Radiation Hard Pixel Development for the LHCb VELO Upgrade

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on behalf of LHCb VELO Upgrade Group

10th International "Hiroshima" Symposium

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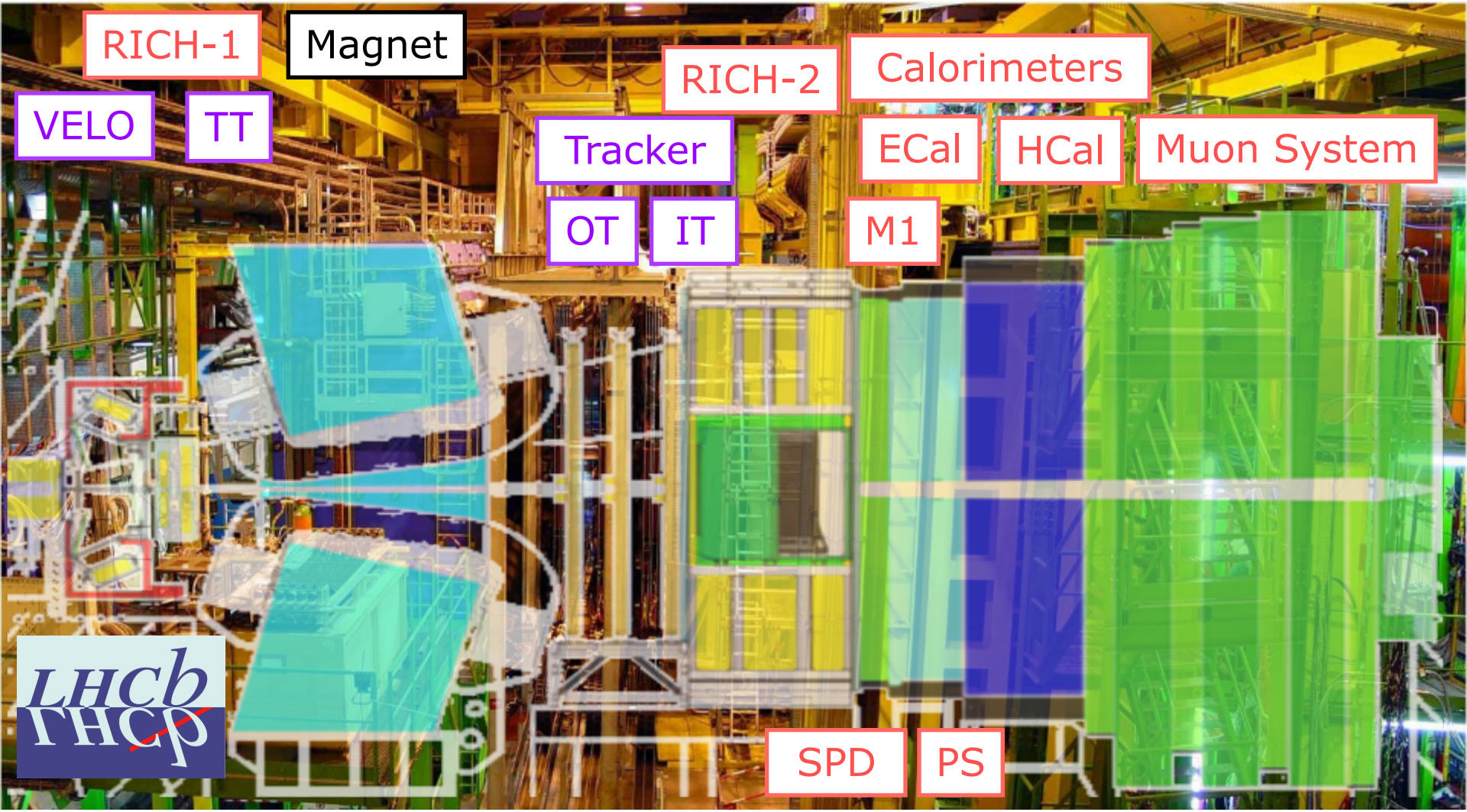
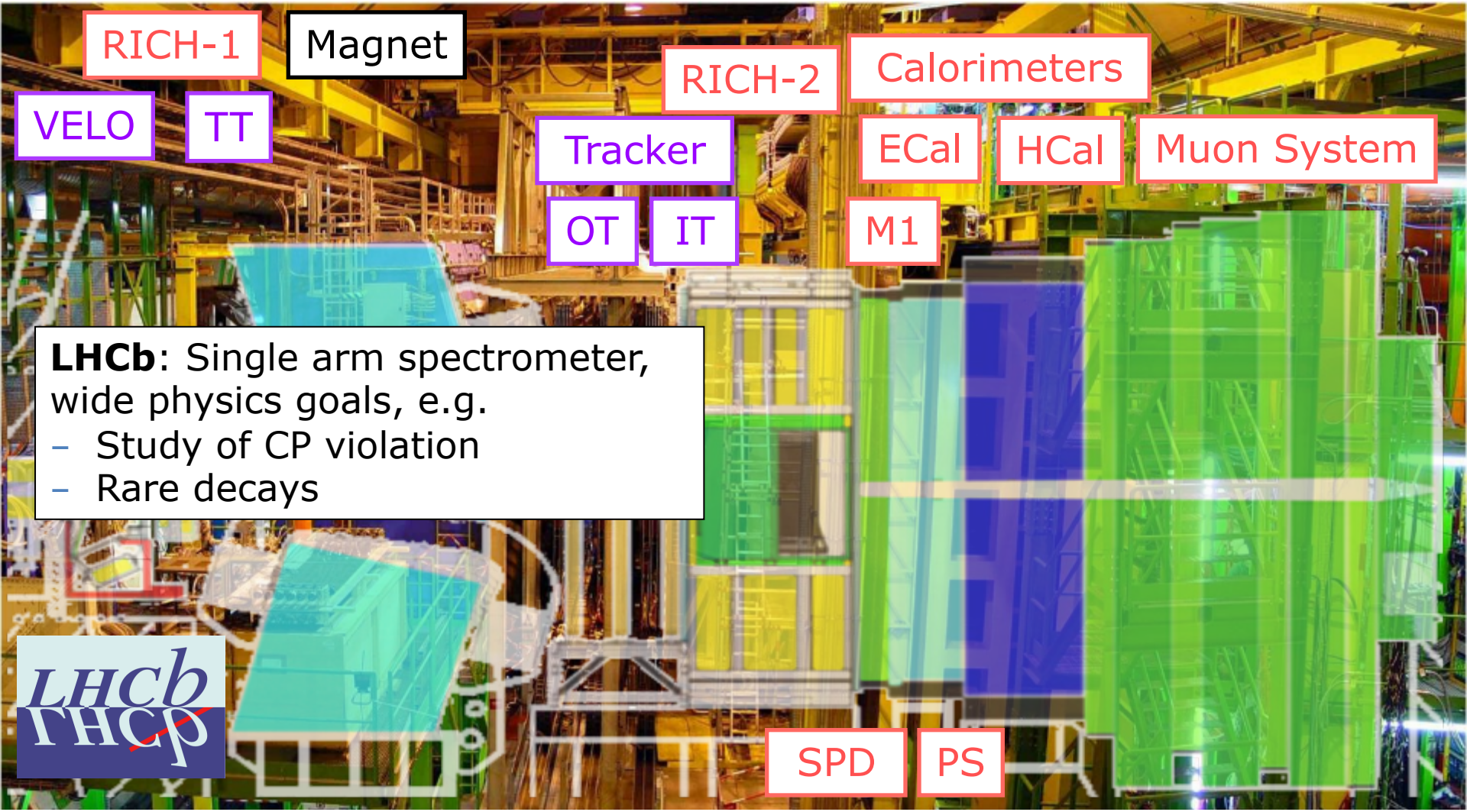
LHCb overview

LHCb overview



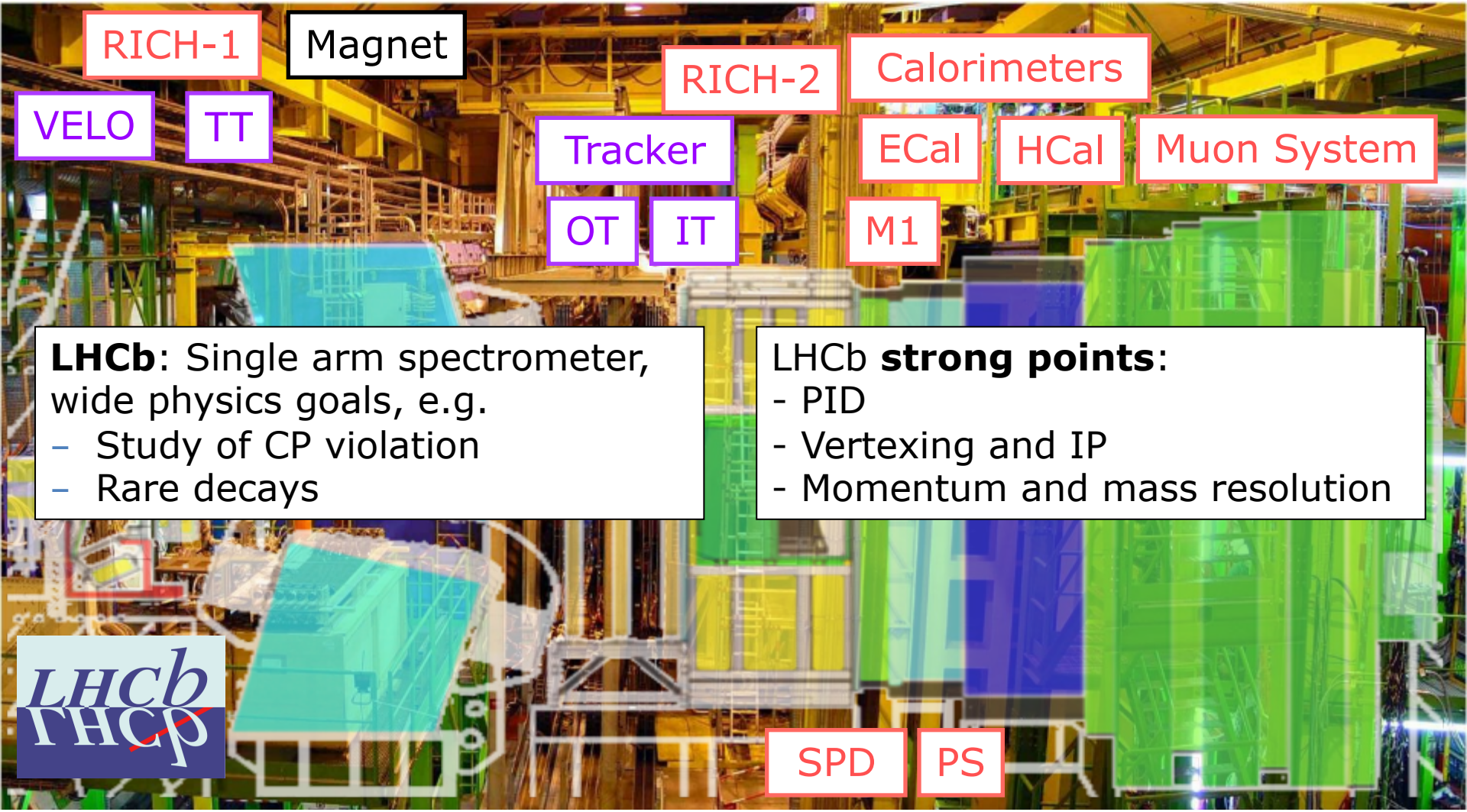
LHCb overview



LHCb: Single arm spectrometer, wide physics goals, e.g.

- Study of CP violation
- Rare decays

LHCb overview



LHCb: Single arm spectrometer, wide physics goals, e.g.

- Study of CP violation
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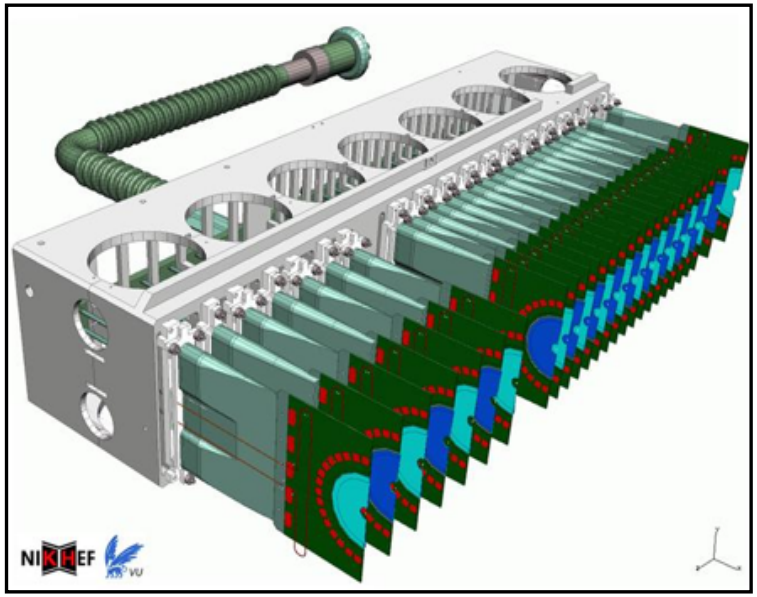
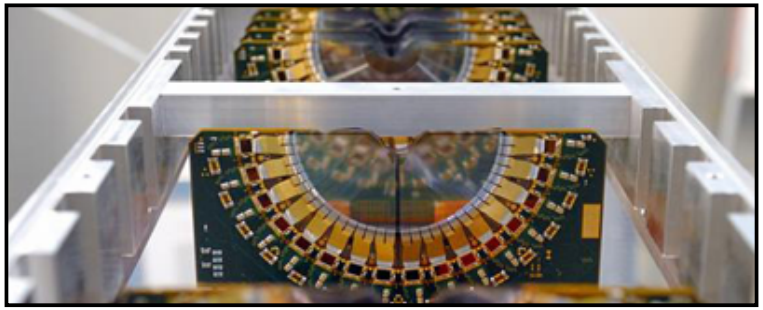
LHCb **strong points**:

- PID
- Vertexing and IP
- Momentum and mass resolution

LHCb Vertex Locator (VELO)

- **VE**rtex **LO**cator: silicon microstrip detector surrounding collision region
  - Two halves can be moved in with stable beams: safer operation!
  - Readout rate of 1MHz
  - 84 sensors in 42 modules: 2048 **silicon strips**. One sensor for radial and and one for azimuthal position
  - 8 mm away from beam line
  - Excellent performance, crucial for physics





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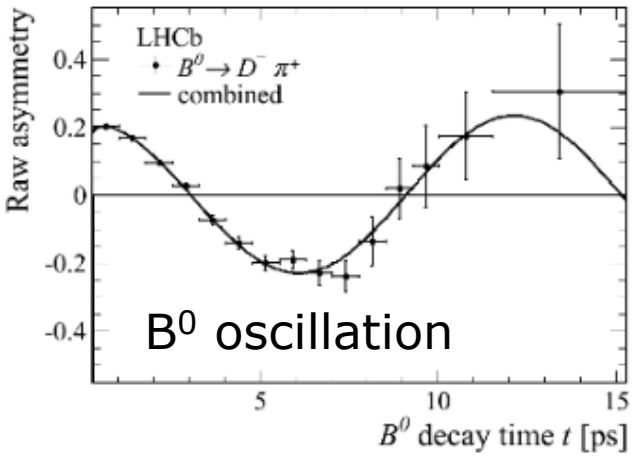
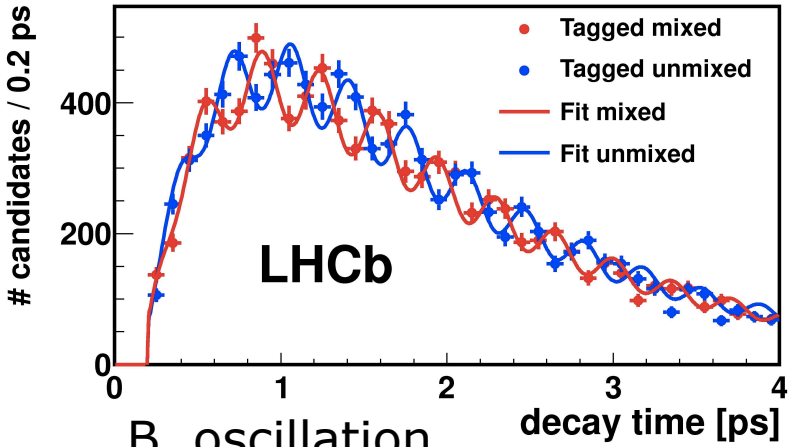


B^0 oscillation

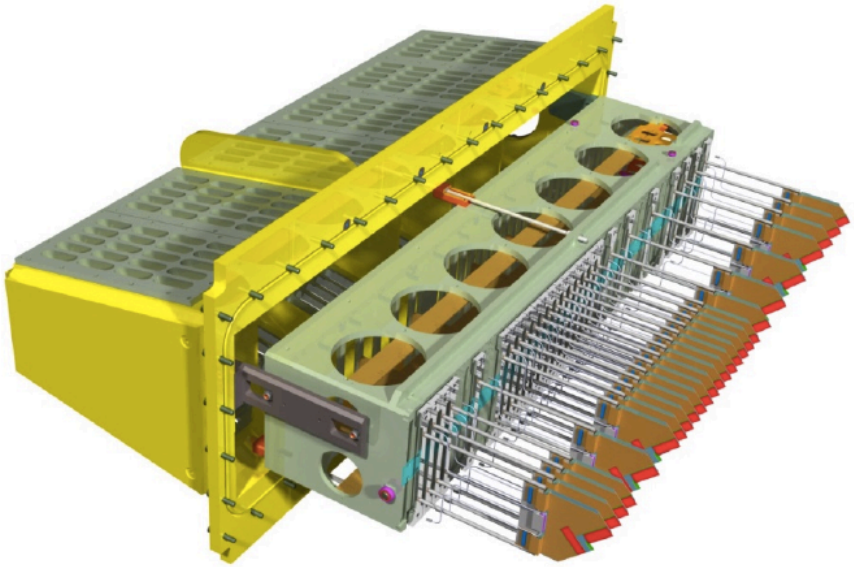


B_s oscillation

VELO Upgrade (I)

- LHCb Run III: provide order of magnitude increases in precision on physics key parameters
  - Will increase luminosity x5 (up to $2x10^{33}$ $cm^{-2}s^{-1}$) and move to software-based trigger
  - 40 MHz read-out of the detector

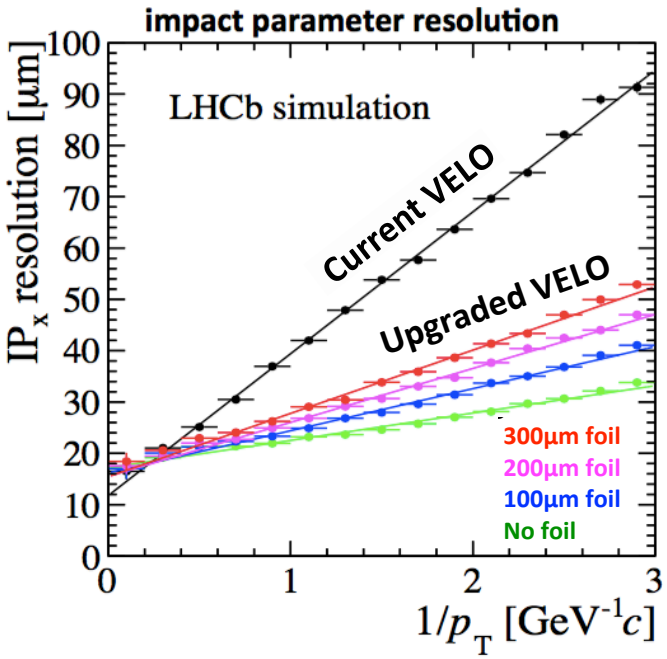
- Requires **upgrade of VELO**! We'll move from strips to **pixels (VeloPix)**
  - Allow less occupancy and irradiation
  - Easier pattern recognition!

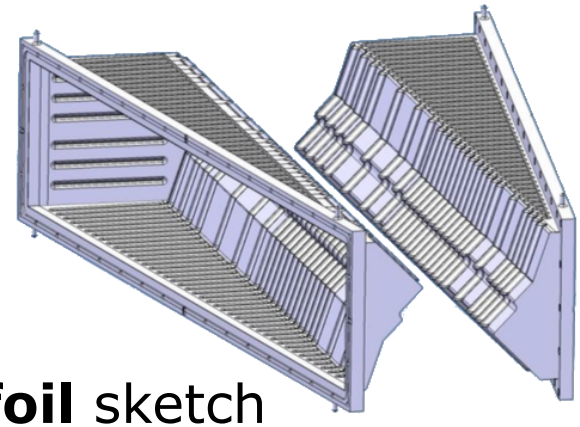


VELO upgrade (II)

- Other requirements
  - 52 modules, closer from beam (5.1mm)!
  - Higher track multiplicity

  … withstand the **larger irradiation** expected: 370 MRad or 8×10^{15} n_{eq} /cm^2
  - Hottest region with pixel hit rates of 900 Mhits/s: total data rate more than **3 Tbit/s**!
  - Separated from the beam vacuum by a 250 μm **RF foil**
  - Better physics performance (e.g., in terms of **IP resolution**)

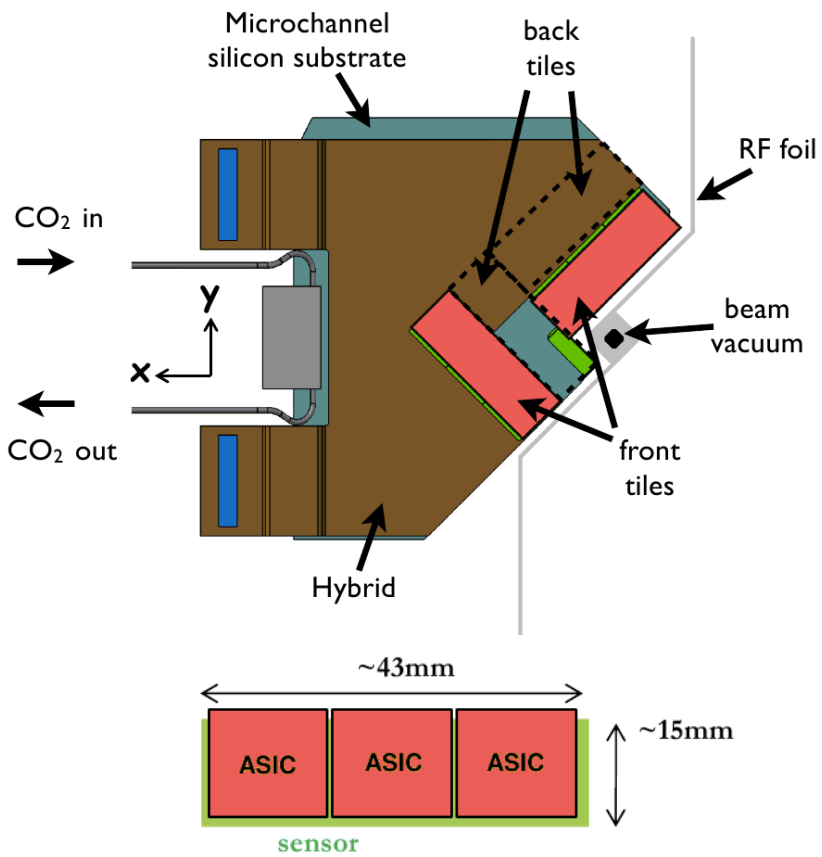




RF foil sketch

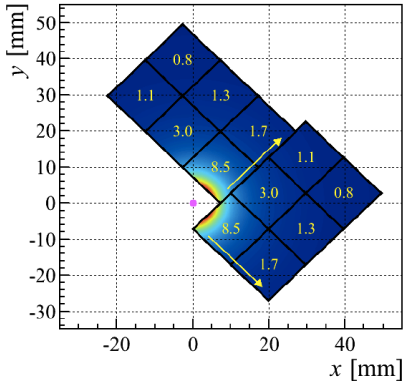
Modules

- The modules will be composed by **4 sensors** (2 on each side of substrate) and a **substrate for cooling**
  - Sensors powered and read-out via hybrid board and Kapton cables
  - Silicon substrate, with internal micro-channels for CO_2 cooling
  - Each sensor (43mm x 15mm) bonded to three VeloPix ASICs
  - Elongated pixels between ASICs give complete coverage

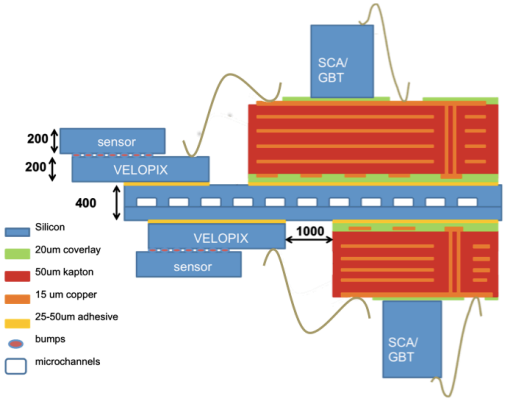


ASICs: VeloPix and TimePix3

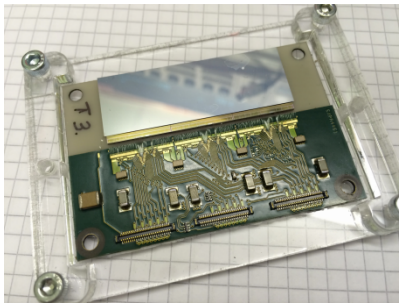
- **VeloPix:** pixel readout chip designed specifically for VELO upgrade
  - 256 x 256 pixel matrix
  - 130 nm technology
  - Data driven binary readout
  - **Design to be submitted for production later this year**



Mean number of particles crossing an ASIC per event

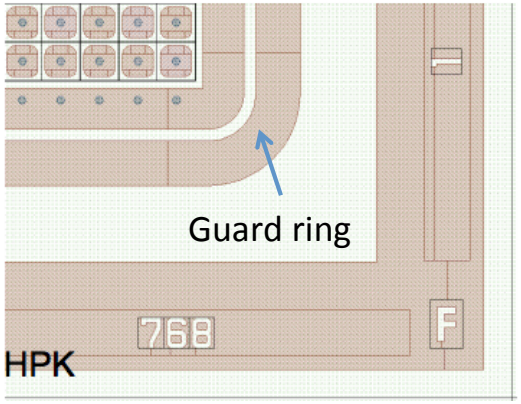


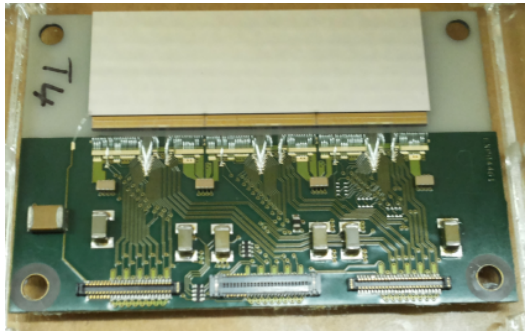
- **Timepix3:** precursor to VeloPix, similar, but...
  - Analogue readout
  - High precision timing information (σ_t = 1.5 ns)
  - Ideal chip for testing and characterizing sensor performance



Sensors

- 55 x 55μm pixel size, with baseline thickness 200μm
- Currently undertaking extensive sensor evaluation program using test beam and source data:
  - Two different vendors (**Hamamatsu (HPK), Micron**)
  - n-in-p (baseline) and n-in-n type (150μm thick)
  - Need to withstand non homogeneous irradiation and 1000 V bias: **constraints on guard ring design** (different sizes 150-600μm)
  - Different implant widths (35-39μm): try to maximize efficiency

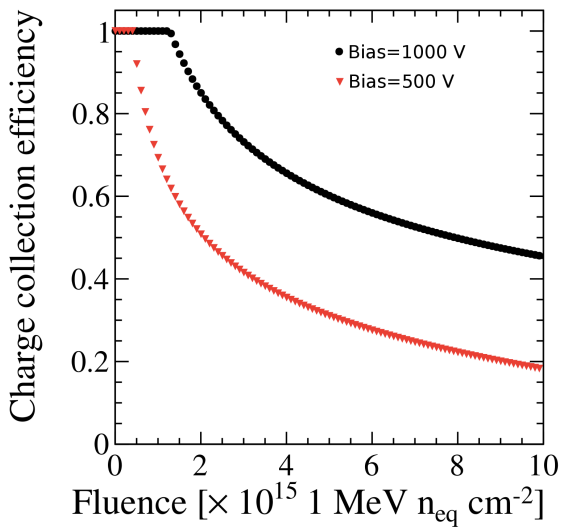


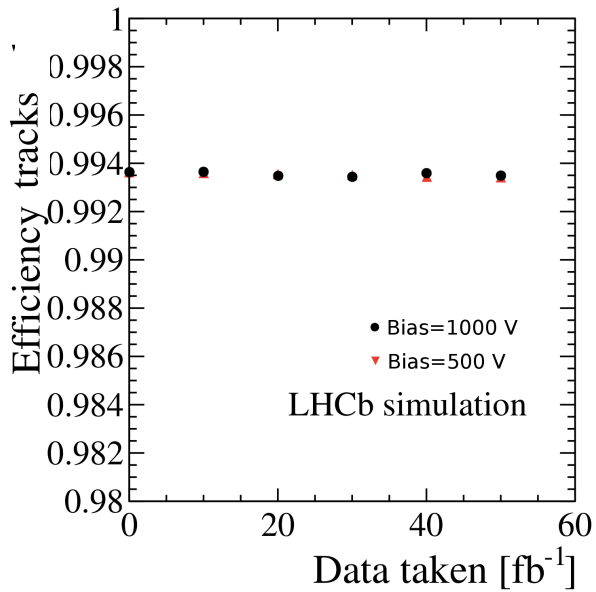


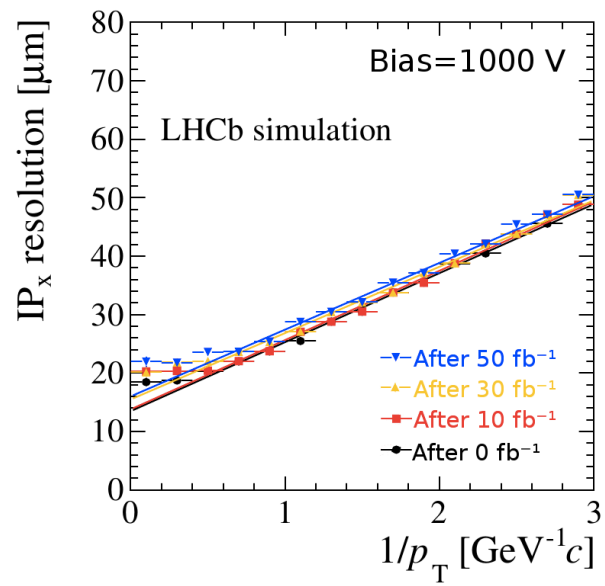
Sensor tile on a hybrid board

Expected performance after irradiation

- Charge collection efficiency decreases with radiation damage…



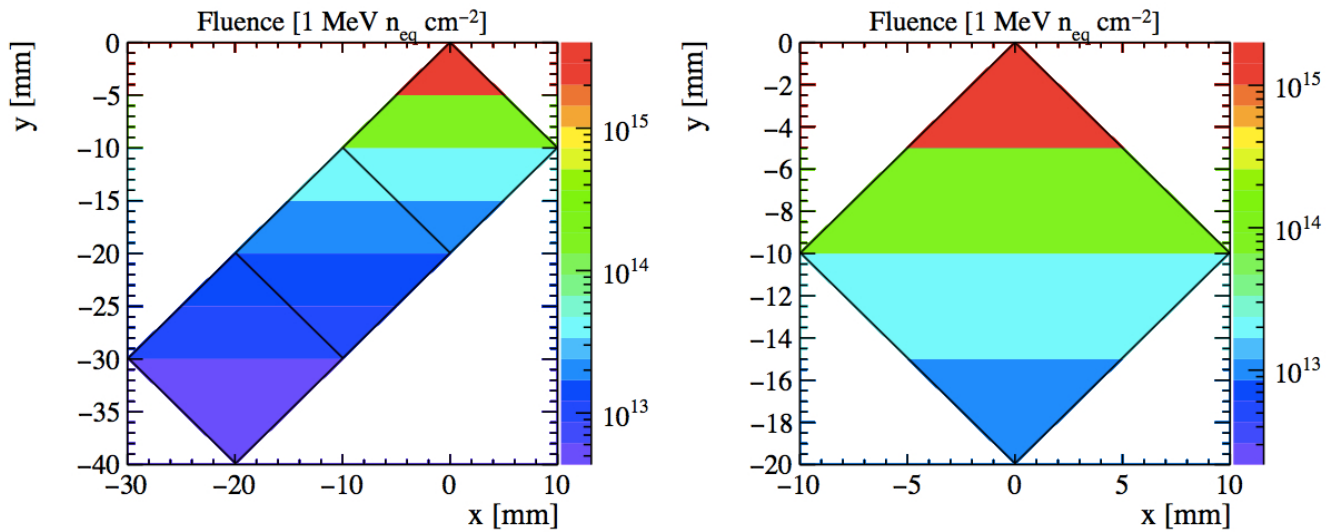




…but effect **not propagated** to track reconstruction efficiency or IP resolution thanks to hit redundancy in the tracking system!

Testing sensors

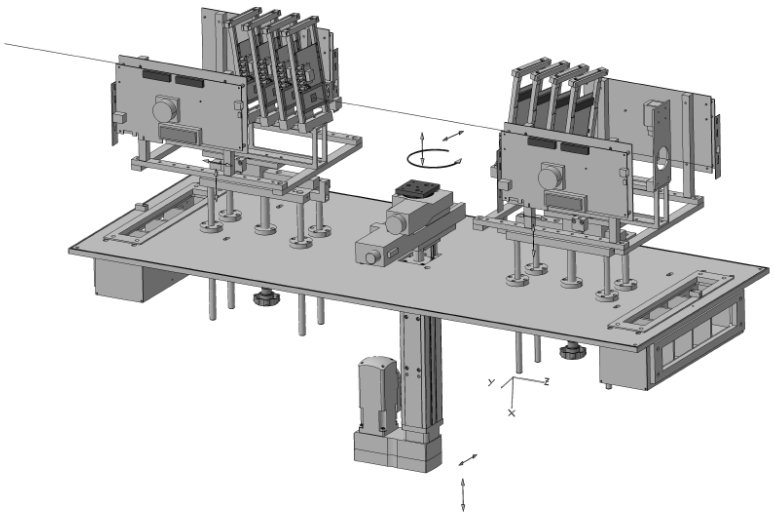
- Sensors **irradiated** in 5 different facilities, with both neutrons and protons, uniformly and non-uniformly
  - Example sensor irradiation fluence: non uniform dose, to best reflect final running conditions

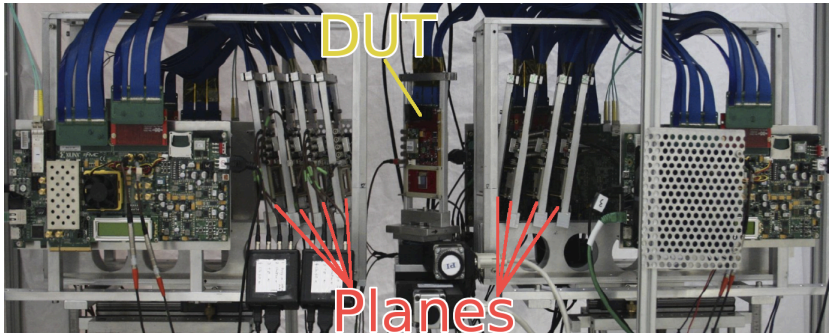


  - Performance post-irradiation has been measured in testbeams and lab

Telescope for testbeams

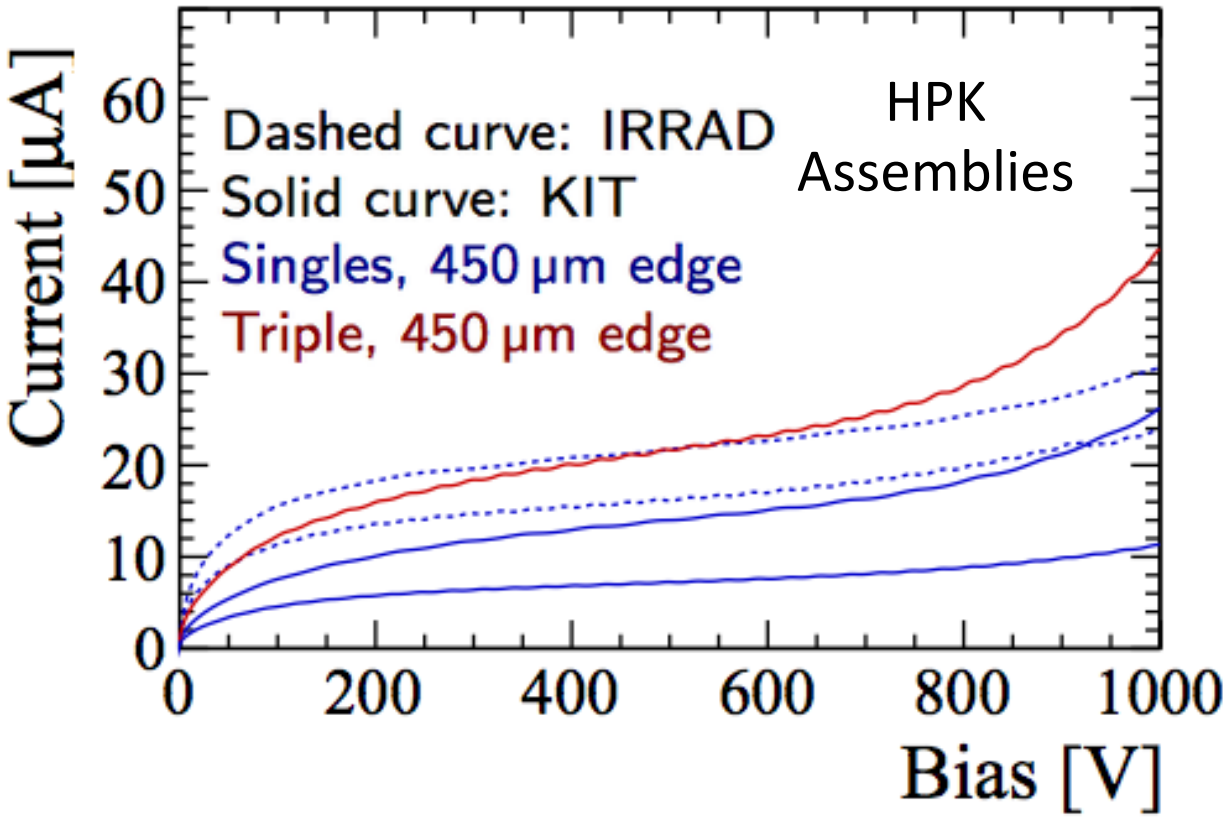
- **Telescope** built specifically for VELO upgrade studies
  - 8 Timepix3 detector planes
  - Provides precise measurement of particle locations and timing
  - Resolution at the DUT plane 2 μm (with 180 GeV/c π and p beam)





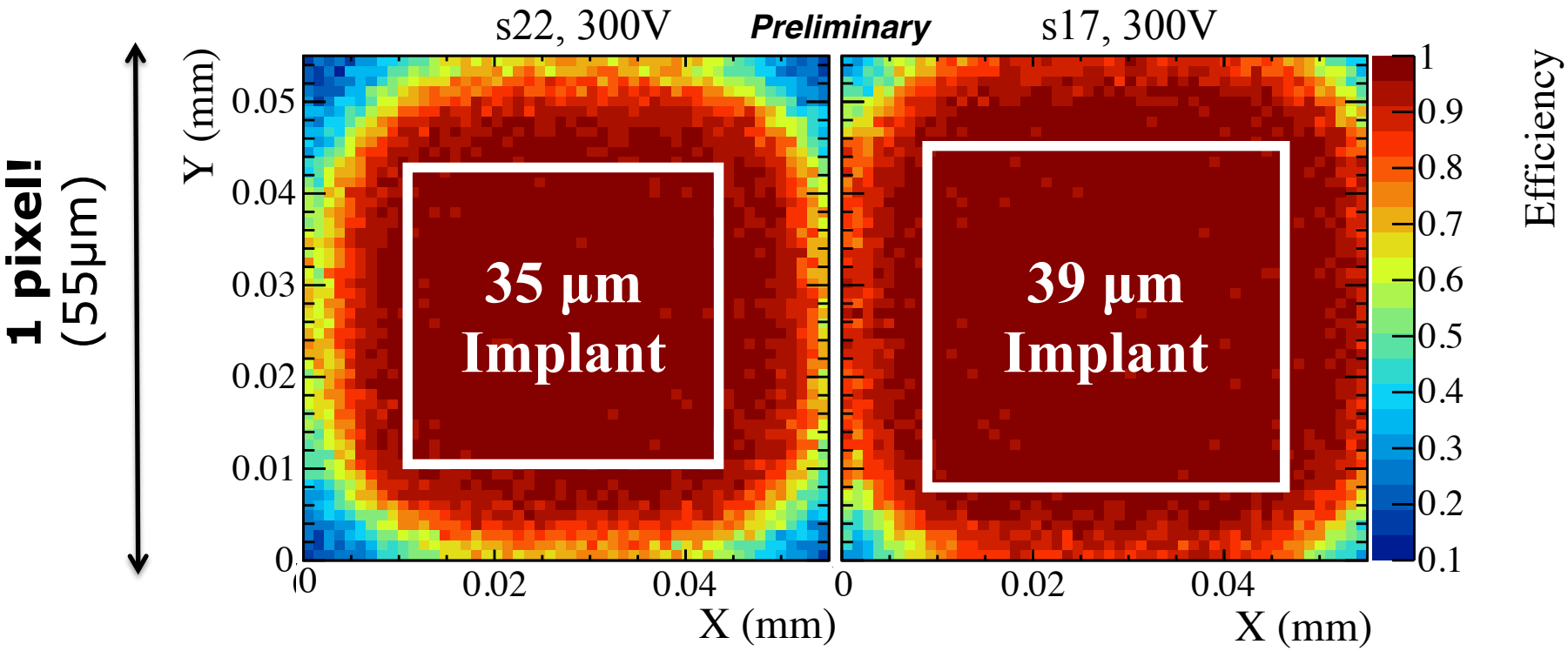
Sensors alive!

- Sensors tolerate required 1000V bias after non-uniform irradiation (<$4x10^{15}$ n_{eq} /cm^2)



Efficiency

- Intrapixel efficiency on neutron irradiated sensors:
  - Efficiency **decreased in the corners** (expected)
  - Larger implant significantly increases efficiency in pixel corners



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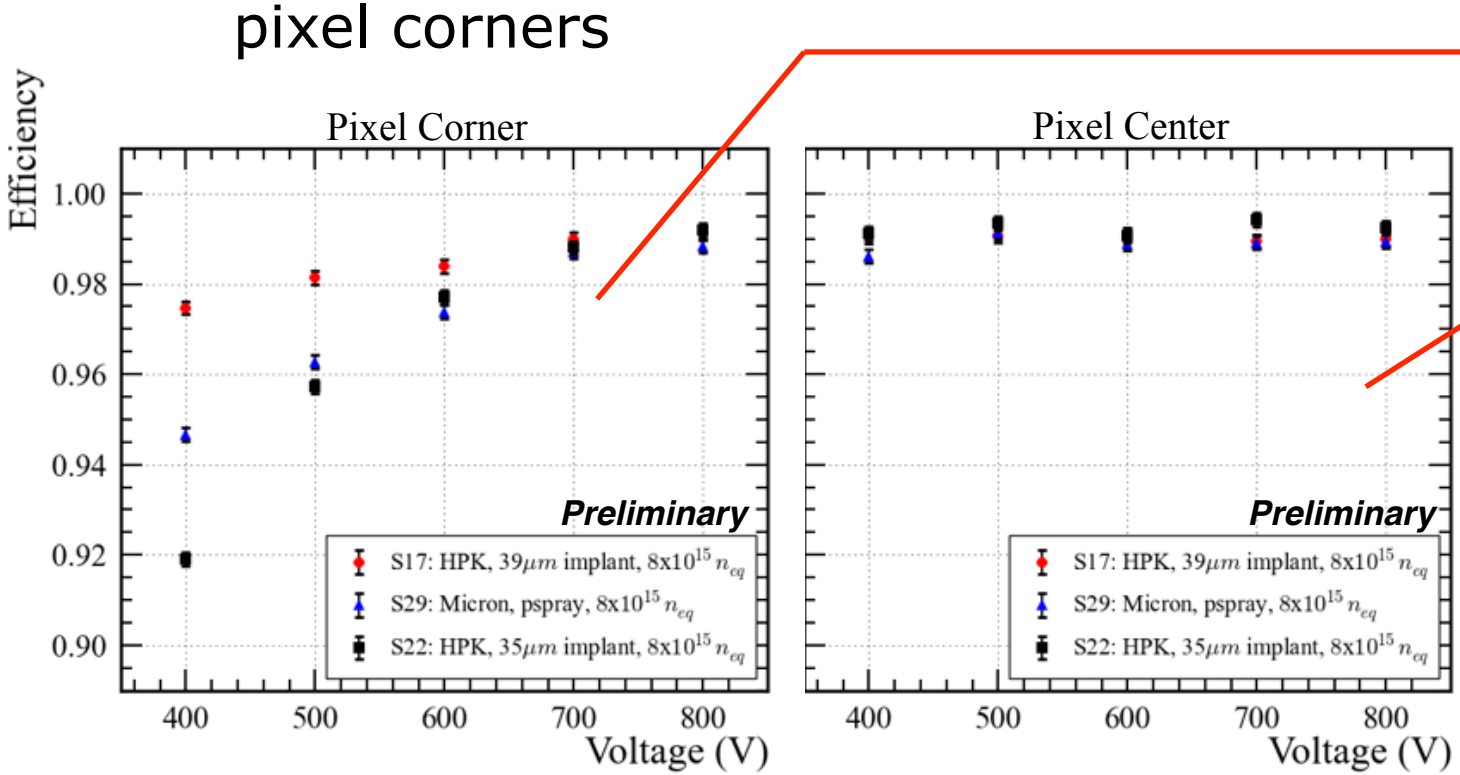
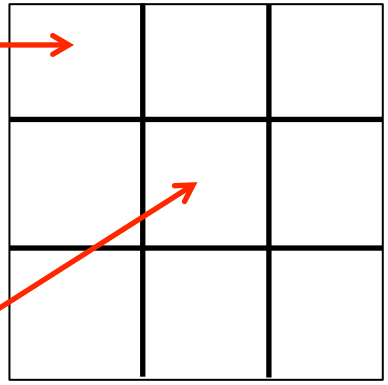
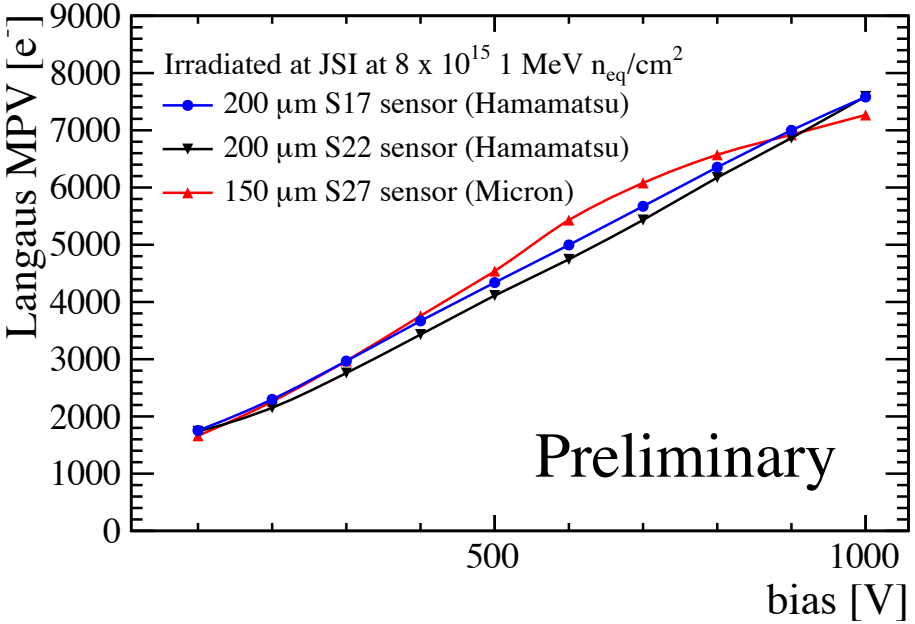
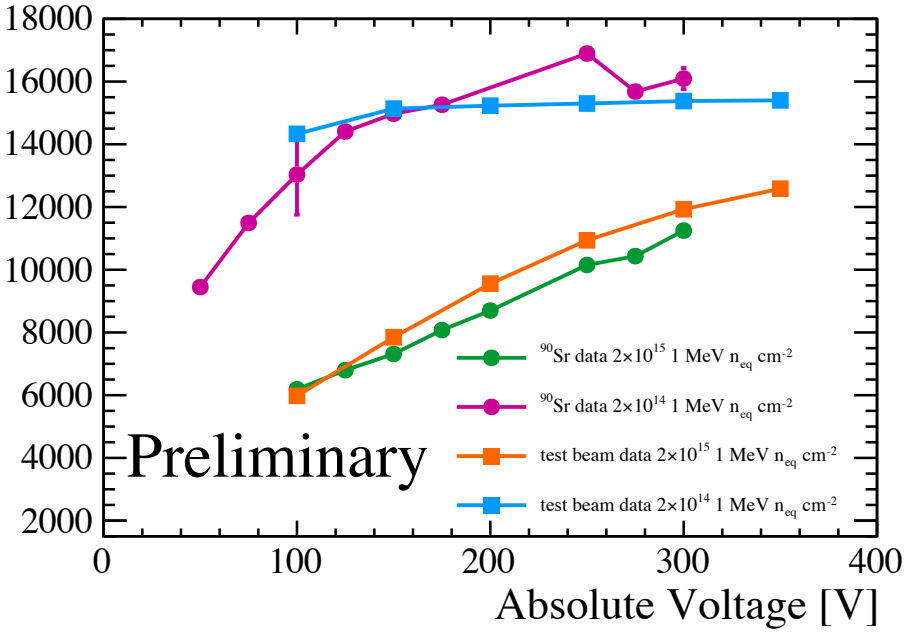




Charge collection

- Charge collection efficiency
  - Same charge collected for different thickness
  - Results both from source and test beam data!



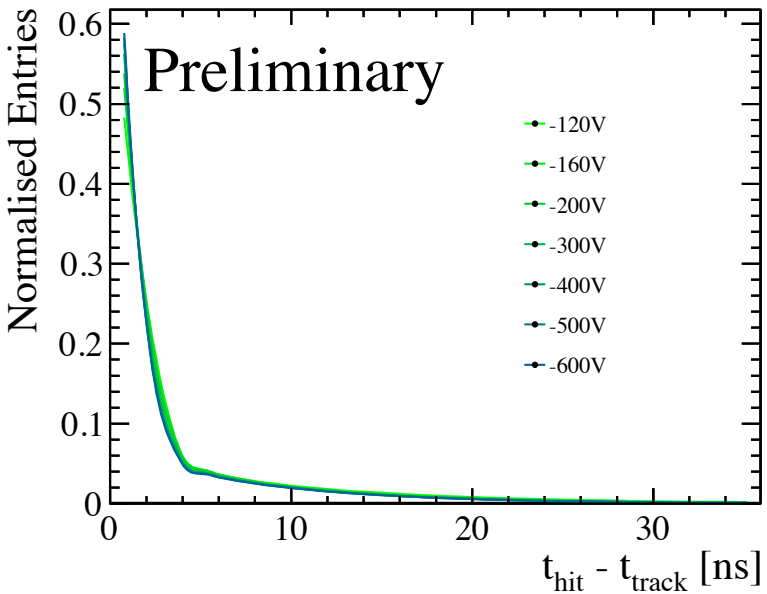


Different fluence regions in non-uniformly irradiated HPK single

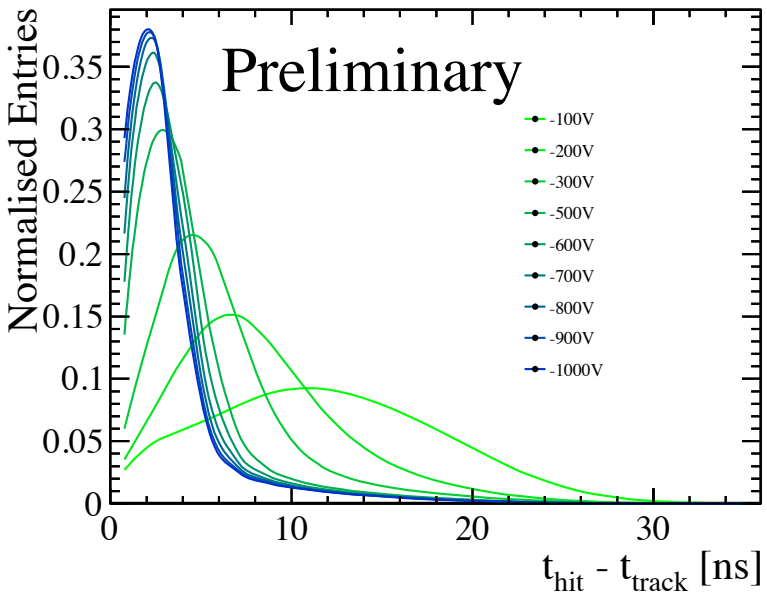
Time response (I)

- Timepix3 gives hit time information and telescope gives accurate track time!
  - Tail in time residual distribution due to discriminated **time-walk effects** - larger for irradiated sensors

HPK sensor before irrad



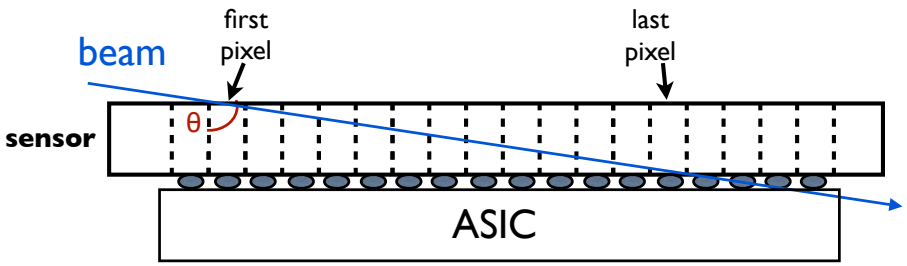
HPK sensor after irrad



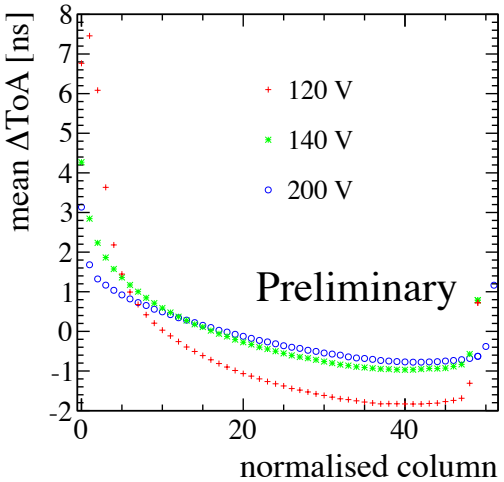
  - Resolution < 1ns!

Time response (II)

- Look into **Time of Arrival** (ToA) for different pixels in a cluster at **grazing angle** (86°)



  - For every pixel, compare ToA with average ToA from cluster
  - Difference between pixels affected by bias
  - Effect more important for irradiated sensors



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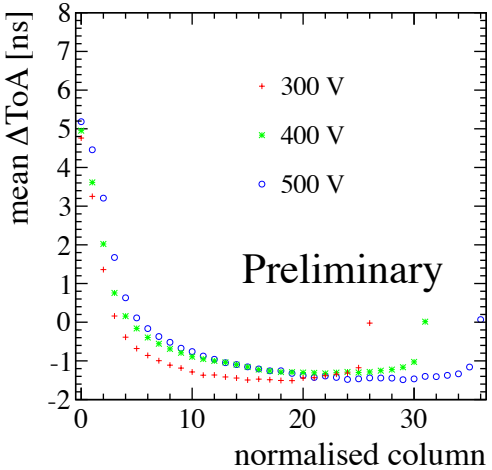
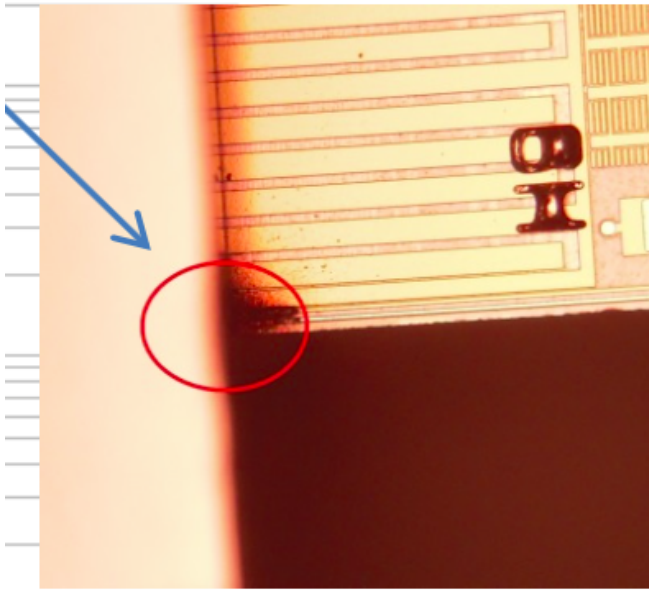


HPK sensor after irrad

Parylene coating

- Parylene coating: **avoid sparking** on n-in-p sensors
  - Parylene is a thin transparent coating
  - Provides protection and acts as an electrical insulator
  - Have parylene coated some of our sensors under scrutiny….



  - Some coated HPK irradiated triples breakdown before 1000 V (parylene coating damaged)
  - Degradation with respect to pre-irradiation! Temperature? Currently under study

Conclusions

- Luminosity increased by a factor of 5: keep or **improve** the performance of the current VELO (thinner, closer to beam line)
- New silicon pixels ASIC under design: **VELOPIX**
- Now in sensors R&D phase, with several prototypes and **irradiation** campaign
- Extensive testing program using lab, source, and testbeam data, VELO upgrade **well on its way**, start thinking about construction!