Mapping the CMS inner tracking system with unprecedented precision

Phil Baringer[(1)], Zach Flowers[(1)], Maxime Gouzevitch[(2)], and Anna Kropivnitskaya[(1)]

on the behalf of CMS collaboration

[(1)]University of Kansas

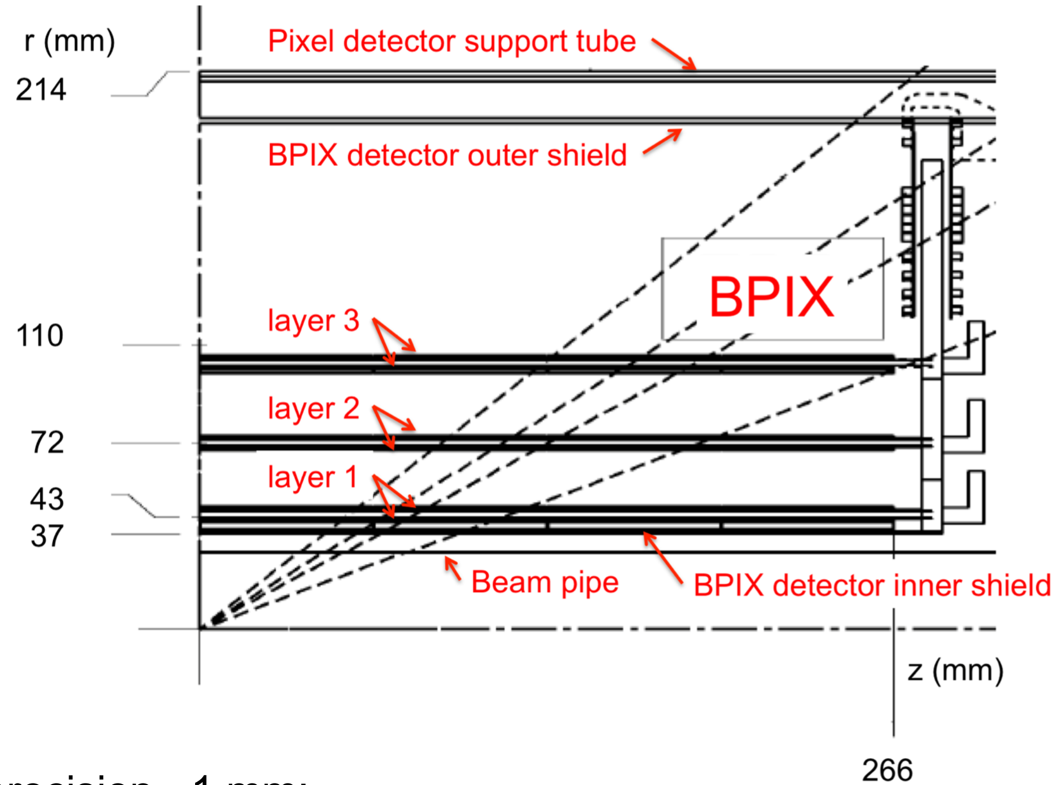
[(2)] Institut de Physique Nucleaire de Lyon

Mapping with Nuclear Interactions (NIs)

NI mapping is important for:

- track position resolution
  → b tagging performance;
- search for long-lived particles;
- CMS tracker upgrade designs:
  an accurate measurement
  for the beam pipe position
  → safe installation of Phase-1
  pixel in Spring 2017;
- Beam pipe could be shifted
  during data taking;

Original barrel pixel detector (BPIX) :



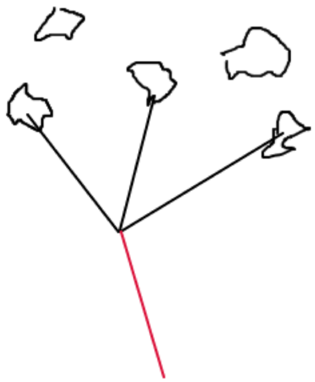
- Survey group using optical tools: precision ~1 mm;
- NI provides measurements during CMS operation on the sub mm level.

Selection and Reconstruction

p-p collisions at 13 TeV from the single muon collection:

- Study with 2015 re-reconstructed data (2.5 fb^{-1}), published in JINST October 2018:
  http://dx.doi.org/10.1088/1748-0221/13/10/P10034

- Study with part of 2018 prompt-reconstructed data (4.3 fb^{-1}):
  CERN-CMS-DP-2019-001: http://cds.cern.ch/record/2664786?ln=en

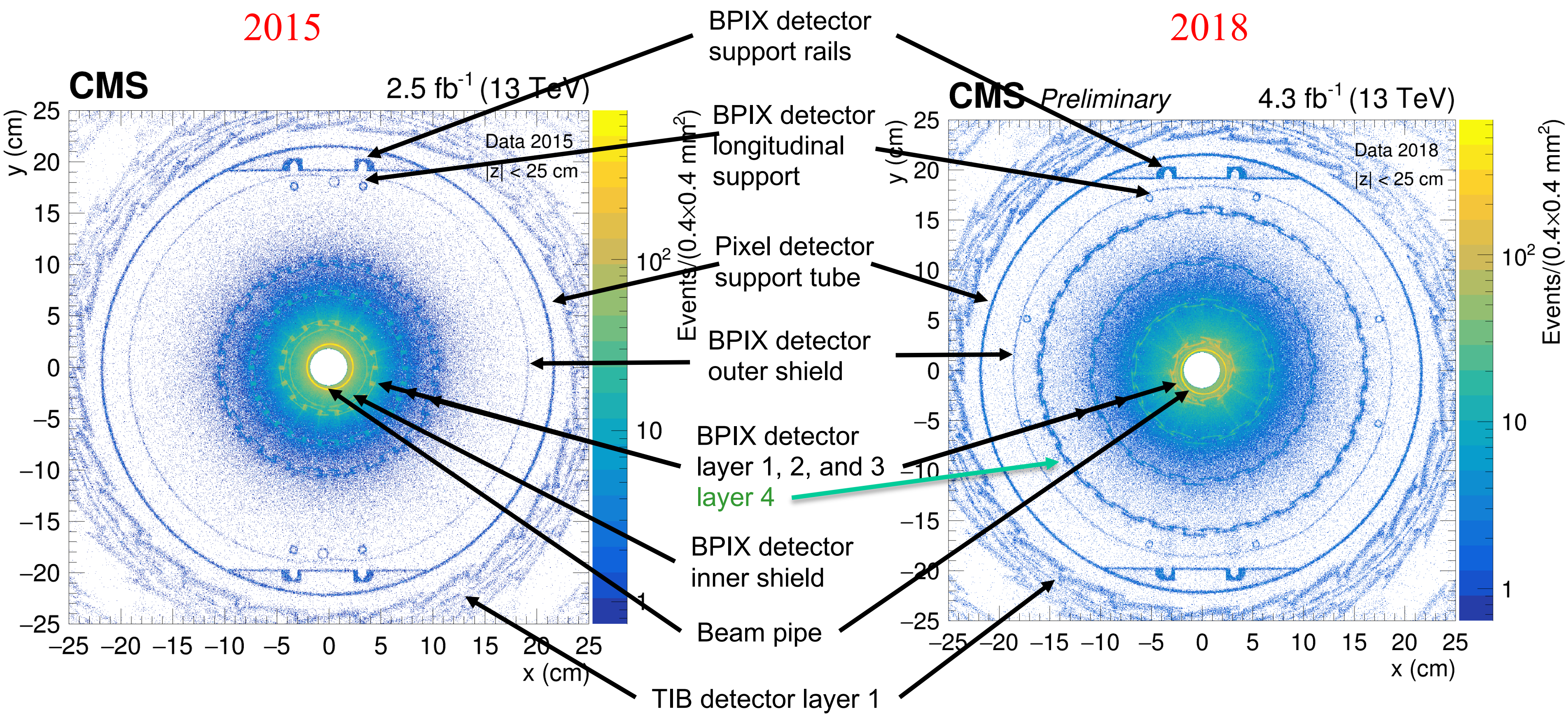


NI displaced secondary vertex requirements:

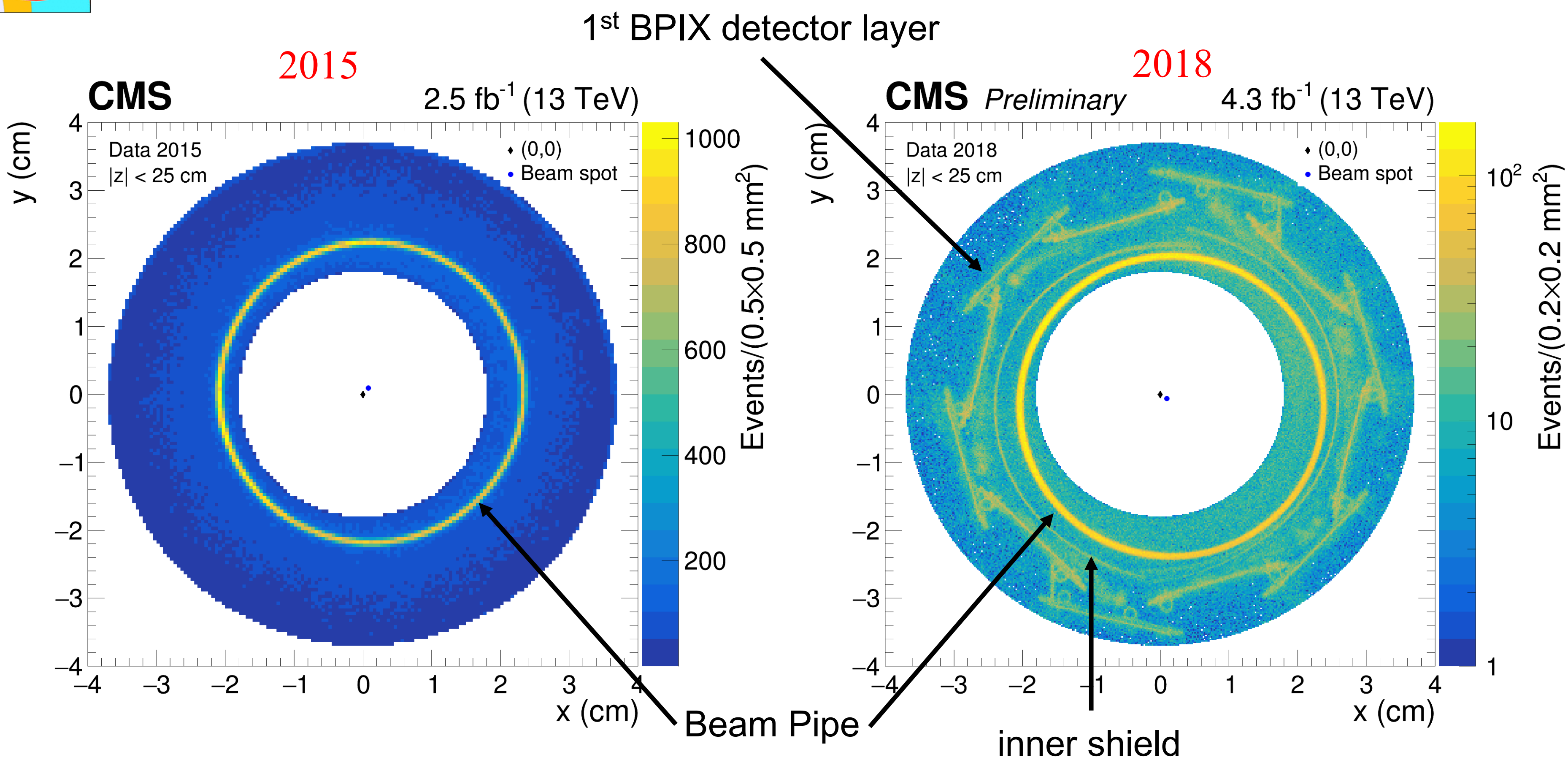
- at least 3 tracks incoming or outgoing from the vertex;
- invariant mass of the outgoing system > 1 GeV

to suppress light mesons, baryons, and photon conversions.

Inner Tracker Hadrography x-y Plane



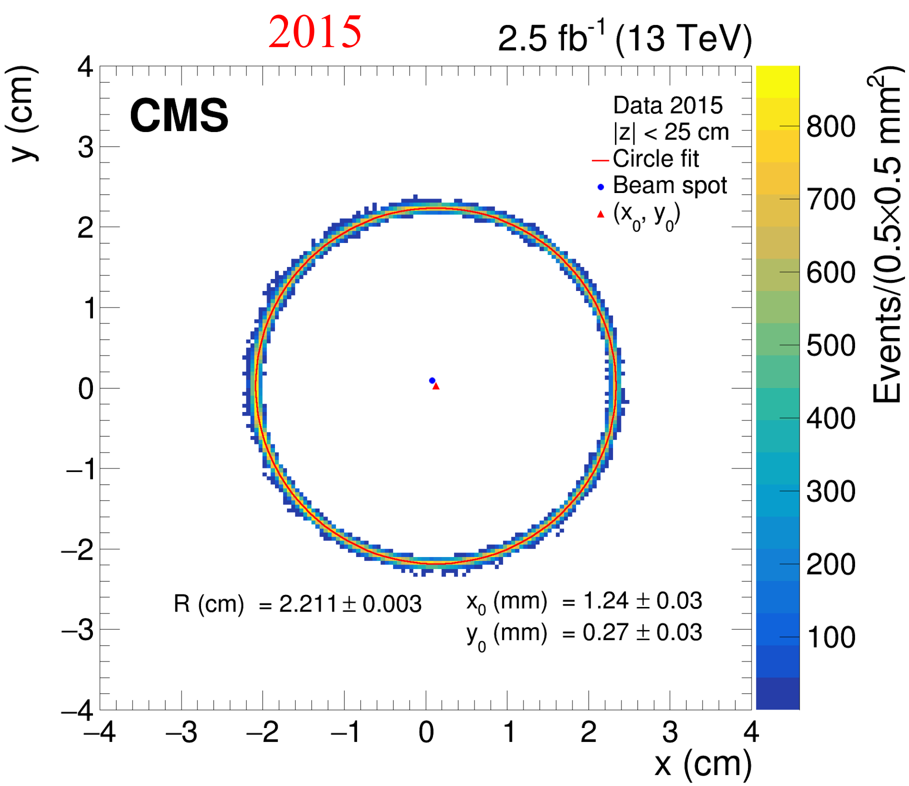
Beam Pipe Region x-y Plane

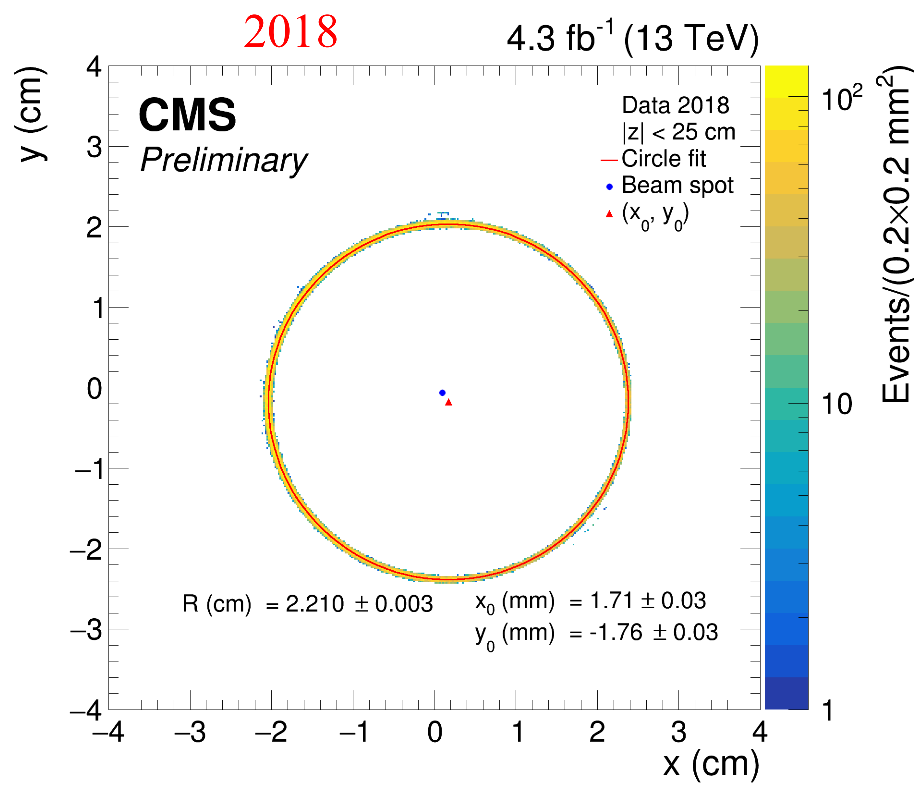


- Beam spot: (0.8;0.9) mm for 2015 and (1.0;-0.6) mm for 2018.
- Regions with r < 1.8 cm & r > 3.7 cm were removed.
- In 2018 Phase-1 pixel is closer than original pixel in 2015.

Fit Results: Beam Pipe x-y Plane

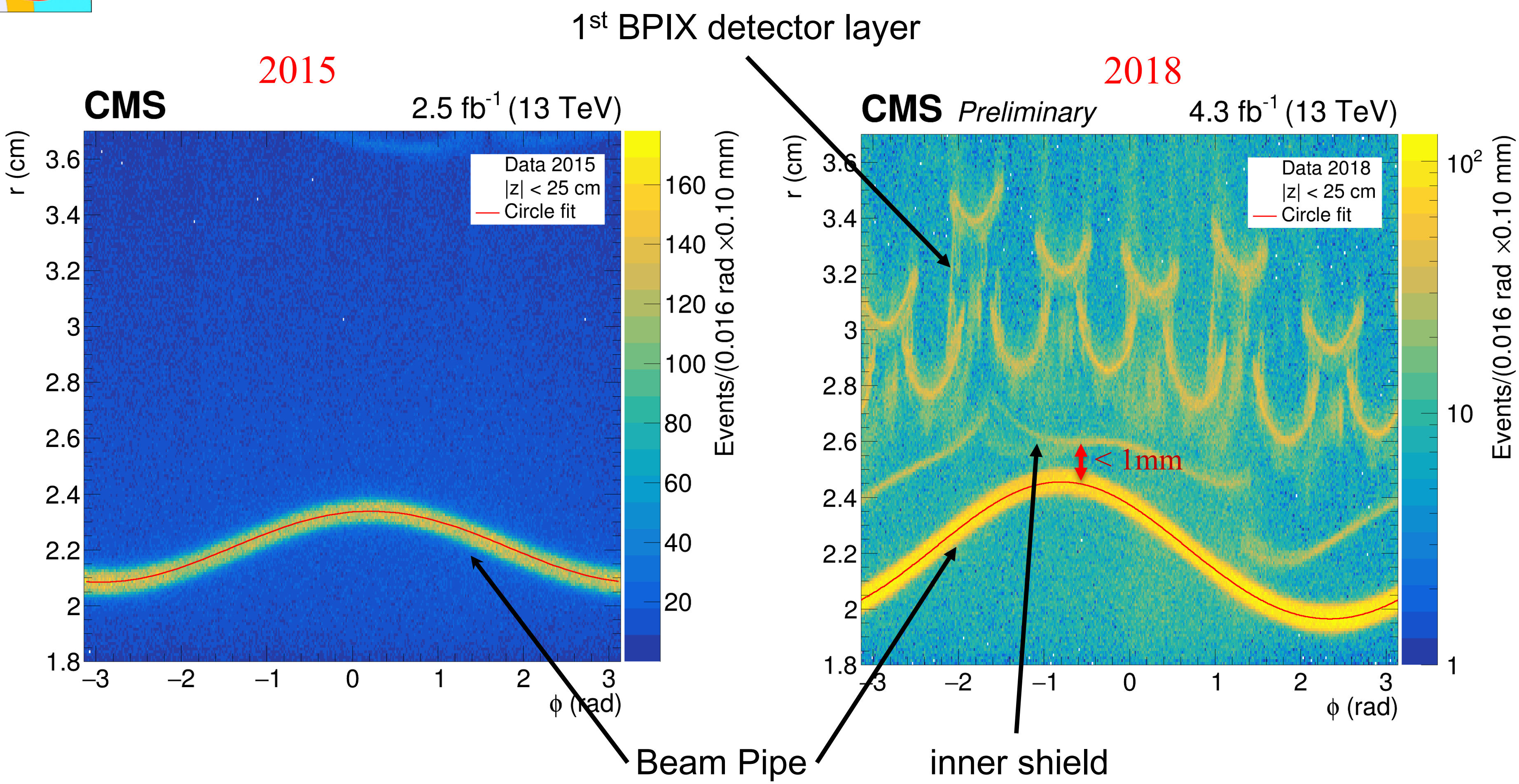
The beam pipe is fit with a circle of radius R and center (x_0, y_0) after background subtraction





- From 2015 to 2018 the survey group moved the beam pipe by around 2.3 mm (0.5 mm is survey resolution) downward in y to correspond to the new position of the beam. NI measurements confirm this shift.

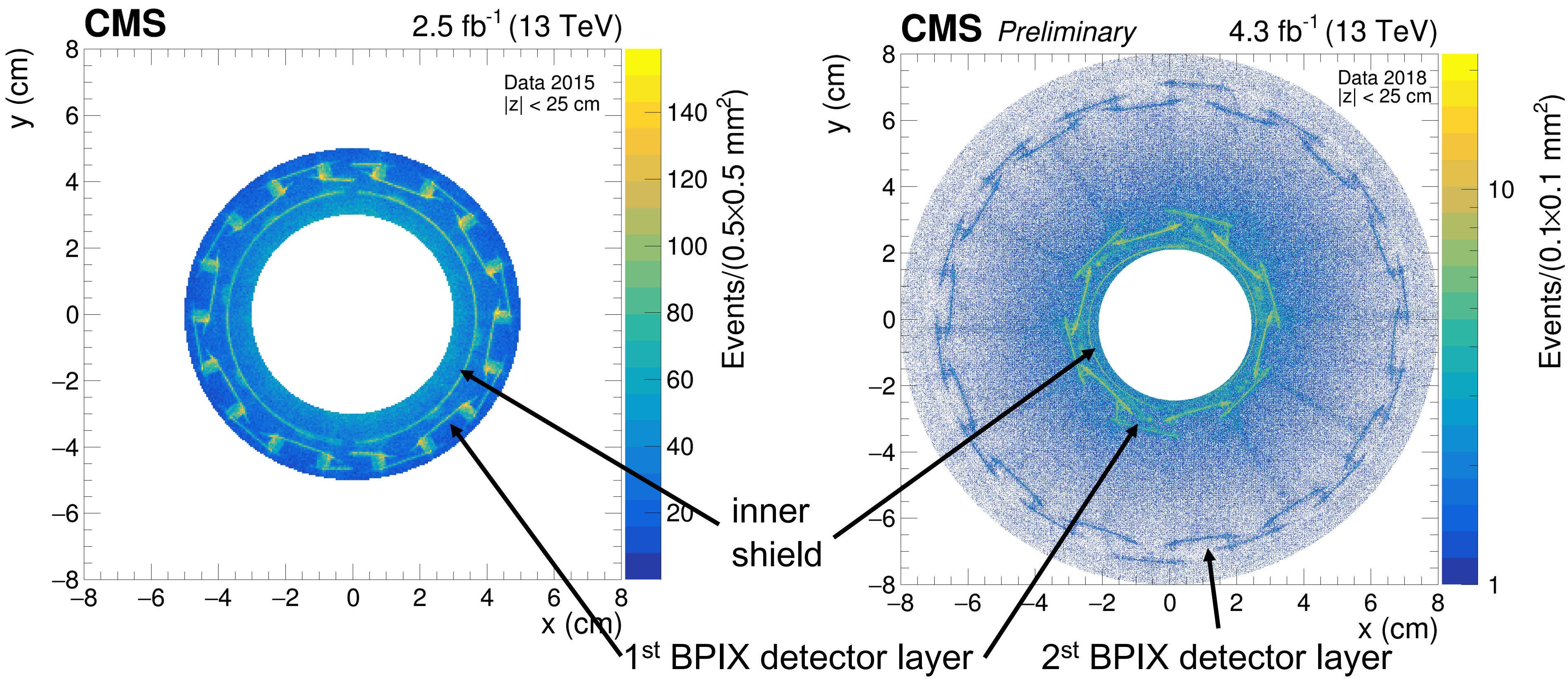
Fit Results: Beam Pipe ϕ-r Plane



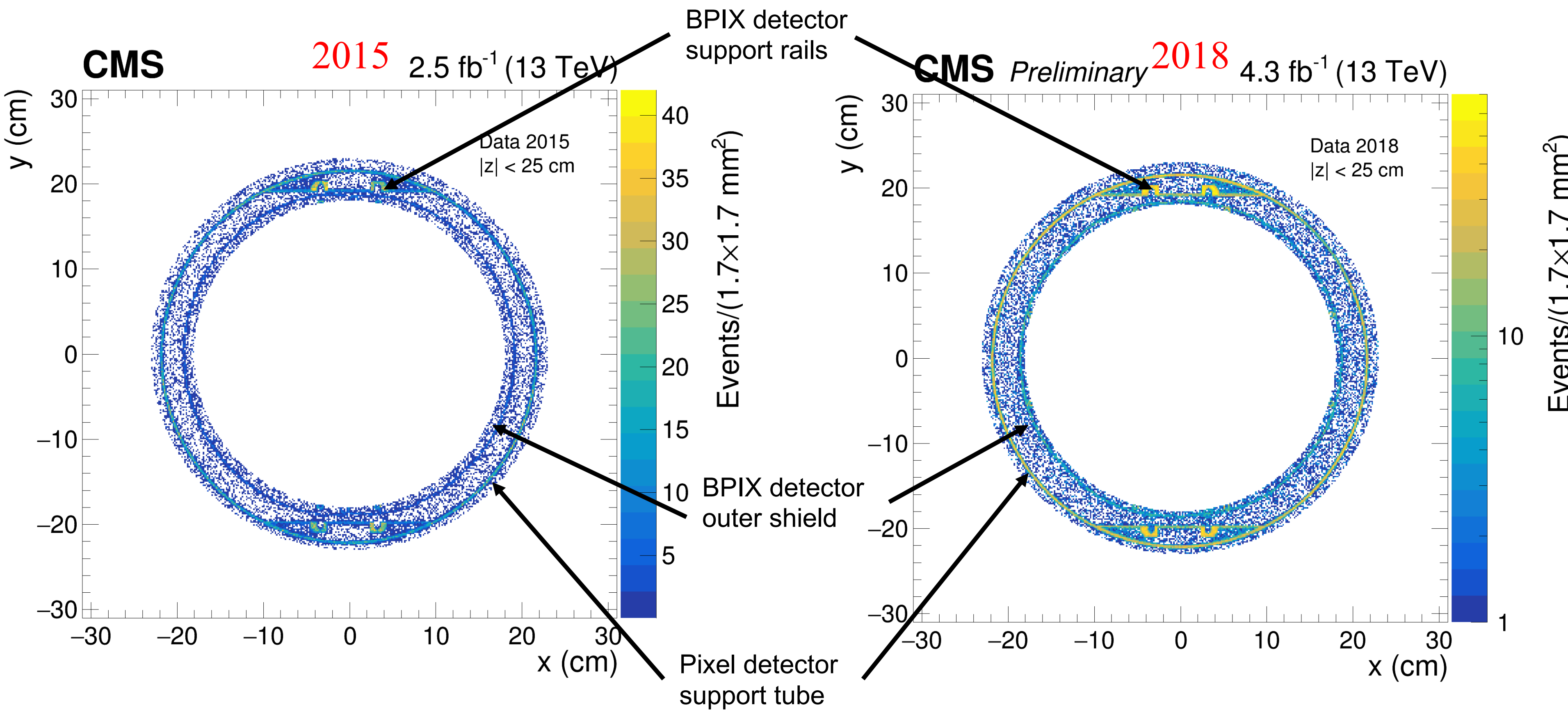
- Sinusoid shape indicates it is offset from CMS center (0; 0).
- Be careful for 2018: in some places distance between beam pipe and shield is less than 1mm.

Inner Part of BPIX Detector

Original BPIX detector (2015) vs. Phase-1 BPIX detector (2018)

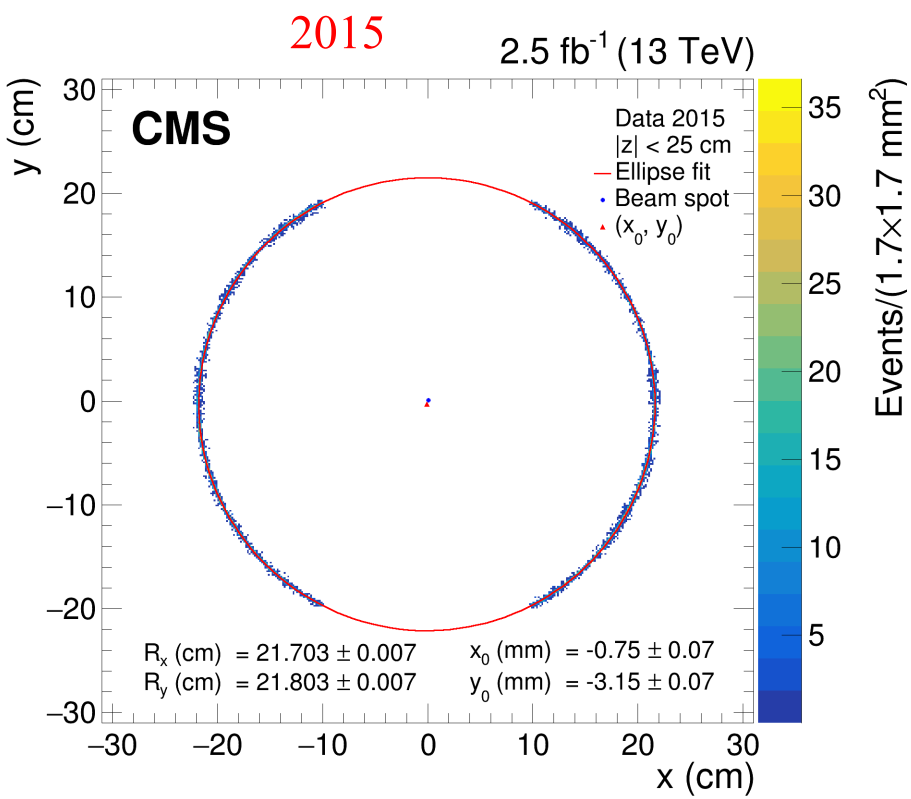


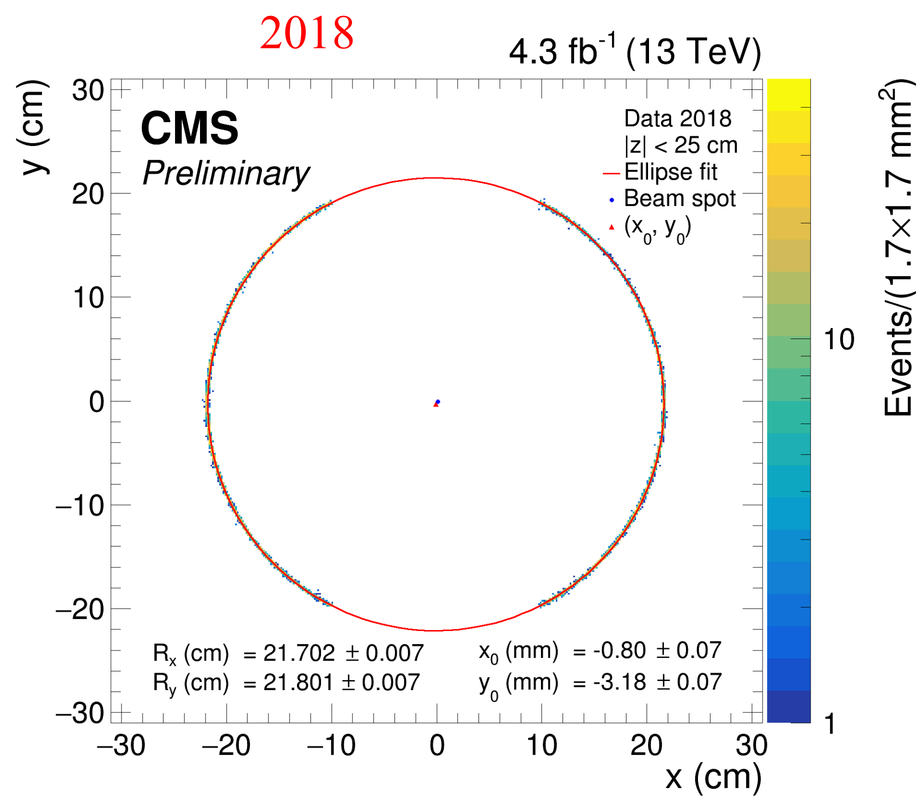
Pixel Detector Support Tube x-y Plane



Fit Results: Pixel Detector Support Tube x-y Plane

The pixel detector support tube is fit with an ellipse
with R_x & R_y, and center (x_0, y_0) after background subtraction

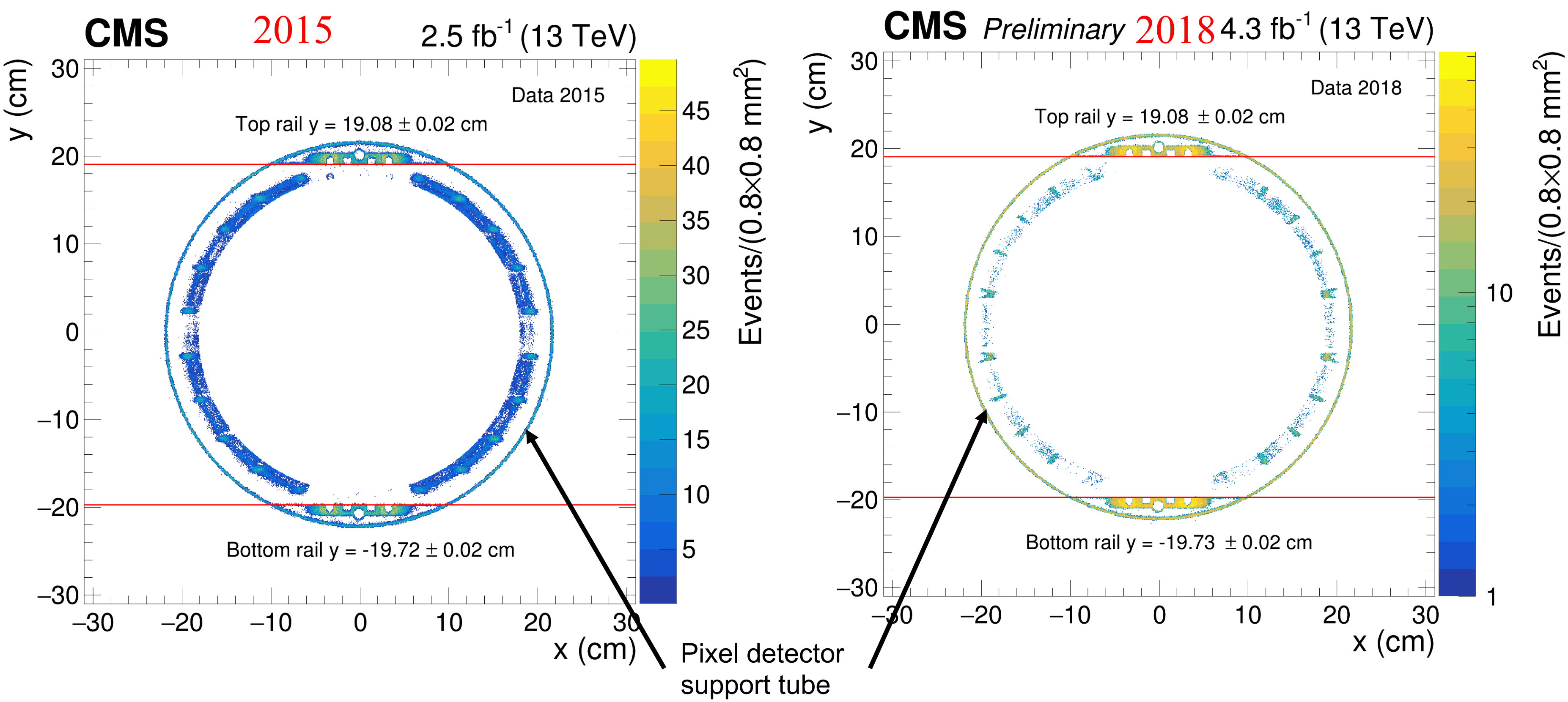




- The position didn't change from 2015 to 2018 as expected: it wasn't moved since installation.

Fit Results: BPIX Detector Support Rails

The combined tracking detector barrel and endcap regions after background subtraction



- The position of the BPIX detector support rails is defined by its inner edge.
- It is estimated by maximizing the derivative of the density of nuclear interactions in y.
- Its position didn't change from 2015 to 2018 as expected: it wasn't moved since installation.

Results

A summary of the measurements and their uncertainties:
statistical (negligible) $\oplus$ systematic uncertainties

Object	R (cm)	x_0 (mm)	y_0 (mm)
Beam pipe (published 2015)	2.211 ± 0.003	1.24 ± 0.03	0.27 ± 0.03
Beam pipe (preliminary 2018)	2.210 ± 0.003	1.71 ± 0.03	-1.76 ± 0.03

Object	R (cm)	x_0 (mm)	y_0 (mm)
Pixel detector support tube (published 2015)	R_x: 21.703 ± 0.07 R_y: 21.803 ± 0.07	-0.75 ± 0.07	-3.15 ± 0.07
Pixel detector support tube (preliminary 2018)	R_x: 21.702 ± 0.07 R_y: 21.801 ± 0.07	-0.80 ± 0.07	-3.18 ± 0.07

BPIX detector support rails **(published 2015)**	
Bottom (cm)	Top (cm)
-19.72 ± 0.02	19.08 ± 0.02

BPIX detector support rails (preliminary 2018)	
Bottom (cm)	Top (cm)
-19.73 ± 0.02	19.08 ± 0.02

- Only systematic uncertainties are provided, since statistical uncertainties are negligible.
- The structures are measured with sub mm precision.

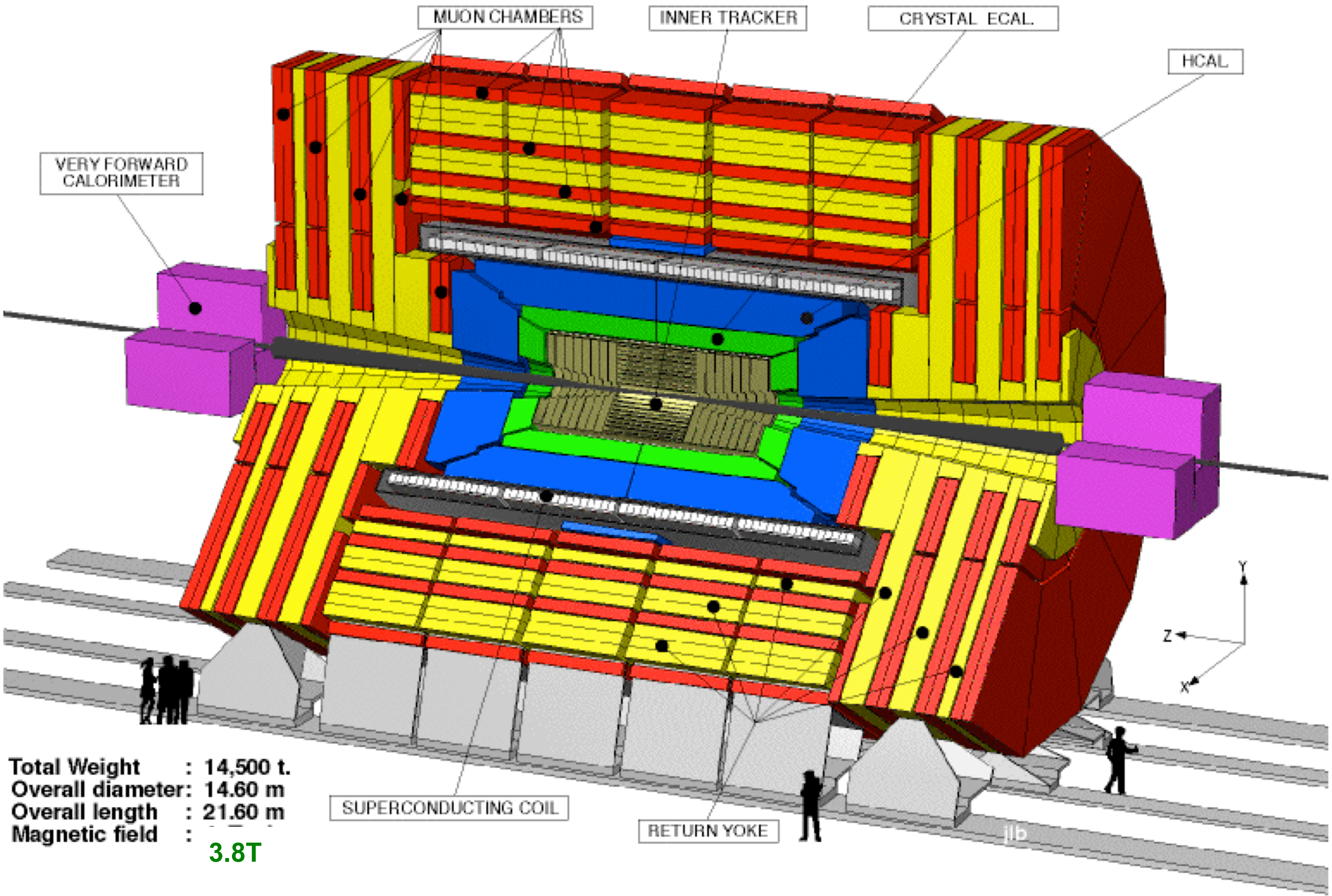
Summary

- The positions of the beam pipe, pixel detector support tube, and BPIX support rails were measured with sub mm precision.
- From 2015 to 2018 the beam pipe was moved by around 2 mm downward in y to correspond to the new position of the beam. NI and survey measurements confirm this shift.
- Phase-1 pixel detector is much closer than original one to the beam pipe: at some places distance less than 1 mm.
- Pixel detector support tube and BPIX support rails positions didn't change from 2015 to 2018 as expected: they weren't moved since installation.

Thanks to NSF support

Back up slides

CMS Detectors

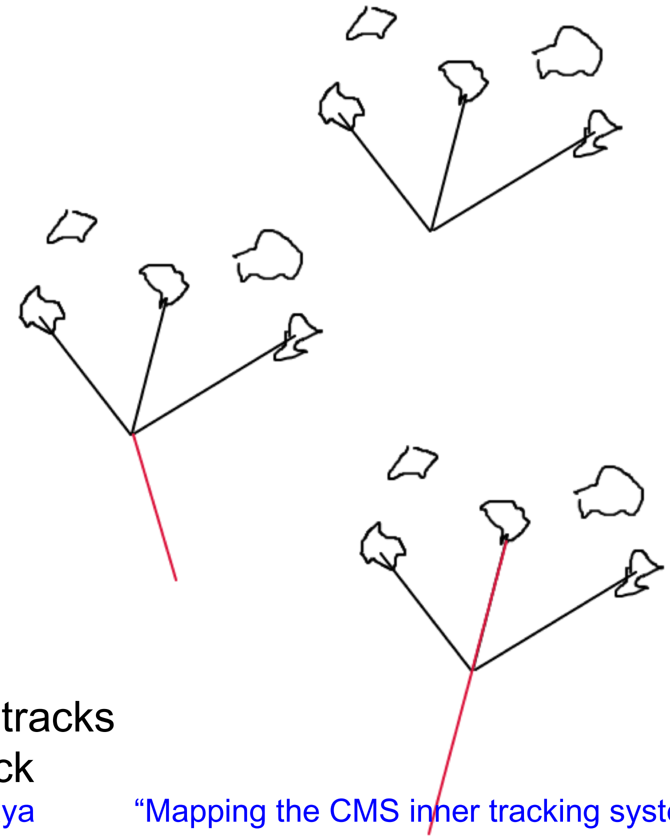


Nuclear Interactions

Nuclear interactions (NIs) are interactions of hadrons (pions, kaons, protons,…) with material.

The identification of an NI relies on the reconstruction of displaced secondary vertices. The applied set of quality criteria includes: at least 3 tracks incoming or outgoing from the vertex, invariant mass of the outgoing system larger then 1 GeV (to suppress decays-in-flight of light mesons and baryons as well as photon conversions).

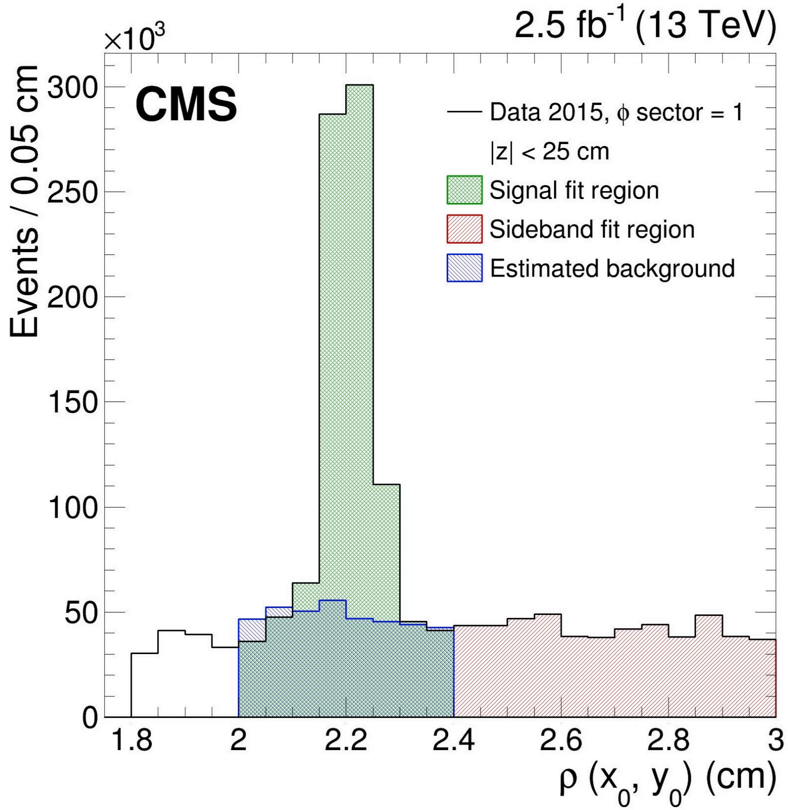
- NI with at least 3 outgoing tracks and no incoming track:
  - NI before first 2 pixel layers
  - NI induced by neutral hadrons
- NI with 1 incoming track and at least 2 outgoing tracks:
  - NI after 2 pixel layers and induced by charged hadron
- NI with 1 « merged » track and at least 2 outgoing tracks:
  - NI after 2 pixel layers and induced by charged hadron, with one of the outgoing tracks having similar momentum to incoming track



Beam Pipe Fit

To measure the beam pipe radius and position we perform a fit using a circle within the signal region from 2.0 to 2.4 cm in $\rho = \sqrt{(x-x_0)^2 + (y-y_0)^2}$, where x_0 and y_0 are the coordinates of the center.

Before fitting we have subtracted combinatorial background in the signal region:
- (BG +2√BG) for 2015,
- 2×BG for 2018 to suppress contribution from inner shield, which is very close to beam pipe, is subtracted from the 2D (x-y) plot before the fit, where BG is the estimated background.



To estimate the background we have divided the 2D (x-y) plot into 40 slices in ϕ and plotted as a function of ρ. We have fit each slice with an exponential function, $|p_1|\exp(p_2\rho)$, in the sideband region from 2.4 to 3.0 cm and extrapolated it into the single region.

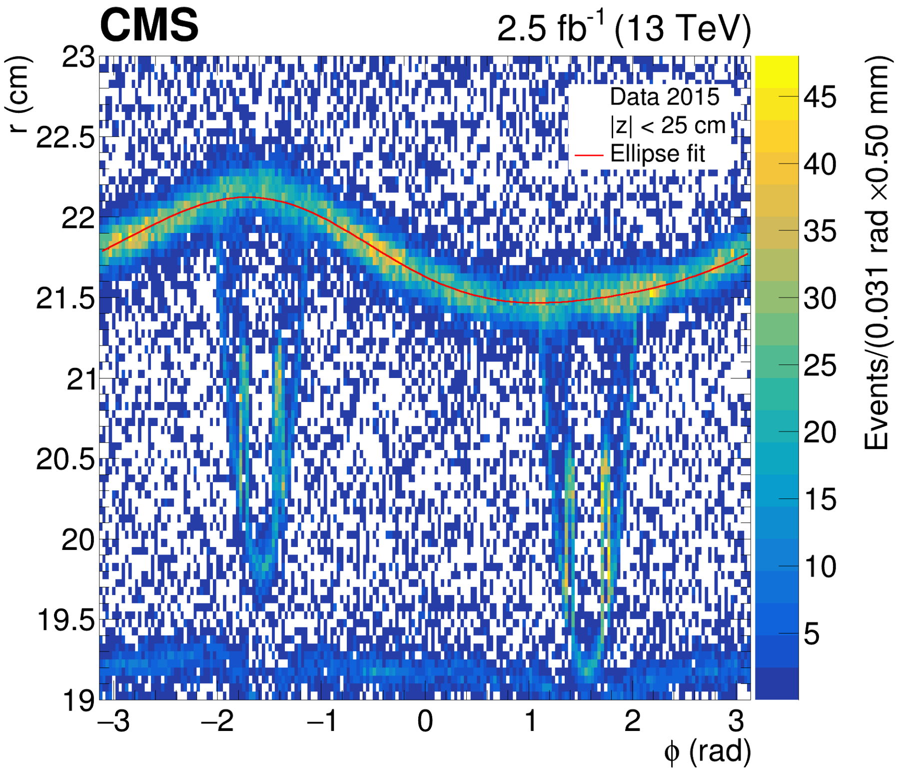
Pixel Detector Support Tube Fit

To measure the pixel detector support tube radius and position we performed a fit with an ellipse within the signal region from 21.1 to 22.3 cm in $\rho = \sqrt{(x-x_0)^2 + (y-y_0)^2}$, where x_0 and y_0 are the coordinates of the center.

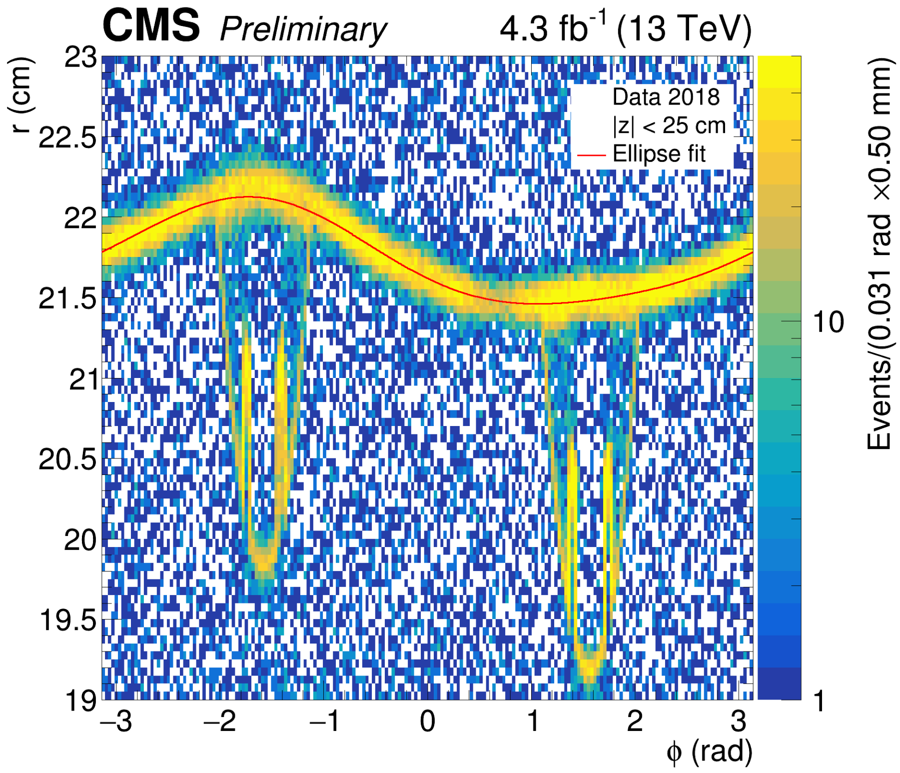
Before fitting, we have subtracted the combinatorial background in the signal region.
To estimate the background we have divided the 2D (x-y) plot into 40 slices in ϕ and plotted as a function of ρ. We have fit each slice with an exponential function, $|p_1|\exp(p_2\rho)$, in the sideband region from 19.6 to 21.1 cm and extrapolated it to the signal region.
$(BG + 2\sqrt{BG})$ is subtracted from the 2D (x-y) plot before the fit, where BG is the estimated background. Additionally, we have removed ϕ slices with extra structures in the signal region.

Fit Results: Pixel Detector Support Tube ϕ-r Plane

2015



2018



The structure with radius around 21.5-22.5 cm corresponds to the pixel detector support tube.

Systematic Uncertainties Sources

The same systematic checks for beam pipe and pixel detector support tube were performed. Below only significant sources of systematic uncertainty for each subsystem are listed:

For the beam pipe:

- background shape variation (0.02 mm), when we replace exponential fit with horizontal line with a constant fit for the combinatorial background;
- the impact of the resolution of the secondary vertices, estimated by using a pion gun Monte Carlo simulation (0.01 mm);
- fit bias as estimated by simulating disks with a given radius and center position (<0.01 mm);
- fit shape as estimated by replacing a circle with an ellipse (<0.01 mm).

For the pixel detector support tube:

- fit bias estimation (0.04 mm) was done as for the beam pipe;
- background shape variation (0.04 mm) was done as for the beam pipe;
- the impact of the resolution of the secondary vertices (0.04 mm);
- background subtraction (0.01 mm): subtract (BG+4√BG) instead of (BG+2√BG).

For the BPIX detector support rails:

- 1/√12 of the bin width in y (0.02 cm) as for a uniform/flat distribution.