CMS SILICON TRACKER OPERATION

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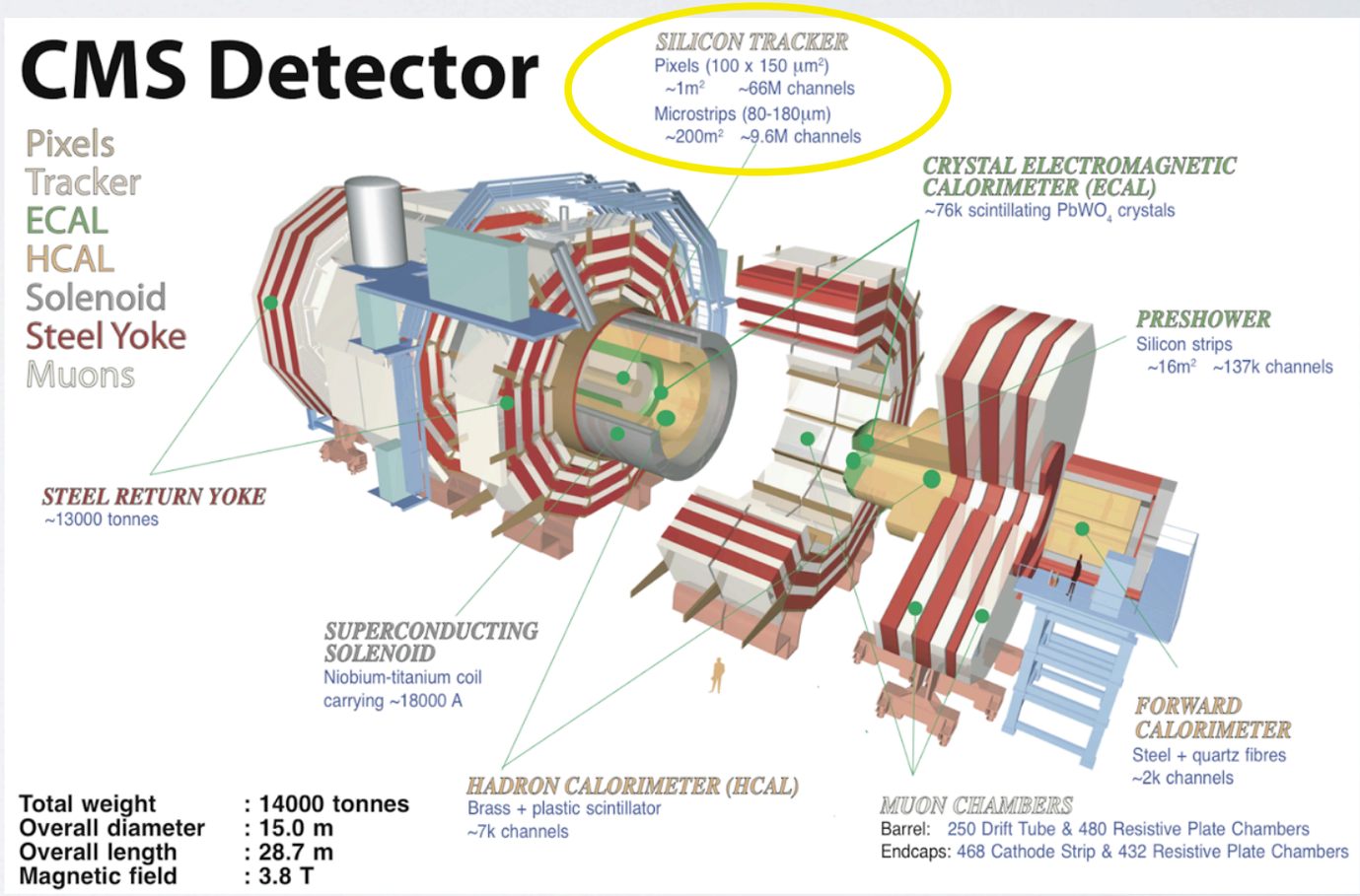
on behalf of the CMS Collaboration

RD13
Florence, 3rd - 5th July 2013

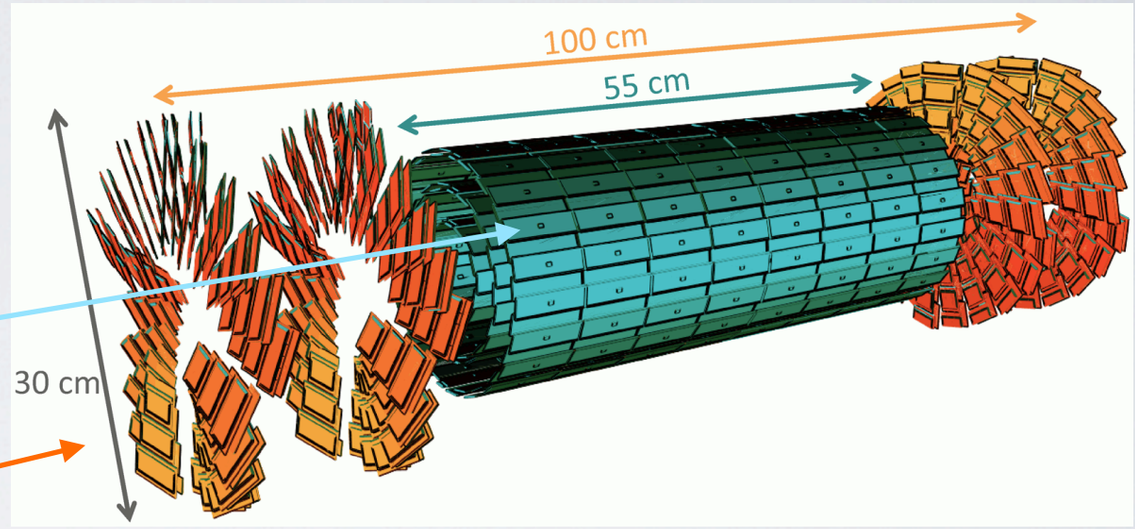
OUTLINE

- CMS Experiment
- CMS Pixels and Strips
  - geometry, sensor and status
- Performance and issues encountered during data taking
  - ROC
  - sensor



CMS TRACKER DETECTOR

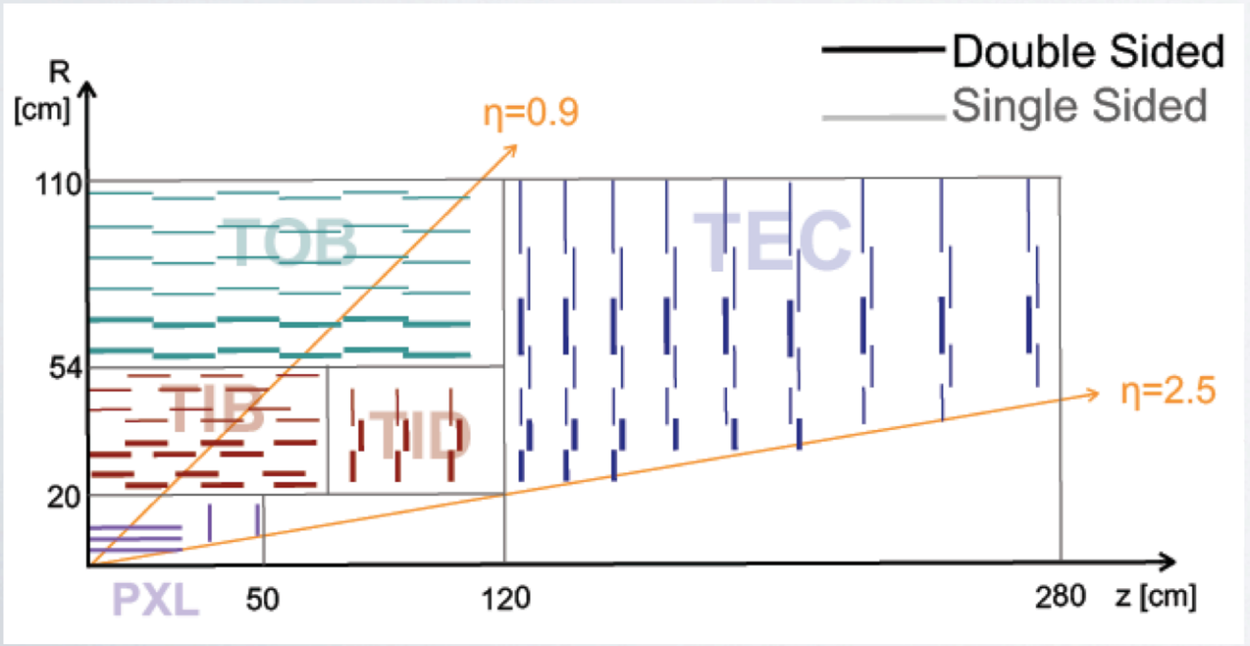
- Composed of silicon pixels and strips
  - analog readout



PIXEL
n+-in-n silicon sensor
- 100μm x150 μm
- 52x80 pixel read by one ROC

Pixel Barrel (BPix):
3 layers (56 cm long) placed at r = 4.3, 7.2, 11.0 cm
48M pixels, 11520 ROCs, 1120 readout links

Pixel Endcap (FPix):
4 disks placed at z = ±34.5, ±46.5 cm
inner (outer) radius = 6 (15) cm
18M pixels, 4320 ROCs, 192 readout links

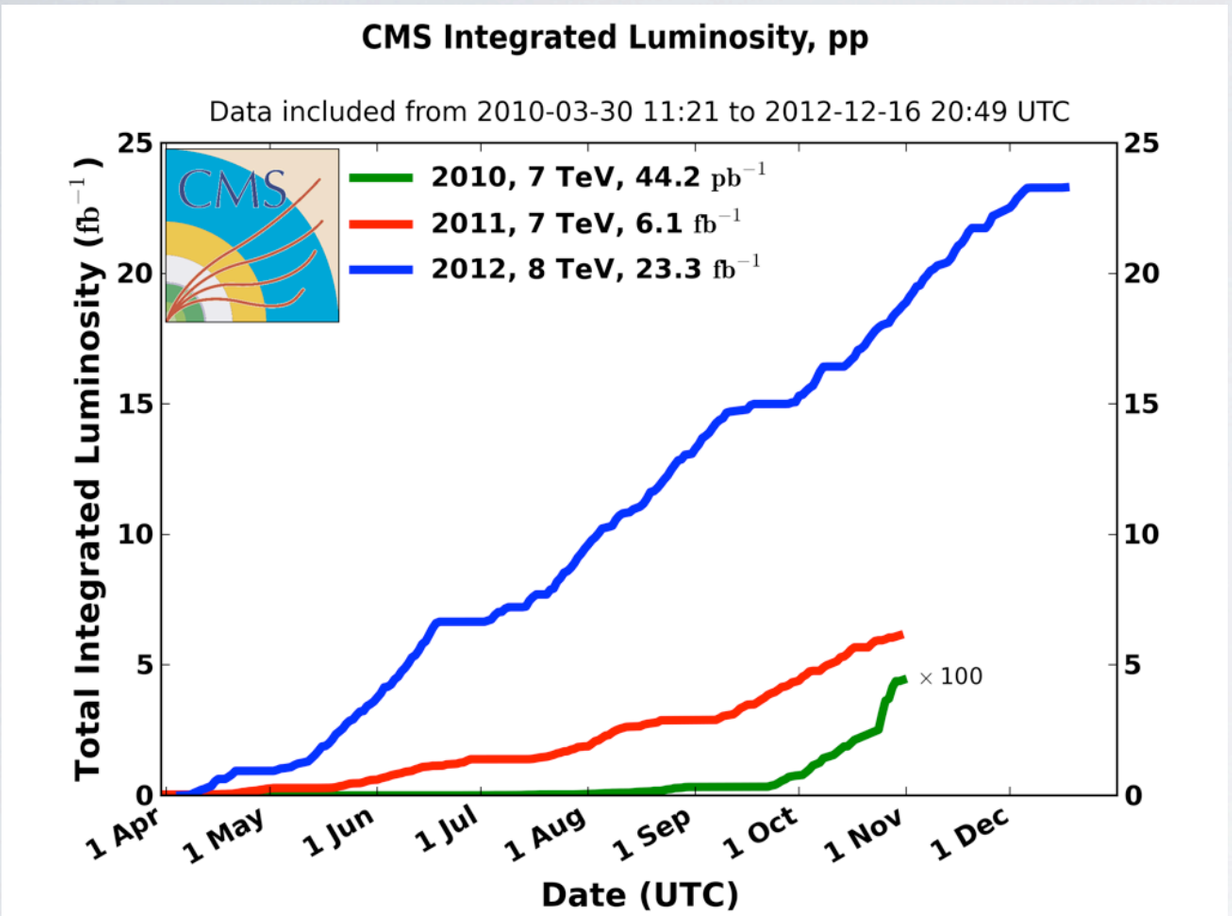


STRIP
200 m^2 active silicon sensor area (p-in-n)
9.6 M strips in 15 148 modules

strip pitch from 80 to 205 μm
20 < r <55 cm, thickness: d = 320 μm
r > 55 cm, thickness: d = 500 μm

generally measure rϕ direction.
Some radii ('Double'): additional 2nd modules rotated by 100 mrad (stereo modules), measurements for η(track)

CMS DATA AND PILE UP



Period	$\sqrt{s}$ (TeV)	Delivered Lumi (fb^{-1})	Data Taking efficiency (%)	Validated Data (%)
2010	7	0.044	92.2	88.6
2011	7	6.13	90.5	90.1
2012	8	23.3	93.5	90

4.5% loss due to downtime
1.7 % loss due to deadtime

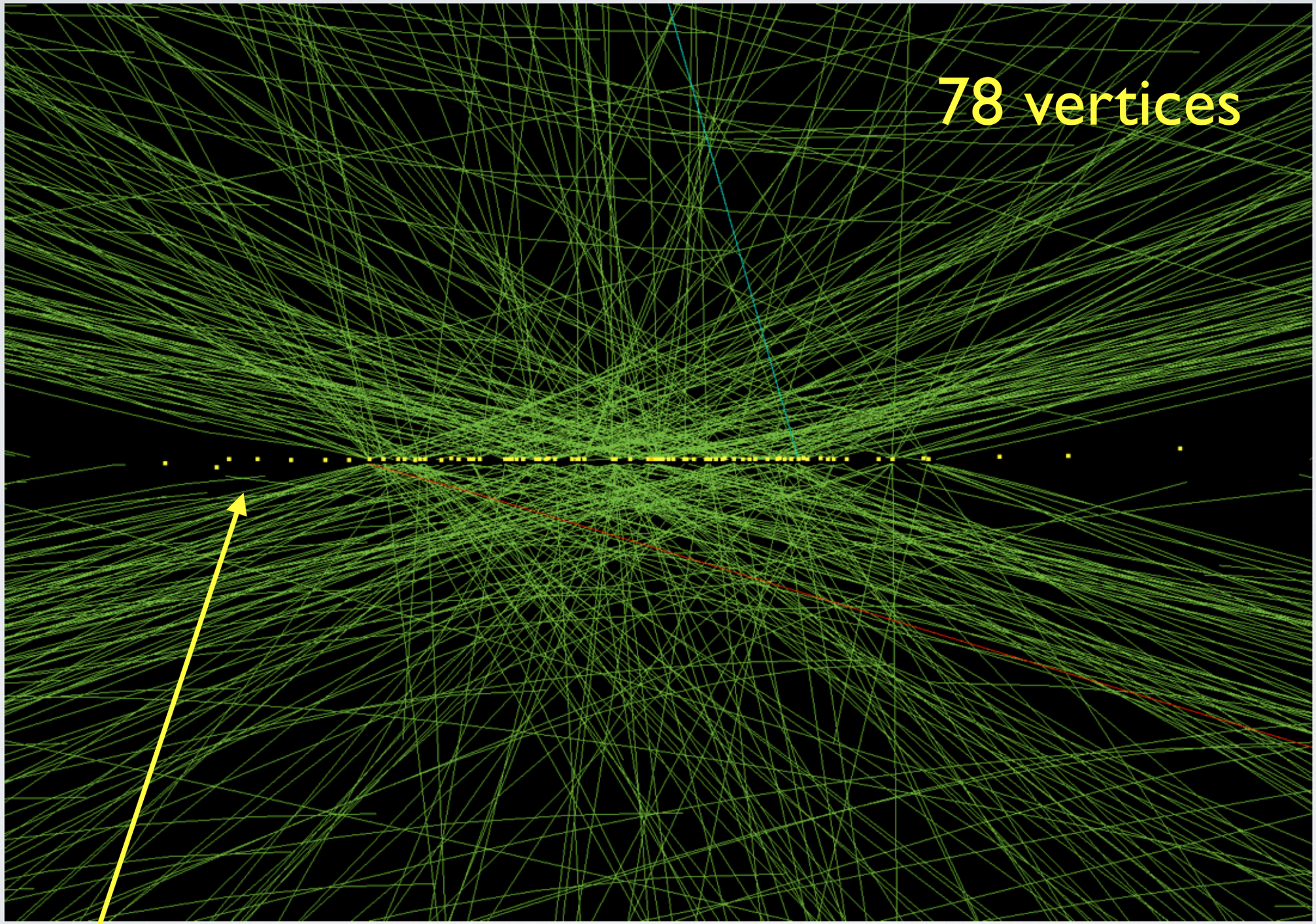
average PU in 2012:
21 interactions / bunch crossing

In 2012 LHC reaches the 77%
of the design inst. luminosity
with a bunch spacing of 50 ns

Year	peak PU *
2010	3.5
2011	18.6
2012	34.5

*excluding high pile-up run

HIGH PILE UP RUNS

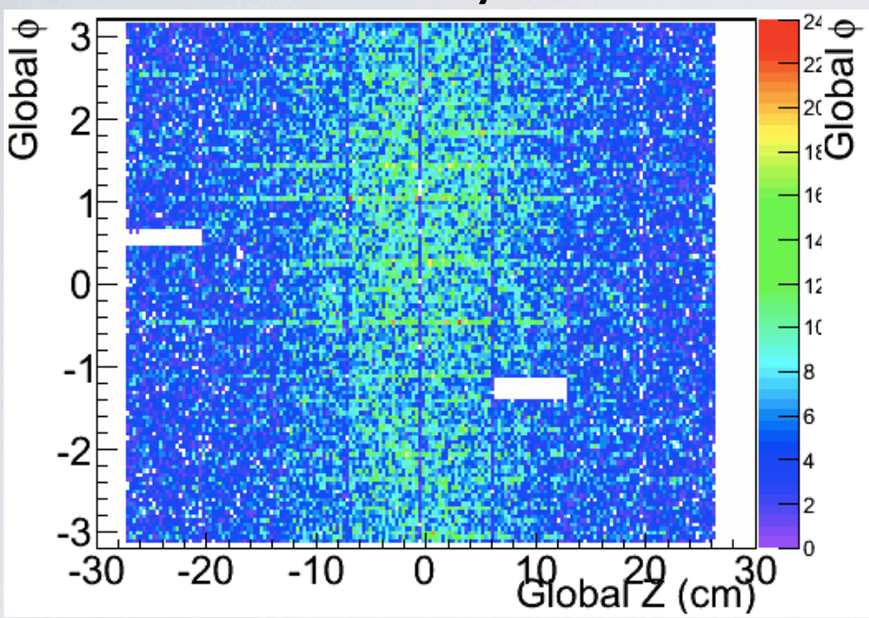


due to pT cut in event display

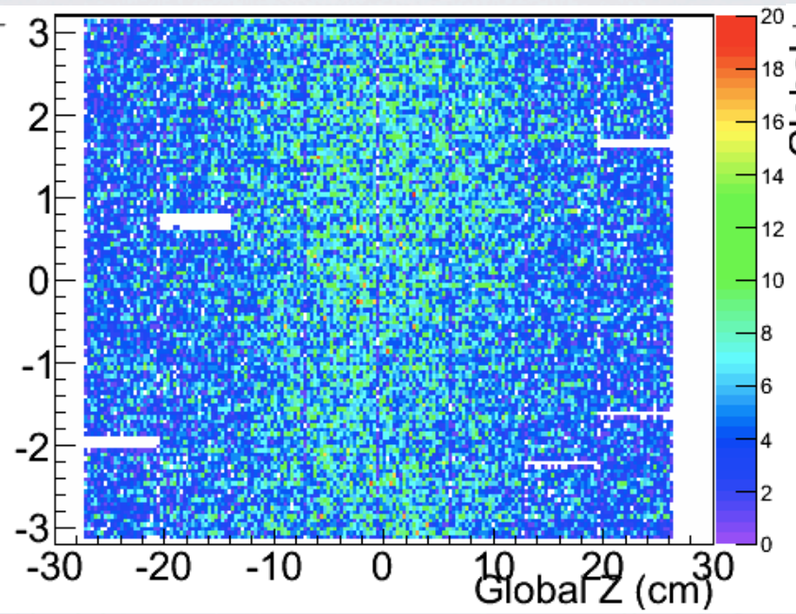
See Valentina Gori ‘s talk on tracking performance

CMS PIXEL STATUS

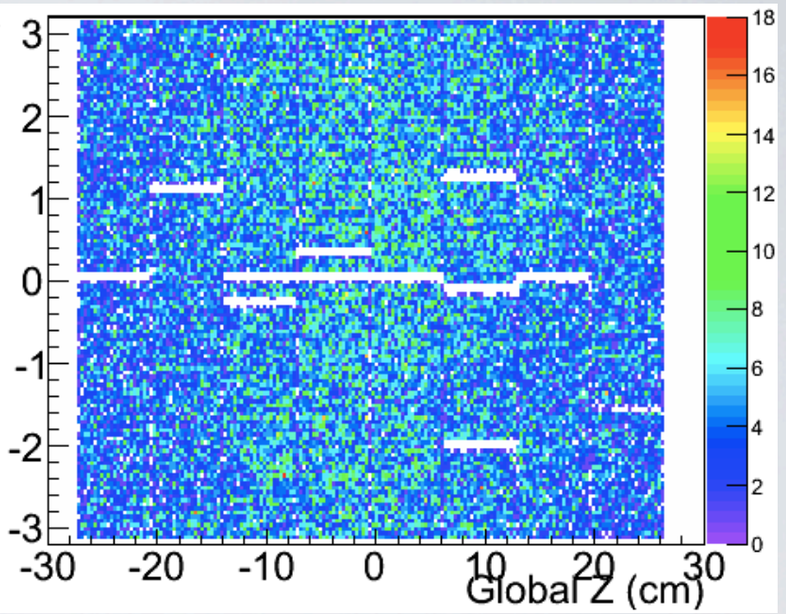
BPIX Layer 1

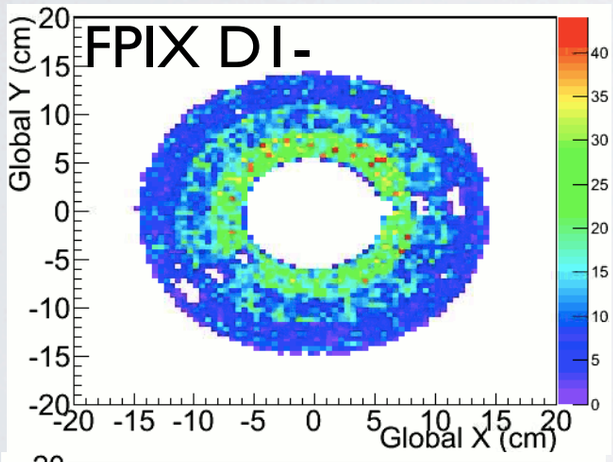


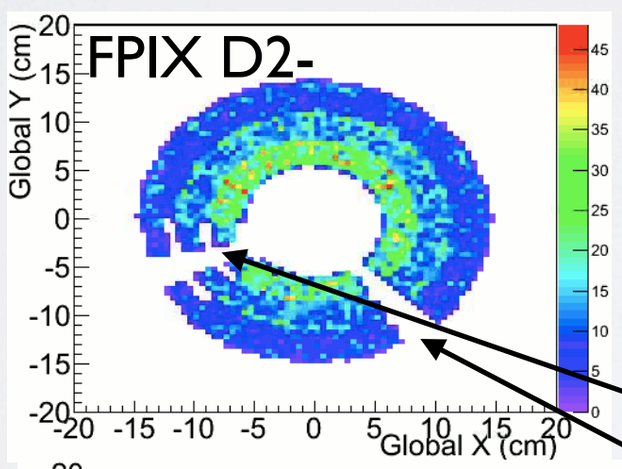
BPIX Layer 2

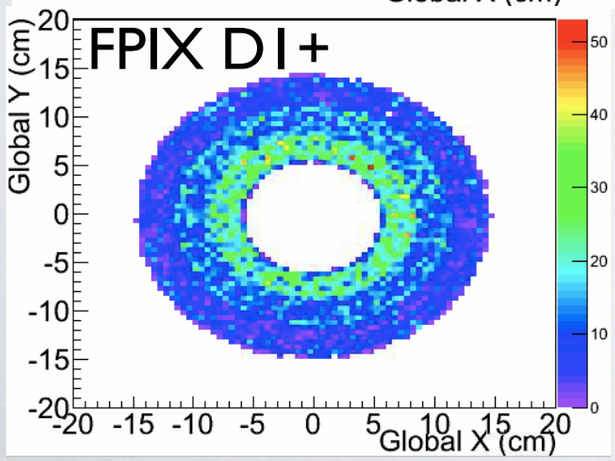


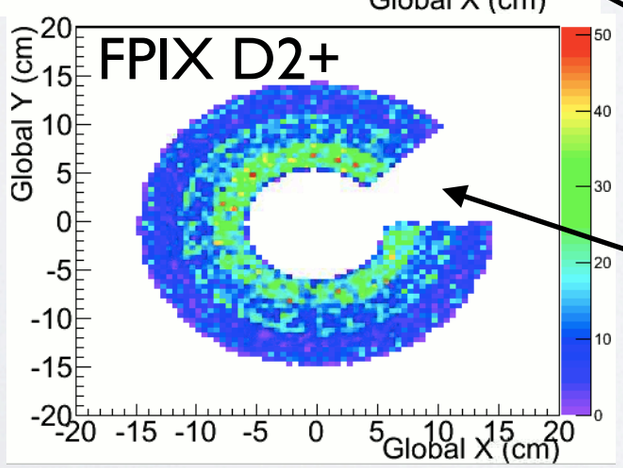
BPIX Layer 3











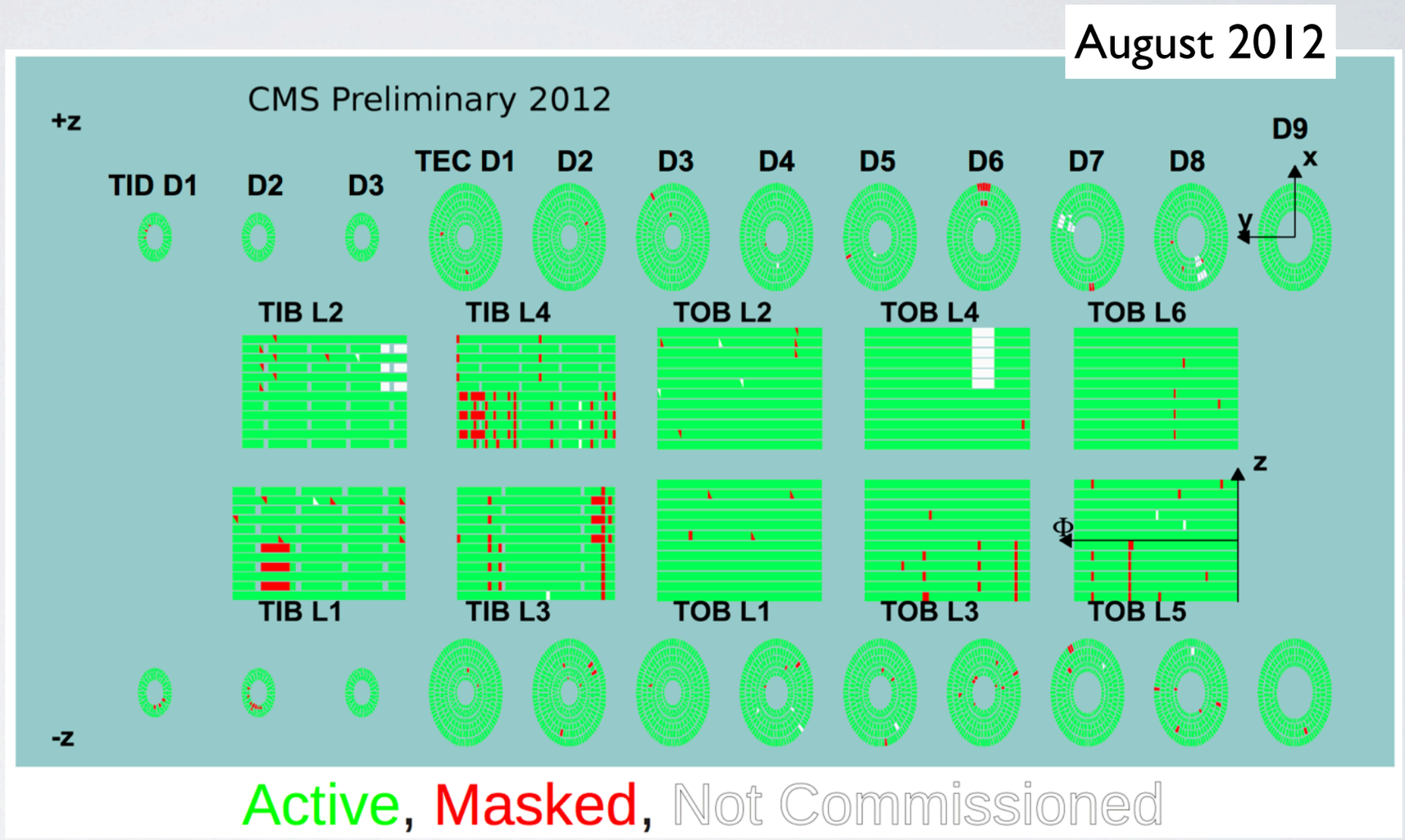
Channel out:
- BPix: ~2.3%
- FPix: ~7.2%

"Slow" channels
- Long rise time in analog readout
- Pixel addresses misread
- ROCs or events miscounted if headers lost

Optical readout

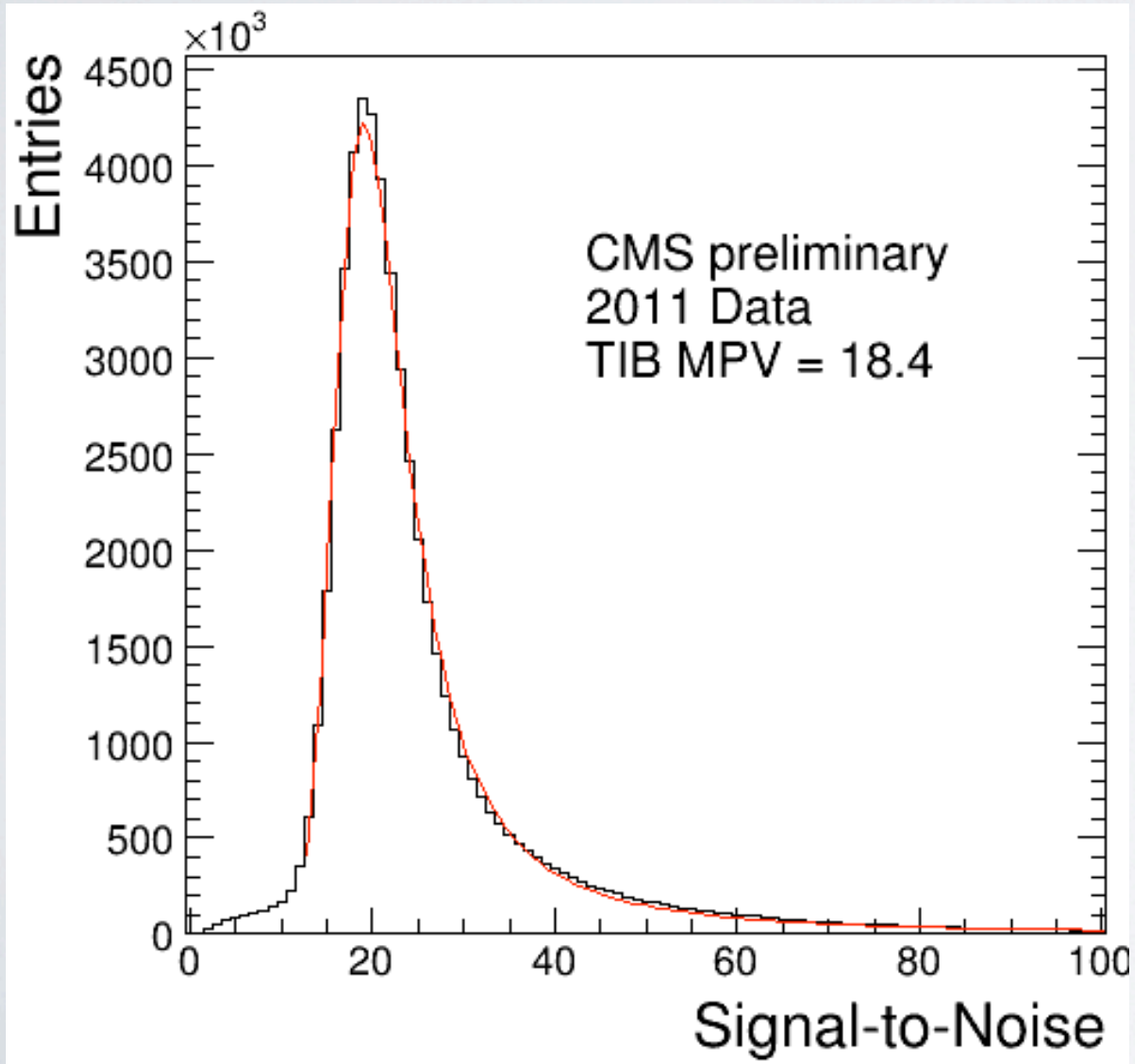
STRIP STATUS

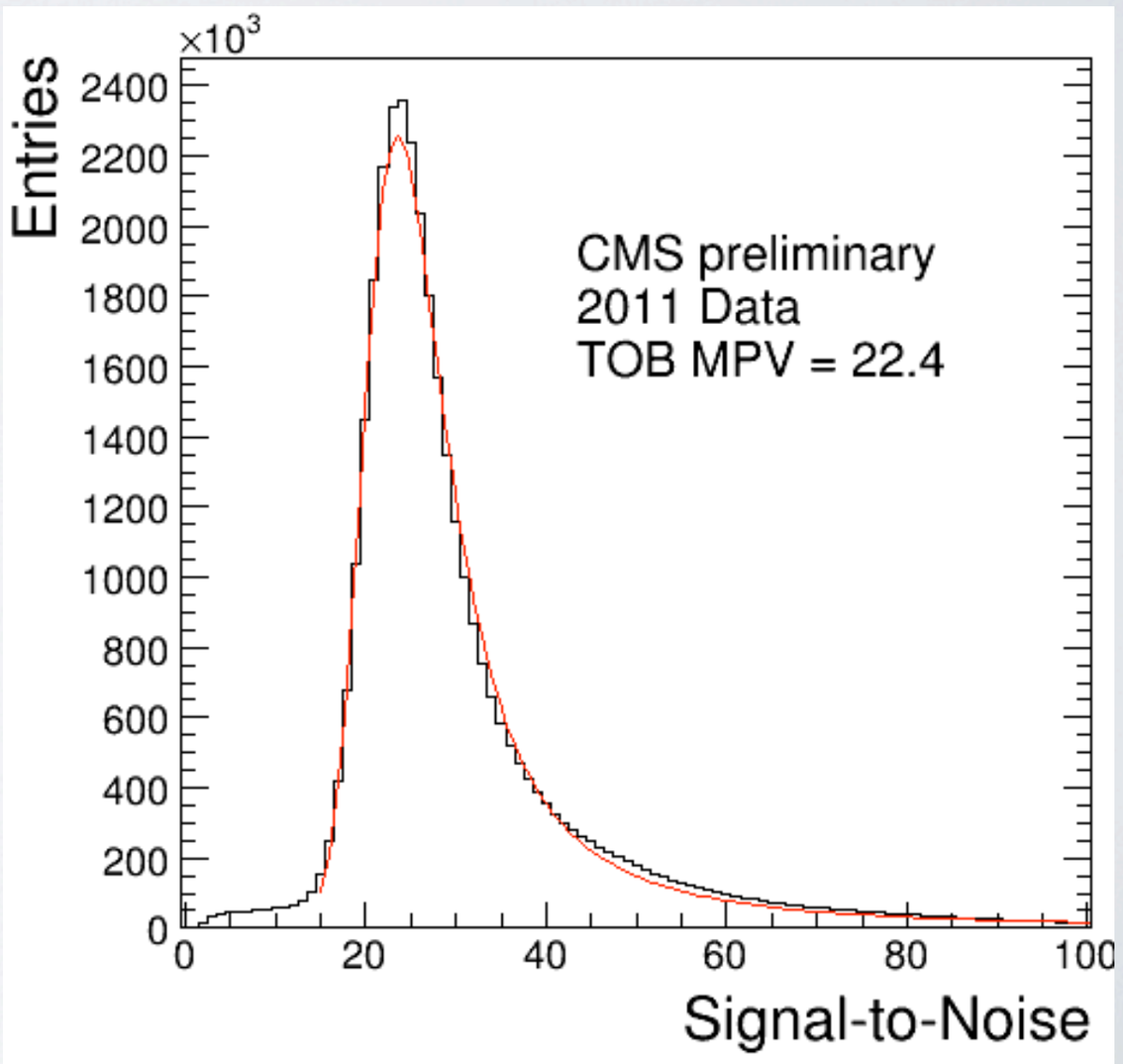
- Active fracion > 97.5%
- Stable:
  - 2008: 98.5%
  - 2011: 97.75 %
- Potentially recoverable in 2013/14 shutdown:
  - 2-3 control rings (0.7-1.0%)
- Reasons for masking
  - Control ring shorts
  - Control rings missing
  - HV line shorts
  - HV lines open
  - fibres, Communication and Control Units (CCU)



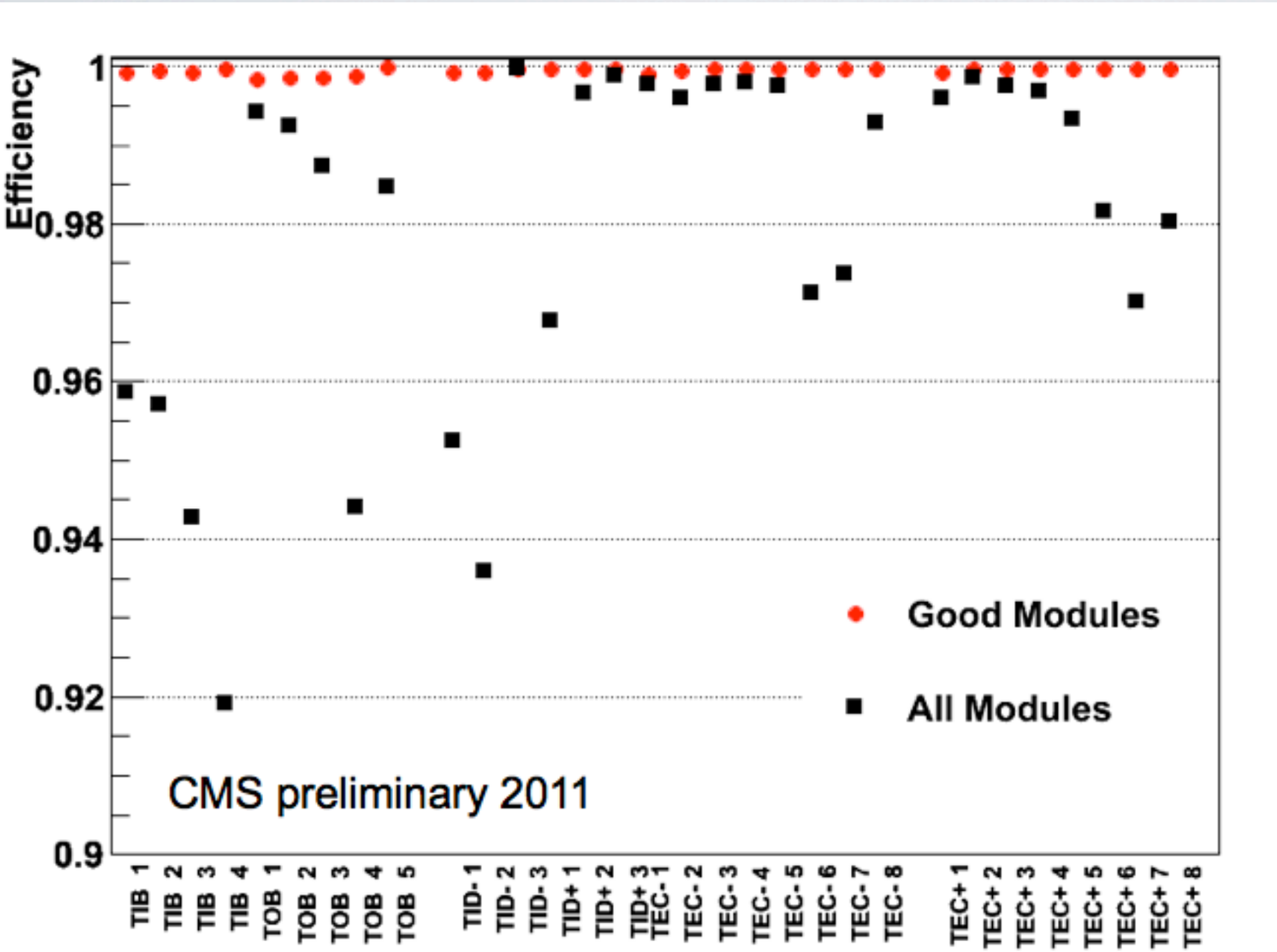
STRIP: S/N

- Clusters on track only, charge corrected for track angle.
- Distributions nicely follow Landau distributions convoluted with Gaussian resolution.
  - MPV thin sensors (TIB): ~18
  - MPV thick and long sensors (TOB): ~22





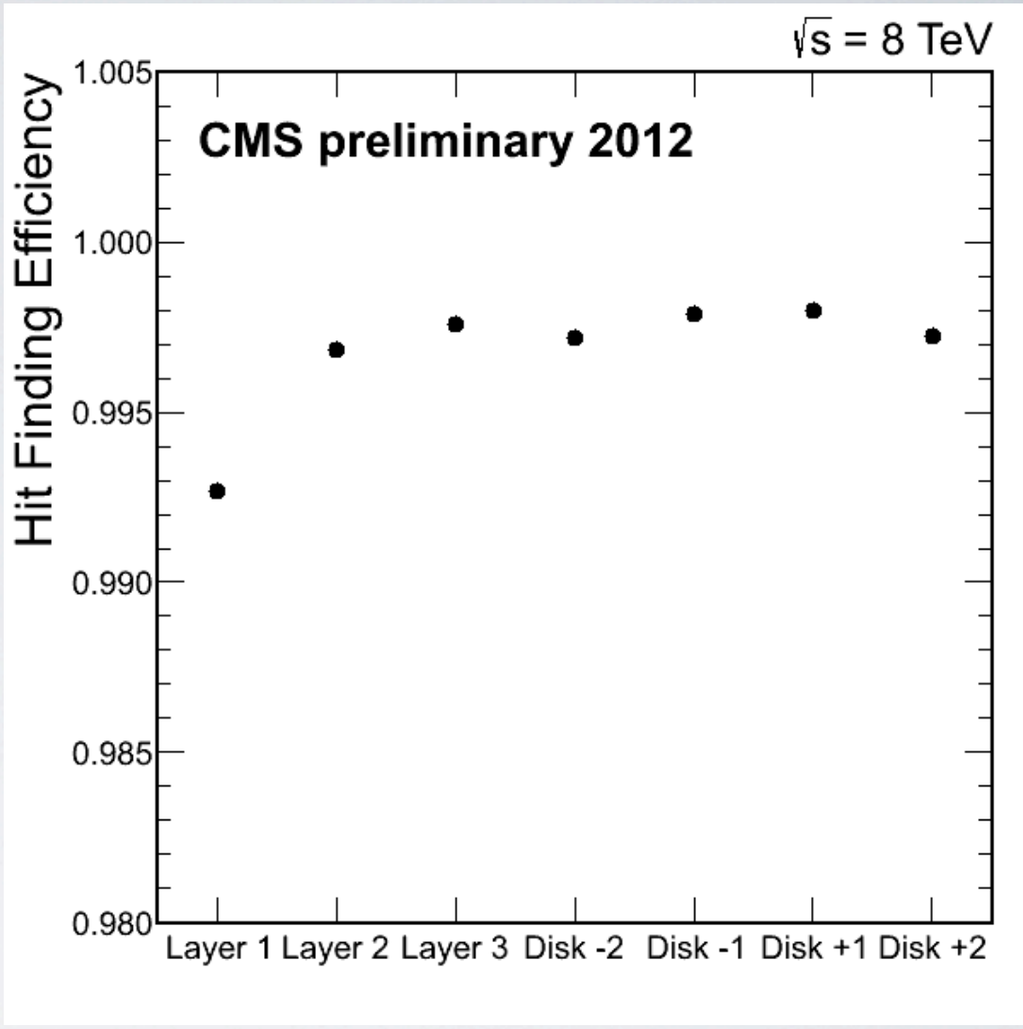
STRIP HIT EFFICIENCY

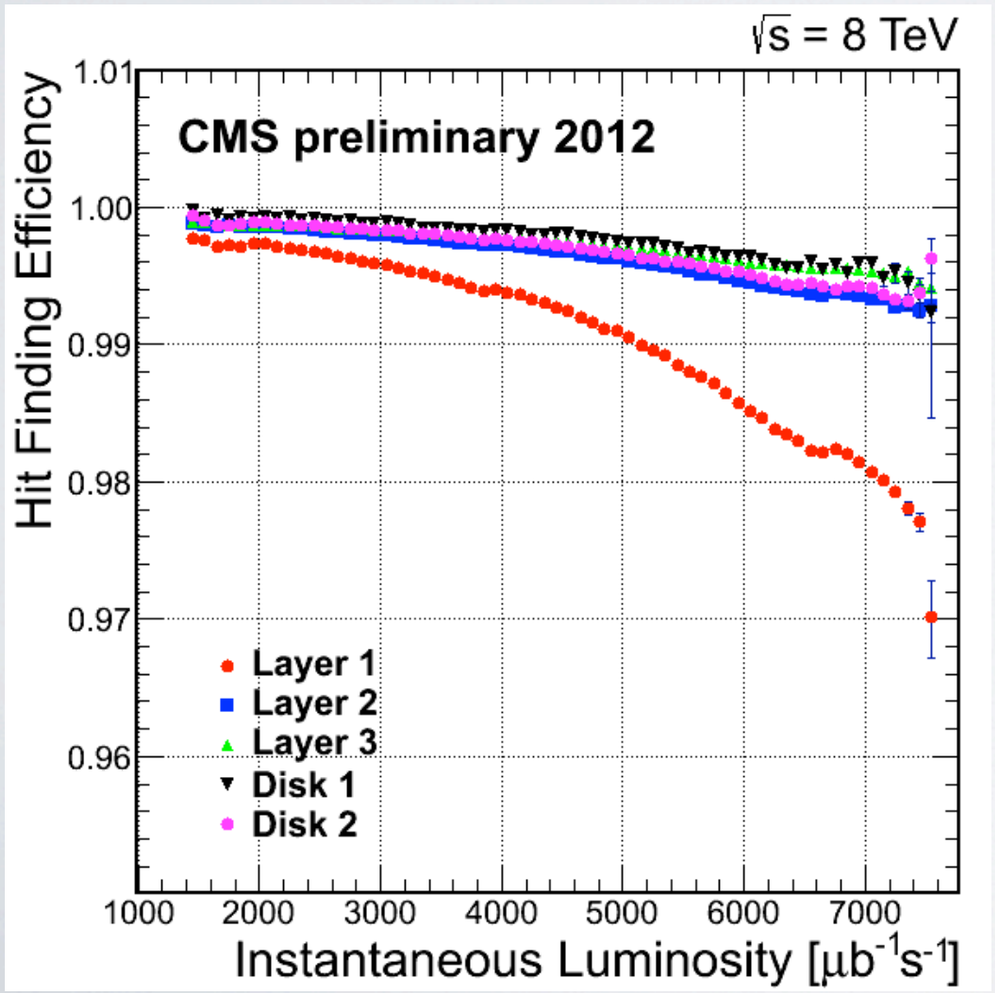


- Strip efficiency is very high
  - ~ 100% considering only modules included in the readout

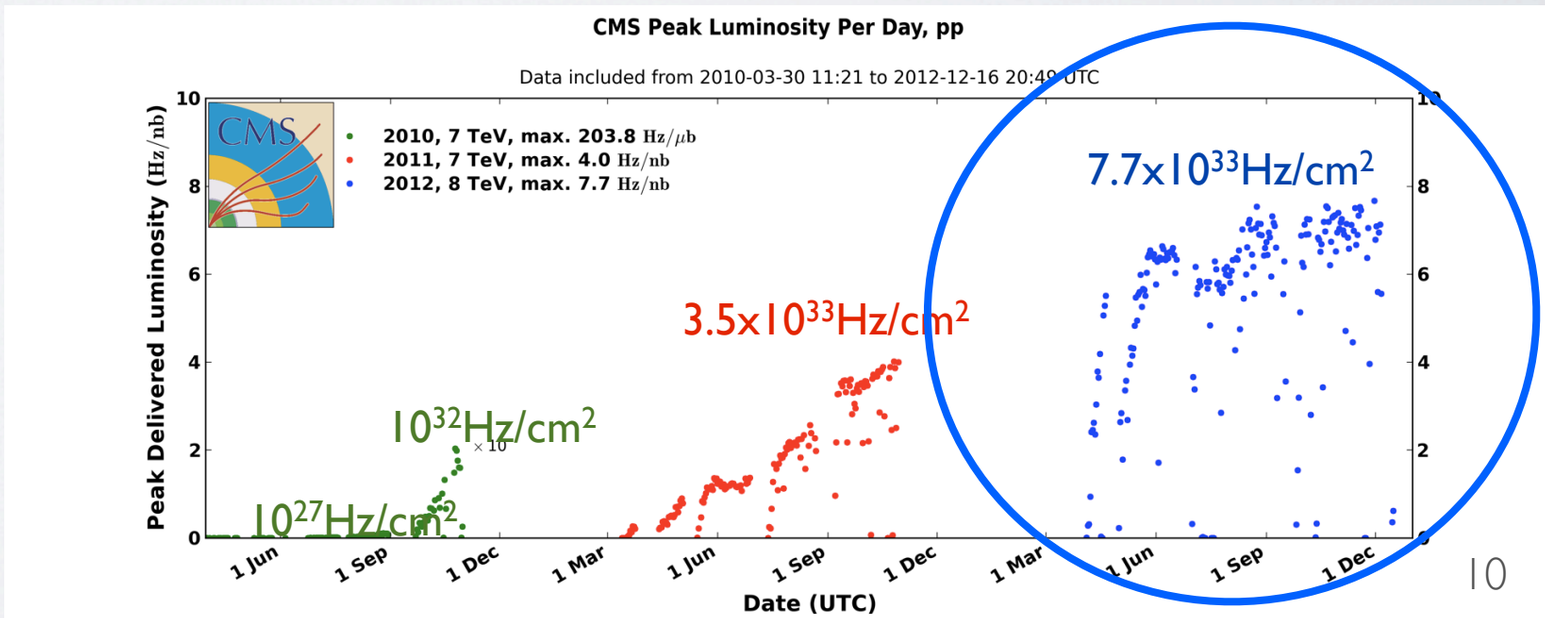
PIXEL HIT EFFICIENCY

- Pixel hit efficiency in general > 99%.
- Hit efficiency depends on the instantaneous luminosity due to the occupancy



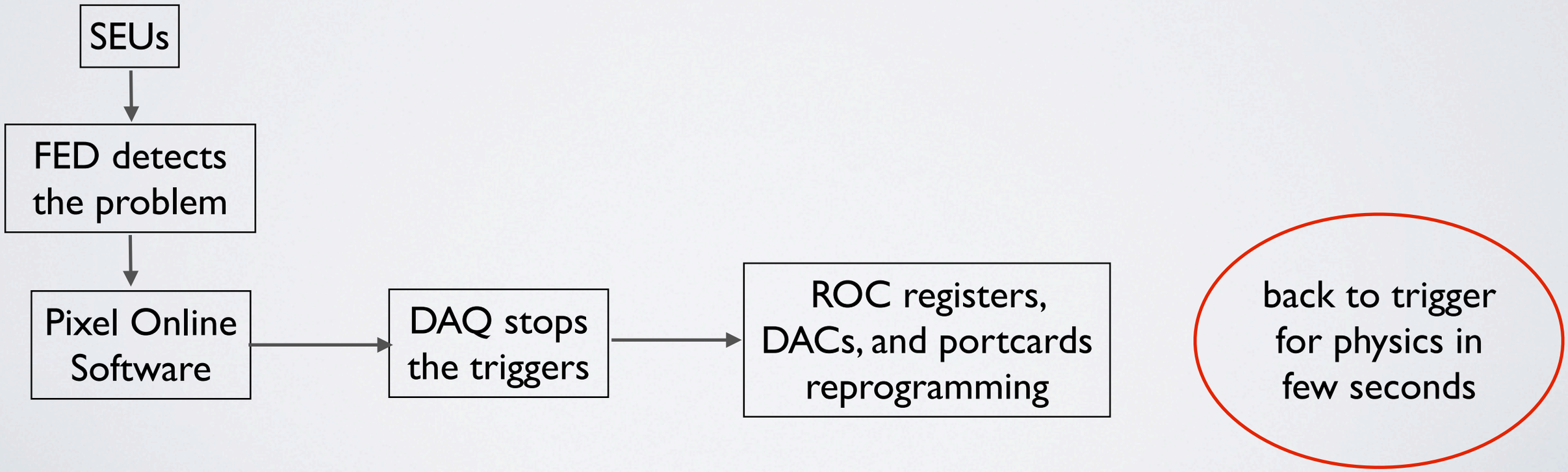


SEU candidates and DAQ errors are excluded
Only runs with more than 1300 bunches are included



PIXEL: SINGLE EVENT UPSET

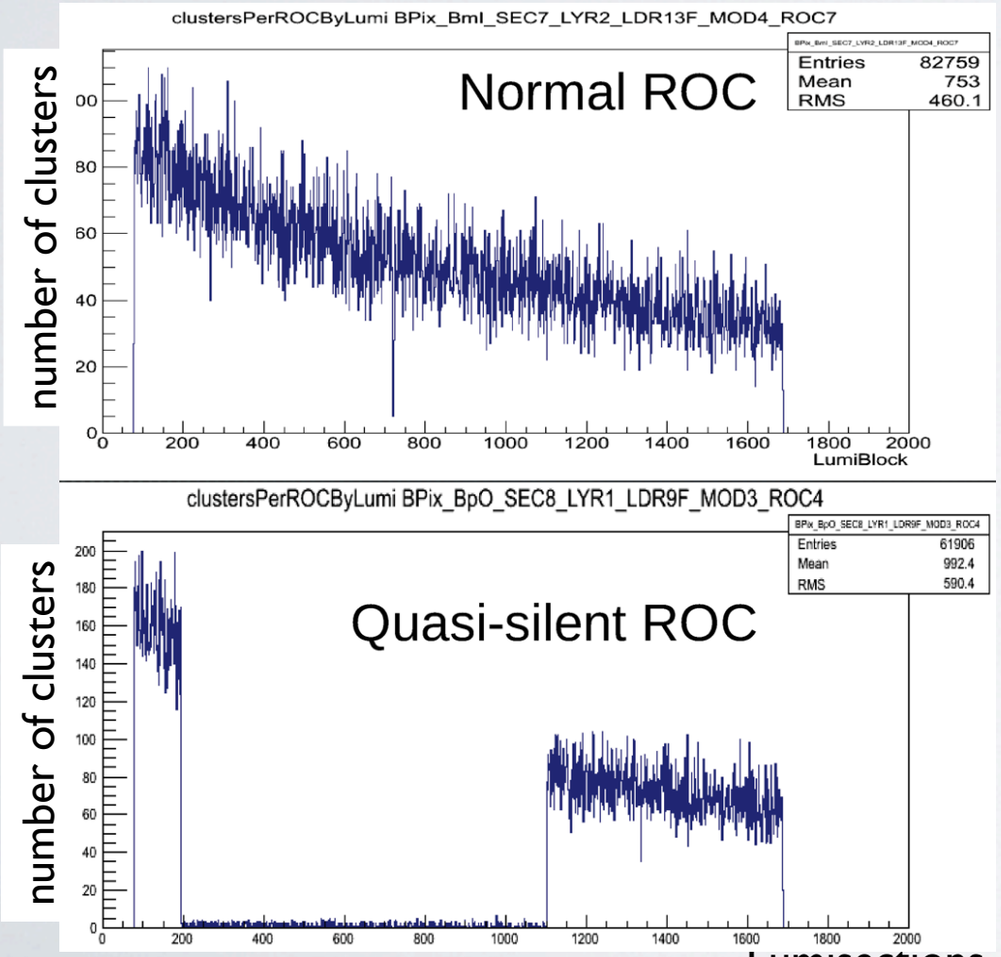
- SEU events refer to a bit flip in the ROC or auxiliary electronics
  - caused by ionization;
- Consequences:
  - interrupt data taking
  - degradation of data quality
- They increase with the inst. luminosity.
- Two classes:
  - it doesn't compromise data taking. No action needed
    - Single Pixel and single ROC (<0.1‰)
  - it compromises data taking. It need to be fixed
    - auxiliary electronics (~1%)
      - Stop the trigger and reprogram the ROC registers, DACs, and portcards

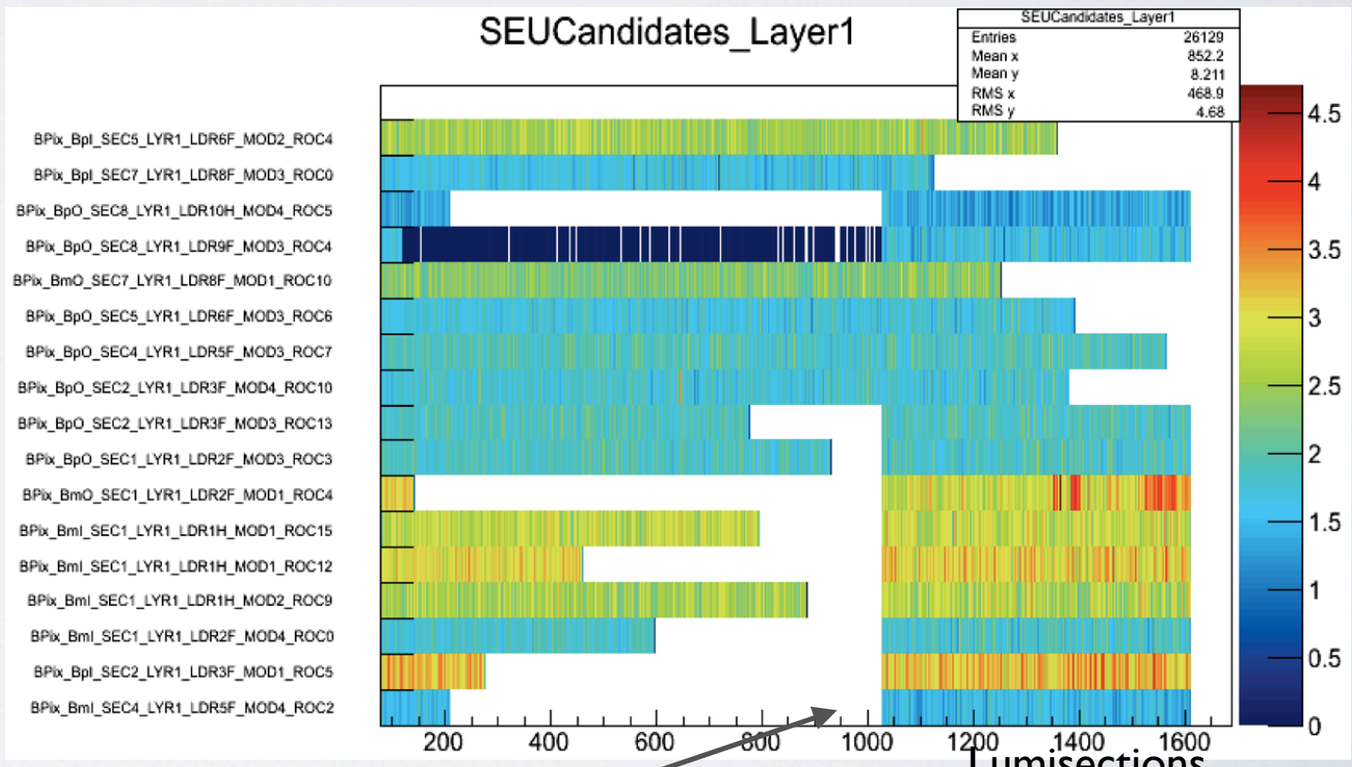


PIXEL: SINGLE EVENT UPSET

- Two mechanisms to detect SEU
  - monitoring the off channels
  - searching the Out of Sync (OOS) errors

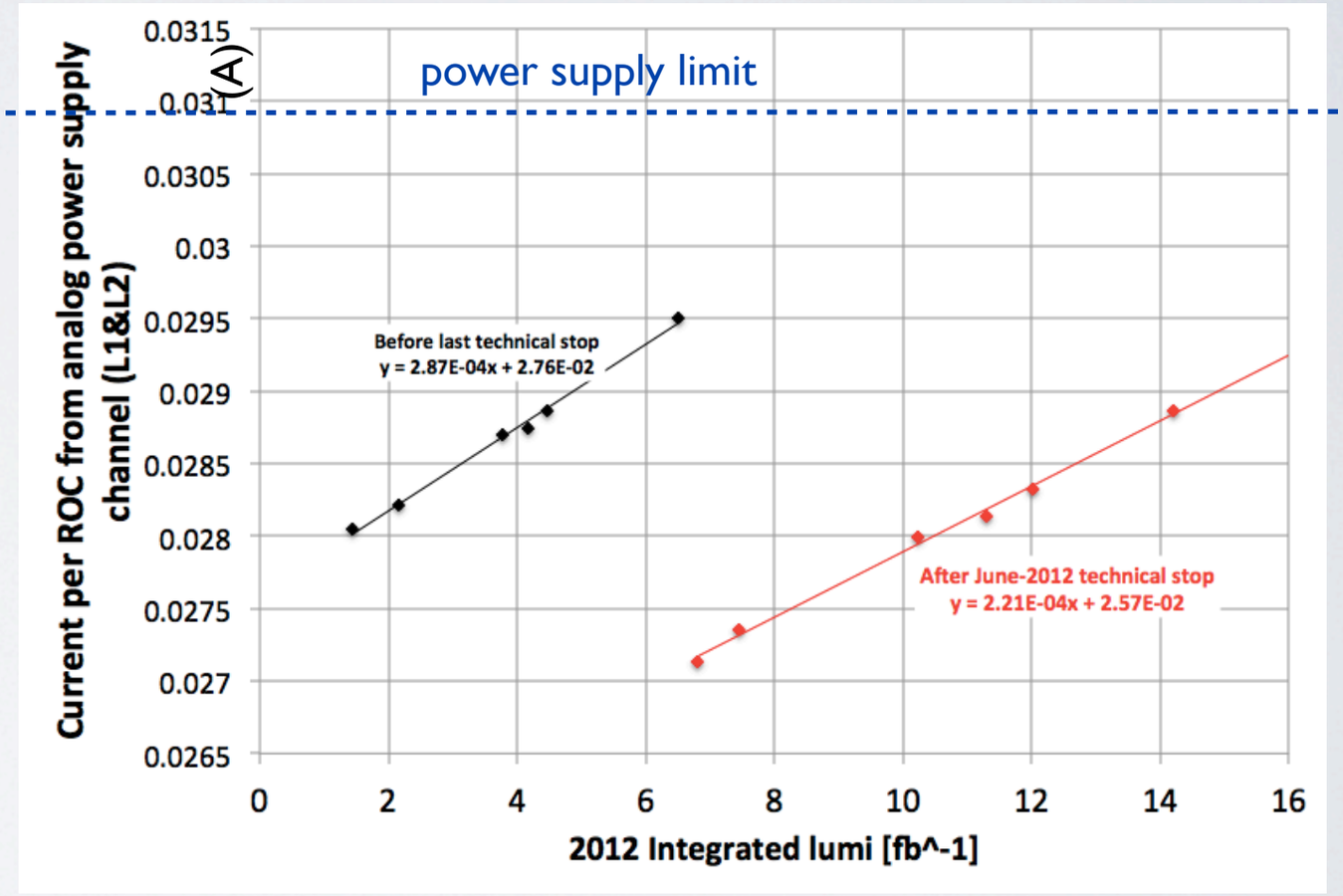
1 SEU (needing treatment) every ~73 pb^{-1} of data:
~1.5 SEUs / LHC fill





PIXEL: ANALOG CURRENT

- ROC Analog circuit current increases linearly with radiation damage
  - Slower preamplifier rise time
  - Higher pixel threshold
- Biggest operational concern: power supply current limit per channel
  - Limit 6 A, operate ~5.5 A
- Fixed by recalibration
- Possible mechanism
  - change in DAC setting meaning
  - Caused by bulk damage in diode used for reference voltage



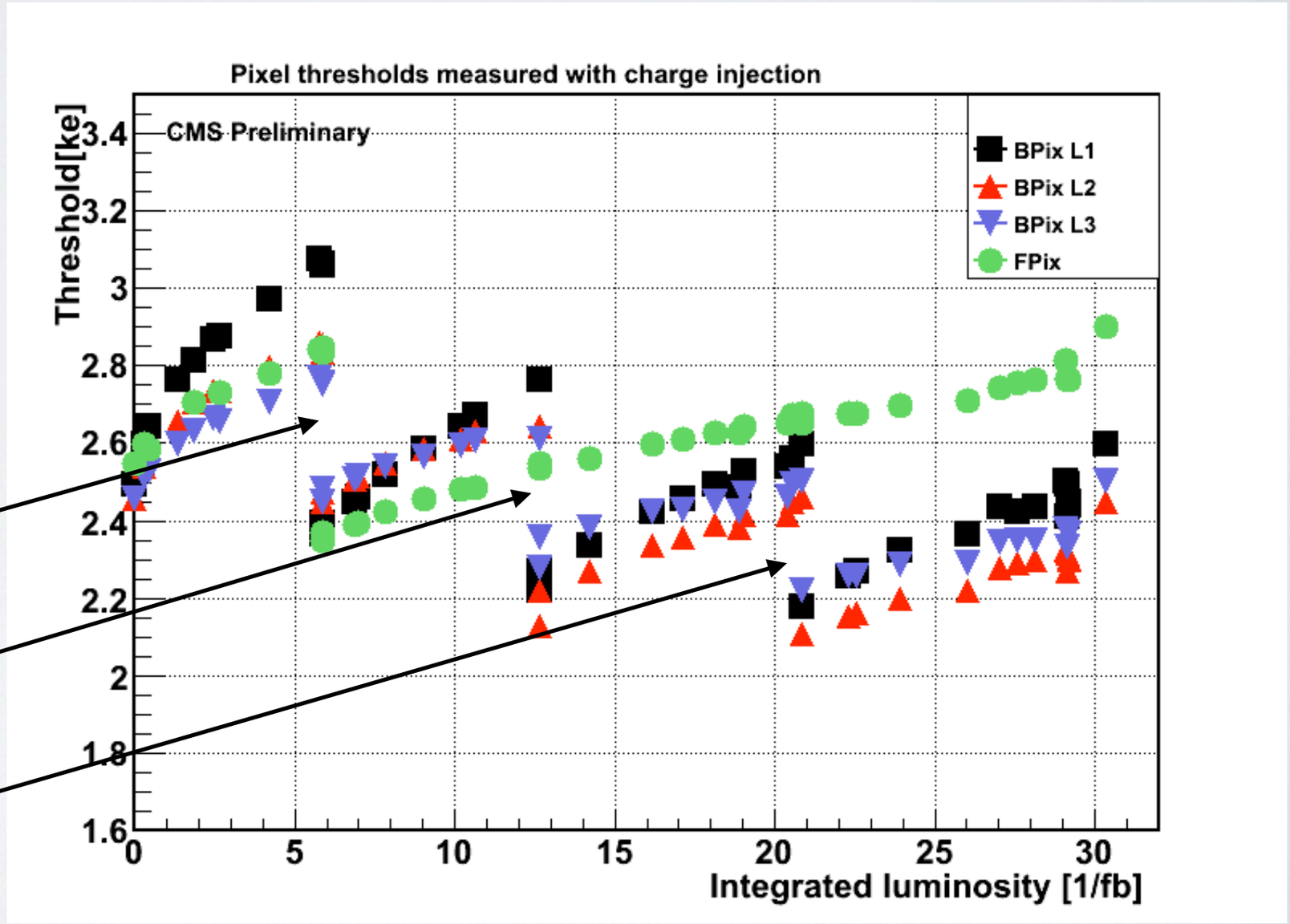
PIXEL THRESHOLDS

- Pixel thresholds depend on the integrated luminosity
- Threshold optimization during technical stops

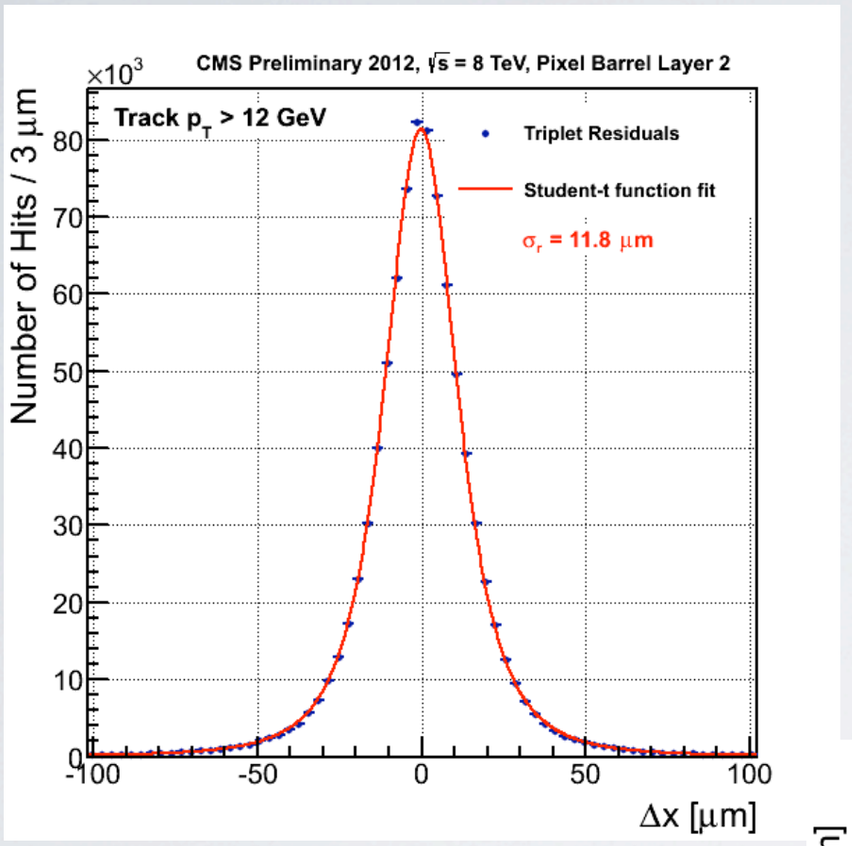
End of 2011 run

June 2012 technical stop

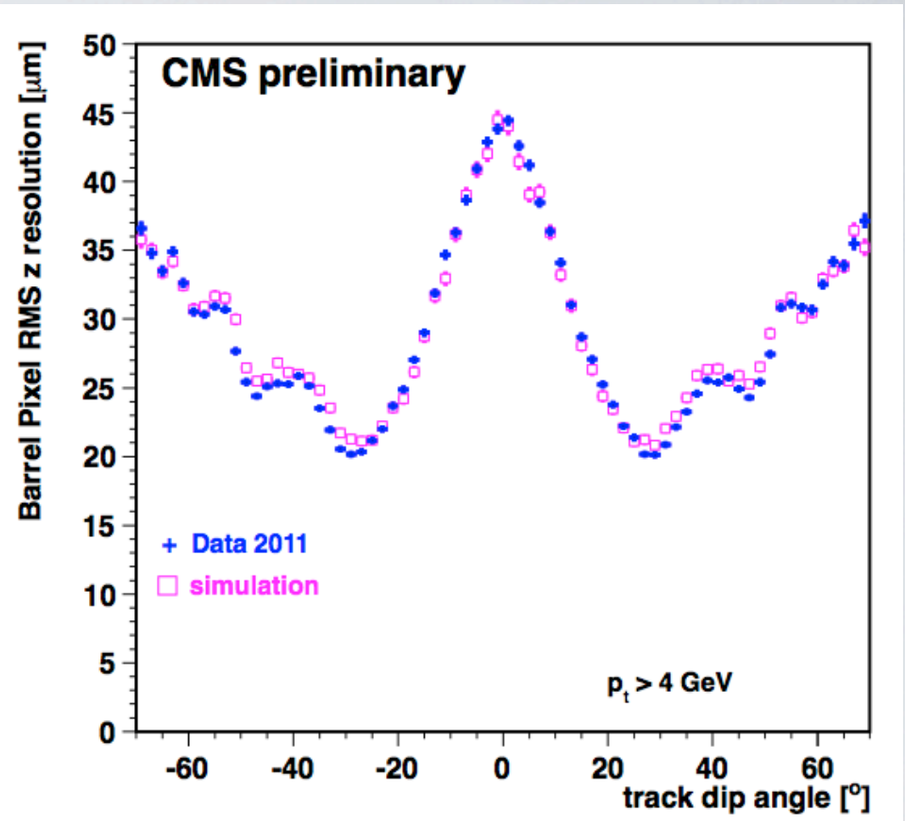
September 2012 technical stop



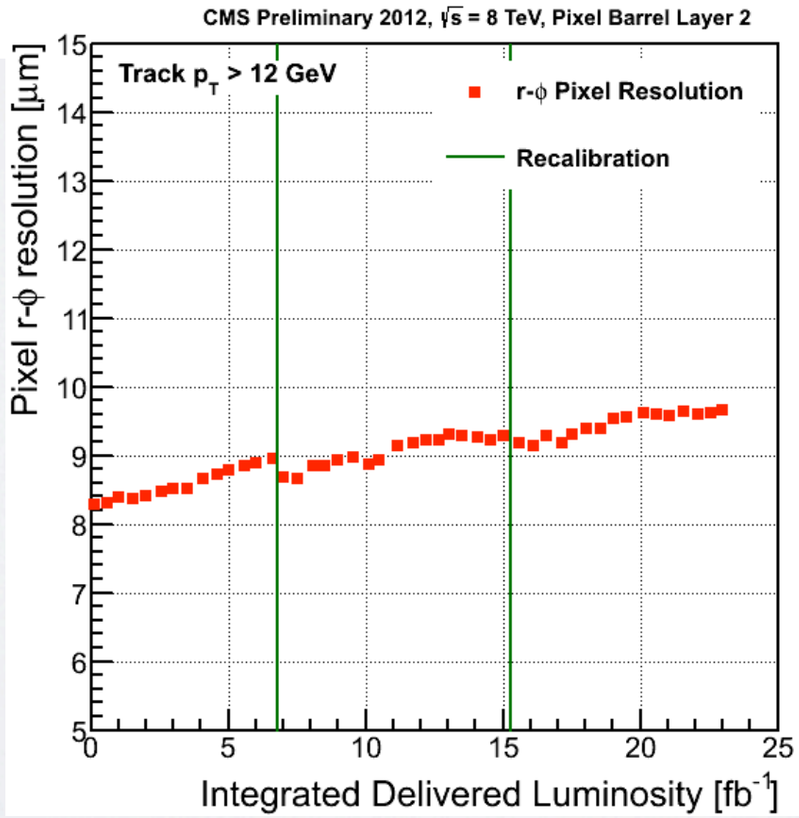
PIXEL RESOLUTION



z direction resolution in barrel pixels



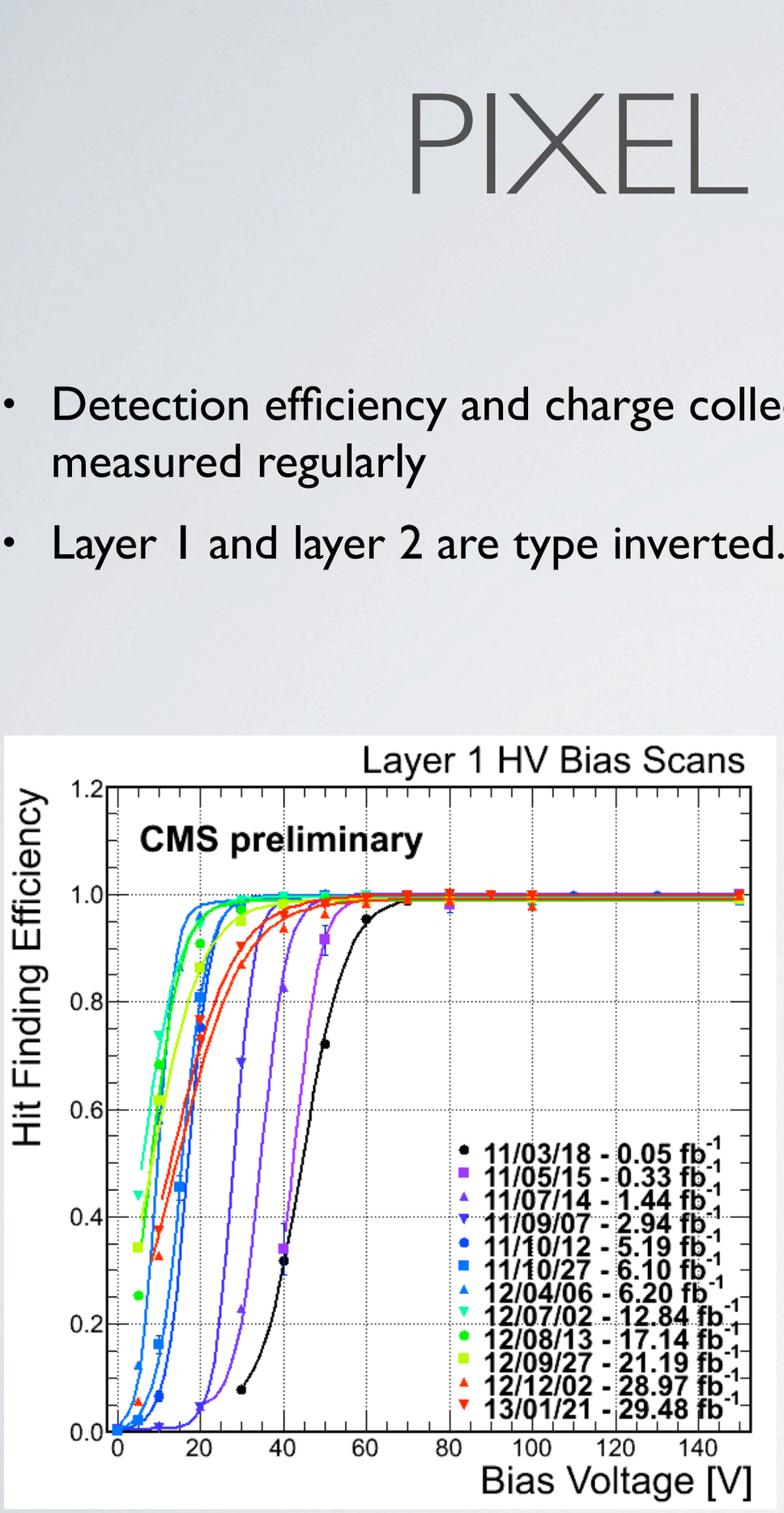
pixel triplet resolution transverse plane



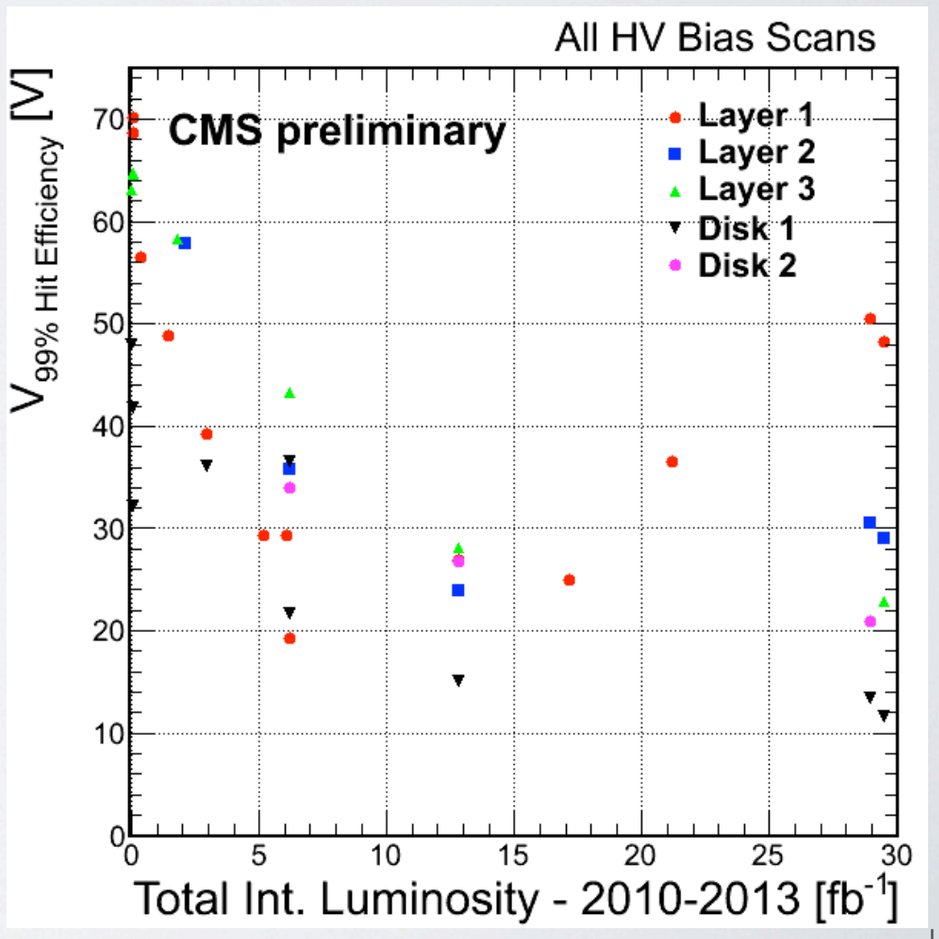
intrinsic resolution of pixel detector (barrel, layer2), from pixel triplets

PIXEL BIAS SCANS

- Detection efficiency and charge collection efficiency vs bias voltage measurement have been measured regularly
- Layer 1 and layer 2 are type inverted.



Nominal Voltage
150V for BPIX
300V for FPIX



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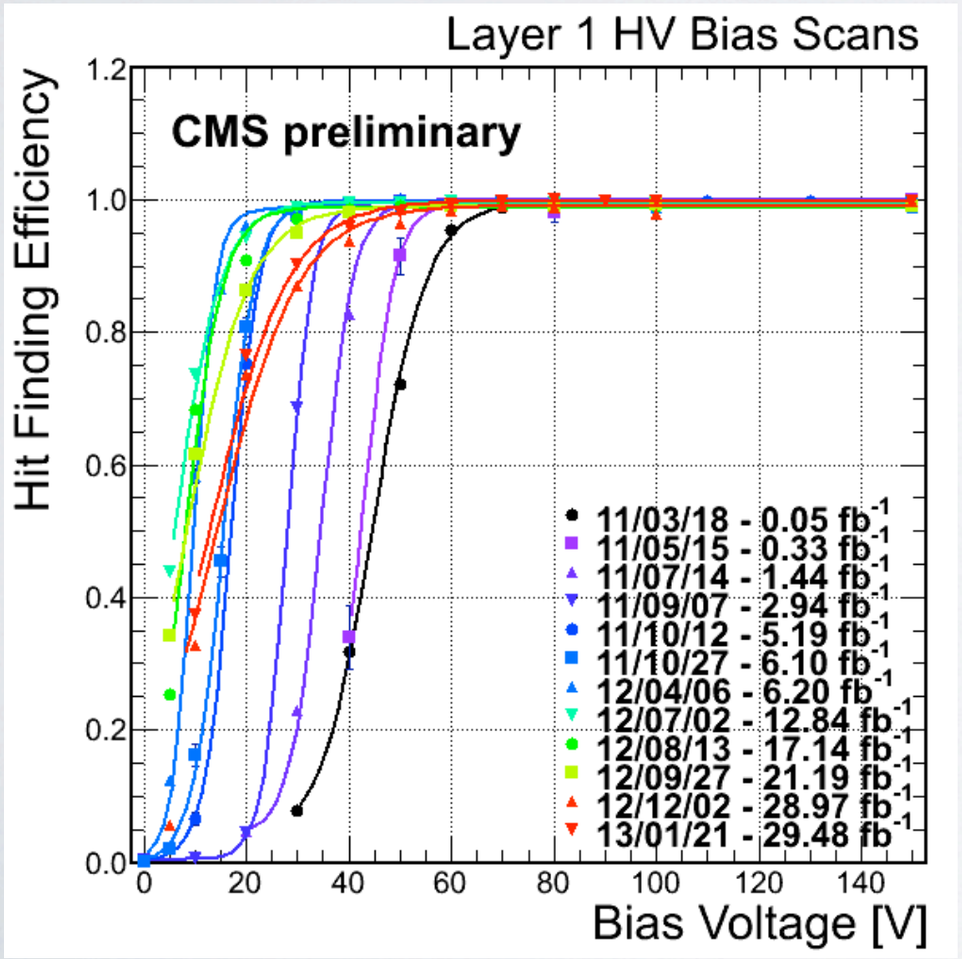

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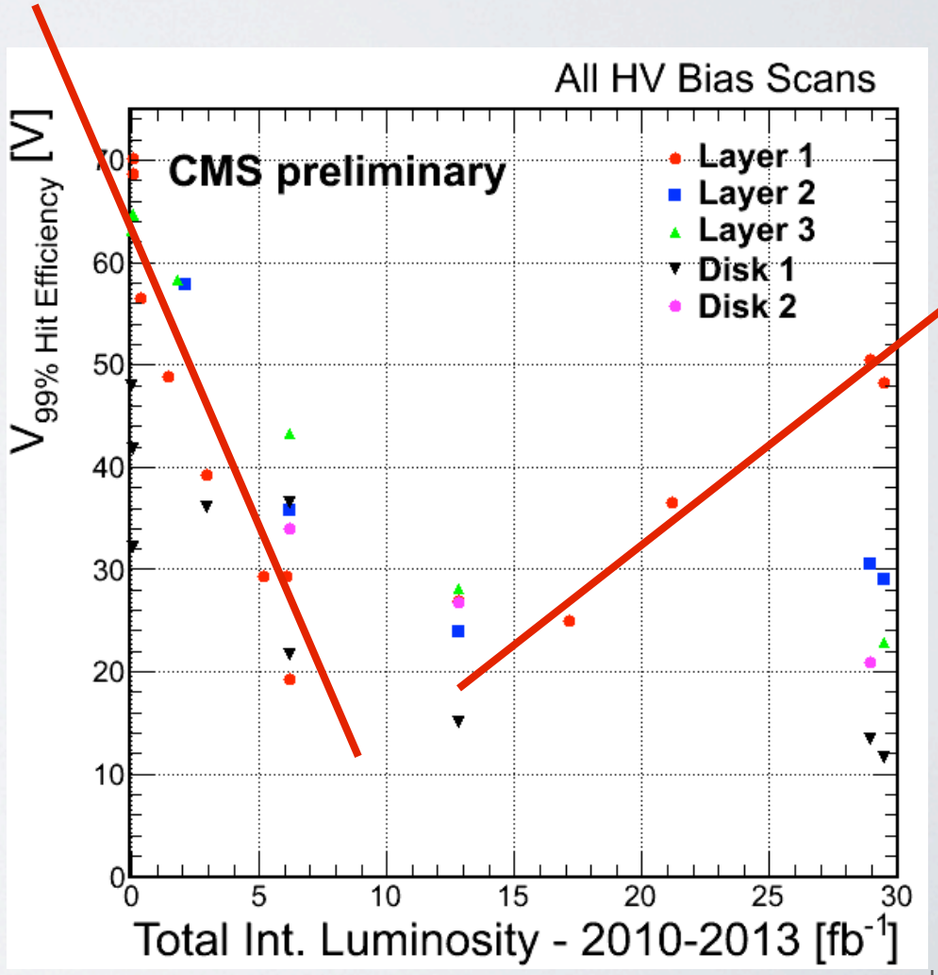
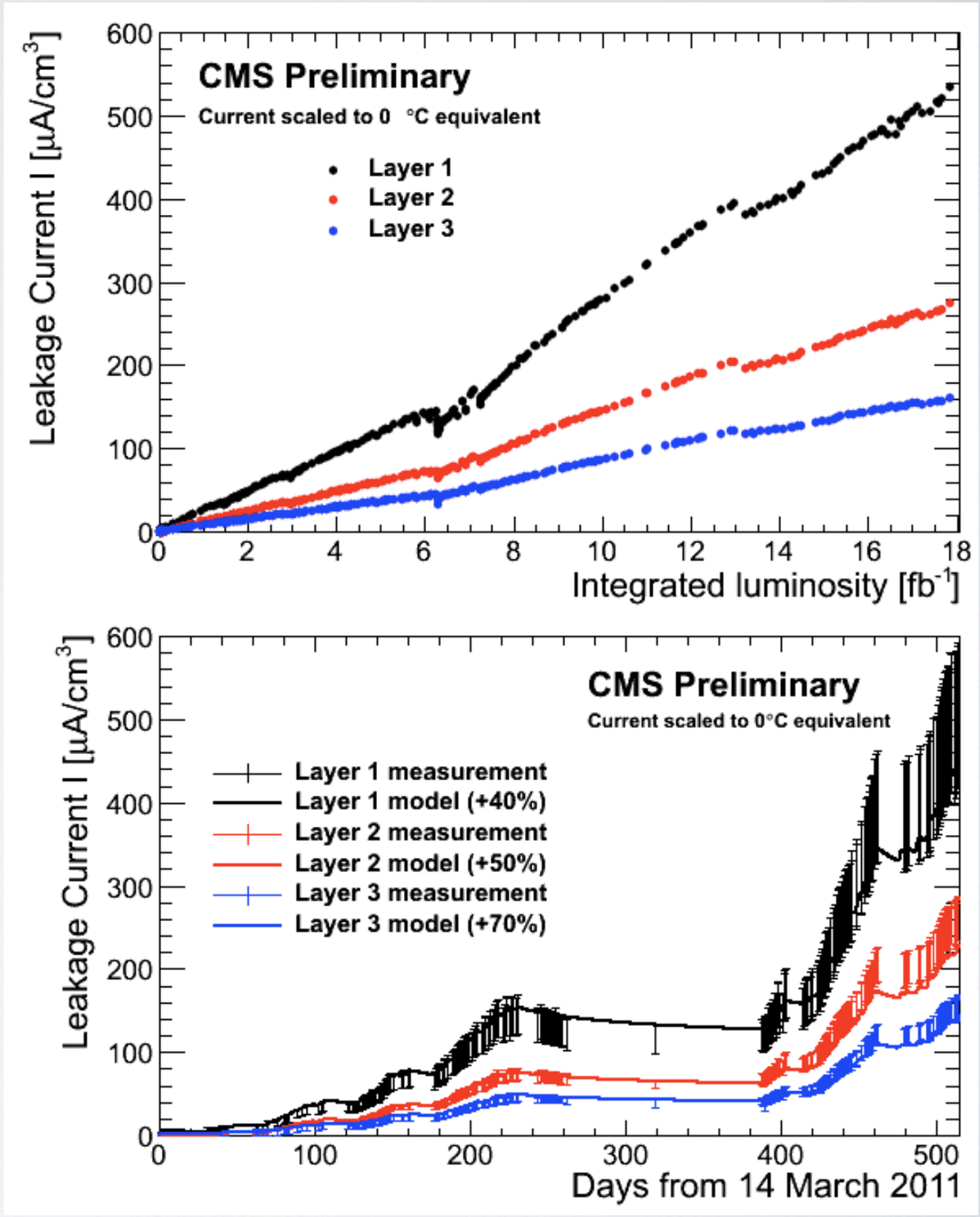
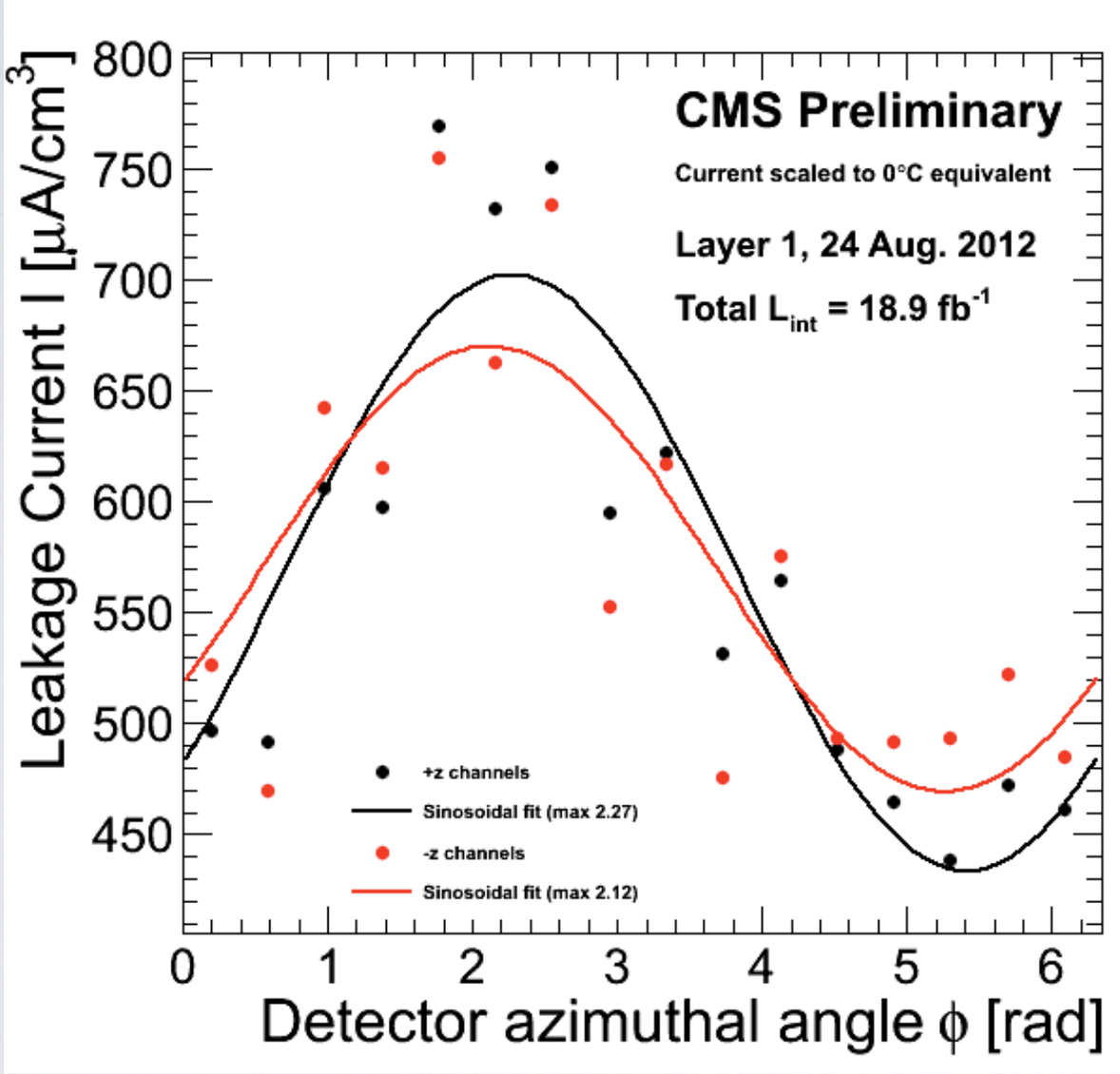


PIXEL: LEAKAGE CURRENT

- Leakage current expected to increase linearly with fluence
  - Due to bulk silicon damage
  - Partial recovery due to annealing
- Good shape agreement with models (fluka)
- Normalization low by 40-70%

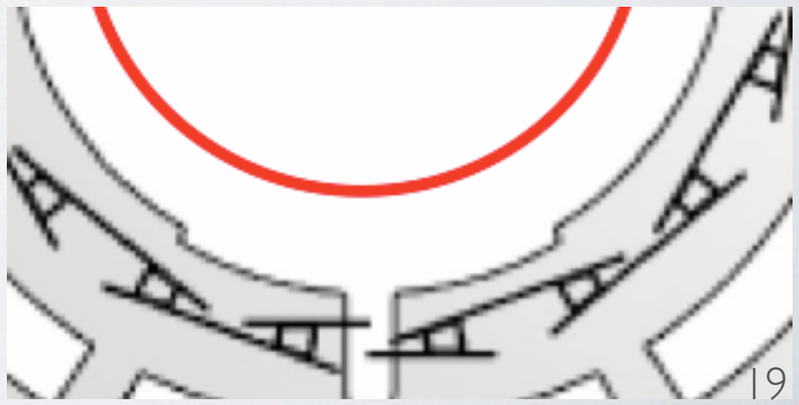


PIXEL: LEAKAGE CURRENT



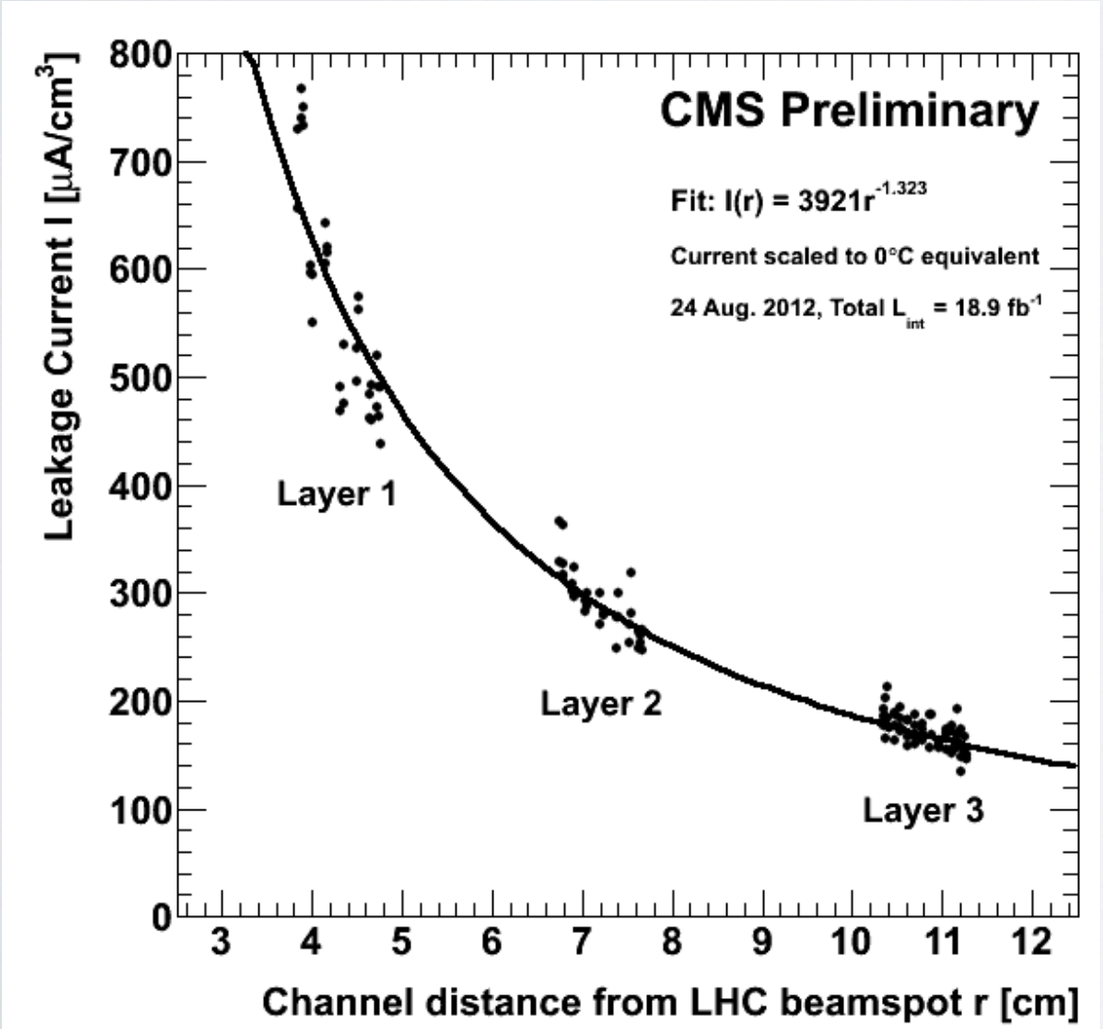
- An azimuthal dependence is observed
- LHC Beam Spot is not at the center of Pixel Detector
  - W.r.t pixel, LHC beam spot (x,y) = (-2.4mm, 3.9mm) → φ ~ 2.12
- 30% effect on potential Layer 1 lifetime
  - new (better) position after LS1
- Geometric issues also impact data rates → where readout issues emerge

Can also see impact of staggered geometry

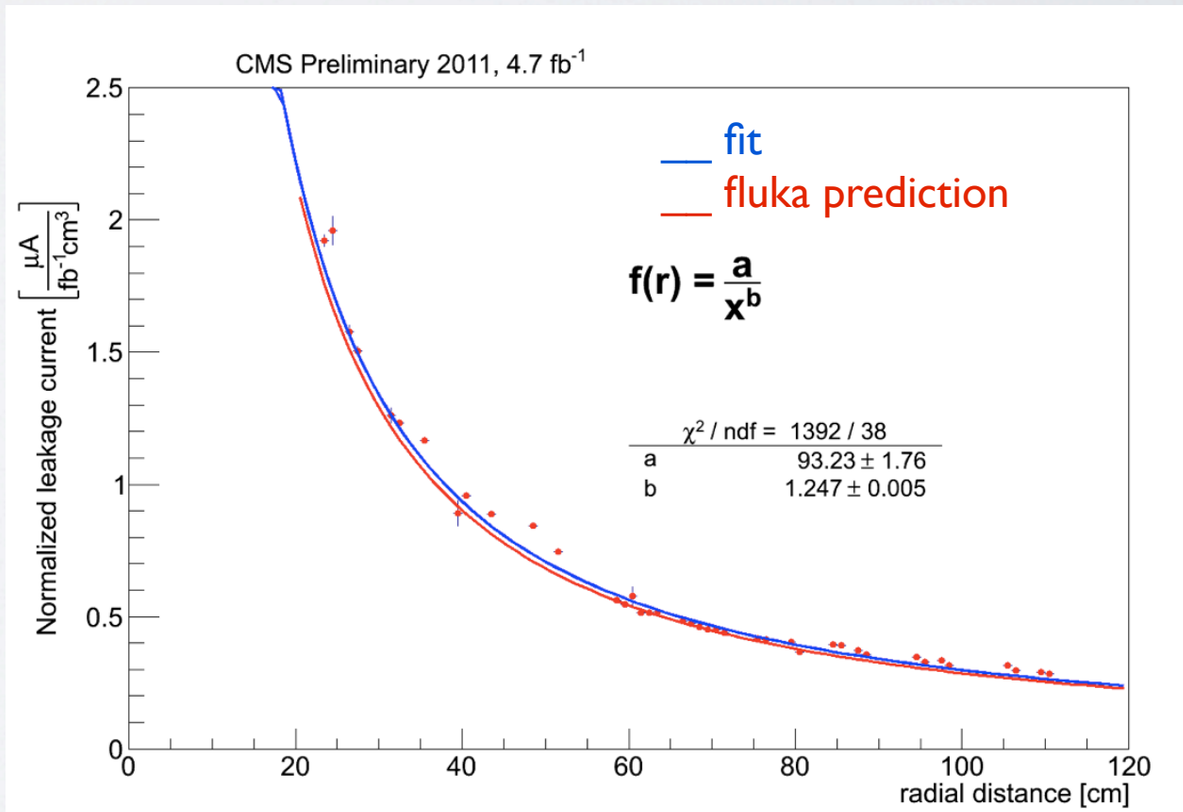


CURRENT VS RADIUS

- Pixels: beam spot offset allows measurements at different radii
- Independent leakage current fits give good agreement in radial dependence
- Fitting function: a/x^b

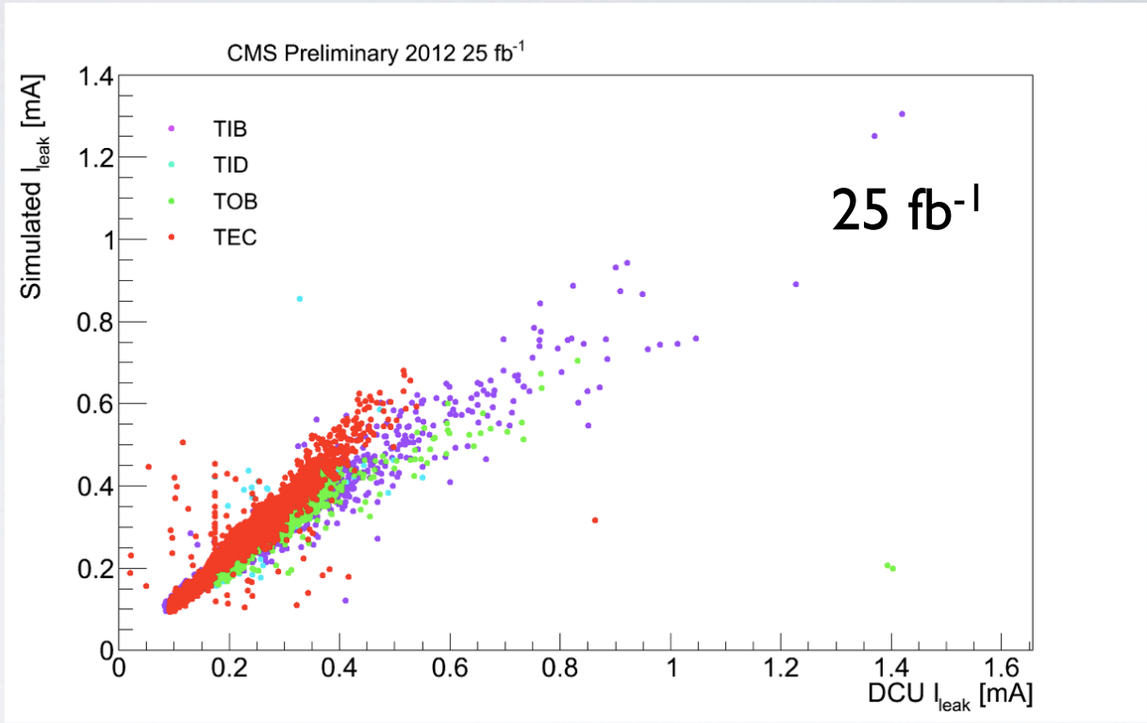


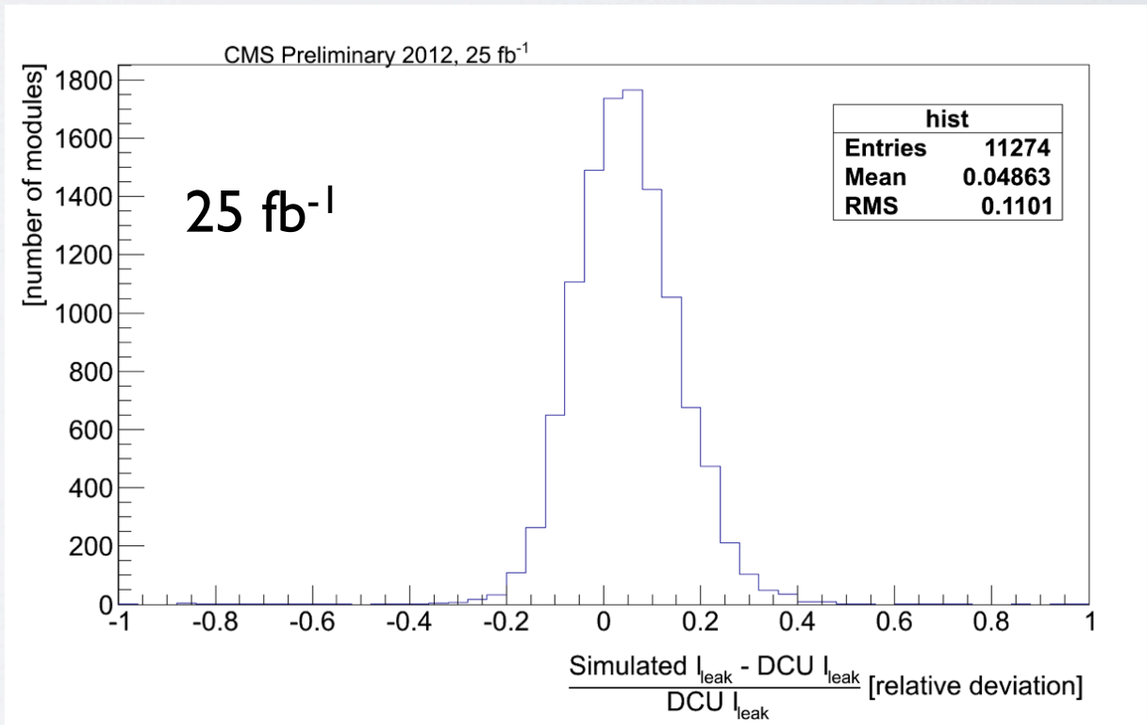
fitted parameter	pixels (18.9 fb-1)	strips (4.7 fb-1)
a	3921 ± 5	93.23 ± 1.76
b	1.3228 ± 0.0008	1.247 ± 0.005



STRIP: LEAKAGE CURRENT

- Average strips measurements agree with model (fluka) within 5-20%
  - varying over time and detector region
  - Better agreement detector regions with temperature T < 20˚C
    - strip tracker temperature not uniform





SUMMARY

- CMS tracker detector operated well during the past three years of data taking
- Few channels lost:
  - Pixels: slow channels, broken readout
  - Strips: control rings missing or with shorts, open HV lines or with shorts
- Main issues related to:
  - Single event upset
    - rate as expected and under control
  - Irradiation
    - Models agree in shape for both pixel and strips
      - Pixel models needs to be rescaled of 40% - 70%
      - Strip models agree within 5-20% depending on the temperature
- High detection efficiency and excellent resolution
- Shutdown maintenance work:
  - repair broken readouts (pixel) and recover control rings (strips)
  - recover slow pixel channels
  - insertion of additional sensors for ‘upgrade’ chip testing
  - cooling maintenance

OTHER CMS TALKS

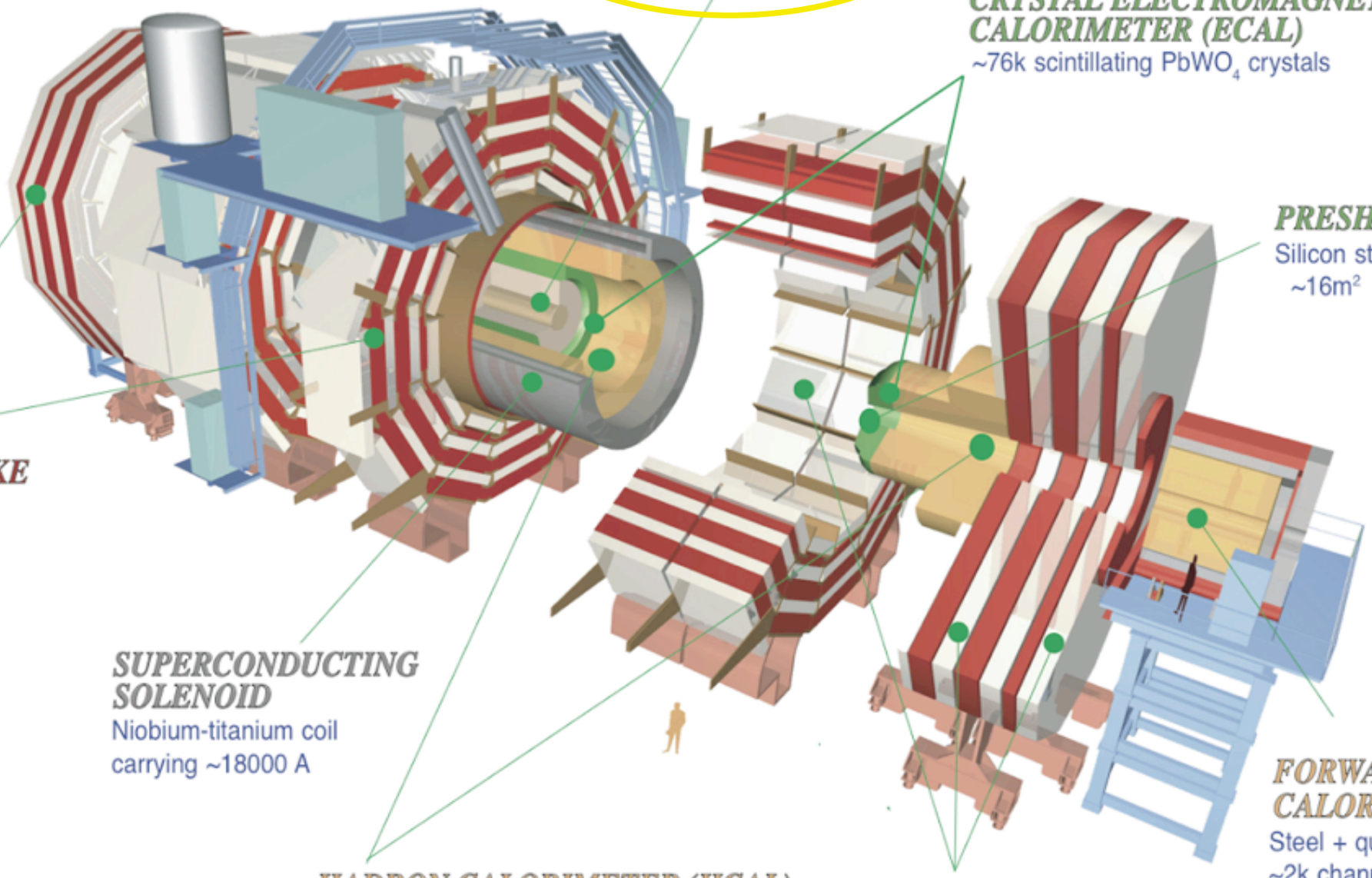
- Current detector:
  - Valentina Gori: "Tracking performances in CMS"
  - Marco Musich: "The Alignment of the CMS Silicon Tracker"

- Upgrade studies:
  - Mauro Menichelli: "The Phase-1 upgrade of the CMS silicon pixel detector"
  - Teppo Maenpaa: "Performance of different silicon materials for the upgraded CMS tracker"

BACKUP SLIDES

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

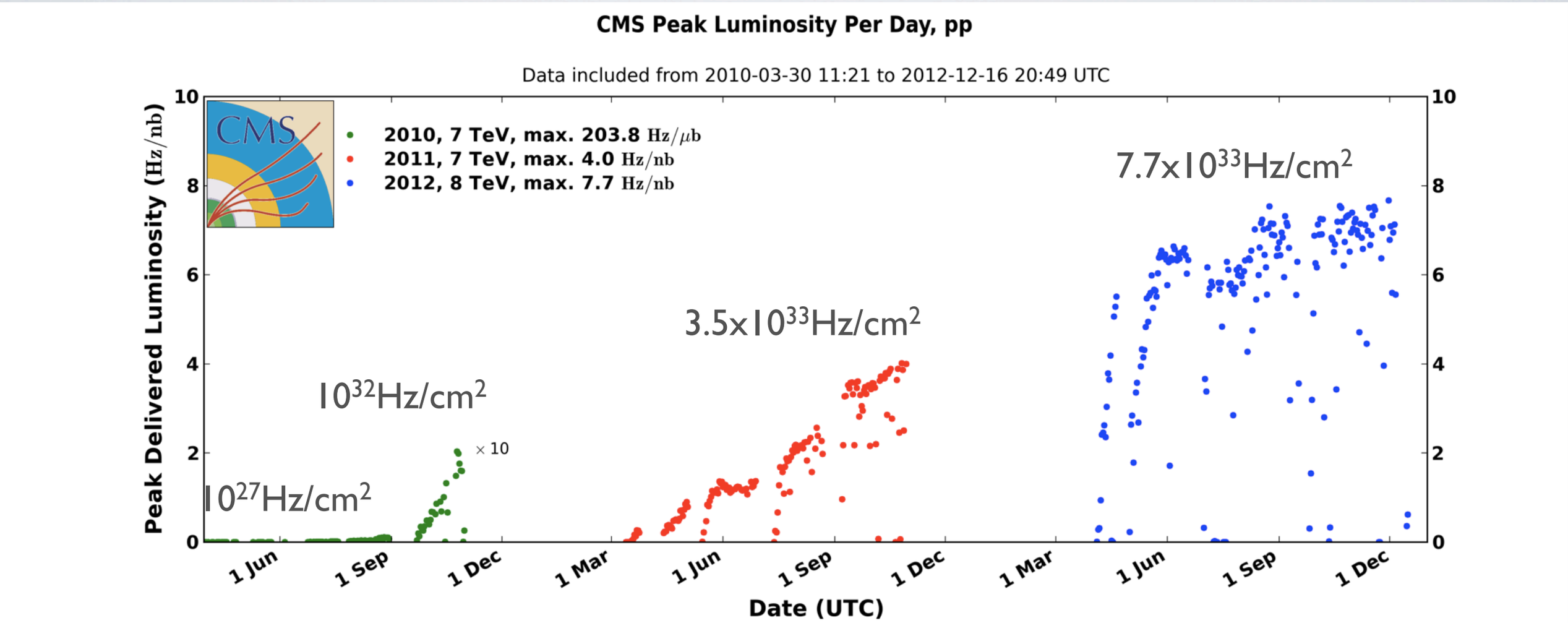
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

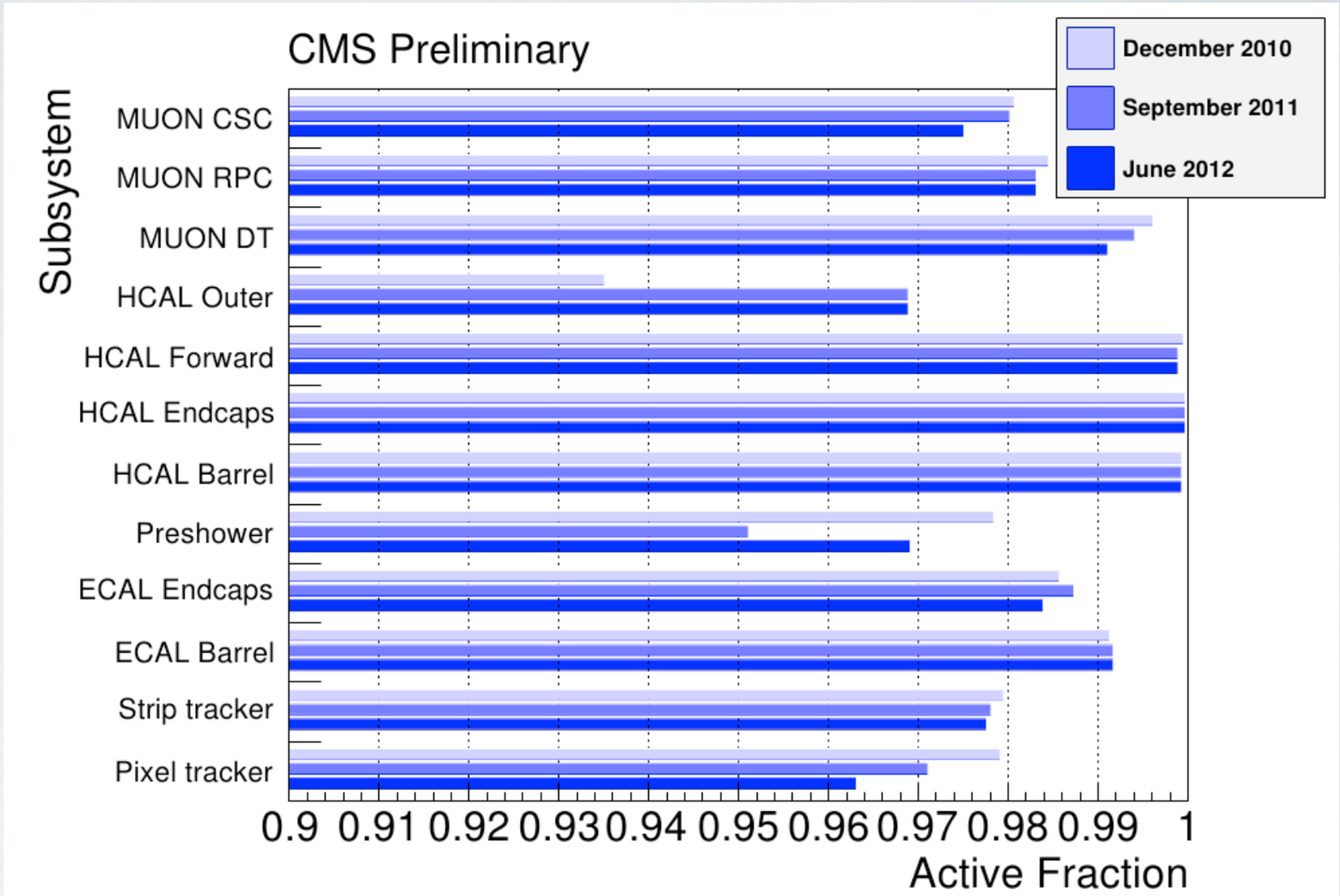
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

INSTANTANEOUS LUMINOSITY



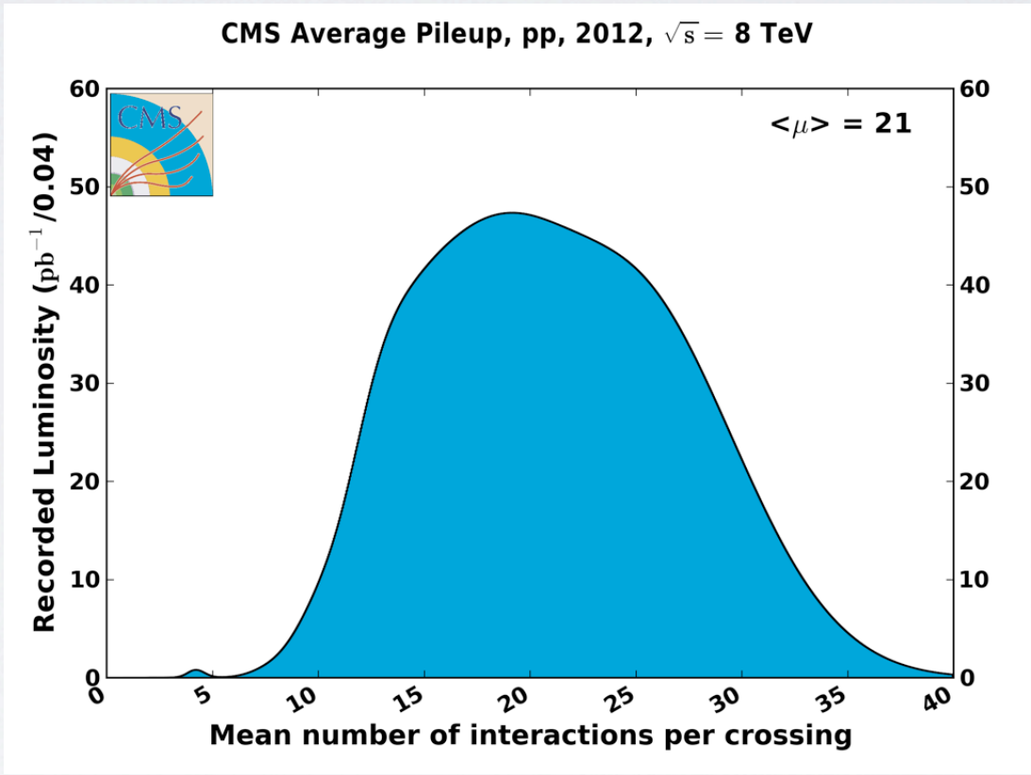
- In 2010: instantaneous luminosity increased by 5 orders of magnitude
- In 2011: instantaneous luminosity reached 40% of the nominal LHC value
- In 2012: The LHC reached 77% of the nominal inst. luminosity

ACTIVE FRACTION

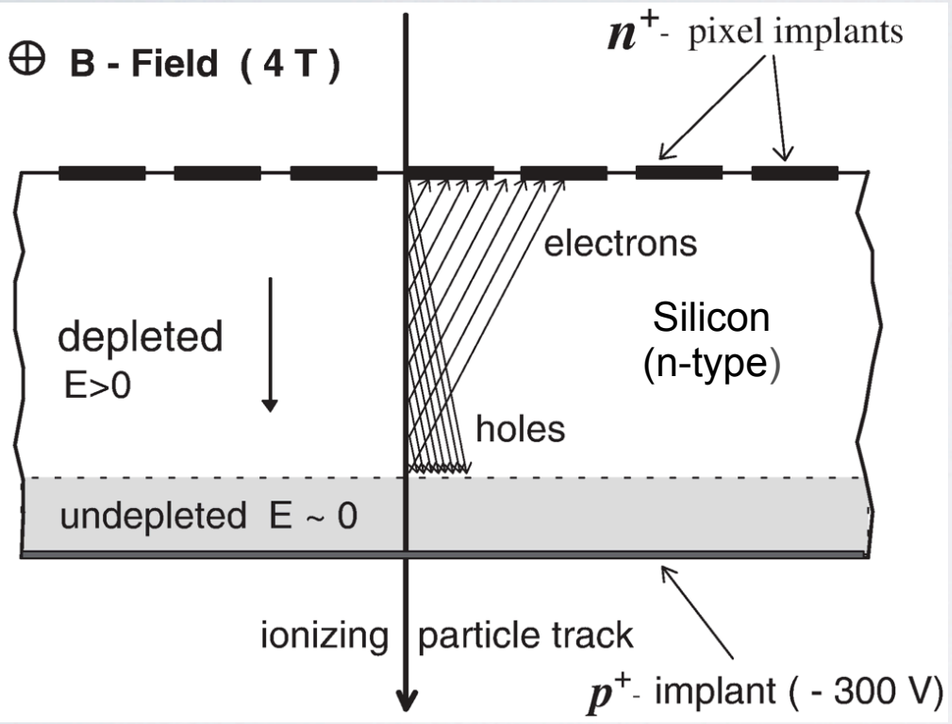


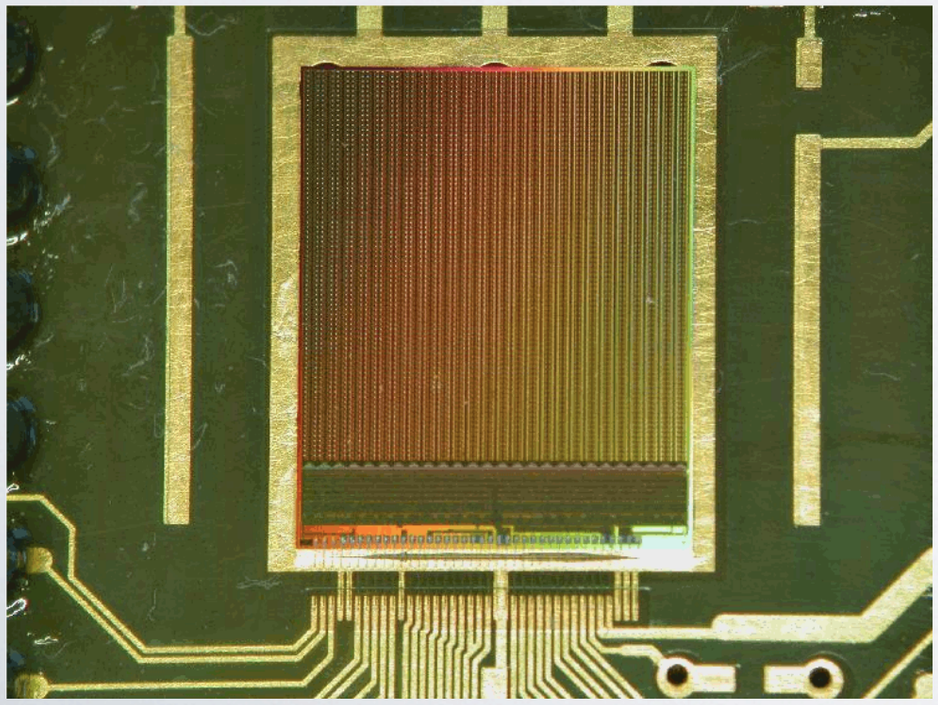
- Active fraction in 2012:
  - Pixel: 96.3 %
  - Strip: 97.5%

PILE UP


CMS Average Pileup, pp, 2012, $\sqrt{s} = 8$ TeV
CMS
<μ> = 21
Recorded Luminosity (pb^{-1}/0.04)
Mean number of interactions per crossing
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60

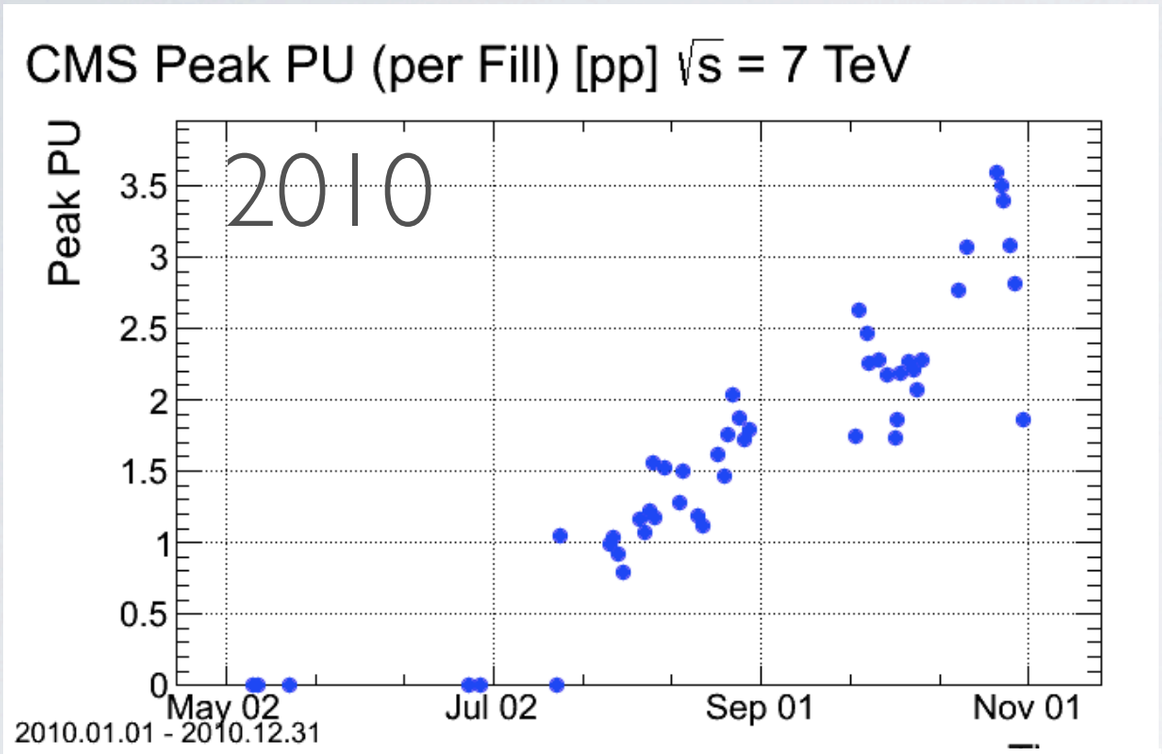
CMS PIXEL SENSOR AND ROC

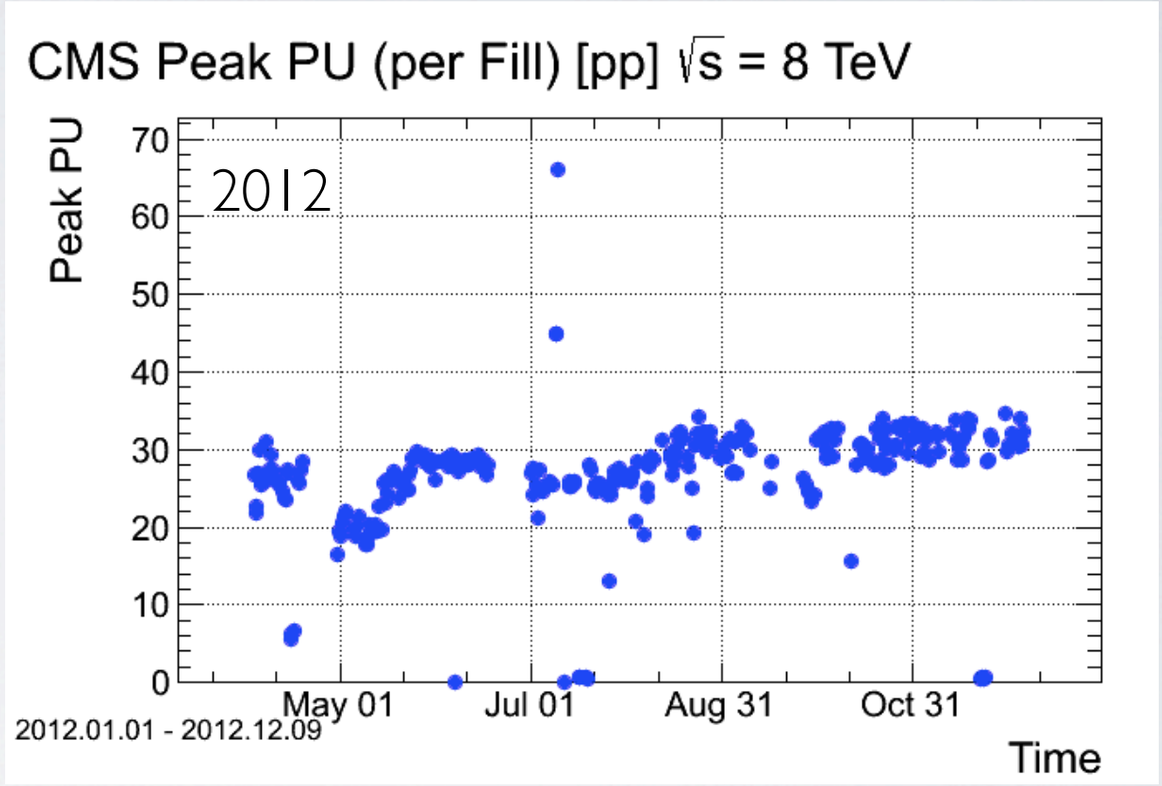


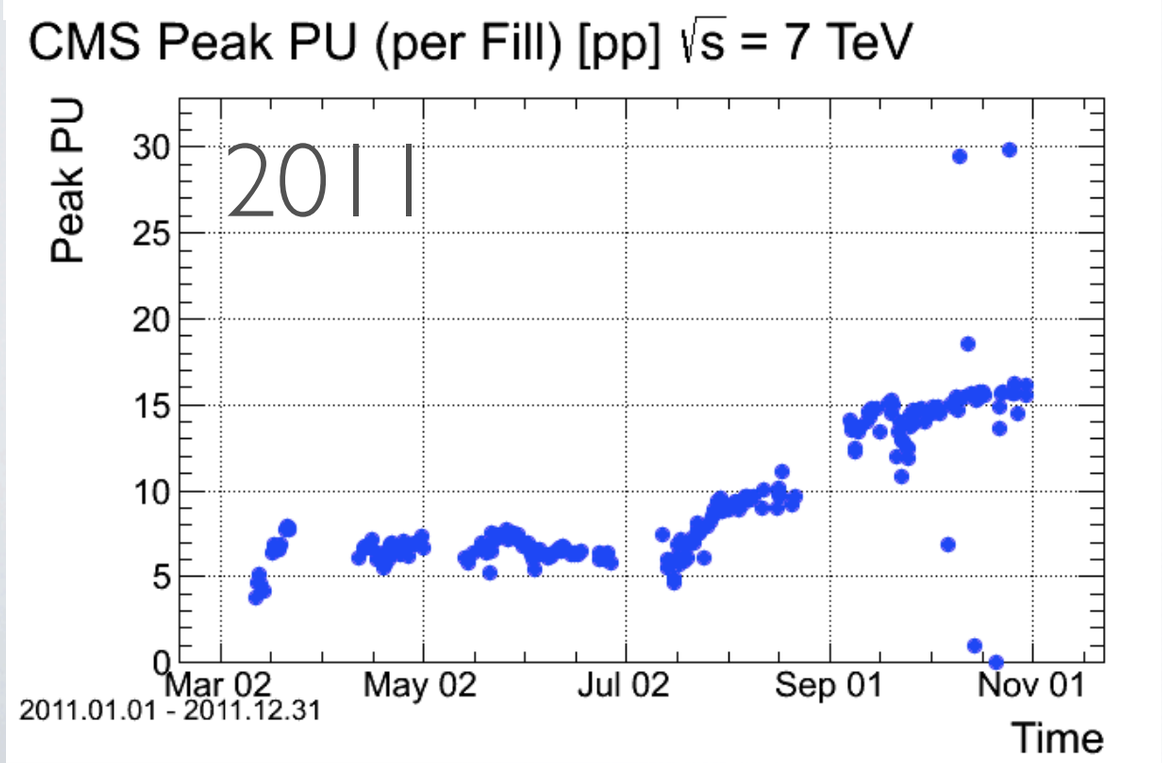


- n-in-n silicon sensors
- Each sensor has 52 x 80 = 4160 pixels;
- Pixel size: 100μm x 150μm;
- The ReadOut Chip (ROC) designed by PSI and manufactured by IBM;
- Automatic zero-suppression;
- 26 DACs to regulate settings, each pixel has a 4-bit DAC for fine adjustments (trimming);
- Double-column drain architecture:
  - Hits stored in a buffer until trigger confirmation;
  - Single 25ns-wide bunch-crossing readout;

PILE UP (2010-2012)





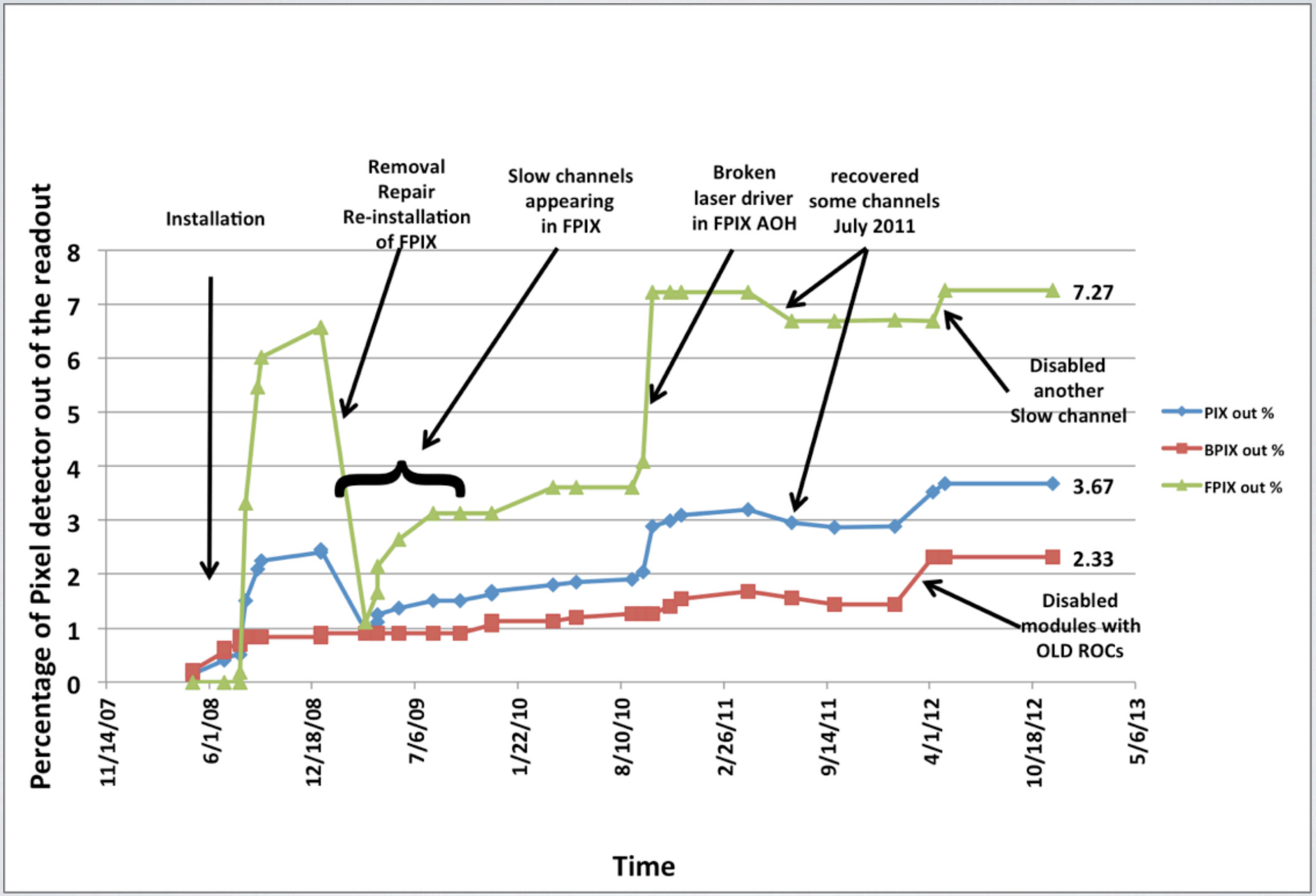


Year	peak PU *
2010	3.5
2011	18.6
2012	34.5

*excluding high pile-up run

average PU in 2012:
21 interactions / bunch crossing

CHANNEL OUT OF READOUT

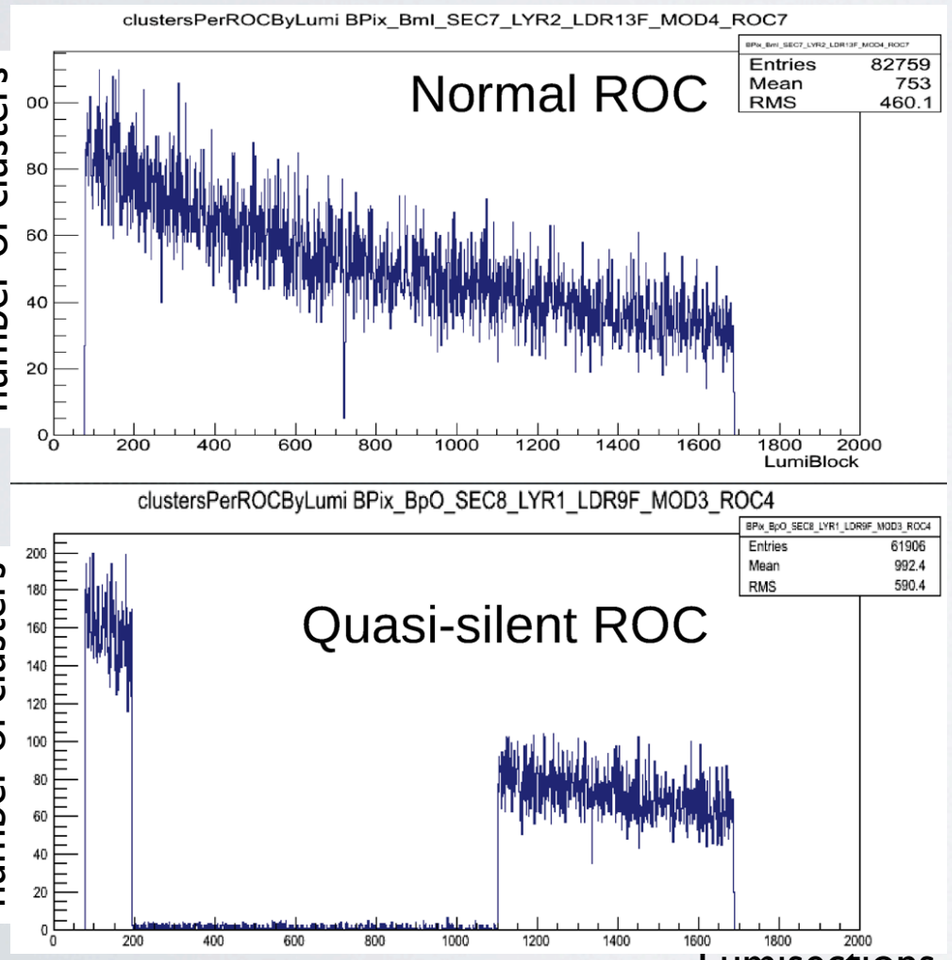


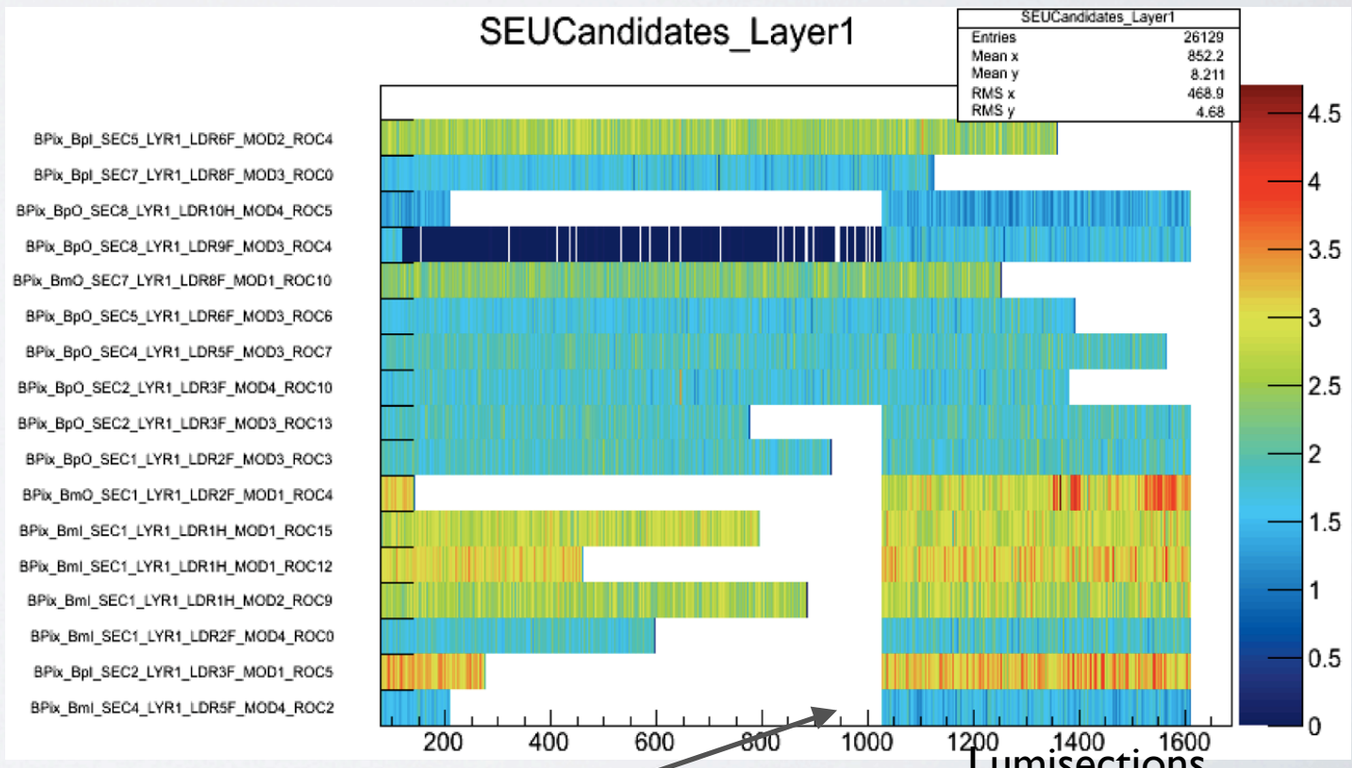
PIXEL: SINGLE EVENT UPSET

- Two mechanisms to detect SEU
  - monitoring the off channels
  - searching the Out of Sync (OOS) errors

The FED (Front End Driver) turns a channel off in case of consecutive timeouts.
If not recovered after 3 tries, the mechanism leaves the channel off;

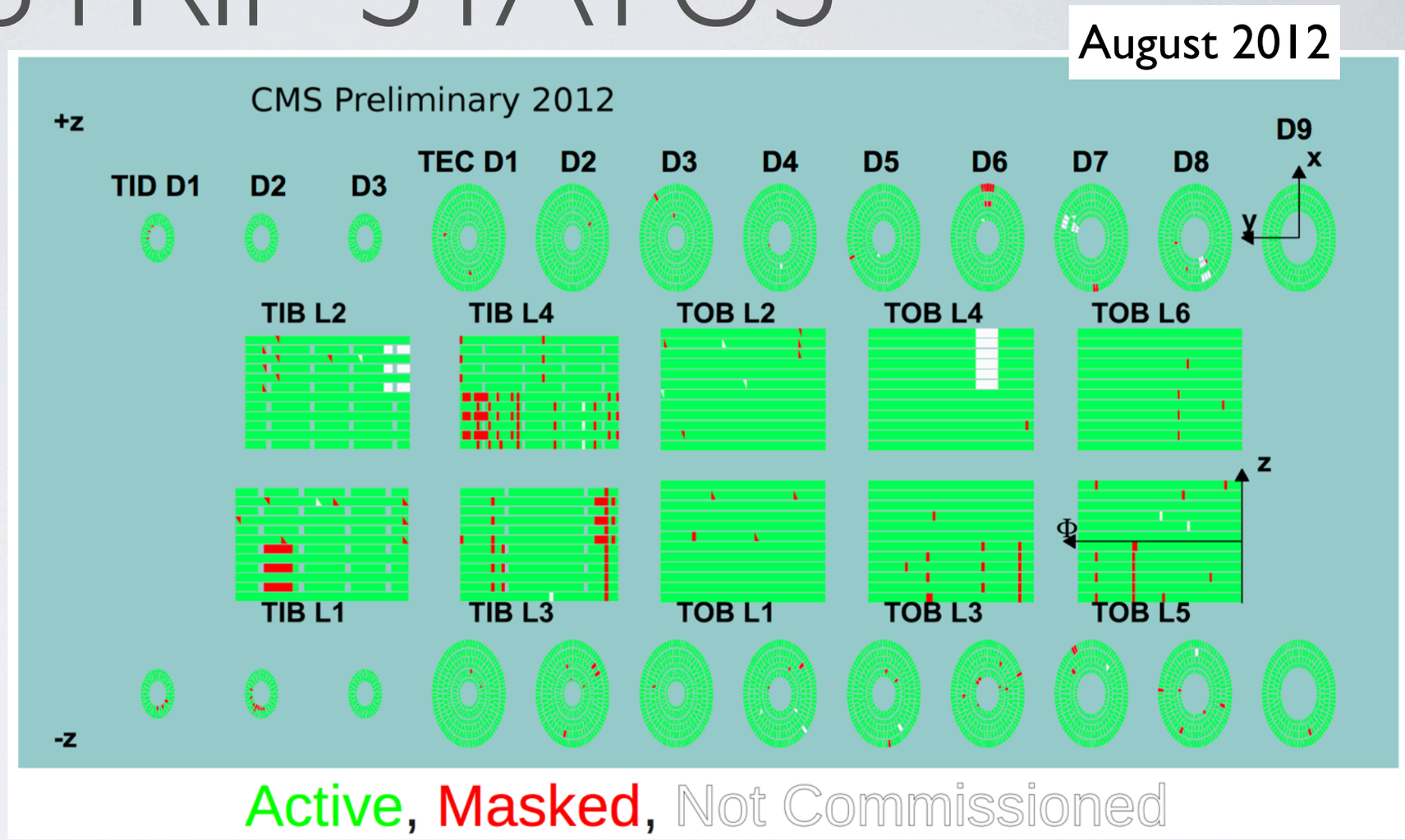
If X OOS errors happen in Y events, the recovery mechanism is triggered;
from optimization: (X,Y) = (8, 100,000)



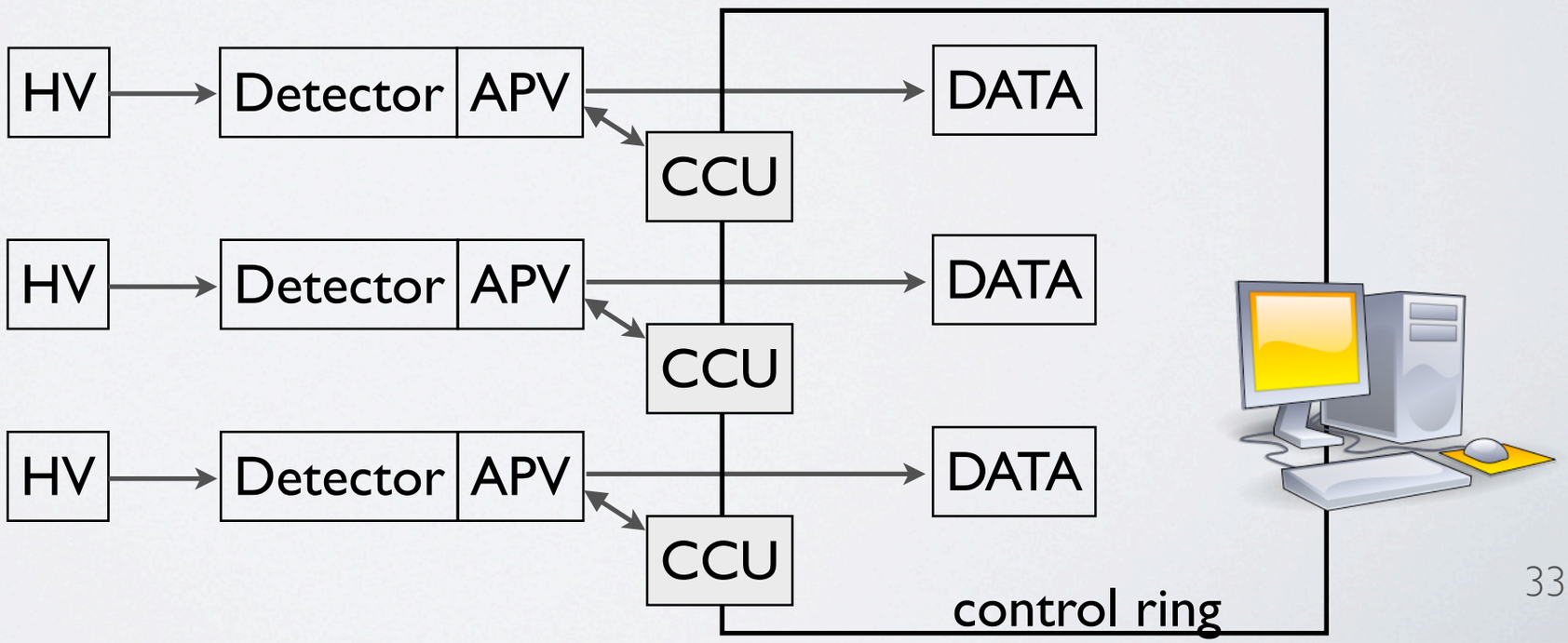


STRIP STATUS

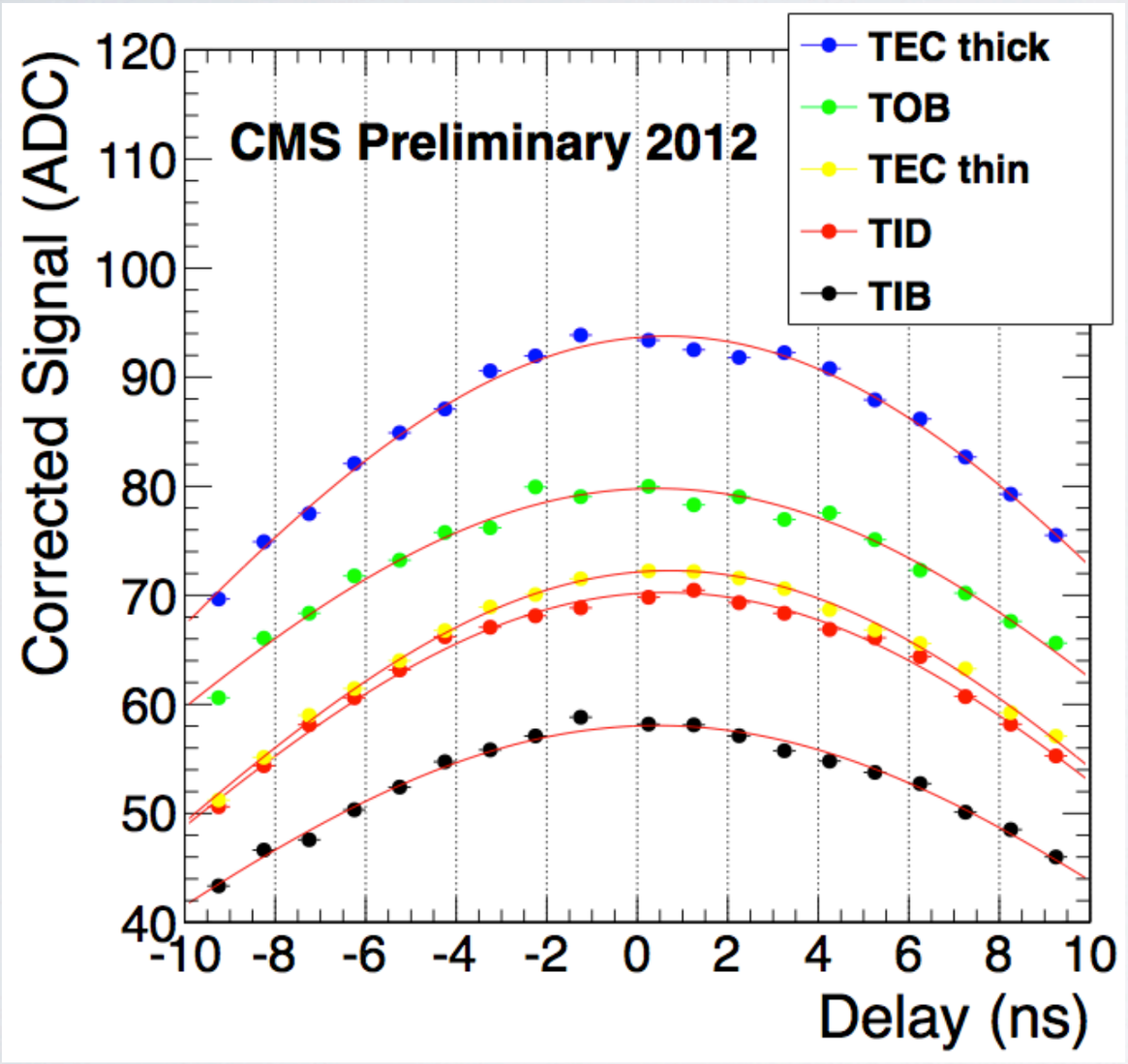
- Active fracion > 97.5%
- Almost stable:
  - 2008: 98.5%
  - 2011: 97.75 %
- Potentially recoverable in 2013/14 shutdown:
  - 2-3 control rings (0.7-1.0%)



- Reasons for masking
  - Control ring shorts
  - Control rings missing
  - HV line shorts
  - HV lines open
  - fibres/CCU/....



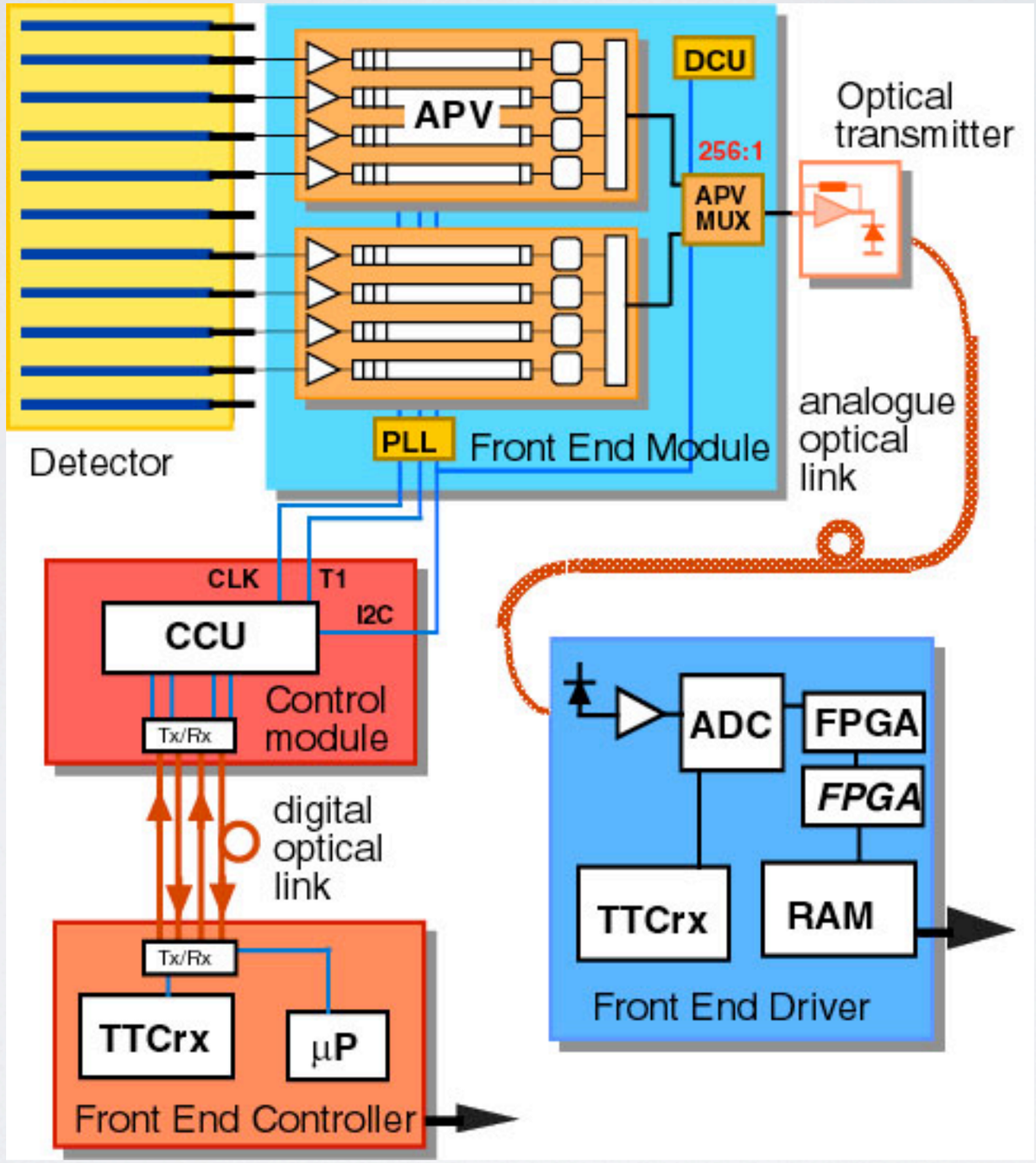
STRIP: TIME ALIGNMENT



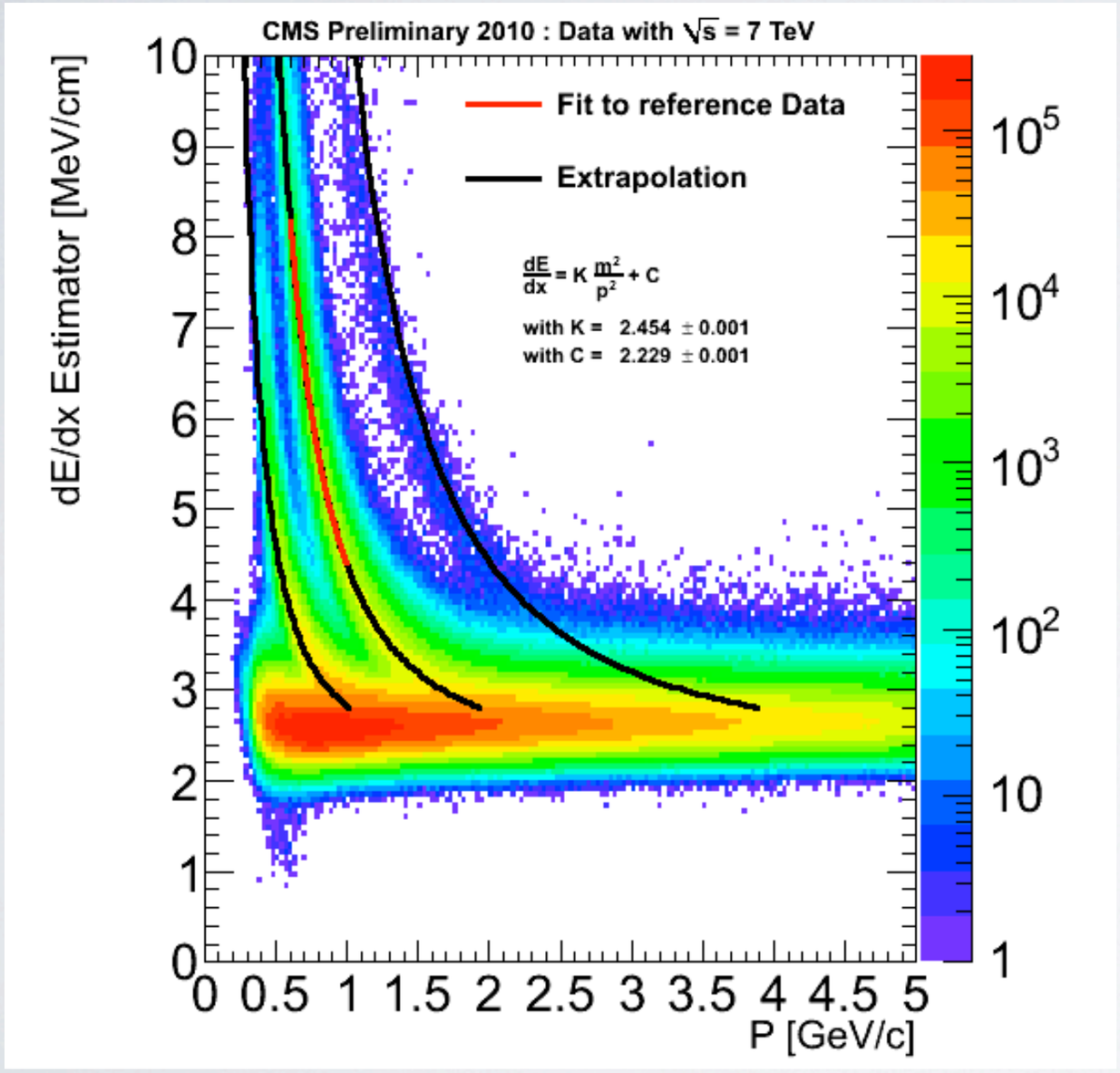
- The readout must be aligned in time with the LHC clock
- Check of the alignment:
  - Time delays in steps of 1.04 ns
    - smallest possible adjustment
  - Signal maximum at 0 means current fine timing is perfect.
  - Largely stable compared to 2011
    - no adjustments needed.

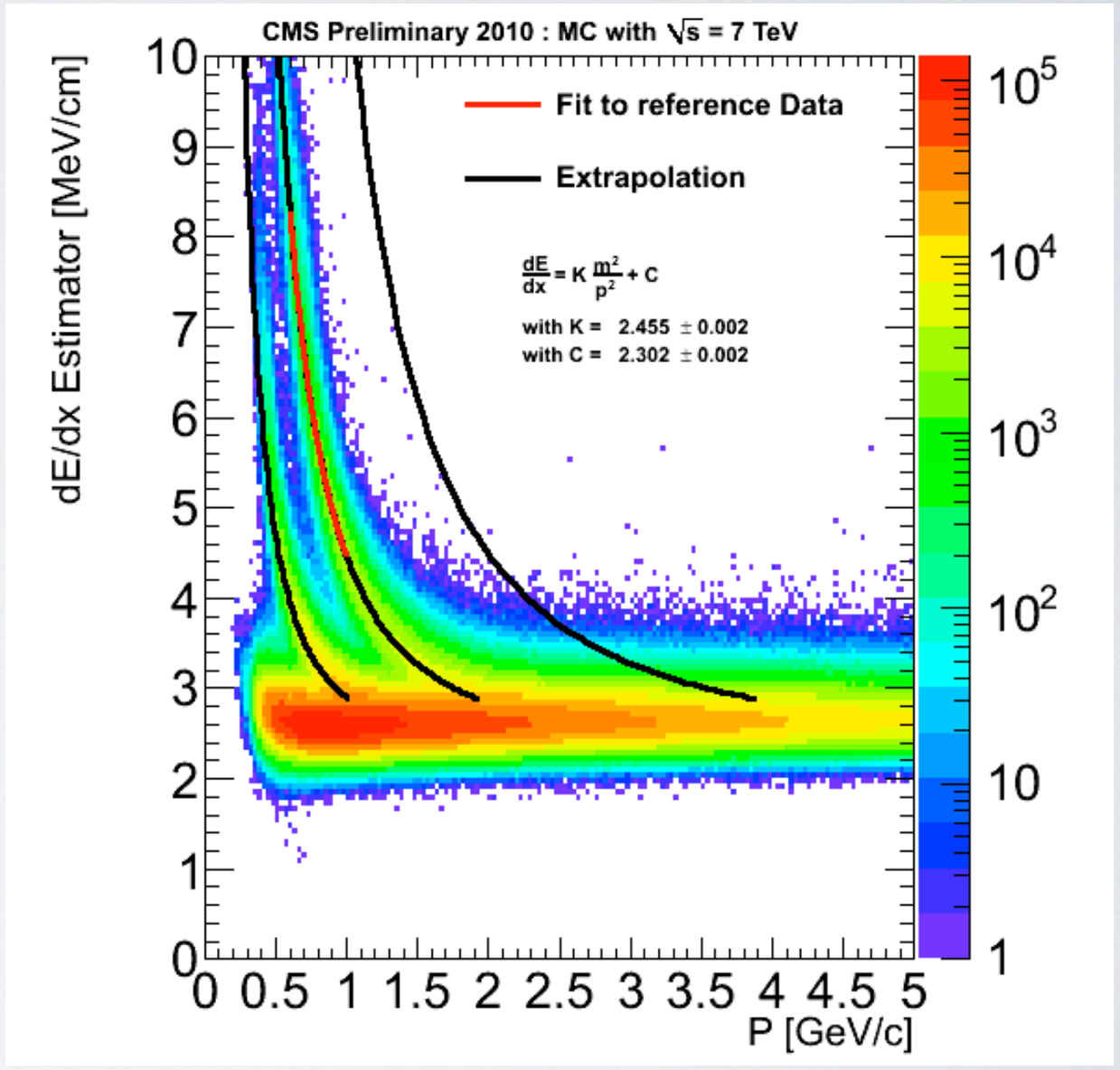
- If timing off: miss peak of signal, signal-to-noise ratio degraded.
- If far off, efficiency may suffer

STRIP READOUT SCHEME

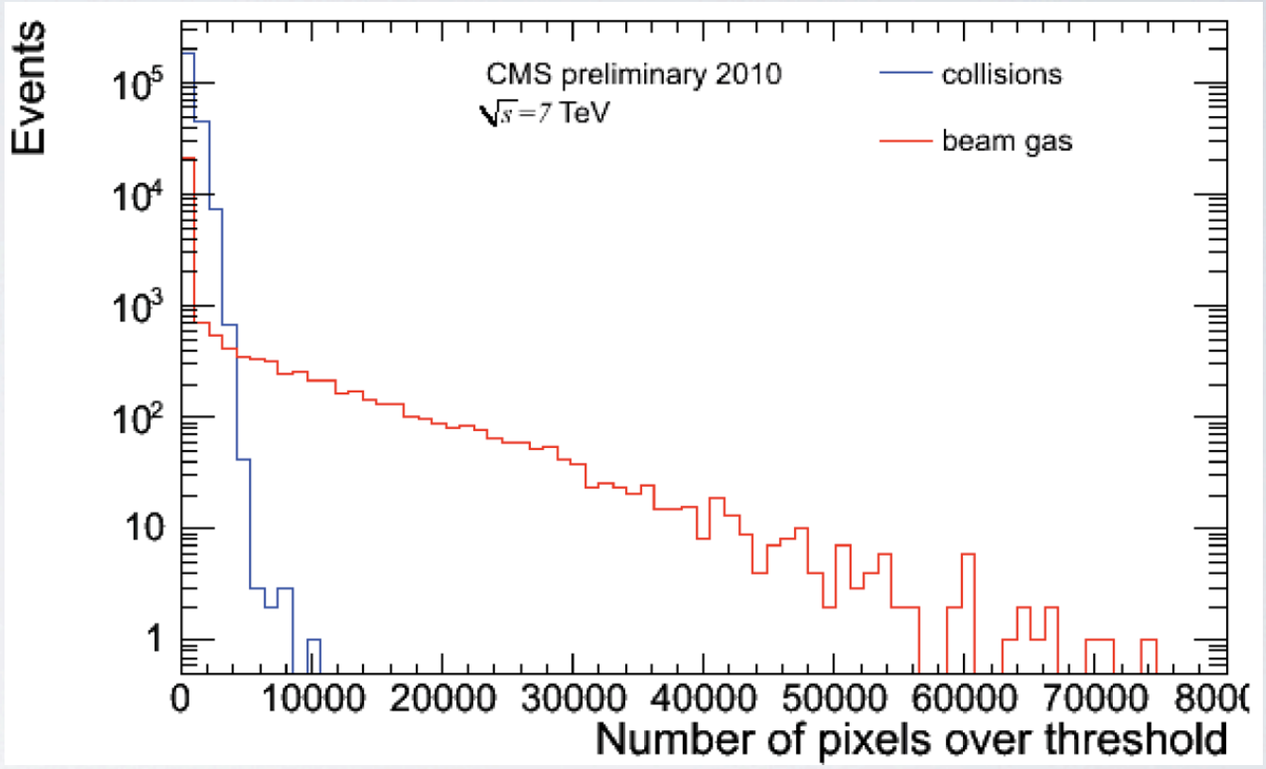


STRIP: dE/dx


CMS Preliminary 2010 : Data with √s = 7 TeV
Fit to reference Data
Extrapolation
dE/dx = K m²/p² + C
with K = 2.454 ± 0.001
with C = 2.229 ± 0.001
dE/dx Estimator [MeV/cm]
P [GeV/c]


CMS Preliminary 2010 : MC with √s = 7 TeV
Fit to reference Data
Extrapolation
dE/dx = K m²/p² + C
with K = 2.455 ± 0.002
with C = 2.302 ± 0.002
dE/dx Estimator [MeV/cm]
P [GeV/c]

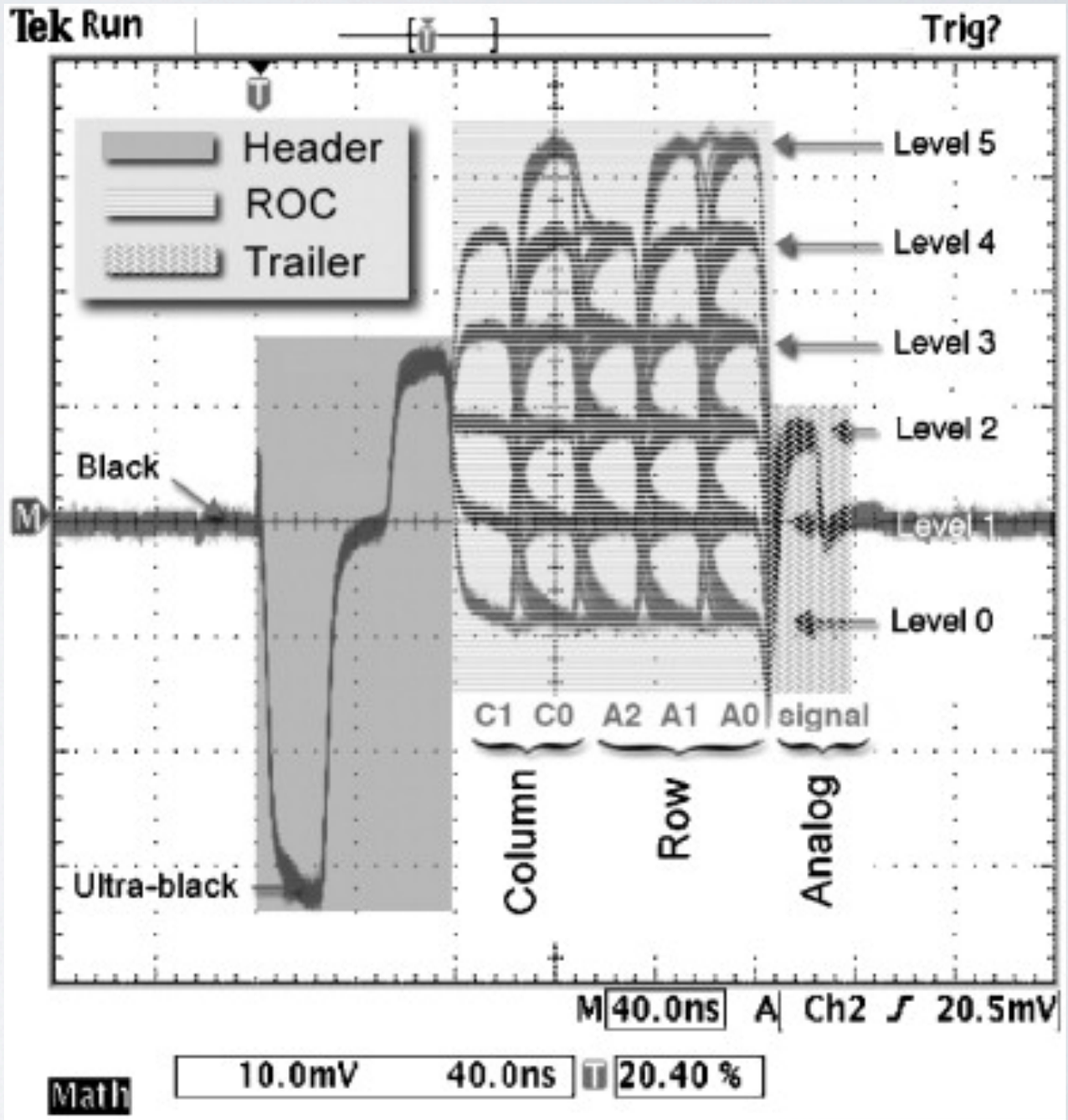
PIXEL: BEAM GAS EVENTS



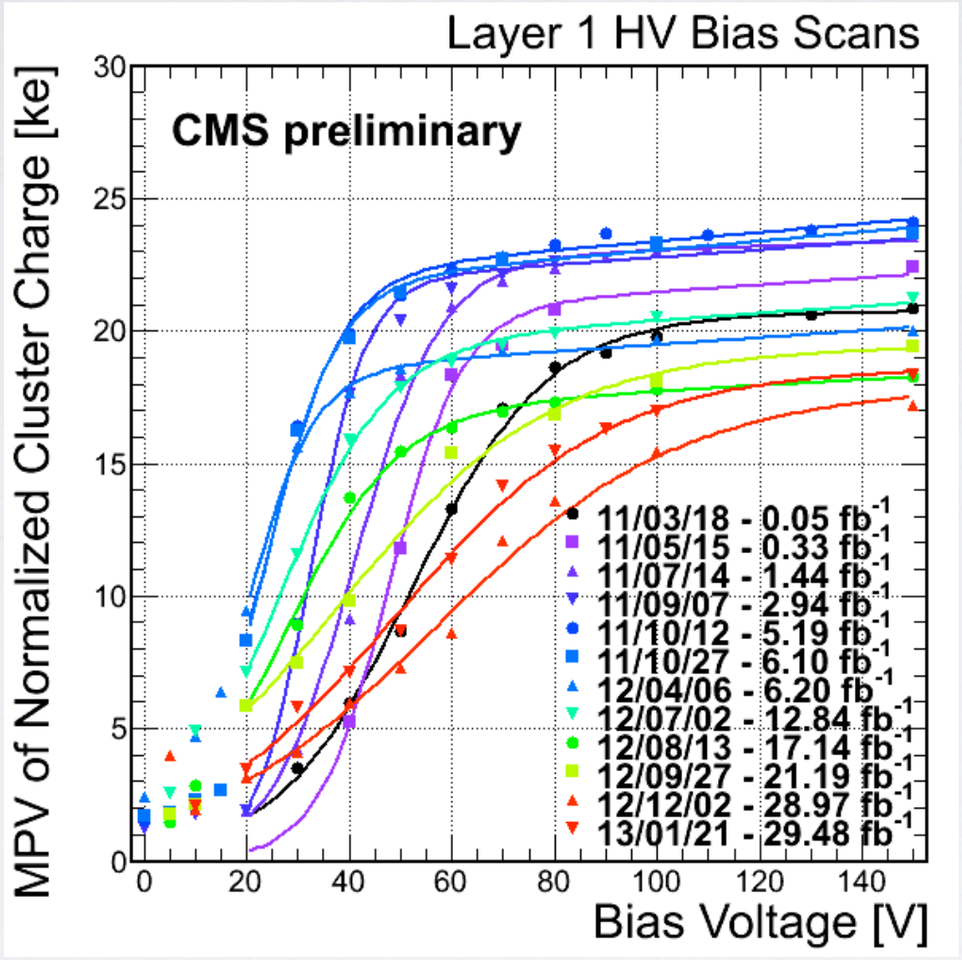
- Major issue during 2010
  - important source of downtime
  - beam interact with gas molecules
    - particle flying along z direction
    - Grazing tracks along BPIX: high number of active pixels
- Solved with the implementation of the "busy mechanism":
  - triggers are stopped to allow the readouts to catch up;
- A joint between two elements of the machine (at 18.5 m from CMS) caused bad vacuum and high deadtime in the pixel detector. Fixed in 2011/2012 winter stop.

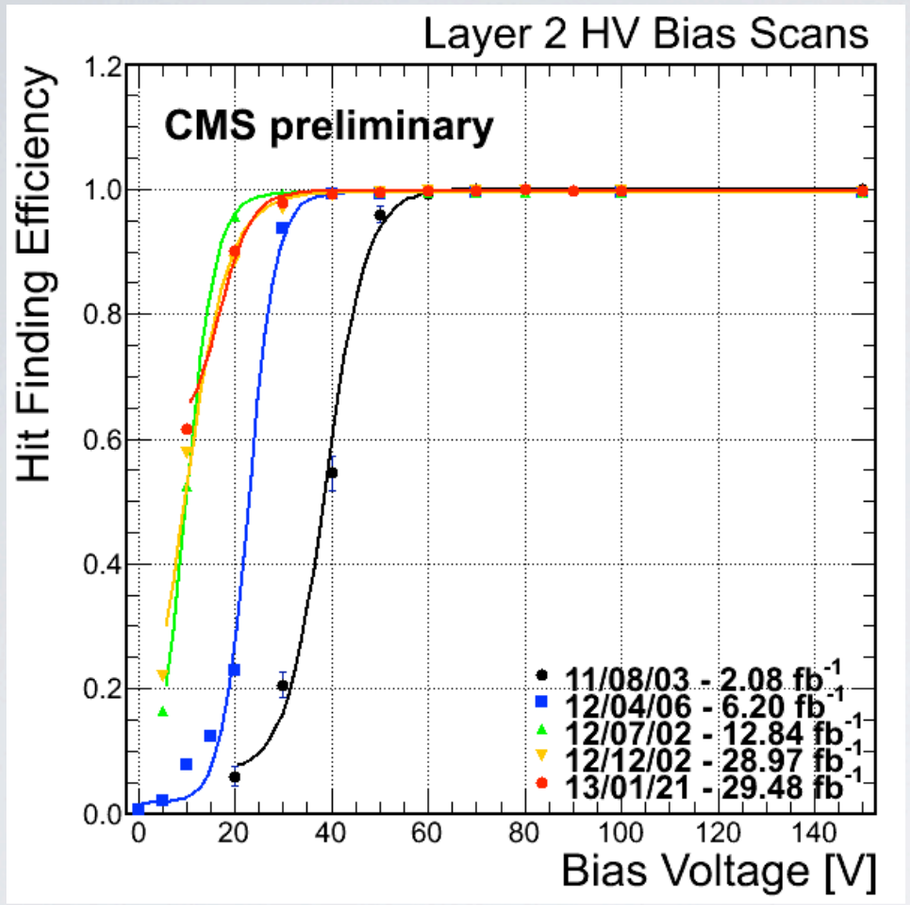
PIXEL ANALOG READOUT

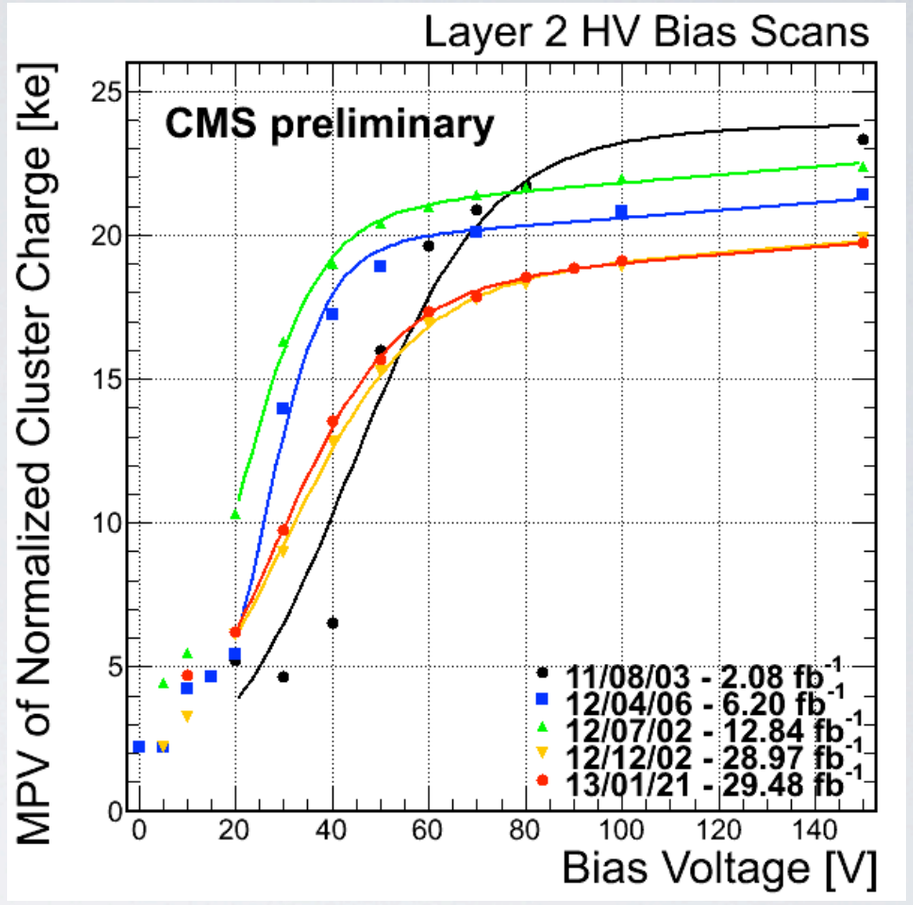
Hit pixel triggers readout of double column to buffer
Double columns read out sequentially when trigger received
ROC header followed by address and analog signal for each pixel

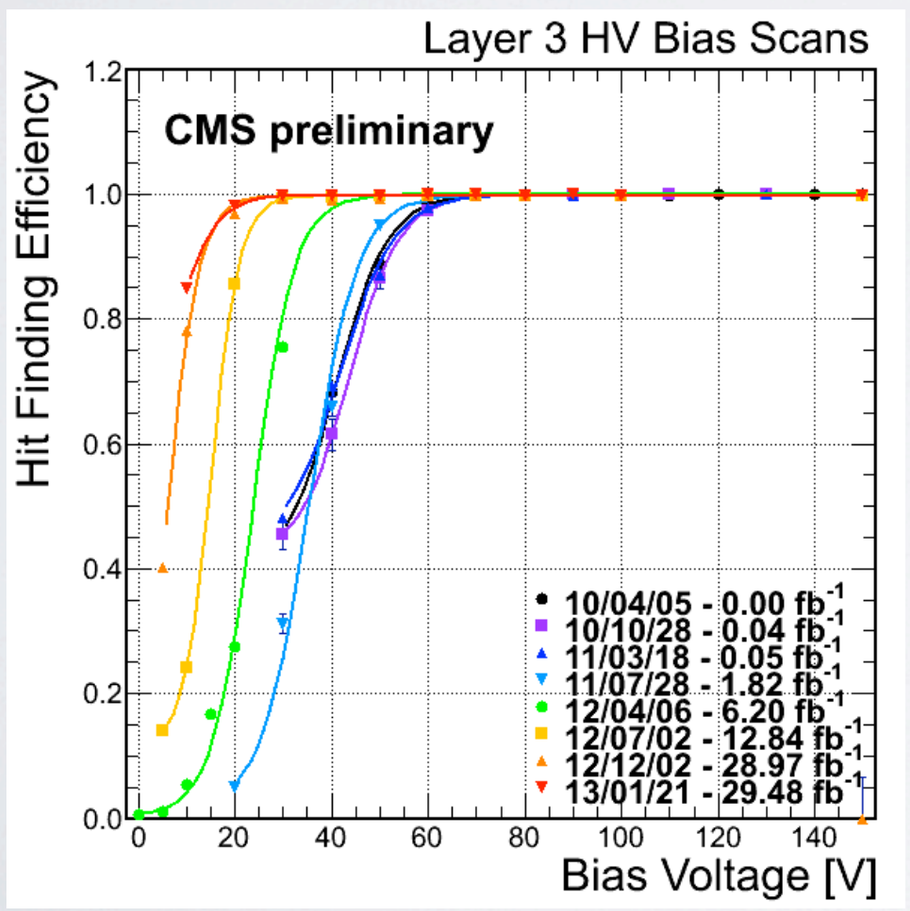


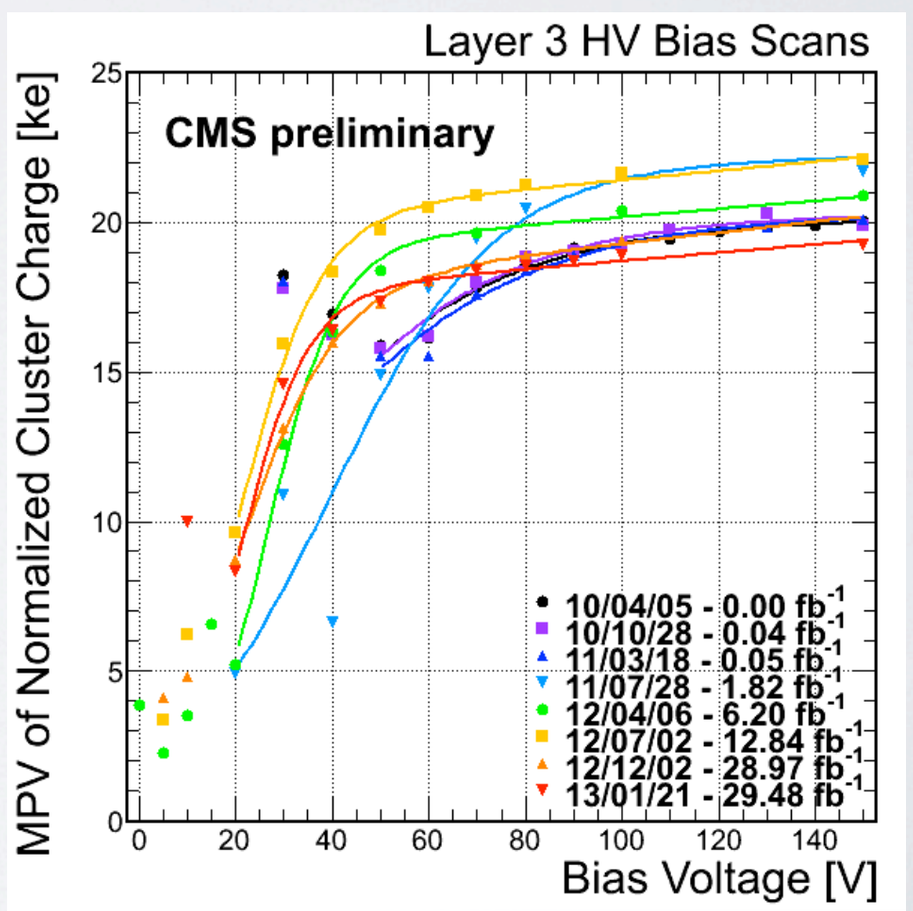
MPV IN BIAS SCAN

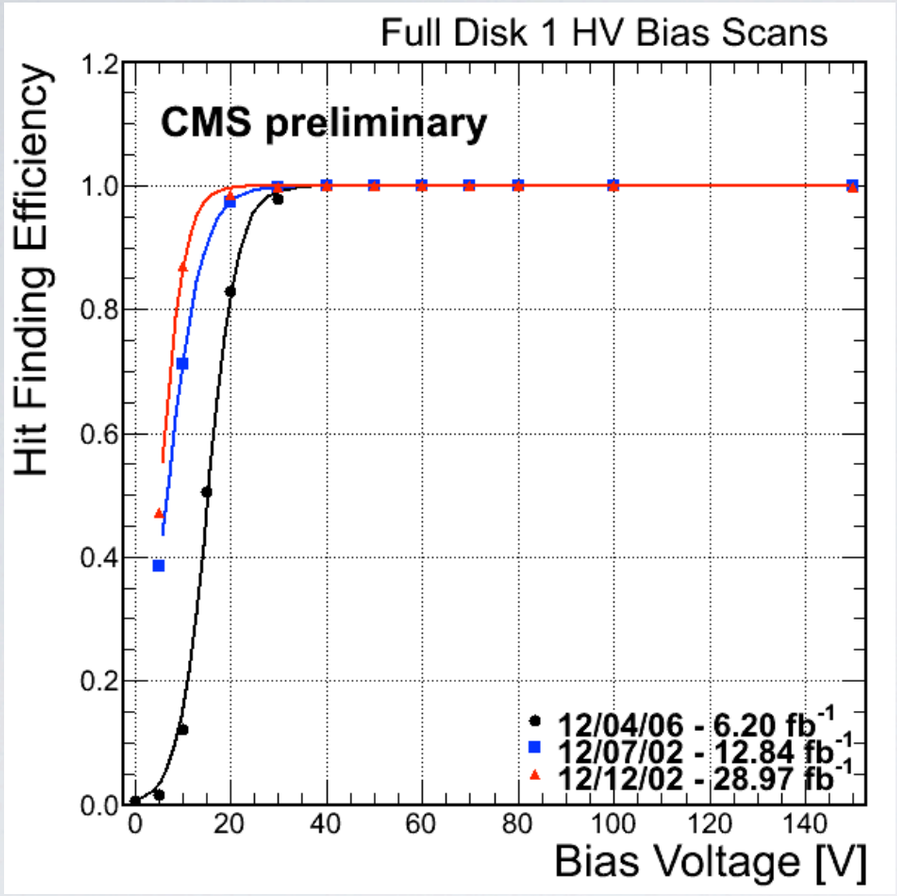


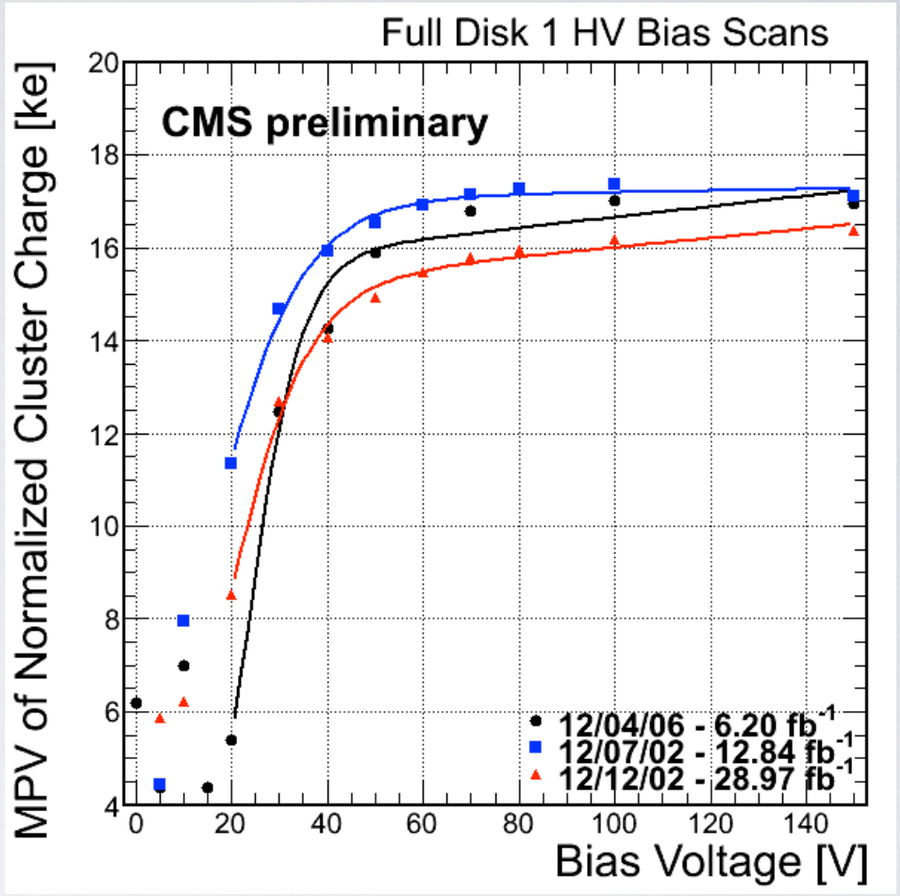

Layer 2 HV Bias Scans
CMS preliminary
Hit Finding Efficiency
Bias Voltage [V]
11/08/03 - 2.08 fb-1
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1
13/01/21 - 29.48 fb-1

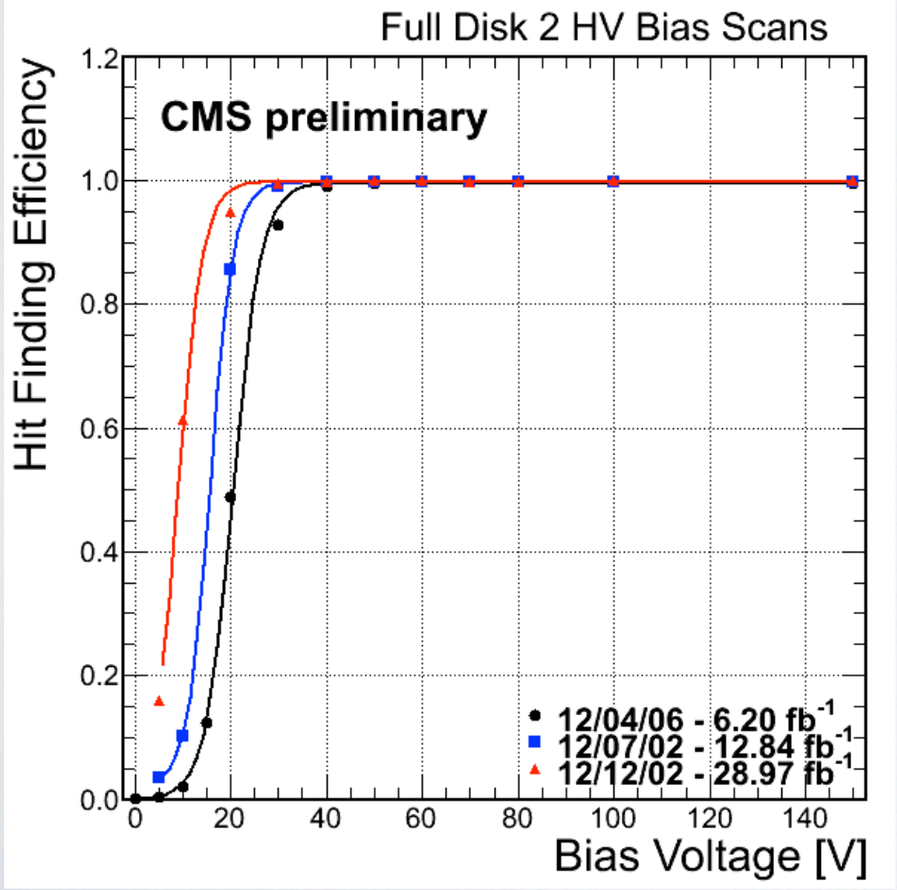

Layer 2 HV Bias Scans
CMS preliminary
MPV of Normalized Cluster Charge [ke]
Bias Voltage [V]
11/08/03 - 2.08 fb-1
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1
13/01/21 - 29.48 fb-1

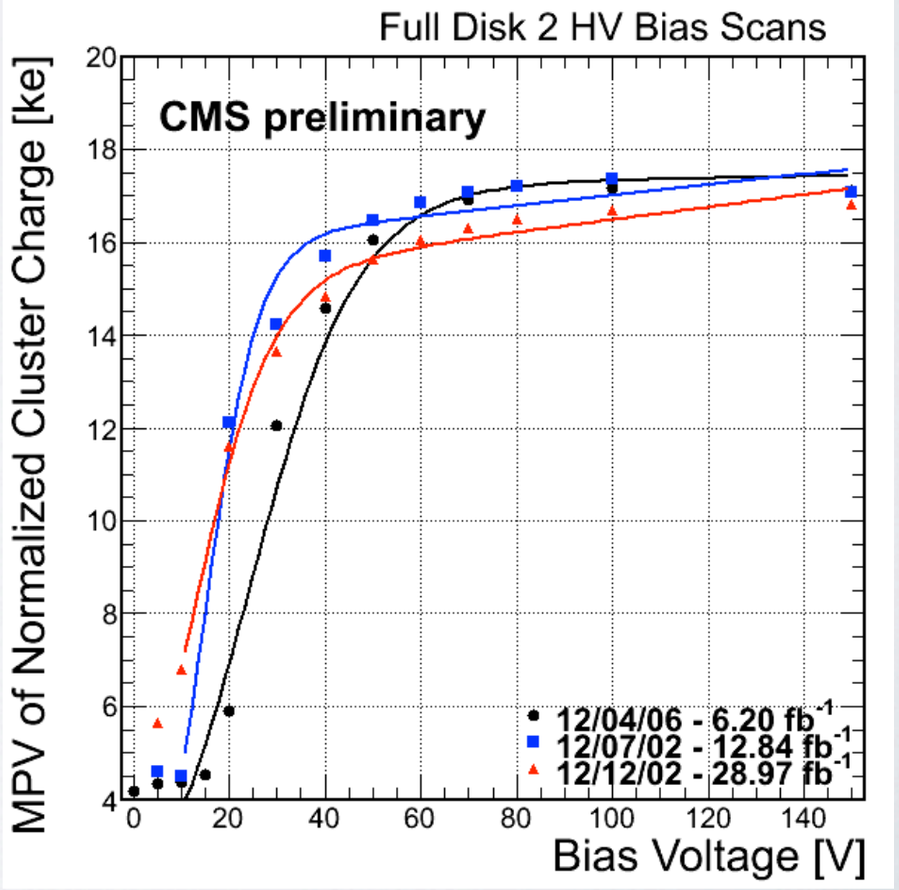

Layer 3 HV Bias Scans
CMS preliminary
Hit Finding Efficiency
Bias Voltage [V]
10/04/05 - 0.00 fb-1
10/10/28 - 0.04 fb-1
11/03/18 - 0.05 fb-1
11/07/28 - 1.82 fb-1
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1
13/01/21 - 29.48 fb-1


Layer 3 HV Bias Scans
CMS preliminary
MPV of Normalized Cluster Charge [ke]
Bias Voltage [V]
10/04/05 - 0.00 fb-1
10/10/28 - 0.04 fb-1
11/03/18 - 0.05 fb-1
11/07/28 - 1.82 fb-1
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1
13/01/21 - 29.48 fb-1

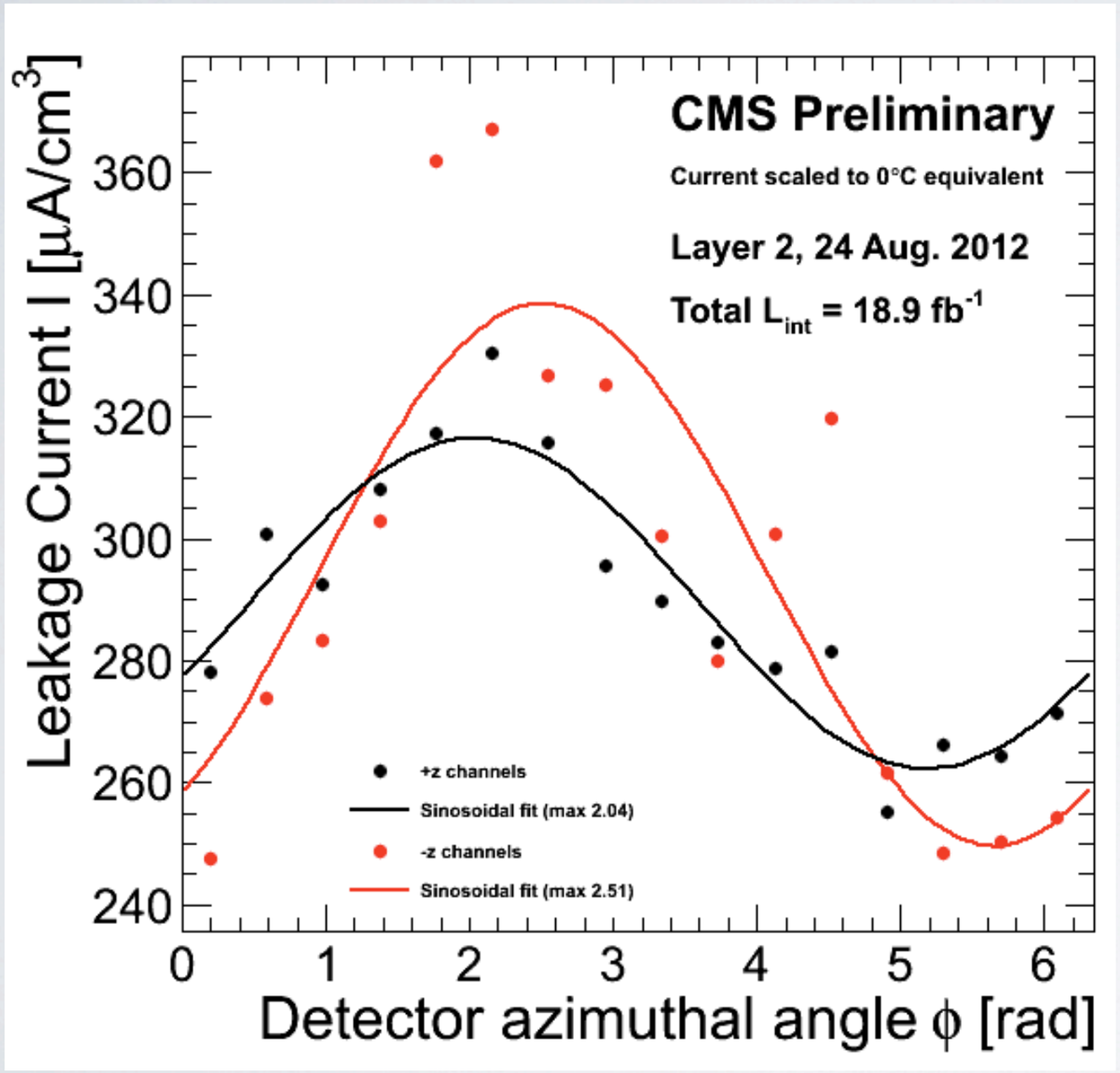

Full Disk 1 HV Bias Scans
CMS preliminary
Hit Finding Efficiency
Bias Voltage [V]
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1

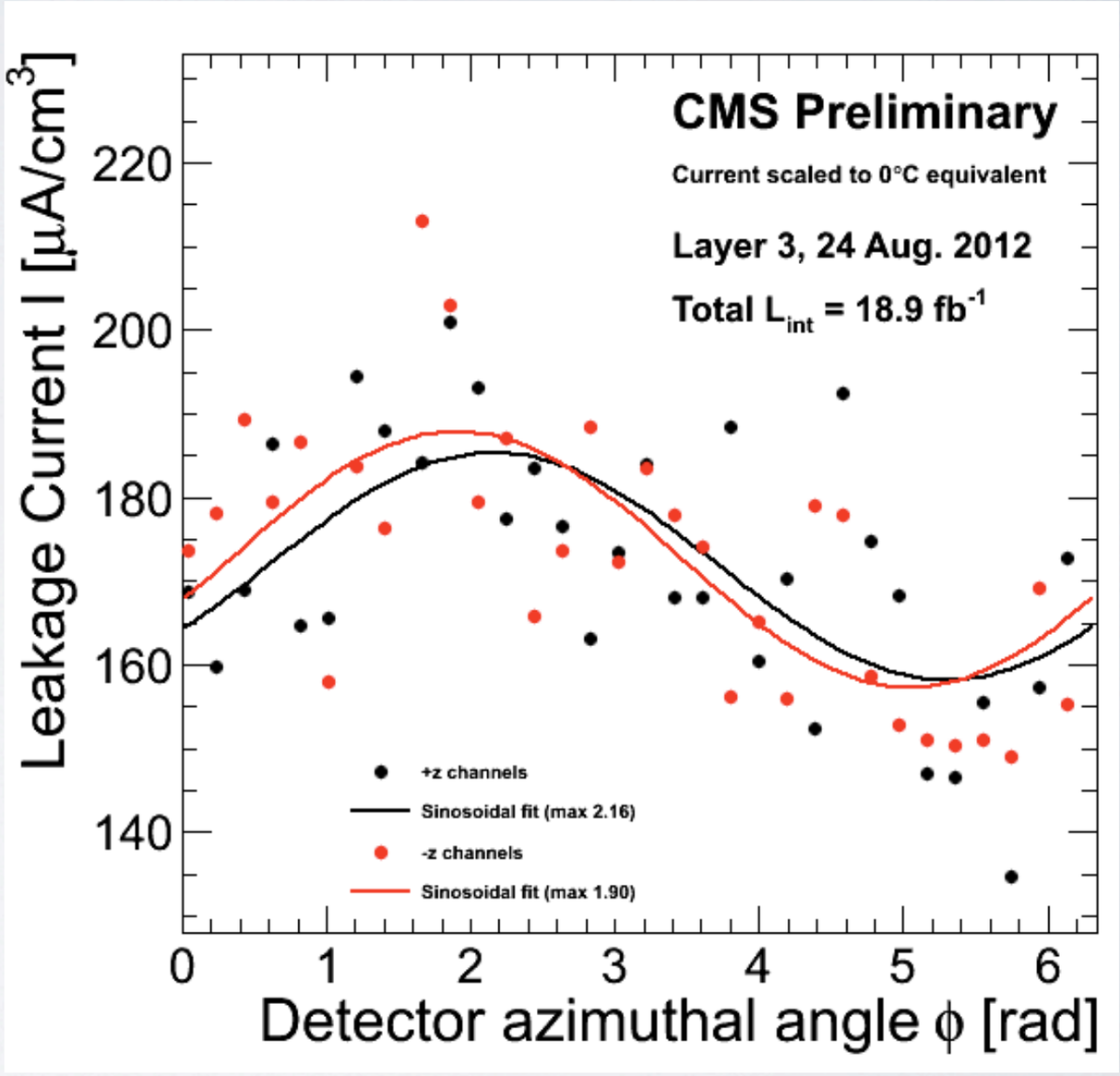

Full Disk 1 HV Bias Scans
CMS preliminary
MPV of Normalized Cluster Charge [ke]
Bias Voltage [V]
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1


Full Disk 2 HV Bias Scans
CMS preliminary
Hit Finding Efficiency
Bias Voltage [V]
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1


Full Disk 2 HV Bias Scans
CMS preliminary
MPV of Normalized Cluster Charge [ke]
Bias Voltage [V]
12/04/06 - 6.20 fb-1
12/07/02 - 12.84 fb-1
12/12/02 - 28.97 fb-1

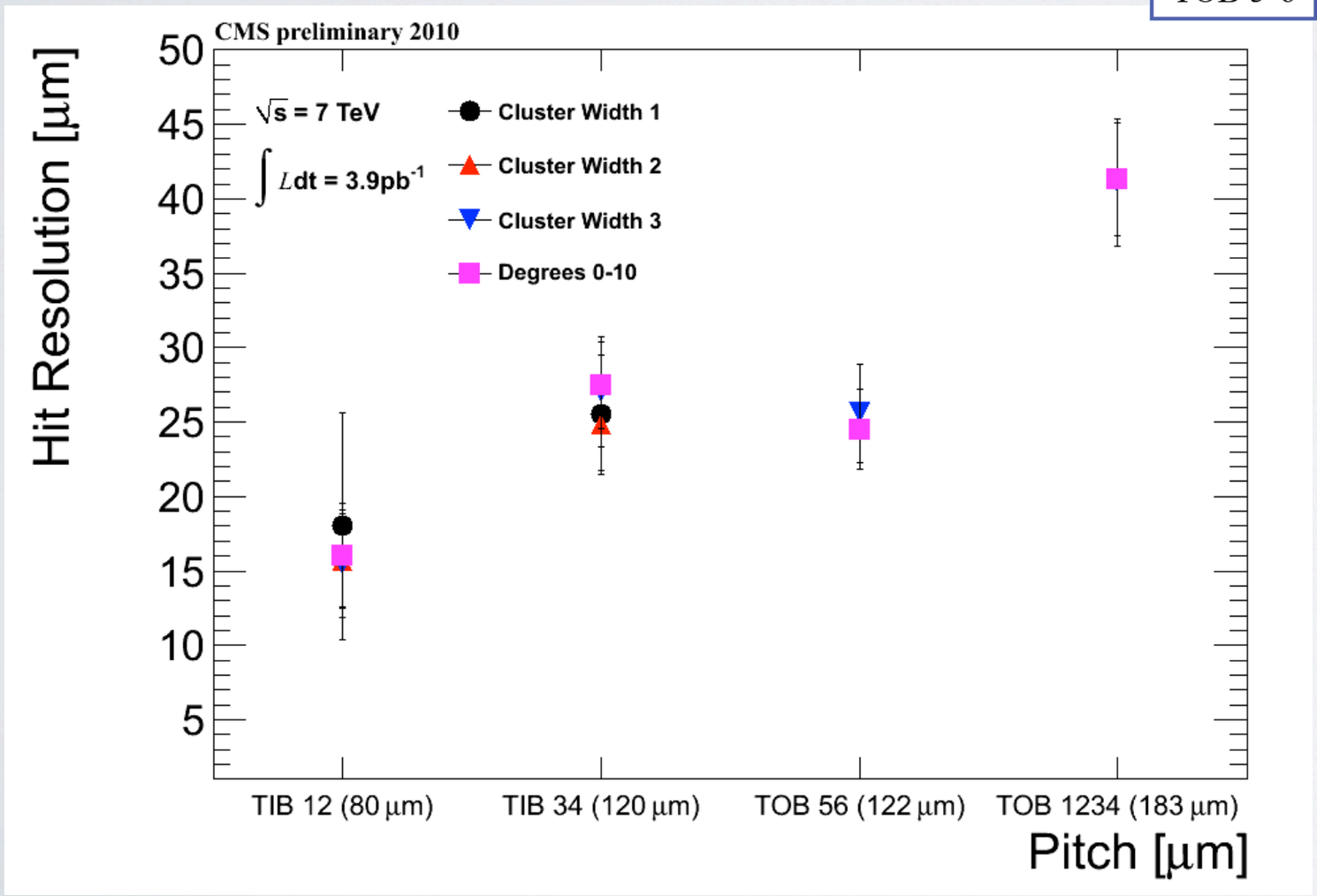
LEAKAGE CURRENT





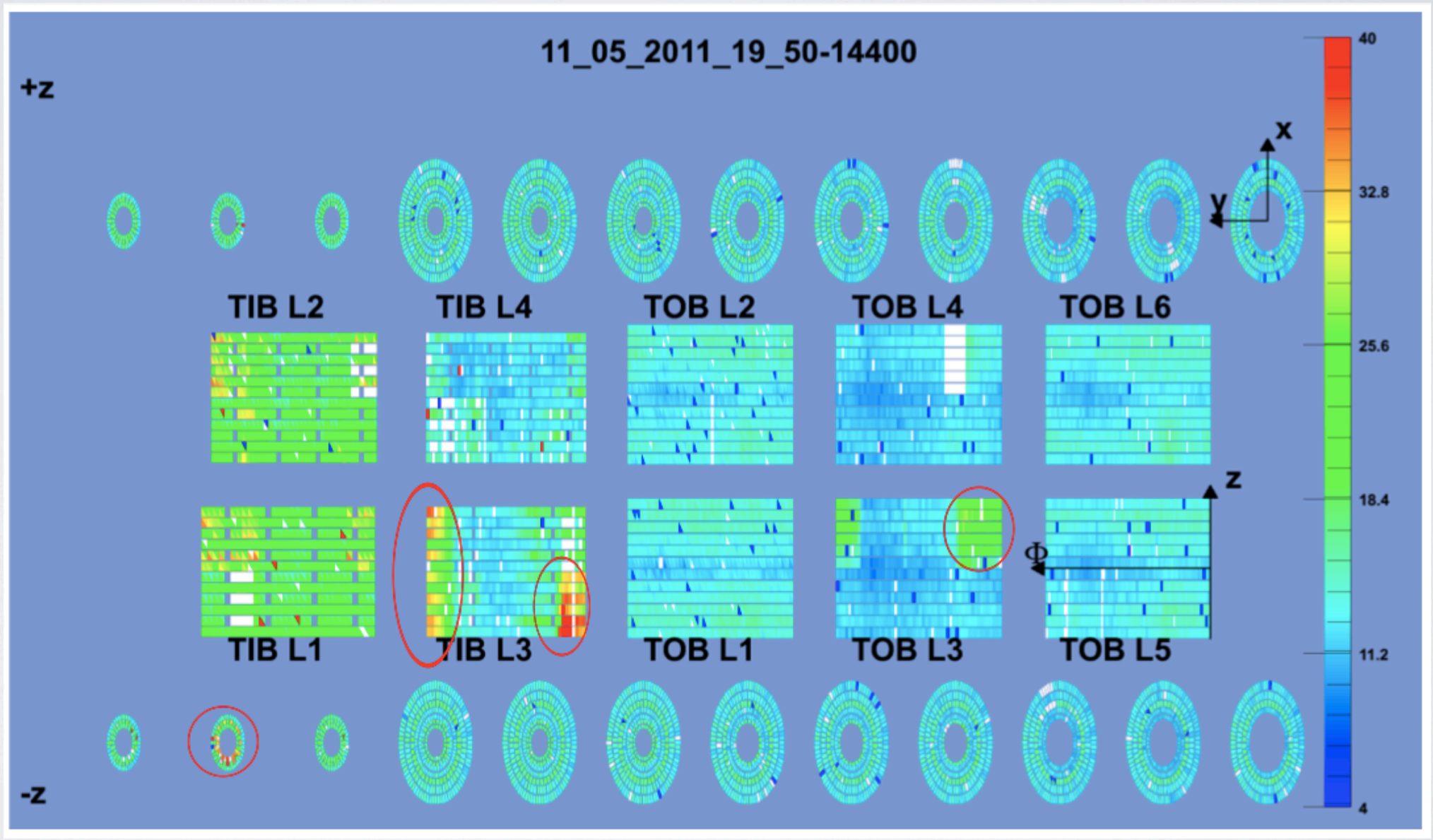
STRIP RESOLUTION

Sensor Layer	Pitch [µm]	Resolution [µm] vs. cluster size			
		1	2	3	4
TIB 1-2	80	15.0±4.6	14.0±3.6	13.7±4.2	
TIB 3-4	120	24.1±5.2	24.7±4.1	22.1±7.0	
TOB 1-4	183		29.2±9.2	36.1±5.1	24.5±10.3
TOB 5-6	122		12.6±8.3	22.0±4.6	16.3±4.6



STRIP TEMPERATURES

- Not all the strip detector regions have direct cooling



Pixel operates at 17˚C in 2011 and 10 ˚C in 2012