

UK CMS Upgrade Oversight Committee

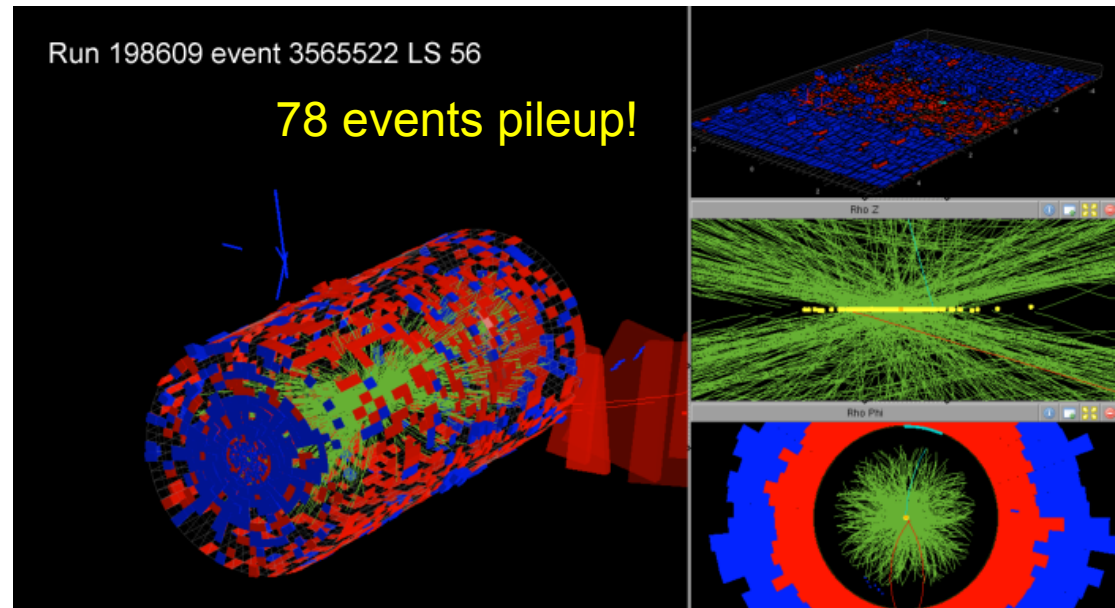
25 September 2012

University of Bristol
Brunel University
Imperial College London
Rutherford Appleton Laboratory

Geoff Hall

Overview

- CMS status
- LHC status and future plans
- Revisit motivation for upgrades, in view of PPRP proposal
- Review R&D background and current status
- Recent WP progress
- Finances

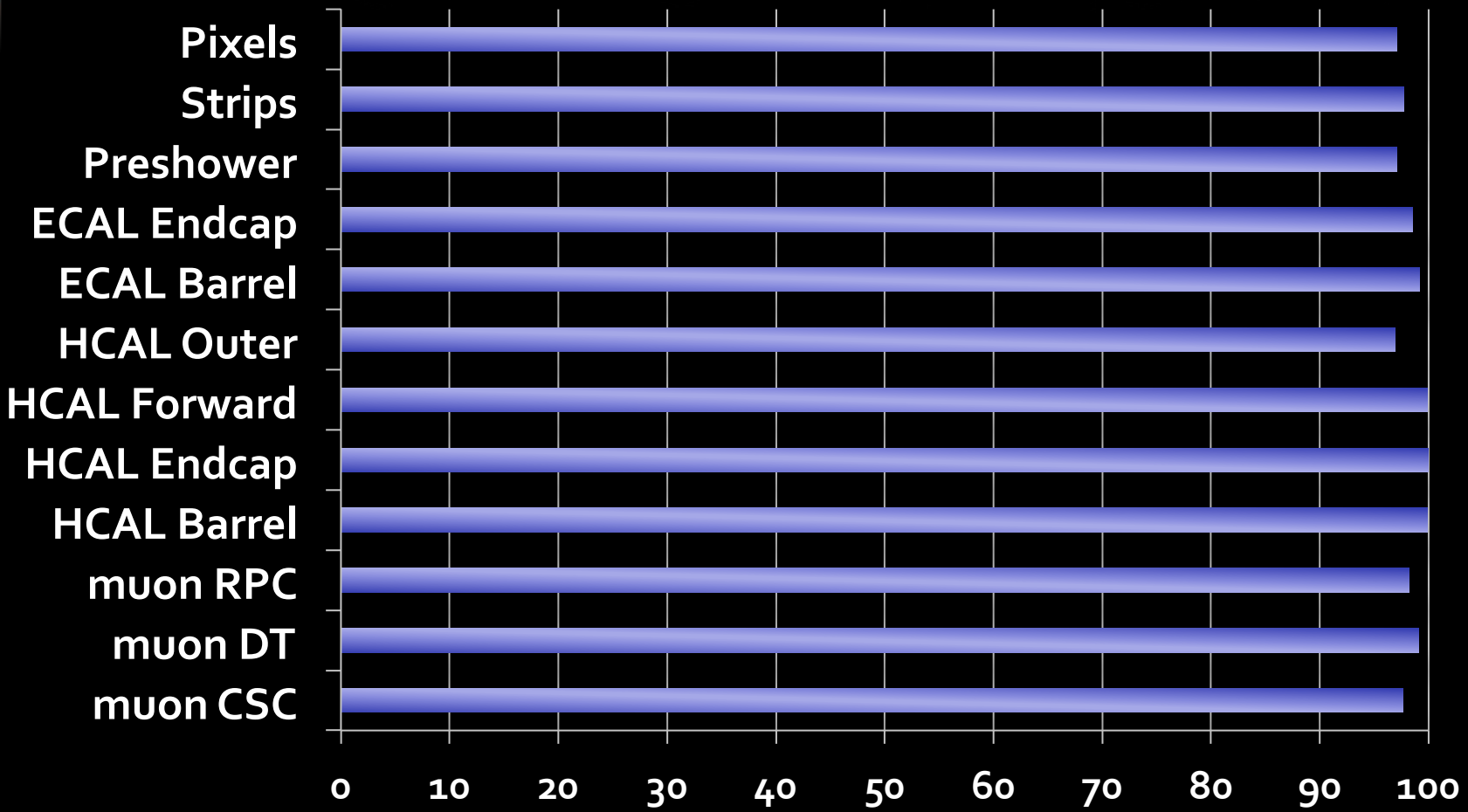


CMS STATUS



July 4th 2012
 The Status of the Higgs Search
 J. Incandela for the CMS
 COLLABORATION

Current Operational Status*



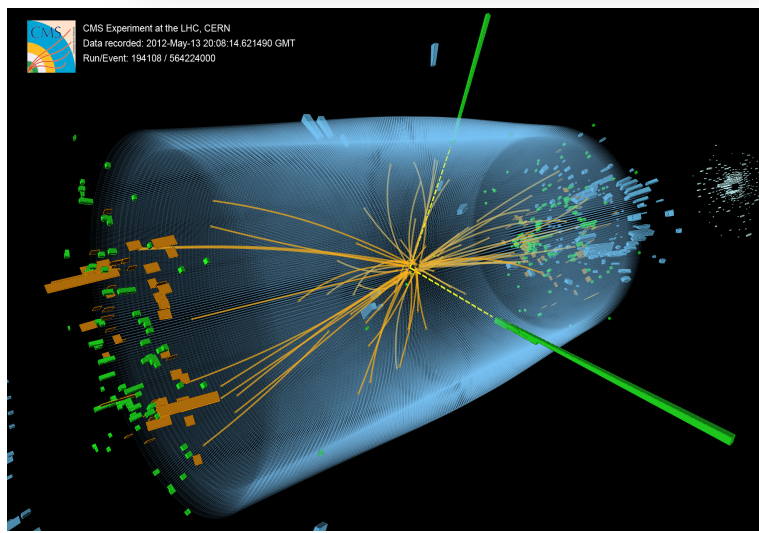
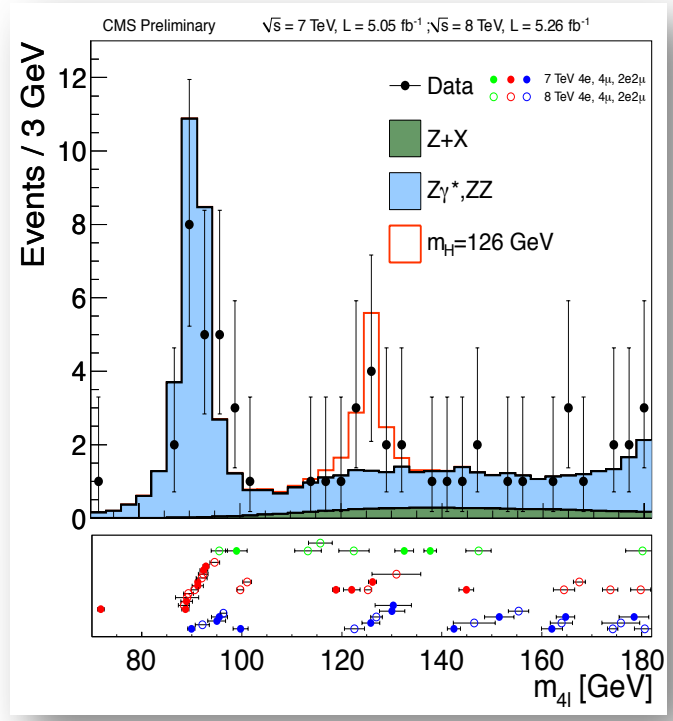
Pixel Tracker	Strip Tracker	Preshower	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Forward	HCAL Outer	Muon DT	Muon CSC	Muon RPC
97.1%	97.75%	97.1%	99.16%	98.54%	99.92%	99.96%	99.88%	96.88%	99.1%	97.67%	98.2%

*As of June 15 2012₄

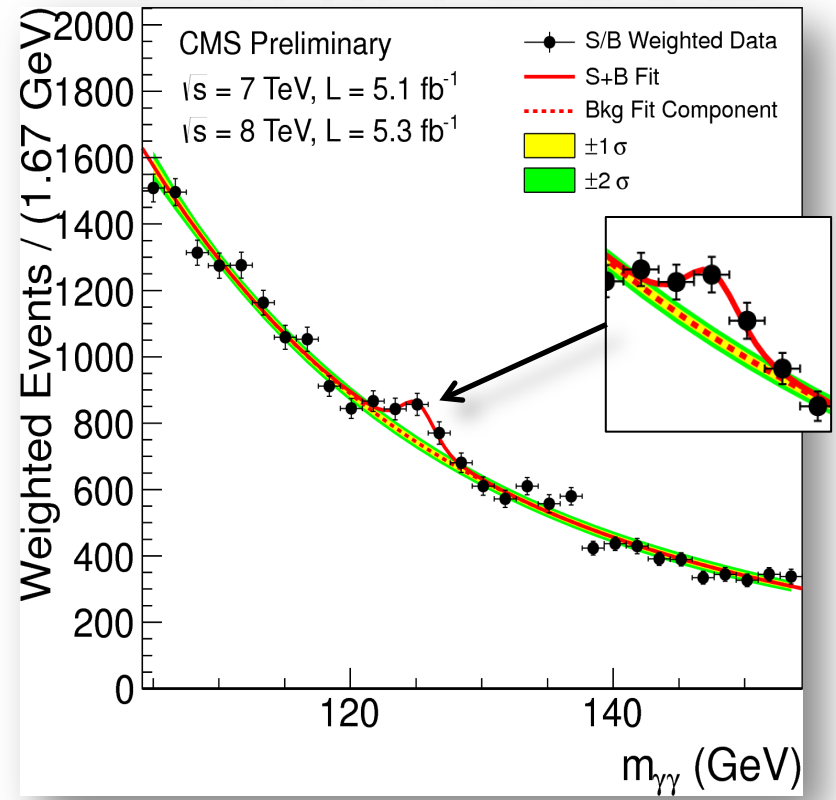


J. Incandela for the CMS

July 4th 2012 The Status of the Higgs Search COLLABORATION



4 July 2012



half design energy,
 one third of integrated luminosity
 five times higher pileup
 than originally expected

New physics

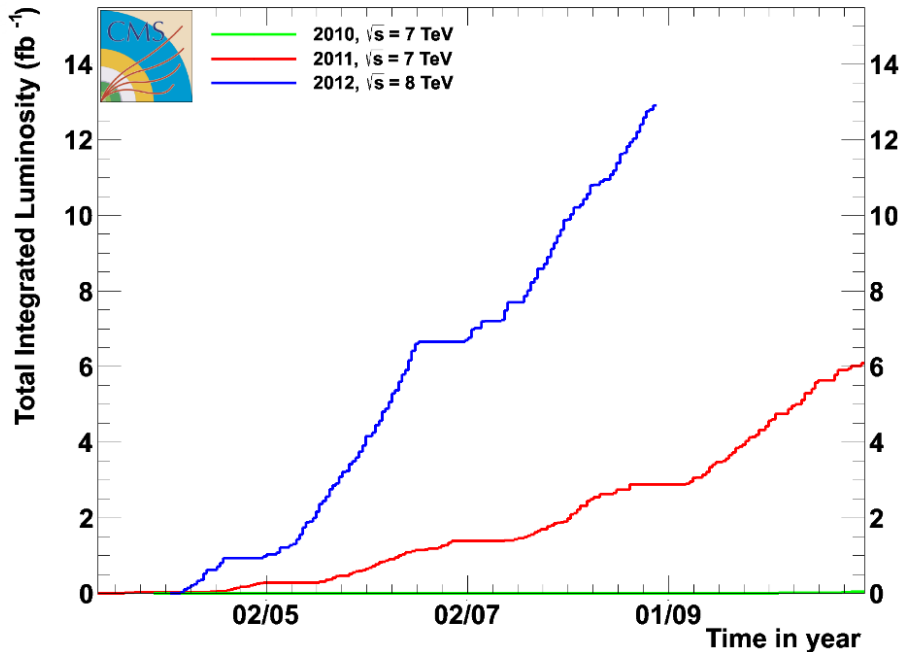
- CMS has already made one major discovery
 - still to prove it is a Higgs boson by measuring all its properties and couplings
 - it was expected to require much more data
- CMS has excluded large areas of phase space for the simplest SUSY models and new heavy vector bosons
 - moving on to more complex models where mass of putative Higgs may give hints (“natural” SUSY)
 - many other physics papers published...
- **Further investigations require much more data**
 - eg 2012 data insufficient to prove if 125 GeV boson spin 0 or 2
 - searching for rare phenomena: ~2B events will be stored in 2012

LHC STATUS

Comparison 2010 – 2011 - 2012



CMS Total Integrated Luminosity, p-p



- 2010: 0.04 fb⁻¹
 - Machine commissioning
- 2011: 6.1 fb⁻¹
 - Production
- 2012: 13 fb⁻¹ so far
 - Higher energy
 - Smaller beta*
 - Increased bunch current

24-Aug-2012 08:32:07					Fill #: 2998		Energy: 4000 GeV		I(B1): 2.13e+14		I(B2): 2.16e+14	
	ATLAS	ALICE	CMS	LHCb								
Experiment Status	PHYSICS	STANDBY	STANDBY	PHYSICS								
Instantaneous Lumi [(ub.s) ⁻¹]	7728.0	0.000	7537.3	28.4								
BRAN Luminosity [(ub.s) ⁻¹]	7707.1	2.030	7399.0	27.0								
Fill Luminosity (nb) ⁻¹	0.0	0.0	514.0	2.1								
BKGD 1	0.550	0.736	2.065	0.272								
BKGD 2	158.291	0.000	6.755	9.490								
BKGD 3	2.522	7.467	19.376	0.167								
LHCb VELO Position	001	Gap: 58.0 mm	STABLE BEAMS	TOTEM: STANDBY								

LHC future plans

- LHC operational conditions in 2012
 - 8 TeV, 50ns bunch spacing, $L_{inst} \sim 8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
 - target $\sim 25 \text{ fb}^{-1}$ with LS1 delayed 6 months
- Long term plan: Long Shutdowns (*later dates may change*)
 - LS1: March 2013-2015 - upgrade to full energy
 - 14 TeV, 25 (50?) ns bunch spacing, $L_{inst} < 2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - LS2: 2018 - improve collimation and other machine elements
 - 14 TeV, $L_{inst} < 4(?) \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - LS3: 2022 - upgrade for very high luminosity
 - 14 TeV, $L_{inst} \sim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (levelled)
- LHC machine consistently outperforming expectations
 - no scope for relaxation if physics reach to be maximised

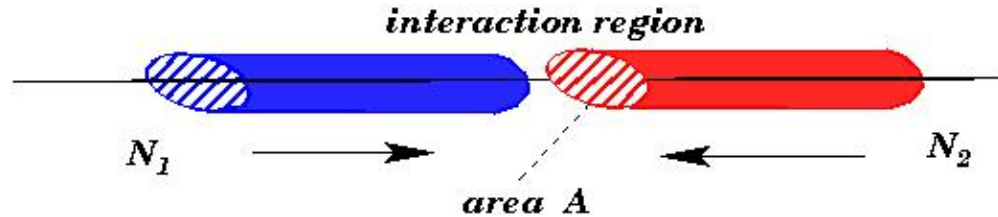
MOTIVATION FOR UPGRADE

The need for upgrades

- CMS and the LHC are working so well, with outstanding results, so why is an upgrade needed?
 - maintain physics performance in high pile-up conditions
 - trigger must maintain low p_T/E thresholds and 100 kHz rate
 - inner detector will be damaged by radiation
 - pixel tracker loses data at high rate
- Why is it needed now? (+ *time needed to build the systems*)
 - luminosity much higher than expected, and much sooner
 - pile-up has dramatic impact on trigger
 - tracking degrades significantly
 - original designs were limited by technology of the time
- Eventually (~2022) a brand new tracker is required
 - must be ready for large scale production by 2017

Luminosity

$$L_{inst} = \frac{N^2 k_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F$$



$$N_{events} = L\sigma$$

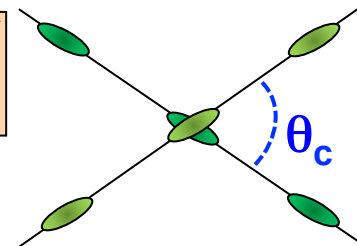
- Nearly all the parameters are variable (and not independent)

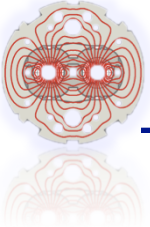
- **Number of bunches per beam**
- Number of particles per bunch
- Normalised emittance
- Relativistic factor (E/m_0)
- **Beta function at the IP**
- Crossing angle factor
 - Full crossing angle
 - Bunch length
 - Transverse beam size at the IP

k_b	—	Total Intensity
N	}	Beam Brightness
ϵ_n		
γ	—	Energy
β^*	}	Interaction Region
F		

$$F = 1 / \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2}$$

Presently $F \approx 0.8$





Comparison with nominal & pile-up



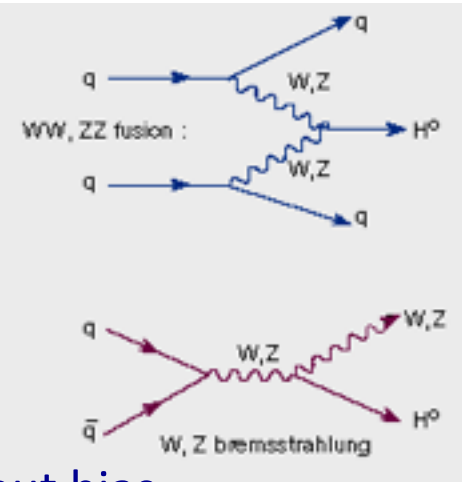
- **pile-up** \approx number of events per bunch crossing
 - ie $\mu = N\sigma$
 - Tracker also sees particles looping in B field
- For same L, 2x bunch spacing \rightarrow 2x pile-up
- **CMS designed for 14 TeV, $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and 25 ns**

Parameter	2010	2011	2012	Nominal
N (10^{11} p/bunch)	1.2	1.5	1.6	1.15
k (no. bunches)	368	1380	1380	2808
Bunch spacing (ns)	150	75 / 50	50	25
ϵ_n ($\mu\text{m rad}$)	2.4-4	1.9-2.4	2.2-2.5	3.75
β^* (m)	3.5	1.5 \rightarrow 1	0.6	0.55
L ($\text{cm}^{-2}\text{s}^{-1}$)	2×10^{32}	4.0×10^{33}	7.6×10^{33}	10^{34}
μ	3	19	35	23

Examples of physics impact

- Tracker degradation gives overall loss of data/quality

- and, e.g., significant losses of b quark jets



- Potential losses at trigger level

- WH associated production

- trigger on W (single e/μ) to measure H properties without bias

- p_T thresholds will rise significantly before LS2 (next slide)

- For $H \rightarrow b\bar{b}$ $H \rightarrow \tau\tau$ Higgs couplings measurements

- may only be possible using VBF production topology

- trigger on correlations between jets, especially forward jets

- pile-up is extreme.

Sample trigger menu from current L1 trigger

Algorithm	8 TeV 7E33 ~25 PU		14 TeV 2E34 50 PU	
	Thresh (GeV)	Rate (kHz)	Thresh (GeV)	Rate (kHz)
Single EG	22	10	46	10
Single IsoEG	18	9	31	9
DoubleEG	13, 7	9	22, 12	9
Single Muon	16	9	50	9
Dble Muon	10, open	5	35, open	5
EG+Mu	12, 3.5	3	21, 6	3
Mu+EG	12, 7	2	25, 15	2
SingleJet	128	2	188	2
DoubleJet	56	10	132	10
QuadJet	36	2	96	10
Double Tau	44	2	56	2
MET	36	7	84	7
HTT	150	2	511	2

Example 14 TeV trigger menu
 ▶ Using current bandwidth allocation
 ▶ Based on MC - still needs to be fully validated & finalised

Single lepton thresholds are very high

Combined rate of current single lepton triggers *only*
 ~ 140 kHz at 14 TeV 2E34

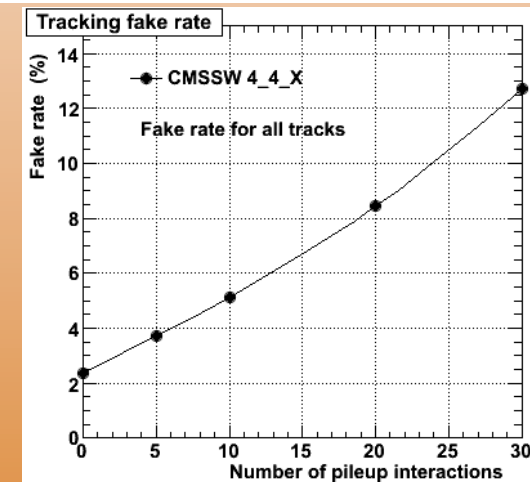
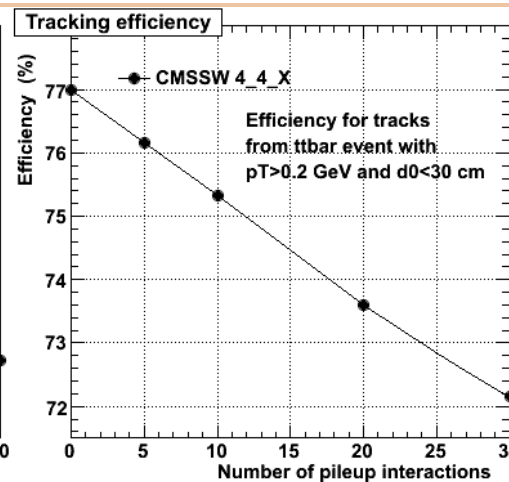
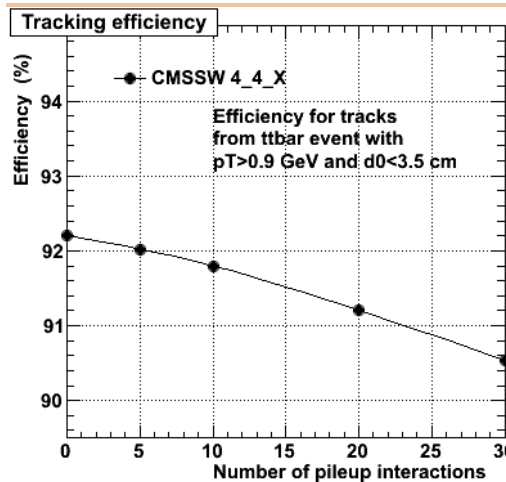
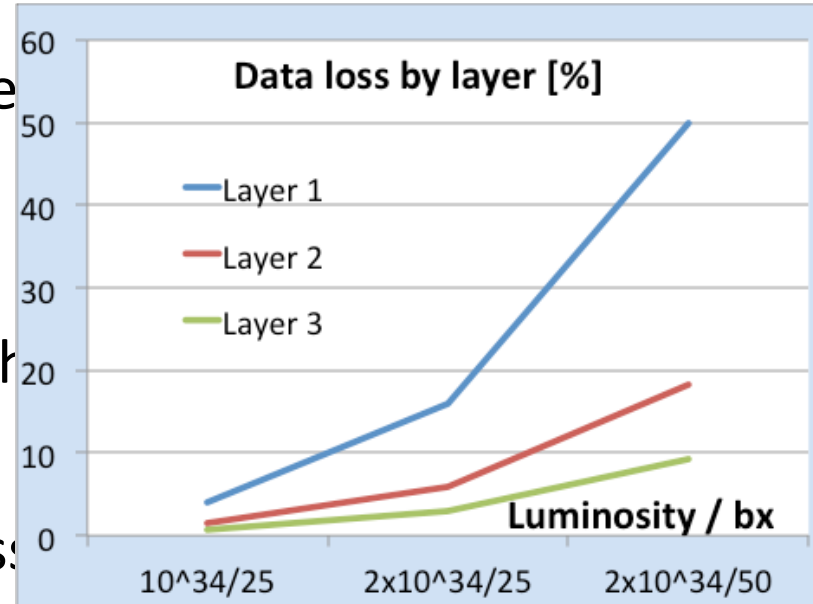
Cannot maintain current thresholds with current L1 trigger at 14 TeV 2E34

Multi-jet trigger thresholds affected by both \sqrt{s} and PU

IMPACT ON CMS

Tracking at high pileup

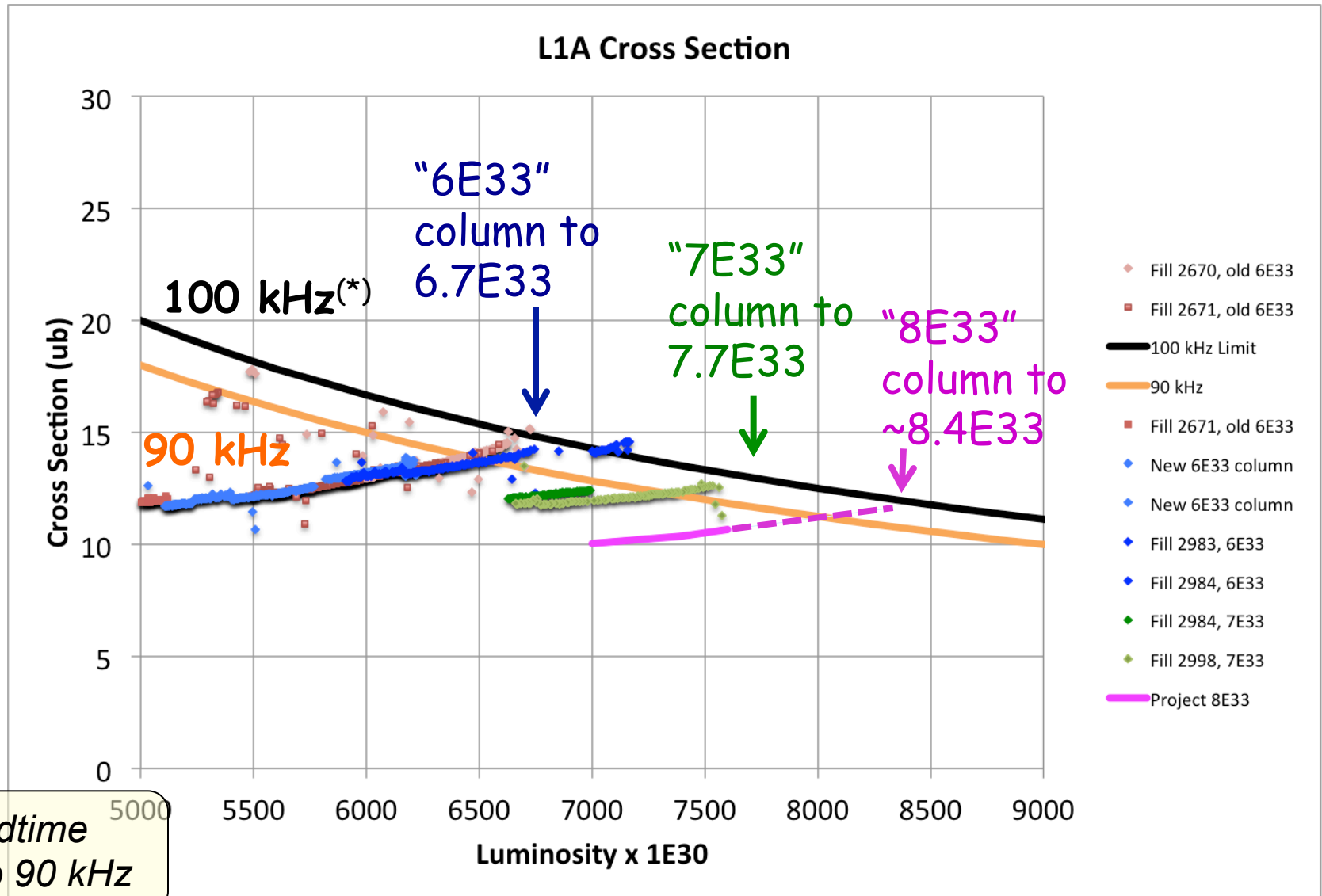
- Tracking efficiency is reduced – affected by
- Fake track rates are increased
- Primary vertices merge
- Resolution worsens, due to wrong hit assignment
- Increased CPU and memory use
- Inner pixel layers: dynamic data loss



Pixel dynamic inefficiency not included can be sizable effect



L1 Total Cross Section vs. Luminosity (Limits of Prescale Columns)

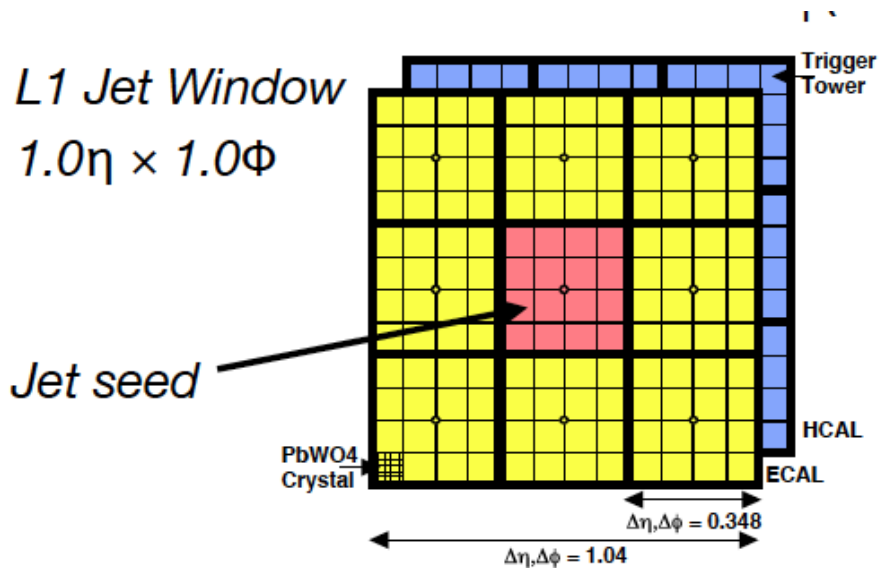




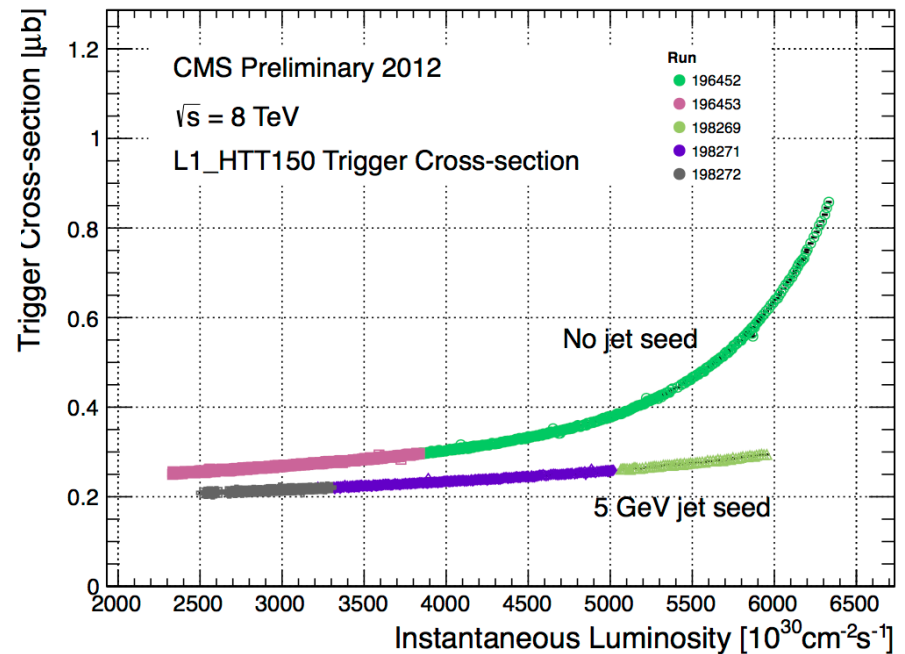
Improved Pile-up Handling in L1 Jets

- Increased jet seed threshold to 5 GeV in Global Calorimeter Trigger since June Technical Stop

GCT team



- Significantly reduces exponential rise in xsec





But... Problem is only Postponed...

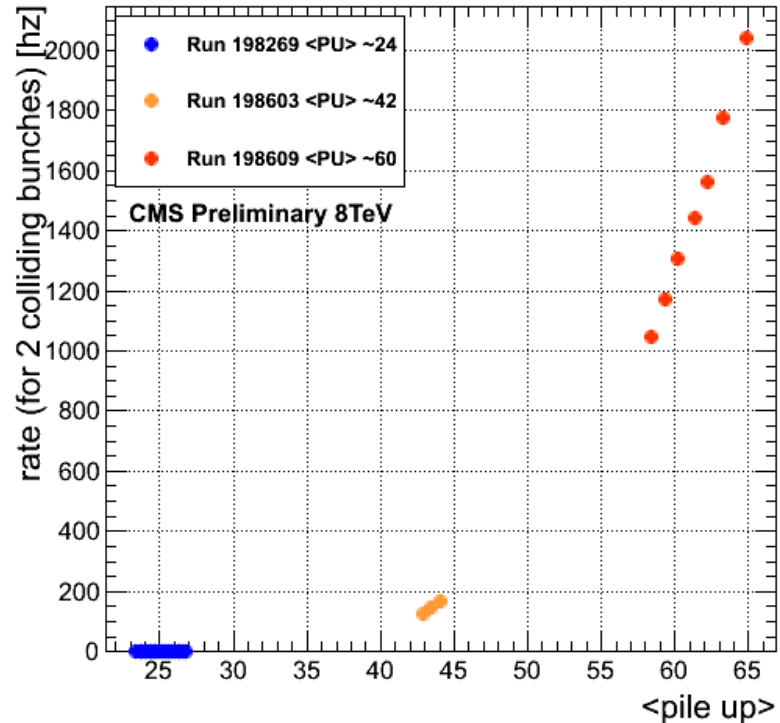
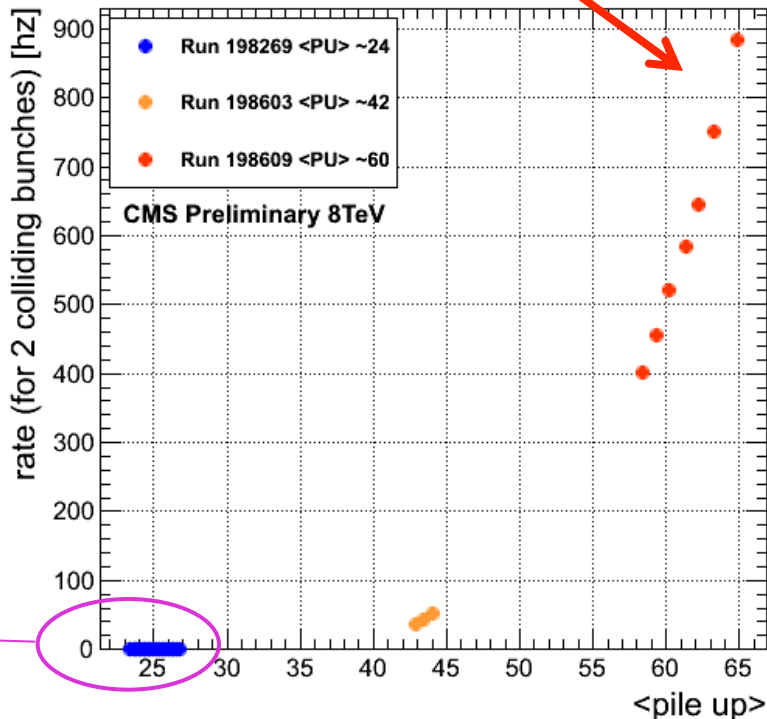
- ★ Blow-up seen to return at higher pile-up (special fills)
 - Can further increase the seed threshold and jet threshold in HT
 - But better yet is an upgraded L1 trigger !

L1_HTT200

0.5 MHz @ 50 ns !

L1_QuadJetC40

C.Battilana



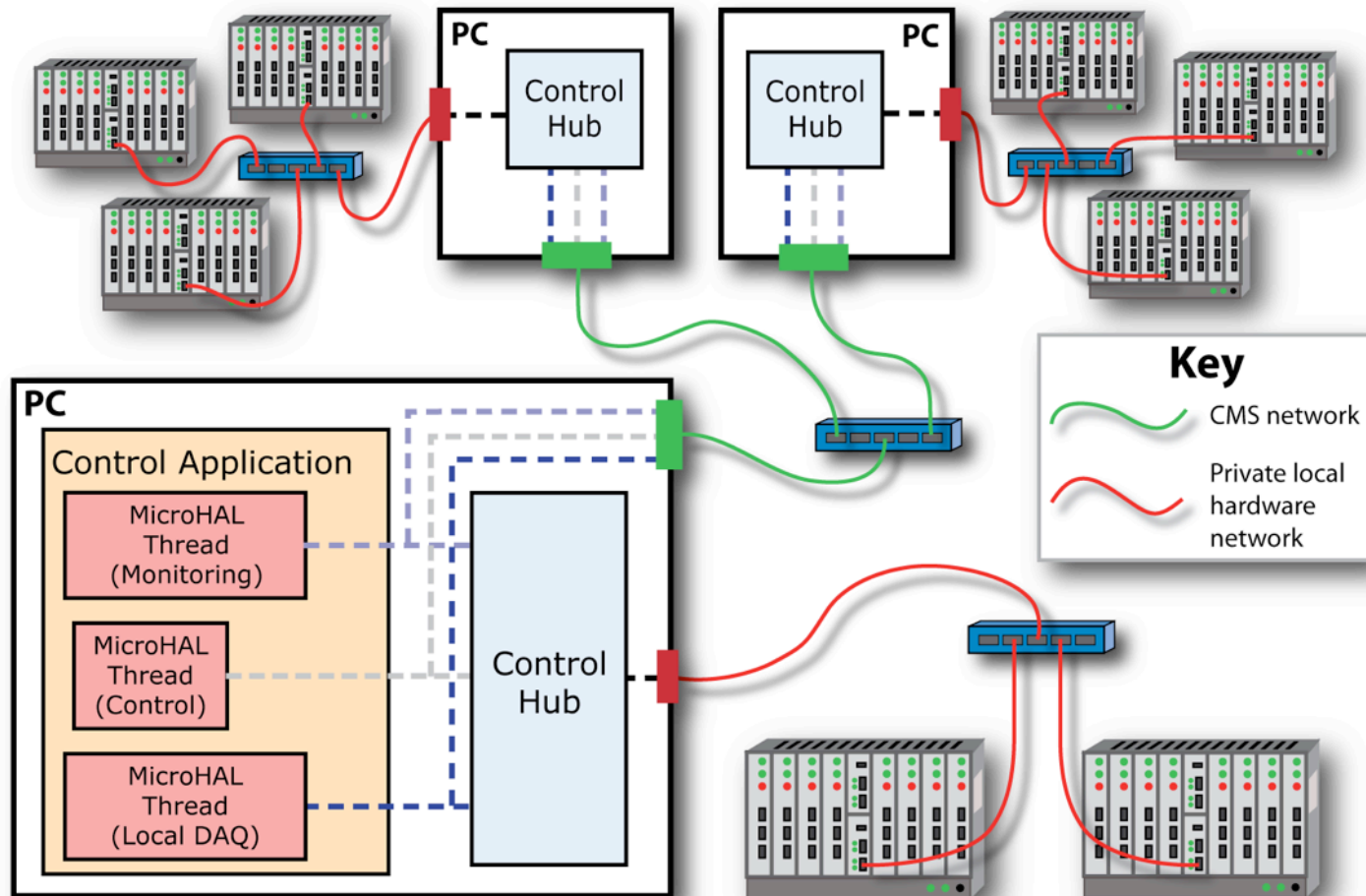
Lumi @ 50ns: 1E34 1.4E34

UK R&D since 2009

UK CMS upgrade R&D achievements

- WP1 – software and simulations
 - IPbus (μ TCA control) (10/11) adopted as common CMS-wide standard (02/12)
 - simulation studies for trigger and tracker upgrades in TDRs (09/12)
- WP2 – Outer microstrip tracker readout
 - CBC 128 channel ASIC (03/11) developed in single design iteration & evaluated
 - CBC2 256 channel ASIC submitted (07/12), with trigger data, due (10/12)
 - DAQ & FED studies, with CBC module beam tests (09/11)
- WP3 – L1 calorimeter trigger system
 - Mini-T5 (02/10) & MP7 (07/12) processor boards delivered and working
 - CMS review recommended UK hardware for future baseline (12/11)
 - original new trigger architecture proposed (02/11) and demonstrated (03/12)
- WP4 – pixel DAQ
 - Long experience in Tracker DAQ and DQM
 - UK proposal to design and deliver new pixel FED accepted (11/11)
 - modified trigger hardware, IPbus and pixel ROC test beam experience (7/12)

Online Control System



- ▶ IPbus: scalable, hierarchical software/firmware system

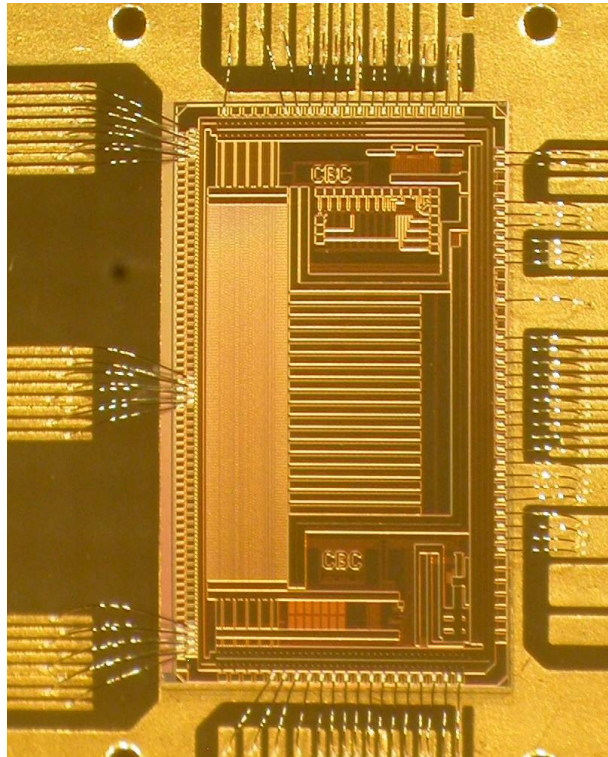
Track reconstruction code optimisation

- Example of ongoing efforts to improve high pile-up performance
 - also relevant to current operation
- New search method to reduce time spent in the two [pixel] triplet seed generators based on k-D trees
 - Using k-D tree code in both generators gives significant decrease in CPU time
 - negligible reduction in tracking efficiency

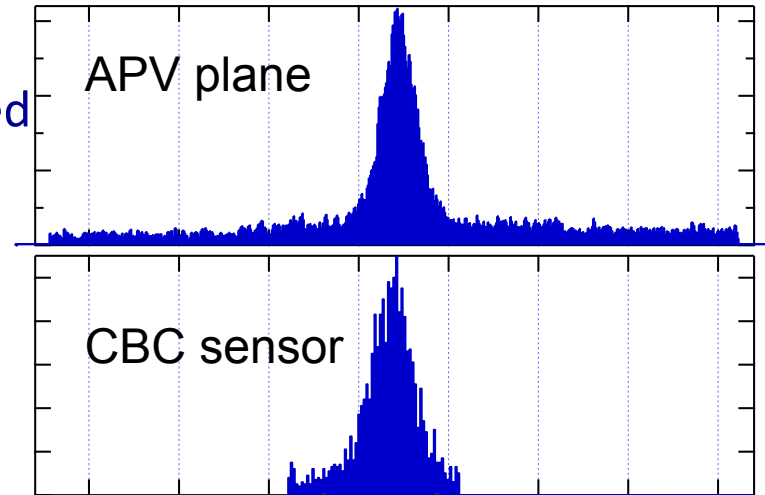
	Standard	Large Tip k-D tree	LargeTip and HLT k-D tree
LargeTIPGenerator	3.94% (28s)	0.83% (6s)	0.84% (6s)
HLTGenerator	1.37% (10s)	1.38% (10s)	0.74% (5s)
CombinedHitGenerator	5.31% (38s)	2.20% (16s)	1.58% (11s)

WP2: Phase II Outer Tracker readout

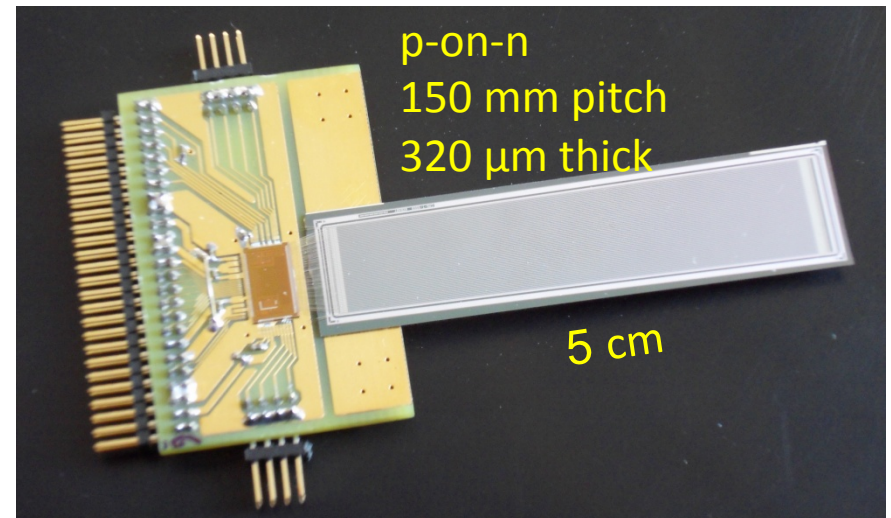
- CMS Binary Chip: 130nm CMOS
 - 128 channel binary ASIC, non-zero suppressed
 - Amplifier, pipeline, memory, logic, control
 - many new features, excellent performance
 - tested in beam with 5cm μ strips



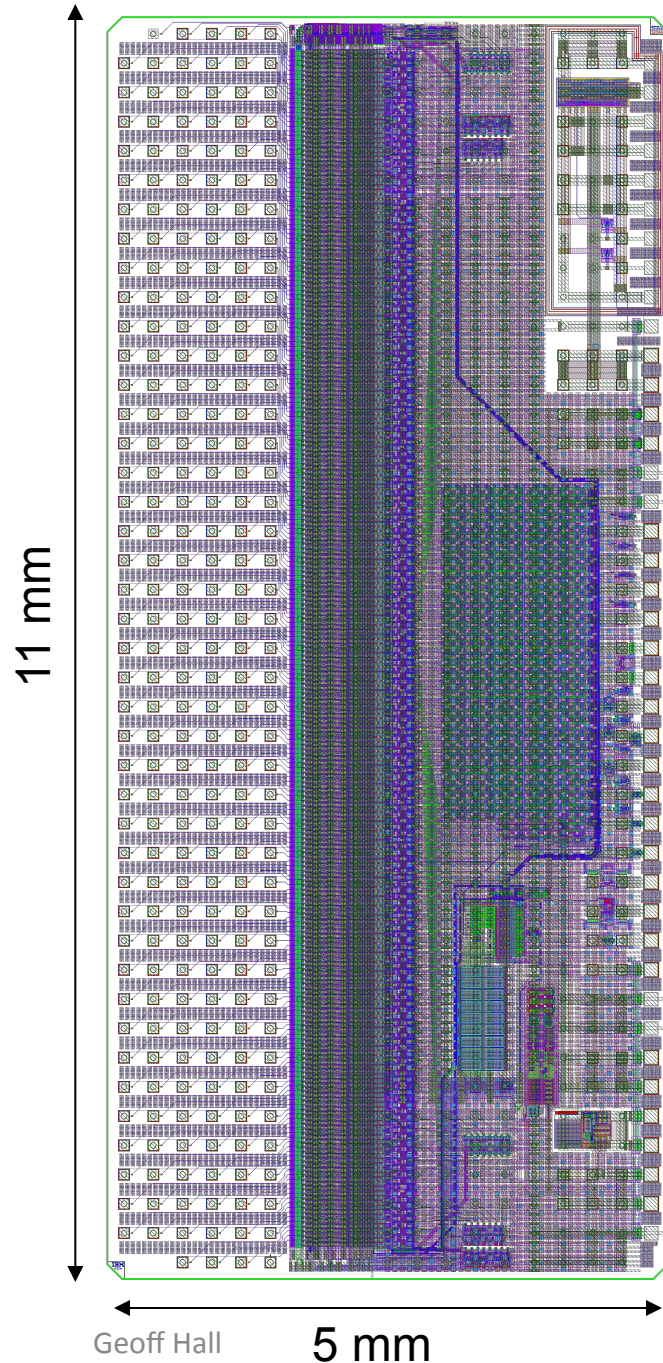
beam profile



5 mV / division



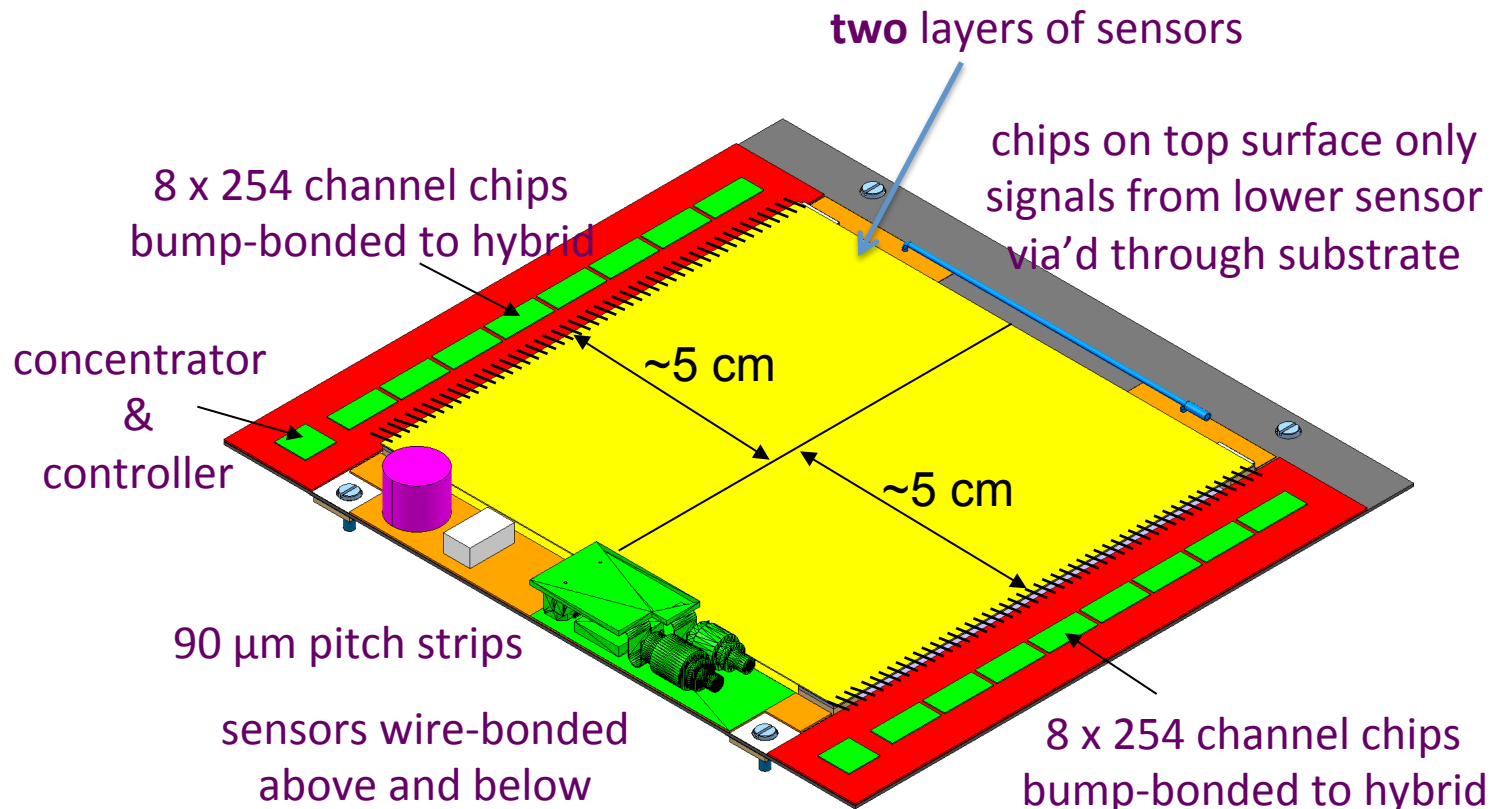
CBC2 design



- 250 μm pitch C4 layout
 - back edge wire-bond pads for wafer probe
- 254 channels
 - allows correlation between 127 top & 127 bottom strips
- architecture based on CBC prototype
 - front end, pipeline, readout architecture, powering features,
- submitted July 2012
 - wafers expected ~ October
- tested, functional CBC2 is final deliverable of current Upgrade programme

2S PT-module with CBC2

- **Track & trigger** module under development with CERN, Lyon, ..
 - CBC2 logic correlates hits on two sensors to reject those from low p_T tracks
 - many issues to construct such a module

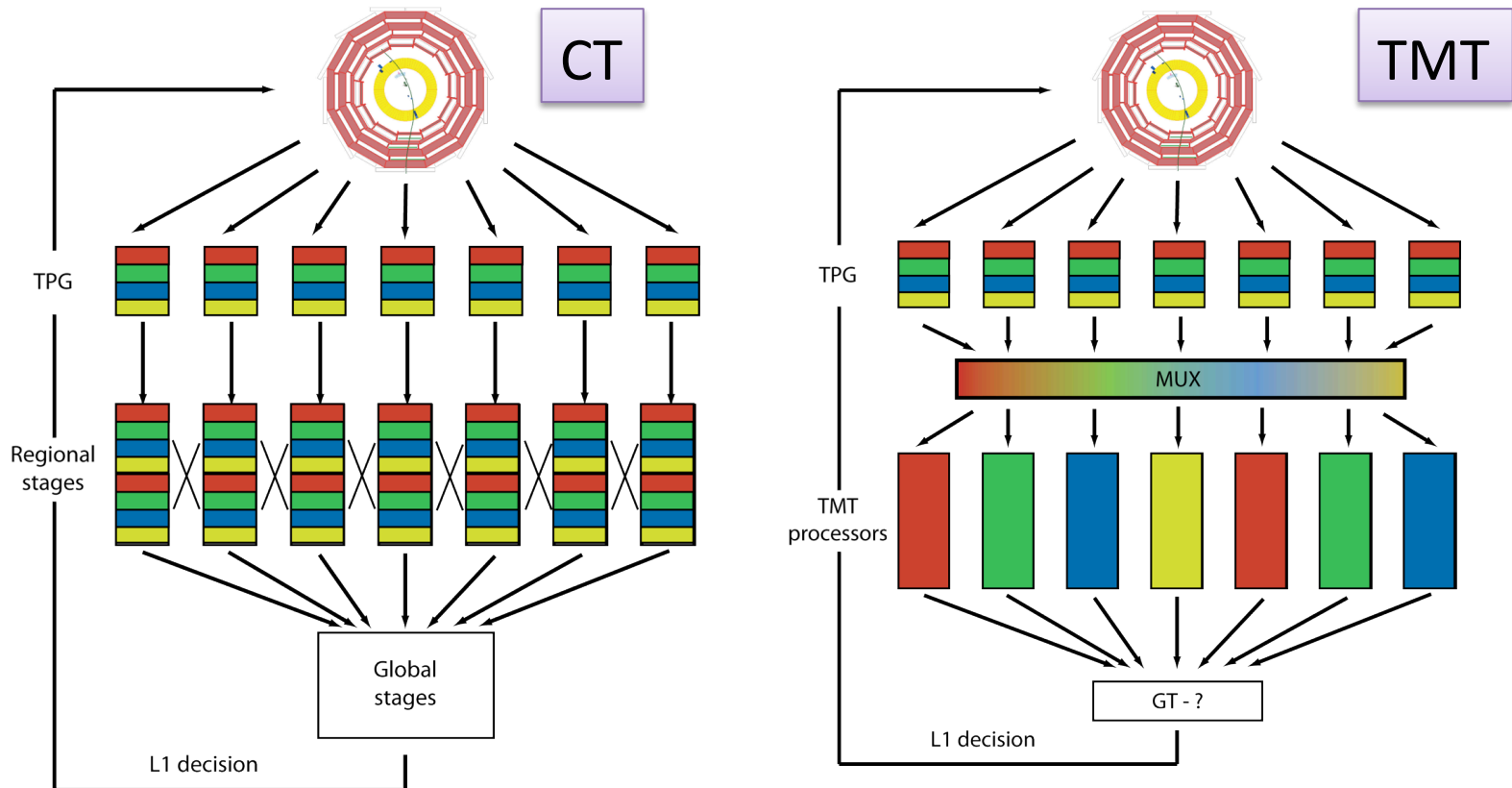


WP3: calorimeter trigger

- Brand new architecture proposed (*but hardware is agnostic*)
 - possible because of technology progress (FPGAs & links)
 - TMT = boundary-less calorimeter processing
 - decision postponed but concern about trigger after LS1 growing
 - actions to install complete new optics advancing
- Demonstrator using mini-T5 (*Virtex-5 FPGA*)
 - emulates $\frac{1}{4}$ of present CMS calorimeter trigger
 - TMT versions of present algorithms (much faster)
 - HL-LHC algorithms already in firmware
 - latency (potential concern) measured
- MP7: final board delivered August 2012 (*Virtex 7 FPGA*)
 - already producing impressive results in very early tests

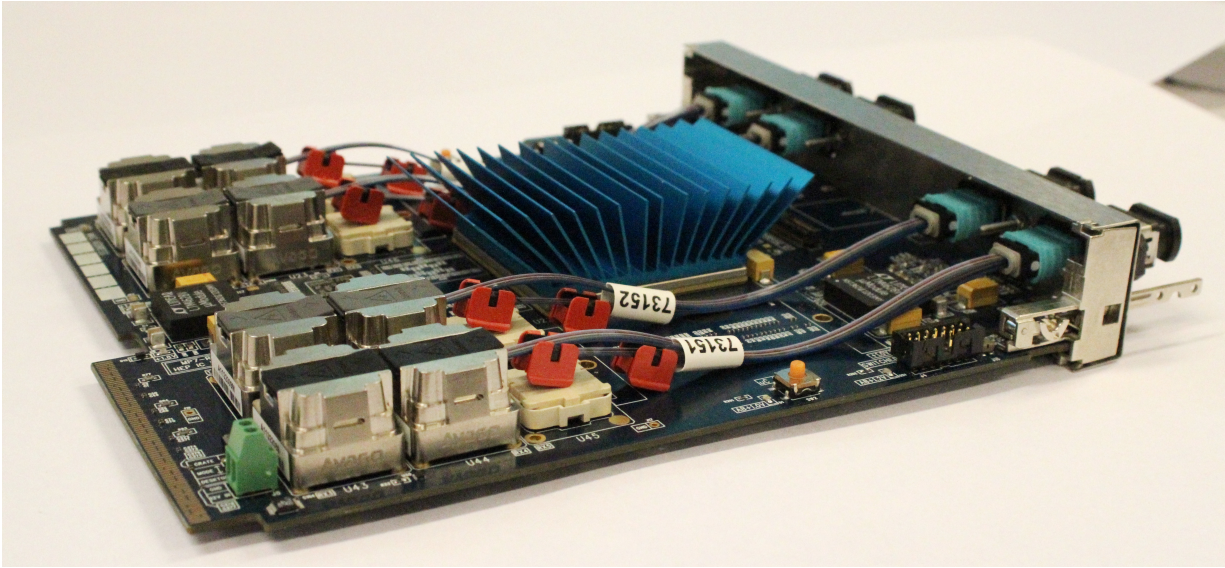
Trigger Architecture

- Options: Conventional Trigger vs Time Multiplexed Trigger
 - TMT: all calorimeter data to single processor
 - Allows more flexibility in trigger design & avoids boundaries and data sharing



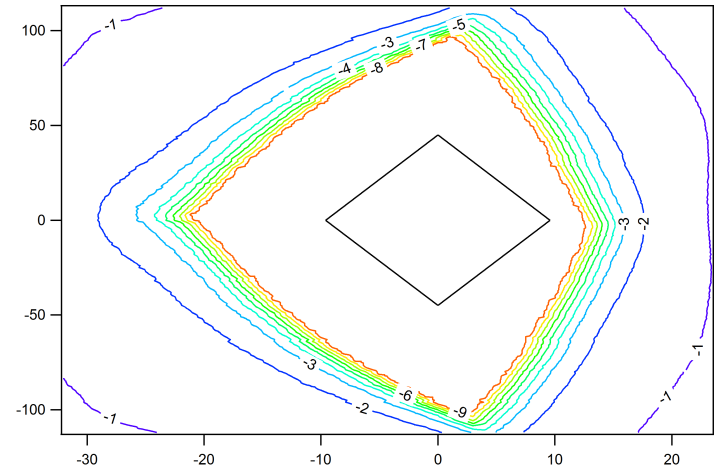
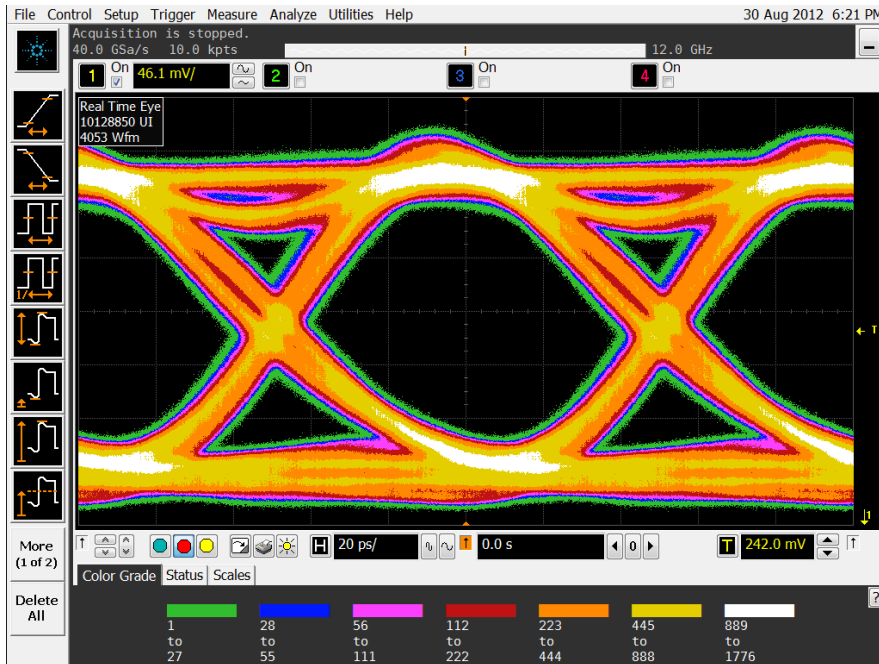
MP7 Prototype

Preliminary Results



- 1Tb/s - All 96 optical links operating at 10Gb/s simultaneously
 - x4 bandwidth of any previous card in CMS
 - 1.0 - 1.4 Tb/s of optical I/O (*Tracker FED ~ 25 Gbps*)
 - (*TWEPP 2012 suggests this board is well in advance of anything else...*)
- All peripherals operating (RAM, CPLD, MMC, etc)
- Cooling will be improved
 - verify contributions to power consumption when diagnostics available

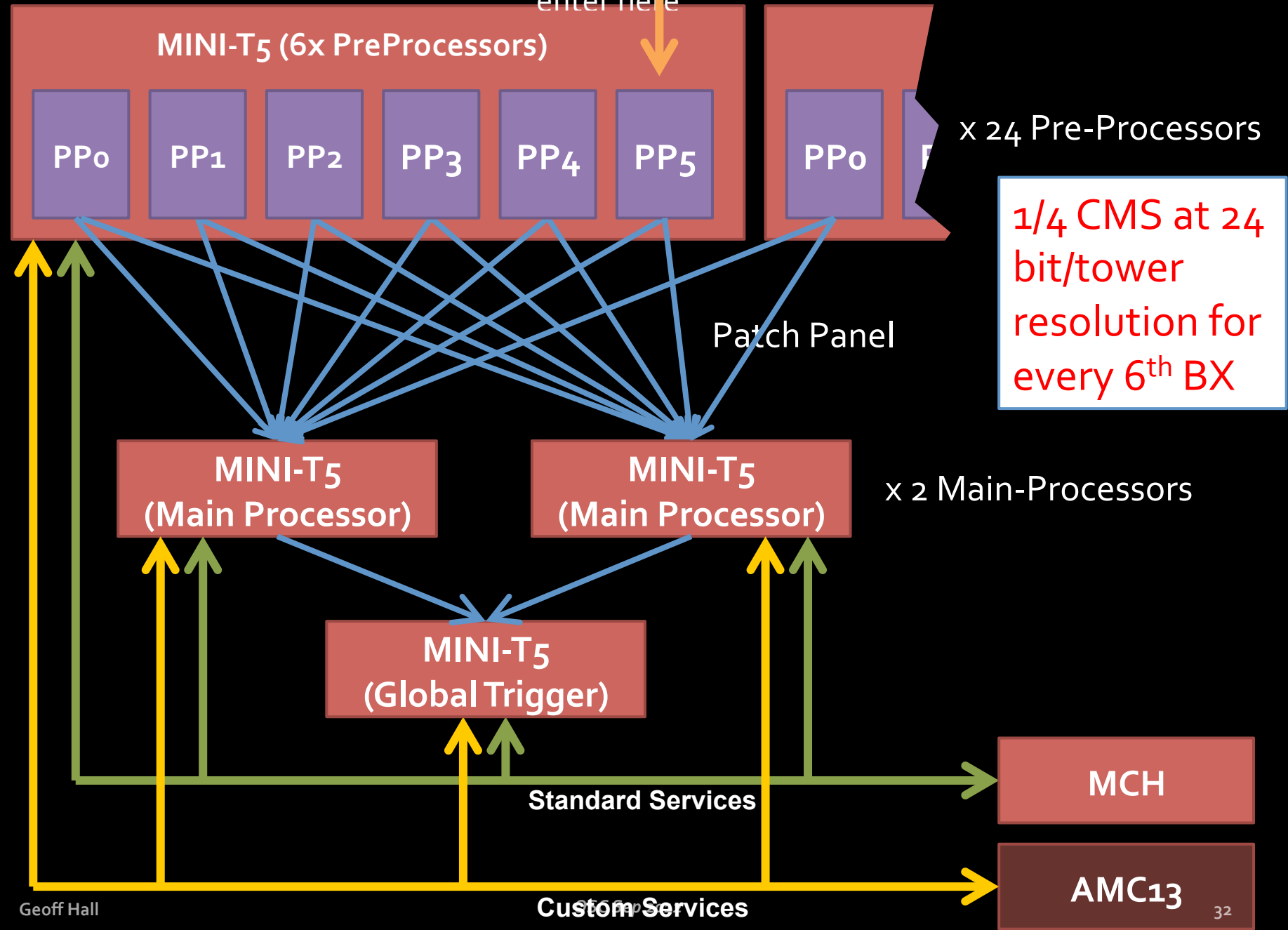
MP7 - Preliminary results



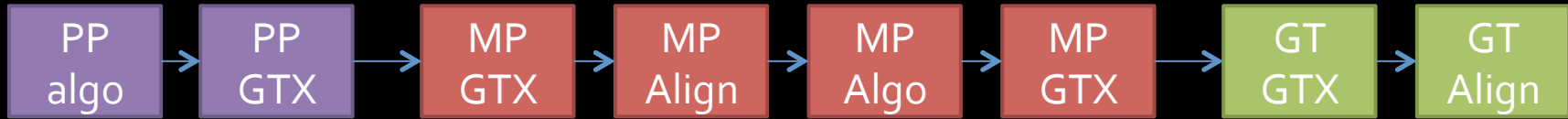
- Clean optical eye (left) and electrical received eye (right).
 - pre-emphasis in the optical receiver, should improve the eye even more.
- PCB manufacturing improvements are possible should we need them.

Demonstrator

ECAL & HCAL Trigger Primitive Data would enter here

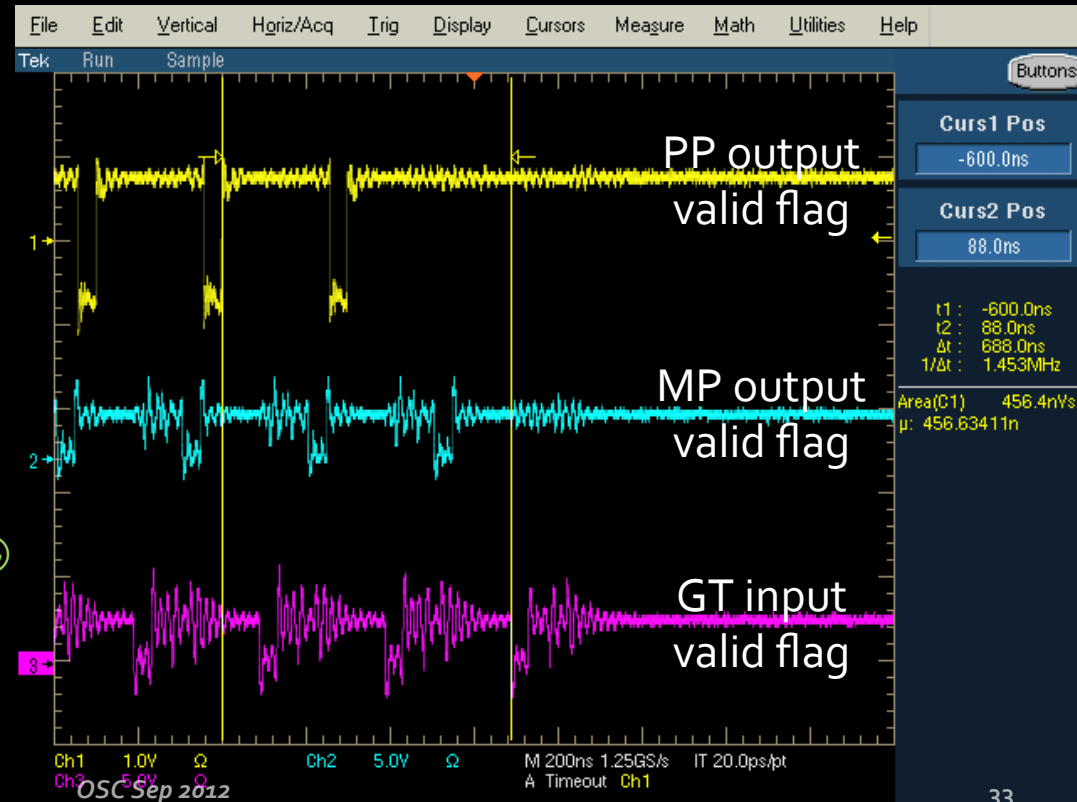


Latency – Time-Multiplexed CMS GCT



Total latency is:

1 Link latency (PP to MP)	6.5 BX	161.6ns
1 Algorithm latency	3.7 BX	92.8ns
1 Link latency (MP to GT)†	7.5 BX	182.4ns
1 Time-Mux period	10 BX	250 ns
Total	27.7 BX	686.8 ns



Look at that – the maths works, phew! 😊

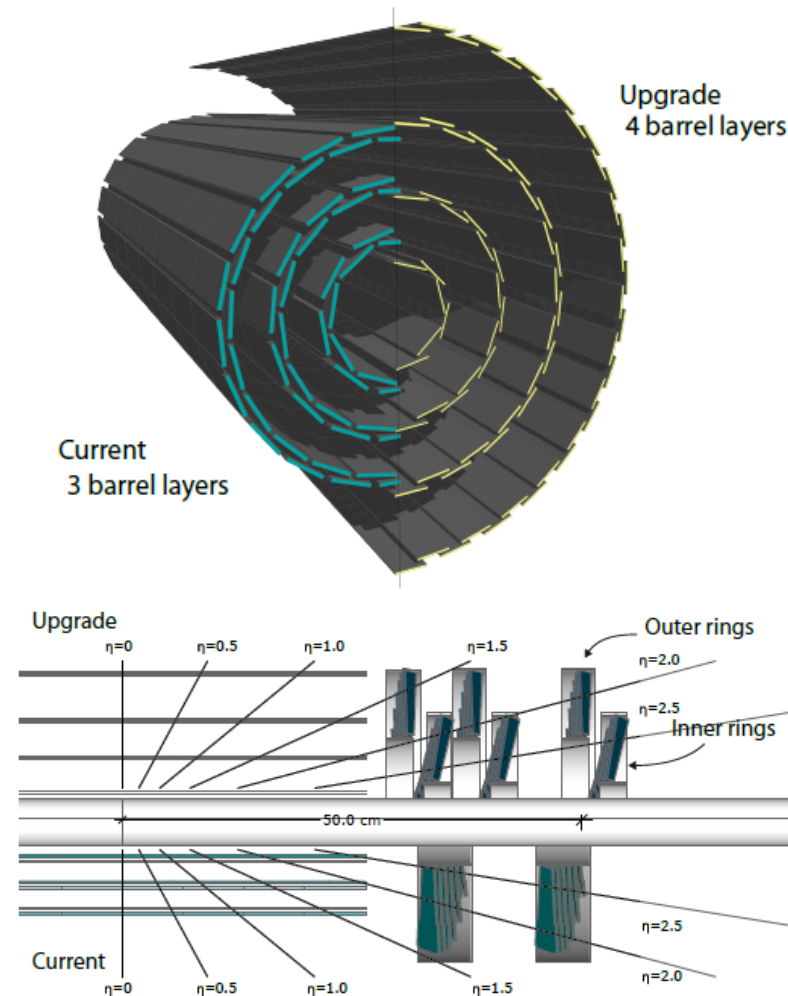
†Making allowances here for the firmware bug

WP4: pixel DAQ

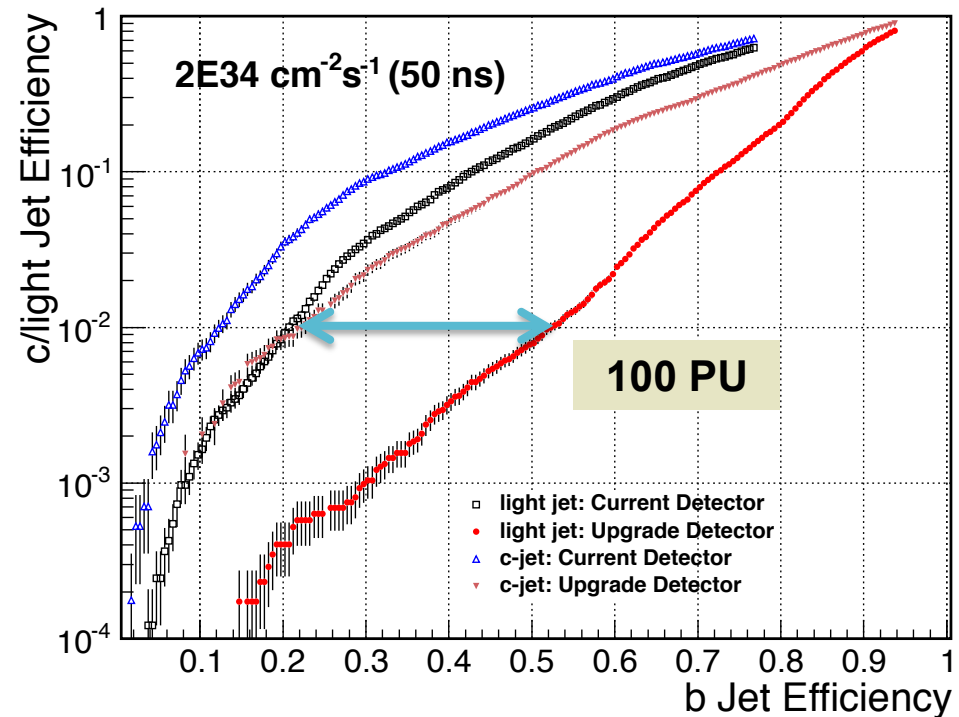
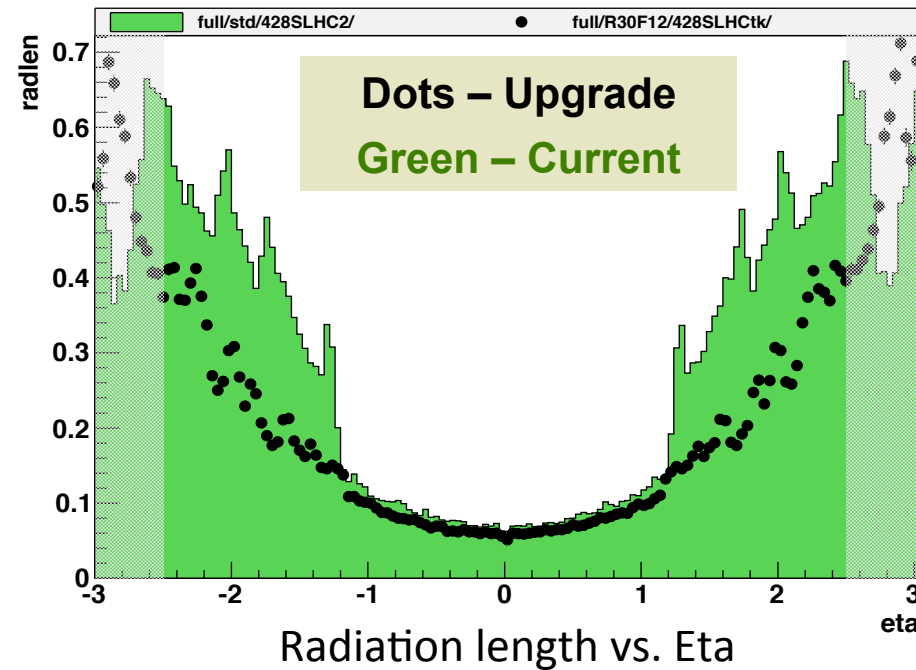
- Pixel detector will be replaced at end of 2016
 - improved performance for high pile-up environment
- TDR released with UK proposal for pixel FED & DAQ responsibility
 - subject to PPRP approval
 - builds on UK expertise in Tracker DAQ and R&D to date from all existing WPs, with sharing by all UK groups
 - WP1: IPbus & simulations
 - WP2: SFED development
 - WP3: mini-T5/MP7 hardware & firmware
- Very positive response from CMS
 - UK is highly regarded, and we gain expertise in strategic area
 - strengthens pixel project & matches long term μ TCA adoption (we are “experts”)

Phase I pixel upgrade

- Replacement is a lower mass detector with 4 barrel layers and 3 endcap disks per side
 - less material & better layout means less conversions & interactions
 - better IP resolution and b-tagging efficiency
 - improved seeding efficiency & lower fake rates from extra tracking layer
 - 4th layer provides better track projection to the strip tracker
 - higher readout efficiency and less deadtime with new ROC and digital readout chain



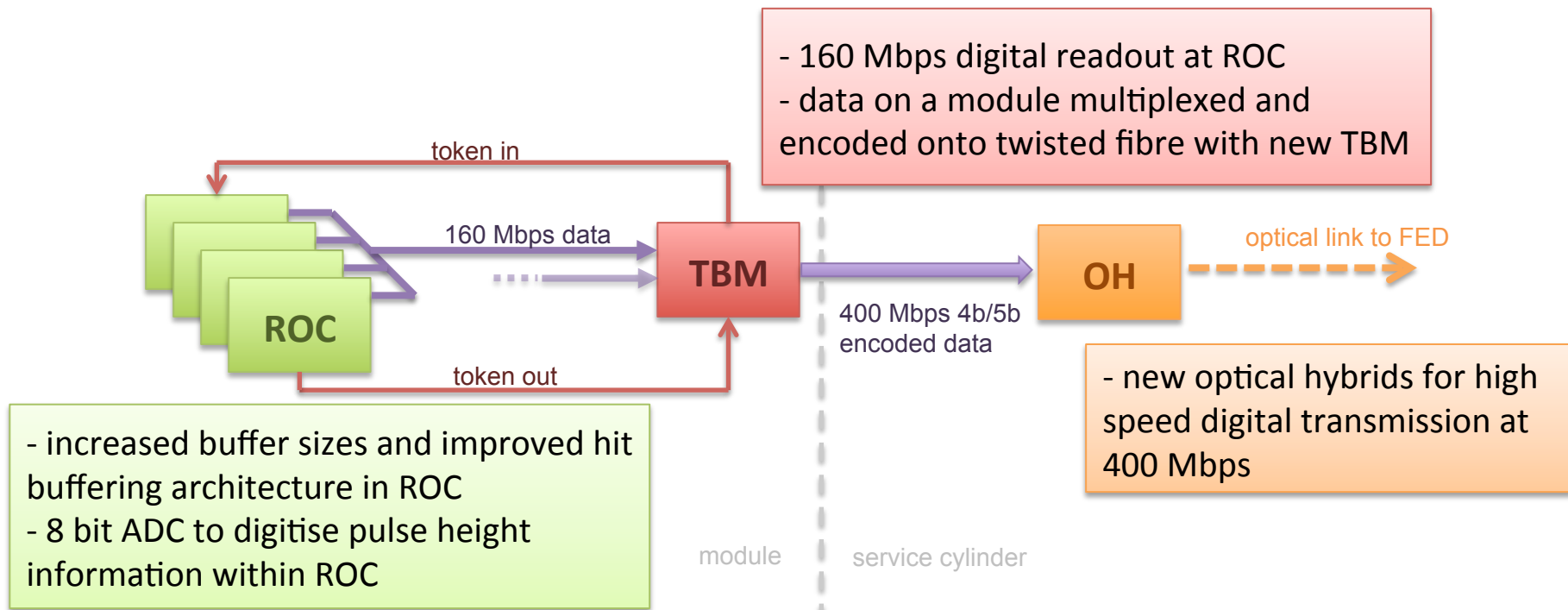
Phase I pixel upgrade



- substantially reduced detector mass, despite twice number of channels
 - CO_2 cooling, improved mechanics, optimised layout of services
- b-jet efficiency improvement of 30%, for a 1% fake rate at 100 PU

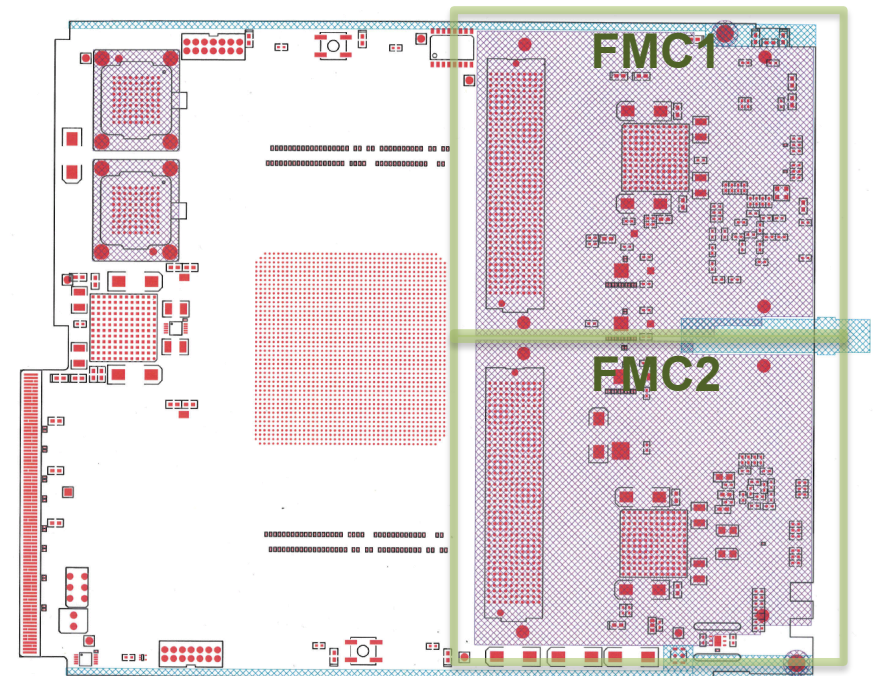
New ROC and readout chain

- New ROC and readout scheme required for efficient operation up to 100 PU
 - estimated ~50% data loss at 100 PU (50 ns bunch spacing, $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at $r = 3.9 \text{ cm}$)
 - requirement is for < 3% data loss at new 2.9cm reduced radius

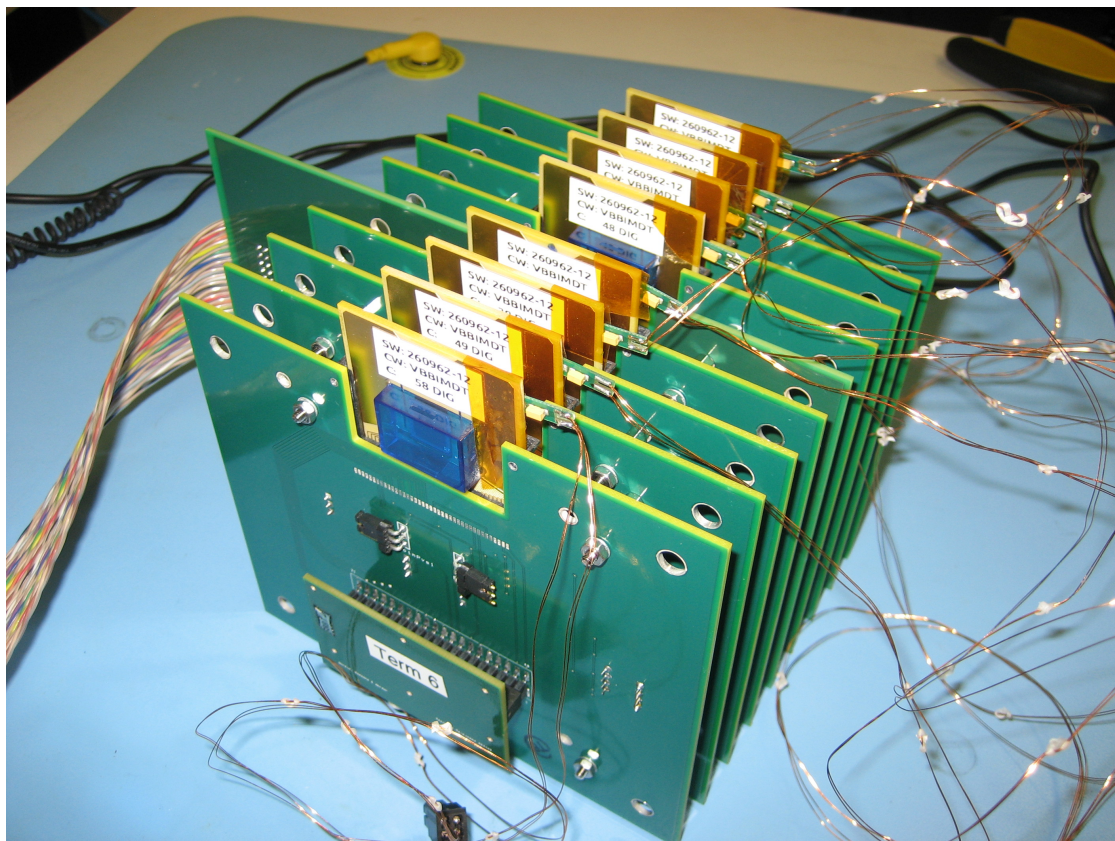


Phase I pixel FED

- New DAQ required
 - new digital optical links
 - more channels so higher data throughput
- FED prototype based on MP7
 - mezzanine cards for prototyping and maximum flexibility
 - reusing MP7 design mitigates risk and benefits from firmware & software investment



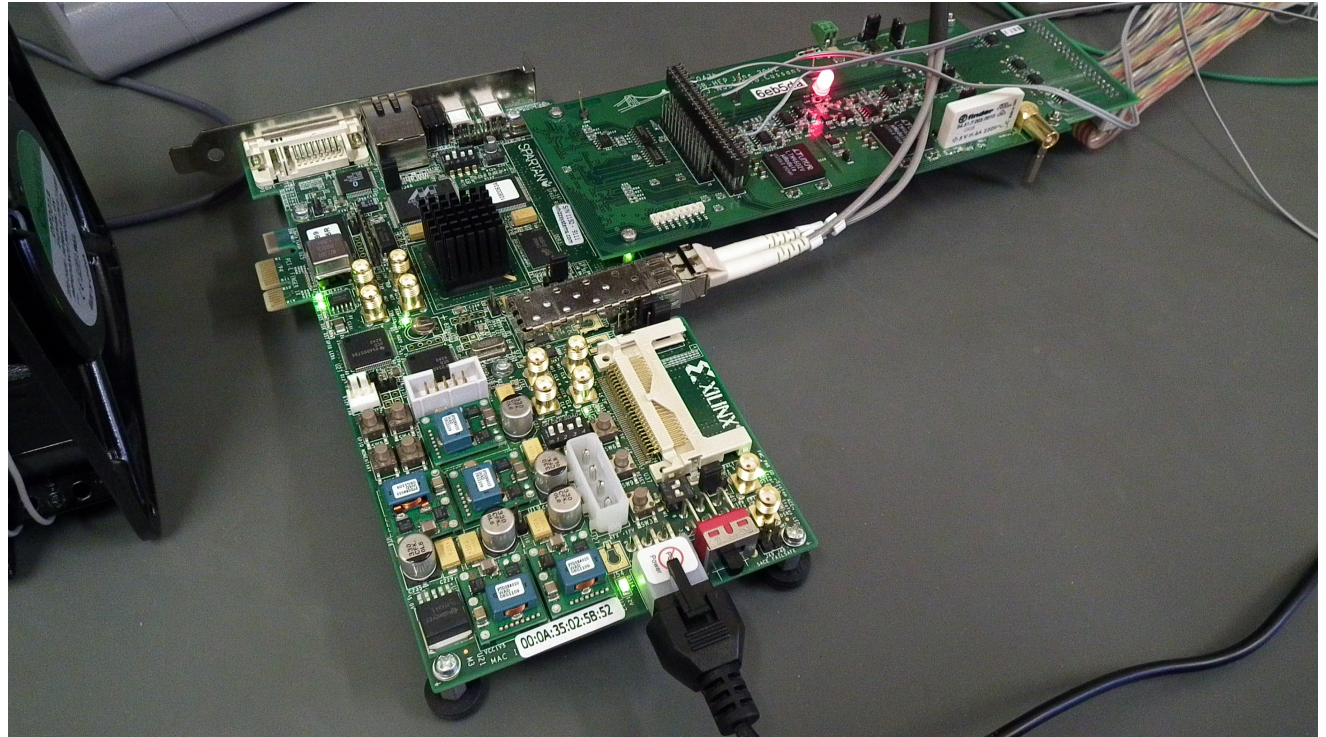
Pixel beam telescope



- Modular system
 - Variable number of ROCs
 - Variable readout system
 - Standard ROC carriers
 - Easy to replace ROCs
- Successfully used in beam test in July 2012

Pixel DAQ board

- First FED firmware test bed
 - Xilinx evaluation board with custom adapter
- First application
 - high rate test beam in October



PPRP proposal: Work Programme

- Builds and continues R&D progress to date
 - detailed plans based on (best knowledge of) CMS schedule
- WP2: prepare for construction of Phase II tracker
- WP3: construct new calorimeter trigger
- WP4: deliver pixel FEDs and implement new DAQ

WP2 objectives: next ~ 6 years

- complete CBC development for SS-pT module
 - bring chip to final state ready for mass production
- develop hardware & software for mass production test
 - extensive experience from LHC production
- major role in definition, construction and evaluation of prototype modules
 - in collaboration with groups responsible for other module components
- contribute to ancillary chips development and PS-pT (strixel layer) module
- contribute to tracker construction
 - procurements, integration and commissioning

WP3 deliverables

No	Month	Deliverable
M3.1	9	Updated algorithms and software for current L1 calo trigger
M3.2	15	CMS L1 Calo trigger ready for post-LS1 running
M3.3	24	Design studies for $> 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ trigger ready; architectural choices made by CMS; sign-off point on $> 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ hardware production
M3.4	40	Hardware systems ready for $> 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ trigger
M3.5	48	$> 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ trigger in operation
M3.6	60	Technical design of post-LS3 trigger complete; sign-off point on LS3 prototype production
M3.7	72	Delivery of track trigger prototype

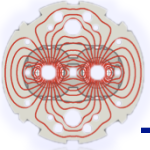
WP4 deliverables

No	Month	Deliverable
M4.1	6	prototype FMC-FED hardware available
M4.2	18	standalone prototype FED, multi ROC readout
M4.3	18	standalone prototype FEC, multi-module control
M4.4	24	demonstrator FED & FEC with readout & control of pilot blades
M4.5	24	demonstrator fast link integrated with central DAQ hardware
M4.6	33	final FED hardware ready for production
M4.7	39	final firmware & software for full system ready for deployment
M4.8	45	delivery of full Pixel DAQ

Summary

- Very good progress continues in all WPs
 - 6 year plan now incorporated in PPRP bid, which is under review
- CMS and LHC upgrade planning
 - pixel TDR released, Trigger TDR ~March 2013
- Finances
 - spending increased: commitments on MP7 & CBC2
 - Working Margin now £120k and will reduce in remaining 6 months
 - Need more MP7s for new demonstrator
 - Reserve in case of CBC2 problems
 - SSC reporting changed again: no PPD staff costs visible
 - Travel now handled by universities
- Not yet finished the R&D but the UK investment has been timely, immensely helpful and put us in a strong position for the future.
 - Thanks!

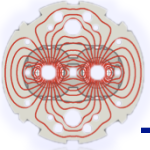
Further information



Long Shutdown 1



- End March 2013 – November 2014
- Consolidation for 6.5 – 7.0 TeV operation
 - Measure all splices and repair defective ones
 - Repair of magnet interconnects after 2008 event with new design (clamp, shunt)
 - Finish installation of pressure release valves
 - Exchange of weak cryo-magnets and DFBA's
 - Relocation of equipment to reduce radiation effects on electronics
 - Installation of collimators with integration beam position measurement, injection absorbers refurbishment
 - Injection kickers reduction of heating
 - Experiments consolidation and upgrades
- Plus a lot of other work ongoing
 - Cryogenics, Quench Protection, electrical infrastructure, cooling & ventilation, Radio Frequency, beam dump absorber & magnet, change of dump switches (radiation), electron cloud mitigations ...



Potential Performance after LS1



- Determined by the performance of the injector chain
- Different collimator scenarios, not detailed here
- LHC Injector Upgrade (LIU) fruits after LS2

	Number of bunches	β^* [m]	Half X-angle [μ rad]	Ib SPS	Emit SPS [μ m]	Peak Lumi [$\text{cm}^{-2}\text{s}^{-1}$]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	2800	0.50	190	1.2e11	2.8	1.1e34	23	~30
50 ns	1380	0.40	140	1.7e11	2.1	1.8e34 β^* level	81 β^* level	?
25 ns low emit	2600	0.40	150	1.15e11	1.4	2.0e34	48	52
50 ns low emit	1200	0.40	120	1.71e11	1.5	2.2e34	113	?

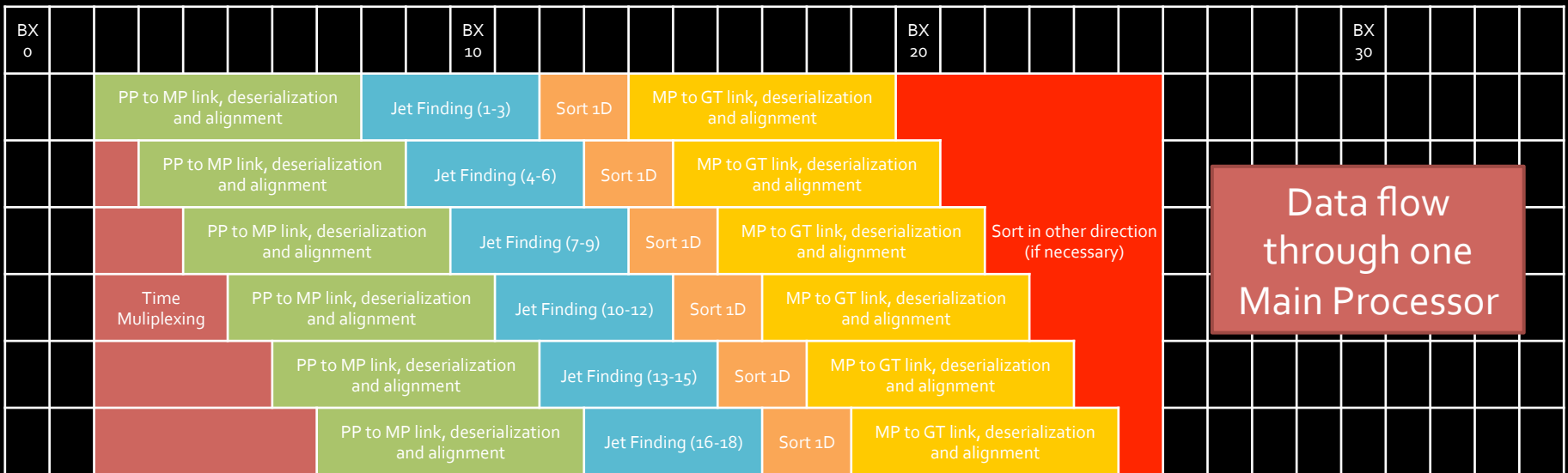
Presently at 4 TeV, $\beta^ = 0.6$ m, half X-angle 145 μ rad*

Latency – Time-Multiplexed CMS GCT

Original GCT timing specification



TMT GCT timing using Mini-Ts



TMT latency, 23 BX

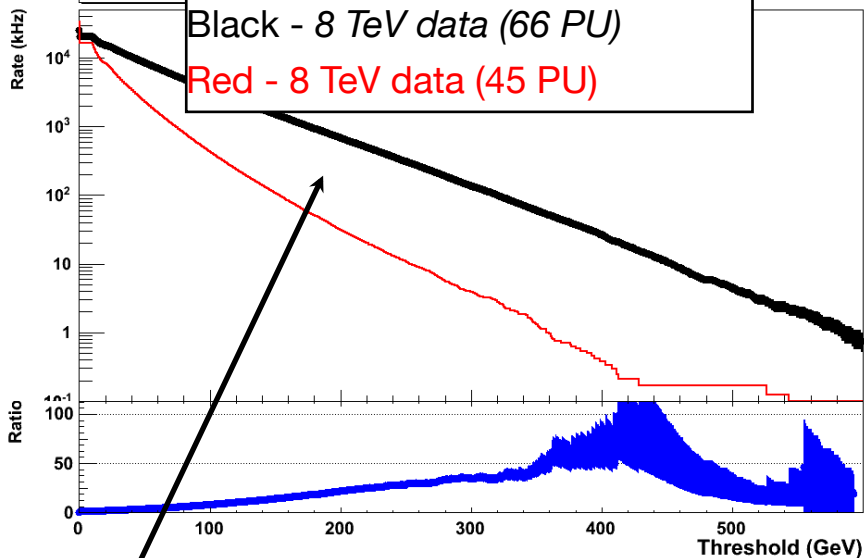


- Using the 6 data frames needed instead of the 10 used in the demonstrator system

Sample trigger rates from current L1 trigger

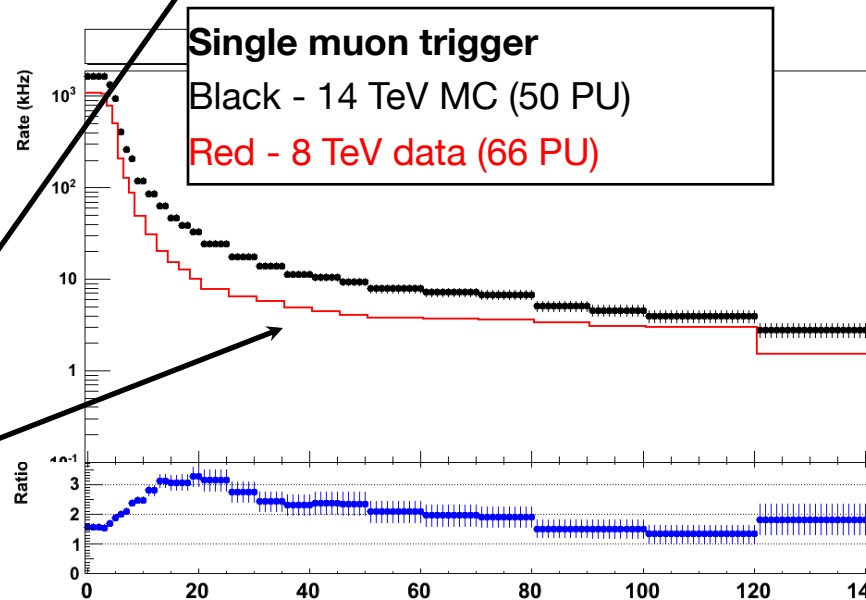
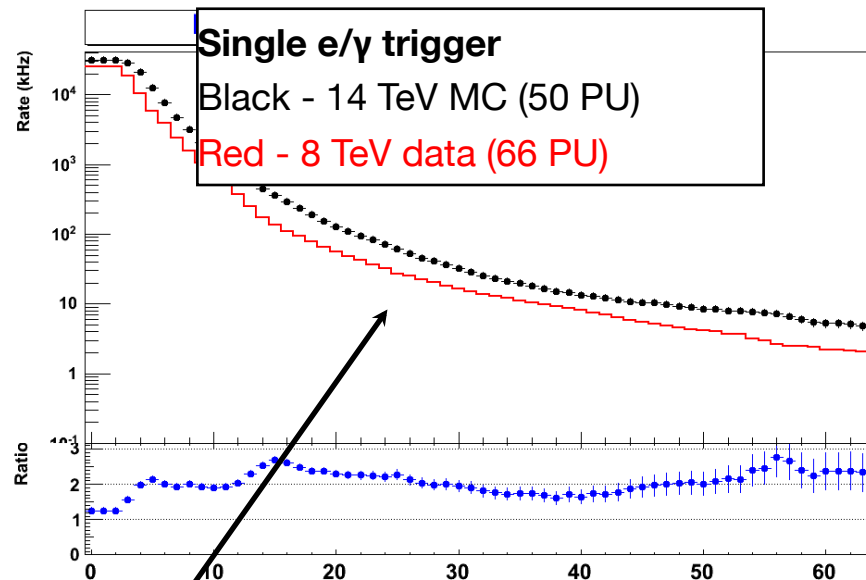
Rates shown for $L_{inst} = 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

H_T (E_T sum of jets)
 Black - 8 TeV data (66 PU)
 Red - 8 TeV data (45 PU)

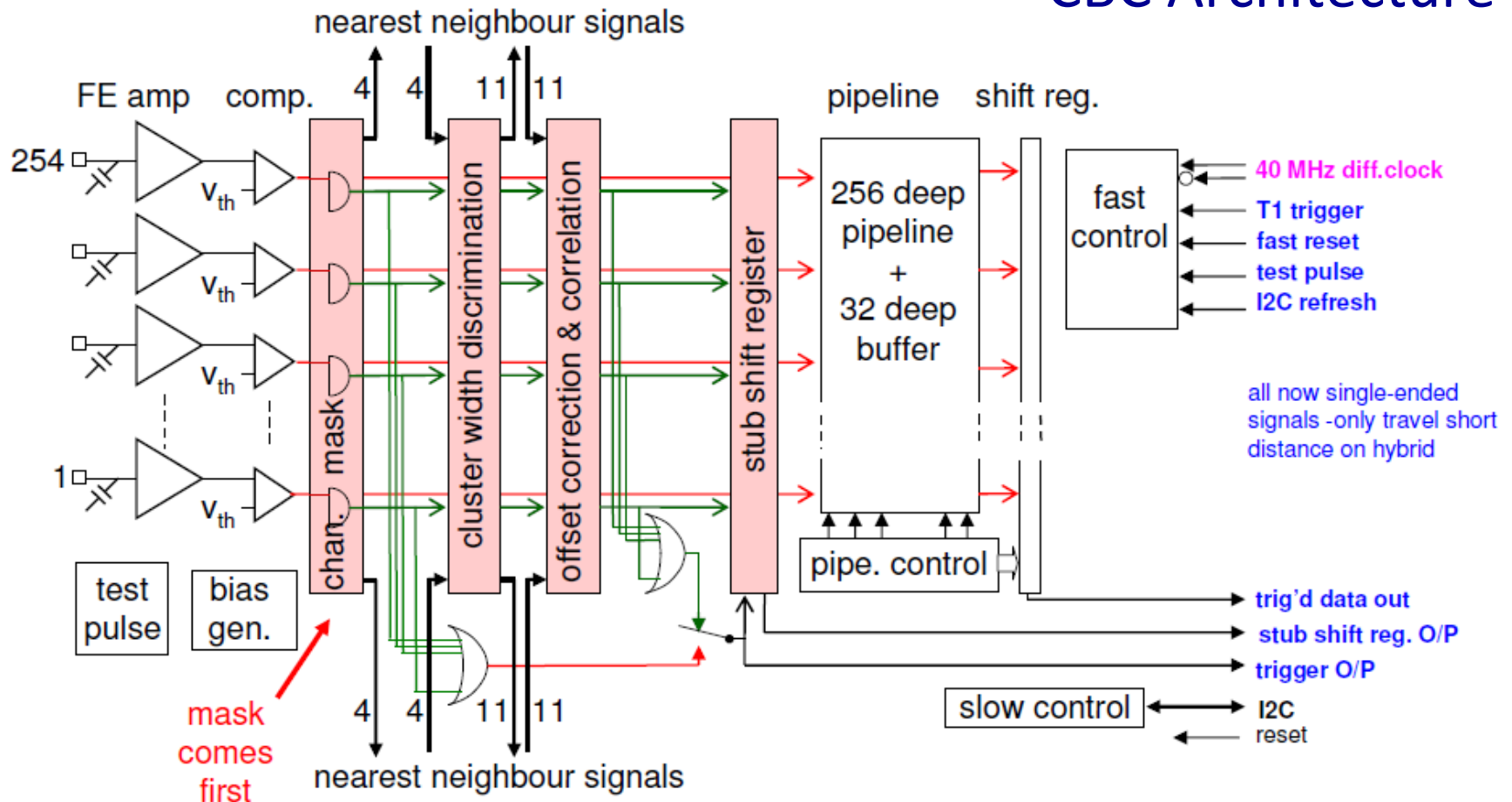


Jet trigger rates strongly dependent on PU

Poor control of lepton rates at high thresholds due to poor p_T resolution



CBC Architecture



blocks associated with Pt stub generation

channel mask: block noisy channels (but not from pipeline)

cluster width discrimination: exclude wide clusters

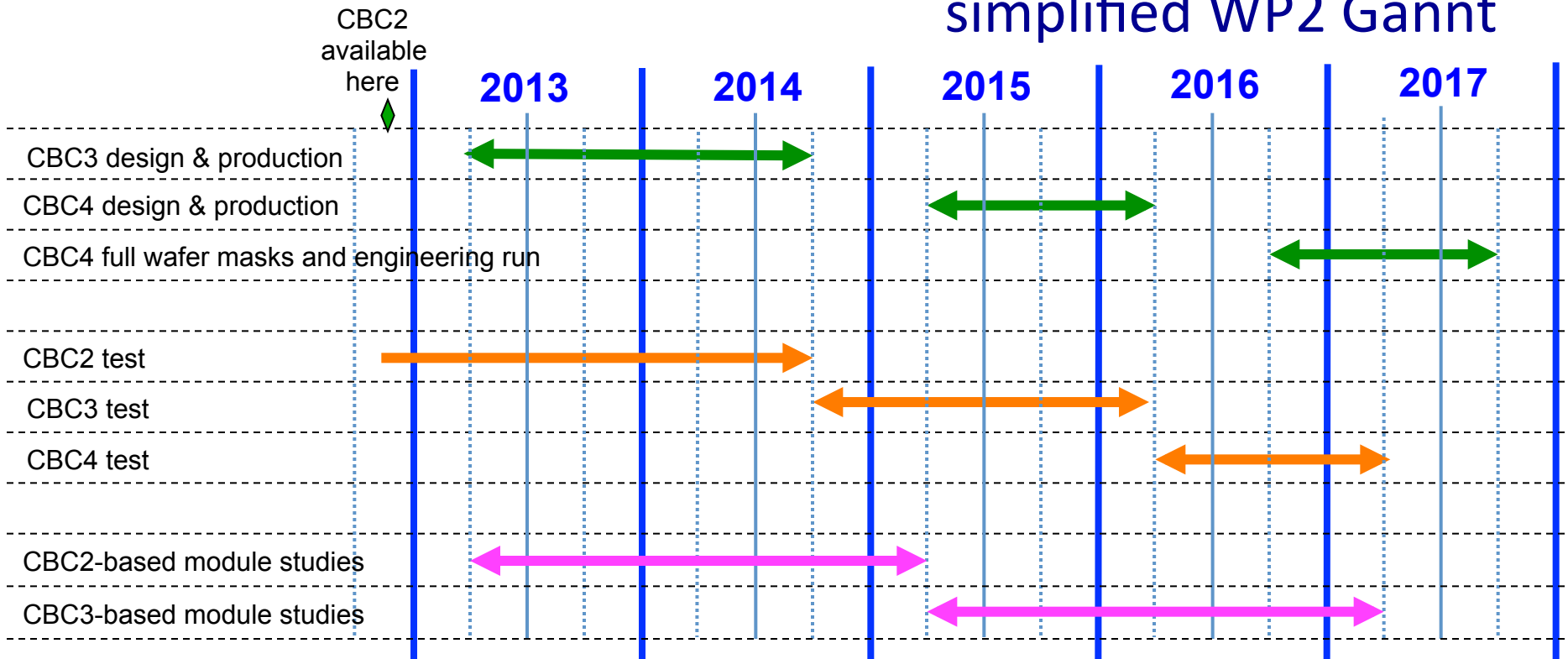
offset correction and correlation: correct for phi offset across module and correlate between layers

stub shift register: test feature - shift out result of correlation operation at 40 MHz

fast OR at comp. O/P and correlation O/P: - can select either to transmit off-chip

for normal operation choose correlation O/P

simplified WP2 Gantt



- CBC3 should be very close to final chip - available late 2014
 - includes architecture for formation and high speed transmission of stub information
- CBC4 pre-production iteration (2015/16) allows final bug fixes before full-wafer engineering run in 2017