From physical data to publication

SHINE Autumn School

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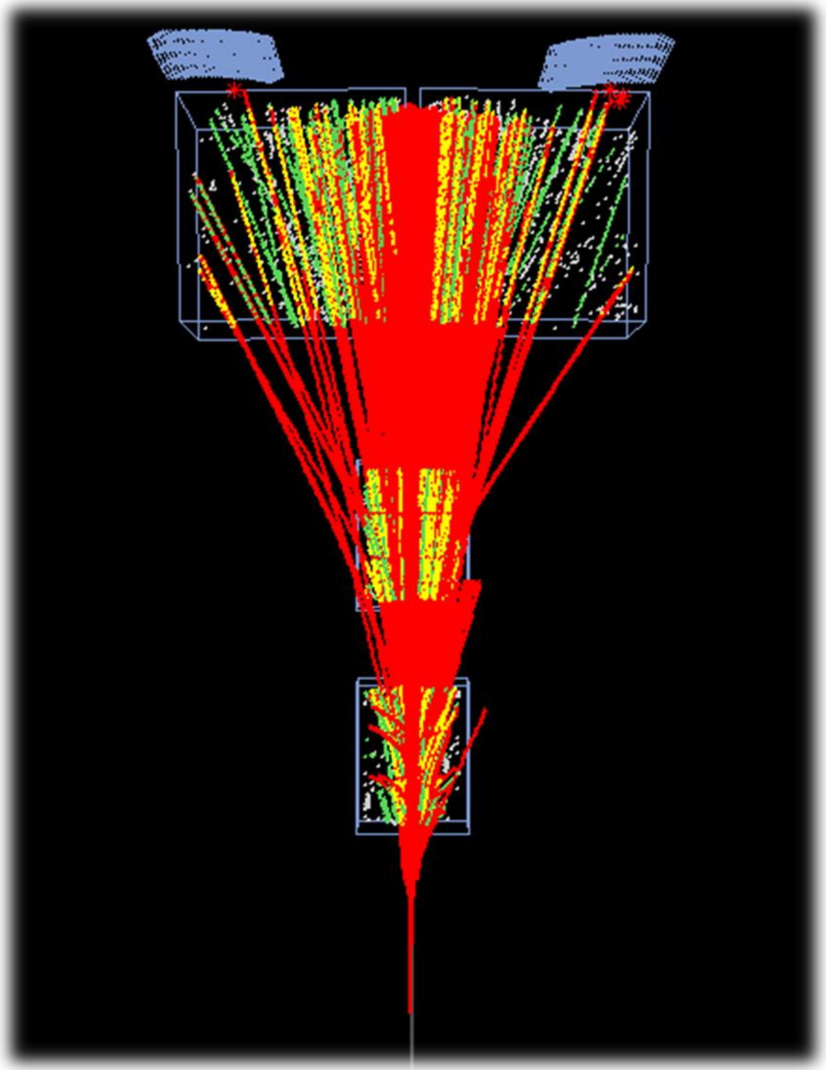
Properly published results

- New measurements are motivated by questions and problems emerging from existing data and models.
- Measurements in HEP are:
  - long-lasting and expensive;
  - very difficult to repeat;
  - founded by public funds

Need for results useful *forever* and for *everyone*



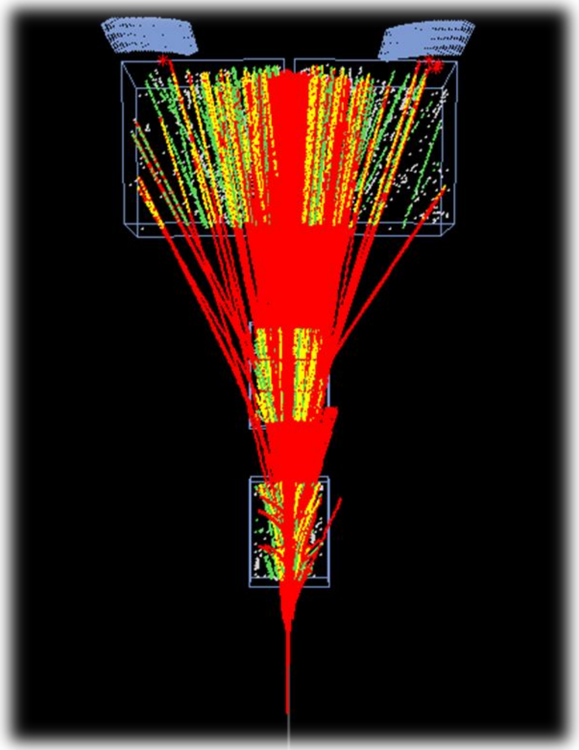
What are useful results

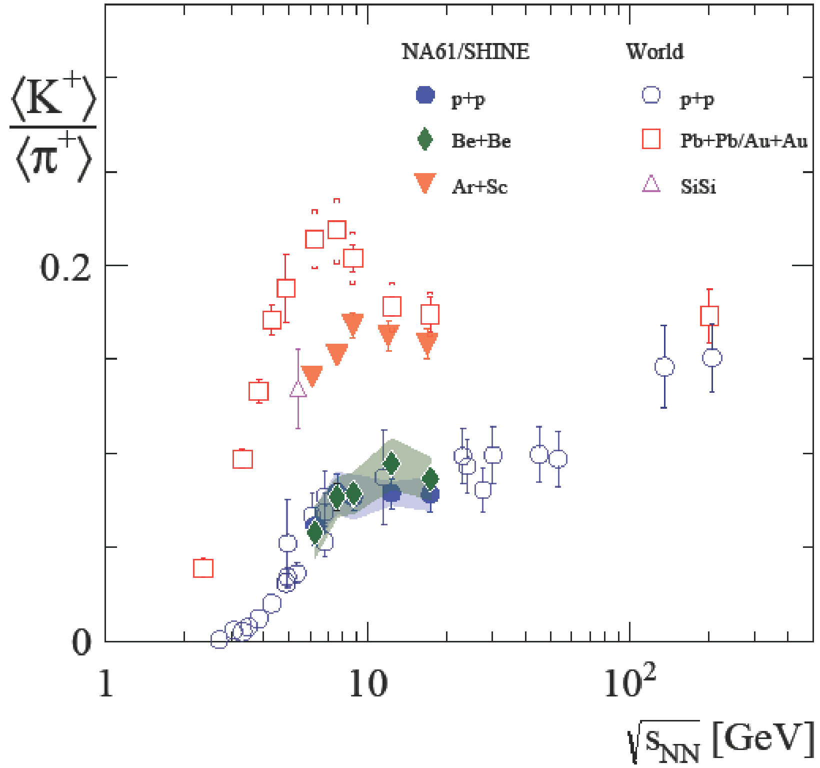
Reconstructed events with vertices and tracks with momentum, charge

Hard to say what interesting physics is there

Exception: CERN Open Data

What are usefull results?





Reconstructed data: event with vertices, track (q, p, dEdx …), centrality etc.

Extracted and compiled information which can be directly related to interesting physical phenomenon

Useful information

- I have a model - What do I need to do to compare it to new measurements?

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Detector description

Reconstruction

Calibration

Useful information

- I have a model - What do I need to do to compare it to new measurements?

Reconstruction

Detector description

Calibration

I will spend a lot of time, first, developing a model and then comparing it to ``new measurements``.
Moreover, ``new measurements`` from a different experiment or detector configuration are available then I have to start comparison again.

Meet half-way (from experiment side)

Results which are useful for everyone contain:

- Definition of quantities used in the analysis
- Precise, model and detector independent, definition of event and track selection – the TRUE selection (aim of the model developer)
- Adjust selection of MEASURED data to be close to TRUE one (experiment responsibility)
- Correct data for differences between the TRUE and MEASURED selection (experiment responsibility)

Definition of quantities - examples

.. the rapidity is calculated in the collision center of mass system: y = atanh(β_L), where $\beta_L = {}^{p_L}/_E$ is the longitudinal (z) component of the velocity, p_L and E are particle longitudinal momentum and energy given in the collision center of mass system.

arXiv:2009.01943

For more complicated measures there are whole sections devoted to define final quantities:

Intensive and strongly intensive measures of multiplicity and particle type fluctuations

arXiv:2009.01943

Two-particle correlations in pseudorapidity and azimuthal angle

Eur. Phys. J. C77, 59 (2017)

True vs measured event - examples

The final results refer to identified hadrons produced in inelastic p+p interactions by strong interaction processes and in electromagnetic decays of produced hadrons. Such hadrons are referred to as primary hadrons.

TRUE

arXiv:2009.01943

7.1 Event selection

Inelastic p+p events were selected using the following criteria:

- *(i) no off-time beam particle detected within a time window of ±1.5 μs around the trigger particle,*
- *(ii) beam particle trajectory measured in at least three planes out of four of BPD-1 and BPD-2 and in both planes of BPD-3,*
- *(iii) the primary interaction vertex fit converged,*
- *(iv) z position of the interaction vertex (fitted using the beam trajectory and TPC tracks) not further away than 20 cm from the center of the liquid hydrogen target (LHT),*
- *(v) events with a single, positively charged track with absolute momentum close to the beam momentum (see Ref. [25]) are removed in order to eliminate elastic scattering reactions. 7.2*

arXiv:2009.01943

MEASURED

True vs measured track selections - example

The analysis was performed in the kinematic acceptance limited by the detector geometry and the statistics of inclusive dE/dx spectra. The acceptance is given in the form of two sets of tables: (i) three-dimensional tables representing the high efficiency region of the detector, (ii) two-dimensional tables defining the dE/dx fit range. The acceptance tables can be found in Ref. [32].

TRUE

arXiv:2009.01943

7.2 Track selection

In order to select tracks of primary charged hadrons and to reduce the contamination of tracks from secondary interactions, weak decays and off-time interactions, the following track selection criteria were applied:

(i) track momentum fit at the interaction vertex should have converged,

(ii) total number of reconstructed points on the track should be greater than 30,

(iii) sum of the number of reconstructed points in VTPC-1 and VTPC-2 should be greater than 15 or the number of reconstructed points in the GAP TPC should be greater than 4,

(iv) the distance between the track extrapolated to the interaction plane and the interaction point (impact parameter) should be smaller than 4 cm in the horizontal (bending) plane and 2 cm in the vertical (drift) plane,

(v) the total number of reconstructed dE/dx points on the track should be greater than 30,

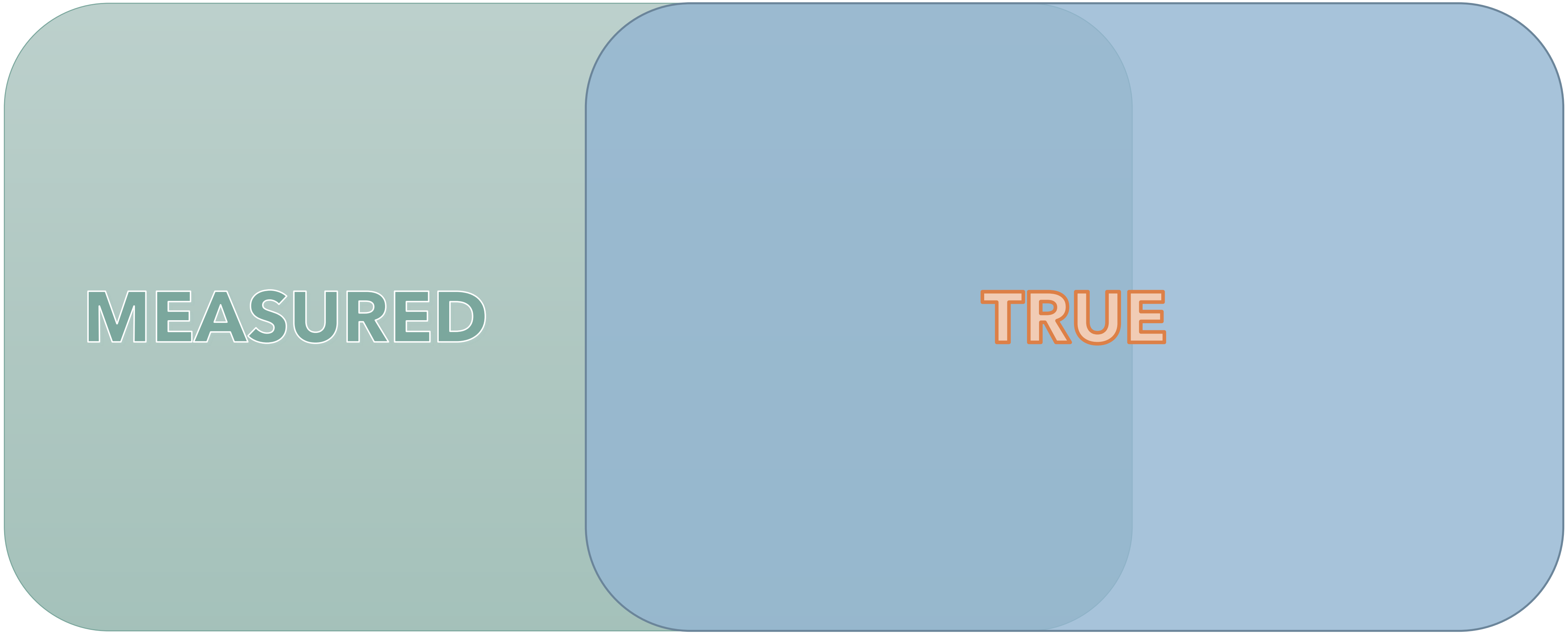
(vi) the track lies in the high efficiency region of the detector and the dE/dx fit acceptance maps given in Ref. [32].

MEASURED

arXiv:2009.01943

Correct data for differences between the TRUE and MEASURED selection

Nothing is perfect. There are lumps in it.
JS

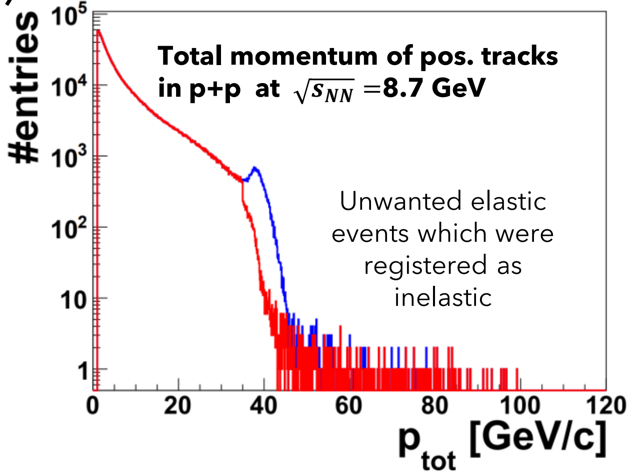


Biases

Systematic biases are differences between the TRUE result for a given sample and MEASURED one for this sample.

Systematic biases are independent of event statistics and are usually quantified using either data-based procedures (consistency checks, e.g. time dependence of input parameter) or using simulated events with statistics much larger than the data statistics (Monte-Carlo).

Example:
Gain of elastic events (trigger bias) which are then removed by event selection (bias due to loss of inelastic events labeled as elastic)



Other examples: detector geometrical acceptance, centrality selection in A+A interactions, etc.

Two types of biases – simple examples

Event migration

- All TRUE events and only TRUE events are measured $M_M = M_T$, but MEASURED number of tracks is biased $N_M \neq N_T$, e.g. contribution of non vertex tracks (so-called feed-down), detector acceptance

Loss/gain of events

- Multiplicity of all events is correctly MEASURED $N_M = N_T$ but some events are lost, and some unwanted events are gained $M_M \neq M_T$, e.g. trigger inefficiency, off-time interactions

Biases in real experiment

In real experiments biases are due to both bin migration and lost/gain of events/tracks and should be corrected for.

Example from previous slide for inclusive analysis: gain/loss of tracks and bin migration due to wrong reconstruction

Corrections

If I understand how my detector works and know possible biases I can correct them.

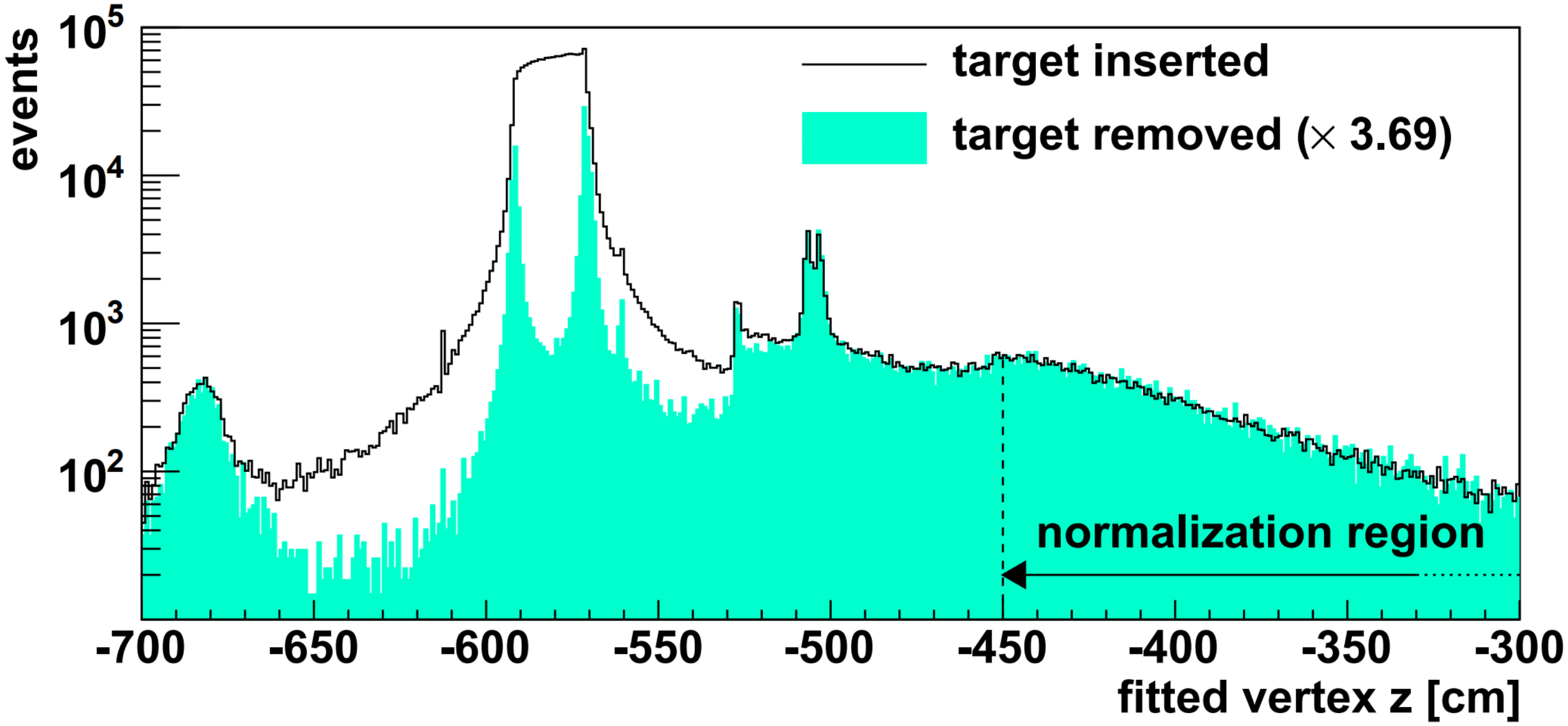
How to close gap between MEASURED and TRUE?

- Data-based corrections
- MC-based corrections

Data-based corrections

Preferred type of corrections

Known a priori biases (or found during analysis) may lead to corrections based on additional measurements, e.g. data taking without target to estimate non-target contribution.



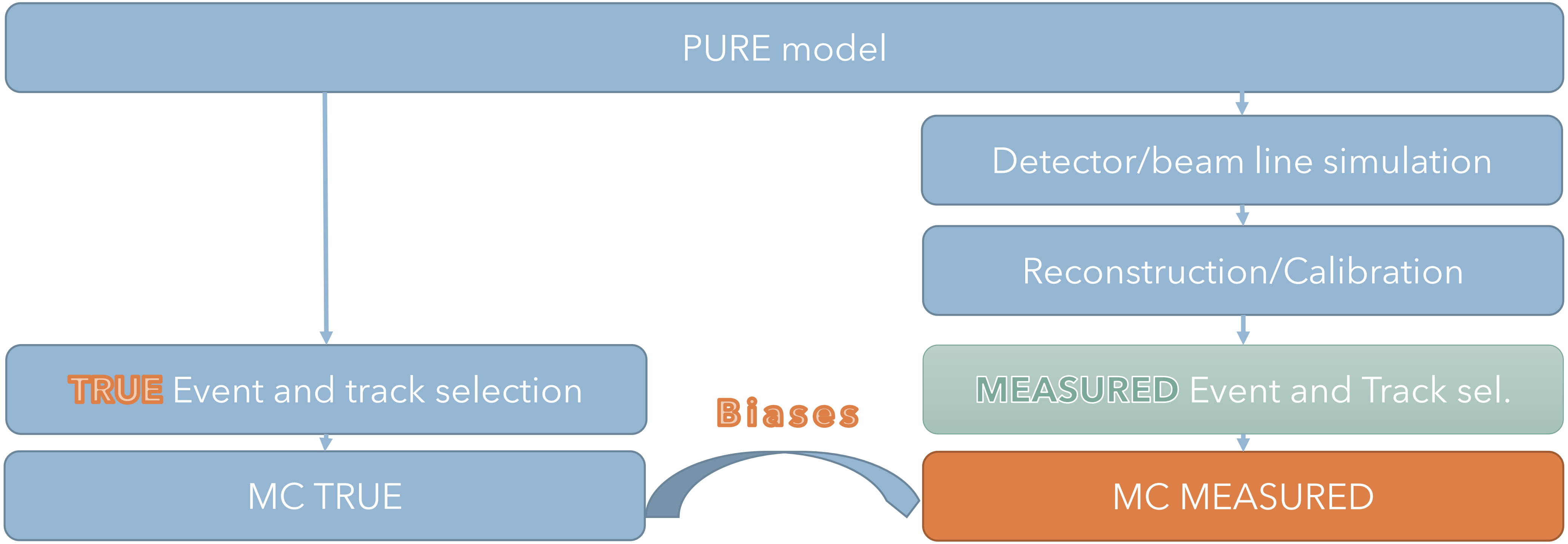
$$q_T = \frac{1}{1-\varepsilon}(q_i - \varepsilon q_R)$$

$\varepsilon - normalization\ factor$

Eur. Phys. J. C (2014) 74: 2794

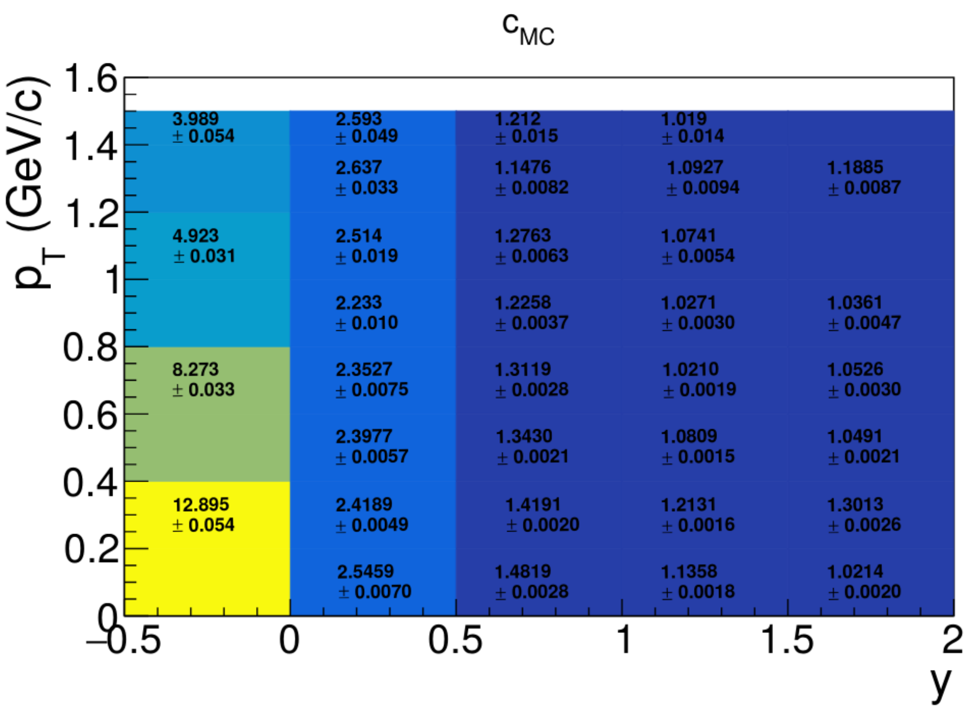
MC-based corrections

It is based on a simulation of a PURE model through detector simulation and reconstruction/calibration procedure



MC-based correction - examples

- Model should be as close to the data as possible
- Weighting/subtraction correction
  - multiplicative correction factor, $c_i = \frac{N_T^{MC}}{N_M^{MC}}$, where i – small bin in the experimental phase-space acceptance (example below)
  - subtraction correction (see data-based correction slide)



EPJ C 80:460 (2020)

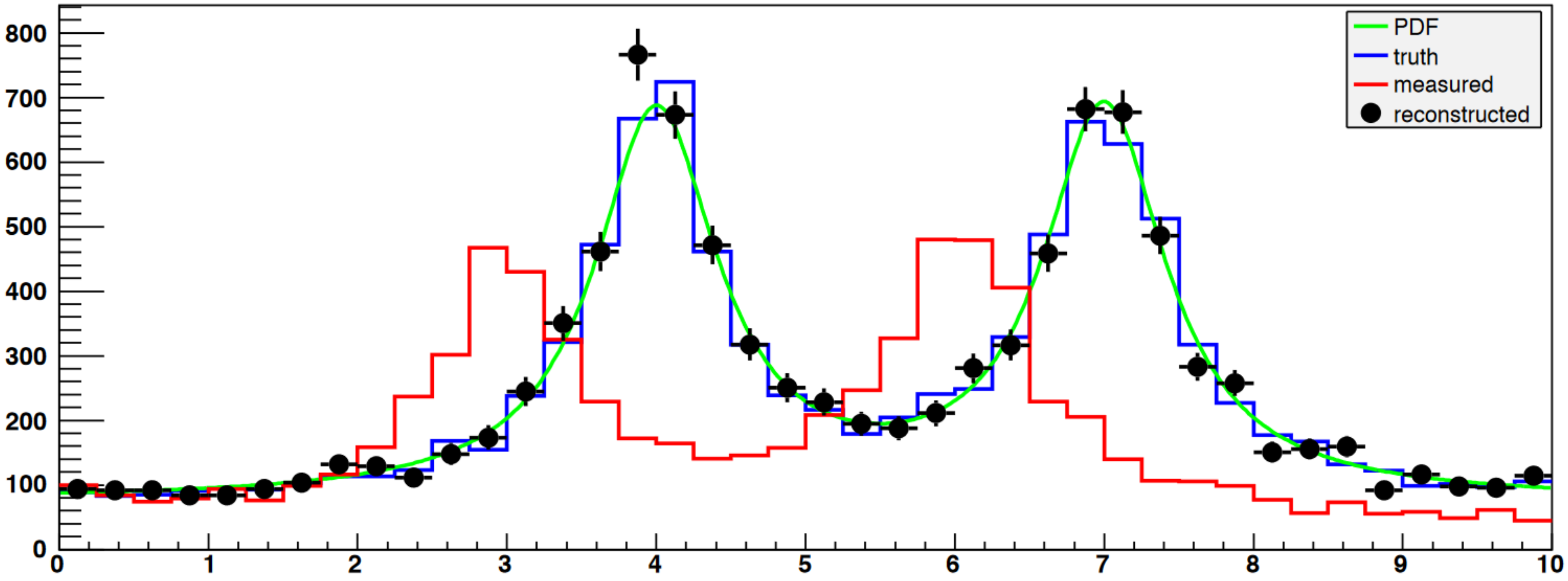
MC-based corrections - examples

- Unfolding (deconvolution, unsmearing) – We parametrise the measurement effects using a *response matrix* that maps the (binned) TRUE distribution onto the MEASURED one. Example: RooUnfold

  pros: correction includes loses/gains and migration, ready libraries e.g. RooUnfold, less model dependent
  cons: R has to be obtained from statistics much larger than the data, it is ill-posed problem, if N is n-dimensional then R is (n+1)-dimensional but only 1D and 2 D cases are coded (e.g. RooUnfold), TRUE needs to be binned (RooUnfold)

https://gitlab.cern.ch/RooUnfold/RooUnfold

Unfolding example



Tim Adye, Unfolding algorithms and tests using RooUnfold

Uncertainty estimation

- Statistical uncertainty

- Systematic uncertainty

Statistical uncertainty

It quantifies difference (statistical fluctuations) between a true result for a finite event sample and a result for the infinite sample of events. Statistical fluctuations are caused by:

- indeterministic nature of collisions at high energies, e.g. event multiplicity
- statistical fluctuations on a measurement process, e.g. measured dE/dx

How to estimate statistical uncertainty

- Uncorrelated input quantities, e.g. event multiplicity, number of produced particles in small phase-space bin → standard deviation, σ
- Correlated input quantities, e.g. correlation function, higher than first moments, intermittency
  - Following GUM: covariance and correlation coefficient estimation
  - Nonparametric method of assessing errors: jackknife, boostrap, subsampling, etc.

GUM – Guide to the Expression of Uncertianty in measurement

Systematic uncertainty

Systematic biases are independent of event statistics and they should be identified and corrected for.

The uncertainty in the estimation of the corresponding corrections is called a systematic uncertainty.

Systematic biases which were neglected or overlooked are called systematic mistakes (errors). Some of the biases may be known before/during data taking others will be found during analysis in consistency checks, e.g. time-dependence of a detector response

Example - Energy of projectile spectators measured by a forward calorimeter (FC)

The forward calorimeter (photodetectors) response depends on temperature, T.

Systematic uncertainty estimation:

- T dependence is known
  Then the systematic bias is known and corrected for.
- The bias was ignored (mistake):
  - It appeared during consistency checks as a failed test and contributed to systematic uncertainty

    A posteriori systematic uncertainty (should be avoided!)

  - The effect is known to exist but not measured. If it can be estimated one can estimate its uncertainty on a systematic effect by propagating different input parameters into MC simulation chain.

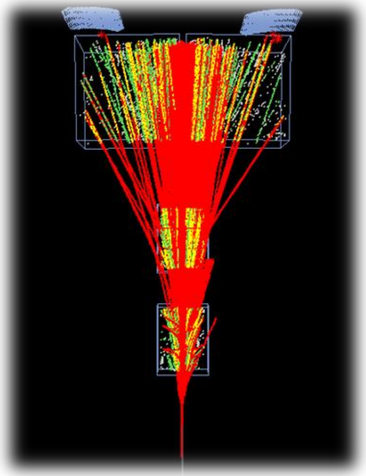
    A priori systematic uncertainty

Systematic uncertainty – recomended procedure

1. Identify and correct for systematic effects
2. Estimate uncertainties (statistical and/or systematic) of *input parameters* to the corrections
3. Propagate them to the final results - calculate *a priori systematic uncertainty*
4. Perform cross checks/consistency tests. If failed, go back to 1. After several loops:
5. Guess *a posteriori systematic uncertainty* based on failed consistency checks

For details see, R. Barlow, arXiv:hep-ex/0207026

Towards useful results



DATA

Event and track selection

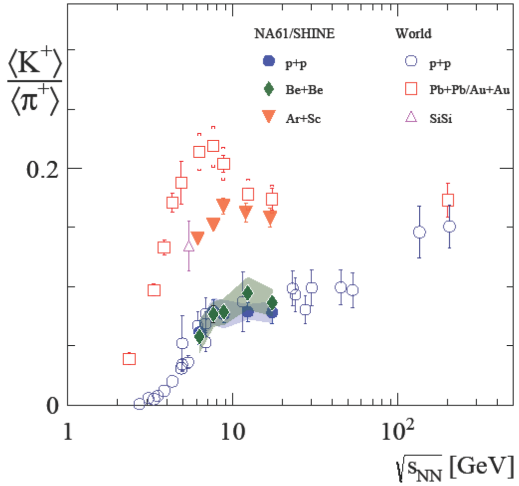
Measured data

Corrections:
Data and MC based

Corrected data

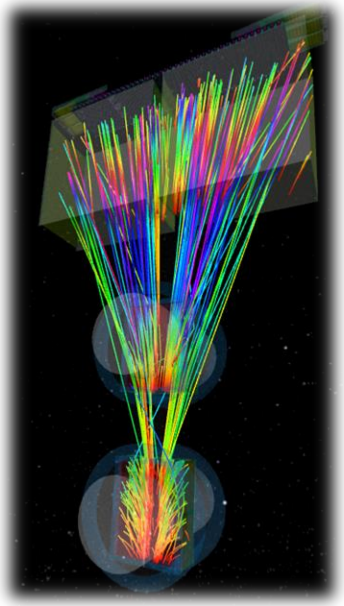
Uncertainty estimation

USEFUL RESULTS



The end

Thank you and good luck!



Bibliography:

- Marek Gazdzicki, Lecture on fluctuations 2018
- GUM, JCGM 2008
- Bradley Efron, The Jackknife, the Bootstrap and Other Resampling Plans, CBMS-NSF, 1987

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Ill-posed problem

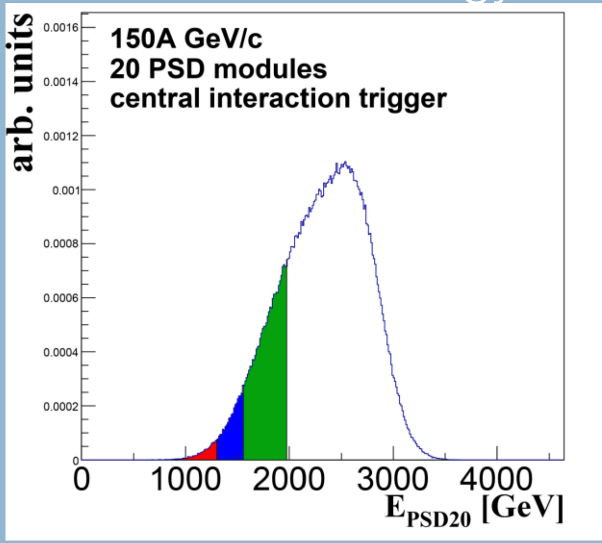
A problem which does not meet the three Hadamard criteria:

- Having a solution
- Having a unique solution
- Having a solution that depends continuously on the parameters or input data

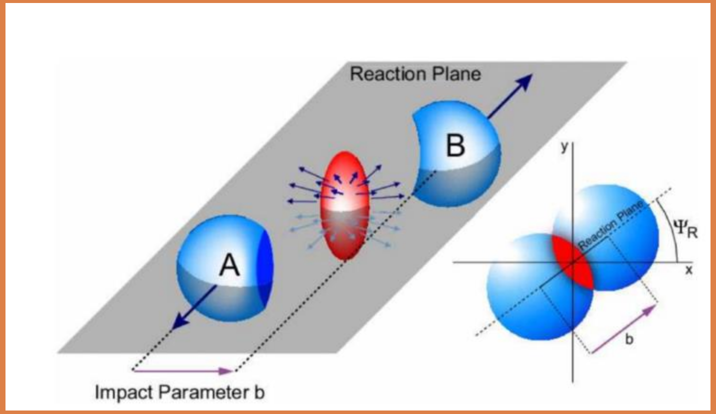
Meet half-way (both sides) – example of event selection

Central A+A events are the most violent collisions of a given ion at a given energy. There are several ways to define it:

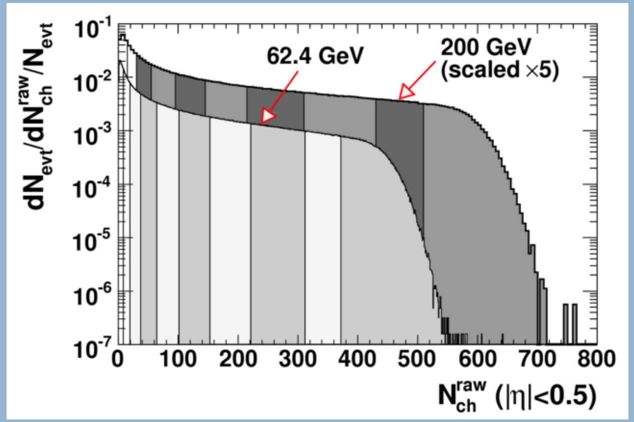
Forward energy/forward calorimeter energy



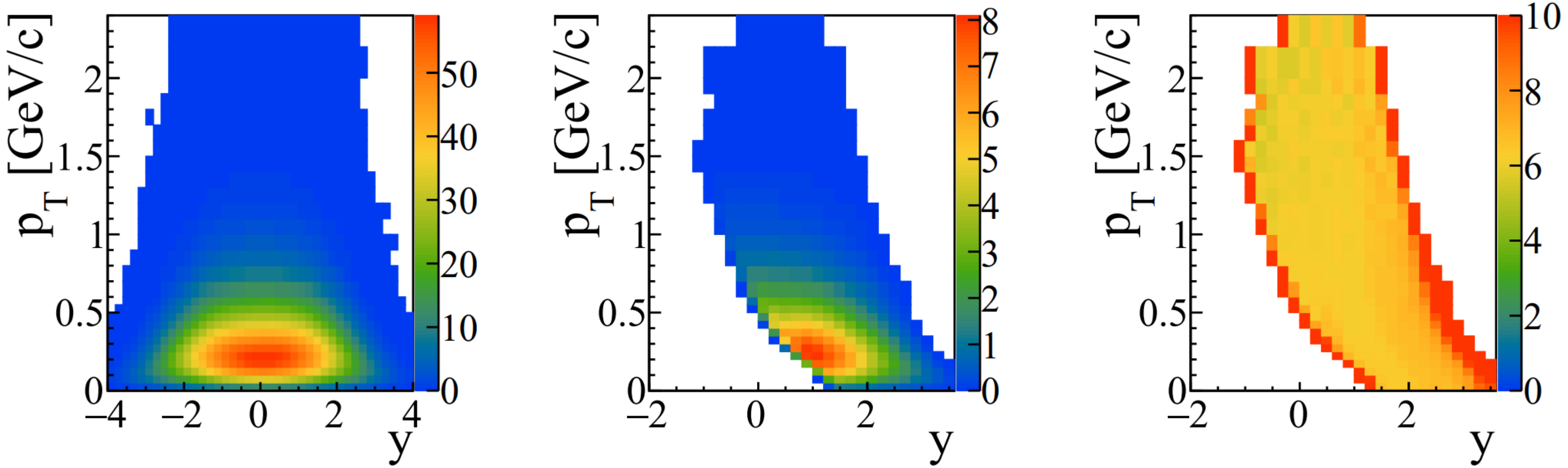
Impact vector $\vec{b}$, which connects nuclei centers in plane perpendicular to beam direction



Multiplicity in a given phase-space acceptance



Geometry and detector efficiency



M. Lewicki