EXPERIMENTAL UNCERTAINTIES A PRIMER OF:

DOING GLOBAL ANALYSIS WITH ATLAS

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What are the experimental uncertainties?

Uncertainties are estimators of how far the measured value lies from the true one.

Back in 70es many papers in HEP did not even discuss uncertainties

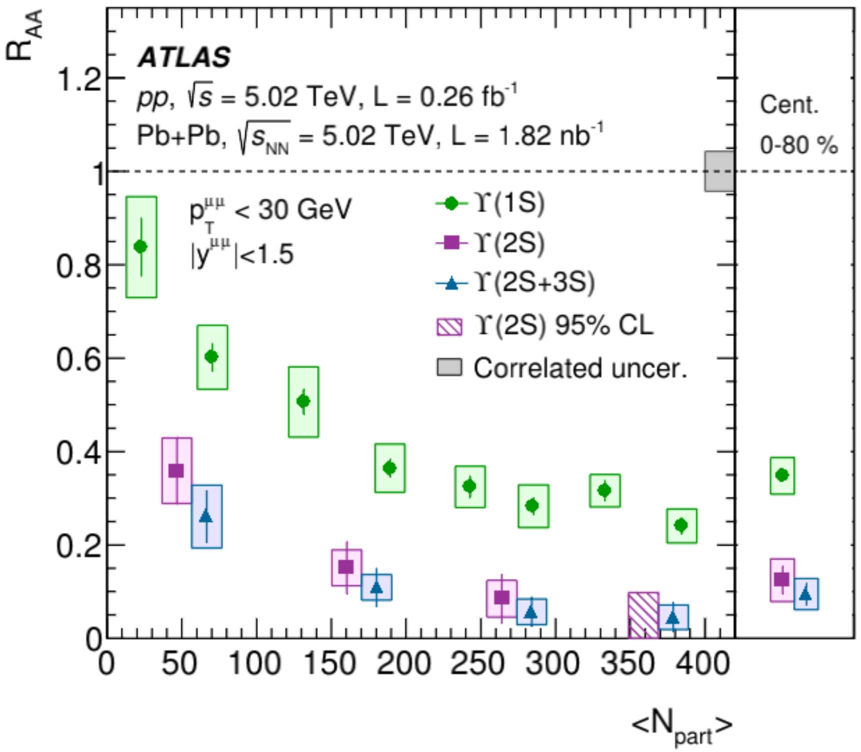
For modern results, the measurements and even experiments, are designed build and optimized to minimize the uncertainties

Uncertainty is the central and sometimes the most important result in many modern publications

Nuclear Physics B [redacted] (1977) 365–389

an increase of particle density in the central region, of the order of 0.28 particles per unit of rapidity and unit of log s, giving evidence for an important violation of Feynman scaling.

Please, watch your language!



Uncertainties ≠ errors !!!

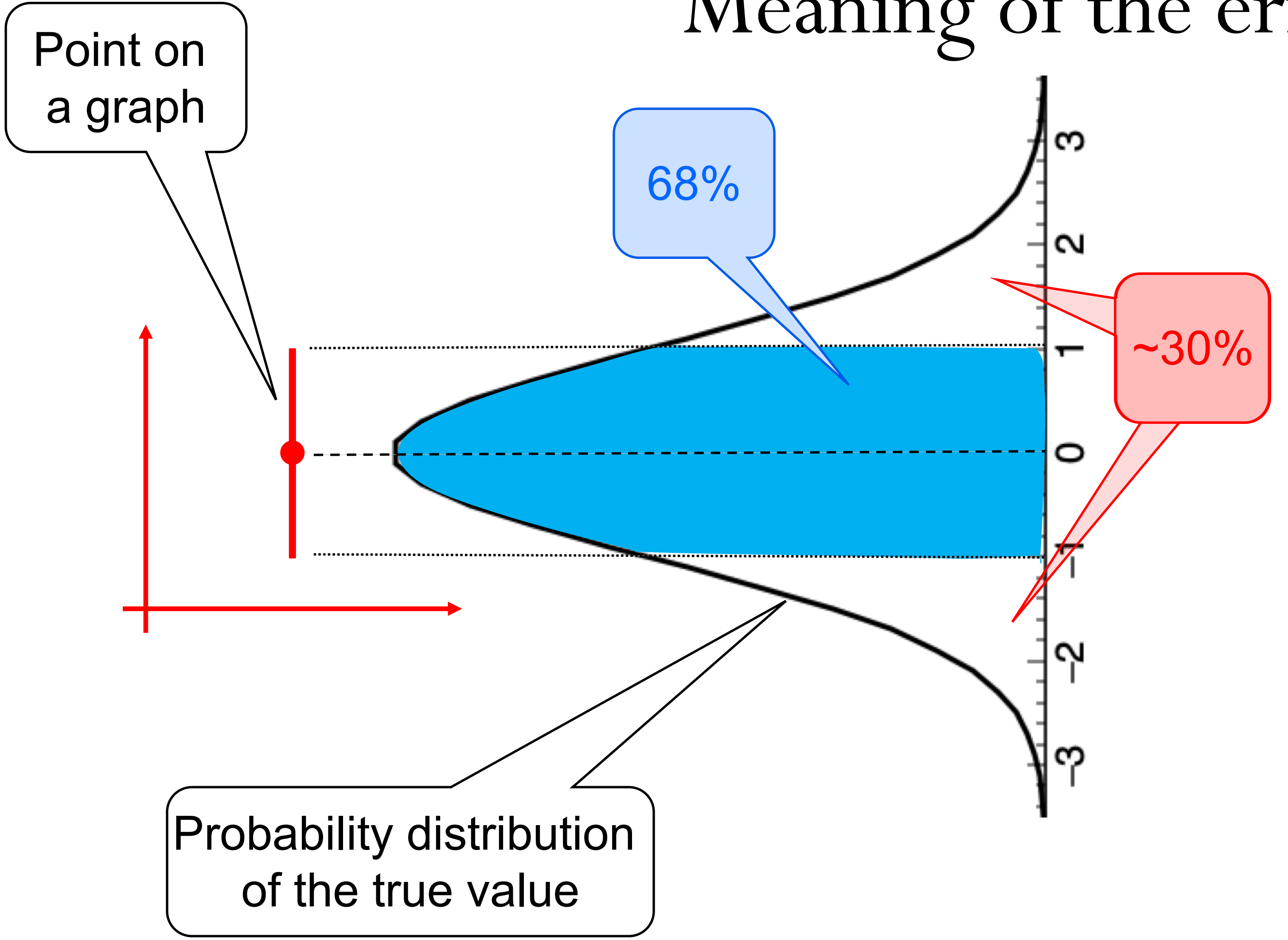
Typical statement in scientific publications

Error bars on experimental points indicate the statistical uncertainly…

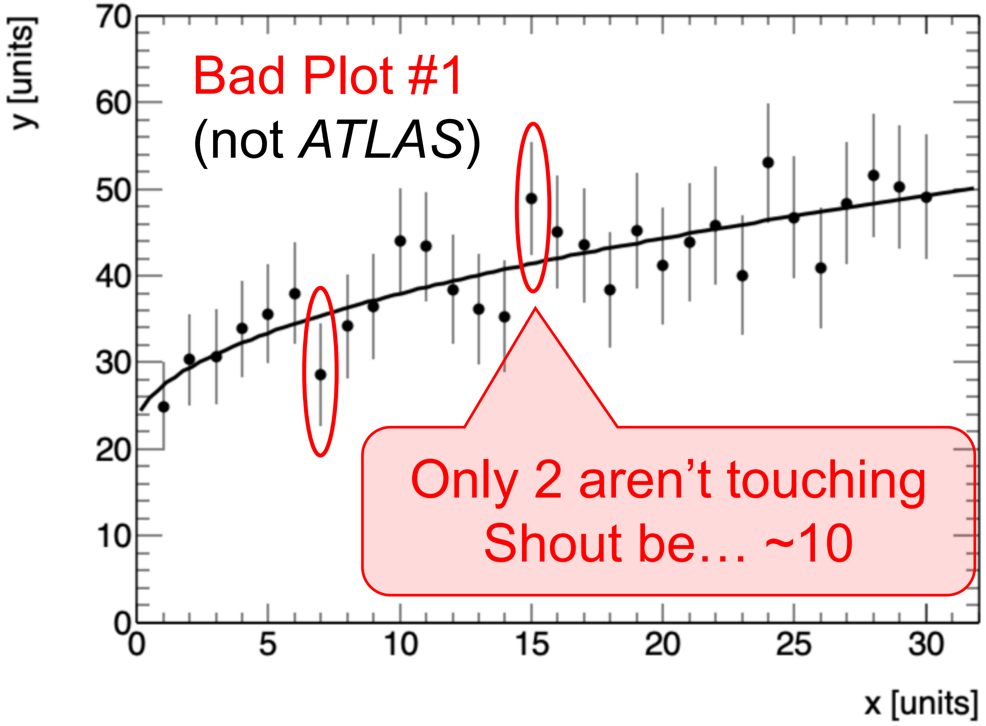
Bar on experimental points indicate the statistical error…

Catastrophe! Erratum notice to the editor

Meaning of the error bar.



This is only a convention, but unless specified, absolute majority of people would understand the error bar as the most probable distance (RMS) from the marker to the true value



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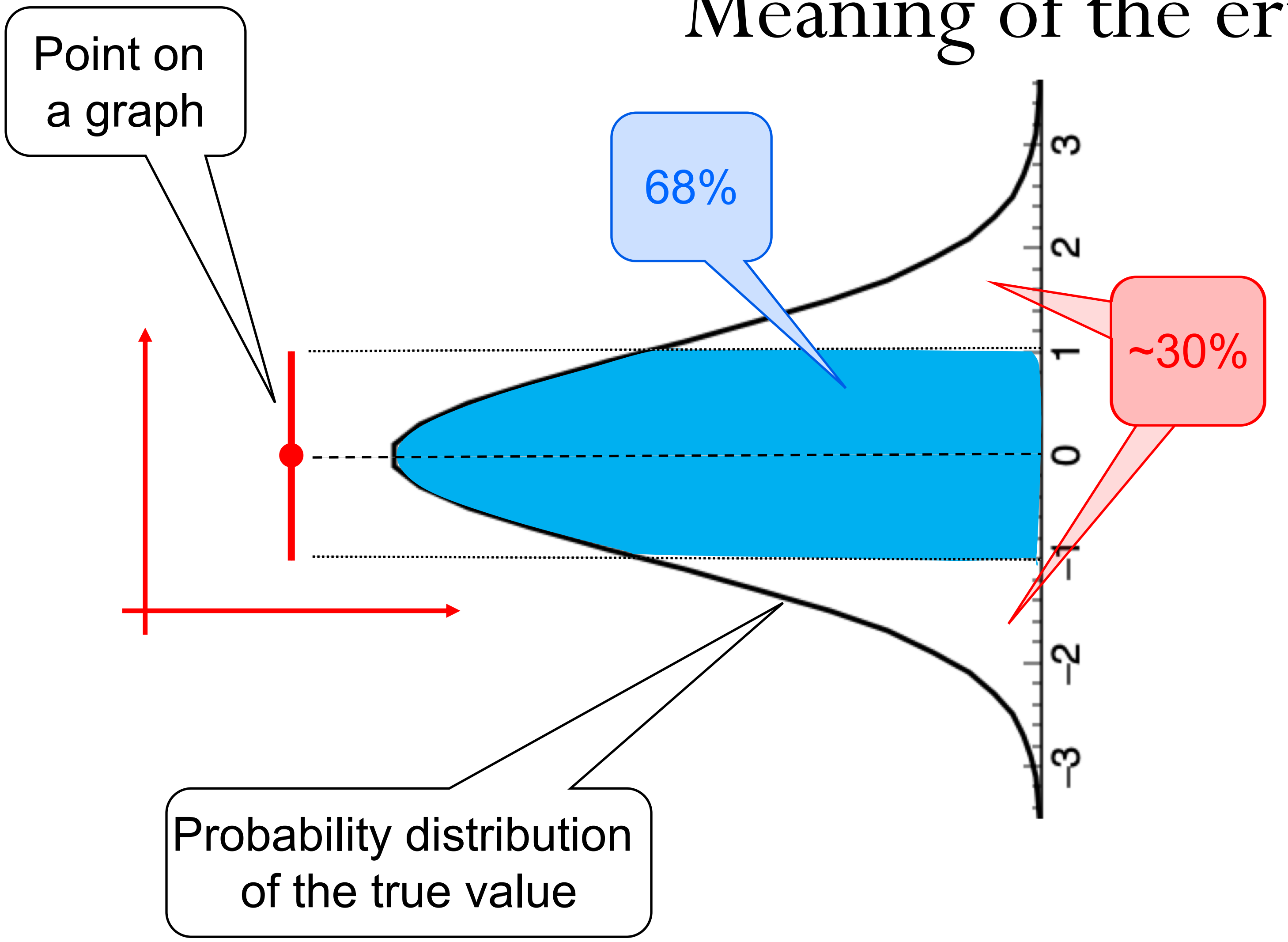

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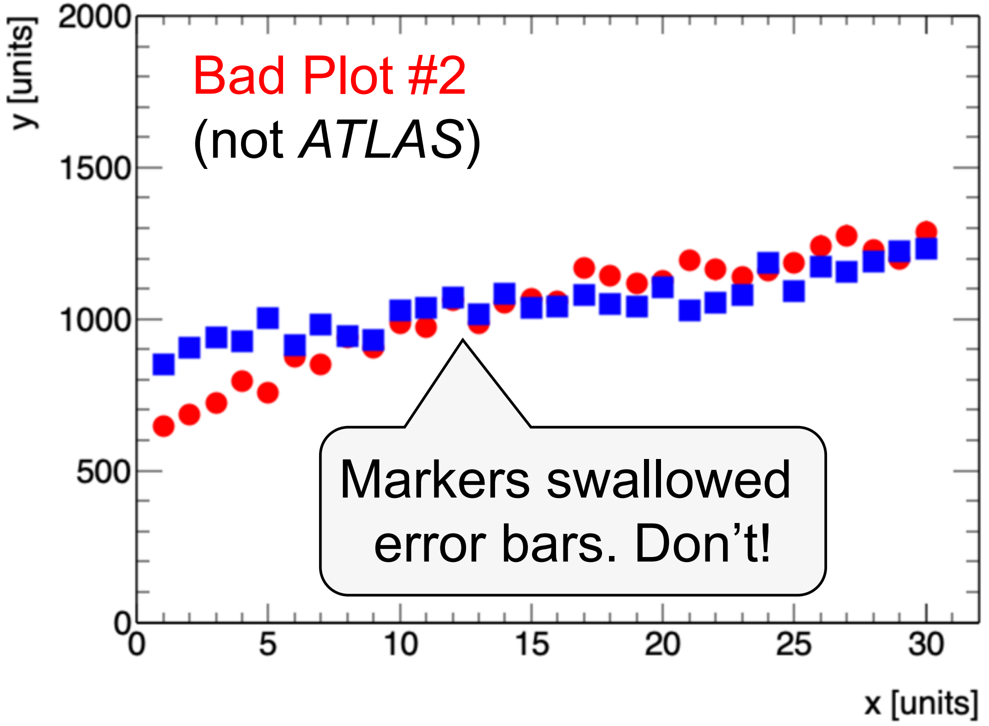


Some customs and heritage

This Letter presents a measurement of $W^{\pm}Z$ production in 1.02 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment in 2011. Doubly leptonic decay events are selected with electrons, muons and missing transverse momentum in the final state. In total 71 candidates are observed, with a background expectation of $12.1 \pm 1.4(\text{stat.})^{+4.1}_{-2.0}(\text{syst.})$ events. The total cross section for $W^{\pm}Z$ production for Z/γ^{*} masses within the range 66 GeV to 116 GeV is determined to be $\sigma^{\text{tot}}_{WZ} = 20.5^{+3.1}_{-2.8}(\text{stat.})^{+1.4}_{-1.3}(\text{syst.})^{+0.9}_{-0.8}(\text{lumi.})$ pb, which is consistent with the Standard Model expectation of $17.3^{+1.3}_{-0.8}$ pb. Limits on anomalous triple gauge boson couplings are extracted.

Statistical uncertainties are coming from the size of the data set

Systematic uncertainties are coming from the ATLAS detector limitations and the analysis procedure

Luminosity uncertainty are coming from the LHC? LUCID? VdM scan?

Model expectation uncertainty are … wait a sec, why are they in the experimental paper?

Background expectation… Aren't they a part of the procedure?

Long time ago on a planet called PHENIX…

People used to say that there are no ‘statistical’ or ‘systematic’ uncertainties, there are uncertainties of
Type “A”: uncorrelated point-by-point
Type “C”: fully correlated, scaling uncertainty for all point
Type “B”: somewhat correlated point-by-point

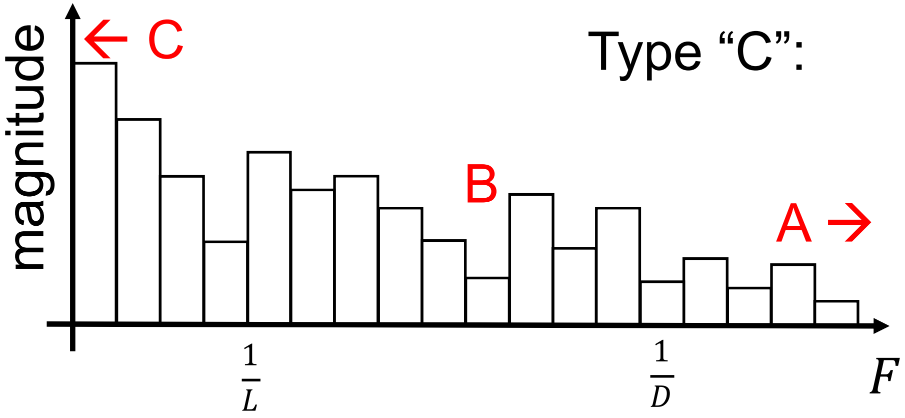
Or you can think of it in terms of a Fourier transform.

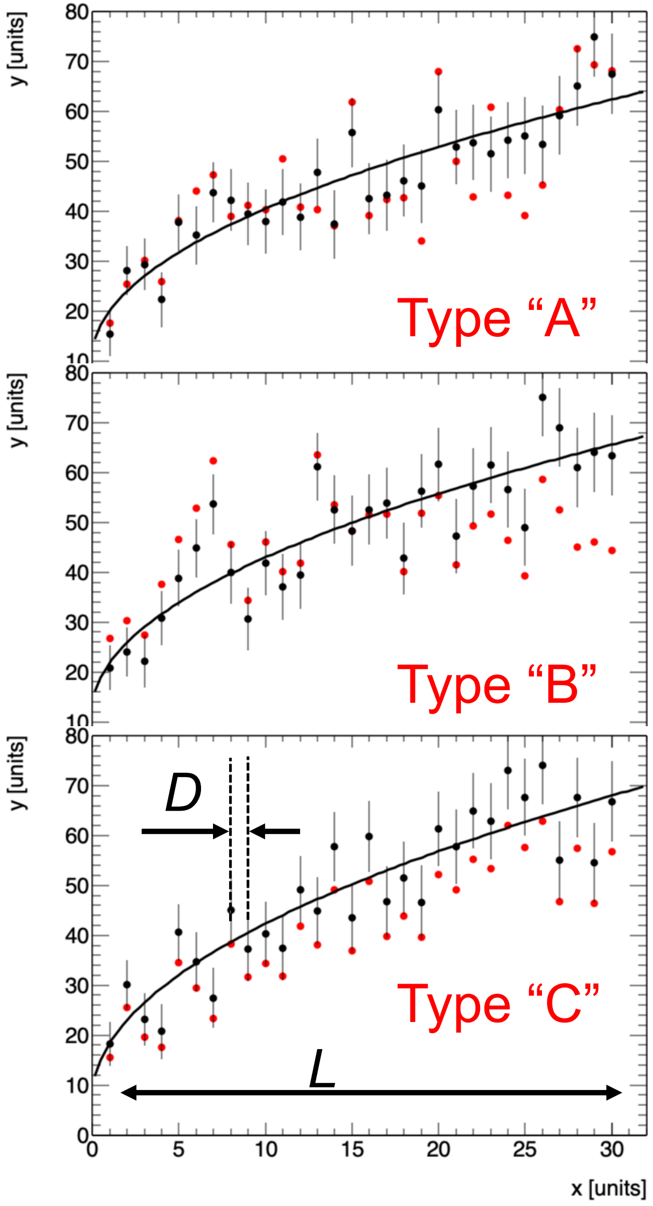
Uncertainty generating frequency

Type “A”: $\frac{1}{D} \ll F$

Type “B”: $\frac{1}{L} \leq F \leq \frac{1}{D}$

Type “C”: $F \ll \frac{1}{L}$





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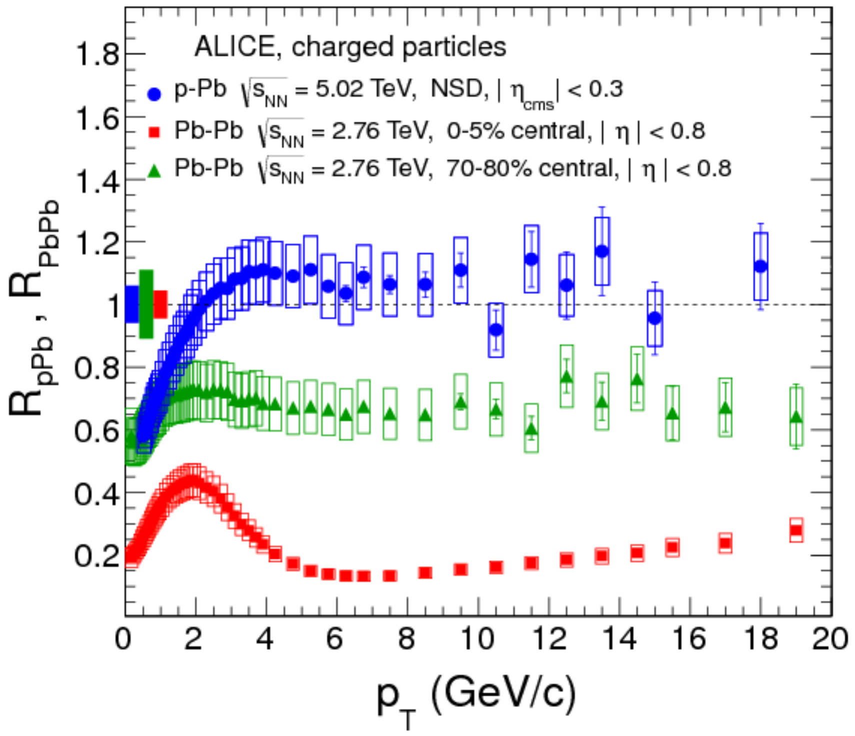
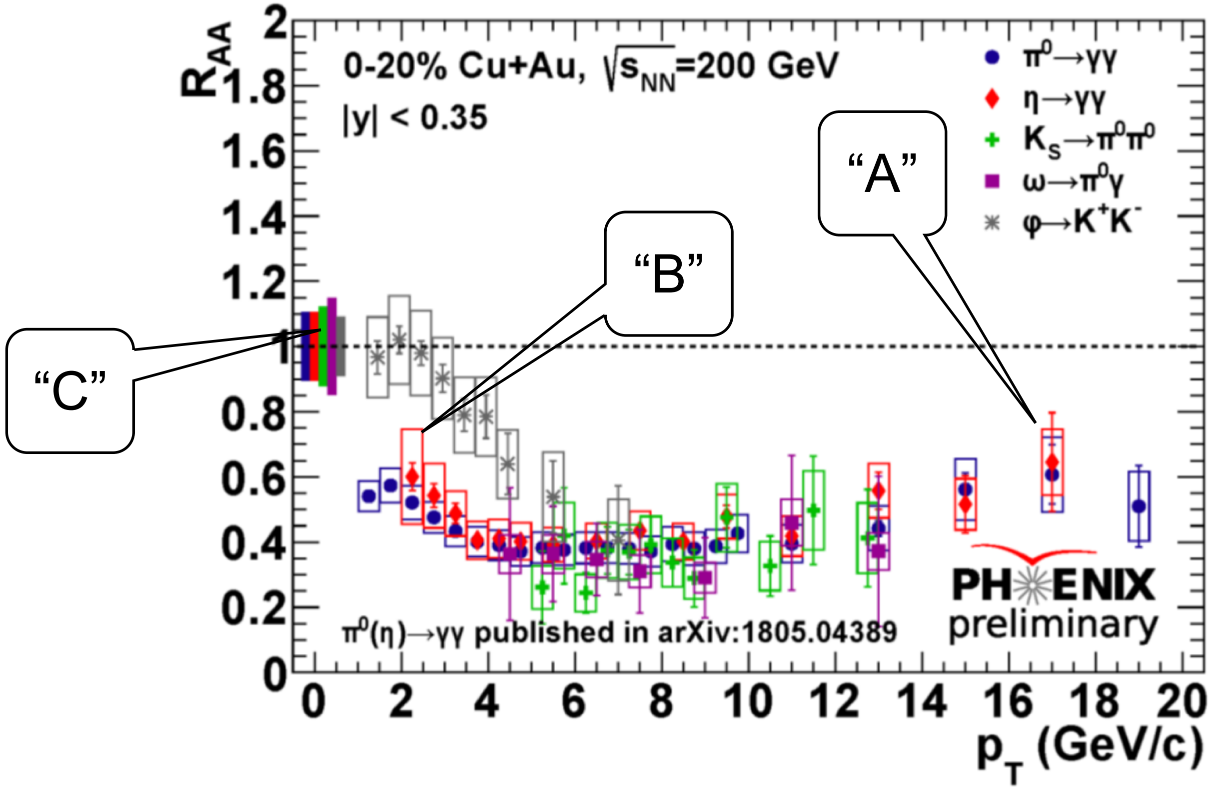
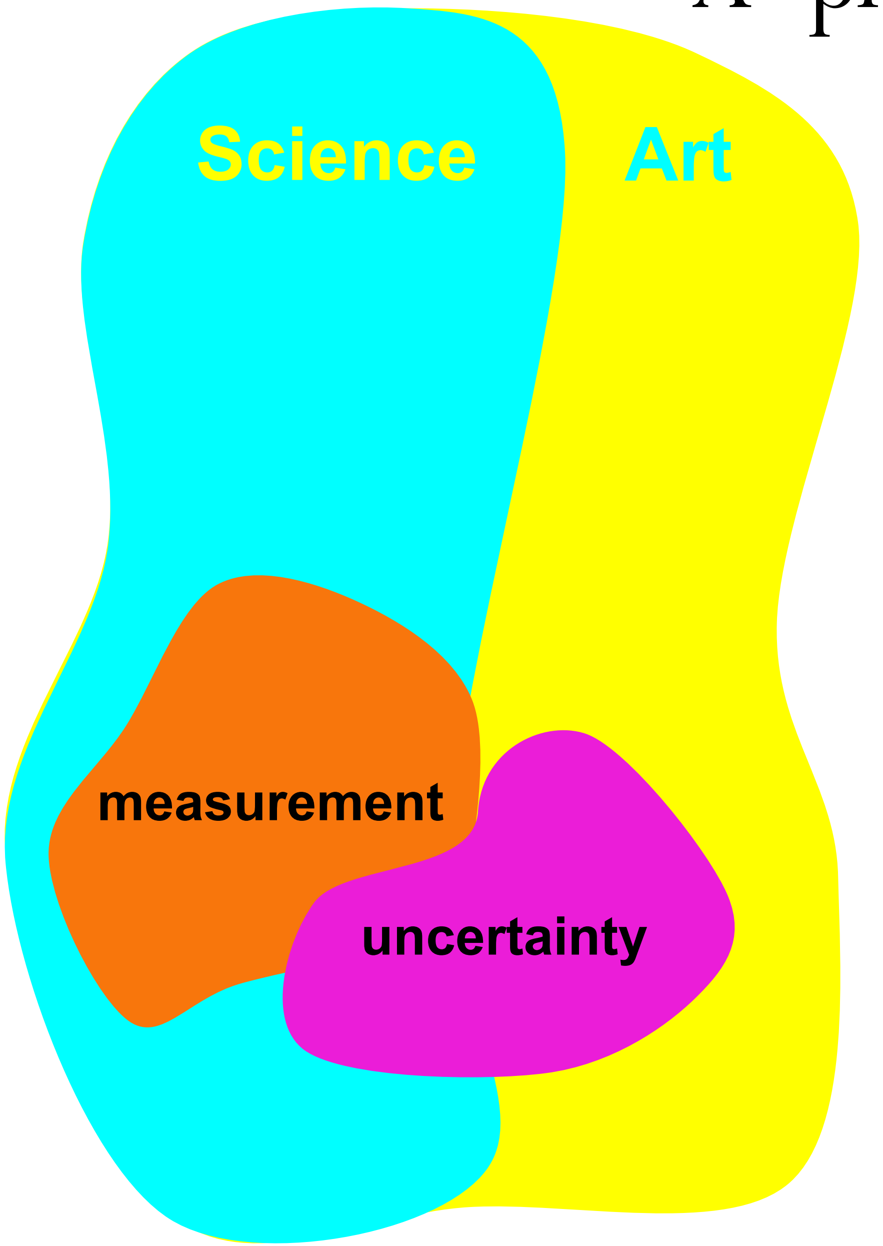




A ‘philosophical revelation’



No experiment is ideal

No measurement is possible without loss of information

Doing physics analysis = correcting for the losses

Every correction is based on assumptions and therefore comes with an uncertainly

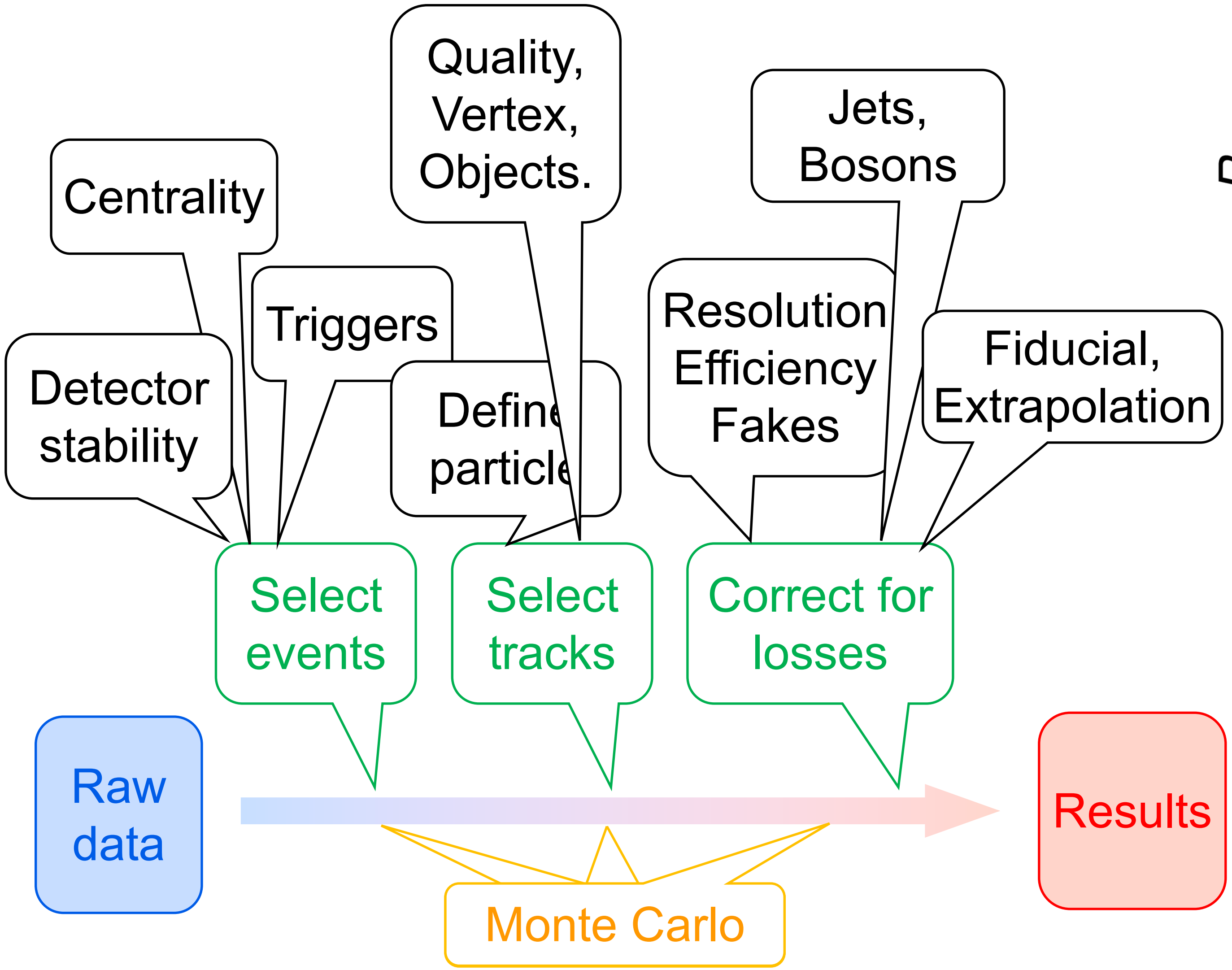
If you would know the uncertainty on the correction, you would do it a part of the correction, would not you?

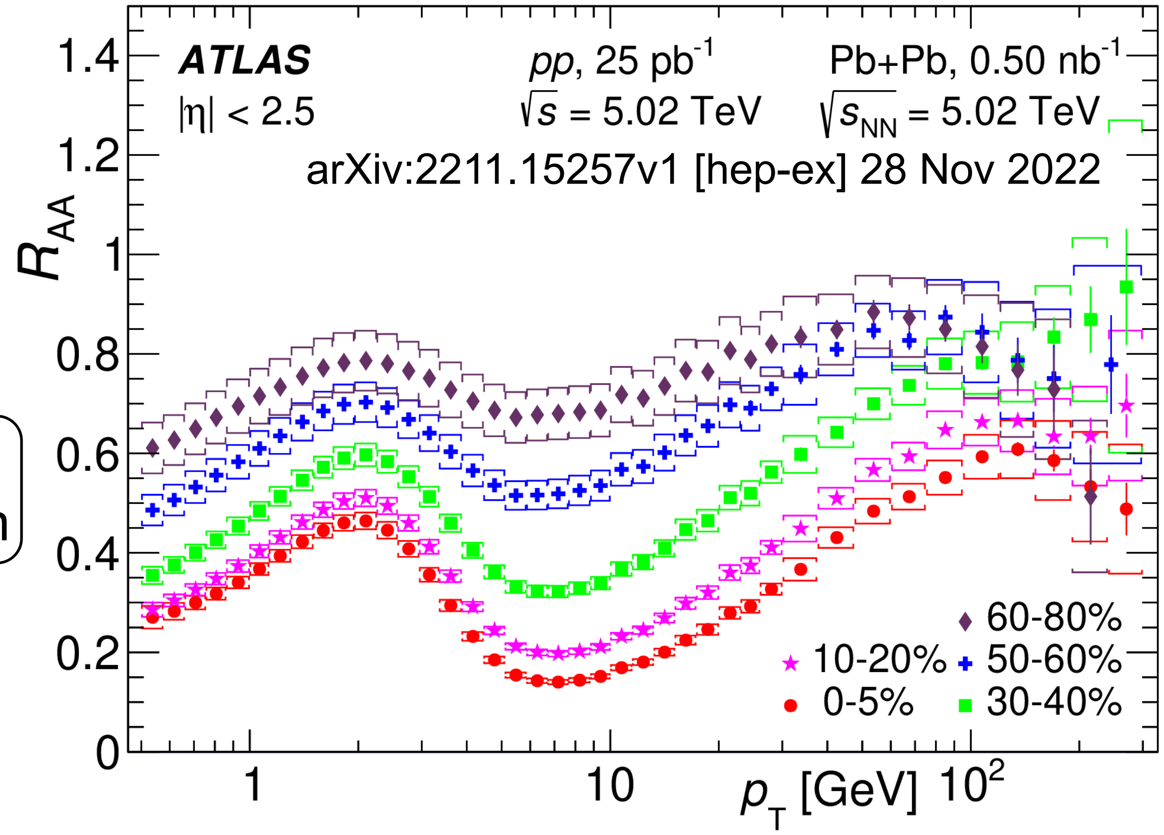
Uncertainty is the part of the correction that you <u>do not know</u> how to do :(

Systematic uncertainty is always an estimator

Global heavy ion analysis → R_{AA}

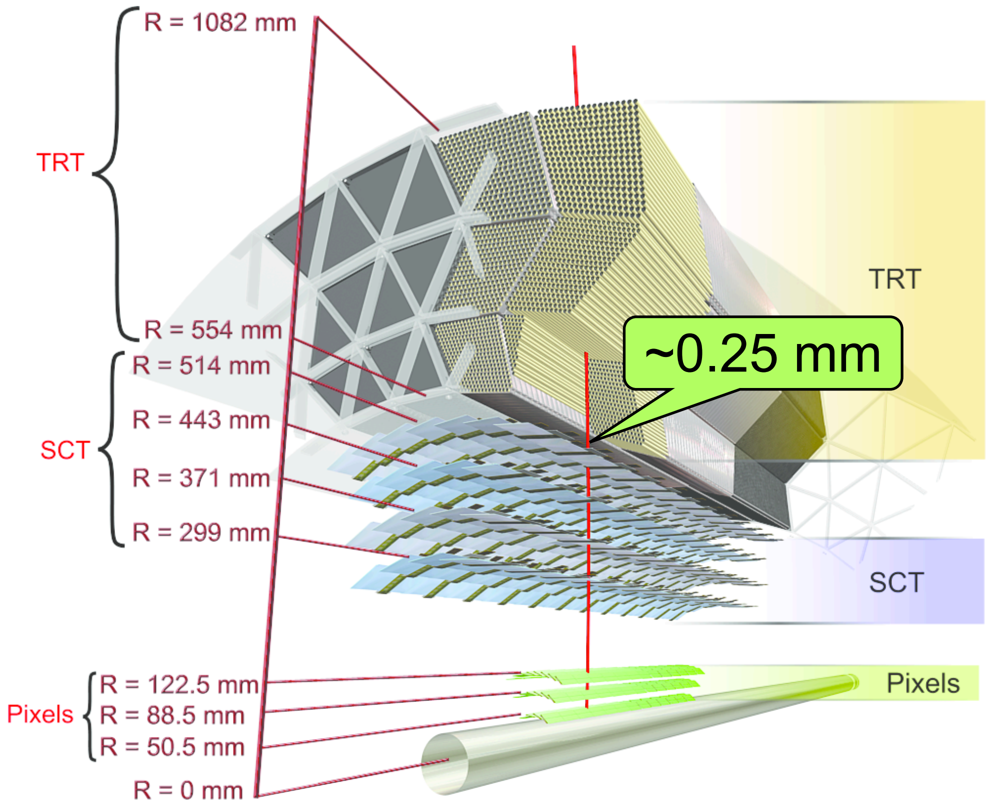
What does it mean to make an analysis?





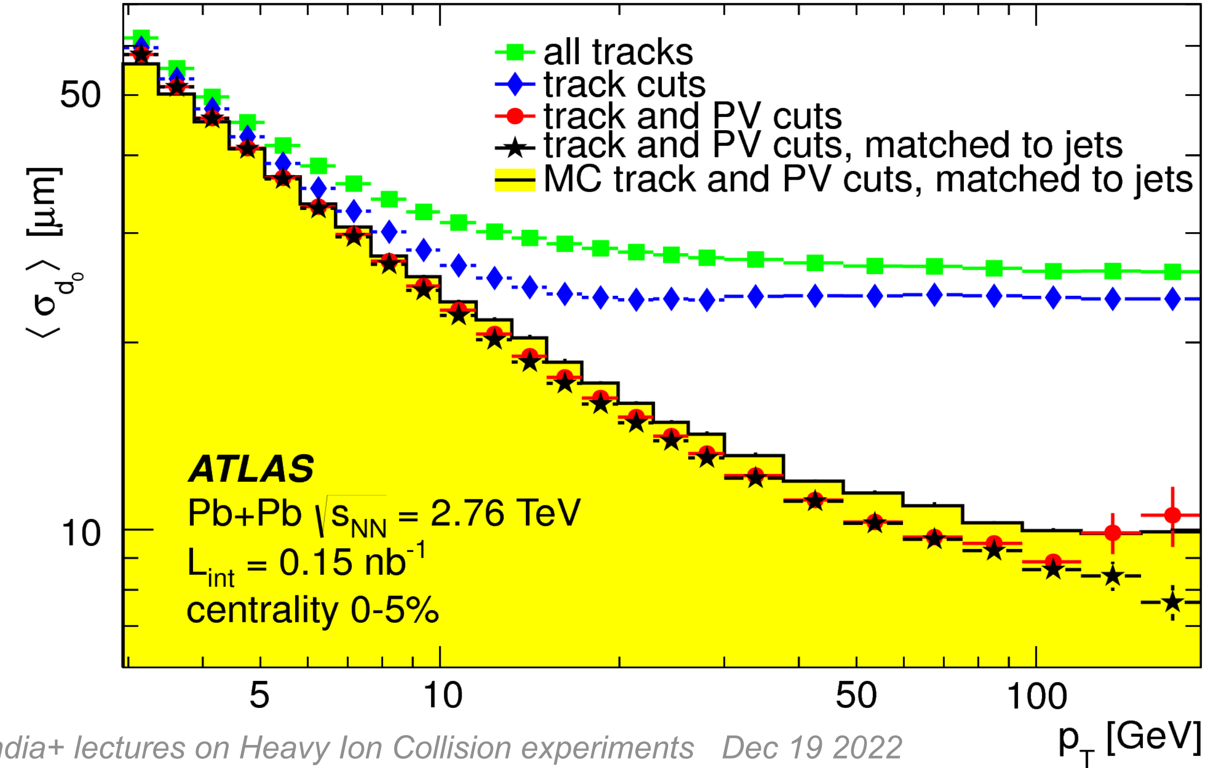
Selection cuts

A 100 GeV particle over 0.5 m in 2 T magnetic field deflects from a straight line by ¼ mm
This is more than multiple scattering, but one shall care about the backgrounds



Backgrounds are:

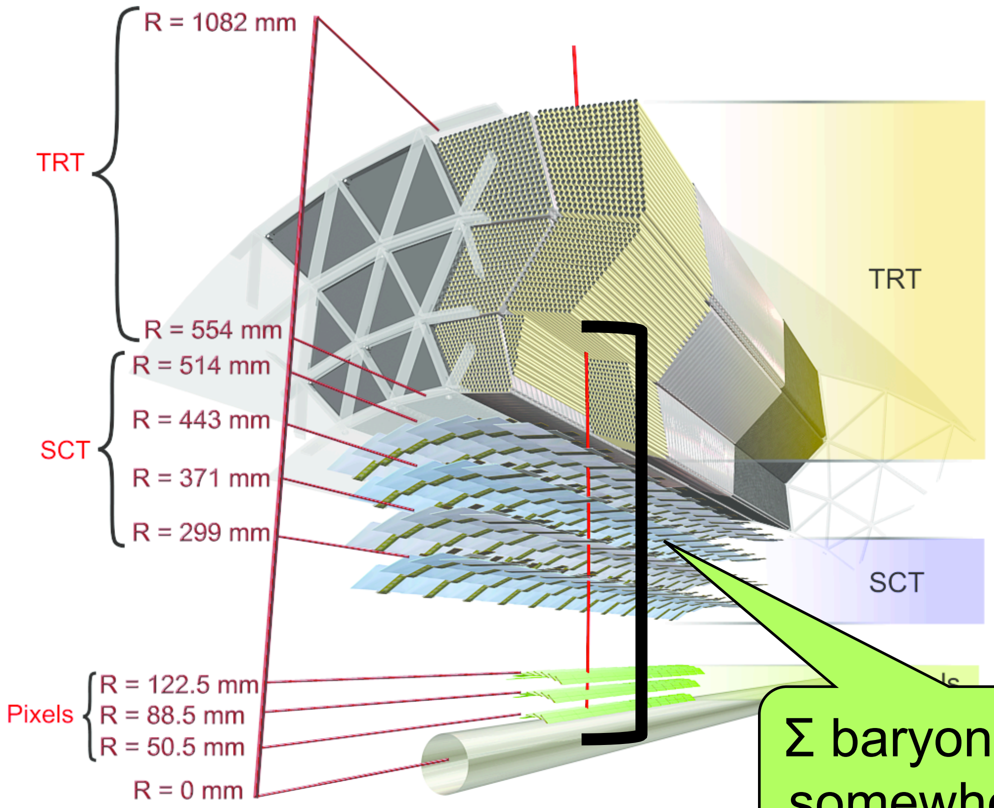
Region	p_T	Problem	Cure
low	1 GeV	Occupancy	Quality cuts
Intermediate	10 GeV	Secondaries	TTVM
High	100 GeV	Scattering	Jets



Define what you measure!

"This analysis of the charged-particle spectra refers to primary charged particles with a mean lifetime greater than 0.3×10^{-10} s, directly produced in the nucleus-nucleus interactions or long-lived charged particles created by subsequent decays of particles with shorter lifetimes [48]."

Σ baryon in



Σ baryon decays somewhere here

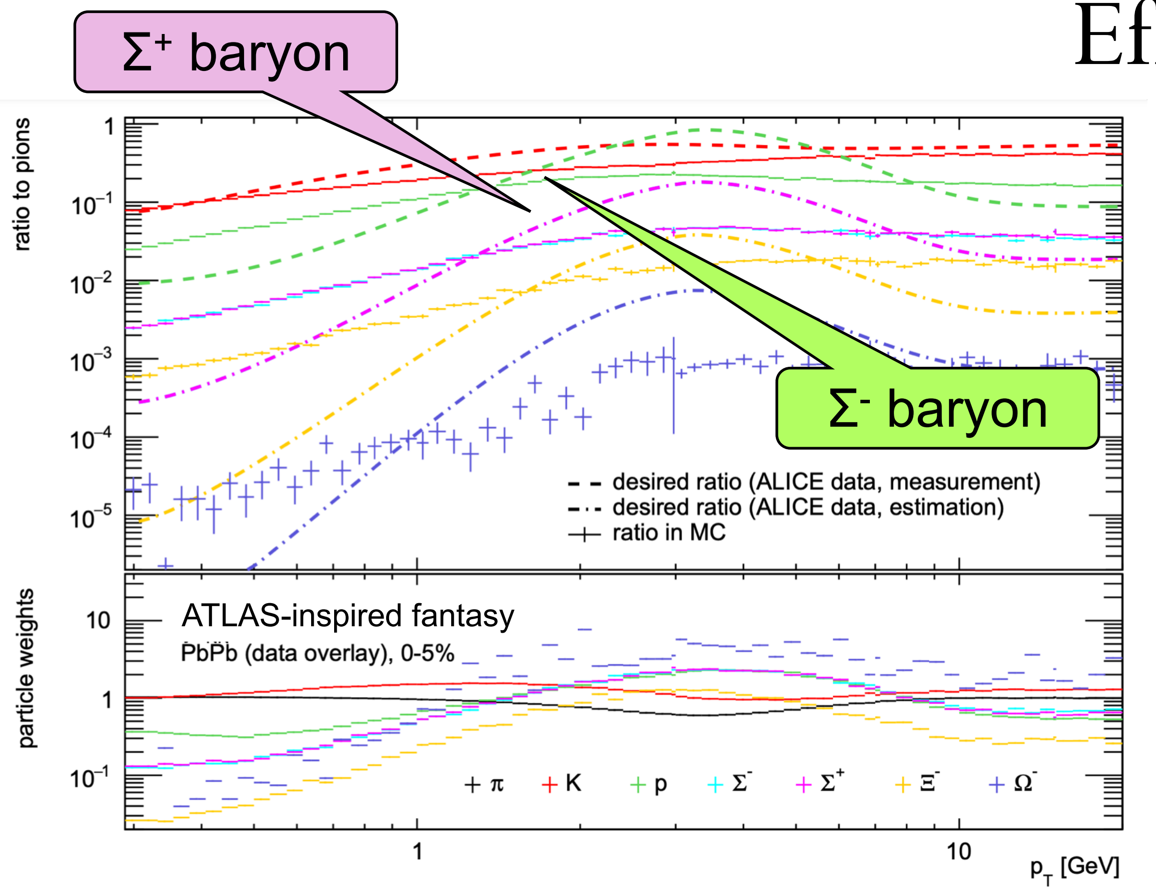
If it Σ baryon traversers ATLAS it leaves a tracks that shall be legitimately counted

If it decays, its daughter tracks would be rejected by TTVM cuts

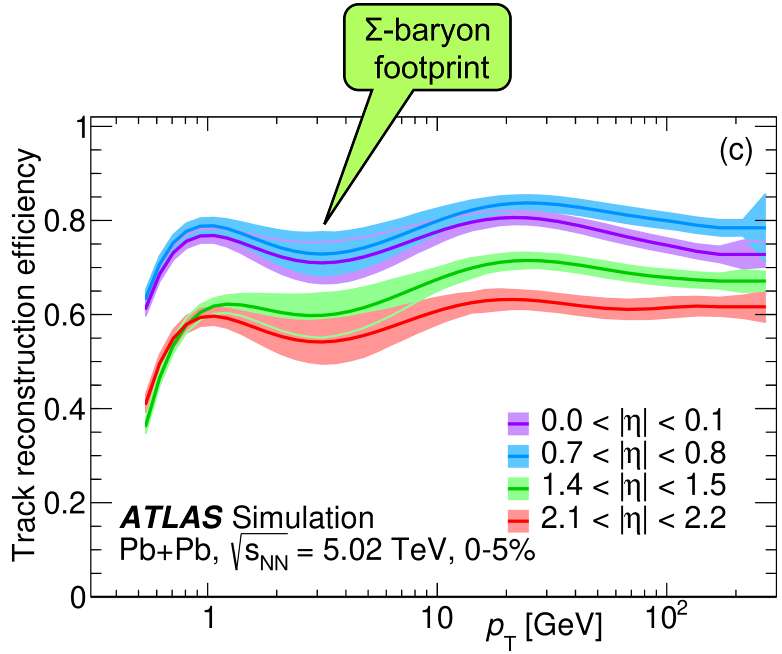
If you think that one can choose a definition that Σ baryon is not primary this would only rename the problem without solving it

The real problem is that ATLAS has no particle ID and the measurement shall rely on the existing data

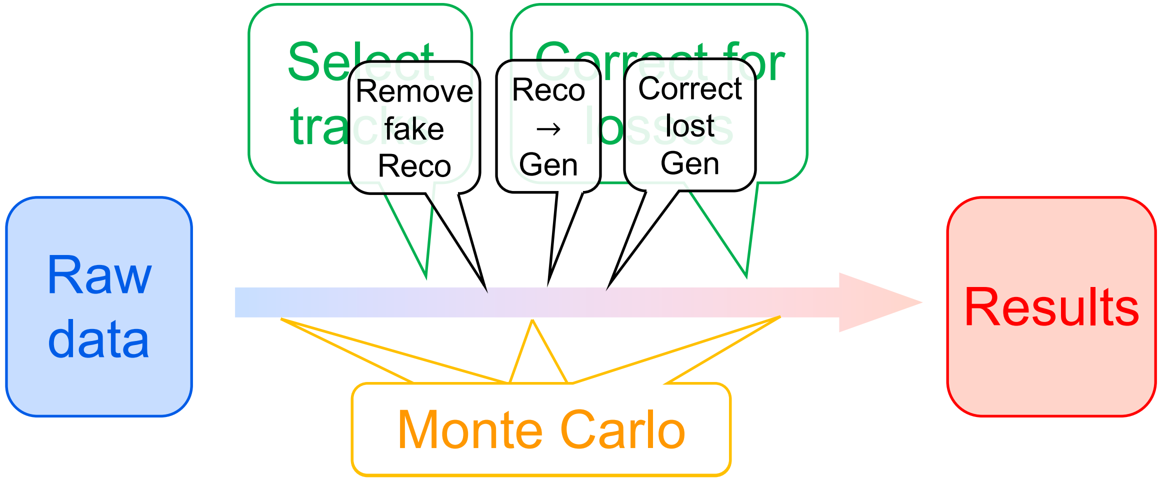
Efficiency

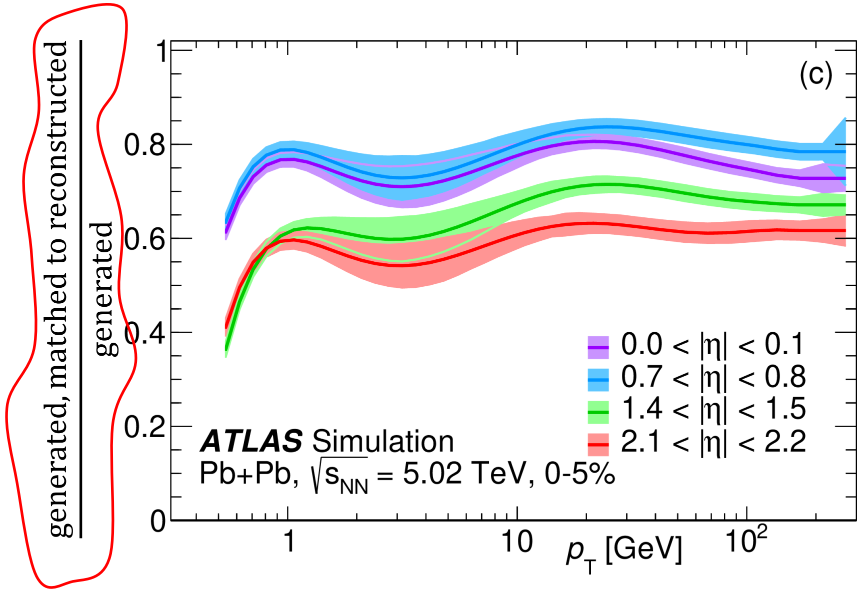


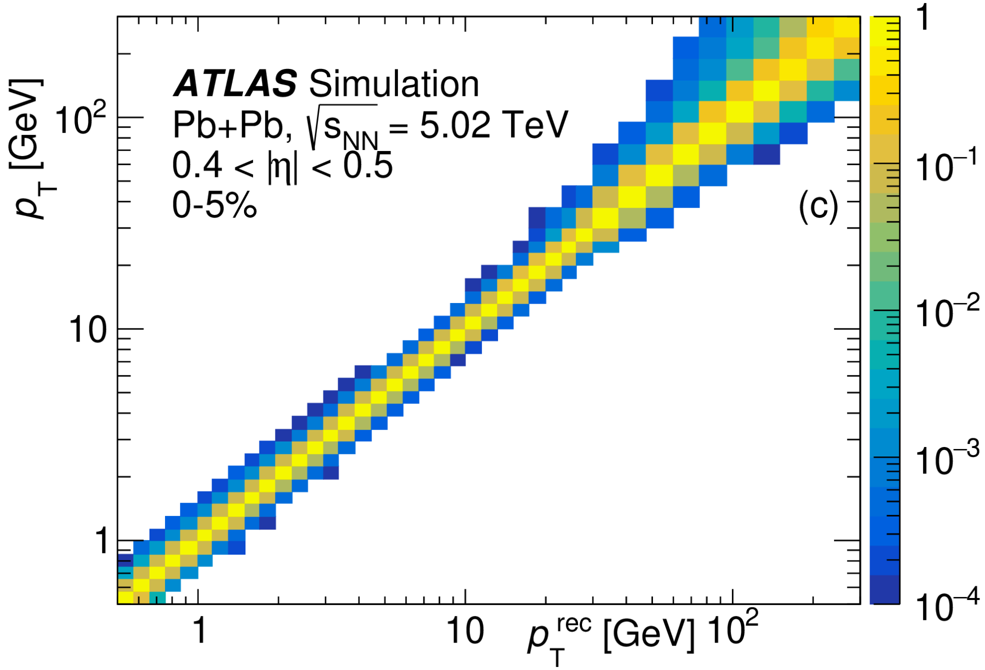
This is a correction on particle composition, part of which ATLAS can't measure. This must be accounted in systematic uncertainties.

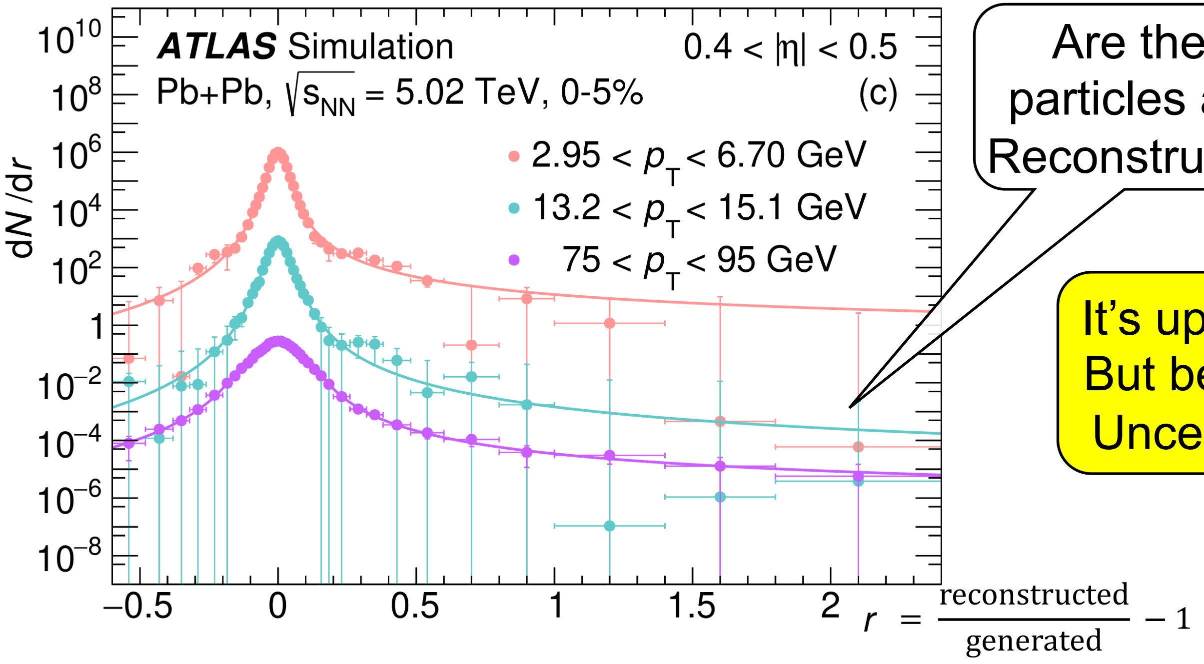


Efficiency vs. resolution





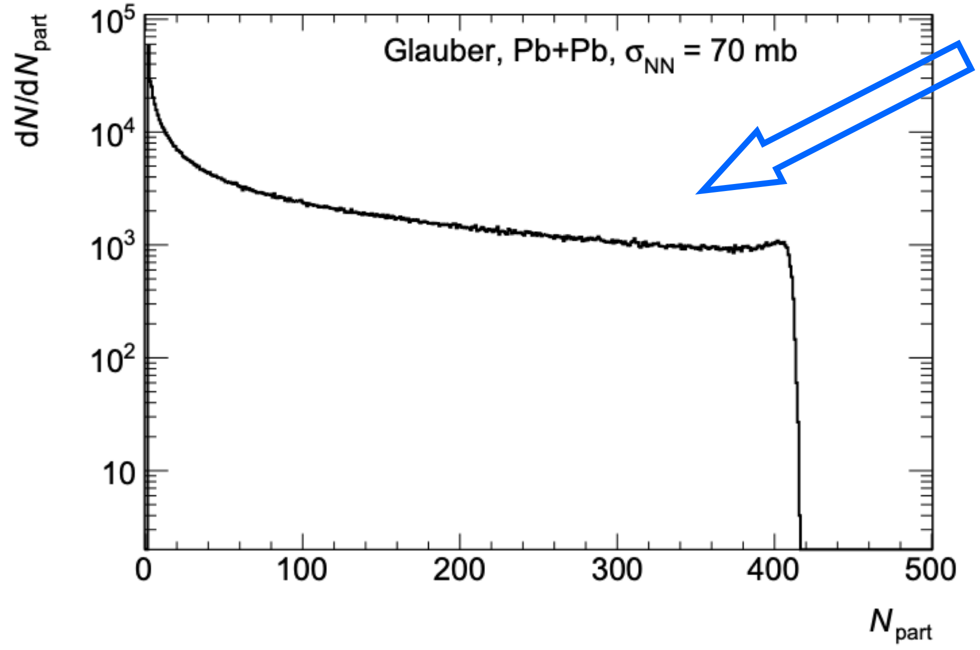




Are these particles at all Reconstructed?

It's up to you :) But beware of Uncertainties!

Special HI systematic: centrality

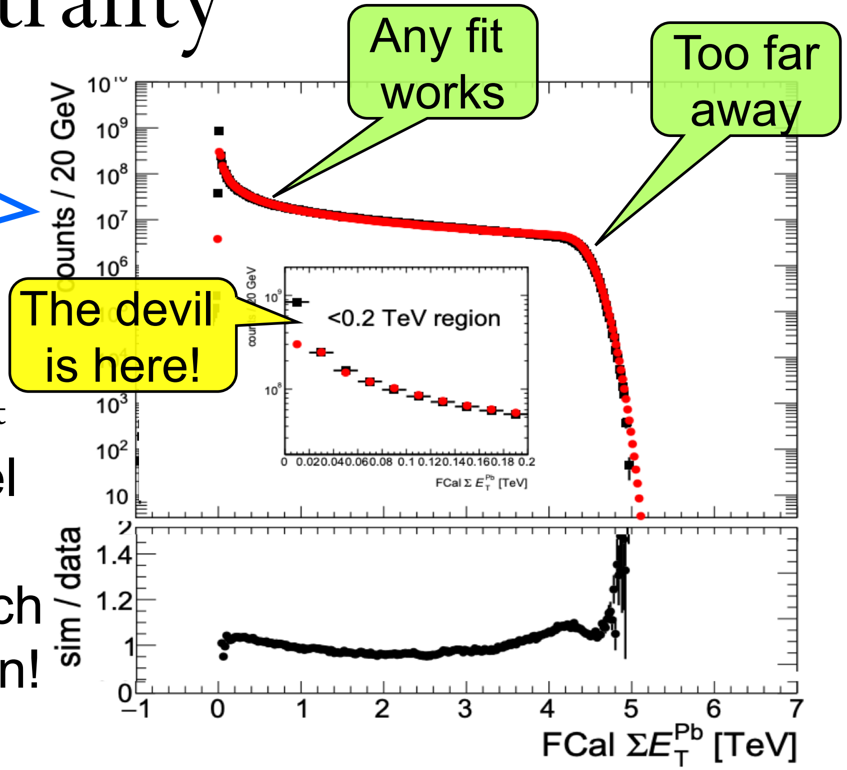


MC Glauber model
Detector response
Particle production model

$$n_{ch} \sim E_T \sim x \times N_{coll} + \frac{1}{2}(1-x) \times N_{part}$$

A.k.a. two-component model

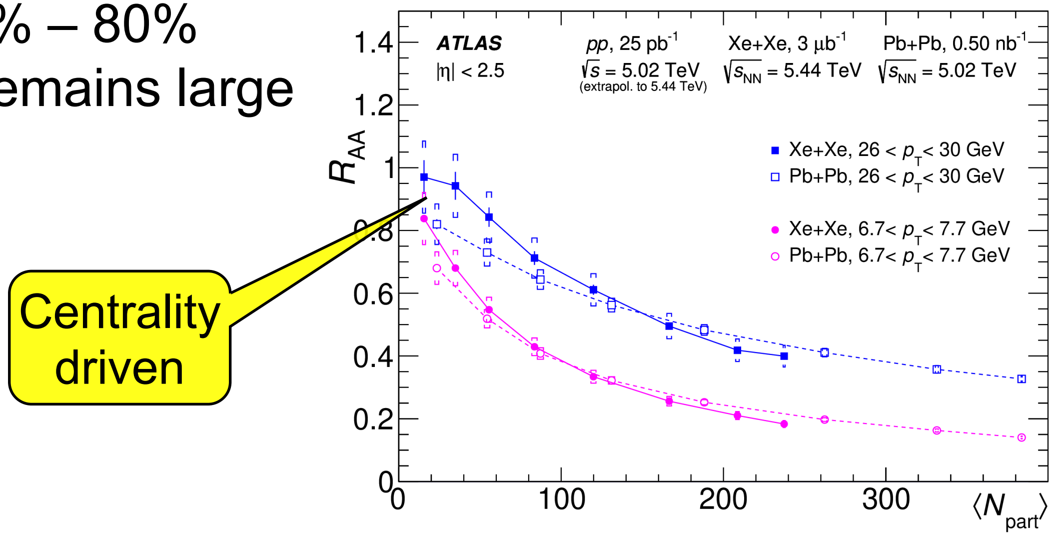
None of them matter as much as the MB event composition!



In practice, everyone fits detector response above 90% – 80% while the uncertainty on the missing 10% – 20% still remains large

There are measures to improve the situation:

- understand photonuclear collisions
- use the Zero Degree Calorimeters
- calibrate centrality with EW bosons
- or simply use n_{ch}



As an example about systematics

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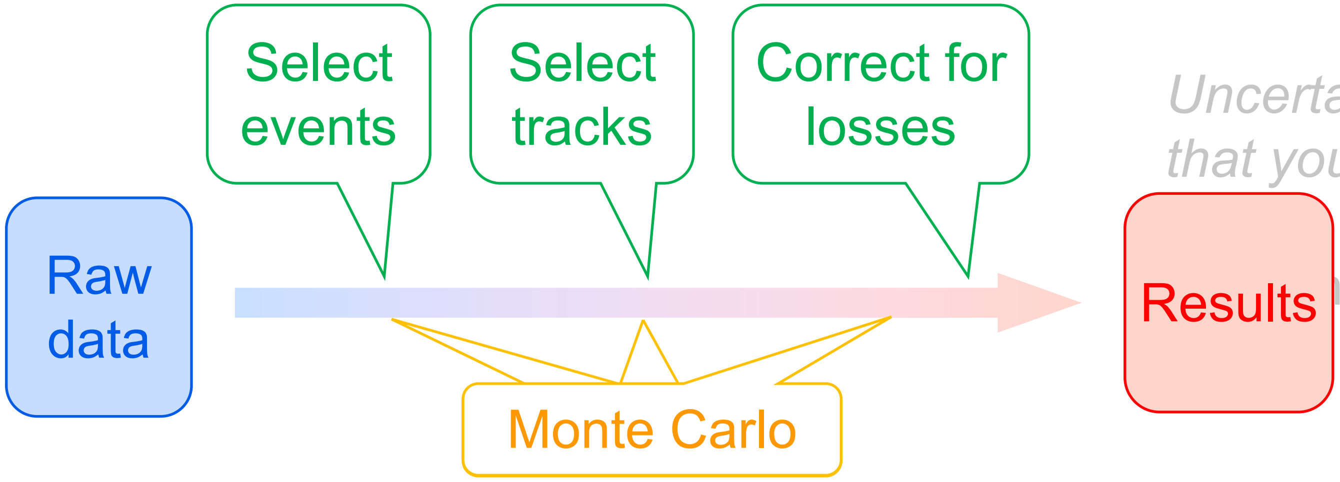


atic uncertainty is always an estimator

A tool to reduce uncertainties is… redundancy

Redundancy allows you measuring the same things in different ways, thus getting a feeling of (estimator of) the uncertainties.

Redundancies at the level of the physics principles.

Good detector = detector with redundant subsystems

Redundancies at the level of the detector design and measurement methodology

Good measurement = more than one measurement of the same value

Redundancies at the level of algorithms

Good measurement = measurement that passed the closure test

Redundancies at the level of data samples

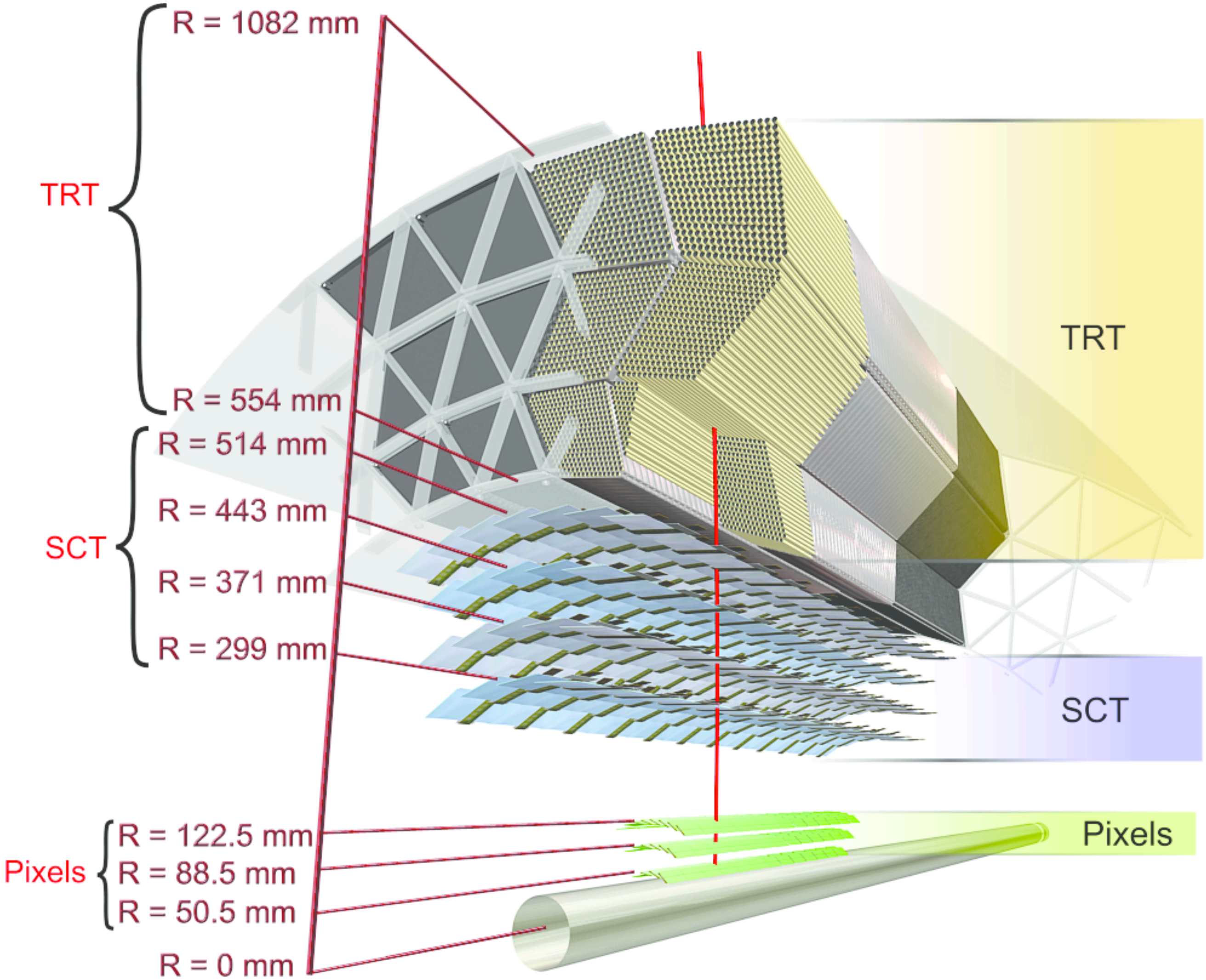
More statistics = smaller systematic uncertainties that can be worked out

Redundancies at a human level

Two independent analyses are better than one. In most cases…

LHC	CMS	ATLAS
LEP	OPAL	ALEPH
Tevatron	CDF	D0
VEPP-200	CMD	SND
RHIC	STAR	PHENIX

Redundancy at the detector subsystem level



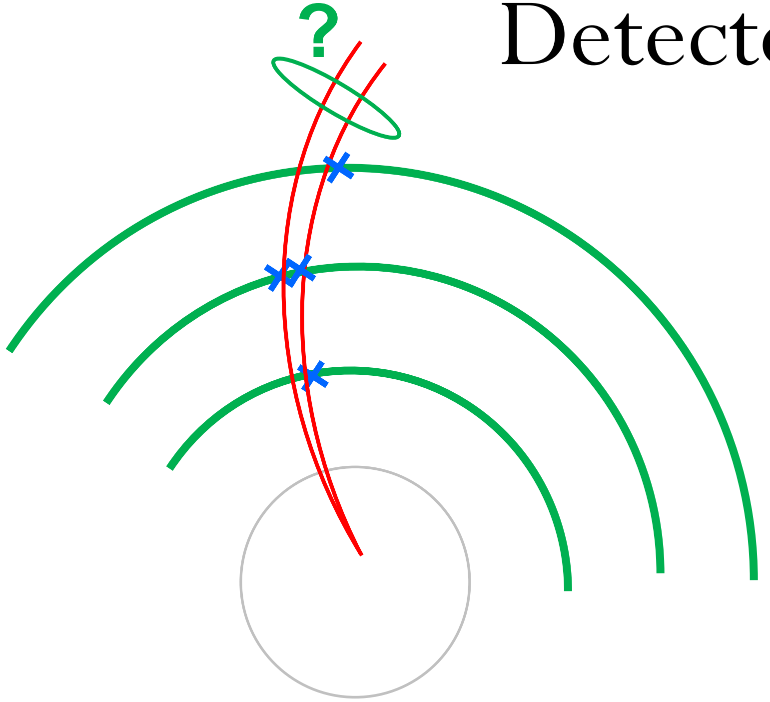
Warning:
Coming to financing institutions and saying "I want a redundant detector" is a terrible idea

In most cases, however, redundancy comes from totally different considerations, but it is still there

In ATLAS Inner Detector (ID) tracking system Pixel detector and SemiConductor tracker (SCT) each can do independent tracking

As a result, subsystems can recalibrate each other or even do more than that.

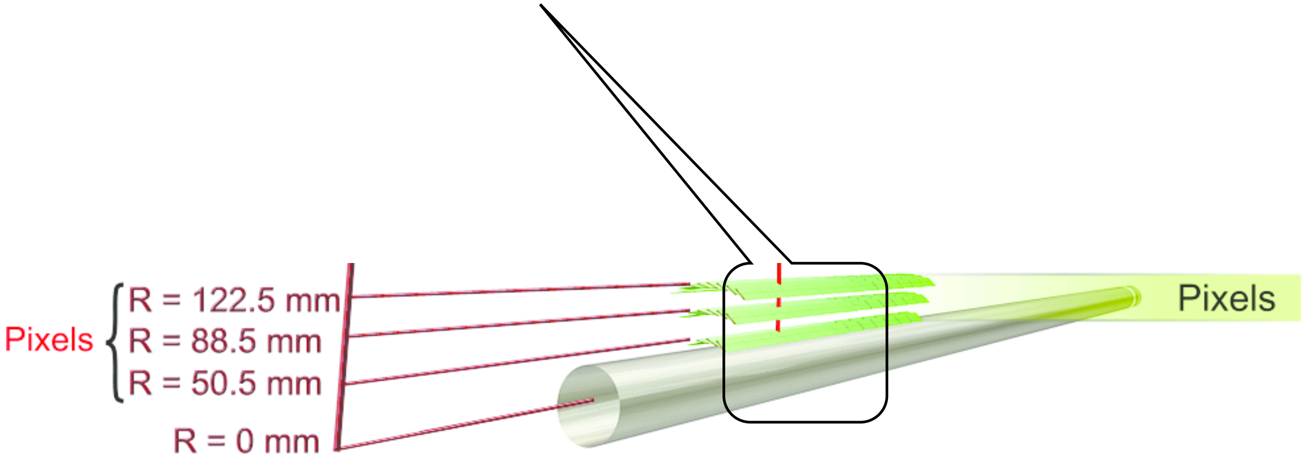
Detector and algorithmic redundancy



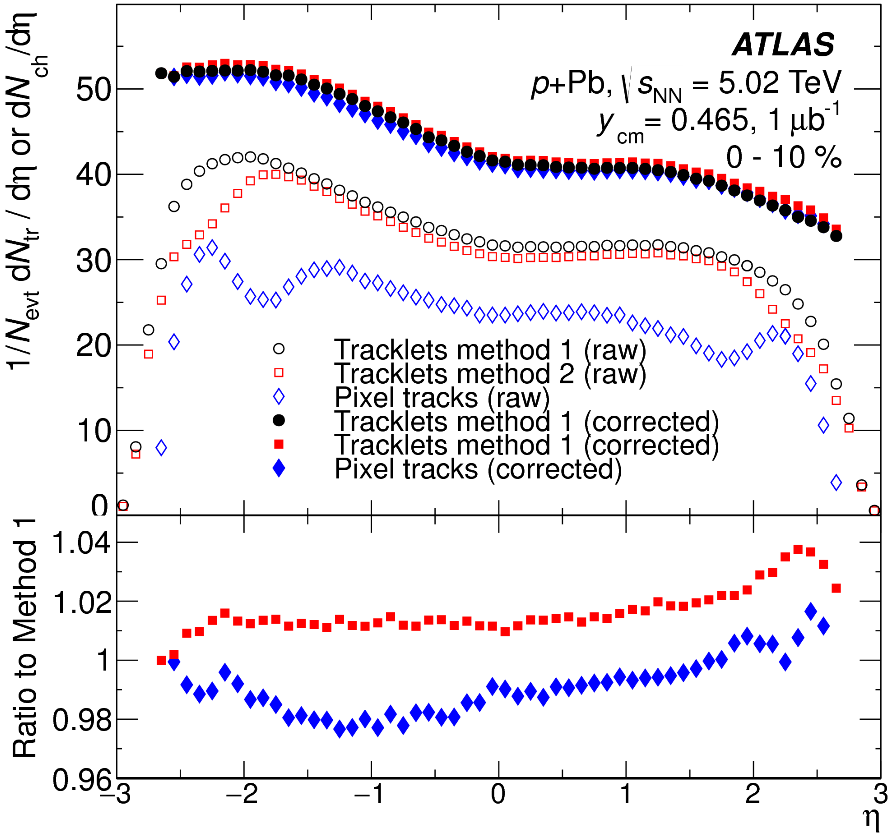
Method 1: innermost layer: one hit – one tracklet.
outer layers: either confirm it or not
multiple confirmation merge together

Method 2: innermost layer: one hit – many tracklets
outer layers: confirm several tracklets
then shuffle detectors to remove combinatorial

Method 3: short tracks made out of 3 layers



Detector and algorithmic redundancy

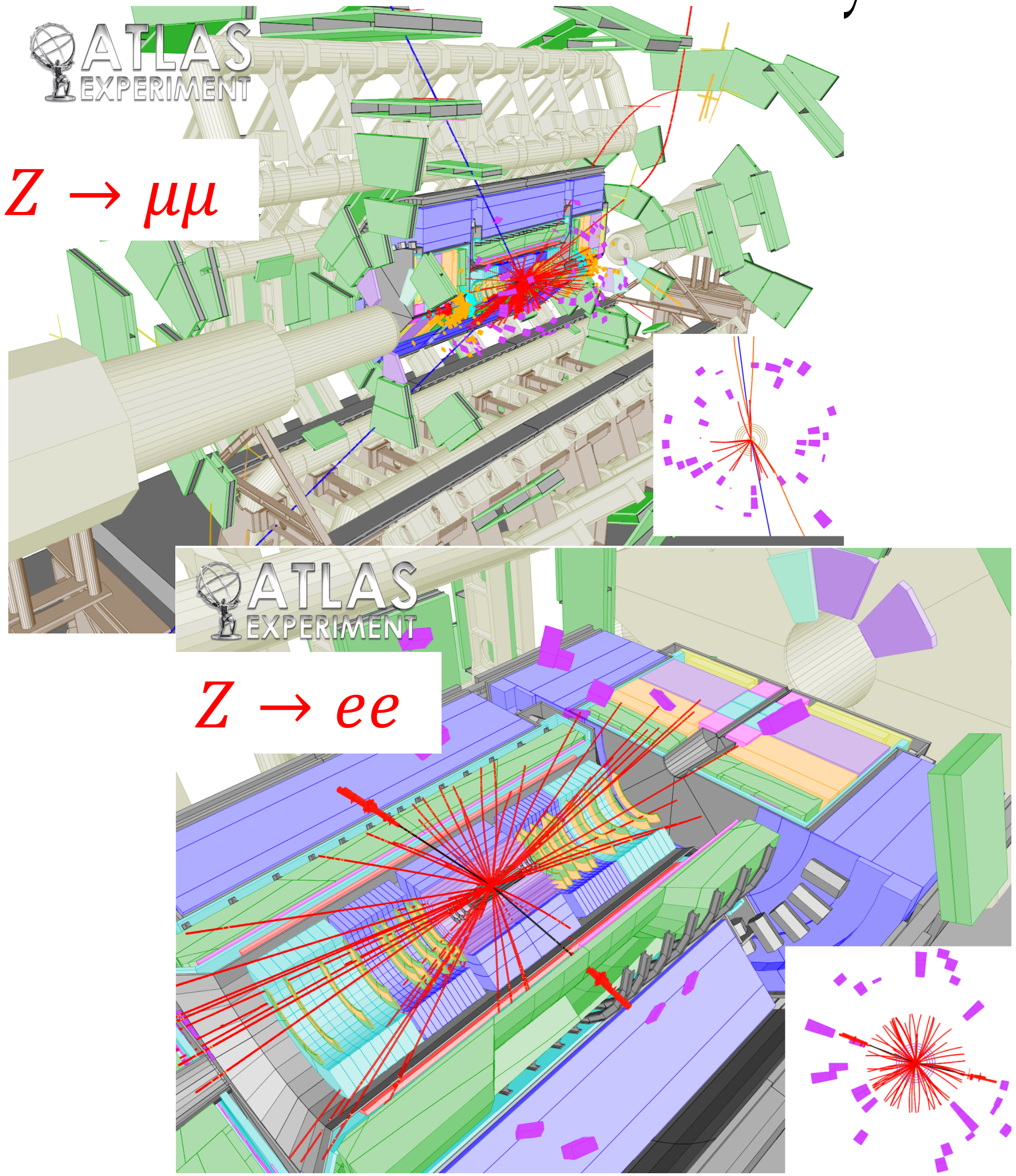


Method 1:	innermost layer:	one hit – one tracklet.
	outer layers:	either confirm it or not
	multiple confirmation merge together	
Method 2:	innermost layer:	one hit – many tracklets
	outer layers:	confirm several tracklets
	then shuffle detectors to remove combinatorial	
Method 3:	short tracks made out of 3 layers	

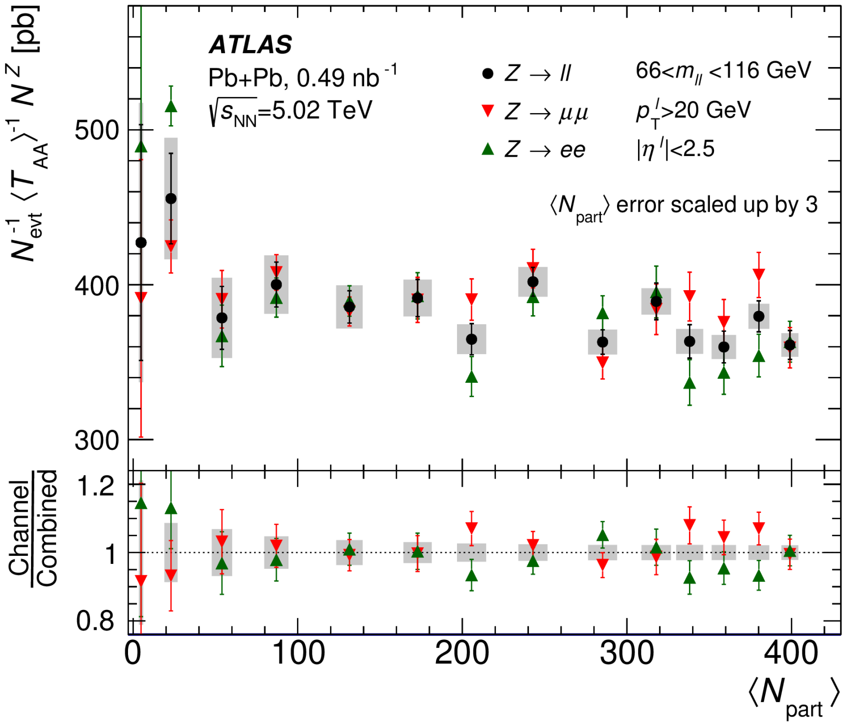
A very powerful handle on systematic uncertainty
But only on the part that comes from secondaries and fakes
Many other sources of uncertainties would not be affected at all

It is very important in the analysis to understand what systematics your cross checks verify!

Redundancy at the physics principle level

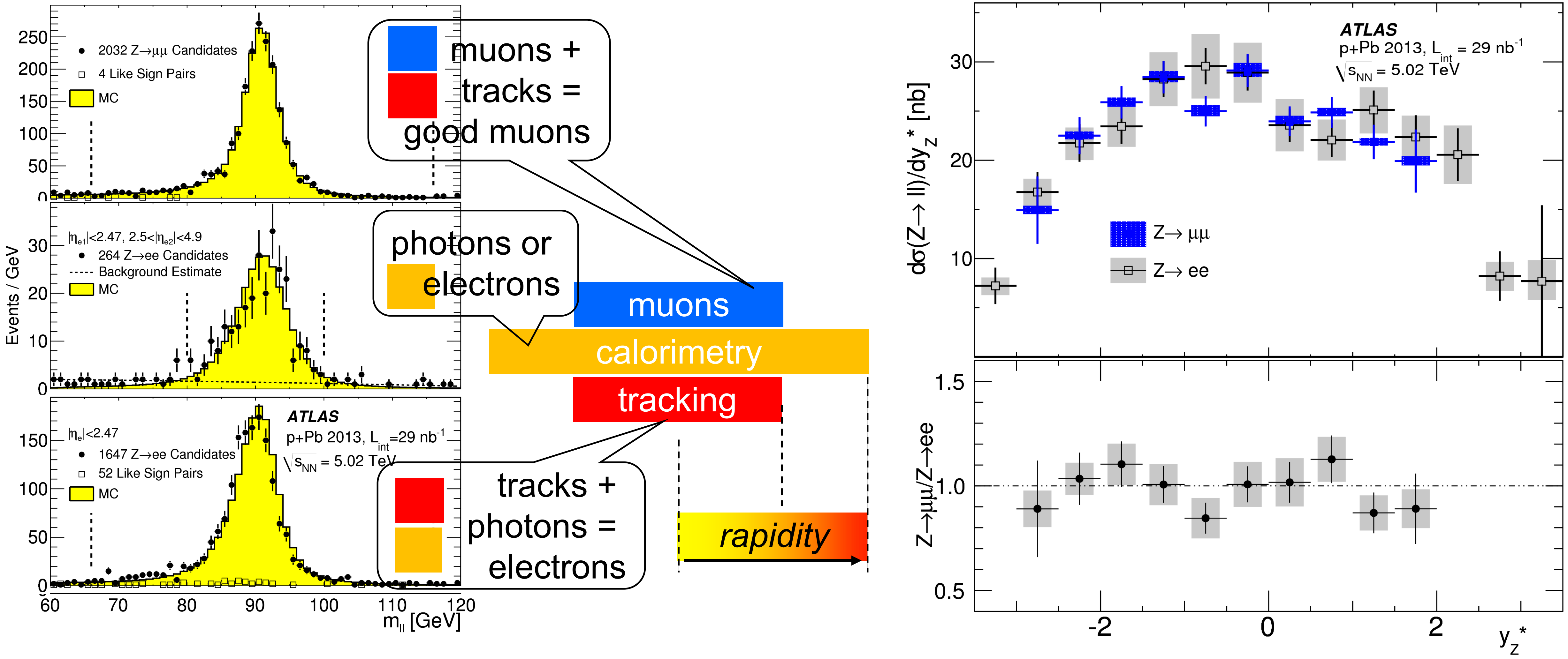


A classical example of the 'redundant' measurement. For almost every aspect $Z \to ll$ does not care about whether it is an electron or a muon



Of course, the gain in Pb+Pb is mostly statistical, but it also suppresses the systematics.

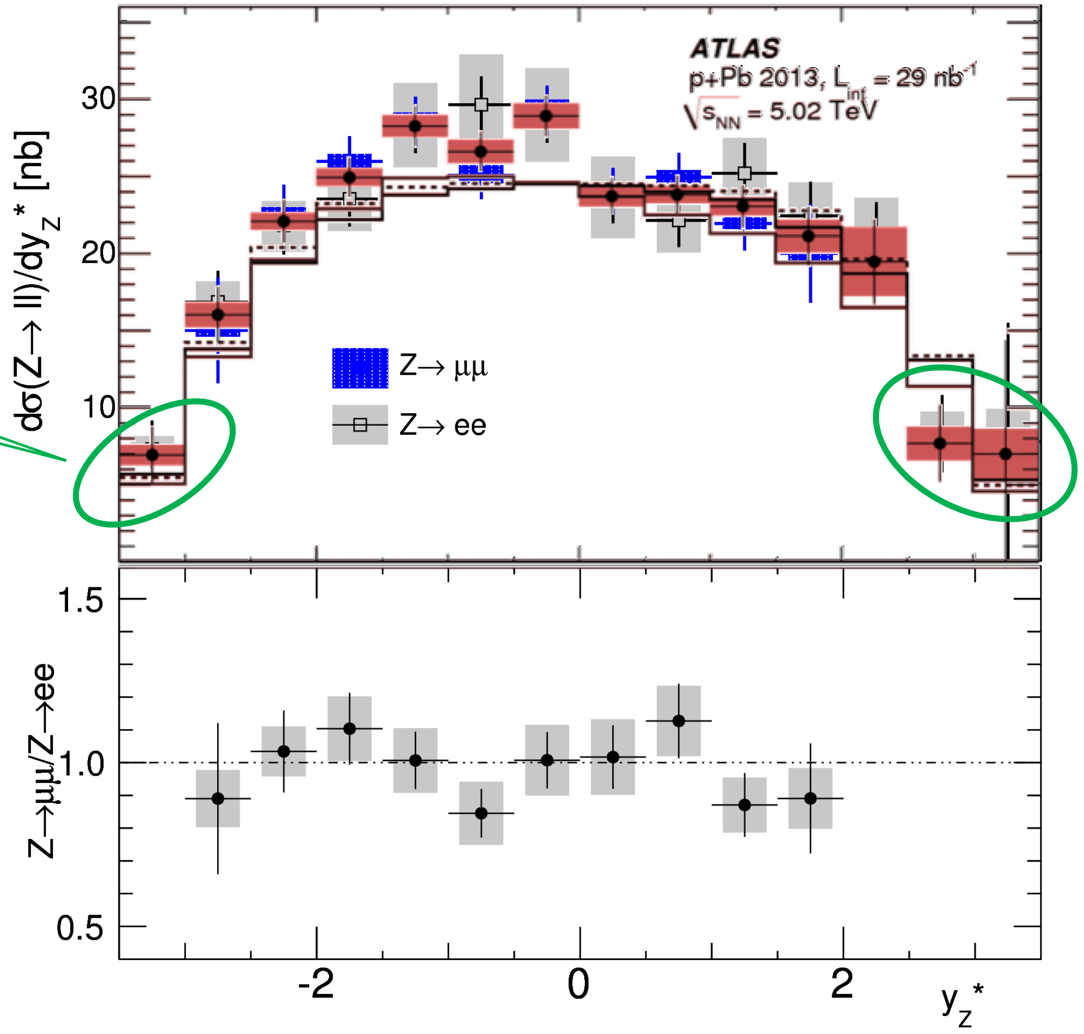
Redundancy at the physics principle level



In inclusive Z boson measurements the most interesting region is at high rapidity

Redundancy at the physics principle level

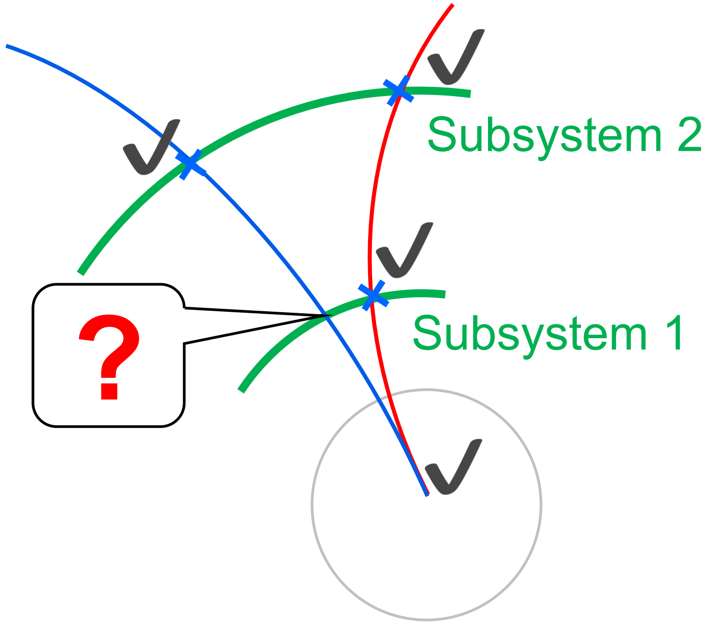
If there is only one channel in this region, how comes the points moved, and systematic changed?



Remember Type "C" systematic uncertainty?

If one knows what it is for $Z \to \mu\mu$ and $Z \to ee$ one can move all points using the more precise measurements

Self-calibration: Tag-and-probe method



Let's take a well-known physics process: $J/\psi \rightarrow \mu\mu$ $\phi \rightarrow KK$ $\gamma \rightarrow ee$ and
Reconstruct it with only part of the detector.

For example, $\mathrm{Z} \rightarrow ee$:

We identify the 1st electron in subsystems 1 & 2
And the 2nd electron in subsystem 2 only
Using an invariant mass peak, we make sure it was a Z boson
Then we exactly know where shall be a muon in subsystem 1

We can measure detector efficiency right from the data, w/o any MC!
But there is a better way, called "scale factors"

$$\epsilon = \epsilon_{MC} \times SF, \qquad SF = \frac{\epsilon_{\mathrm{data}}^{\mathrm{T\&P}}}{\epsilon_{\mathrm{MC}}^{\mathrm{T\&P}}}$$

Advantages: data have biases, it's very difficult to get rid of all of them
even if you can live w/o MC efficiency for some processes, you can't do it for all

To take away

In modern physics the uncertainties are the essential, and sometimes the most important and the most time-consuming part of the measurement

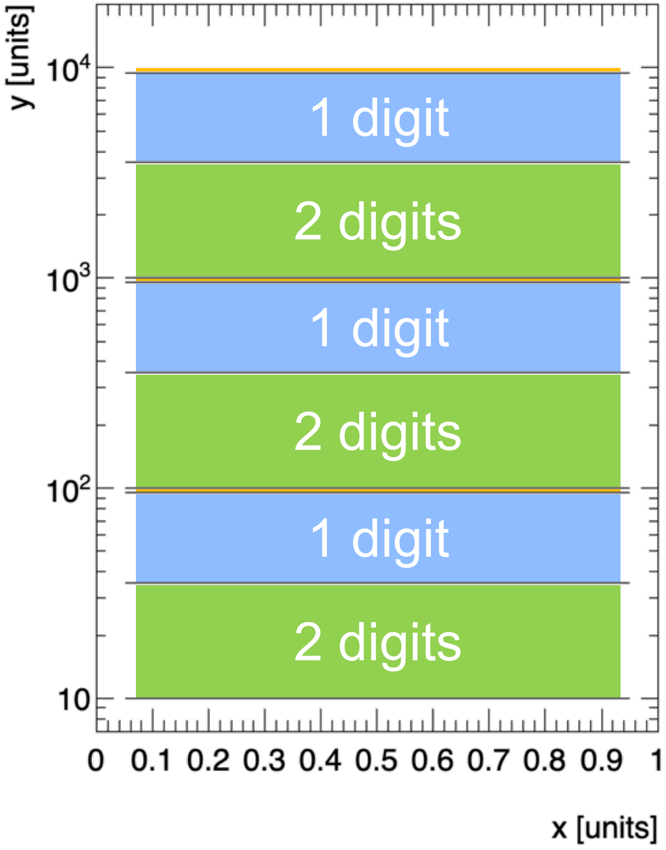
Some old conventions about uncertainties often do not work: breaking uncertainties into ‘statistical’ and ‘systematic’ is usually artificial, the real question is in the correlations between them

Uncertainties are generated at every step that you do in your analysis (except drinking coffee). There is no such thing ‘*let’s neglect this uncertainty*’. There is ‘*let’s estimate this uncertainty and show that it is much smaller than the others*’

The real tool to suppress the uncertainty is to do the measurement in another *independent* way. Redundancy of your apparatus, methods, algorithms may help you in that

Working on uncertainties the main difficulty is not to cheat on yourself. To understand what part of the uncertainty you are trying to untangle and not to pretend that you can know better that you can

About presenting experimental uncertainties



https://pdg.lbl.gov/2011/reviews/rpp2011-rev-rpp-intro.pdf

The basic rule states that if the three highest order digits of the error lie between 100 and 354, we round to two significant digits. If they lie between 355 and 949, we round to one significant digit. Finally, if they lie between 950 and 999, we round up to 1000 and keep two significant digits. In all cases, the central value is given with a precision that matches that of the error. So, for example, the result (coming from an average) 0.827 ± 0.119 would appear as 0.83 ± 0.12, while 0.827 ± 0.367 would turn into 0.8 ± 0.4.

The same example we were looking at before

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I'd probably fail to derive the rule with these numbers, and nobody forces you to follow it, but…

This rule says:

do not pretend that you know the uncertainty better than you can

do not pretend that you know the results better than the uncertainty