2010 Vienna Conference on Instrumentation

3D Silicon Pixel Sensors

Recent Test Beam Results

Per Hansson, SLAC

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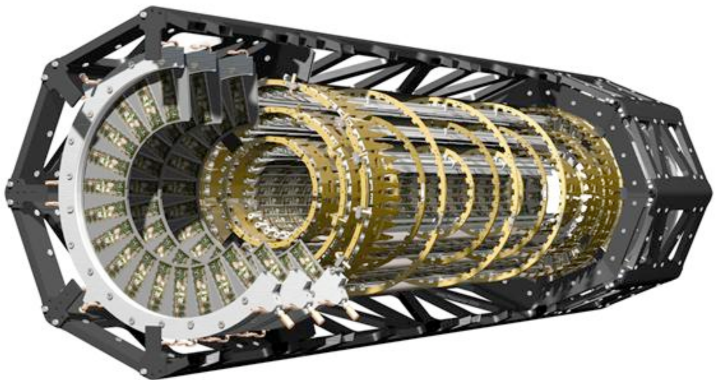
Outline

- Introduction
- 3D pixel sensors for Atlas upgrade
  - Performance in magnetic field
  - Charge sharing and resolution
  - Tracking efficiency
  - Active edge
- Summary

SLAC NATIONAL ACCELERATOR LABORATORY

Motivation

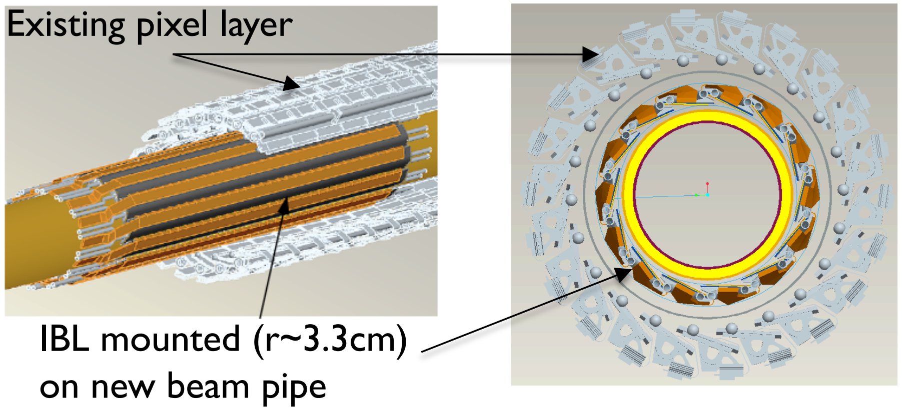
- Pixel detectors: current technology choice in HEP for innermost tracking and vertexing
- New developments largely driven by upgrades



Atlas pixel detector

- Atlas pixel detector CERN LHC
  - LHC p-p collisions at 7→14TeV ($L \sim 10^{34} cm^{-2} s^{-1}$)
  - 2T magnetic field
  - Innermost pixel layer (B-layer) 5cm from IP
  - Designed for fluence of 10^{15}n eq. cm^{-2}

- Atlas Insertable B-Layer (IBL)
  - Increase physics performance
  - Protect against B-Layer degradation ($300 fb^{-1}$)
  - Rate limitations after LHC upgrades
  - Insert new barrel <u>inside</u> innermost layer
  - Installation with new beam pipe (>)2014
  - 3 competing sensor technologies



3D Pixel Sensors

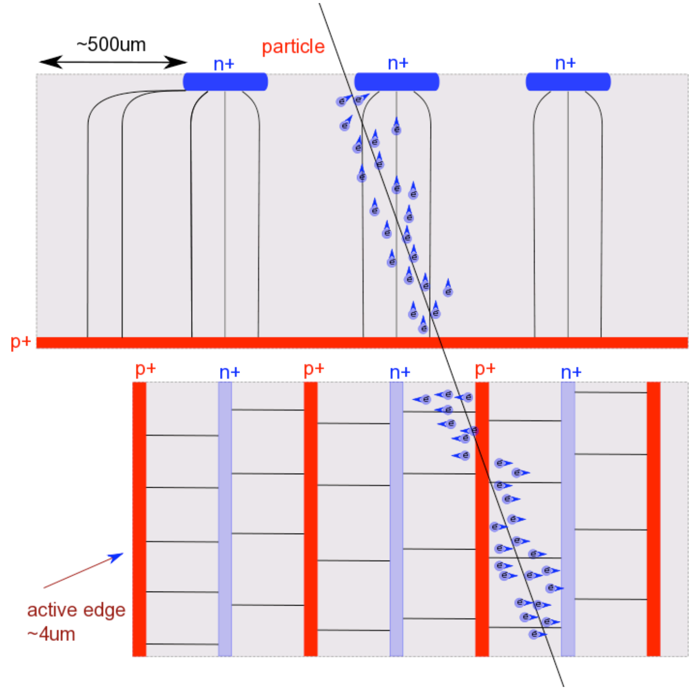
- New design proposed in 1997
- Electrodes processed inside bulk

Features of 3D design
Decouple drift-length from sensor thickness
High average electric field
Short collection path
The edge is an electrode

Signal efficiency/ Radiation hardness

Low depletion voltage ~10V

Active edge (~4um)

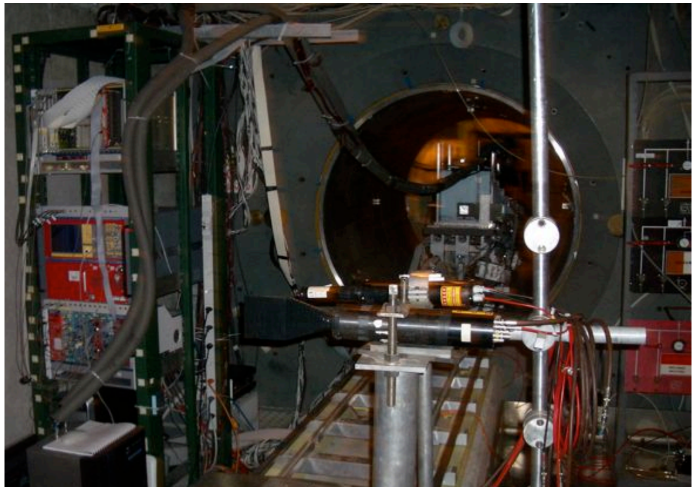


- Scope of test beam 2009: demonstrate (part of the) requirements for Atlas IBL
  - Magnetic field compatibility
  - Small dead regions: active edge
  - Efficiency and tracking resolution
  - Radiation tolerance $>5\times10^{15}$n eq. cm^{-2}
  - Thermal management

Covered here:

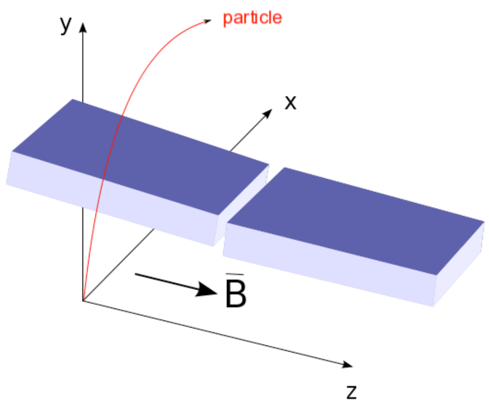
Parker, Kenney , *NIMA 395 (1997), 328;Parker, Kenney, IEEE Trans. Nucl. Sci. NS48 (2001), p. 1629;C. DaVia, NIMA 509 (2003), p 86; Kenney, Parker, Walckiers, IEEE Trans. Nucl. Sci. NS48 (2001), p. 2405; C. Kenney et al., IEEE Trans. Nucl. Sci. NS46(1999), p. 1224*

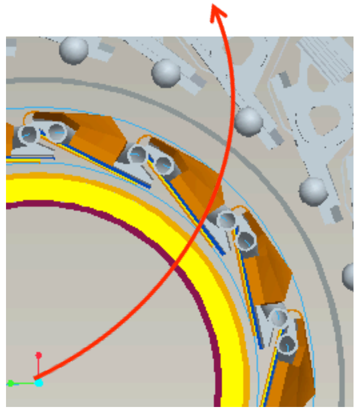
2009 Test Beam Setup

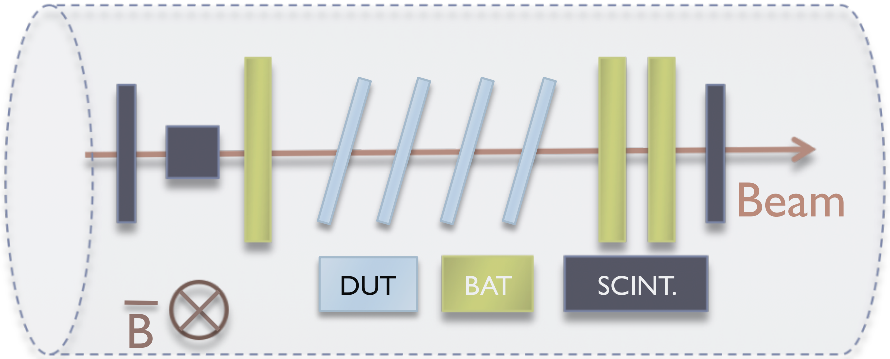


- CERN North Hall
  - 180GeV pions from CERN SPS target
- Bonn Atlas Telescope (BAT)
  - Two-sided Si micro-strips (50um pitch)
  - Analog read-out; integrated DAQ & online DQ
- Trigger: two scintillators (+ veto)
- Morpurgo large superconducting dipole
  - 1.57T measured at DUT's

- Driven by Atlas IBL layout and requirements
  - 2T solenoid magnetic field in beam direction
  - Momentum measurement in r×ϕ
  - Sensor tilt angle: 10-25° degrees

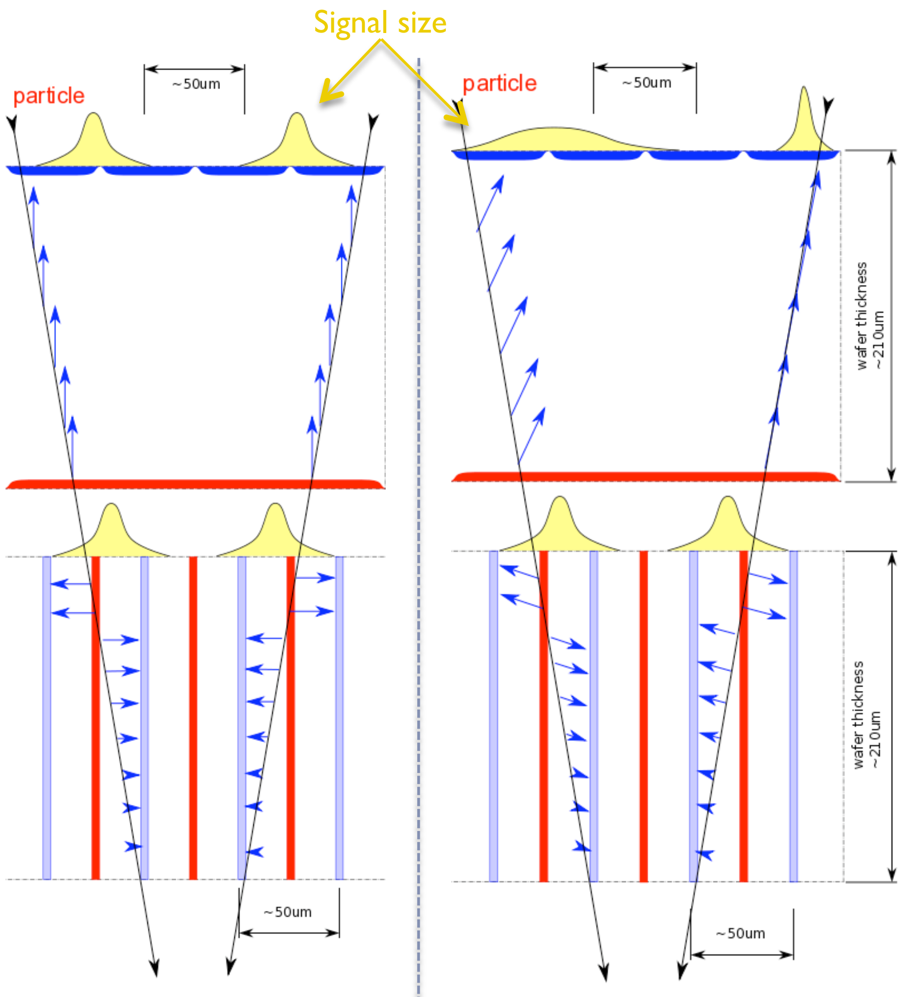






3D & Planar in Magnetic Field

Atlas barrel solenoid configuration



No magnetic field

Magnetic field

Planar sensors

- Orthogonal electric- and magnetic field
- Focusing or de-focusing drifting charges
- Minimum cluster size at Lorentz angle incidence

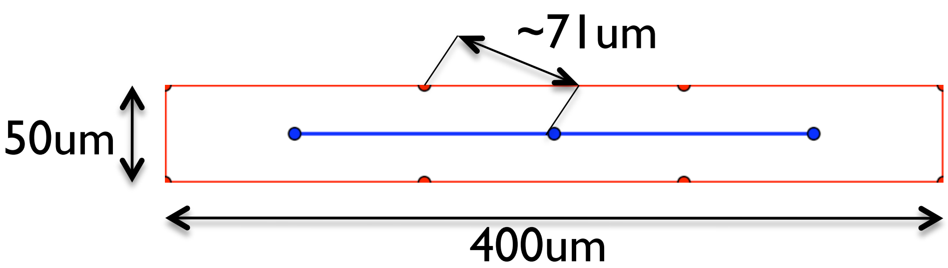
3D sensors

- Coplanar electric- and magnetic field
- Lorentz angle out of coplanar
- Depends on hit position
- Possibly small surface effects

Expect very small effect from magnetic field in 3D sensors!

Devices Under Test

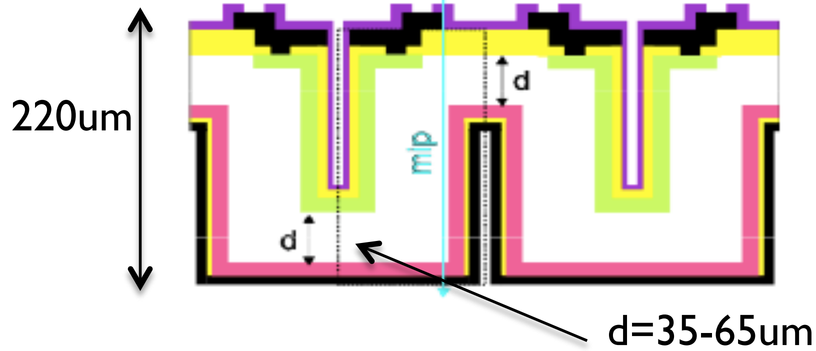
- CIS-Stanford full-3D
  - p-type bulk with active edge
  - Holes doped and filled
- FBK-IRST mod-3D
  - p-type bulk with partial column overlap: 90 & 150um
  - Holes doped but unfilled
- Atlas planar for reference



Modified 3D sensors

- Partially overlapping electrodes
- Simplified wafer handling
- Double-sided double-type columns

Piemonte, Boscarding, et. al, NIMA541 (2005) 441
G. Pellegrini, et. al, NIM A 592 (2008) 38–43



- Sensor consist of 18x160 pixels
- Bump-bonded to Atlas front-end chip
- Pixel module DAQ: calibration, external trigger, etc.

All 3D DUT's behave and have similar performance

Atlas 3D Pixel Collaboration

- Atlas Upgrade R&D project

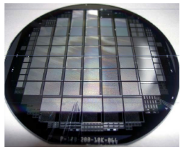
  "Development, Testing and Industrialization of Full-3D Active-Edge and Modified-3D Silicon Radiation Pixel Sensors with Extreme Radiation Hardness for the ATLAS experiment"

- 15 institutions

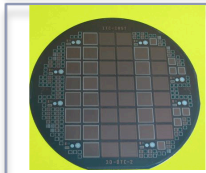
  Barcelona, IFAE Barcelona, Bergen University, Bonn University, Calabria University, CERN, Czech Technical University, Freiburg University, INFN Genova, Glasgow University, The University of Hawaii, Lawrence Berkeley National Laboratory, The University of Manchester, The University of New Mexico, Oslo University, SLAC, Stony Brook University, University of Udine, University of Trento

- 4 processing facilities
- Common goal:
  Demonstrate performance requirements and production capabilities for Atlas upgrades

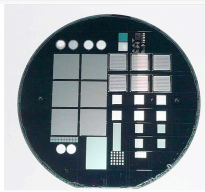
The Stanford Nanofabrication Facility



SINTEF



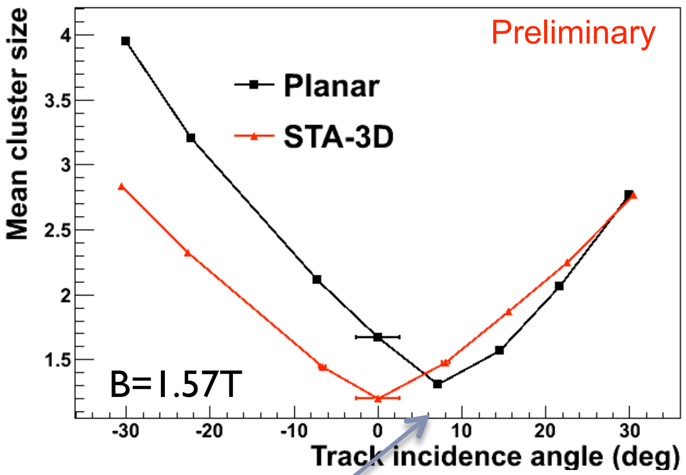
ITC irst — FONDAZIONE BRUNO KESSLER



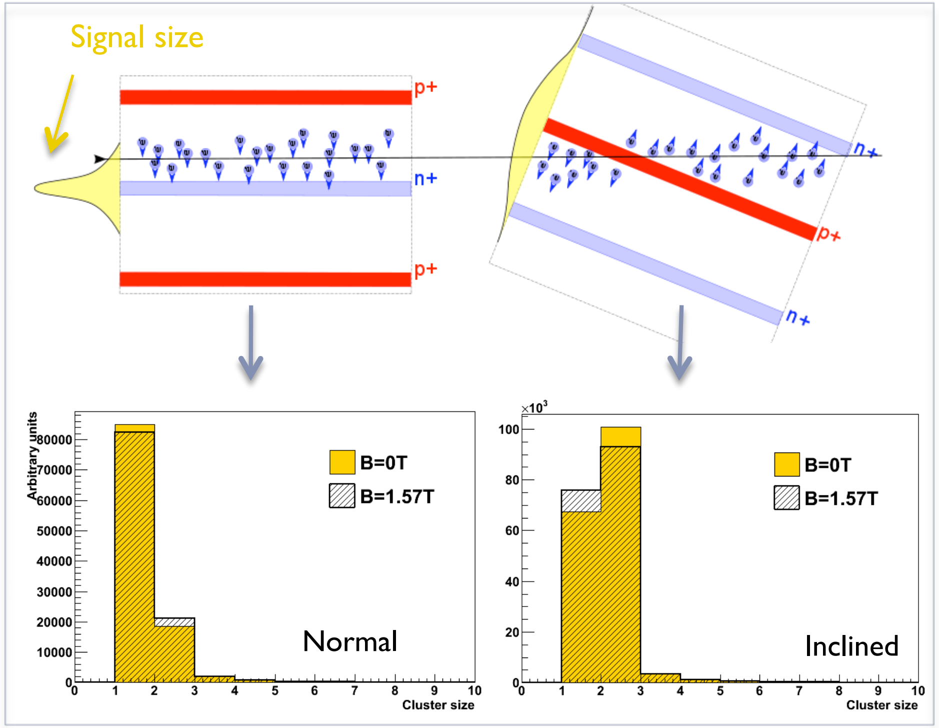
cnm — Centre Nacional de Microelectrònica — IMB

Cluster Size

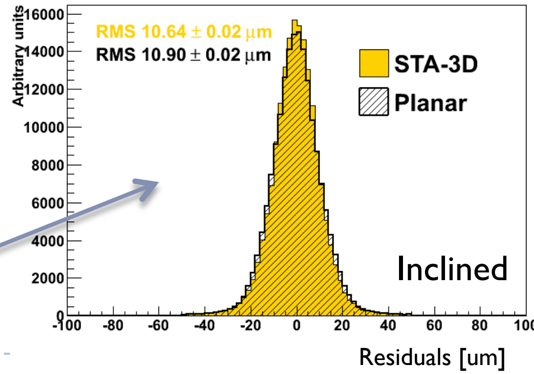
- Charge sharing between pixels is important
  - Cluster size related to tracking resolution (& signal size after irradiation)
  - Tilt angle has large impact



Planar: minimum at Lorentz angle



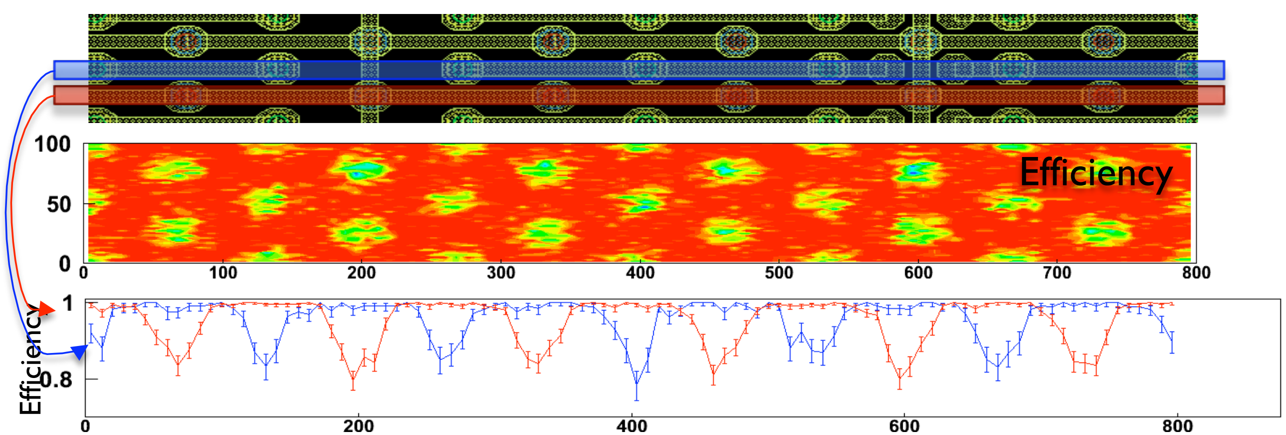
- 3D sensors insensitive to magnetic field
- Measured resolution similar to planar sensor



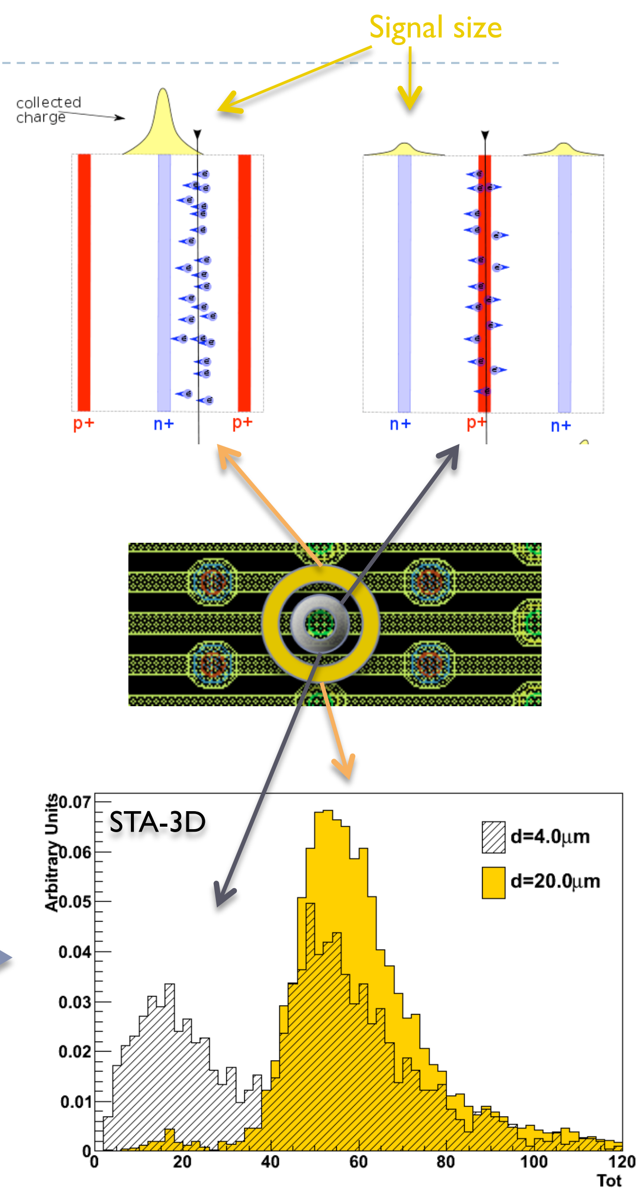
Track resolution not de-convoluted

Tracking Efficiency

- Electrodes are parallel to track at normal incidence
- Striking feature of 3D design

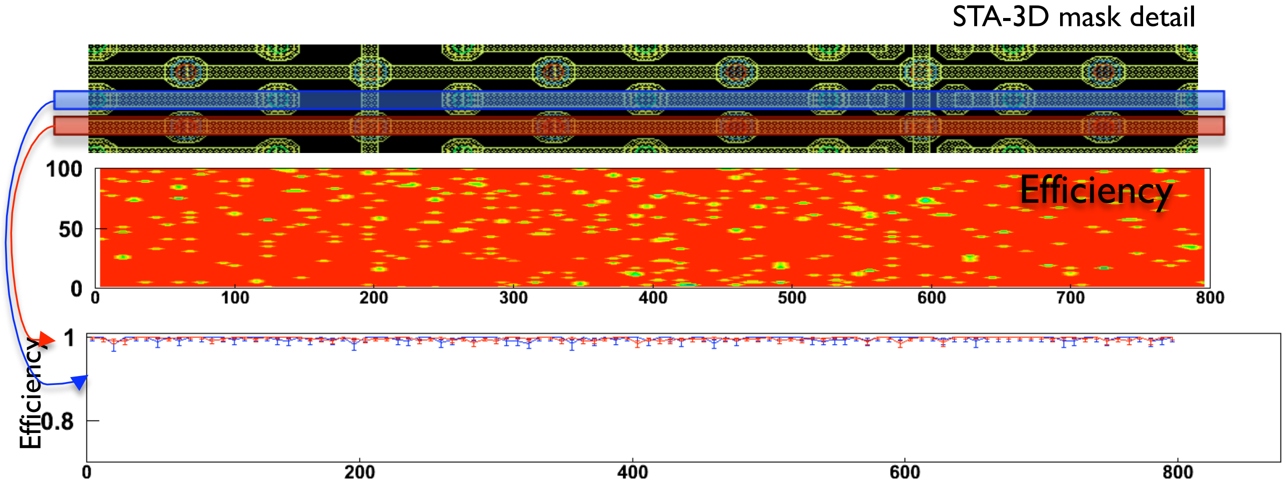


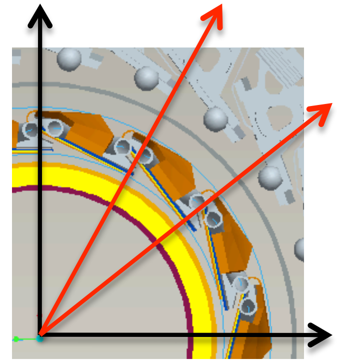
- Holes etched and filled (DRIE)
  - Doped polysilicon or passivation only
- Study charge collection in electrode region
  - Measure 40-60% signal loss J. Hasi, PhD Thesis
- Novel electrode treatment exist ➔ lower signal loss (on-going analysis)

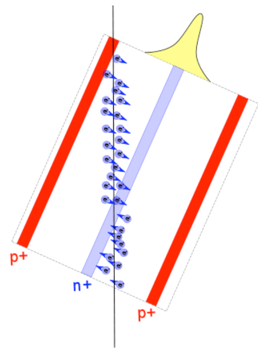


Tracking Efficiency

- Atlas IBL layout has tilted sensors (10-25°)
- Particle track mostly through normal bulk







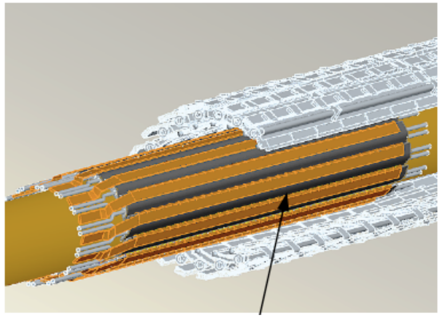
- Recover efficiency with tilted sensors
- 3D sensors >99.8% efficiency with ~15° angle

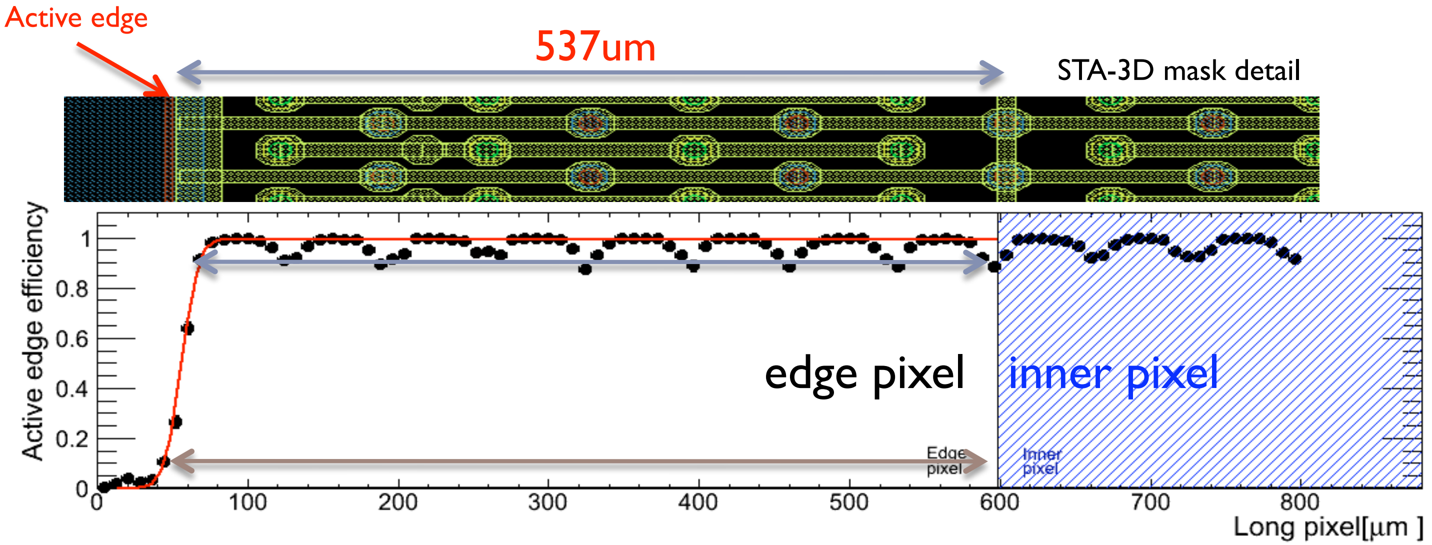
Magnetic field ON

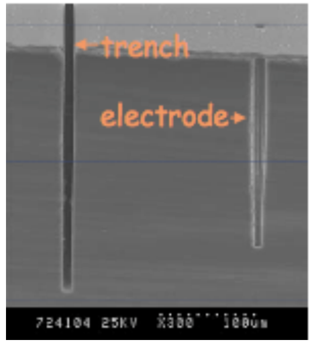
	0°	15°
STA-3D	96.7	99.8
FBK-3E7	99.0	99.8
Planar	99.9	99.9

Active Edge

- Traditional Si sensors have large ~1mm inactive regions at edges
  - Atlas IBL radial envelope ~**7mm**: no overlap possible in z
- 3D sensors with active edge Kenney, et. al , *NIMA 596 (2006), 328.*
  - Trench etched and doped similar to electrodes: edge is an electrode!







- 3D sensors active to a few microns from edge (w/ B-field)
  - Minimize dead area between modules (IBL)
  - Minimize material overlap/budget
  - Allow access to "forbidden" regions (e.g. forward detectors) FP420: arxiv:0709.3035v1 (2007)

Edge turn-on (σ=9um)		
Efficiency	10%	90%
Edge point [um]	555	531
Active edge [um]	6±9um	

Summary

- Verified low sensitivity to magnetic field
- 3D sensors are a good candidate for Atlas IBL
  - Radiation hard and low thermal management
  - >99.8% efficient with tilted tracks
  - Resolution similar to planar sensors
  - Sensitive to a few microns from mechanical edge
- Test beam plans 2010
  - Analysis of sensors with novel electrode treatment
  - Test beam with irradiated sensors and IBL front-end chip (IBL qualification program)

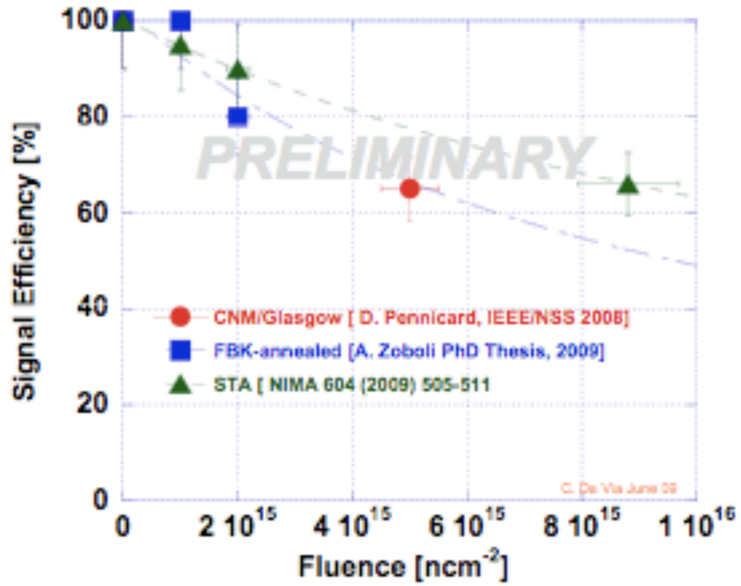
Additional Material

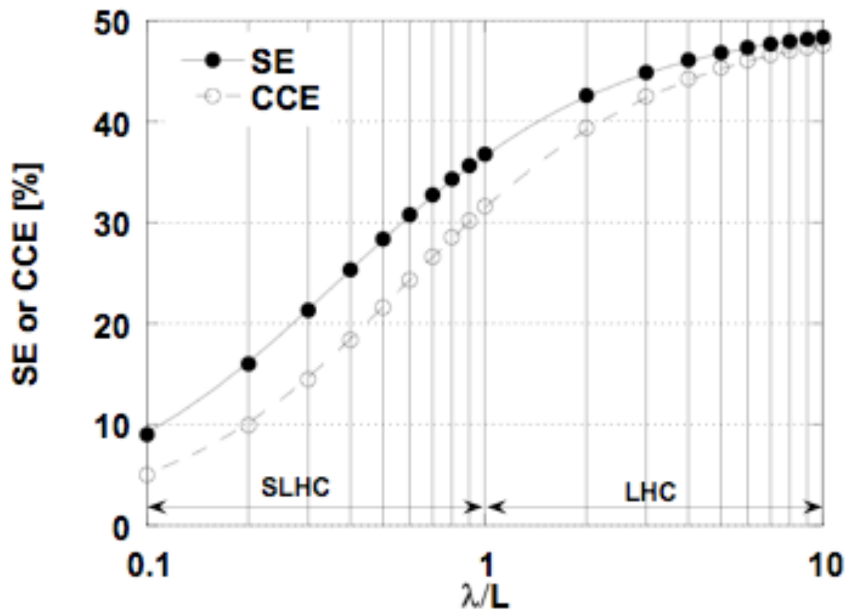
Radiation Hardness Studies

- Signal efficiency depends on
  - Effective drift length λ
  - Inter-electrode distance L
- λ /L decreases after after irradiation
  - Planar: L=sensor thickness
  - 3D: L $\neq$ sensor thickness
- 3D: tune electrode distance for radiation hardness

Da Via, Watts, NIMA,603,319(2009)

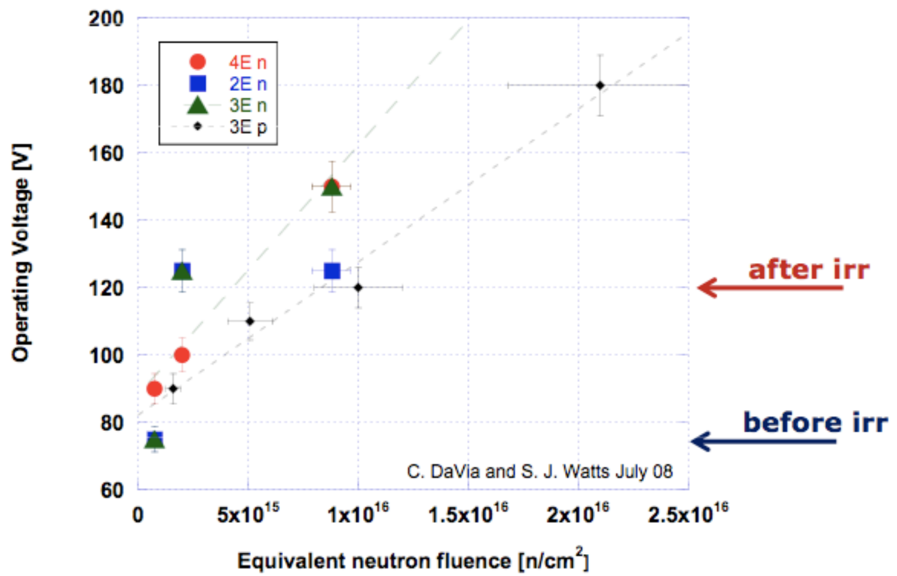
Fluence [ncm^{-2}]	MPS [e^{-}]
0	17250
1x10^{15}	16380
5x10^{15}	12075

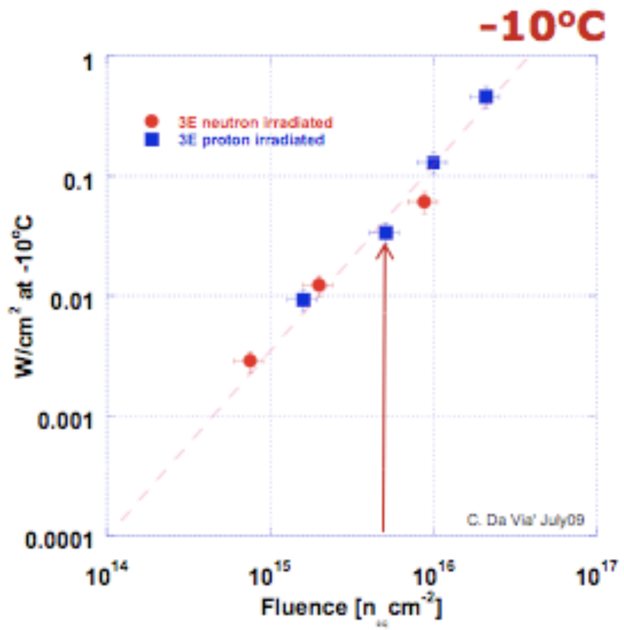




Operating Voltage and Power

- Using Atlas FE-I3





Modified-3D

SIMULATIONS AND DATA SHOWS THAT THE RESPONSE OF FULL 3D AND 3D-DDTC IS VERY CLOSE IF THE ELECTRODE PENETRATION STOPS 25 mm FROM THE SURFACE BEFORE AND AFTER IRRADIATION

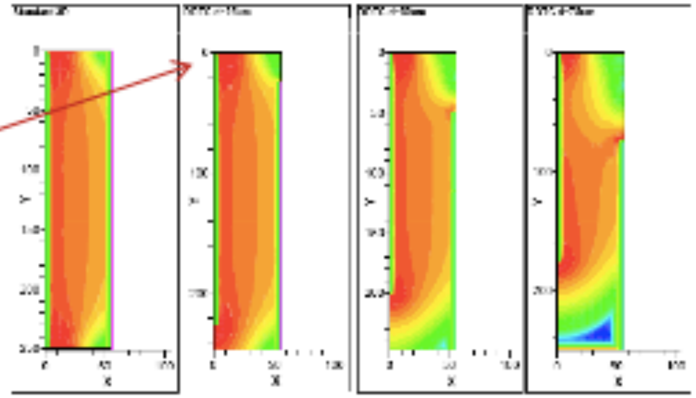


Figure 6.2: Electric field distribution taken from a 2-D cross-section of the 3-D structure along the diagonal that connects two columns of opposite doping types. Four cases are here represented: one standard 3D detector and three 3D-DDTC detectors with d spacing of 25, 50 and 75 µm.

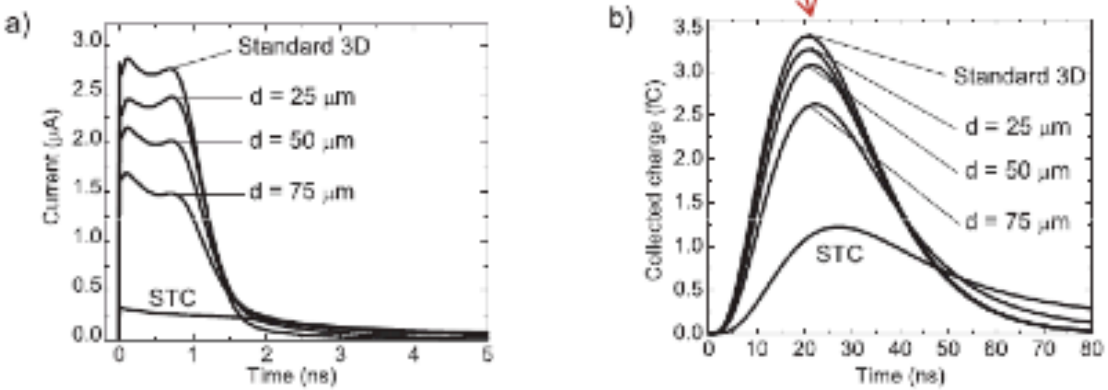
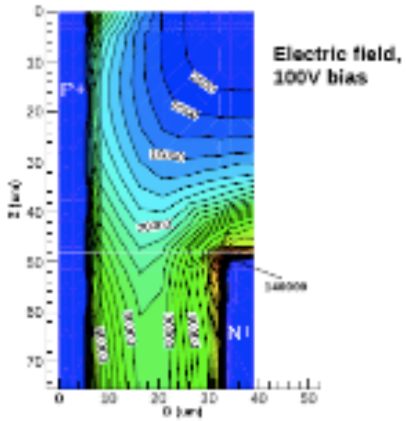
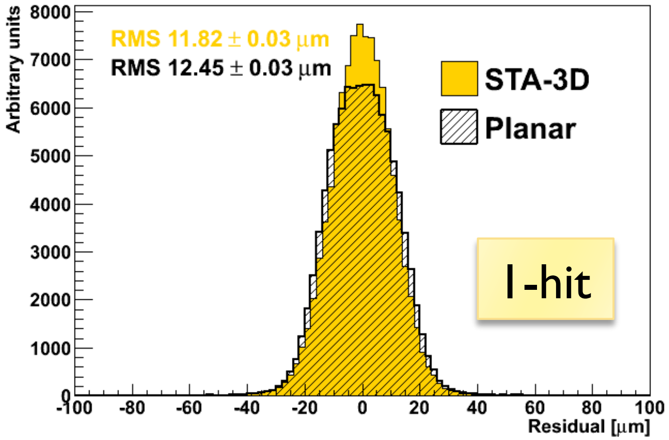


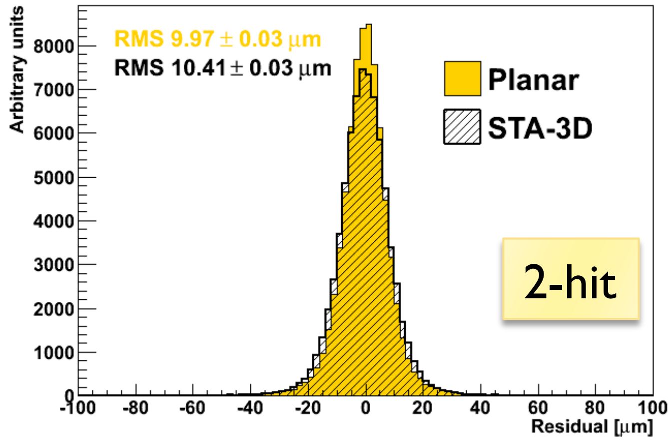
Figure 6.3: Simulated transient signals in 3D detectors of different geometries, biased at 16V, in response to a MIP particle: a) current signal; b) equivalent charge signal at the output of a semi-gaussian shaper with 20ns peaking time.

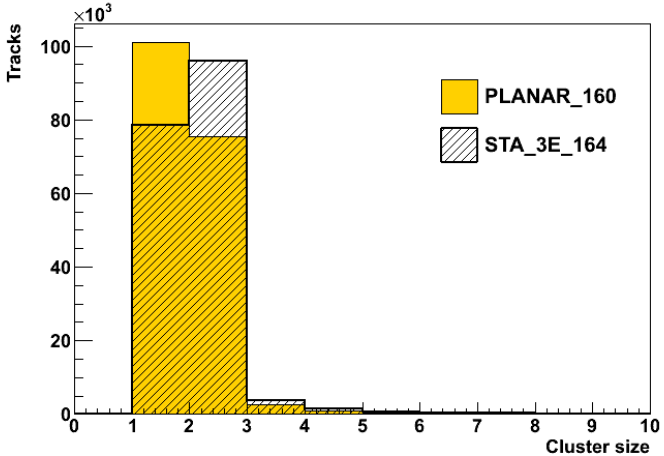


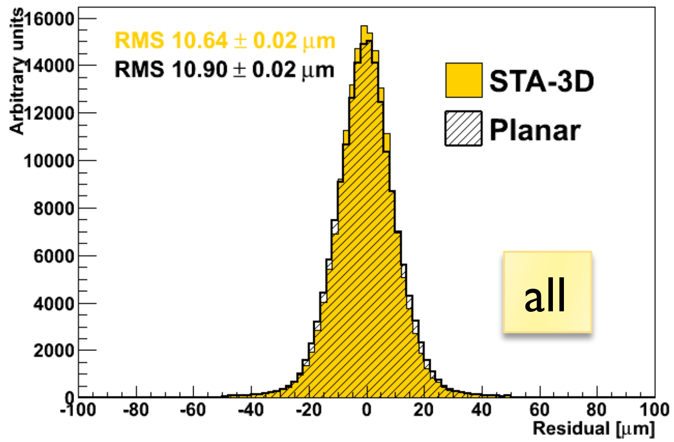
Simulations (from A. Zoboli PhD thesis, Trento, March 2009)
D. Pennicard, Glasgow IEEE/NSS 08

Residuals (B=1.57T)

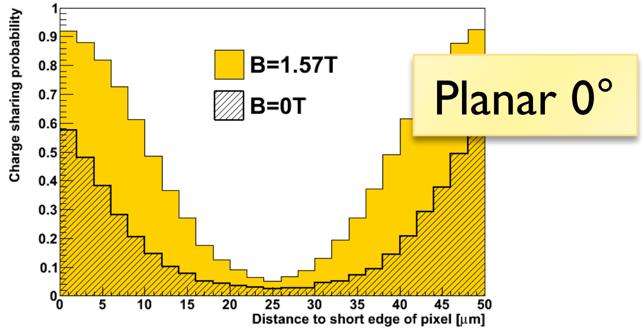


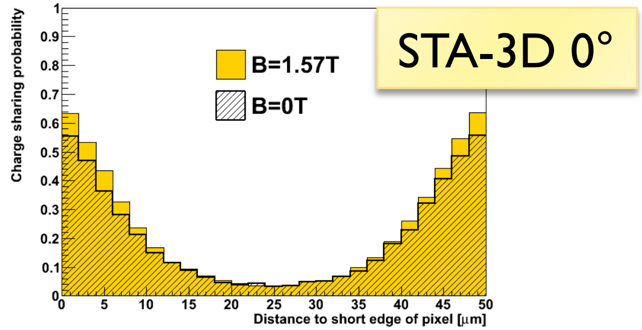


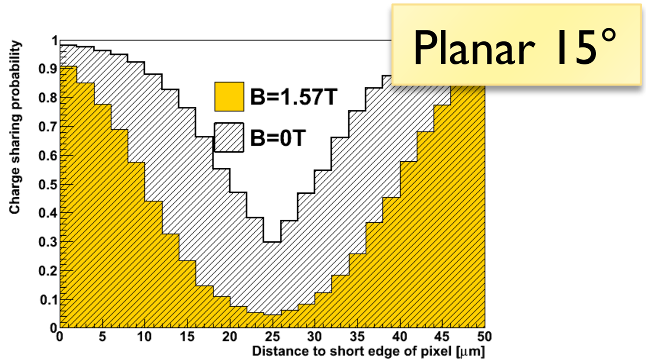


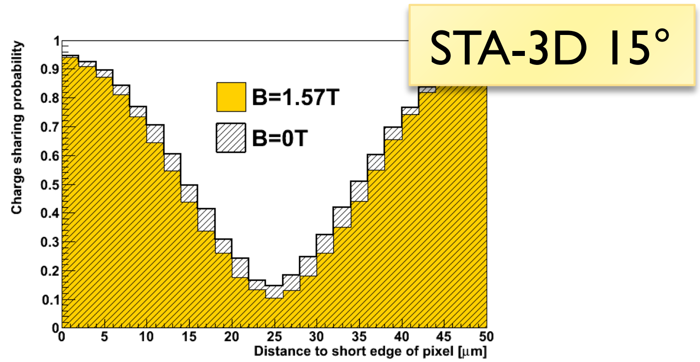


Charge Sharing Probability







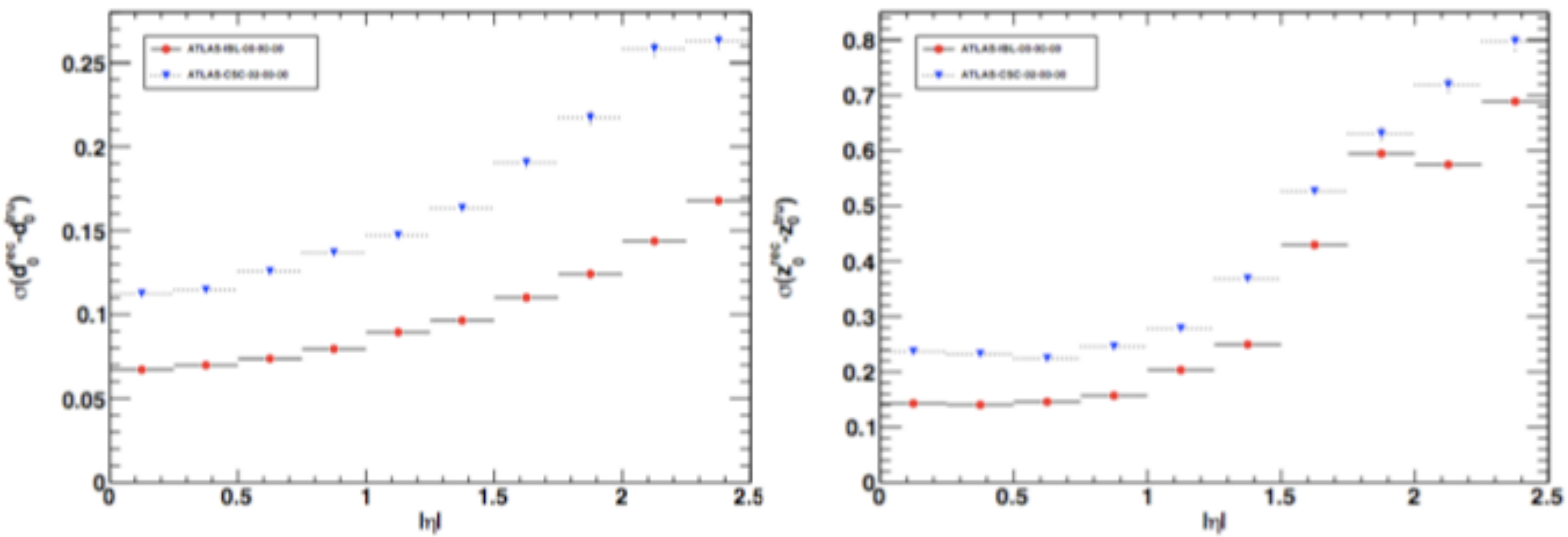


IBL Physics Performance

Preliminary simulation

- Additional (light) layer closer to IP
- Improves tracking in general
  - 30% improvement for impact parameter resolution (pT-dependent)
- Important for many analyses using tracking
  - tt, light Higgs, etc,

1 GeV muons



D.Tsybychev