Bayesian unfolding of charged-particle p_T spectra with ALICE at the LHC

Mario Krüger

Goethe-University Frankfurt am Main

XIIth Quark Confinement and the Hadron Spectrum Conference

August 1st, 2018

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

IKF Institut für Kernphysik Frankfurt

ALICE

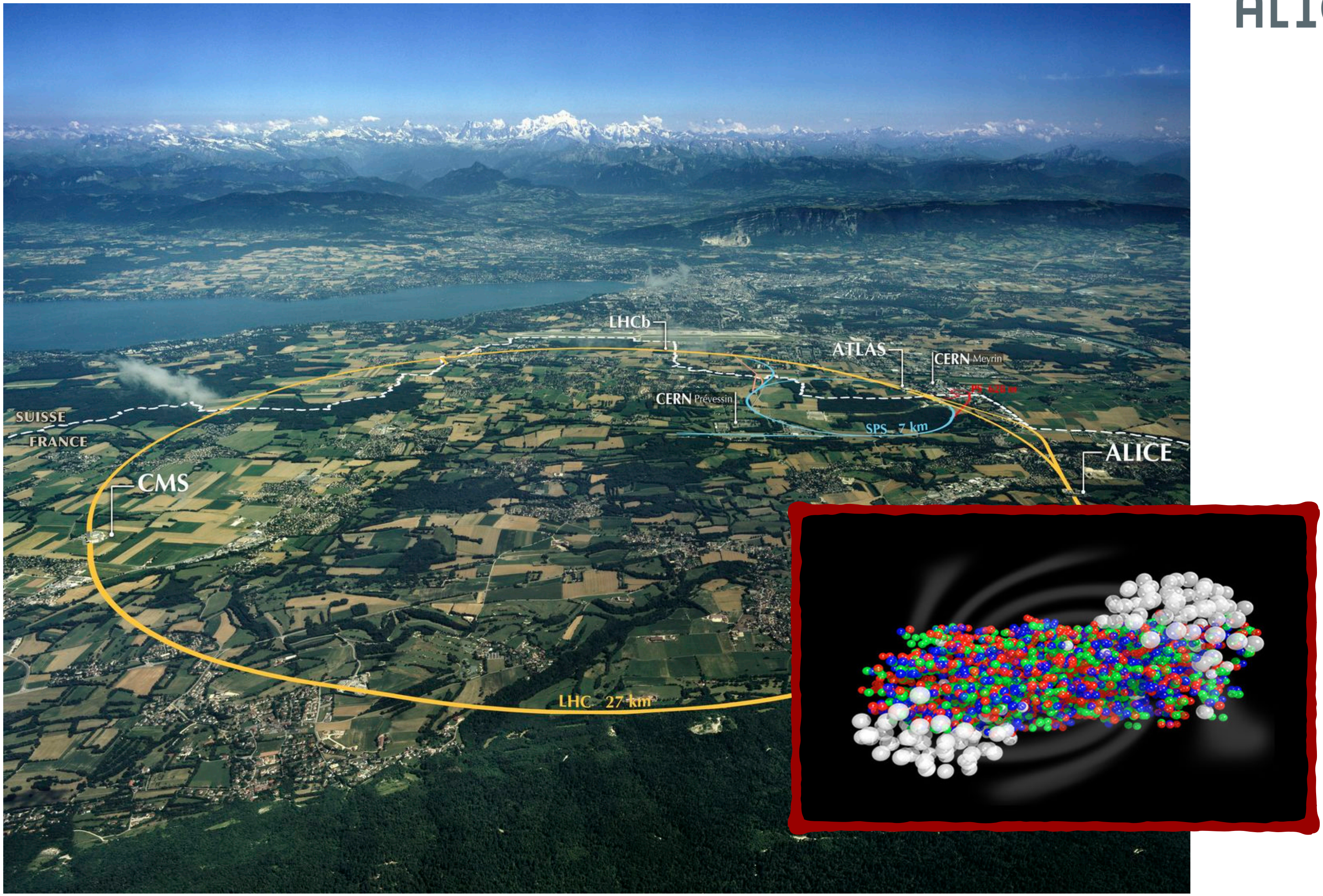
Outline

- Motivation
- ALICE experiment
- Unfolding of multiplicity distributions
- Unfolding of p_T spectra
- Summary

ALICE at CERN-LHC

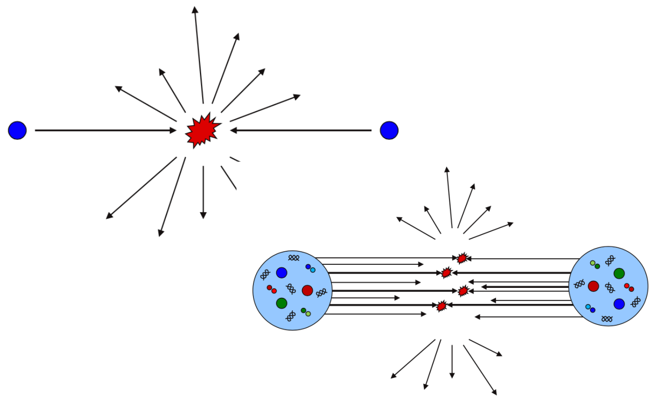
https://3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2015/554babea955c1.jpg

ALICE at CERN-LHC



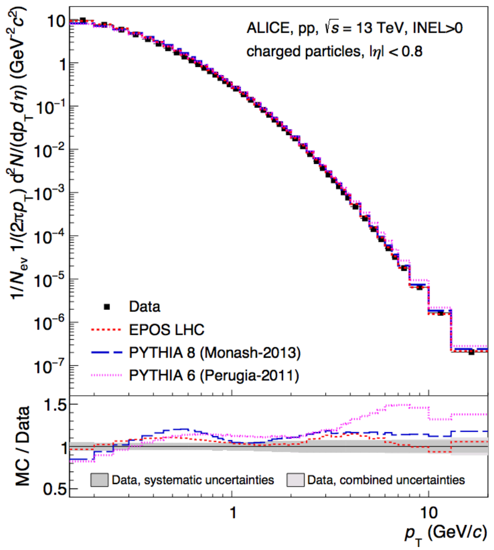
https://3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2015/554babea955c1.jpg http://www.scinexx.de/wissen-aktuell-bild-21730-2017-08-04-34019.html

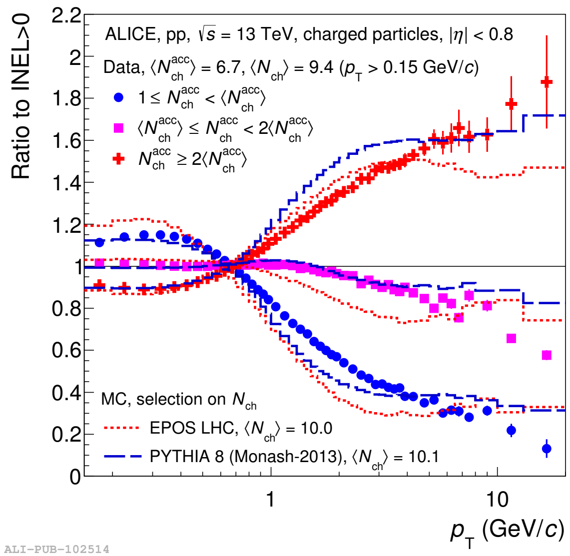
Motivation



- charged particle production
- pp collisions:
  - Reference for Pb-Pb
  - Effects of multiple parton interactions
  - Hadronization beyond independent string fragmentation (color reconnection, CR)

Motivation





Phys. Lett. B 753 (2016) 319-329

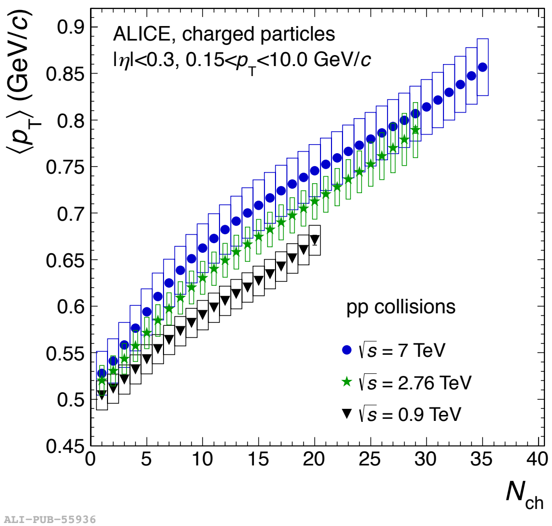
- charged particle production
- pp collisions:
  - Reference for Pb-Pb
  - Effects of multiple parton interactions
  - Hadronization beyond independent string fragmentation (color reconnection, CR)

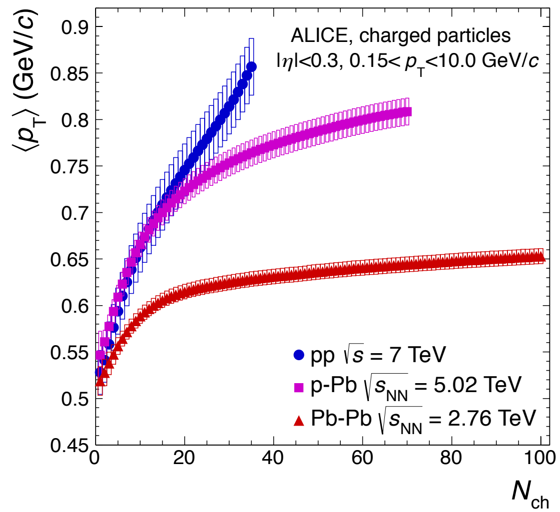
- Shape of transverse-momentum (p_T) spectra dependents on multiplicity (N_{ch}) of event

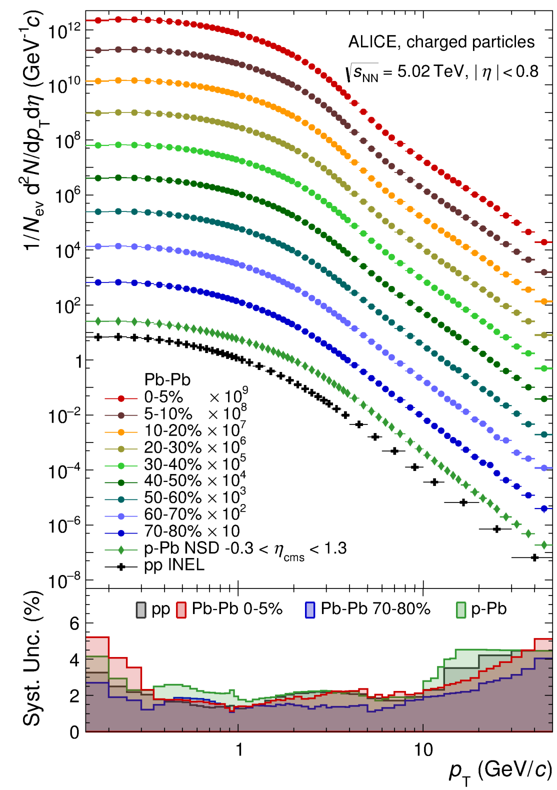
  → Differential measurement

Motivation

Phys. Lett. B 727 (2013) 371-380







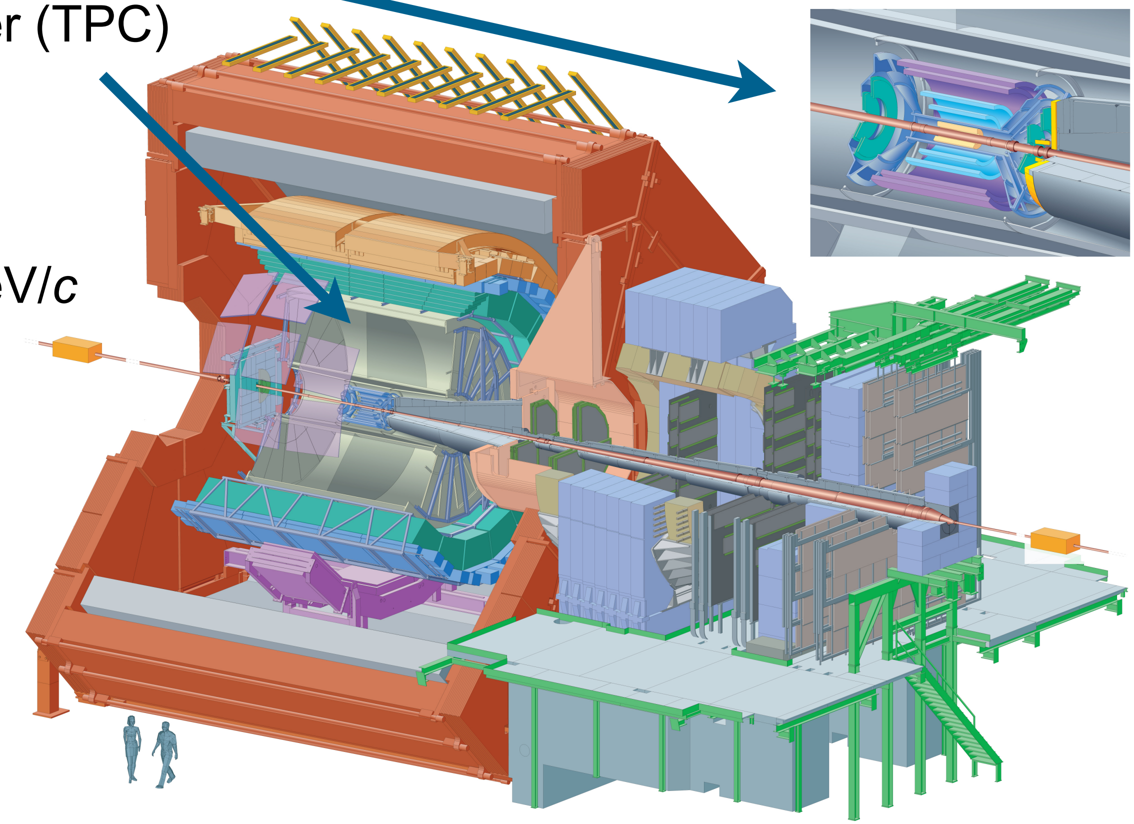
arXiv:1802.09145

- <p_T> characteristic for spectral shape
- Hot topic: spectra with high multiplicity in pp vs. Pb-Pb
- Goal: full spectral shape as function of multiplicity N_{ch}

→ **Bayesian unfolding**

ALICE

- ALICE detectors for tracking:
  - Inner Tracking System (ITS)
  - Time Projection Chamber (TPC)



- Primary charged particles
  - 0.15 GeV/c < p_T < 10 GeV/c
  - $|\eta| < 0.8$

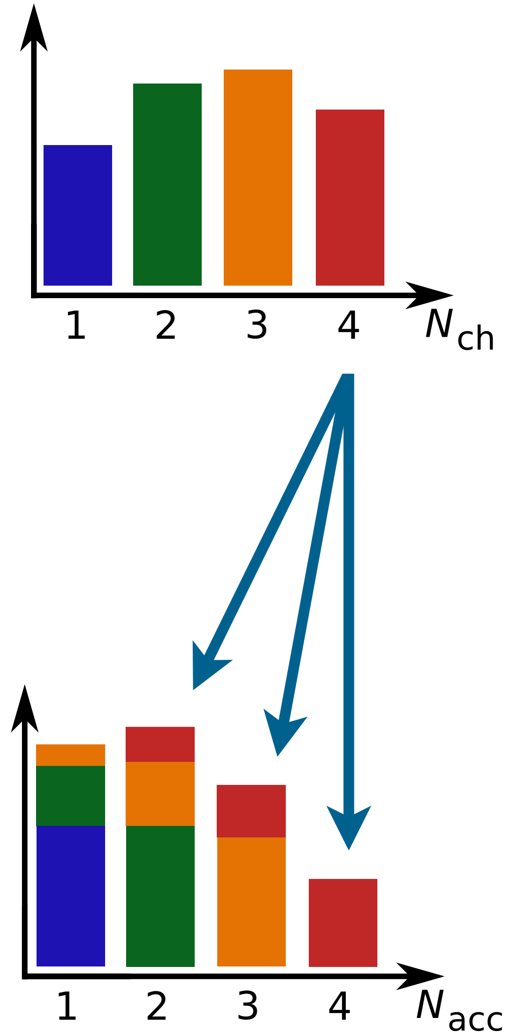
Measured multiplicity
≠
True multiplicity

True vs. Measured Multiplicity

True multiplicity:
$\boldsymbol{N_{ch}}$

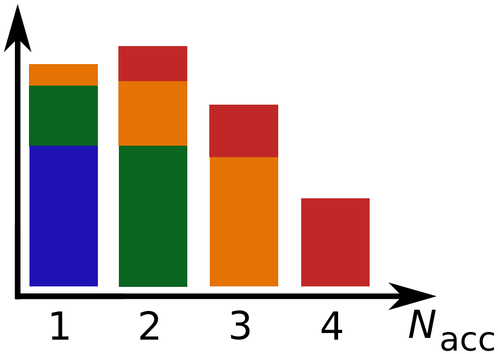
Detector response
$N_{ch} \rightarrow N_{acc}$

Measured multiplicity:
$\boldsymbol{N_{acc}}$

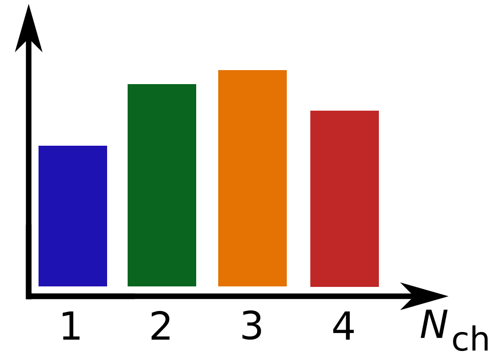


True vs. Measured Multiplicity

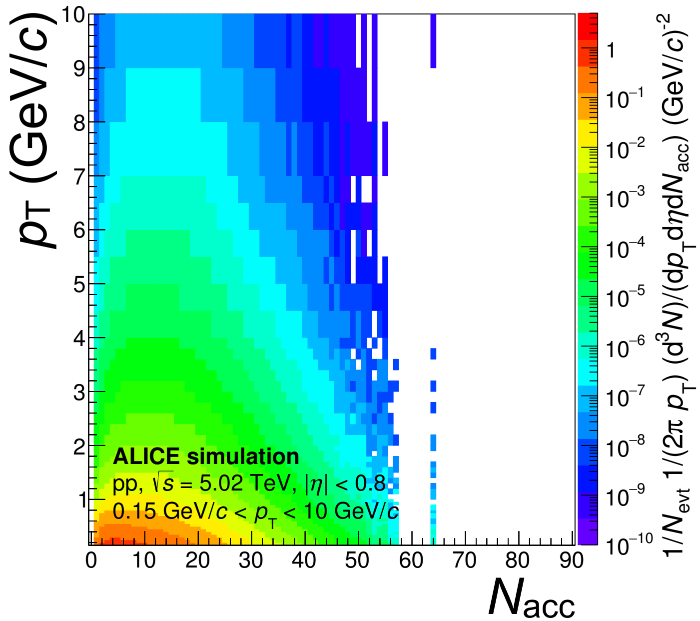
Measurement

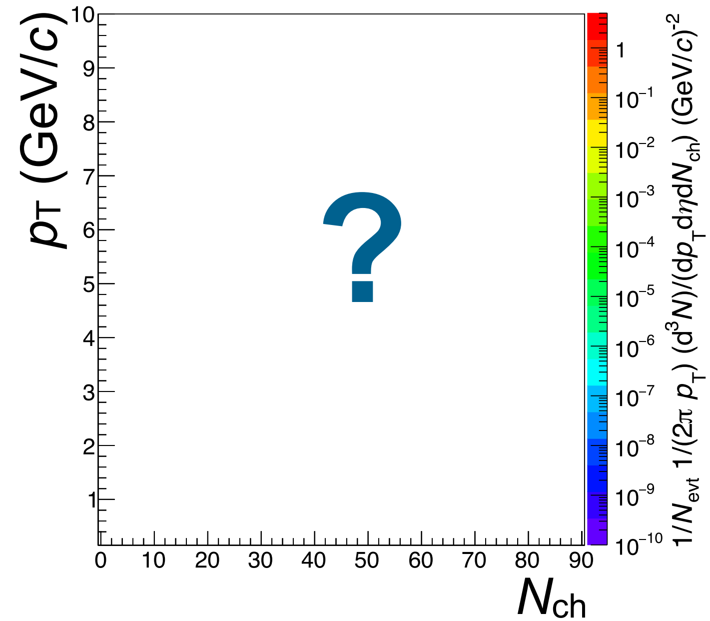


Truth

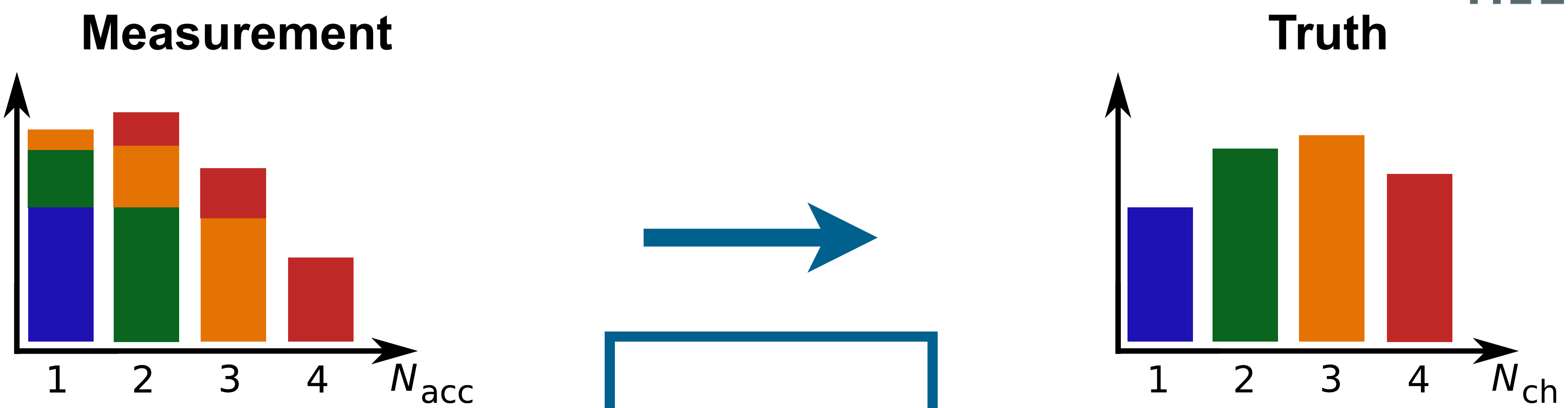


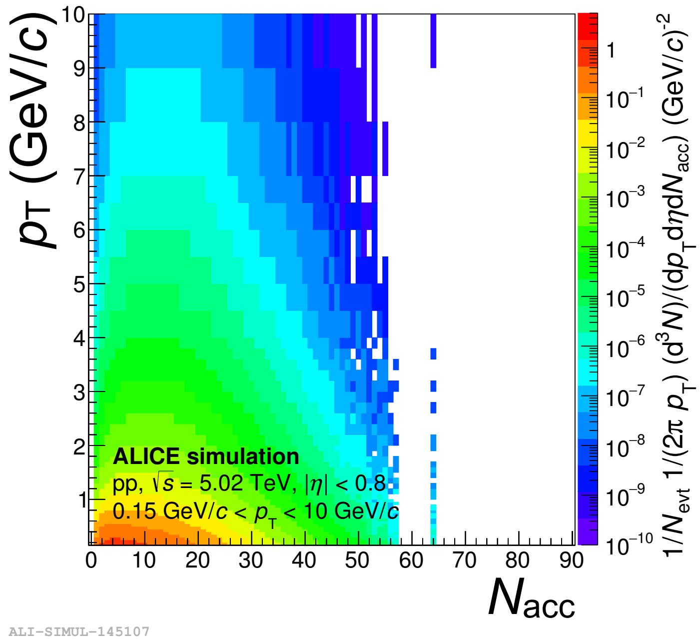
Detector Response

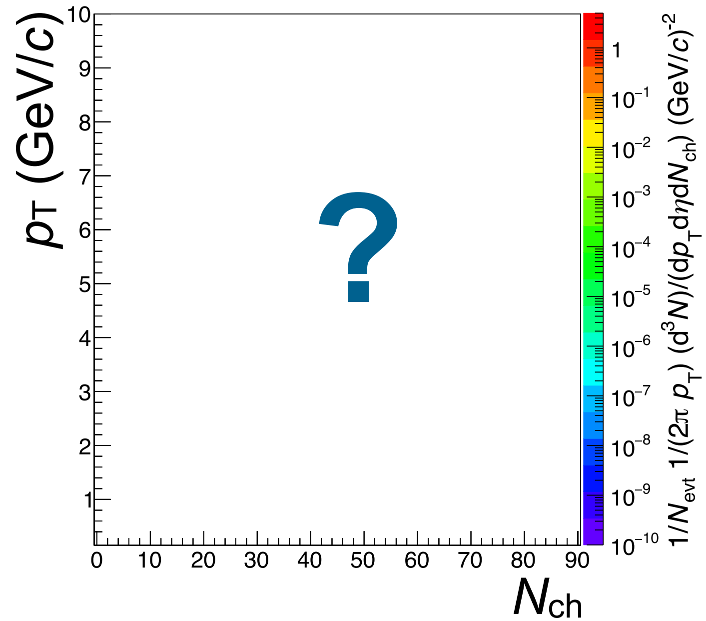




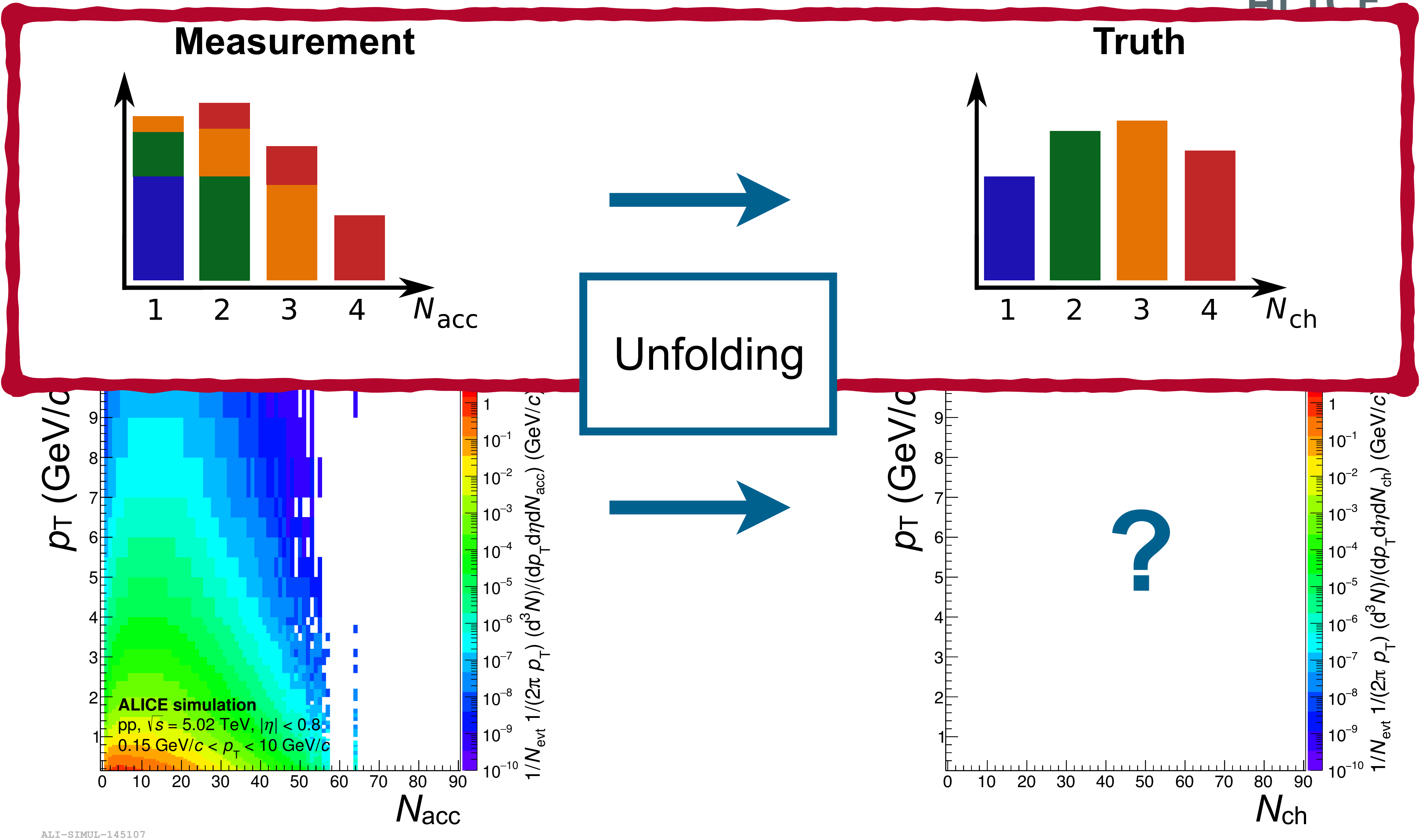
True vs. Measured Multiplicity



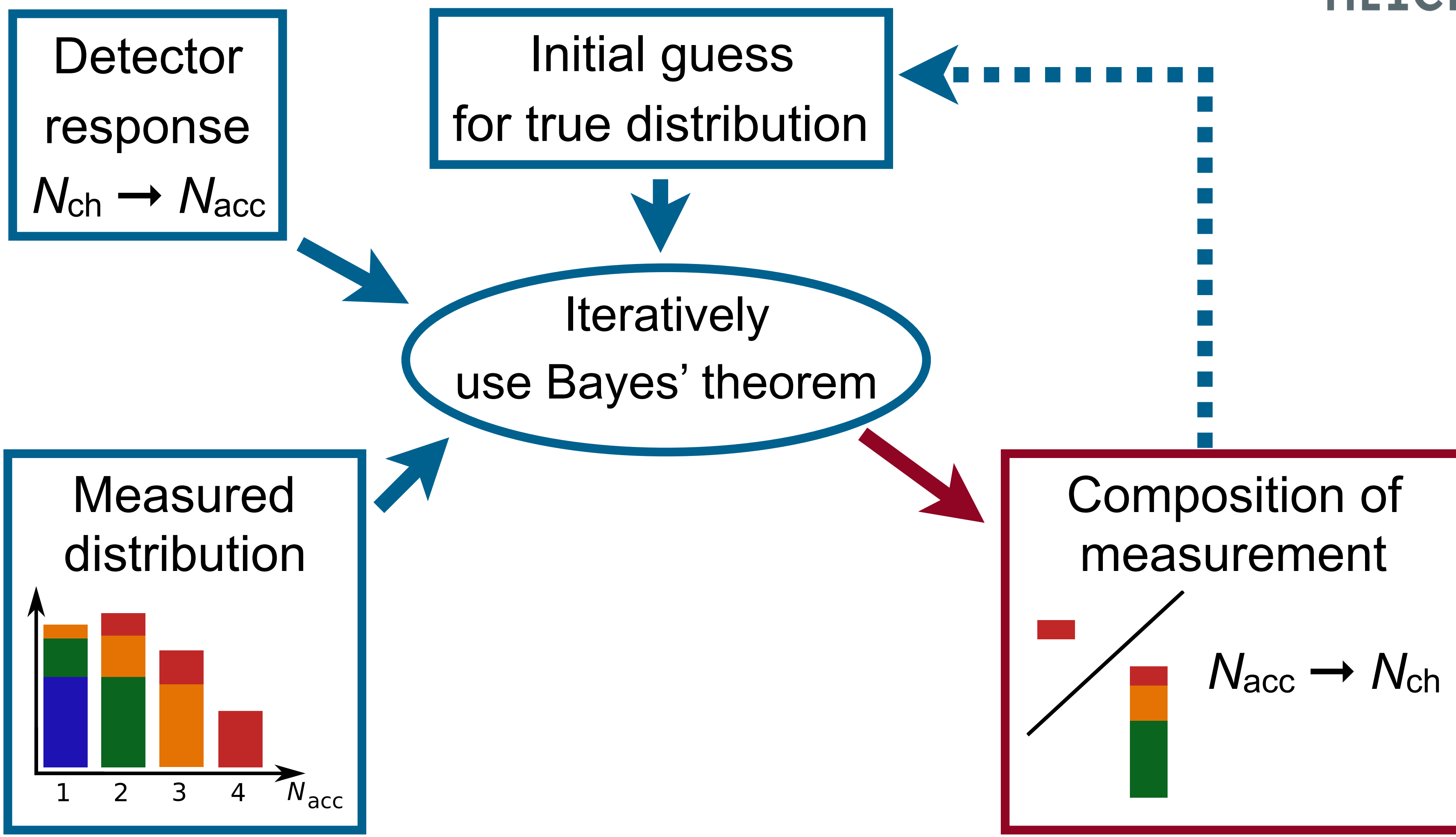




True vs. Measured Multiplicity



Unfolding Procedure

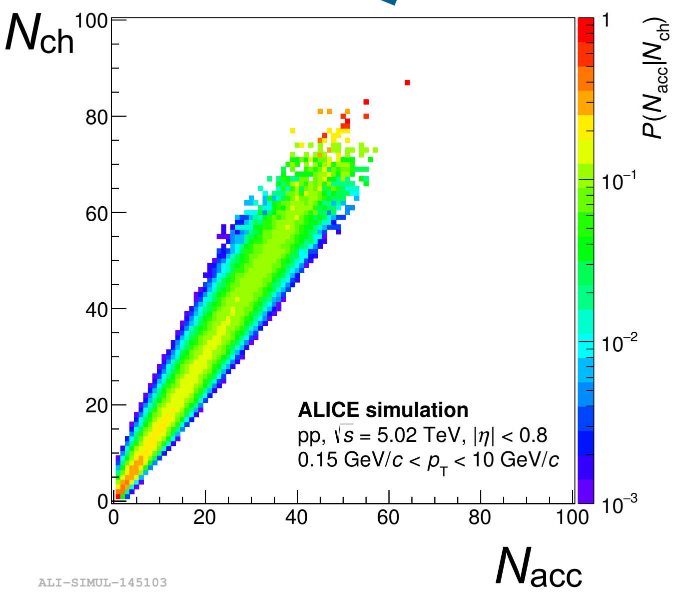


Method following Nucl. Instr. Meth. Phys. Res. A 362 (1995) 487-498

Unfolding Procedure

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{P(N_{\mathrm{acc}})}$$

Bayes' Theorem



Unfolding Procedure

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{P(N_{\mathrm{acc}})}$$

Bayes' Theorem

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{\sum_{N'_{\mathrm{ch}}} P(N_{\mathrm{acc}}|N'_{\mathrm{ch}}) \cdot P(N'_{\mathrm{ch}})}$$

Unfolding Procedure

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{P(N_{\mathrm{acc}})}$$

Bayes' Theorem

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{\sum_{N'_{\mathrm{ch}}} P(N_{\mathrm{acc}}|N'_{\mathrm{ch}}) \cdot P(N'_{\mathrm{ch}})}$$

$P_0(N_{\mathrm{ch}})$

Initial guess

Unfolding Procedure

$$P(N_{\rm ch}|N_{\rm acc}) = \frac{P(N_{\rm acc}|N_{\rm ch}) \cdot P(N_{\rm ch})}{P(N_{\rm acc})}$$

Bayes' Theorem

$$P(N_{\rm ch}|N_{\rm acc}) = \frac{P(N_{\rm acc}|N_{\rm ch}) \cdot P(N_{\rm ch})}{\sum_{N'_{\rm ch}} P(N_{\rm acc}|N'_{\rm ch}) \cdot P(N'_{\rm ch})}$$

$P_0(N_{\rm ch})$

Initial guess

$$\hat{n}(N_{\rm ch}) = \sum_{N_{\rm acc}} P(N_{\rm ch}|N_{\rm acc}) \cdot n(N_{\rm acc})$$

Unfolded multiplicity distribution

Measured multiplicity distribution

Unfolding Procedure

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{P(N_{\mathrm{acc}})}$$

Bayes' Theorem

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{\sum_{N'_{\mathrm{ch}}} P(N_{\mathrm{acc}}|N'_{\mathrm{ch}}) \cdot P(N'_{\mathrm{ch}})}$$

$P_0(N_{\mathrm{ch}})$

Initial guess

$$\hat{P}(N_{\mathrm{ch}}) = \frac{\hat{n}(N_{\mathrm{ch}})}{\sum_{N'_{\mathrm{ch}}} \hat{n}(N'_{\mathrm{ch}})}$$

$$\hat{n}(N_{\mathrm{ch}}) = \sum_{N_{\mathrm{acc}}} P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) \cdot n(N_{\mathrm{acc}})$$

Unfolded multiplicity distribution

Measured multiplicity distribution

Unfolding Procedure

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{P(N_{\mathrm{acc}})}$$

Bayes' Theorem

$$P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) = \frac{P(N_{\mathrm{acc}}|N_{\mathrm{ch}}) \cdot P(N_{\mathrm{ch}})}{\sum_{N'_{\mathrm{ch}}} P(N_{\mathrm{acc}}|N'_{\mathrm{ch}}) \cdot P(N'_{\mathrm{ch}})}$$

$P_0(N_{\mathrm{ch}})$

Initial guess

n_{iter}

$$\hat{P}(N_{\mathrm{ch}}) = \frac{\hat{n}(N_{\mathrm{ch}})}{\sum_{N'_{\mathrm{ch}}} \hat{n}(N'_{\mathrm{ch}})}$$

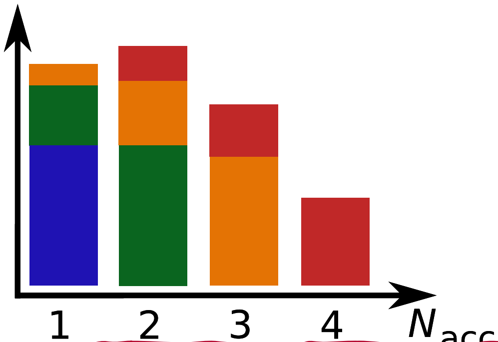
$$\hat{n}(N_{\mathrm{ch}}) = \sum_{N_{\mathrm{acc}}} P(N_{\mathrm{ch}}|N_{\mathrm{acc}}) \cdot n(N_{\mathrm{acc}})$$

Unfolded multiplicity distribution

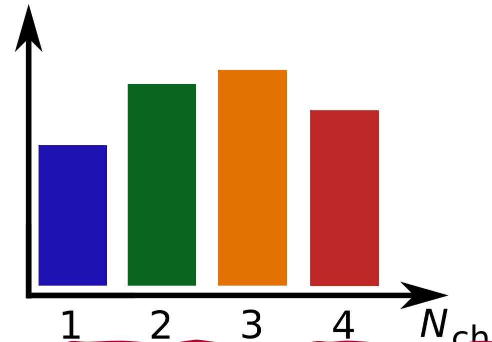
Measured multiplicity distribution

Unfolding of p_T Spectra

Measurement



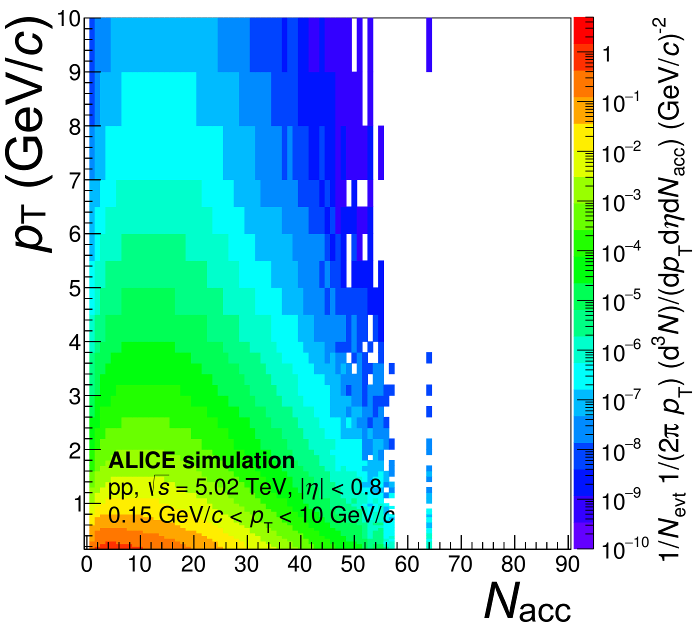
Truth

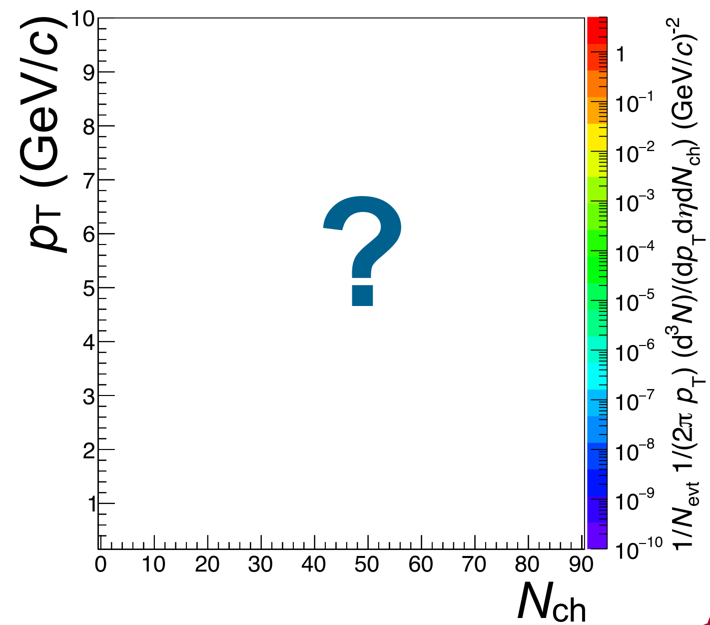


Multiplicity:
Event characteristic

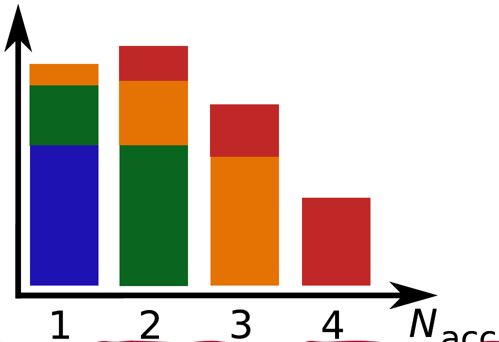
Unfolding

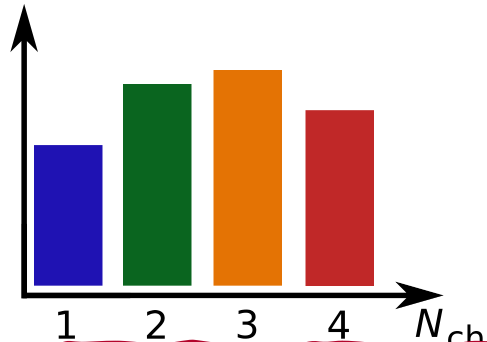
p_T distributions

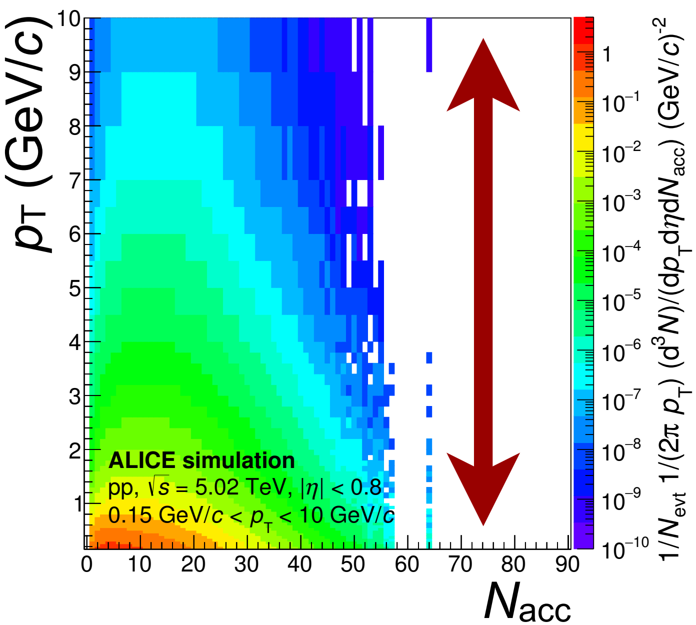




Unfolding of p_T Spectra — p_T Resolution



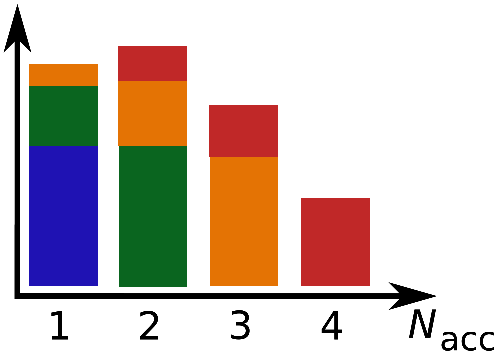




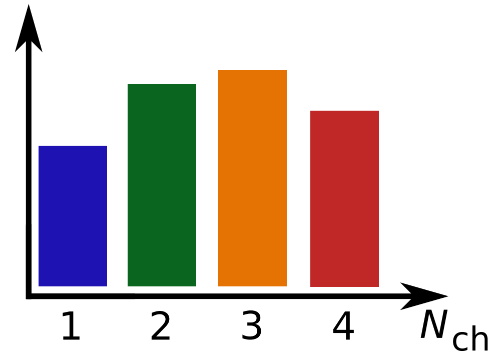
- 2D problem
- p_T resolution of tracking detectors
  - $p_T^{true} \rightarrow p_T^{meas}$
  - only small effect on p_T spectra

Unfolding of p_T Spectra — Events vs. Particles

Measurement



Truth

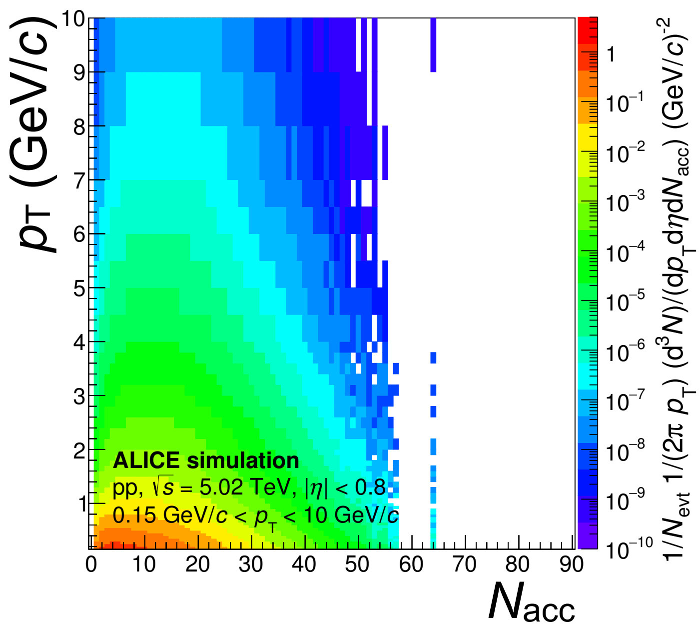


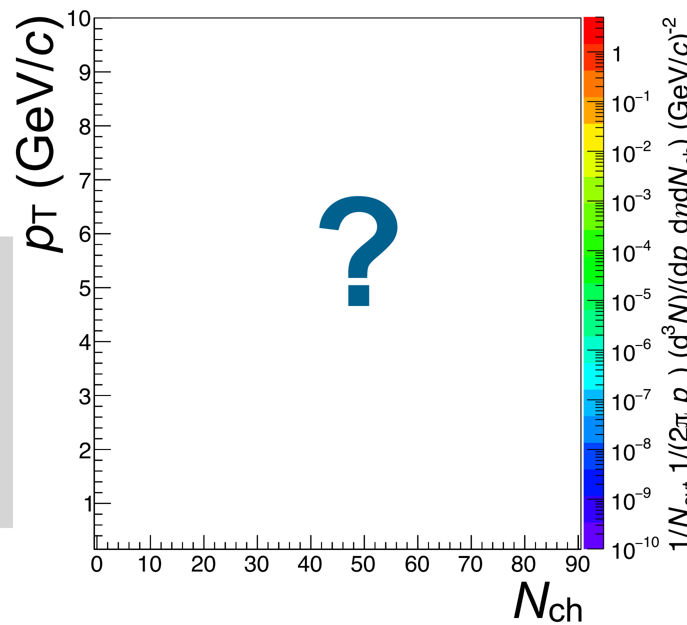
Probability for an event with multiplicity N_{ch} to be measured with multiplicity N_{acc}

$$P(N_{\mathrm{acc}}|N_{\mathrm{ch}})$$

$$P_{\mathrm{part}}(N_{\mathrm{acc}}|N_{\mathrm{ch}})$$

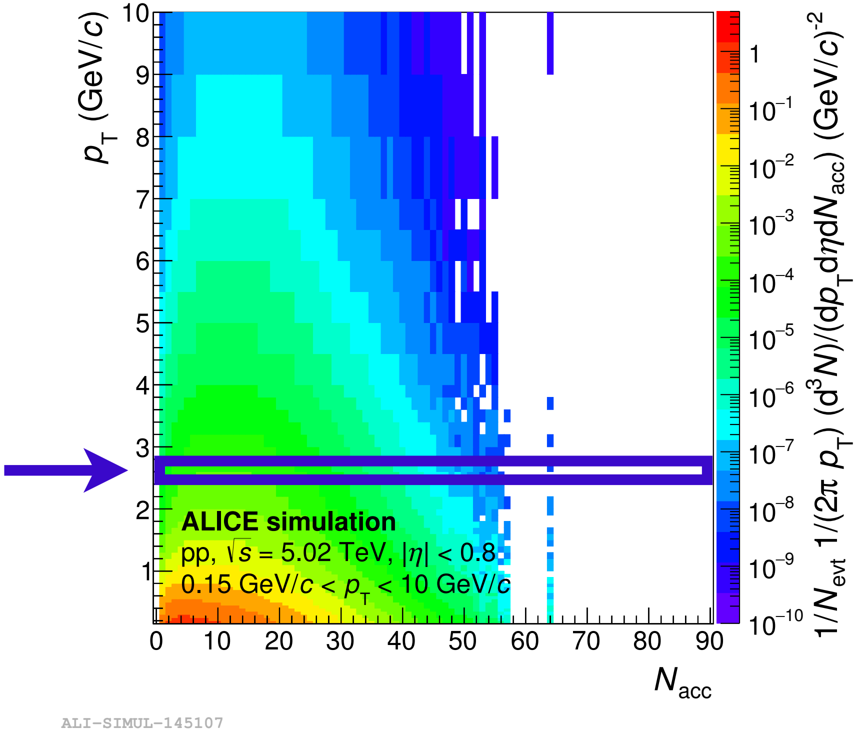
Probability for a primary charged particle originating from an event with multiplicity N_{ch} to contribute to an event with multiplicity N_{acc}





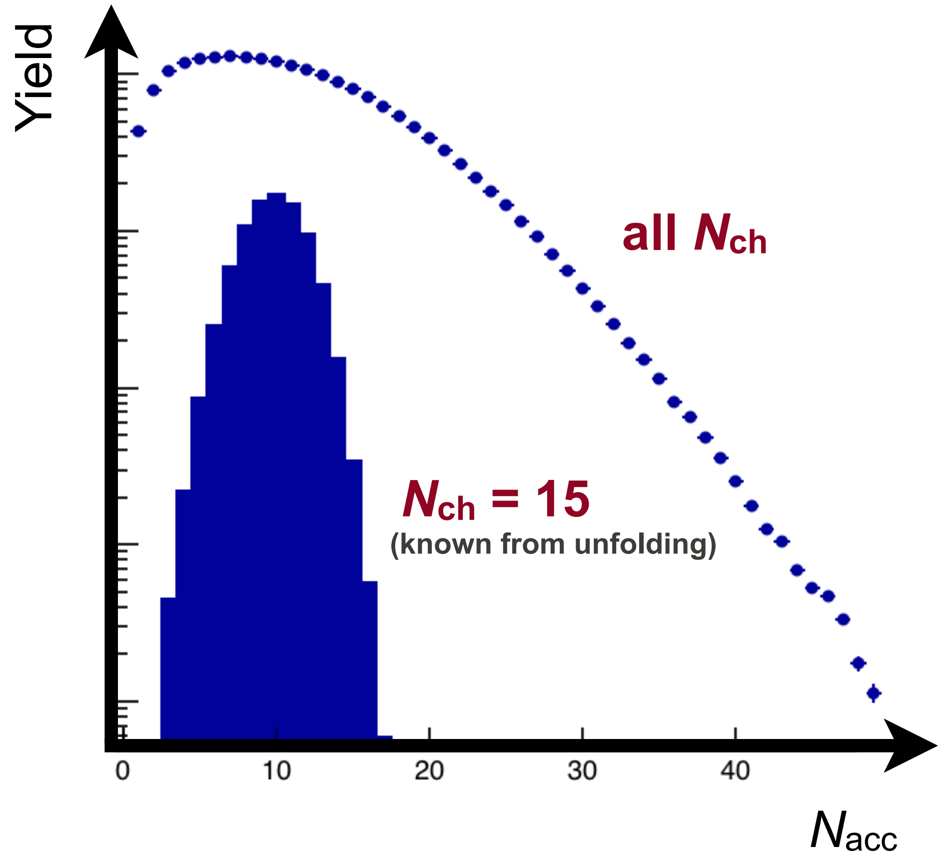
ALI-SIMUL-145107

Unfolding of p_T Spectra — p_T Differential

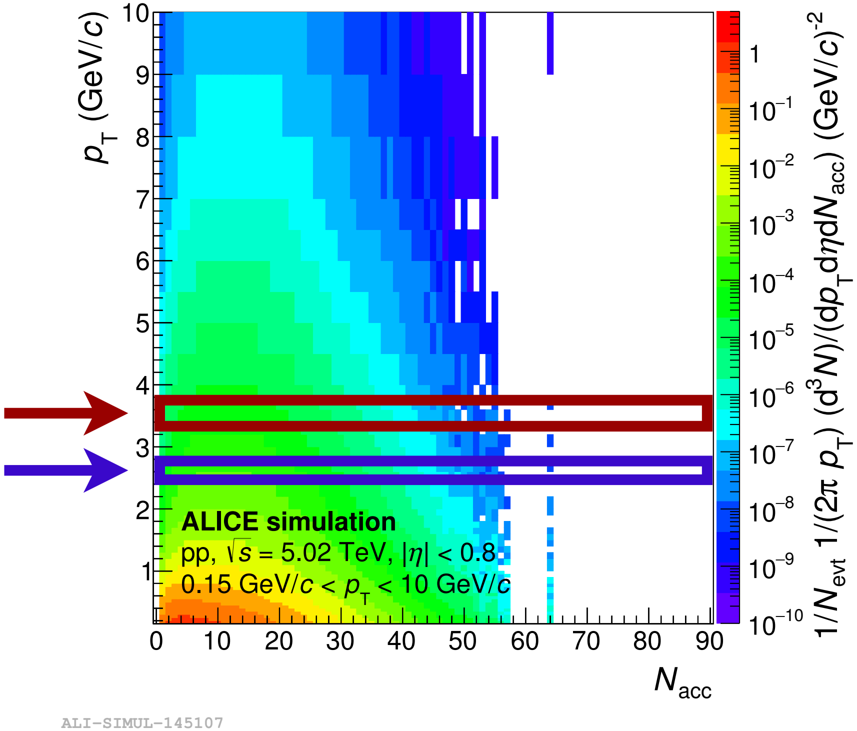


- Bayesian unfolding for p_T slice

  → Composition with respect to N_{ch}

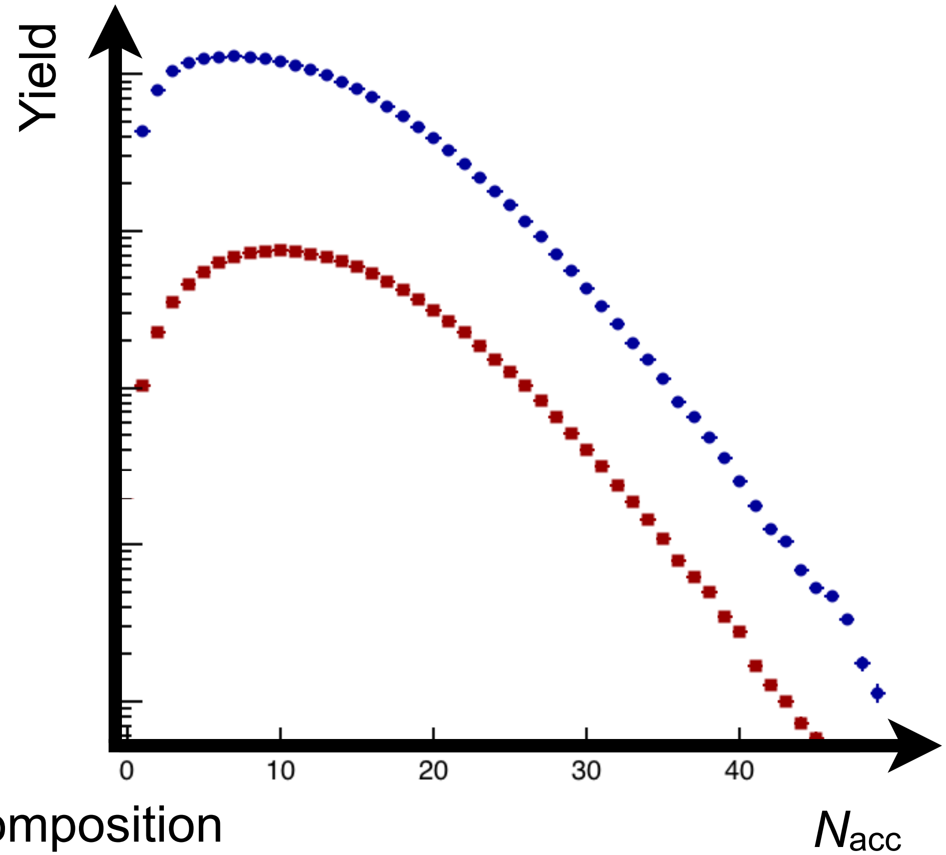


Unfolding of p_T Spectra — p_T Differential



- Bayesian unfolding for p_T slice

  → Composition with respect to N_{ch}

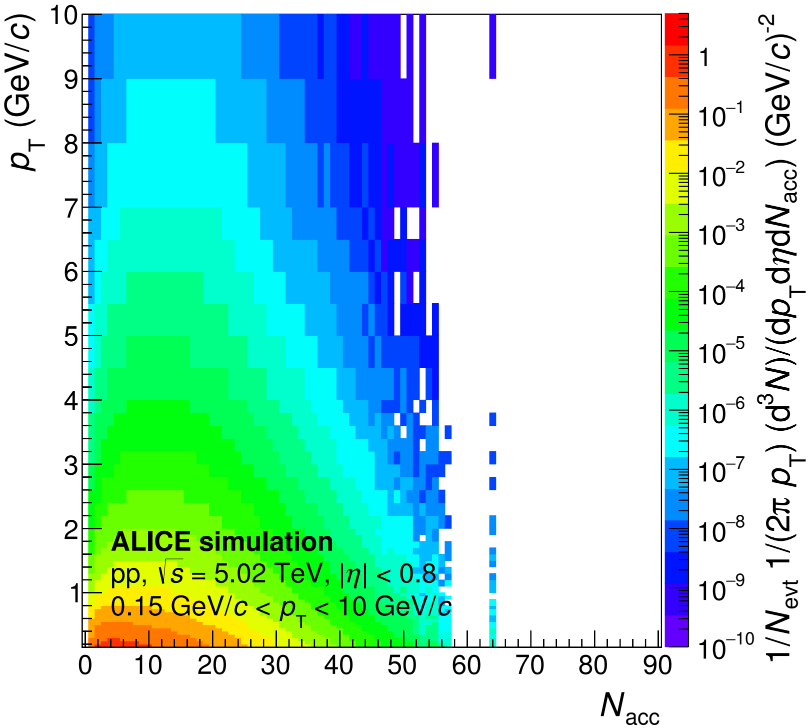


- p_T dependent measured N_{acc} distribution input for unfolding procedure

  → Each N_{acc} distribution: Different N_{ch} composition

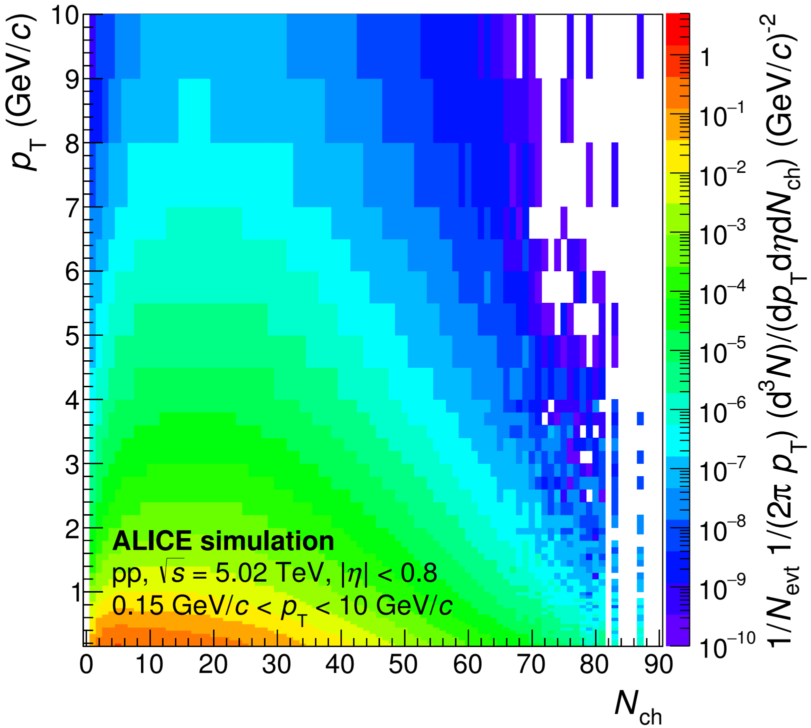
Measured and Unfolded p_T Spectra

Measured p_T spectra



ALI-SIMUL-145107

Unfolded p_T spectra



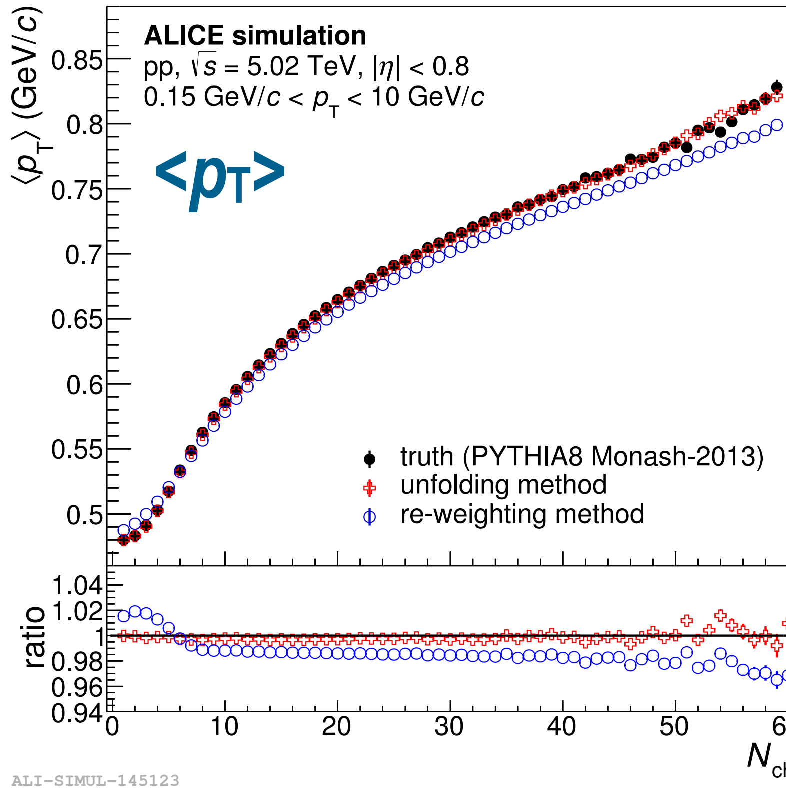
ALI-SIMUL-145111

- Multiplicity dependent charged-particle p_T spectra up to $N_{ch} \approx 80$
- Best possible resolution ($\Delta N_{ch} = 1$)

MC Studies

Closure test:

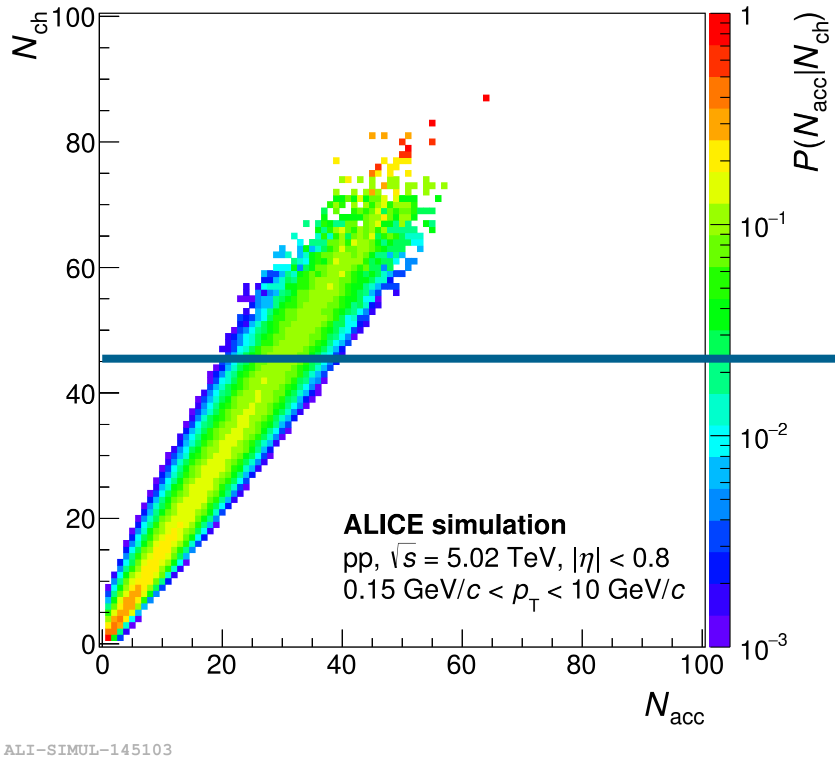
- Unfolding of p_T spectra from MC
- Comparison with MC truth p_T-spectra
- Difference: Important indicator for systematic uncertainty of procedure



Re-weighting Method

as done in Phys. Lett. B 727 (2013) 371-380

Response matrix



$$P(N_{acc}|N_{ch})$$

$$\sum_{N_{acc}} P(N_{acc}|N_{ch}) = 1$$

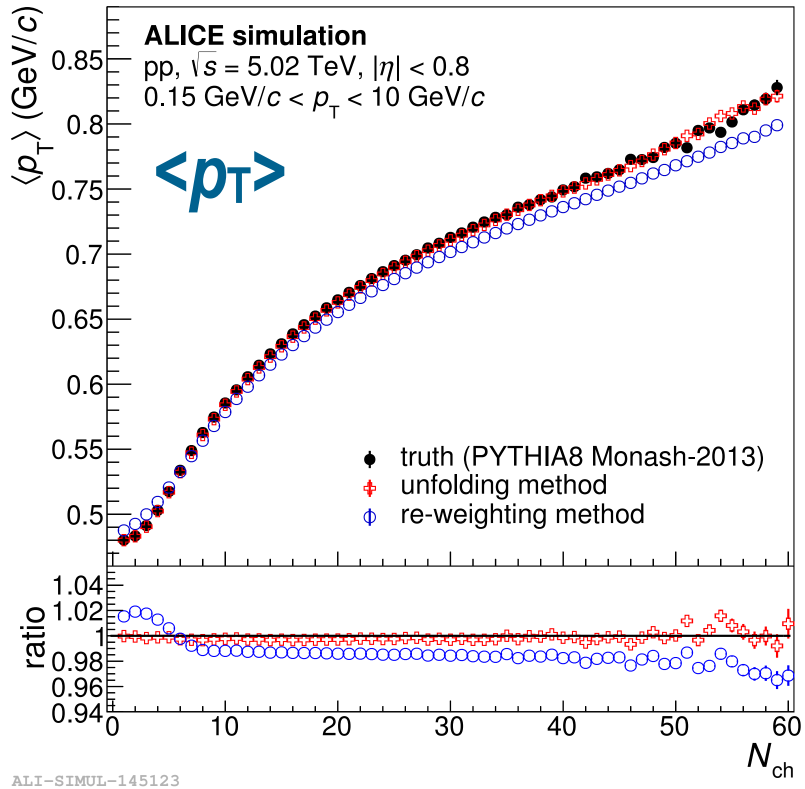
$$\langle p_T \rangle (N_{ch}) = \sum_{N_{acc}} P(N_{acc}|N_{ch}) \langle p_T \rangle (N_{acc})$$

MC Studies

Closure test:

- Unfolding of p_T spectra from MC
- Comparison with MC truth p_T-spectra
- Difference: Important indicator for systematic uncertainty of procedure

- Alternative method (*re-weighting*) to obtain <p_T> vs. N_{ch} (as in [1])
  ➞ Bias covered by assigned syst. unc. in previous publication
- Bayesian unfolding more accurate
  ➞ <p_T> results have lower syst. unc.

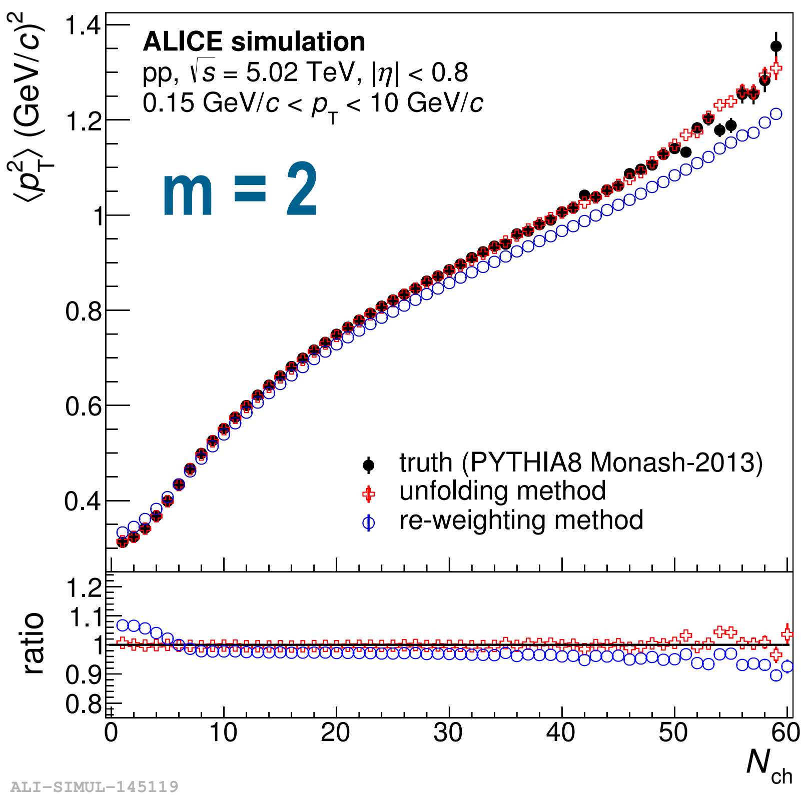


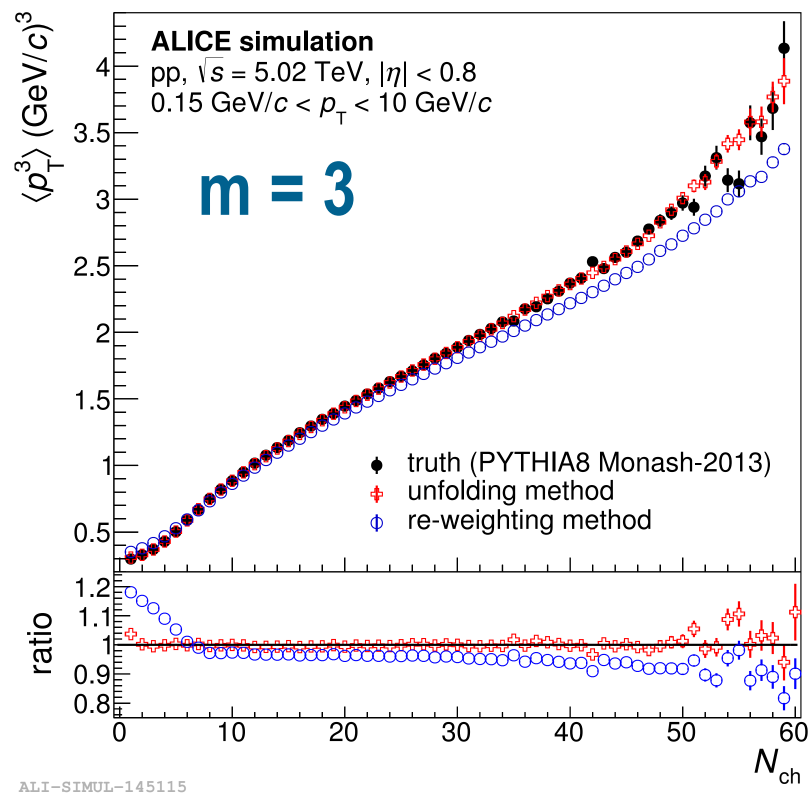
[1] Phys. Lett. B 727 (2013) 371-380

MC Studies

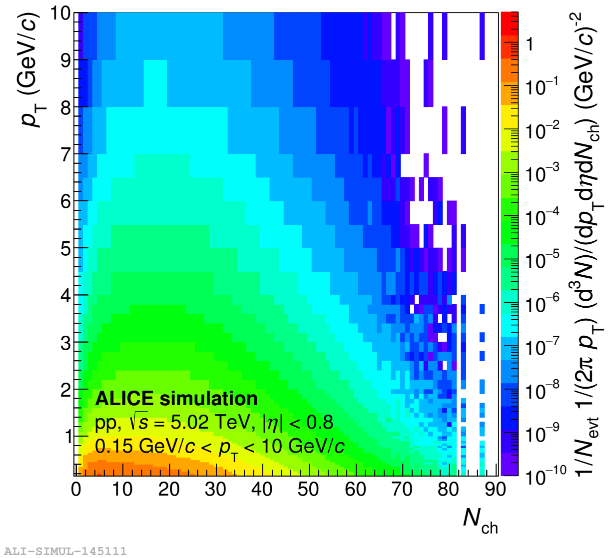
- Bayesian unfolding: Higher moments in good agreement with MC truth as well

$$\langle p_{\mathrm{T}}^{m} \rangle = \frac{\int_{p_{\mathrm{T}}} f(p_{\mathrm{T}}) p_{\mathrm{T}}^{m} \mathrm{d}p_{\mathrm{T}}}{\int_{p'_{\mathrm{T}}} f(p_{\mathrm{T}}) \mathrm{d}p'_{\mathrm{T}}}$$





Summary and Outlook



- Bayesian unfolding method for multiplicity dependent charged-particle p_T spectra
- Method validation via MC closure test
  → reduced systematic uncertainties
  compared to re-weighting method

Outlook:

- Application to data
- Study of energy and system size dependence
- High multiplicity in pp vs. Pb-Pb