**

#### <u>3D CAD of cooling plant</u>

CAD Manifold



20

#### Working assumptions for the LHC Luminosity Upgrades







Note: LS2 and LS3 dates will very likely change. When will quads have to be replaced? what Will be the integrated luminosity before LS3 ? ...













- Cumulative loss of signal expected, due to hadron damage to crystals and ageing of photosensors
  - Studies pioneered by ETHZ NIM A 545 (2005) 67, NIM A 564 (2006) 164, NIM A 622 (2008) 266, NIM A 684 (2012) 57
- Replacement of end caps needed when 10% of light remains

### => replace end caps after 500 fb<sup>-1</sup> to keep ECAL coverage to η<2.6</p>





### **ECAL Electronics**



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### **CMS** Construction: CH Contributions





Important management roles since the 1990s







Pixel upgrade 2017

