The R&D for ATLAS pixels for sLHC

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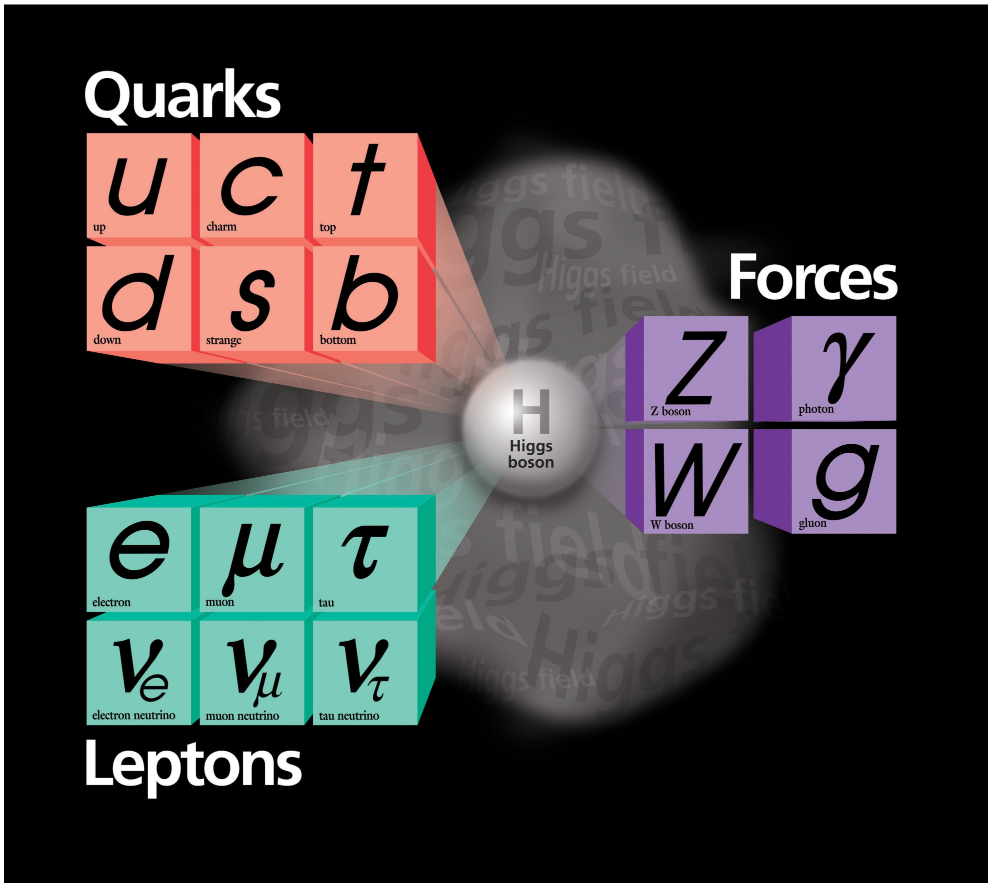
LPNHE

Outline

- Introduction
- LHC & ATLAS
- The LHC upgrade
- The Pixel upgrade
- The IBL project
- The R&D for a new Inner Detector: the Planar Pixel Sensor Upgrade (PPSU) project
- Conclusions

INTRODUCTION

The Standard Model (SM)



Matter is made out of fermions:

- 3 generations of quarks and leptons

Forces are carried by Bosons:

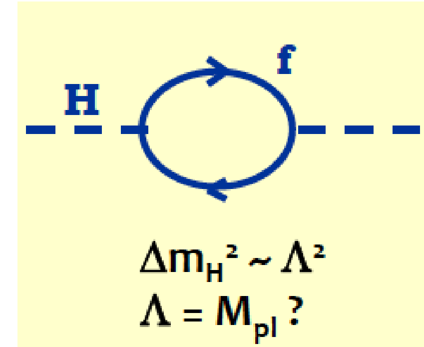
- Electroweak: γ,W,Z
- Strong: gluons

Higgs boson:

- Gives mass to gauge bosons via EW symmetry breaking
  - **Not found yet**

The SM limits

- Mass hierarchy problem
  - why the Higgs boson is so much lighter than the Planck mass?



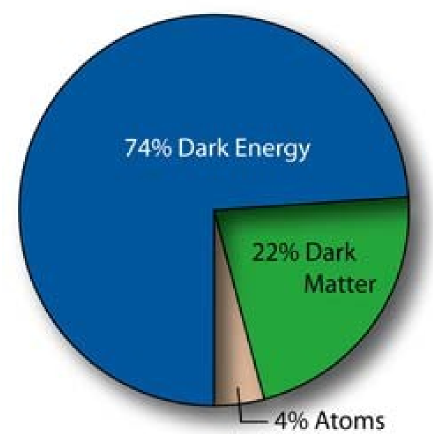
- Matter / antimatter asymmetry

Now: No antimatter now!

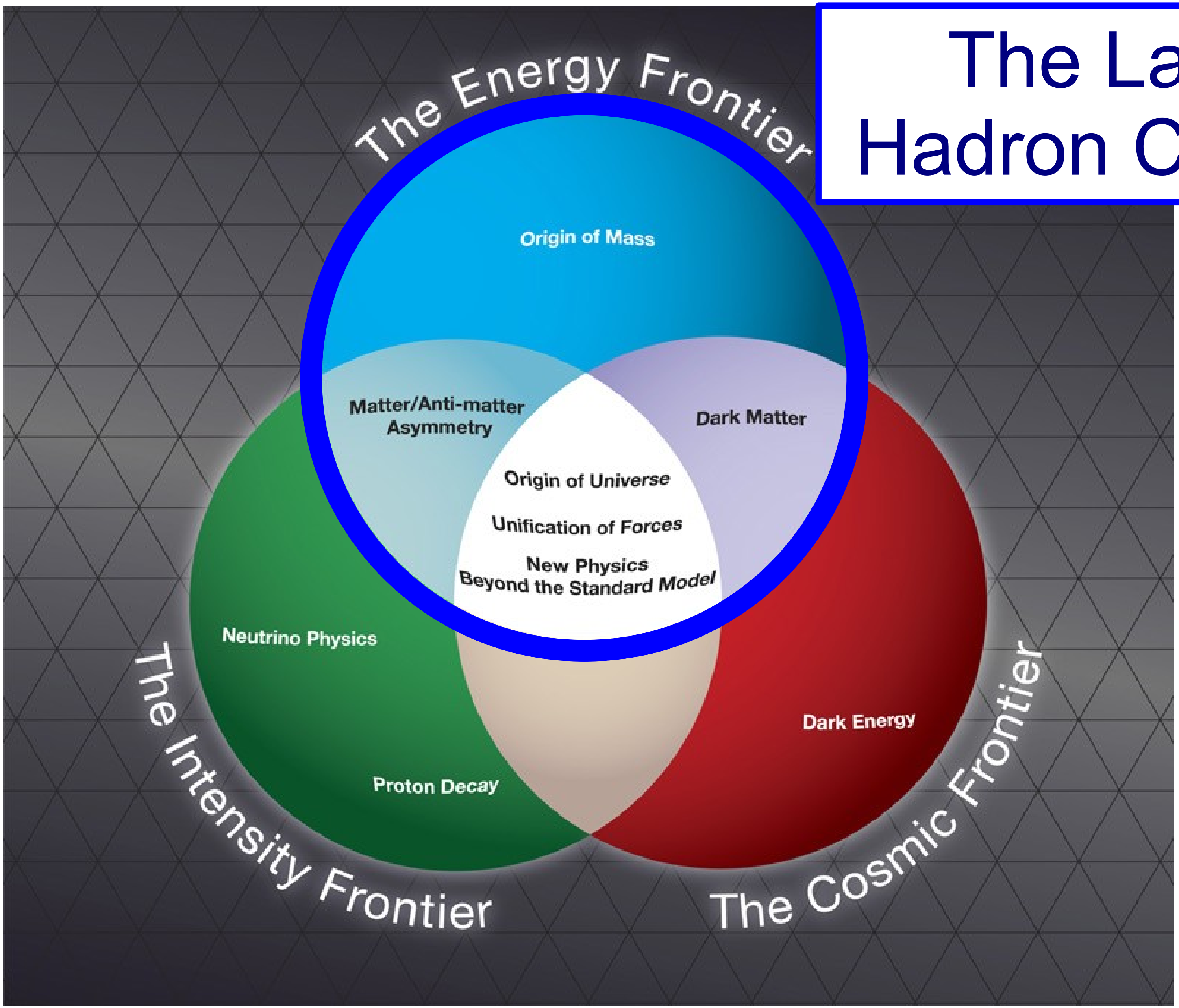
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} = \frac{\text{Baryons}}{\text{photons}}$$

$$= (6.1 \pm 0.3) \times 10^{-10}$$

- Dark matter & dark energy



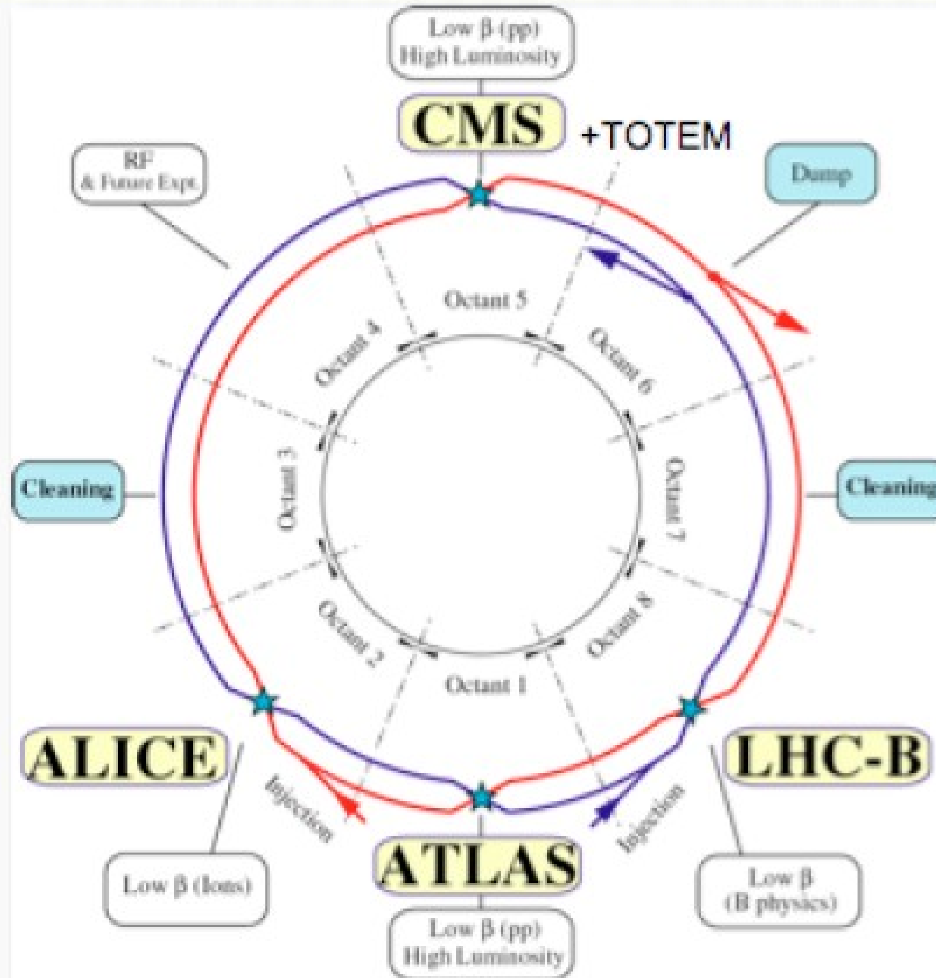
How to address these problems?



The Large Hadron Collider

LHC & ATLAS

LHC in a nutshell



- 1232 superconducting dipoles
  - 15m long at 1.9 K, B=8.33 T
  - Inner coil diameter = 56 mm

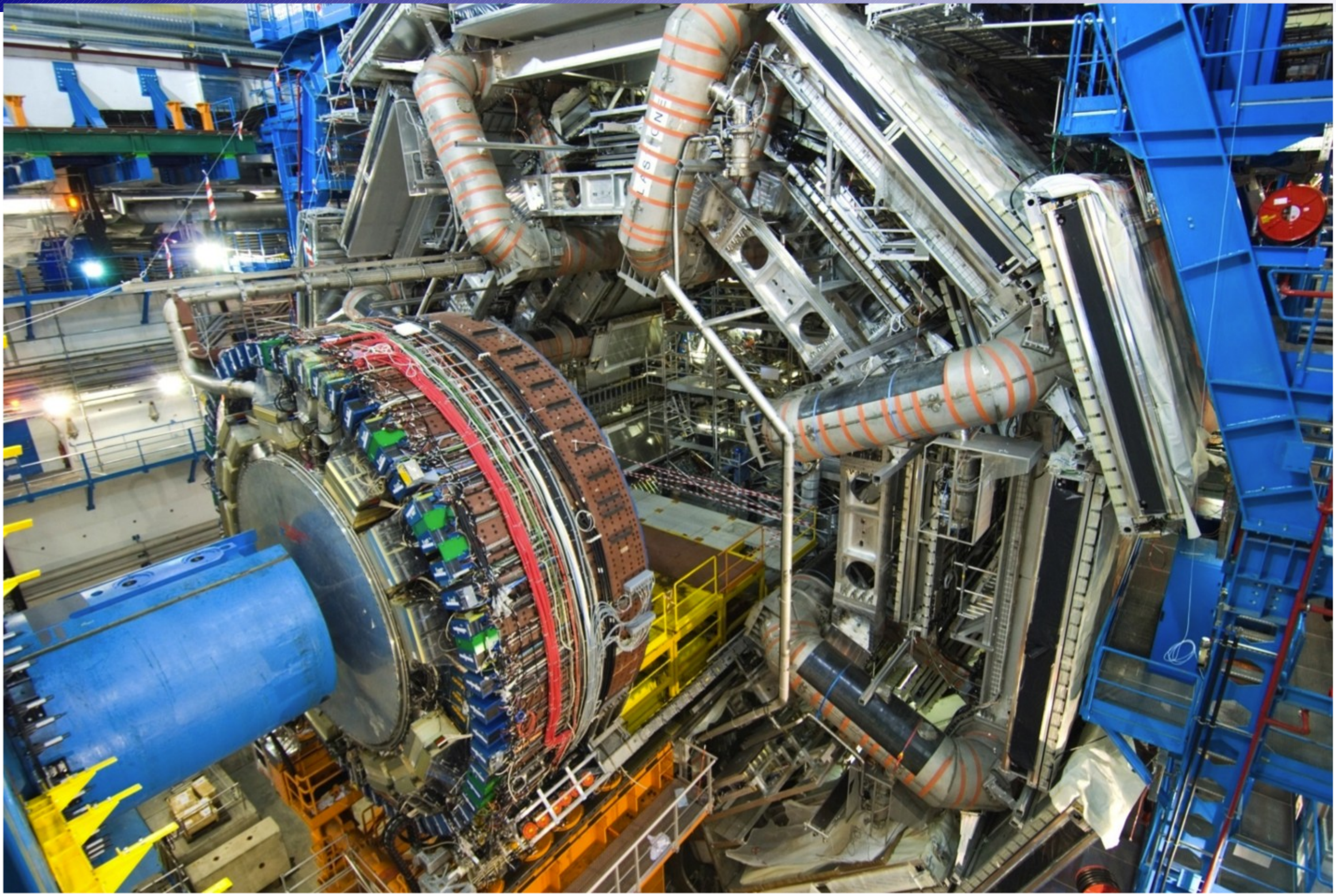
design

- beam-energy 7 TeV (7x TEVATRON)
- Luminosity 10^{34} $cm^{-2}s^{-1}$ (>100x TEVATRON)
- Bunch spacing 24.95 ns
- Particles/bunch 1.1 10^{11}
- Stored E/beam 350 MJ ~ 80kg of TNT

- Also : Lead Ions operation
  - Energy/nucleon 2.76 TeV / u
  - Total initial lumi 10^{27} cm^{-2} s^{-1}

- 8 independent sectors
  - Challenge for control, powering
- 10 GJ stored in magnets
- Warm insertion regions for beam dump, cleaning, acceleration

ATLAS

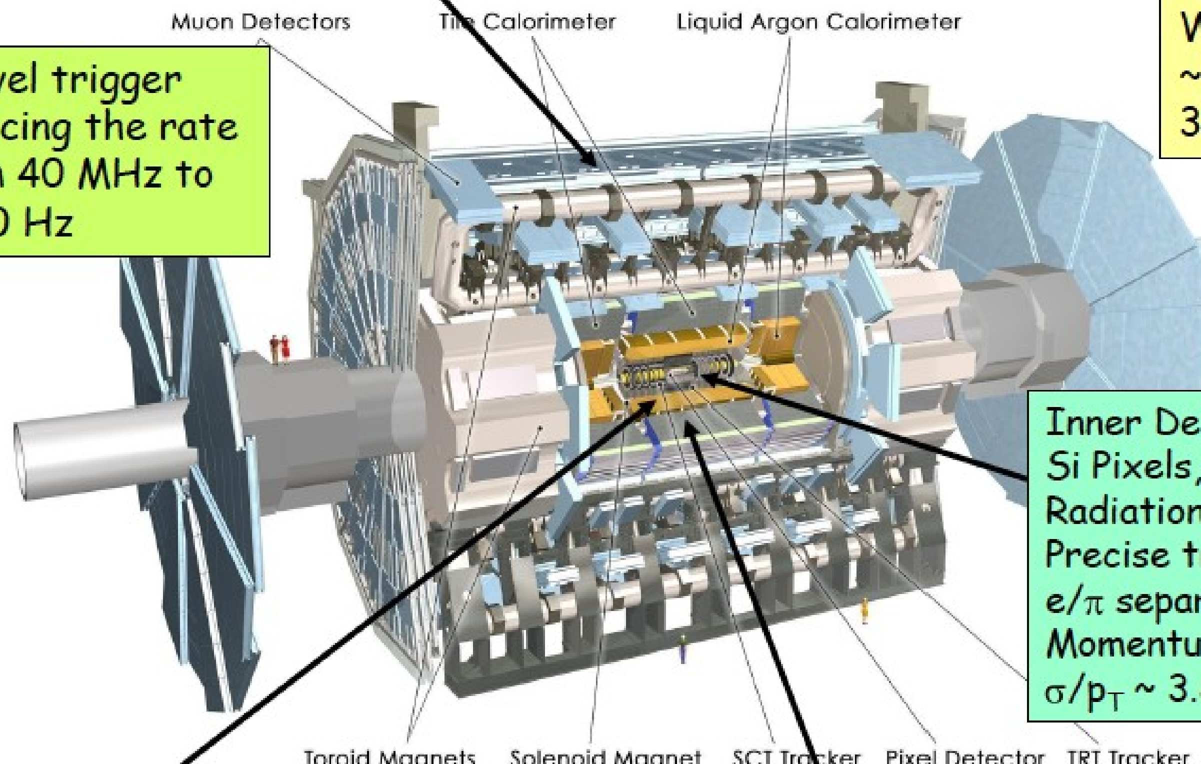


ATLAS facts

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz

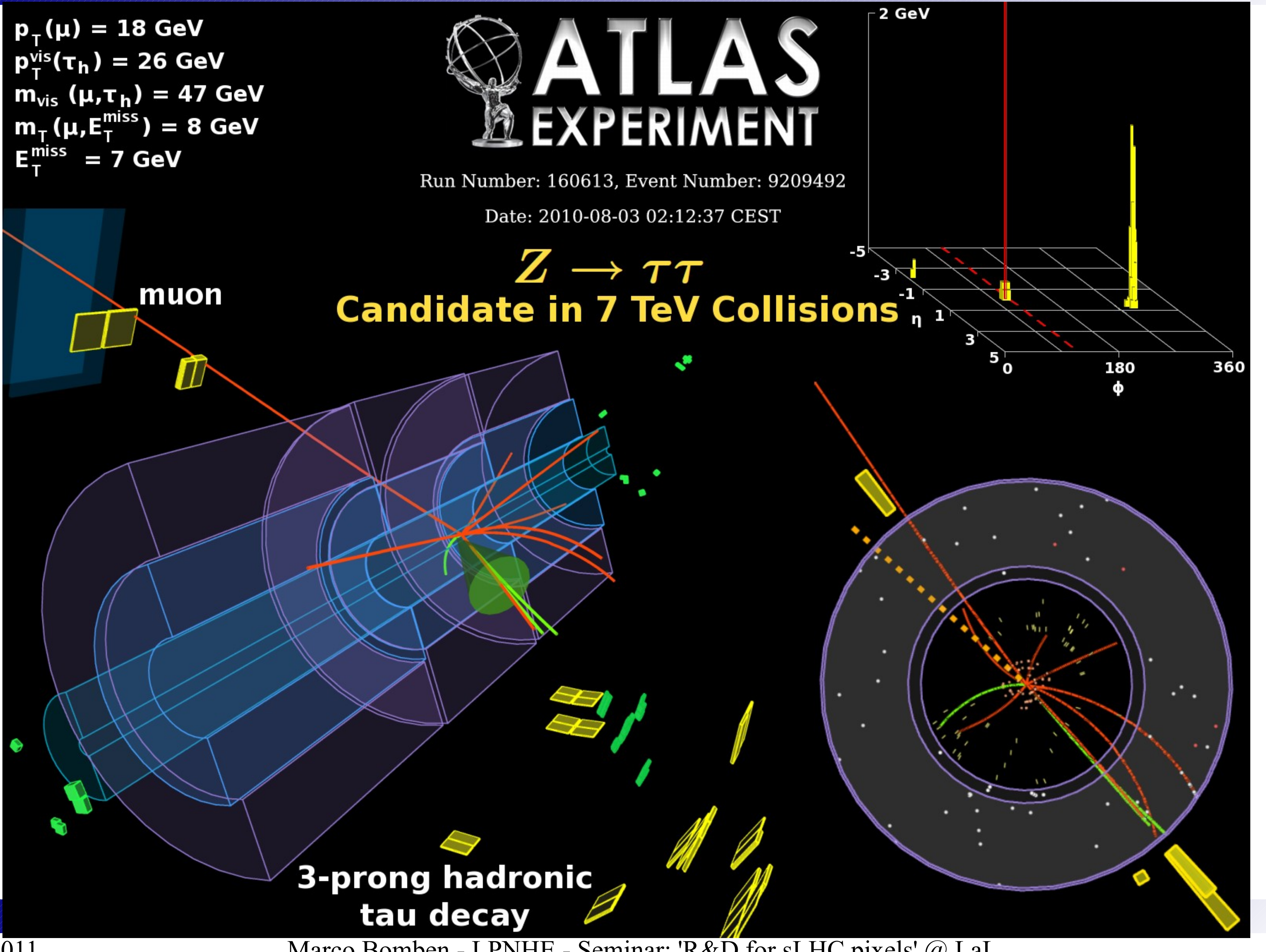


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

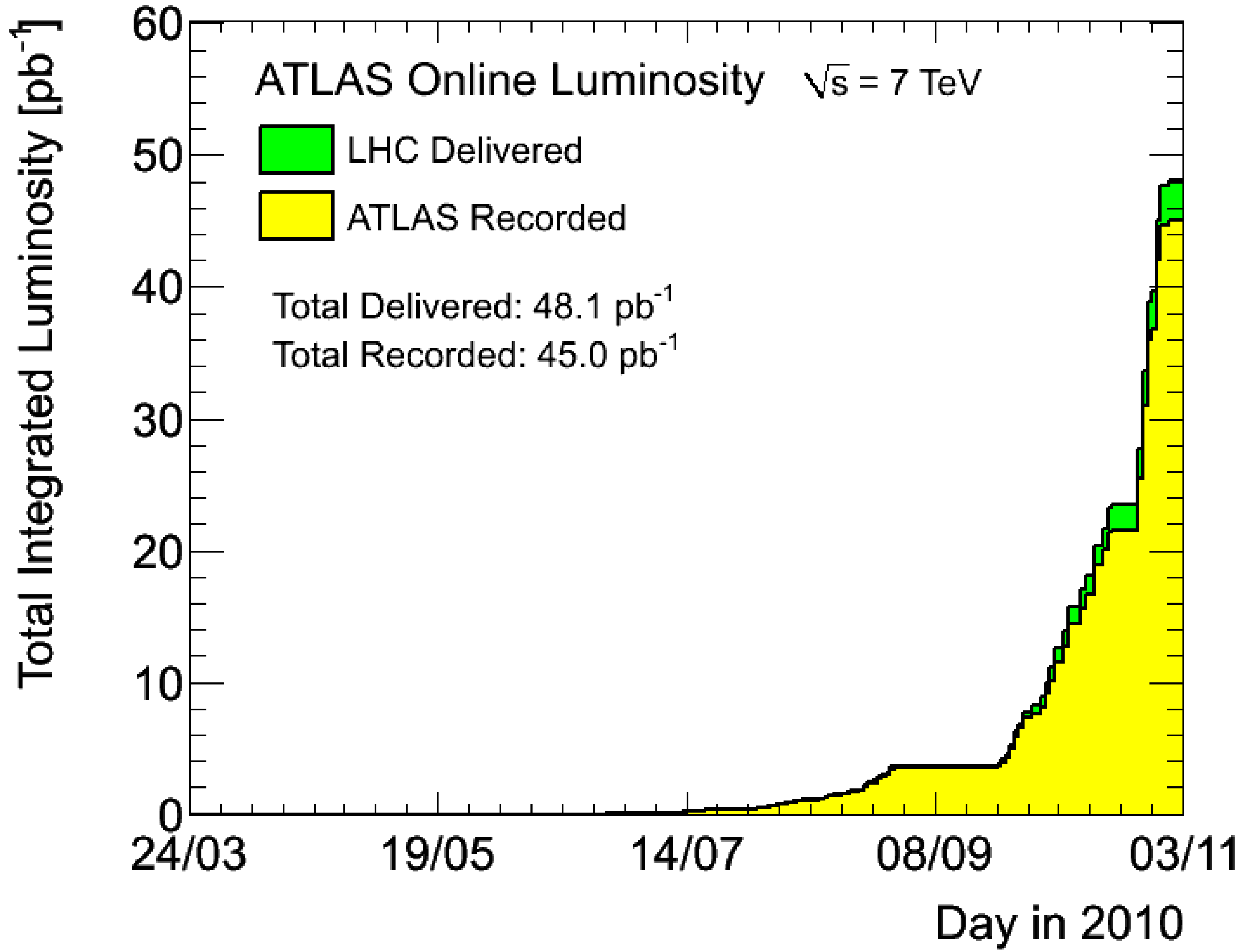
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Z → ττ

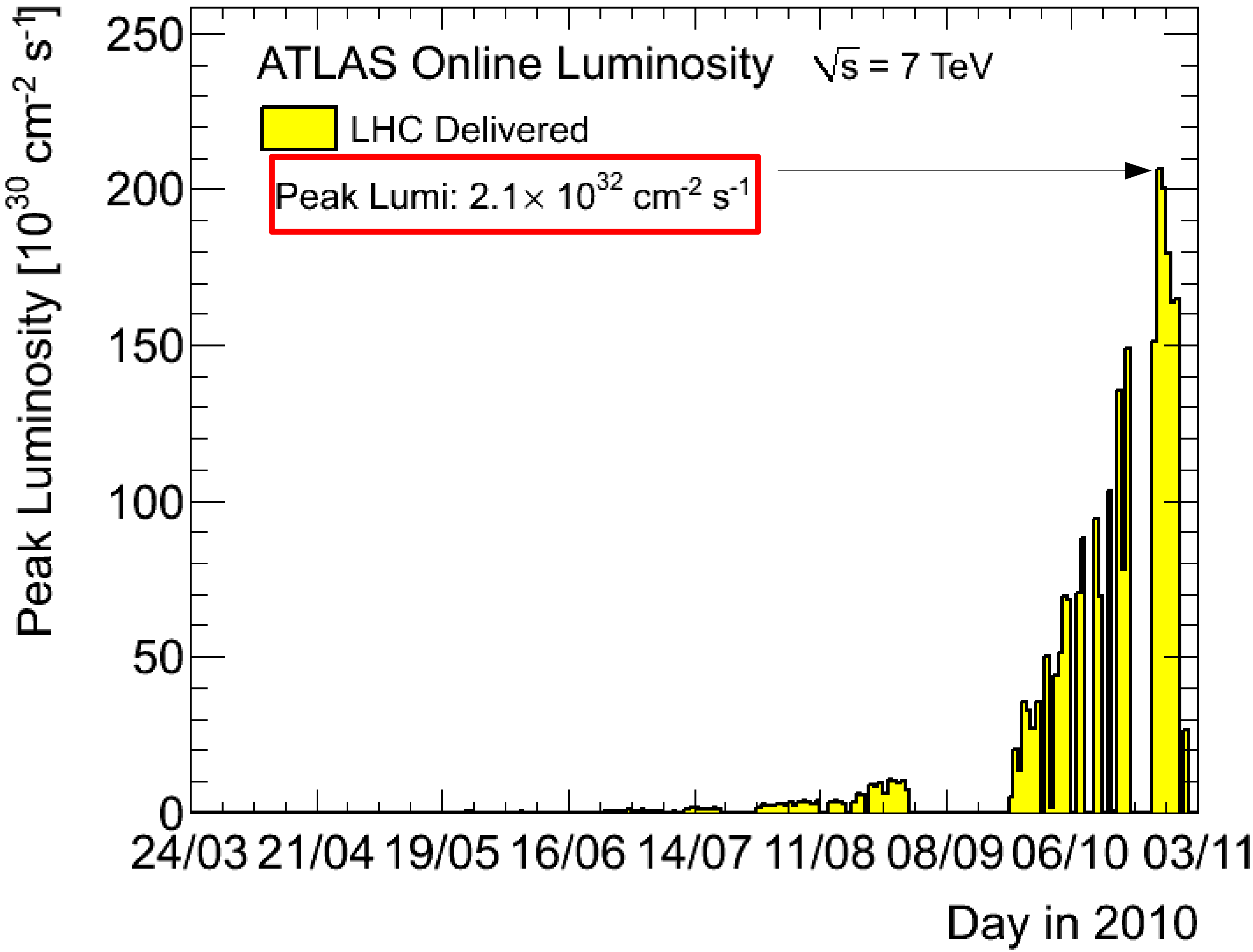


$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
$m_{vis}(\mu,\tau_h)$ = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
Z → ττ
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
2 GeV
-5
-3
-1
η
1
3
5
0
180
360
φ

Integrated luminosity



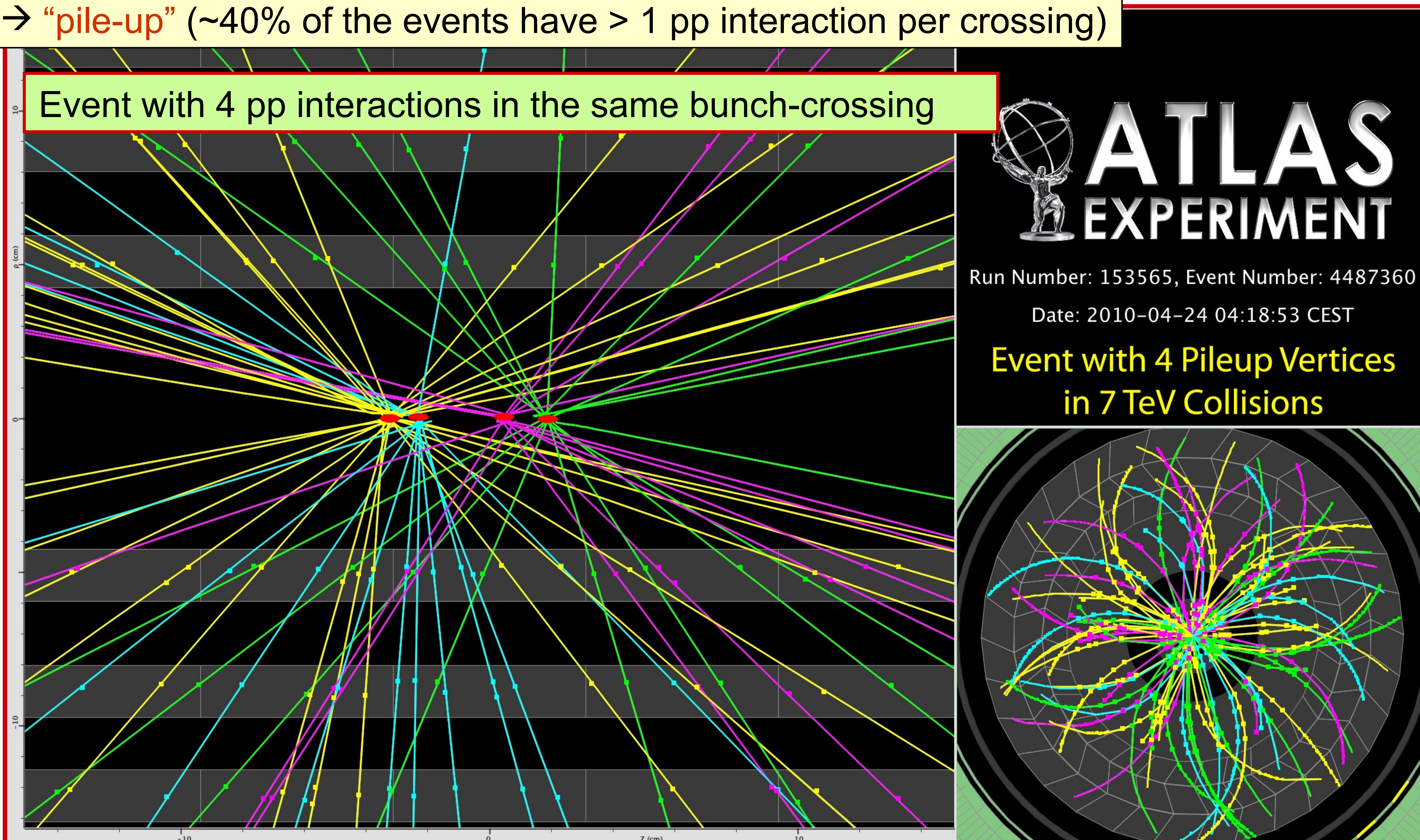
Peak luminosity



Pile up

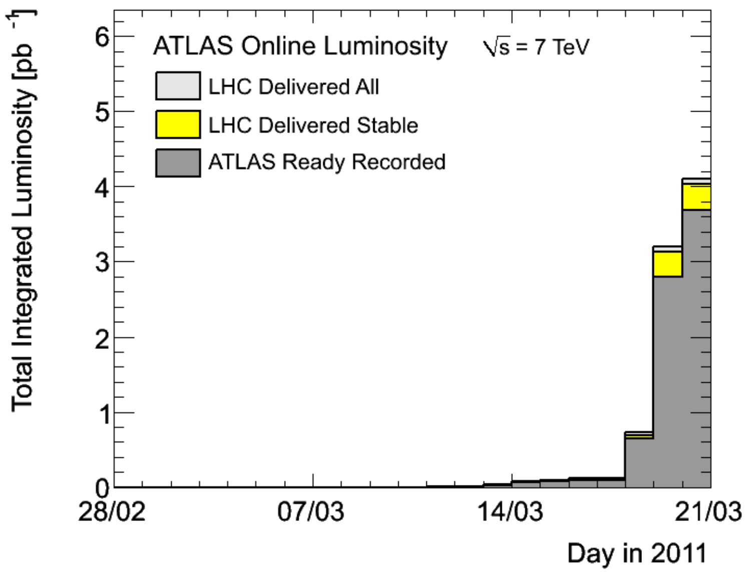
Max peak luminosity: $L \sim 1.6 \times 10^{30}\ cm^{-2}s^{-1}$
→ average number of pp interactions per bunch-crossing: up to 1.3
→ "pile-up" (~40% of the events have > 1 pp interaction per crossing)

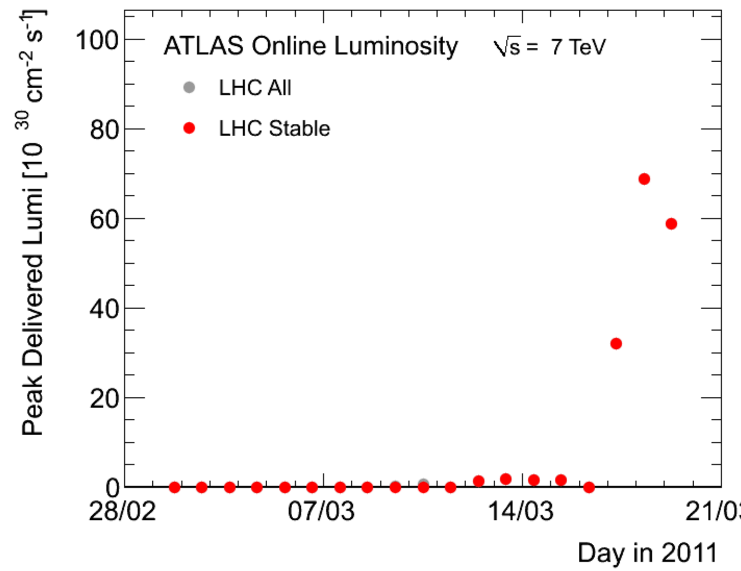
Event with 4 pp interactions in the same bunch-crossing

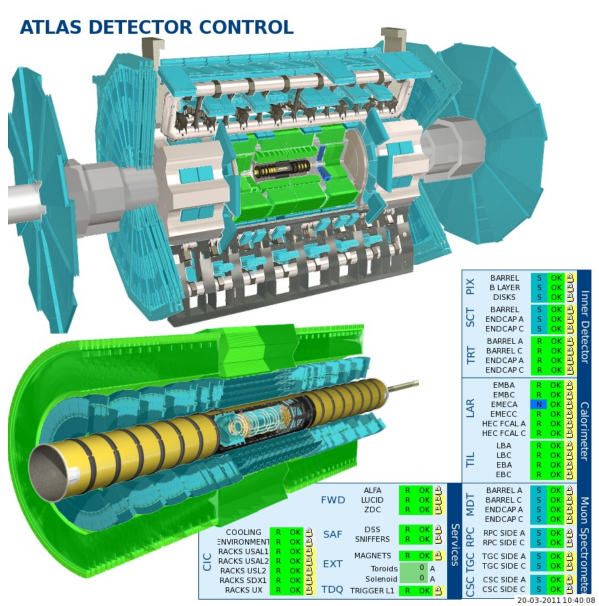


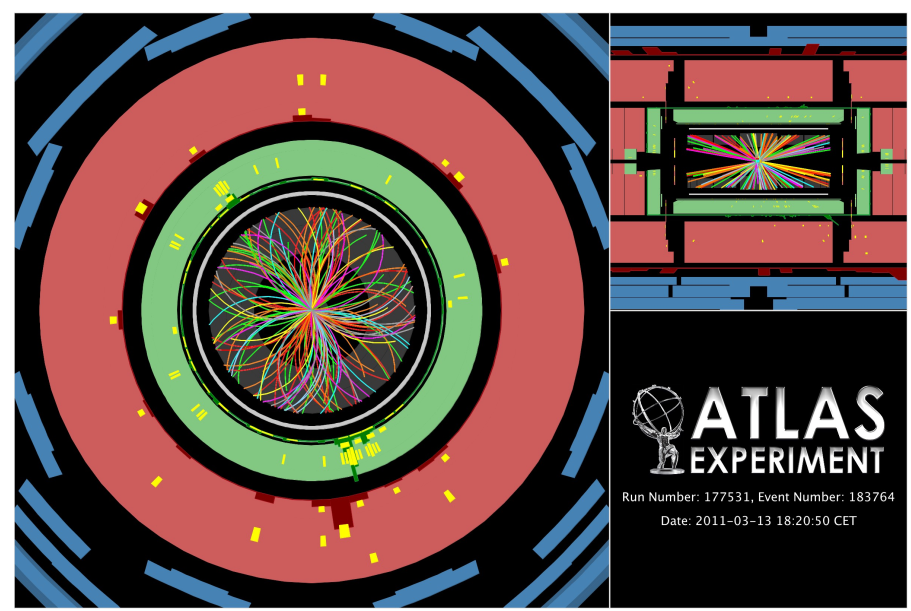
~ 10-45 tracks with p_T >150 MeV per vertex
Vertex z-positions : −3.2, −2.3, 0.5, 1.9 cm (vertex resolution better than ~200 μm)

First 2011 collisions







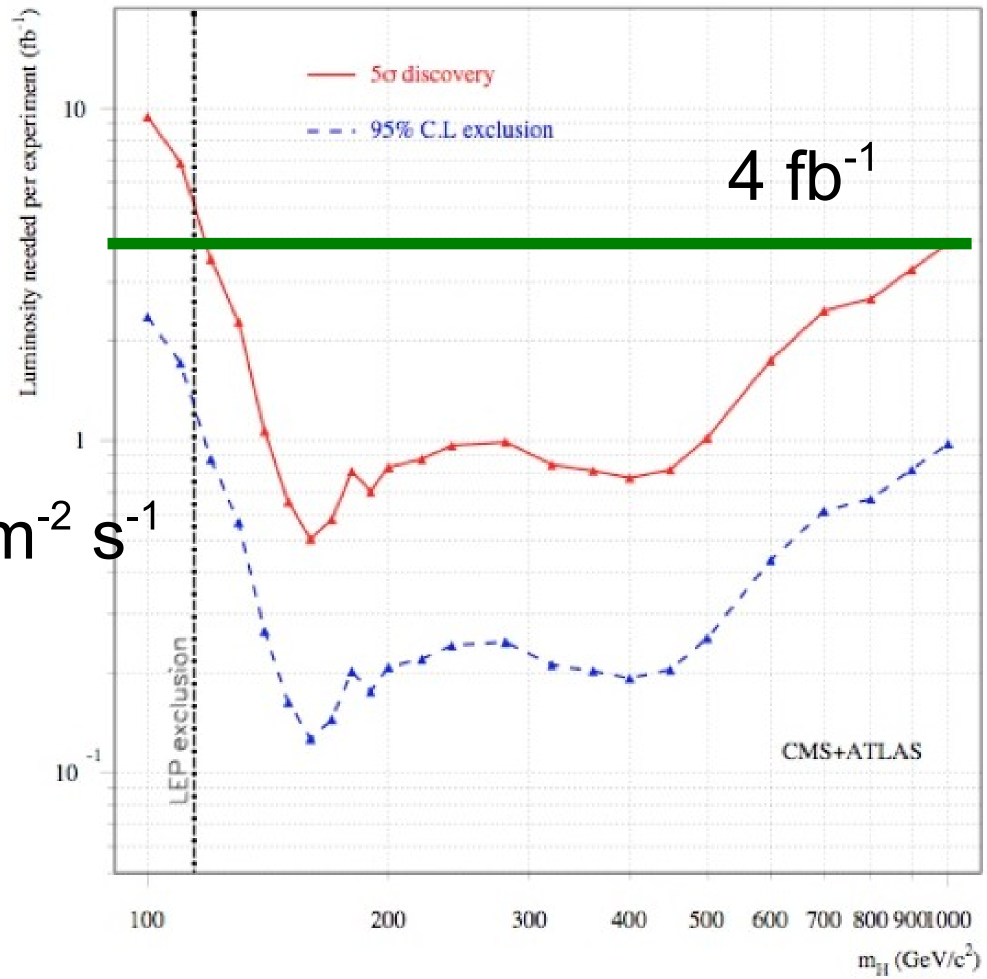


LHC upgrade

The LHC in the high lumi area

- We have seen that the LHC is a discovery machine built to study
  - → **The ElectroWeak Symmetry Breaking mechanism**
  - → **The shortcomings of the Standard Model**
- The discovery potential of the LHC can be enhanced by increasing its luminosity
- Infact, **whatever is discovered**, we'll want, at least, to
  - → **Improve the measurement of its properties (masses, couplings, etc)**
  - → **Test further predictions of the theories put forward to explain it**

Physics case for a sLHC



$L_{peak} \sim 2x10^{32}\ cm^{-2}\ s^{-1}$

By 2011-12 we may have a good picture of the TeV-scale physics

"Within 2/3 years of data taking, the SM Higgs boson will be discovered, or entirely excluded, over the full mass range" The super-LHC review – M. Mangano

What can the LHC achieve with extended, higher luminosity operations (SLHC)?

1. Improve measurements of new phenomena seen at the LHC. E.g.
   - Higgs couplings and self-couplings
   - Properties of SUSY particles (mass, decay BR's, etc)
   - Couplings of new Z' or W' gauge bosons (e.g. L-R symmetry restoration?)
2. Detect/search low-rate phenomena inaccessible at the LHC. E.g.:
   - $H \rightarrow \mu^+\mu^-$, $H \rightarrow Z\gamma$
   - top quark FCNCs
3. Push sensitivity to new high-mass scales. E.g.
   - New forces (Z', W_R)
   - Quark substructure
   - ....

Energies/masses in the few-100 GeV range. Detector performance at SLHC should equal (or improve) in absolute terms the one at LHC

Very high masses, energies, rather insensititive to high-lum environment.
Not very demanding on detector performance
Slightly degraded detector performance tolerable

The LHC in the future

Chamonix 2011 decisions:

- LHC running in 2012 to benefit from potential for reaching more than 5 fb^{-1} before first long shut down.
- Remain at 3.5 TeV beam energy due to unacceptably high risks for machine operation at beam energies above 3.5 TeV

Peak lumi goal: $L = 1\ 10^{34}\ cm^{-2}\ sec^{-1}$

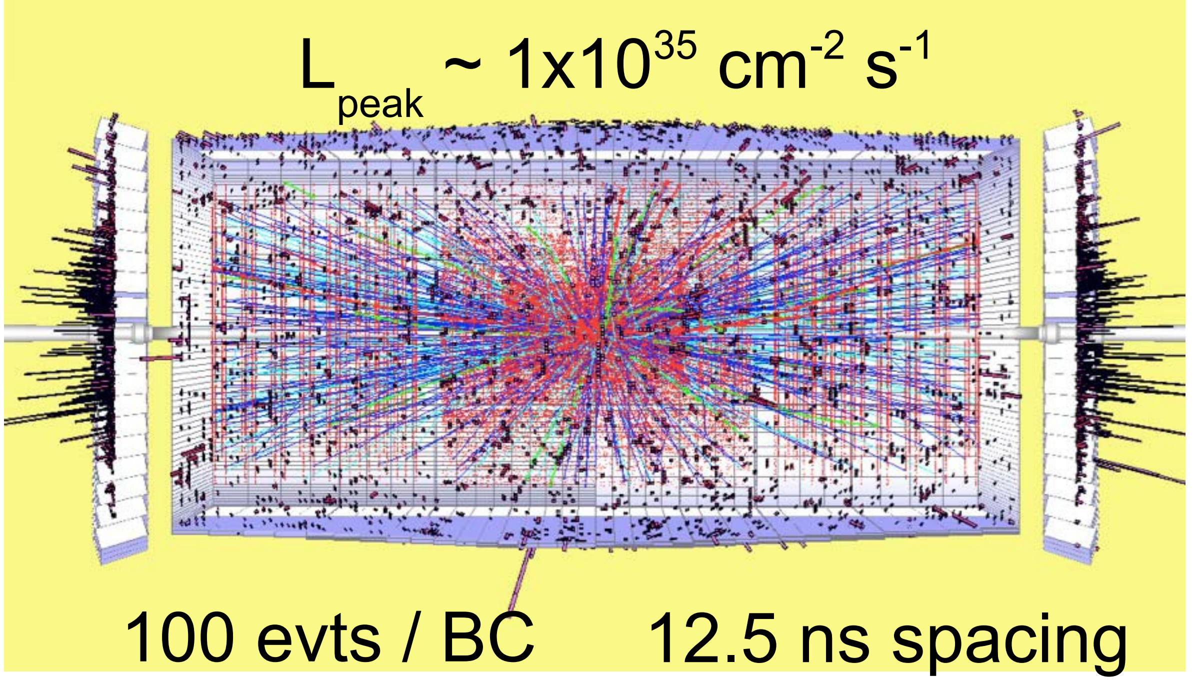
- Prepare for 18 month long shutdown in 2013 – 2014
- Commissioning and operation at 7 TeV in 2015 and 2016

sLHC Upgrade LHC in 2017 to be compatible with operation with above nominal beam intensities (LINAC4 & Collimation upgrade)

Peak lumi goal: $L \geq 5\ 10^{34}\ cm^{-2}\ sec^{-1}$

ACES 2011 Workshop, CERN, March 2011 Oliver Brüning BE-ABP 8

High luminosity implications

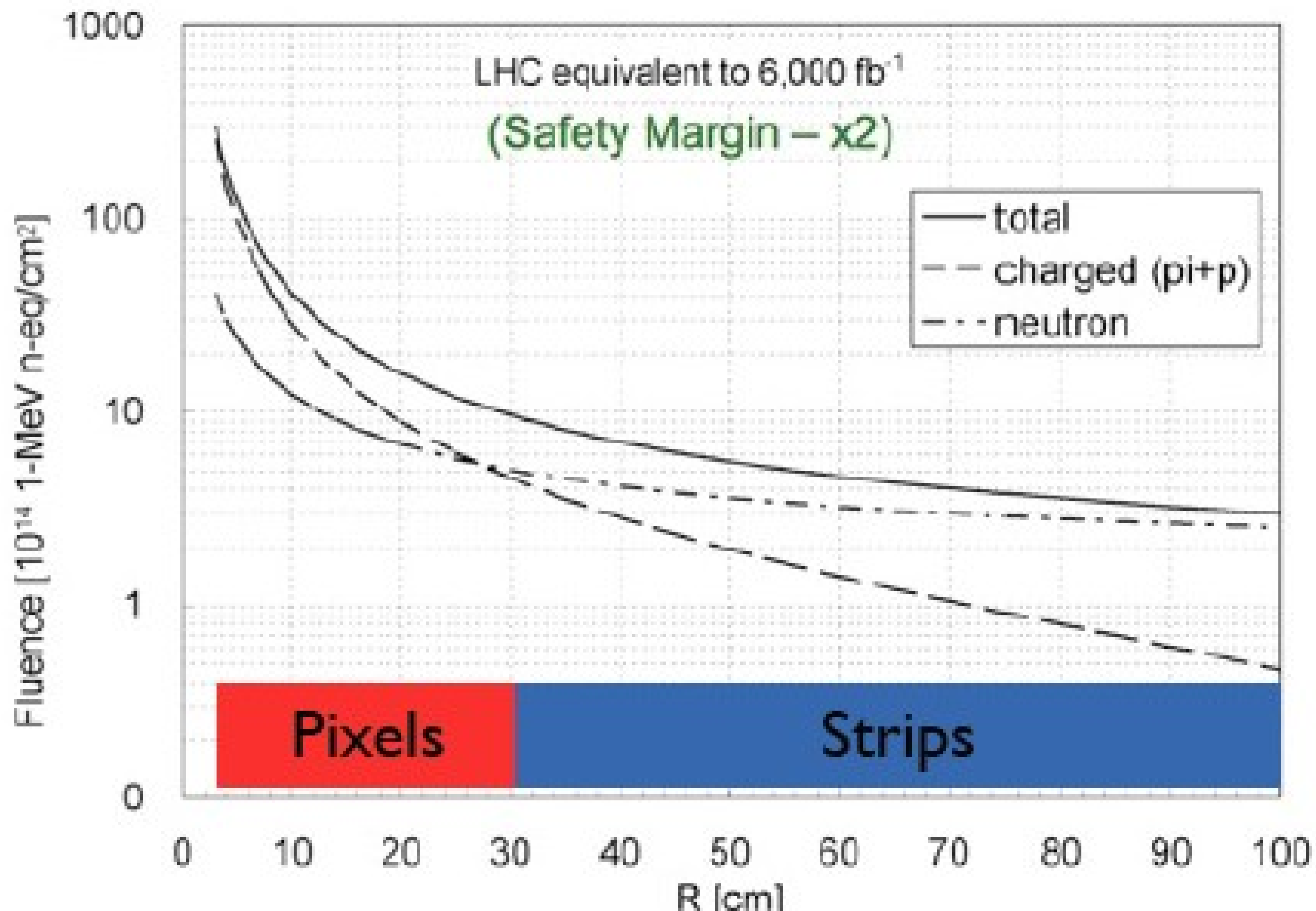


- More pile-up & higher rate events

➔ **Faster electronics**

➔ **Higher granularity subdetectors**

High luminosity implications



- fluences for the innermost pixel layer: **1.5×10^{16} n_{eq}/cm^2 (3 ab^{-1})**

➔ **Radiation hard components**

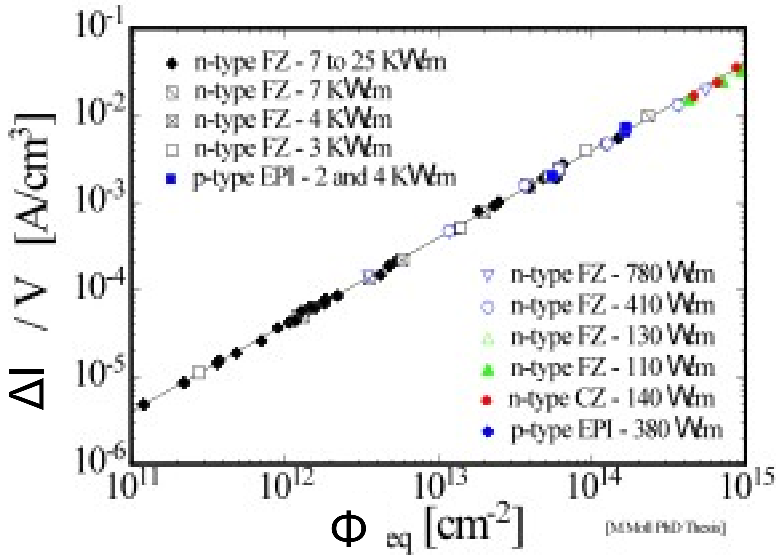
Macroscopic effects

Increase of leakage current
- can be helped with cooling

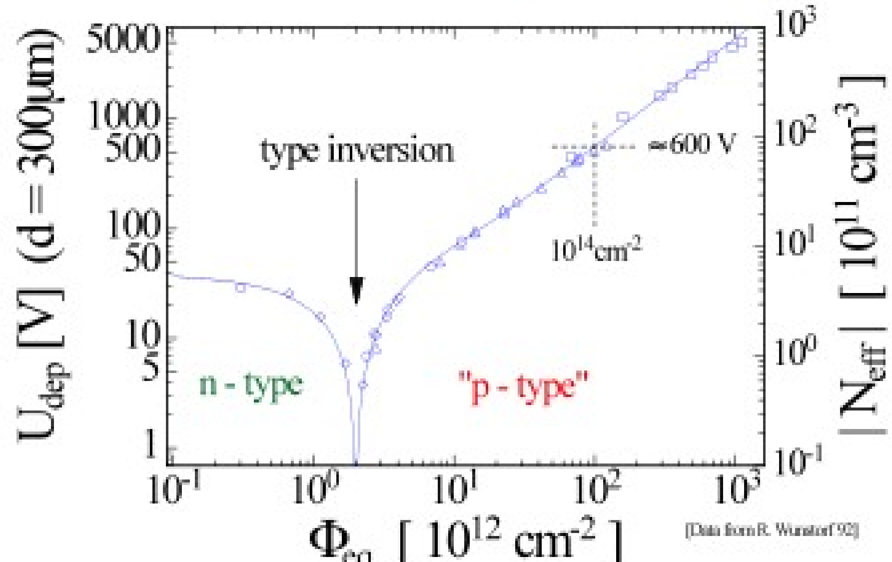
Change of the full depletion voltage V_{dep} (effective doping concentration N_{eff}).
- every p-n-junction has a finite breakdown voltage

Decrease of the charge collection efficiency
- limited by partial depletion, trapping, type inversion

Change of the leakage current:

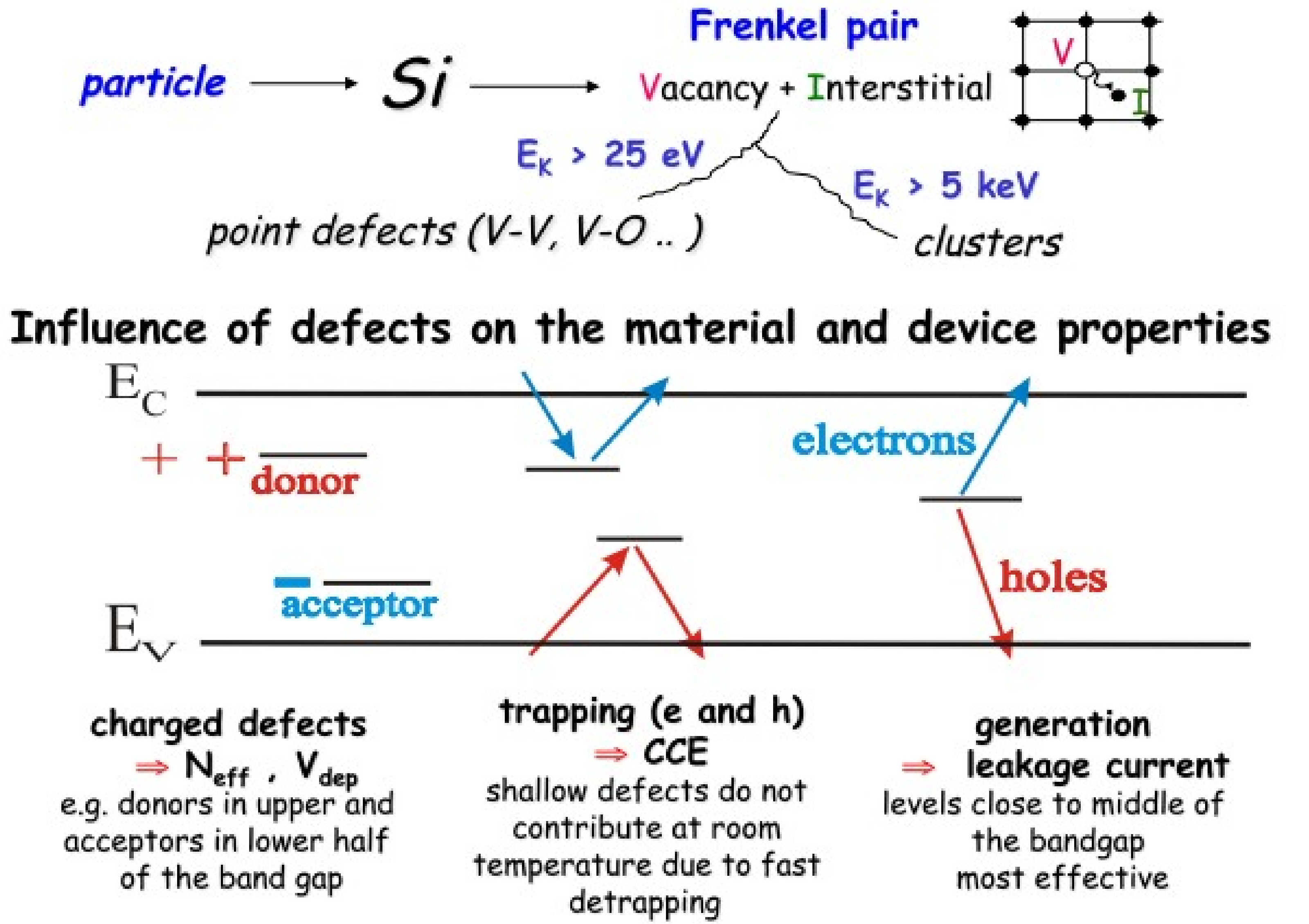


Evolution of the N_{eff} for n-type initial doping:



Panja Luukka, The Fifth International Forum on Advanced Material Science and Technology (IFAMST5 2006)

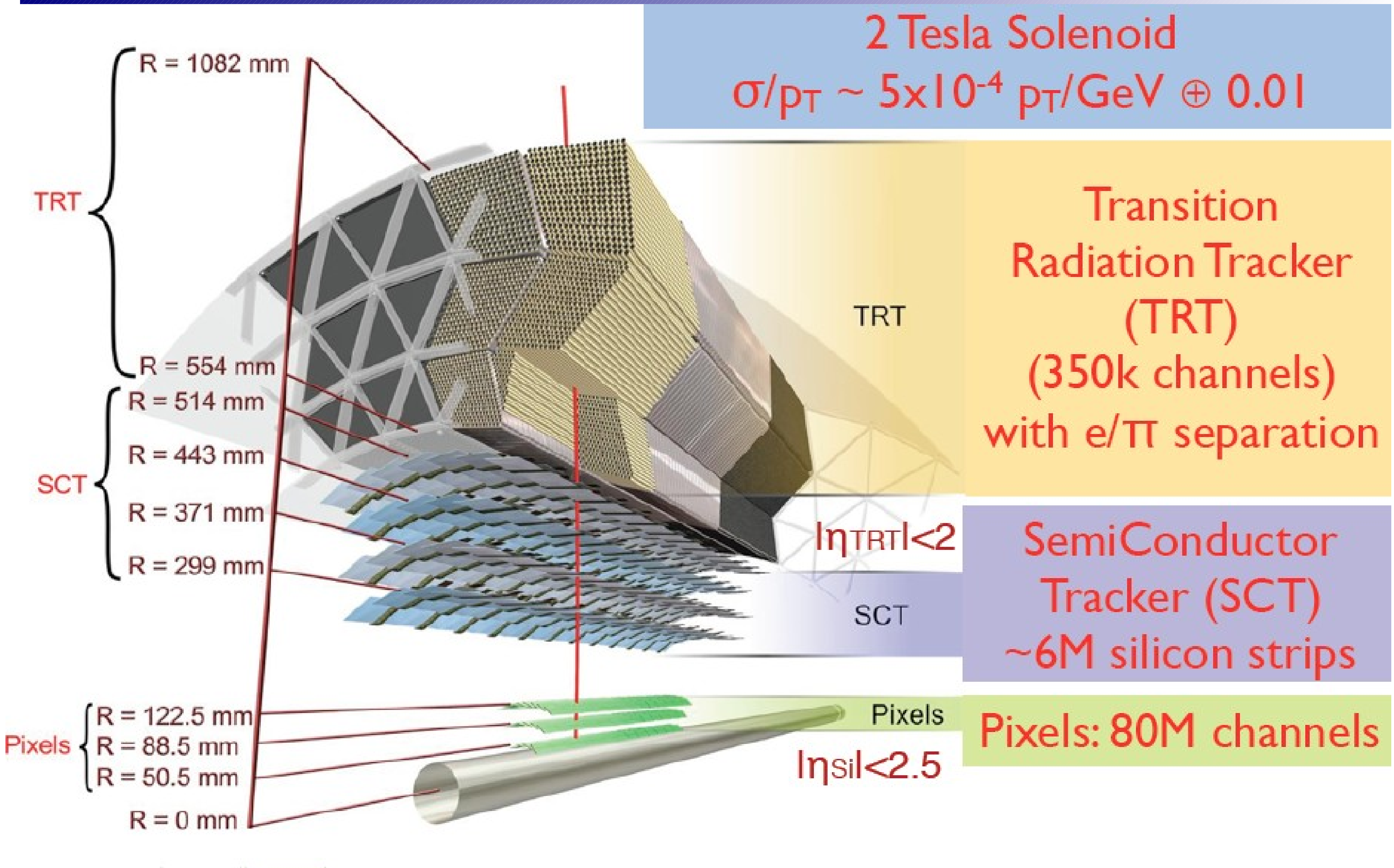
Radiation damage in silicon detectors



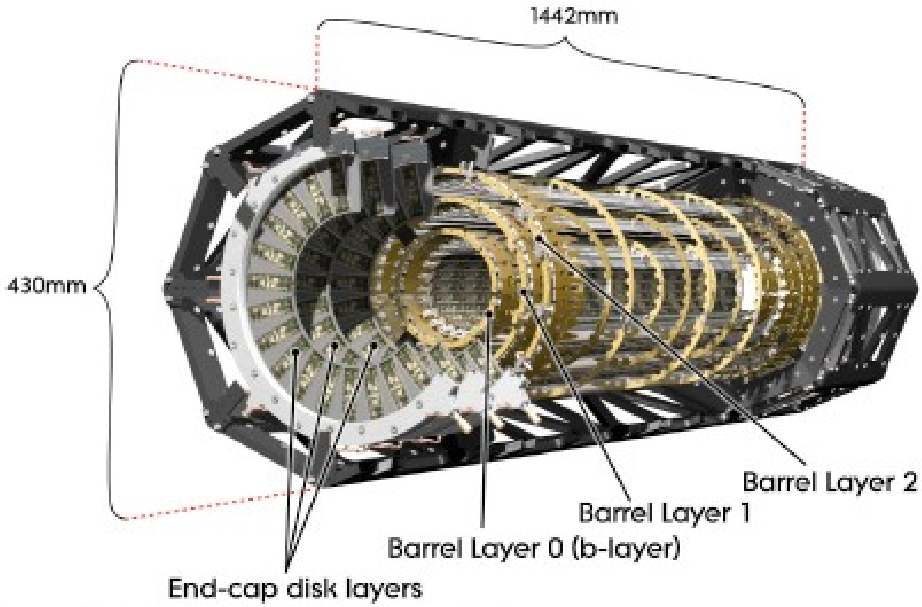
Panja Luukka, The Fifth International Forum on Advanced Material Science and Technology (IFAMST5 2006)

THE PIXEL UPGRADE

The current Inner Detector

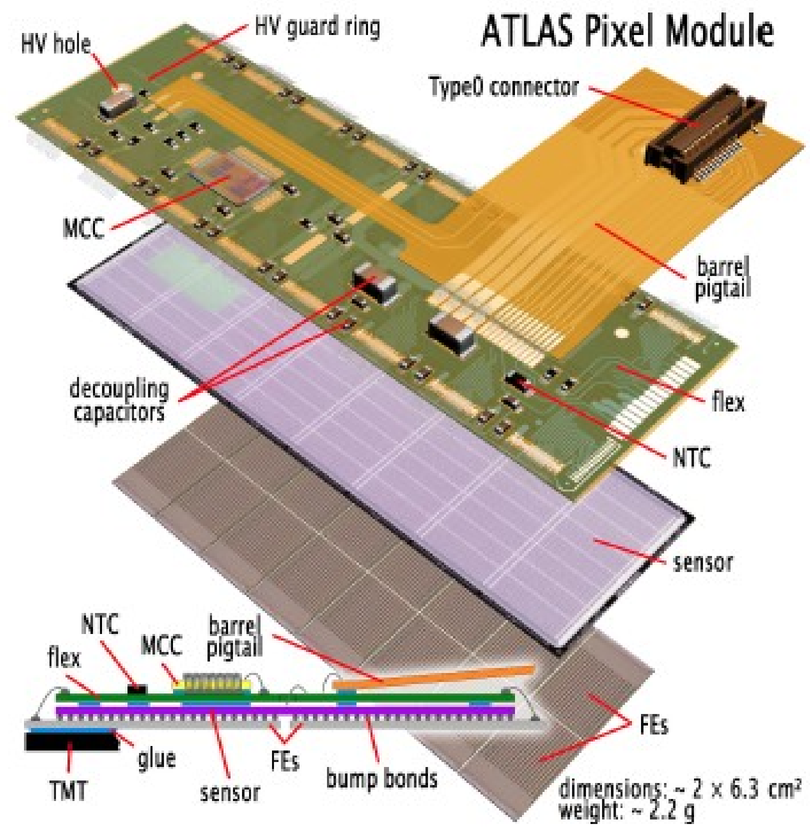


The current ATLAS Pixel detector



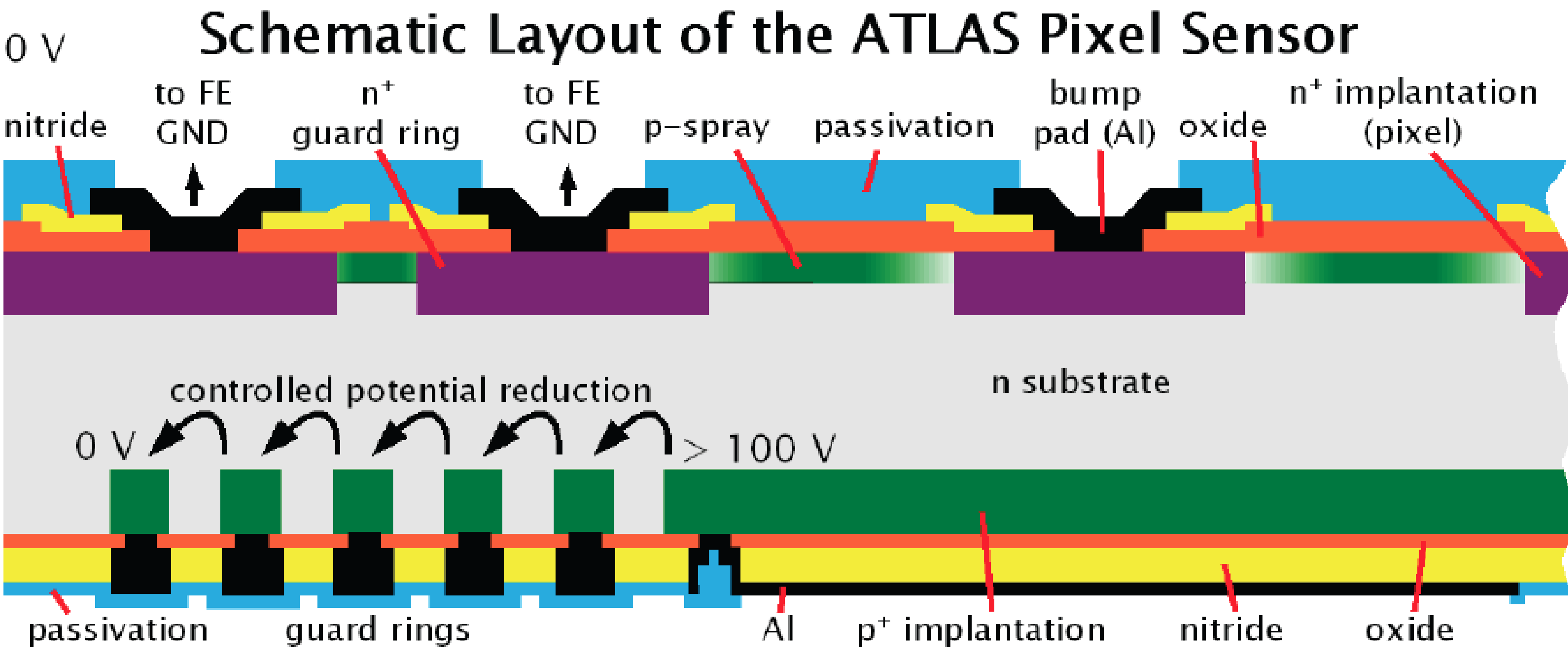
- ATLAS Pixel Detector
  - 3 barrels + 3 forward/backwarc disks
  - 112 stave and 4 sectors
  - 1744 modules
  - 80 million channels

- **ATLAS Pixel Module**
  - 16 front-end chips (FE-I3) module with a Module Controller Chip (MCC)
  - 46080 R/O channels 50 µm x 400 µm (50 µm x 600 µm for edge pixel columns between neighbour FE-I3 chips)
  - Planar n-in-n DOFZ silicon sensors, 250um tick
  - Designed for 1 x 10^{15} 1MeV fluence and 50 Mrad
  - Optolink R/O: 40÷80 Mb/link

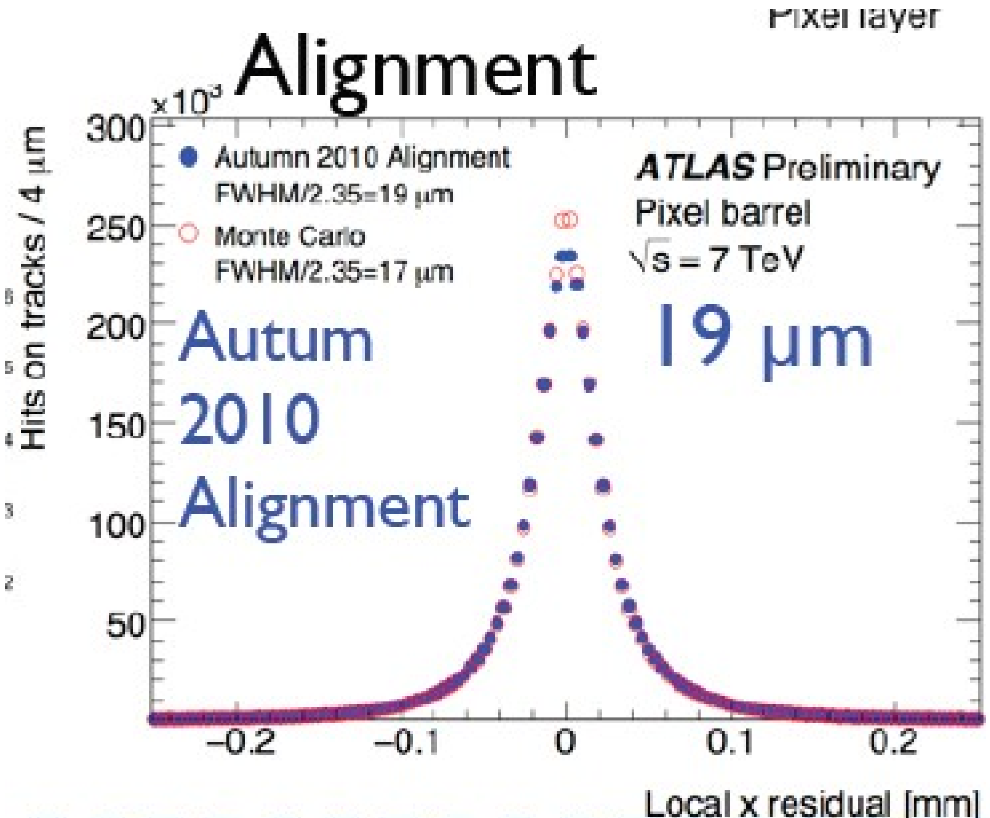


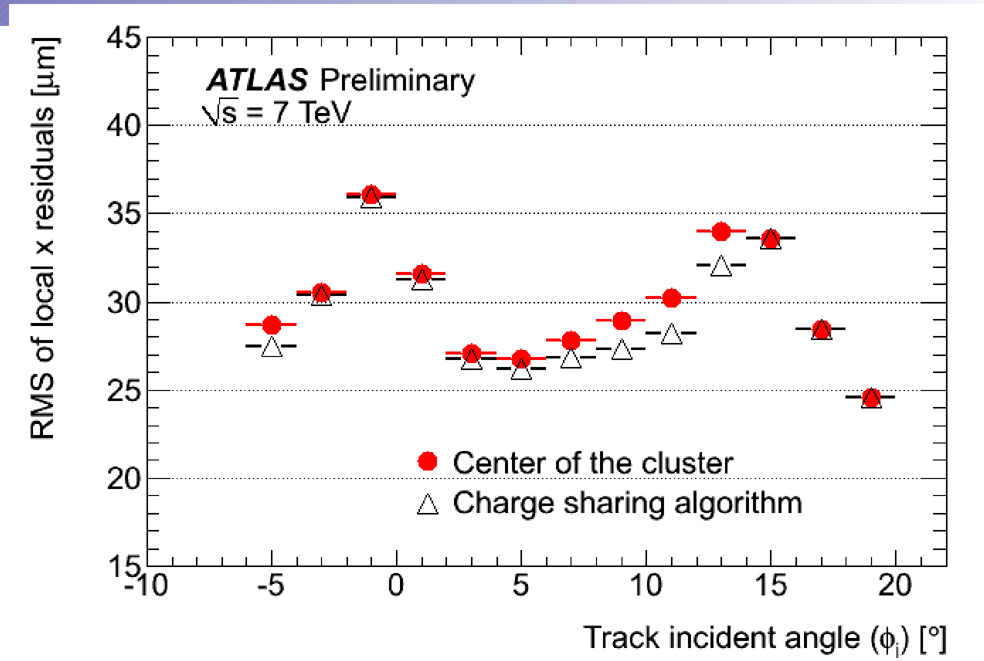
IPRD10, Siena 9.6.2010 - Alessandro La Rosa (CERN)

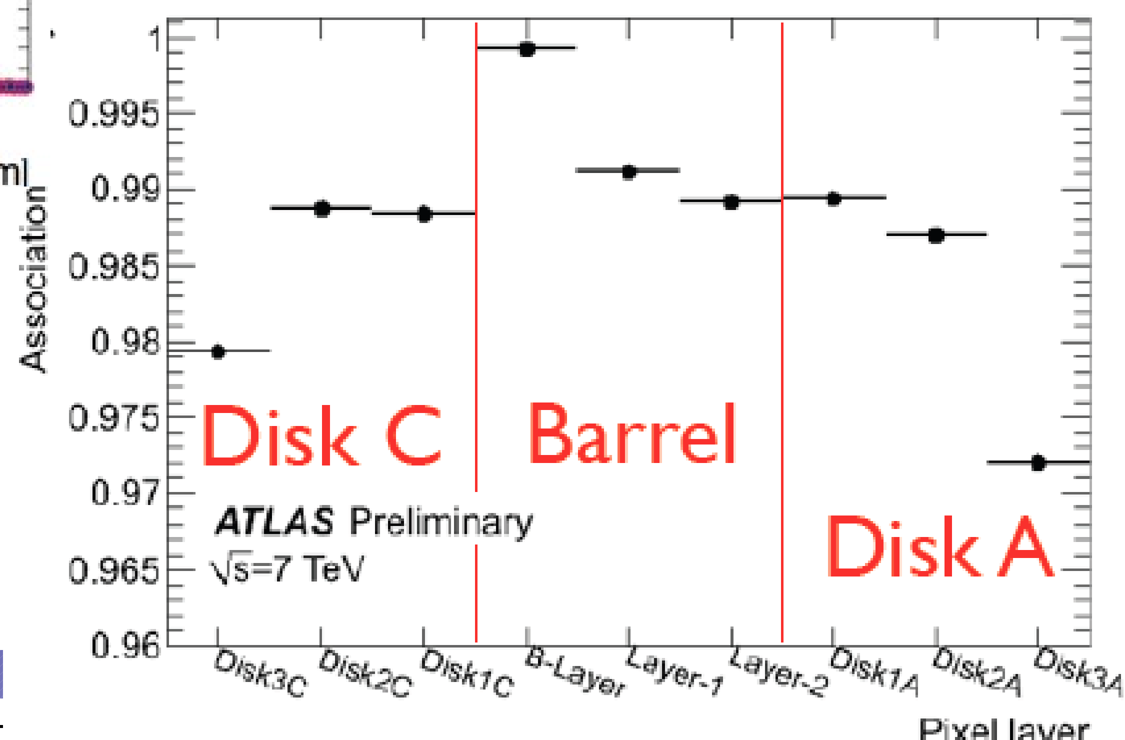
The ATLAS Pixel Sensor



Pixel performances



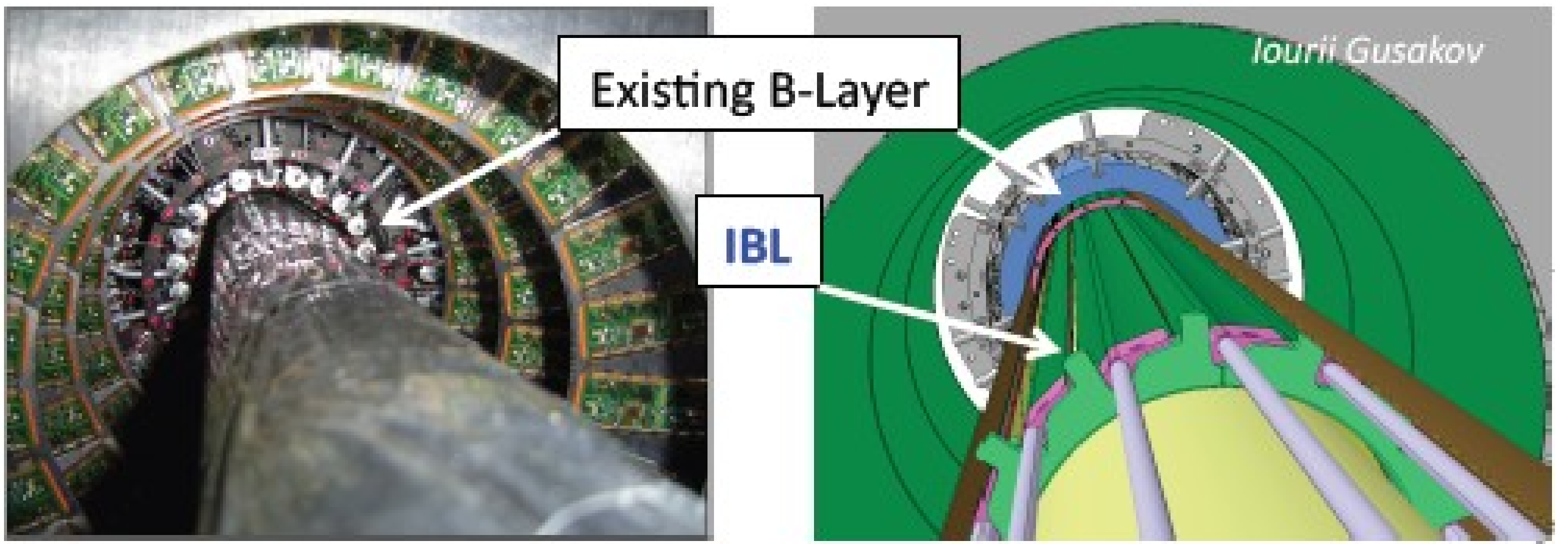




THE INSERTABLE B-LAYER

A 4th pixel layer: Insertable B Layer

- Add a 4th low-mass Pixel layer inside the present B-layer: the Insertable B-Layer



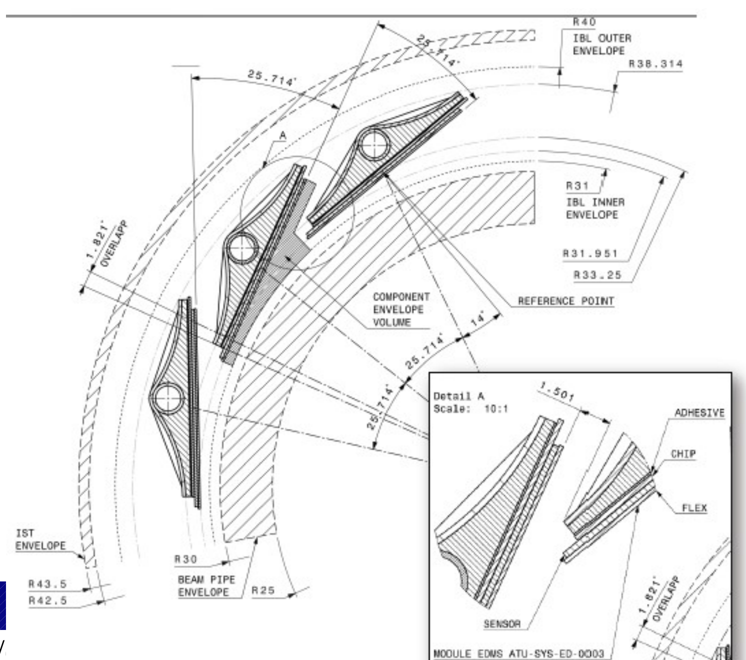
3.2 cm from IP

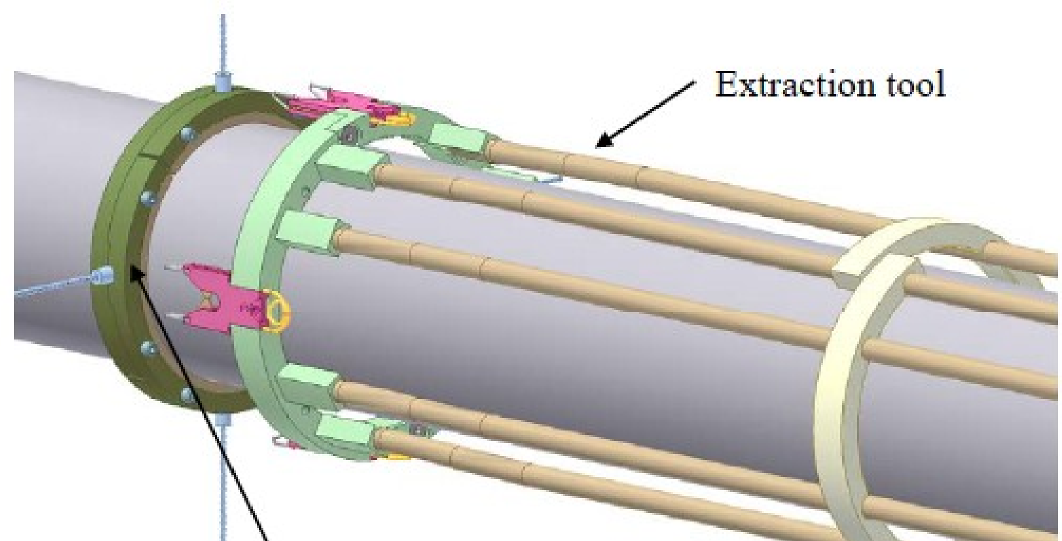
- To improve performance of existing system
- To maintain performance of existing system when present B-layer starts degrading

Scheduled for 2013

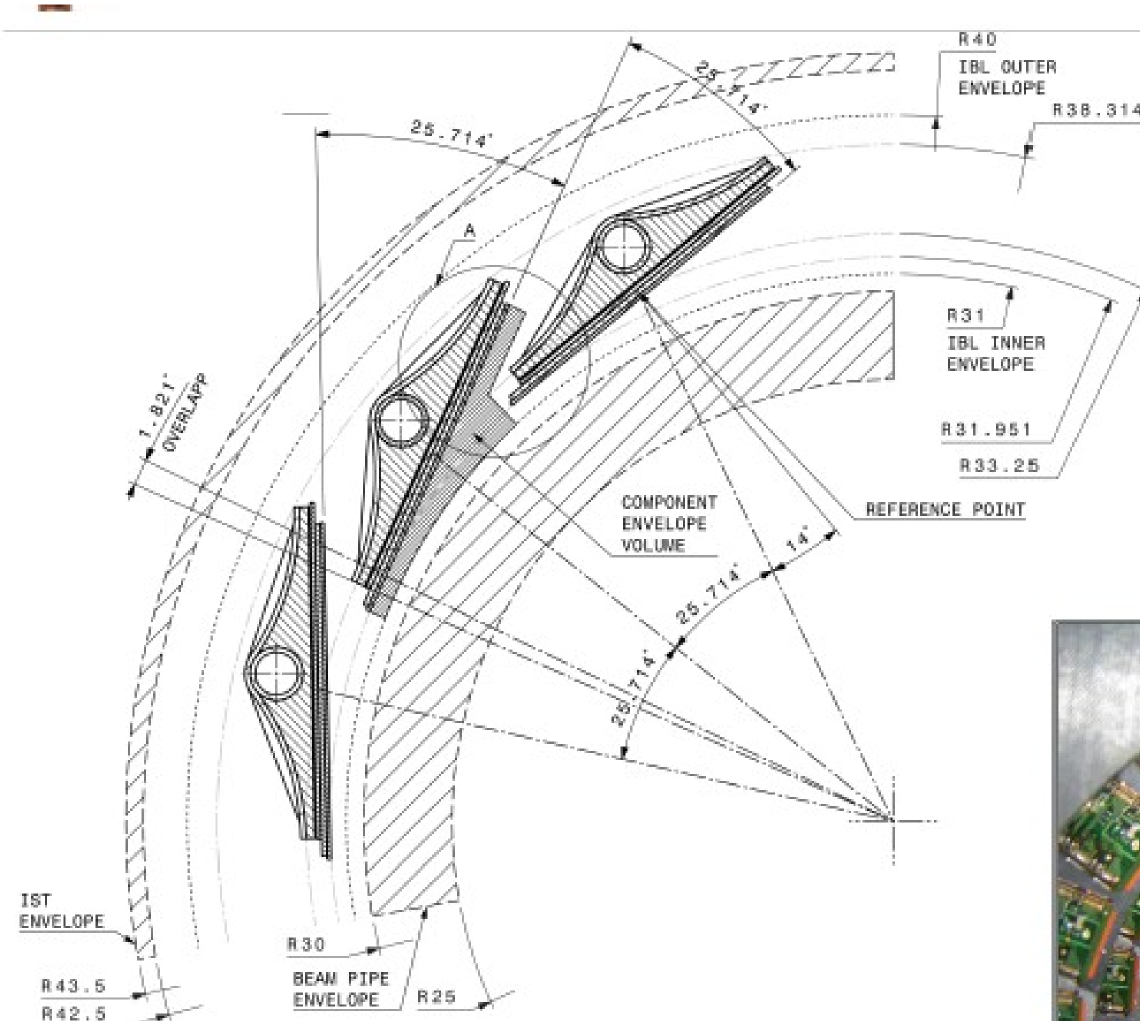
Why is IBL important

- This will be the first real upgrade project in the community
- ➔ Most of the problems and technologies necessary later for sLHC will be tested and solved already. Excellent test bench for later.
- ➔ The IBL is the "technology" bridge to sLHC. Its specification required us to develop and use new technologies, which are directly relevant for sLHC





IBL - layout



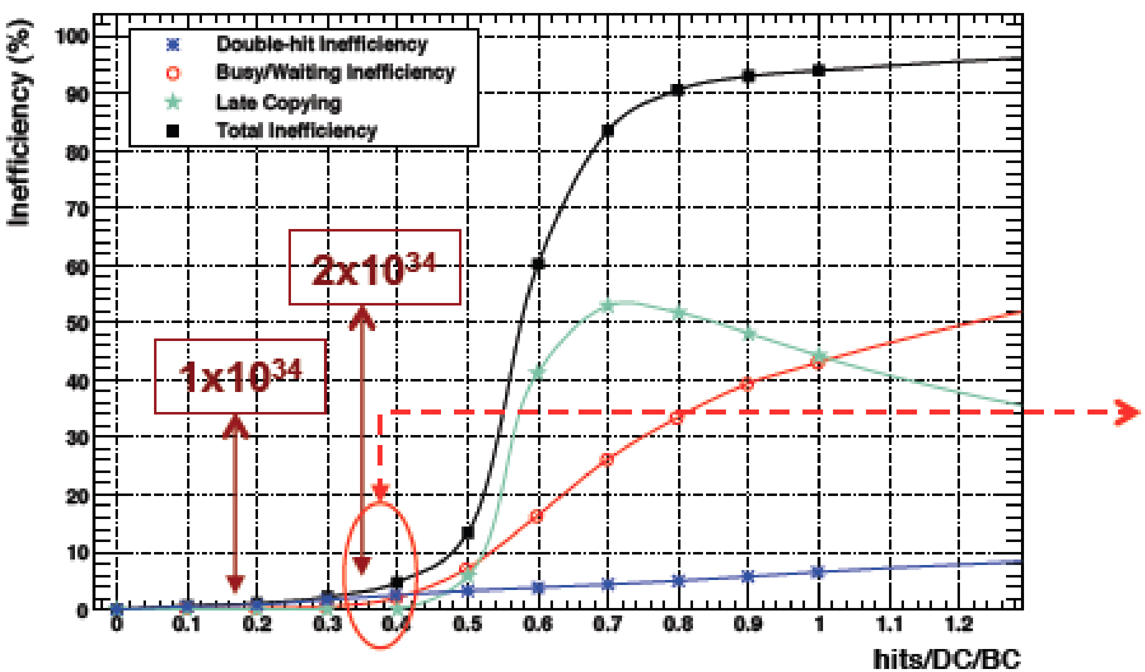
- ***Beam-pipe reduction:***
  - Inner R: 29 → 25 mm
- ***Very tight clearance:***
  - "Hermetic" to straight tracks in Φ (1.8º overlap)
  - No overlap in Z: minimize gap between sensor active area.
  - Coverage in η (2σ-vertex spread): 2.6
- ***Material budget:***
  - Stave, el.serv. Module: 1.16 % X_0
  - IBL Sup.Tube (IST): 0.28 % X_0

- *Beam-pipe (BP) extracted by cutting the flange on one side and sliding (guiding tube inside).*
- *IBL Support Tube (IST) inserted.*
- *IBL with smaller BP inserted in the IST*

IBL - Luminosity effects

- The current Pixel R.O. designed for a peak luminosity of 1 x 10^{34} $cm^{-2}s^{-1}$.
- A luminosity at least twice that high is expected before the sLHC end
- Event pileup: redundancy in track measurement to control the fake rate
- High occupancy: induce readout inefficiencies
- Affects the B-layer more than other layers
- Would thereby limit the *b* tagging efficiency.
- **IBL**: low occupancy (with respect to SCT/TRT) reduces track fakes
- FE-I4 has higher bandwidth than existing readout.

FE-I3 inefficiency vs occupancy for B-layer

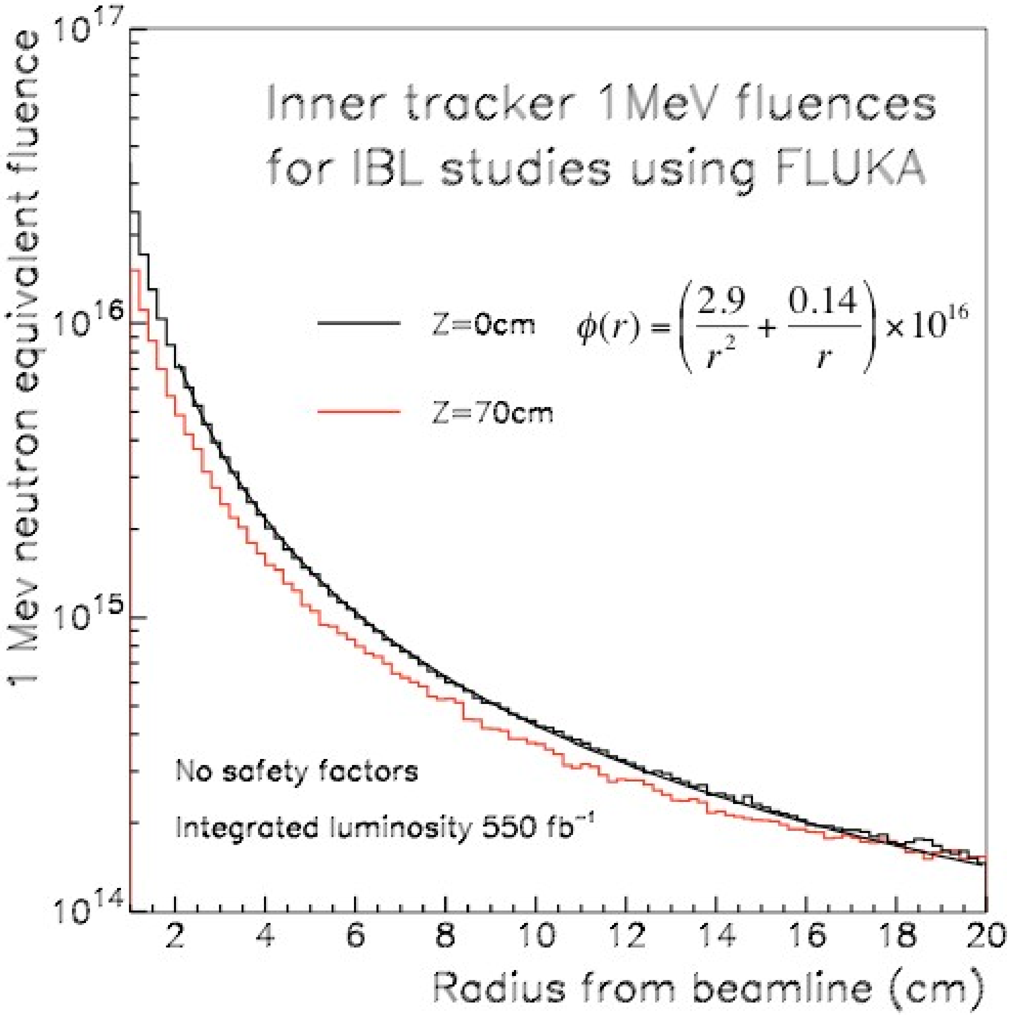


FE-I3 has 5% inefficiencies at the B-layer occupancy for 2.2×10^{34}. Steep rising function of occupancy: no safety margin.

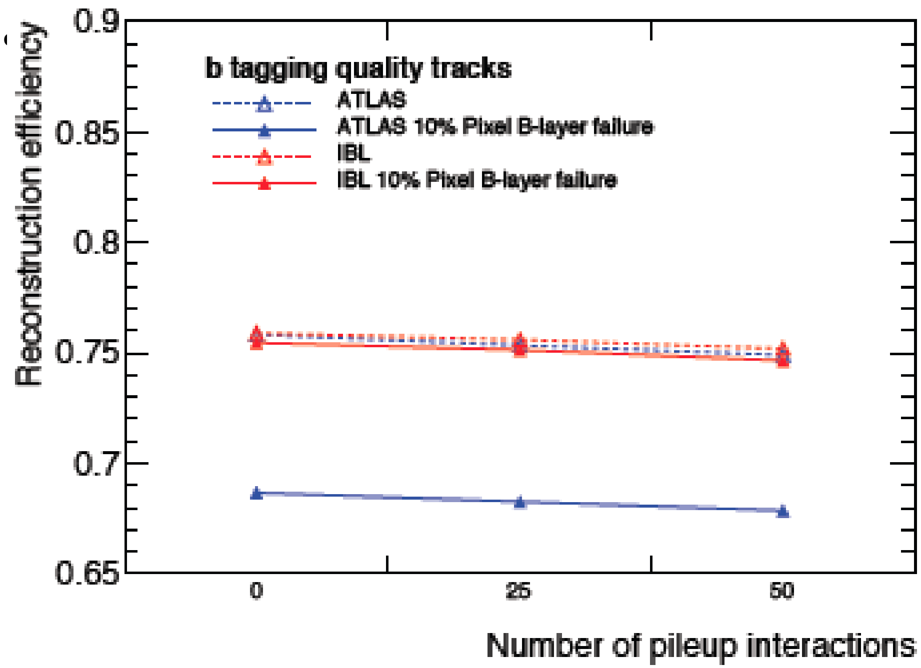
IBL – Radiation effects

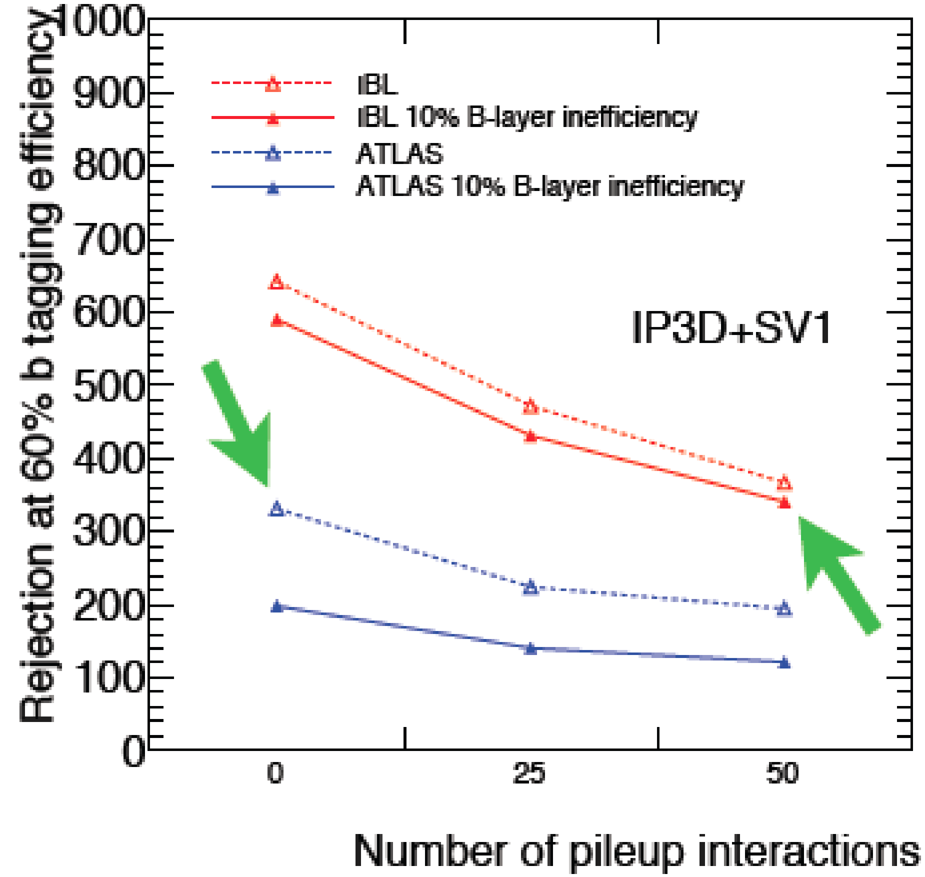
IBL designed for 550 fb^{-1} (provides margin should luminosity evolve more rapidly than expected or should 2020 HL-LHC shutdown be delayed)

- NIEL dose @ 3.2 cm: 3.3×10^{15} n_{eq}/cm^2
- Safety factor: 5×10^{15} n_{eq}/cm^2
  - TID: 250 Mrad



IBL performances





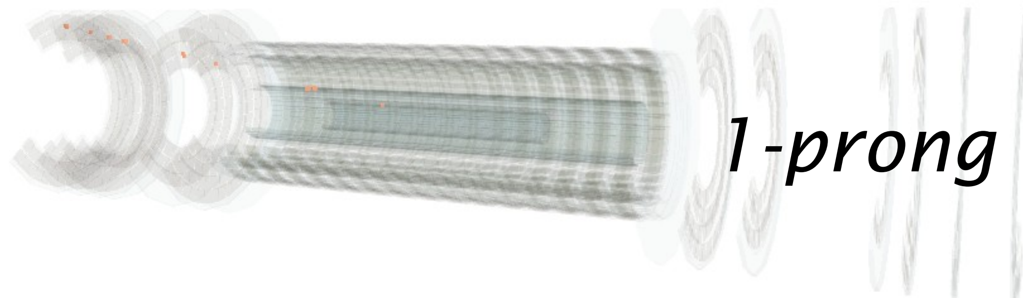
In a scenario with a 10% cluster inefficiency in the actual B-layer, the IBL recovers tracking efficiency and impact resolution

- Only minor effect on b-tagging performances
- Performing better than ATLAS w/o defects and pileup!

Montecarlo studies on IBL

$$\tau \longrightarrow \pi^{-}, \pi^{0}, \nu_{\tau}$$

|eta| < 2.5



1-prong *

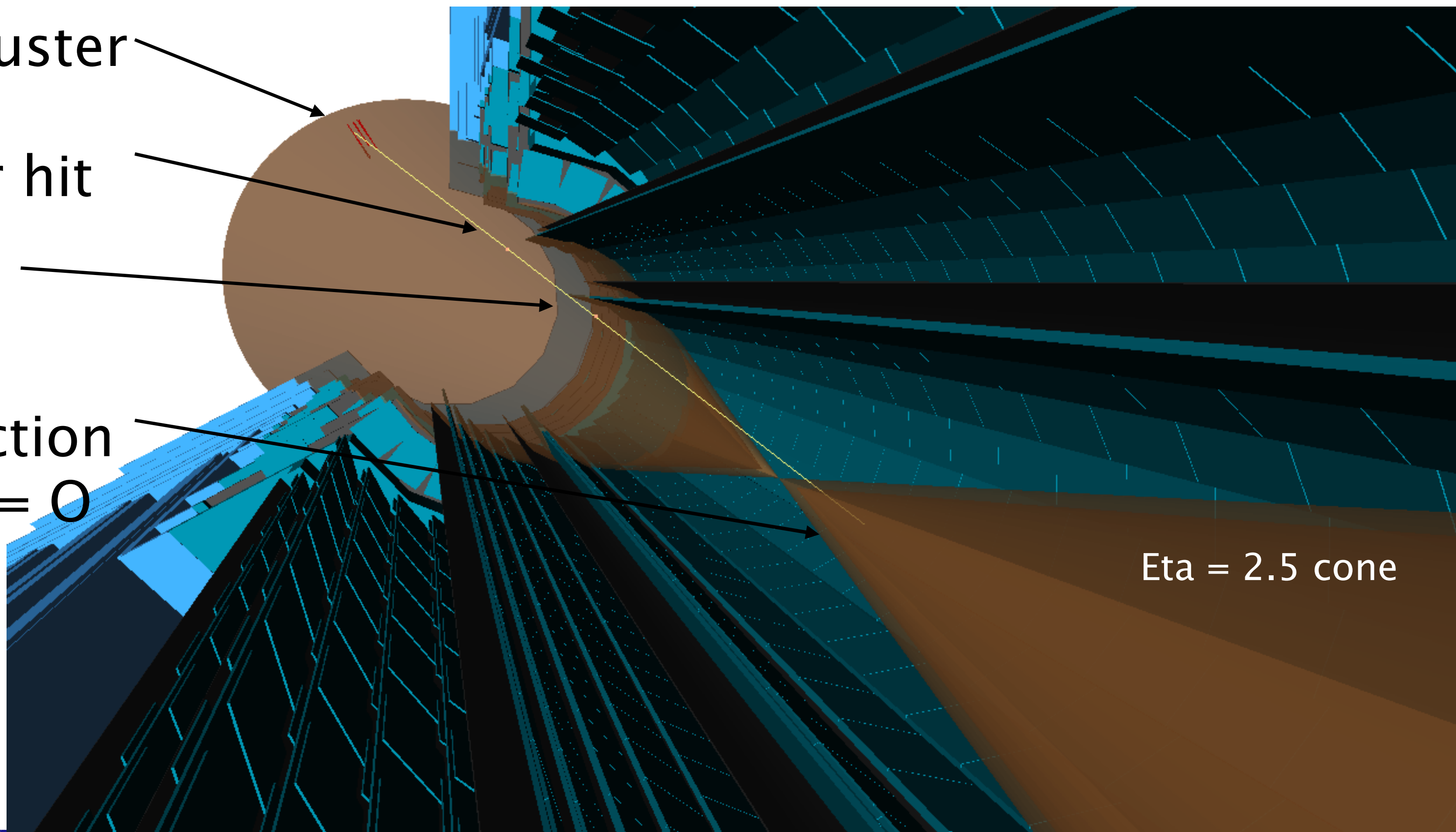
Montecarlo studies performed by the PPS group @ LAL

SCT cluster

B-layer hit

IBL hit

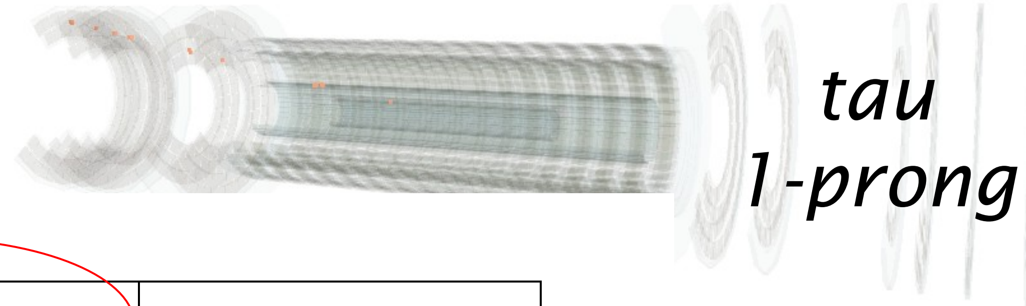
Interaction Point != O



John Idárraga

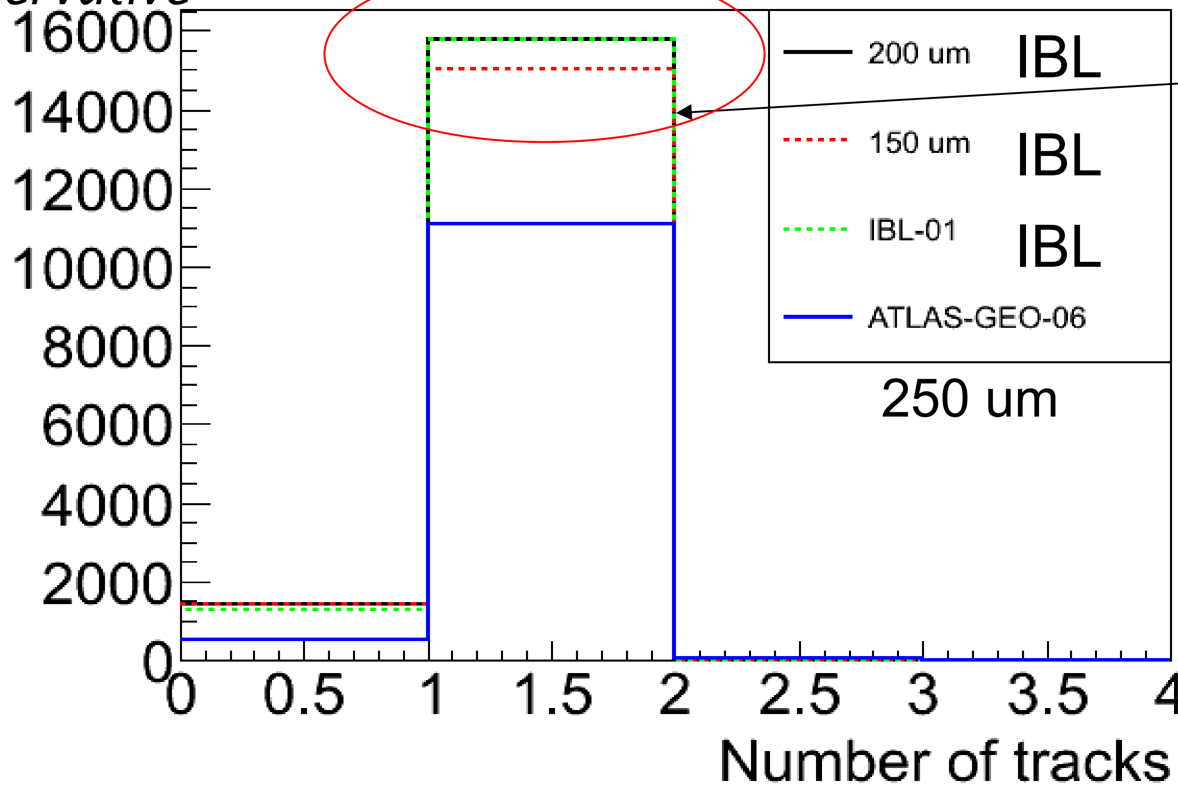
τ → 1 prong

$\tau \longrightarrow \mu, \bar{\nu}_\mu, \nu_\tau$



tau 1-prong

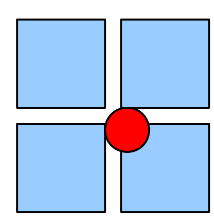
Geo desc
As in n-in-n
conservative



Too thin might not be the best idea in some cases

FEI3: 3500e ~ 12keV
FEI4: 3000e

2000e ?



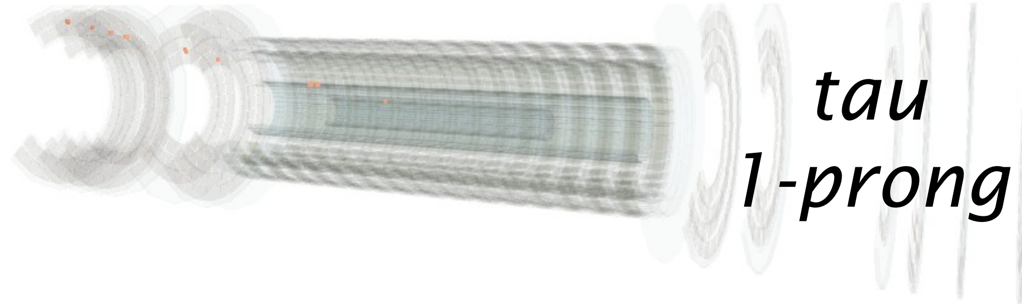
Double Triple quad

Mip in 150 um
13000e ~45keV

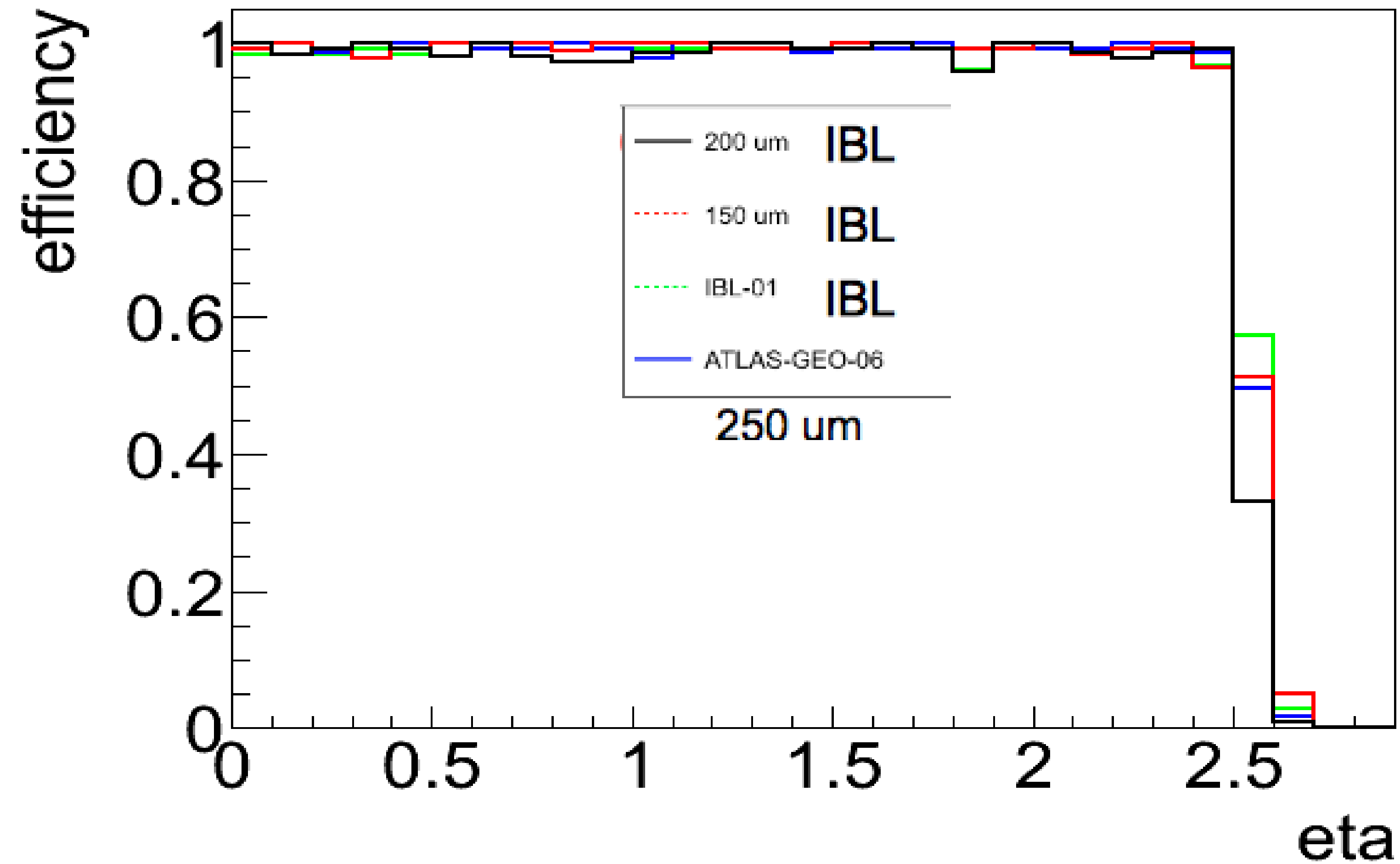
IBL + Pixel + SCT + TRT

τ → 1 prong

$$\tau \longrightarrow \mu, \bar{\nu}_\mu, \nu_\tau$$



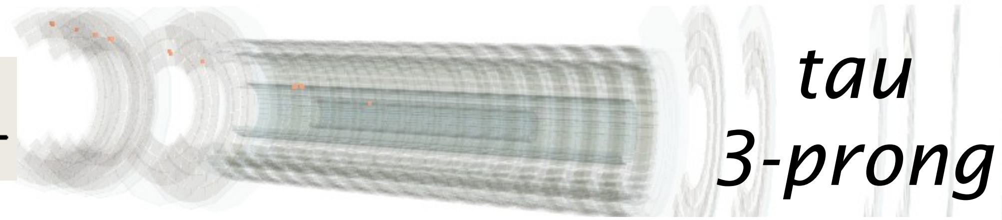
Geo desc
As in n-in-n
conservative

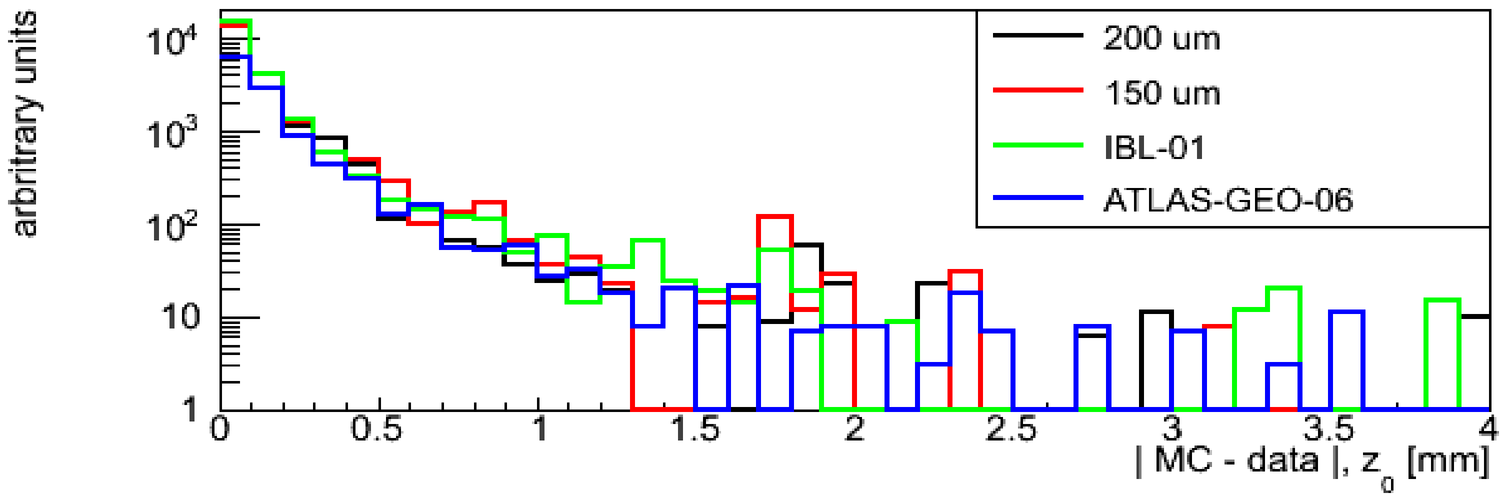


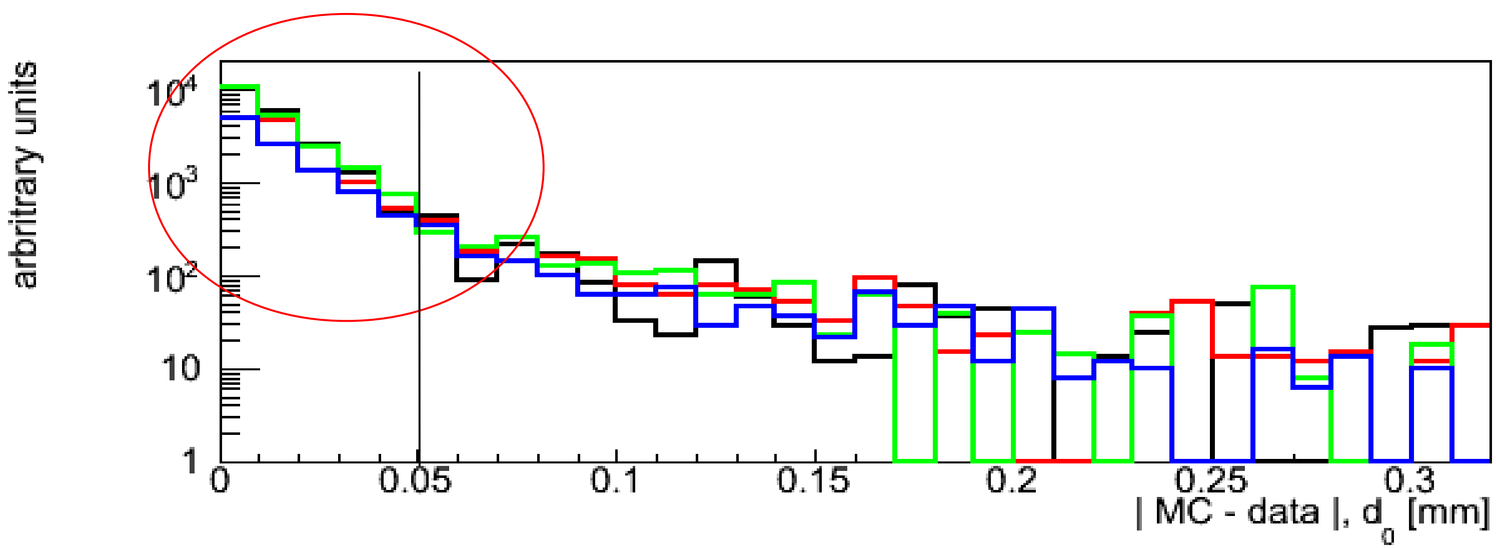
IBL + Pixel + SCT + TRT

τ → 3 prong

$$\tau \longrightarrow \pi^-, \pi^+, \pi^-, \nu_\tau$$



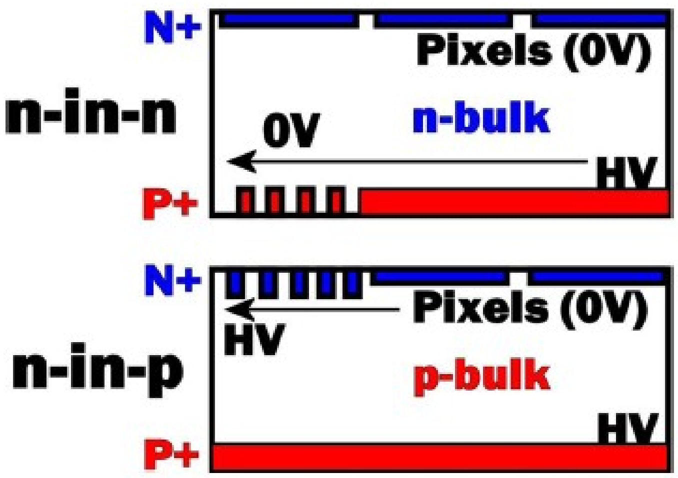




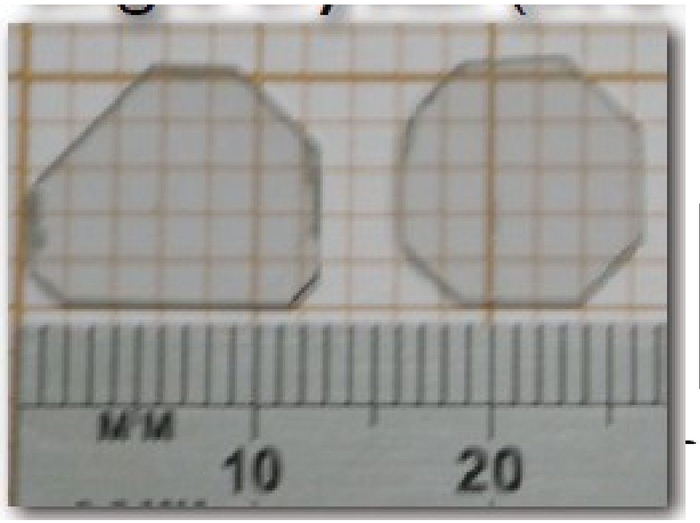
John Idárraga

Sensor options for the IBL ...and sLHC

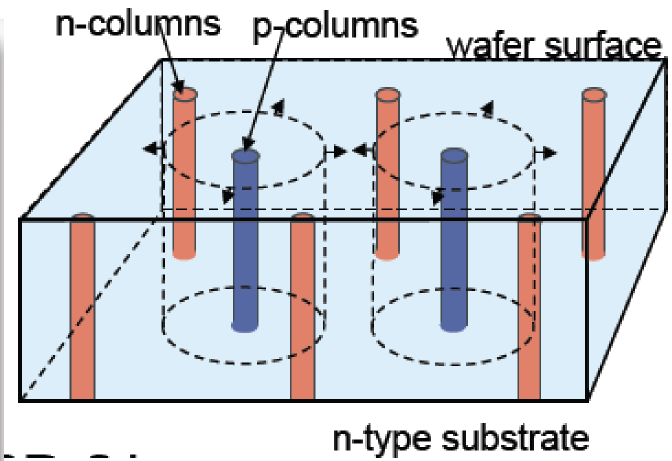
PLANAR



DIAMOND



3D



- More details in the next slides

- Very low noise
- No cooling
- No doping needed
- Low capacitance
- Very high BD field
- Expensive
- Difficult to realize large sample of single crystal sensors

- Implants through the detector
- Highly segmented sensor
- Low depletion voltage
- Fast signal
- High rate capable
- Inefficiency regions correspinig to column
- Low cost large production to be proven

THE PLANAR PIXEL UPGRADE

The ATLAS Planar Pixel Sensor R&D

- Aim: Explore the suitability of planar pixel sensors for highest fluences
- Approved ATLAS R&D project since 2009: 17 institutes, > 80 scientists

IBL + Long Term
(2017 or 2020)

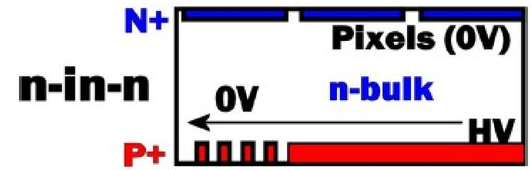
ATLAS project	R&D on Planar Pixel Sensor Technology for the ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	*Institute Document No.*	*Created:* 10/01/2008	*Page 1 of 19*
		Modified: 07/05/2009	*Rev. No.:* 1.1

D. Dobos, B. Di Girolamo, H.Pernegger, S. Roe, A. La Rosa[1], V. Vrba, P. Sicho, J. Popule, M.Tomasek, L. Tomasek, J. Stastny, M. Marcisovsky, M. Havranek, J. Bohm[2], A. Lounis, N. Dinu, M. Benoît, R. Tanaka[3], G. Calderini, D. Lacour, H. Lebbolo, G. Marchiori, J. Ocariz, P. Schwemling[4], M. Barbero, F. Hügging, H. Krüger, N. Wermes[5], H. Lacker[6], I. M. Gregor, U. Husemann, P. Kostka[7], C. Gößling, R. Klingenberg, D. Münstermann, A. Rummler, G. Troska, T. Wittig, R. Wunstorf[8], J. Grosse-Knetter, M. George, A. Quadt, J. Weingarten[9], L. Andricek , M. Beimforde, A. Macchiolo, H.-G. Moser, R. Nisius, R. Richter, P. Weigell[10], D. Cauz, M. Cobal, C. del Papa, D. Esseni, M. P. Giordani, P. Palestri, G. Pauletta, L. Selmi[11], Y. Unno, S. Terada, Y. Ikegami[12], M. Cavalli, I. Korolkov, M. Lozano, C. Padilla, G. Pellegrini, M. Ullan[13], T. Affolder, P. Allport, G. Casse, T. Greenshaw, I. Tsurin[14], M. Battaglia, T. Kim, S. Zalusky[15], I. Gorelov, M. Hoeferkamp, S. Seidel, K. Toms[16], V. Fadeyev, A. Grillo, J. Nielsen, H. Sadrozinski, B. Schumm, A. Seiden[17]

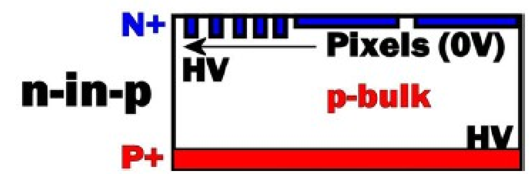
17 institutions: [1]CERN, [2]AS CR, Prague, [3]LAL Orsay/ University Paris-sud XI, [4]LPNHE / University Paris VI, [5]University of Bonn, [6]HU Berlin, [7]DESY, [8]TU Dortmund, [9]University of Goettingen, [10]MPP and HLL Munich, [11]Università degli Studi di Udine – INFN, [12]KEK, [13]IFAE-CNM (Barcelona), [14]University of Liverpool, [15]UC Berkeley/LBNL, [16]UNM, Albuquerque, [17]UCSC, Santa Cruz

Why planar sensors?

- Planar pixel is a proven technology
  - the current n-in-n pixel detector.
  - Modules shown to work after 10^{15} neq/cm2
  - If strips not adequate any more, pps would be the natural option



- Potential for a low-cost large-area production with n-in-p
  - Only one side is patterned



- Research directions
  - Radiation damage studies
  - Active area optimization and geometry redesign
  - Advanced simulation studies
  - High rate capable electronics
  - Low cost module production

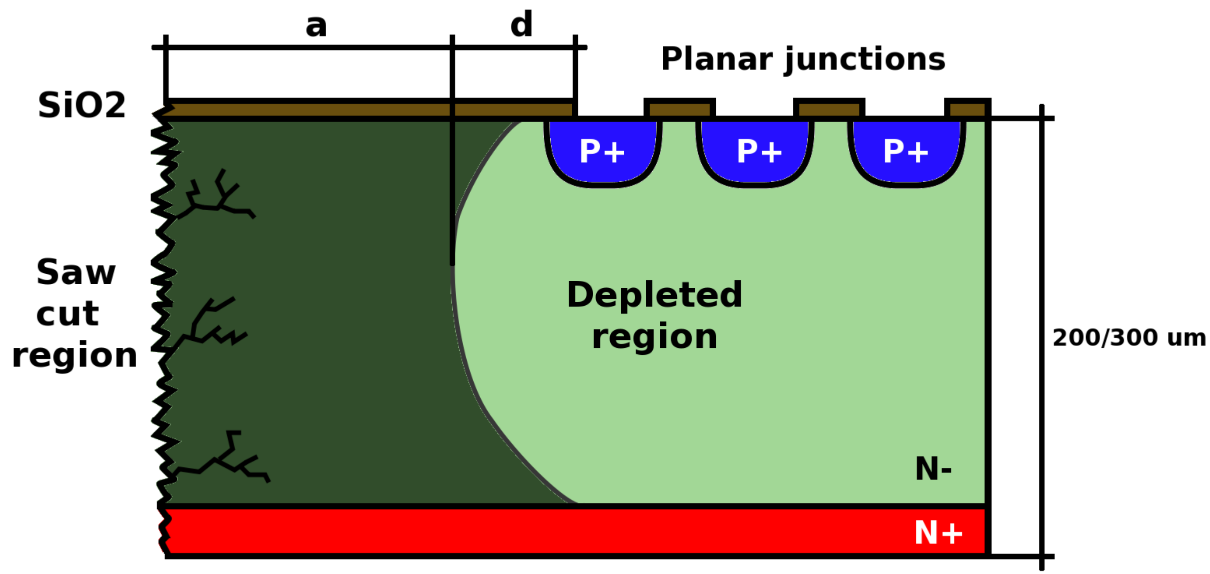
TCAD simulation

- Technology Computer Aided Design offers the possibility to simulate the behavior of a sensor under several conditions
  - Reverse bias
  - Illuminated by light
  - At high/low temperature
  - As been exposed to high fluences
- And monitor the interesting quantities
  - IV / CV curves
  - GR potentials
  - CCE
  - Electric field

Simulation saves you money but needs very precise inputs to produce reliable information

Geometry - Dead edge

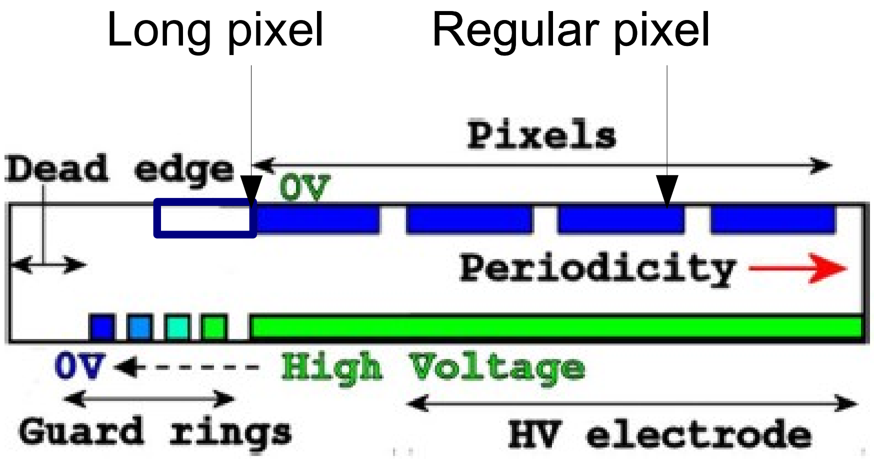
Dead edge is an inactive area whose porpouse is to protect the cut area (full of generation centers) from high electric field



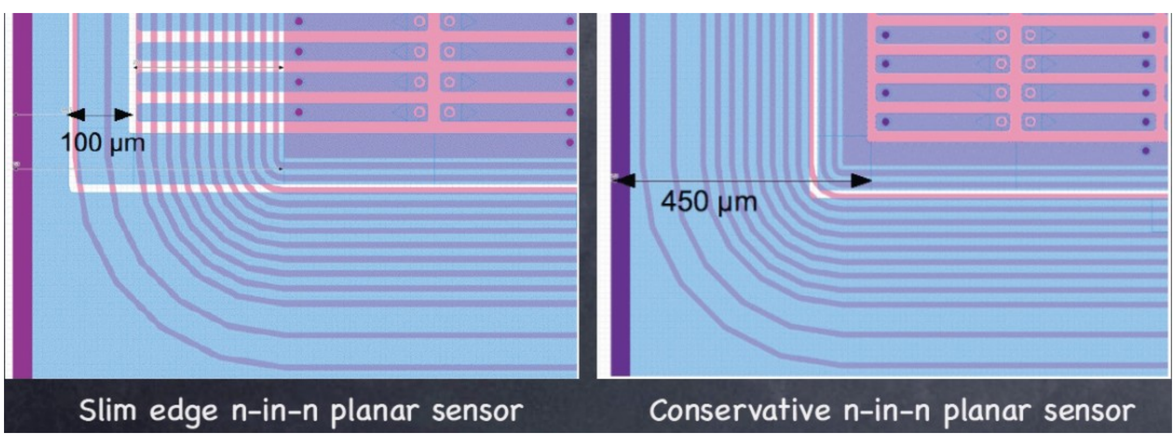
- “It is not possible to obtain the full geometrical coverage in z as the Pixel detector does, where
modules are tilted in z and are partially overlapped, because there is not enough space. However the
gap between modules is minimized using a sensor design with active or slim edges.” IBL TDR

Geometry optimizations

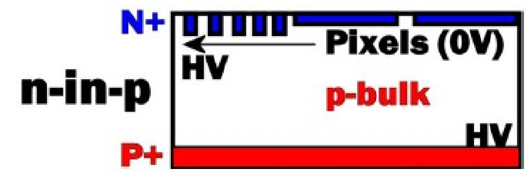
Attempt to recover active area



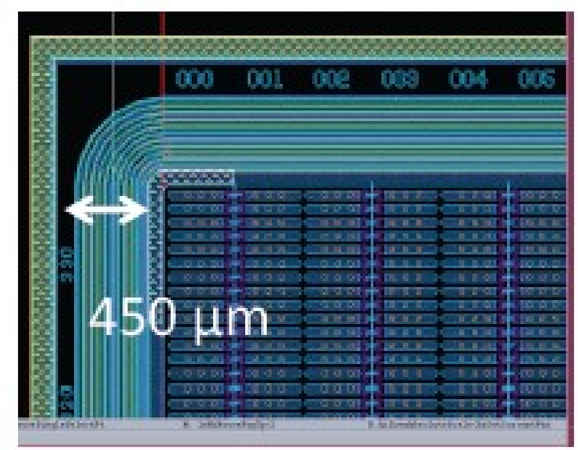
n-in-n



Longer pixel “under the guard-ring”



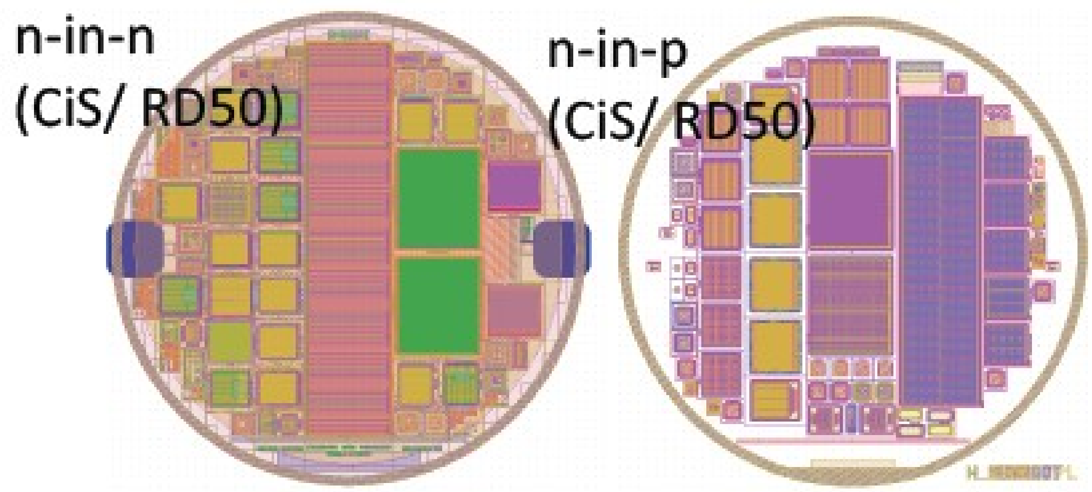
n-in-p



Reducing GRs structure width

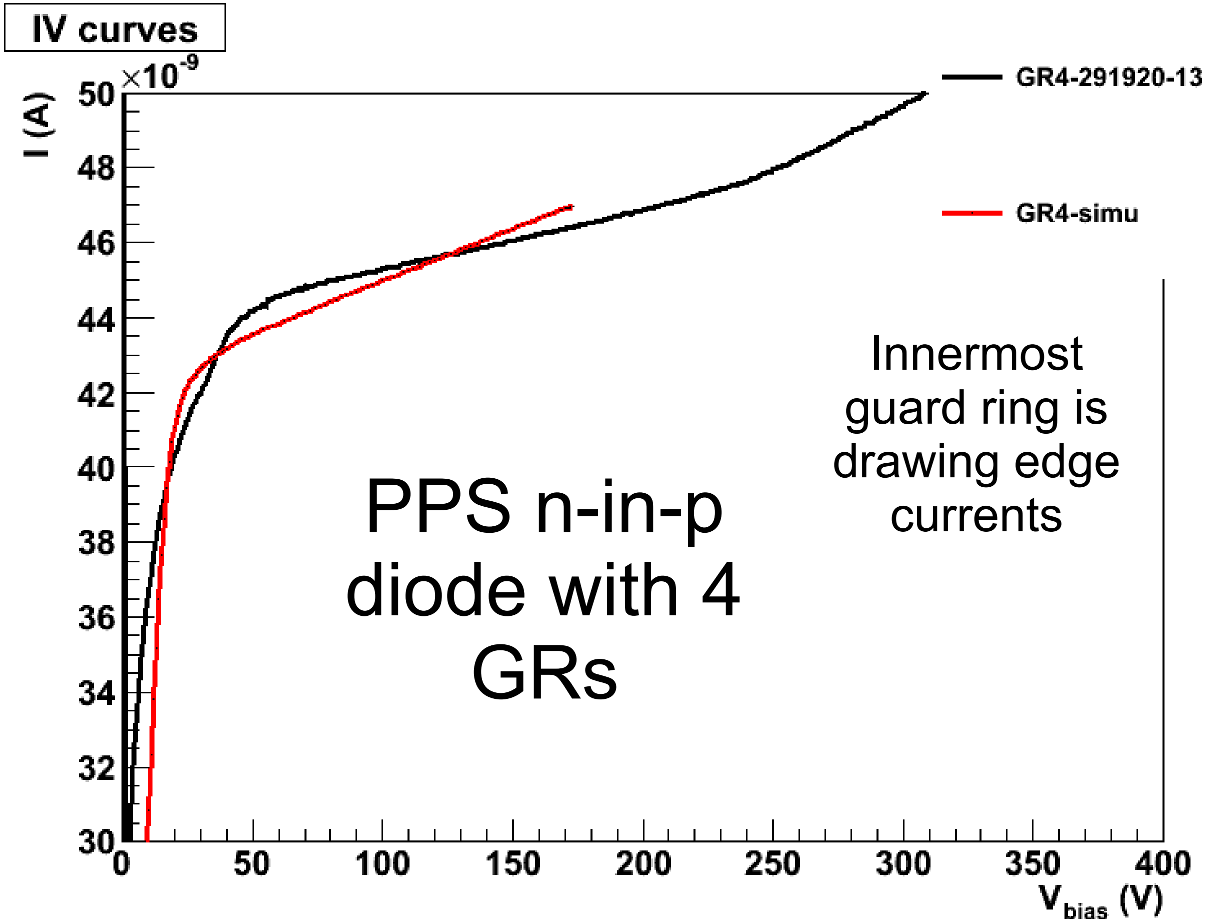
First PPS sensor submission

- Based on an intense design and simulation work, a first submission of planar sensors was made

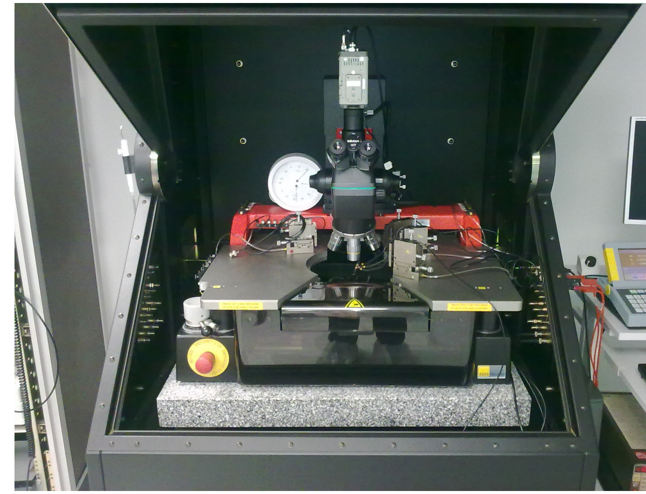


- Current ATLAS R.O.C. ("FE-I3") compatible sensors
- New ATLAS R.O.C. ("FE-I4") compatible sensors
- Diodes, test structures

Test on prototypes



Tuning for bulk concentration and generation lifetime for simulation

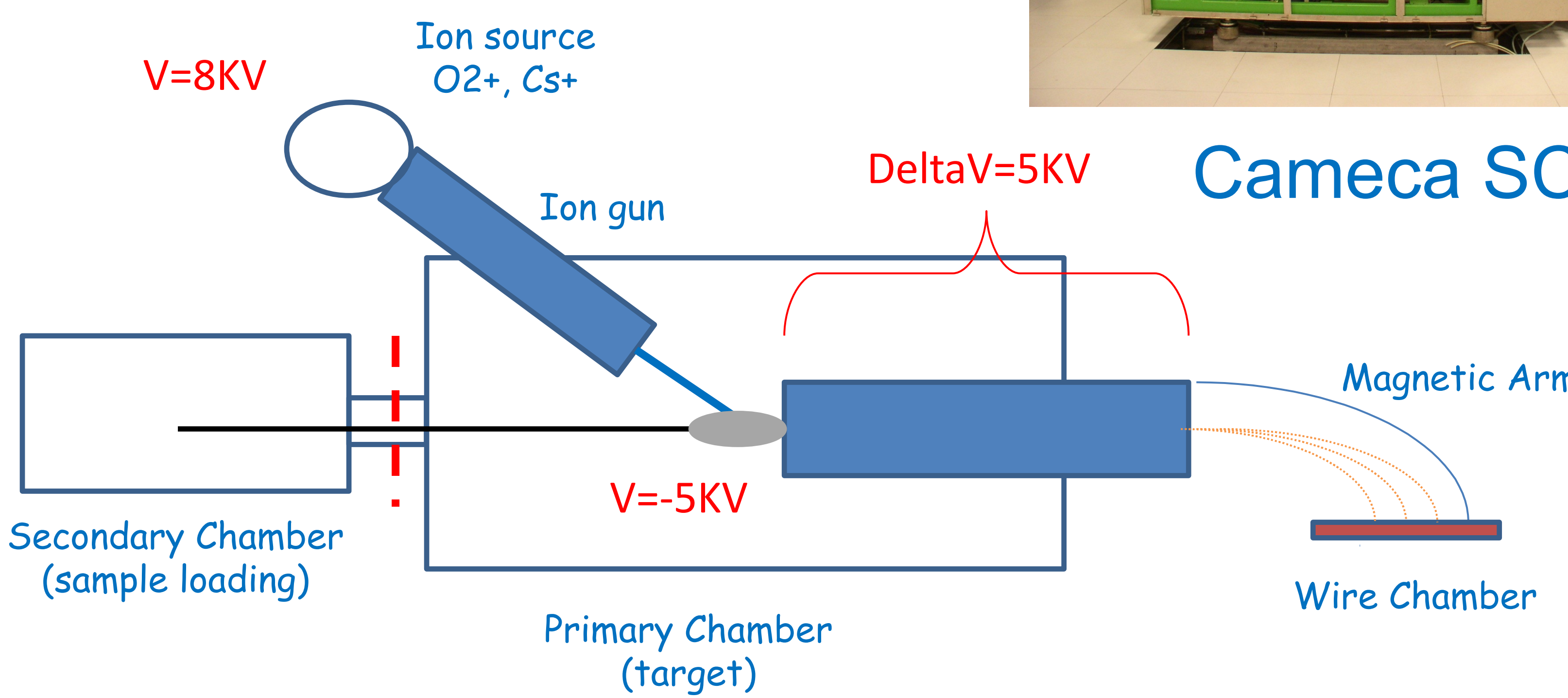


Measures were taken in our clean room

SIMS measurements

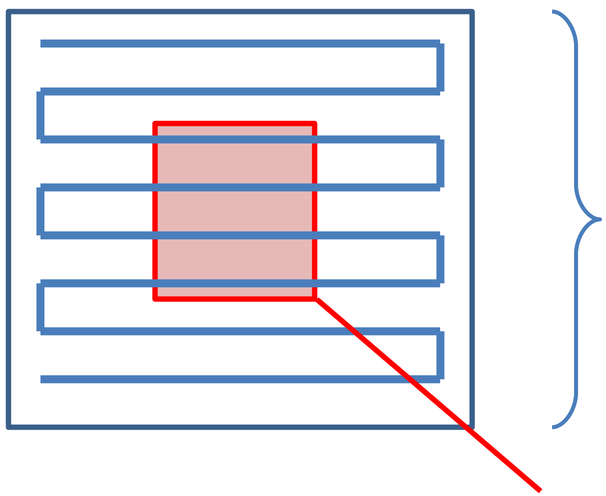
- SIMS: Secondary Ion Mass Spectroscopy

Cameca SC-Ultra

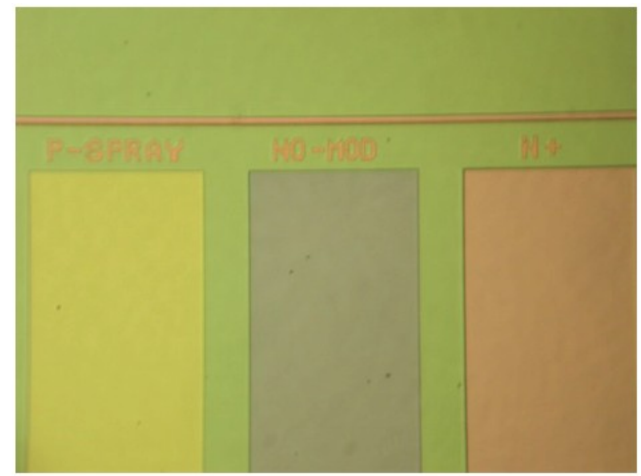


SIMS principle

- An ion beam is scanning (and escavating the sample)

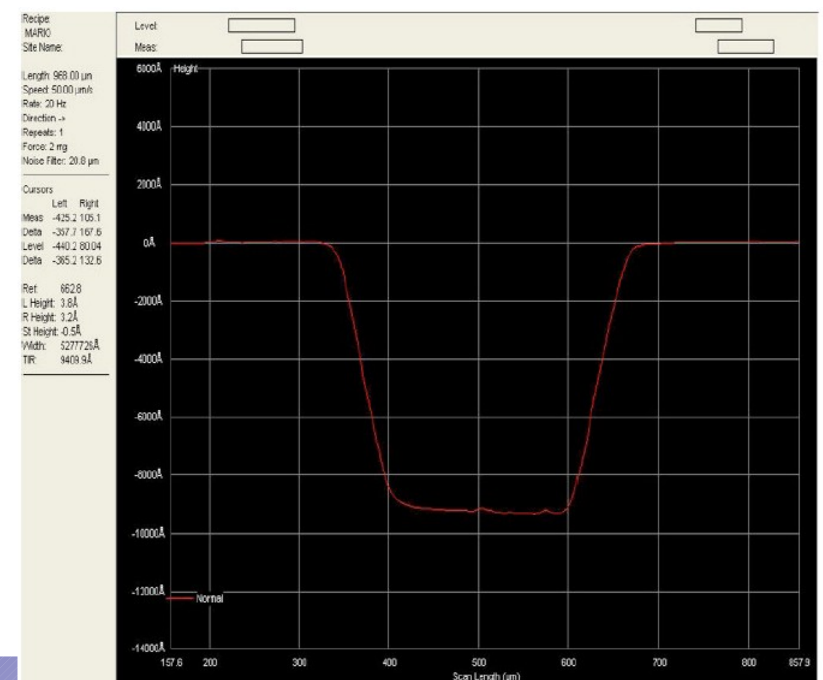


200-250 um

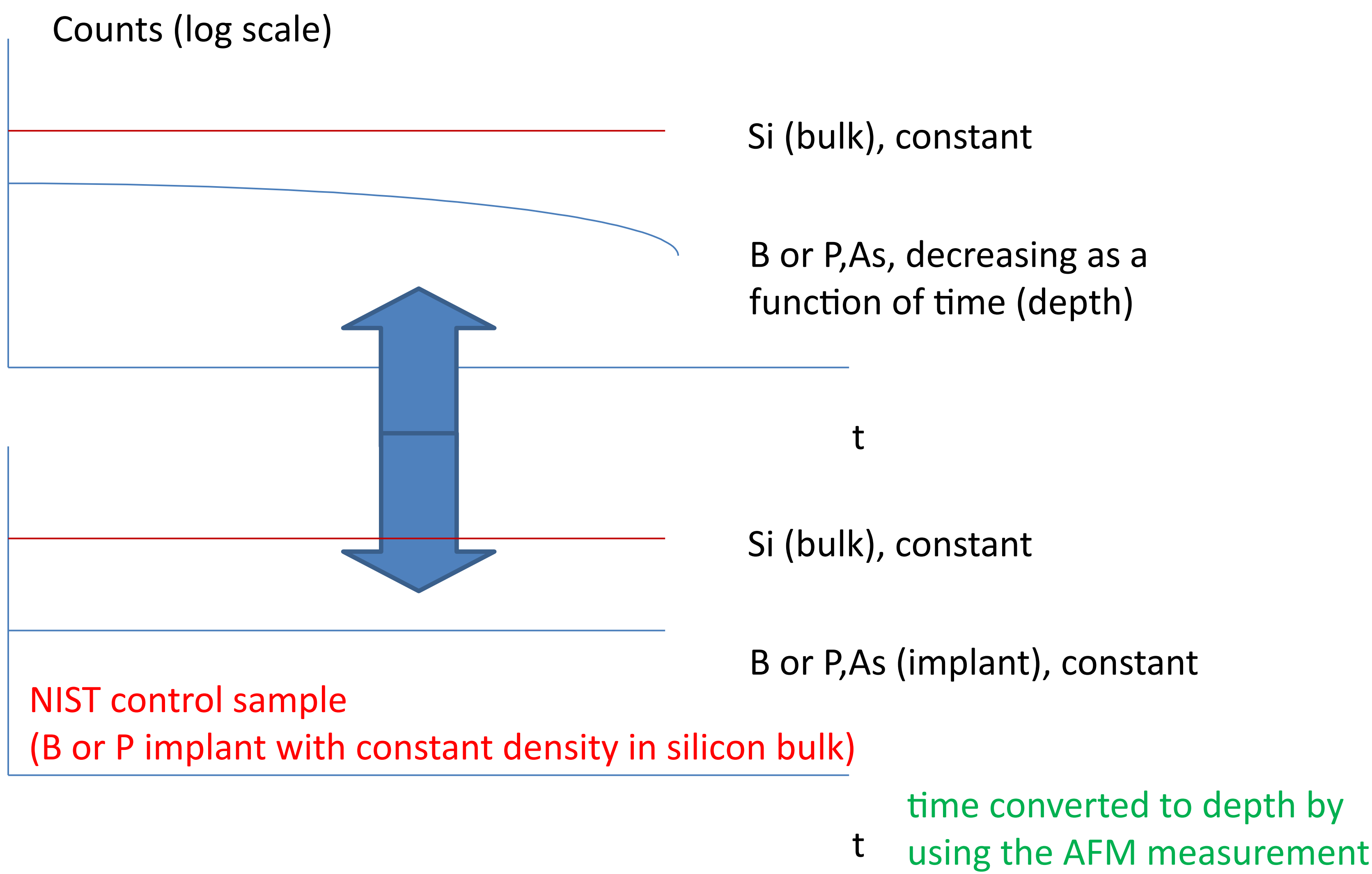


Restricted region analyzed
(to avoid scattering from walls)

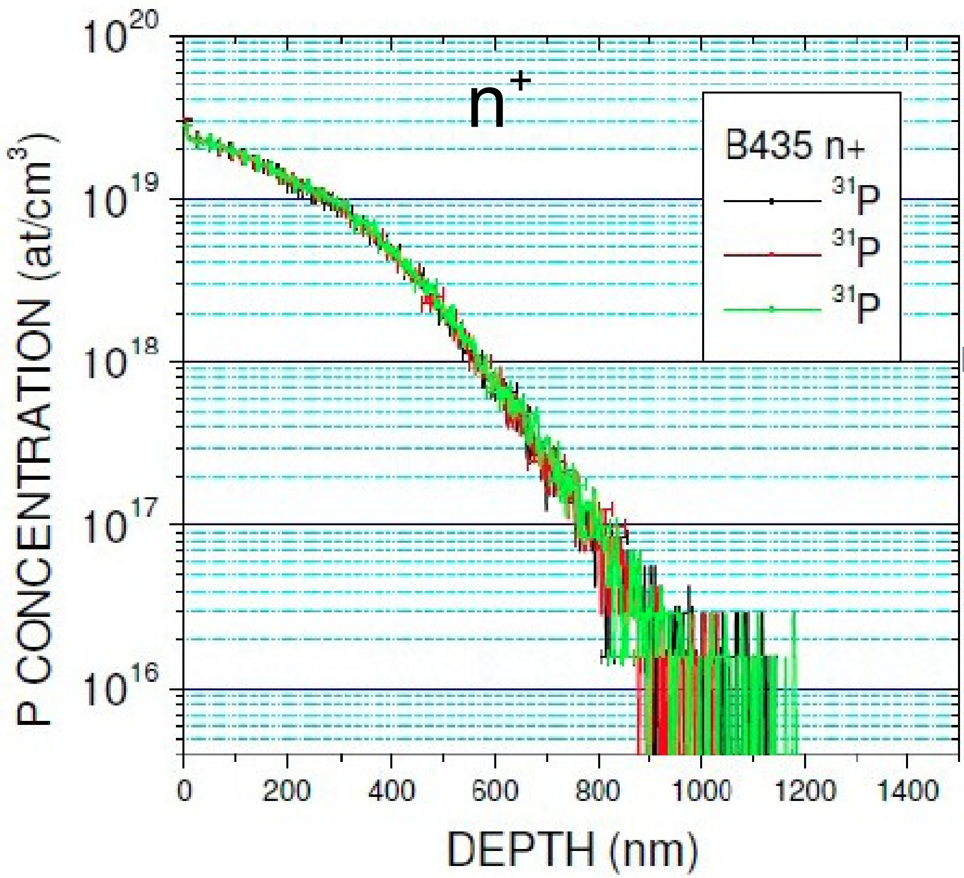
Measured with AFM



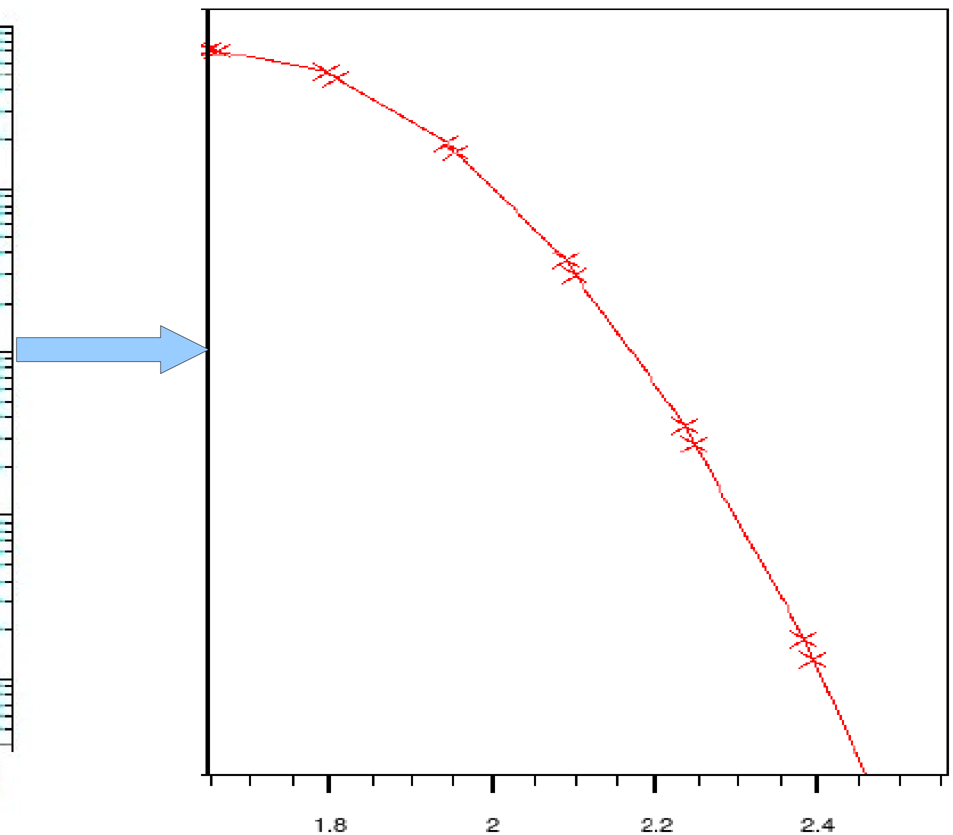
Doping profile measurement



Example: pixel implant



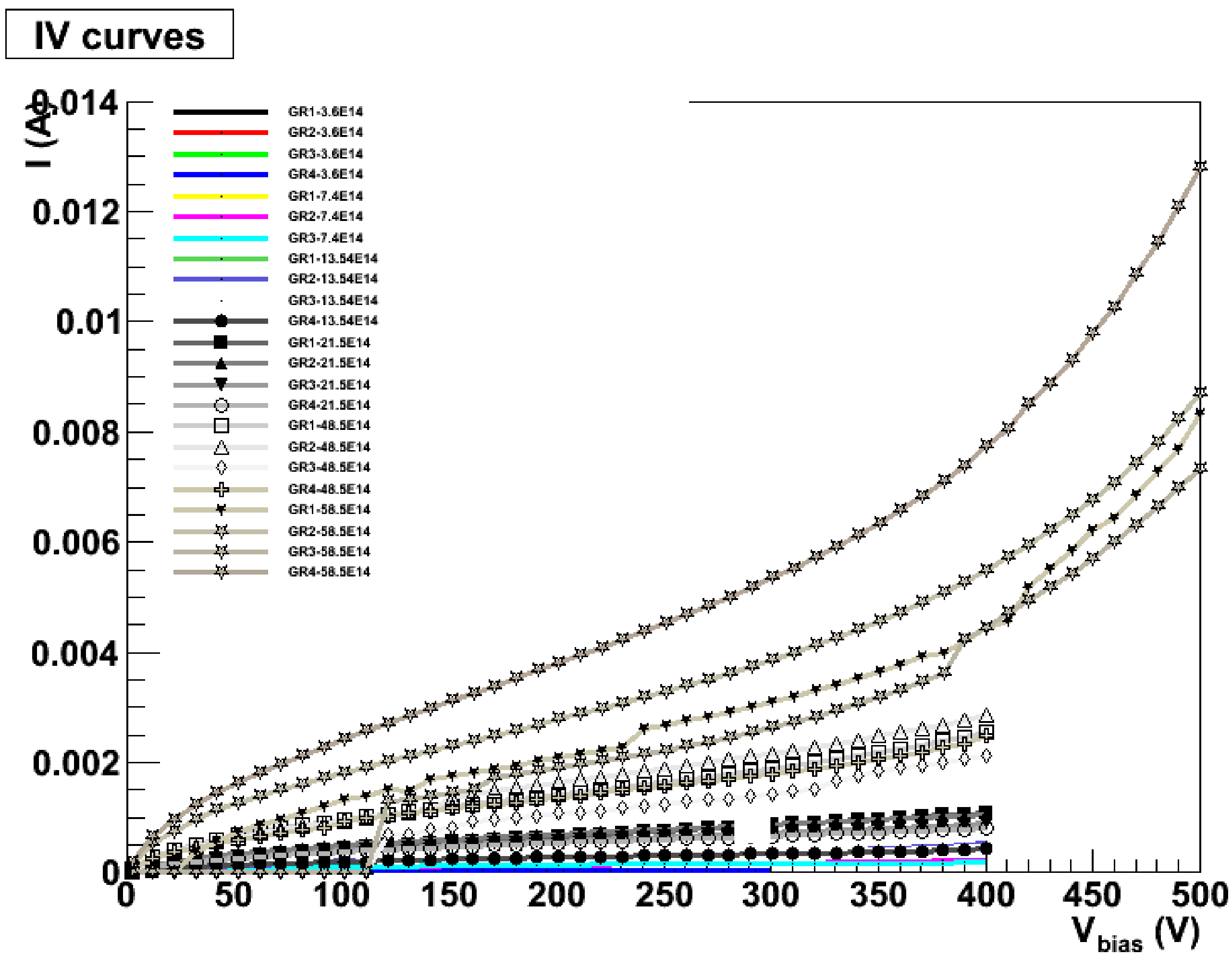
3 points per sample



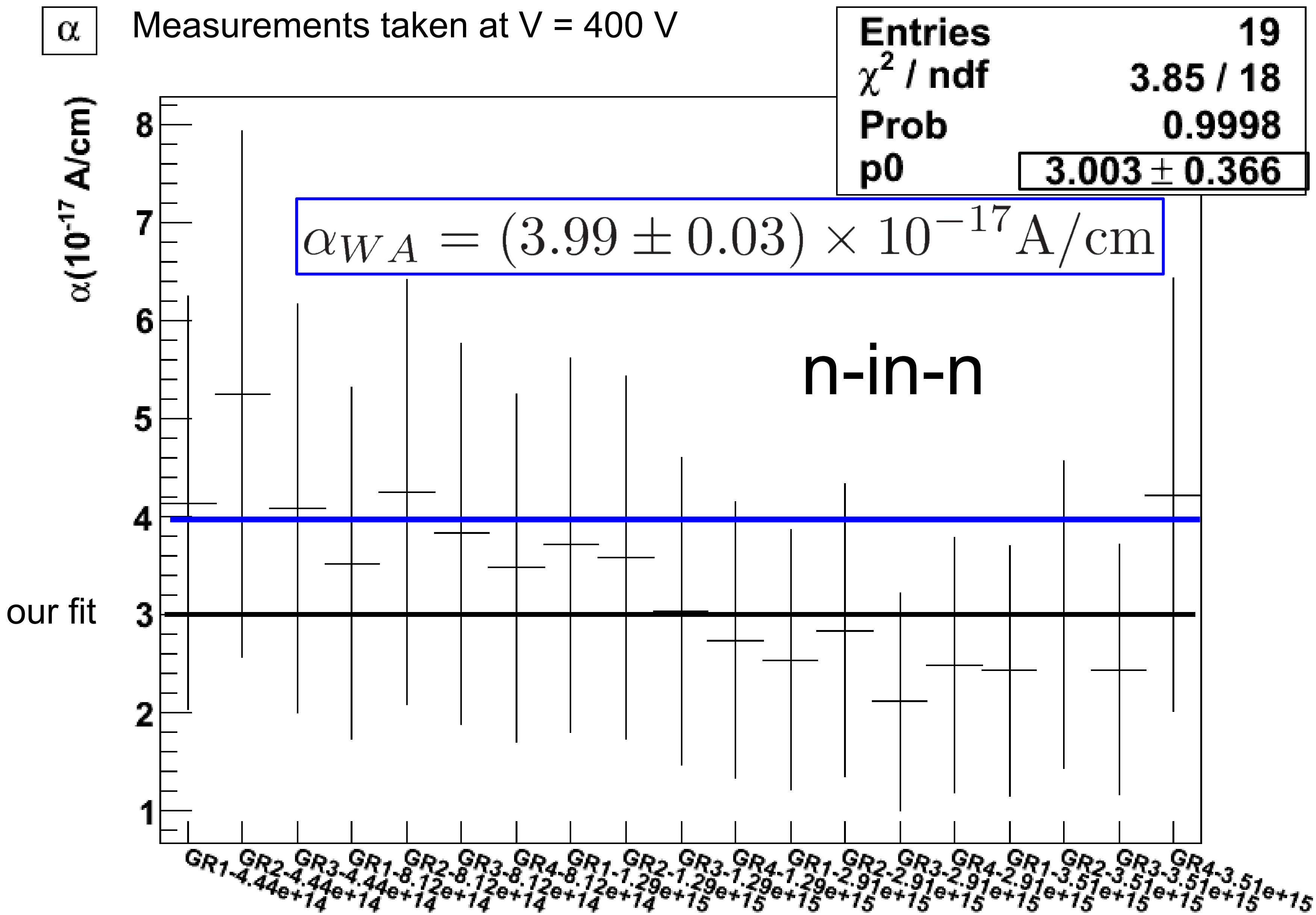
- Concentration profiles are used inputs for the simulation
  - Same for p+, moderate and non-moderate p-spray

Irradiation campaings

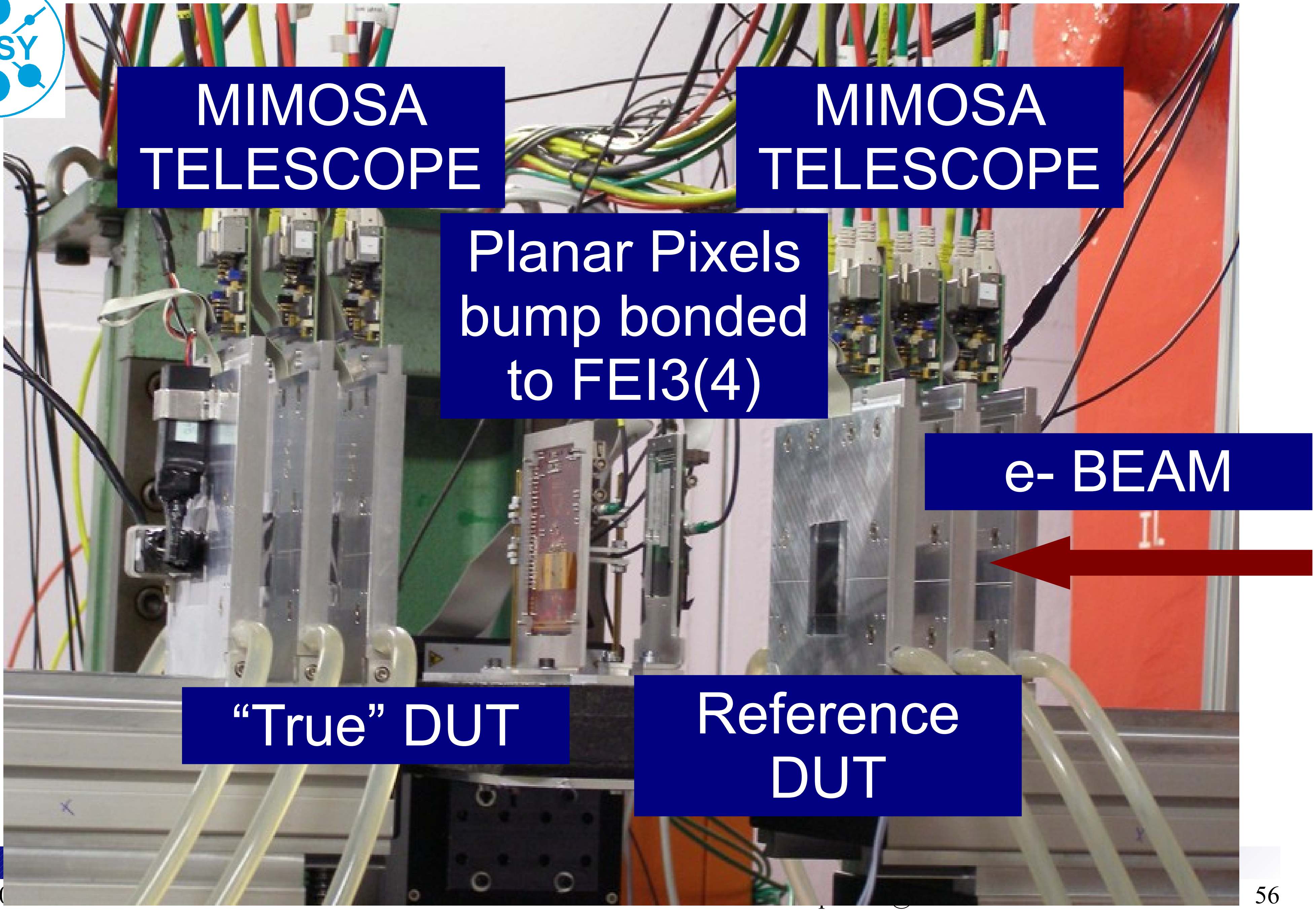
- 24 GeV/c proton at CERN (with step of fluence $2x10^{14}$ to $4x10^{15}$ n_{eq}/cm^2)
- MeV neutrons irradiation in Ljubjiana (Up to $1x10^{16}$ n_{eq}/cm^2)



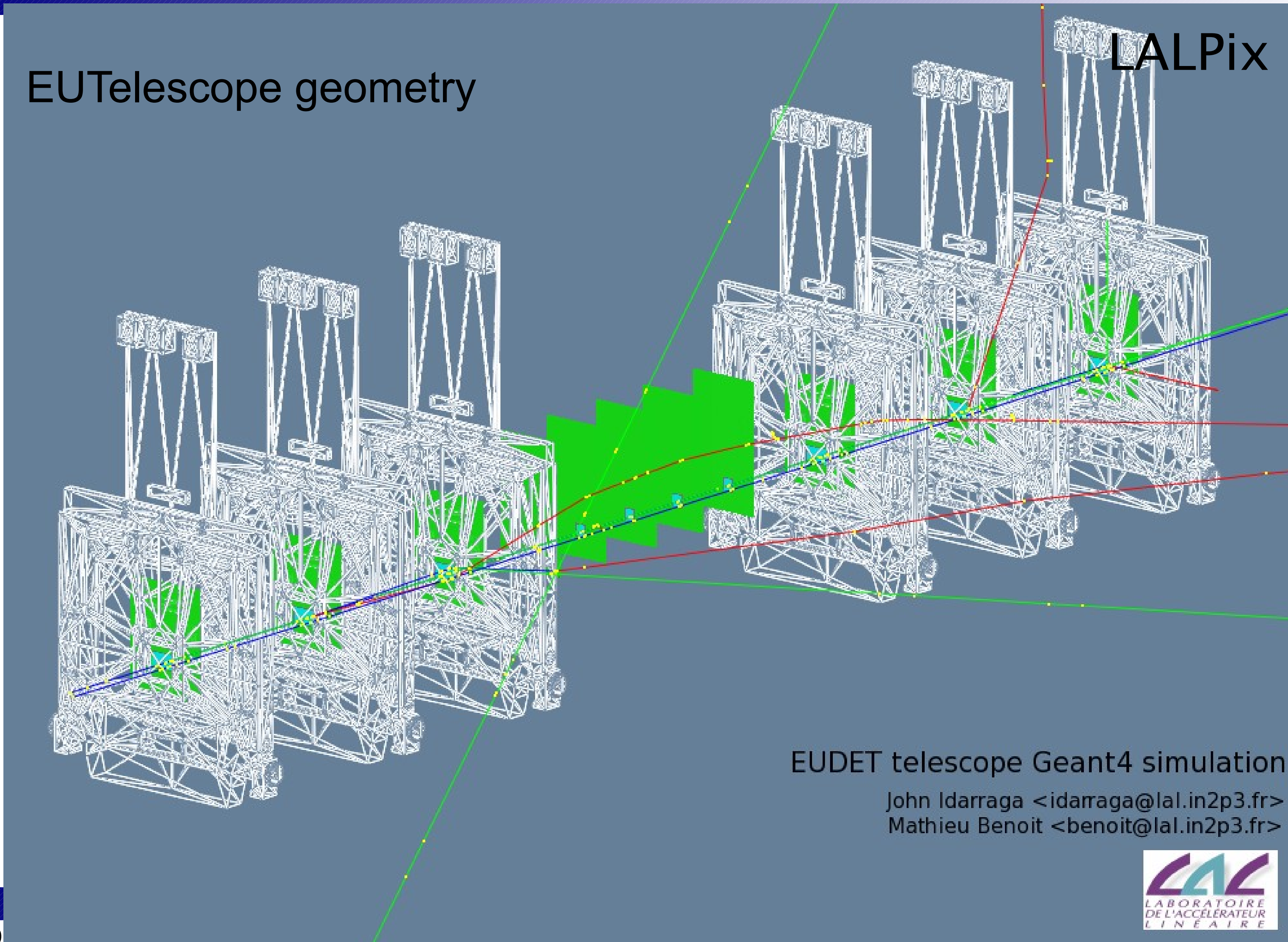
Current increase rate



Test beams

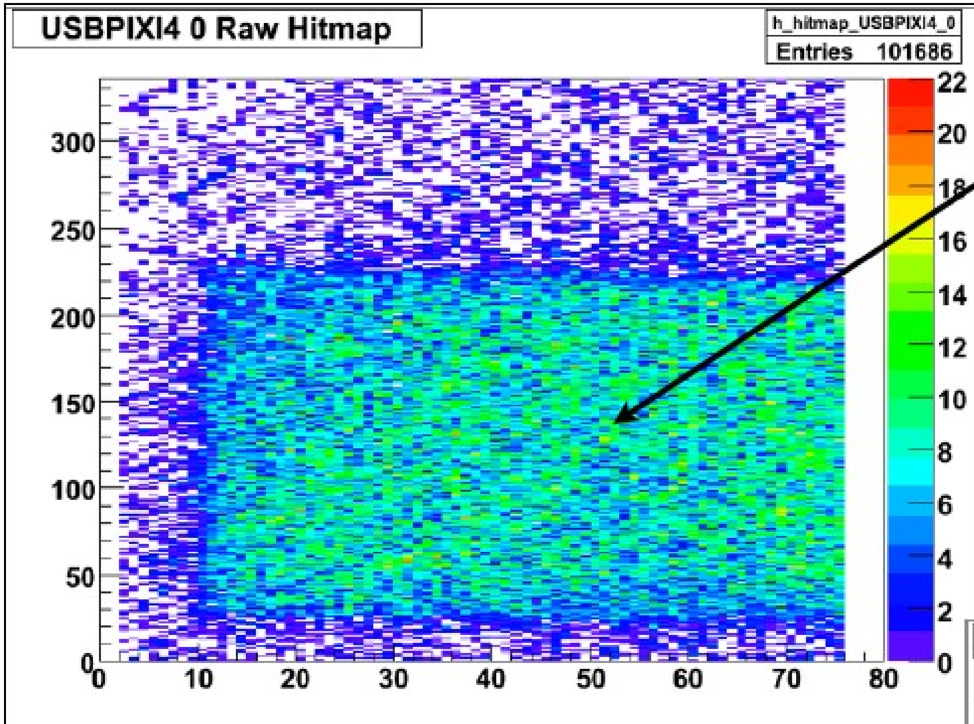

MIMOSA TELESCOPE
MIMOSA TELESCOPE
Planar Pixels bump bonded to FEI3(4)
e- BEAM
“True” DUT
Reference DUT

Telescope simulation

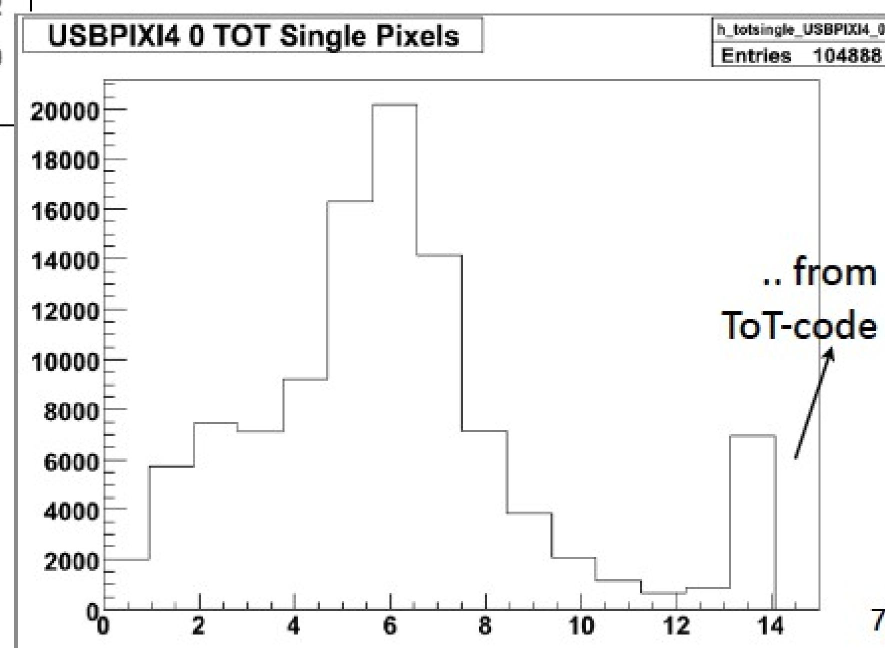


Pictures from a test beam

FIRST Highlight from data-taking



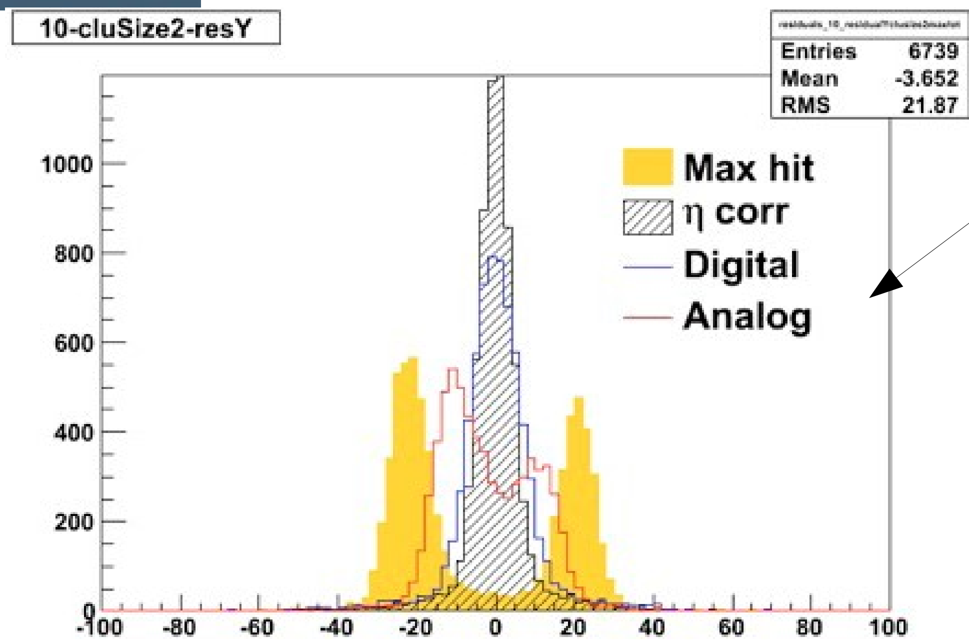
First beam seen with FE-I4 Module !!!!



FE-I4 Module SCC-17 (slim edge)

➡ See Expected peak !

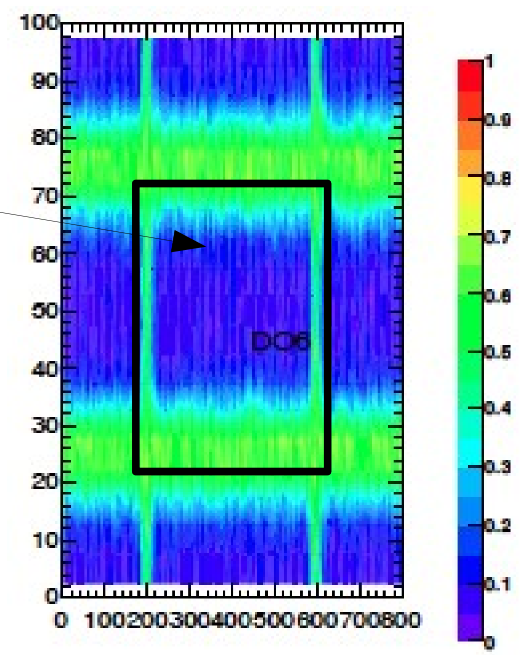
Test beam data analysis

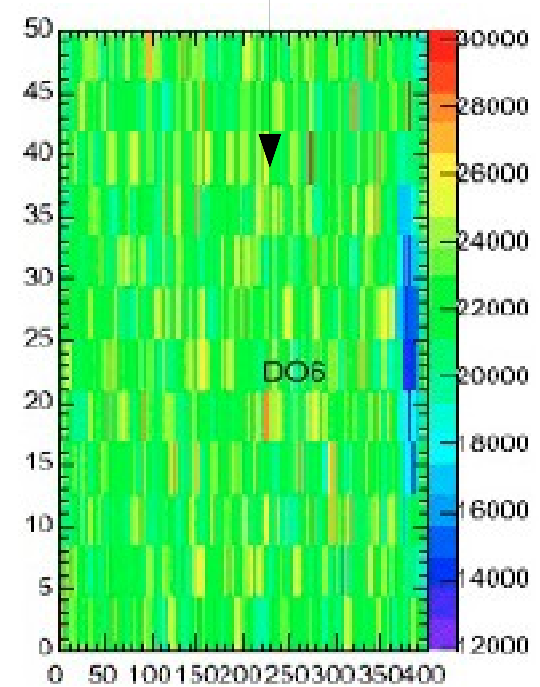


- Space point resolution
  - Different cluster-algorithms are compared

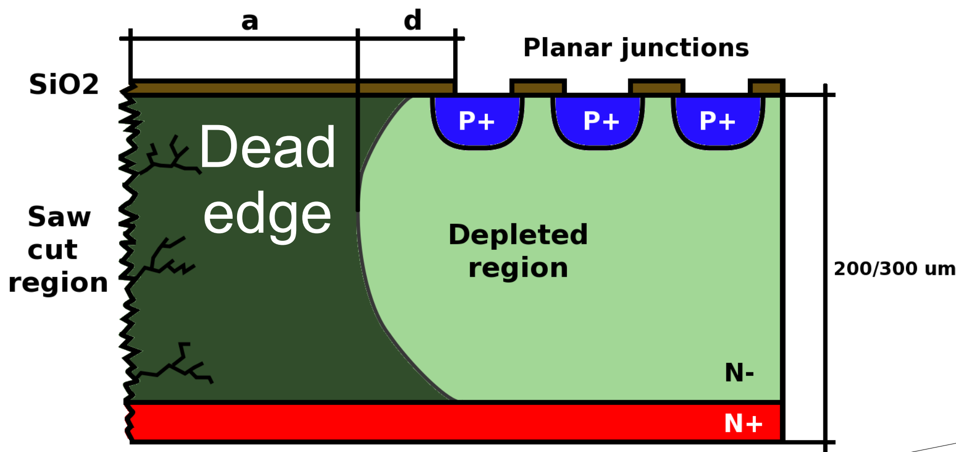
- Collected charge profile per single cell

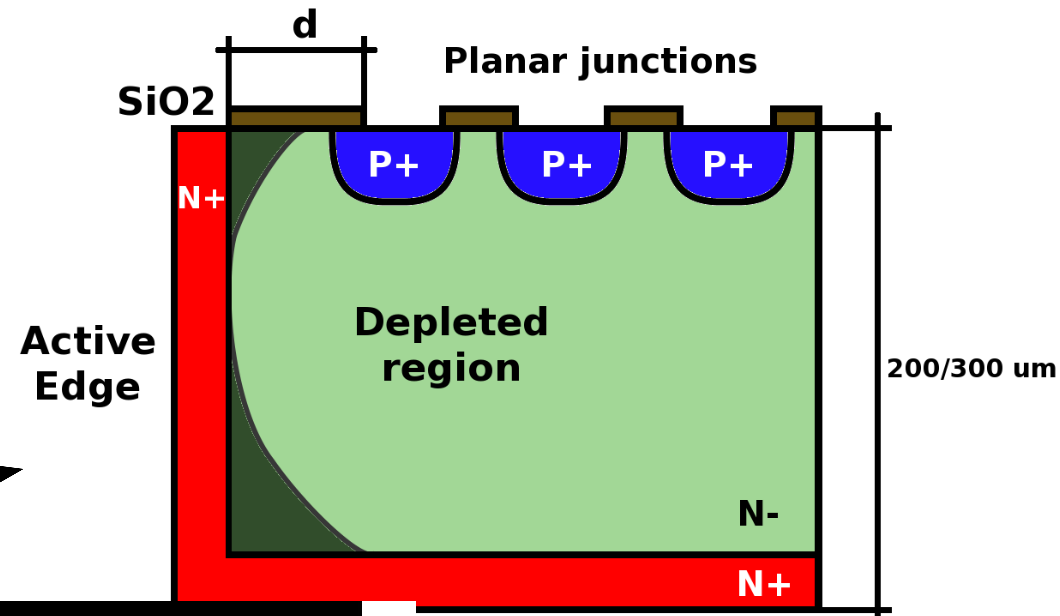
- Charge sharing among pixel cells



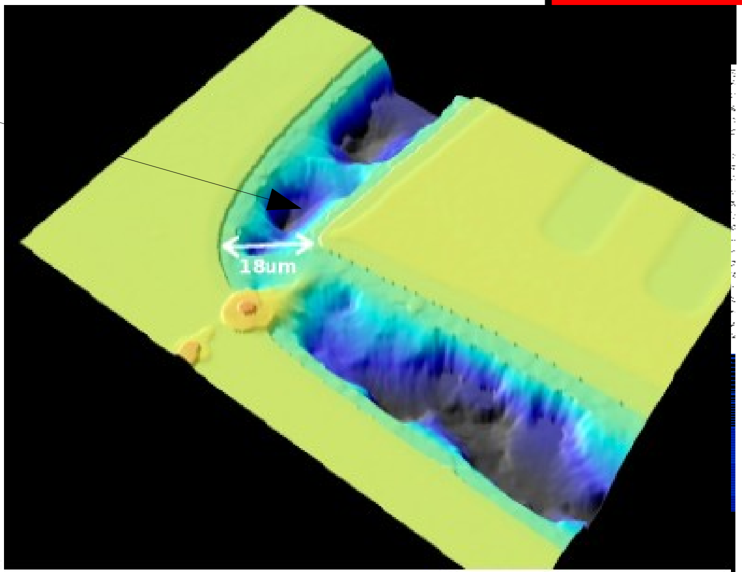


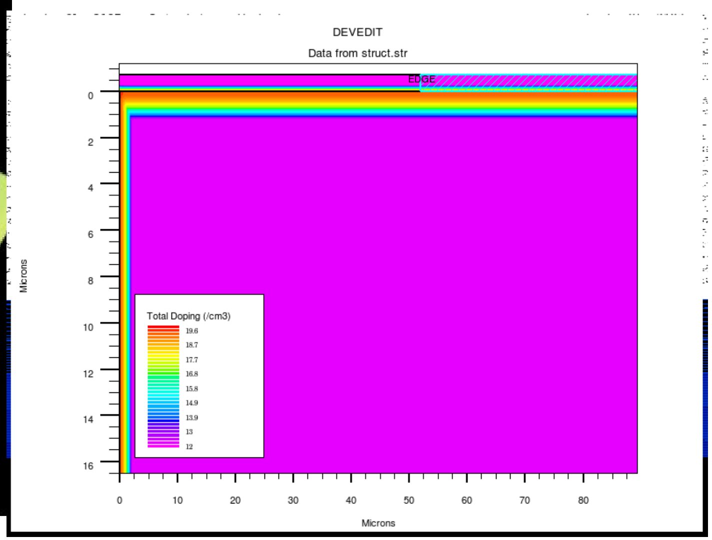
Ideas for new submission





Cut lines etched with Deep Reactive Ion Etching (DRIE) and doped





[C. Kenney, et al., IEEE TNS 48-6 (2001) 2405]

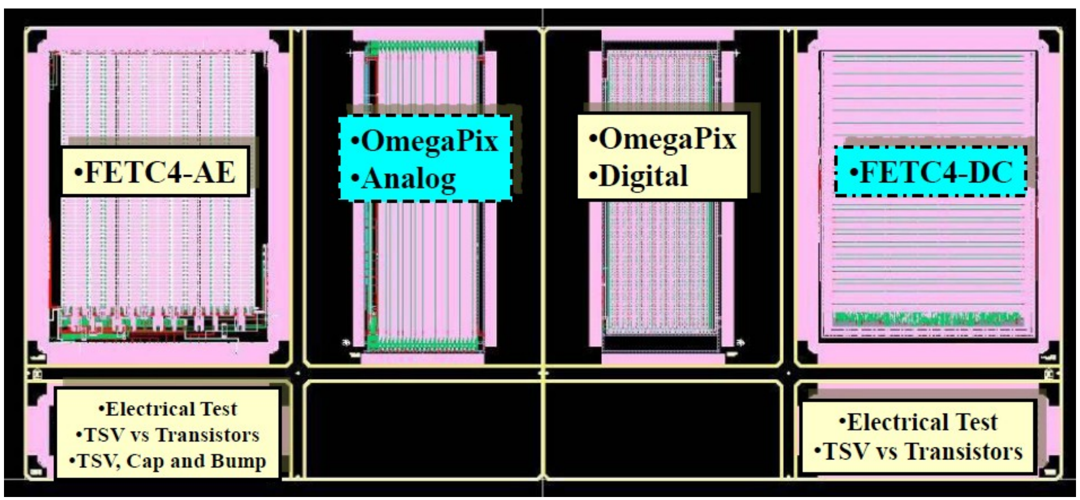
Electronics: collaboration with LaL

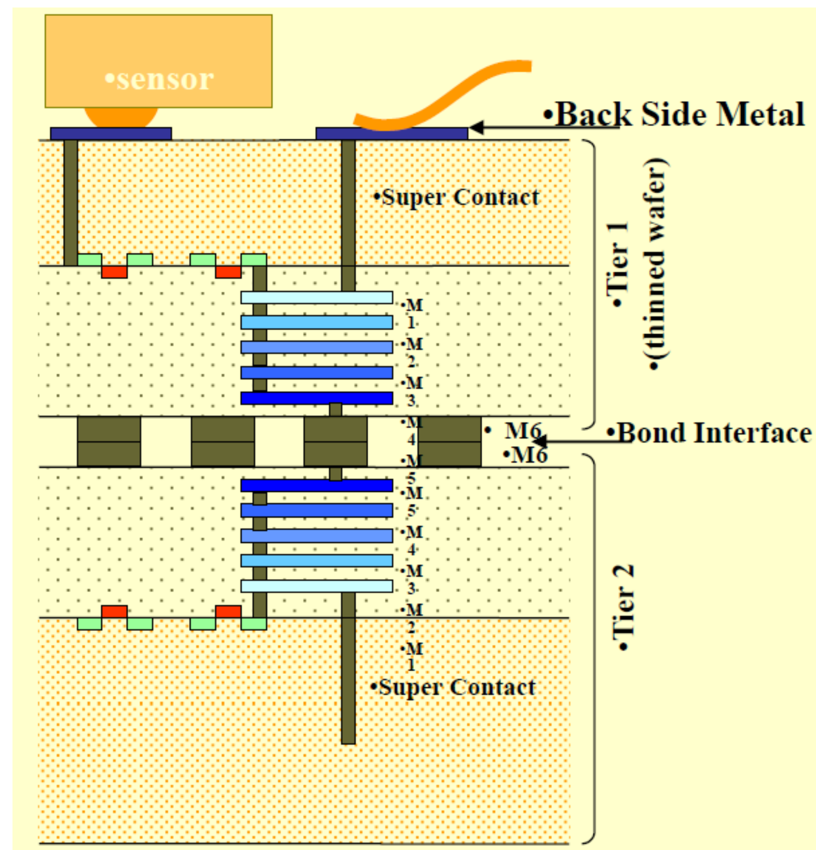
3D/Vertical Integration R&D of the OmegaPix chip (Chartered Tezzaron)

3D/VI MemDyn circular buffer memory

Significant support from IN2P3, ANR, AIDA

OmegaPix (LAL, LPNHE)





- Exploratory OmegaPix chip (LAL, LPNHE) with small pixel size 50x50 um, matrix of 24 columns x 64 rows
- Goals: low threshold (1000 e), low noise 100 e) low consumption (3 uW/pixel)

CONCLUSIONS

Conclusion & Outlook

- LHC will turn into a High Luminosity machine after 2017
- A completely new detector is needed, coping with higher rates and large radiation fluence
- The PPSU R&D group is working on the new Pixel Tracker for ATLAS
- Key parameters for the new detector are
  - Radiation hardness
  - Low material budget and optimized geometry
  - Charge collection efficiency
- Detailed simulations, and measurements, performed at test beams, after irradiations and on test structures, are driving the new pixel design

That's it!