CMS Upgrades with emphasis on Pixel Upgrade

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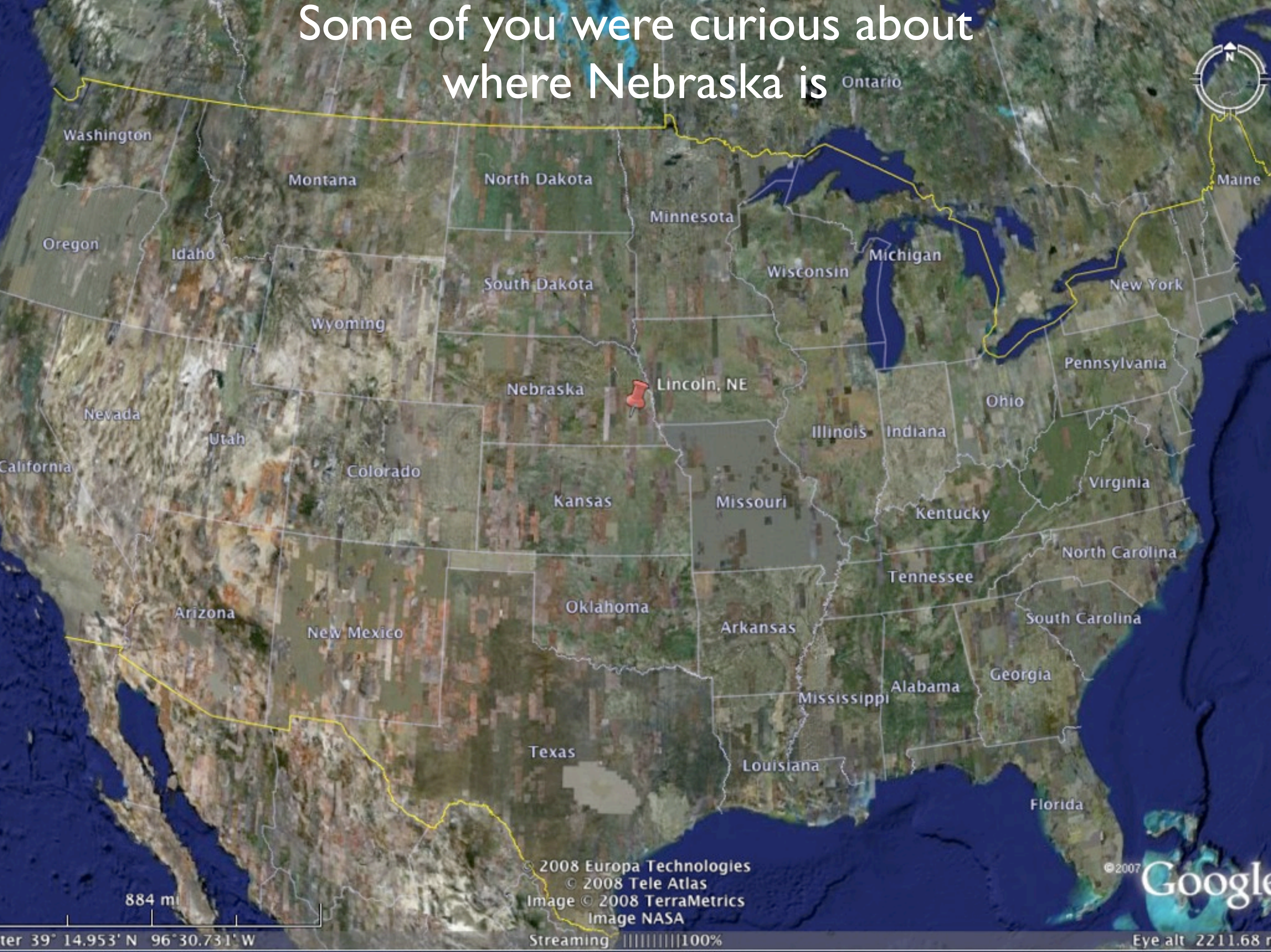
INSTR14 Conference, Novosibirsk

Some of you were curious about where Nebraska is



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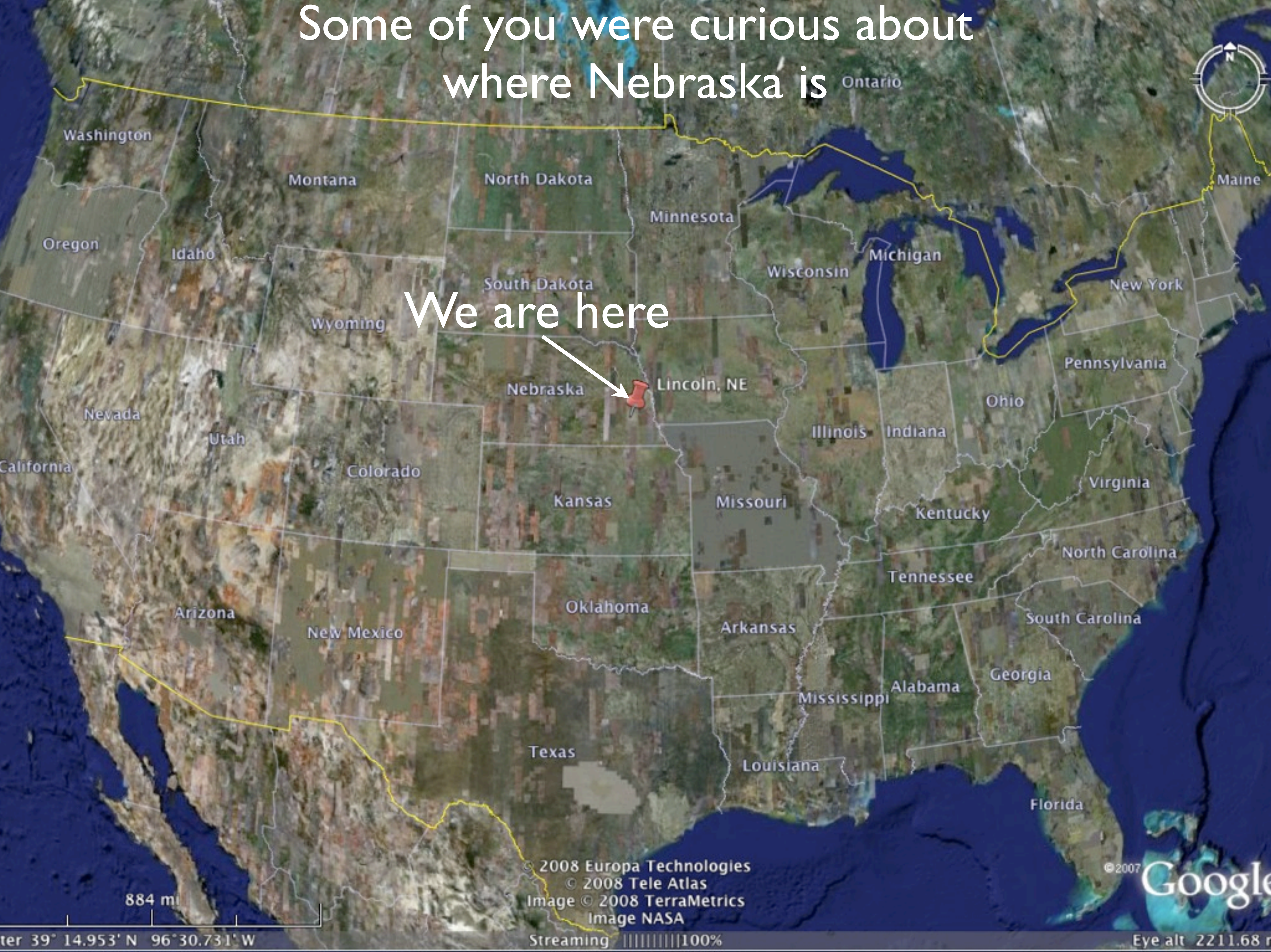

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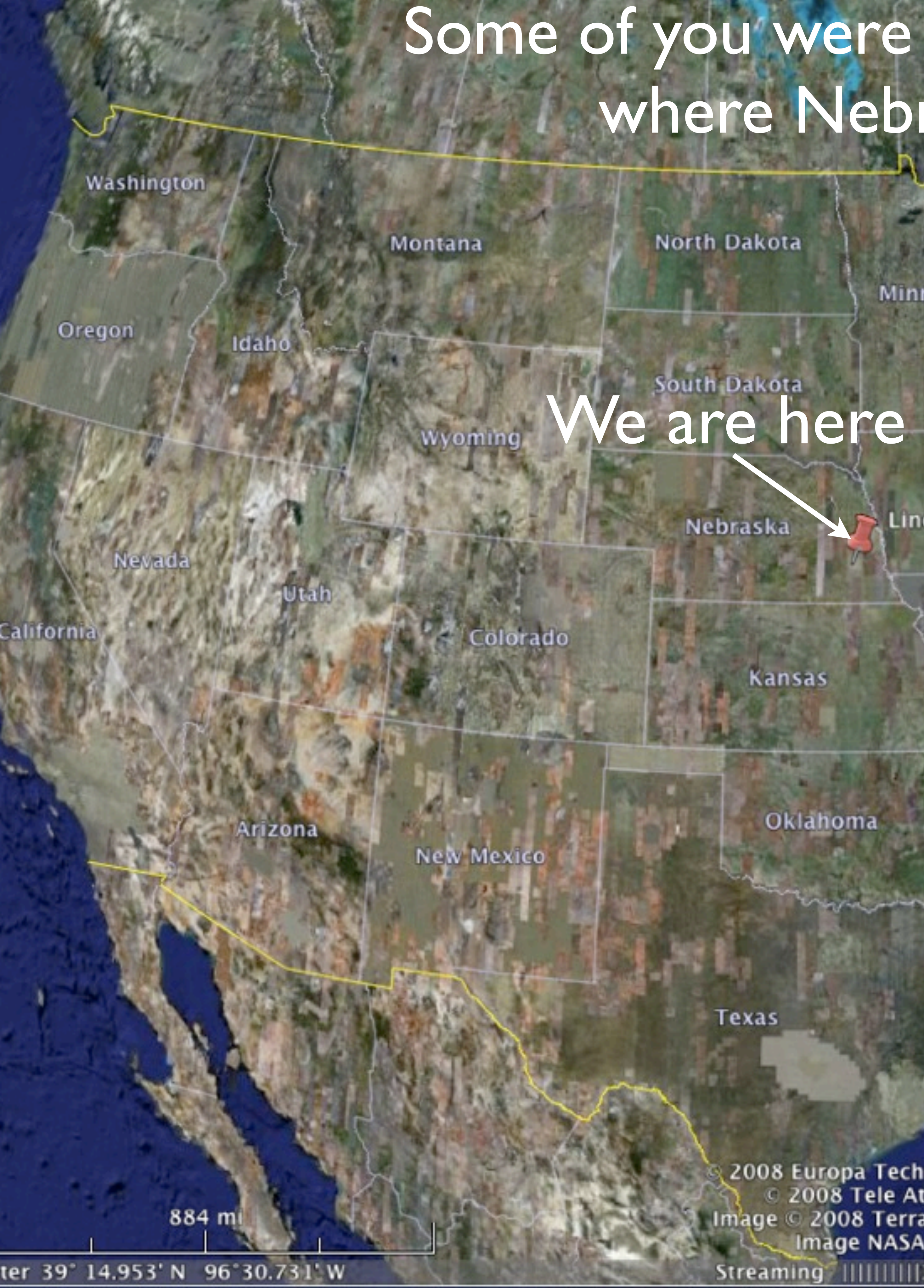
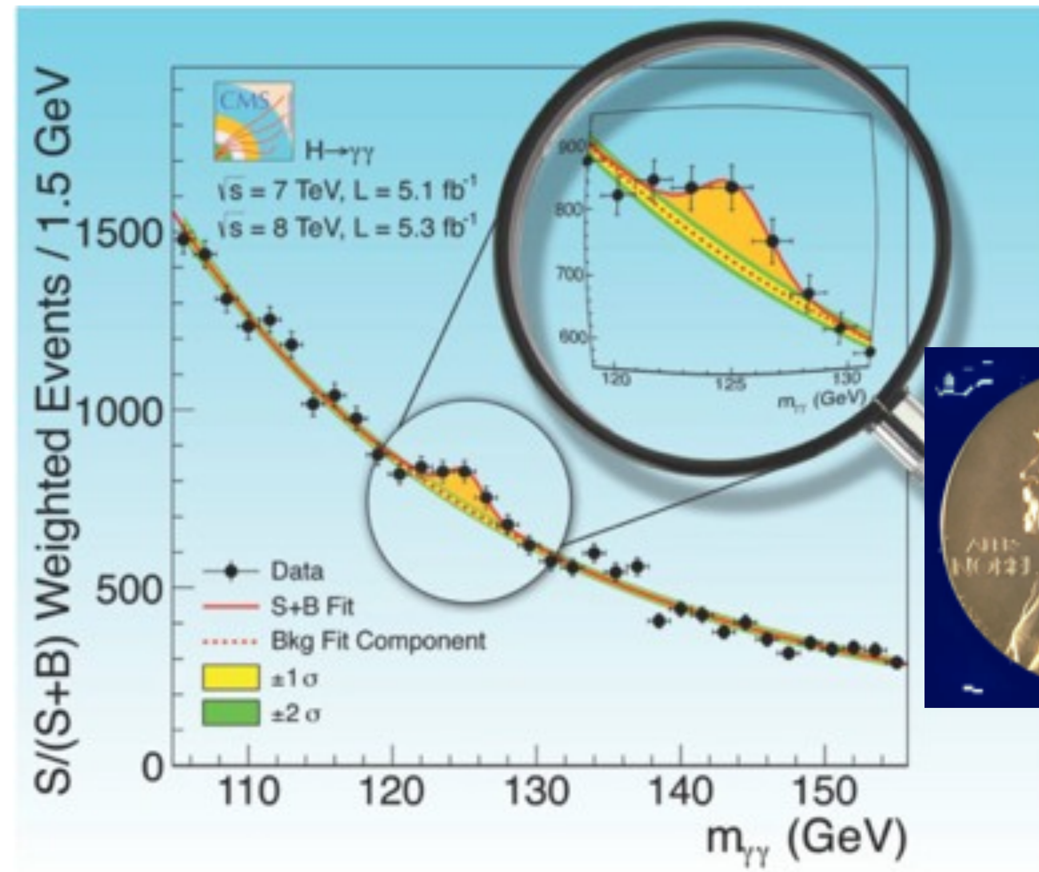


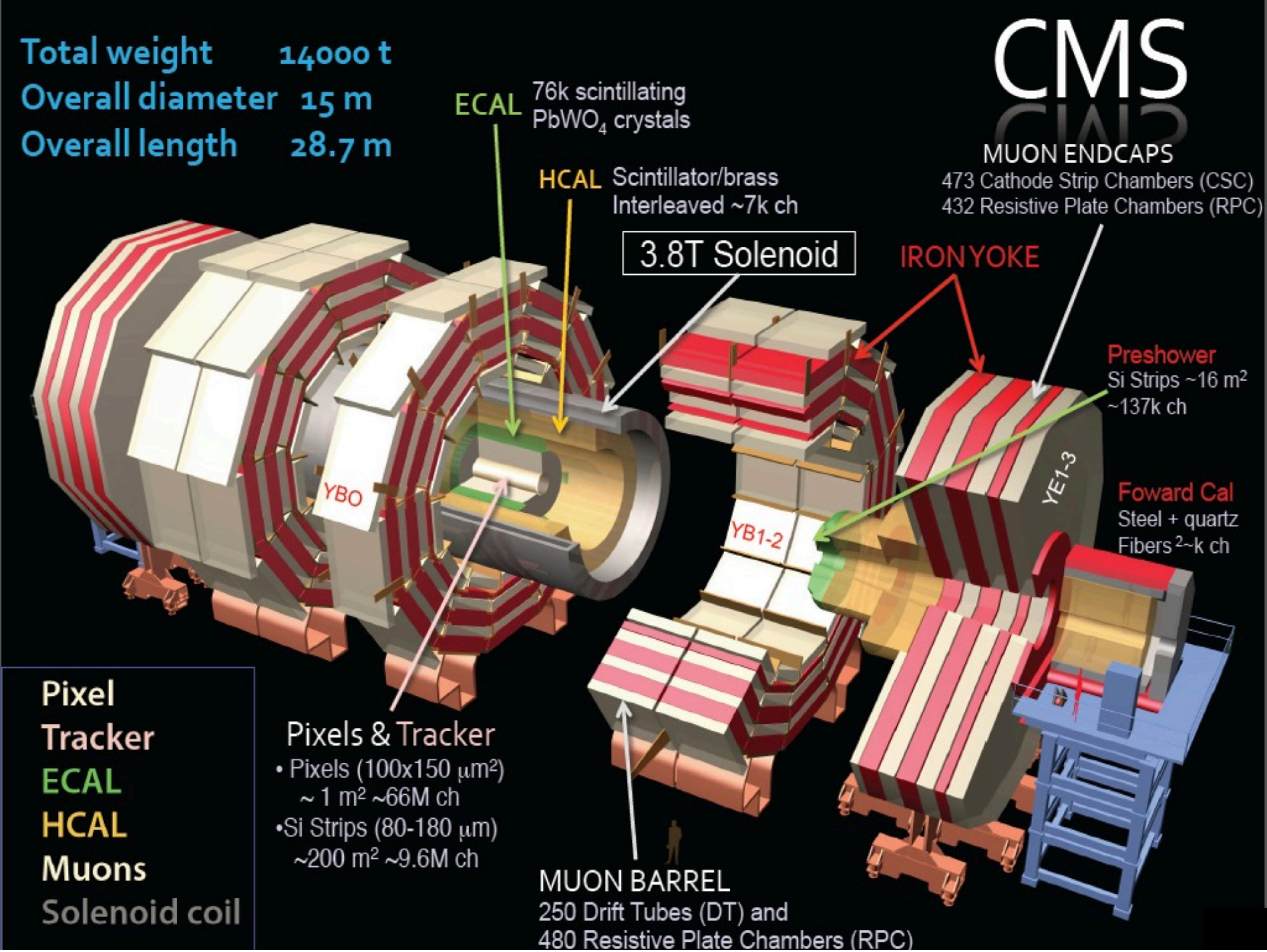
Physics and Project Overview

- LHC: $\sqrt{s}$=7,8 TeV found a light Higgs
- $\sqrt{s}$=13,14 TeV finds?
  - Detailed properties of the Higgs.
  - Compatible with SM?
  - What makes Higgs so light?
- Challenge: Higher L_{int} ,L_{inst}
  - "Pileup" will at least double from 25 to 50+
  - Expect 400/fb by LS2

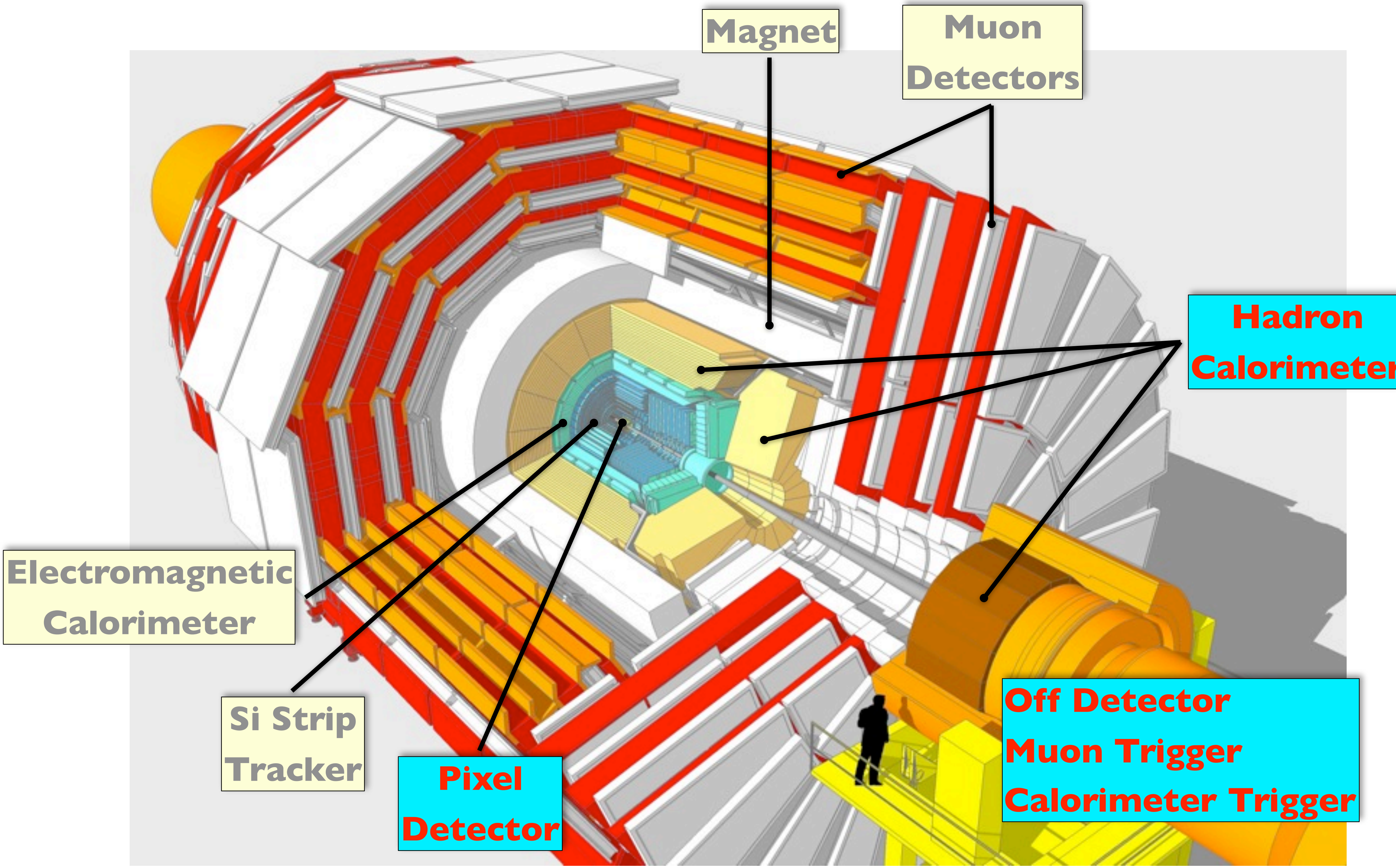


Basic Goal of the CMS Phase-1 Upgrade

- Preserve the ability to reconstruct all the Standard Model objects and Missing Energy at higher luminosity than the original design
    - Achieve the same or better efficiency, resolution, trigger thresholds, and background rejection at 14 TeV with 50 or pile-up than at 8 TeV with less than 20 pile-up
- Evolutionary upgrades to existing detectors when access is possible:
    - Hadron Calorimeter
    - Pixel Detector
    - Level 1 Trigger


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m2
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers 2~k ch
YB0
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm2)
~ 1 m2 ~66M ch
•Si Strips (80-180 μm)
~200 m2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

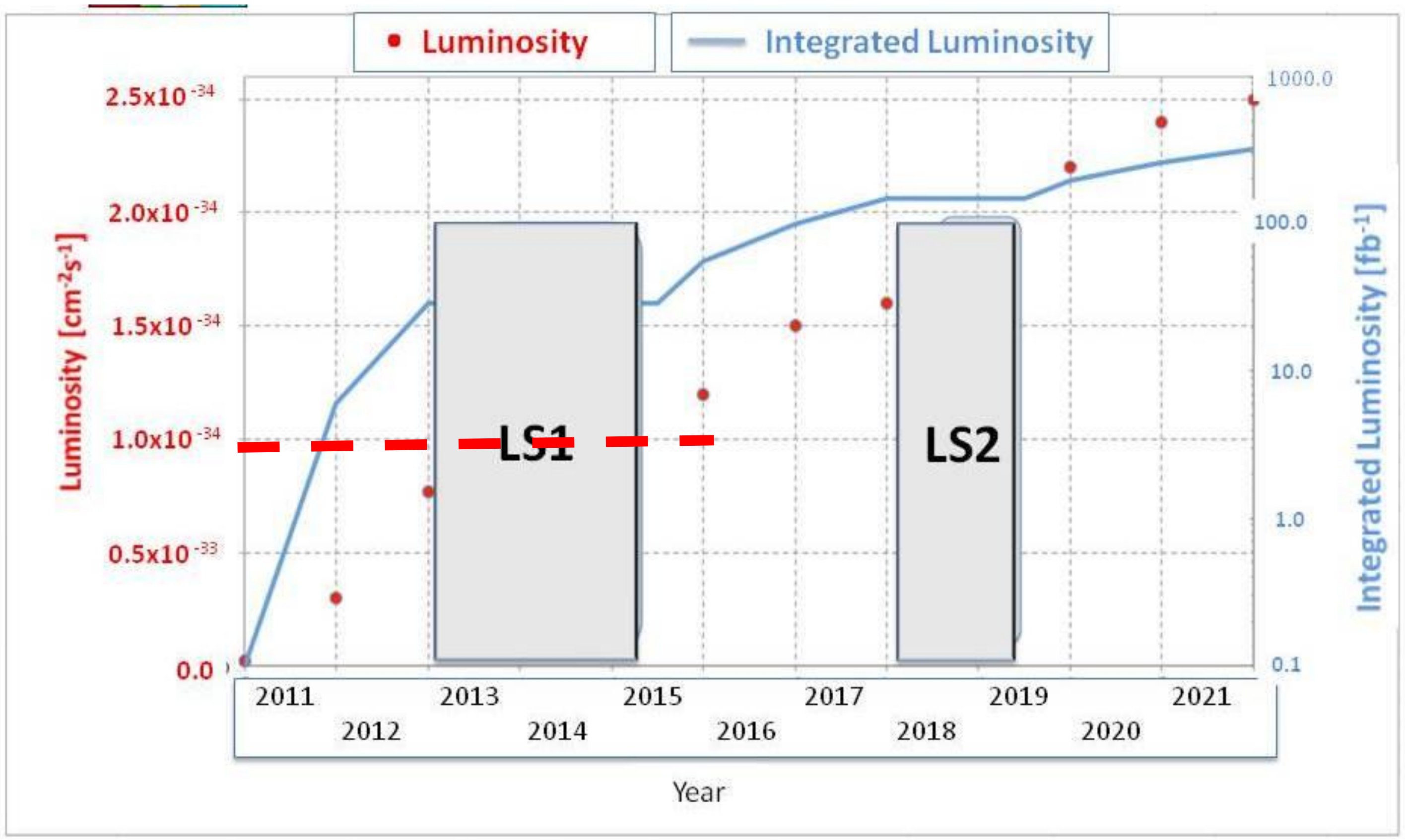
Scope of CMS Phase-1 Upgrade



Brief Description of the Phase-1Project

- Hadron Calorimeter (HCAL):
  - New "frontend" photosensors with higher gain allows longitudinal granularity and includes timing information to deal with the higher pileup.
  - Accompanying "backend" electronics, provides increased bandwidth to handle the resulting larger volume of information
- Pixel Tracker (PIX):
  - New 3 layer endcap detector, replacing current 2 layer one, new 4 layer barrel detector, replacing current 3 layer one, which improves tracking and vertexing, and decreases multiple scattering and conversion due to less mass in the tracking volume and mitigates data loss due to modern readout chip electronics.
- Level 1 Trigger (TRIG):
  - Conversion to modern electronics system (μTCA) with high bandwidth optical links and large FPGAs allowing more sophisticated algorithms to run on the expanded amount of data available the calorimeter and muon system.

LHC Performance & Schedules

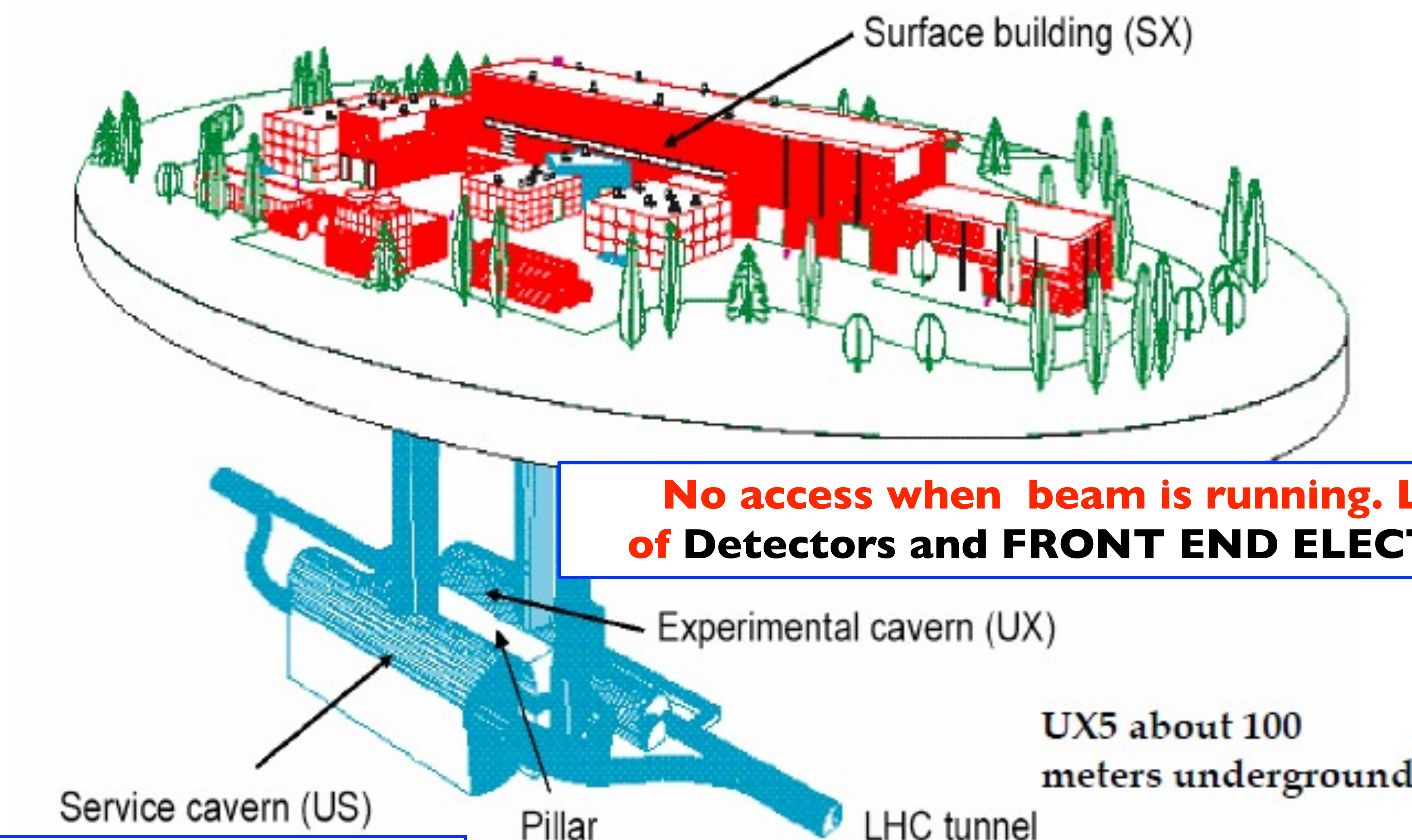


Conditions
- ~ 2×10^{34} by LS2, higher after LS2
- ~ $200 fb^{-1}$ by LS2, ~ $500 fb^{-1}$ by LS3
- 25ns is the plan, but … easier and more reliable at 50ns?
- Integrated luminosity is the goal

For the Upgrades
- "Baseline" PU~50, study ~100
- Lumi-leveling will come into play

	Number of bunches	β* [m]	Half X-angle [μrad]	Ib SPS	Emit SPS [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~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	?

CMS at LHC Point 5



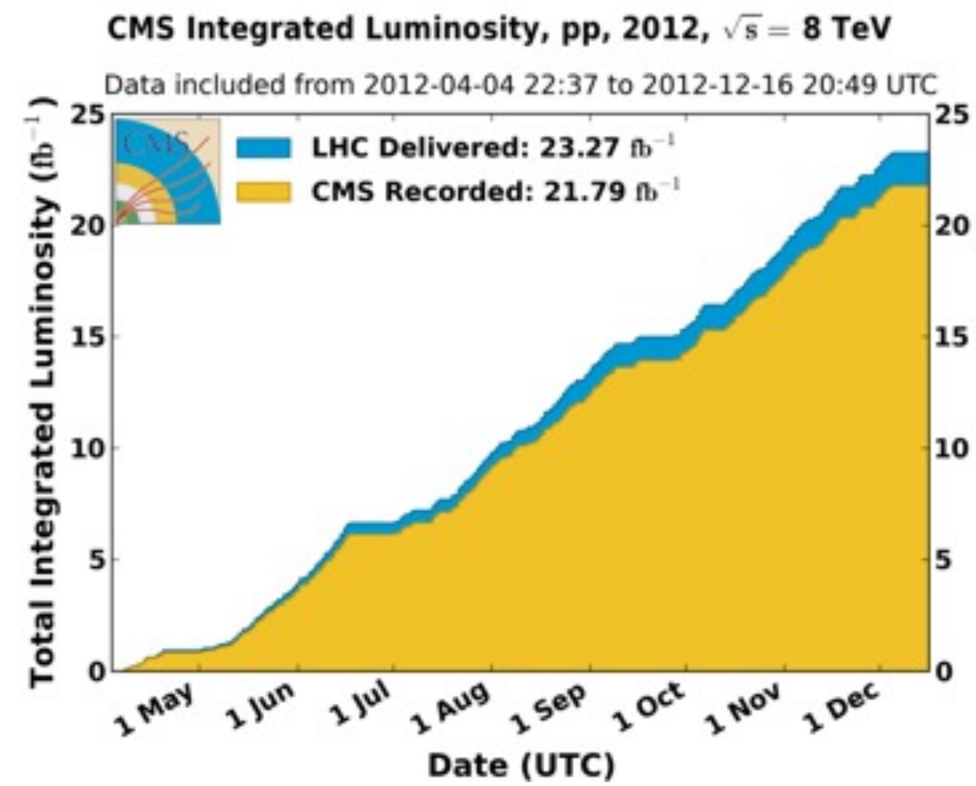
No access when beam is running. Location of Detectors and FRONT END ELECTRONICS

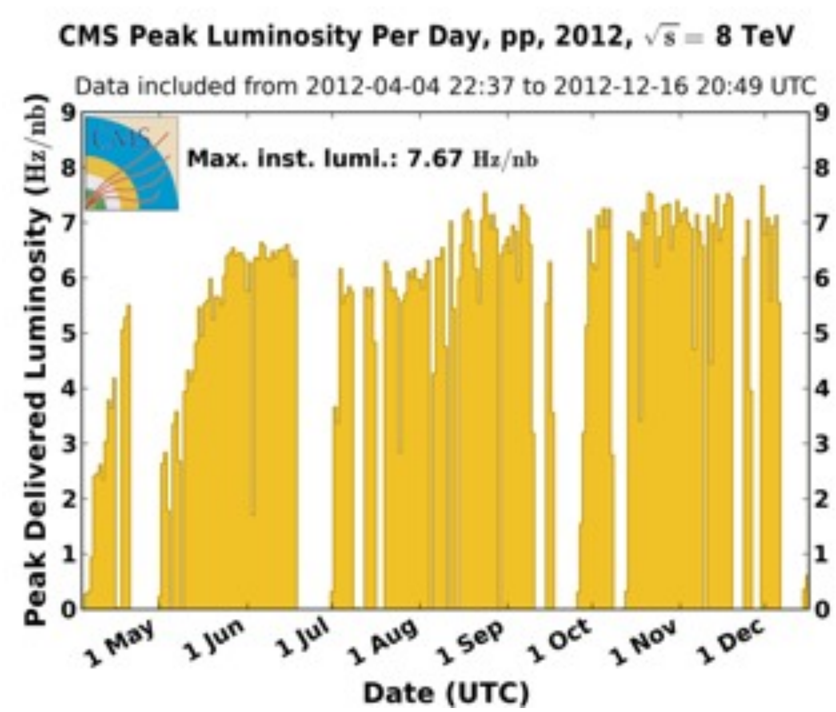
Can be accessed when beam is running. Location of BACKEND ELECTRONICS and TRIGGER

LHC Luminosity Performance

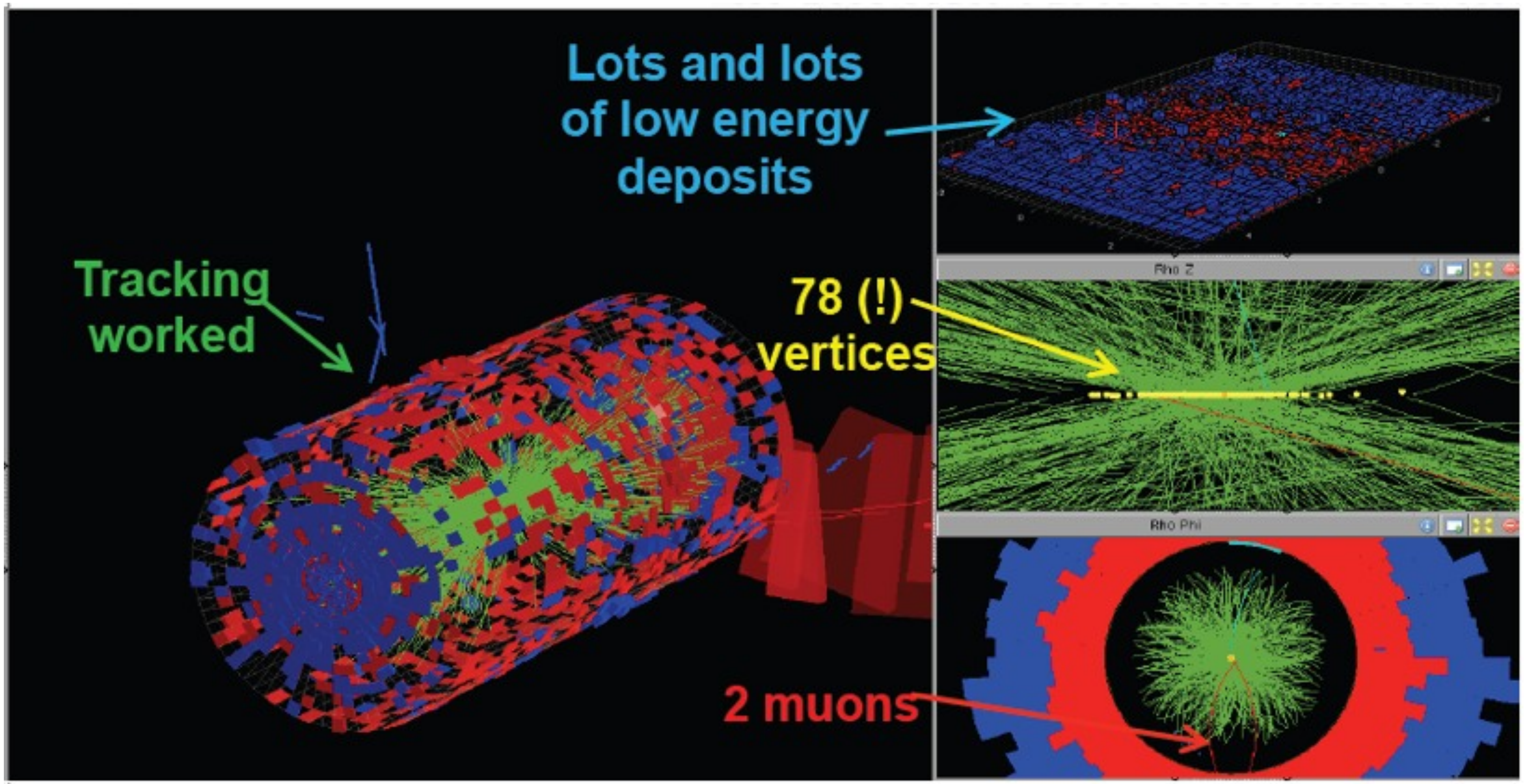
- LHC delivered >23 fb^{-1}
- Peak Luminosity: 7.67×10^{33} $cm^{-2}s^{-1}$
  - above "LHC energy-scaled" design luminosity already.
- Bunch spacing 50 ns (design is 25ns)
- But, pileup at beginning of store up to 34
  - LHC operated well-above design pileup.

The swift achievement of high luminosity and the excellent understanding of the machine make the projections of very high luminosity in the next few years quite credible





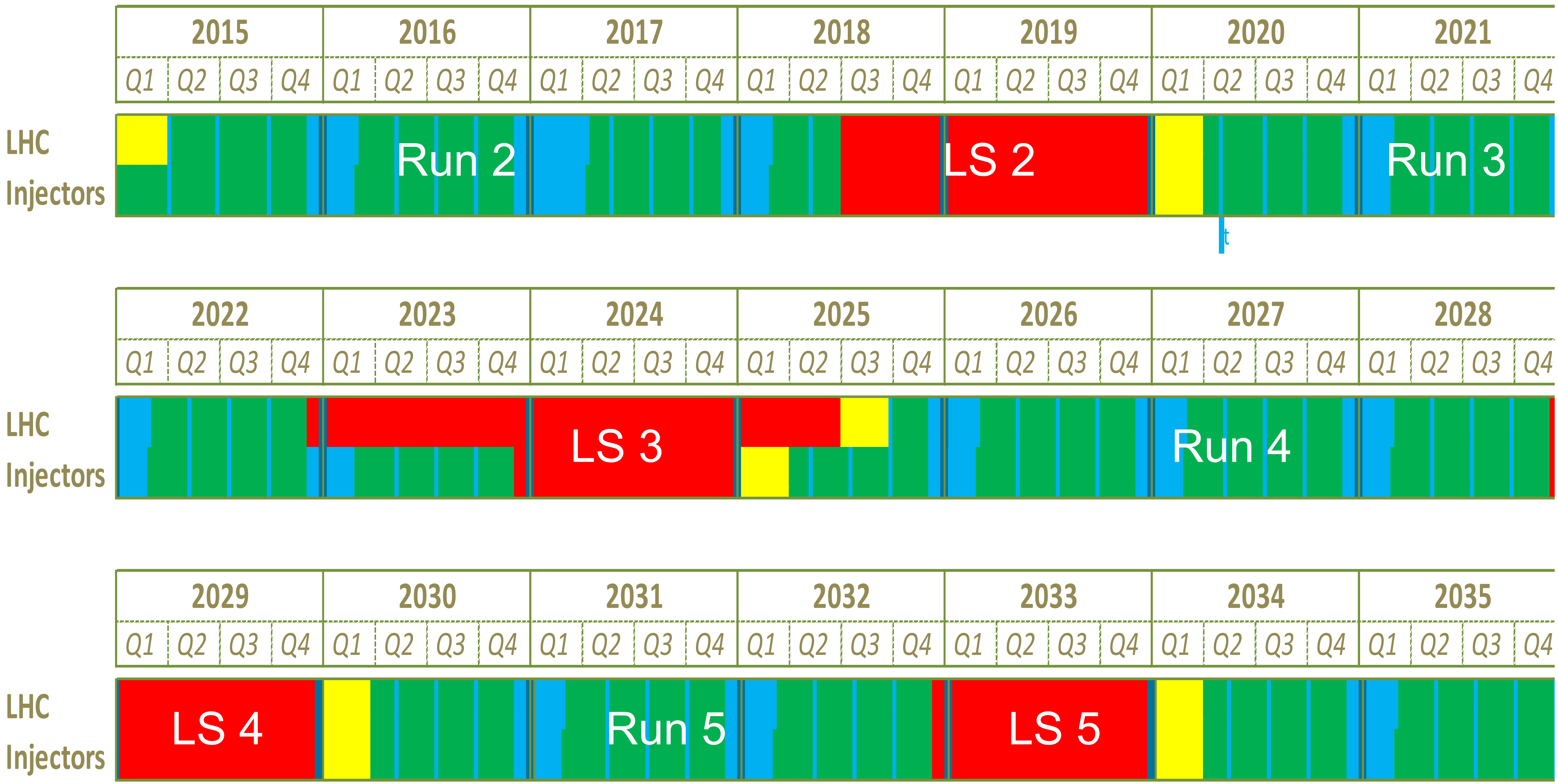
The Challenge



- The CMS Upgrade is LUMINOSITY DRIVEN
  - Pileup mitigation is the biggest issue
  - Single event upsets are also a problem
  - Radiation damage is an issue for detector longevity
- If overall performance can be improved as we deal with these, so much the better

LHC schedule beyond LS1

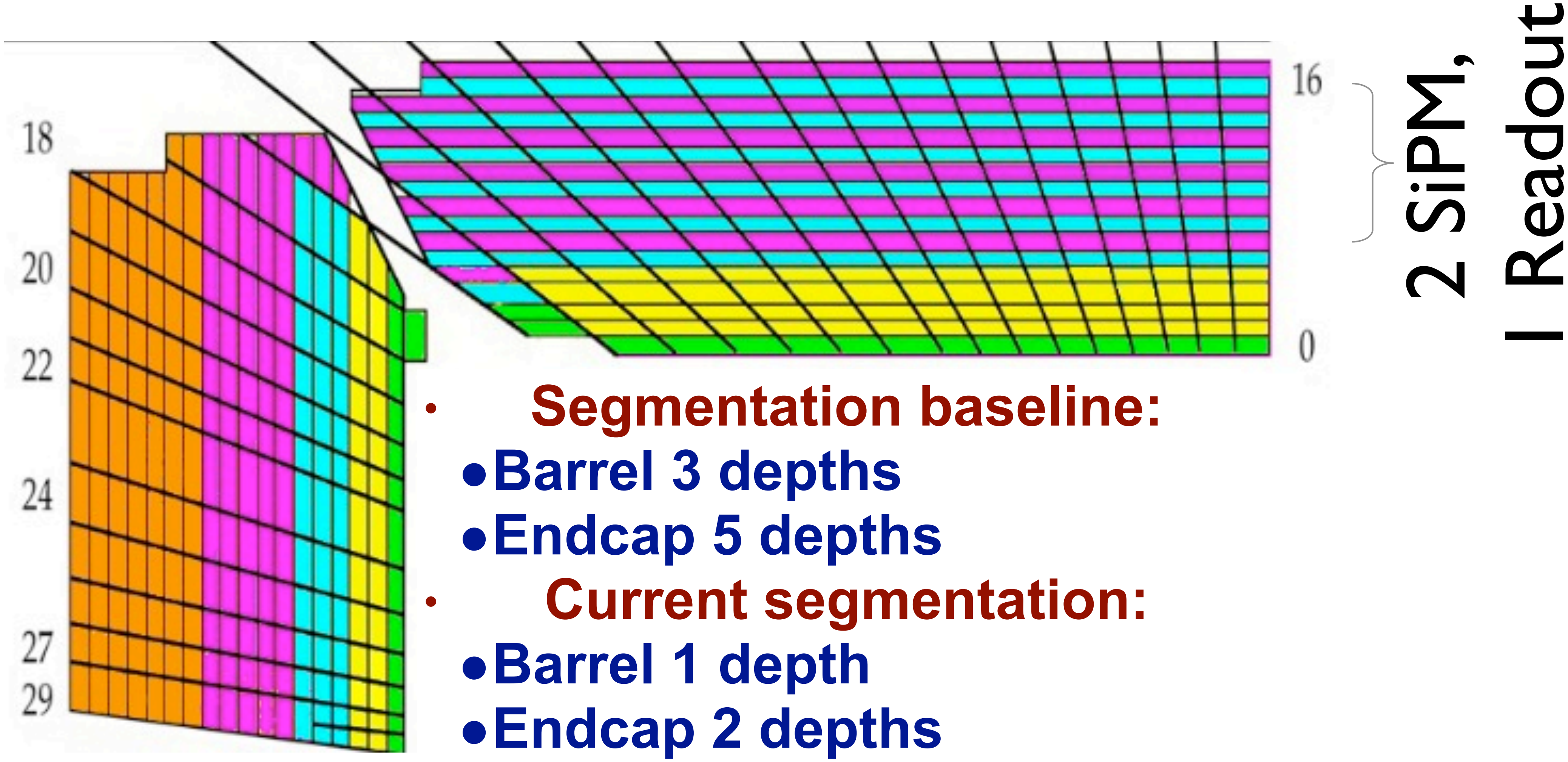
Only EYETS (19 weeks)   (no Linac4 connection during Run2)
LS2   starting in 2018 (July)   18 months + 3months BC (Beam Commissioning)
LS3   LHC: starting in 2023 =>   30 months + 3 BC
      injectors: in 2024   =>   13 months + 3 BC



Installation Opportunities

- **CMS must return from each shutdown with upgrades needed to cope with the most challenging conditions foreseen for the next operating period**
- The installation schedule depends on access to the Collision Hall
  - Opening/Closing CMS to access the detectors inside the solenoid takes 2 months
    - A **Long Shutdown (LS)** is ~ 1 year or more provides time for installation
    - A **Technical Stop (TS)** is ~ 3 months (e.g. winter shutdown - YETS) so available work time is at best 1 month
    - **An Extended Technical Stop (ETS)** is ~5-6 months (e.g. an extended winter shutdown) gives time to do some installation
      - **This is proposed for winter 2016/2017 since CMS believes that the pixel upgrade will be needed before LS2**
- Trigger electronics work in the Underground Service Cavern (USC) can take place during running but must not impact operations
- Phase-2 of CMS upgrades will take place after LS3 and will be **much** more extensive than the Phase-1 upgrades

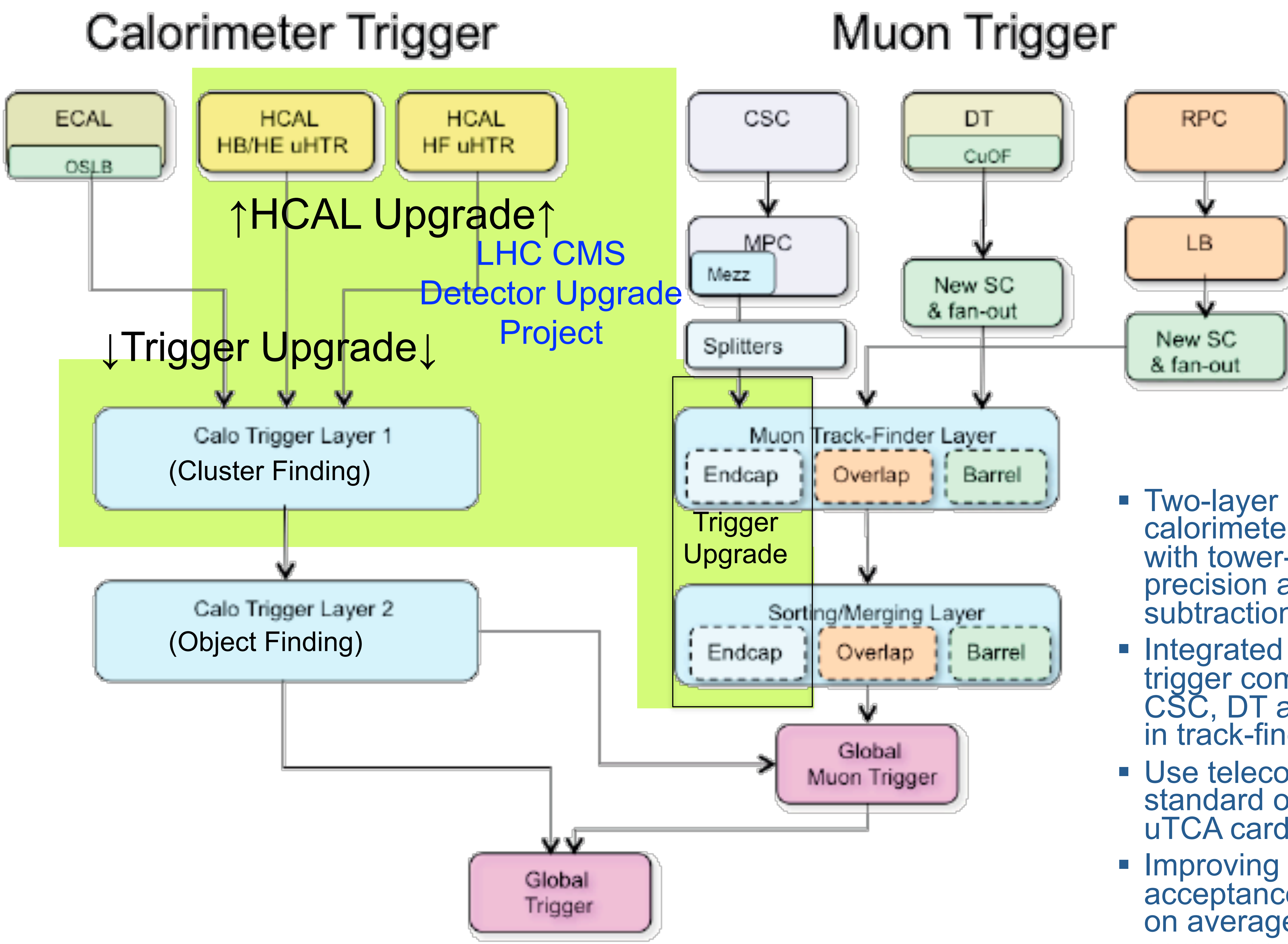
HCAL Phase-1 Upgrade



- **Segmentation baseline:**
  - **Barrel 3 depths**
  - **Endcap 5 depths**
- **Current segmentation:**
  - **Barrel 1 depth**
  - **Endcap 2 depths**

- Increased gain of SiPMs and high data link volumes allow for increased depth segmentation of the calorimeter
  - Amount of segmentation limited by power/ cooling/volume
- Radiation damage is strongly depth-dependent, requiring depth segmentation for correction without introducing large constant term

Trigger Phase-1 Upgrade



- Two-layer calorimeter trigger with tower-level precision and PU subtraction
- Integrated muon trigger combining all CSC, DT and RPCs in track-finding
- Use telecom standard optical fiber uTCA cards
- Improving trigger acceptances by 40% on average (x2 in some cases)

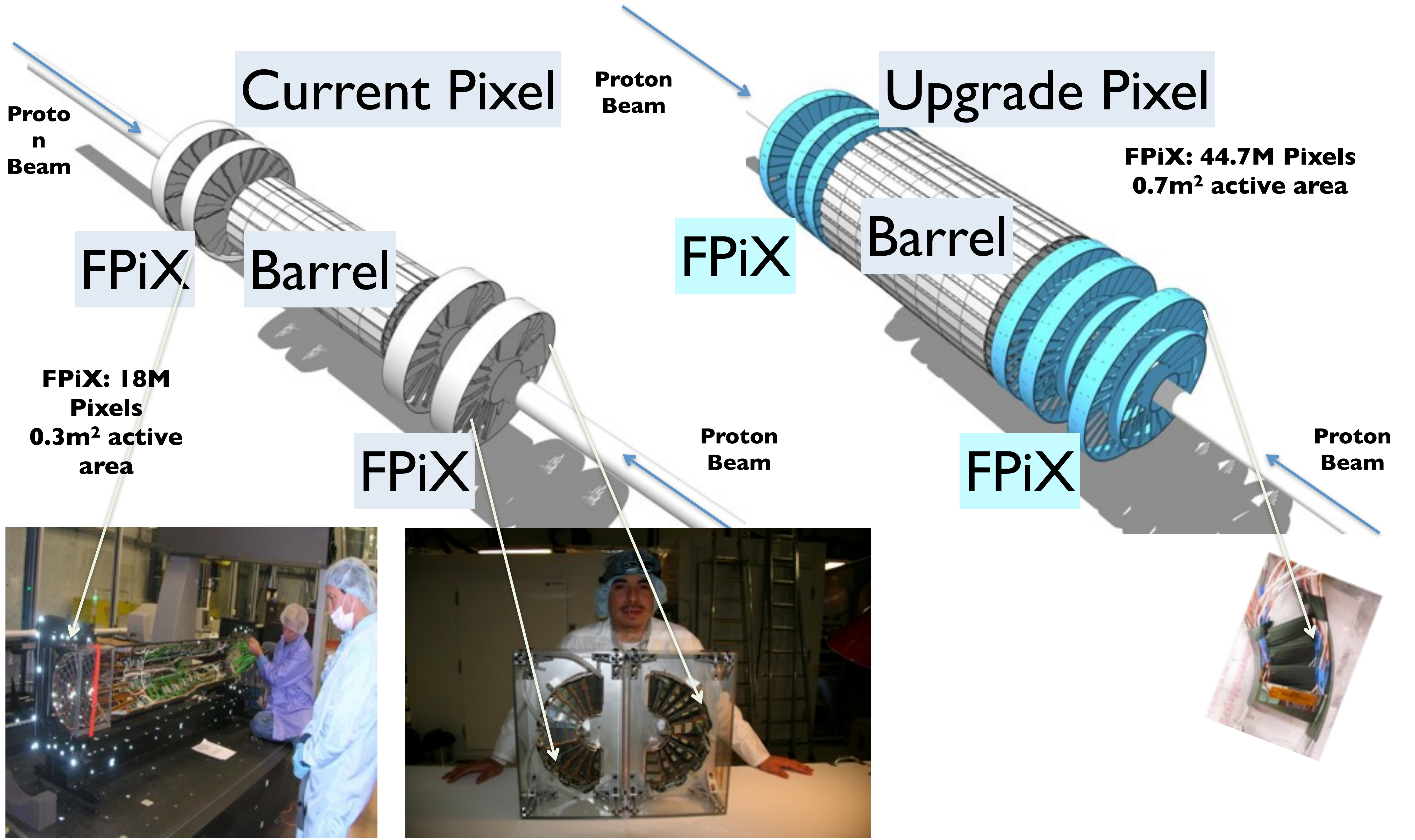
Pixel Phase-1 Upgrade

- There are later talks by my colleagues on other upgrades of CMS
- I will now finish by focusing on the Phase-1 pixel detector upgrade which is currently underway with the goal to install a new detector in the EYTS of 2016/2017

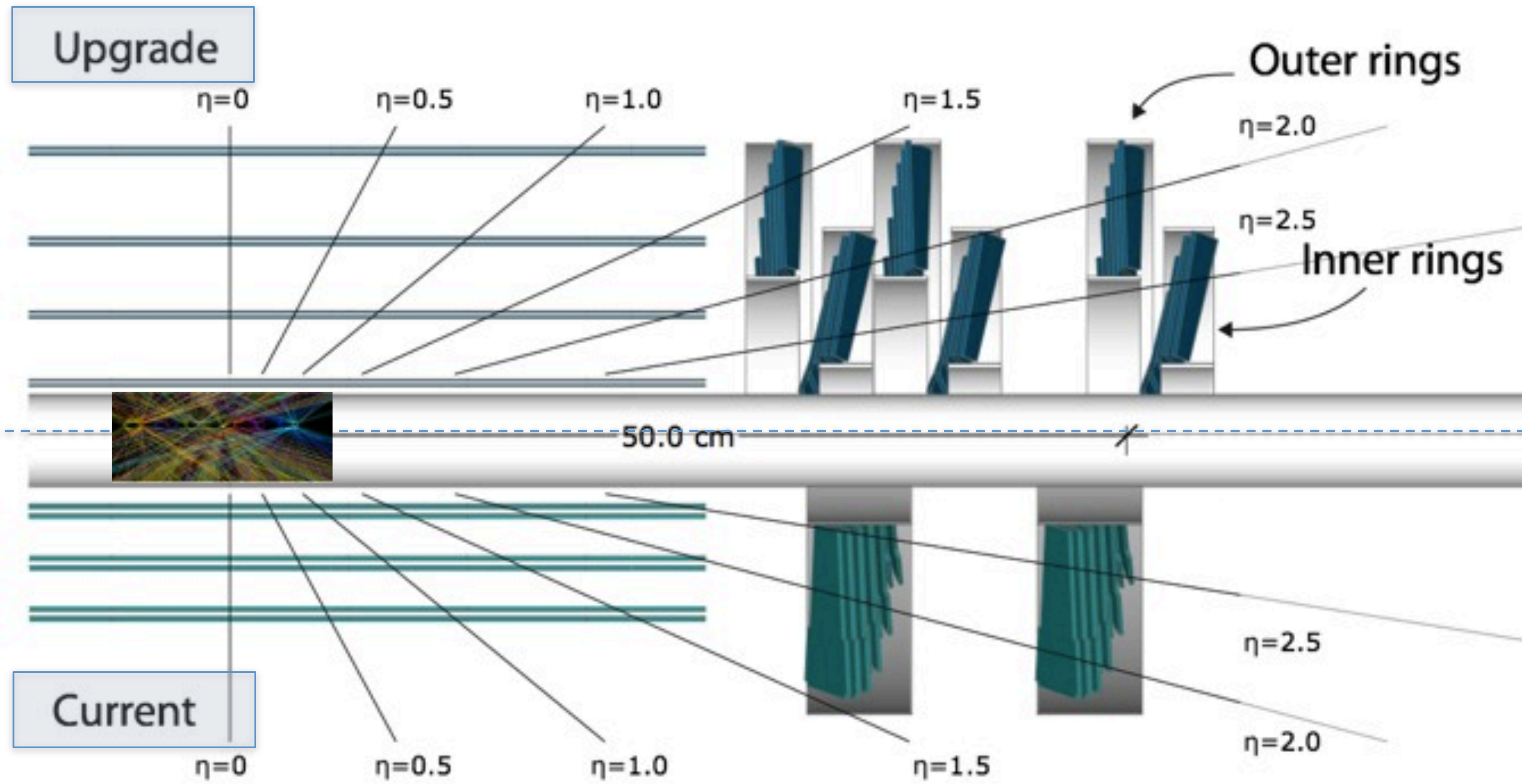
The New Pixel Detector

- Low mass, digital readout robust in high pileup, 4 barrel layers, 3 forward/backward disks, "quickly" installable
- The new detector mitigates the risks and losses we would have if we leave the current detector in until LS2 or beyond
- Maximizes physics potential, especially if we can install it as early as possible when ready, as we collect a large fraction of our integrated luminosity after LS1

Phase-1 Upgrade Pixels



Requirements



<u>Pixel Upgrade:</u>

- Baseline L = 2×10^{34} cm^{-2}sec^{-1} & 25ns → 50 pileup **(50PU)**
- Tolerate L = 2×10^{34} cm^{-2}sec^{-1} & **50ns** → 100 pileup **(100PU)**
- **Survive Integrated Luminosity of 500fb^{-1}**
- (Evolutionary upgrade with) **minimal disruption of data taking**
- **Same detector concept**: higher rate readout, data link & DAQ w/ less material forward
- **Robustify tracking** : 4 hit coverage;)

System Parameters: Present & Upgrade

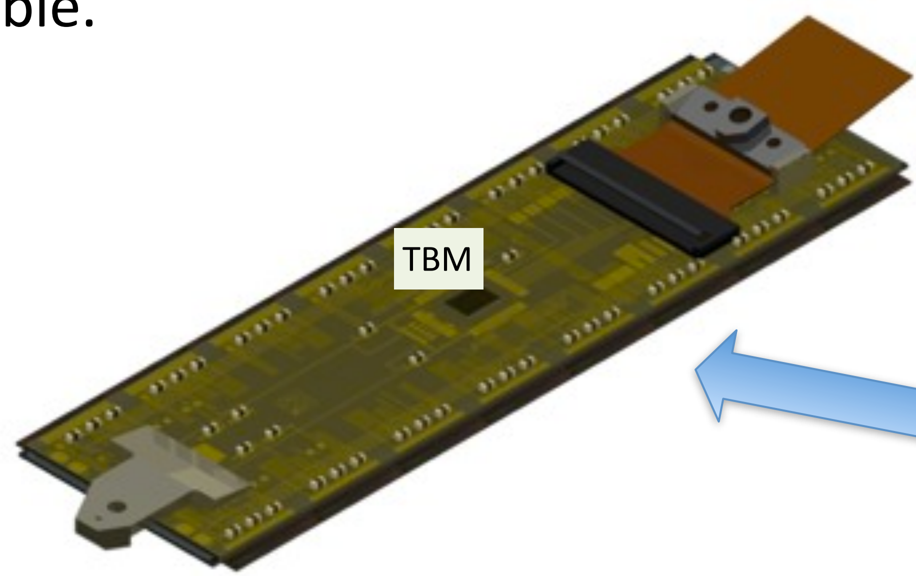
Parameter of Pixel System	***Present***	***Upgrade***
# layers (tracking points)	3	**4**
beam pipe radius (outer)	29.8 mm	22.5 mm (LS1)
innermost Disk (layer) radius	6.0 (4.4) cm	4.5 (2.95) cm
outermost Disk (layer) layer radius	14.0 (10.2) cm	16.1 (16.0) cm
pixel size (r-phi x z)	100μ x 150μ	100μ x 150μ
In-time pixel threshold	3400 e	1800 e
pixel resolution (r-phi x z)	13μ x 25μ	13μ x 25μ (or better)
cooling	C_6F_{14} (monophase)	CO_2 (biphase)
material budget X/X_0 (η=0)	6%	5.5%
material budget X/X_0 (η=1.6)	40%	20%
pixel data readout speed	40MHz (analog coded)	400Mb/sec (digital)
ROC pixel rate capability (loss)	~3.8% @ 120 MHz/cm^2	~1.6% @ 150 MHz/cm^2 Layer 1: ~3% @ 580 MHz/cm^2
control & ROC programming	TTC & 40MHz I^2C	TTC & 40MHz I^2C

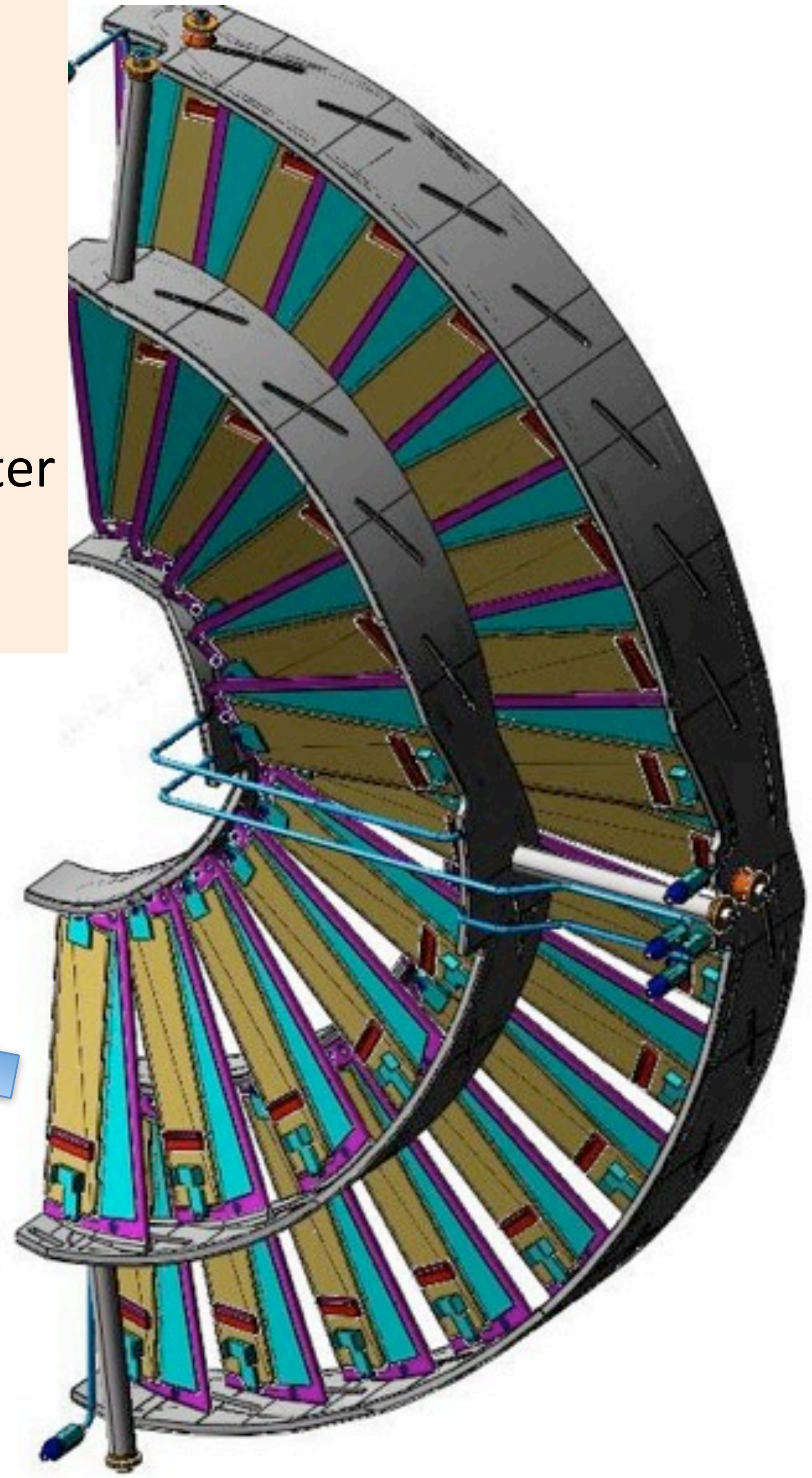
Half Disk Detail

Upgrade (672 modules)

A module consists of one type of sensor bump bonded to a 2x8 array of Read Out Chips (ROCs). One module is mounted on each side of a blade. Signals go right to the flex cable.

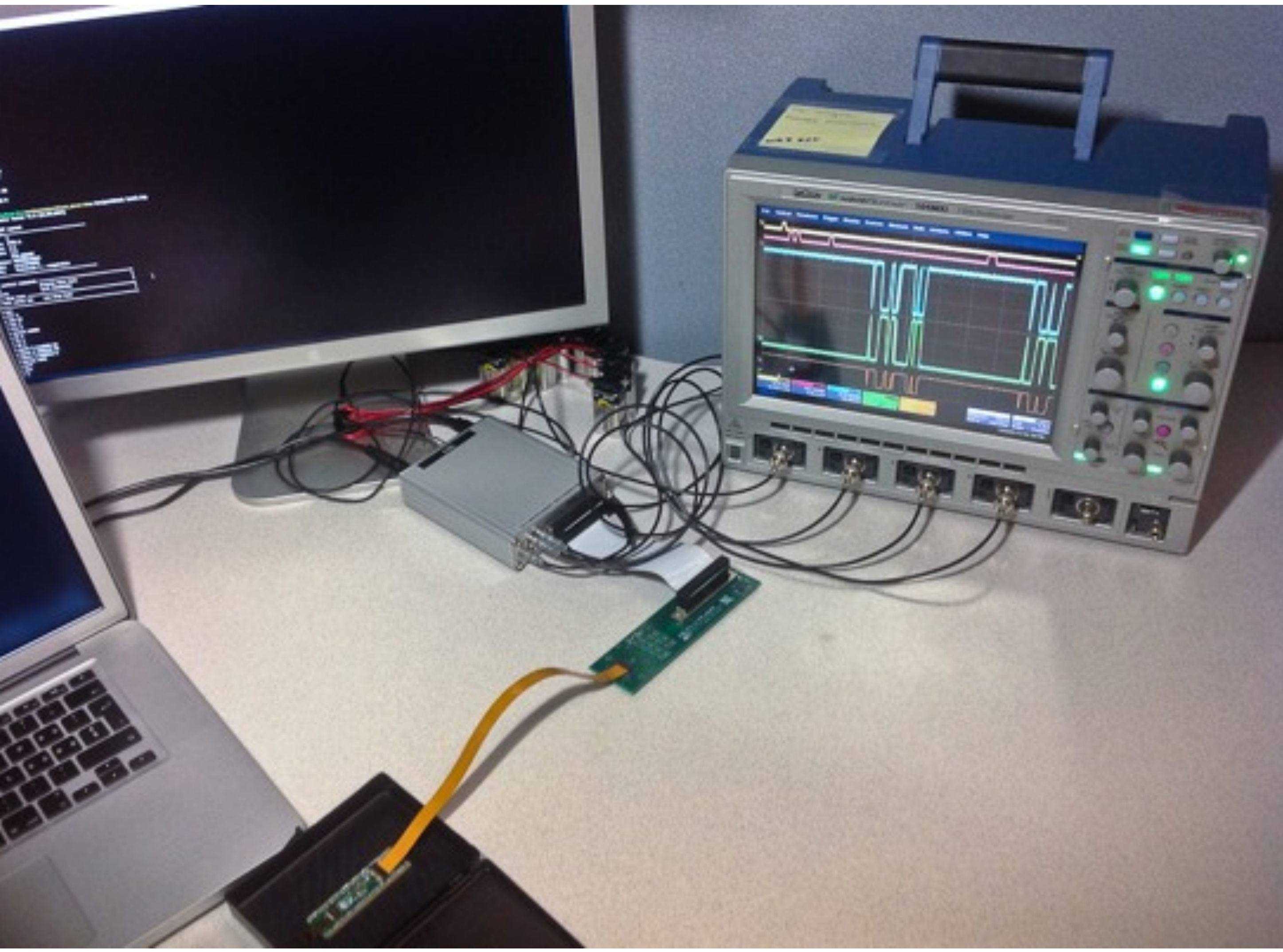
A half disk: (12/FPiX)
34 Modules (outer)
(17 Blades)
and 22 Modules (inner)
(11 Blades)
Accommodates new module design, independent inner/outer ring for easier maintenance. (Notice the cooling lines).

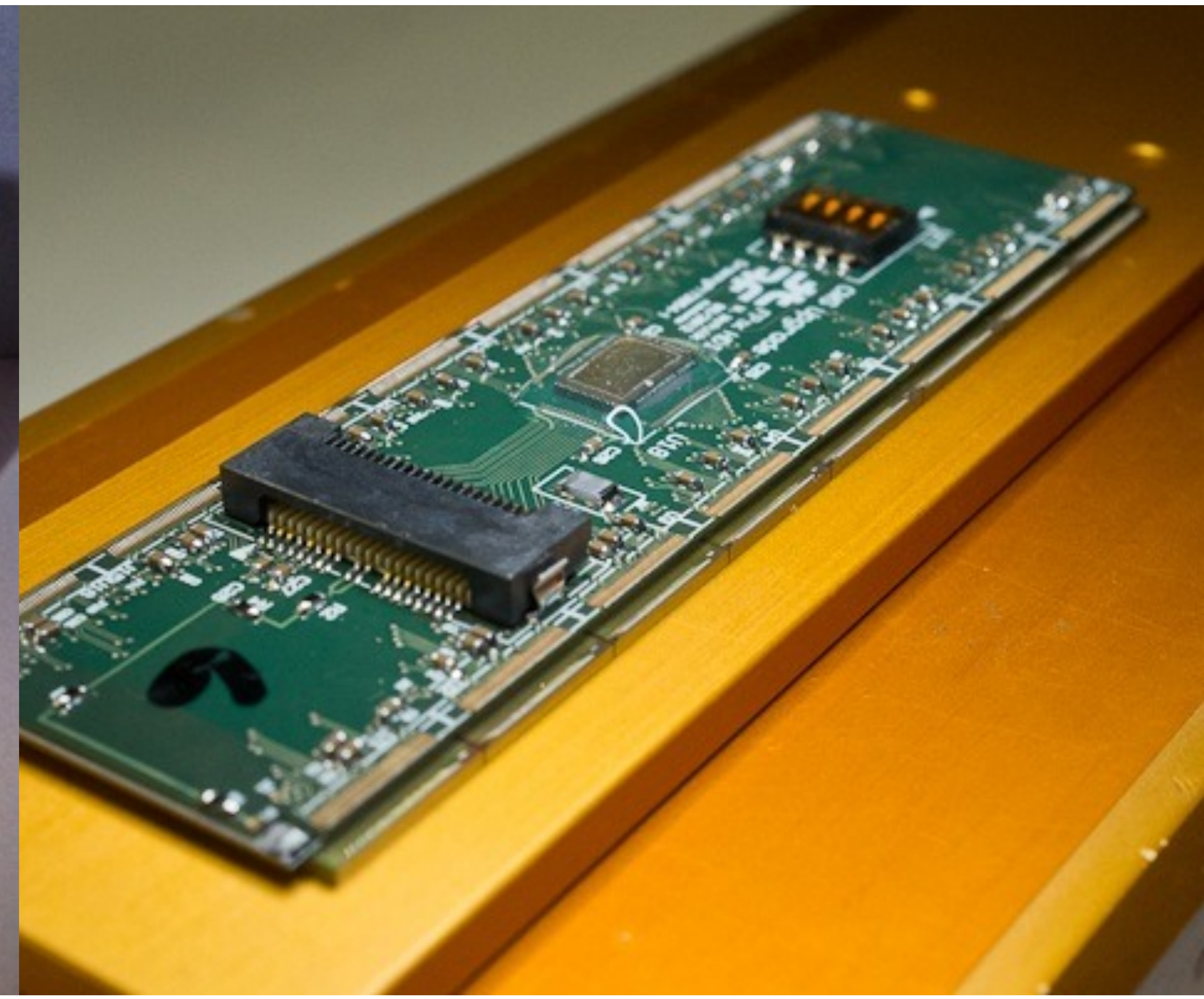


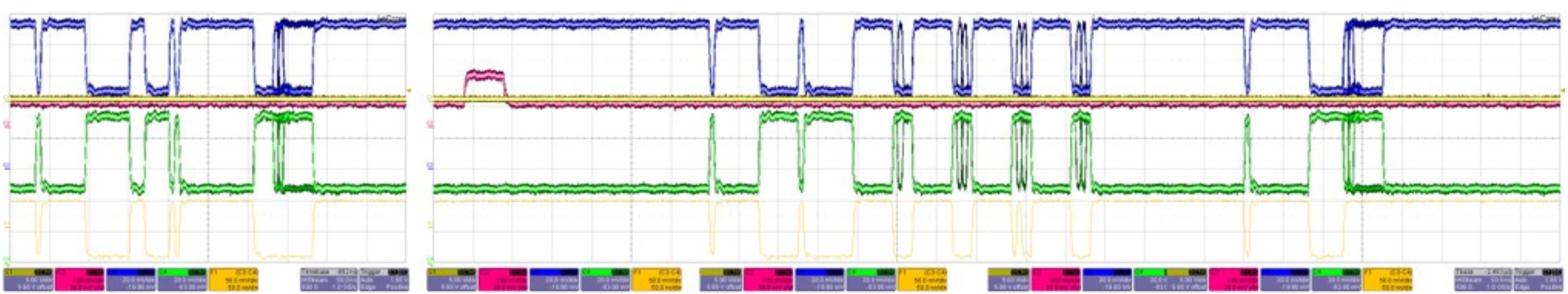


The new, digital ROC and Token Bit Manager (TBM) allow efficient operation at high rate, provide protection against giant events, and allow signals from the ROCs to be multiplexed: ~ 2x output bandwidth

1st Prototype Modules Built



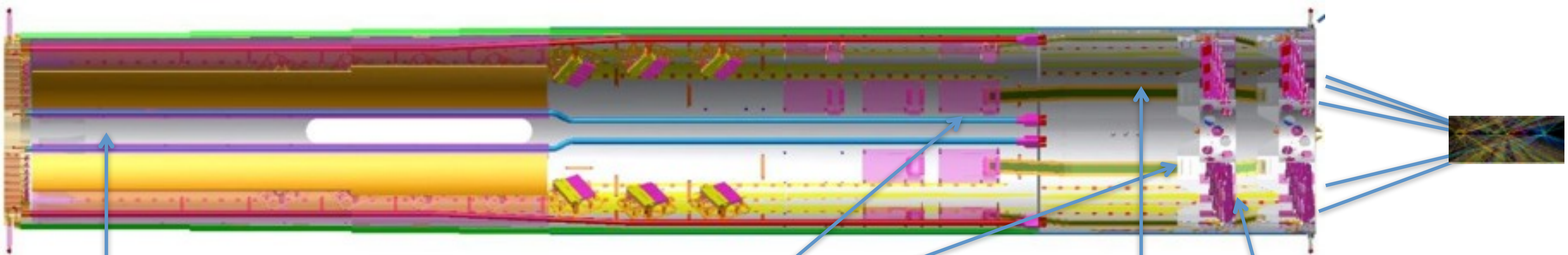




Half Cylinder Support Structure

Current Half Cylinder (1 of 4)

Number of Half Disks goes from 2 to 3 per Half Cylinder: Increased robustness, better efficiency at high rate and less fake tracks

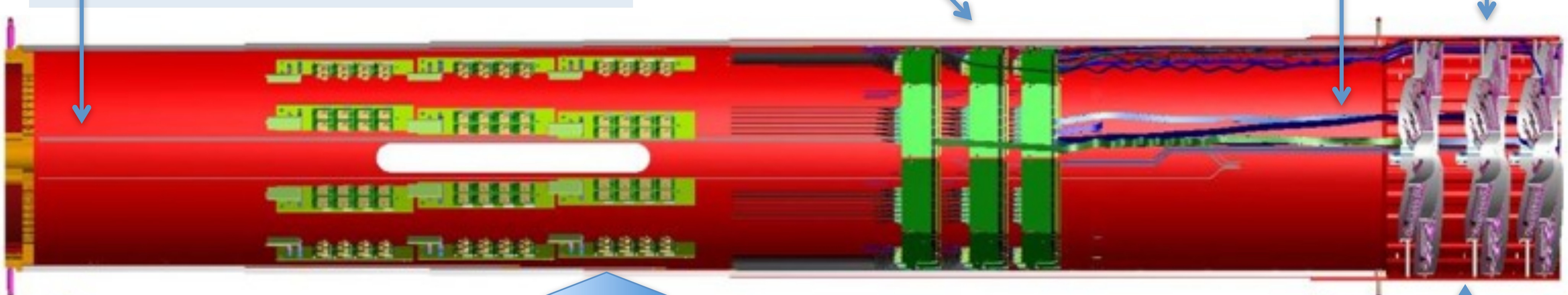


Changing cooling to CO_2 plant: Reduction in mass.

Support Electronics: Boards out of tracking volume & new low mass flex cable

Half Disk and module design uses carbon (less material), replaces Al/Be

Upgrade Half Cylinder (1 of 4)



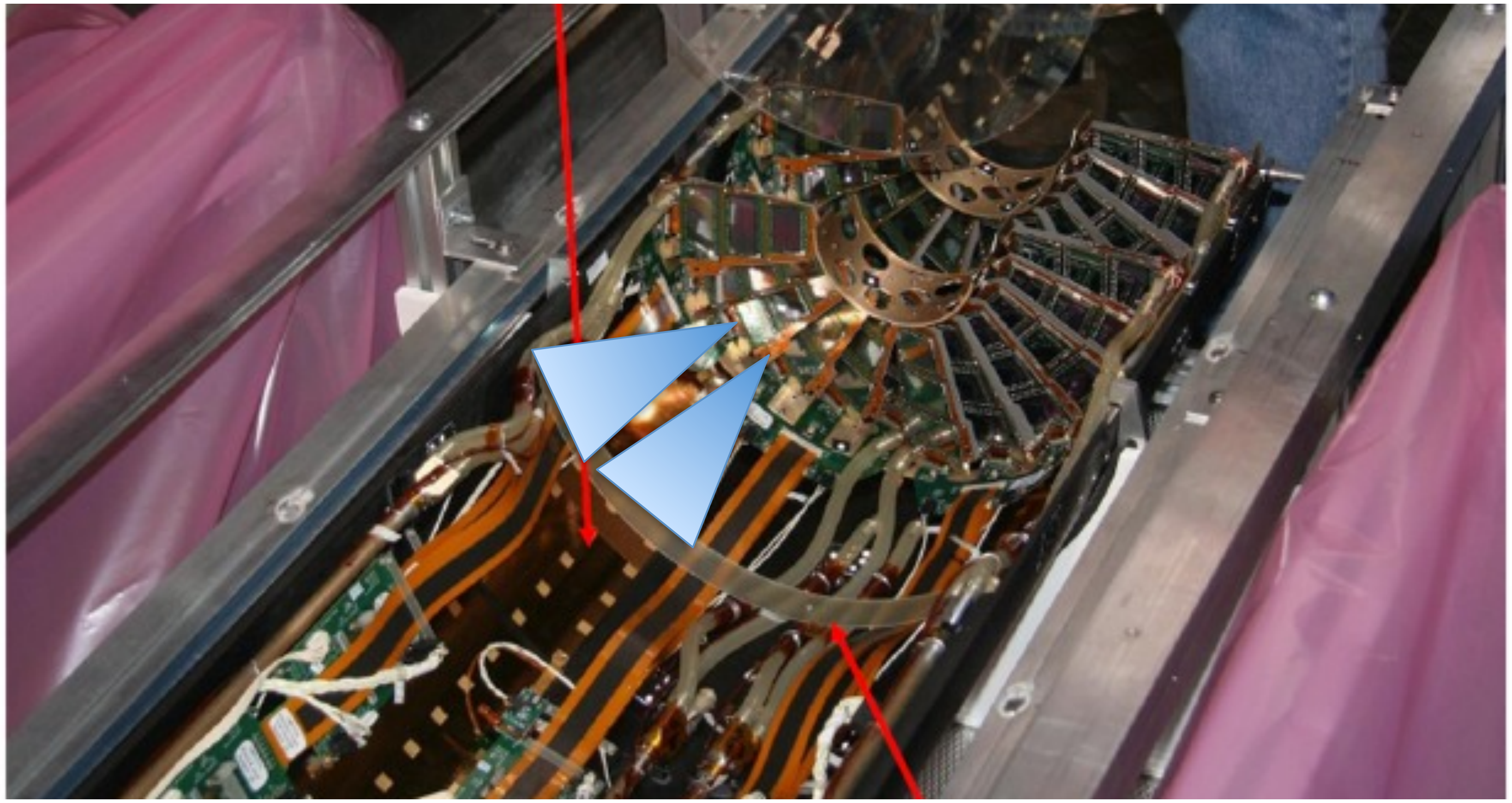
- 4 hits to eta of 2.5
- Inner radius 4.5 cm

Adding DC-DC converters: Cables to Half Cyl. same, power needs x2

Half Cylinder expanded in girth for Larger Radius, higher acceptance Detector

Pilot Detector

- Install 4 modules at each end (z) at the location of the 3rd disk in present FPiX (Summer 2014)
- Head start with detector in the LHC environment
  - Identify beam related challenges / Operational experience
- Test many new parts and software *in situ*



Physics Performance

- Improvement from new detector can't be summed up by one number
- But it is characterized by higher efficiencies, lower fake rates, lower dead-time/data-loss, extended lifetime of detector
- Leads to better muon ID, b-tagging, photon/electron ID, tau reconstruction. Both offline and in the HLT
- (In principle, could also improve MET since "particle flow" has become an important tool in CMS.)
- The above forms the foundation for vast majority of our physics analyses, whatever they may be in the future
- Using full simulation of current and upgraded detector, measure tracking efficiency, fake rate, b-tagging etc as a function of pile-up

Data Loss Dominated by Buffers

Table 2.1: Values of dynamic data loss used in the simulations of the current and upgrade pixel detector operating at 1×10^{34} cm^{-2}s^{-1} (25 ns crossing time) and 2×10^{34} cm^{-2}s^{-1} (25 ns and 50 ns crossing time) for each barrel layer and forward disk and for particular bunch crossing intervals.

Detector	Radius (cm)	% Data loss for (cm^{-2}s^{-1} @ ns) 1×10^{34} @ 25	2×10^{34} @ 25	2×10^{34} @ 50
Current detector				
BPIX1	4.4	4.0	16.0	50.0
BPIX2	7.3	1.5	5.8	18.2
BPIX3	10.2	0.7	3.0	9.3
FPIX1 and 2		0.7	3.0	9.3
Upgrade detector				
BPIX1	3.0	1.19	2.38	4.76
BPIX2	6.8	0.23	0.46	0.93
BPIX3	10.2	0.09	0.18	0.36
BPIX4	16.0	0.04	0.08	0.17
FPIX1–3		0.09	0.18	0.36

The Basic Problem to be Solved

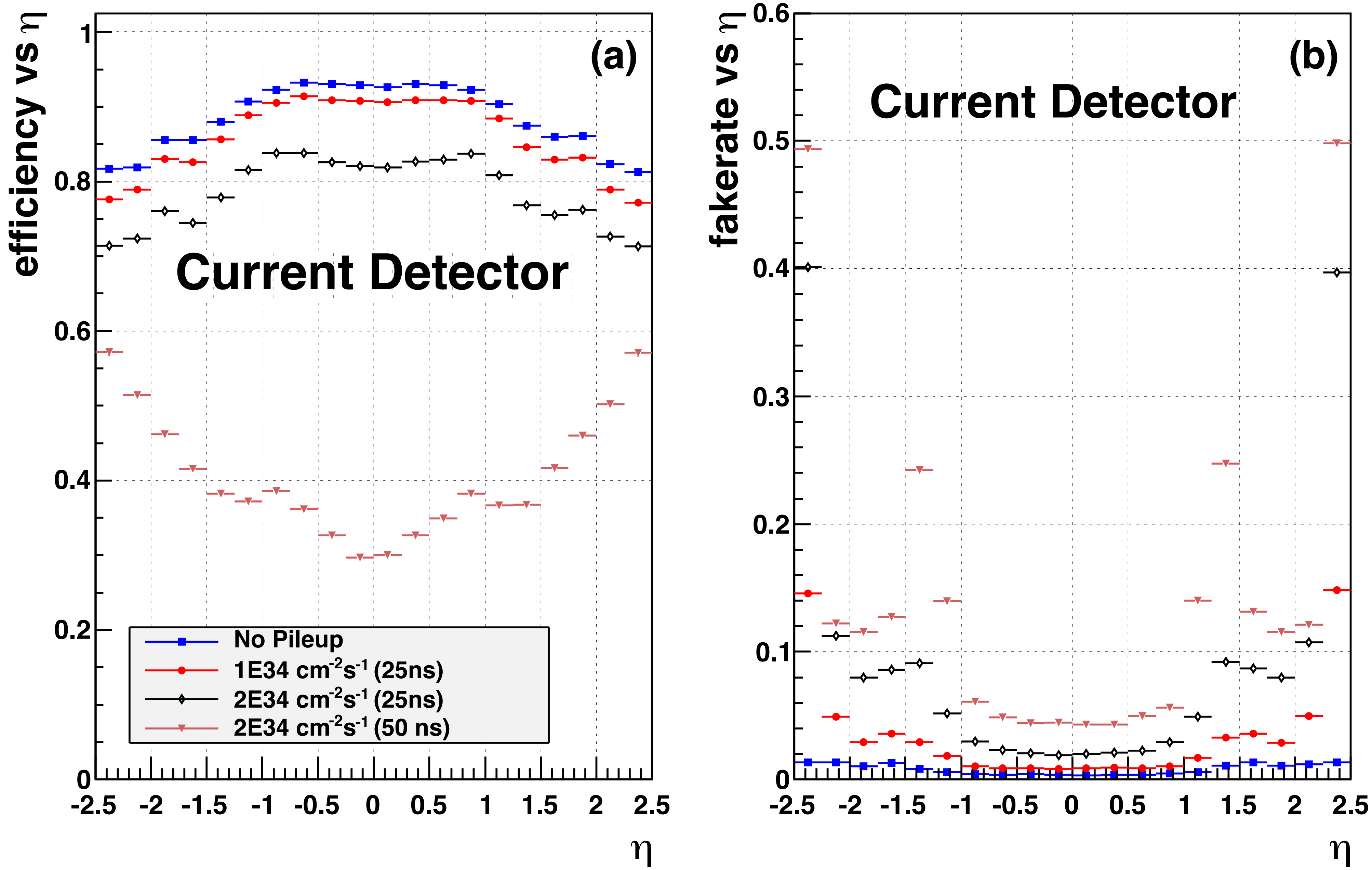


Figure 2: (a) Efficiency of track reconstruction and (b) rate of fake tracks with the current pixe
detector, for a $t\bar{t}$ event selection and various beam conditions.

Tracking Improvements

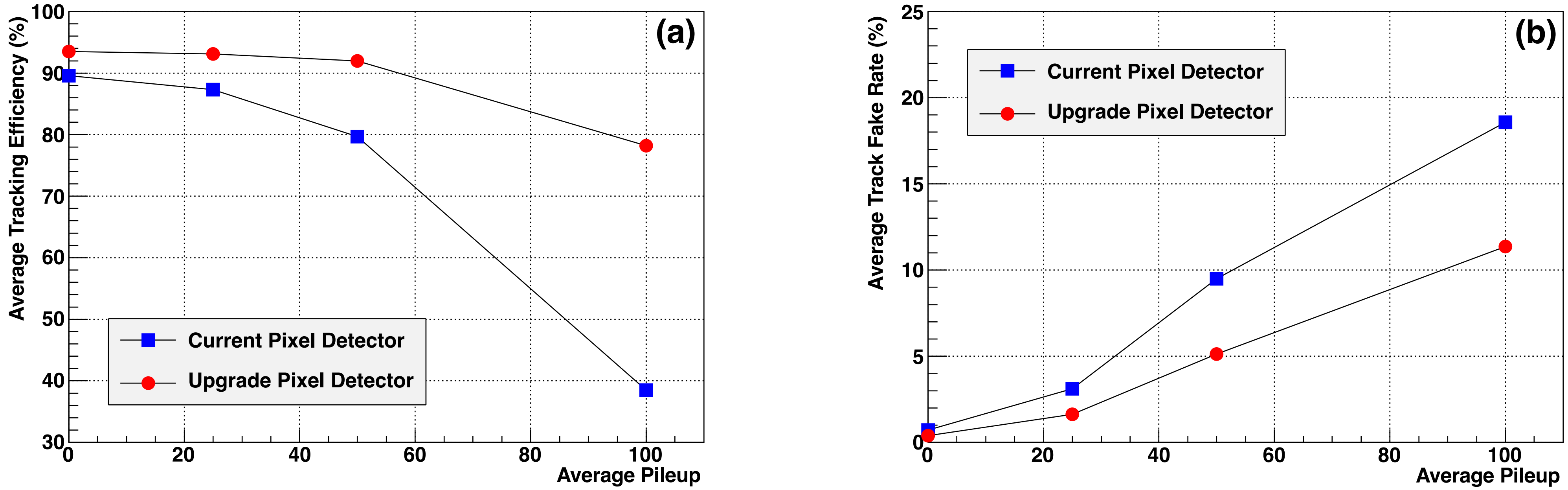


Figure 8: Average tracking efficiencies (a) and fake rates (b) as a function of pile-up, for the $t\bar{t}$ event selection.

Impact Parameter Improvements

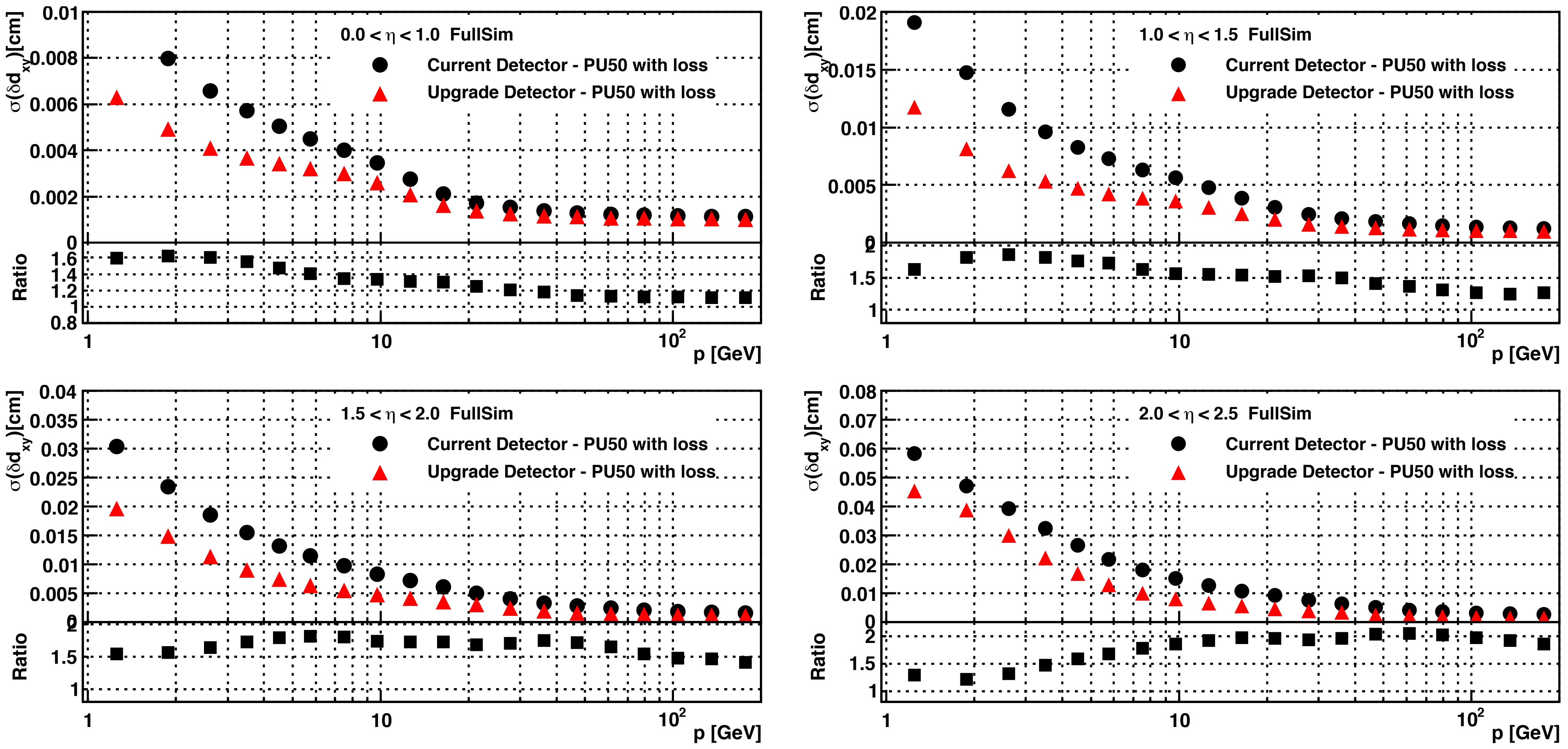
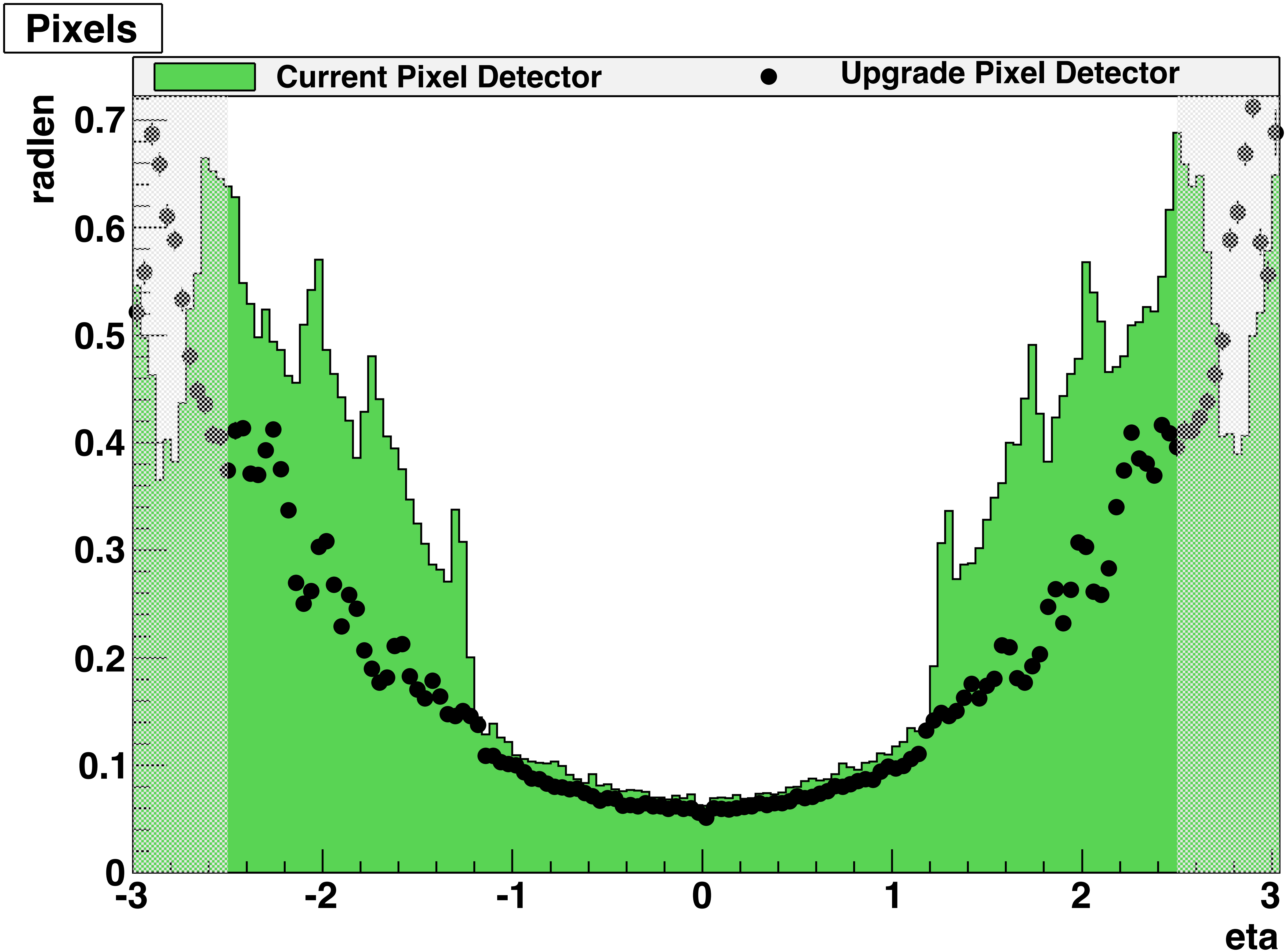
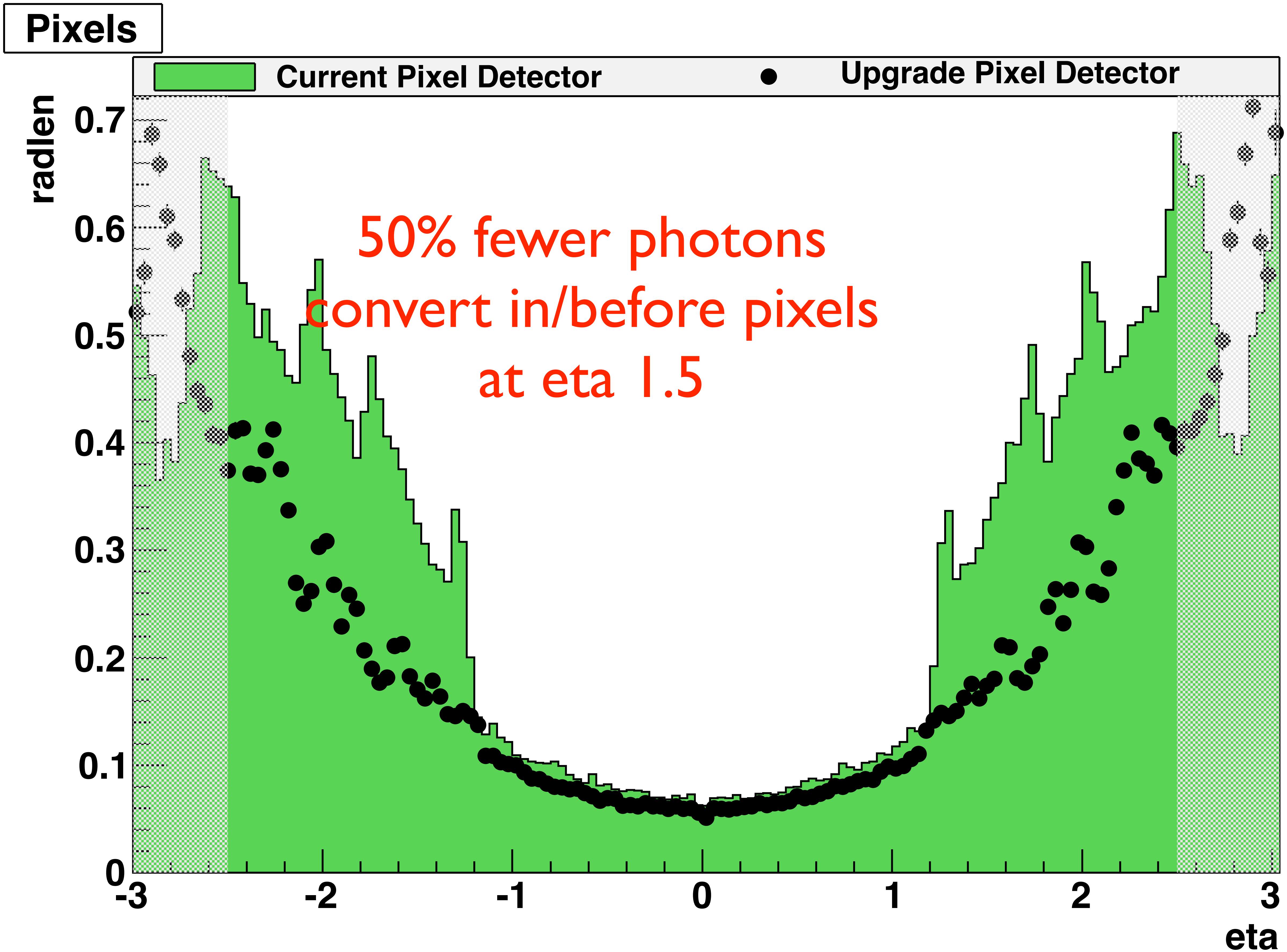


Figure 9: Transverse impact parameter resolution for muon tracks as a function of momentum, for different pseudo-rapidity regions. The current and new detectors are respectively represented with black dots and red triangles.

Less Material



Less Material



Vertexing Improvements

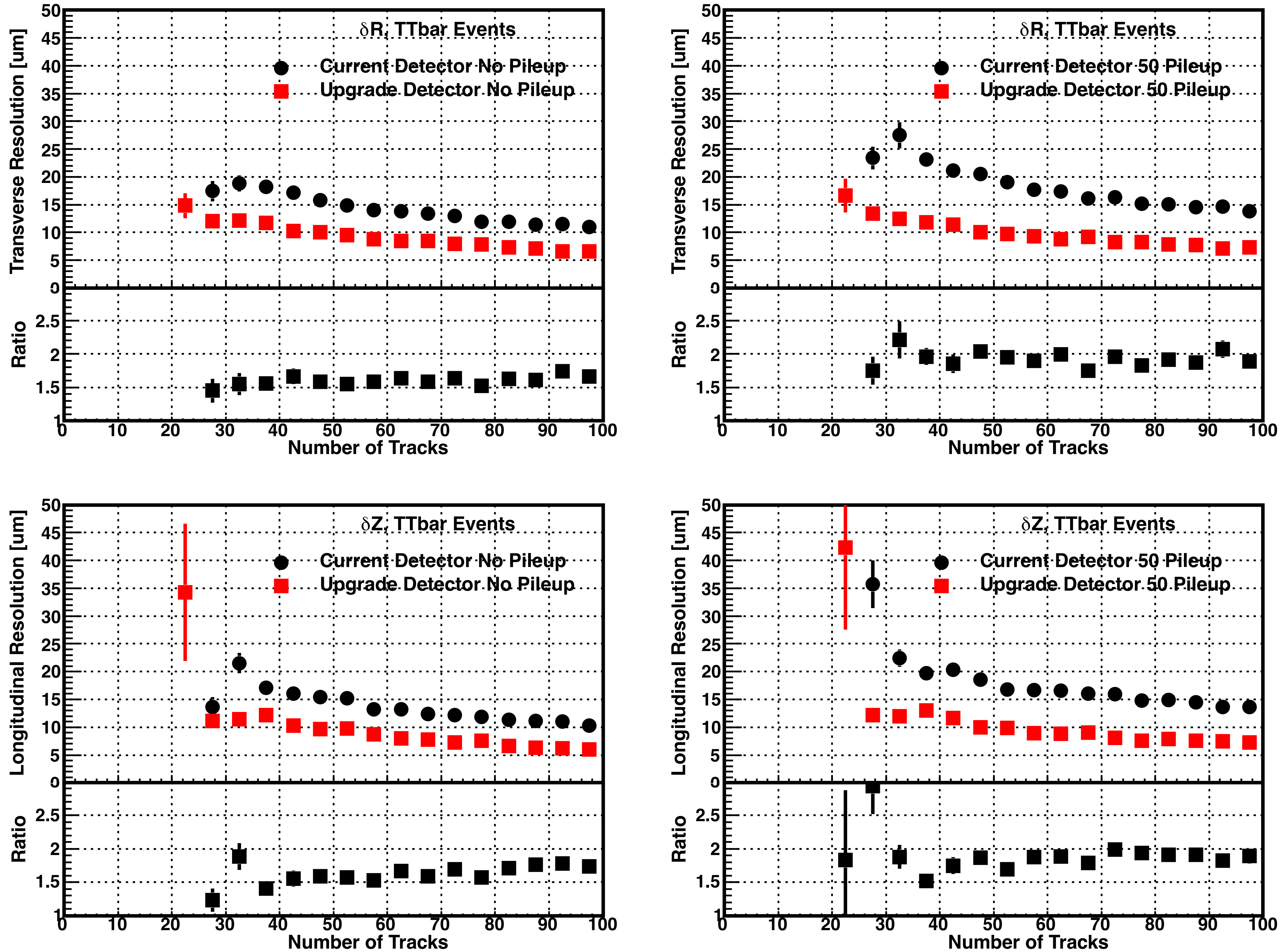


Figure 10: Transverse (δ_R) and longitudinal (δ_Z) primary vertex position resolutions as a function of the number of tracks; without pile-up (left) and at a 50 pile-up (right). The current and new detectors are respectively represented with black dots and red squares.

B-Tagging Improvements

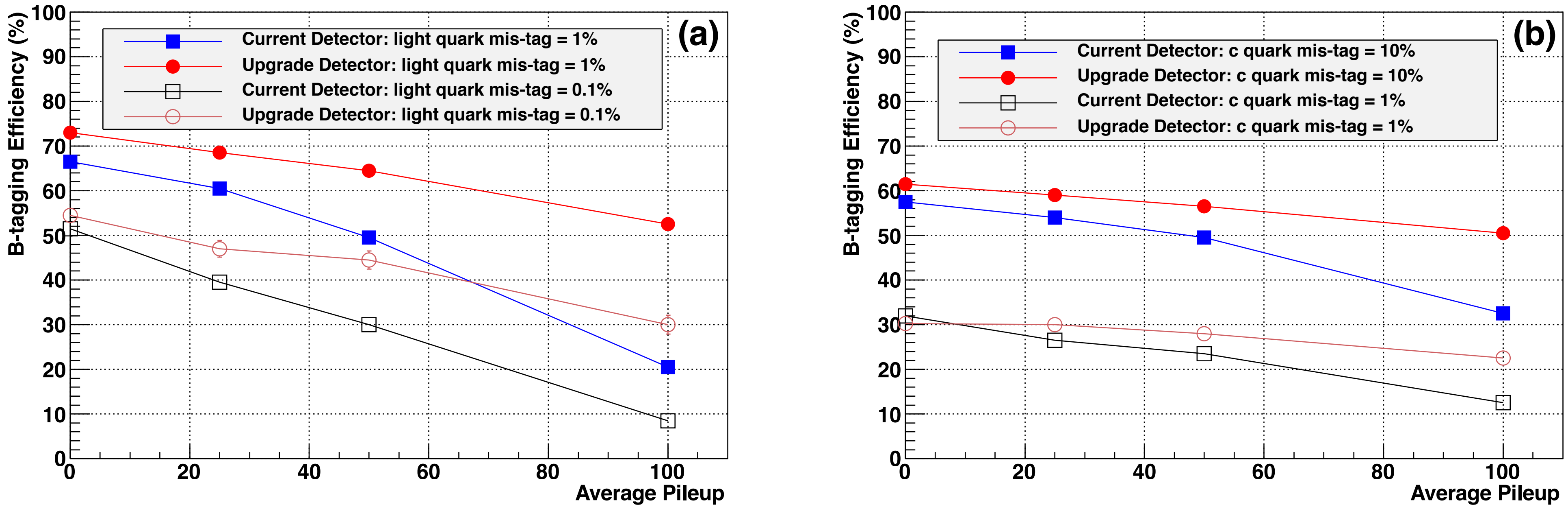


Figure 12: b-tagging efficiency as a function of pile-up for few typical values of mis-tagging fractions of light quark-jets (left) and c-jets (right). The current detector points are in blue and black, the new detector points are in red.

Physics Performance

- Estimate how improvements to tracking efficiency and fake rate impact a representative set of physics analyses that depend on the pixels
- Estimate relative improvements of signal selection for 14 TeV with 50 pile-up (using full simulation as before) and using current analysis selections as the baseline for comparison

ZH→llbb

- Analysis based on: 0) triggering on muon/electron events; 1) kinematic reconstruction of Z from di-muons or di-electrons; 2) reconstructing invariant mass from two b-tagged jets; 3) multivariate
- Higher muon/electron ID efficiency helps with (0-1), better b-tagging helps with (2).
- Improvements to high-level trigger too

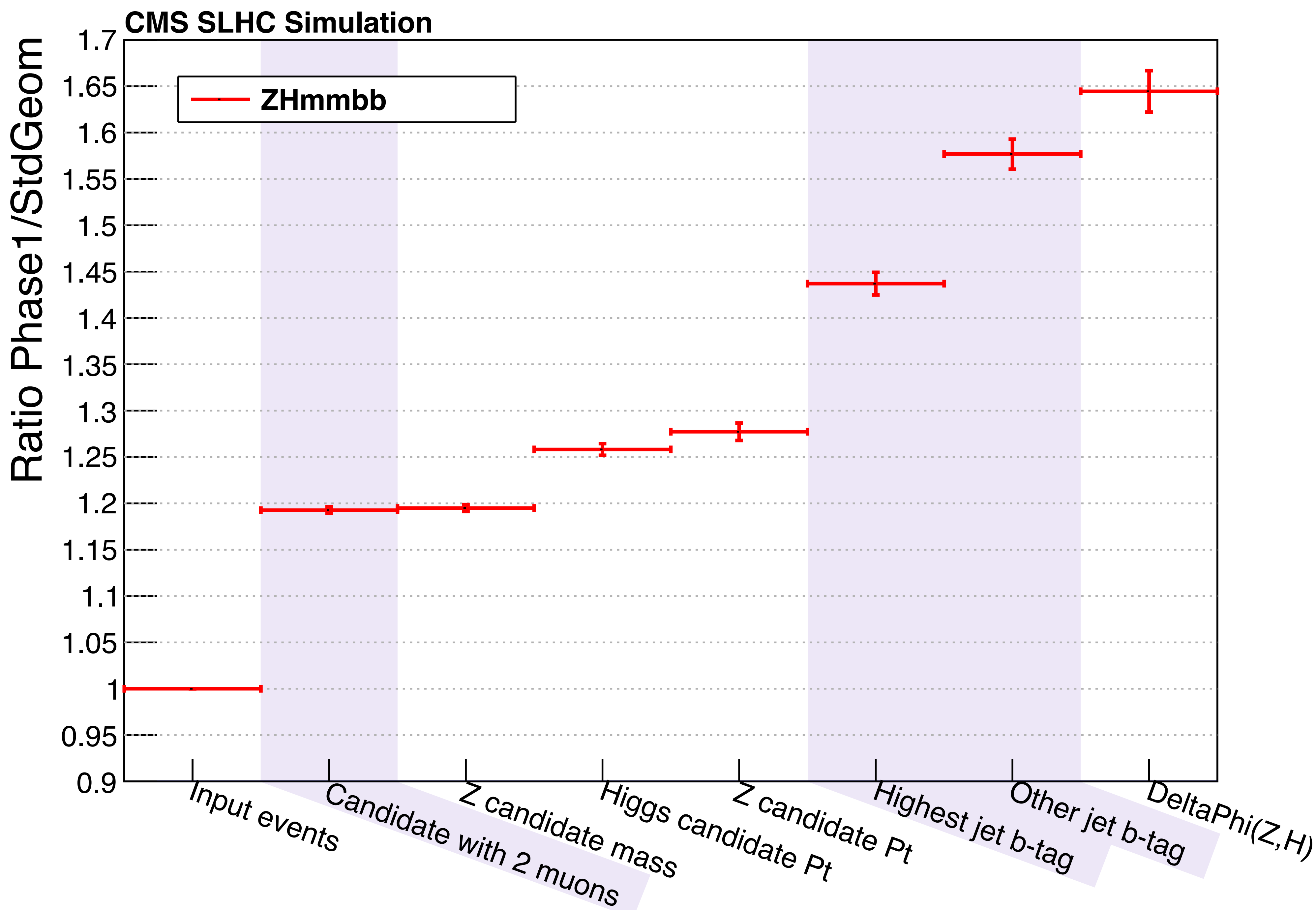


Figure 14: The ratio of the number of events each sequential cut for the upgraded detector relative to the current detector. The cuts where the largest improvement from the upgraded detector are expected are highlighted.

ZH→llbb

- di-electron channel sees similar improvement as the di-muon channel
- Additional improvements would come from improvements to the HLT (which was not simulated in detail). Simple estimates from requiring 3 pixel hits on lepton increase relative improvement from 65% to 75% for a single lepton trigger
- If we pessimistically assume that the background scale at the same rate as the increases in signal efficiency, then for 300/fb at 14 TeV, the $ZH \rightarrow \mu\mu bb$ measurement will go from 3.6σ to 4.9σ significance
- In other words, for the same amount of integrated luminosity, the improvements from the upgrade could lead to a sensitivity consistent with what is needed for an observation with this subchannel.

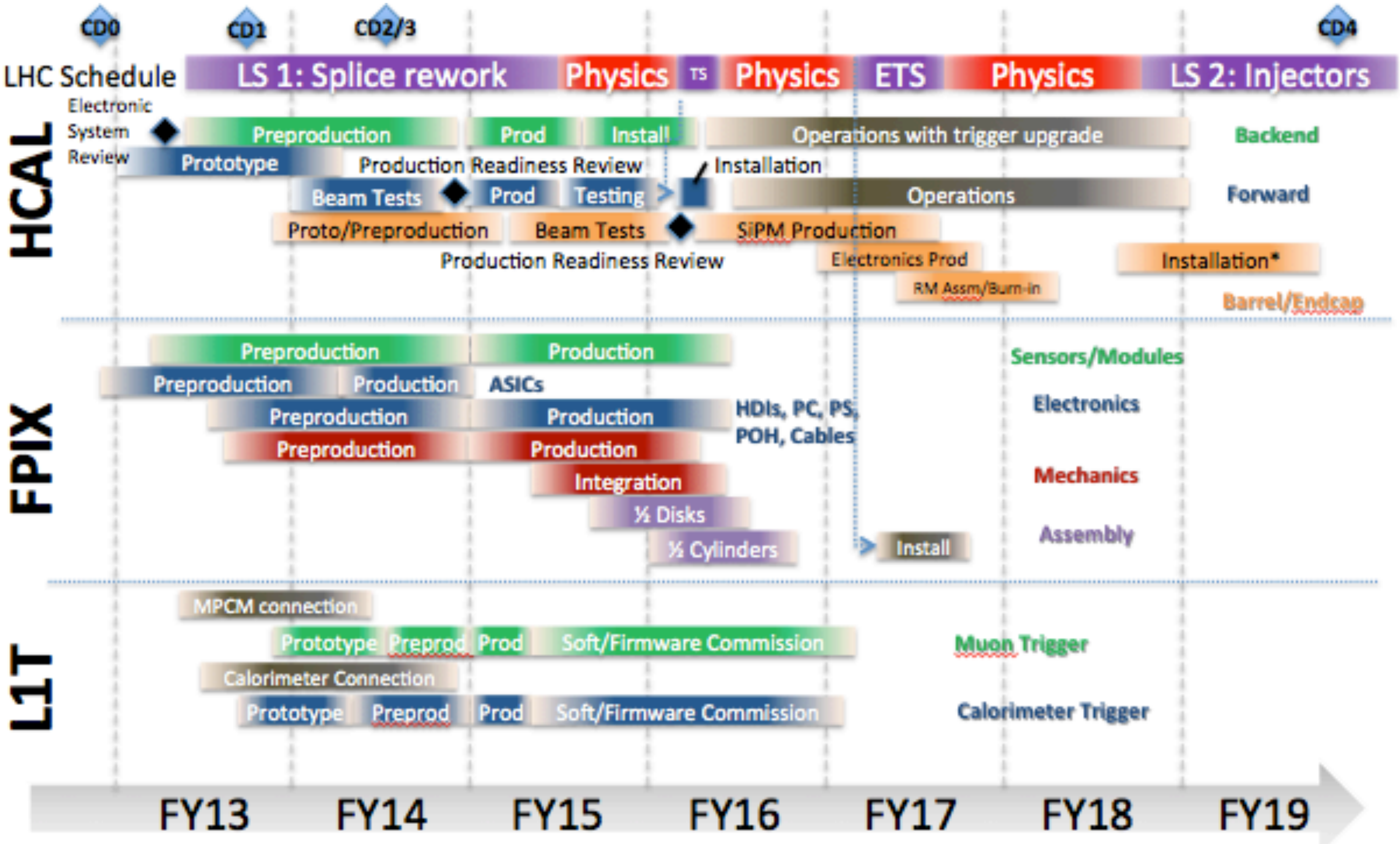
Conclusions

- CMS is preparing for first campaign of upgrades to the experiment to best take advantage of the excellent performance of the LHC
- The first major upgrade of the detectors is planned be the pixel detectors in the extended year-end technical stop of 2016/2017
- These evolutionary upgrades will give us an experiment that performs at a higher level even than we have had before

Backup Material

LHC CMS Detector Upgrade Project

Schedule Overview



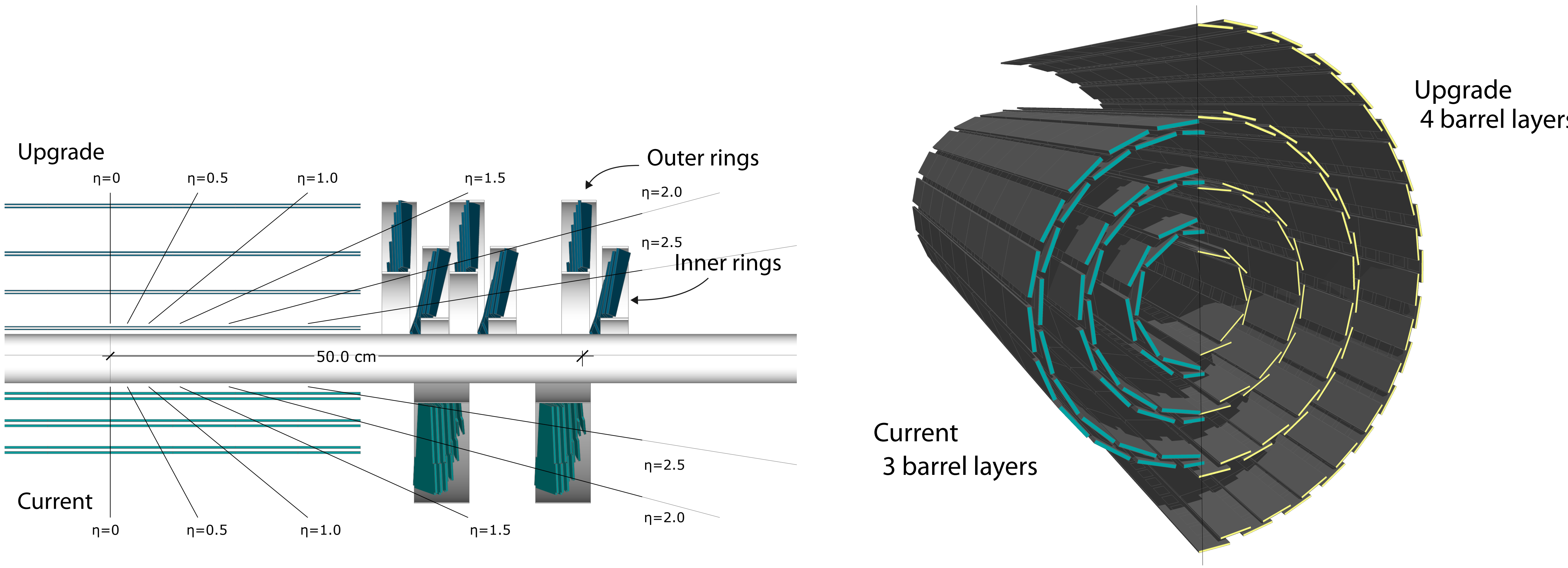


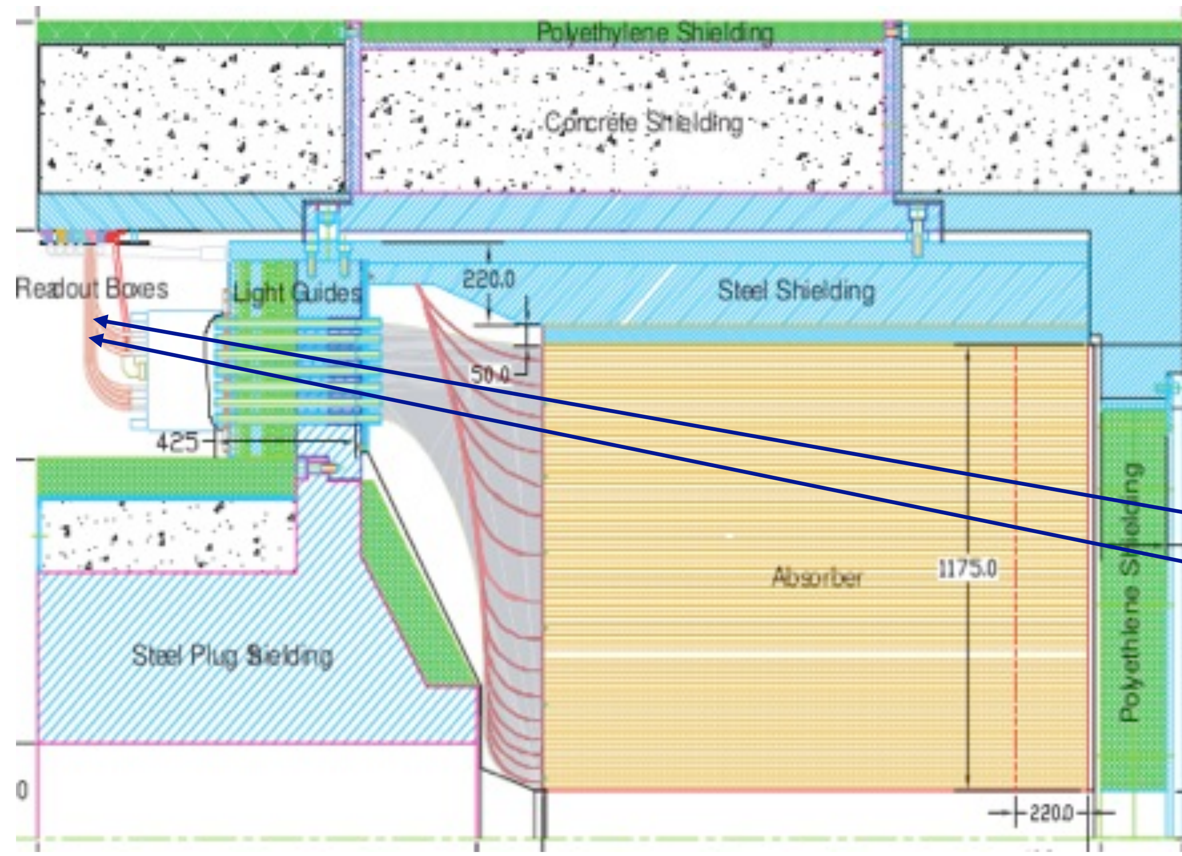
Figure 3: Left: Conceptual layout comparing the different layers and disks in the current and upgrade pixel detectors. Right: Transverse-oblique view comparing the pixel barrel layers in the two detectors.

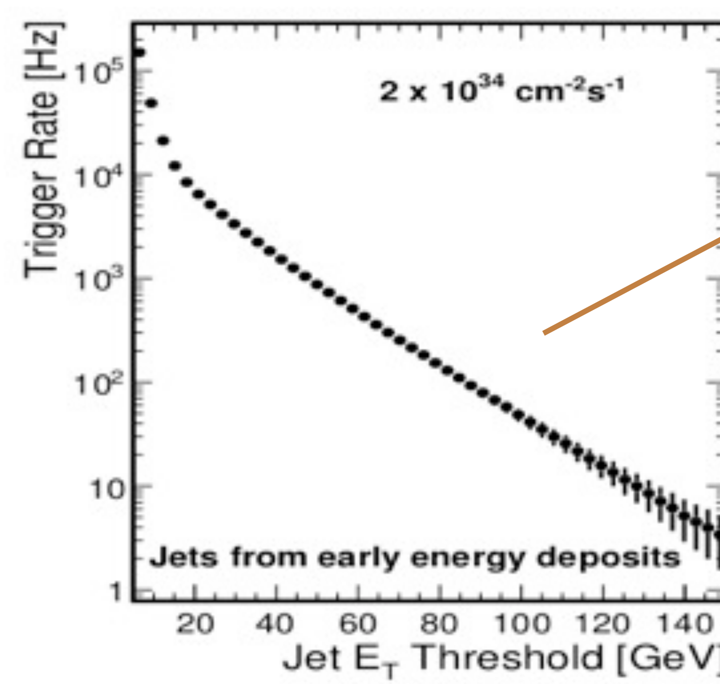
Barrel/Endcap Requirements

- Requirements to provide performance required for Higgs – vector-boson-fusion (VBF) channel – and SUSY – missing transverse energy (MET) – and other LHC physics efforts
  - Compensate radiation damage effects to maintain adequate jet resolution
    - Limit signal decrease to less than 95% for $|\eta|<2.7$ for 500 fb^{-1}
    - Limit signal decrease to less than 60% for $|\eta|<1.4$ for 3000 fb^{-1}
  - Within the constraints of radiation damage, maintain particle flow performance, lepton id and isolation as observed at 25 pileup/50 ns to 50 pileup/25 ns operation
  - Determine bunch-crossing and hit time with 2 ns precision for energy deposits above 10 GeV in the presence of 50 pileup events and 25 ns bunch crossings
  - Reduce fake jet rate in $1.4<|\eta|<3.0$ by a factor of two (at fixed efficiency) to improve VBF Higgs efficiency

Forward Calorimeter Requirements

- The Forward Hadron Calorimeter (HF) is important for VBF Higgs production "tagging jets"
- Particles (muons from decay-in-flight, punch-through particles) passing through the HF PMTs produce spurious signals in the PMTs
  - Signals from backgrounds appear earlier (by ~4 ns) than signals from showers in the calorimeter
  - Signals from backgrounds often affect only a small portion of a PMT
- <u>Requirement</u>: Reject background signals separated by at least 2 ns in time from nominal, and recover channel performance when just a small portion of the PMT is affected.





Fake jets from early energy deposits as observed in 2012

Tracking Studies

The four pileup scenarios as given in Section (2.1) were studied: $\overline{\mathrm{PU}} = 0, 25, 50, 100$. The $\overline{\mathrm{PU}} = 0$ scenario does not represent a realistic running condition of the LHC, but rather is used to factorize improvements from the geometric changes in the upgrade separately from the improvements to the readout chip efficiencies. The $\overline{\mathrm{PU}} = 25, 50, 100$ scenarios correspond to the original nominal LHC beam conditions and to upgraded LHC conditions with 25 ns and 50 ns bunch spacing.

The track reconstruction efficiency and fake rate presented are defined as follows:

$$\text{Tracking efficiency} = \frac{\text{Number of truth tracks matched to reconstructed tracks}}{\text{Number of truth tracks}} \quad (2.1)$$

$$\text{Track fake rate} = \frac{\text{Number of reconstructed tracks not matched to truth tracks}}{\text{Number of reconstructed tracks}} \quad (2.2)$$

where for (2.1) the only truth tracks considered are those from the signal interaction with (truth) $p_{\mathrm{T}} > 0.9\,\mathrm{GeV}$. For the track fake rate given in (2.2) all reconstructed tracks with reconstructed $p_{\mathrm{T}} > 0.9\,\mathrm{GeV}$ are considered.

B-Tagging Improvements

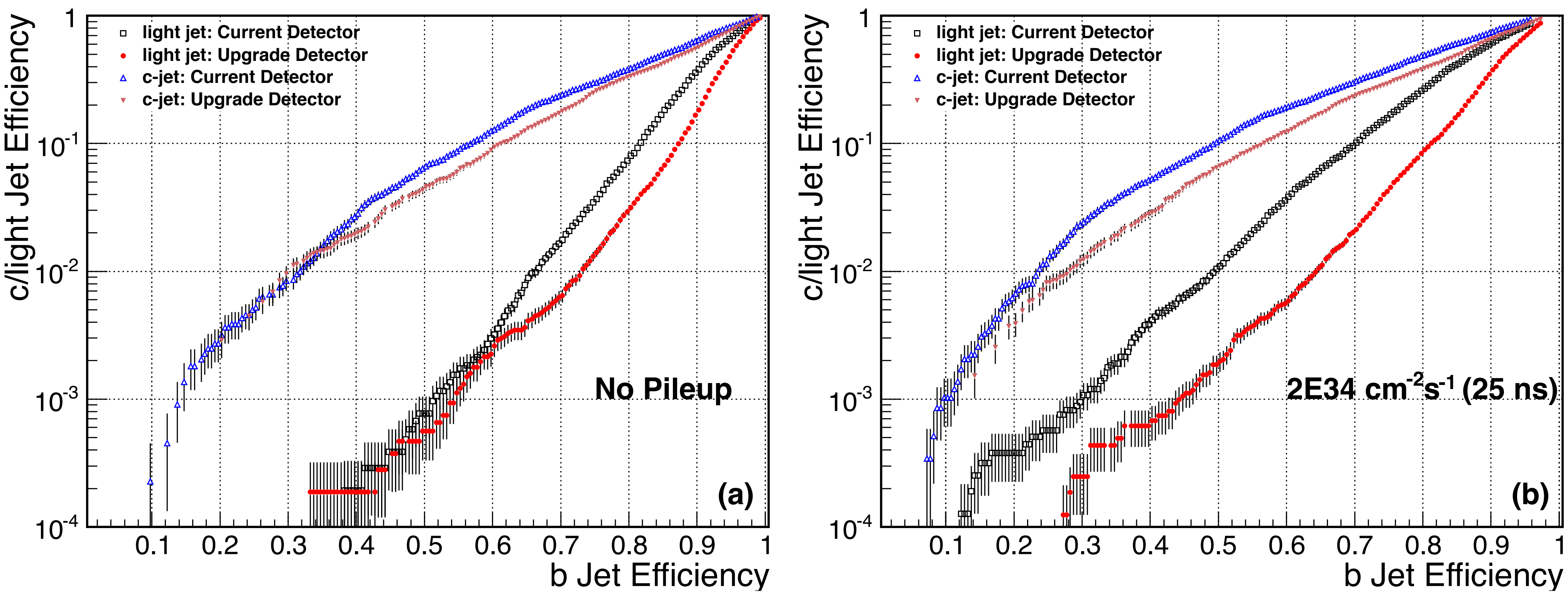
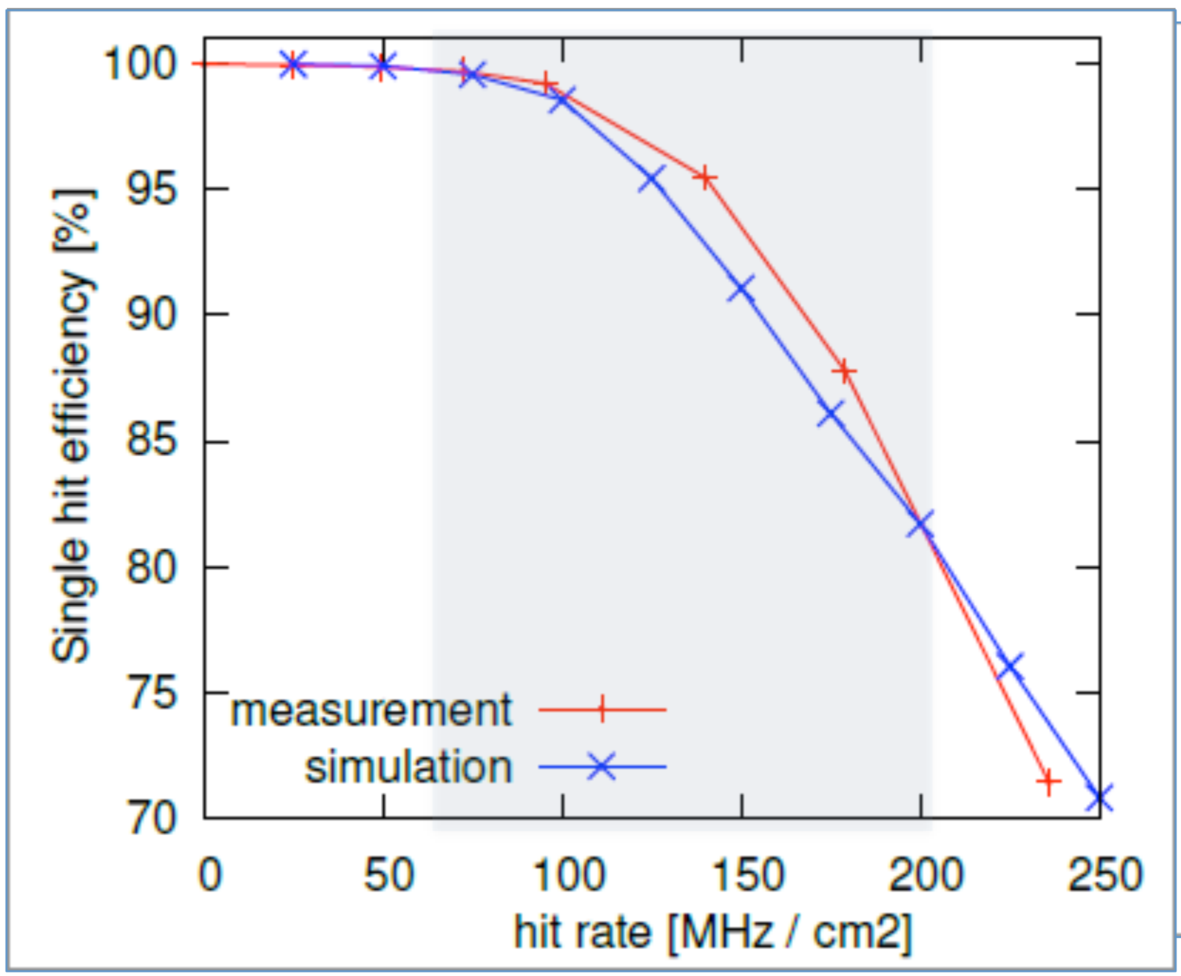


Figure 11: Fraction of c-jets or light quark-jets misidentified as b-jets as a function of the efficiency to tag the genuine b-jets, without pile-up (left) at a 50 pile-up (right), the current detector points are in blue and black, the new detector points are in red.

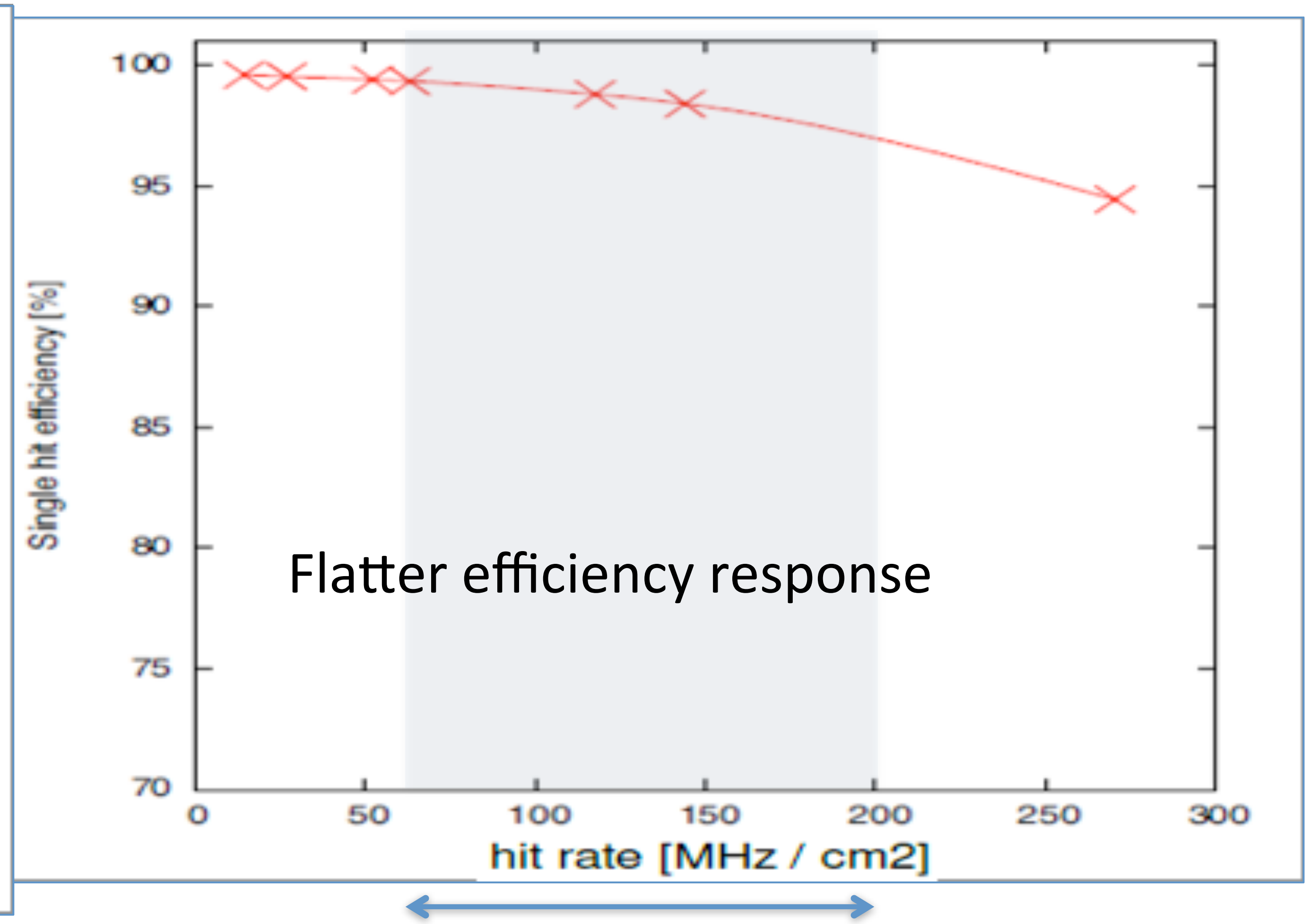
The Luminosity Cliff

- Expected fluence in the Innermost disk
  - The old and the new ROC are contrasted for the same geometry using x-rays

Current Pixel Detector



Upgrade Pixel Detector



$H \to ZZ \to 4l$

- Analysis based on: 0) triggering on di-lepton events; 1) kinematic reconstruction of 2 Zs from isolated dileptons; 2) reconstructing invariant mass of Higgs
- Higher muon/electron ID efficiency helps with (0-1)
- As with ZH, there would be HLT improvements too

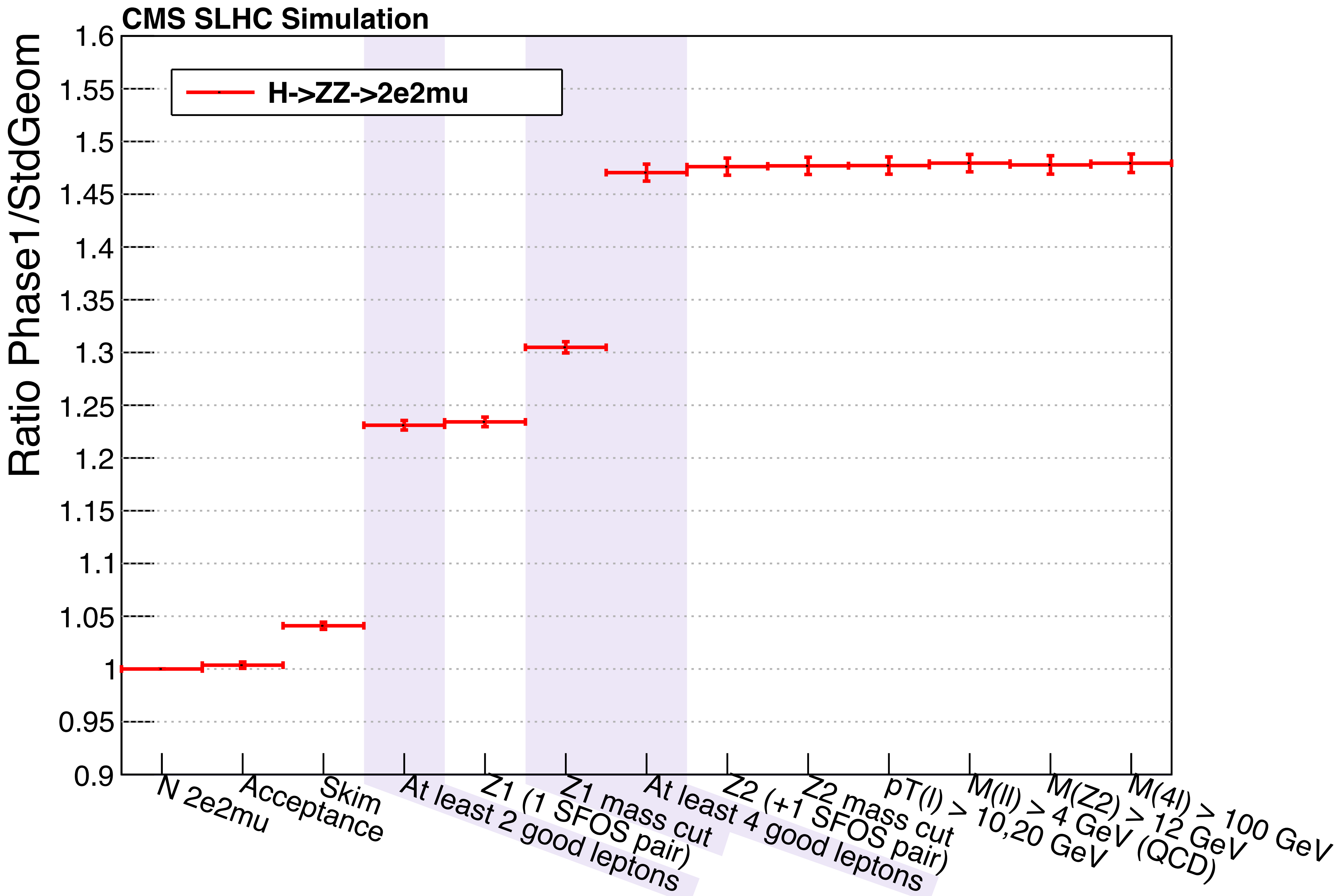


Figure 15: Cut flow chart for the $H \to 2e2\mu$ channel. The ratio of the numbers of events selected with the upgrade detector and the ones selected with the current detector is plotted with $PU = 50$.

$H \rightarrow ZZ \rightarrow 4l$

- As with ZH, the tracking efficiency (and fake rate) improvements compound and lead to higher signal efficiencies.
- The 4mu and 4e channels see similar improvements as the 2e2mu channel 40%-50%
- Again, this leads to sensitivity improvements

$\gamma\gamma$+MET Analysis

- Di-photon events with large MET as signature of new physics
- Largest backgrounds from $\gamma\gamma$ events with fake MET, and fake γ's with real MET (EW)
- Small backgrounds from $W\gamma\gamma$ and $Z\gamma\gamma$
- Events placed in 4 categories: $\gamma\gamma$; ee; eγ; fake fake
- Improvements come mainly from photon identification, in particular lower fake rates
- Estimate these fakes by fitting the Z peak in ee and eγ events and comparing rates

Figure 44: The Z-mass peak is shown for the Standard and Phase 1 Pixel geometry at $\overline{\text{PU}} = 50$. The calculated fake rates are 7.0% and 1.25% for the Standard and Phase 1 Pixel detector, respectively.

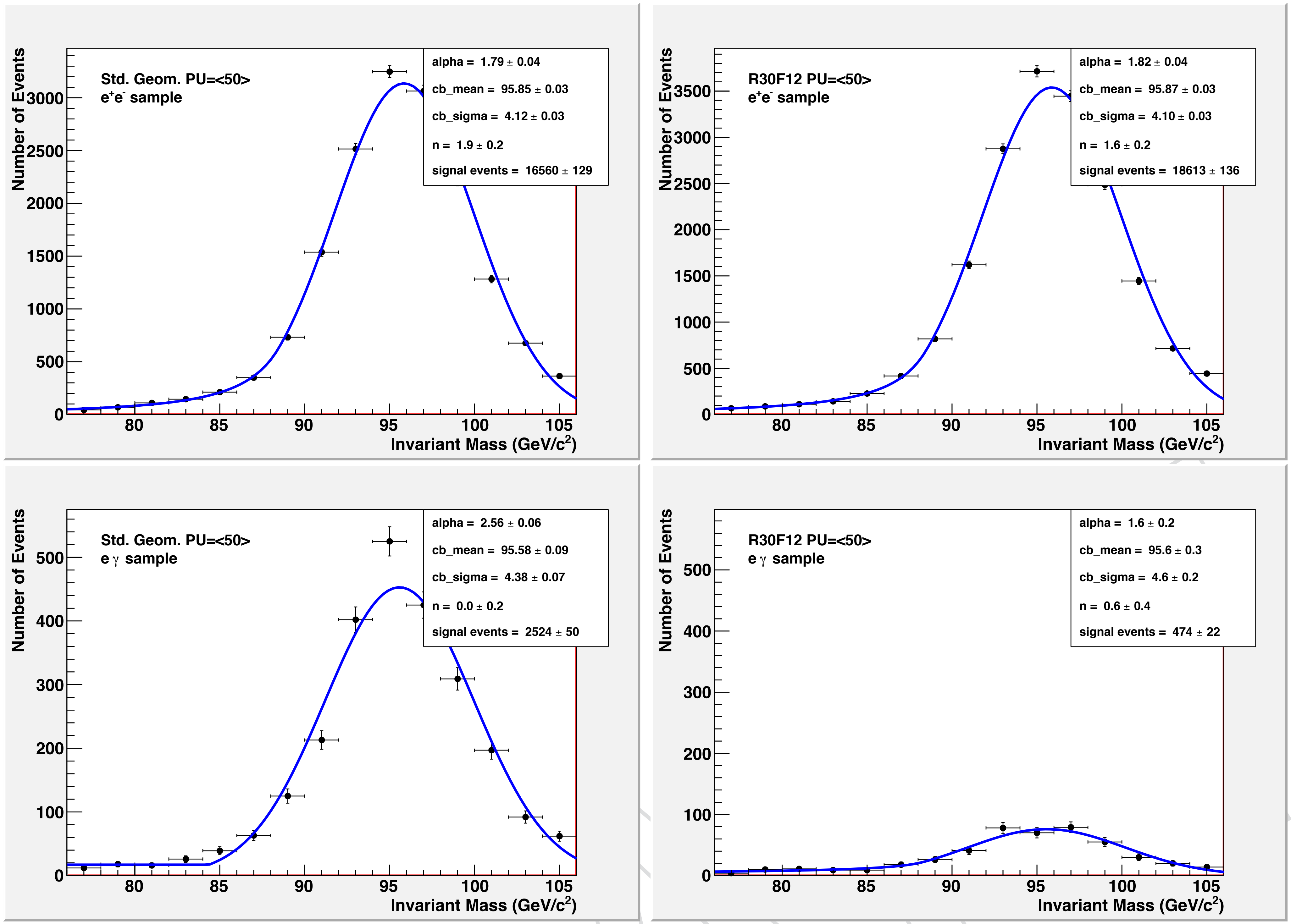


Figure 44: The Z-mass peak is shown for the Standard and Phase 1 Pixel geometry at $\overline{\text{PU}} = 50$. The calculated fake rates are 7.0% and 1.25% for the Standard and Phase 1 Pixel detector, respectively.