# Test beam facility at CYRCé for high particle rate studies with a CMS Upgrade module: design and simulation

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On behalf of the CMS Collaboration

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# High Luminosity upgrade for the LHC: HL-LHC

- Increase the luminosity: from 300 $fb^{-1}$ (2011-2023) to 3000 $fb^{-1}$ (2026-2037)

- The goal for HL-LHC: Peak Luminosity: 5.0 (7.5) x $10^{34}$ $cm^{-2}$ $s^{1}$; Integrated Luminosity over 10 years: 3000 (4000) $fb^{-1}$; PU: 150-200

- Silicon sensors for the CMS Tracker:
  - Need for radiation-hard silicon sensors (fluence: ~2.5 x 1016 $n_{eq}/cm^2$ in the center of CMS; Total Ionization Dose: 10 Mgy)
  - Need for higher granularity to reduce occupancy
  - Control of sensors and readout electronics through beam tests is necessary to examine the behavior of silicon sensors in real conditions

# The CYRCé cyclotron

- CYRCé (CYclotron pour la ReCherche et l'Enseignement), a low energy cyclotron for radionuclide production for medical applicationsis located at IPHC (Strasbourg)

- Cyclotron Characteristics:
  - 25 MeV protons (large energy deposition)
  - High intensities (up to 100 nA → $10^{12}$ protons/second)
  - 85 MHz time structure (about twice the LHC frequency)
  - Bρ = 0.72 Tm
  - Gaussian profile

- The cost, construction schedule, and manpower have been estimated for a new beam line dedicated to the tests of the CMS Tracker modules and funding has already been accepted

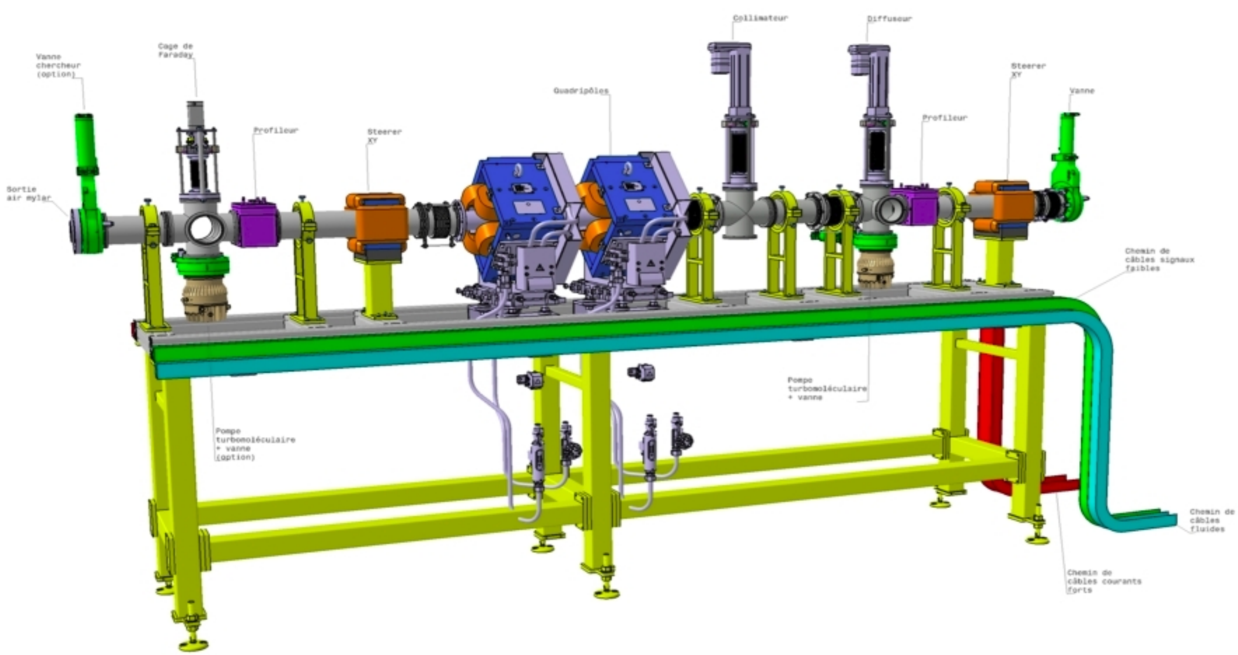
- Simulations have been performed to study the physics behind it; they proved that it can be used for tracking

- Construction of the beam line has already started

- The project could also be of interest for other experiments. Contacts: jeremy.andrea@iphc.cnrs.fr; ulrich.goerlach@iphc.cnrs.fr

# New beam line under construction

- Beam size at the entrance of the beam line (from dipole switching magnet) 2 cm x 1 cm
- Quadrupoles reduce the size to a few millimetres (2 mm)
- Diffuser: can enlarge the beam size up to 25 mm for irradiation purposes
- Steering magnet: controls the position of the beam in the beam pipe
- Beam position monitoring with profiler
- Beam line available from summer 2019 (while LHC in LS2), very accessible



# New pixel telescopes

- A telescope is an array of highly segmented detectors that can reconstruct with high accuracy particle tracks.

- A new detector under development (usually named as Detector Under Test, DUT) can be tested for channel efficiency, cluster size, cross talk between adjacent channels etc.

- Comparison: Existing CMS technology uses a Monolithic Active Pixel Sensor chip with an integration time of 115.2 μs or 8.68 kHz readout frequency.

- Integration time in Phase II tracker modules (and other HL-LHC sensors) is 25 ns → 40 MHz (x4600 the today's CMS telescopes readout frequency).

- We cannot test Phase-II modules at nominal rates with the old CMS telescopes. That's why new telescopes are being developed (e.g. CHROMIE – CMS High Rate telescOpe MachInE, see N. Deelen's talk).

# Simulation goals

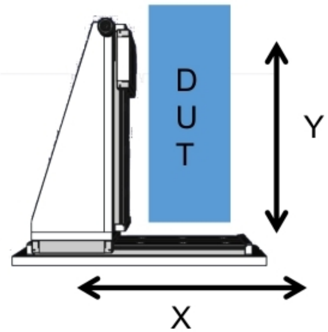
- Main difficulty: 25 MeV protons
  - are stopped by about 3 mm of silicon
  - deposit large amounts of energy
  - have a large multiple scattering

- Goals:
  - Investigate resolution for DUT and telescope
  - Study energy deposition per strip/pixel, cluster size for strip sensors and pixel modules, multiple scattering of protons

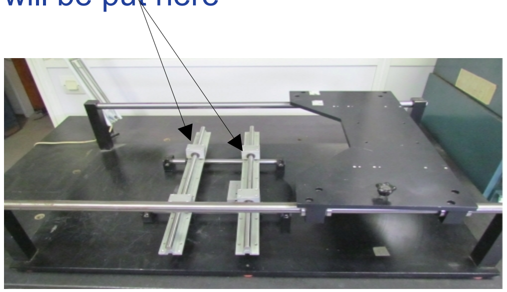
# The future mini-telescope at IPHC

- A mini-telescope adapted to a 25 MeV proton beam is being designed and constructed for the new beam line at IPHC, as simulation studies showed that the project is feasible and can be used for tracking

- Design:
  - Two CMS pixel Phase-I module planes,
  - Modules sandwiching the DUT on shifting (on trail) planes to accommodate different sizes of DUT
  - Pixel modules positioned at ~+/- 1 cm from the DUT
  - DUT on a x-y table, with 15 cm x 15 cm shifts
  - Box for cooling under investigation
  - LV and HV power supplies, FC7 cards available



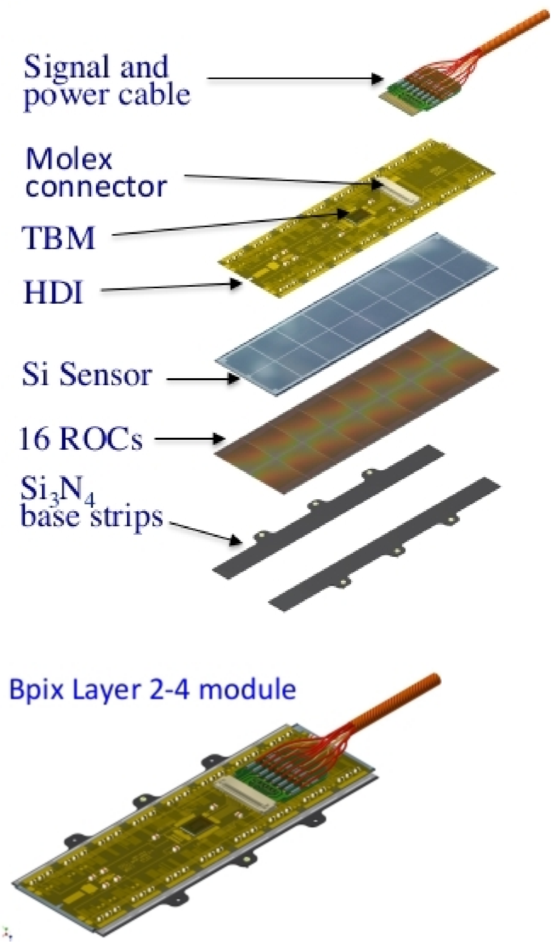

2 Phase-I pixel modules will be put here



# Simulation characteristics (1)

- 2S module DUT: 2 Si sensors (102700 μm X 94108 μm X 320 μm), with spacing between the sensors: 2 mm
- Strip pitch: 90 μm
- Active depth: 240 μm
- 1 BPIX module in front of the DUT and 1 BPIX module behind the DUT (1 cm distance between the edge surfaces of each sensor and the nearest BPIX module)
- BPIX module: 66.6 mm X 25 mm X 460 μm, 2 rows X 8 ROCs
- Pixel size: 150 μm X 100 μm
- 1 PVT ($C_9H_{10}$) scintillator (66.6 mm X 25 mm X 2 mm) in front of the front BPIX module
- 25 MeV proton beam in z-direction
- Origin: Center of World
- Scintillator: z = -10 cm
- 100000 events

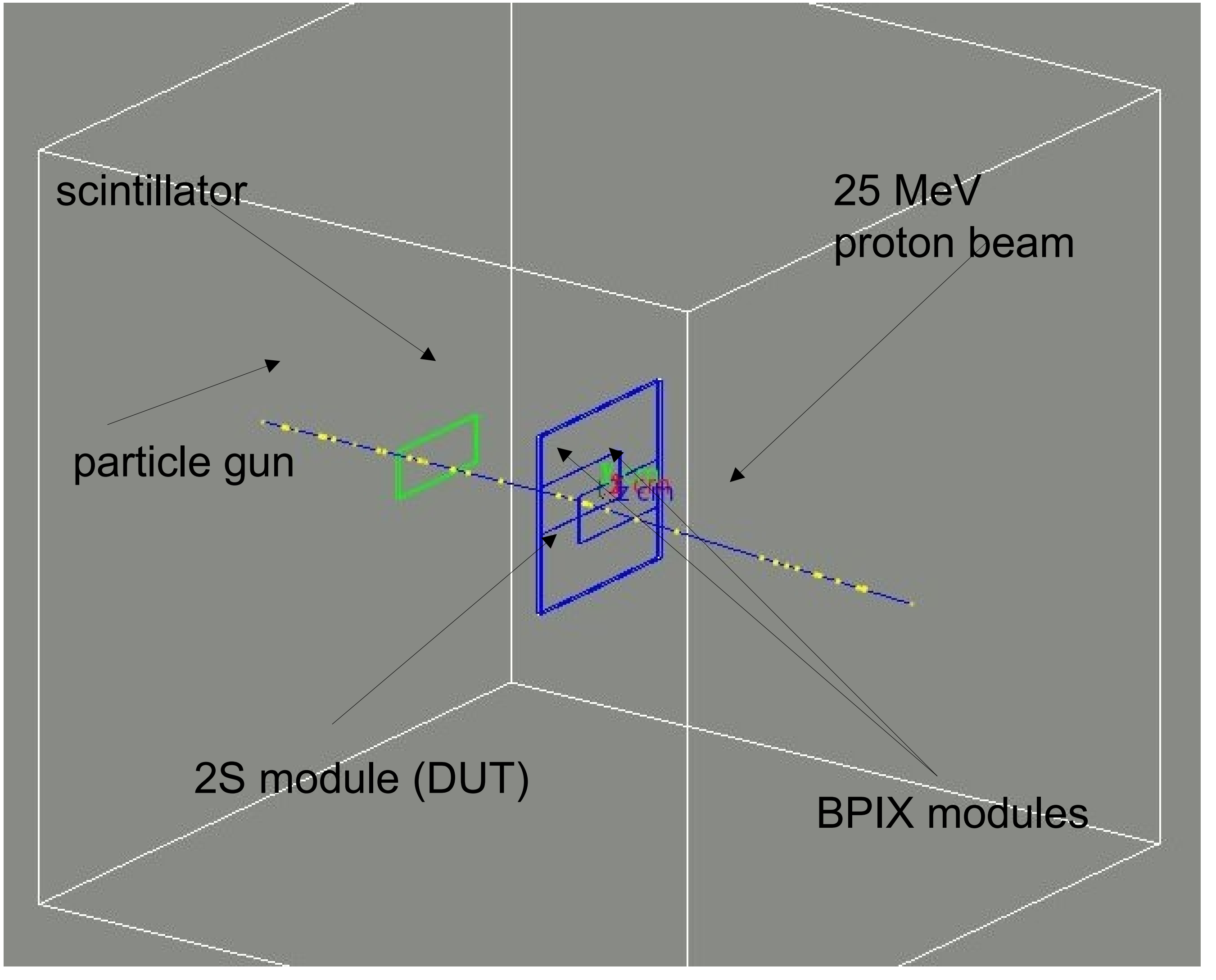
# Simulation characteristics (2)



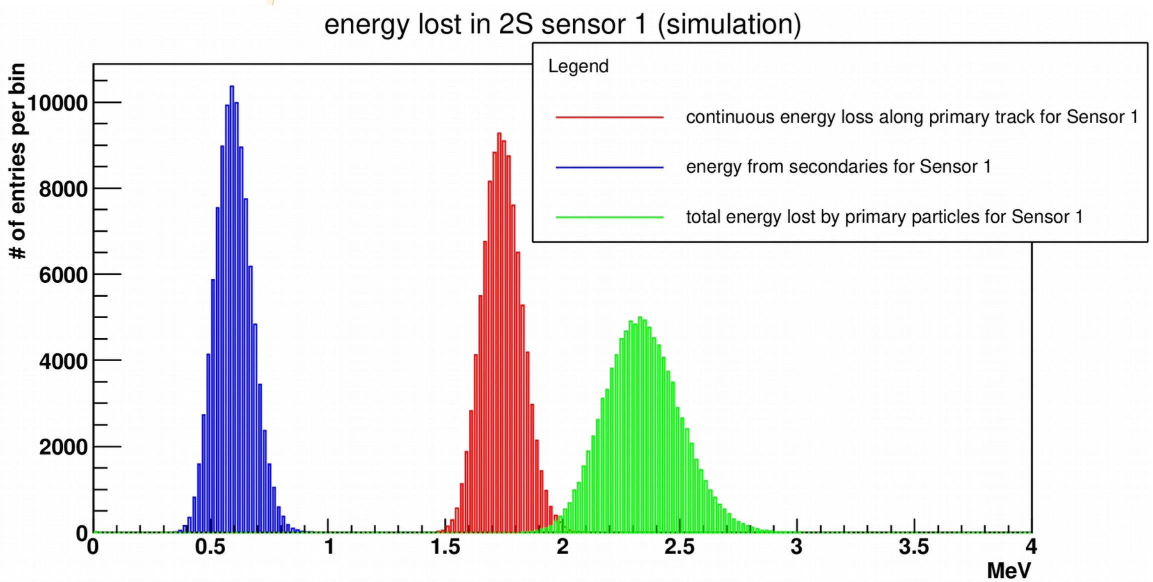

- Physics processes:
  - Ionizations
  - Bremsstrahlung
  - Pair production
  - Annihilation
  - Photoelectric effect
  - γ production
  - Compton scattering
  - Rayleigh scattering
  - Klein-Nishina model for the differential cross section

- General Particle Source (GPS) used instead of a particle gun:
  - sigma = 100 keV
  - position = (-1, 0, -20) cm
  - type: beam
  - shape: ellipsoid
  - halfx = halfy = 1 mm, halfz = 0.5 cm

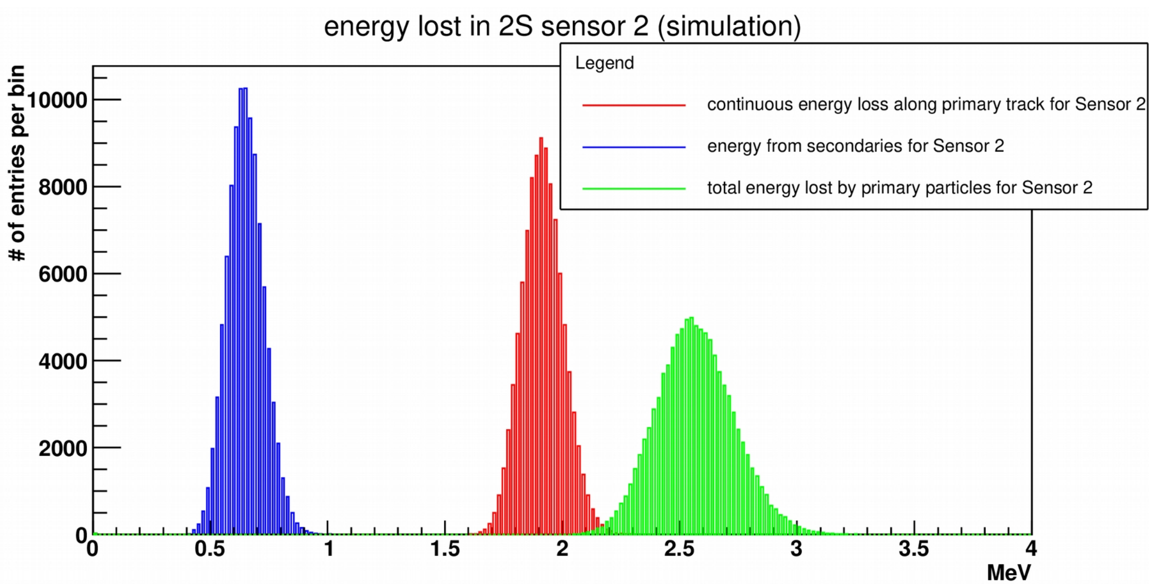
# Visualization of the simulated geometry



# Energy distributions

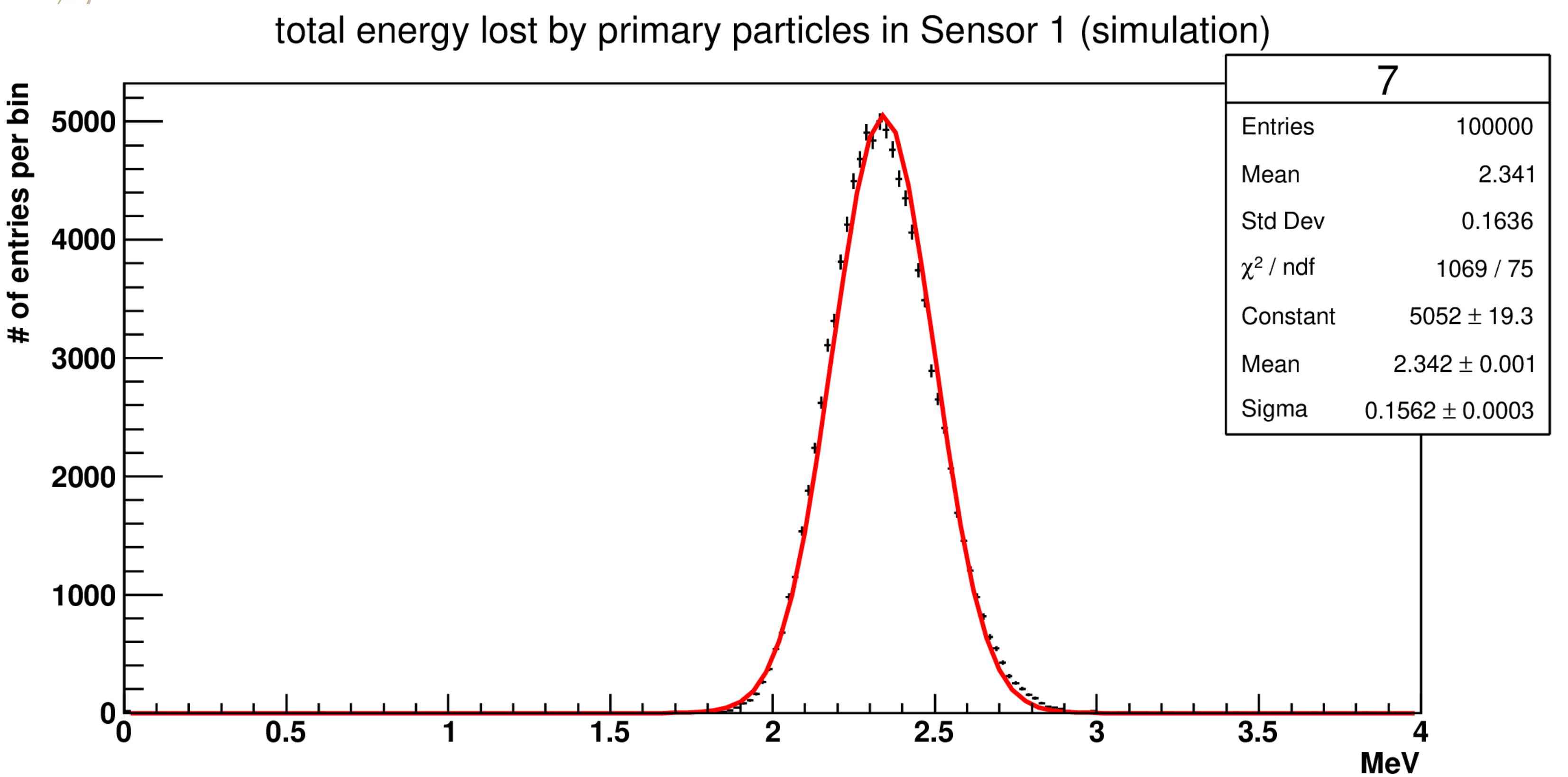



Total energy lost in Sensor 1: mean value = 2.341 MeV, standard deviation = 0.1636 MeV

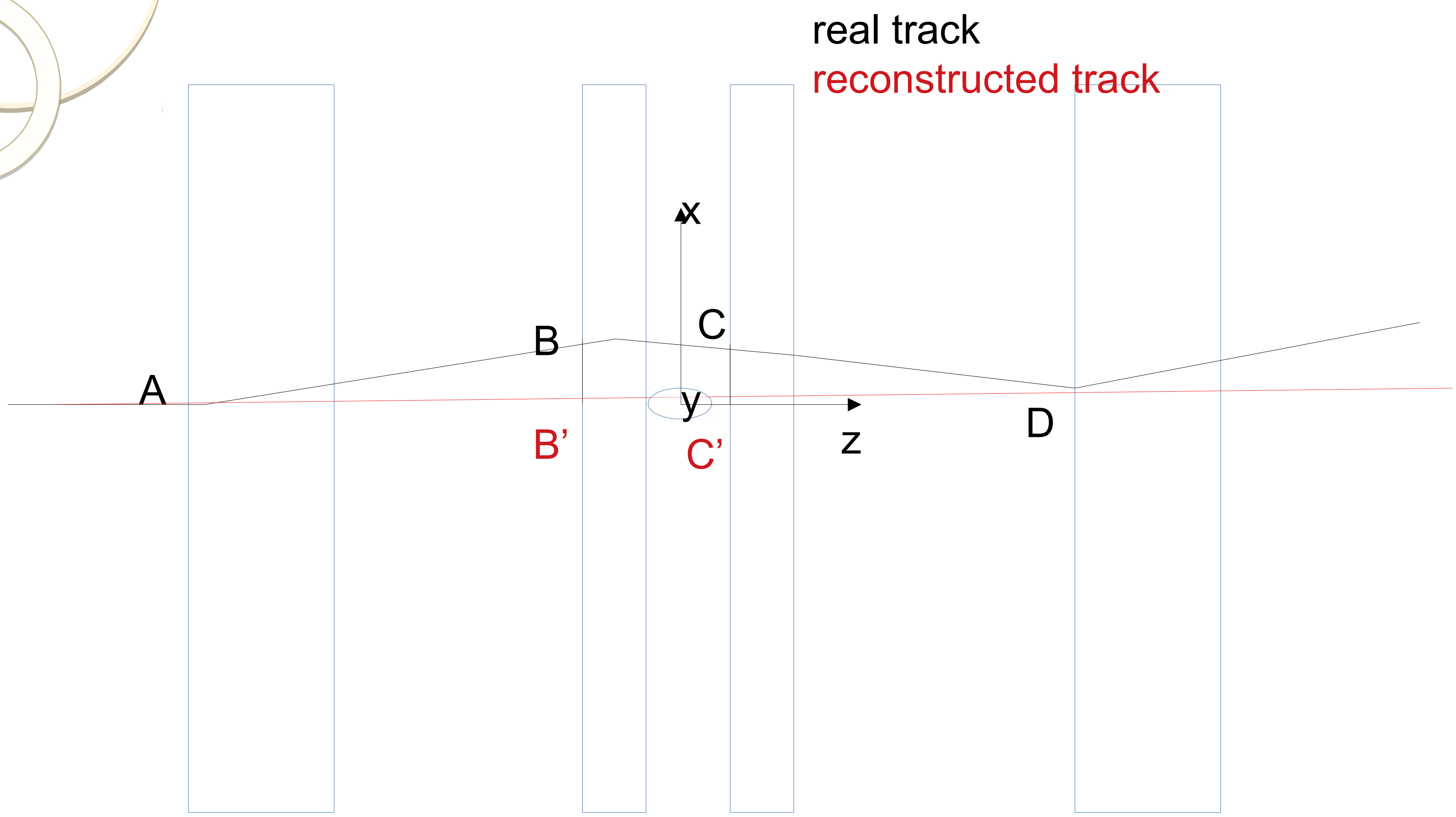



Total energy lost in Sensor 2: mean value = 2.567 MeV, standard deviation = 0.1687 MeV

# Total energy lost by protons in the first 2S sensor



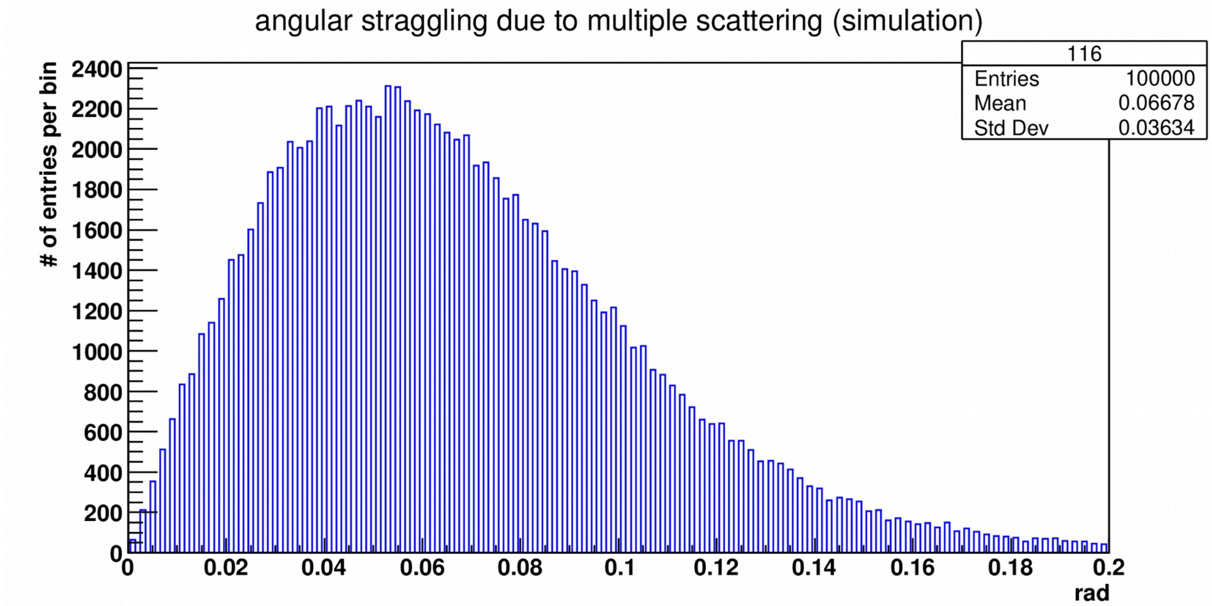
# Calculation of residuals

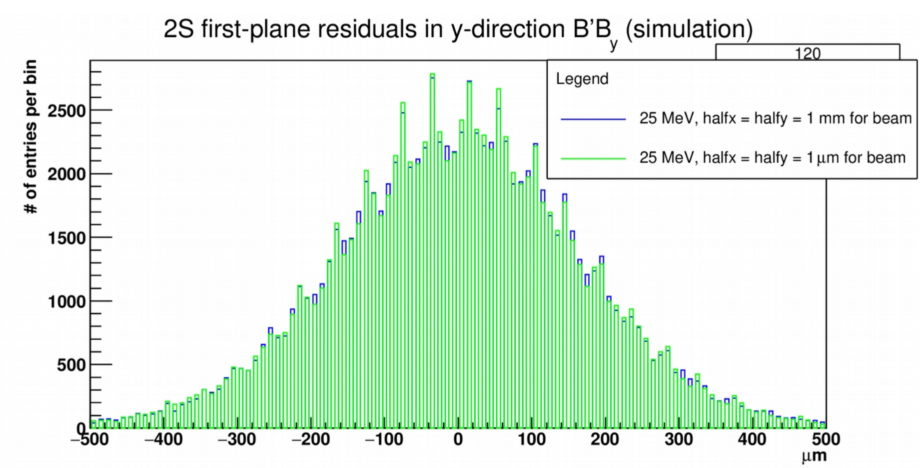


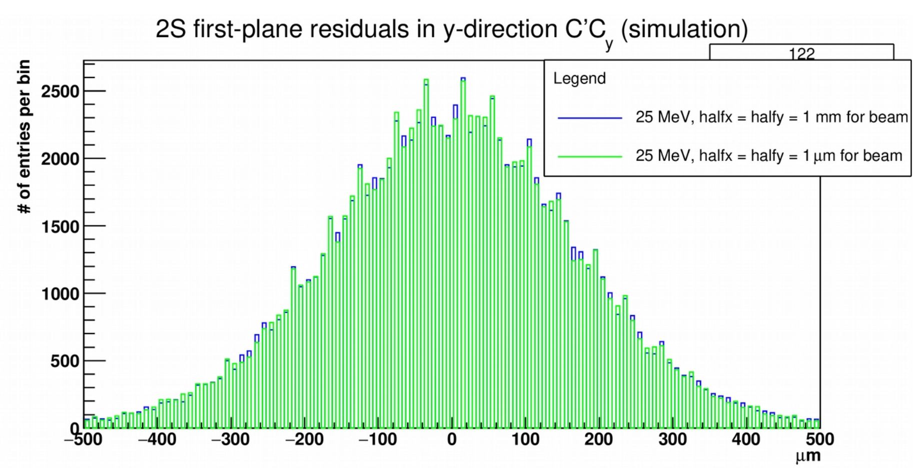

strip length // x-axis
strip pitch // y-axis

$$deflection\ angle = acos\left(\vec{u}_A \cdot \vec{u}_D\right), \vec{u} : momentum\ direction\ unit\ vector$$

# Multiple scattering and resolution



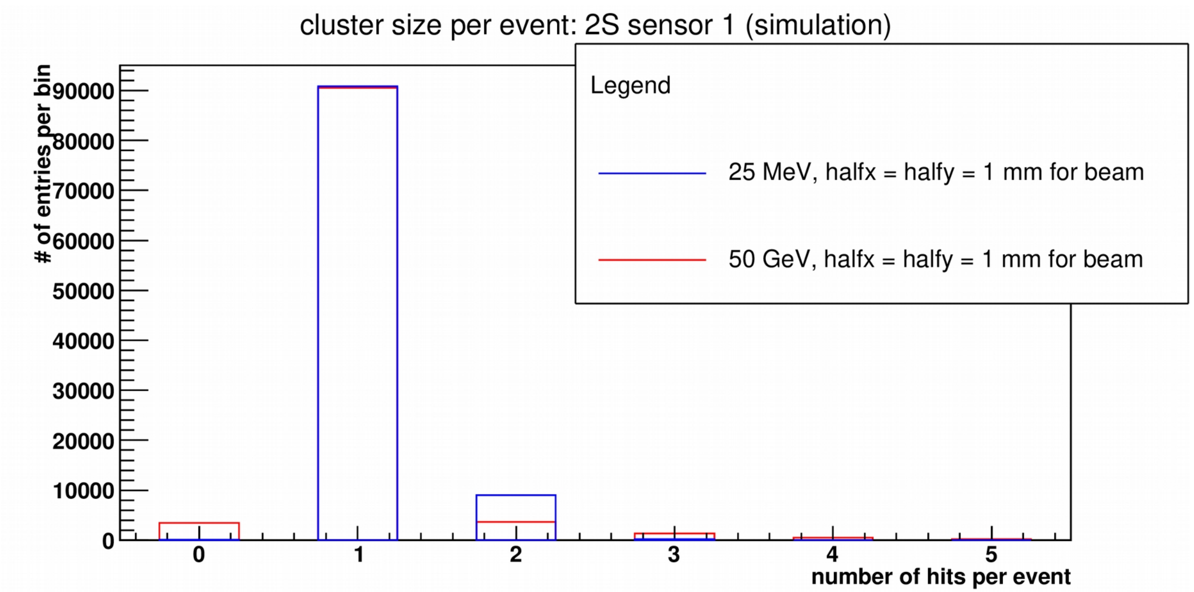



# Hits in pixels and strips

- In both pixel modules 1 and 2 mostly ROCs 6 and 14 have been hit, and in rare occasions ROCs 5 and 13. (1-8 upper row, 9-16 lower row.)

- In both 2S sensors 1 and only rows b are hit. Hits counted only in strips b 455-568 (~120 strips fire). (Rows defined as follows: a for x>0, b for x<0. GPS pointed at x = -1 cm.)

The plot basically shows the number of strips with a hit in the first sensor per event.



# Conclusions

- Even with large energy deposition (~10 MIPs) and relatively large multiple scattering, a 25 MeV proton beam can be used for tracking with a reasonable resolution

- The beam line and the mini-telescope could be of interest for tests of front-end electronics (FE) under high particle rate and high occupancy, to study the performance and saturation effects vs. track rate, and to monitor in situ effects of radiation damage

# Future plans

- The following will be completed in the near future:
  - Development of tracking and alignment algorithms
  - Pre-calibration of modules
  - Commissioning of the telescope (spring 2019)
  - Beam tests in Strasbourg (the first one scheduled for summer 2019)

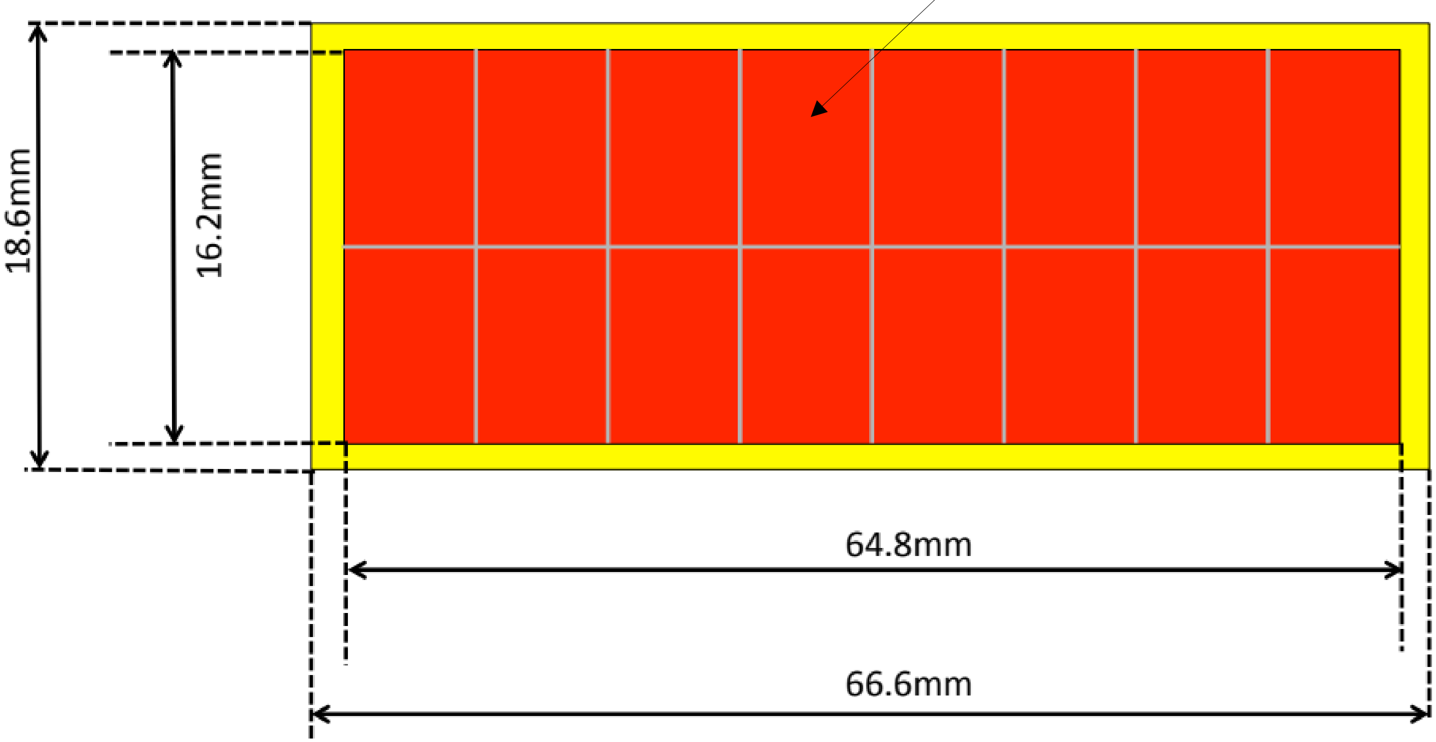
- We could benefit from the knowledge of the mechanics and DAQ of CHROMIE

# Backup

# BPIX (barrel pixel) modules

Sensor silicon area 18.6x66.6mm²
Number of ROCs=2x8
Pixel size 100x150um² (size twice as wide at chip boarders)
Number of pixels 80x52
Sensor active area 16.2x64.8mm² since
2*(80*0.1mm+0.1mm)=16.2mm
8*(52*0.15mm+2*0.15mm)=64.8mm

Deposited energy calculated for each pixel

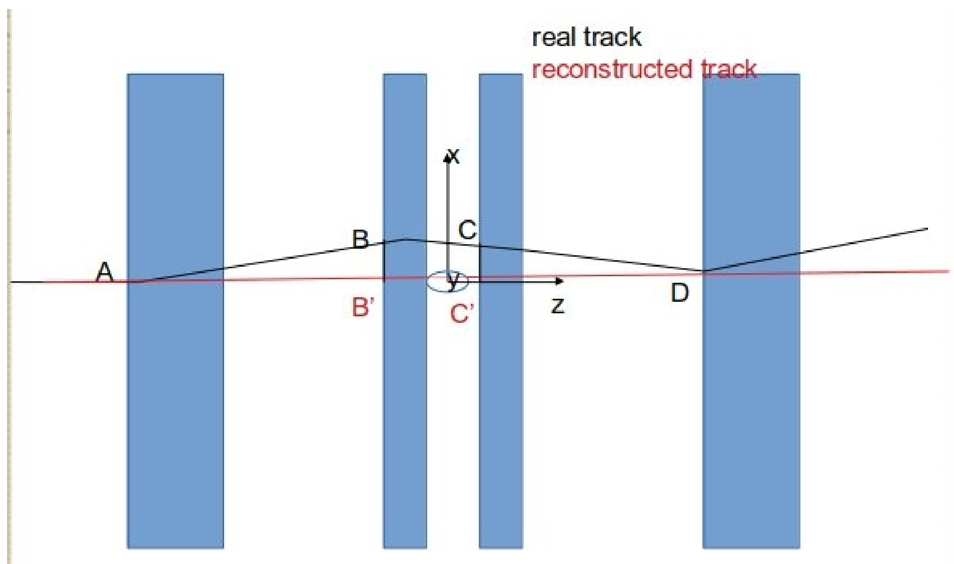


# Definition of hits in strips and pixels

- 2S → strips: 5σ noise threshold → set at 5000 electrons
- BPIX → pixels: 5σ noise threshold → set at 1000 electrons
- For each event Geant4 calculates the stored energy in each strip/pixel, respectively, and when dividing this energy by the energy required for a single electron-hole production in silicon (= 3.67 eV) one can get the charge collected in each pixel/strip in electrons. If this charge exceeds the threshold of 5000/1000 electrons, respectively, we consider that we have got a hit in the examined pixel/strip in the current event.

# Calculation of A, B, C, D impact points (1)

- Attempt to perform a local reconstruction
- Simplifications made to estimate residuals
- Impact points $Q_{pixel}$ = A, D; $Q_{strip}$ = B, C, where A, B, C, D are defined above



# Calculation of A, B, C, D impact points (2)

- Weight $w_{pi}$ for each pixel with a hit = charge collected in the current pixel over the total charge collected in all pixels of the current module that have counted a hit in the current event

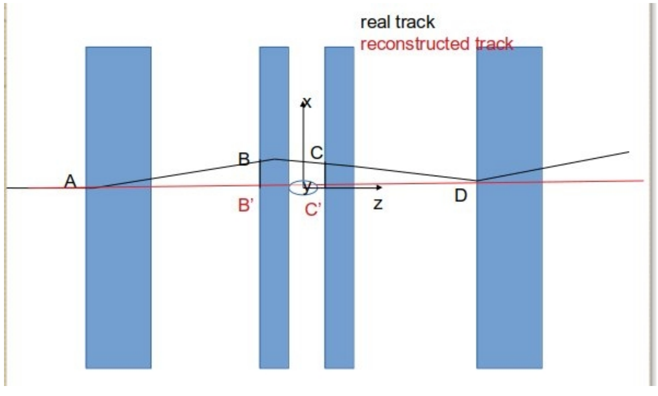
- Weight $w_s$ for each strip with a hit = 1 over the total number of strips of the current sensor that have counted a hit in the current event (no charge info from CMS Binary Chip)

- $N_{pixels}$: the total number of pixels with a hit in the current module, $P_{pi}$: the geometric center of the front surface (in the way of the beam) of the i-th pixel that has counted a hit

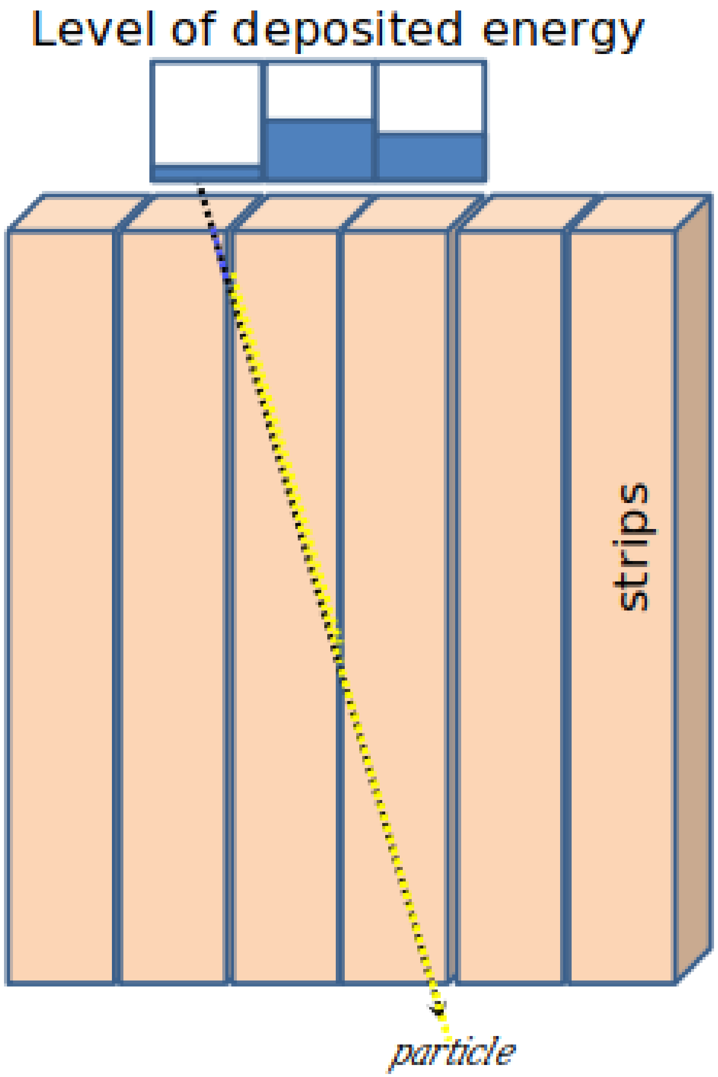
- $N_{strips}$: the total number of strips with a hit in the current sensor, $P_{si}$: the geometric center of the front surface (in the way of the beam) of the i-th strip that has counted a hit

$$A, D = Q_{pixel} = \frac{1}{N_{pixels}} \sum_{i=1}^{N_{pixels}} w_{pi} P_{pi}$$

$$B, C = Q_{strip} = \frac{1}{N_{strips}} \sum_{i=1}^{N_{strips}} P_{si}$$



# Sensitive 2S sensors



# Other outputs of the simulation

- Track length of primary protons
- Track lengths of secondary δ-electrons
- Numbers of different types of new particles created per sensor
- Energy deposition per strip/pixel
- Number of hits per strip/pixel
- Charge per strip