ROLLING WITH RUTHERFORD
DRAFT SUPPLEMENTARY TEACHER NOTES

DESCRIPTION
This supplement builds on the Rolling with Rutherford activity to give students the chance to understand how physicists manage and account for uncertainty in their measurements. Students use the histogram they made after rolling marbles and then visually identify as well as calculate estimates for the uncertainty in each bin and the uncertainty in the central value of number of hits obtained.

STANDARDS ADDRESSED
Next Generation Science Standards

Science and Engineering Practices

4. Analyzing and interpreting data
5. Using mathematics and computational thinking

Crosscutting Concepts

3. Scale, proportion, and quantity.

Common Core Literacy Standards

Reading

9-12.4 Determine the meaning of symbols, key terms . . .

9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

MP2. Reason abstractly and quantitatively.

IB Physics

Topic 1: Measurement and Uncertainties

1.2.6 Describe and give examples of random and systematic errors.

1.2.7 Distinguish between precision and accuracy.

1.2.8 Explain how the effects of random errors may be reduced.

1.2.11 Determine the uncertainties in results.

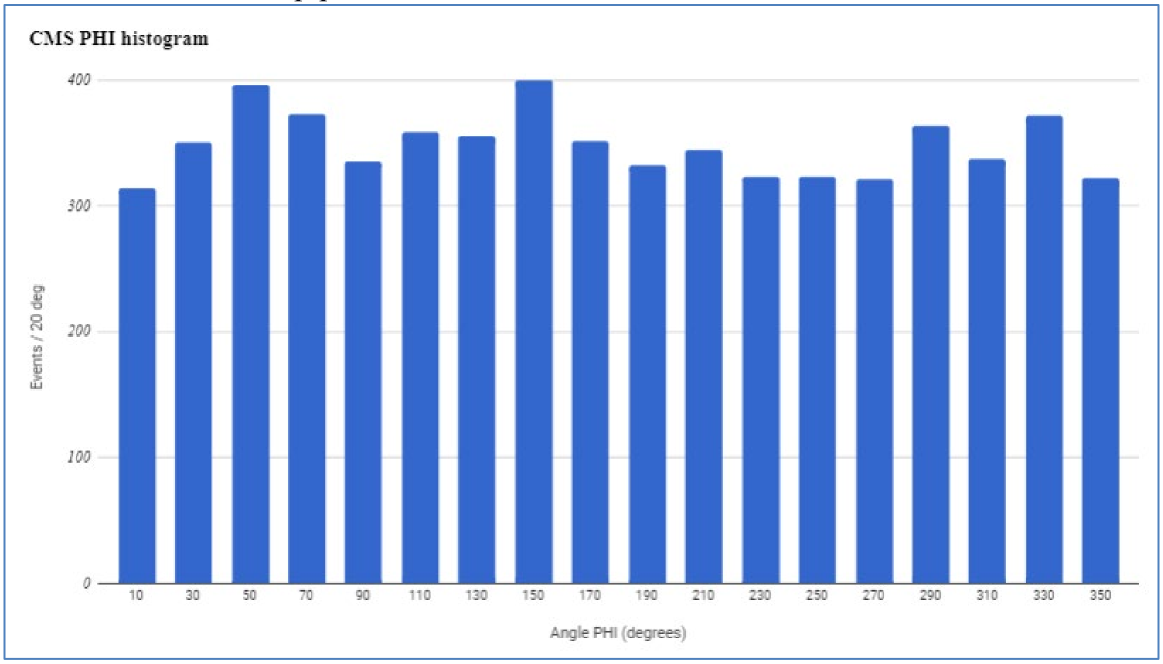
ENDURING UNDERSTANDINGS
Uncertainty in measurements can be calculated and accounted for in results.

LEARNING OBJECTIVES
Students will know and be able to:

- Apply simple statistical analysis to experimental data.

BACKGROUND MATERIAL
Measurements in particle physics are often a matter of counting in order to create histograms. However, when you count something once and get a result N, you may not get N the next time you count it. For example, the plot below shows counts of muons emerging

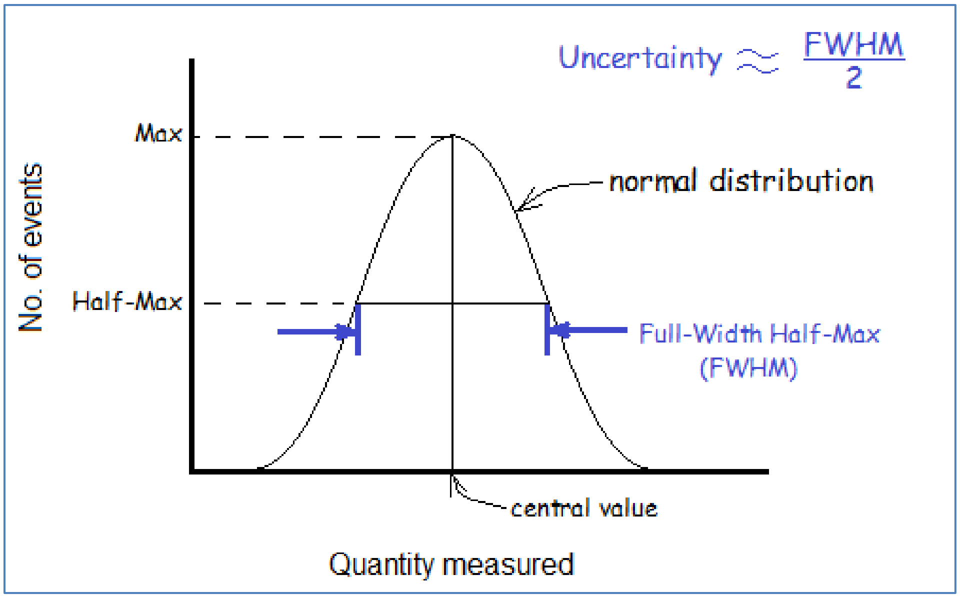
from collision events in CMS. They are sorted in 20-degree bins based on the angles ϕ around the LHC beam pipe from which the entered the detector.



As you can see, we get pretty much the same result in each bin at around 350 counts but not always the same result, even though the number should not depend at all on the value of ϕ. This is due to natural statistical fluctuation. Particle physicists observe a rule of thumb in counting experiments that the uncertainty in a count N is $\pm\sqrt{N}$. In the plot above, $\sqrt{N}$ ranges from about 17 to 20 for each bar; applying error bars of, then, 17-20 above and below each bin puts them all in much the same range. (It is not perfect, though. We expect that, with more data and, therefore, higher statistics, the bins we get relatively even closer to each other.)

We will ask students to create error bars for their Rolling with Rutherford results for each bin of their histogram.

In a Gaussian or Poisson distribution, the standard deviation in the distribution is a little less than the half of the full width of the distribution at half the maximum value (Full-Width Half-Maximum over 2, or FWHM/2), as show below:



The FWHM/2 estimate of the uncertainty in the central value is a little pessimistic but perhaps serves all the better for it.

We will ask students to estimate the uncertainty in the most likely number of hits using this approach.

Prior Knowledge

Students should have completed the Rolling with Rutherford activity.

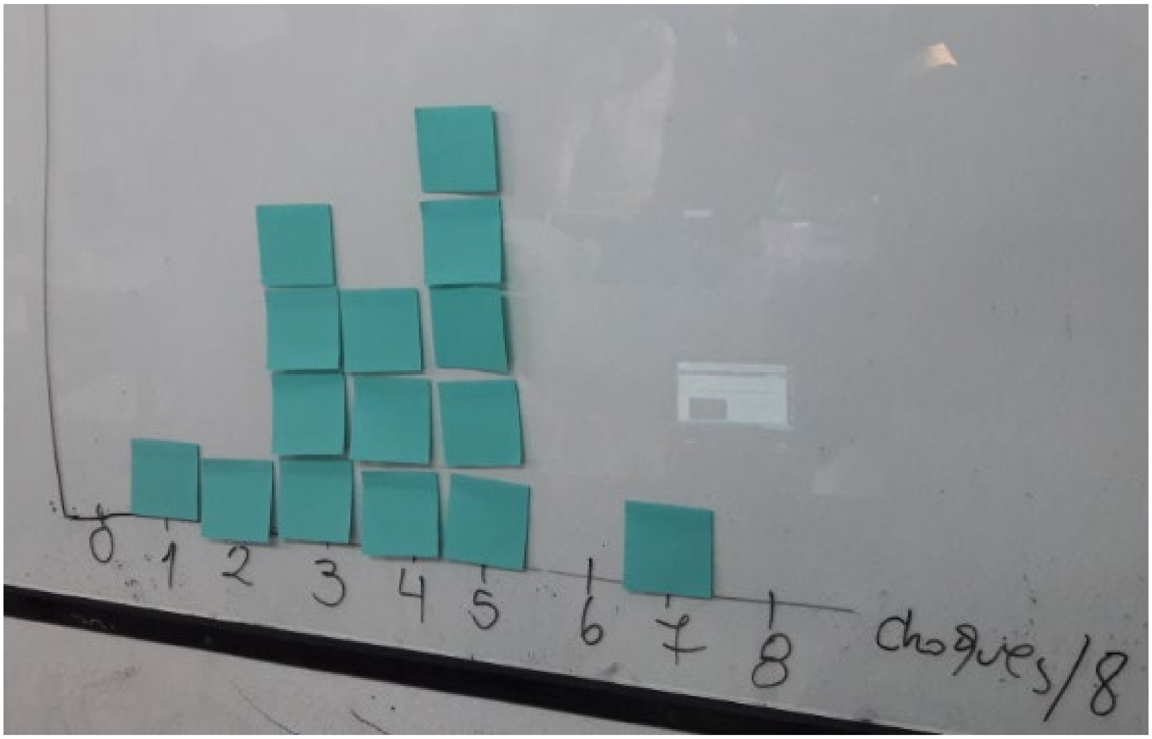
Resources/Materials

- Histogram from Rolling with Rutherford
- Digital camera (optional)
- Computer and printer (optional)
- Ruler
- Calculator

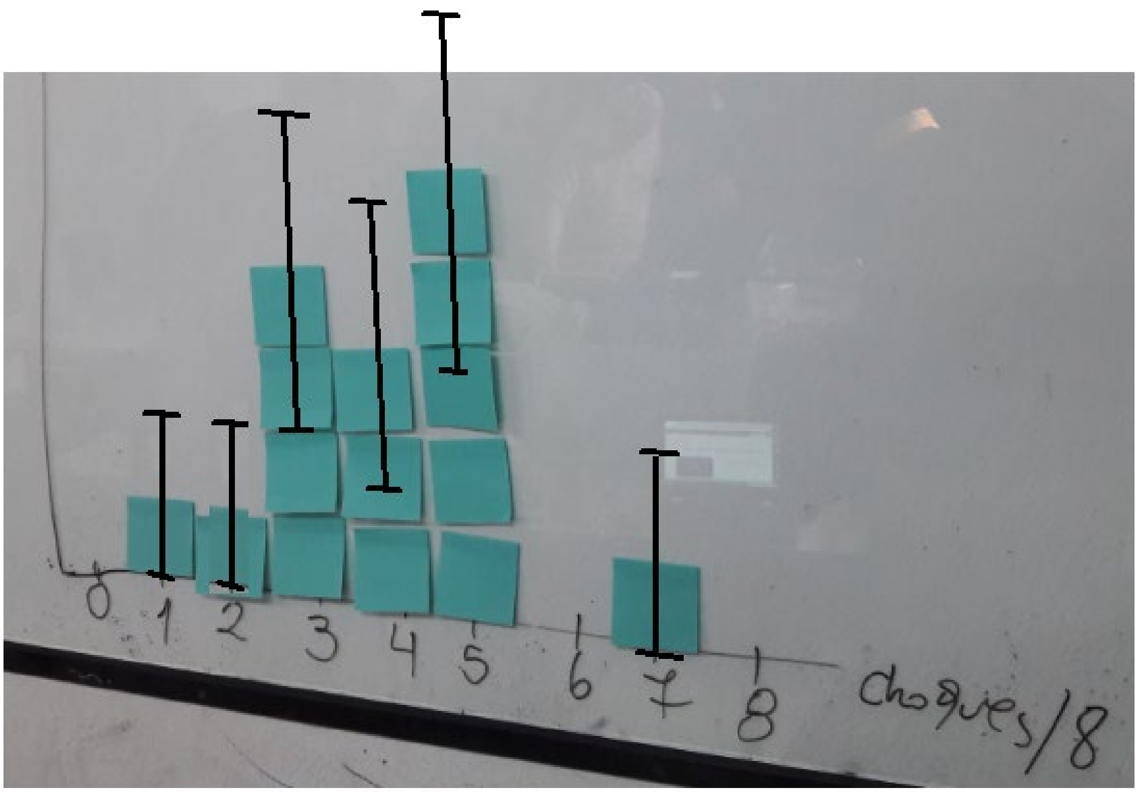
Implementation

The teacher has two choices. This can be a whole class activity using the histogram the students made in the front of the class or the teacher can take a photo of the histogram and print it out for student analysis in class.

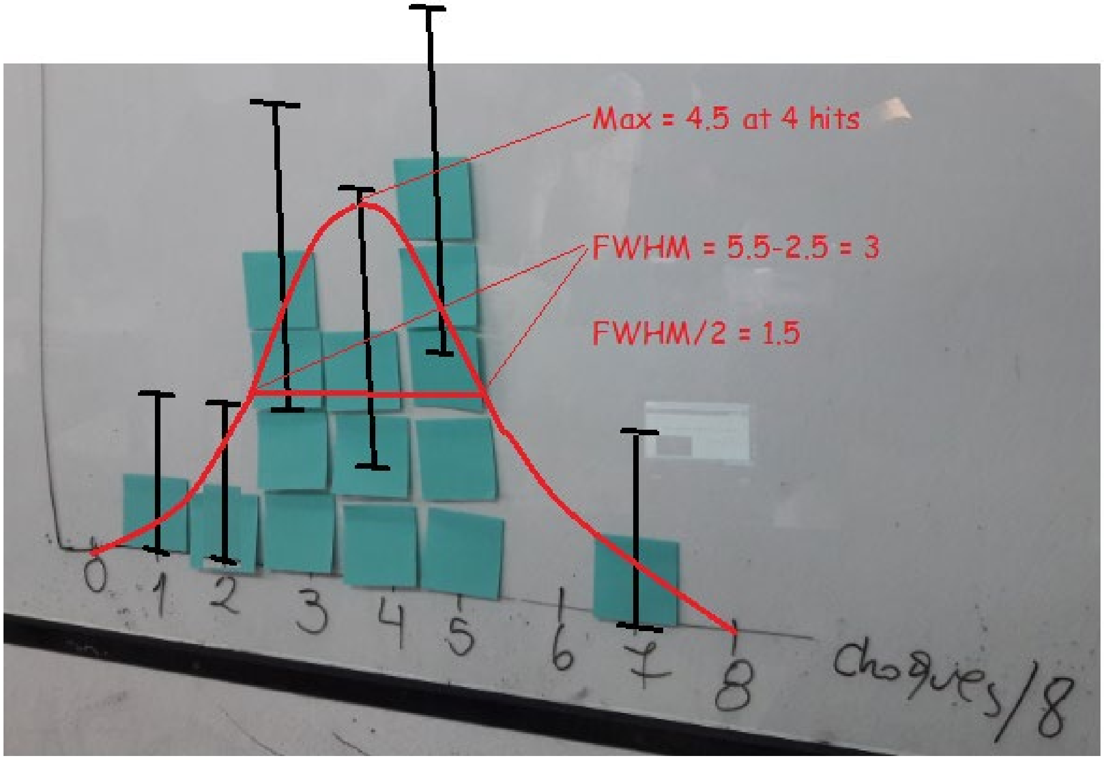
Here is an example of a histogram made with sticky notes:



The teacher can take an image like this (or, probably, better) and reprint it for small groups of students to analyze. The teacher can alternatively make this a whole class exercise. Either way, first we apply $\pm\sqrt{N}$ to make an error bar for each bin:



Then we make an estimated Gaussian on the plot and find FWHM/2:



Thus, the result is a central value of 4±1.5 hits Students working individually or in groups may get slightly different results. The class can compare and discuss differing results.

RESOURCES

- [For $\pm\sqrt{N}$: Only scant references have been found so far; we are working on this.]
- Lab notes on counting statistics from University of Tennessee Knoxville at http://electron6.phys.utk.edu/phys250/Laboratories/counting_statistics.htm.
- FWHM in Wikipedia: https://en.wikipedia.org/wiki/Full_width_at_half_maximum.

ASSESSMENT

- None.