Vernier Analysis Update

Run 12

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The Hourglass Effect and Crossing Angle - β^*, θ_{XZ} and θ_{YZ}

Introduction to β^*, θ_{XZ} and θ_{YZ}

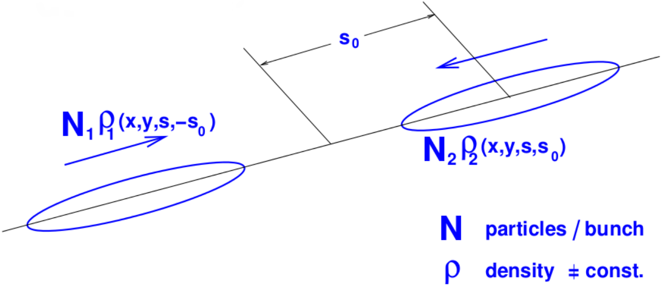
The overall thrust of the Vernier Analysis is to determine the absolute luminosity delivered to PHENIX by RHIC. The vernier scan itself allows us to recover estimates for most of the parameters which are used to calculate luminosity, but the presence of the beam squeezing parameter, β^* and non-zero crossing angles in the X-Z plane and Y-Z plane (θ_{XZ}, θ_{YZ}) introduce z-dependence into the parameters which are extracted from the vernier scan, namely the beam-widths, σx and σ_y.

Introduction to β^*, θ_{XZ} and θ_{YZ}

Luminosity for any colliding beam accelerator can be modeled as the convolution of the two bunch densities:

$$\mathcal{L} = 2N_{blue}N_{yellow}f_{bunch}N_{bunch}\iiiint_{\infty}^{\infty}\rho_{blue}(x,y,z-ct_0)\rho_{yellow}(x,y,z+ct_0)dxdydzdt \quad (1)$$

If the densities in equation 1 are simple Gaussians, the normalizations may be extracted from the integrand, and the integration can be performed analytically. This corresponds to the simple colliding bunch model:



Introduction to β^*, θ_{XZ} and θ_{YZ}

The simple normalized Gaussian beam profile for any single dimension, $x_i, i = x, y, z$ may be written, and normalized as follows:

$$\rho(x_i) = \frac{e^{-\frac{(x_i-\mu)^2}{2\sigma_{x_i}^2}}}{\sigma_{x_i}\sqrt{2\pi}} \tag{2}$$

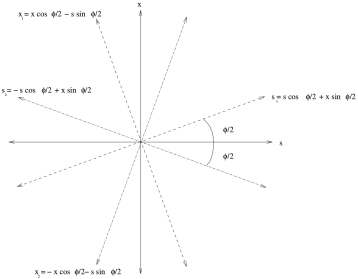
If all profiles are of this form, then the densities are separable, and we may perform the integration. However, higher order beam effects introduce complications which will prevent us from separating the densities, as well as performing the integration analytically.

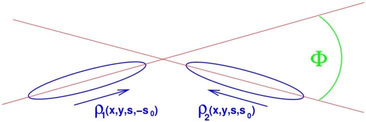
Introduction to β^*, θ_{XZ} and θ_{YZ}

There are three transformations which we can perform on our profile, to generate the most realistic overlap integral. Once we have a form that we are happy with, we may integrate out the x and y degrees of freedom, leaving a distribution in z and t. This distribution is sampled randomly to create a simulated z-vertex profile, which we can seed with experimentally extracted data, and tune until sufficient convergence is achieved.

Introduction to β^*, θ_{XZ} and θ_{YZ}

The crossing angle may be applied in either the X-Z plane or Y-Z plane (or both). Schematically:





Left: rotation transformation, Right: bunches crossing at an angle, Φ relative to each-other.

Introduction to β^*, θ_{XZ} and θ_{YZ}

We transform our coordinate system, thus giving us shifted coordinates to account for non-zero θ_{XZ} and θ_{YZ}. Because crossing angles are all small, $(-0.2rad < \theta < 0.2rad)$, we can use the small angle approximation.

$$x_{blue} \rightarrow x cos\frac{\phi}{2} - z sin\frac{\phi}{2} \tag{3}$$

$$z_{blue} \rightarrow z cos\frac{\phi}{2} + x sin\frac{\phi}{2} \tag{4}$$

$$x_{yellow} \rightarrow x cos\frac{\phi}{2} + z sin\frac{\phi}{2} \tag{5}$$

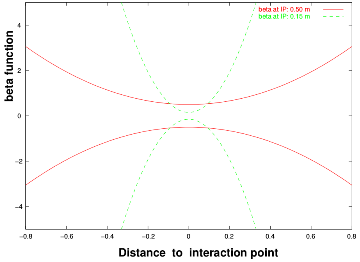
$$z_{yellow} \rightarrow z cos\frac{\phi}{2} - z sin\frac{\phi}{2} \tag{6}$$

$$sin\frac{\phi}{2} \rightarrow \frac{\phi}{2} \tag{7}$$

$$cos\frac{\phi}{2} \rightarrow 1 + \frac{\phi^2}{4} \tag{8}$$

Introduction to β^*, θ_{XZ} and θ_{YZ}

To the left, we can see an example of a beta-function which effectively pinches the transverse profiles of the beam down to a focused point at the center of the interaction region. We must therefore transform the widths of our transverse distributions like so:



$$\sigma_{x_i} \rightarrow \sigma_{x_i}\sqrt{1+\left(\frac{z}{\beta^*}\right)^2} \quad (9)$$

Introduction to β^*, θ_{XZ} and θ_{YZ}

The correction procedure:

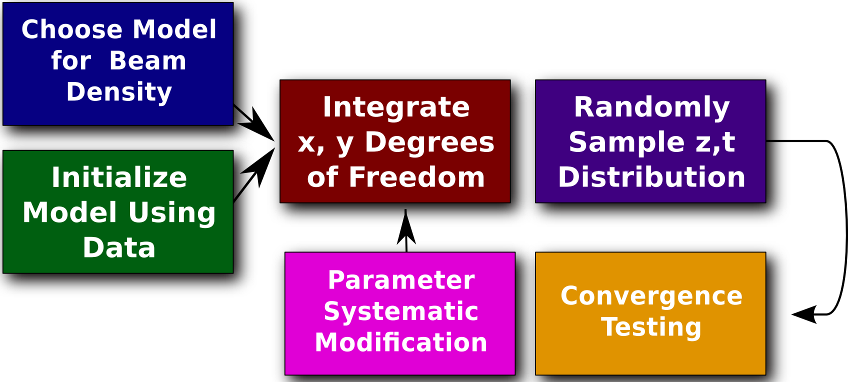
- Begin with model for luminosity, make reasonable assumptions
- Modify model to account for real effects
- Numerically integrate to z-t distribution
- Sample z-t distribution to obtain z-vertex profile
- **Next:** Matching simulated distribution to data using statistically significant method (i.e., not "by eye" which has been done in past analyses"
- **Next:** Correct luminosity by scaling simple model of luminosity of data to match simulated luminosity.

The Simulation

Simulating The Vernier Scan

- The vernier scan can be simulated with a collection of variables defining the dynamics of the scan. We simulate each scan step, model the z-vertex profile for the step, and modify the simulation until matching is good.
- The goal of the hourglass simulation is to confirm that CAD has provided the correct value for β^* and to correct for the presence of any crossing angle between the beams.
- The β^* correction was on the order of a 30% correction in 2009, whereas the crossing angle correction was a 1% correction.
- For Run 12 scans, CAD advertised the $200GeV$ value of β^* as $85cm$ and the $510GeV$ value as $65cm$

Simulation Overview



Simulation Parameters

```
AVG_NUMBER_IONS_BLUE_BEAM 120.029e9
AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ -0.08e-3
CROSSING_ANGLE_YZ 0.
FILLED_BUNCHES 107
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MAX_COLLISIONS 5
MULTIPLE_COLLISION_RATE 0.001
RUN_NUMBER 359711
VERTICAL_BEAM_WIDTH 0.0238342
X_OFFSET -0.1
Y_OFFSET 0
ZDC_COUNTS 592
ZDC_VERTEX_DISTRIBUTION_NAME zdc_zvtx_step_0
Z_BUNCH_WIDTH_CENTRAL_GAUSIAN 55.95
Z_BUNCH_WIDTH_LEFT_GAUSSIAN 35.15
Z_BUNCH_WIDTH_LEFT_OFFSET -70.2
Z_BUNCH_WIDTH_RIGHT_GAUSIAN 27.65
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 2.0
```

Free Simulation Parameters

Although any parameter can be varied, most are fixed based on input from other constraints along the analysis chain.

Free parameters are:

- β^*
- θ_{XZ} or θ_{YZ}

Caveats:

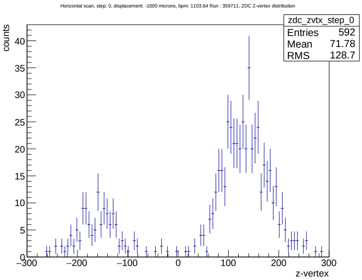
- Crossing angle in XZ plane does not affect the shape of the z-vertex profile when a vertical beam displacement is simulated
- Crossing angle in the YZ plane does not affect the shape of the z-vertex profile when a horizontal displacement is simulated
- **Solution:** Simulate only one crossing angle, swap horizontal/vertical elements for vertical scans.

Exploring the Parameter Space

Exploring the Simulation Parameter Space

In order to tune the Hourglass Simulation, I identified how various beam parameters affected the final z-vertex profile.

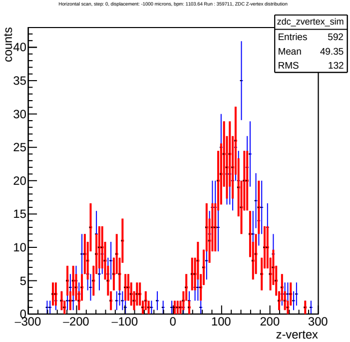
- Stretching/Squeezing of distribution
- Asymmetry in peak heights
- Individual Peak Widths
- Peak Separation
- Peak Scaling



Shown: the zdc z-vertex histogram profile for -1000 micron beam separation, $200\,GeV$, run 359711. Characteristic hourglass effect (peak separation) and crossing angle effect (peak asymmetry).

Hourglass Parameters - **Simulation** and **Data**

AVG_NUMBER_IONS_BLUE_BEAM 120.029e9
AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ -0.08e-3
CROSSING_ANGLE_YZ 0.
FILLED_BUNCHES 107
HORIZONTAL_BEAM_WIDTH 0.0245674
MAX_COLLISIONS 5
MULTIPLE_COLLISION_RATE 0.001
RUN_NUMBER 359711
VERTICAL_BEAM_WIDTH 0.0238342
X_OFFSET -0.1
Y_OFFSET 0
ZDC_COUNTS 592
ZDC_VERTEX_DISTRIBUTION_NAME zdc_zvtx_step_0
Z_BUNCH_WIDTH_CENTRAL_GAUSIAN 55.95
Z_BUNCH_WIDTH_LEFT_GAUSSIAN 35.15
Z_BUNCH_WIDTH_LEFT_OFFSET -70.2
Z_BUNCH_WIDTH_RIGHT_GAUSIAN 27.65
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 2.0



Here, we manually scale the simulation parameters to a achieve a reasonable match for a scan step, -1000 microns (x), for 359711.

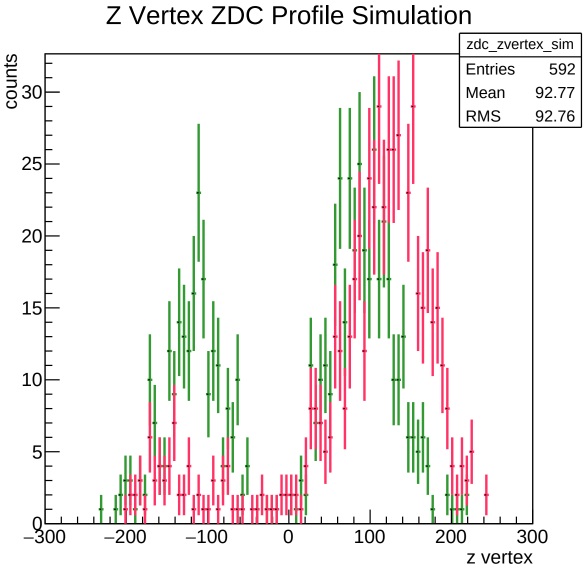
Note that we use a general model for the z-profile (triple Gaussian, more on this later), and achieve good matching through scaling this profile.

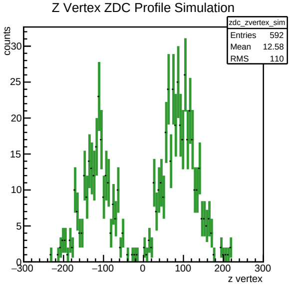
Hourglass Parameters

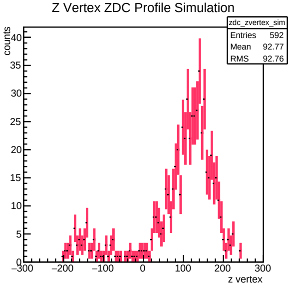
Starting from a reasonably matched spectra, we can now explore how modifying the various parameters affect the output profile.

Smaller end of parameter range is shown in **green** while larger end of parameter range is shown in **pink**

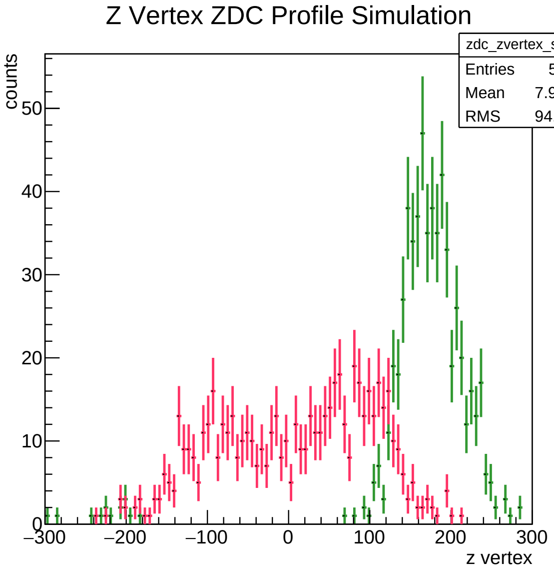
Large and Small β^*

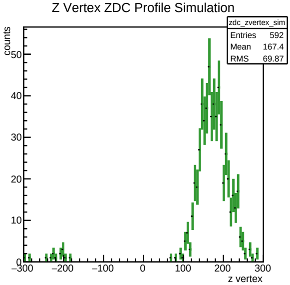


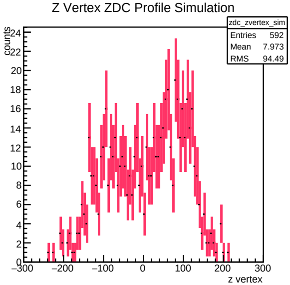




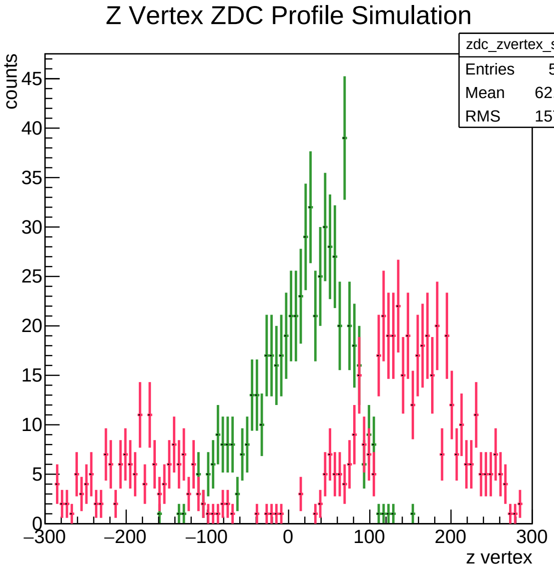
Large and Small σ_x

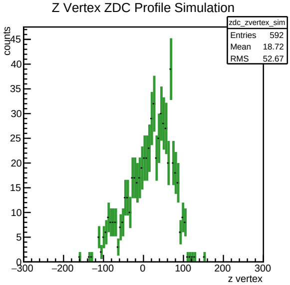


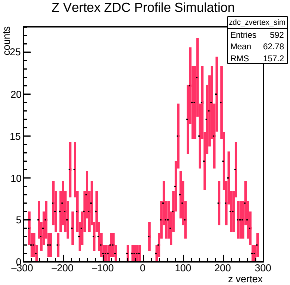




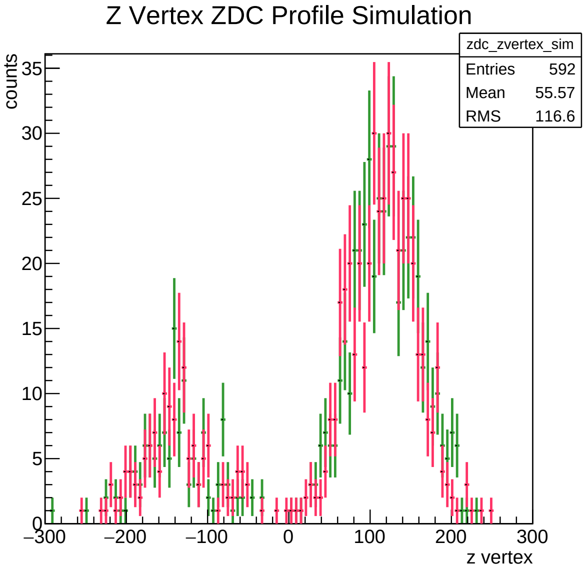
Large and Small Z-bunch profile

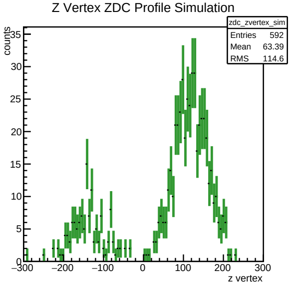


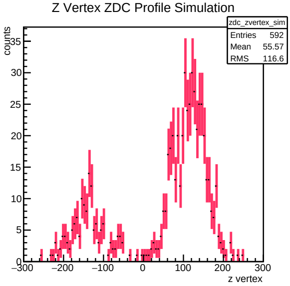




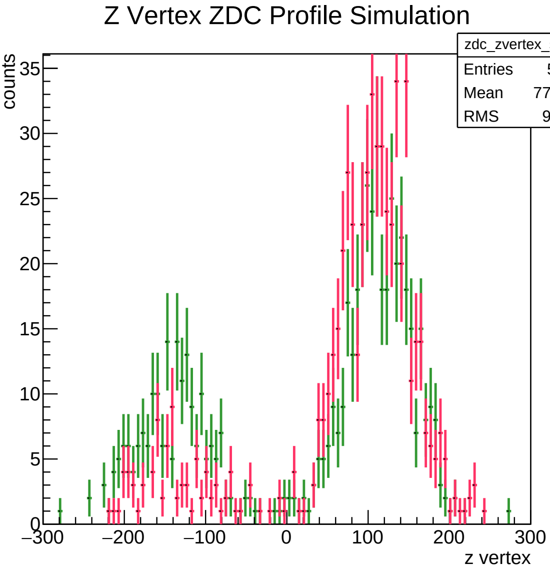
Large and Small σy

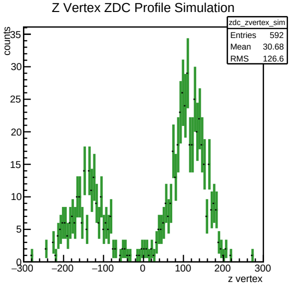


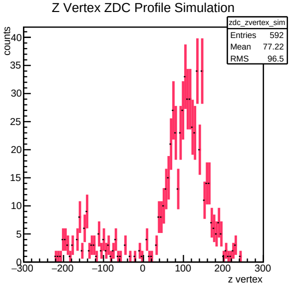




Large and Small θ_{XZ}







Exploring the Parameter Space

Based on our exploration, we have confirmed/discovered that the following parameters map to the following z-profile behavior:

- Z-Profile Scale $\rightarrow$ Stretching/Squeezing of distribution
- θ_{XZ} $\rightarrow$ Asymmetry in peak heights
- Z-Profile $\rightarrow$ Individual Peak Widths
- Beam Displacement / $\sigma x, y$ $\rightarrow$ Peak Separation
- ZDC yield (not shown) $\rightarrow$ Peak Scaling

Also note that scaling the beam widths OR changing the displacement will change the total amount of overlapping beam. Note too that we cannot observe the effects of vertical-beam width scaling or YZ crossing angle during a horizontal beam displacement.

Modeling Z-Profile

Here, I present my preliminary studies on the affect of z-profile of the bunches in simulation on the final simulated z-vertex distribution.

Results

Preliminary Results from Simulation

Now that we have a reasonable understanding of how each simulation configuration parameter affects the simulated z-profile, we can do two things:

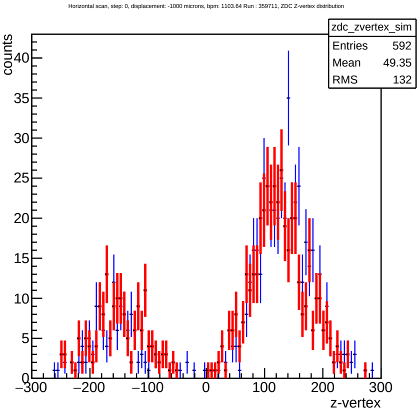
1. Establish reasonable boundaries over to generate simulation configuration files, as well as reasonable parameter step-sizes
2. Make a good guess as to what the best set of parameters are for each scan step

Additionally:

- Absence of functional form for z-profile precludes traditional regression fitting
- Refactoring hourglass simulation to accept config-file for initialization opens door for brute force regression.

359711, -1000 micron x-displacement, $\beta^* = 85cm$, $\theta_{xz} = -0.08 \times 10^{-3} rad$

AVG_NUMBER_IONS_BLUE_BEAM 120.029e9
AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ -0.08e-3
CROSSING_ANGLE_YZ 0.
FILLED_BUNCHES 107
HORIZONTAL_BEAM_WIDTH 0.0245674
MAX_COLLISIONS 5
MULTIPLE_COLLISION_RATE 0.001
RUN_NUMBER 359711
VERTICAL_BEAM_WIDTH 0.0238342
X_OFFSET -0.1
Y_OFFSET 0
ZDC_COUNTS 592
ZDC_VERTEX_DISTRIBUTION_NAME zdc_zvtx_step_0
Z_BUNCH_WIDTH_CENTRAL_GAUSIAN 55.95
Z_BUNCH_WIDTH_LEFT_GAUSSIAN 35.15
Z_BUNCH_WIDTH_LEFT_OFFSET -70.2
Z_BUNCH_WIDTH_RIGHT_GAUSIAN 27.65
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 2.0



Fe

Good agreement between simulation and data.

359711, -450 micron x-displacement, $\beta^* = 85cm$, $\theta_{xz} = -0.08 \times 10^{-3} rad$

AVG_NUMBER_IONS_BLUE_BEAM 120.029e9
AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85.
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ -0.08e-3
CROSSING_ANGLE_YZ 0.
FILLED_BUNCHES 107
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Z_BUNCH_WIDTH_LEFT_OFFSET -70.2
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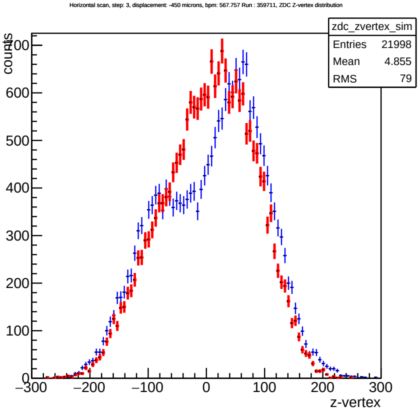
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 1.8



Closer overlap features are not captured between simulation and data.

359711, -150 micron x-displacement, $\beta^* = 85cm$, $\theta_{xz} = -0.08 \times 10^{-3} rad$

AVG_NUMBER_IONS_BLUE_BEAM 120.029e9
AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85.
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ -0.08e-3
FILLED_BUNCHES 107
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MAX_COLLISIONS 5
MULTIPLE_COLLISION_RATE 0.402
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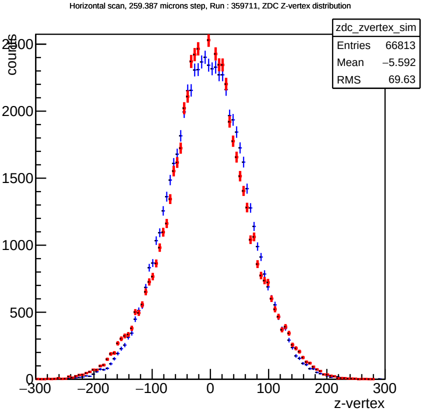
Z_BUNCH_WIDTH_LEFT_GAUSSIAN 35.15
Z_BUNCH_WIDTH_LEFT_OFFSET -70.2
Z_BUNCH_WIDTH_RIGHT_GAUSIAN 27.65
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 2.0



Fe

Good agreement between simulation and data.

359711, -750 micron y-displacement, $\beta^* = 85cm$, $\theta_{xz} = -0.08 \times 10^{-3} rad$

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AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ 0
FILLED_BUNCHES 107
HORIZONTAL_BEAM_WIDTH 0.0245674
MAX_COLLISIONS 5
MULTIPLE_COLLISION_RATE 0.001
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Y_OFFSET -0.075
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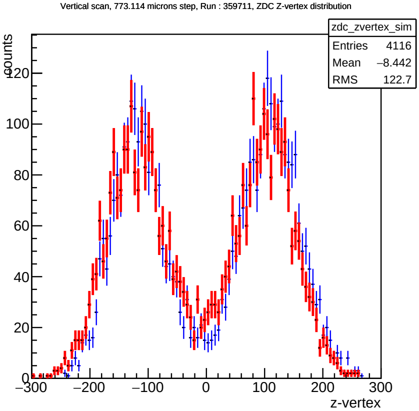
Z_BUNCH_WIDTH_LEFT_OFFSET -70.2
Z_BUNCH_WIDTH_RIGHT_GAUSIAN 27.65
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 2.0



Fe

Apparently, no θ_{YZ}, good agreement between simulation and data.

359711, 750 micron x-displacement, $\beta^* = 85cm$, $\theta_{xz} = -0.08 \times 10^{-3} rad$

AVG_NUMBER_IONS_BLUE_BEAM 120.029e9
AVG_NUMBER_IONS_YELLOW_BEAM 88.1677e9
BBC_ZDC_Z_VERTEX_OFFSET -9.53756
BETA_STAR 85.
BUNCH_CROSSING_FREQUENCY 78213.
CROSSING_ANGLE_XZ -0.08e-3
CROSSING_ANGLE_YZ 0.
FILLED_BUNCHES 107
HORIZONTAL_BEAM_WIDTH 0.0245674
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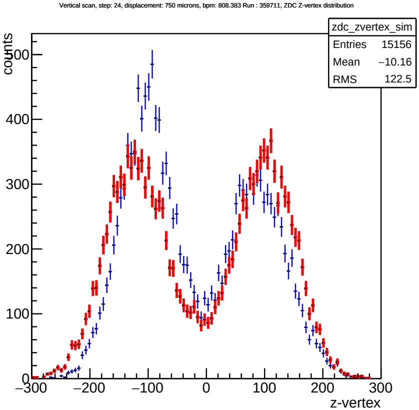
Z_BUNCH_WIDTH_RIGHT_OFFSET 56.7
Z_PROFILE_SCALE_VALUE 2.0



Fe

Data shows presence of θ_{YZ}, makes for poor agreement between simulation and data.

Next Steps Towards More Results

- We have already shown that the bunch z-profile affects the z-vertex profile. Is it valid to simply scale this profile?
- Do we really see a changing crossing angle, or are we seeing fluctuations?

These questions can both be answered, but a few things need to happen first.

- Double check luminosity model (one day)
- Compare simple models to "real" models (one day)
- Use "real" bunch z-profile (next slides), compare to current results.

Using Z-Bunch Profiles Directly

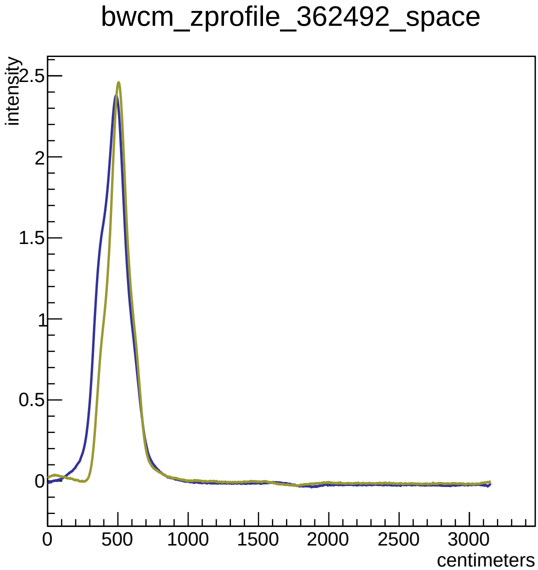
This would have been done sooner, but I do not have direct access to the fine-binned Wall-Current-Monitor data, and there was a 2-3 week lag time in between requesting the data, and receiving the data.

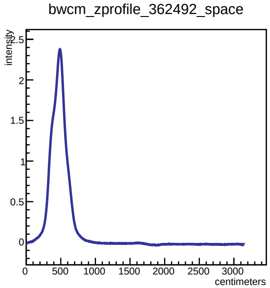
What I propose:

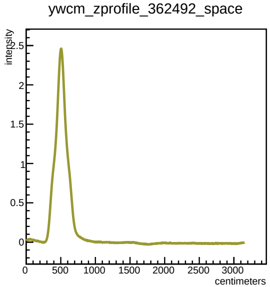
- Normalize each profile, to treat it as a density, ρ_z, such that $\rho(x, y, z, t) = \rho(x, z)\rho(y, z)\rho(z)\rho(t)$
- Directly use this profile, storing it as a TGraph object and using spline-itripolation to approximate a continuous funciton

Caveat: Pictured is the average intensity of each filled bunch, taken in the middle of a vernier scan.

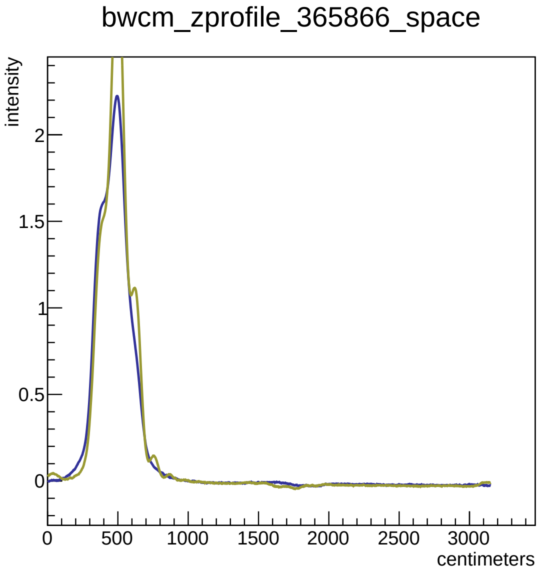
362492 WCM Z Bunch Profile

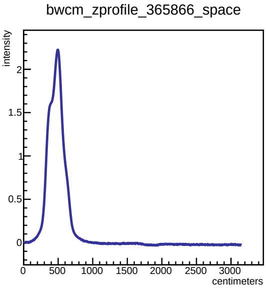


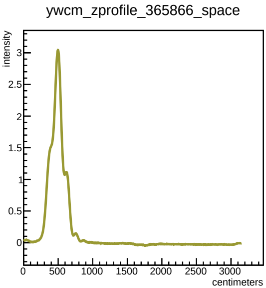




365866 WCM Z Bunch Profile







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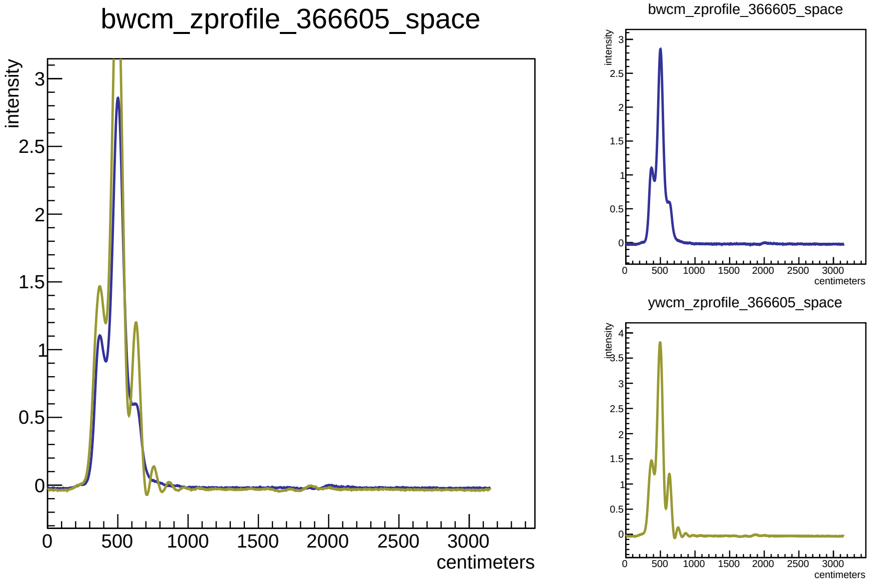

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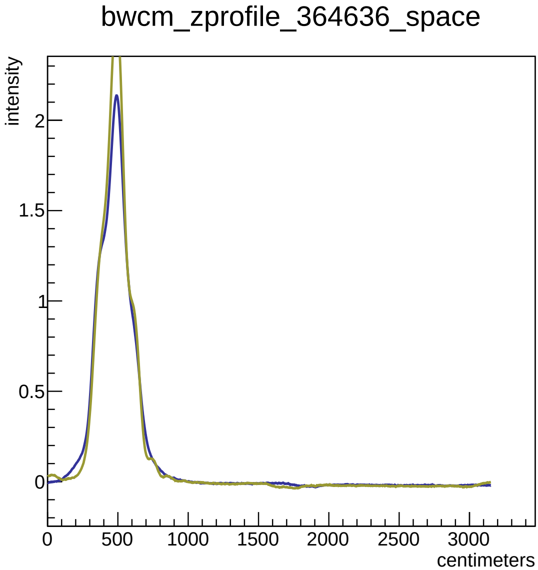

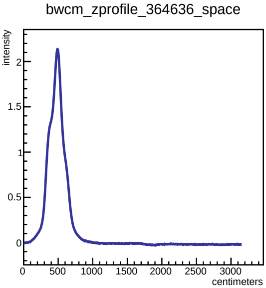

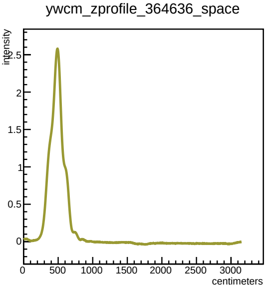

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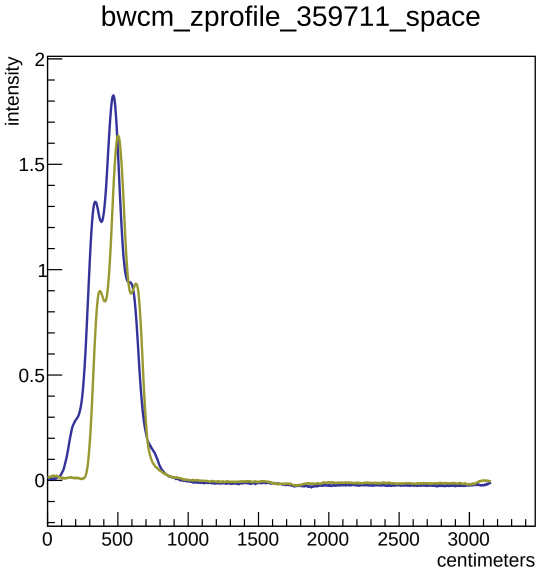
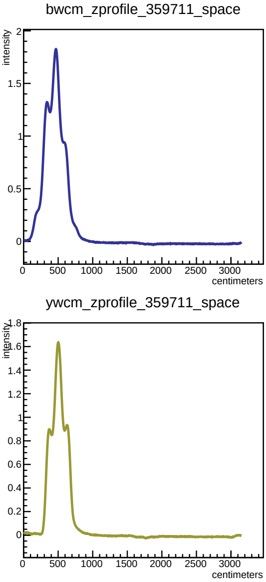
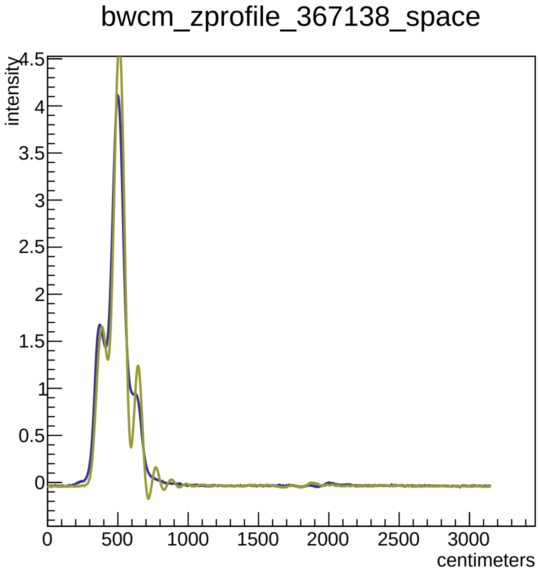
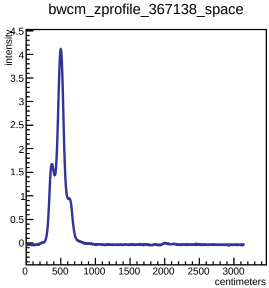
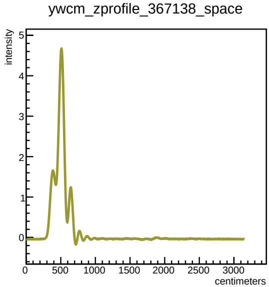




367138 WCM Z Bunch Profile







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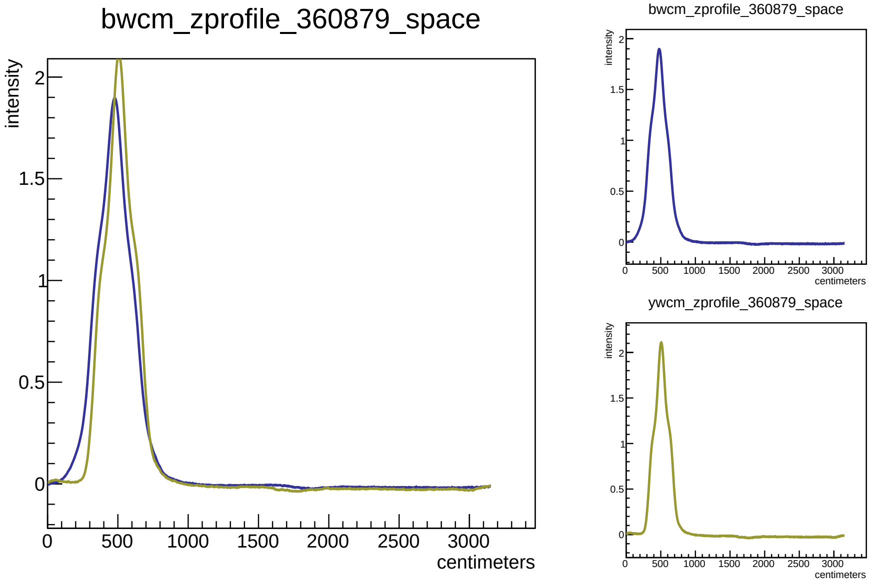

Discussion - WCM Z Bunch Profile

It is clear that sometimes the triple-gaussian profile may be reasonable, but often it is not. It should not be any problem to substitue in the real profile into the simulation.

The End

Thanks for your attention!