Three-Jet Mass Measurement

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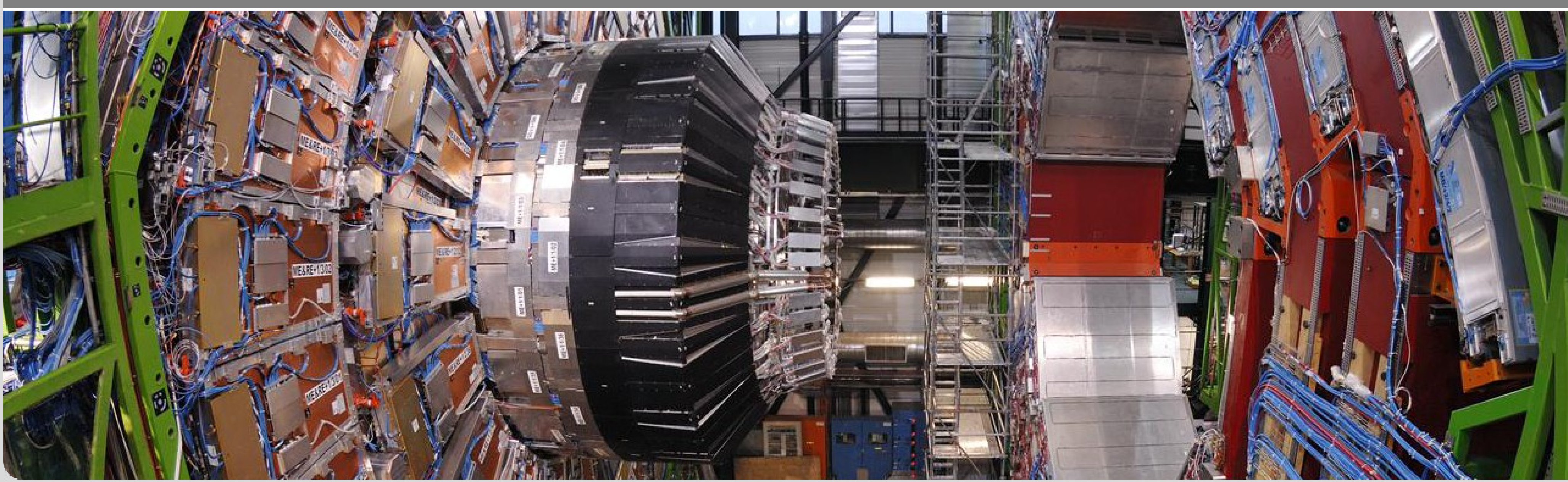
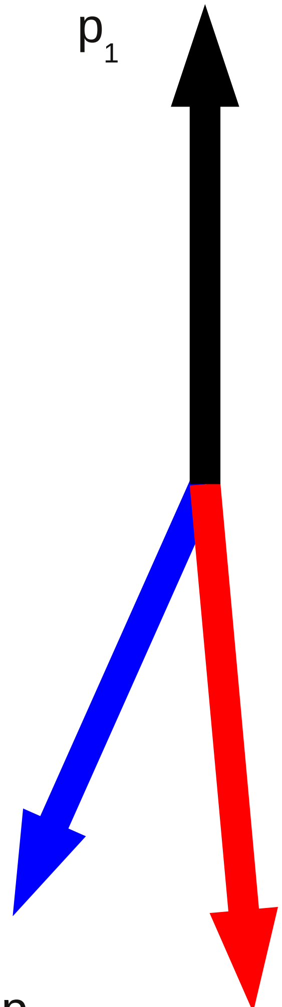


Three-Jet Mass



- Goal: Test perturbative QCD by looking at higher jet multiplicities
- Select three-jet event topologies and measure the invariant mass of the three-jet system

$$m_3^2 = (p_1 + p_2 + p_3)^2$$

- Using maximal rapidity of the three-jet system to define disjunct phase-spaces as done in previous publications

$$y_{\mathrm{max}} = \max(|y_1|, |y_2|, |y_3|)$$

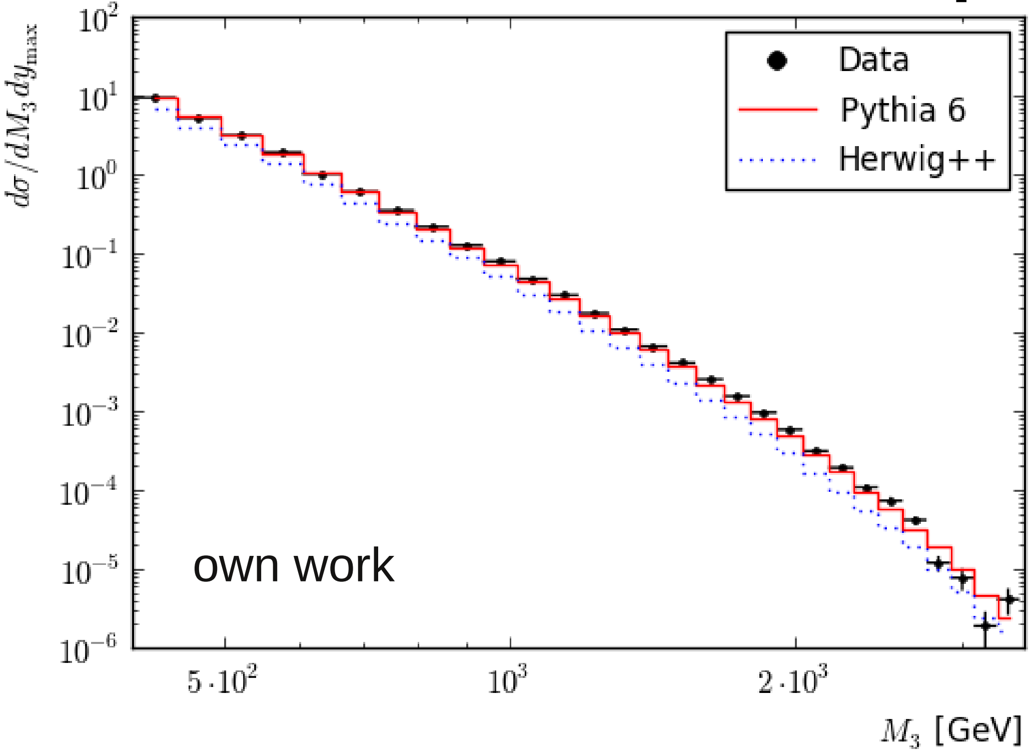
- Measure double differential three-jet crosssection in mass and y_{max}:

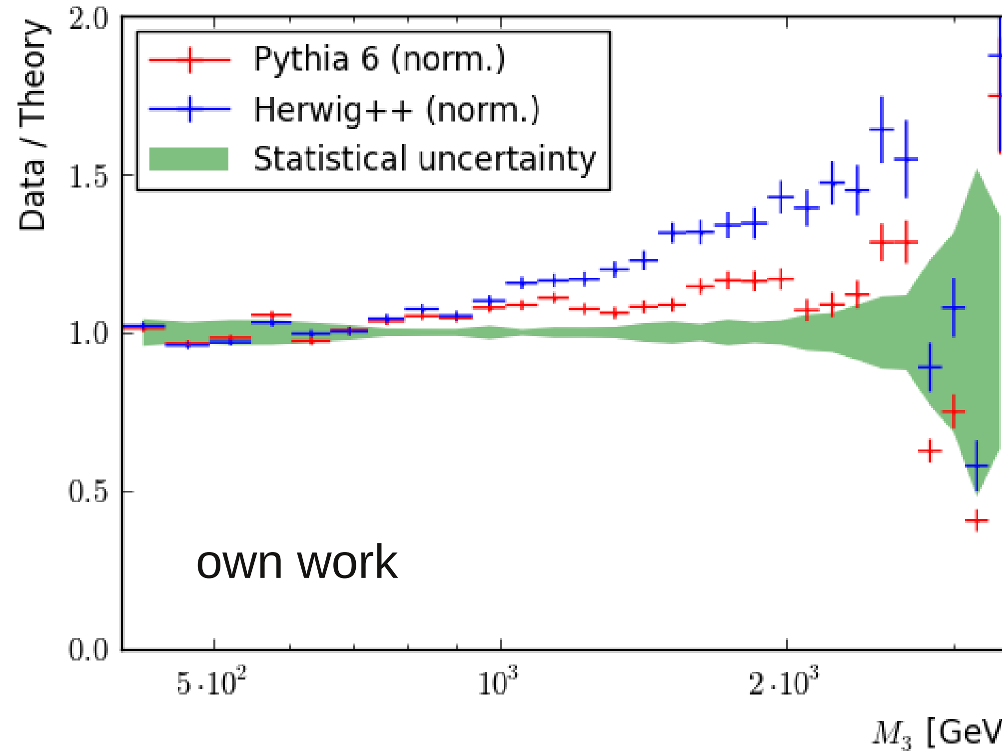
$$\boxed{\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_3 \mathrm{d}y_{\mathrm{max}}}}$$

Event selection

- Dataset: 2011 data (7TeV, 5/fb)
- Trigger: Single jet trigger (p_T thresholds: 30 GeV … 800 GeV)
- Standard good event selection – rejection of beam backgrounds, etc.
- Standard jet reconstruction:
  - Event reconstruction using particle flow algorithm
  - Used jet algorithms: Anti-kT 0.5 and **0.7**
  - Only jets passing quality criteria are considered (“loose PF JetID”)
  - Jet energy correction are applied
- Jet acceptance cuts : $p_T > 50\ GeV, |y| < 3$
- Three-jet event selection cut scenarios
  - **absolute** cut scenario: $p_{T3} > 100GeV$
  - cross-check with other cuts

Reconstruction level comparison

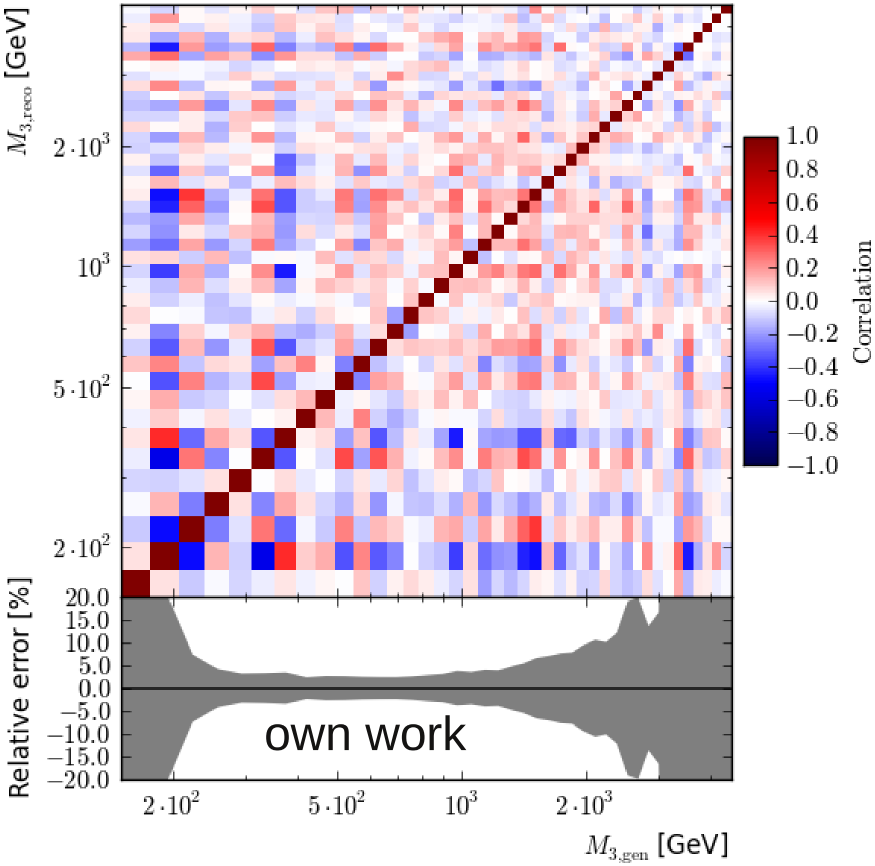


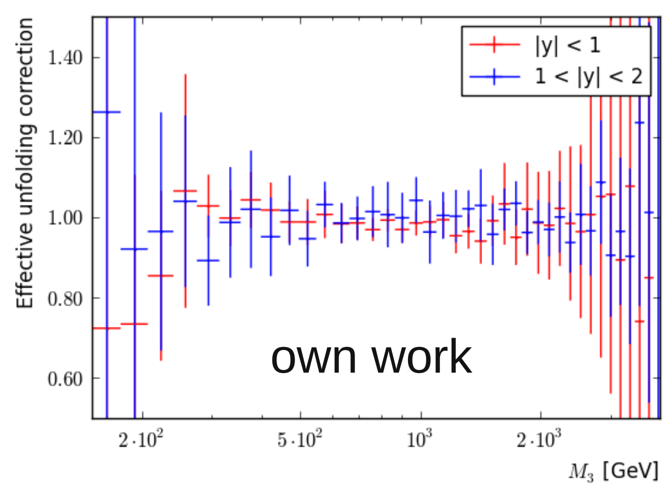


- MC normalization:
  - Pythia predicts cross-section well, Herwig++ needs a larger correction
  - No impact on resolution / unfolding studies using these two generators
- Shape comparison:
  - Below 1TeV: Both MC describe the shape of the data well
  - Above 1TeV : The deviation between data and MC gets larger
  - In general: Pythia is closer to the data than Herwig++

Unfolding: Overview

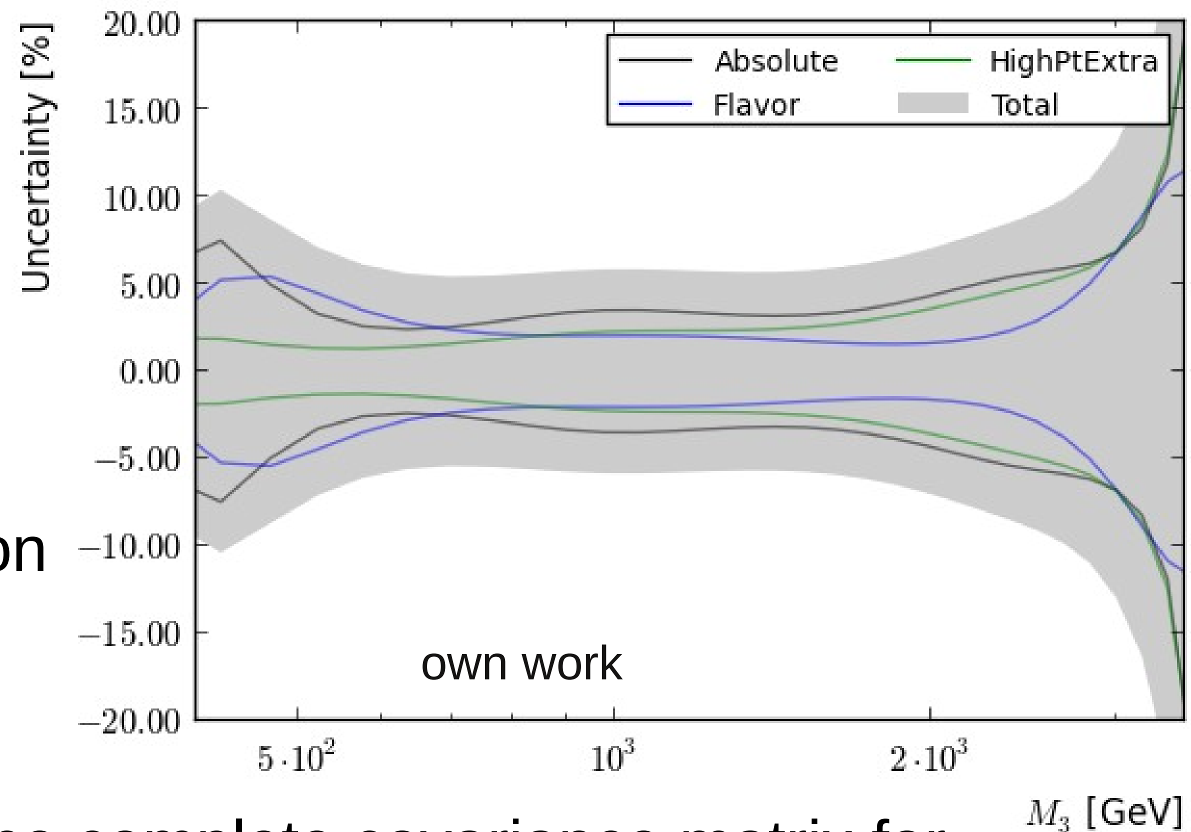
- Bayesian unfolding (4 iterations) + cross-checks with other algorithms
- Uncertainties determined from toy experiments
  - Variation of input histograms within errors for the statistical error
  - Variation of input histograms and detector response for combined unfolding error
- Performed with Monte-Carlo input from Pythia and Herwig++ FullSim
- Final result is average of both generators with the error determined from the spread in the toys
- Unfolding corrections are small, as expected in the three-jet mass ranges above 500 GeV





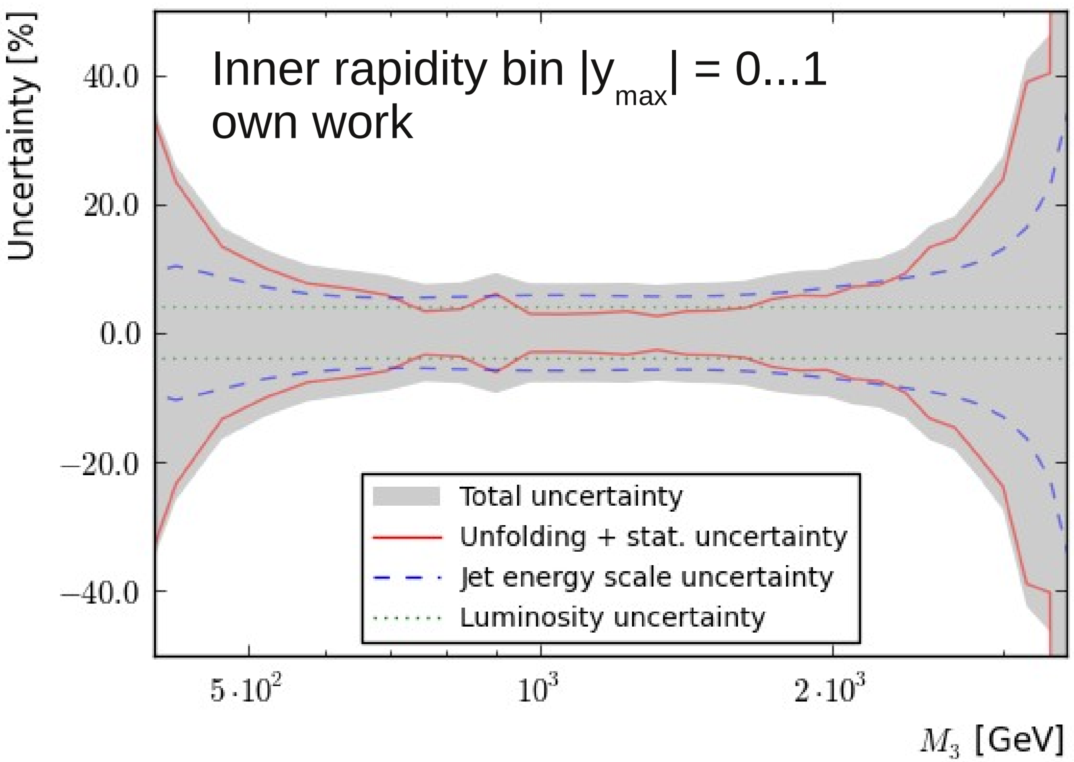
Jet energy uncertainties

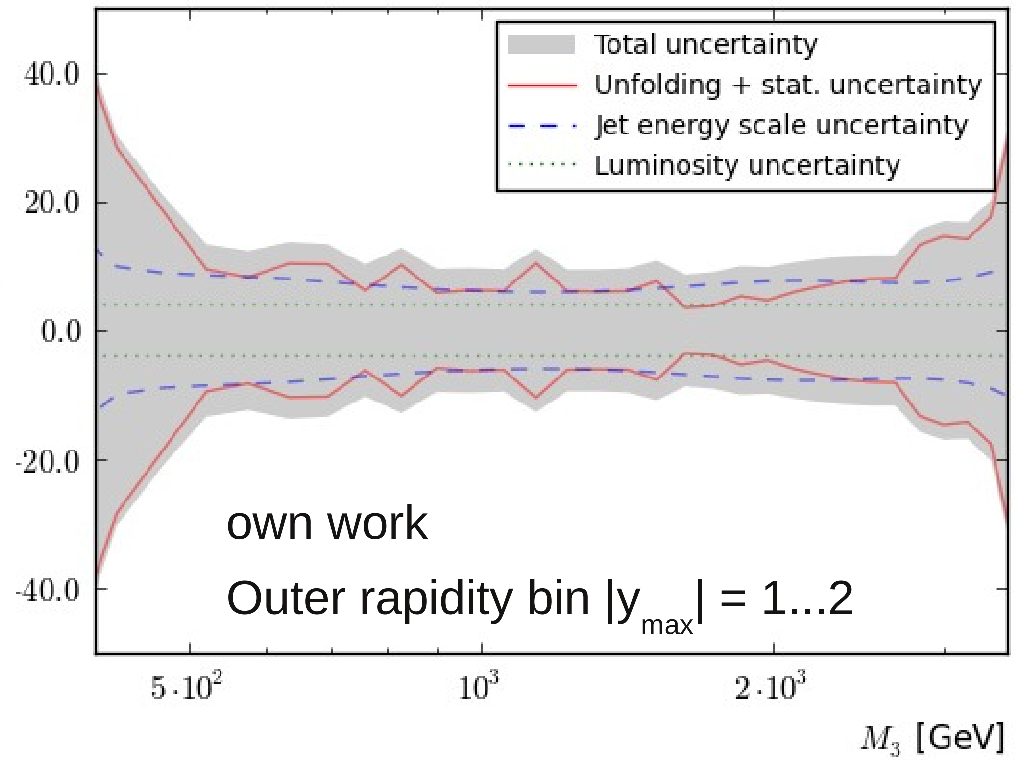
- CMS jet energy uncertainties split into 16 uncorrelated sources
- The influence of each uncertainty source on the three-jet mass was studied in detail



- The four main uncertainty sources are the absolute, flavour, high-p_T extrapolation and pile-up uncertainties
- The result of this study is the complete covariance matrix for the jet energy uncertainties

Measurement: Overview of statistical and systematic uncertainties

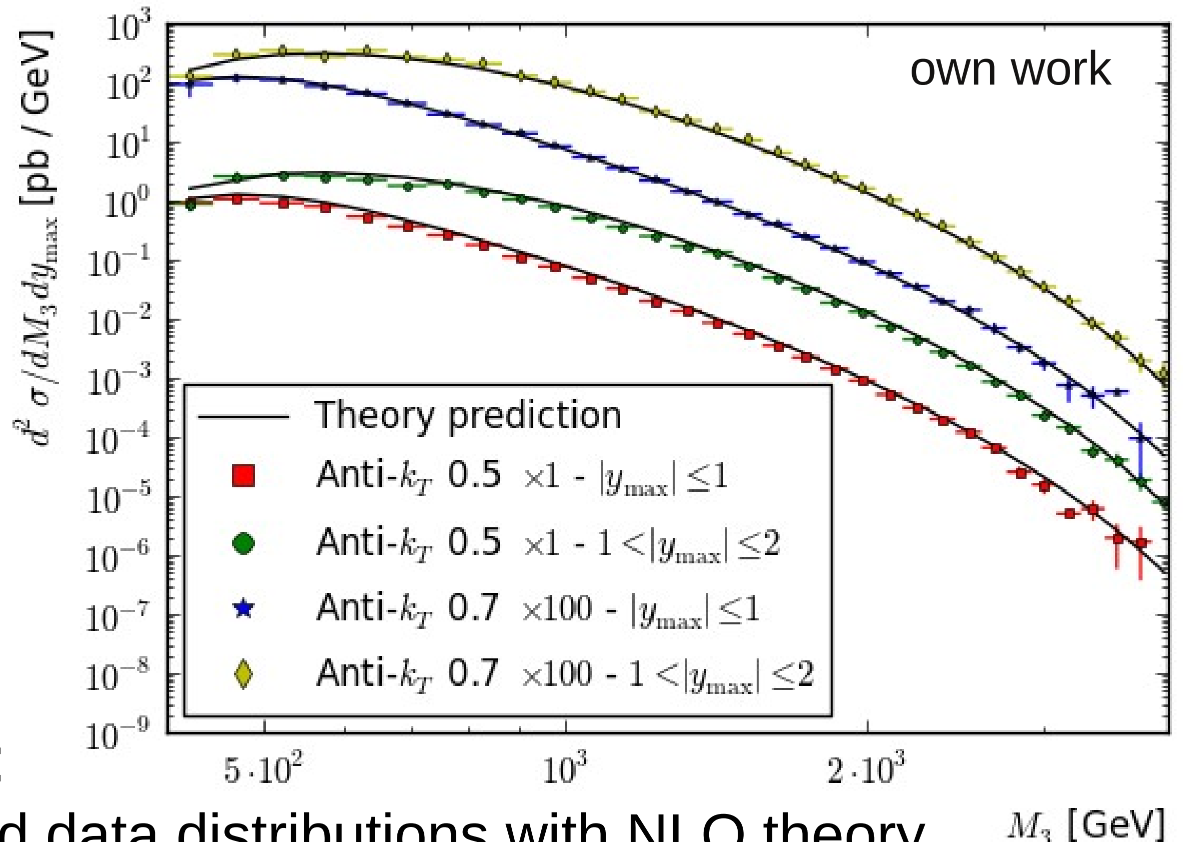




- The three important uncertainty sources are symmetric and of the same order for a large range three-jet masses in both rapidity regions
- Increase in low / high p_T region due to resolution / statistics
- Small fluctuations in the statistical uncertainty at trigger thresholds

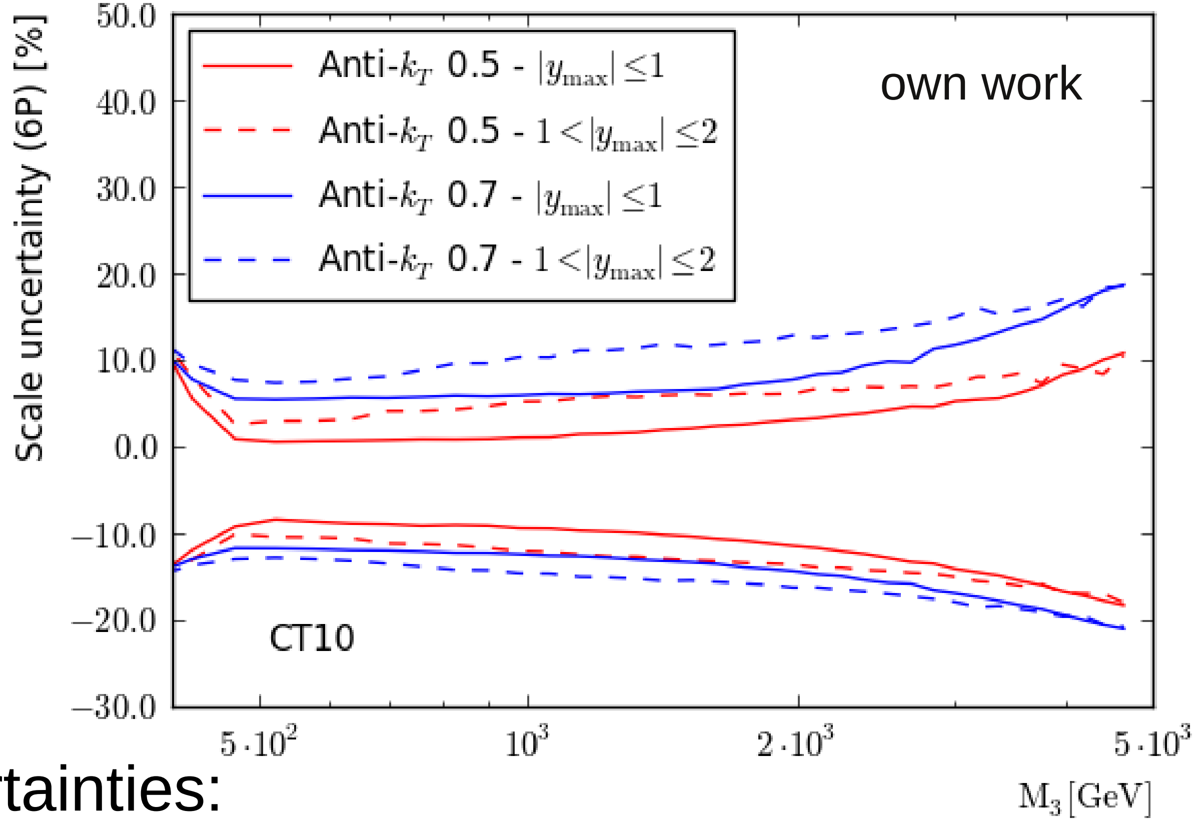
Comparison between Measurement and NLO prediction

- Theory calculations were done using NLOJet++ / fastNLO
- Comparison between the unfolded measurement and the NLO theory prediction shows agreement over several orders of magnitude
  - for different cut scenarios,
  - for different parts of the phase-space ($y_{\max}$),
  - for different jet sizes used in the anti-kT algorithm



- Non-perturbative corrections:
  - In order to compare unfolded data distributions with NLO theory, non-perturbative effects like hadronization have to be included
  - Calculated using Sherpa

Theory: Scale uncertainties

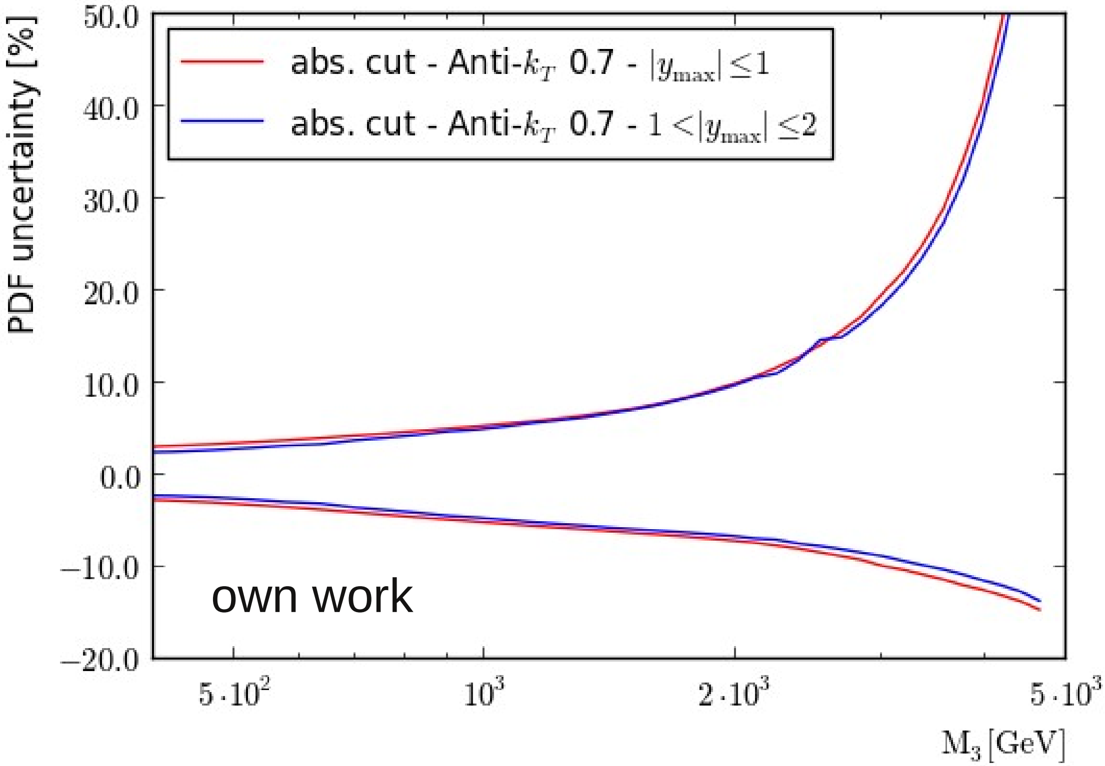


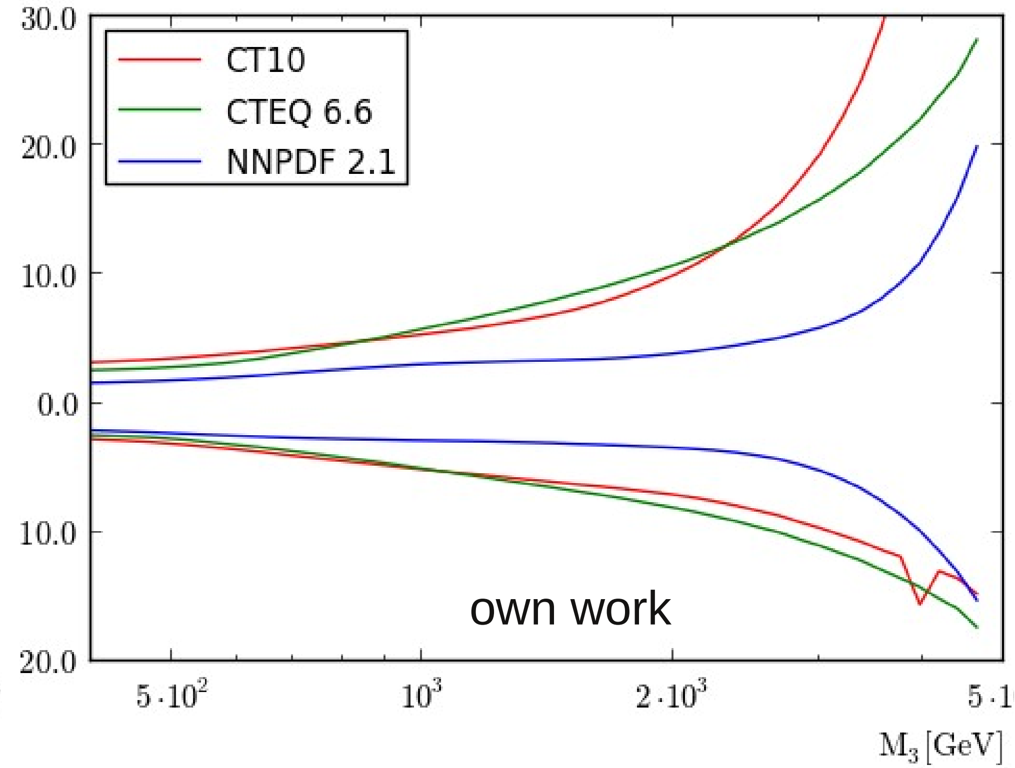
- Scale uncertainties:
  - Normalization and factorization scale $m_3/2$ varied
  - Six-point scale variation with the following scales

$$(\mu_R, \mu_F) = (2 \times \mu, \mu), (2 \times \mu, 2 \times \mu), (\mu, 2 \times \mu), (\mu/2, \mu), (\mu/2, \mu/2), (\mu, \mu/2)$$

- The scale uncertainties in the inner rapidity bin / smaller jet size are smaller than the uncertainties in the outer rapidity bin / larger jet size

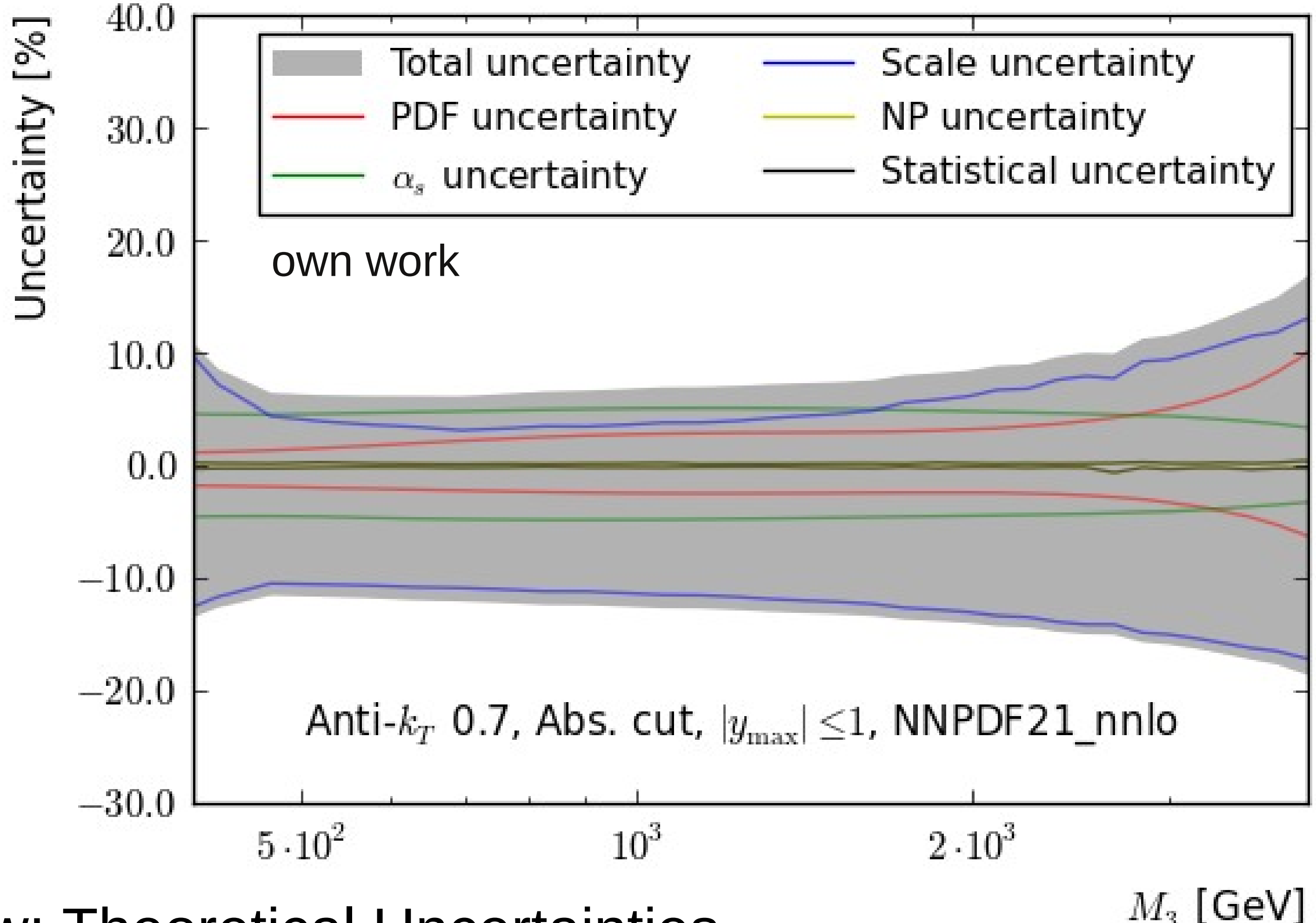
Theory: PDF Uncertainties





- PDF uncertainties:
  - CT10: Variations based on the provided PDF eigenvector sets
    PDF variations scaled down to form 1 sigma confidence intervals
  - NNPDF: Uncertainty based on the variation among the PDF replicas
- The uncertainties for the two cut scenarios, the two phase space regions and the two jet sizes all exhibit a similar behaviour

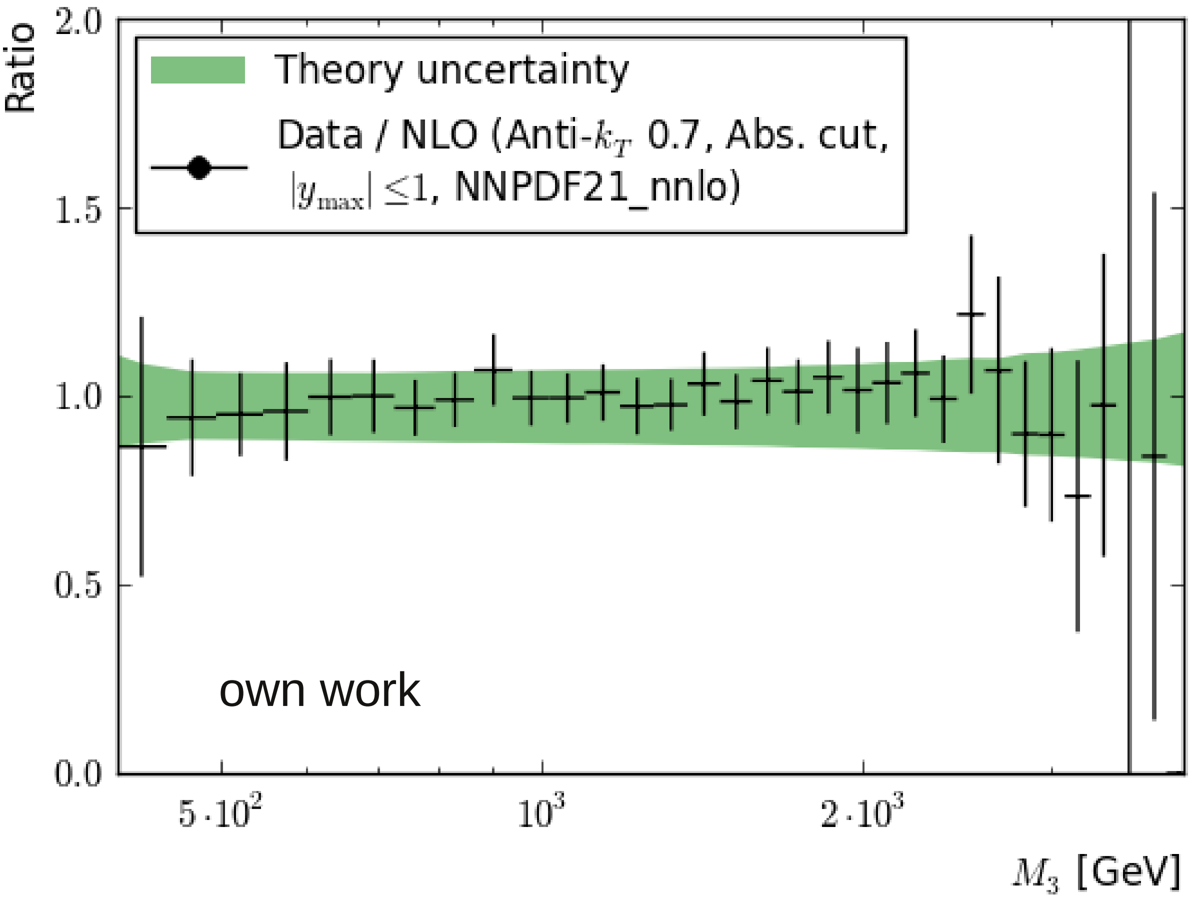
Theory: NP & Uncertainties



- Overview: Theoretical Uncertainties
  - Scale uncertainties dominating
  - PDF & as uncertainties
  - NP uncertainties negligible

Comparison between Measurement and NLO prediction

- The ratio between data and theory was studied for a wide variety of cut selections, rapidity regions, jet sizes and PDFs
- Differences are covered by the uncertainties
- Best agreement is observed for the absolute cut scenario with Anti-kT 0.7 jets



This data over theory ratio is fitted with a constant, **taking all covariances into account**.

The result is **perfectly compatible with 1.**

Summary & Outlook

- **Measurement of double differential Three-Jet mass cross-section**
  - **Unfolded data distribution:** Iterative Bayesian method
  - **Resolution measurement**: Binning optimization
  - **Jet Energy scale**: Detailed study of jet energy scale uncertainties
  - **Correlations:** Available for all uncertainty sources
  - Cross-checks with different cut scenarios, unfolding algorithms, ...
- **NLO theory studies**
  - **K-factors, corrections and uncertainties** for the theory calculation were derived
  - Cross-checks with different PDFs, scale choices, ...
- **Very good agreement between measurement and NLO prediction**

- **Outlook**: Study sensitivity to theory parameters (PDF, a_s)

Backup

Three-jet Mass Resolution

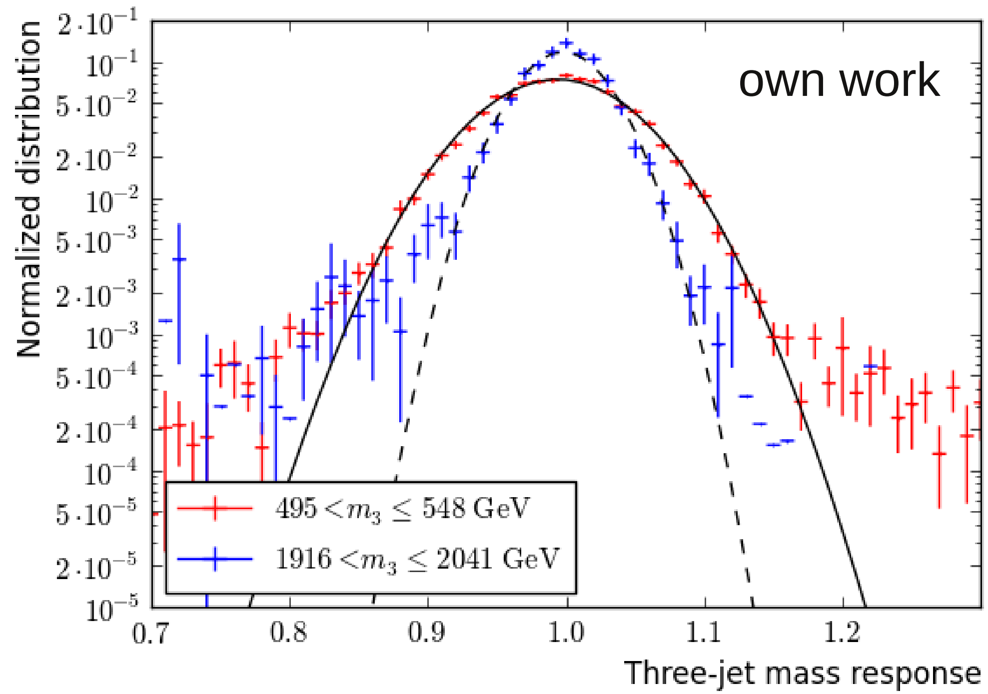
Binning of M3 is following behavior of the Three-jet Mass resolution

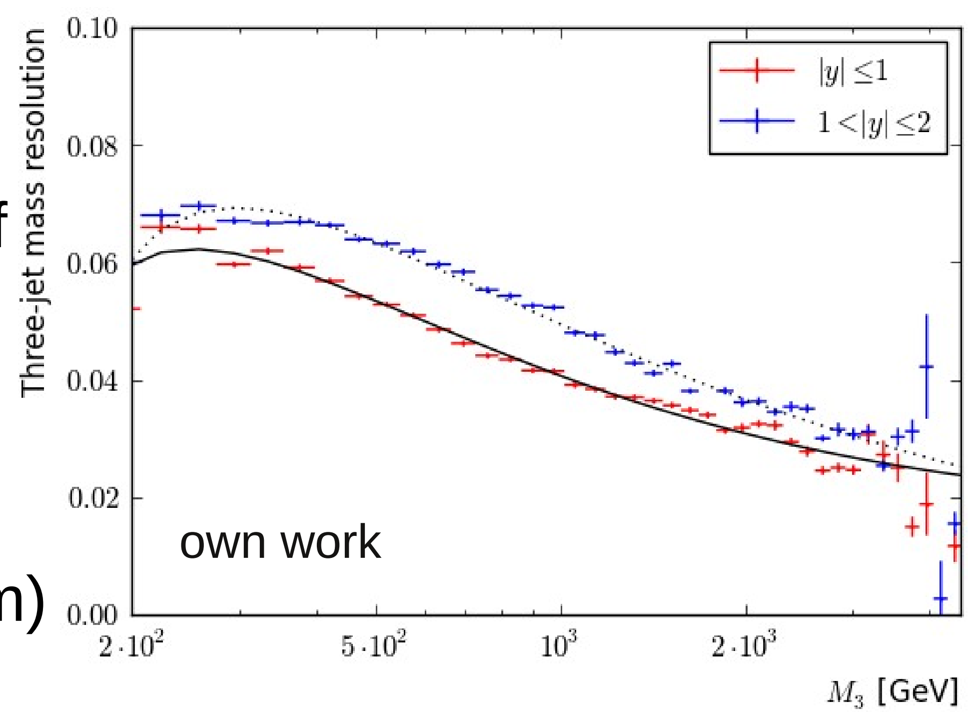
- Resolution taken from Gaussian fits of the Three-jet Mass response
  - Effects of MC modeling and jet energy scale are negligible

- Fitted resolution is given in terms of the modified NSC formula:

$$\frac{\sigma_{m3}}{m_3} = \sqrt{\mathrm{sgn}\,(N)\left(\frac{N}{m_3}\right)^2 + (m_3/\,\mathrm{GeV})^s\,\frac{S^2}{m_3} + C^2}$$

(noise, stochastic and constant term)





Jet energy uncertainties

- CMS jet energy uncertainties split into 16 uncorrelated sources
- Jet momentum is rescaled according to uncertainty:

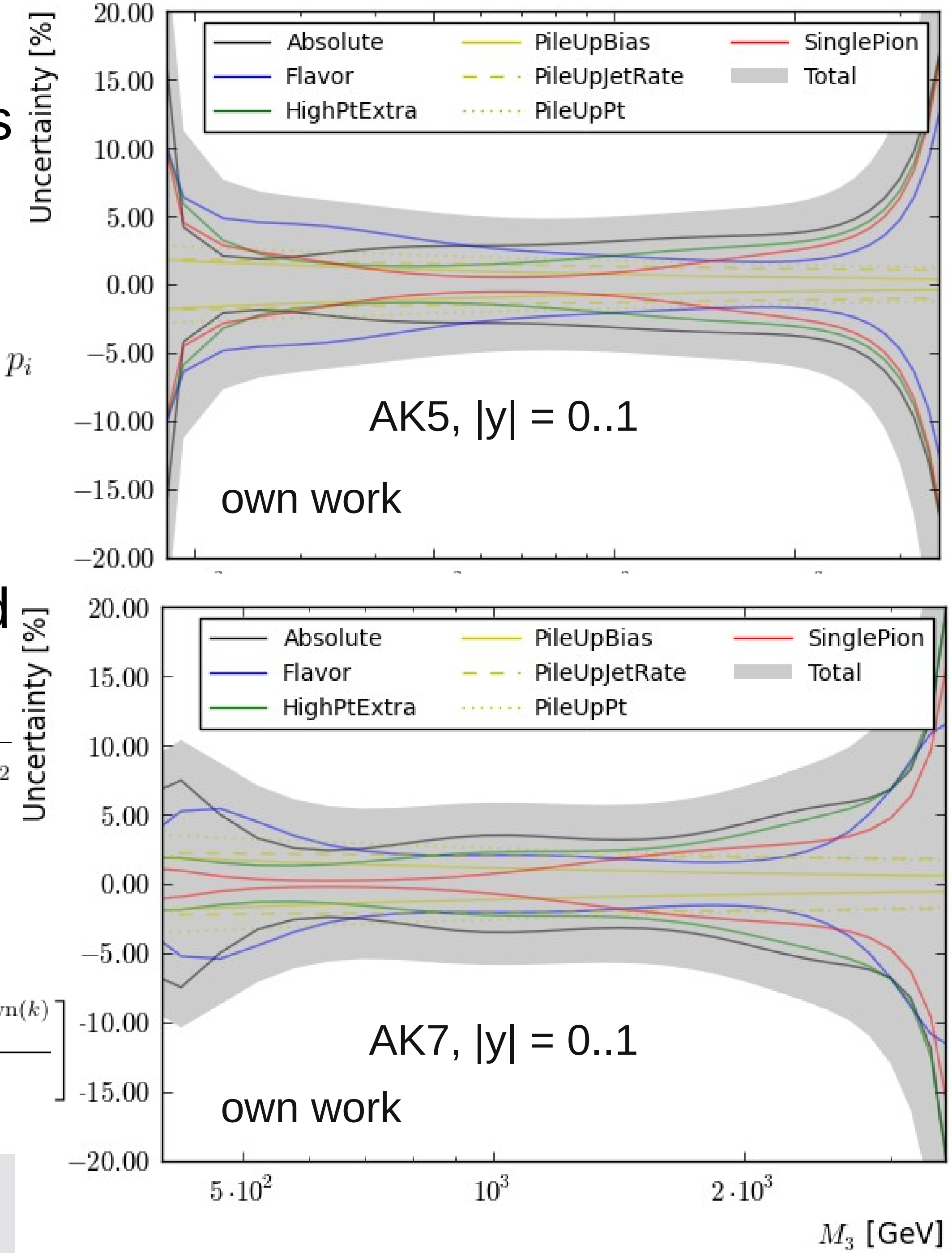
$$p_{i,\mathrm{up}} = \left(1 + \sigma_j^{\mathrm{up}}\left(p_T, \eta\right)\right) p_i, \quad p_{i,\mathrm{down}} = \left(1 - \sigma_j^{\mathrm{down}}\left(p_T, \eta\right)\right) p_i$$

- Rescaled jets are used as input for the analysis
- Asymmetric errors are calculated from the calculated masses:

$$\Delta m_{3,i}^{\mathrm{up}} = \sqrt{\sum_{k=0}^{n_{JEC}} \left[\max\left(m_{3,i}^{\mathrm{up}(k)} - m_{3,i}^{\mathrm{center}}, m_{3,i}^{\mathrm{down}(k)} - m_{3,i}^{\mathrm{center}}, 0\right)\right]^2}$$

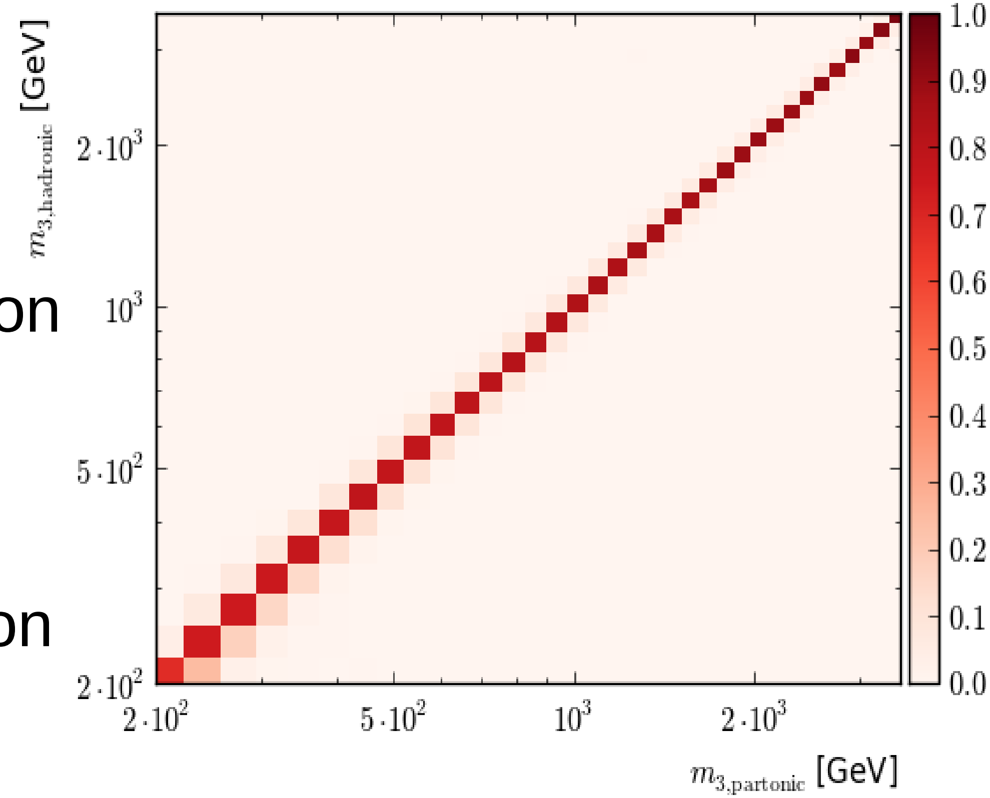
- Bin-correlation matrices from:

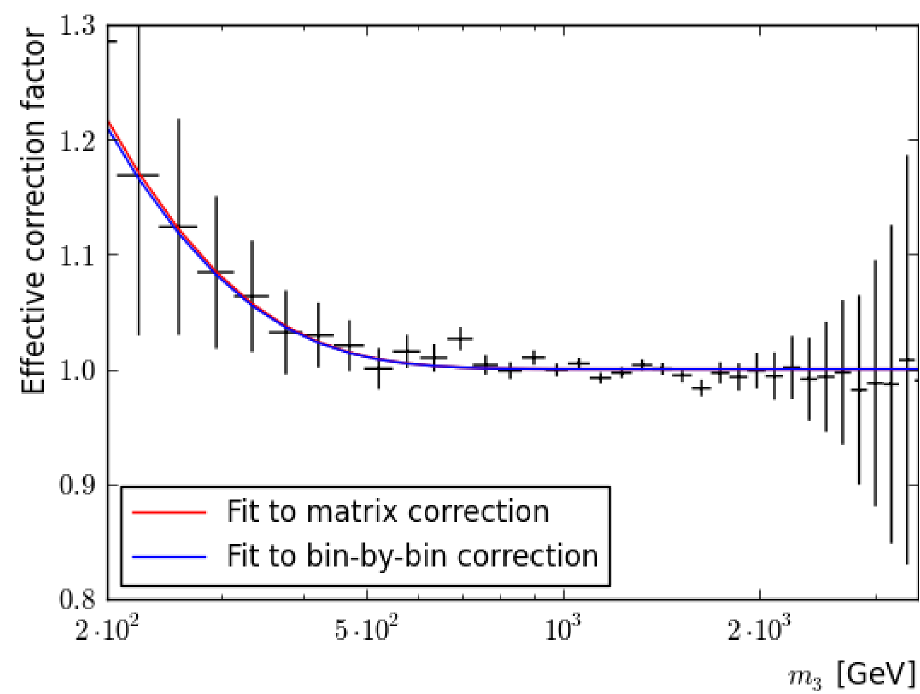
$$\mathrm{cov}_{\mathrm{JEC}}\left(m_{3,i}; m_{3,j}\right) = \sum_{k=0}^{n_{JEC}} \left[\frac{m_{3,i}^{\mathrm{up}(k)} - m_{3,i}^{\mathrm{down}(k)}}{2}\right] \left[\frac{m_{3,j}^{\mathrm{up}(k)} - m_{3,j}^{\mathrm{down}(k)}}{2}\right]$$



Non-perturbative

- In order to compare unfolded data distributions with NLO theory, non-perturbative effects like hadronization have to be included
- Traditionally, determined from the ratio of a MC generator prediction with hadronization and UE simulation switched on/off and applied like a bin-by-bin correction factor to NLO
- LO generator for three-jet events
  - Sherpa
  - ! Herwig++ / Pythia 6 are not LO
- Alternative: For each matrix-level event, the three-jet mass is calculated once with both hadronization and UE and without these effects. The results can be recorded in matrix form





Theory: NLO K Factors

- Differences between the leading order and next-to-leading order prediction were studied
- The K-Factor is defined here as the ratio of the NLO over the LO prediction using the same PDF (here: CT10 NLO)
- **The calculations were done for two different scale choices**:
  - half of the three-jet mass
  - the average p_T of the 3 jets
- In general, the K-Factor for bigger jet sizes is larger than the K-Factor for smaller jet sizes
- K-Factor stays within reasonable range of -50% to +70%