THE UNIVERSITY of TENNESSEE
KNOXVILLE

Correction to Luminosity Measurement for the Pixel Luminosity Telescope at CMS

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Outline

- Introduction
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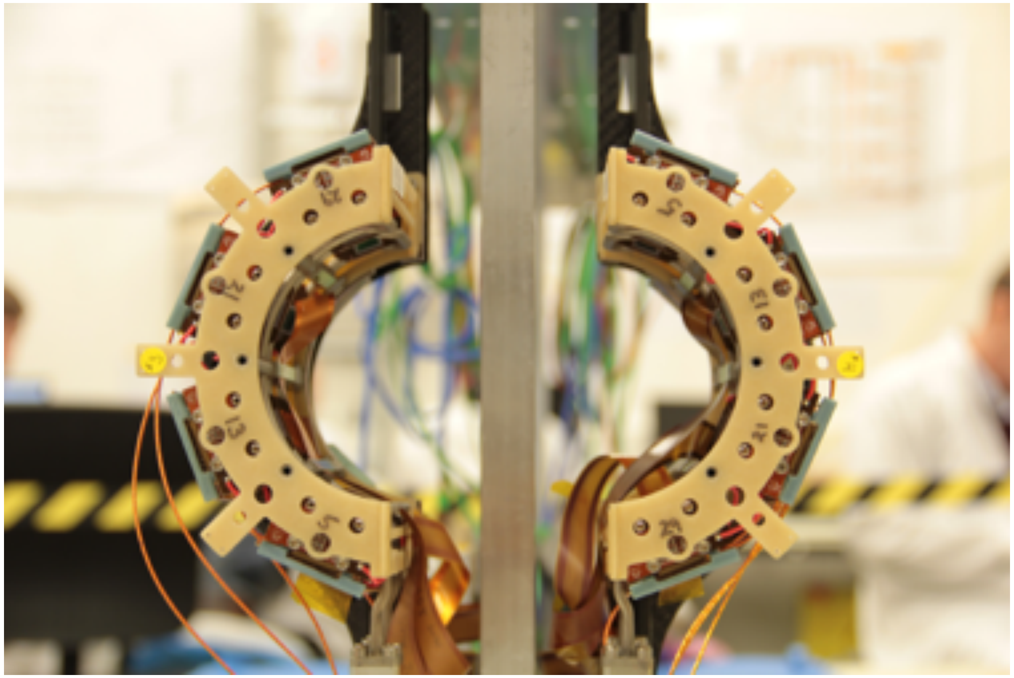
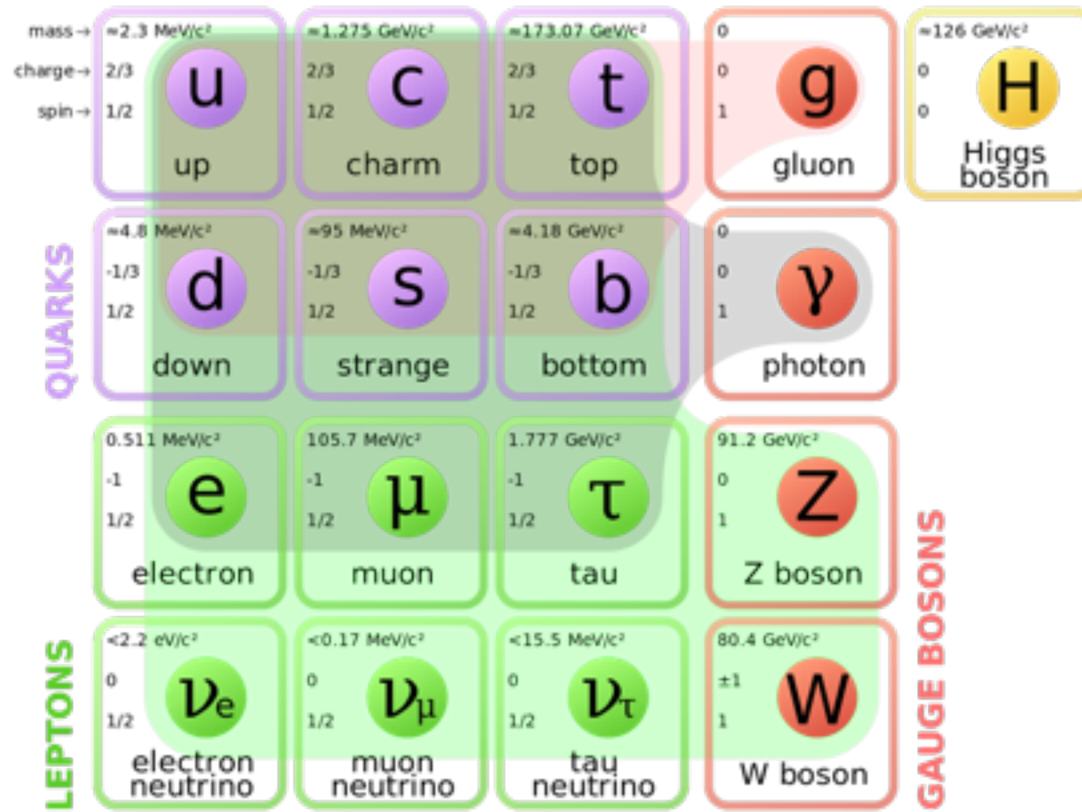
  - Luminosity
  - CMS
- Pixel Luminosity Telescope
  - Track counting
  - Calibration
- Background correction
  - Track Reconstruction
  - Model selection
  - Fits
- Results
- Conclusion



Standard Model of Particle Physics

Particles are treated as excitations of fields having (half) integer spin, and the forces are treated as interactions among excitations of these fields



Matter consists of particles of spin 1/2,

known as fermions

Interaction between elementary particles

- Electromagnetic
- Weak
- Strong

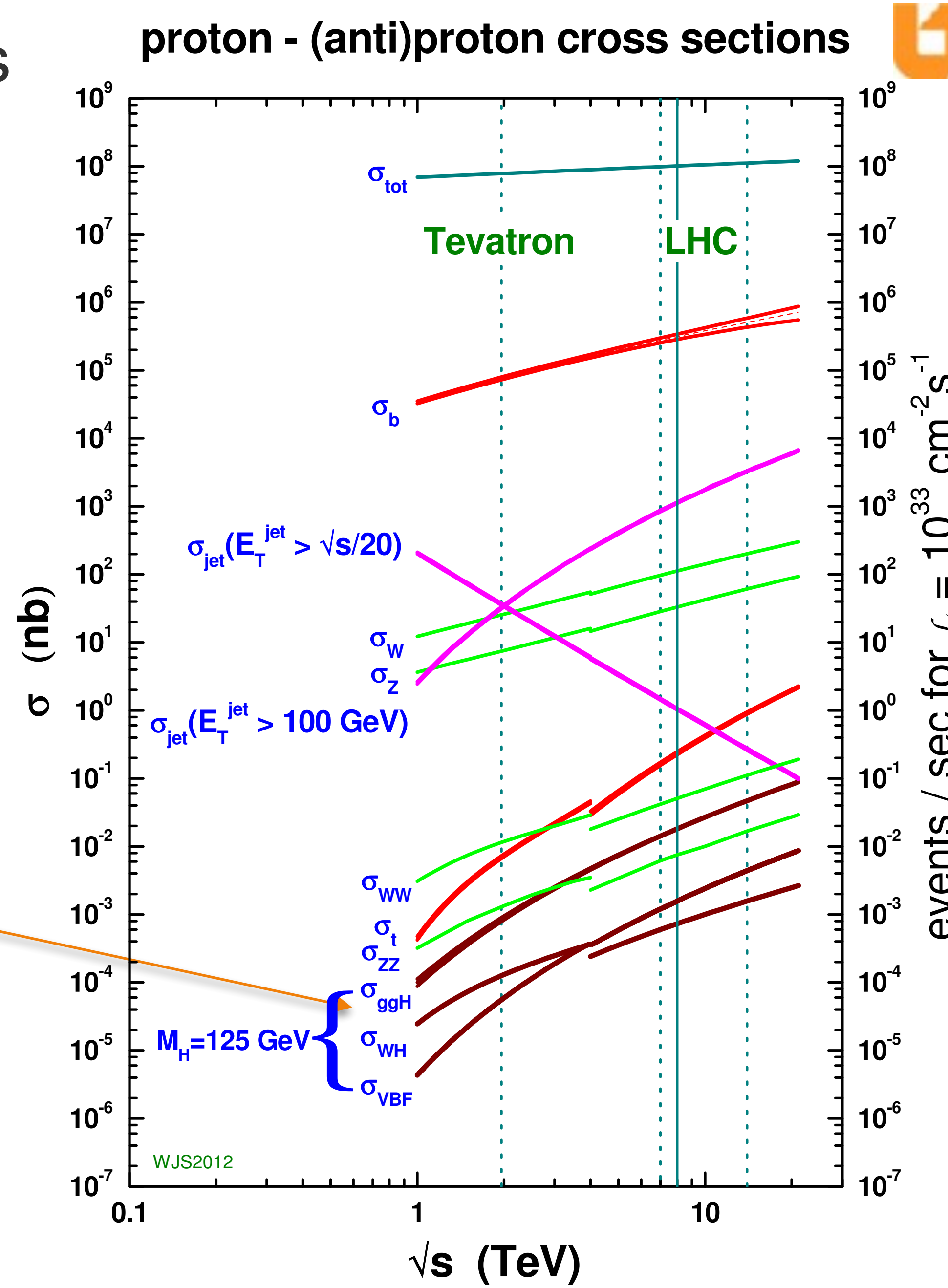
gauge bosons as force mediators

Particles require mass via Higgs mechanism and is mediated by the Higgs particle

Measuring physics process

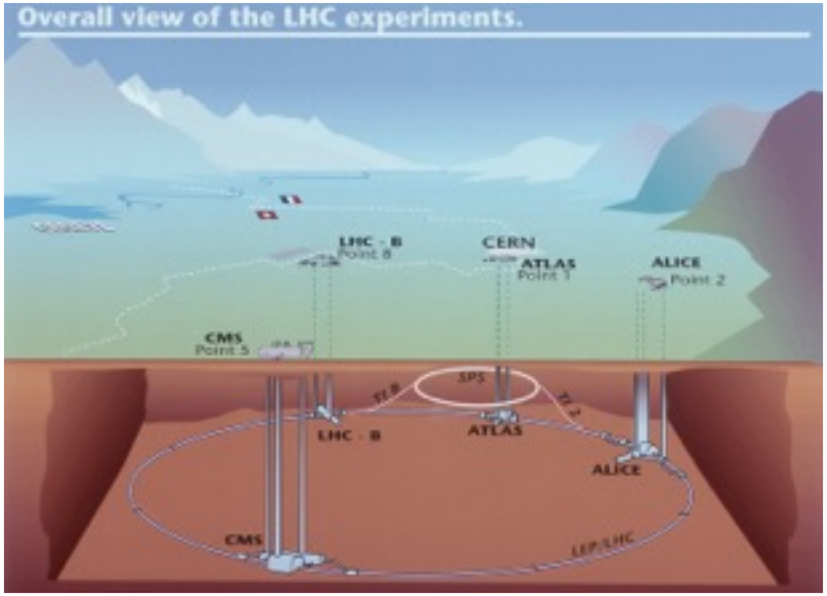
$$R(t) = \mathcal{L}(t) \cdot \sigma_P$$

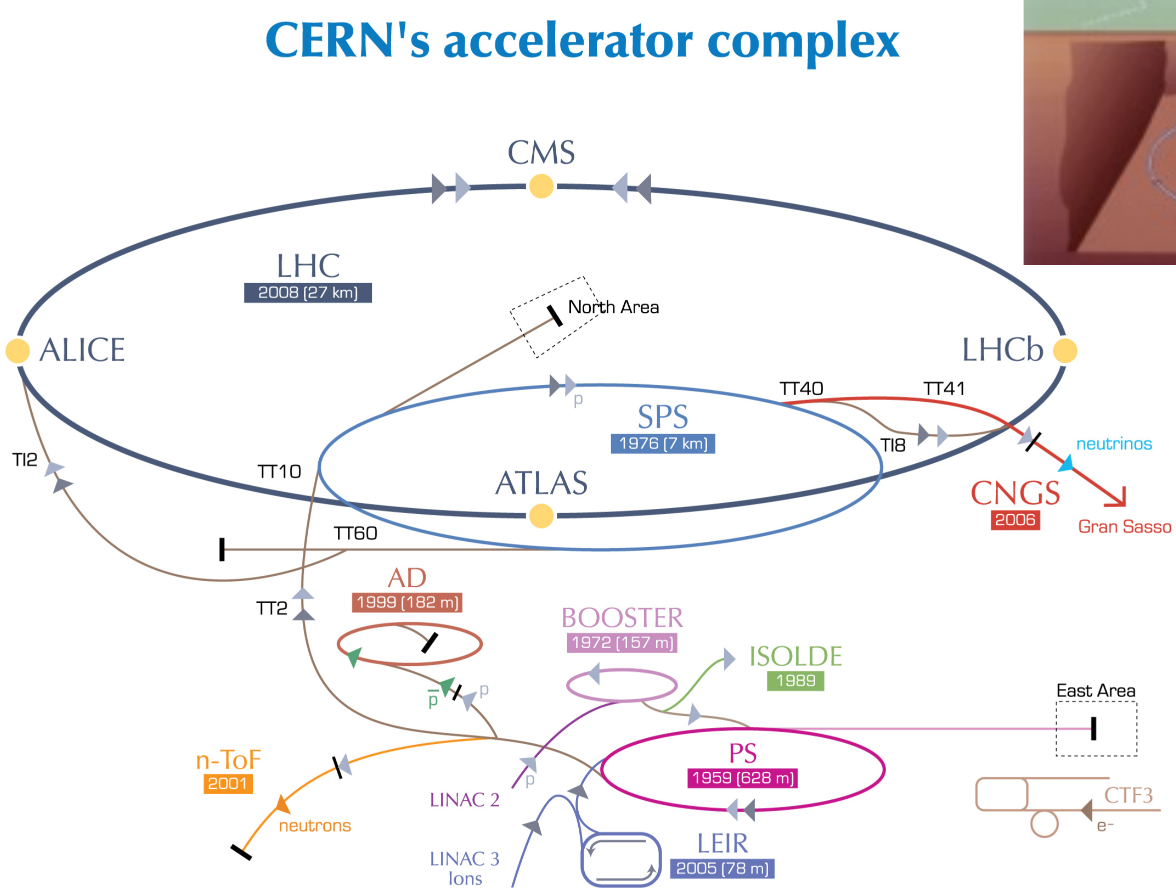
- Theory tells us the rate at which we should be expecting certain signal event to occur.
- Collide Protons, count the number of signals.
- Cross section of Higgs via gluon-gluon process at a given energy and at given Luminosity.
- Improve understanding of SM



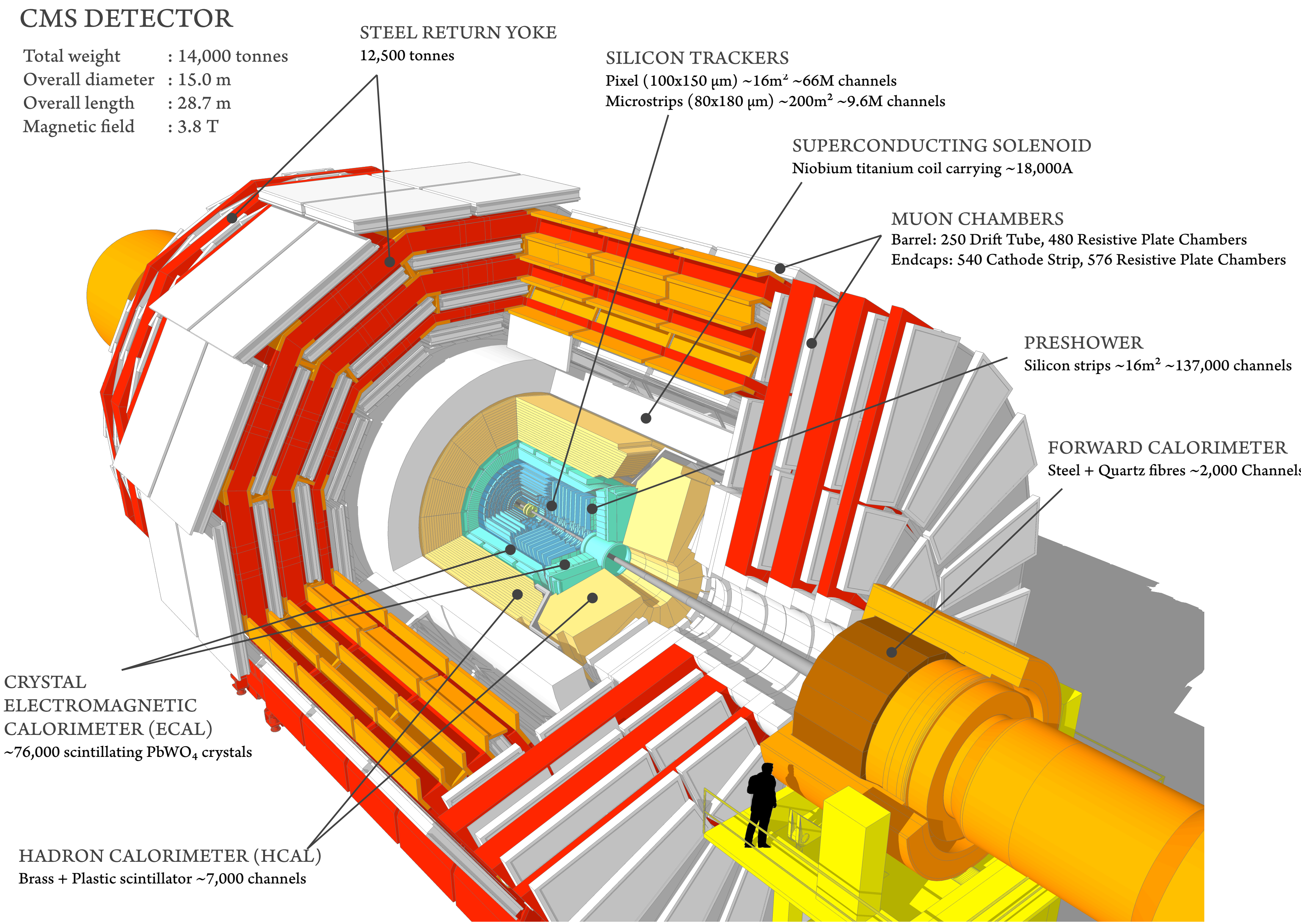
Large Hadron Collider

Proton-proton collider (up to E_{CM}=14 TeV) 27 km in circumference, 50-175m deep

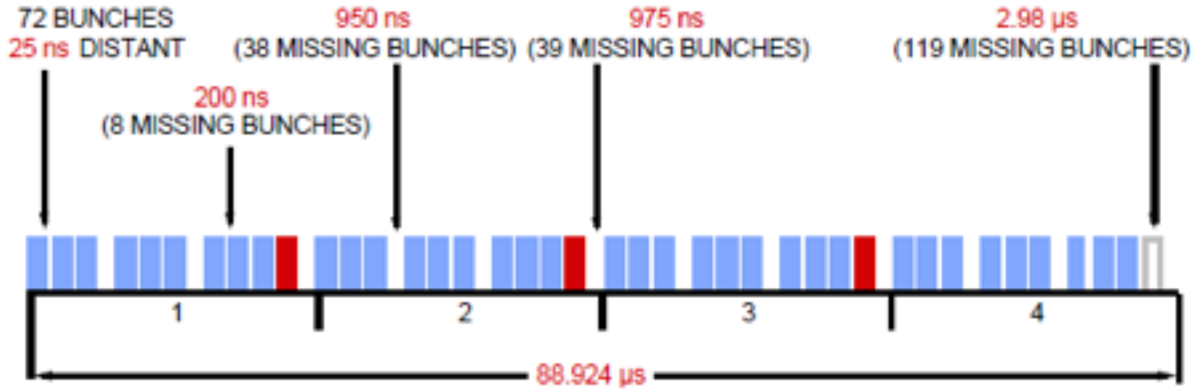




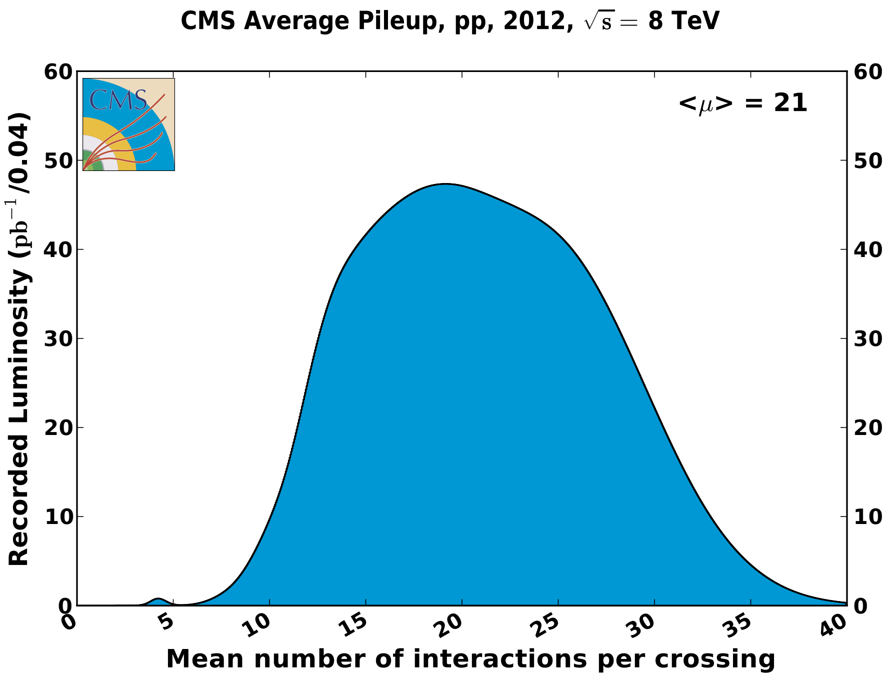
Compact Muon Solenoid (CMS)



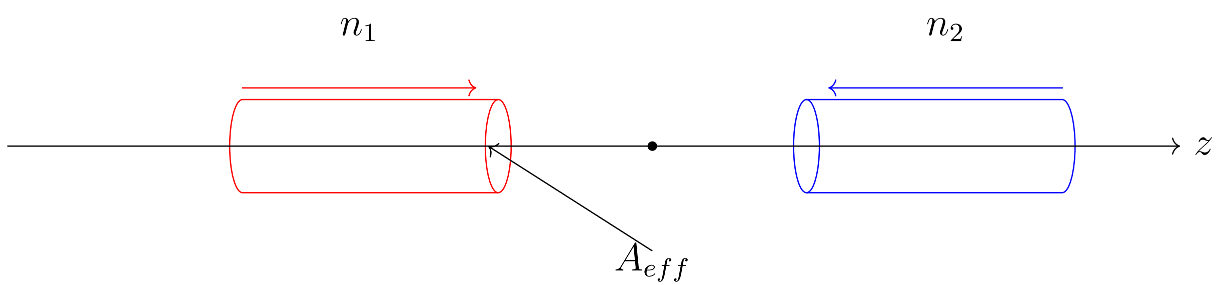
Proton bunches



- LHC circumference = 27 km
- 1 orbit = 11245 Hz ~ 89 micro seconds
- 3564 x 25 ns ~ 89 ms
- 25 ns ~ 7.57 m
- 1 bunch ~ 1.15×10^{11} protons
- 1 bunch crossing ~ 21 pp collisions



Calibration



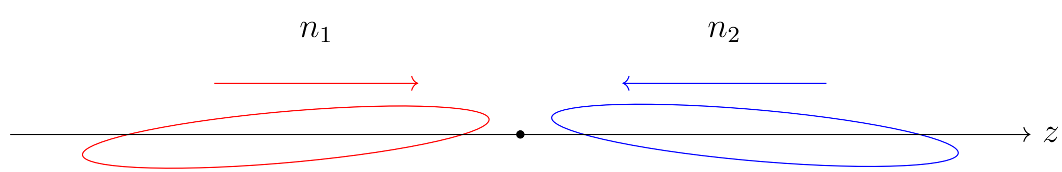
$$R(t) = \mathcal{L}(t) \cdot \sigma_P$$

$$\mathcal{L} = \frac{n_1 n_2 f}{A_{eff}}$$

Assuming a Gaussian profile for the beam distribution in x and y, each characterized with a standard deviation σ_x and σ_y, respectively.

$$A_{eff} = 4\pi\sigma_x\sigma_y.$$

In practice, $\theta_C = 285\mu$ rad to direct the beams after collision into their respective vacuum pipe and to avoid multiple unwanted interactions.

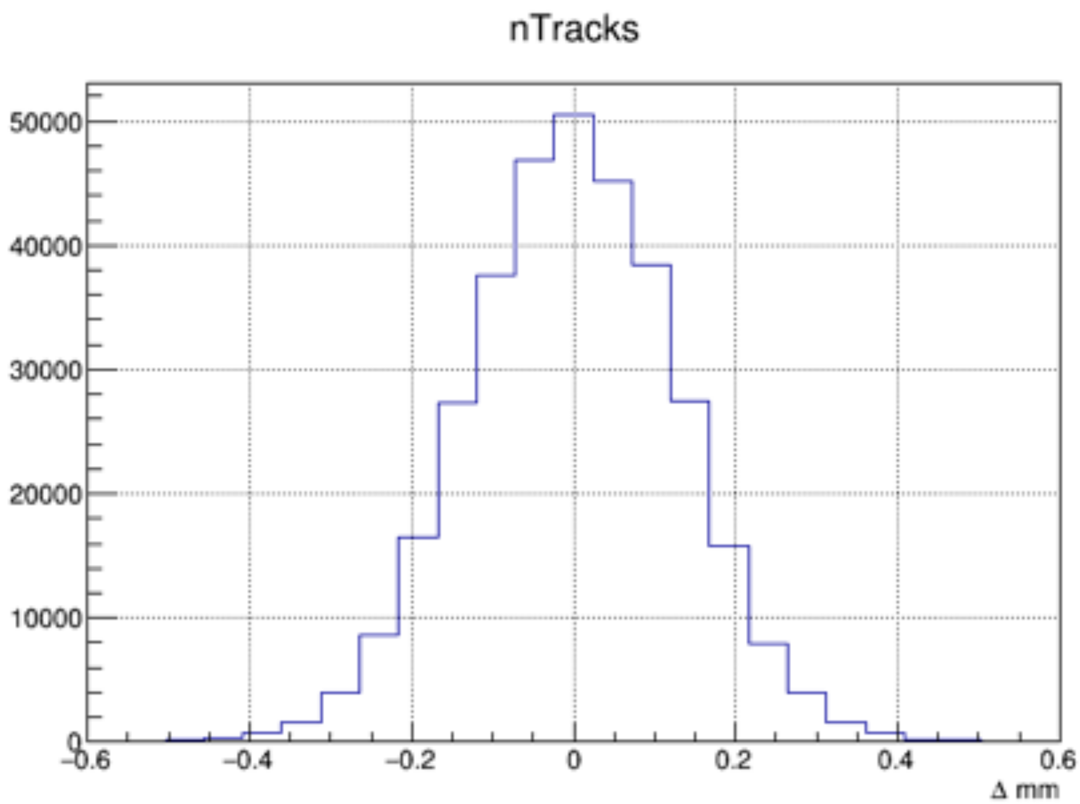


Calibration via VdM scans

Assume that the beam density functions are uncorrelated one can write for the counting rate R as function of displacement in x and y, x and y, respectively

$$R(\delta x;\delta y) = R_x(\delta x)R_y(\delta y)$$

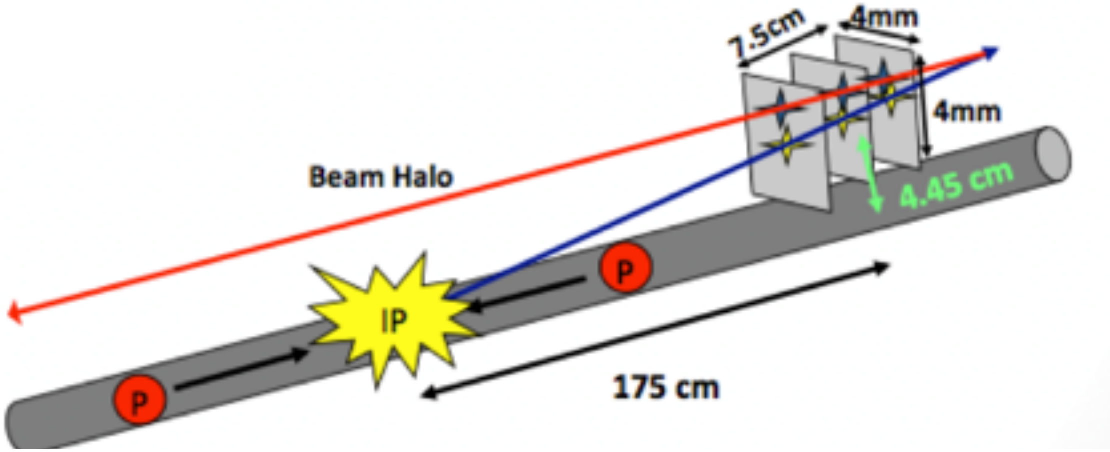
$$A_{eff} = \frac{\int R_x(\delta x)d\delta x}{R_x(0)}\frac{\int R_y(\delta y)d\delta y}{R_y(0)}$$



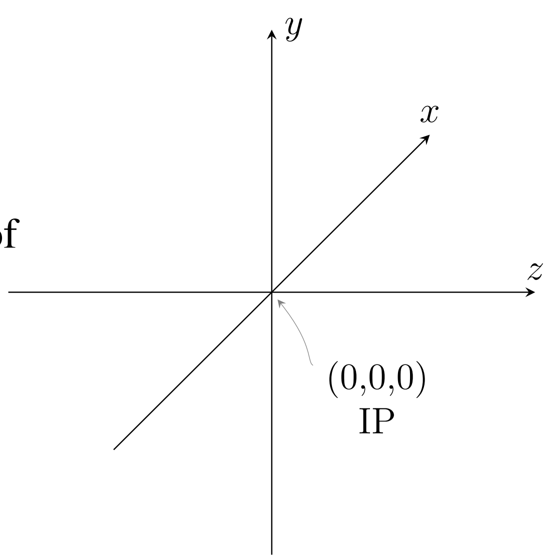
- vdm scans performed with beams well separated bunches
- small per bunch luminosity

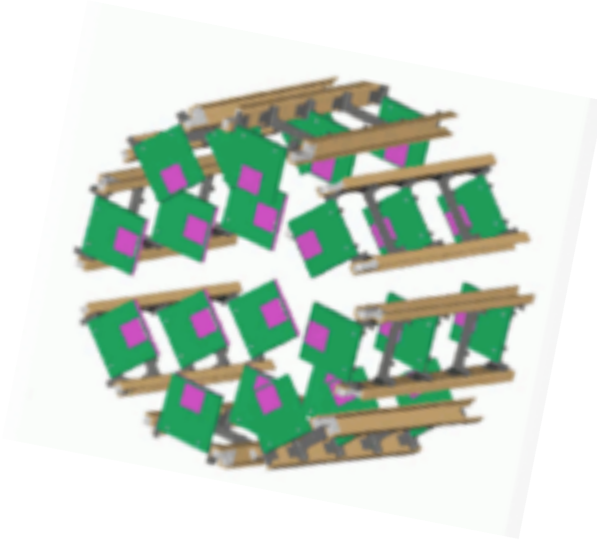
Pixel Luminosity Telescope

- PLT is a dedicated luminosity monitor, came online in 2015,
  - Bunch-by-bunch luminosity (1% statistical precision In 1second at full luminosity)
  - Standalone system of CMS
  - Beam quality
  - Collision point centroid



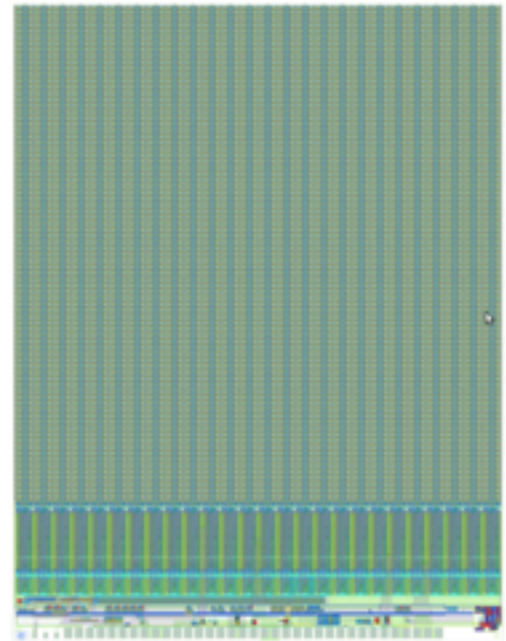
- Placed at ~171 cm forward and backward from the interaction point.
- 8 Telescopes on each side of the interaction point, each with 3 sensors.



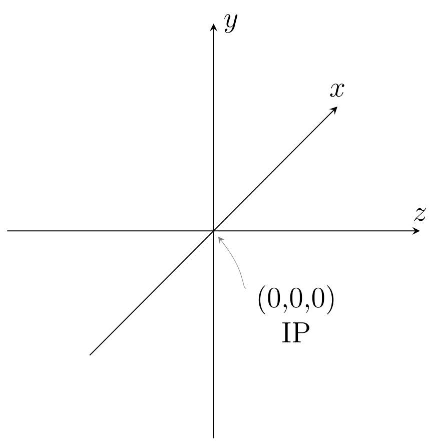


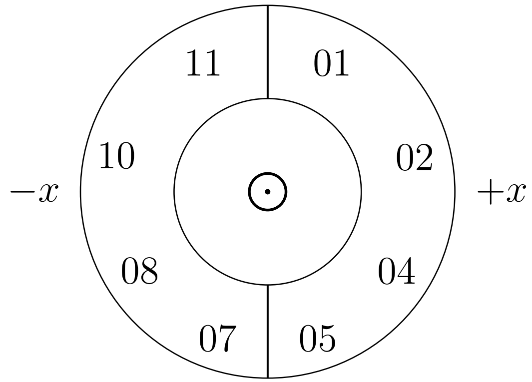
Pixel Sensor

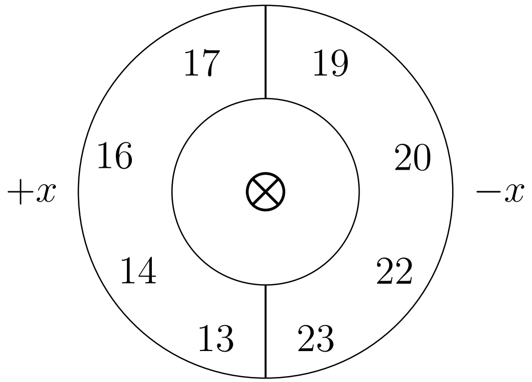
- Each pixel sensor is segmented into of 80 rows and 52 columns of pixels.
- Each pixel is 150 μ m wide and 100 μ m height
- The middle plane is placed 0.102 cm higher than the first plane, and the third plane is placed 0.102 cm higher than the middle plane to maintain an average viewing angle of 0.27 degrees toward the interaction point.



pixel sensor







Readout Modes

- Pixel chip has 2 read-out modes
  - Fast-out feature
    - 3-fold fast-or coincidences at each bunch crossing (40MHz)
    - Signal height is based on number of well separated hits

  - Full pixel readout
    - Address and charge signal of each pixel hit
    - Read out ~2-3 kHz
    - Can be triggered by fast-out (self triggering) or by external trigger

Convert coincidence counts from fast-or to online luminosity, find correction to luminosity by analyzing pixel data

Zero - Counting Algorithm

The PLT detector with limited acceptance times detection efficiency, will only see a subset of the events:

$$\mathcal{L}_{\text{int}} = \frac{\omega \mu f}{\omega \sigma_{\text{inel}}} = \frac{\mu_{\text{vis}} f}{\sigma_{\text{vis}}}$$

The probability of observing n number of events for a time interval (25 ns) with average number of events for any bunch crossing, μ :

$$P(n) = \frac{\mu^n e^{-\mu}}{n!}$$

Total probability, P = P(0) + P(1) + P(2) + … = 1

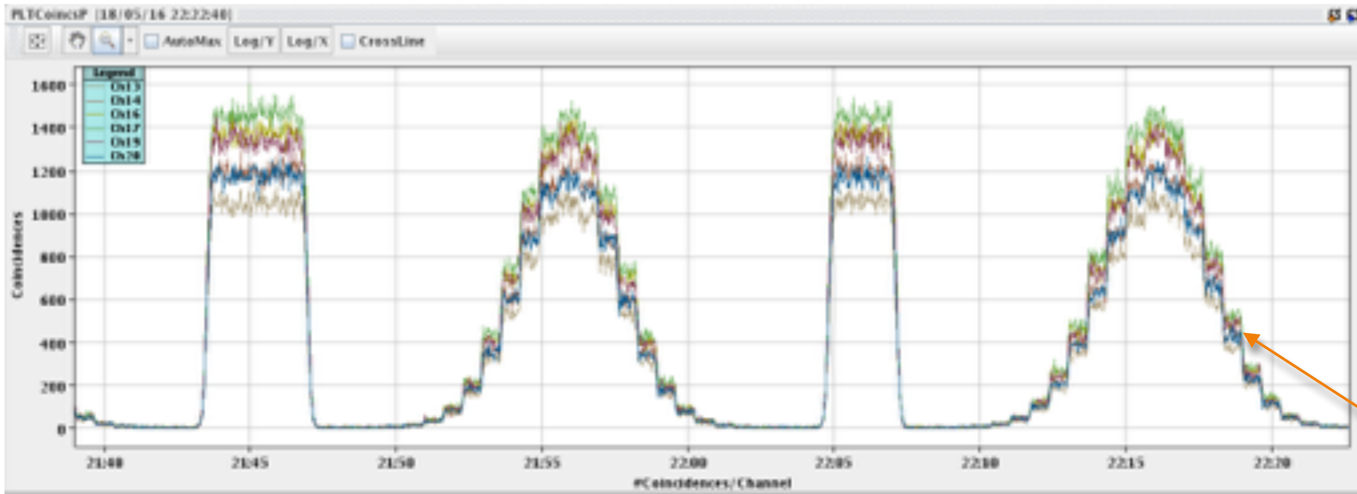
The probability of observing 0 events, therefore,

$$P(0) = 1 - P(1) + P(2) + \ldots = 1 - P(1+)$$

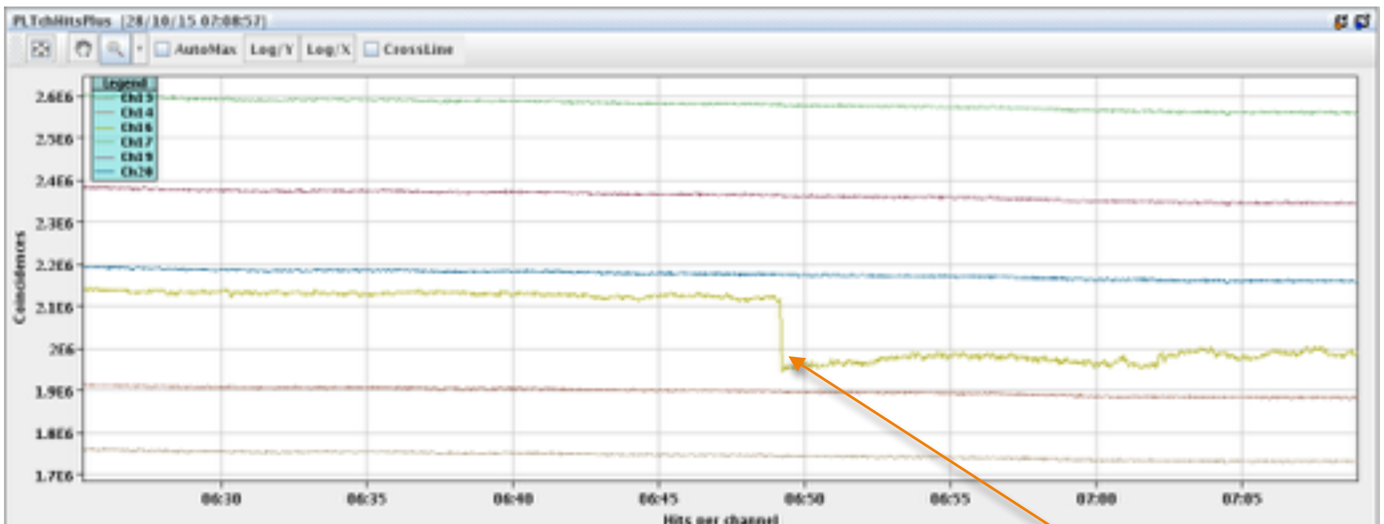
Count the number of triple-coincidences for 4096 orbits.

$$\mu = -\log(1 - P(1+))$$

Operation II - Visualization Dashboard



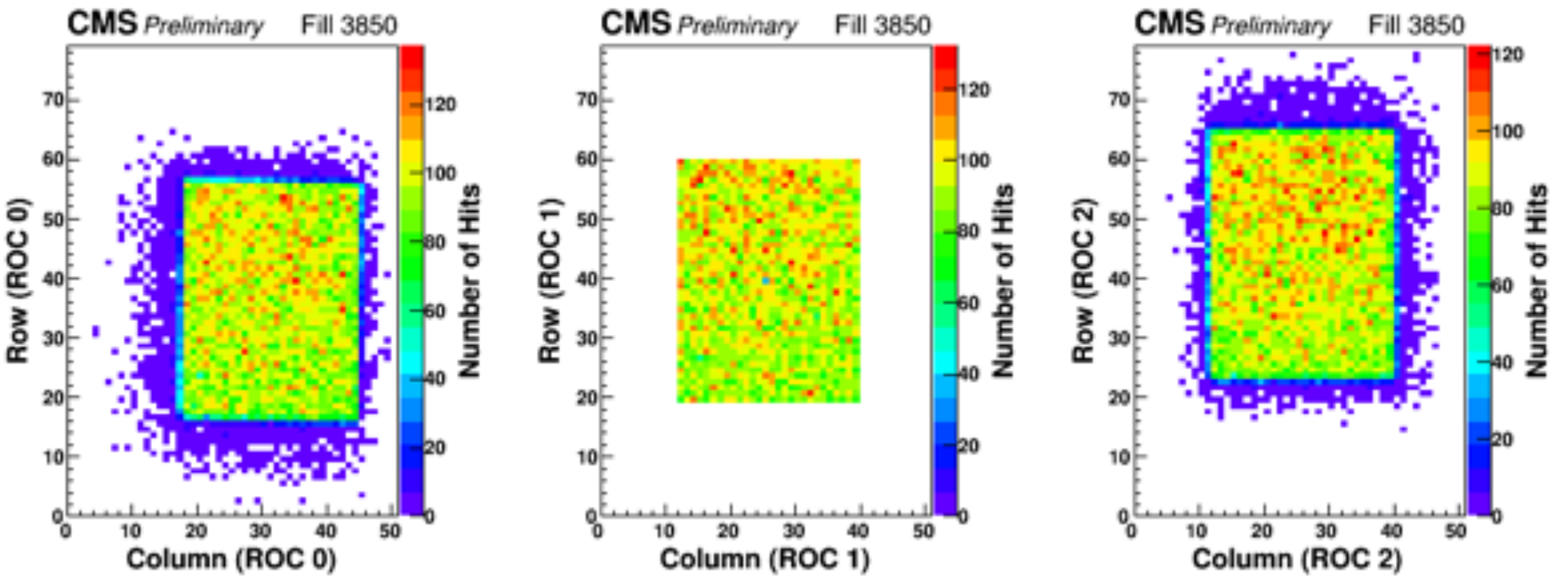
during
beam
scan



1 channel dropped

- Check the running average of each channels
- Send alarms (via email) in case of weird behavior

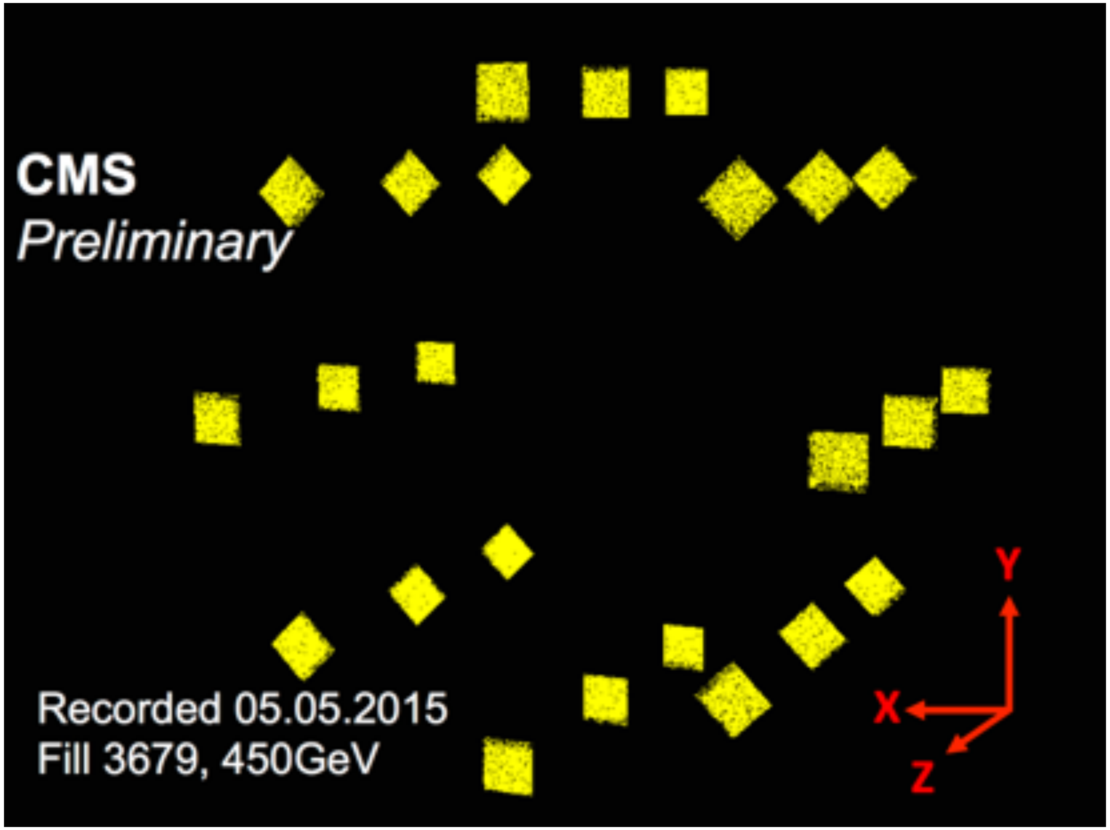
Triple coincidences



Occupancies in a single telescope of the Pixel Luminosity Telescope (PLT) with a mask applied to reduce the active area of the central plane to 4mm x 4mm

Translate coincidence count to luminosity value using zero-counting algorithm

Pixel Data



Find background contribution

Align Telescopes:

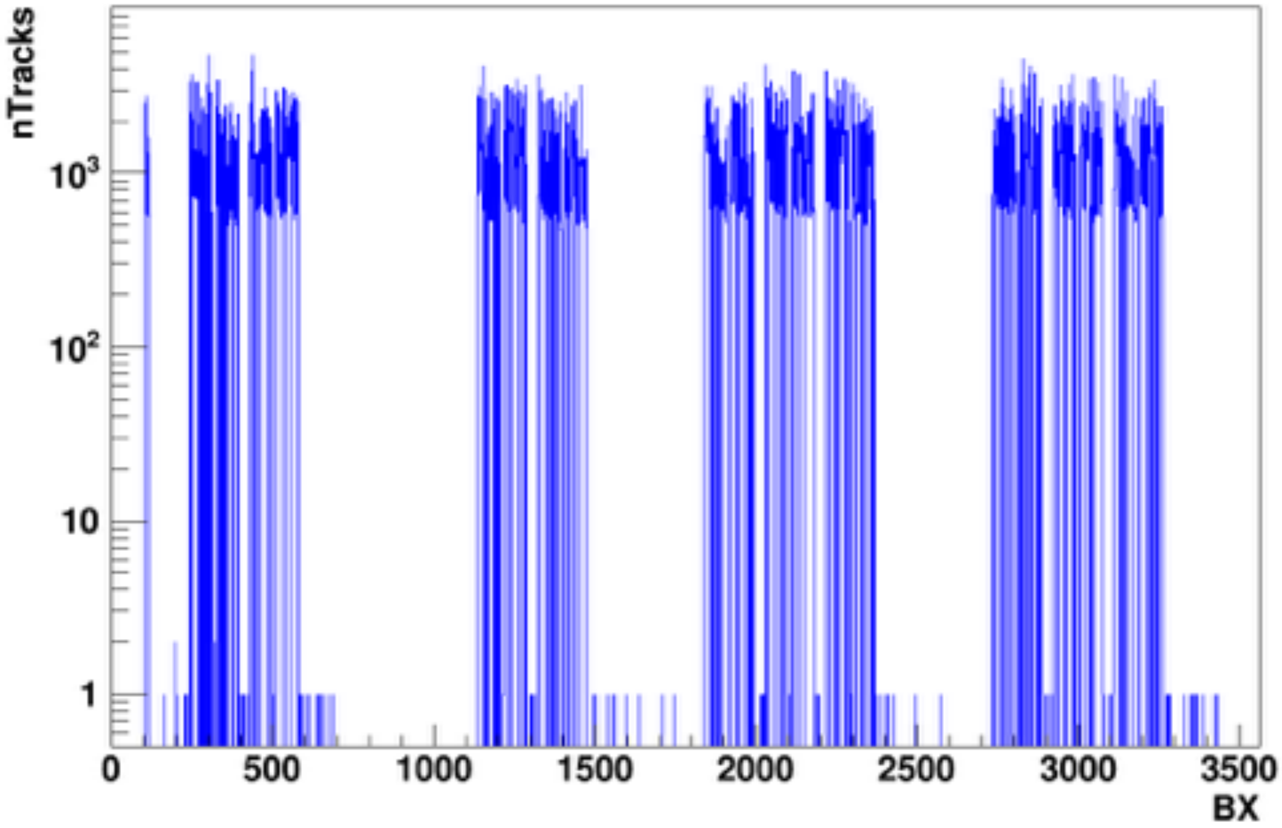
left+bottom row, column: (0,0) in pixel coordinates

⇨ can translate hits to telescope coordinates

Each telescope has a fixed location on the CMS coordinate

⇨ can translate to global coordinates

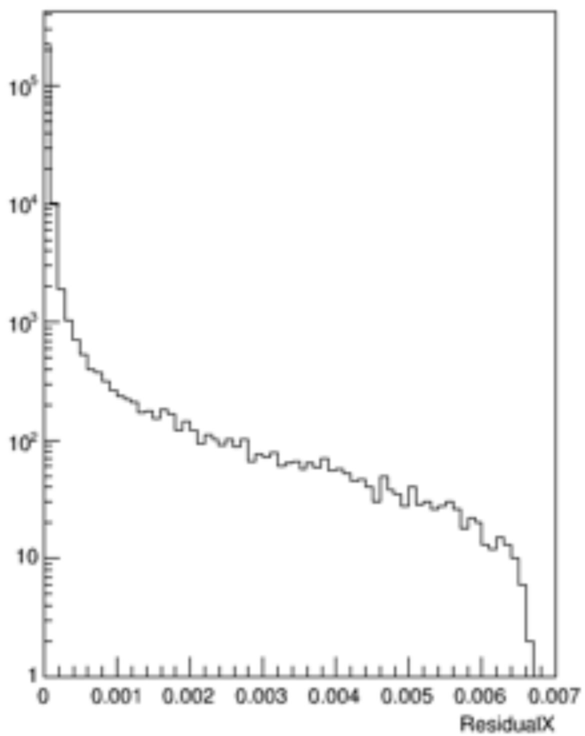
Background calculation - proton bunches

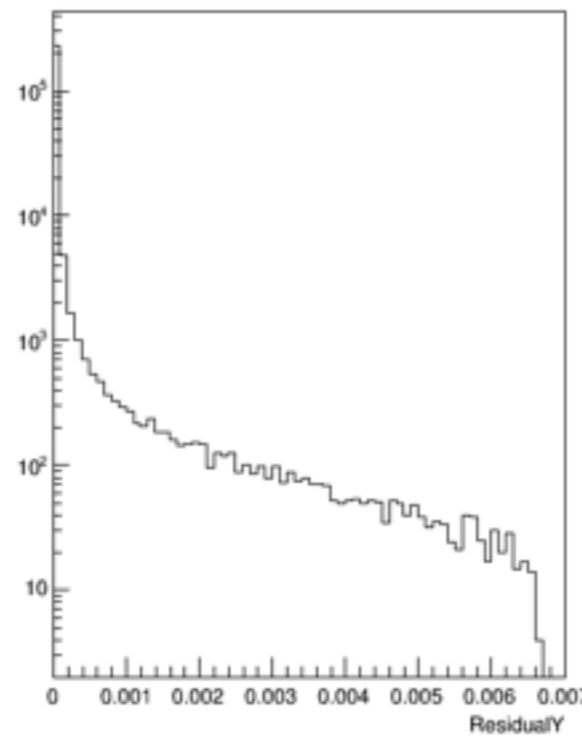


- Height of each bin ==> count of triple-coincidences via pixel data
- Low count from unfilled bunches: << 1% percent contribution to luminosity

Track Reconstruction - Residuals

- Fit a straight line to a set of 3 hits
- Deviation from pixel position to straight line fit

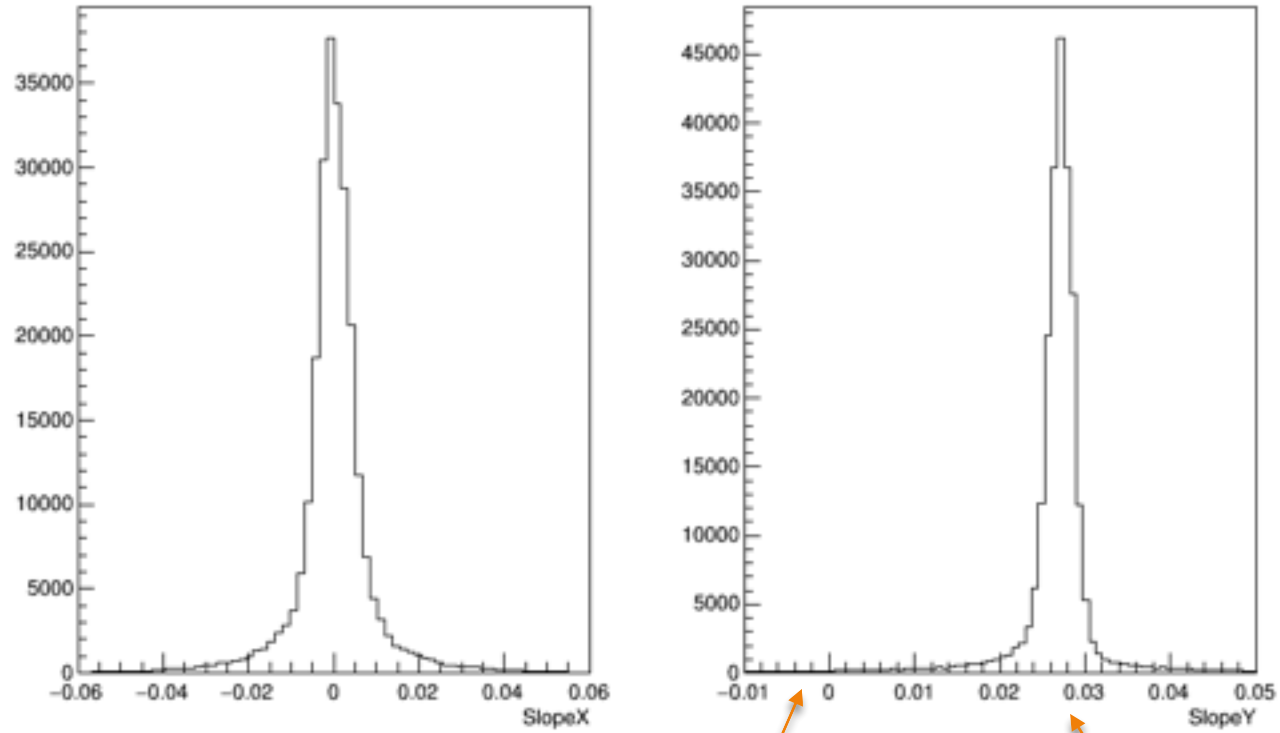




very few tracks with > 3 mm residual

Track Reconstruction - Slopes

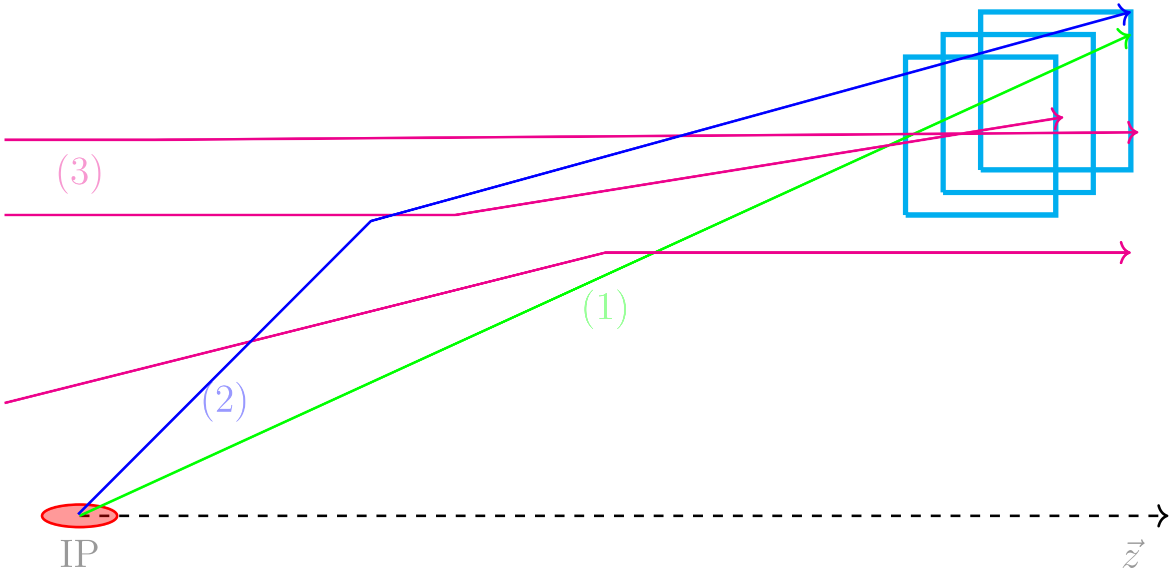
Distribution of slope x and slope y



Why do some tracks have -ve y slopes?

~Position of telescope with respect to IP

Contribution to luminosity



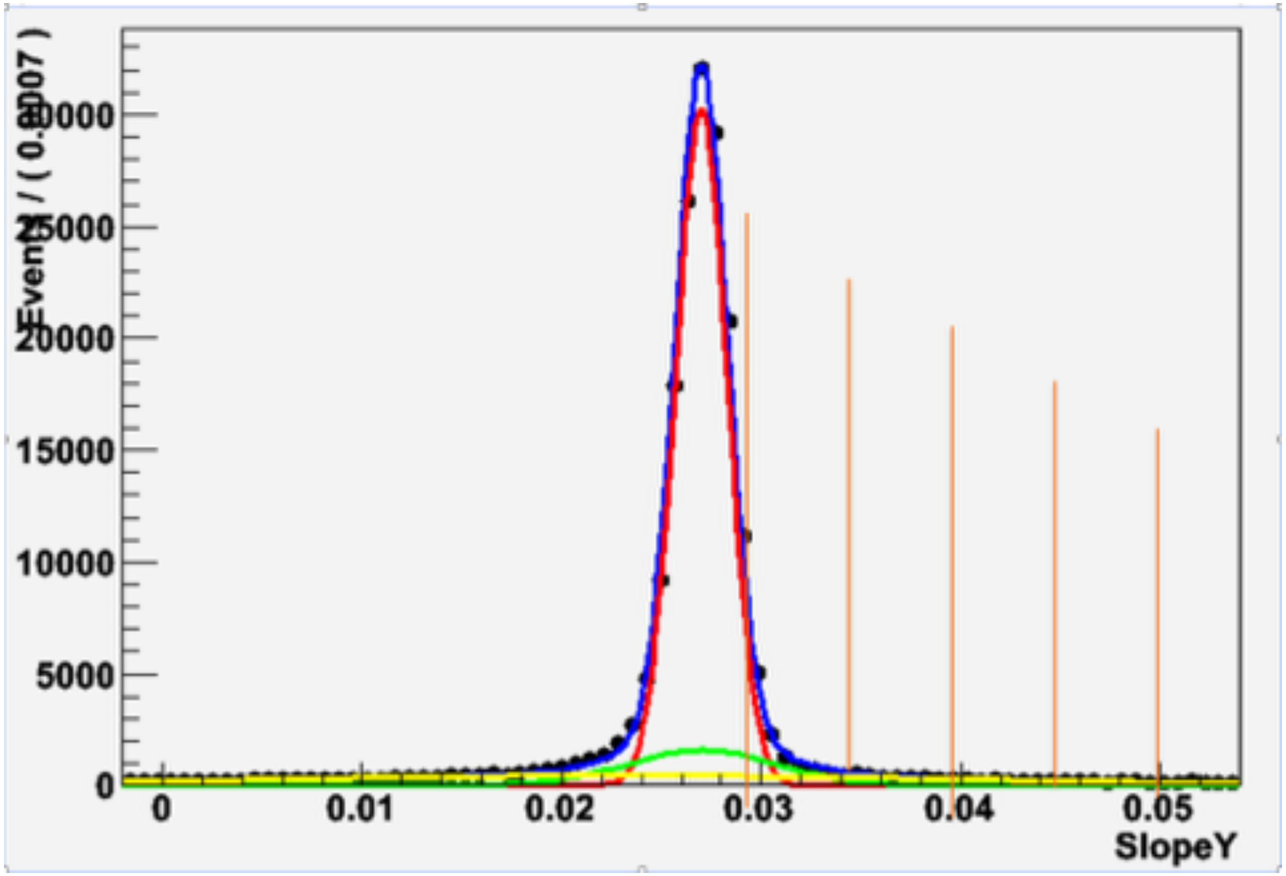
Tracks from several sources that can be distinguished via the track parameters–slopes, residuals. Generally, the tracks that PLT detects can be categorized as follows:

1. Tracks from IP + lumi

2. Tracks from IP with scatter + lumi

3. Tracks parallel to beam from collision with beam gas and obstructions far away from the IP - extra

5 sigma cuts



"apply cuts"

- Apply 4.5, 5, 5.5 sigma cuts to residuals and slopes
- Around ~ 5 sigma, we start cutting into negative y-slopes

2.2% + SBIL * 1.4%

Maximum Likelihood Fits

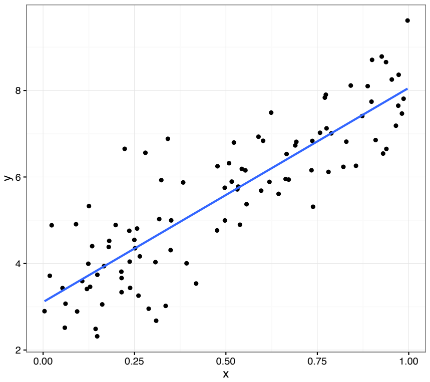
Suppose that we have a sample of some n number of independent observations $x_1, x_2, ..., x_n$ from a theoretical distribution $f(x|\theta)$ where θ is the parameter we would like to find. Let $f(x_1|\theta)$ be the probability of observing x_1 data given theta parameter for function f. Then, the probability of observing $x_1,x_2,...,x_n$ data is given by the likelihood function

$$L(\theta|x) = f(x_1|\theta)f(x_2|\theta)\cdots f(x_n|\theta)$$

What is the best value for the estimate? The best value here is that which minimizes the variance between the estimate and the true value.

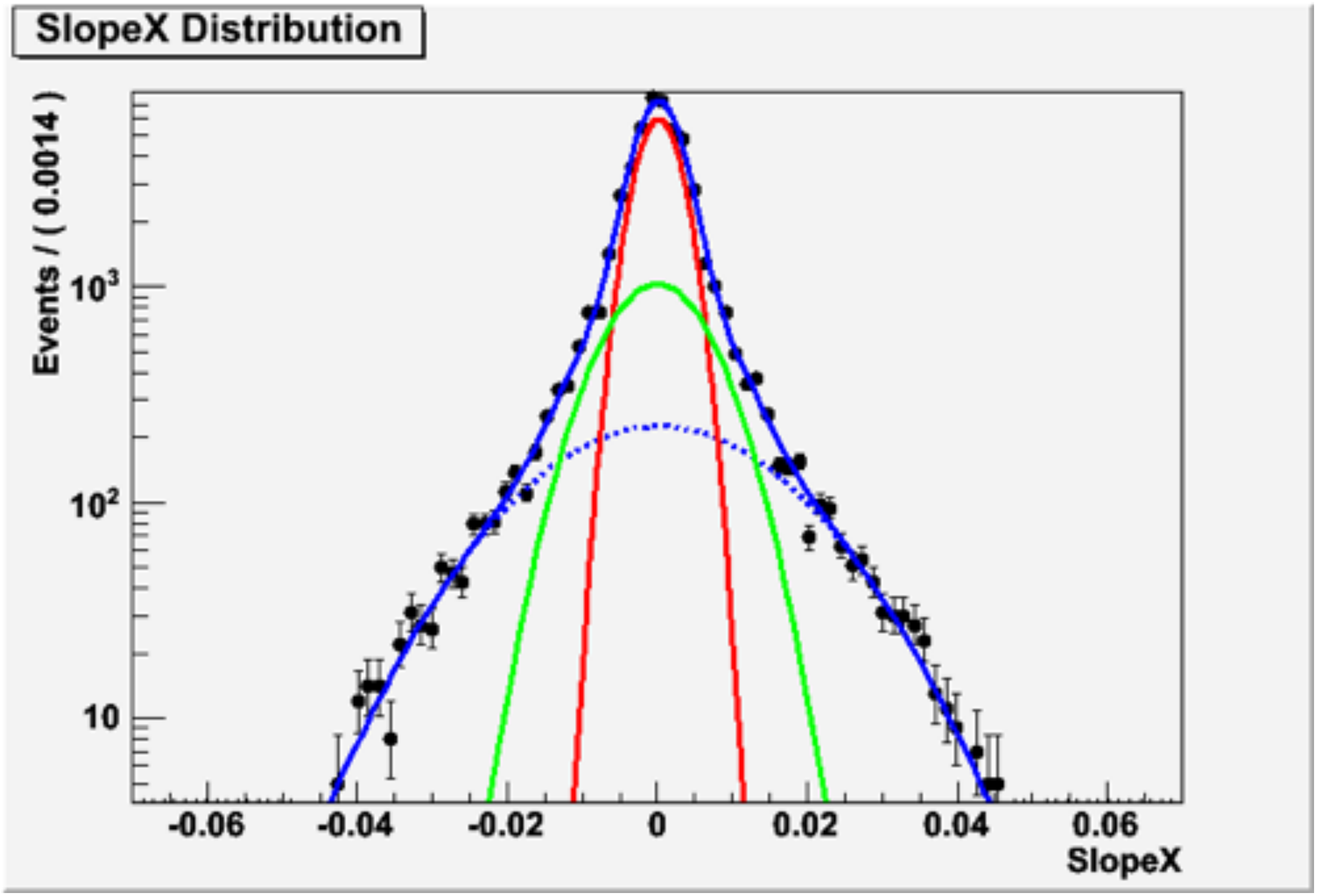
(1) find the best estimate for θ

(2) find the uncertainty on the estimate.



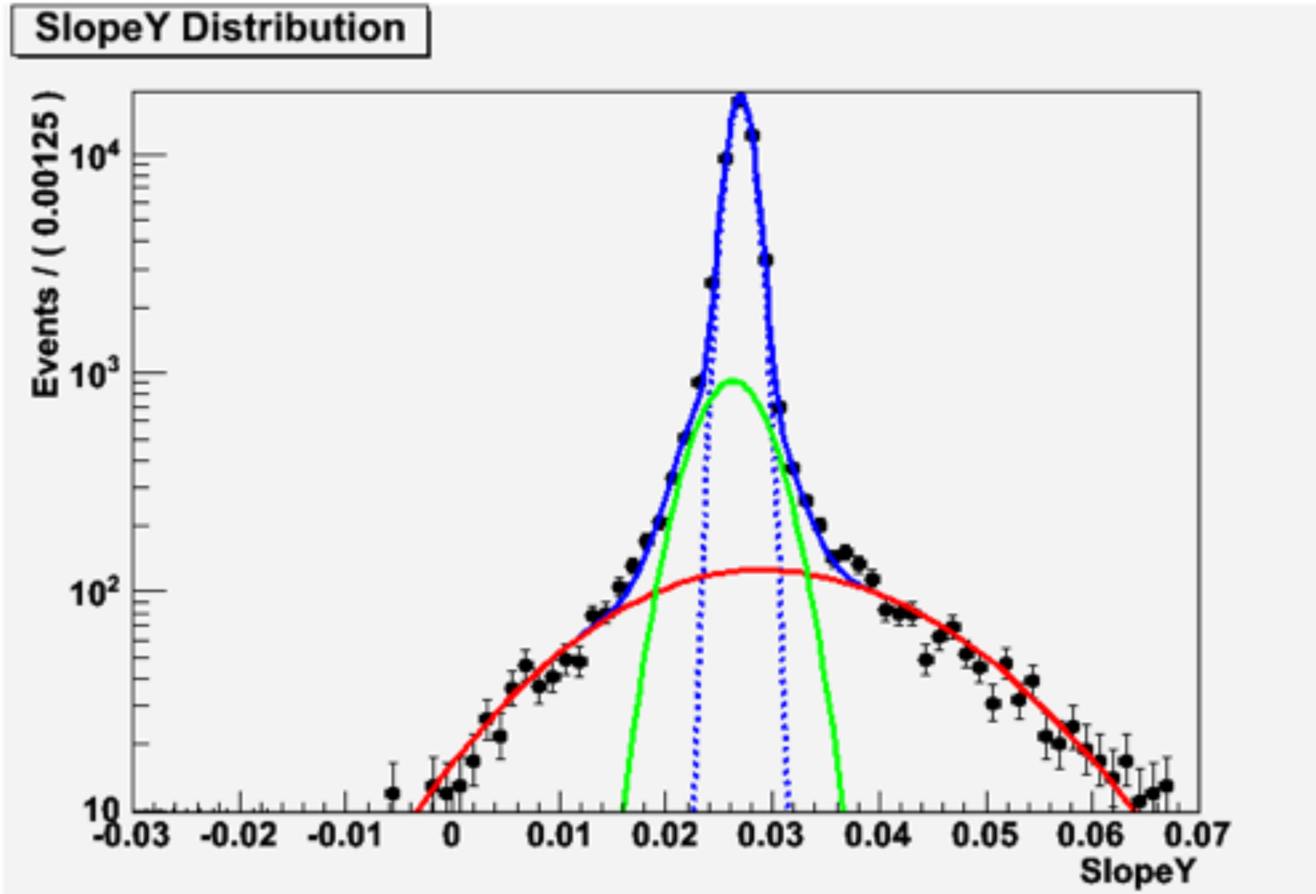
The estimator is thus also described by a probability distribution. This leads us to the second half of the estimation problem: The error on the estimator is given by the standard deviation of the estimator distribution

SlopeX



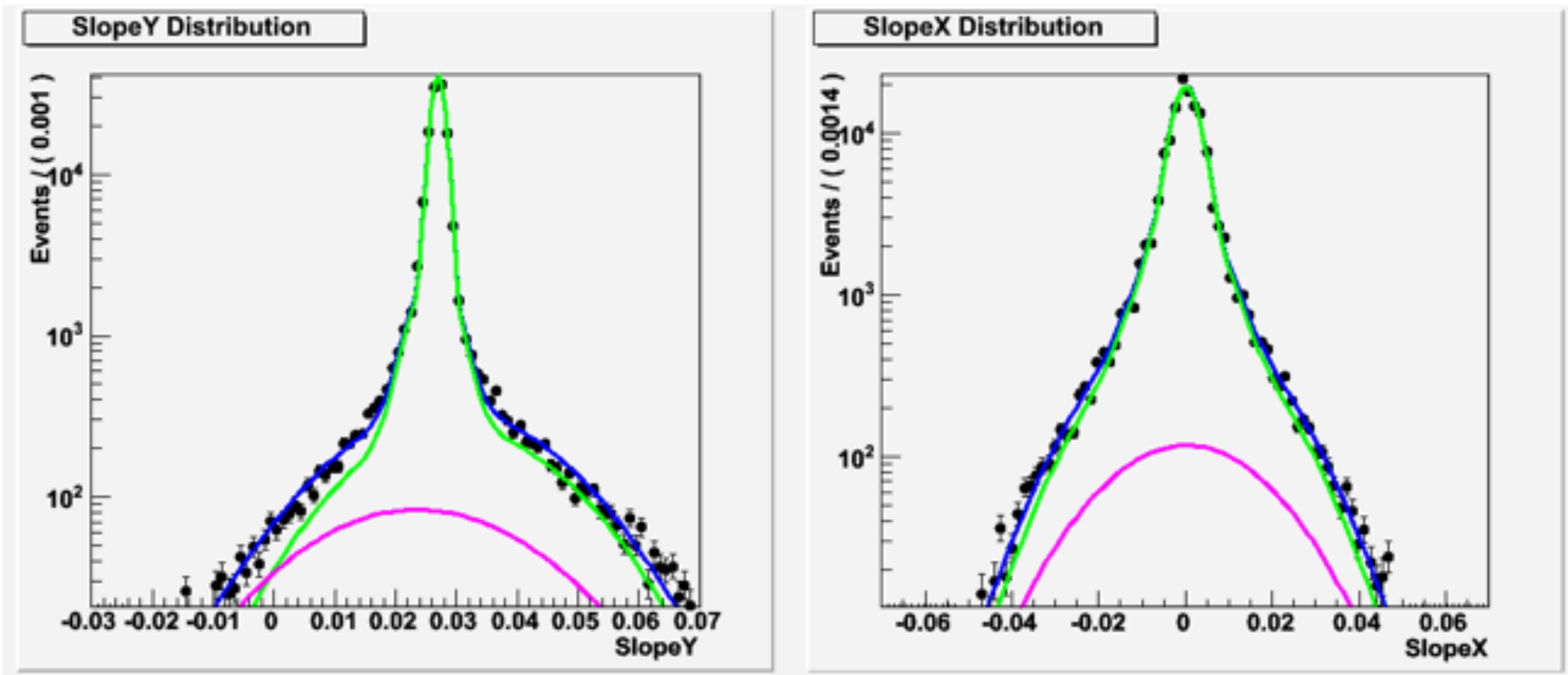
$$VdM\_X = Gaussian_{core}(\sigma_1, \mu_1) + f_1 * Gaussian_{outlier}(\mu_2, \sigma_2) + f_2 * Gaussian(\mu_3, \sigma_3)$$

SlopeY



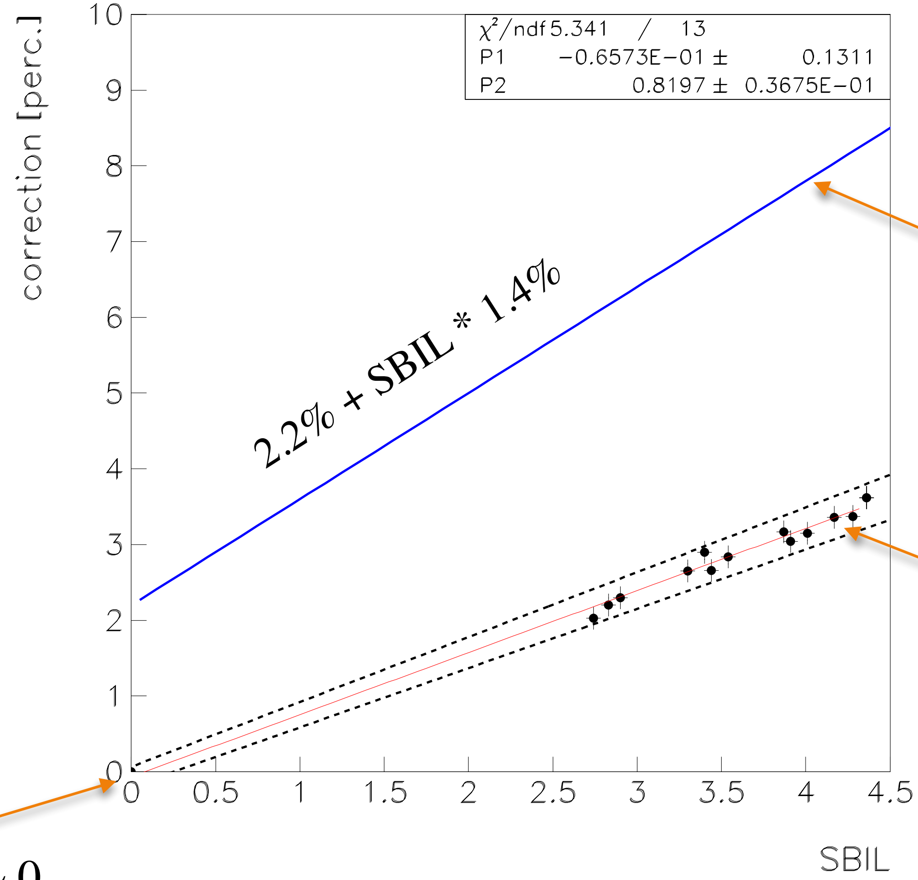
$$VdM\_Y = Gaussian_{core}(\sigma_1, \mu_1) + f_1 * Gaussian_{outlier}(\mu_2, \sigma_2) + f_2 * BiGaussian(\mu_3, \sigma_{31}, \sigma_{32})$$

Combined Fit



$$Combined\_Fit = (VdM\_X + f * Extra\_x) \times (VdM\_Y + f * Extra\_y)$$

Result

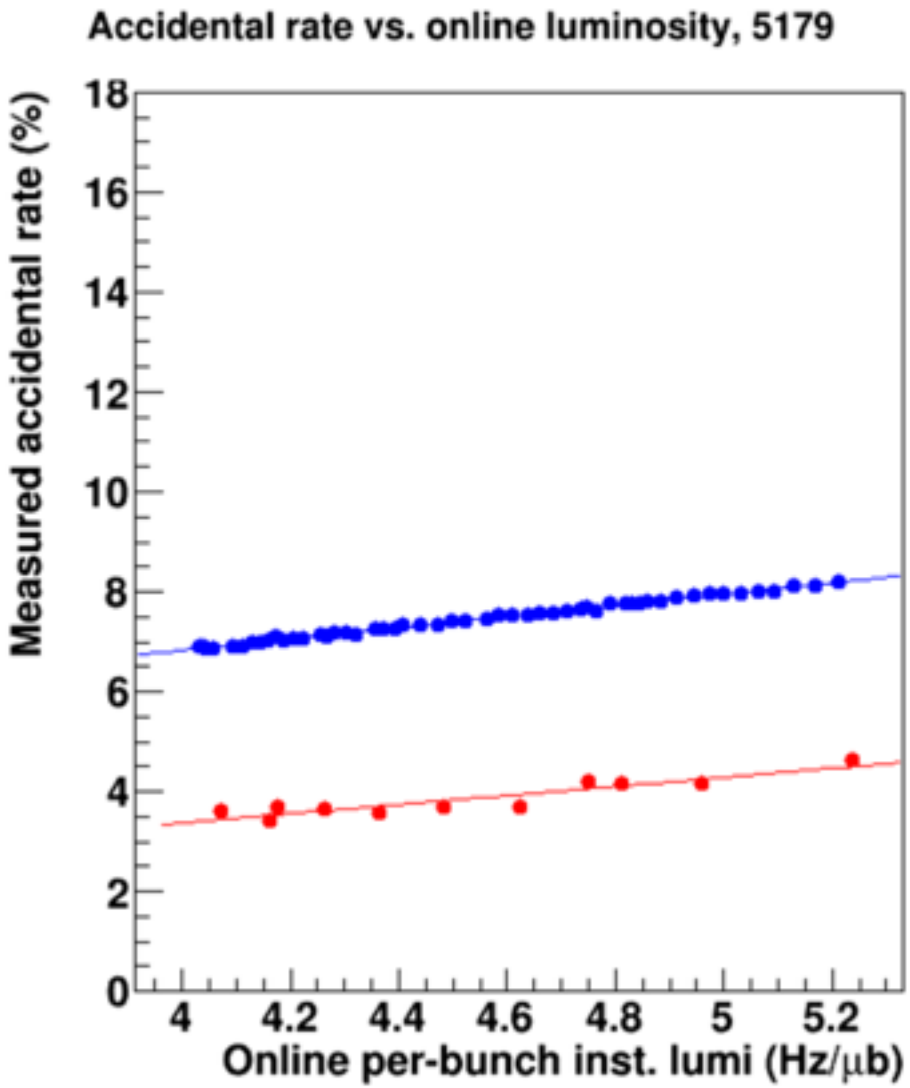


with 5 sigma cut to slopes and residuals

maximum likelihood fit to slopes

vdm at SBIL ~ 0

Result



fit to: a + b x
5sigmaCut: 2.33994 + 1.12203 * SBIL

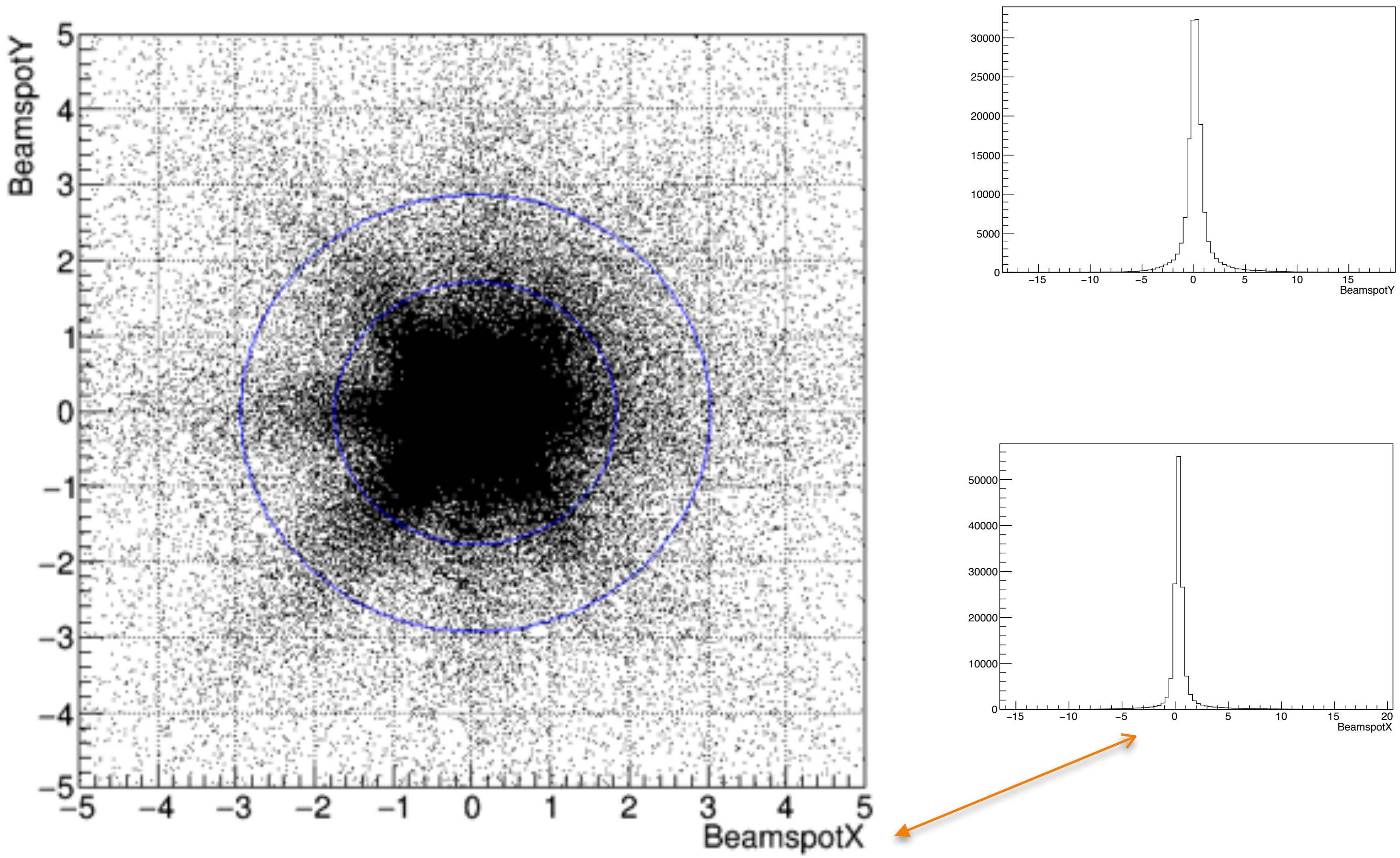
Likelihood fit: -0.259598 + 0.908623 * SBIL

Conclusion

- Operational work - track reconstruction, scripts for data visualization/validation, alarm system
- Correction to the luminosity measurement by the Pixel Luminosity Telescope (PLT) for the CMS experiment at the Large Hadron Collider was calculated for 2015 and 2016 run period using data-driven methods.
- Result from likelihood fits are used to improve the background subtraction from non luminosity contributions.

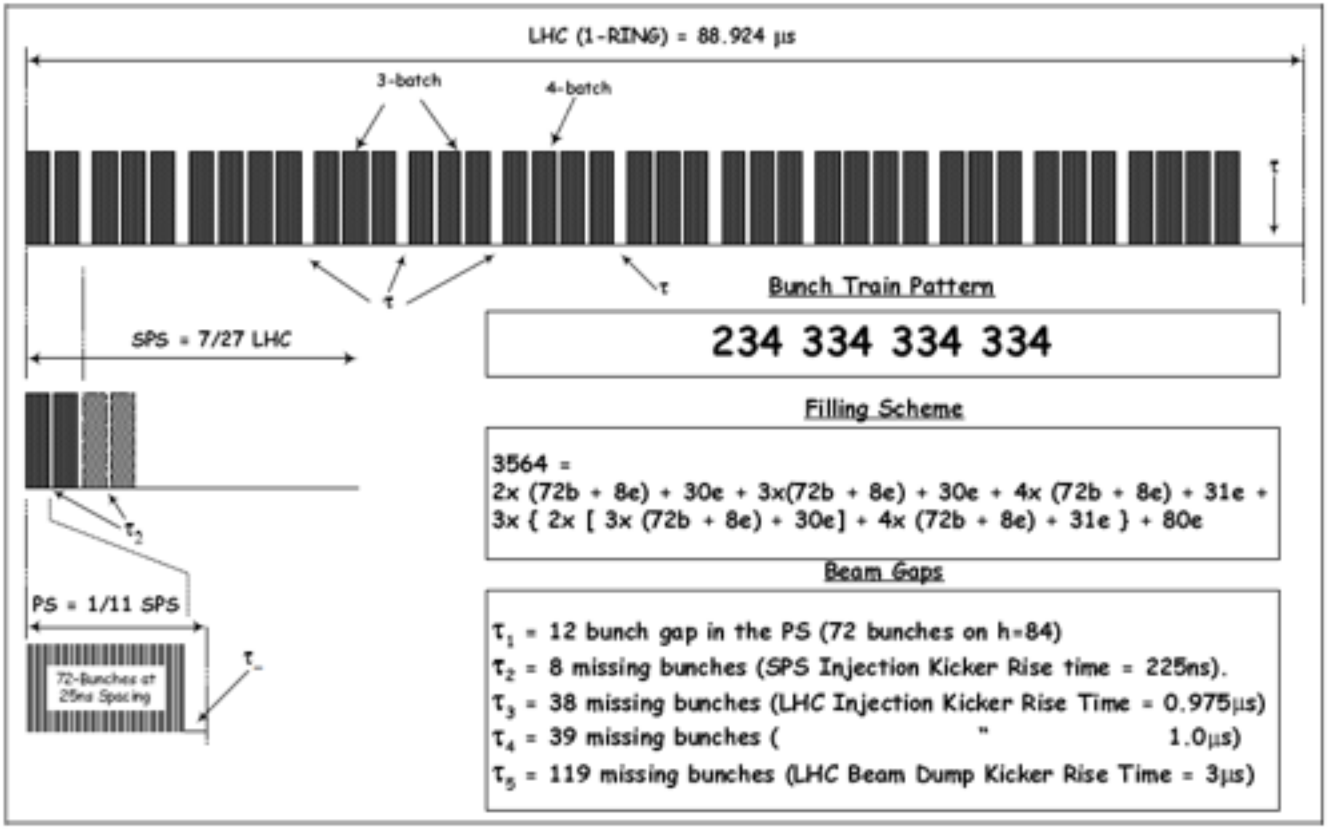
Backup

Track Reconstruction - Beamspot

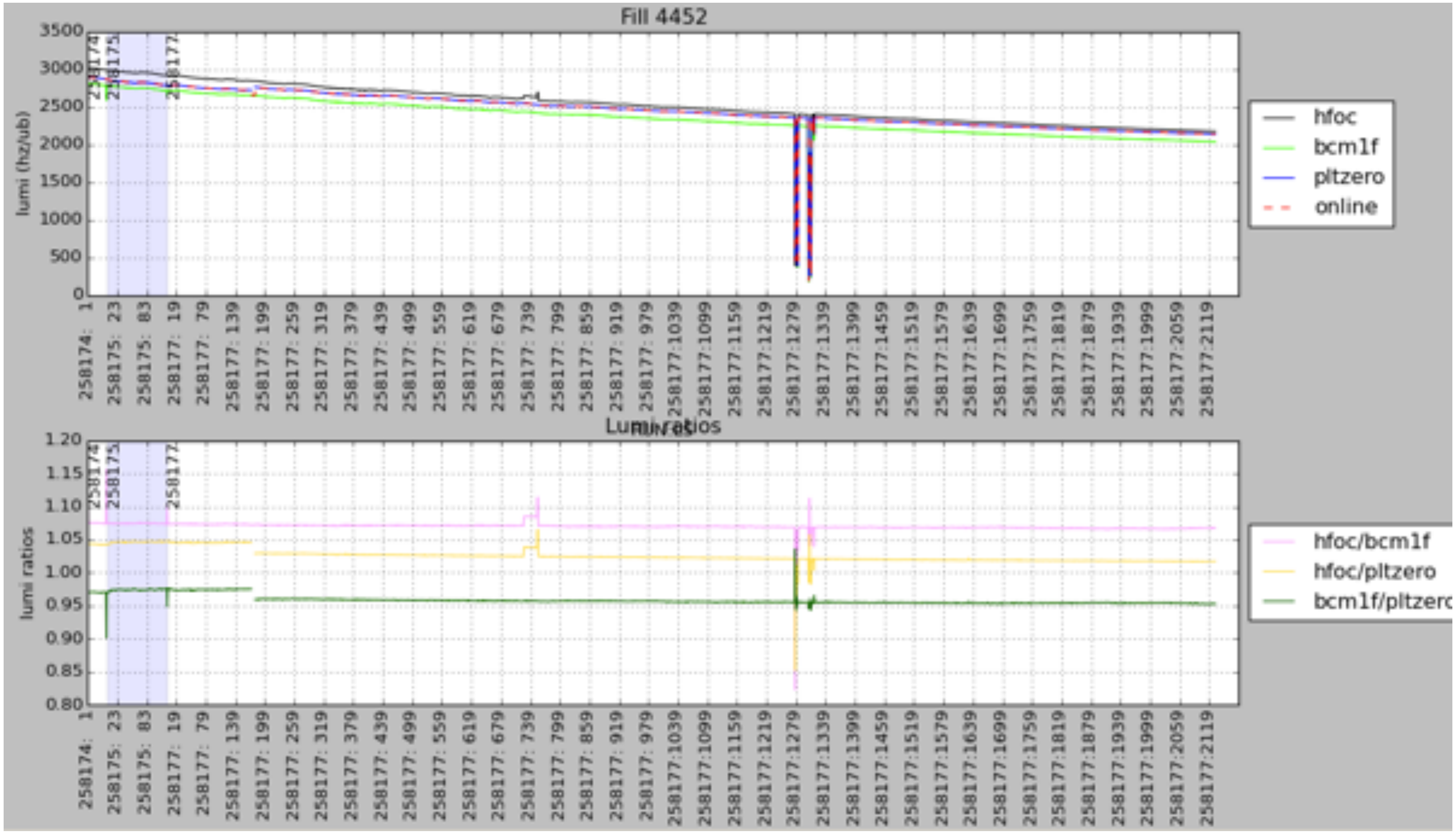


Extrapolation of tracks to z = 0 plane

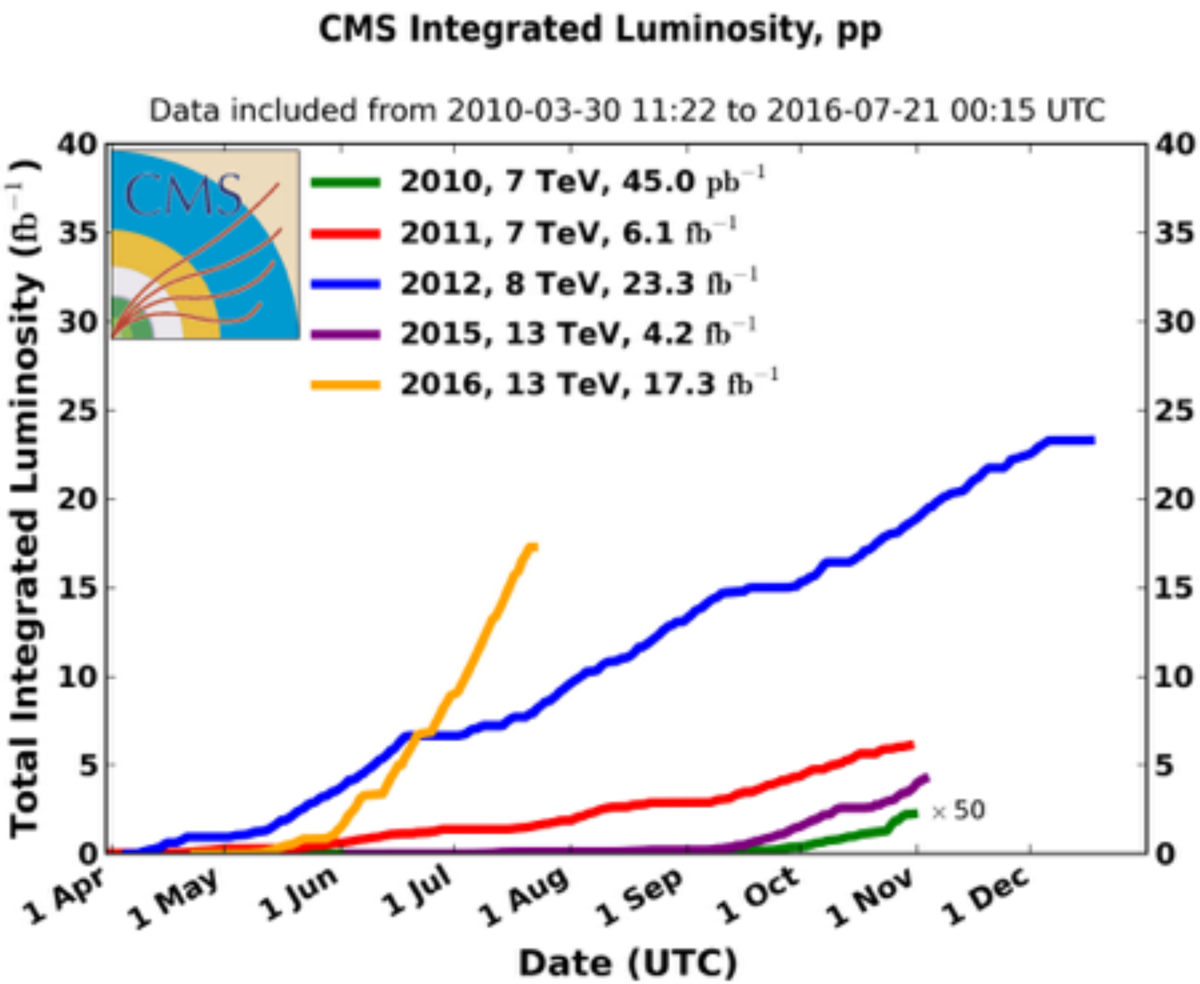
LHC Filling Scheme



Operation III - Data warehouse+Validation

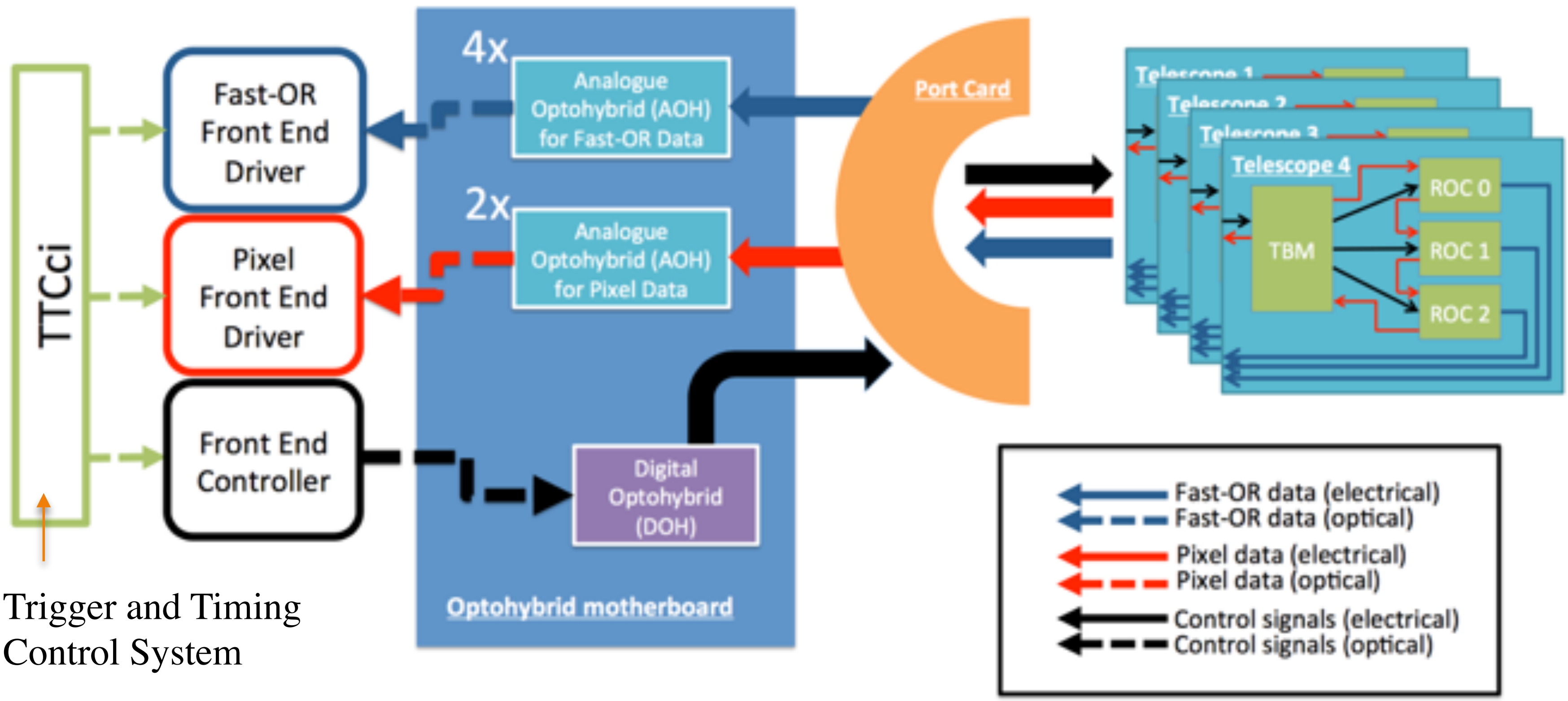


LHC Operations 2015/2016



1 barn = 10^{-28} cm^2

Read Out Chip (ROC)

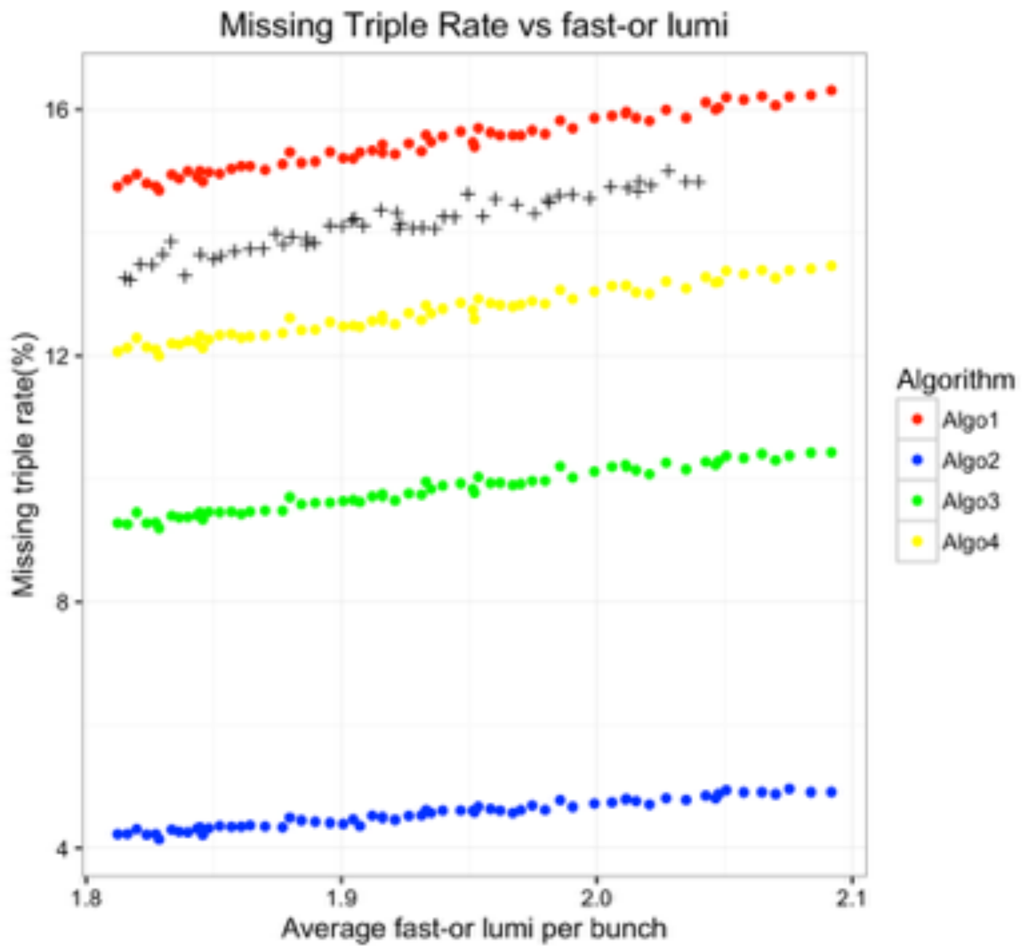


The sensors are read out by a PSI46v2 readout chip (ROC)

Each ROCs from each telescopes are connected to a HDI card, which contains the Token Bit Manager (TBM) chip that handles the readout of the series of ROCs. A port card, which manages the communication and control signals, is connected to half of the telescopes in each side which is then connected to opto- motherboard which converts the electrical signals into optical signals.

Firmware Issue

- The firmware undercounted the triple coincidences when one or more panels had more than 3 double columns hits for a given time period.
- To account for this issue, the correction was described with full pixel data. As this data contains all registered hits, the expected Fast-OR rate was calculated with events that had less than 3 hits.
- This rate can then be compared to an accurate counts from the full pixel data to get the correction factor.



Data Streams

Fast-OR Data

The 52 columns in a sensor is segmented into a group of double columns, 0-26.

Each hit on a double column is registered as a signal. For a given bunch crossing, the hits in double columns per sensor are reported to the FED which tests if there was at least one signal in each of the three planes. This triple-coincidence count rate is translated to luminosity value.

~ 40 MHz, for online luminosity

Pixel Data

Each pixel of a sensor is calibrated beforehand where some amount of charge collected can be translated to some number of hits.

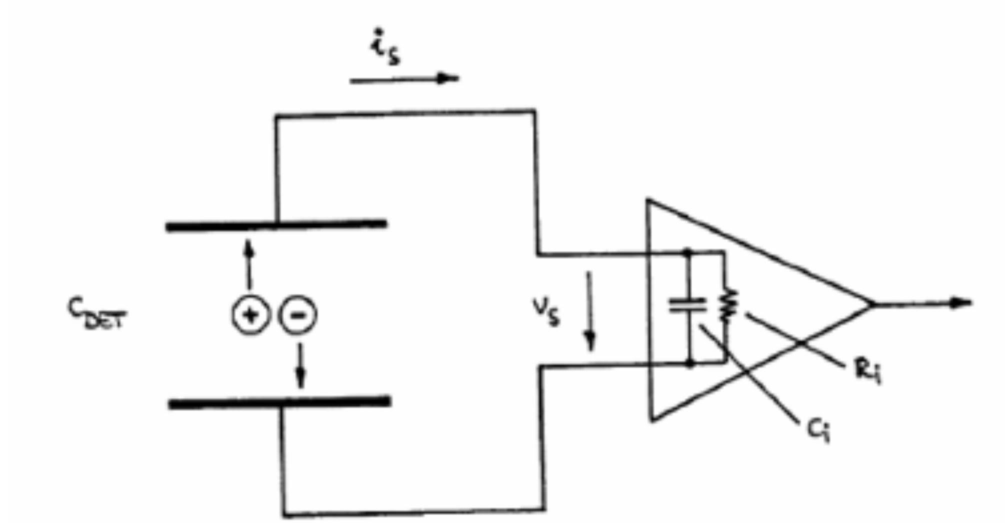
Once a sensor registers a charge signal above some threshold value, the pulse height and pixel address together with the timestamp information is saved to a buffer.

Once the pixel detector receives a valid external signal trigger, the information is transferred to the FED via optical connections.

~ 2-3 KHz, to reconstruct tracks, separate particles coming from the interaction point and from background particles of the beam halo, presenting a powerful tool to determine systematic corrections and measure pixel efficiencies.

Operation Principle

- A particle deposits some of it's energy on the detector medium creating e/h pairs
- Charges move in an electric field → electrical current in an external circuit



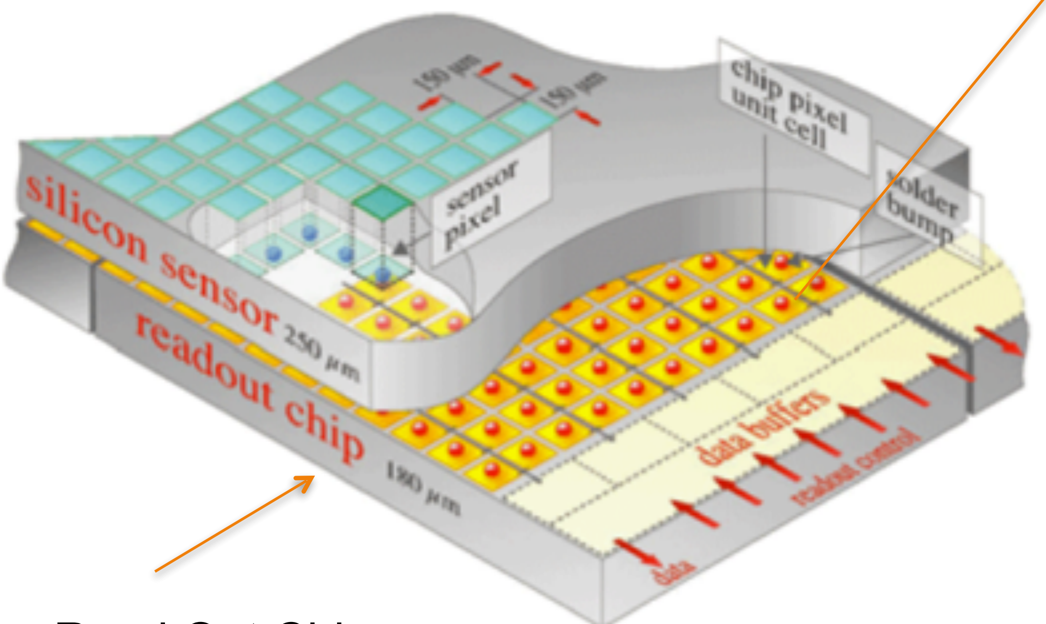
- For particle posi ,
semiconductor detectors
- Ionization energies for gas ~ 20 - 30 eV

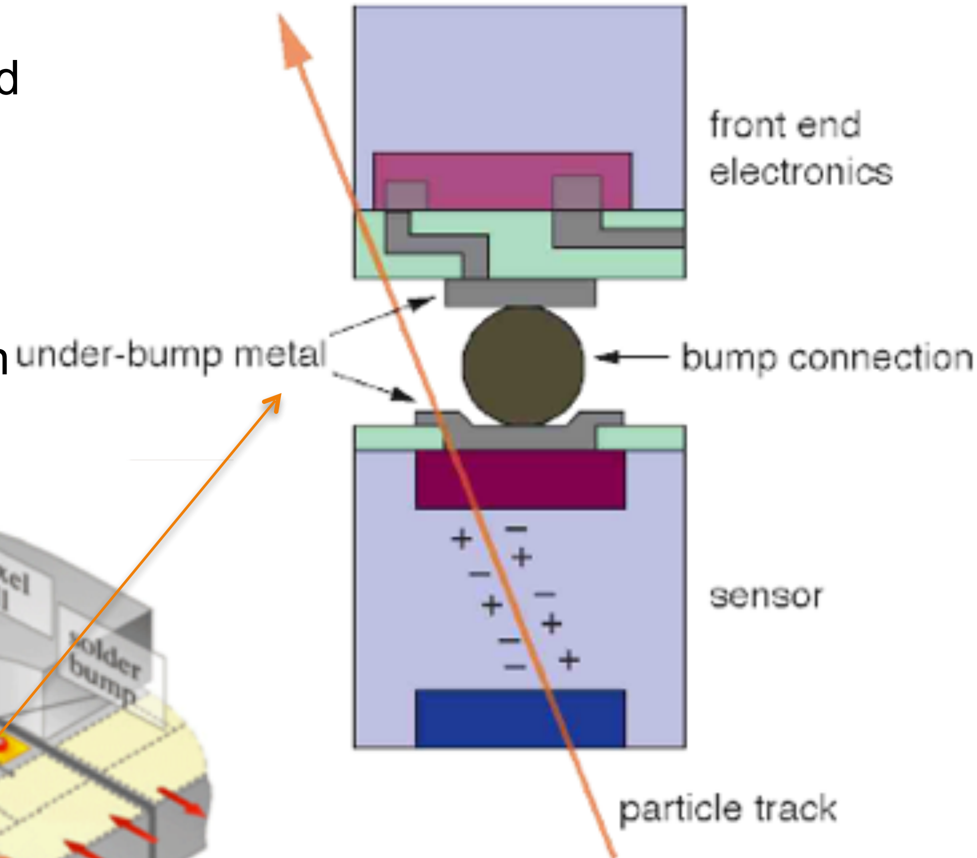
  for semiconductors ~ 1 - 5 eV

Pixel Detectors

Number of thermal e/h pairs created are four orders of magnitude larger than signal for MIP.

Have to remove charge carrier → depletion zone in reverse biased pn junctions





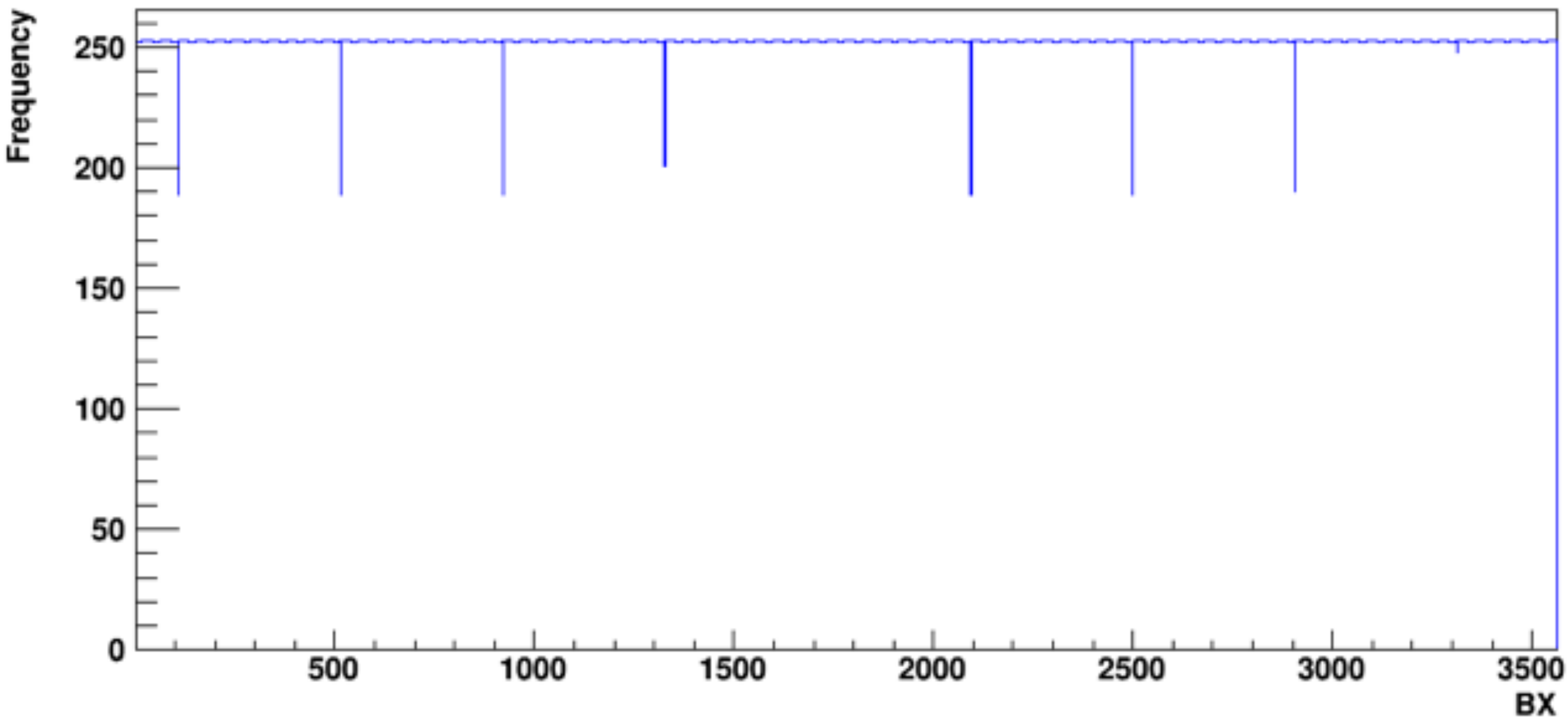
Read Out Chip

L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

Random Trigger

A trigger is used to reduce the amount the data to a more manageable rate.

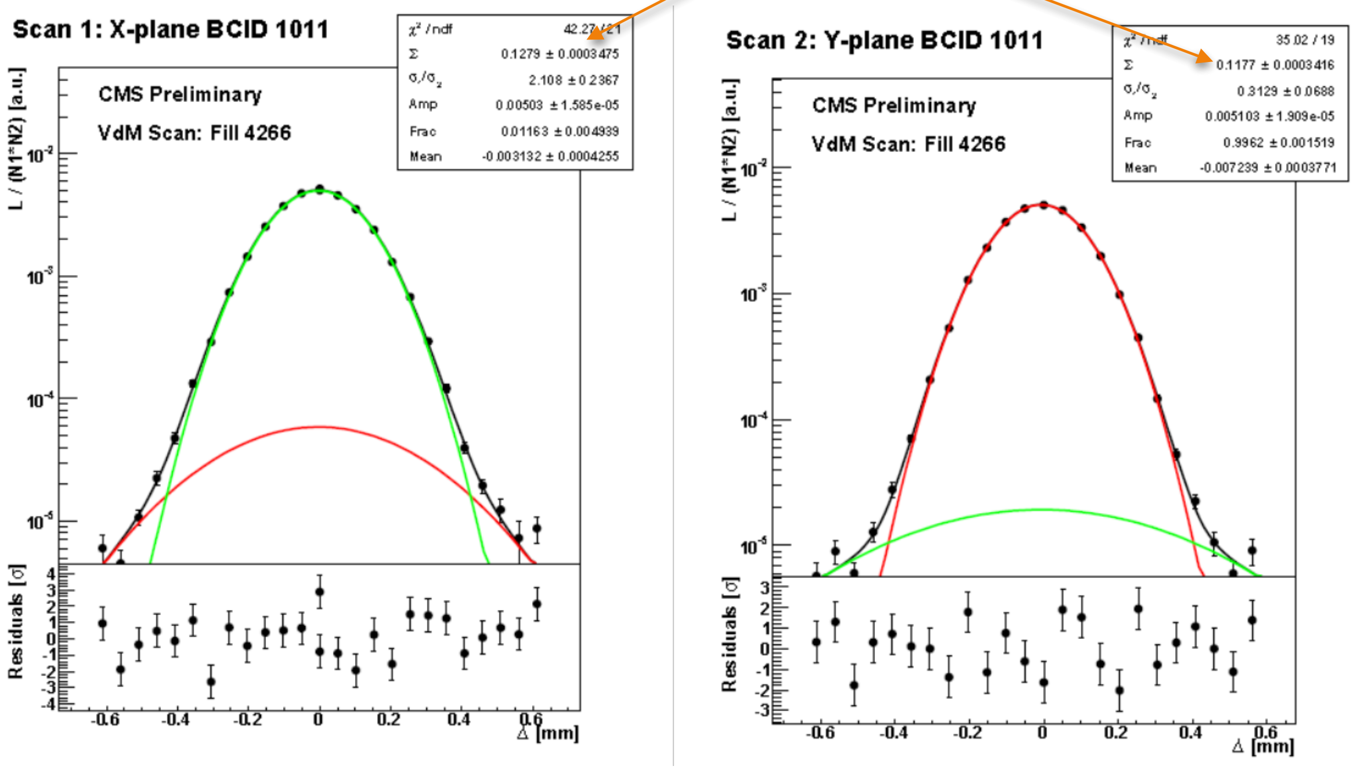
A trigger generated by taking an OR of the fast-or coincidence signals from all of the channels was used in the early 2015 run to maximize the pixel data taken.



A purely random trigger at a rate of 2 kHz was used to avoid any systematic uncertainties in the trigger that could have been introduced by our choice of using fast-or signals for trigger signals.

Calibration via VdM scans

σ_x, σ_y ==> A_{eff}



- Scan beam1, beam2 along x, y direction
- At head-on collision, largest number of pp collision ==> center of beam cross section
- Double gaussian makes a better fit than a single