Calibrating the ATLAS Muon Spectrometer for a Search for Charged Stable Massive Particles

Summary of the master's thesis at the LMU Munich

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LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT

Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

FSP 103 ATLAS

ATLAS EXPERIMENT

Motivation

- many questions left open by the SM: Dark matter, Hierarchy problem, ...

→ various theories extending the SM: Universal Extra Dimensions, Supersymmetry, ...

→ often predict additional particles,
among others charged stable massive particles (charged SMPs)

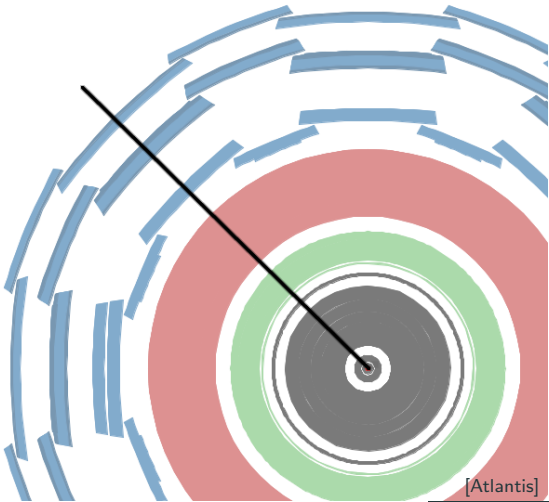
→ can be searched for with ATLAS at the LHC

Charged SMPs

- criteria
  - stable
  - massive
  - charged

search at ATLAS (SUSY→RPV/LL→SMP):

- β measurement
  - from dE/dx in pixel detector
  - from time-of-flight (ToF) in tile calorimeter and muon spectrometer
- benchmark models (SUSY)
  - *R*-hadrons
  - staus
  - charginos
- publications in 2015, 2016, 2019



[Atlantis]

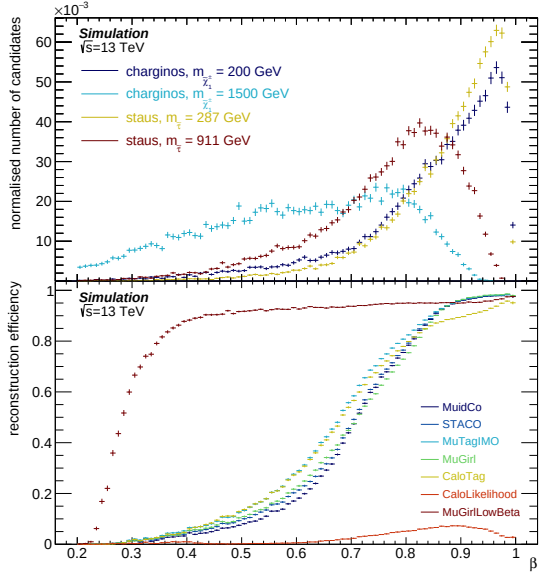
Need for a dedicated reconstruction algorithm: MuGirlStau

- signature of charged SMPs similar to muon, but with delayed hits

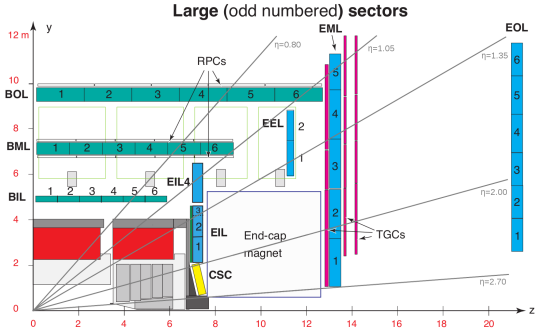
→ reduced reconstruction efficiency for nominal muon reconstruction algorithms

→ need for dedicated reconstr. algorithm: MuGirlStau (R20.7), MuGirlLowBeta (R21)

MC sample: directly produced stable staus (GMSB) and charginos (mAMSB) ⟶

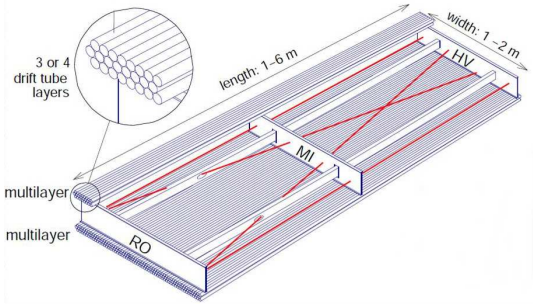


The ATLAS Muon Spectrometer



[ATL-MUON-PUB-2008-006]

Cross-sectional view of the muon spectrometer

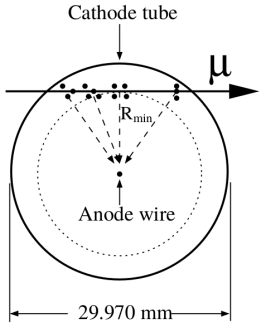


[JINST 3 (2008) S08003]

Overall layout of an MDT chamber

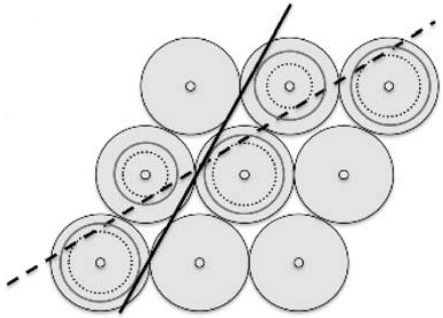
What is different in MuGirlStau?

Nominal reconstruction	Dedicated reconstruction: MuGirlStau
consider one bunch crossing only	consider following bunch crossing as well
$\beta = 1$ for all particles	β as free parameter, seeded by time-of-flight measurement



[JINST 3 (2008) S08003]

Cross section of an MDT tube

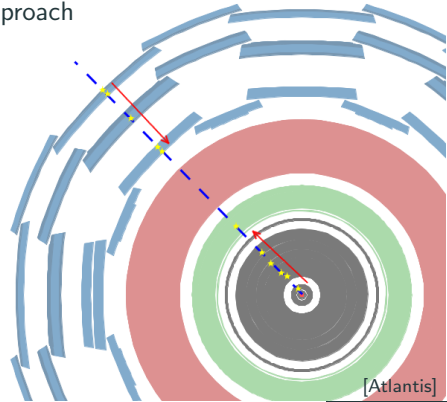


[Eur.Phys.J. C62 (2009) 281]

Correct and incorrect segment reconstruction

What is different in MuGirlStau?, part II

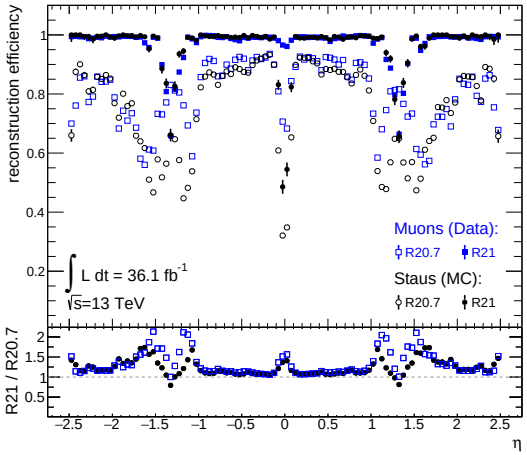
Nominal reconstruction	Dedicated reconstruction: MuGirlStau
consider one bunch crossing only	consider following bunch crossing as well
$\beta = 1$ for all particles	β as free parameter, seeded by time-of-flight measurement
mostly outside-in approach	inside-out approach



[Atlantis]

New dedicated reconstruction algorithm: MuGirlLowBeta

- several reasons for rewriting dedicated reconstruction algorithm from scratch, most importantly reconstruction efficiency:



$$\bar{\varepsilon}(\text{data, R20.7}) = 80.7\%$$

$$\Updownarrow$$

$$\bar{\varepsilon}(\text{data, R21}) = 96.7\%$$

New calibration of the ATLAS MS

- dedicated reconstruction algorithm needs thorough timing calibration
- new version of algorithm renders previous calibration outdated

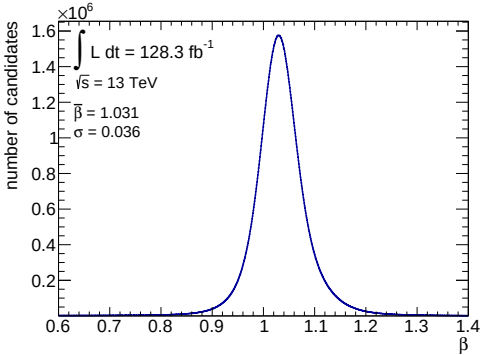
→ new calibration needed

- calibration based on muons with $Z \to \mu\mu$ selection ($t_0 = 0\,\text{ns}$, $\beta = 1$)
- using pp-collision data in from 2015–2018 ($128.3\,\text{fb}^{-1}$)
- calibrated systems in muon spectrometer: Resistive-plate chambers (RPCs), Monitored Drift Tubes (MDTs)
- calibrated quantities: t_0, β

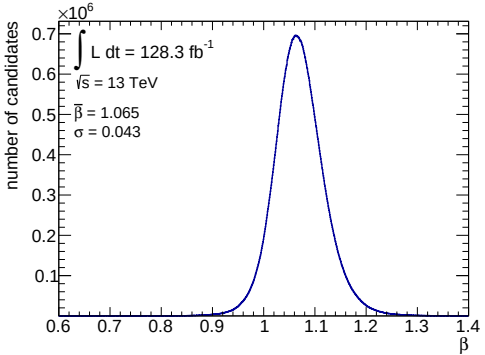
$$t_0 = \text{ToF} - \frac{d}{c}$$

Uncalibrated β distributions

- β distributions: supposed to be Gaussian, centered at 1 with as small as possible width



MDTs



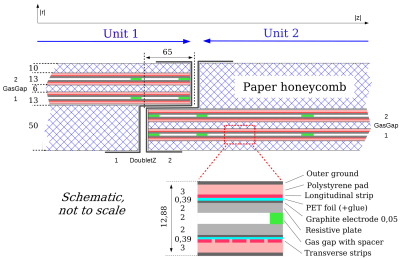
RPCs

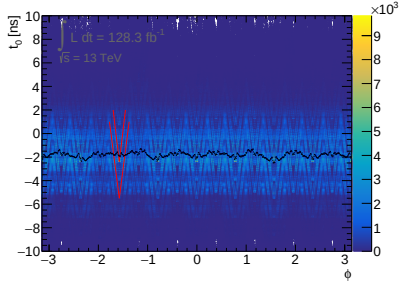
▸ Summary of Calibration ▸ Calibration Steps

Calibration steps

multiple calibration steps taken that improve timing resolution:

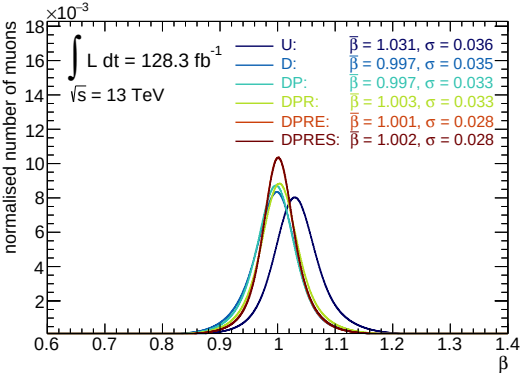
1. Drift-time calibration:
   correct erroneous calculation of drift times in MDTs
2. Propagation-time calibration:
   correct erroneous calculation of propagation times in strips and wires
3. Run-wise calibration:
   correct for run-wise effects
4. Element-wise calibration:
   correct for element-wise effects
5. Pull correction:
   adjust measurement uncertainties



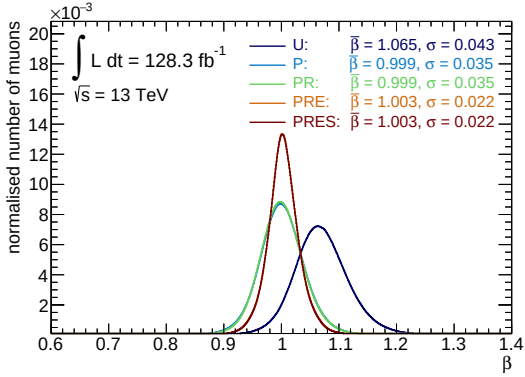


Result of data calibration

- improvement in β by the different calibration steps and final result



MDTs



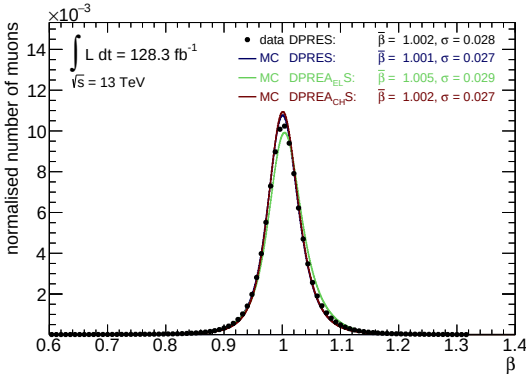
RPCs

Simulation treatment

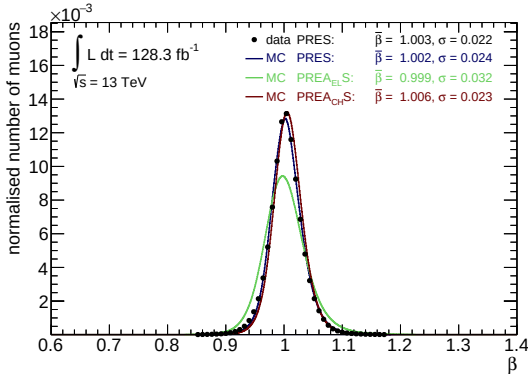
- simulated events used for setting exclusion limits on benchmark models

→ MC needs to be calibrated as well

→ using smearing and unfolding techniques



MDTs



RPCs

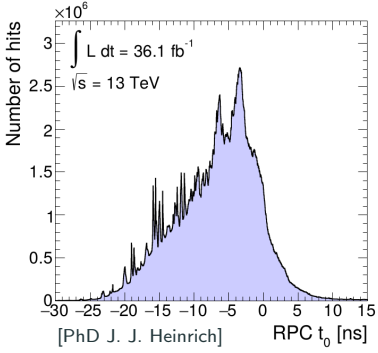
Summary

- charged stable massive particles: predicted in many theories beyond the SM
- searched with ATLAS: ionisation-energy and time-of-flight measurements
- needs dedicated reconstruction algorithm and thorough timing calibration of MS
- timing calibration yields large improvement in β resolution
- MC treatment using smearing and unfolding techniques

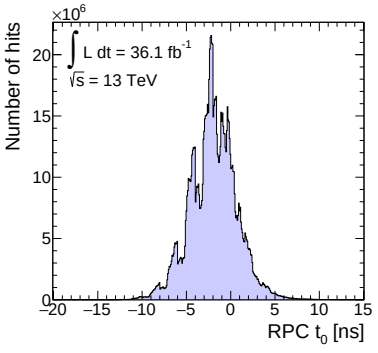
Back-up

Another reason for a new dedicated reconstruction algorithm: MuGirlLowBeta

- another reason for rewriting dedicated reconstruction algorithm from scratch: wrongly computed distance from IP in MuGirlStau, resulting in asymmetric tails in timing measurements



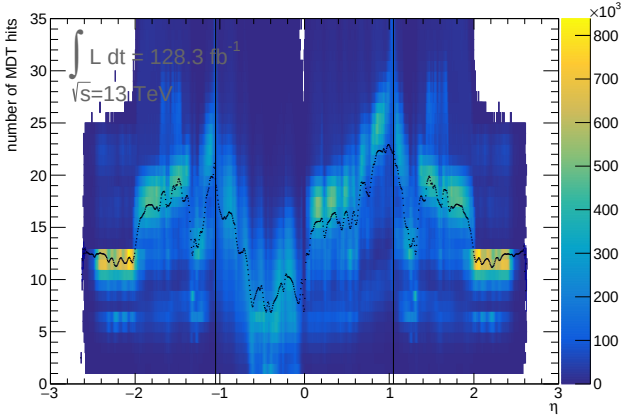
MuGirlStau (old)



MuGirlLowBeta (new)

Missing MDT hits in the barrel region of the ATLAS side C

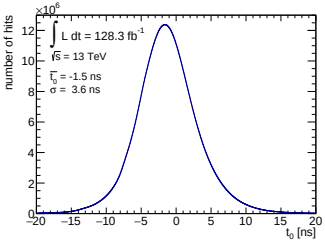
- in the course of this work, bug in MuGirlLowBeta found: MDT hits missing on ATLAS side C in the barrel region:



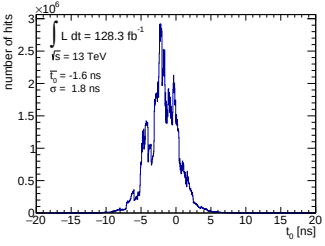
- has small but non-negligible effect on calibration

Uncalibrated t_0 distributions

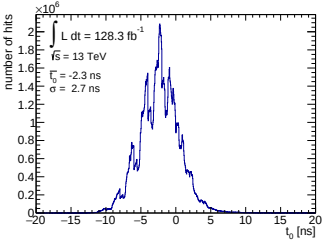
- t_0 distributions: supposed to be Gaussian, centered at 0 ns with as small as possible width



MDTs



RPC η-strips



RPC ϕ-strips

spiky structure for RPCs: result of RPC readout timing-granularity

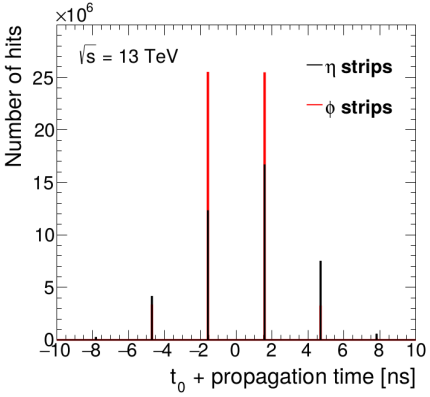
RPC readout timing-granularity

- RPCs part of trigger system

→ read out every 3.125 ns

→ measurements of discrete peaks with a temporal distance of 3.125 ns

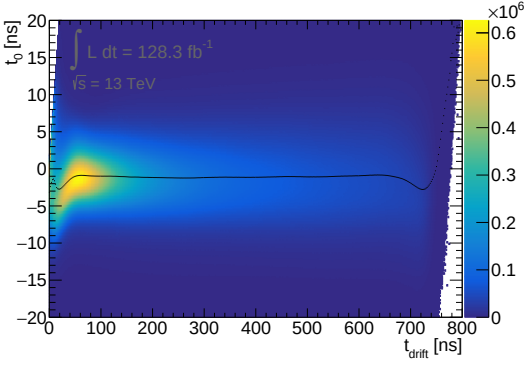
- adding propagation time to t_0 anew: timing-granularity of the RPC readout visible



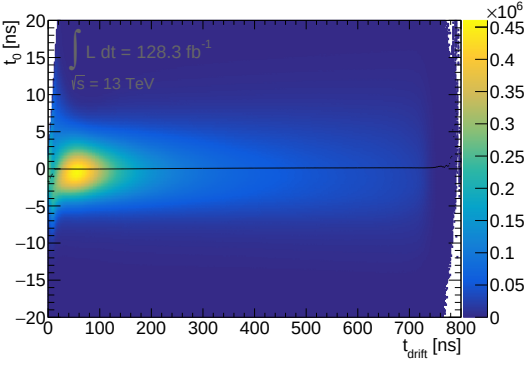
[PhD J. J. Heinrich]

Calibration step I: Drift-time calibration

- for MDTs only
- to correct distortions caused by drift-time calculation and non-linear space–drift-time–relation of the drift gas



uncalibrated



calibrated

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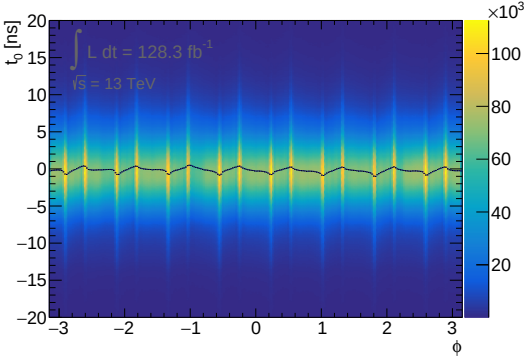
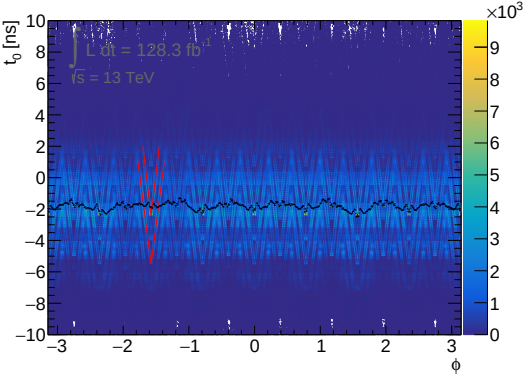
Calibration step II: Propagation-time calibration

- to correct distortions caused by erroneously calculated propagation times
- uncalibrated distributions:



MDTs



RPC η-strips

similar for RPC ϕ-strips, but in z instead of ϕ

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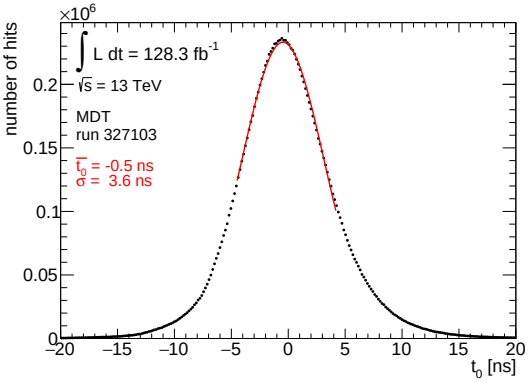
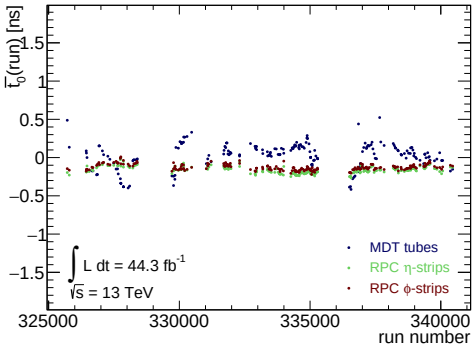
Calibration step III: Run-wise calibration

- to correct run-wise effects



fitting procedure to obtain mean of t_0 per run, for MDTs



mean of t_0 per run in 2017

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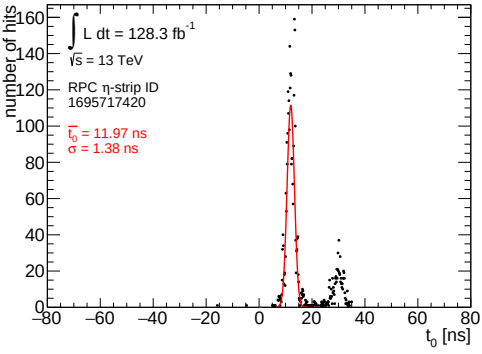
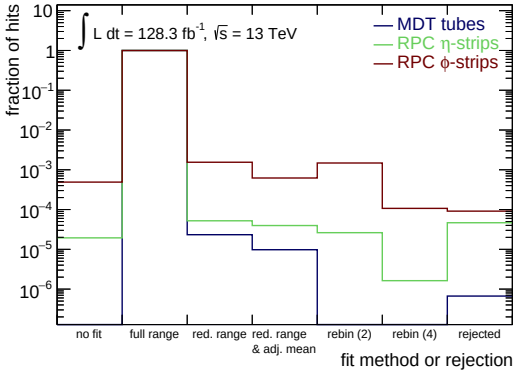
Calibration step IV: Element-wise calibration

- to correct element-wise effects
- multi-fit procedure to obtain mean of t_0 per element



fitting procedure to obtain mean of t_0 per run, for a randomly chosen RPC η-strip



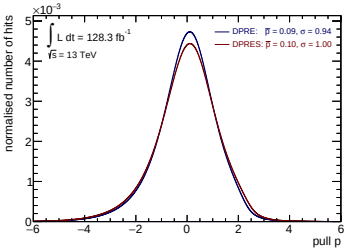
fraction of hits a certain fit method is chosen for or that is rejected

Back to Summary

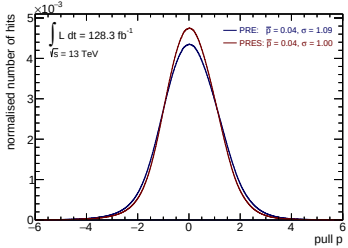
Calibration step V: Pull correction

- to adjust measurement uncertainties

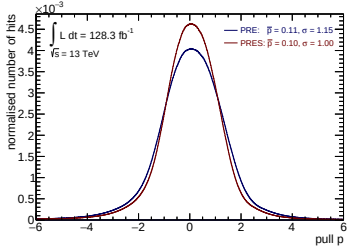
$$p := \frac{1 - \beta_i^{-1}}{\sigma_{\beta_i^{-1}}}$$



MDTs



RPC η-strips

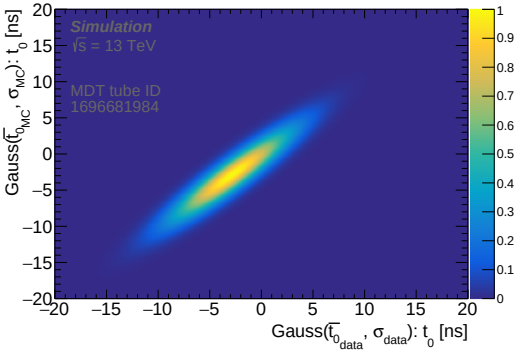


RPC ϕ-strips

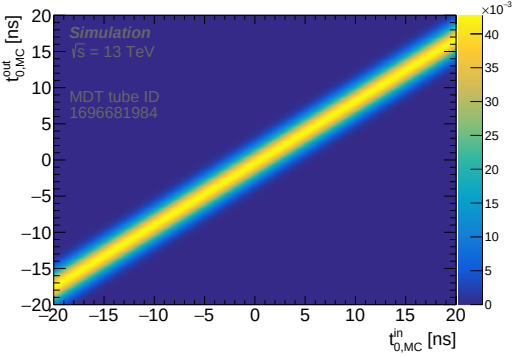
Back to Summary

Simulation treatment: unfolding

- attempt to achieve better agreement between data and simulation by chamber-wise treatment:
  - smearing for chambers overestimating β resolution
  - unfolding for chamber underestimating β resolution:



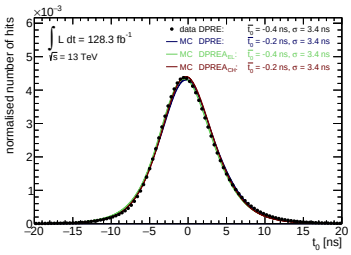
Response matrix



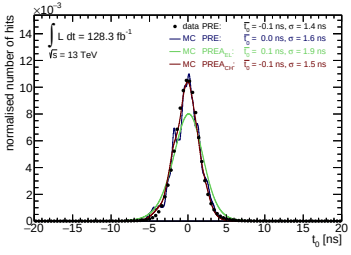
Unfolding matrix

Simulation treatment: result for systems in t_0

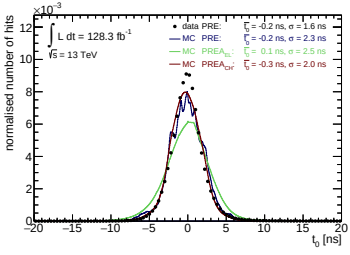
- result after full calibration chain and MC treatment:



MDTs



RPC η-strips



RPC ϕ-strips

Simulation treatment: result for combined systems

- combined result for MS (MDTs+RPCs) after full calibration chain and MC treatment: