# CMS Pixel Detector
# Old .vs. New

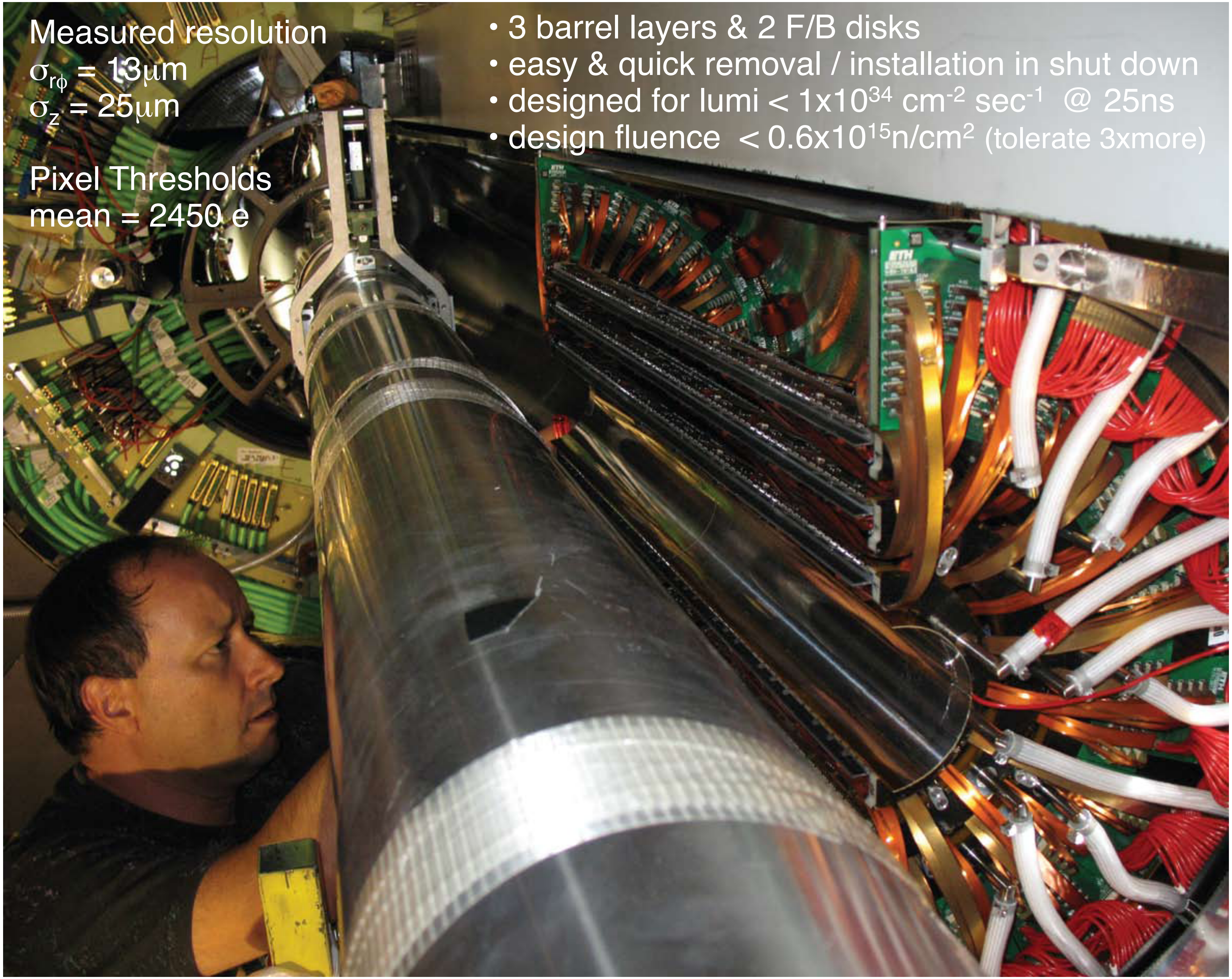
**5th Detector Workshop of the Helmholtz Alliance**
**“Physics at the Terascale”**

**Physikalisches Institut, Bonn**
**14. March 2012**

Roland Horisberger
Paul Scherrer Institute / ETH Zürich

# Installation of Present Pixel Detector

# Present Pixel Detector with 3 hit coverage works very well !



Measured resolution
$\sigma_{r\phi}$ = 13µm
$\sigma_z$ = 25µm

Pixel Thresholds
mean = 2450 e

- 3 barrel layers & 2 F/B disks
- easy & quick removal / installation in shut down
- designed for lumi < $1\times10^{34}$ cm$^{-2}$ sec$^{-1}$ @ 25ns
- design fluence < $0.6\times10^{15}$n/cm$^2$ (tolerate 3xmore)

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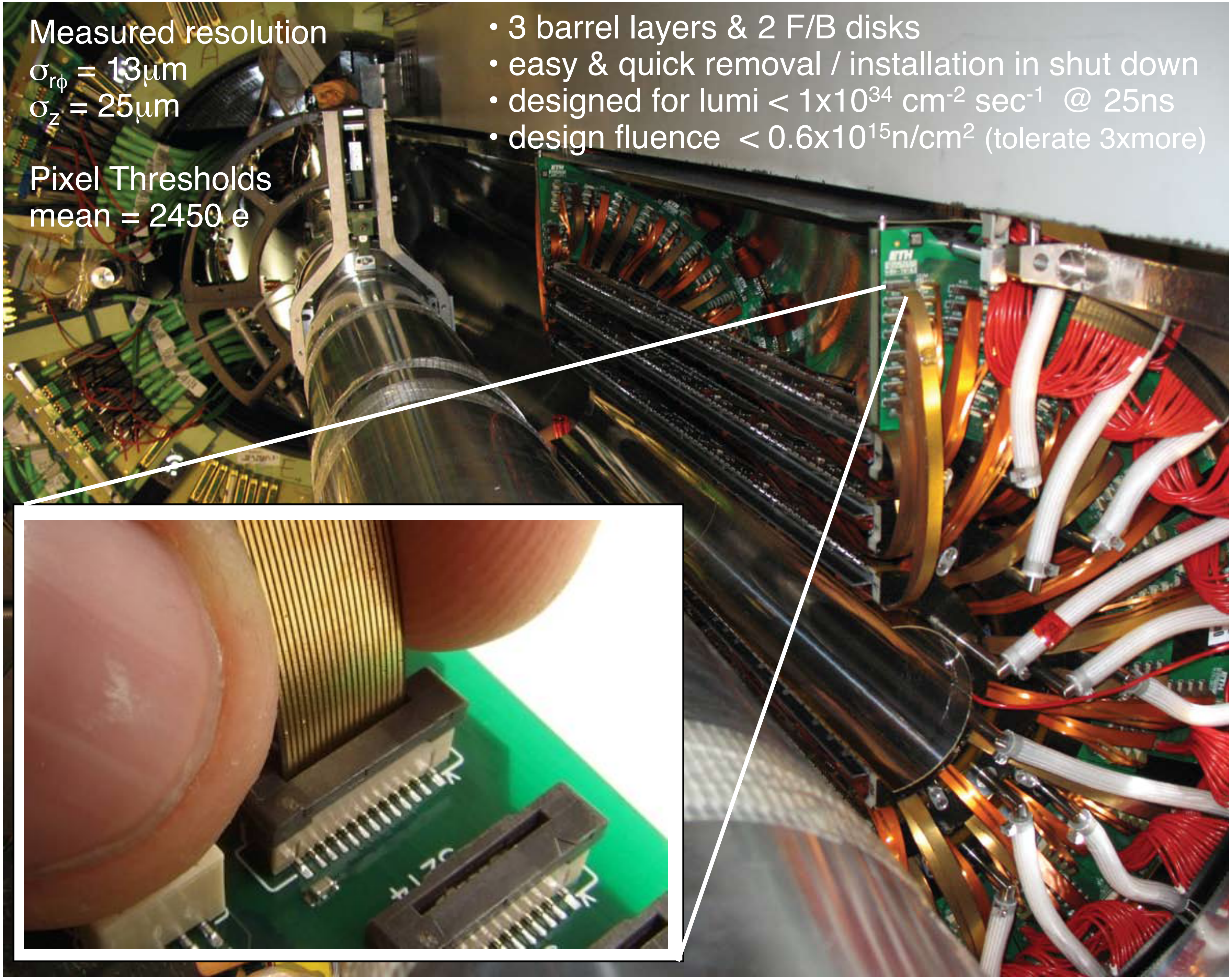
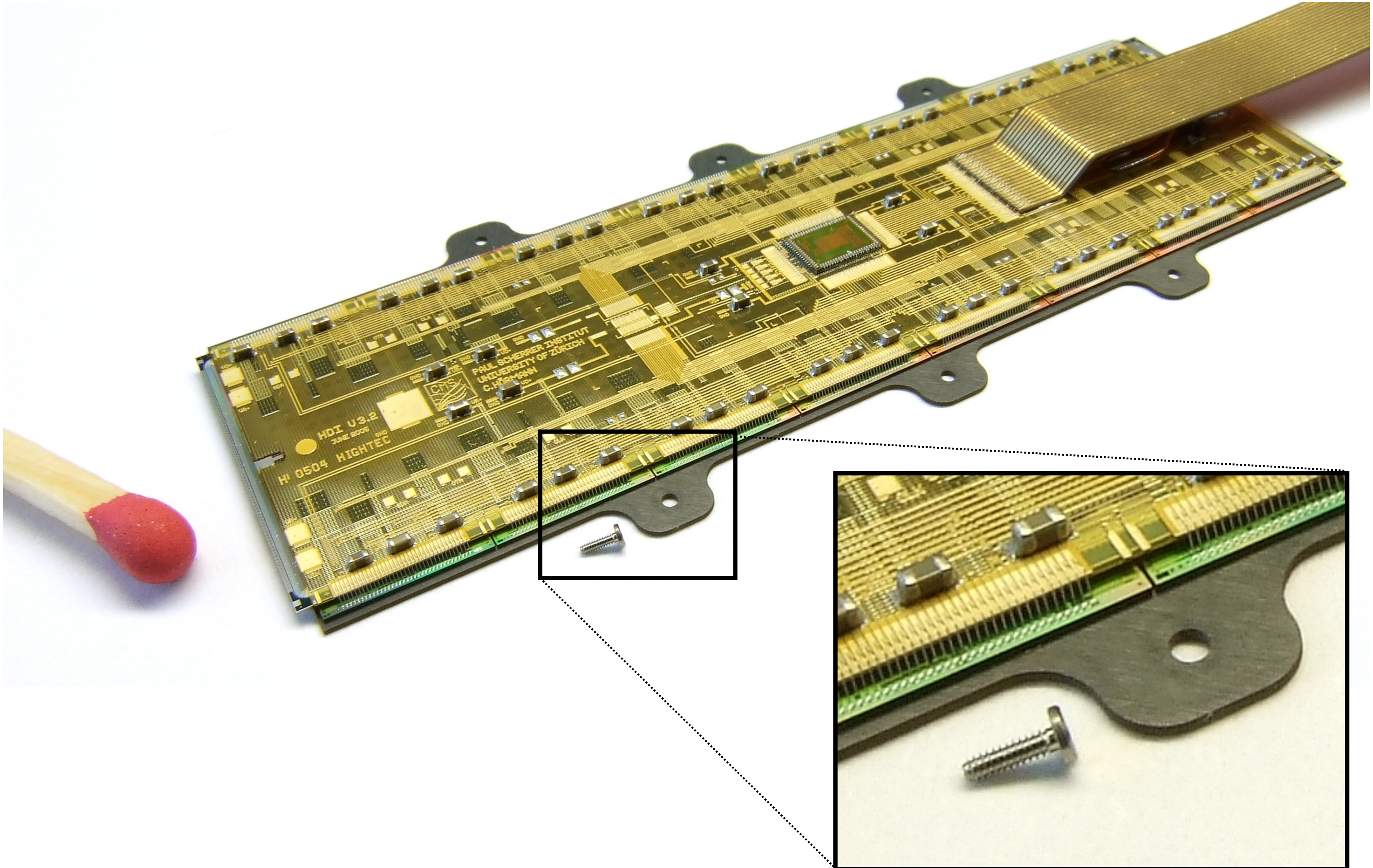


# Barrel Pixel installed, ready for Forward Pixel

# CMS Pixel Modules (BPIX)




Photos: S. Streuli. PSI

# Operation of Present Pixel Detector

- >99% single hit efficiency
- 13 µm resolution in rφ (mesured)
- 25 µm resolution in rz (measured)

- Thresholds of 2450 electrons

Working very well to date

- 97% operational < BPIX+FPIX>
- 99% uptime

Main issues

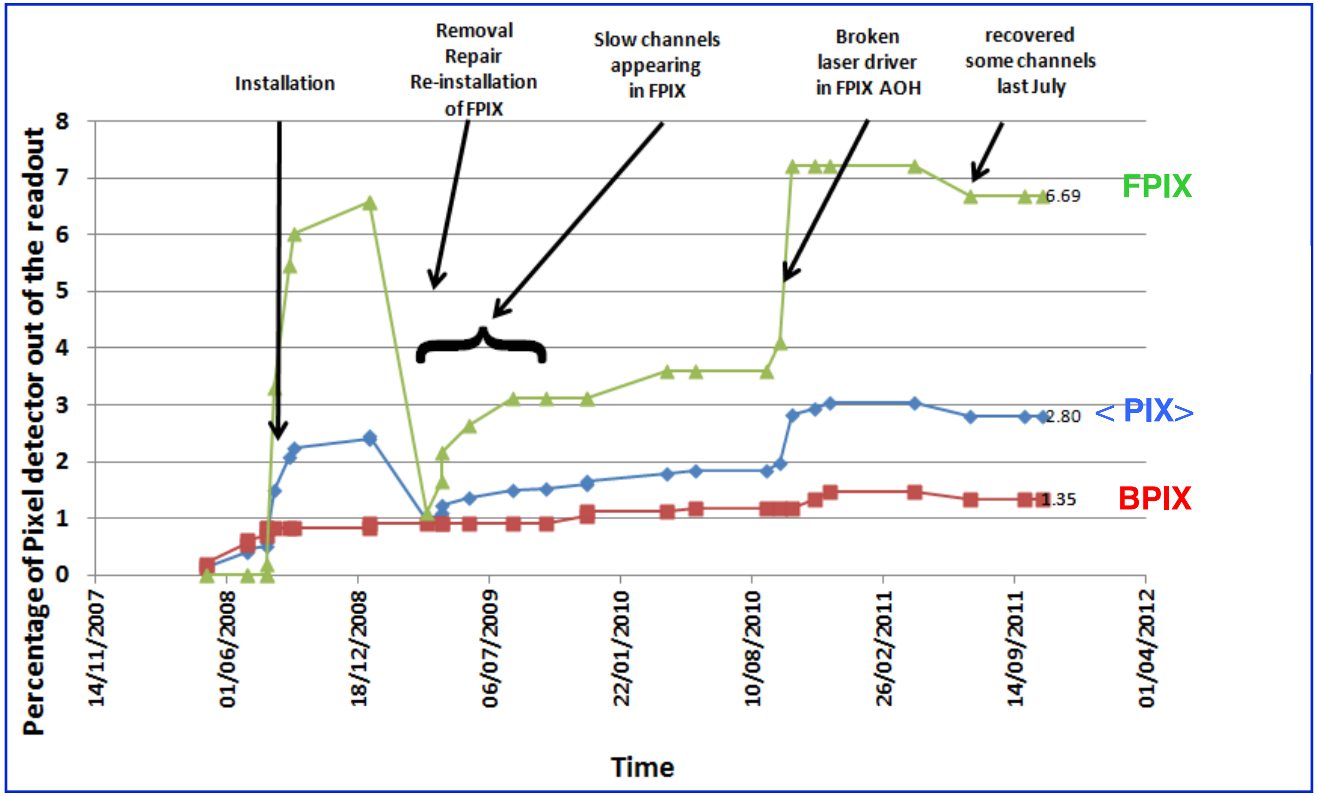
- Beam-background events (PKAM)
- Radiation effects ($I_{leak} \sim r^{-1.25}$)
- Parts failures, though progress made to recover lost parts.

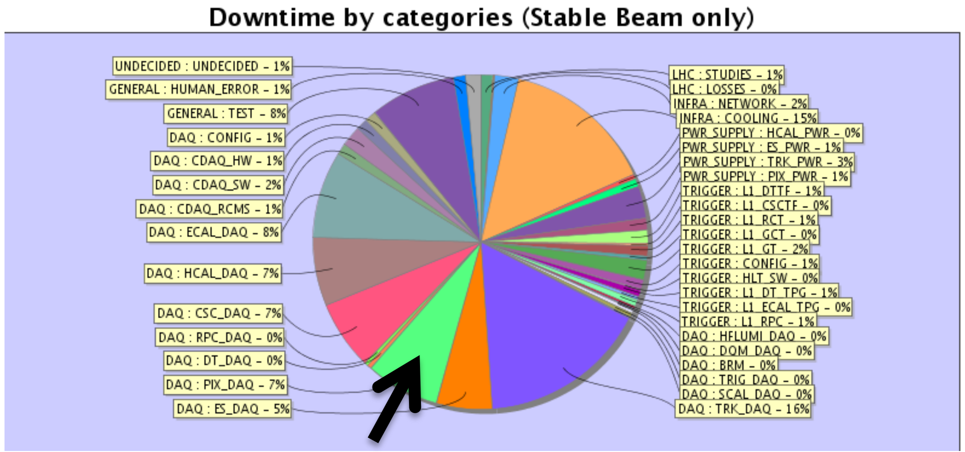
Next removal and service in 2013/14 long shutdown (LS1)

→ remove old beam pipe & install new OD=45mm beam pipe (end 2013)

Very shallow beam induced tracks in BPIX , so called PKAM events → timeouts in Pixel DAQ

Xmas 2011/12 vacuum problem fixed at -18m



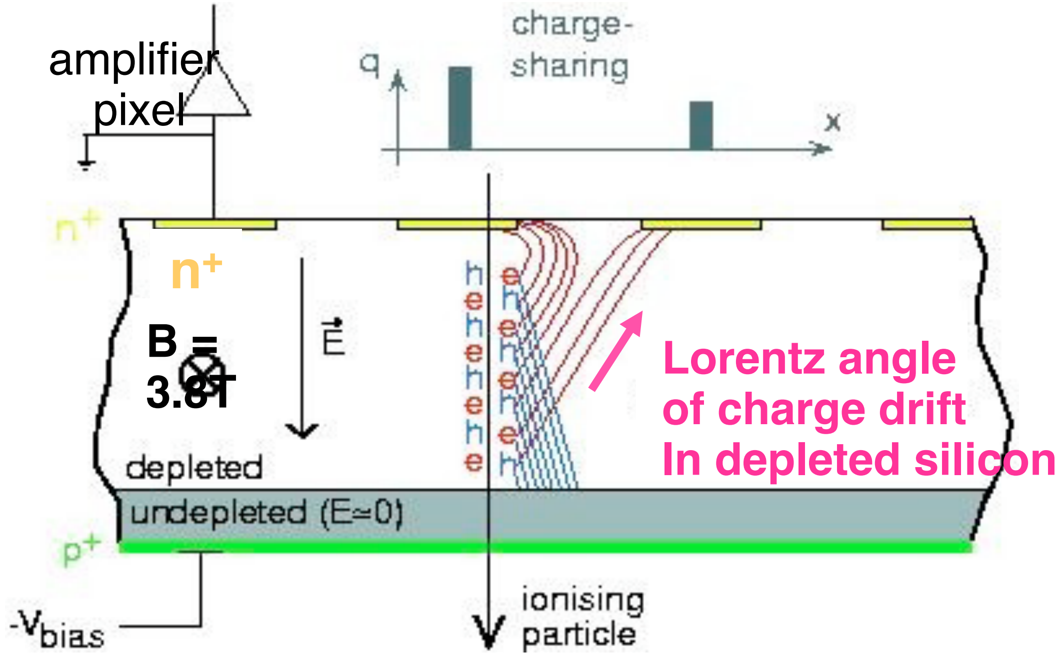
# Pixel Sensor: Precision by Sharing

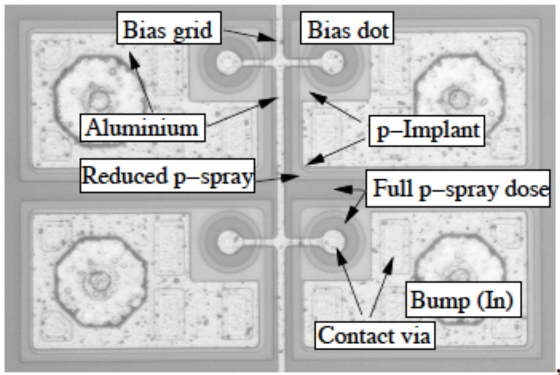
Signal charge sharing by Lorentz angle

→**precise coordinates in rφ → z**

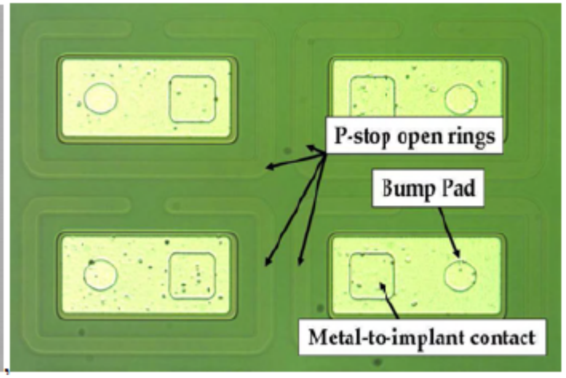
- n+-on-n silicon sensors
  - 100 μm x 150 μm pixels
  - Collecting electrons
    - Strong Lorentz effect
    - Profit from charge sharing for improved resolution
    - rad. degradation → loose rφ resolution but keep robust hits
- Two sensor variants, developed for endcap FPIX and barrel BPIX separately with two vendors
  - P-spray (**BPIX**)
  - Open p-stops (**FPIX**)

see no need for immediate new sensor technology in Phase 1




BPIX sensor




FPIX sensor

Ref: W. Erdmann, Int. J. Mod. Phys. A Vol. 25, No. 7 (2010) 1315

# CMS Pixel Read Out Chip

- **4160 pixel / chip**
- pixel size **100μm x 150μm**
- **251 transistors /pixel** → 60μ²/FET
- **35μW/pixel**, pixel ampl. 20nsec peaking
- on chip regulators 2.6-2.1V → 1.9V
- analog coded readout of addr. & p'height
- operating **pixel threshold = 2500 e**
- radiation hard design (~4 x$10^{15}$ p/cm²)
- designed for pixel hit rates <100MHz/cm²

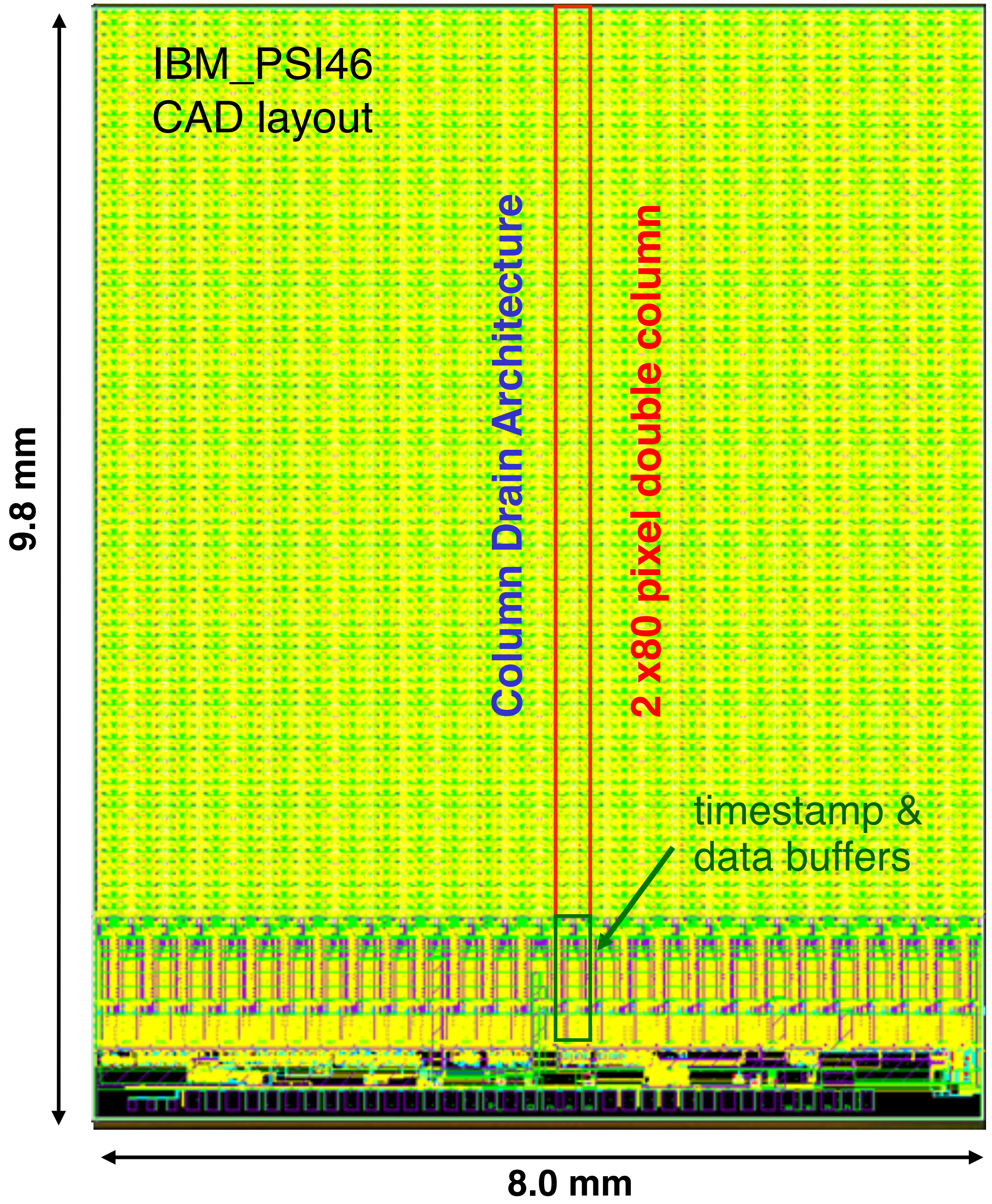
**Time Stamp & Data Buffers in DCOL**

TS buffers 12 deep

DB buffers 32 deep

Buffer depth in DCOL are leading order limitation of ROC eff. at high rate LHC.

Data throughput in Column Drain not our problem yet → later yes



# Limitations of Present Pixel Detector

- Designed for radiation fluences of $6x10^{14} n_{eq}/cm^2$
  - ROC with sensor irrad.tests show at least 3-4 more → rad. damage not main issue

- More passive material in support structures than needed
  - e.g. cooling designed for larger power DMILL readout chip pre-dating 250nm CMOS

- 3 Layer system designed for 20-25 PU events of nominal LHC operation
  - future LHC operation with 50 PU or even 100 PU events will require more robust track seeding by pixel system.
  - defects (thermal contacts & lost modules) in silicon strip TIB need more pixel hits

- Readout designed for nominal LHC conditions of $10^{34}$ Hz/cm$^2$ and 25ns bunch spacing → operations beyond this and 50ns bc timing impose serious limits
  - ROC data losses at 2x $10^{34}$ Hz/cm$^2$ and 25ns ~16% data loss for BPIX layer-1
  - Optical links from pixel modules to FED & DAQ impose limits at 50nsec operations beyond $1.3x10^{34}$ Hz/cm$^2$ ( same for 25ns at $2.6x10^{34}$ Hz/cm$^2$ and 100KHz L1)

- Tracking and vertexing, important to almost all physics analyses, will be compromised for operations significantly above $10^{34}$ Hz/cm$^2$ and/or 50ns

# Proposed Pixel Upgrade

- BPIX 3 Layer → 4 Layers
- FPIX 2x2 Disk → 3x2 Disk

Increase number pixel tracking points 3 → 4

- $CO_2$ cooling based Ultra Light Mechanics
- Shift material budget out of tracking $\eta$–region

Significant $X/X_0$ reduction

- Minimize 1 Layer radius

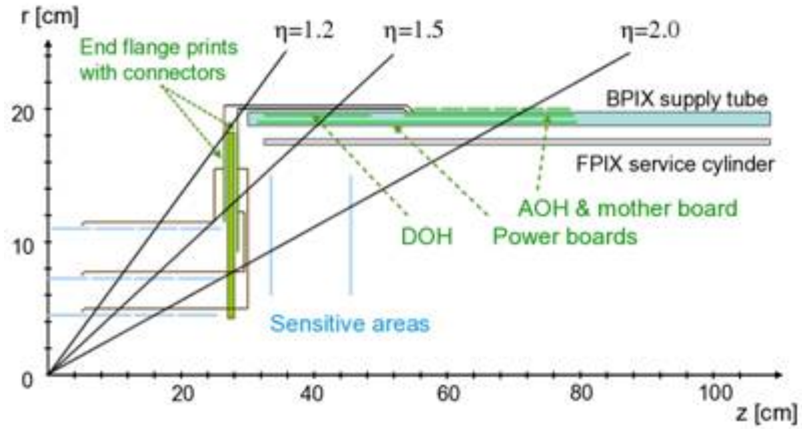
reduced impact $\delta_{xy}$ & $\delta_z$ error

- ROC modifications for operation up to L ~ $2x10^{34}$
- Use same cabling → DC/DC converters for power
  → 320MHz digital readout on fibres

→ pixel tracking & vertexing significant improved and robustified

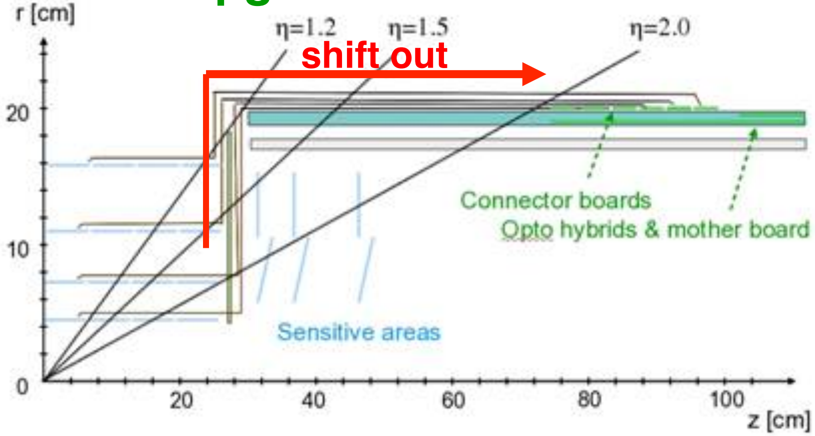
# Shift material budget out of tracking region

**Current BPIX Services**

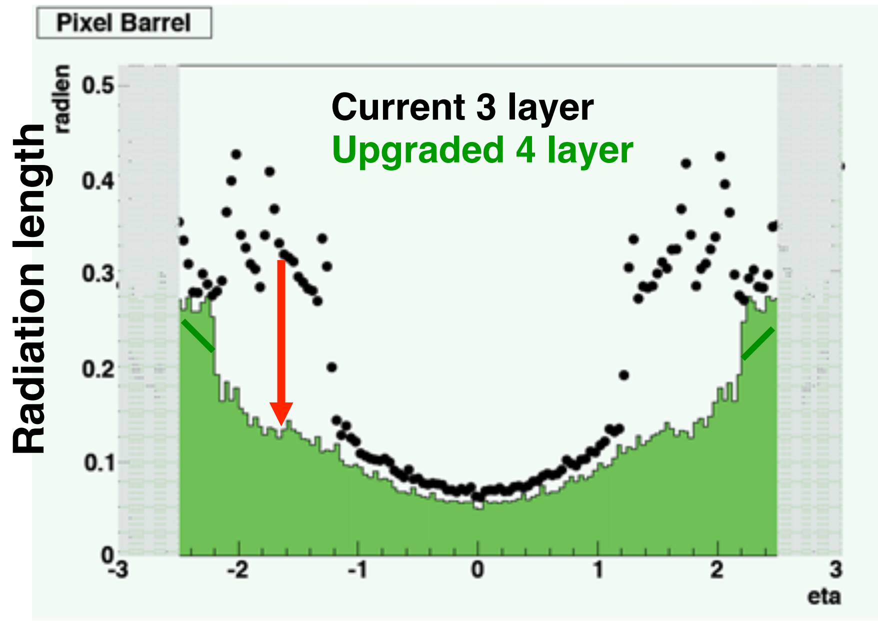


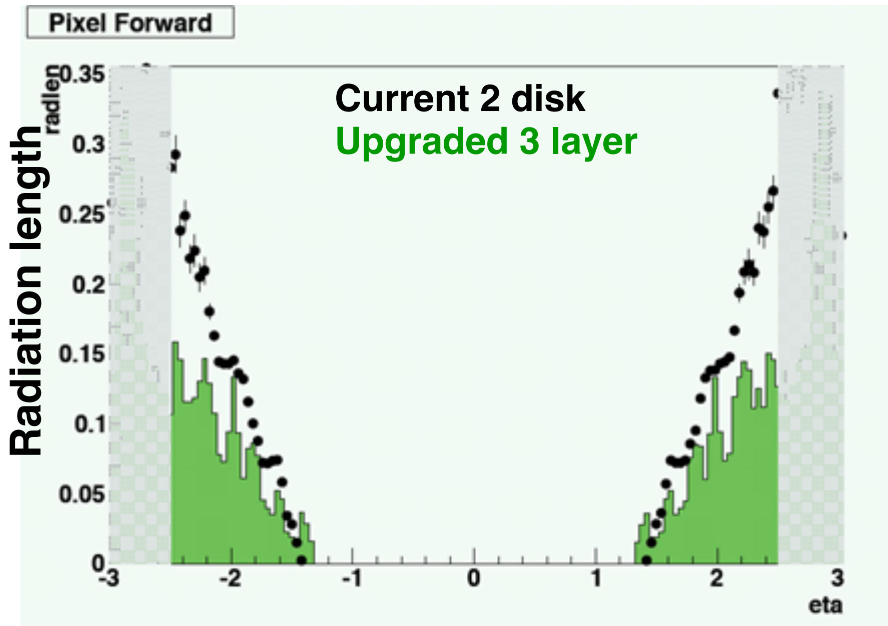

**η<2.2 : weight = 16.9 Kg (3 layer)**

**Upgraded BPIX Services**



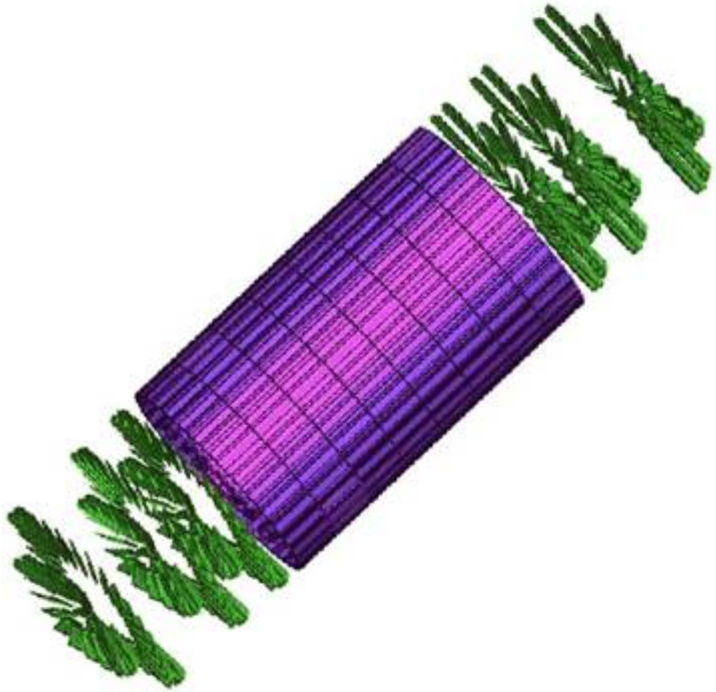

**η<2.2 : weight = 6.5 Kg (4 layer)**

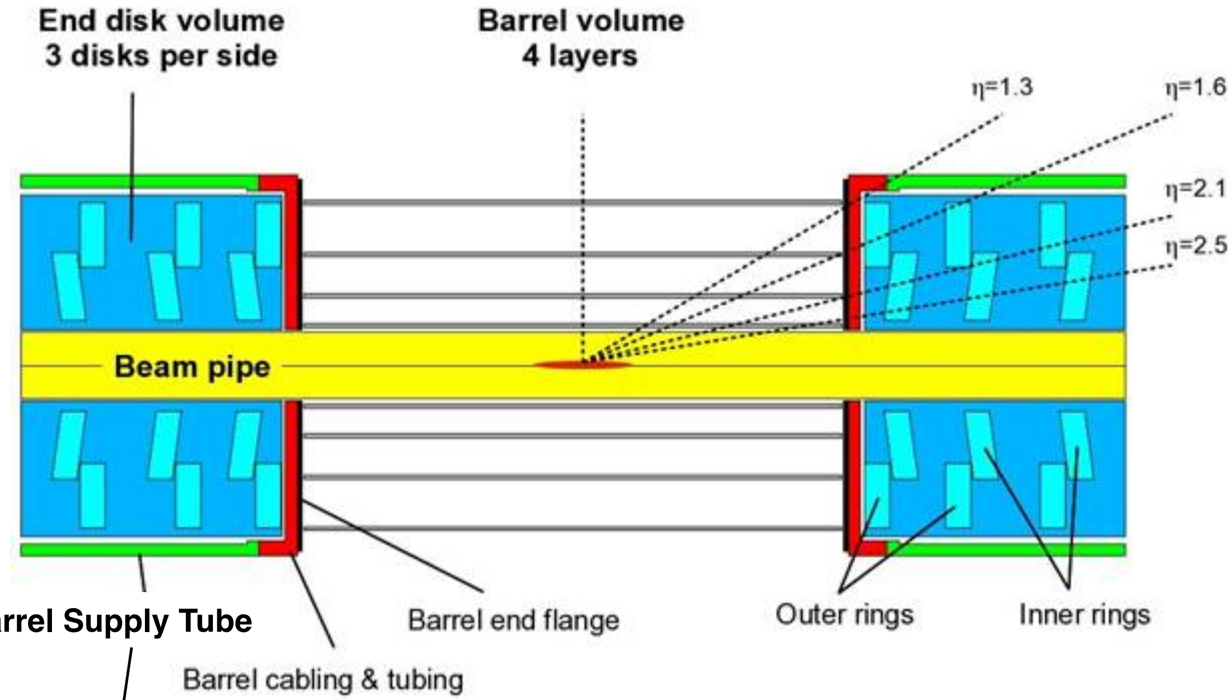


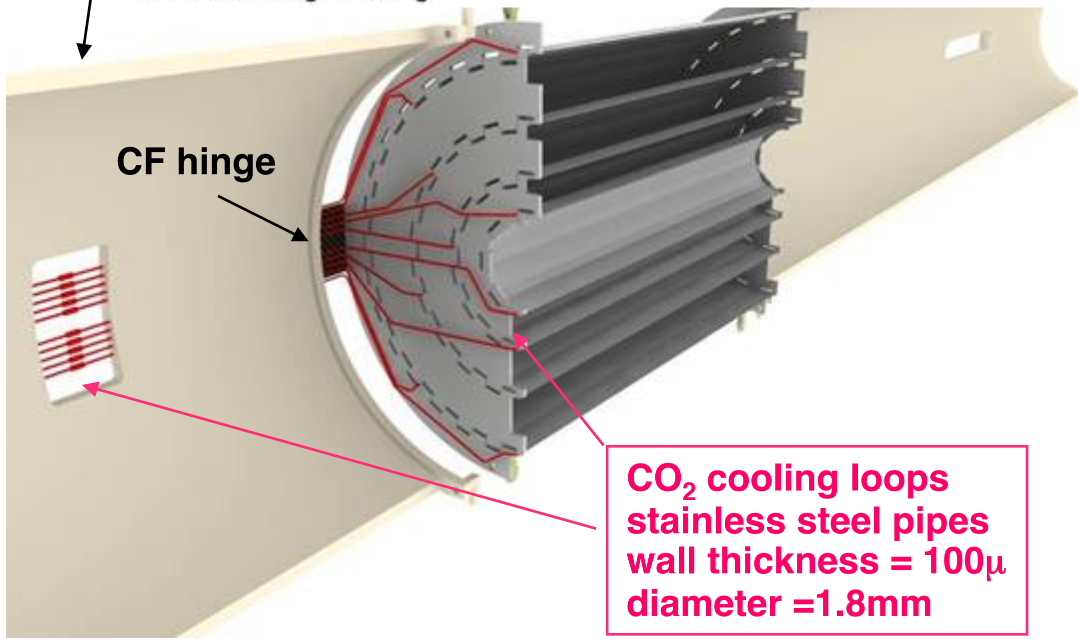

η ~1.5 : γ-conversion for H→ γγ from 22% to 11% for new 4 Layer Pixel System

# BPIX / FPIX Envelope Definition & Insertion into CMS



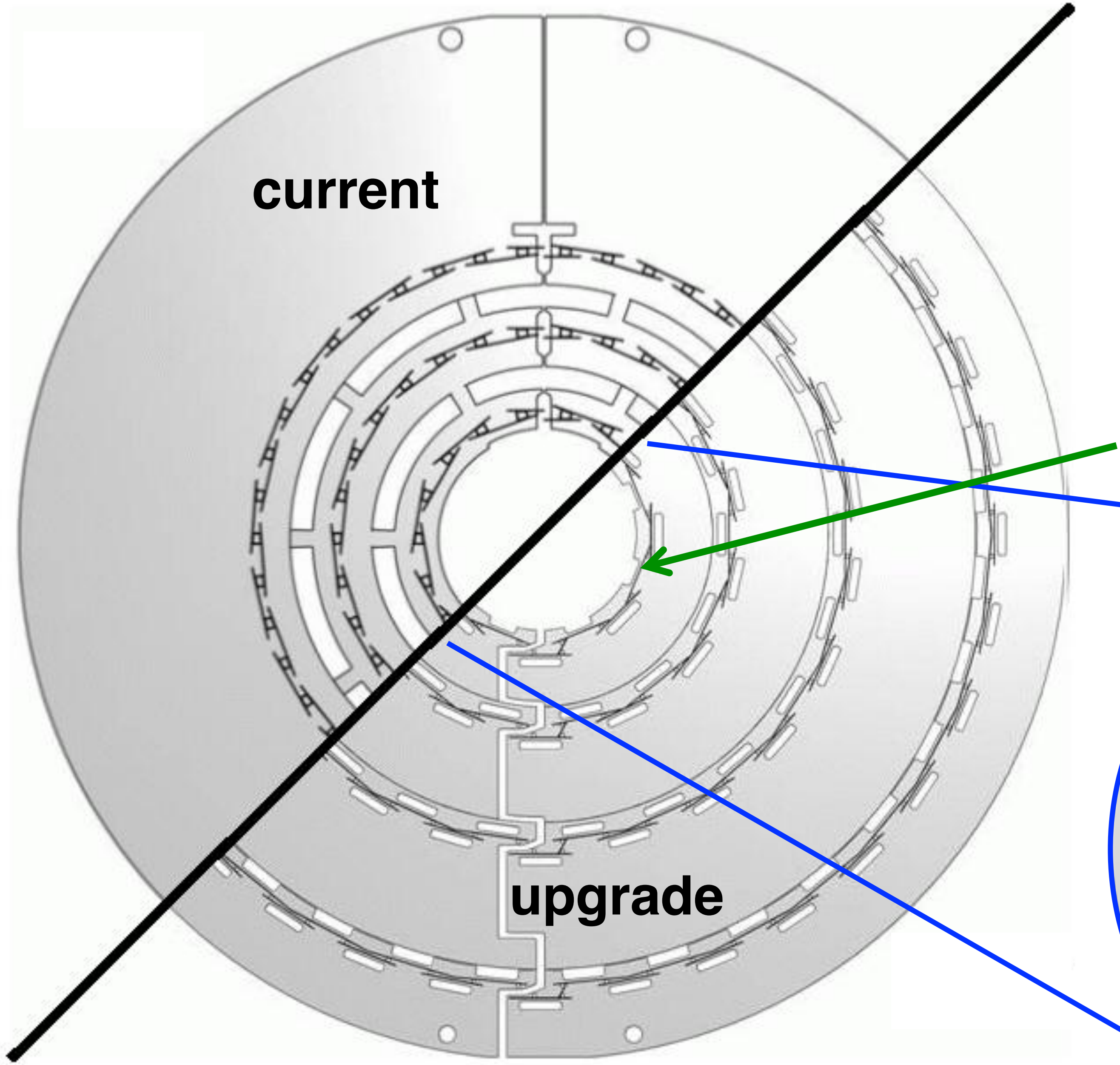



Insertion of new BPIX with 12 face L1 only with closing mechanism !



# BPIX Upgrade Mechanics

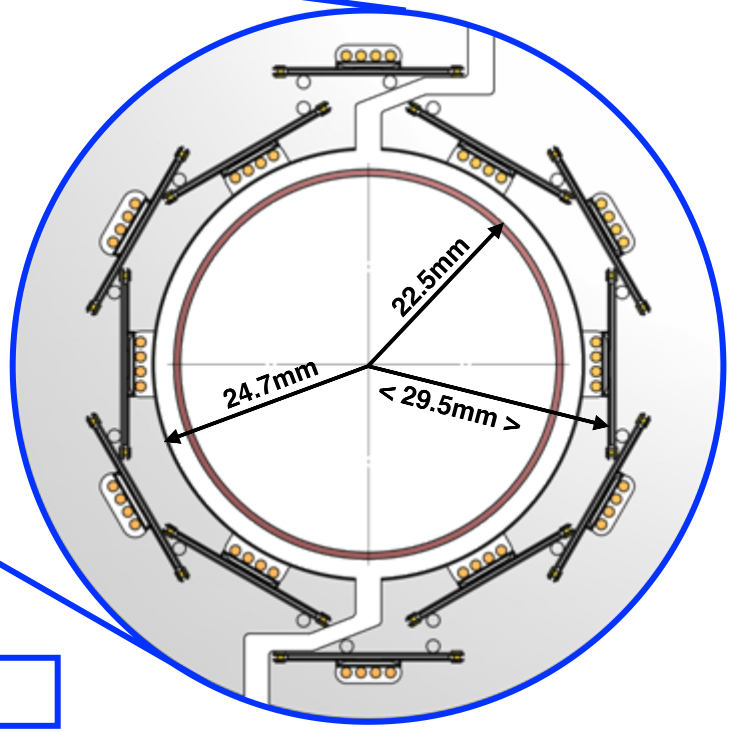
→ **81M pixel** (1.6 x present BPIX)




- **Full module type only**

**Layer 1: r = 30mm; 12 faces**
**Layer 2: r = 68mm; 28 faces**
**Layer 3: r = 109mm; 44 faces**
**Layer 4: r =160mm; 64 faces**

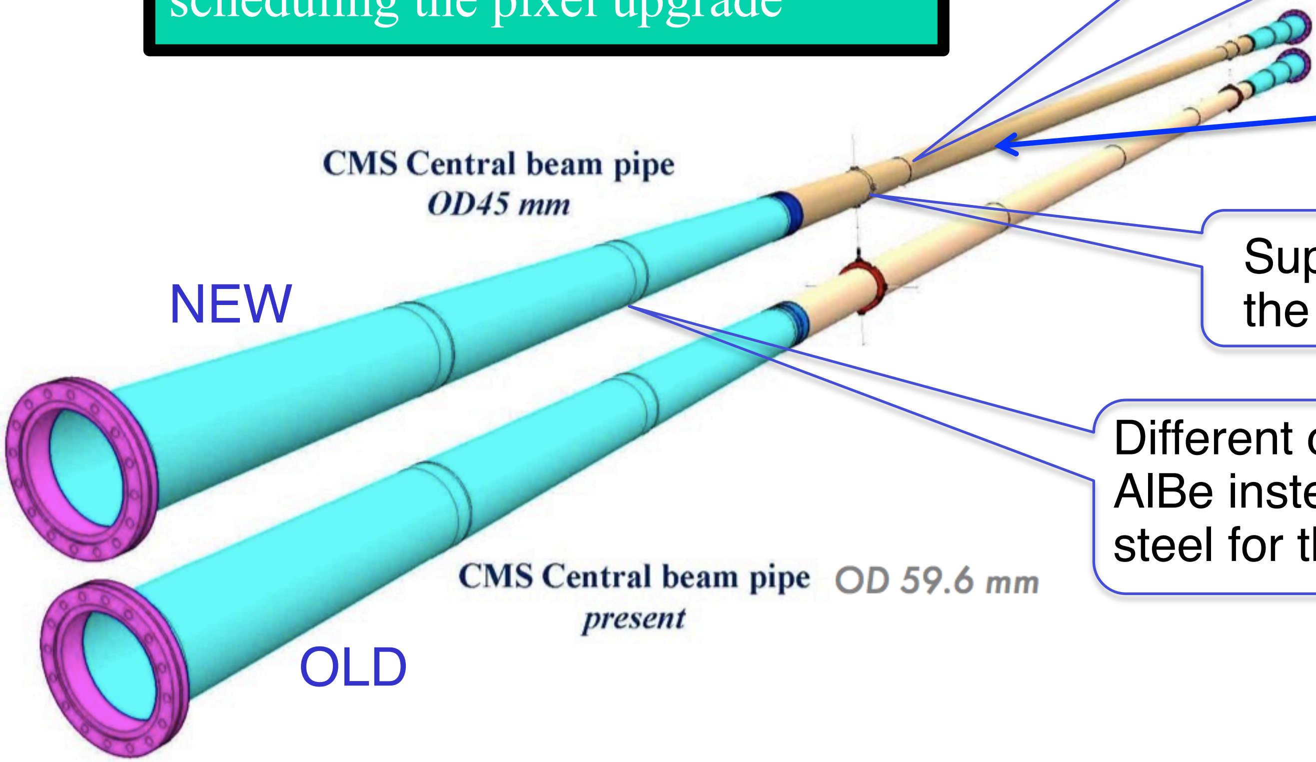
**fall back with old beam pipe**
**Layer 1: r = 39mm ; 16 faces**




**beam pipe OD = 43 mm → 1st Layer: 12 faces <R>=29.5mm**

# New Central Beam Pipe

Beam pipe installation foreseen in LS1 to allow most flexibility for scheduling the pixel upgrade



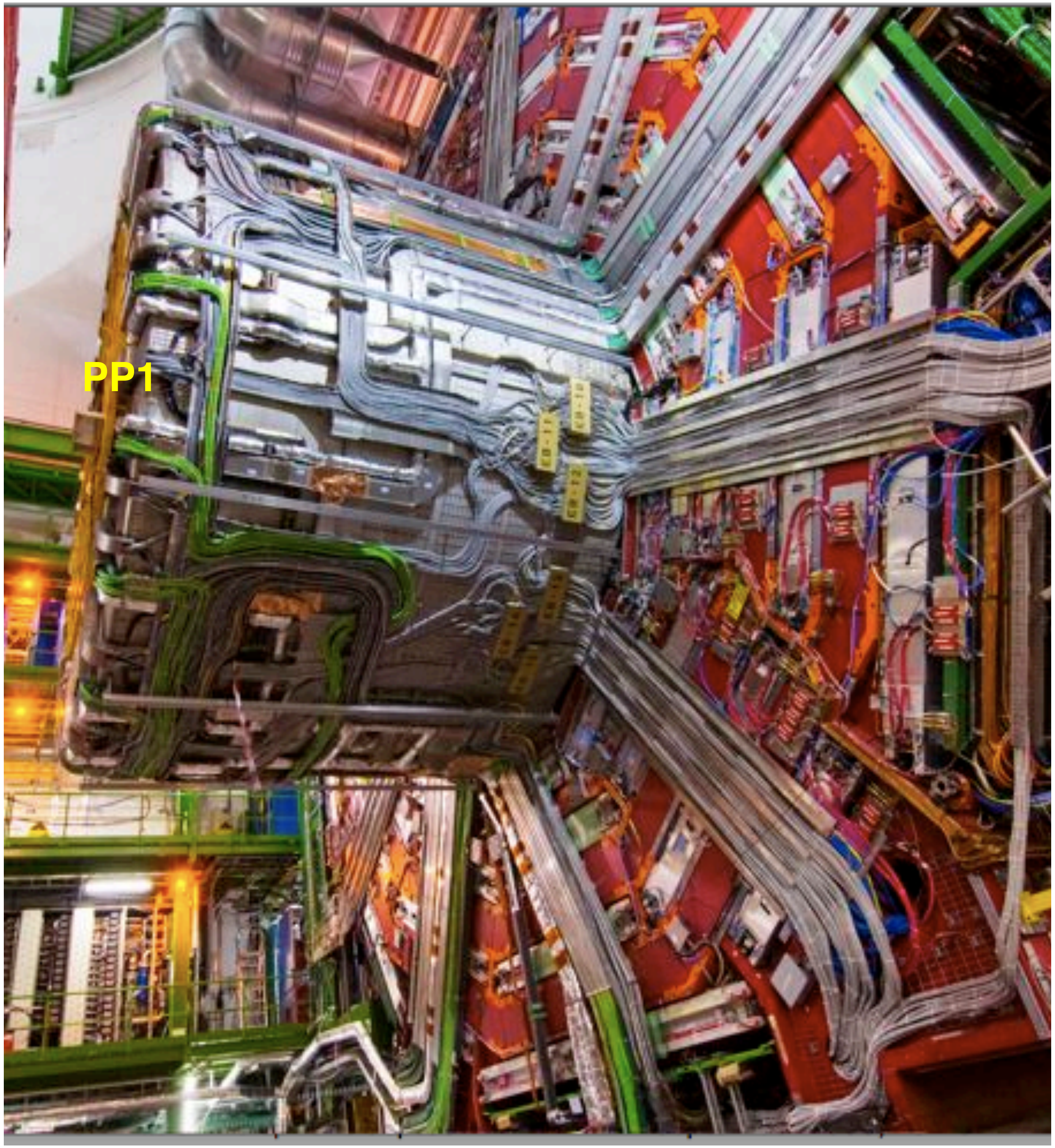

C. Shafer

**New central beam pipe EDR passed in 5. March 2012 → order ongoing**

# Constraint of Present CMS Services

- To bear in mind also, an important boundary condition for the upgrade
  - Must re-use services from balconies to detector "PP1" patch panel
  - Cooling pipes
  - Power cabling
  - Optical cabling

- Pixels and Tracker cables and pipes buried under ECAL/HCAL services



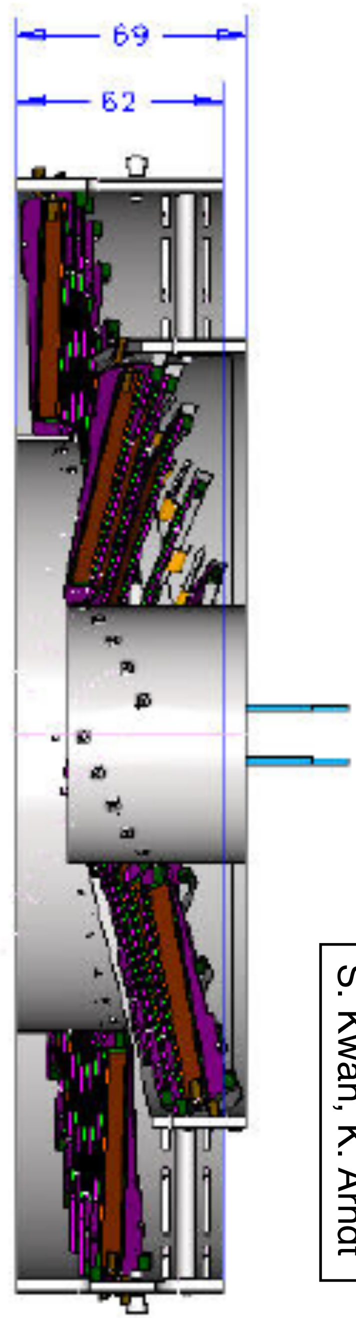

Pixel Phase I Upgrade installation planned 2016/17 Xmas shutdown

→ use same fibres
→ re-use Cu-pipes for $CO_2$ cooling

# Phase I Forward Pixel (FPIX)

- **Forward** (FPIX): Half disks with inner and outer rings
  - All blades using same 2x8 ROC module type on thermal pyrolytic graphite (TPG)
  - Blades on inner ring tilted outward by 12° in to optimize hit coverage
  - All blades are rotated by 20° around radial axis to enhance charge sharing and position resolution.
- Substantially lighter structure than present generation parts, also profiting from $CO_2$ cooling
- 6 disk of 112 sensors each
  - 672 modules
  - 10752 ROCs
  - **~44M pixel (= 2.5 x *present* FPIX)**

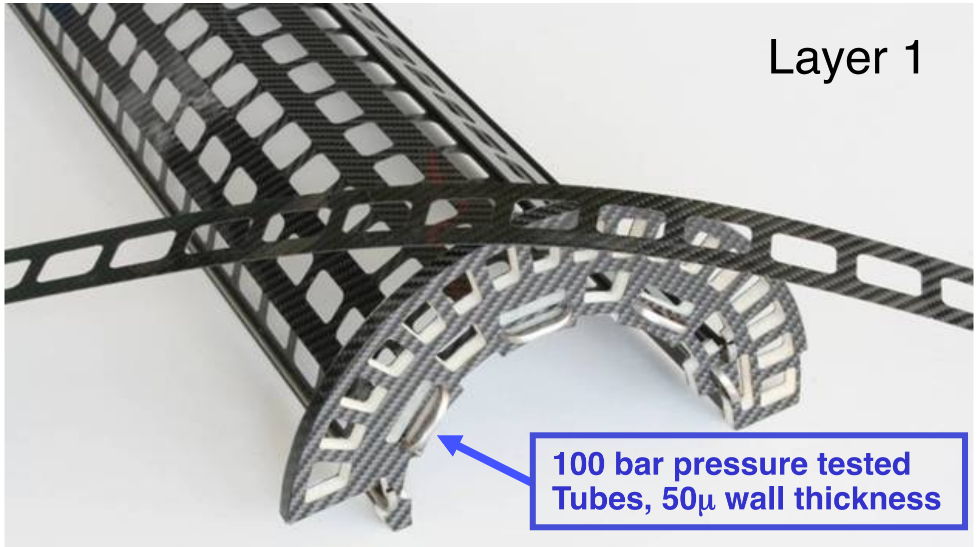
FPIX end cap half disks made by 2x8 sized modules (blades)



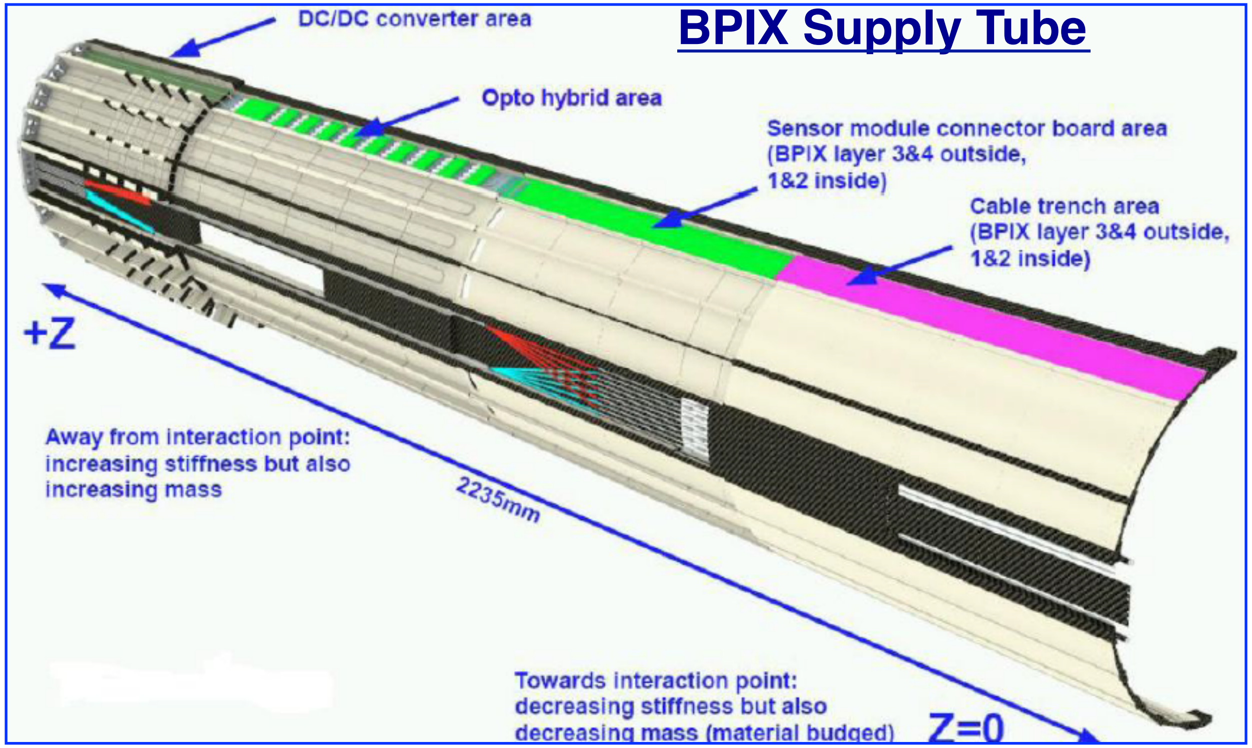

S. Kwan, K. Arndt

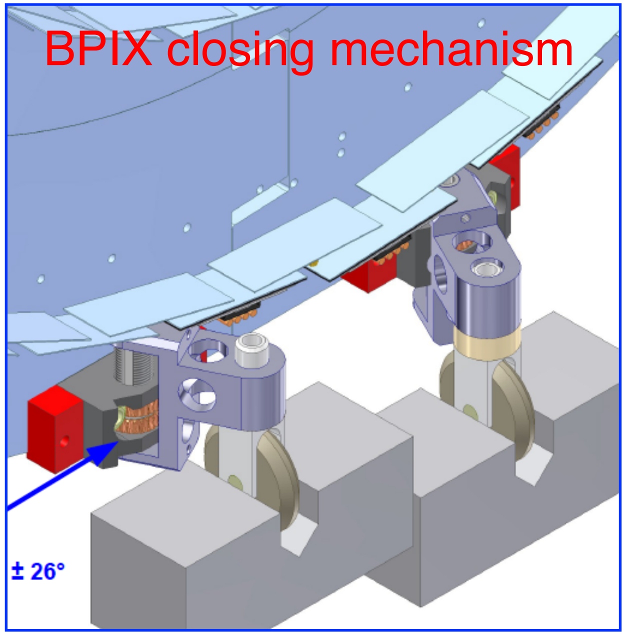
# Ultra Light–Mechanics for BPIX

- UL mechanics with integrated CO2 cooling. Supply Tube heat sources as preheaters for CO2 loops.
- Large effort on insertion procedure and tooling, including fine-adjustment of BPIX positioning around the new beam-pipe




Weight Layer1 42g + 7g $CO_2$ → 30% of old first layer $X/X_0$

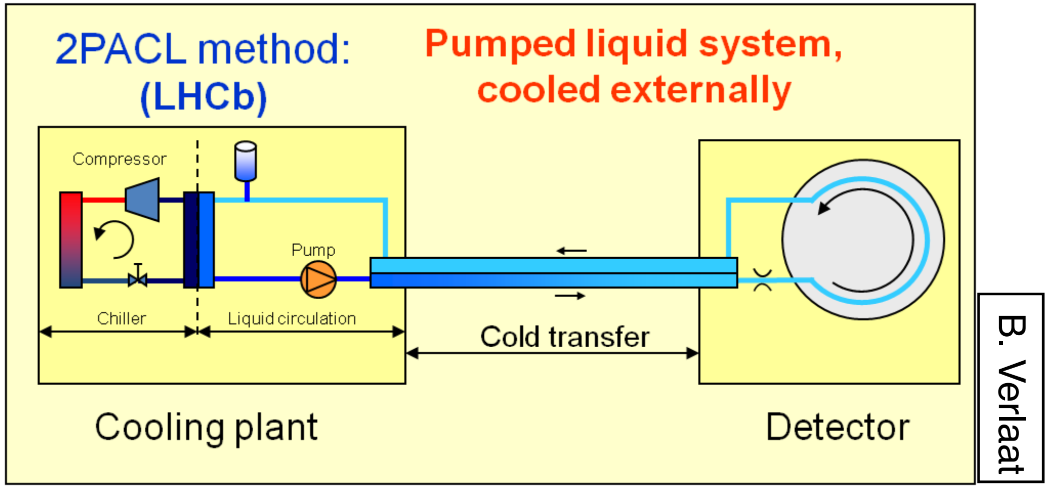


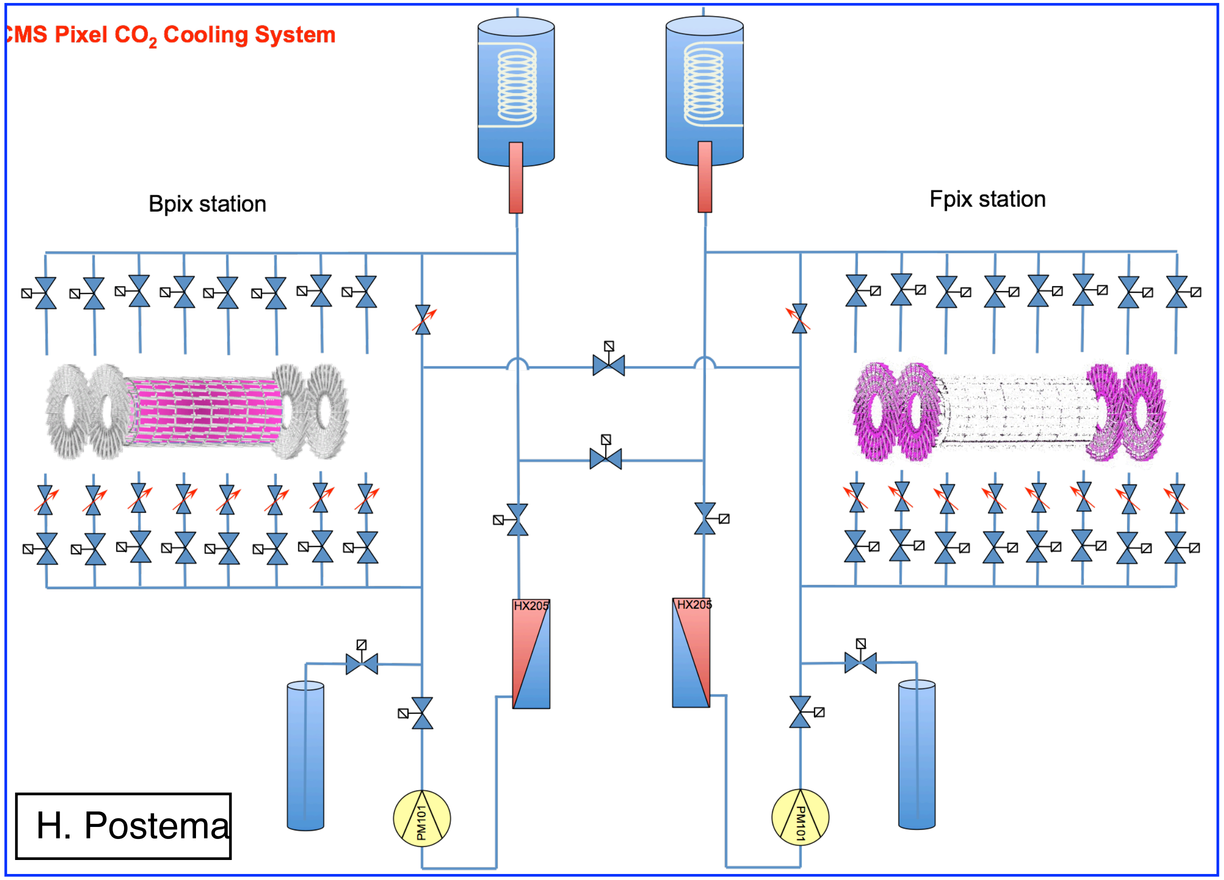




S. Streuli, PSI Villigen

# $CO_2$ Cooling for a Lighter Detector

- Use 2PACL method
  (2PACL = 2-Phase Accumulator Controlled Loop)



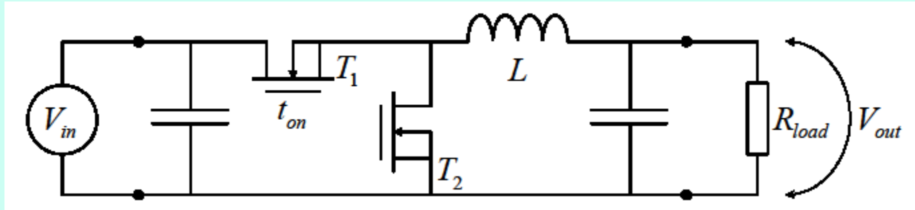




- Two systems will be installed, 1 FPIX, 1 BPIX
- Different temperatures possible for FPIX and BPIX
- ***Redundancy***: BPIX and FPIX can both be run on either one of the two cooling plants

# DC-DC LV Power Converters

- LV power conversion 12V → 2.5V by DC-DC Buck converters
- Efficiency ~ 75-80%
- Use for beginning old CAEN 4603 power supplies
- Total 1183 converters

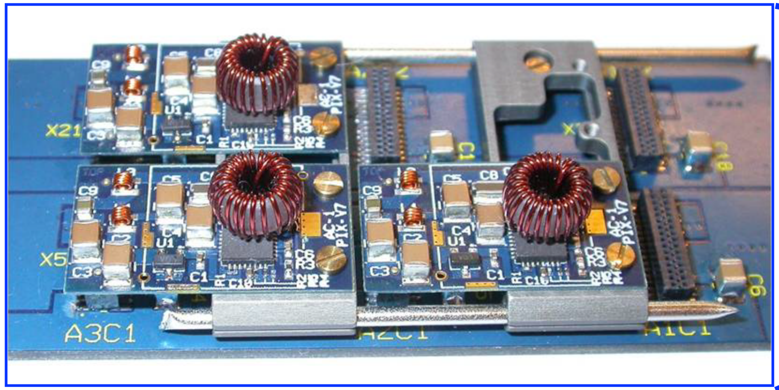
"Buck" converter

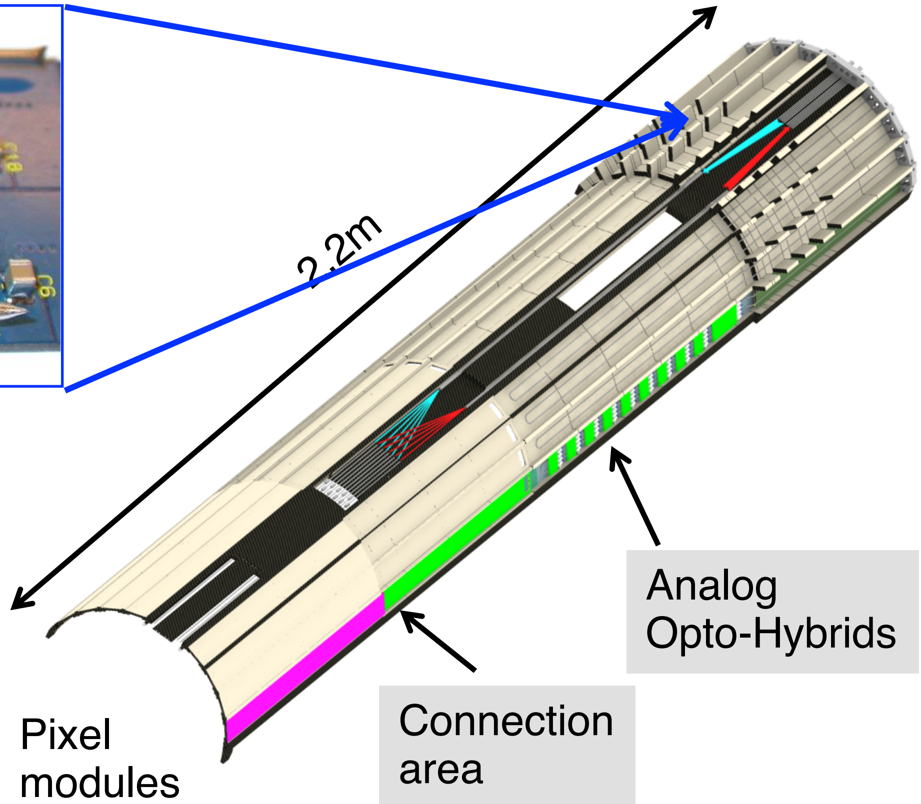



Idea: P = U·I = (rU)·(I/r) with conversion ratio r > 1

Duty cycle $D = t_{on}/T$; $1/D = I_{out}/I_{in} = V_{in}/V_{out} = r$

K. Klein et al. TU Aachen




$CO_2$ cooling of DC-DC converters as pre-heat of the incoming $CO_2$ to reach proper 2-phase state

# New CMS Pixel ROC

Two step development:

**Step1** (Jan. 2012, 250nm CMOS)

pixel rates < 250 MHz/cm$^2$

DC level changes
DB buffer 32→80
TS buffers 12→ 26

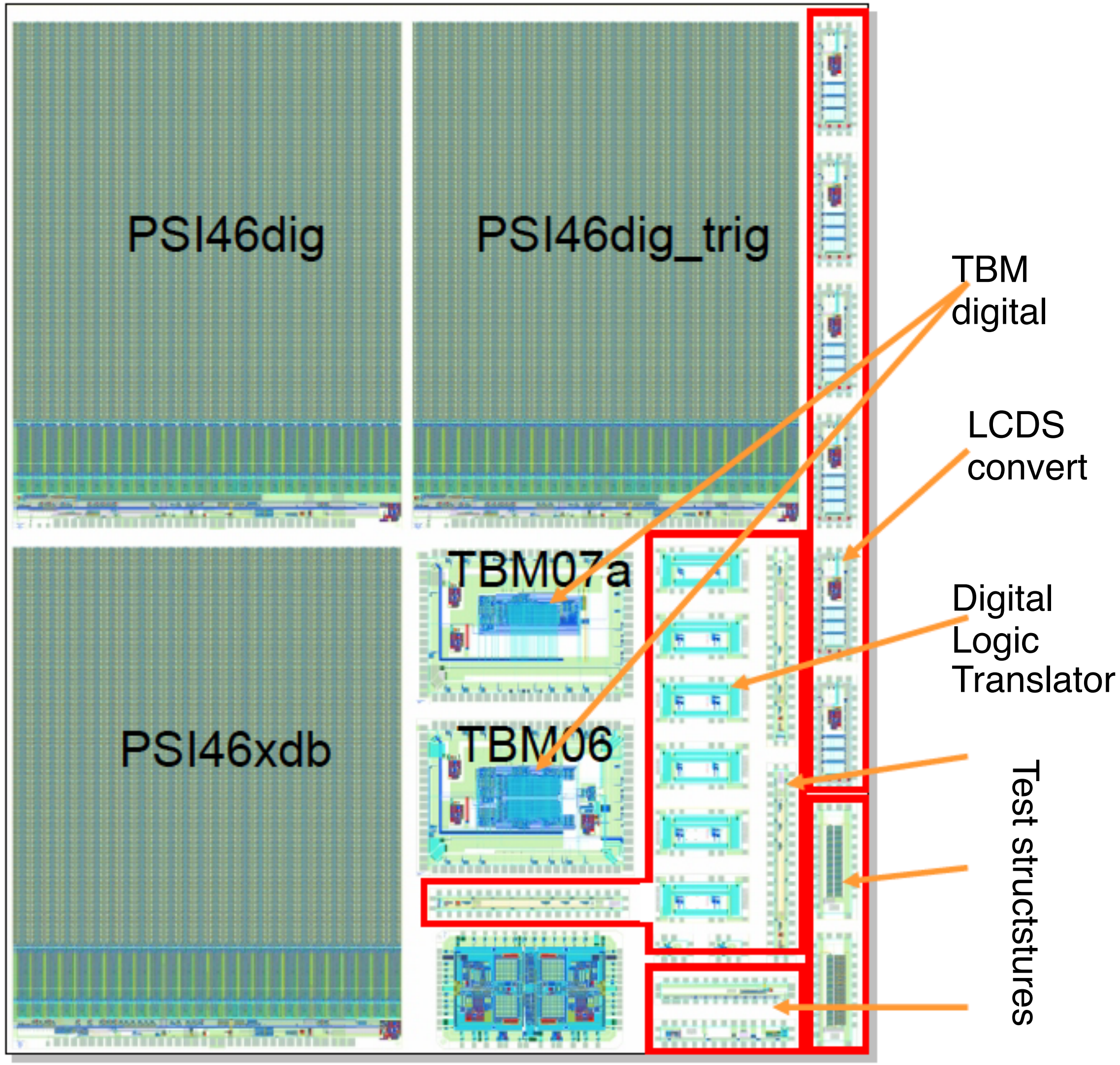
ROC level changes
readout buffer
ADC (8bit) for pixel pulse heights
160Mbit/sec serial digital out
6th metal → less power droop
reduced X-talk → lower thresholds

no changes to PUC & CD-Arch.

**Step 2** (→ Sept. 2012, 250nm CMOS)

pixel rates < 600 MHz/cm$^2$

modify and improve performance of Column Drain Architecure & reduce "reset" data losses in DB




Beat Meier et al. PSI

# Data Read-Out & DAQ Strategy

Smooth start up after installation **very, very important** !

Currently plan to reuse at start up existing front end data cards (FED) and control electronics (FEC) as is. (it's the software stupid!)

Minimal FED modification by de-serializer FPGA on mezzanine boards with 12-channel Zarlink opto-receivers

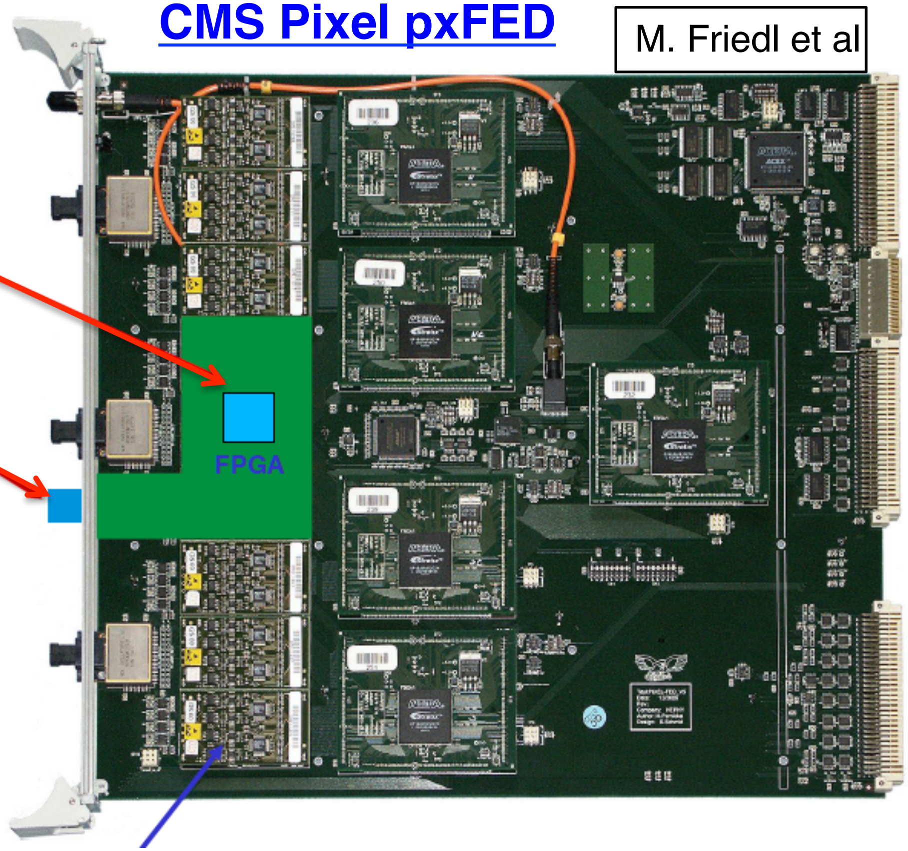
Data output rate of pxFED is currently limited by CMS DAQ to ~200MB/sec and currently limiting factors for higher LHC luminosity at 50nsec operation.

Can be improved to 640MB/sec limit of current pxFED

Longterm solution pursued in direction of uTCA standard. (RAL, UK)

CMS Pixel pxFED

M. Friedl et al

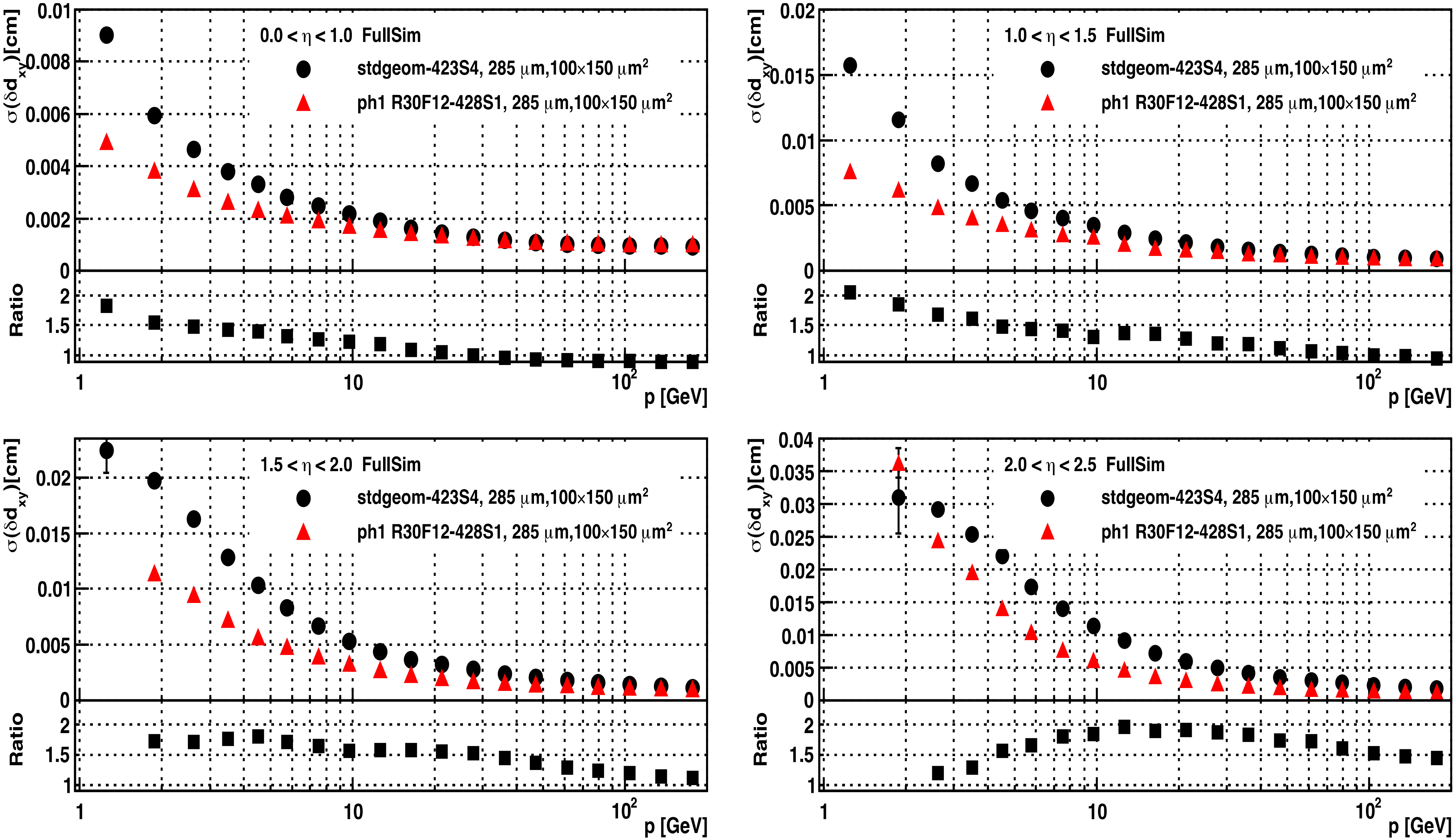



New card replaces 3 present ADC daughter boards processing analogue optical input

# Transverse Impact Parameter of old / new Pixel

new BPIX : Layer 1 with 12 faces → beam pipe OD = 45mm

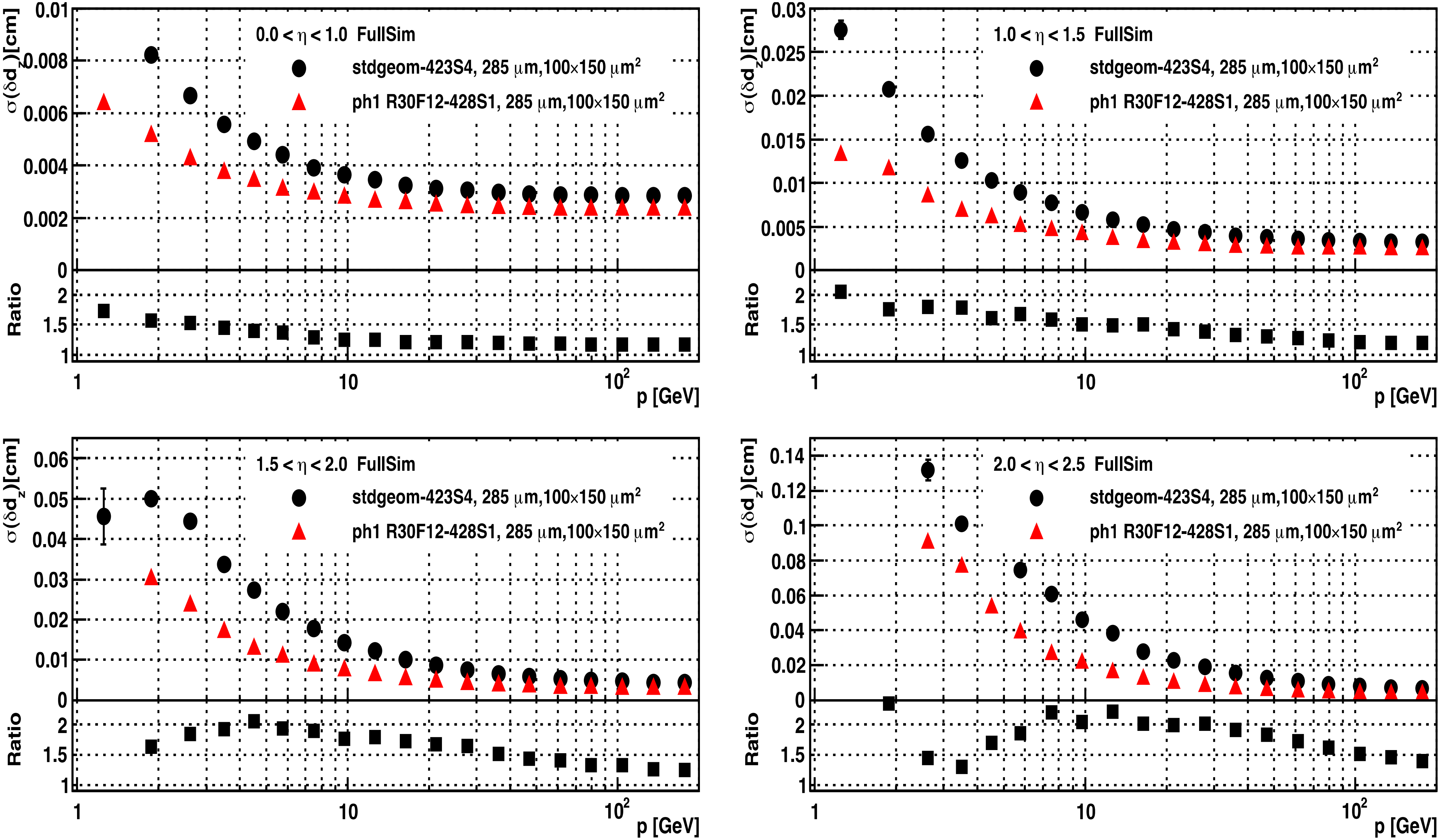
H. Chang / A. Tricomi



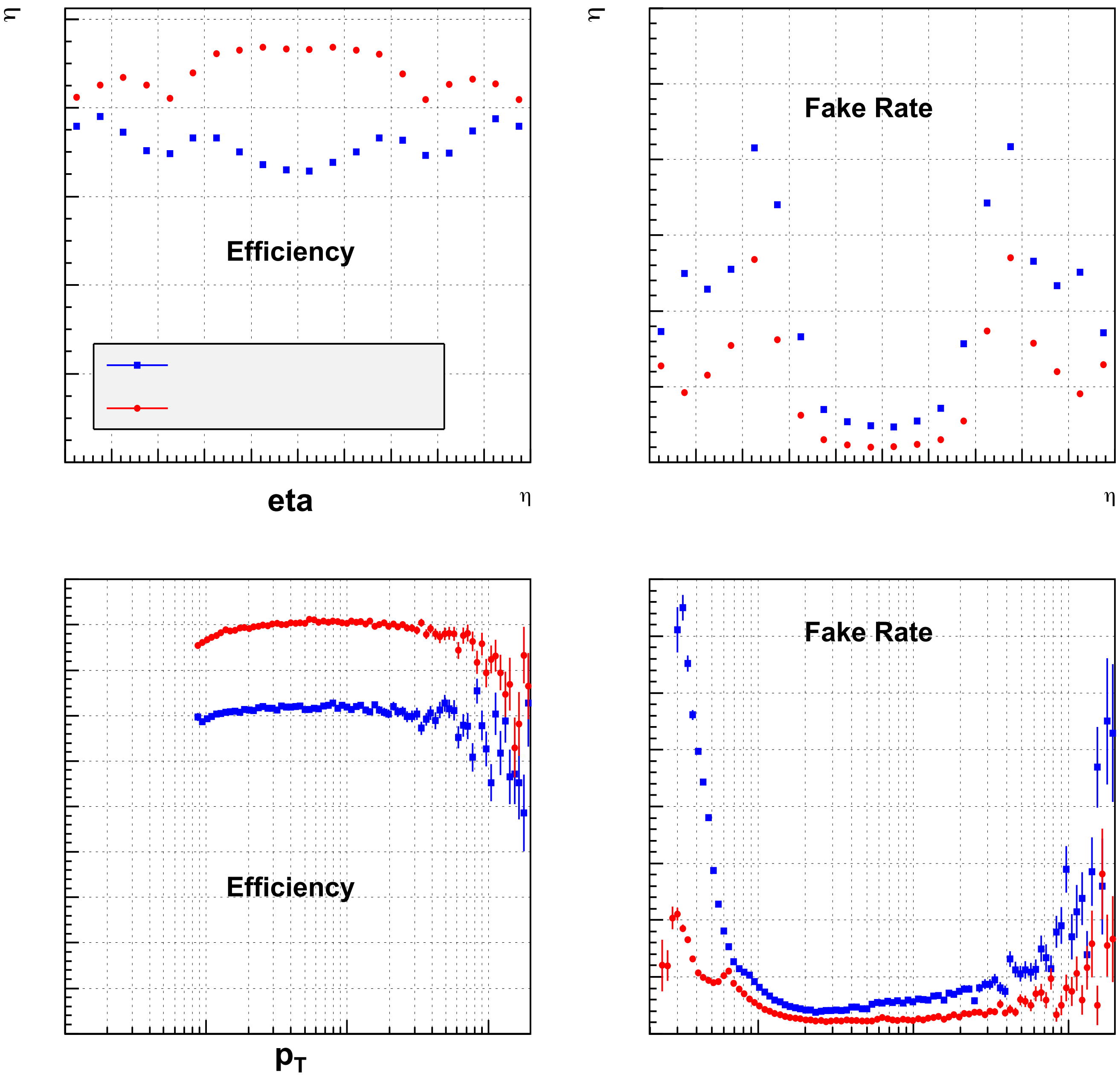
# Longitudinal Impact Parameter of old / new Pixel

new BPIX : Layer 1 with 12 faces → beam pipe OD = 45mm

H. Chang / A. Tricomi



# Tracking / Seeding Efficiencies & Fake Rates




ttbar sample, high purity tracks

~50 PU at 25ns

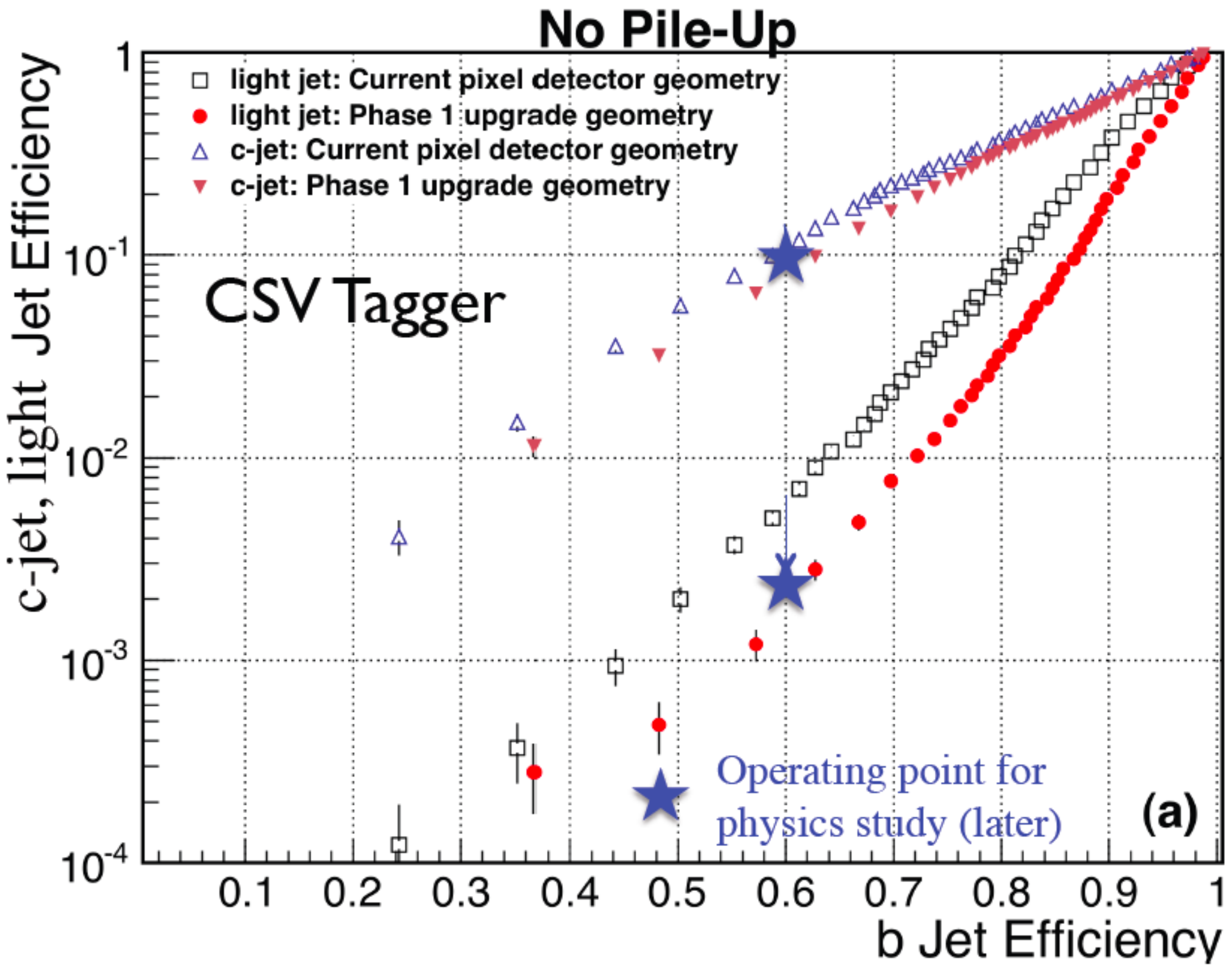
Upgrade improves tracking efficiency, and fake rates at high PU

**Current Pixel Geometry**
**Phase 1 Upgrade Geometry**

H. Chang / A. Tricomi

# b-tagging of Current / Upgraded Pixel System

- <PU>=0, ttbar



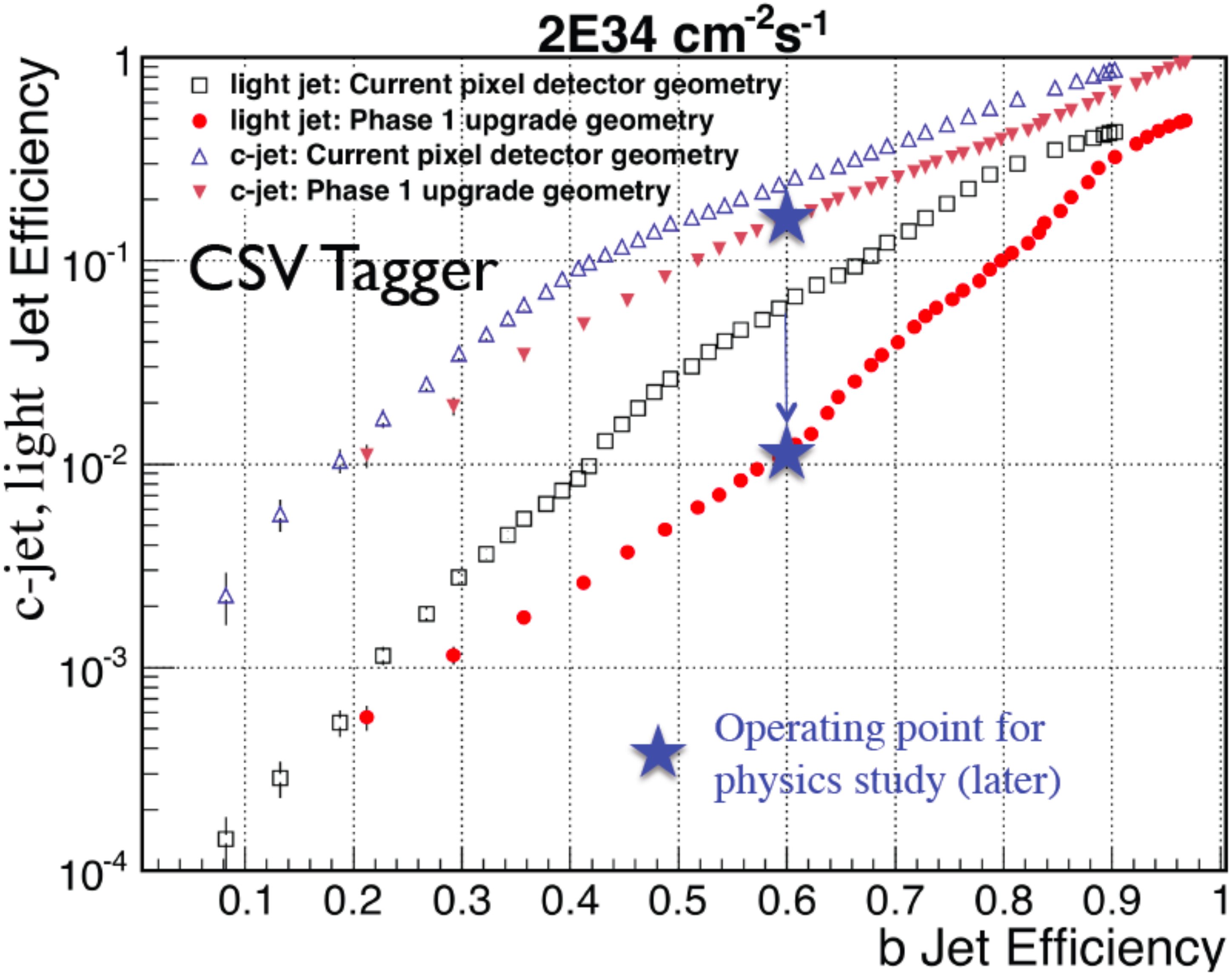

*Technical Proposal results with 16 facet BPIX1 at r = 39mm.*

Present detector good with no pileup but phase-1 detector better

H. Cheung et al

# b-tagging of Current / Upgraded Pixel System

- <PU>=50, ttbar, without additional tuning of b-tag algos




*Technical Proposal results with 16 facet BPIX1 at r = 39mm.*

Significant improvement in b-jet tagging efficiency at fixed mistag rate (or in mistag rate for fixed b-jet tagging efficiency)

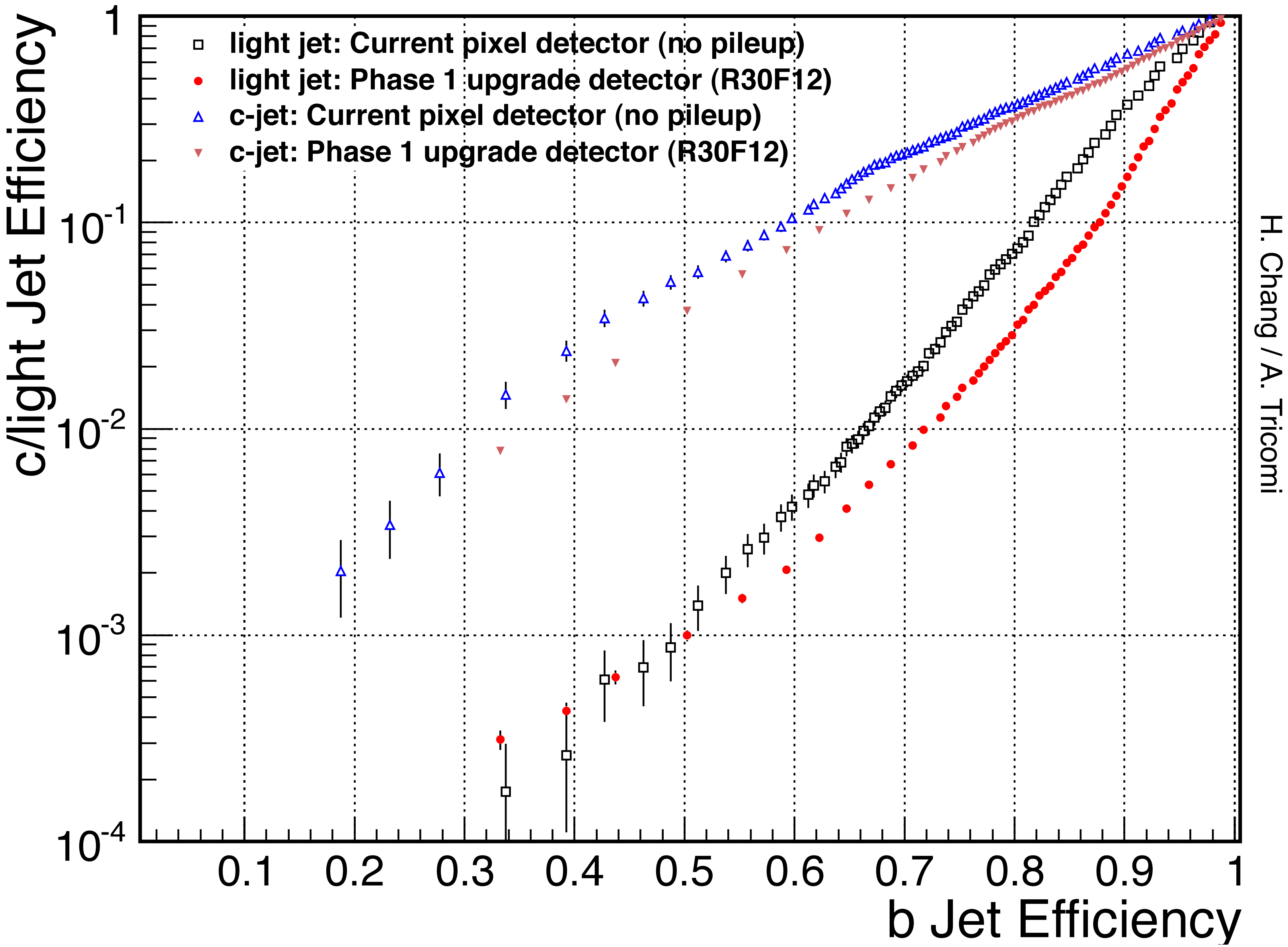
Phase 1 geometry effectively preserves present performance at $2x10^{34}Hz/cm^2$

***Expect further improvement with 12 facet BPIX1 at r = 30mm***

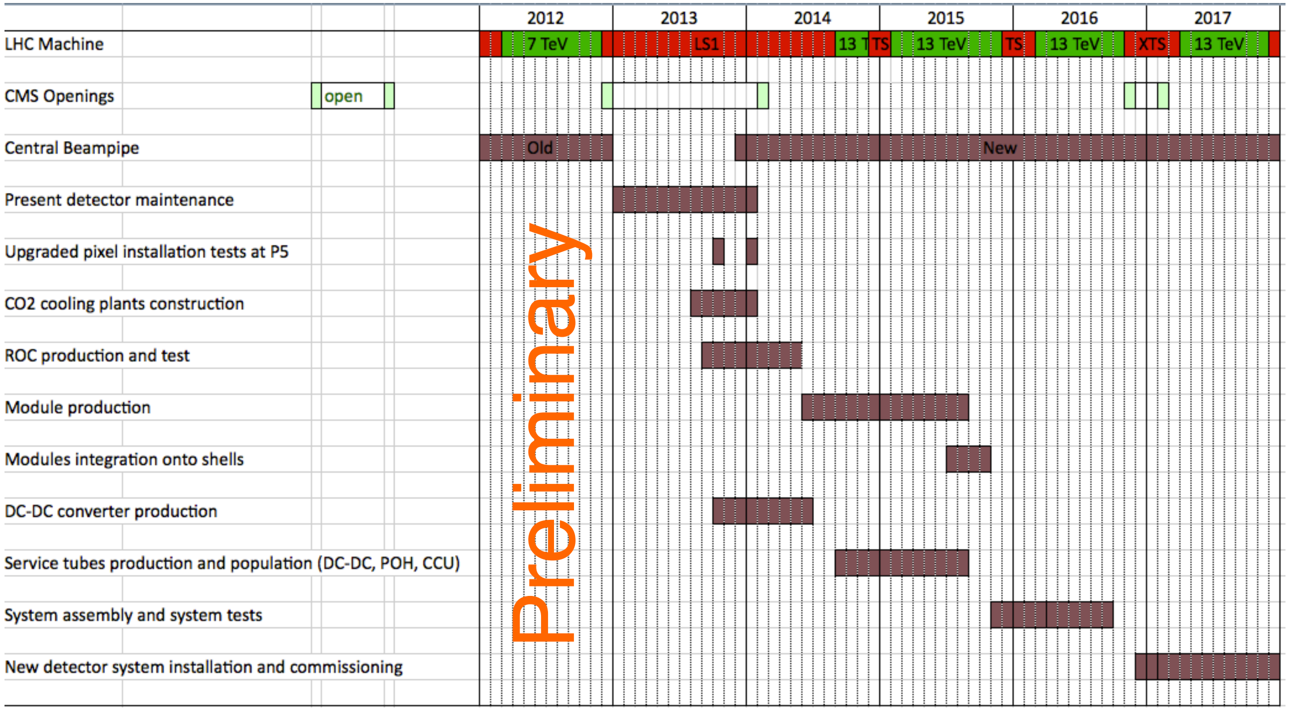
H. Cheung et al

# b-tagging of Current / Upgraded Pixel System

**<u>12 faced Layer 1</u>**: ttbar sample at <PU>=0, high purity tracks



# Project Plan and Timeline



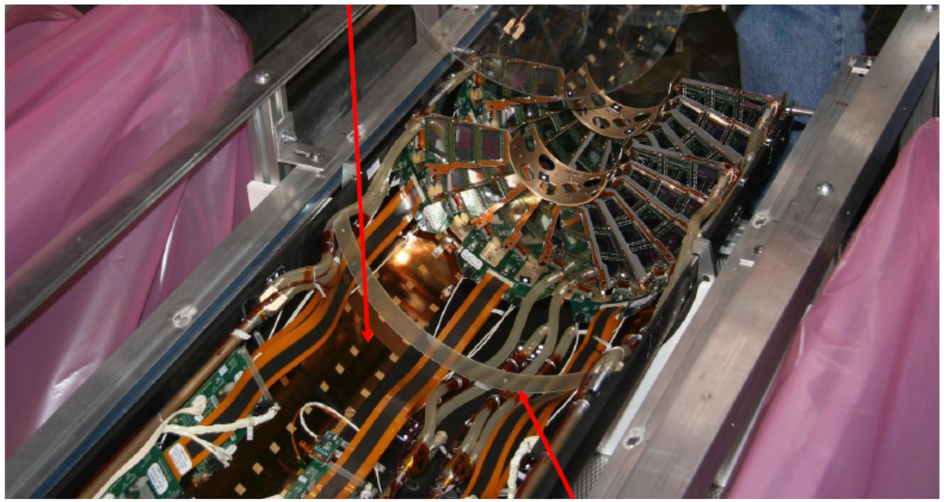

**Currently planned:**

Insertion tests in LS1

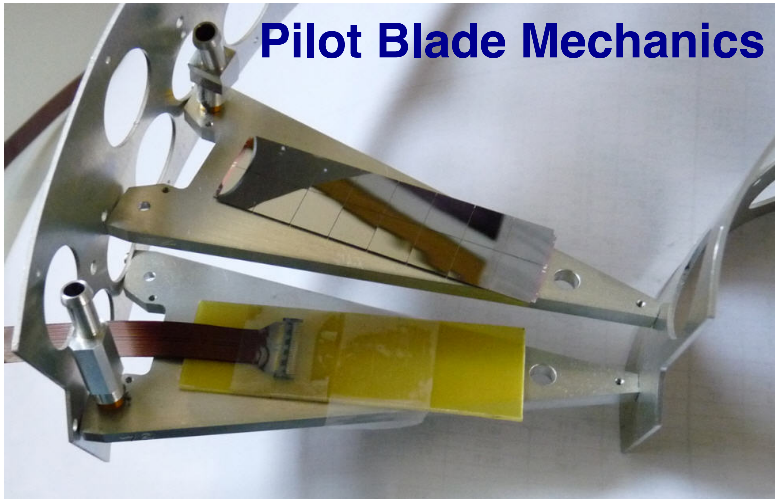
Installation of Pilot system in LS1, commissioning of new system 2015/16

Insertion of new 4 layer pixel system im 2016/17 Xmas shut down **(5 month)**

## Pilot Blade Sytem for present FPIX in LS1



S. Kwan, J. Howell et al.



# Summary & Conclusions

• Pixel upgrade to 4 hit system significantly improves and robustifies pixel track seeding & vertexing

• Reduced and displaced material budget significantly improves impact parameter resolution and therefore vertexing and b-tagging.

• Pixel stand alone tracking crucial in HLT. The 4 hit upgrade will boost HLT triggering capability of CMS. (~ 4x better $\Delta p/p$)

• LHC operations beyond the standard mode (25nsec) and luminosities of $1\times10^{34}cm^{-2}s^{-1}$ poses serious limitations of the current pixel system.

• Data flow limitations by increased instant luminosities (50nsec or $2\times10^{34}cm^{-2}s^{-1}$) and 4$^{th}$ Layer require changes of the present pixel readout chain (ROC changes & Optical 40MHz analog coded → 320 Mbit/sec digital)

• Data transfer from pixel modules to FED electronics is major limitation and DAQ transfer to CMS needs to be improved by factors. (under study in CMS)

# Tolerances of new Pixel & Beam Pipe crucial

**From event with nuclear interactions get actual position of beam pipe, pixel and beam !**

- Information
  - Contacts:
    maxime.gouzevitch@cern.ch
    giacomo.sguazzoni@cern.ch
  - Ref: TRK-10-003
- xy view of reconstructed Nuclear Interactions vertices in Min Bias events at B=3.8T
  - -20cm<z<20cm
  - '×' represents average beam spot position; '+' the fitted beam pipe center
  - First pixel layer is visible
  - Central blank spot is a selection artifact
- More details and high resolution plots:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK