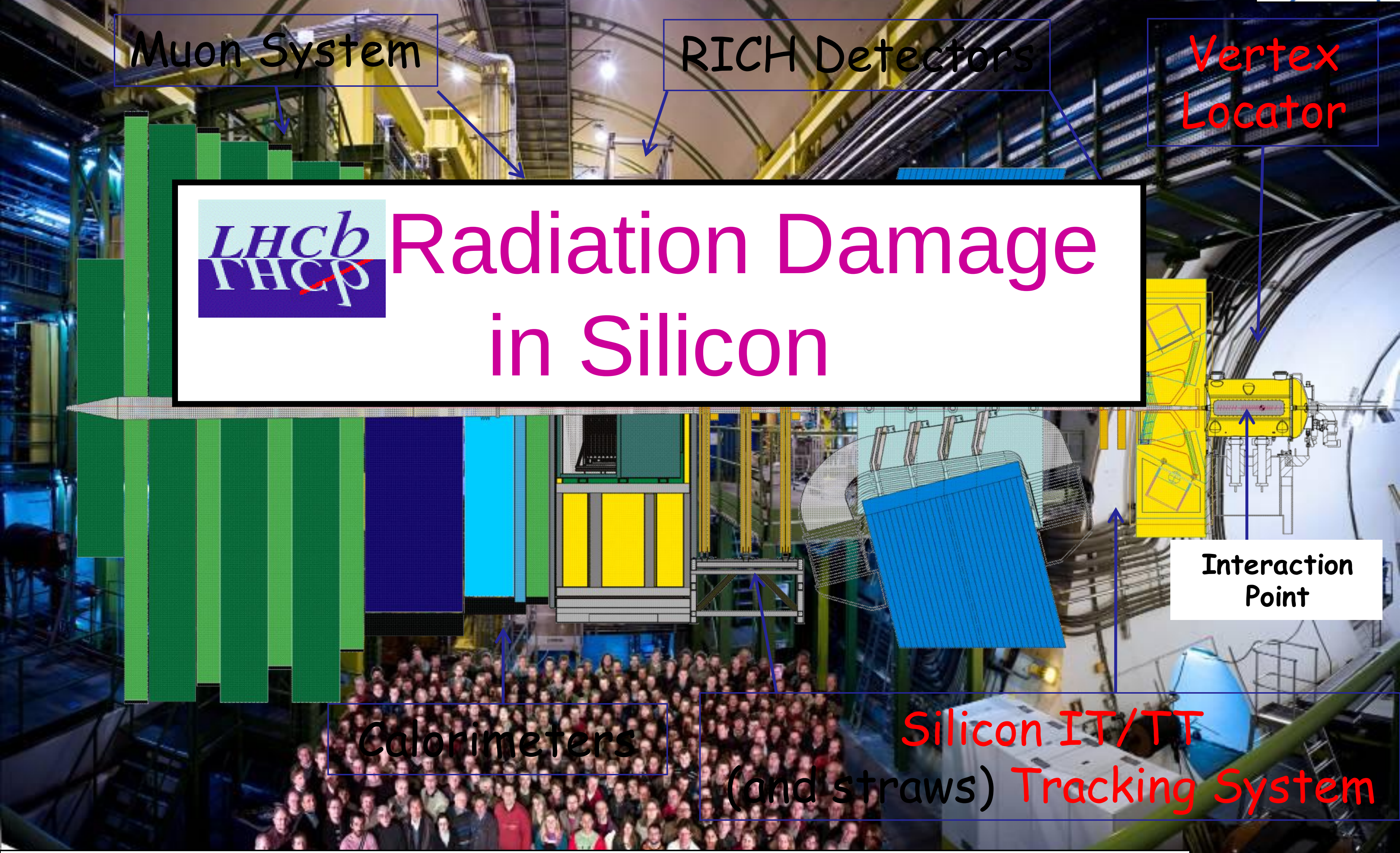
Radiation Damage in Silicon



Chris Parkes for LHCb VELO/ST groups November 2011

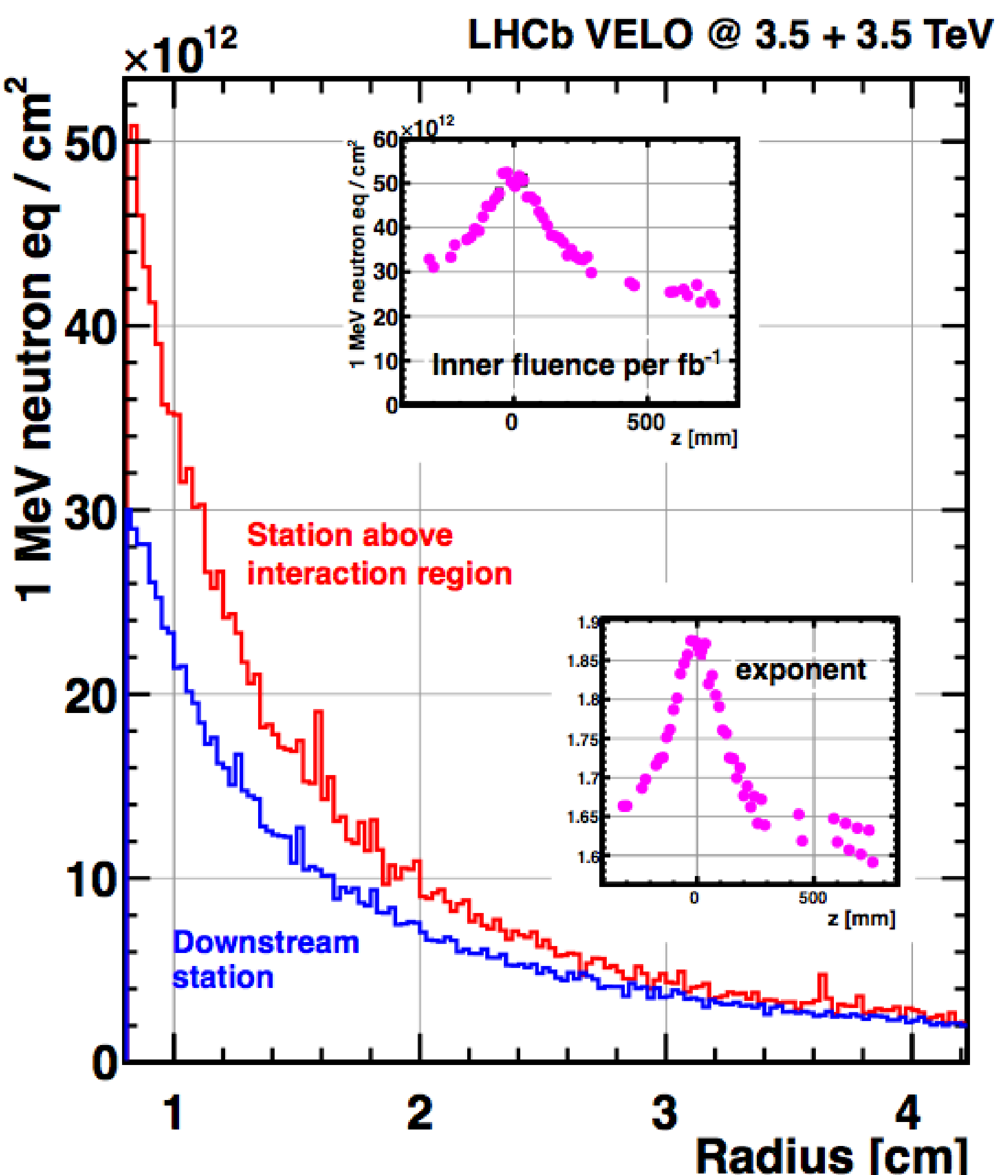
Sensor Details

- VELO
  - – n+-on-n, one module with n+-on-p
  - – oxygenated
  - – 300μm
  - – Double metal for readout
  - – Fabricated by Micron

- ST
  - – p+-on-n
  - – non-oxygenated, no double metal
  - – TT: 500μm, IT: 320μm , 410μm
  - – Fabricated by Hamamatsu

Fluence

VELO Fluence for 1 fb^{-1}



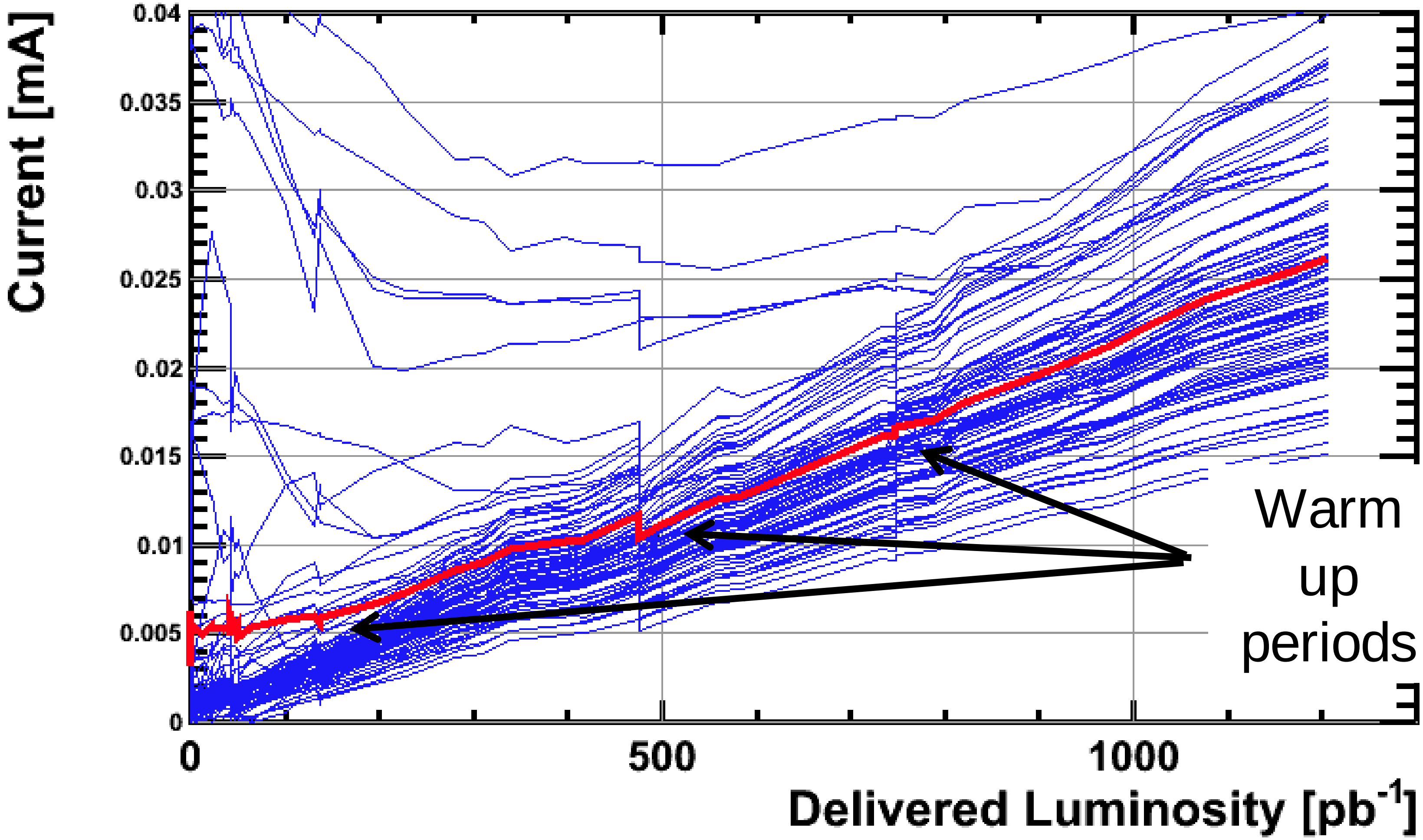
- VELO – 8mm from LHC colliding beams
- Highest Radiation Dose at LHC
- ST dose 2 to 4 10^{12} n_{eq}/cm^2
- LHCb Delivered 1.2fb^{-1} at LHCb
- Hence will focus on VELO today

SECTION I: Currents

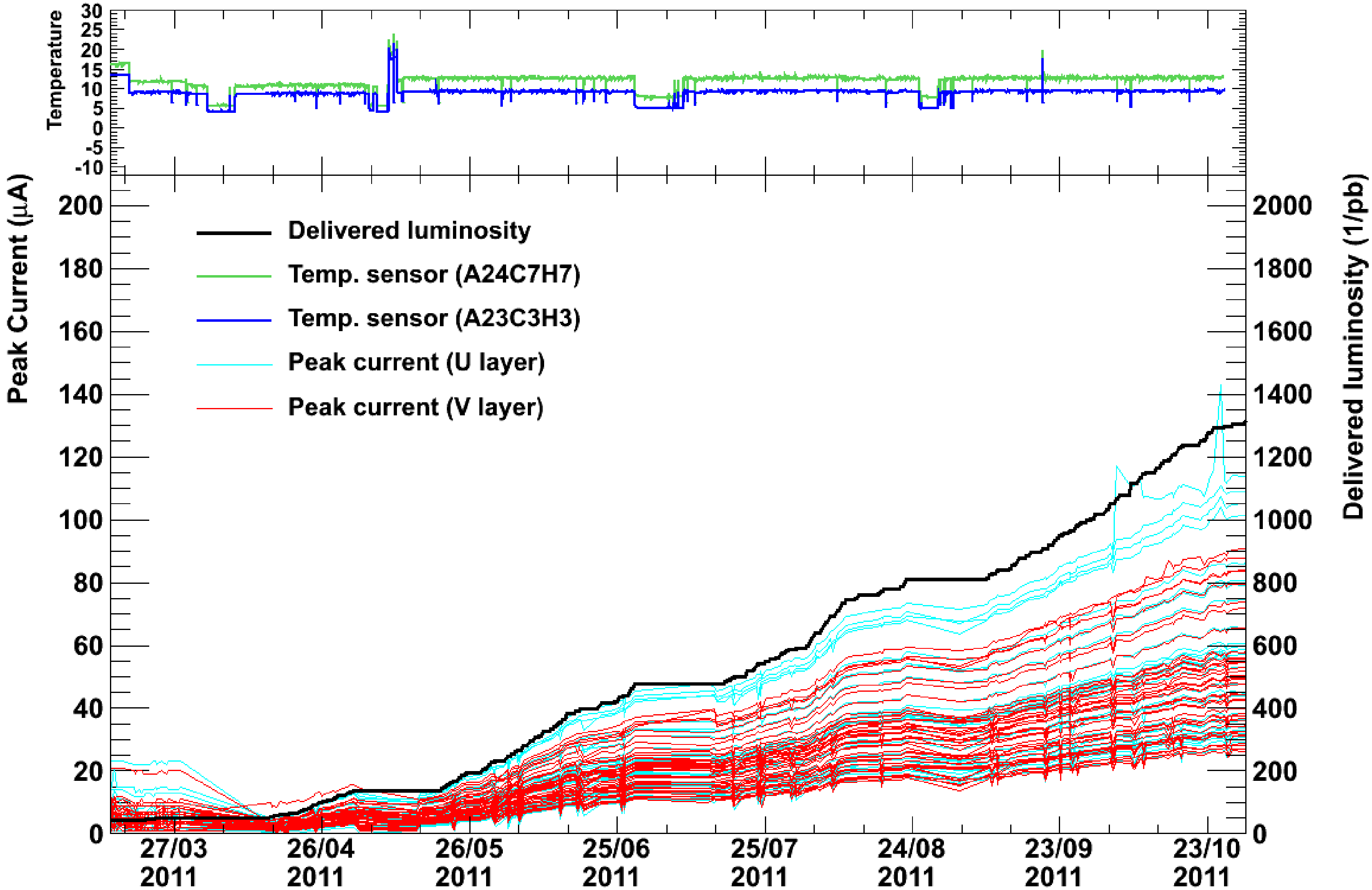
- Current vs Voltage scans
  - Taken weekly
- Current vs Temperature
  - Taken during Technical Stops / shutdowns

Current versus Luminosity

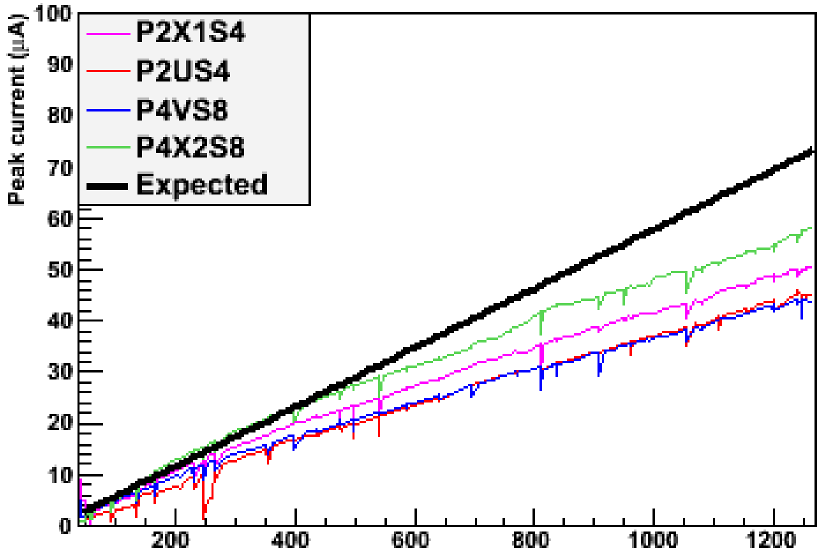
VELO – operated at -7C

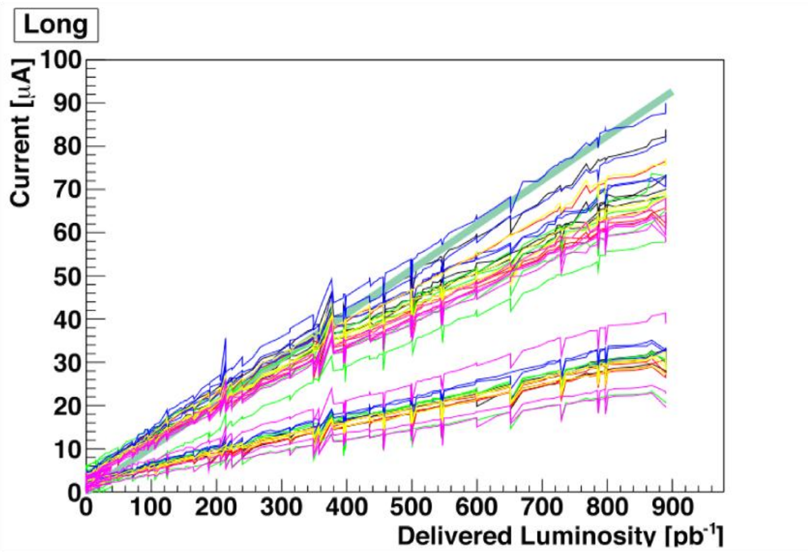


Current evolution in TT



ST – current self-annealing





- IT/ TT operated around 10C, hence currents anneal during run

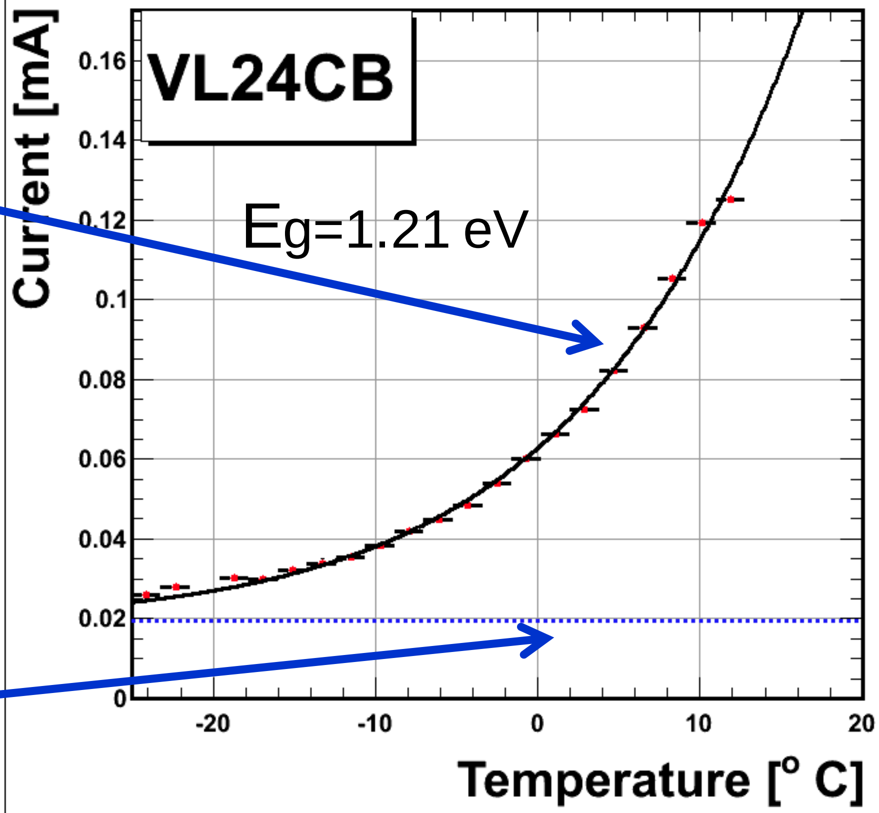
VELO Current Versus Temperature

- Bulk current contribution fitted as

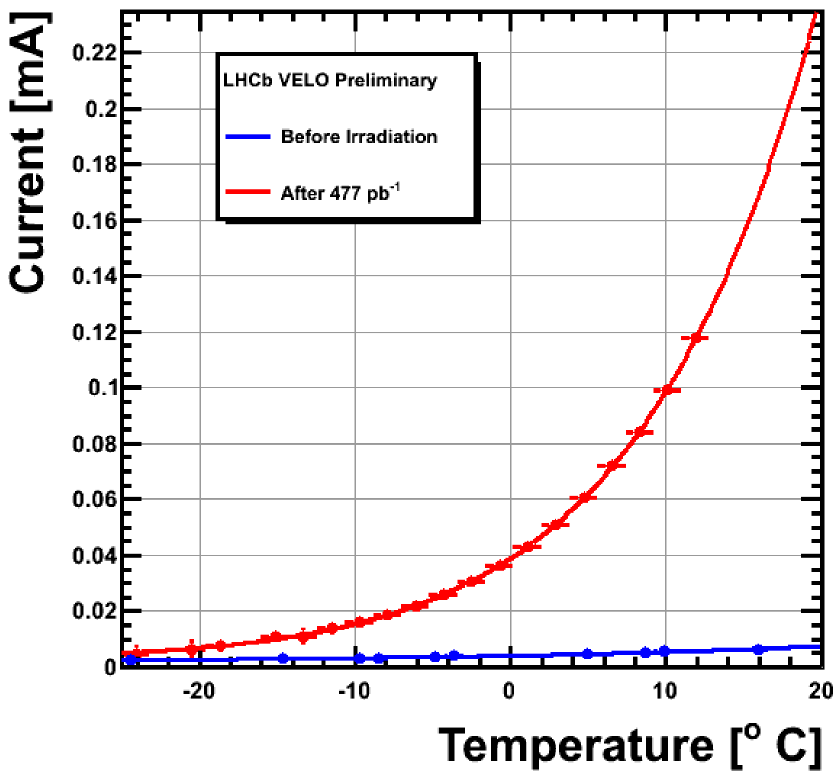
$$I\left(T_{ref}\right) = I(T).\left(\frac{T_{ref}}{T}\right)^2 .exp\left(-\frac{E_g}{2k_B}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right),$$

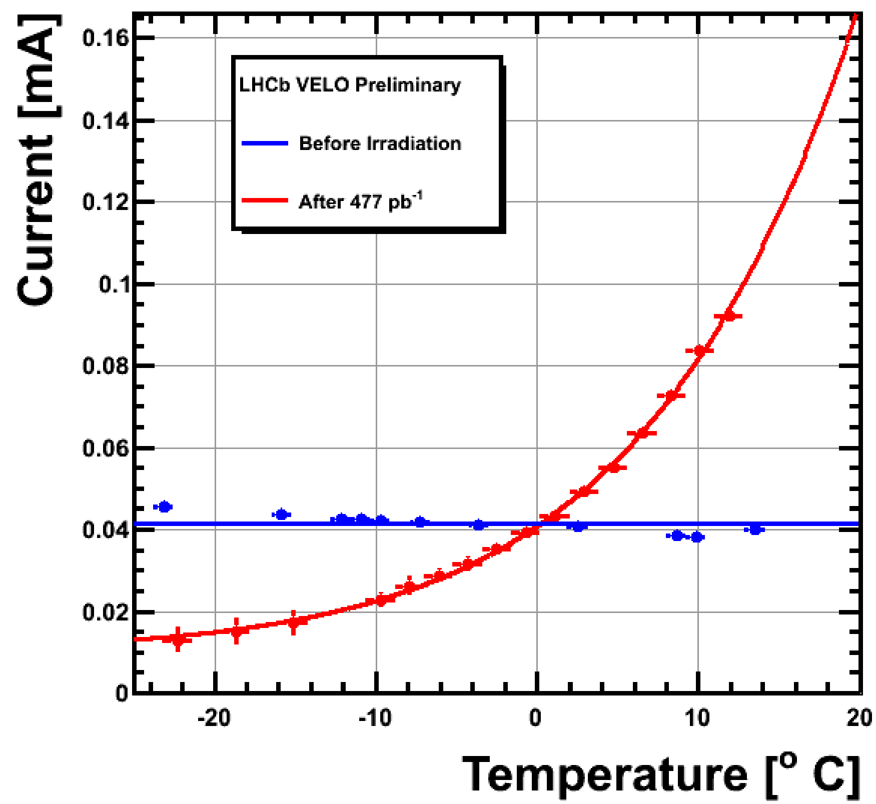
- Surface current contribution assumed to be flat

Example sensor after 821 pb^{-1}



Typical Currents Before / After Irradiation



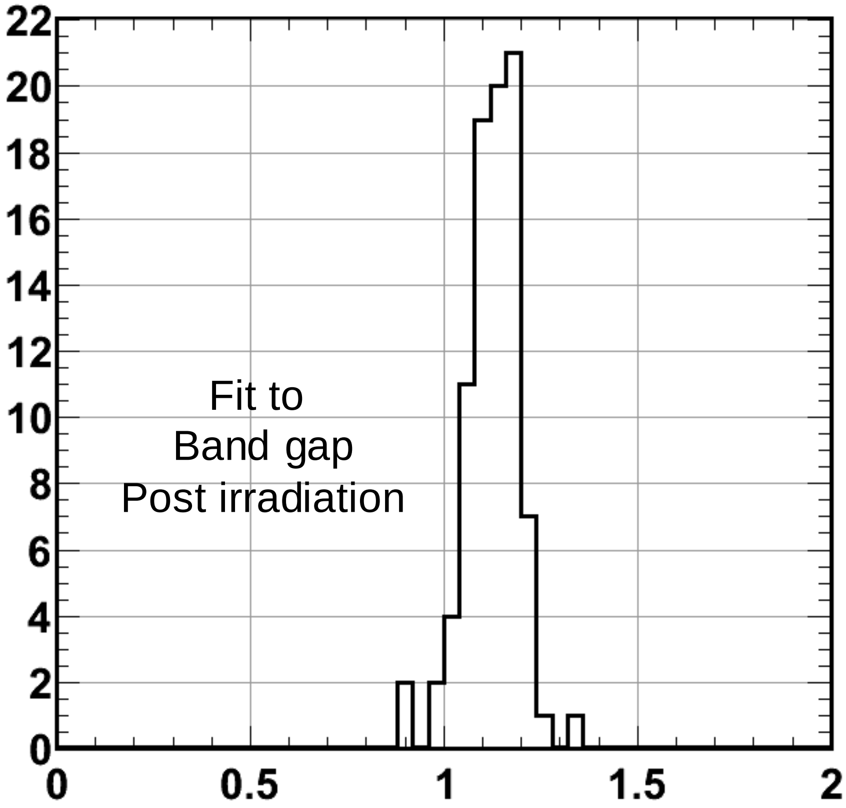


•Bulk current dominated sensor
• before and after irradiation

•Surface current dominated sensor before irradiation,
•Bulk dominated after

Measuring band-gap: Prelim.

- Can use data to measure the effective band-gap E_g



Preliminary	"effective band gap E_g"
100V 480 pb^{-1}	1.12 +- 0.06 eV
150V 480 pb^{-1}	1.11 +- 0.07 eV
150V 821 pb^{-1}	1.10 +- 0.04 eV

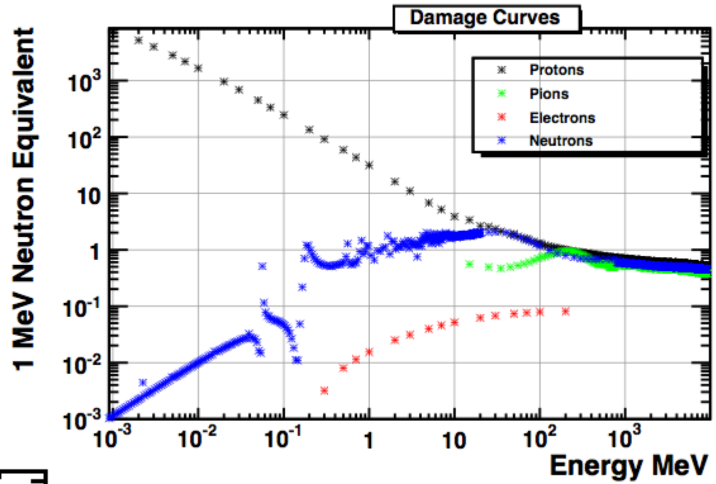
*A.Chilingarov, Generation current temperature scaling, 9 May 2011, https://rd50.web.cern.ch/rd50/doc/Internal/rd50 2011 001-I-T scaling.pdf,

- We measure E_g=1.1
- At previous RD50 meeting Alex Chilingarov E_g=1.2
  - And commented irrad. Values in literature limited

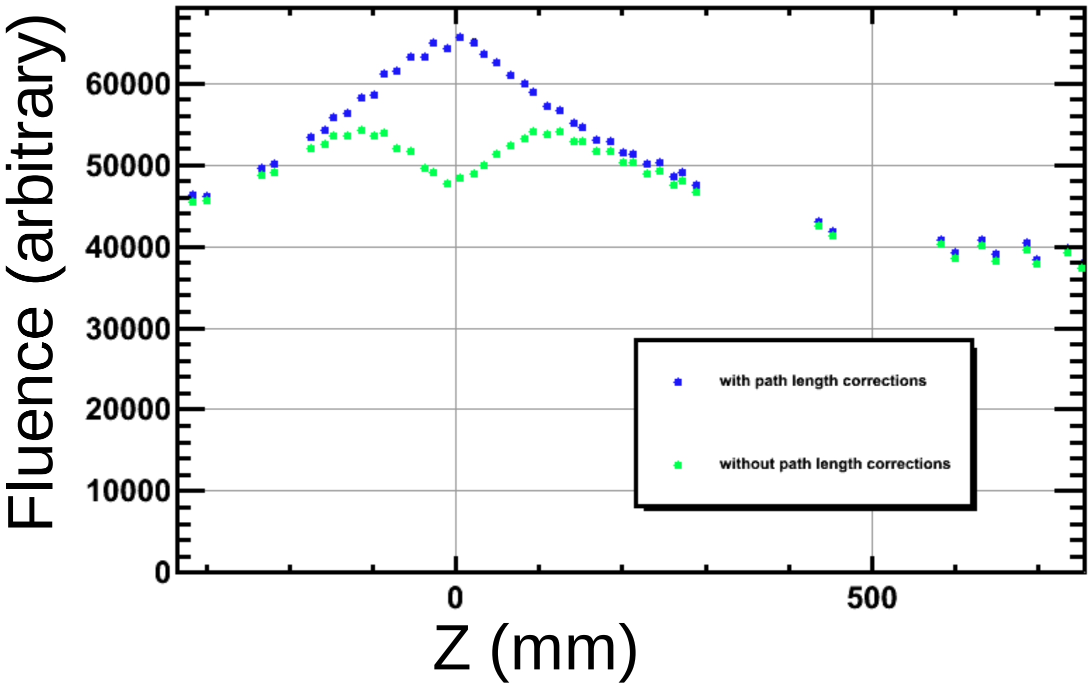
https://rd50.web.cern.ch/rd50/doc/Internal/rd50_2011_001-I-T_scaling.pdf

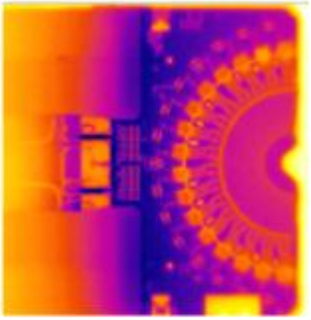
Estimate of Damage

- Use standard LHCb simulation to measure path lengths of particles in silicon
- Use radiation damage tables to convert to damage



A. Vasilescu and G. Lindstrom,
Displacement damage in silicon, on-line compilation.
http: //sesam.desy.de/members/gunnar/Si-dfuncs.html



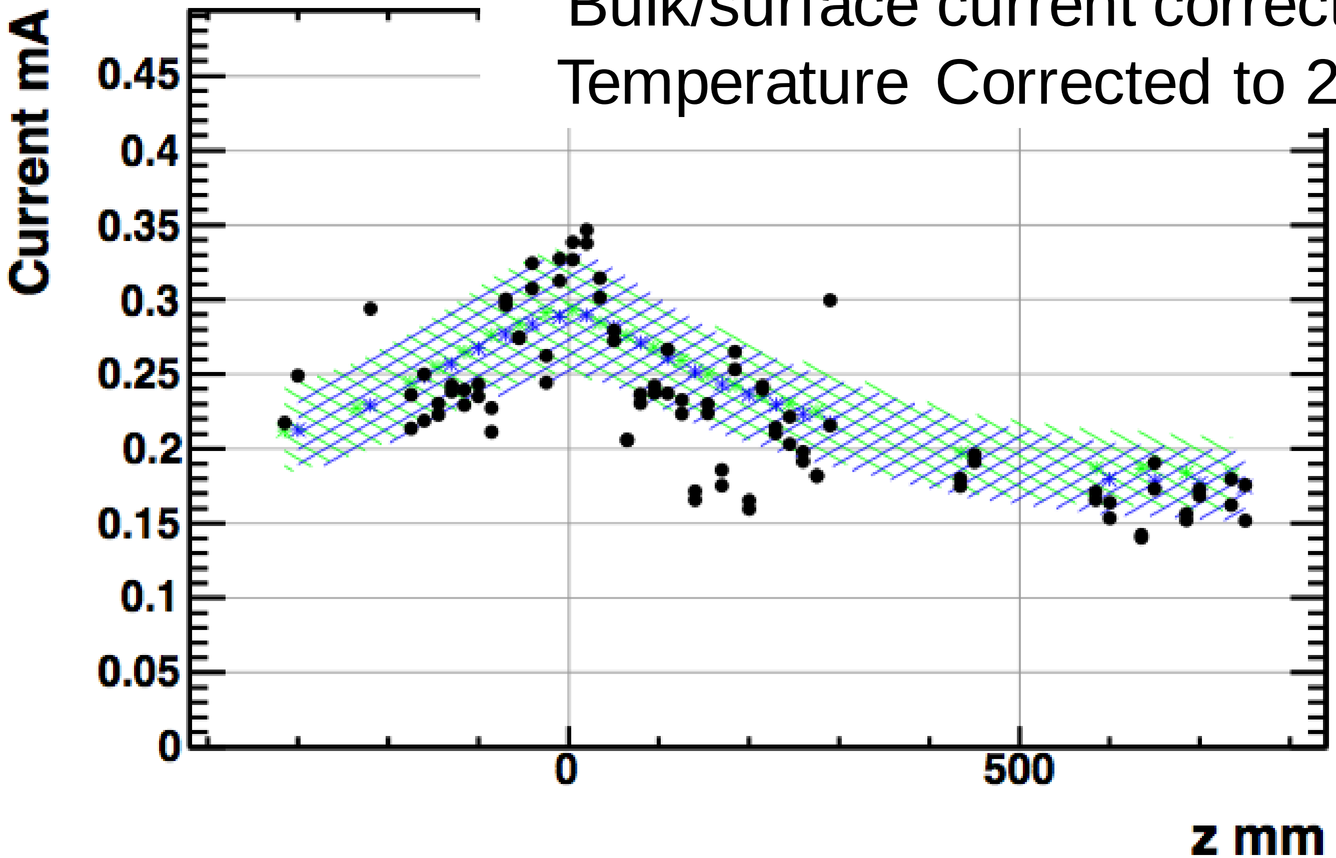


Temperature measured and offset corrected

Comparison data / expectation

- Good agreement between data and expectation
- Not (yet) sensitive to second order effects (low energy particles, thermal neutrons etc.)

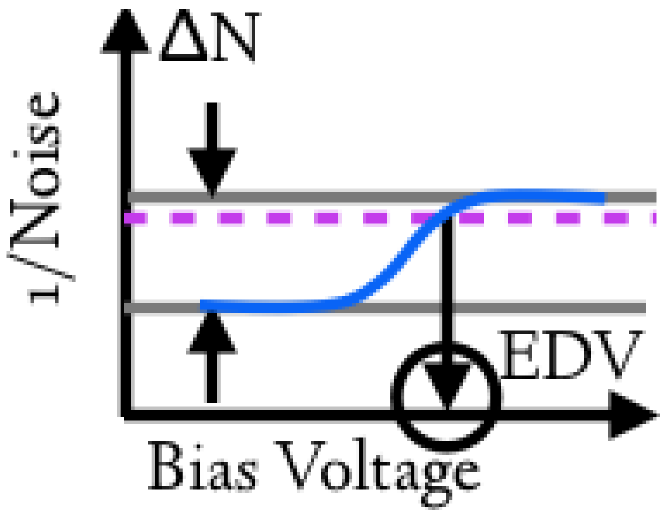
Bulk/surface current corrected
Temperature Corrected to 21C

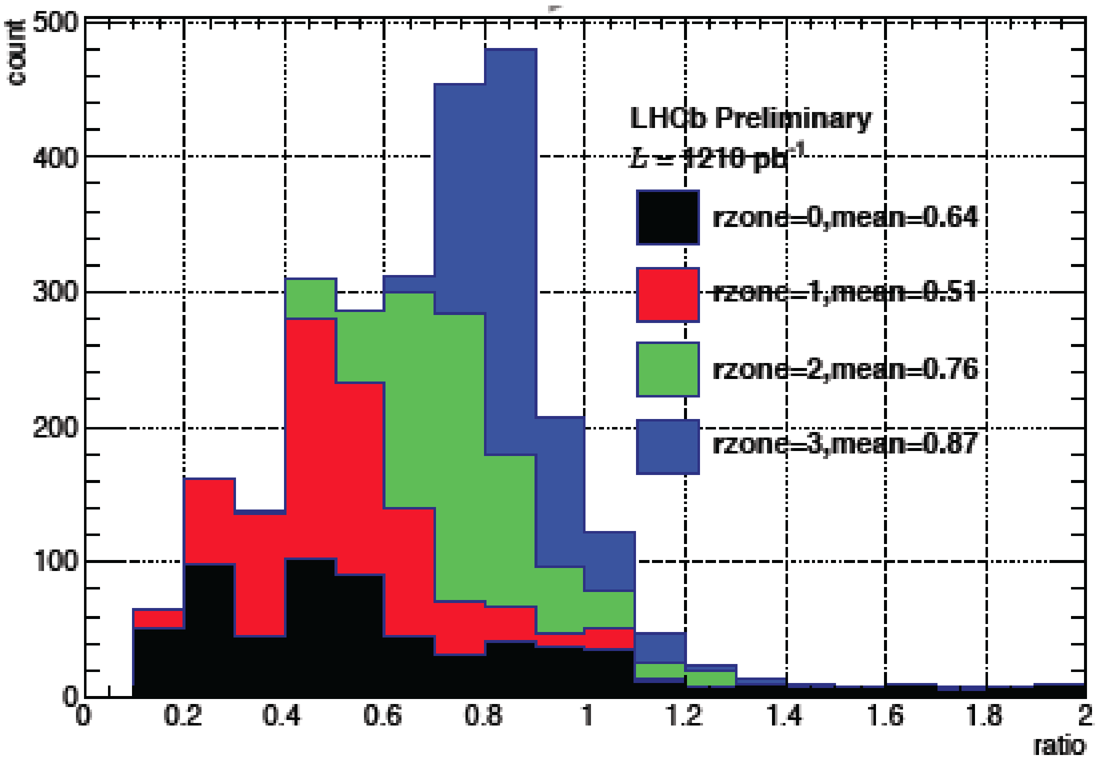


SECTION II: "Depletion" Voltage

- Noise vs Voltage
  - Scans taken monthly
- Charge Collection Efficiency vs Voltage
  - Taken three times per year
  - Requires beam time

VELO: Noise vs Voltage



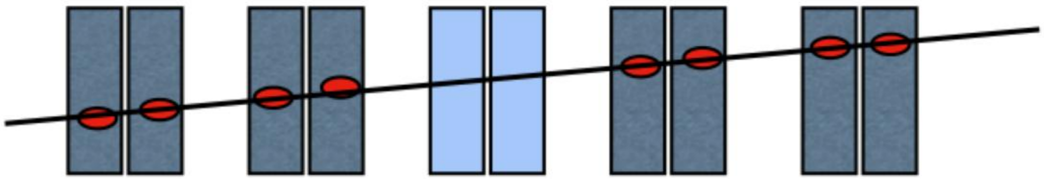


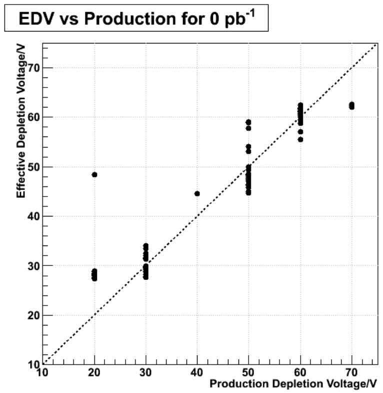
- Ratio of final/initial effective depletion voltage

Analysis of shape of distribution shows we have clearly inverted at sensor tips

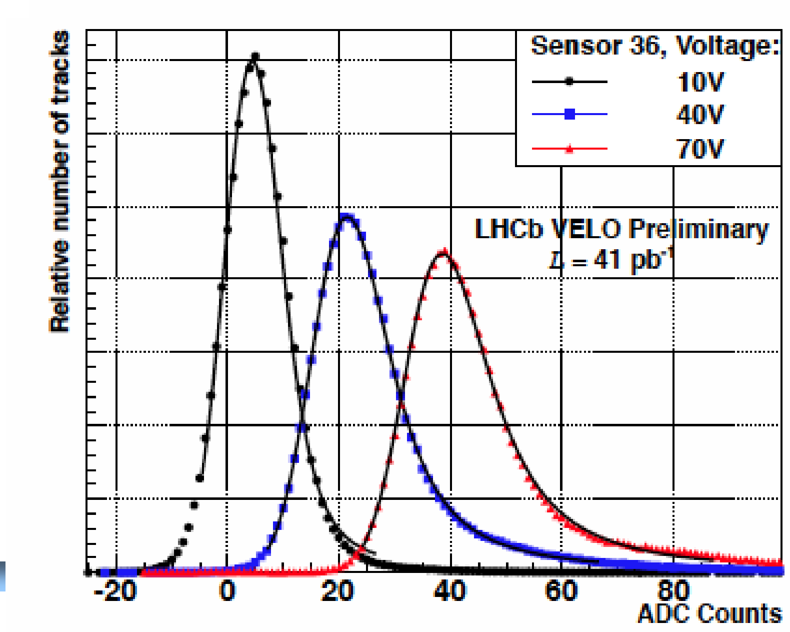
Charge Collection Efficiency

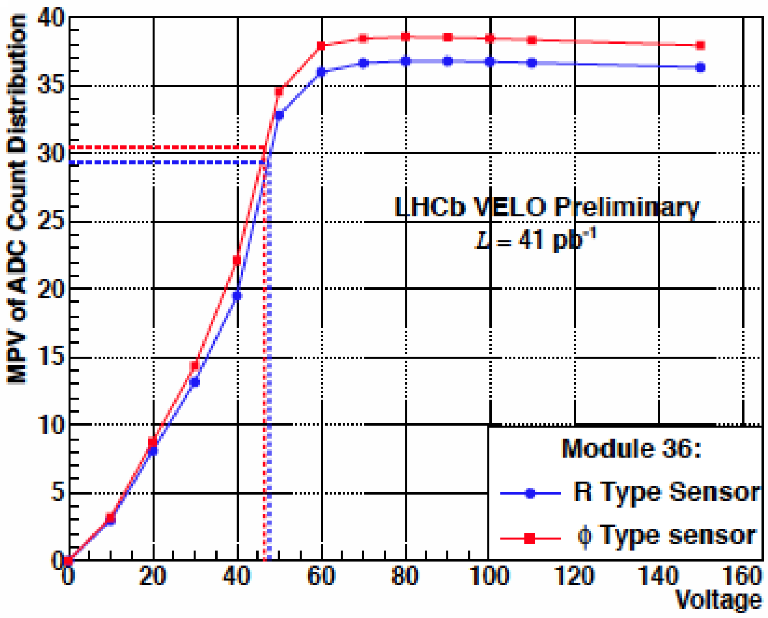
- Scan voltage on a sensor, VELO & ST
- Intercept tracks and measure Landau MPV



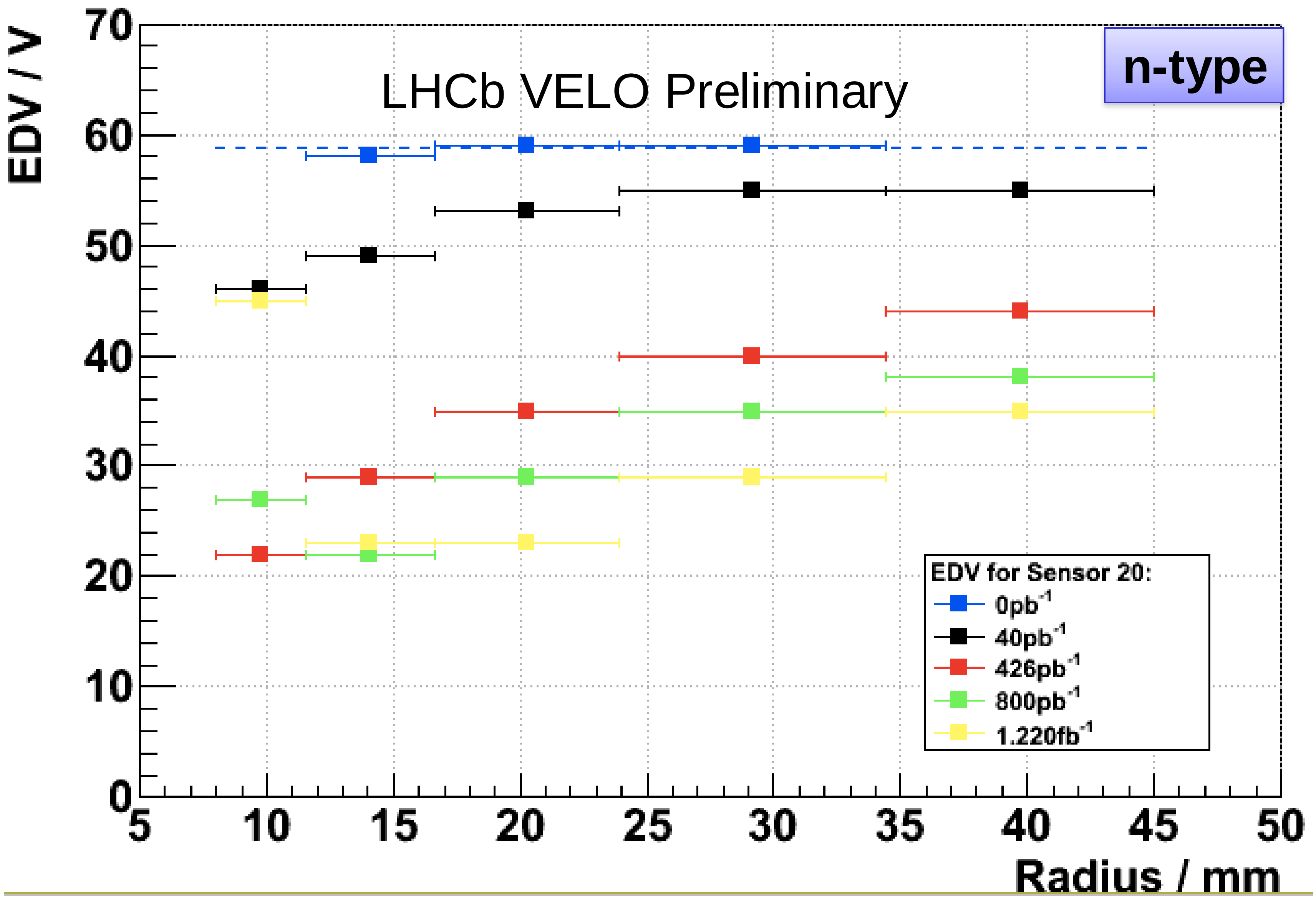


- Extract Voltage gives 80% CCE

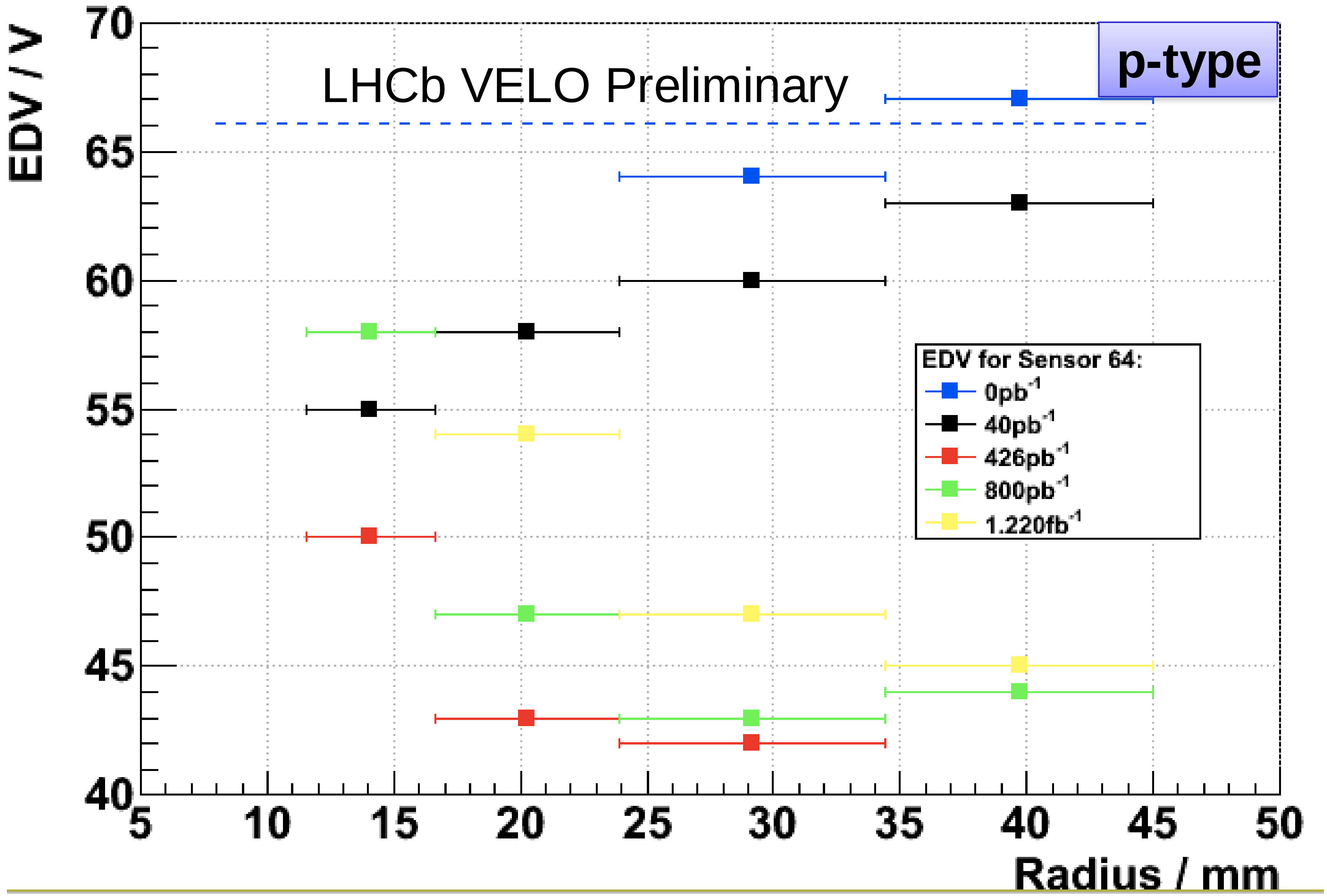




Eff. Depletion Voltage vs Radius

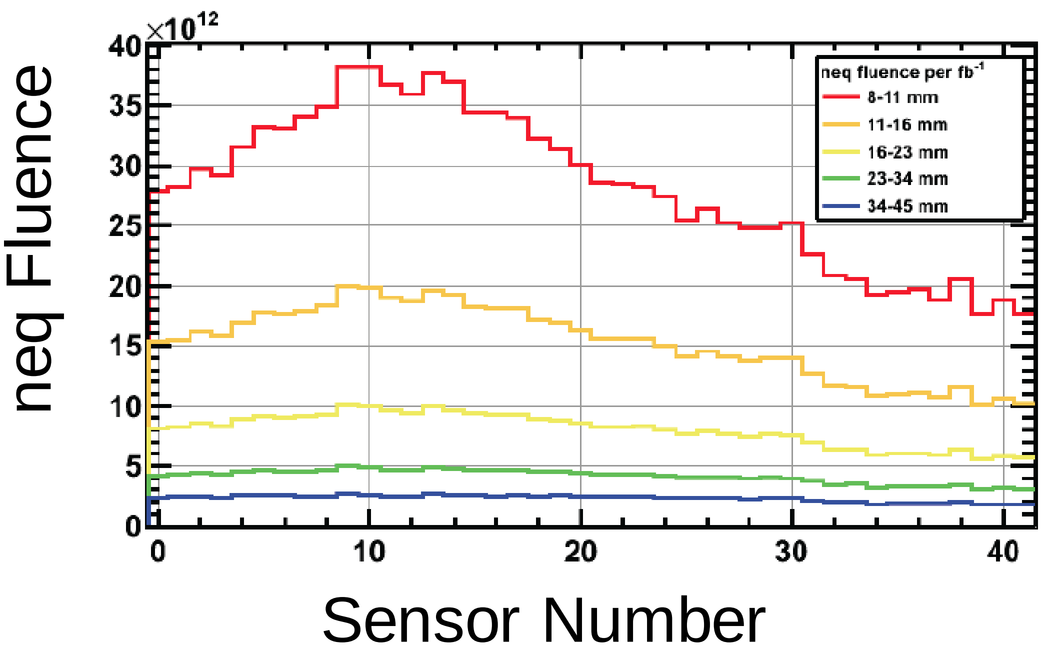


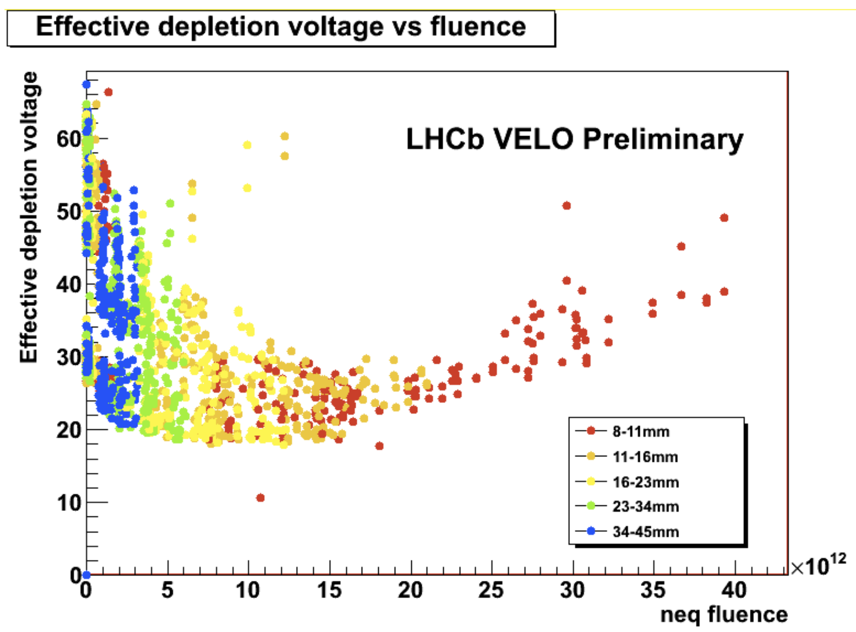
Eff. Depletion Voltage vs Radius



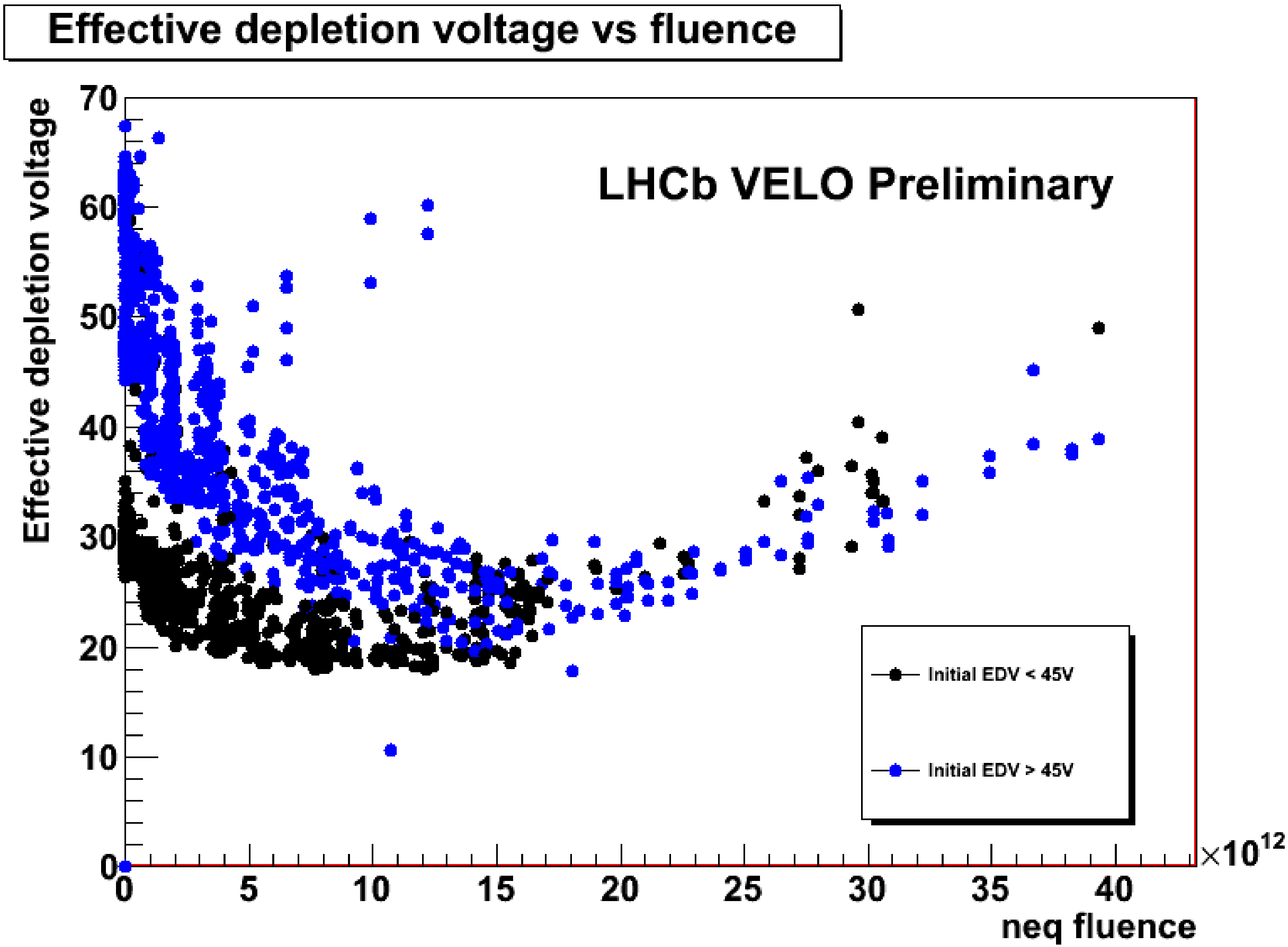
Eff. Depletion Voltage vs Fluence

- Combine:
  - Measured Effective Depletion voltage versus radius
  - Fluence per region per sensor

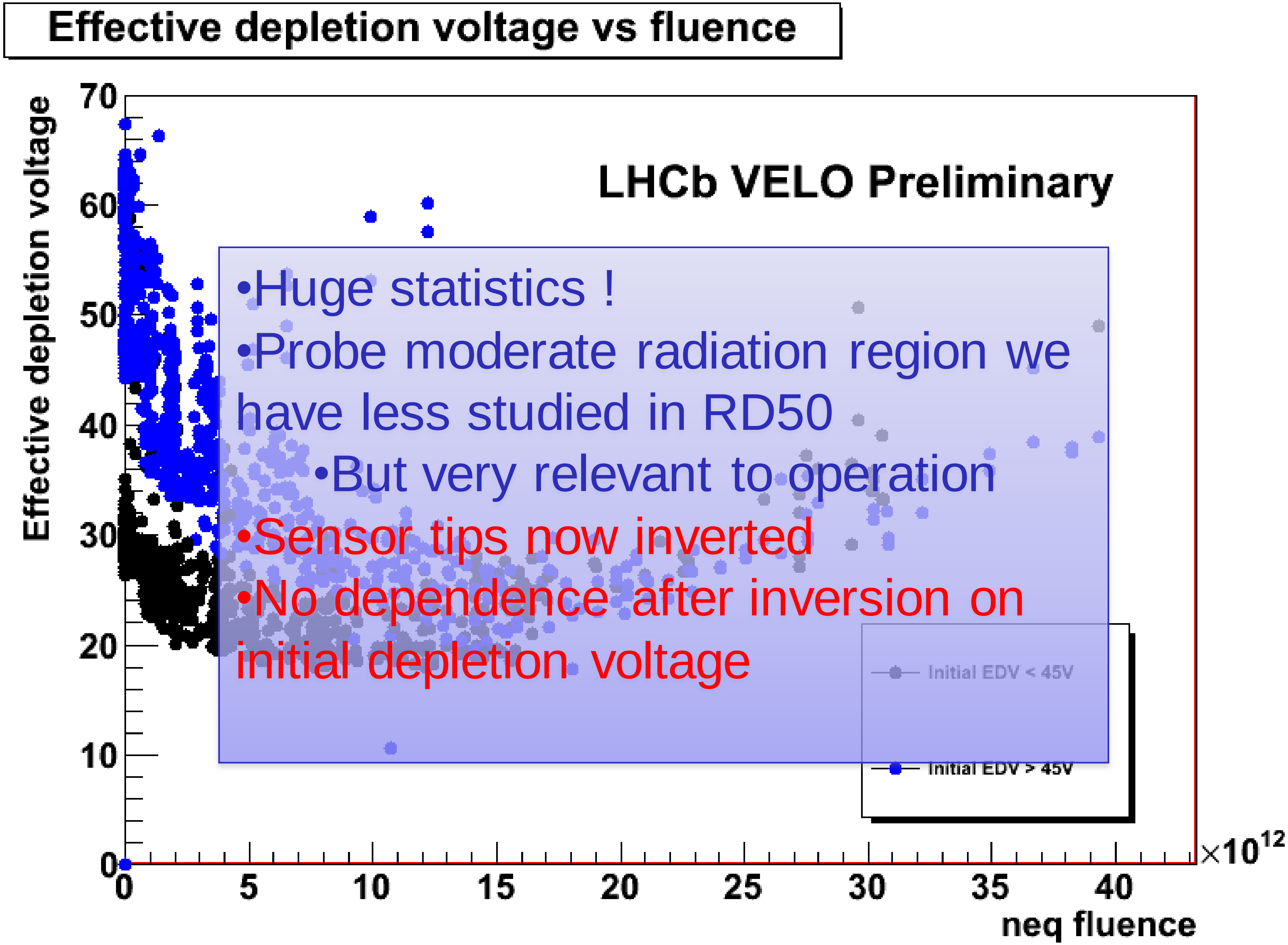




Eff. Depletion Voltage vs Fluence

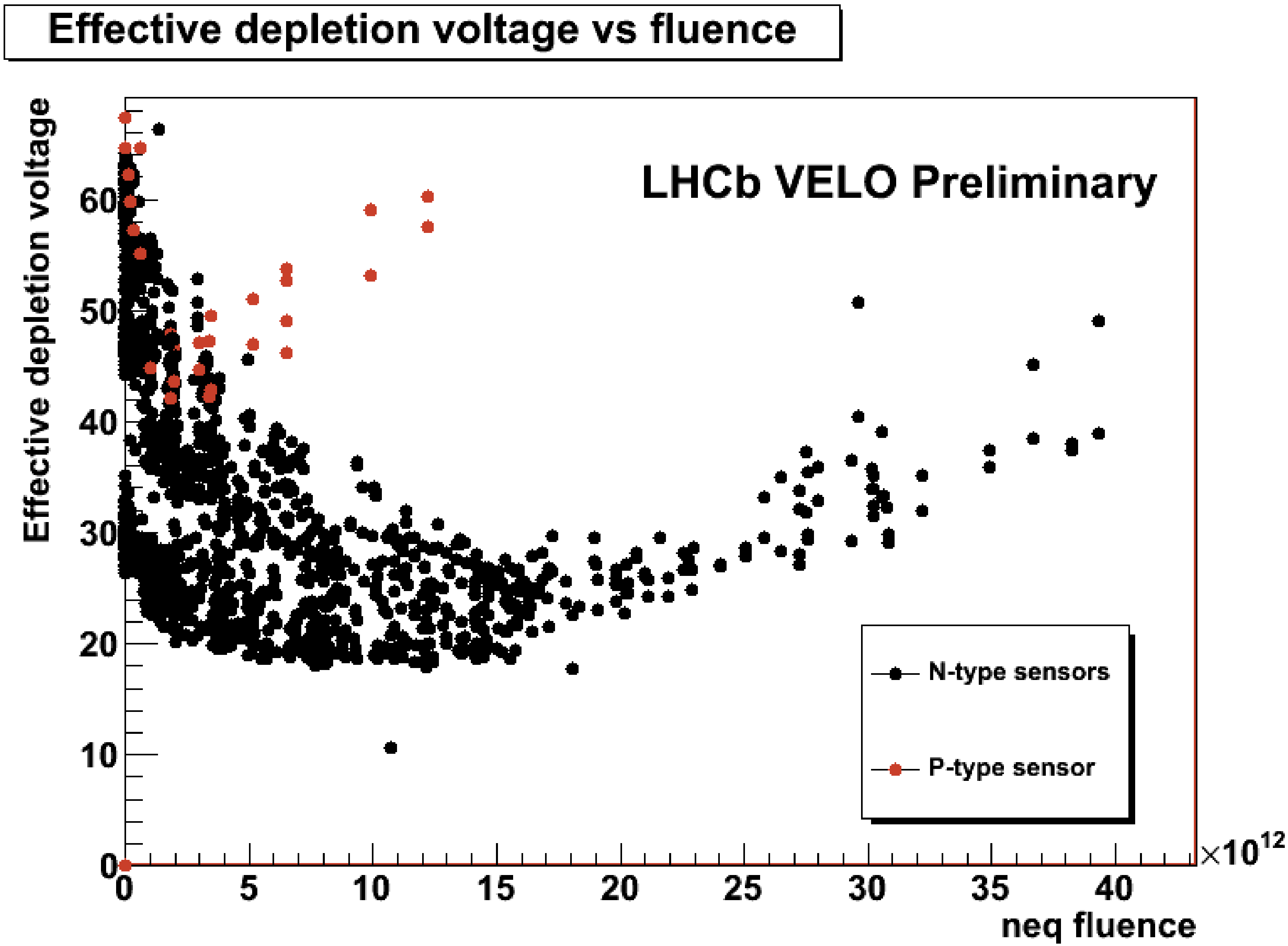


Eff. Depletion Voltage vs Fluence

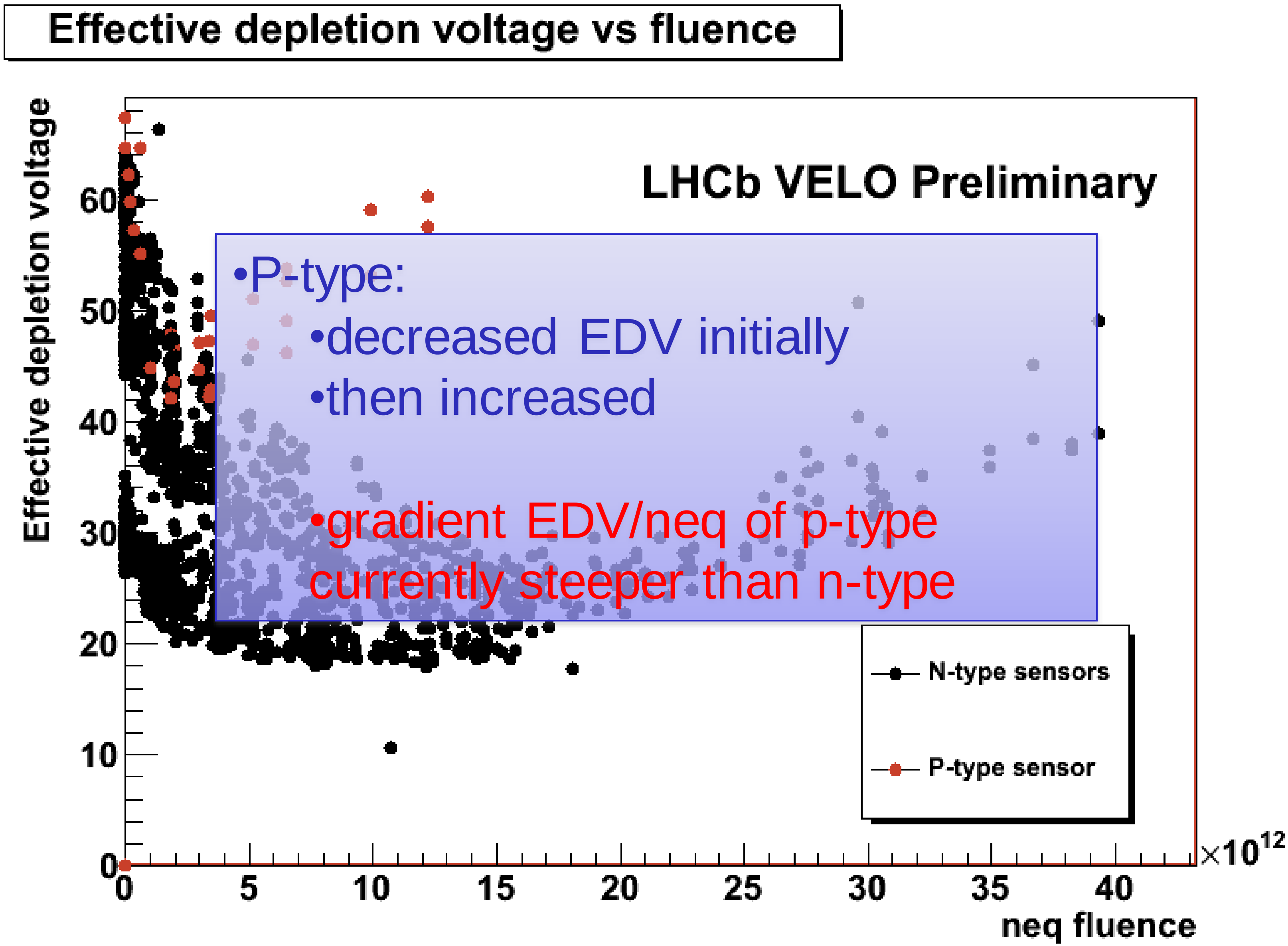


- Huge statistics !
- Probe moderate radiation region we have less studied in RD50
  - But very relevant to operation
- Sensor tips now inverted
- No dependence after inversion on initial depletion voltage

Eff. Depletion Voltage vs Fluence



Eff. Depletion Voltage vs Fluence



- P-type:
  - decreased EDV initially
  - then increased
- gradient EDV/neq of p-type currently steeper than n-type

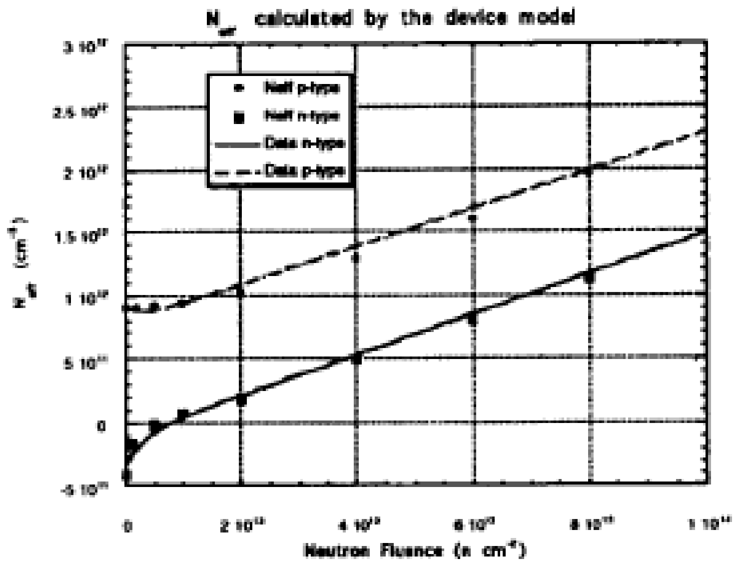
Expected ?

RD-2 1993

(thanks to Steve Watts)

Initial acceptor removal mechanism
Boron Instertial captured by Oxygen/Carbon

➔Decrease in V_{dep} initially

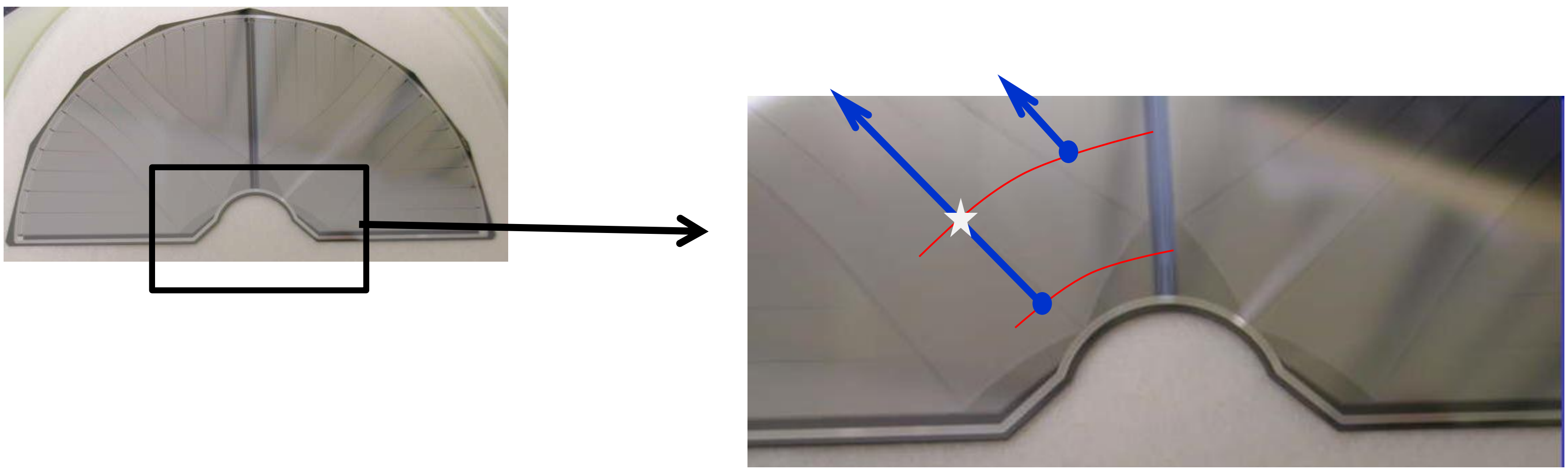


Thanks for discussions: Alexandra, Tony, Gianluigi,, Gregor, Steve Watts, Nobu

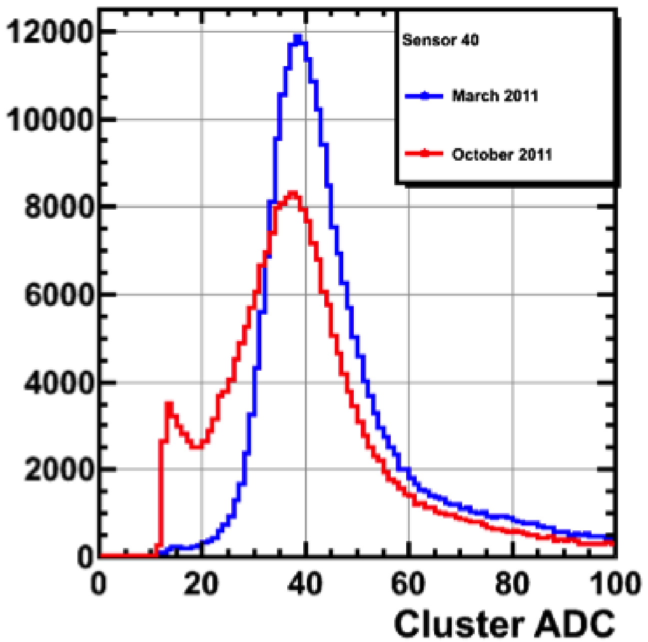
References:

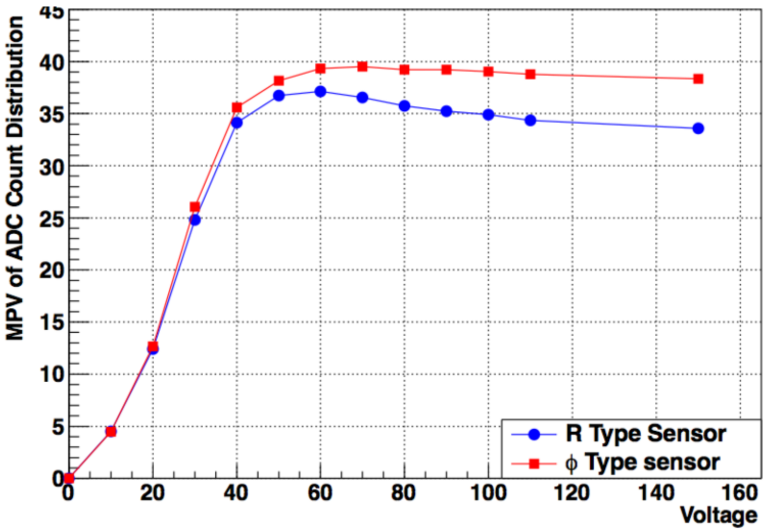
- Lemeilleur et al. RD-2, Nuclear Physics B (Proc. Suppl.) 32 (1993) 415-424
- Watts et al., Nuclear Instruments and Methods in Physics Research A 377 (1996) 224-227
- Unno: NIMA 383 (1996) 159-165 and IEEE Transactions on Nuclear Science, 56 (2009) 468-473
- Eckstein: 12th RD50 workshop, Ljulbjana, Slovenia, June 2008
- Lozano: (work with Gian) : RD50 workshop 2004, "comparison of radiation hardness p-in-n, n-in-n, n-in-p
- V.Cindro: Nuclear Instruments and Methods in Physics Research A 599 (2009) 60–65

SECTION III:
Charge loss with 2nd metal layer



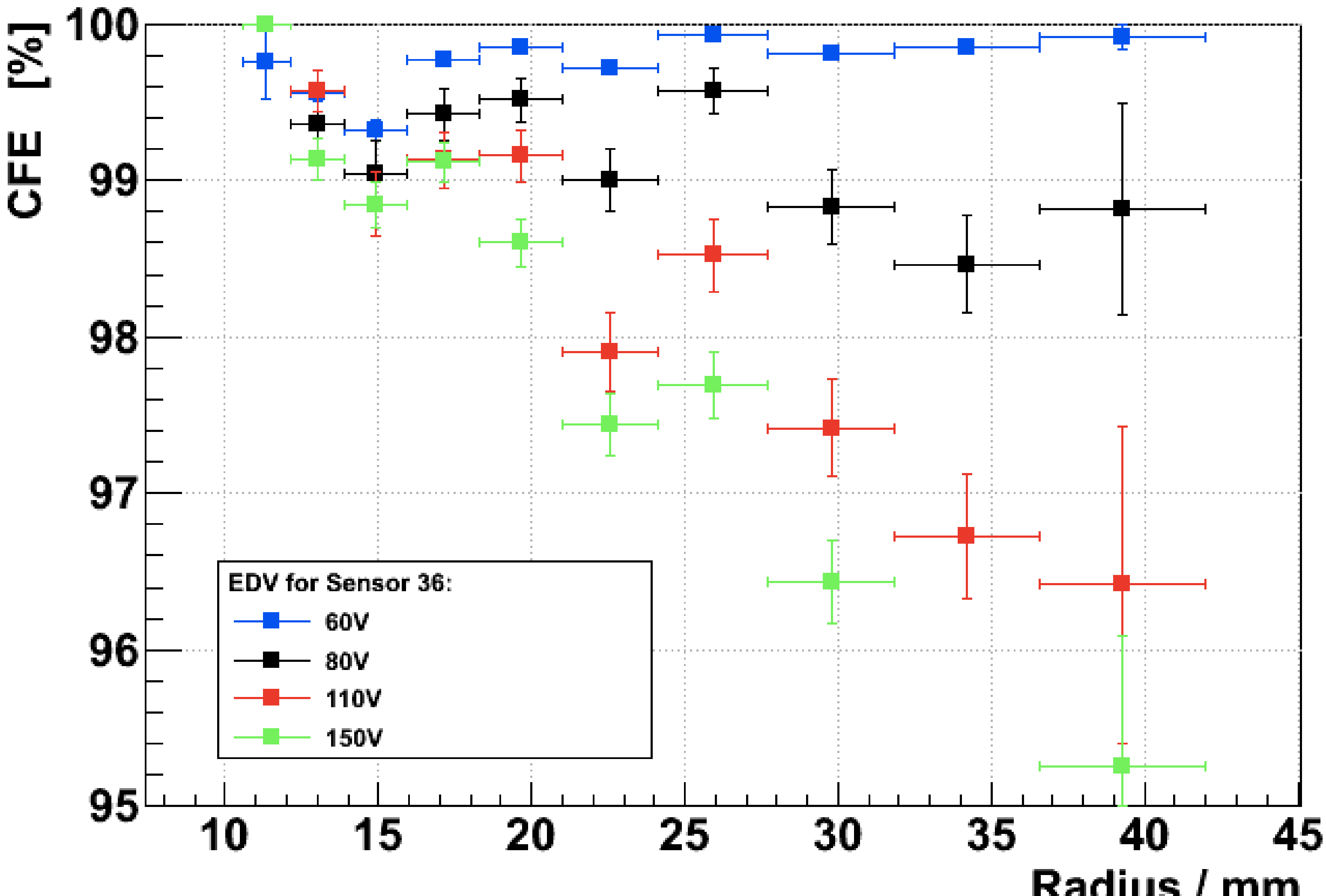
- Sensor strips readout to outside with 2nd metal layer





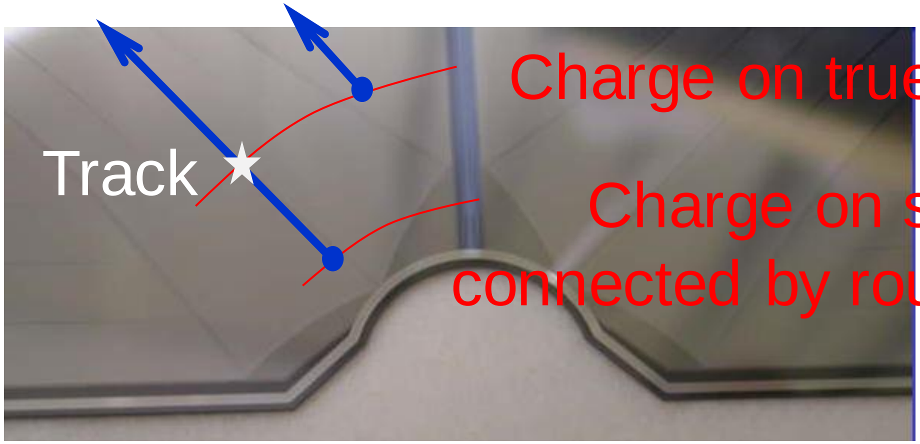
- Second peak in Landau distribution
  - Charge on 2nd metal layer
  - Cluster position associated with double metal crossing strip
- Decrease in MPV
  - Of main cluster
- Worse at **higher** V
- Developed during year with irradiation

Cluster Finding Efficiency vs R



- Worst at high radius – i.e. **less** irradiated region
- And in downstream sensors

Queries



- What is the exact mechanism ?
  - Form of surface damage?
- Why worse at higher voltage ?
- Why worse at outside of sensors ?

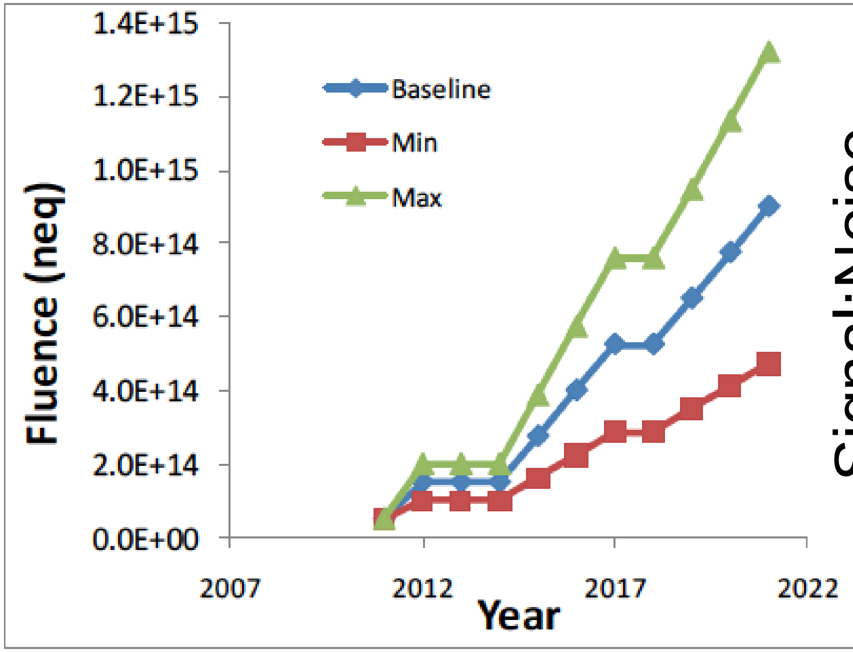
- What will happen in future?

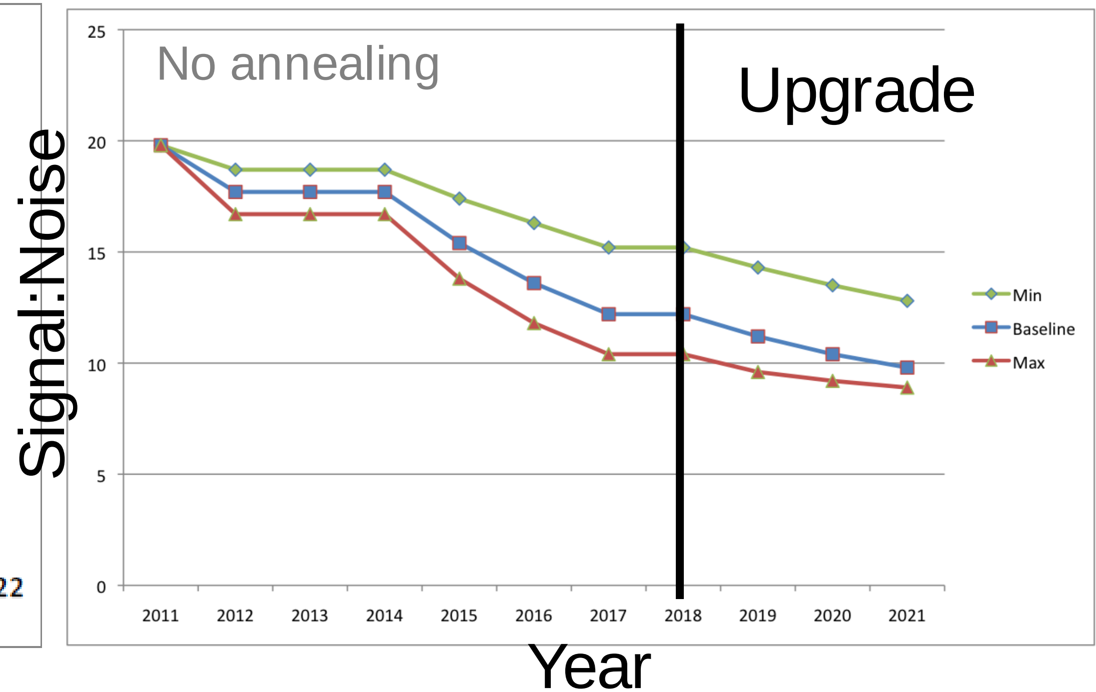
SECTION IV: Future Projections

- Depletion Voltage
- Signal:Noise

Future Signal:Noise Projection

Scenarios: $1fb^{-1}$/year, $2fb^{-1}$ year, $3fb^{-1}$ year, for operational years

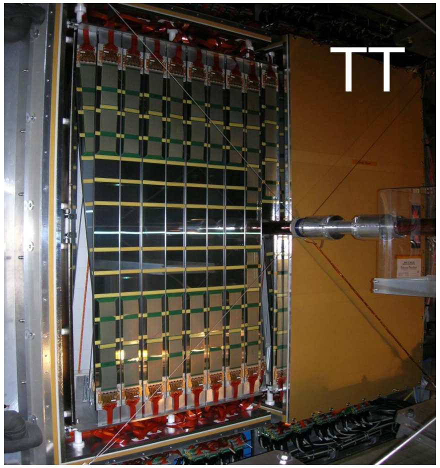




- Operating at -7C and 500V
  - Control annealing to be beneficial when needed

LHCb Radiation Damage Summary

- Most irradiated detector at LHC
- Current change – as expected
- Determination of E_g
- n-type Sensors inverted at tips
  - First at LHC
  - huge statistics to track !
- p-type decrease, then increase
  - Currently p-type gradient steeper than n-type
- Charge loss on 2nd metal layer sensors



Thanks to Stephen for working group organisation

LHCb VELO & ST group

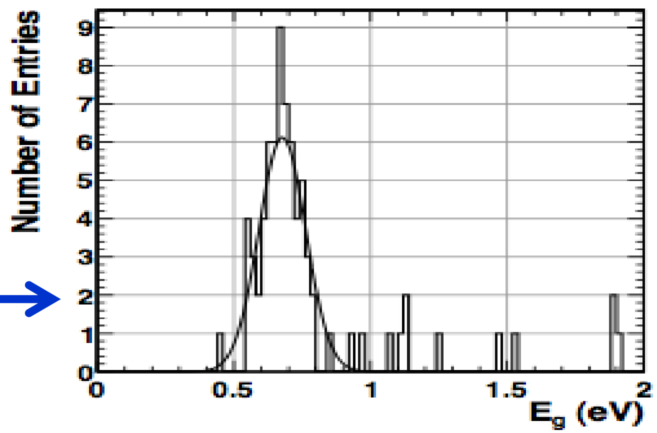
With thanks to:

Michael Moll, Gianluigi Casse, Alexandra Junkes, Tony Affolder

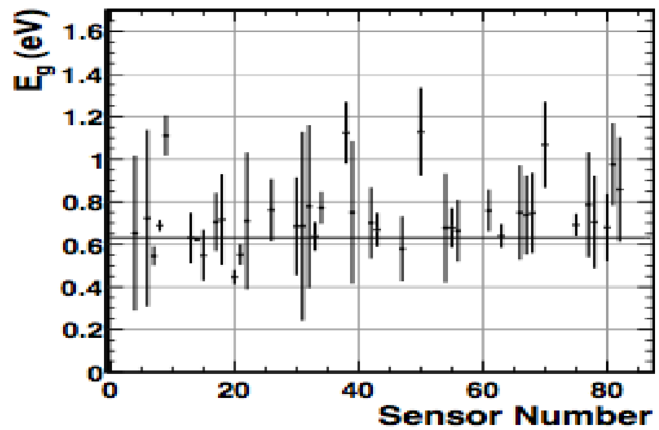
Backup

Measurement of effective E_g

Before
rradiation

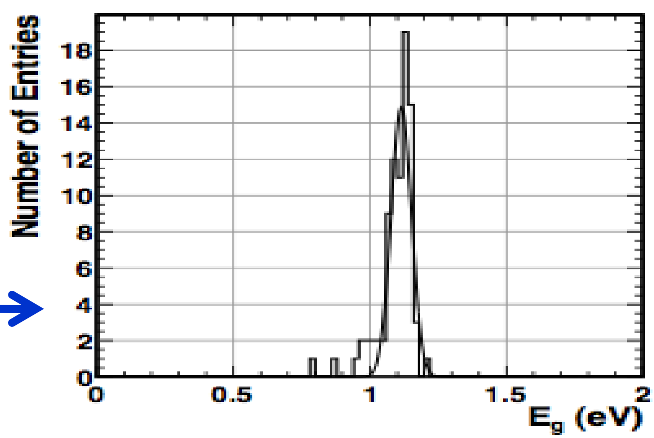


(a)

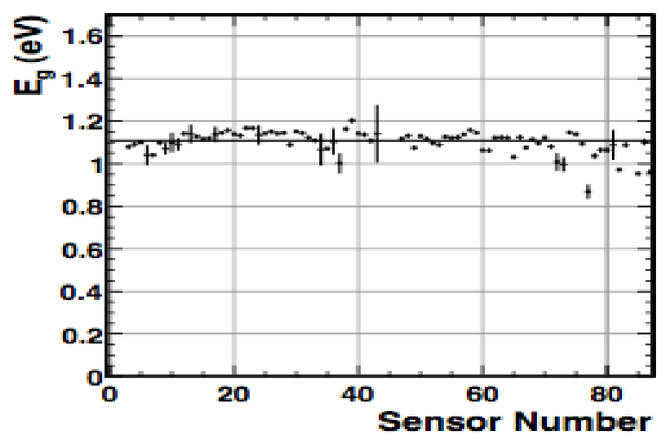


(b)

After
Irradiation

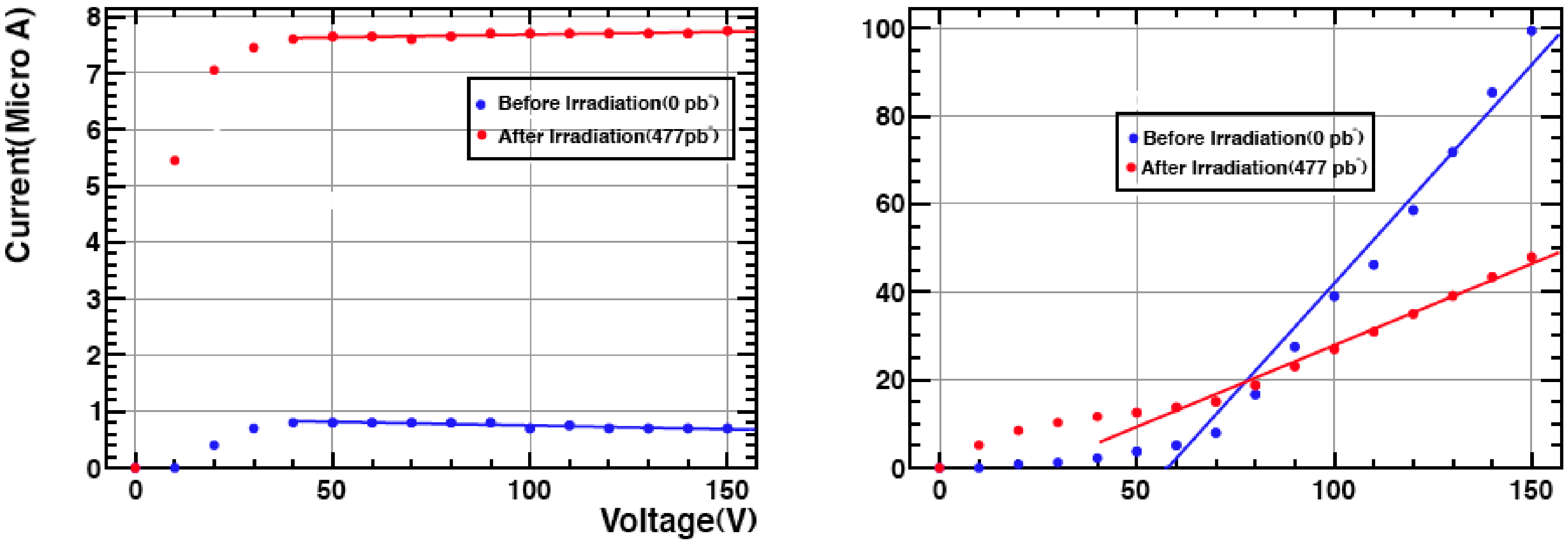


(c)



(d)

Current - Voltage



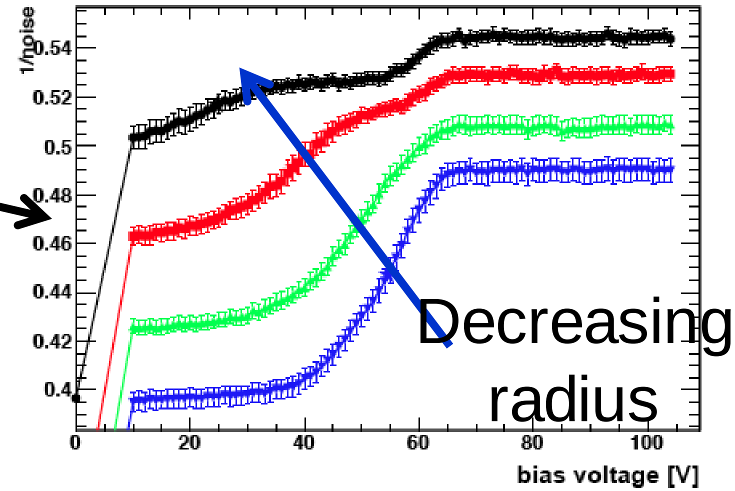
Ankit Gureja

Investigating depletion voltage: Noise vs Voltage

Examples, after 642 pb^{-1} :

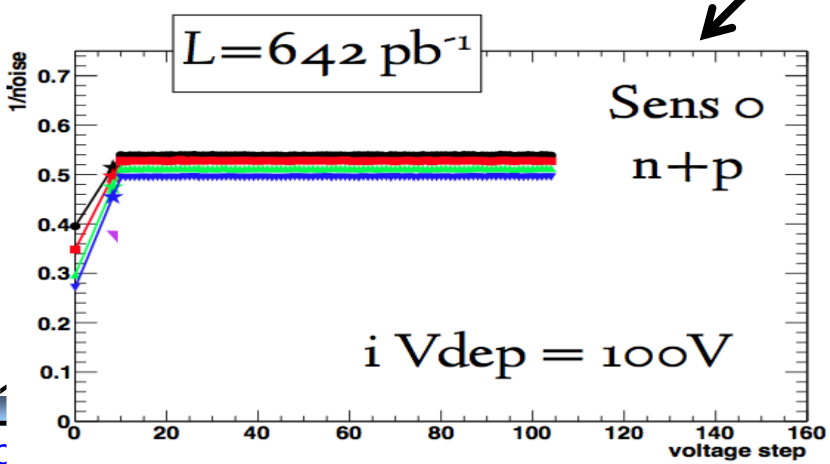
n+n sensor, Initial V_{dep}=70V

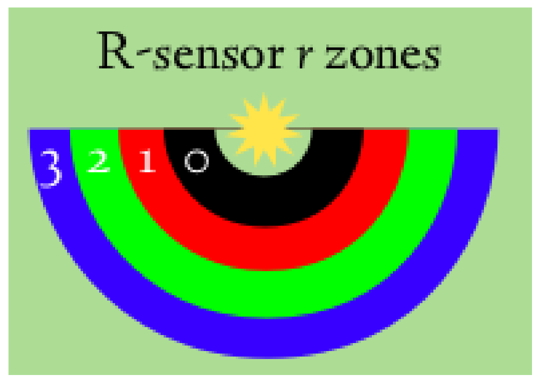
•"Step" in 1/N (corresponding to ~depletion) moves to lower voltages as radius decreases



n+p sensor, initial V_{dep}= 100V

•"Step" in 1/N remains at low voltage for all regions (depletion region grows from strip side)

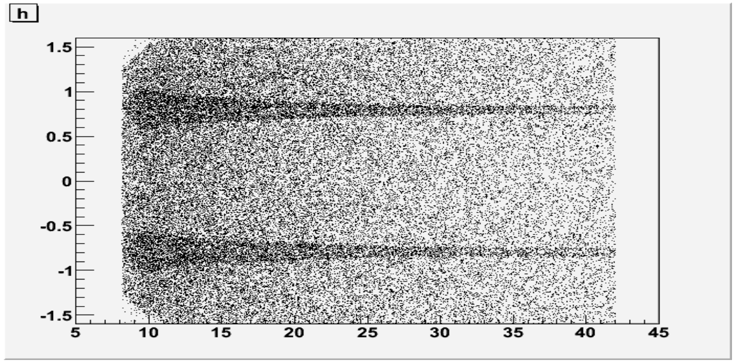


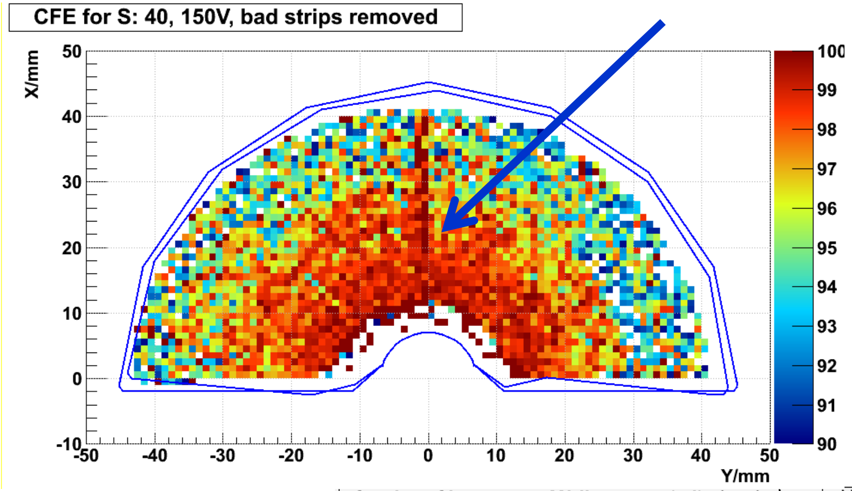


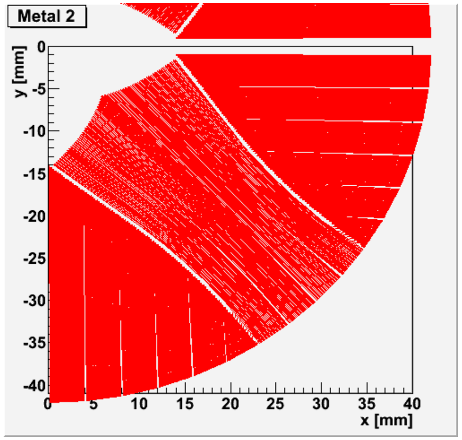
Confirmation of this theory

Location of track intercepts with no associated "small" cluster maps delicate routing line pattern

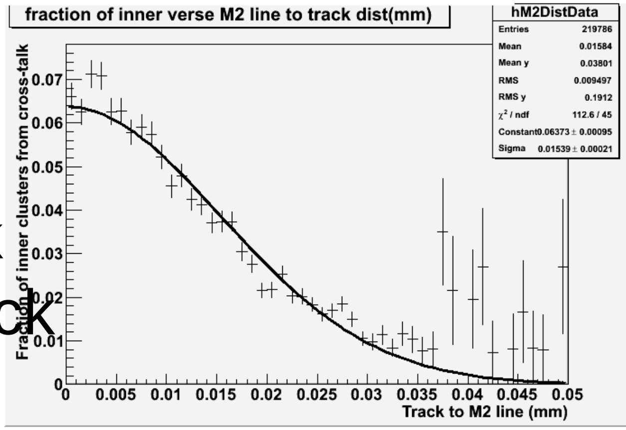
Cluster efficiency maps also show "improvement" away from DM layer







Using new mapping of 2nd metal layer, a correlation of cross talk has been seen with the track proximity to double metal

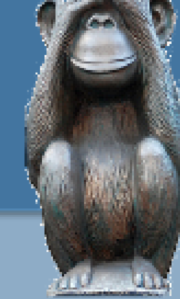


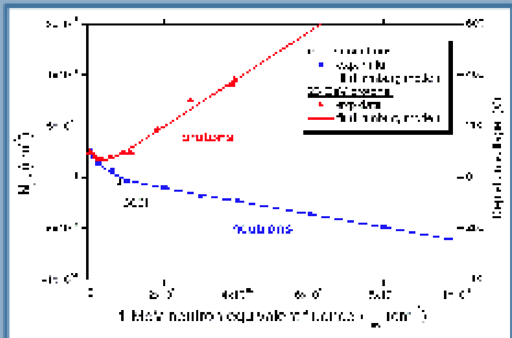
Lifetime estimates (Tony Affolder)

Year	Baseline	Min	Max	Baseline	Min	Max
2011	19.8	19.8	19.8	20.3	20.3	20.3
2012	17.7	18.7	16.7	19.1	19.7	18.5
2013	17.7	18.7	16.7	19.1	19.7	18.5
2014	17.7	18.7	16.7	19.1	19.7	18.5
2015	15.4	17.4	13.8	17.7	18.9	16.6
2016	13.6	16.3	11.8	16.5	18.2	15.0
2017	12.2	15.2	10.4	15.4	17.5	13.7
2018	12.2	15.2	10.4	15.4	17.5	13.7
2019	11.2	14.3	9.6	14.4	16.9	12.6
2020	10.4	13.5	9.2	13.6	16.3	11.7
2021	9.8	12.8	8.9	12.9	15.8	10.9

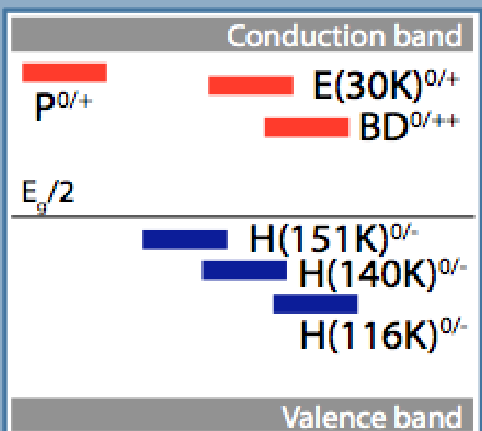
No annealing or anneal for ~9 days at the end of lifetime (80 min at 60 C) gives needed performance to 2017 (excluding the double-metal effects)

Defect balance

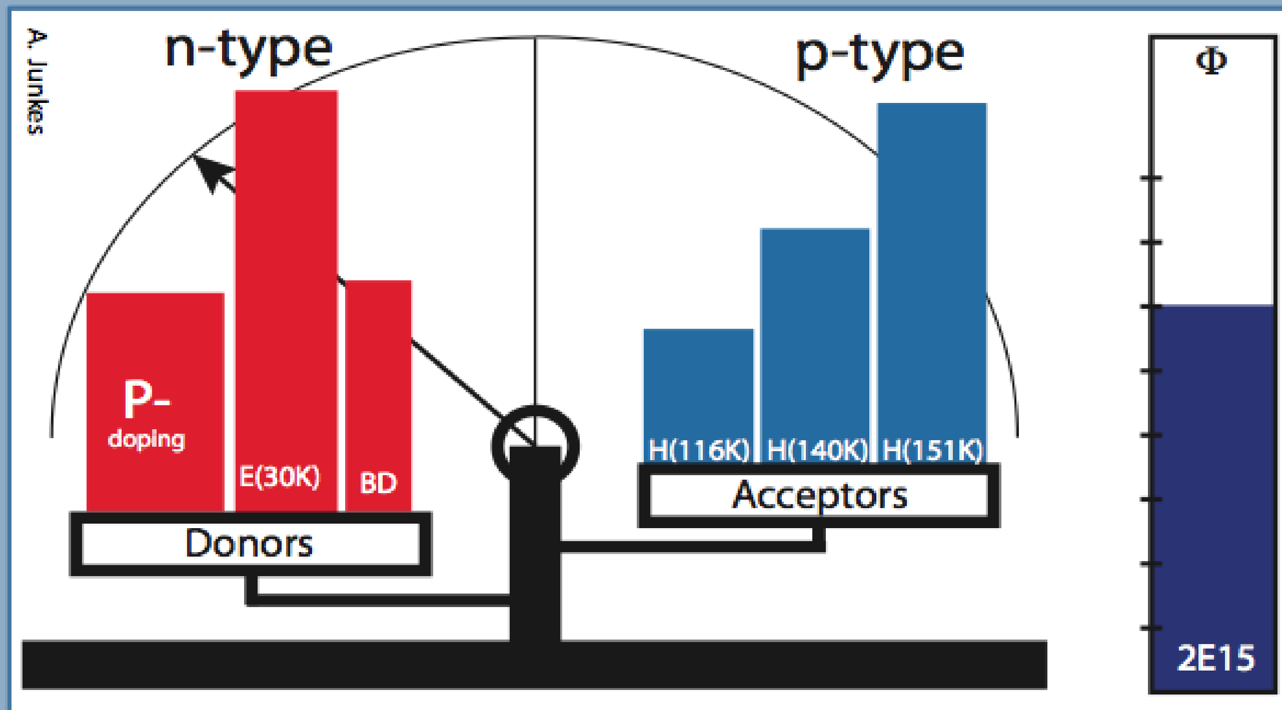




I. Pintilie et al. NIM A 611 (2009) 52



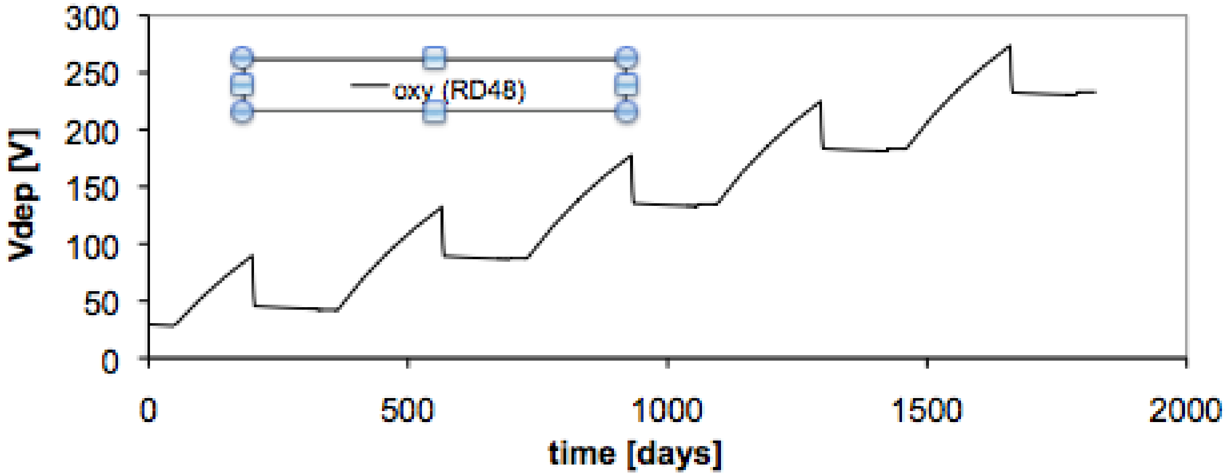
Proton irradiation



Conclusions

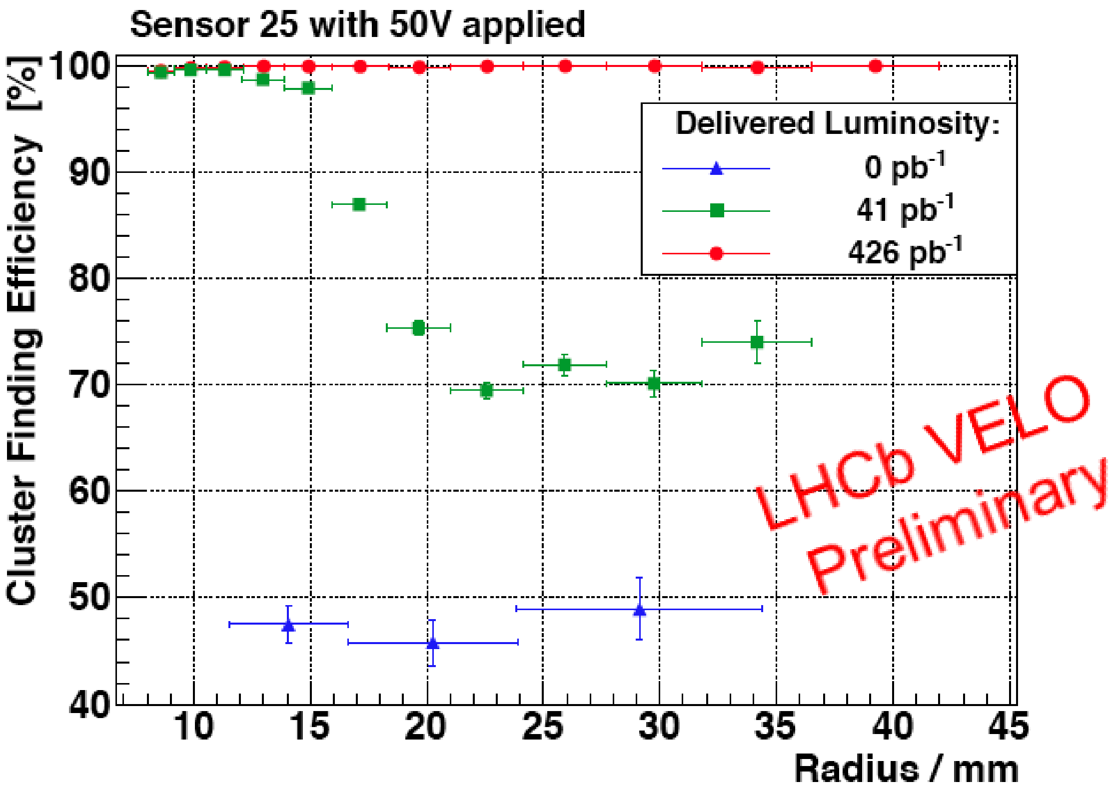
Evolution of V_dep

- 5 years of 1 fb^{-1} per year
- Add 30% to the flux for 14 TeV
- 2x5 day warm up
- Approaching 250 V at the tip, and 1 mA/sensor at 21 degrees



Cluster finding efficiency

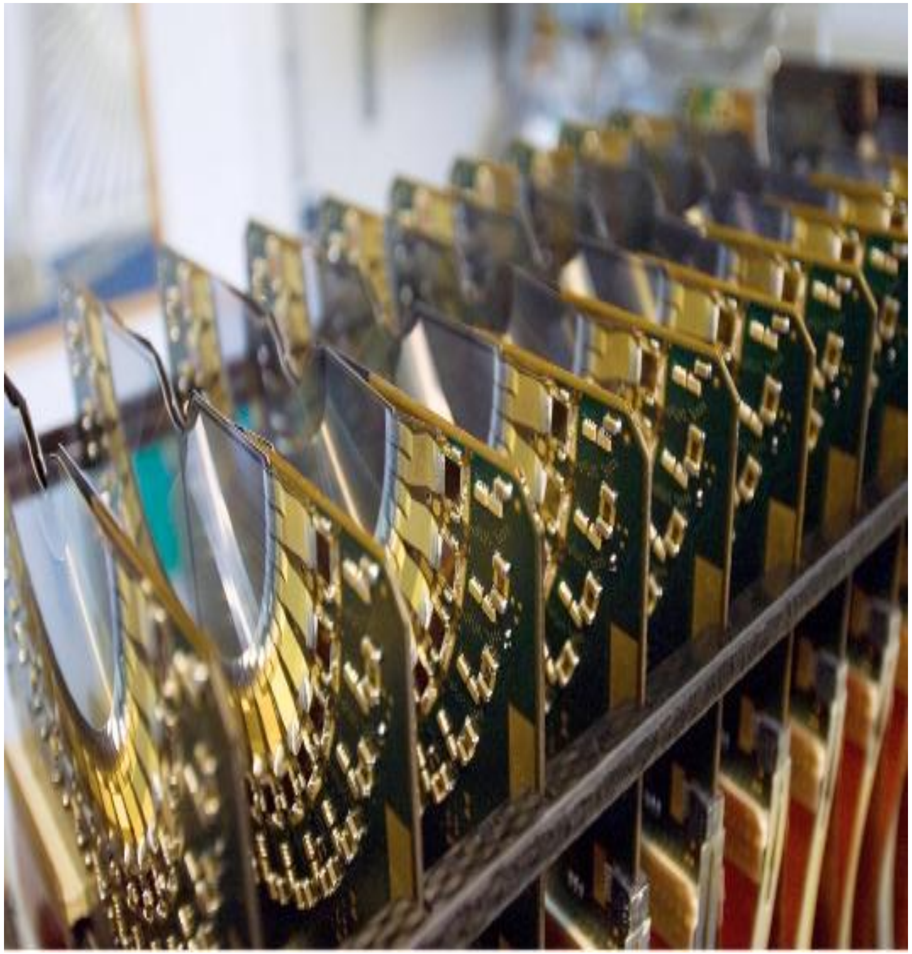
- Beautiful effects seen:
  - When the sensor is under nominal depletion it is more efficient in the innermost, more irradiated zone! (because V_{dep} has dropped here..)



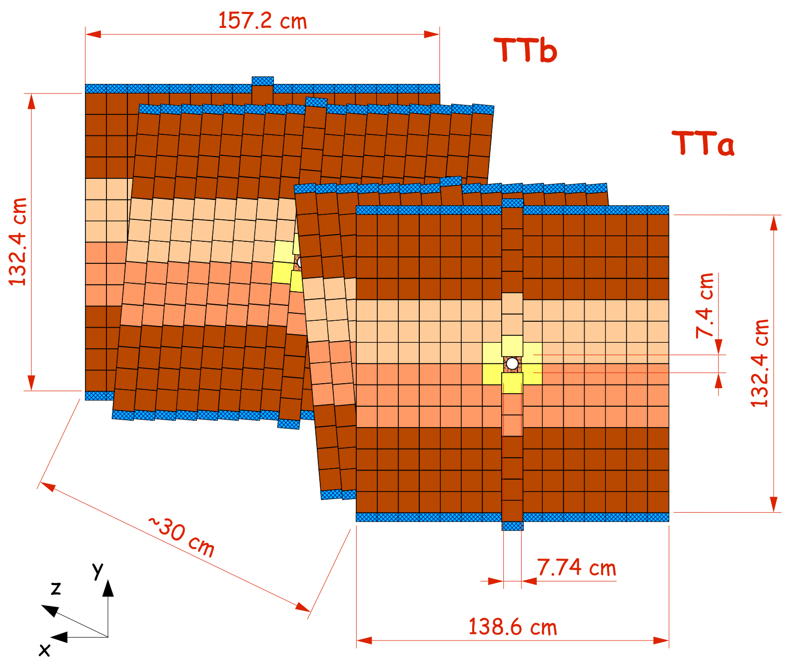
LHCb silicon in 3 slides:

VELO

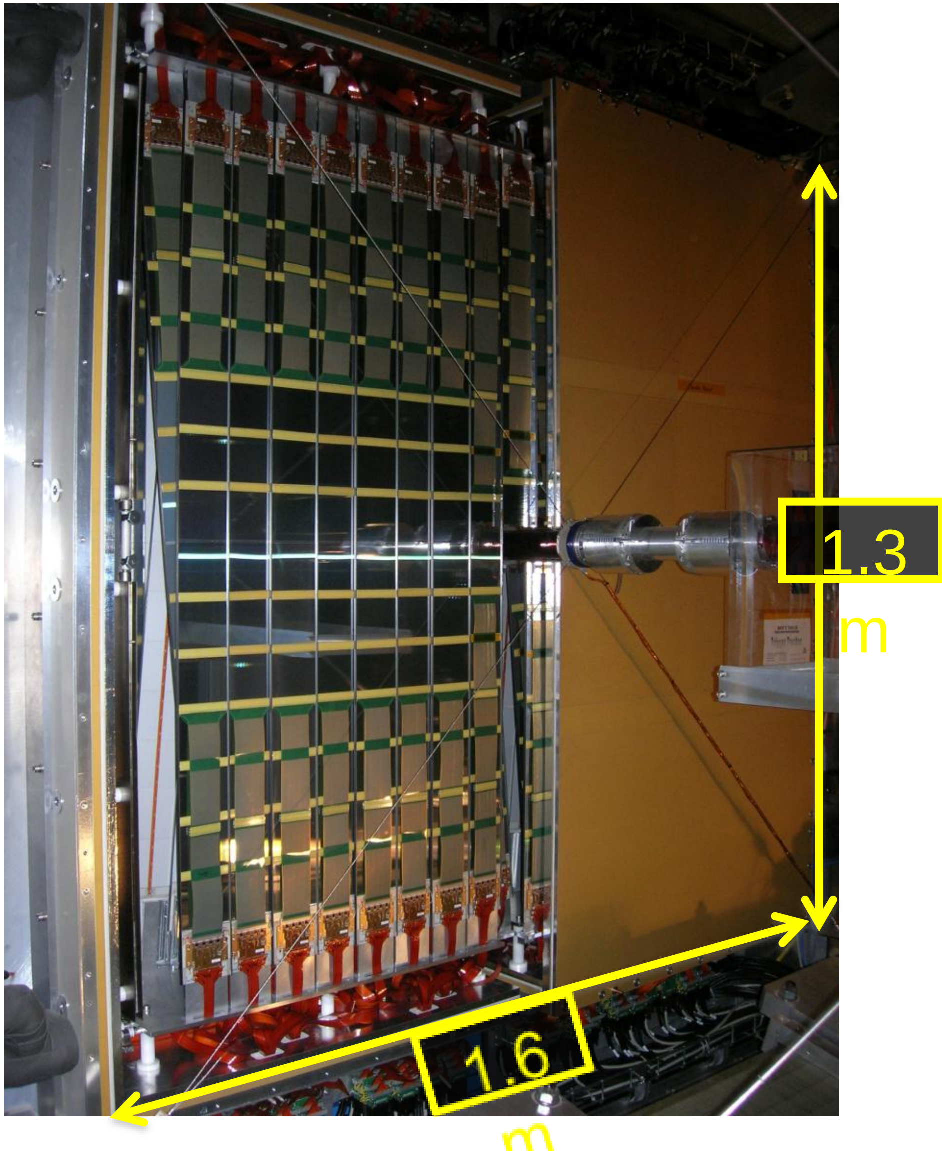
- 88 single sided R and ϕ silicon sensors
- Inner strip 8 mm radius, inner edge 7 mm radius, rettracted to 30 mm during beam injection
- Strip Pitches 40-100 μm
- Evaporative CO2 cooling system
- Silicon operating temperature ~-8^{o}C
- Silicon thickness 300 μm



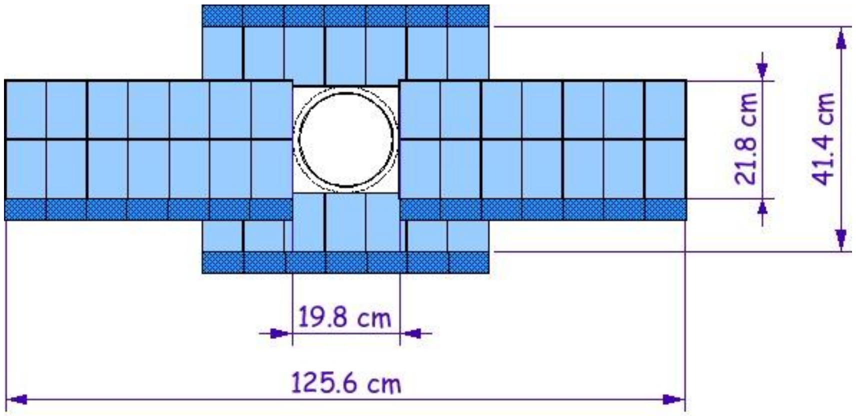
Tracker Turicensis



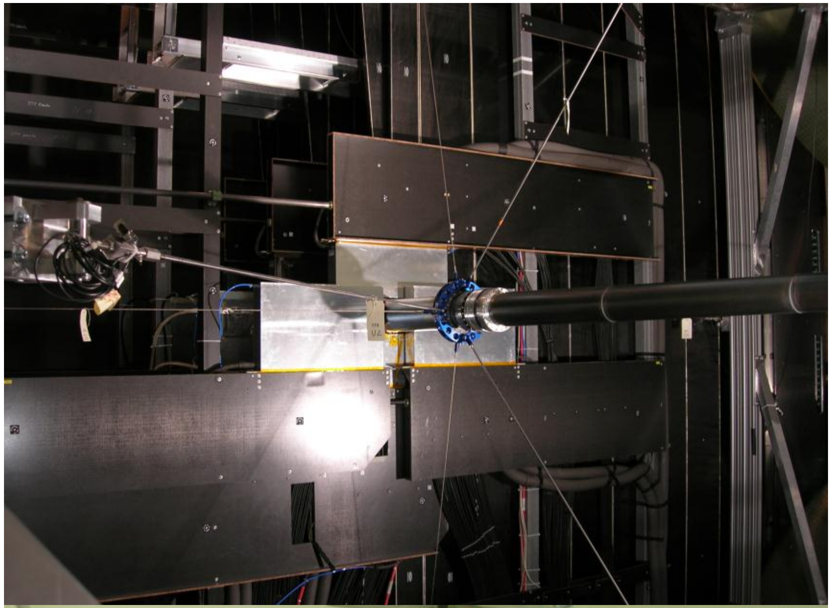
- Silicon micro-strip detectors.
- Four planes (0°, +5°, -5°, 0°).
- Pitch: 183 μm; Thickness: 500 μm.
- Long readout strips (up to 37 cm).
- 143360 readout channels.
- Total Silicon area is 8 m^2.
  - Covers full acceptance before magnet.
- Detectors operate at 0° C.



Inner Tracker



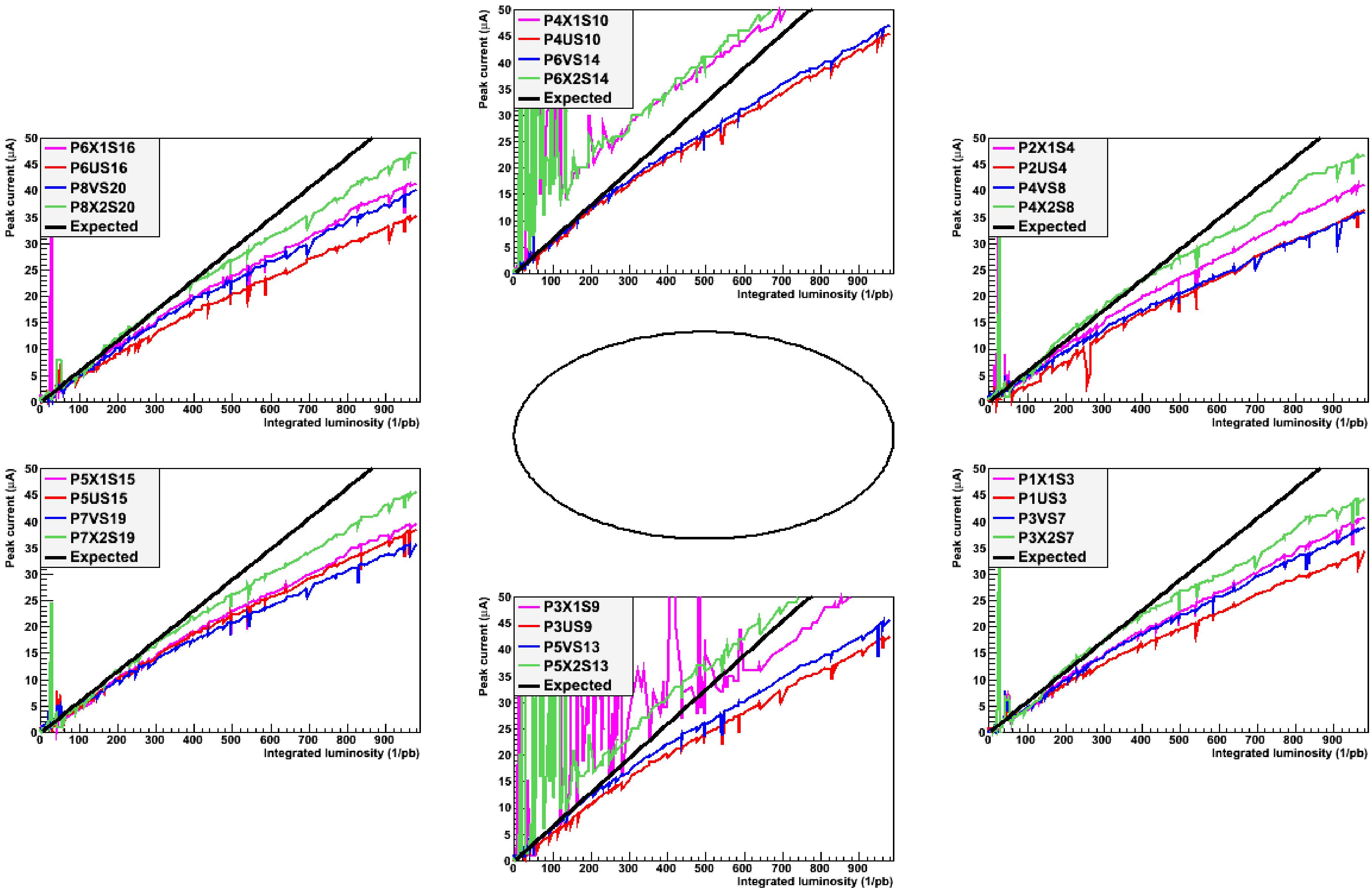
- Silicon micro-strip detectors.
- Three stations in z.
  - Four boxes in each station.
  - Four planes (0°, +5°, -5°, 0°)
- Pitch: 198 μm
- Thickness: 320 or 410μm
- 129024 readout channels.
- Total Silicon area is 4.2 m^2.
  - Covers region around beam with highest flux.
- Detectors operate at 0° C.



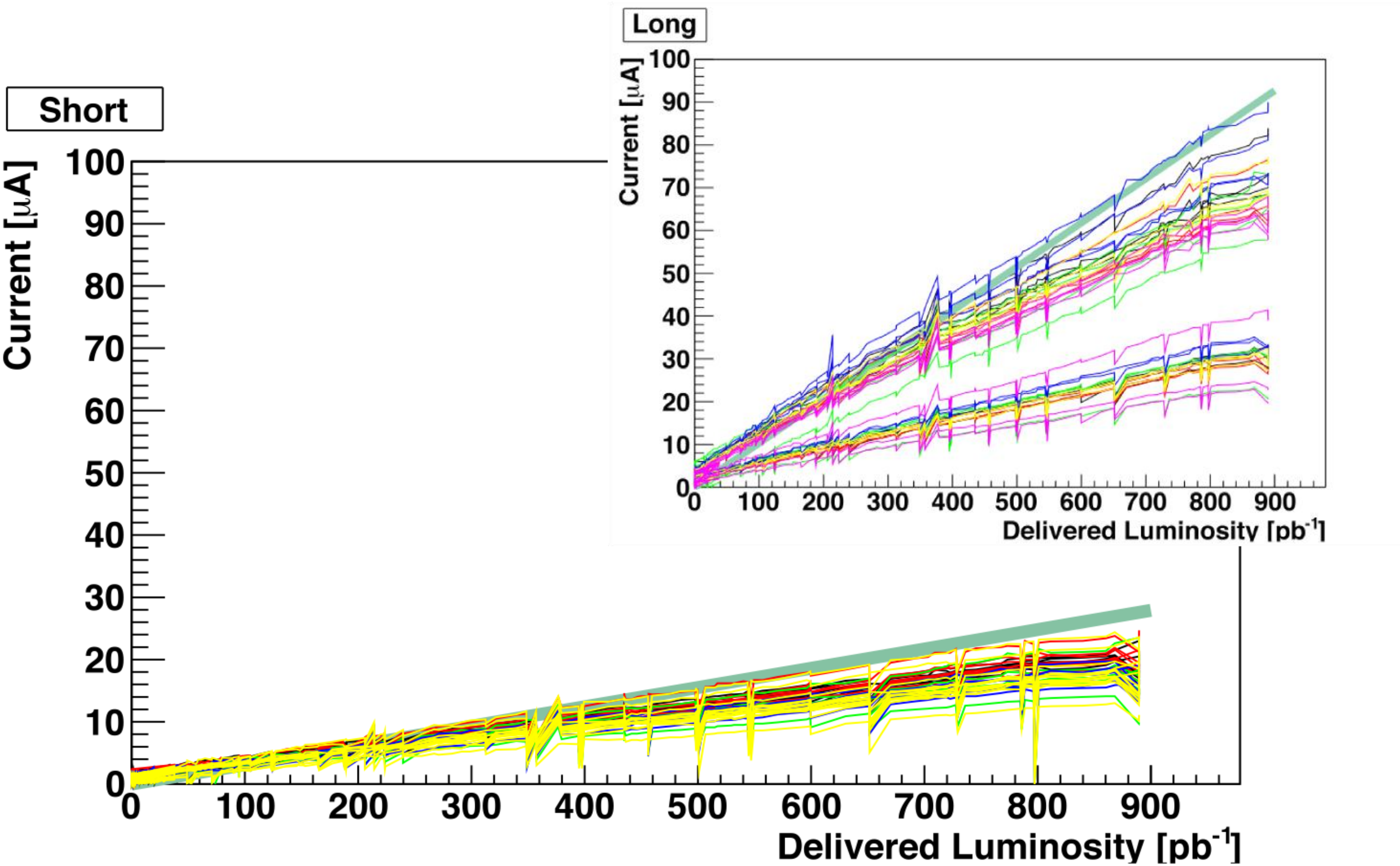
Radiation Part II: LHCb Silicon Tracker

- As for the VELO: Noise scans, CCE scans
- FLUKA has been used to evaluate leakage current evolution
- Current rises of 30-100 μA observed at operating temperatures per fb^{-1}

Leakage current evolution in TT



Current evolution in IT



IT HV-vs-Depletion Voltage

$_b$ from CCE-scan versus V_{dep} from capacitance measurement during