Theory Constraints from Three-Jet Observables

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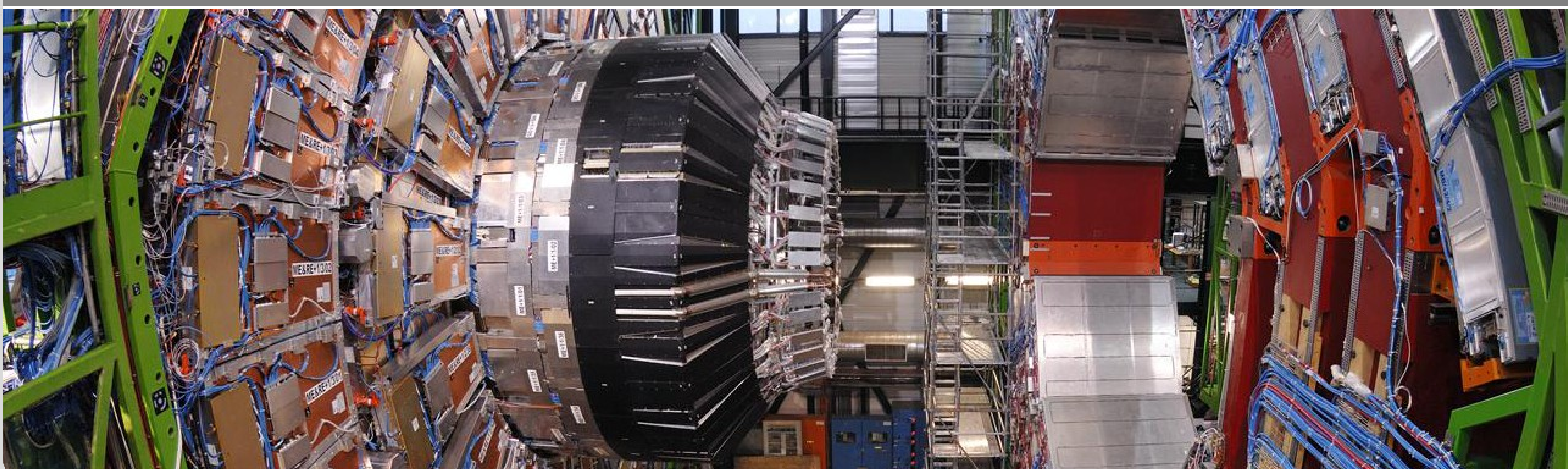
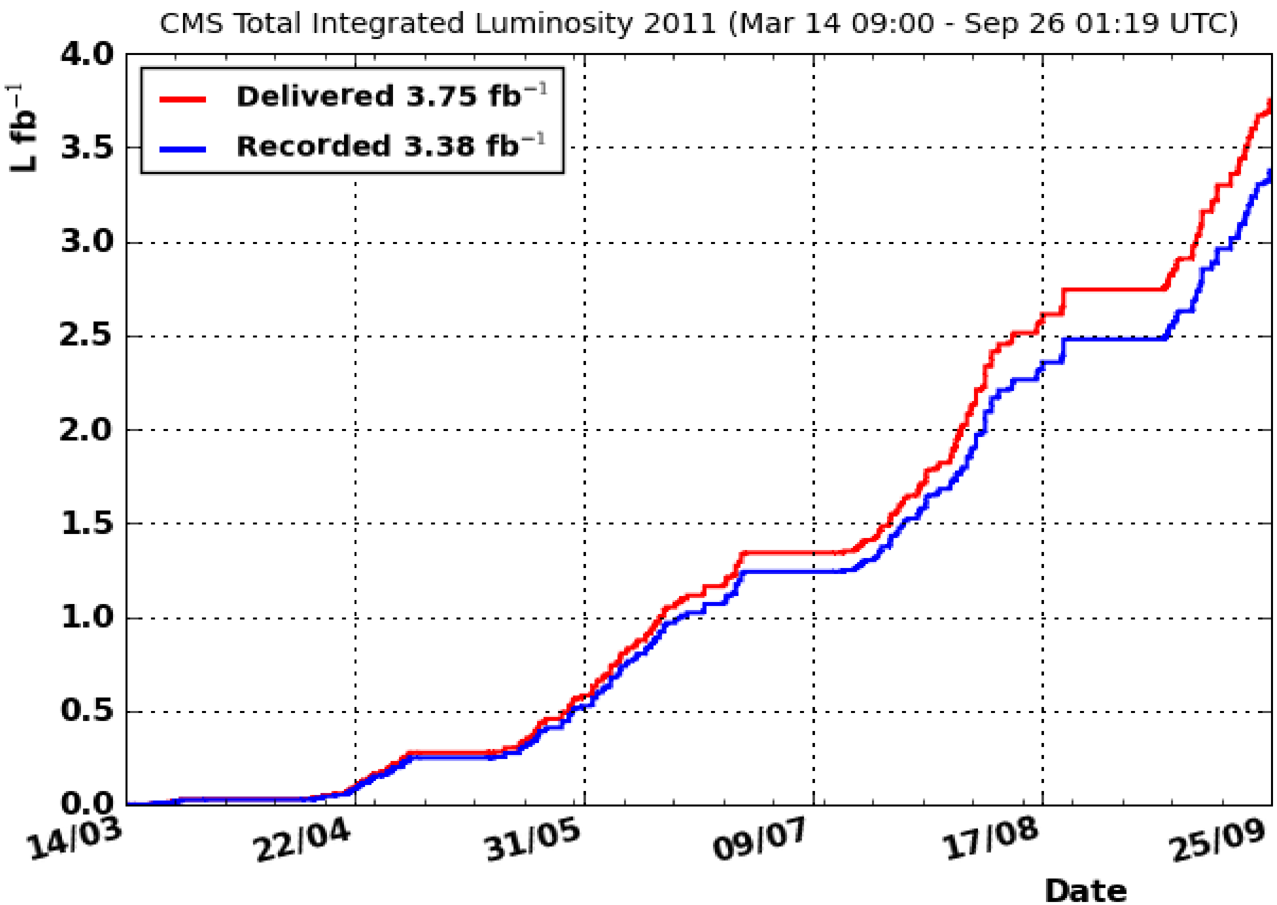
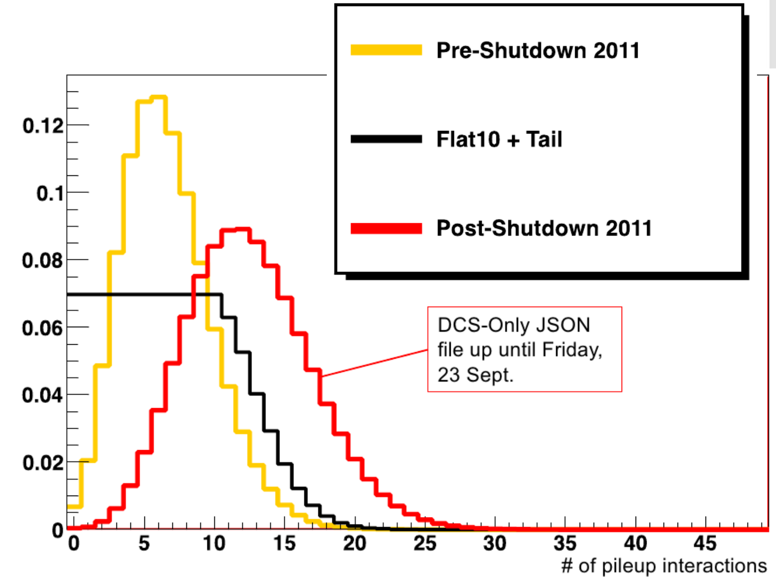


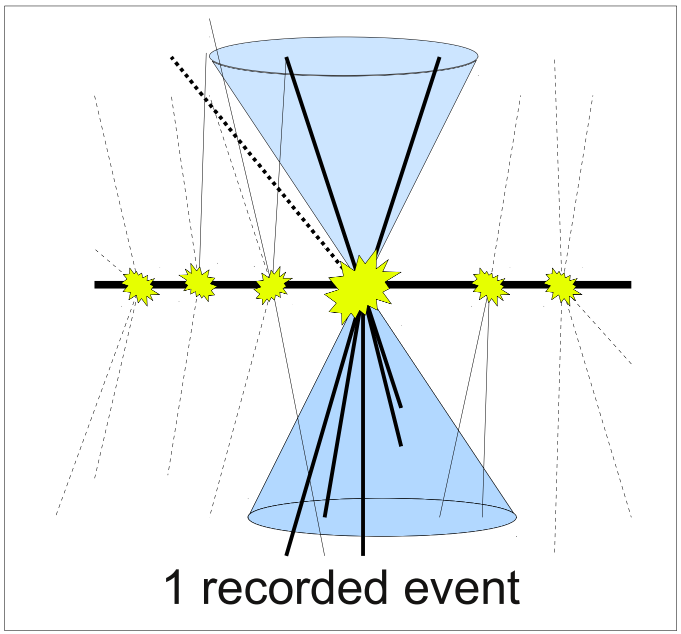
Outline

- **LHC and the CMS Detector**
- Jet Reconstruction in CMS
  - Particle Flow
  - Jet Algorithms
- QCD measurements
  - Recent and upcoming studies
  - NLO calculations
  - Three-jet mass
    - Event selection
    - Resolution
    - Unfolding
    - Pile-up
    - Experimental results
    - Non-perturbative corrections
- Conclusion

LHC data taking in 2011

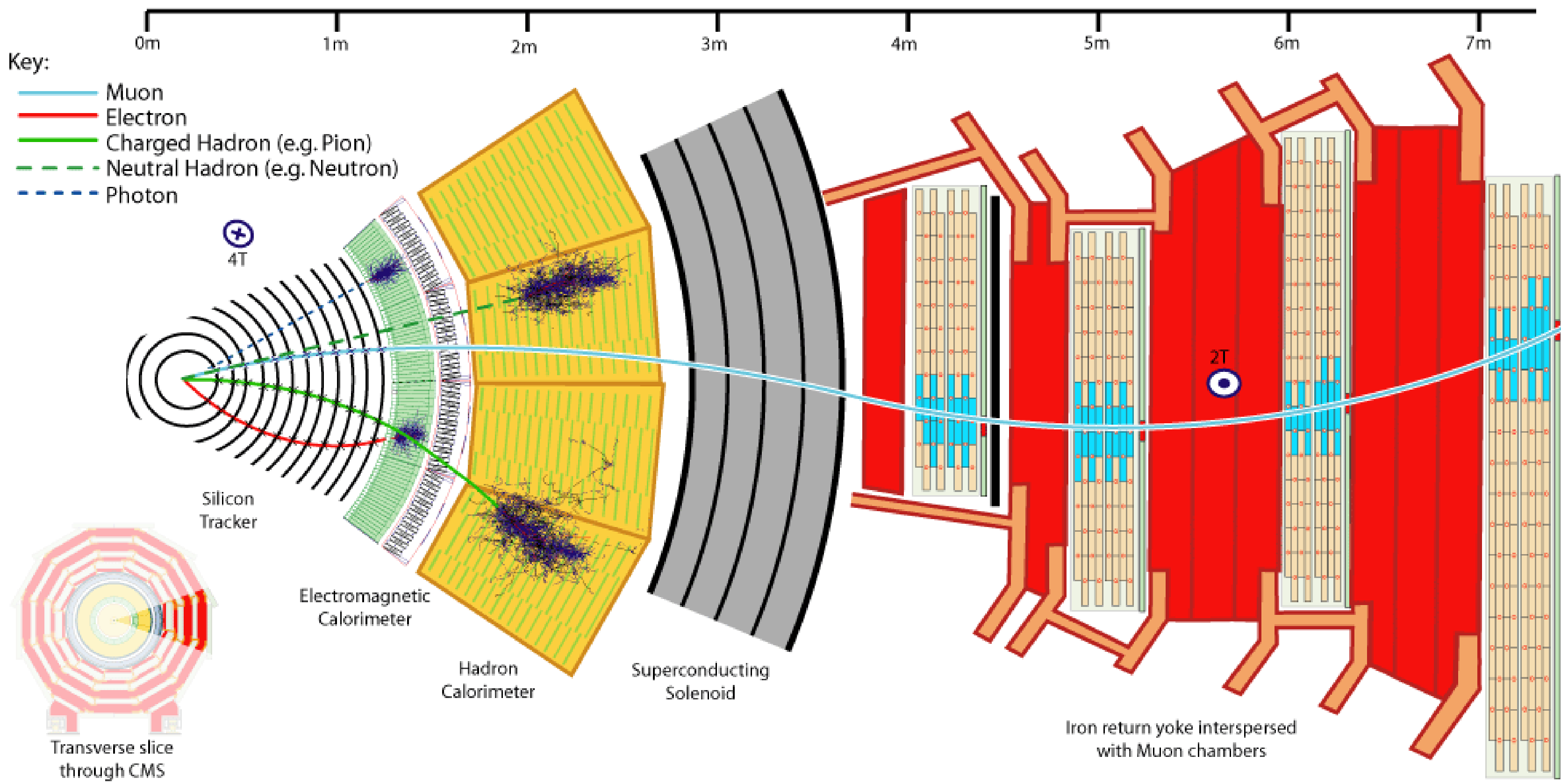






- Increasing luminosity, catching up to the 12/fb collected by the Tevatron
- Increasing number of pile-up

The Compact Muon Solenoid



- Electromagnetic Calorimeter
  - Lead tungstate crystals
- Hadron Calorimeter
  - HB + HE: Brass absorber, plastic scintillator
  - HO: Steel absorber, plastic scintillator
  - HF: Iron absorber, Quartz scintillator

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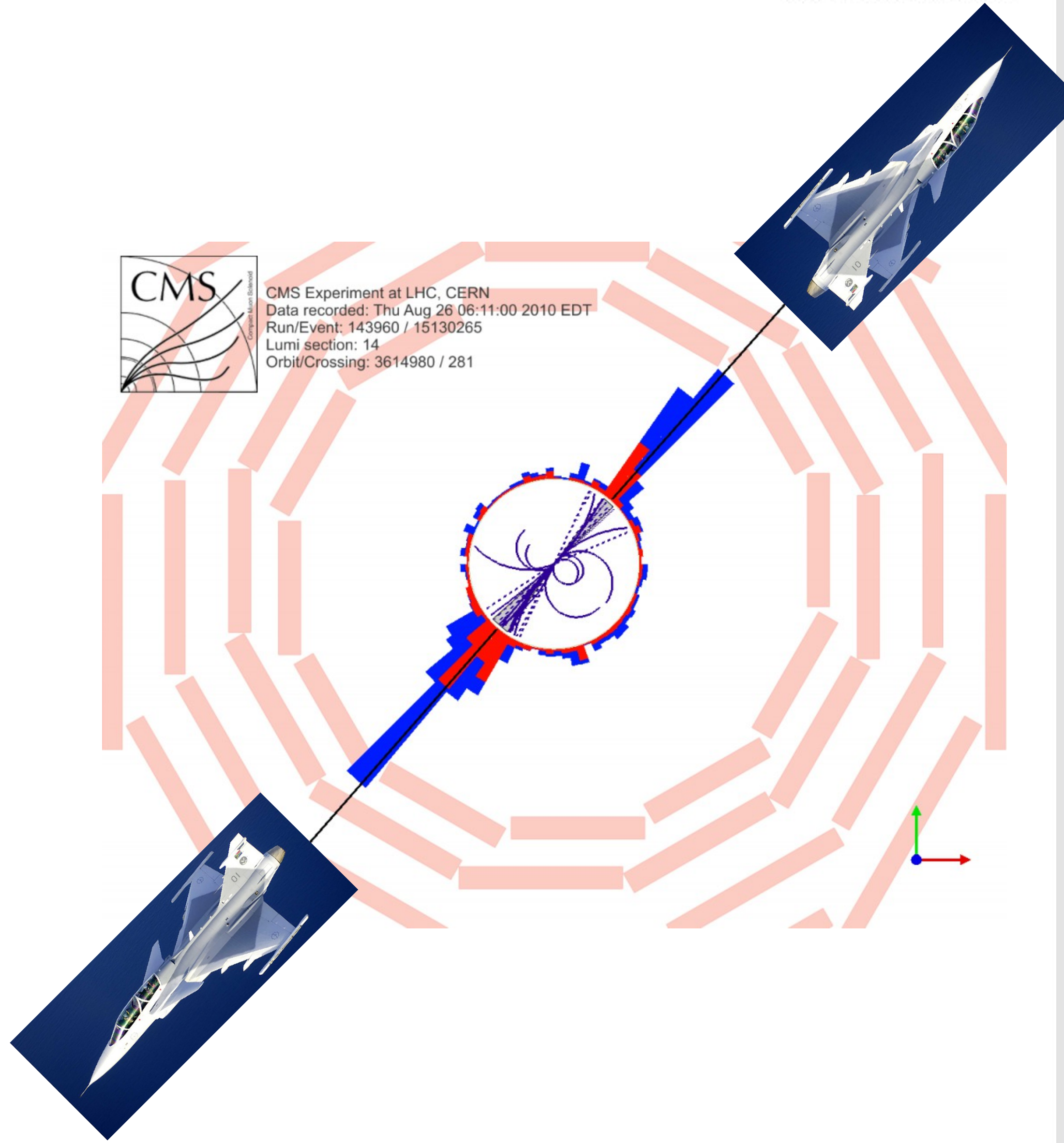
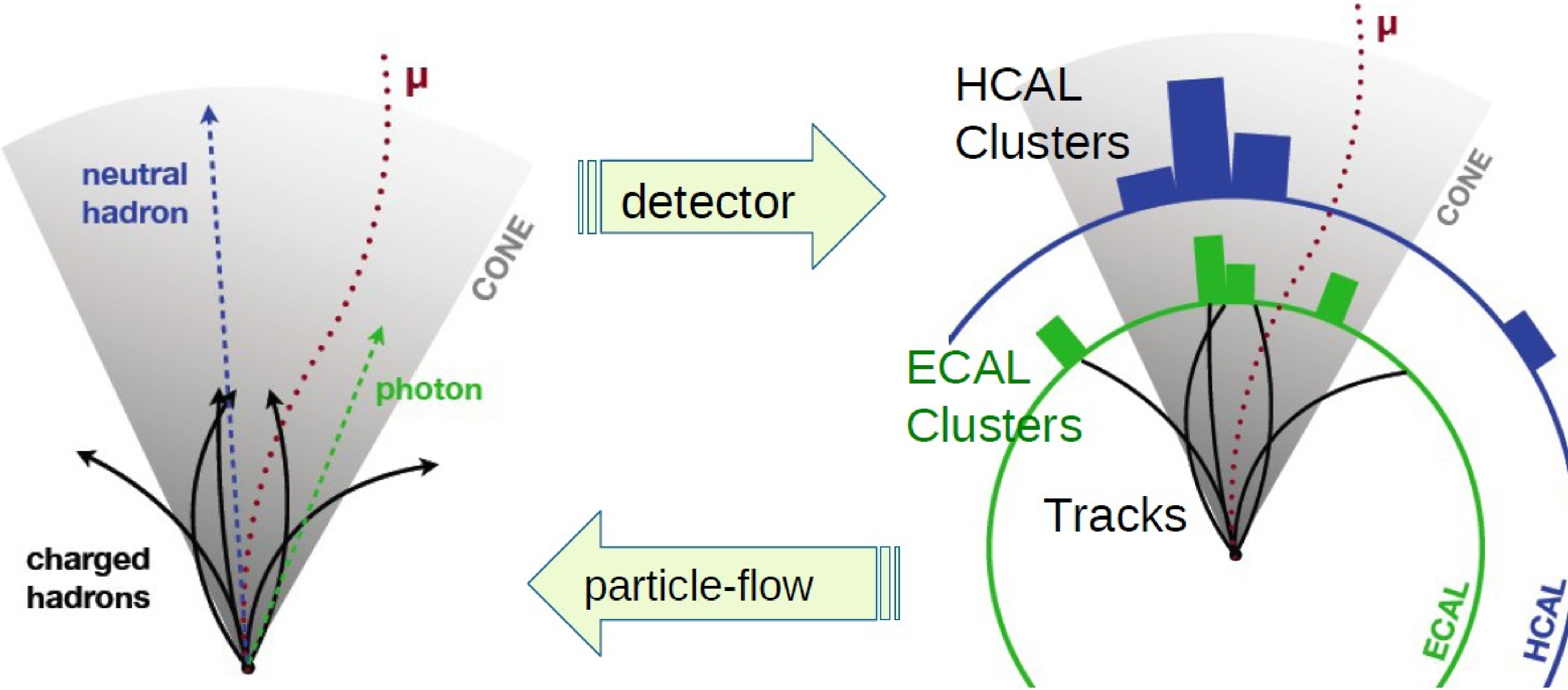


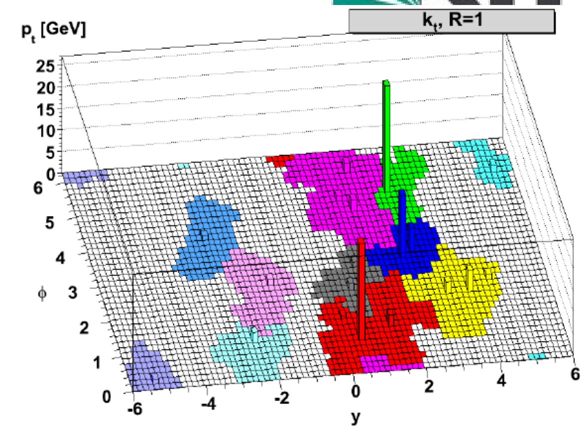
Particle Flow Concept



- Apply signal type-dependent corrections
- Disambiguation
- Particle type association

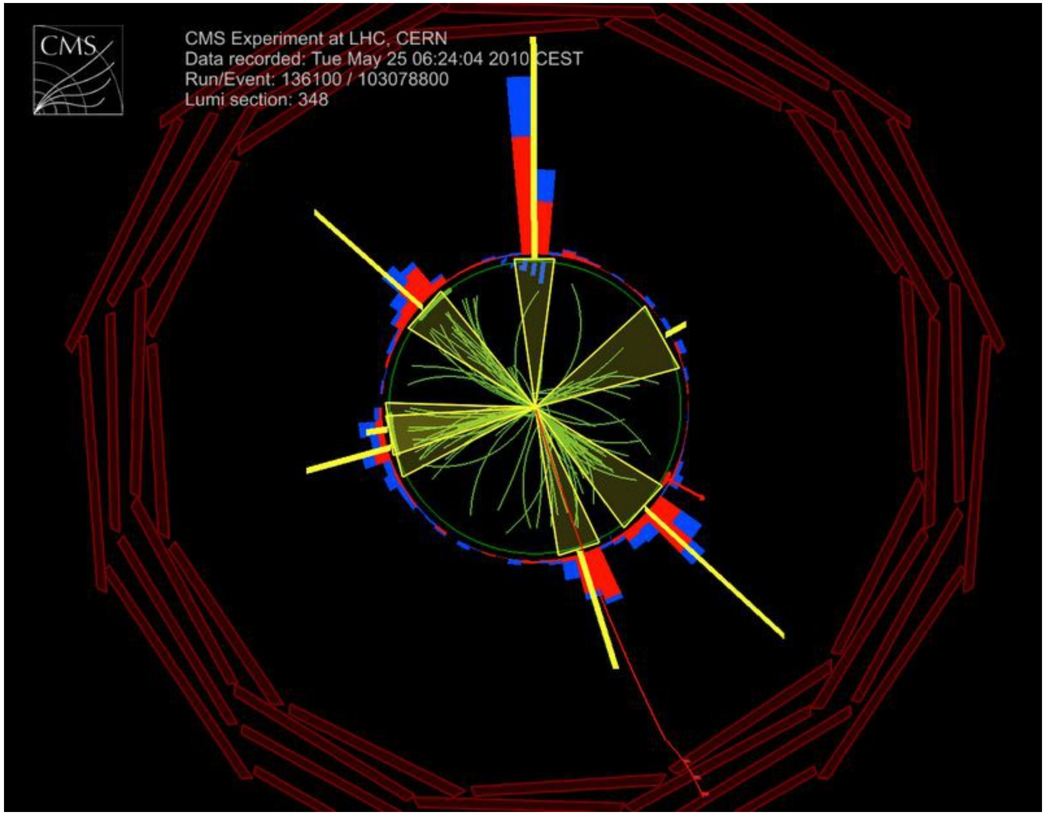
Jet Reconstruction

- Two major Jet Reconstruction Methods:
  - Calorimeter Jets (Calorimeter towers)
  - **Particle Flow Jets** (Particle Flow candidates)



- Two major Jet Algorithms
  - k_T (p = 2), irregularly shaped
  - **Anti-kT (p = -2)**, cone-shaped
  - Cluster input objects together according to:

$$d_{ij} = \min(\mathrm{k}_{\mathrm{Ti}}^{\mathrm{p}}, \mathrm{k}_{\mathrm{Tj}}^{\mathrm{p}}) \frac{(\Delta \mathrm{y}_{\mathrm{ij}})^2 + (\Delta \phi_{\mathrm{ij}})^2}{\mathrm{R}^2} \qquad \mathrm{d}_{\mathrm{iB}} = \mathrm{k}_{\mathrm{Ti}}^2$$



- Jet Energy corrections
  - Detector, reconstruction effects
  - Factorized correction
    - **L1**: Offset / Pile-up
    - **L2**: η dependence
    - **L3**: p_T dependence

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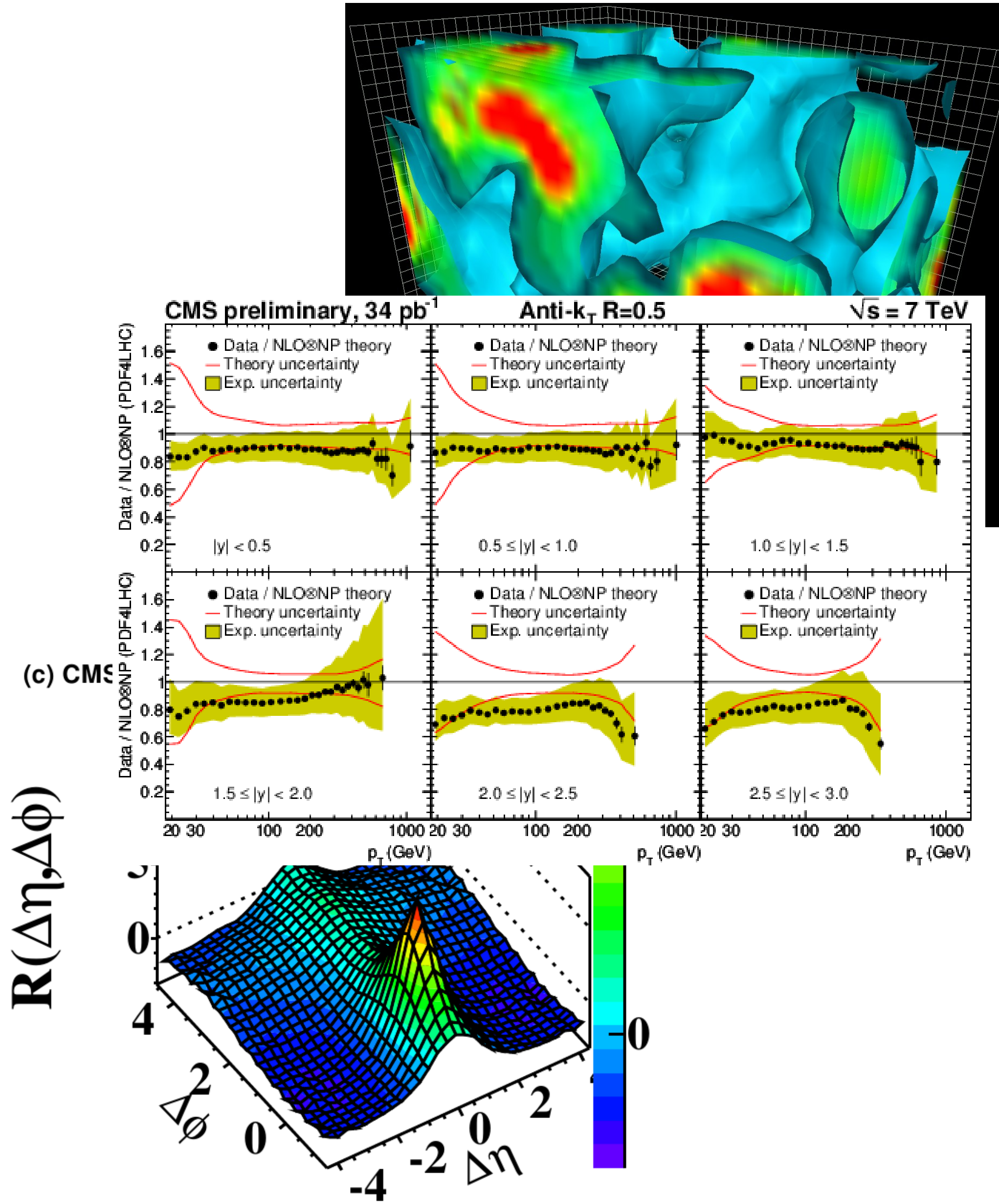
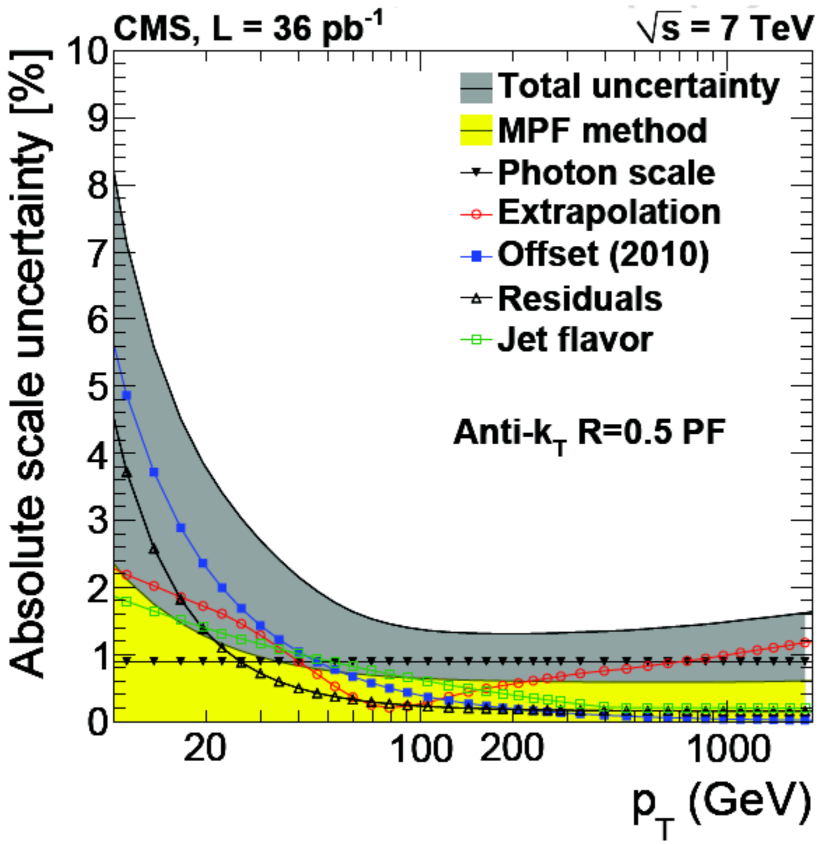
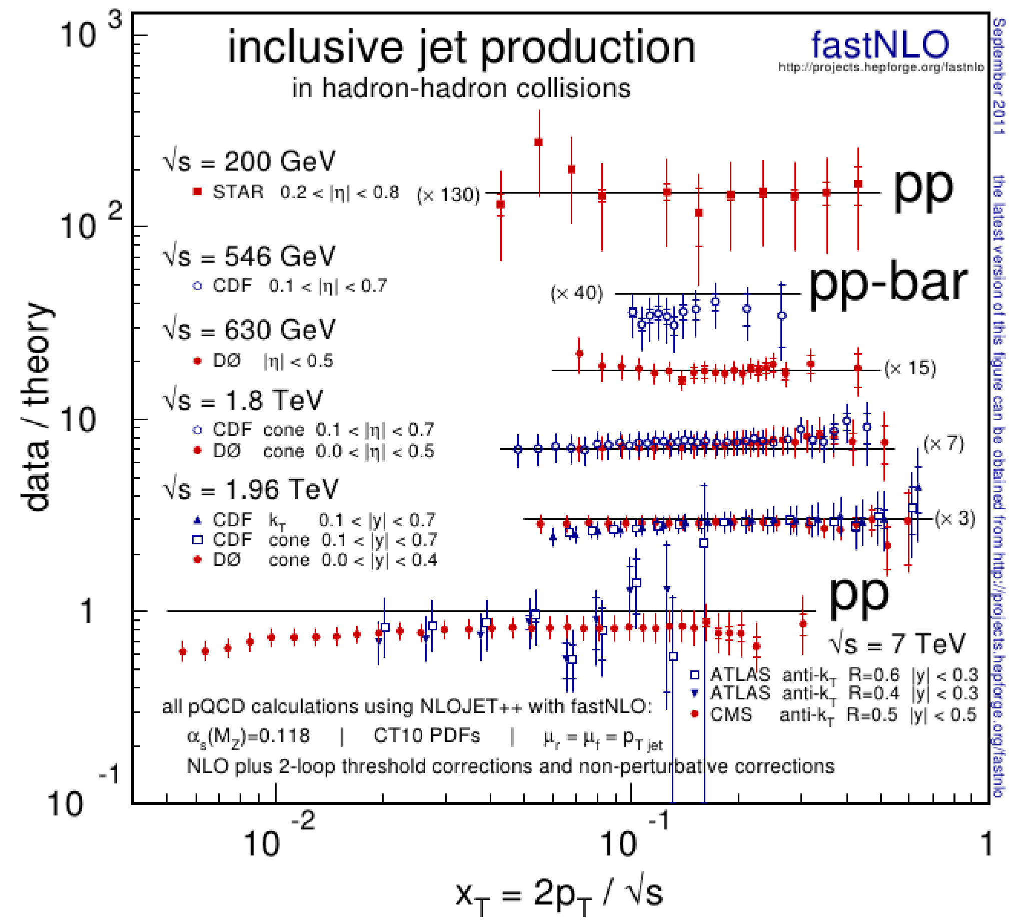


Recent QCD Results

- Outstanding detector performance – Uncertainties well understood
- **pQCD is very successful** in the description of observables such as inclusive and dijet cross sections





CMS: JME-10-011: Jet Energy Calibration and Transverse Momentum Resolution in CMS

arxiv: 1109.1310: Theory-Data Comparisons for Jet Measurements in Hadron-Induced Processes (M. Wobisch, D. Britzger, T. Kluge, K. Rabbertz, F. Stober)

Future QCD measurements: Three-Jet Observables

- Groundwork for looking at more complex observables
- Test pQCD at **higher orders** in α_s
  - ➡ Study events with higher jet multiplicities
  - Observables:
    - Invariant mass of the three-jet system [1]:

$$\frac{d^2\sigma}{dM_3 \; dy_{\max}} \qquad M_3 = \sqrt{(p_{j1} + p_{j2} + p_{j3})^2}$$

    - Differential three-jet rate [2]:

$$R_{32} = \frac{d\sigma_{j\geq 3}}{dX} \Big/ \frac{d\sigma_{j\geq 2}}{dX} \qquad X = p_{T12} = \langle p_{T1}, p_{T1} \rangle, X = H_T = \sum_{i=1}^{3} p_{Ti}$$

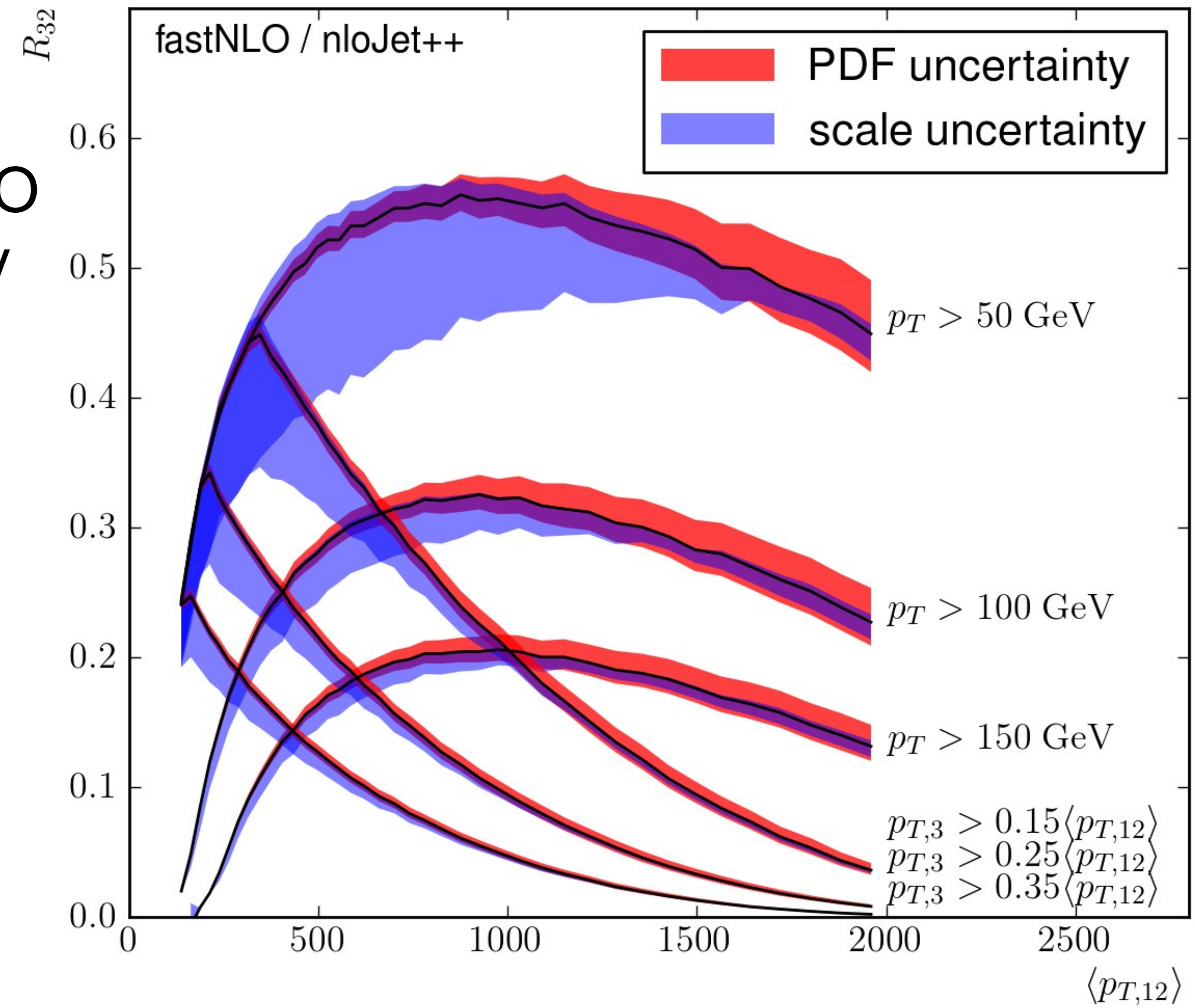
  - Study sensitivity of three-jet observables to PDF and α_s and select topologies where NLO calculation comparisons are less disturbed by theory uncertainties

1) arXiv:1104.1986 from D0:
Measurement of three-jet differential cross sections d sigma-3jet / d M-3jet
in p anti-p collisions at sqrt(s)=1.96 TeV

2) CMS QCD PAS 10-012

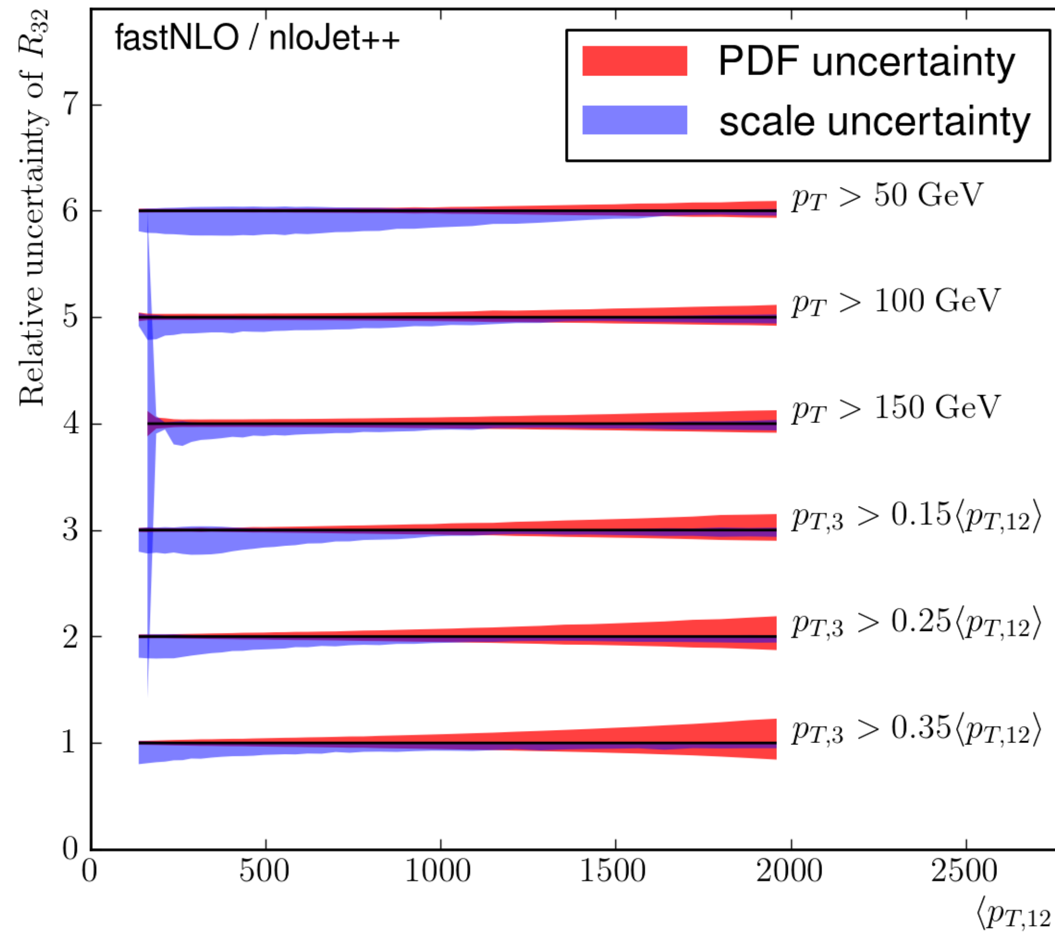
NLO calculations for three jet observables

- Measurement: $R_{32}(<p_{T1},p_{T2}>)$, $\sigma(M_3)$
- In order to perform an α_s measurement, precise NLO calculations are necessary
- 3 jet QCD calculations at NLO with NLOJet++ by Z.Nagy
- Reduce computational complexity by running NLOJet++ within the fastNLO framework



NLO calculations for three jet observables

- Search for an observable and event selection with a high sensitivity to α_s needs well understood theory uncertainties
  - PDF uncertainties
  - Scale uncertainties (6-point)
    - Factorization scale ½, 1, 2
    - Renormalization scale ½, 1, 2



- Current set of cuts: Trade-off between PDF and scale uncertainties

- Aim: Common three-jet selection criteria

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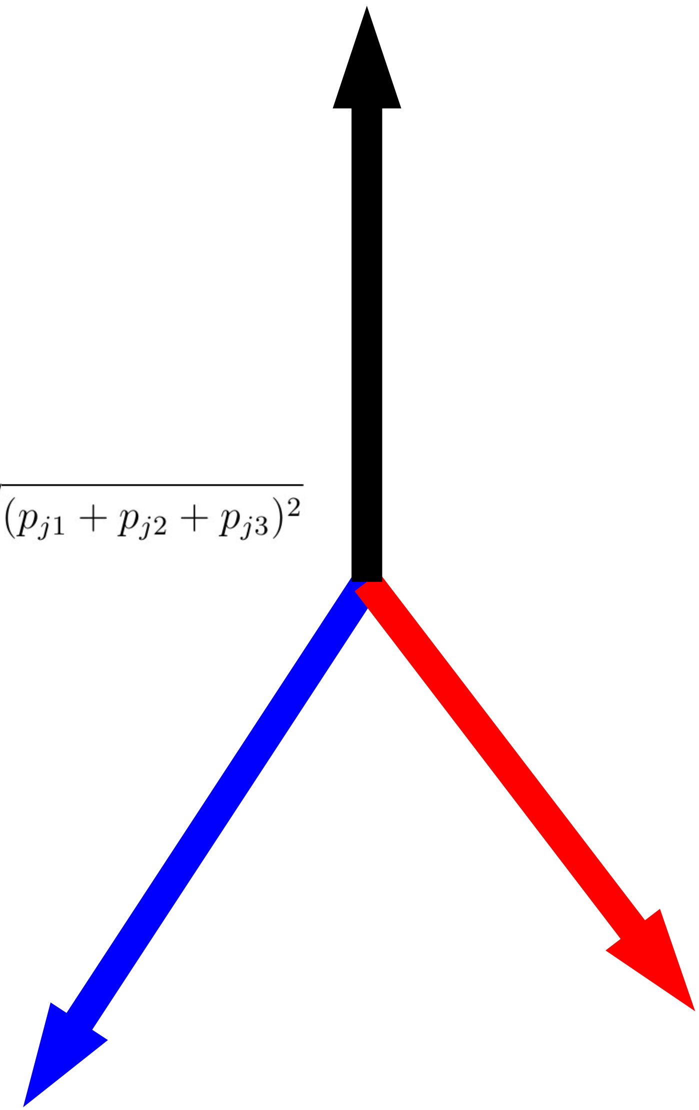
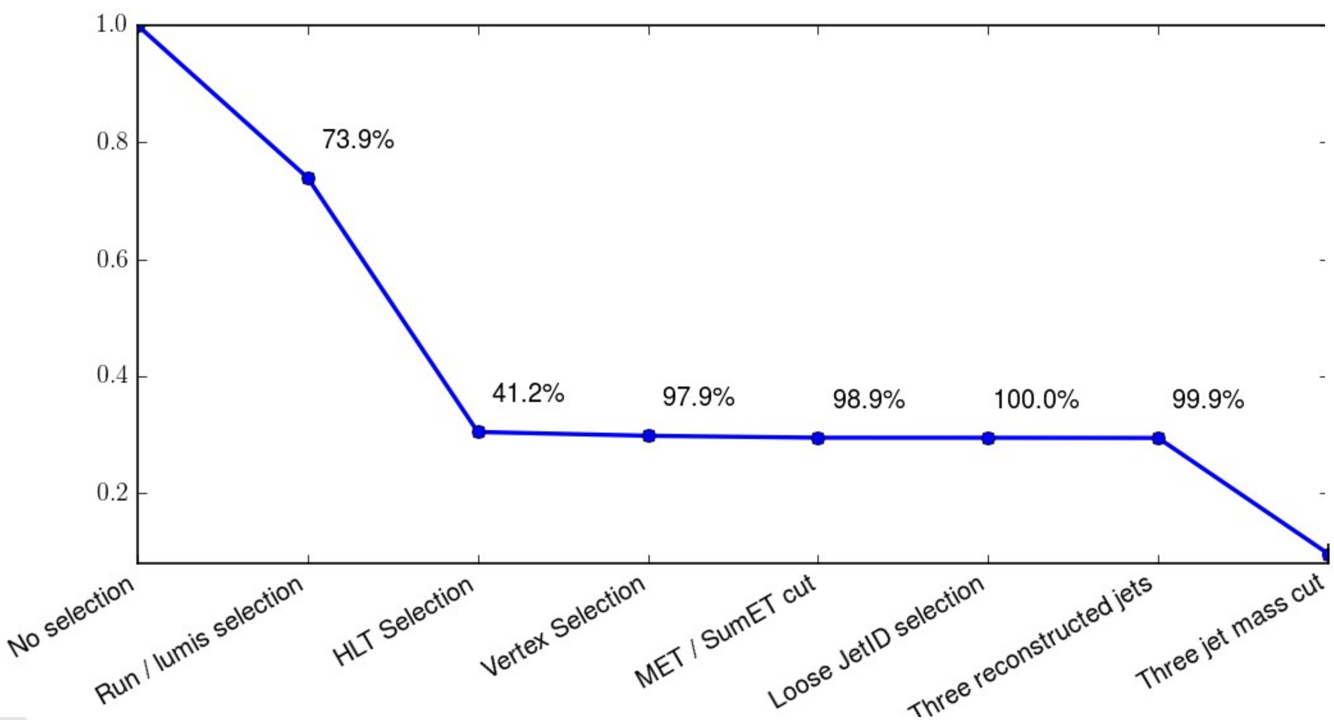
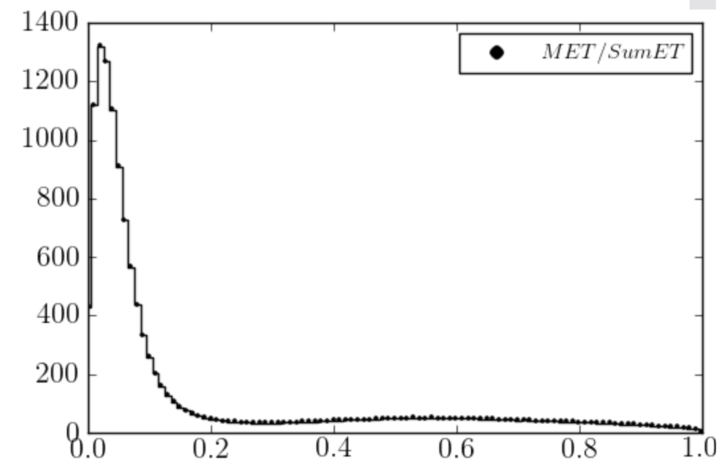
$$M_3 = \sqrt{(p_{j1} + p_{j2} + p_{j3})^2}$$



Overview of cuts

- Standard vertex selection cuts (|z| < 24cm, NDOF > 4, ρ < 2cm)
- Applying a MET / SumET < 0.5 cut
- Loose PF jet id is applied
- Three jet hardness cut:
  - Hard jet p_{T3} > 50 GeV and jet p_{T3} / jet p_{T1} > 0.25





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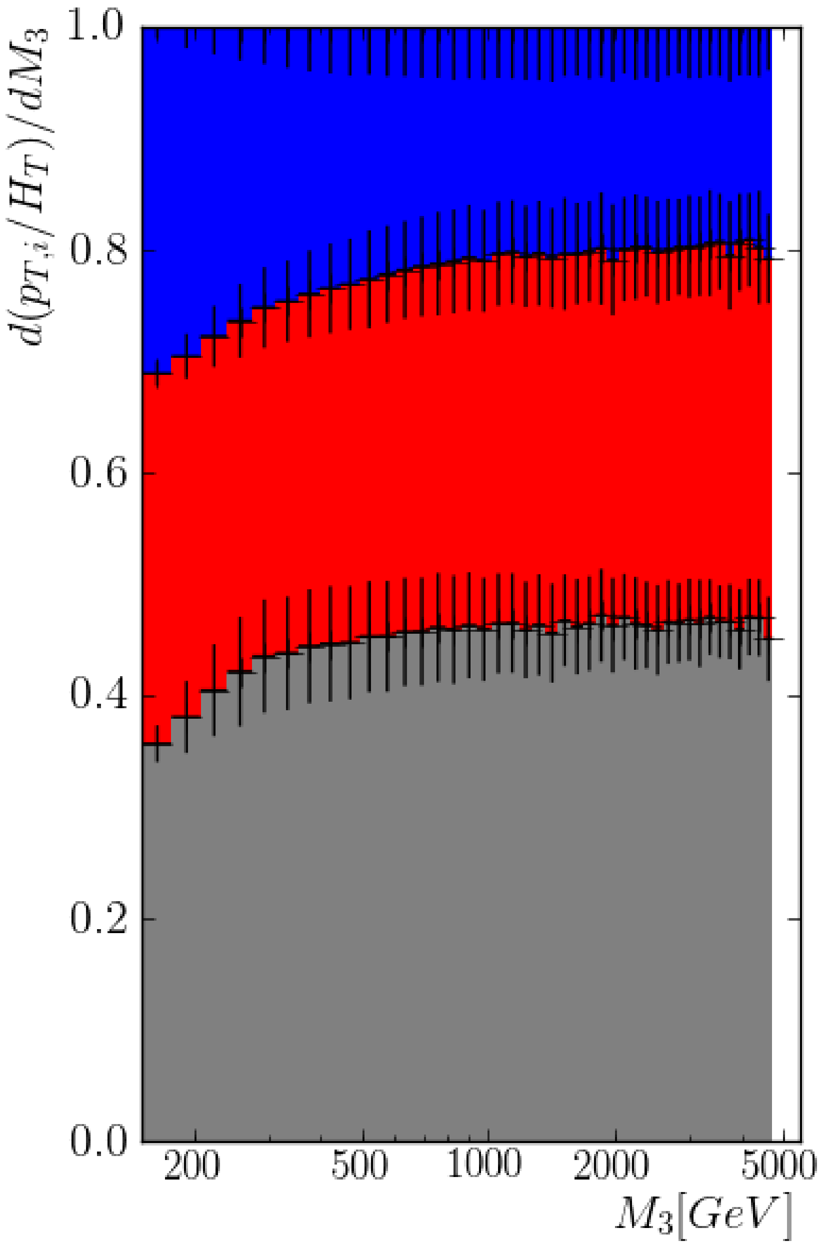
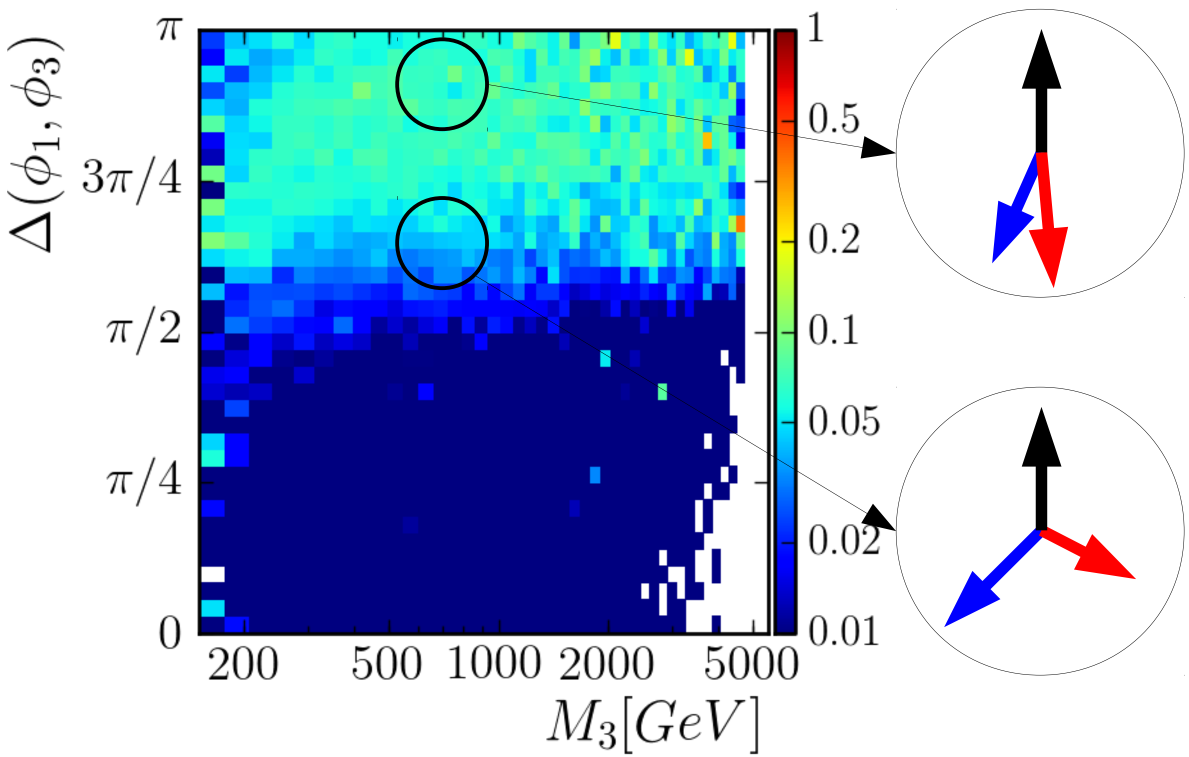
Kinematic properties of the selected events





- The leading jet carries ~45% of H_T, while the 2nd and 3rd jet contribute 35% and 20% respectively
- Typically, 3rd jet has a large separation from the leading jet
(not necessarily mercedes star configuration)

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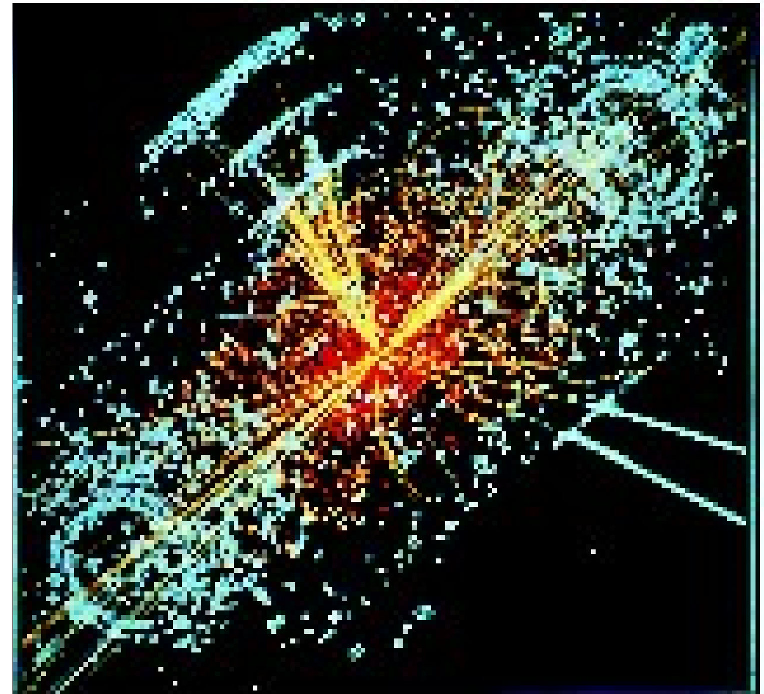
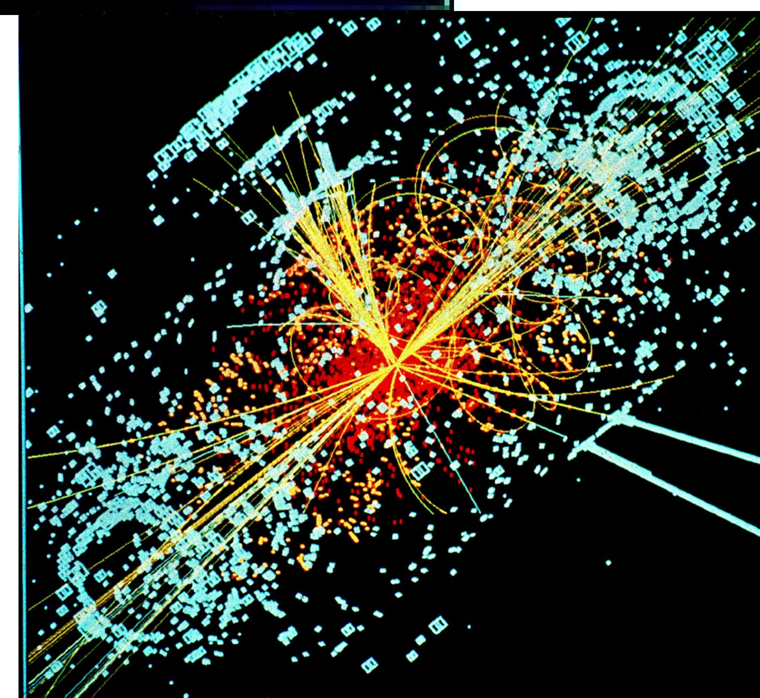
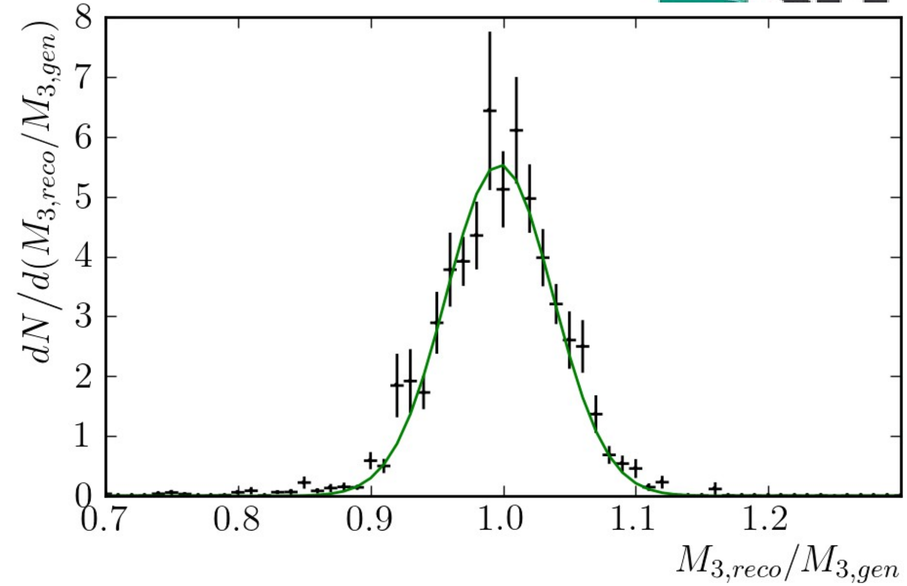
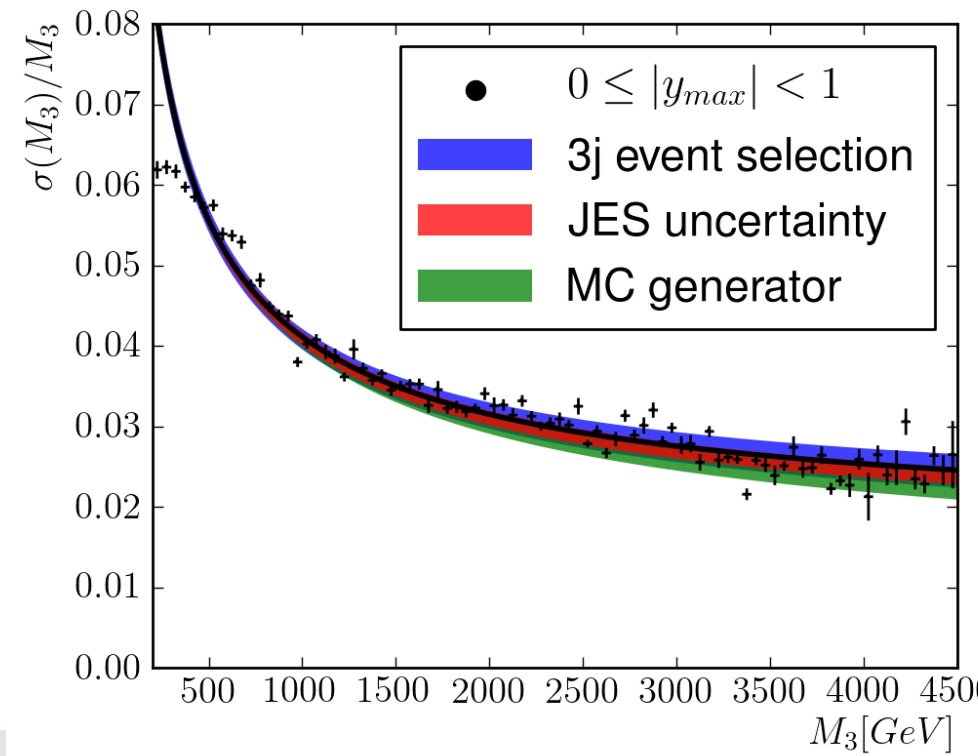




Three-jet Mass Resolution

- Binning of M_3 is based on the Three-jet Mass resolution
- Resolution taken from Gaussian fits of the Three-jet Mass response
  - Small systematic uncertainties due to event selection, used generator and jet energy scale
- The bin width is chosen as two times the resolution
  - A measurement with true value in the bin center is smeared to 68% within the bin





Unfolding – Principle

Measured distributions are distorted by **finite resolution**, limited acceptance and other reasons and therefore do not agree with the true distributions.

Background / Noise

Measured distribution

$$\int_\Omega A(y,x) f(x) dx + b(y) = g(y)$$

Response

True distribution

The goal of unfolding is to find an operator which, applied to the measured distribution, gives the true distribution.

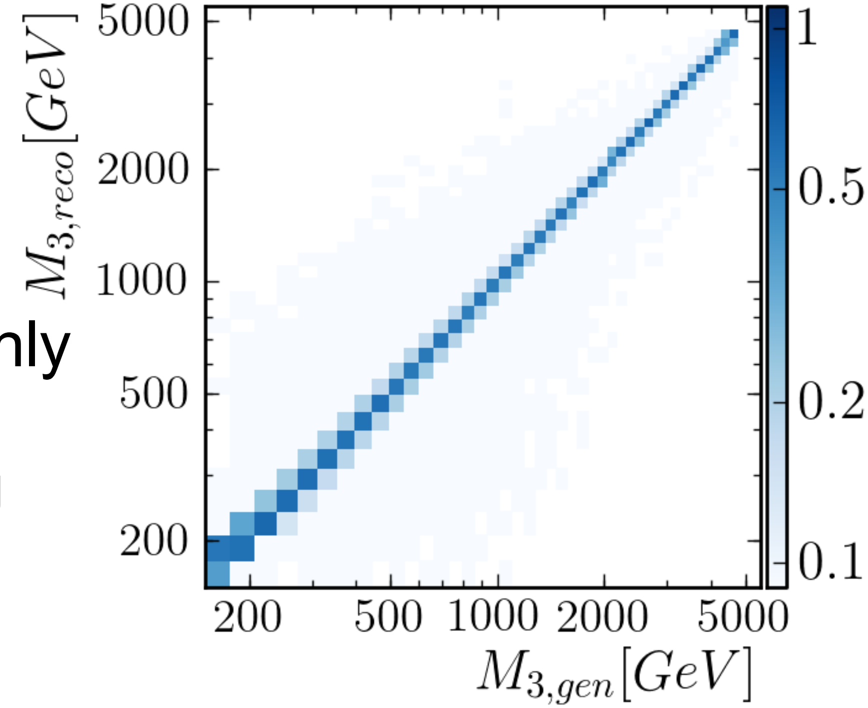
Discretization + Linearization

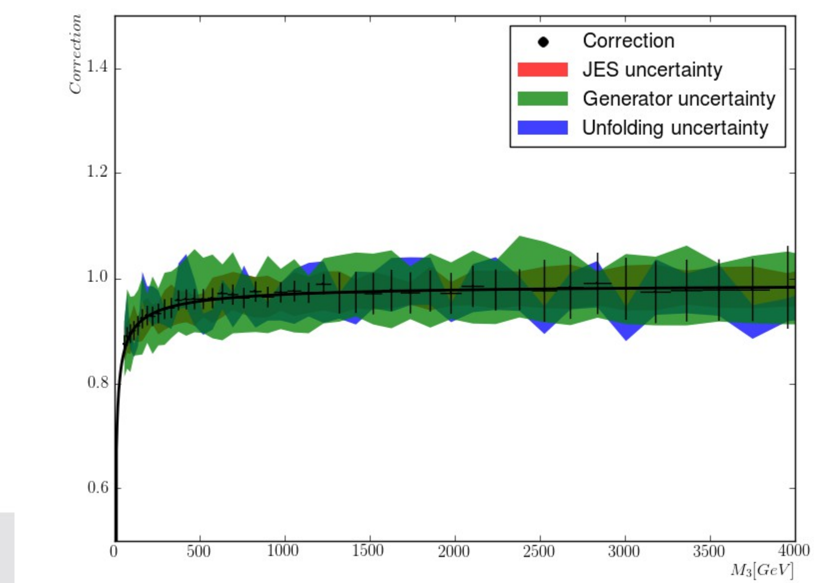
$$A \cdot \vec{v} + \vec{b} = \vec{w}$$

One method to solve this problem is the **Bayesian unfolding**, which uses an iterative approach to converge to the result

Unfolding – Detector Response

- The response matrix is in a very good approximation diagonal with just one off-diagonal element on both sides
- With the calculated binning, there is only a small amount of bin-to-bin migration present, which can be corrected using conventional unfolding methods
- Bayesian unfolding with 5 iterations is applied to the measurement (using the RooUnfold package)
- Both matrix and input histograms are varied in an ensemble test to infer the unfolding error





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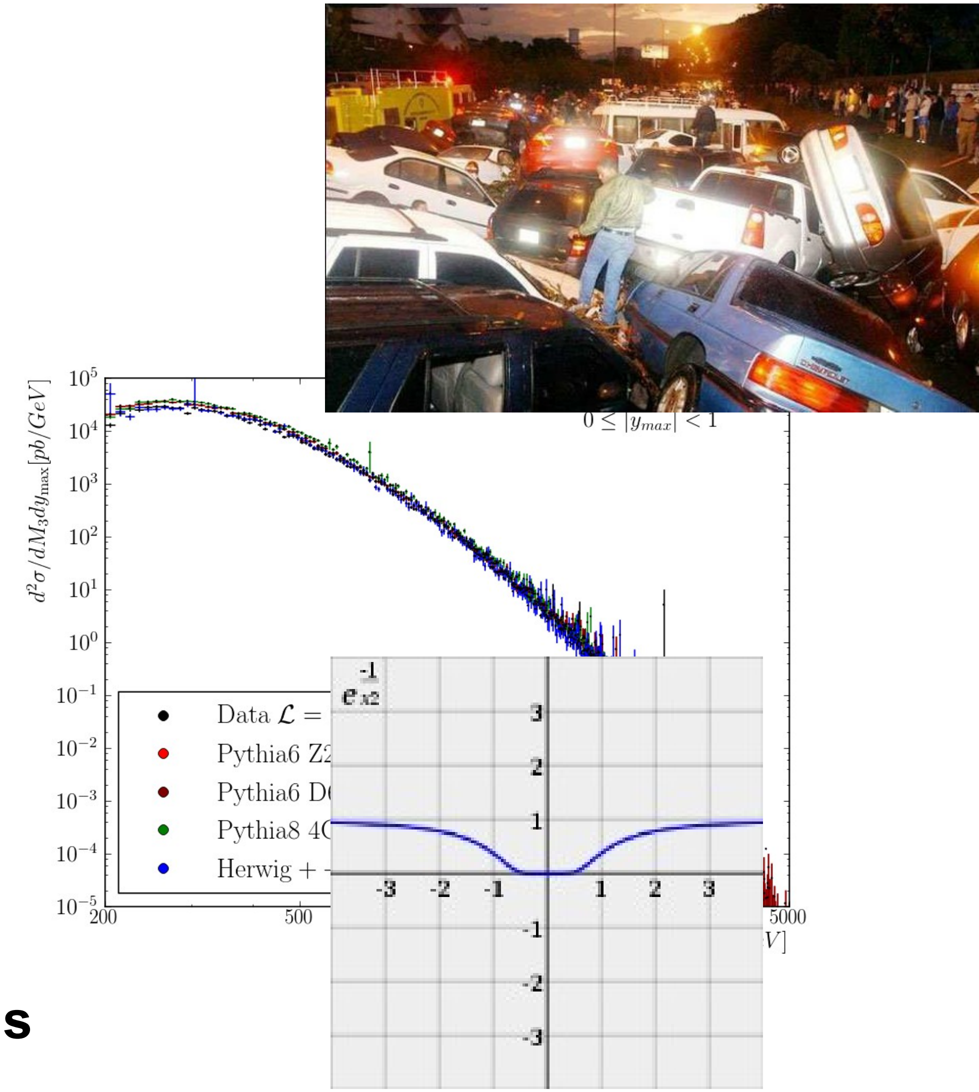
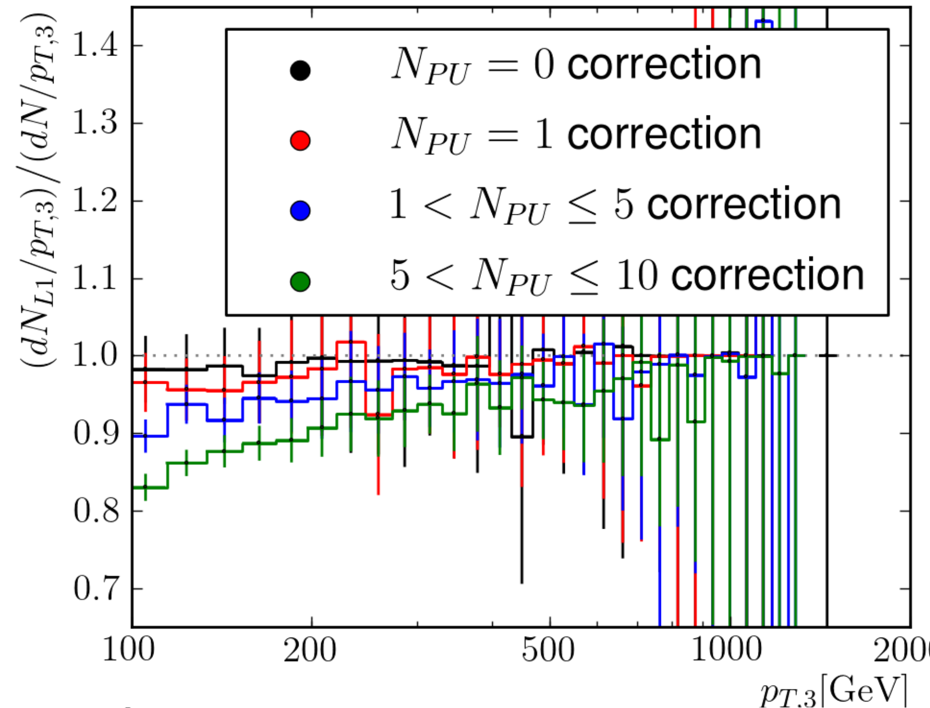
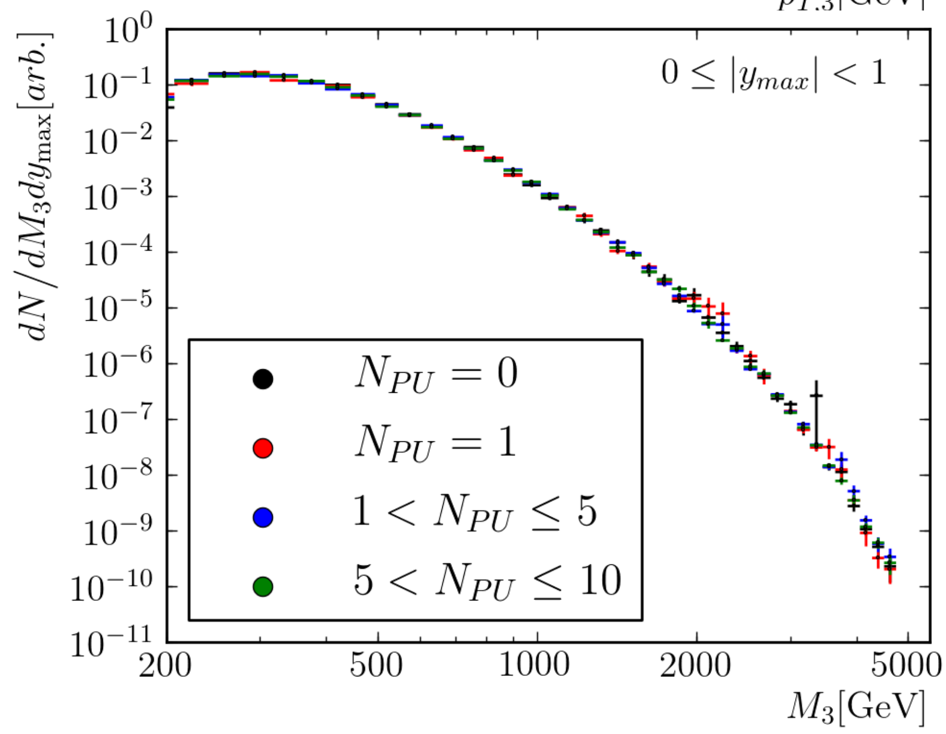


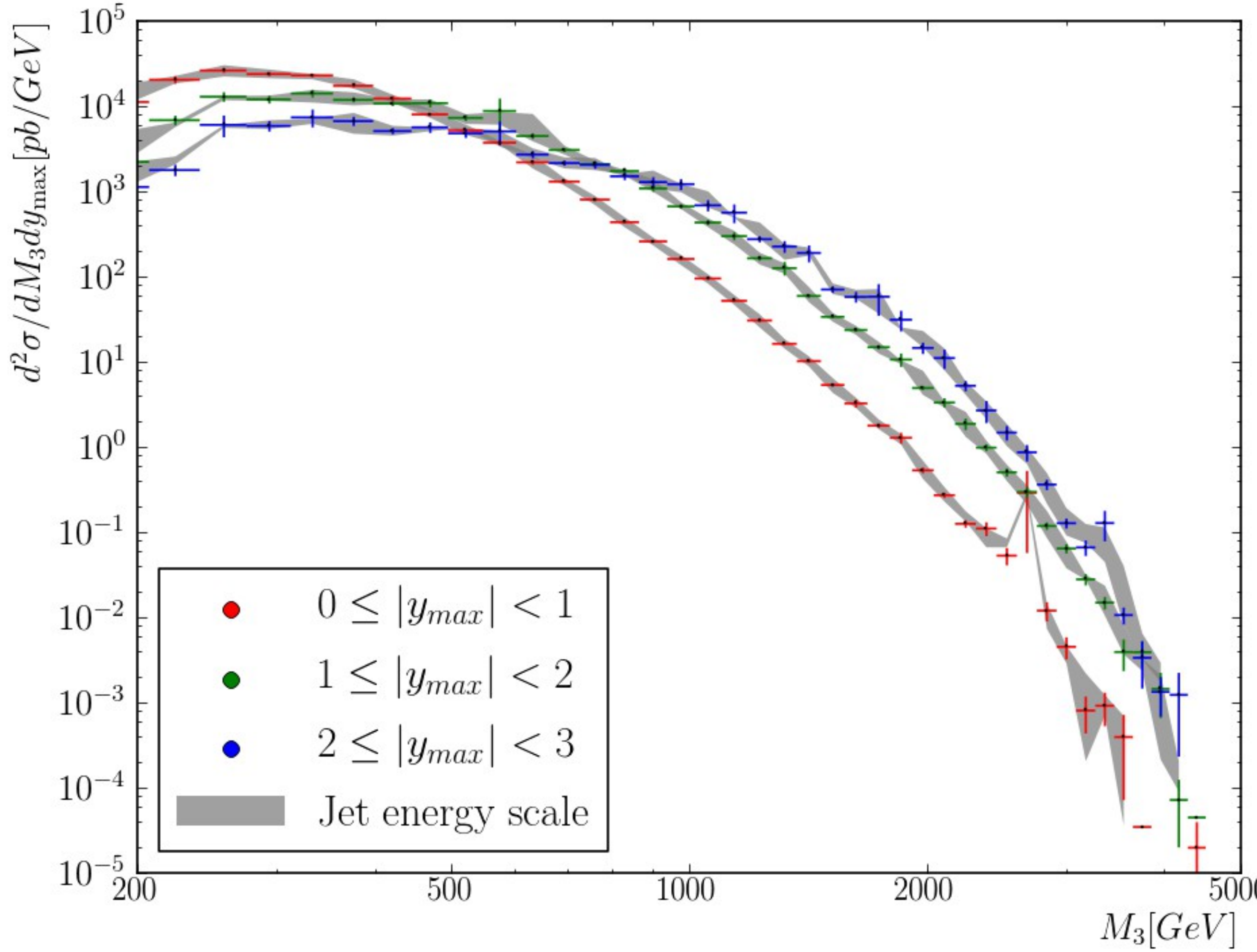
Effect of pile-up on the three-jet mass

- Pile-up jet correction (L1)
  - based on the median jet energy per jet area of the event
  - removes pile-up contributions to the jet energy
- The relative impact of the L1 Fastjet correction on the very sensitive 3rd jet
- Influence can be quite large for the currently used set of cuts
- After applied L1 correction, the shape of the three-jet mass for low amounts of pile-up is consistent with the 0 pile-up distribution



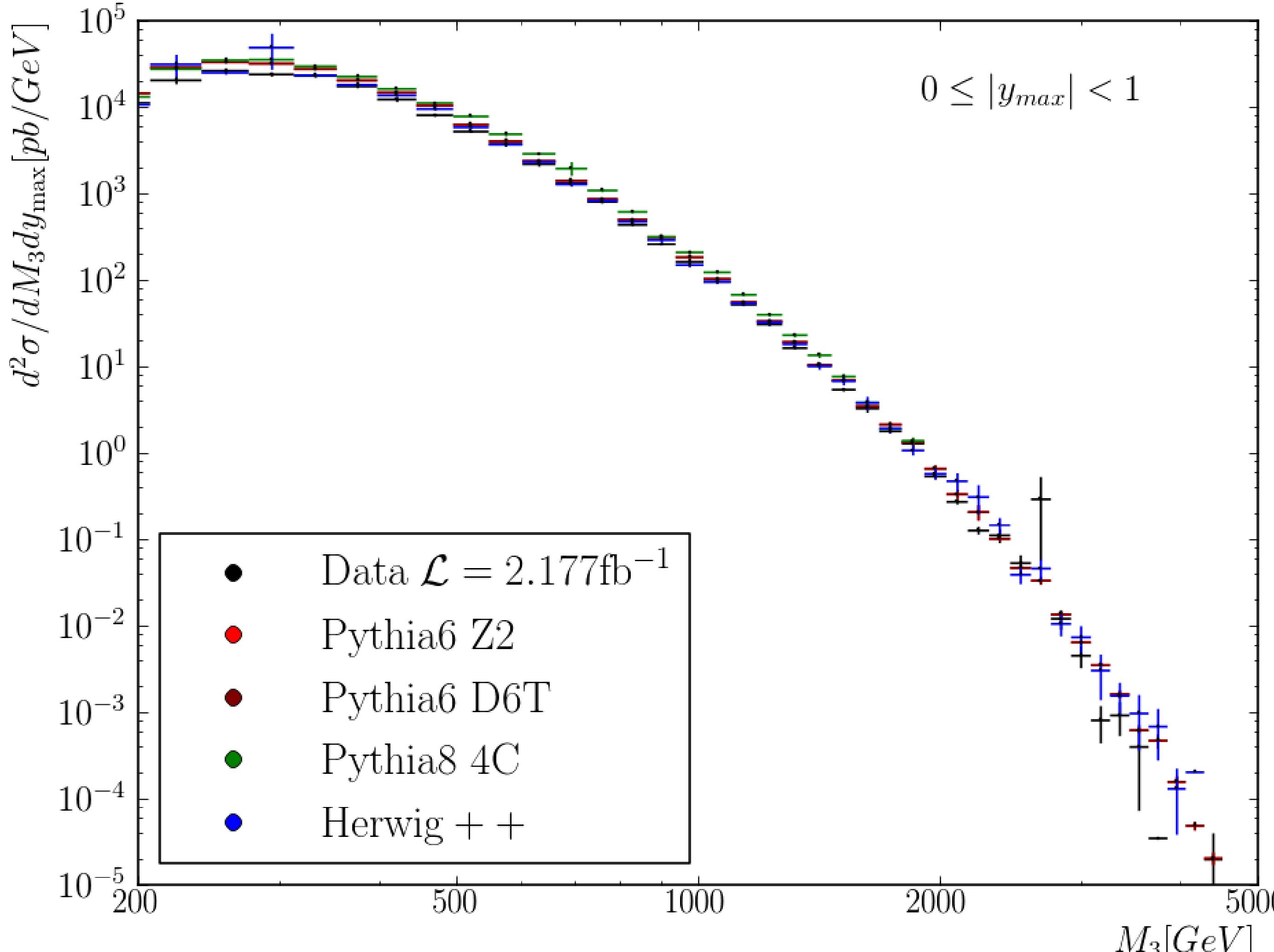


Three jet mass distribution



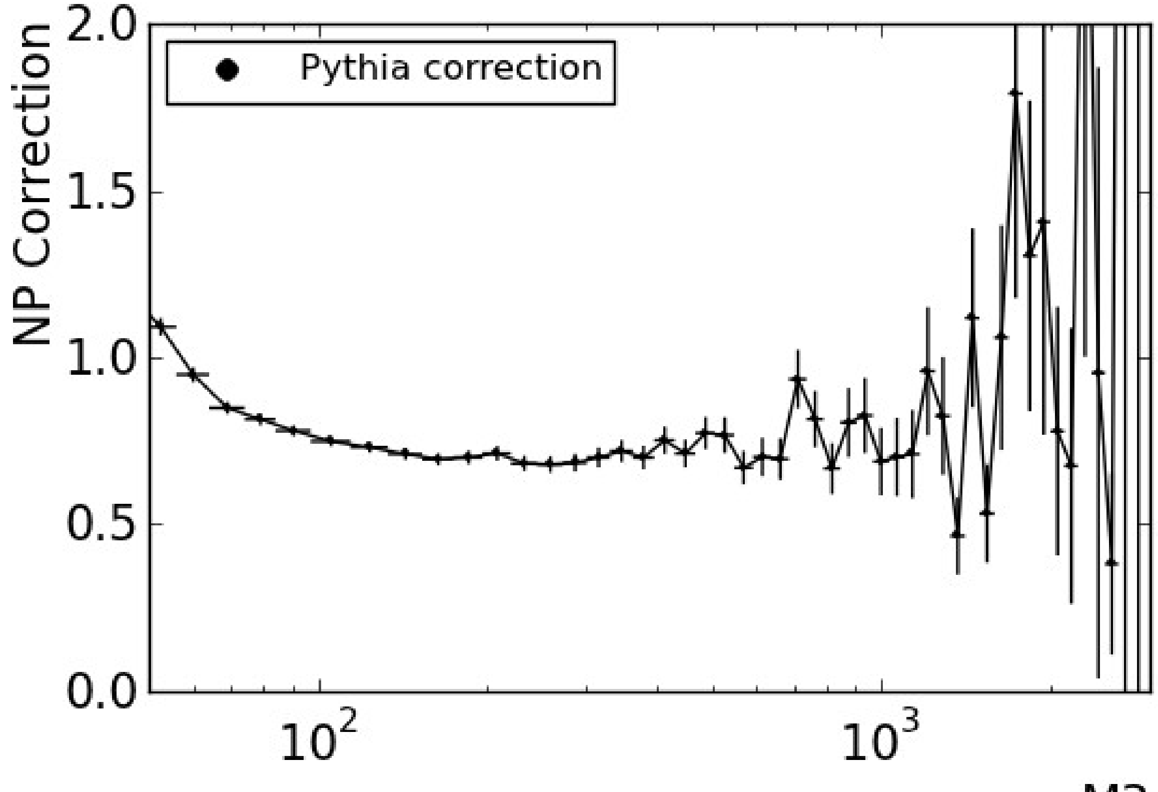
- Since the current dataset also encompasses "Prompt-Reconstruction" data, there are some runs which cause extreme outliers. The imperfect reconstruction is especially noticeable in the high rapidity region, where trigger rates are lower.

Three jet mass distribution



- Quick comparison with the LO generators Herwig++ and Pythia shows that the three jet mass spectrum is quite well described over several orders of magnitude

Non-perturbative corrections



- In order to compare data with NLO calculations, it is necessary to include non-perturbative corrections to include eg. hadronization effects on the theory side.
- NP correction is determined from the ratio of a MC generator prediction with Hadronization and UE simulation switched on/off.
- Pythia ≠ LO for M_3 → Factorize influence of hard ME with MG sample

Conclusion & Outlook

- Presentation of a three-jet mass measurement

✔ Trigger study

✔ Event selection

✔ Three-jet mass resolution
  - ✔ Binning

✔ Study of pile-up effects

✔ Three-jet mass response

✔ Unfolding
  - ✔ Bayesian method

➢ Further systematic uncertainties
  - ➢ JES, JER

✗ Non-perturbative corrections
  - ✗ Herwig++/Pythia

✗ Comparison with NLO calculation

✗ **Fit of α_s**

✗ (Improvement of event selection)

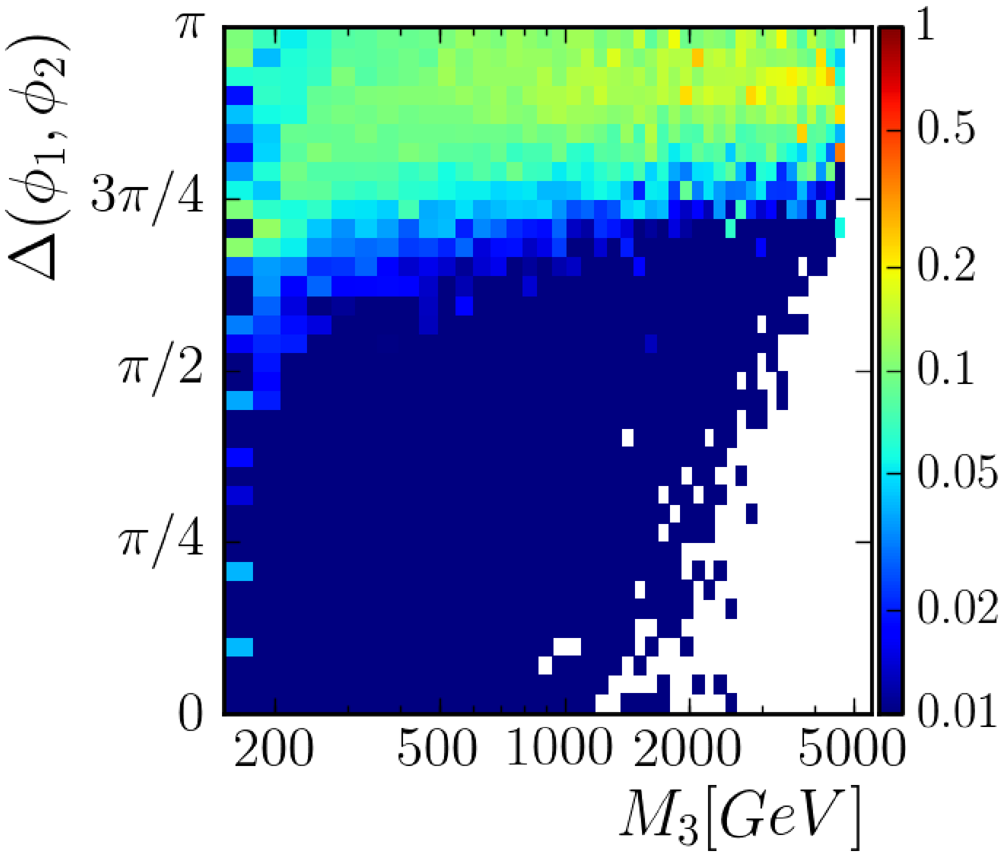
- Goal: Fit NLO predictions to data and measure α_s

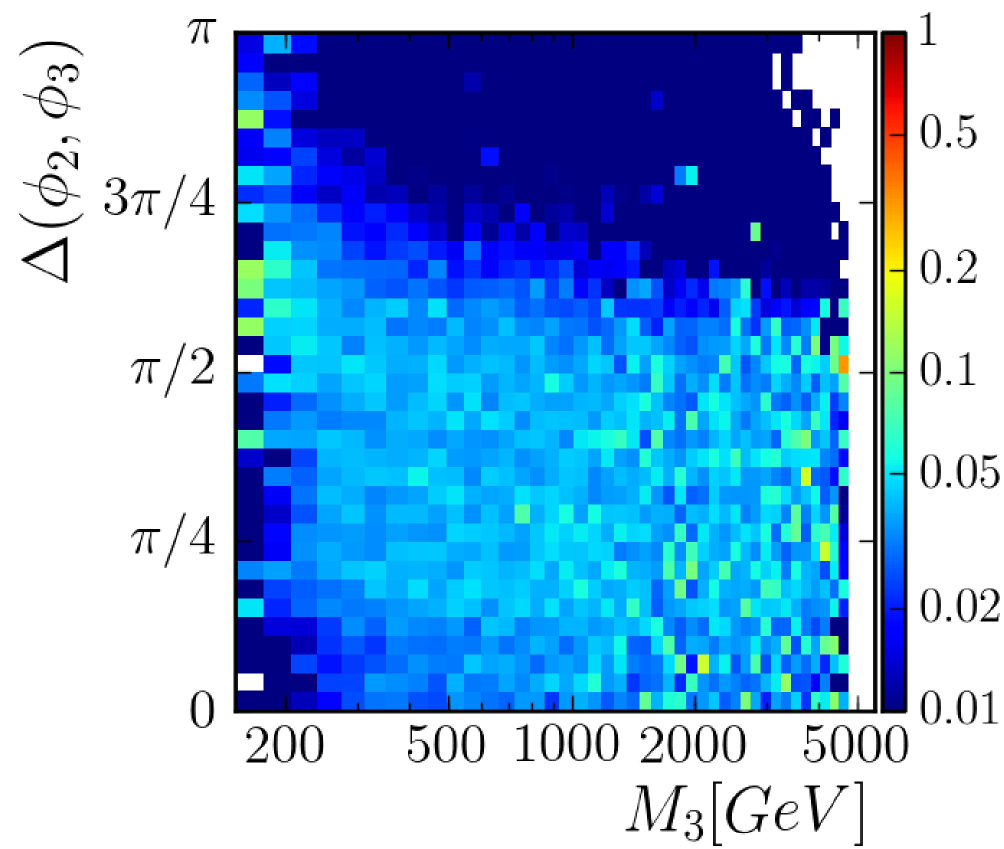
Backup

Technical Details

- Primary Datasets: (2176.7 / pb)
  - /Jet/Run2011A-May10ReReco-v1/AOD (160431 – 163869) 215.2 / pb
  - /Jet/Run2011A-PromptReco-v4/AOD (165088 – 167913) 930.2 / pb
  - /Jet/Run2011A-05Aug2011-v1/AOD (170722 – 172619) 370.8 / pb
  - /Jet/Run2011A-PromptReco-v6/AOD (172620 – 173692) 660.5 / pb
  - /Jet/Run2011B-PromptReco-v1/AOD (175860 – 177053) 735.2 / pb
- Monte Carlo:
  - /QCD_Pt-*_TuneZ2_7TeV_pythia6/Summer11-PU_S3_START42_V11-v1/AODSIM
  - /QCD_Pt-*_TuneD6T_7TeV-pythia6/Summer11-PU_S3_START42_V11-v1/AODSIM
  - /QCD_Pt-*_Tune4C_7TeV_pythia8/Summer11-PU_S3_START42_V11-v2/AODSIM
  - /QCD_Pt-*_Tune23_Flat_7TeV_herwigpp/Summer11-PU_S3_START42_V11-v2/AODSIM
- Anti-kT 0.5 ParticleFlow Jets reconstruction
  - GR_R_42_V19 L1FastJet, L2, L3, (Residual) corrections

Kinematic properties of the selected events

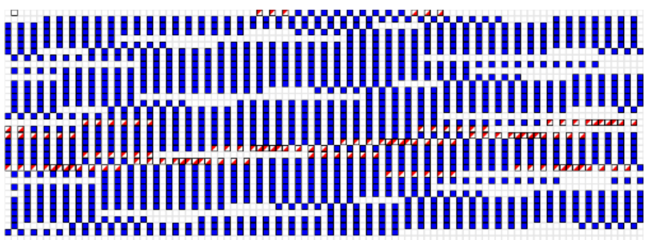




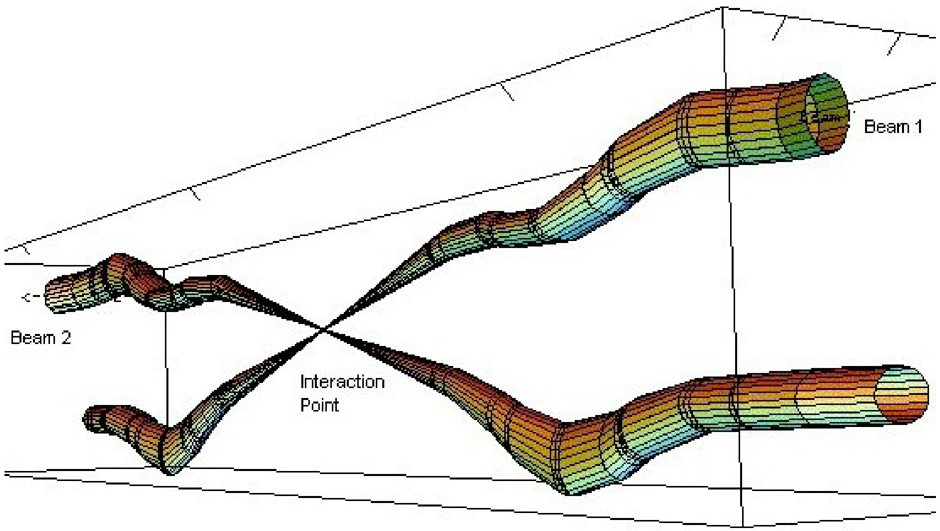
LHC parameters

- 1318 / 1380 bunches (design: 2808)
  50ns separation (design: 25ns)

  Currently doing 25ns tests

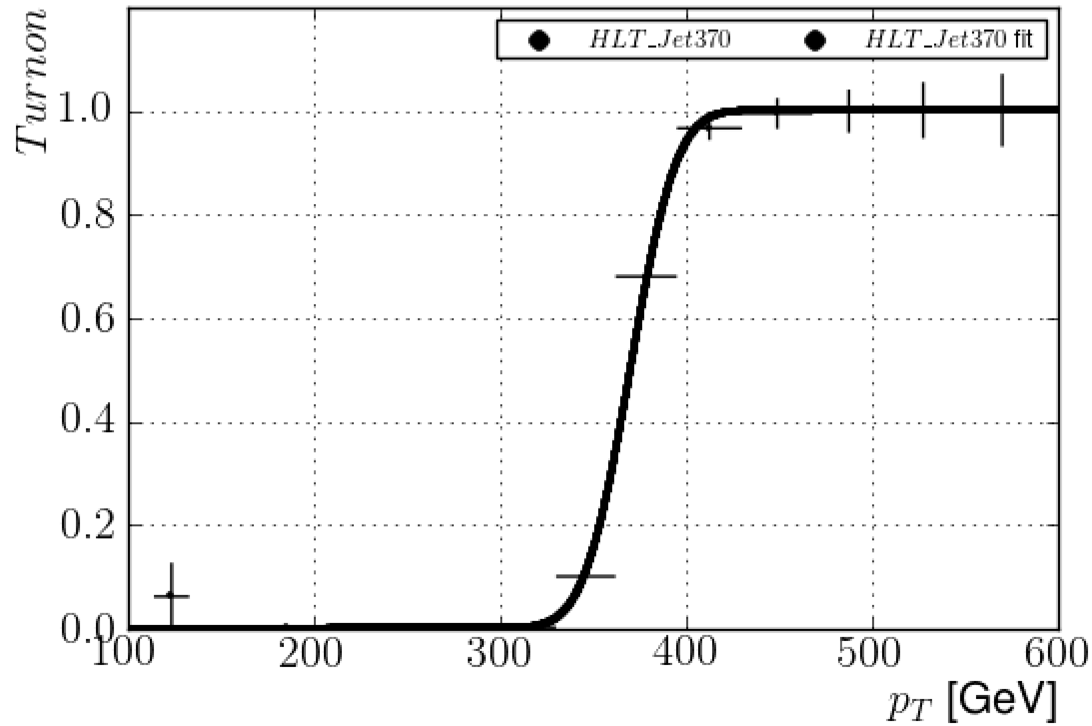


- Crossing angle: 120 μrad
- Major improvement since the last technical stop:
  β^* = 1.5 → 1m (design: 0.55m)
- Increasing number of pile-up



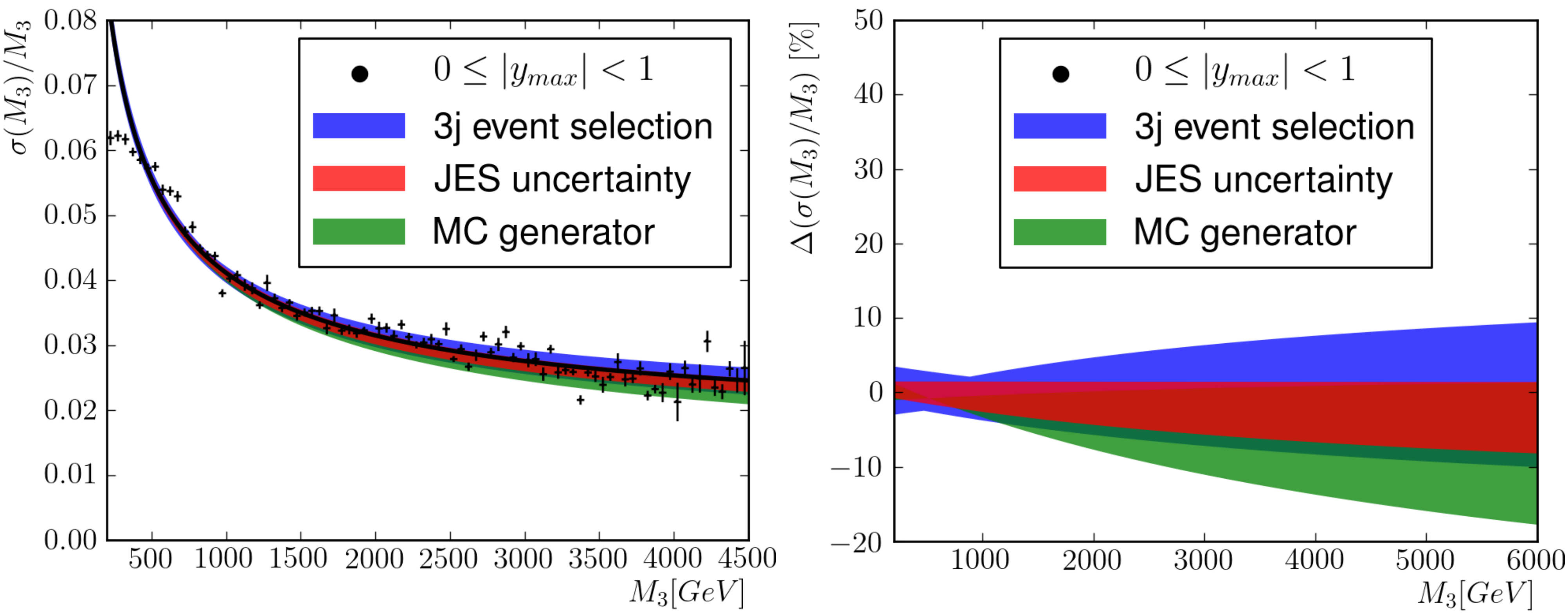
Trigger

Path	p_T Turn-on
HLT_Jet370	491 GeV
HLT_Jet240	357 GeV
HLT_Jet190	294 GeV
HLT_Jet110	193 GeV
HLT_Jet60	110 GeV

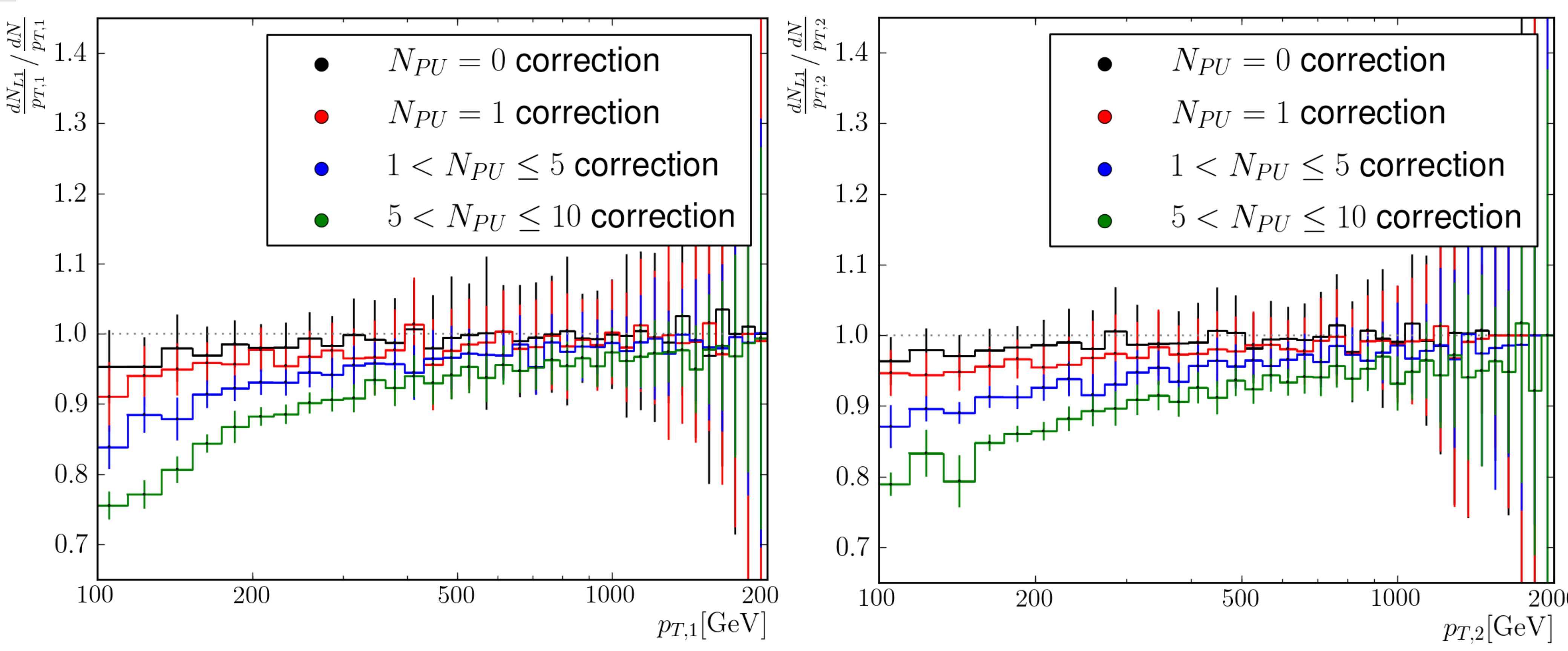


- Based on single jet triggers at the moment
- Turnon point determined by looking at the L1 and HLT objects for a certain trigger and searching for the subset of events fullfilling the next-highest trigger condition
- Ignores the prescale differences between triggers

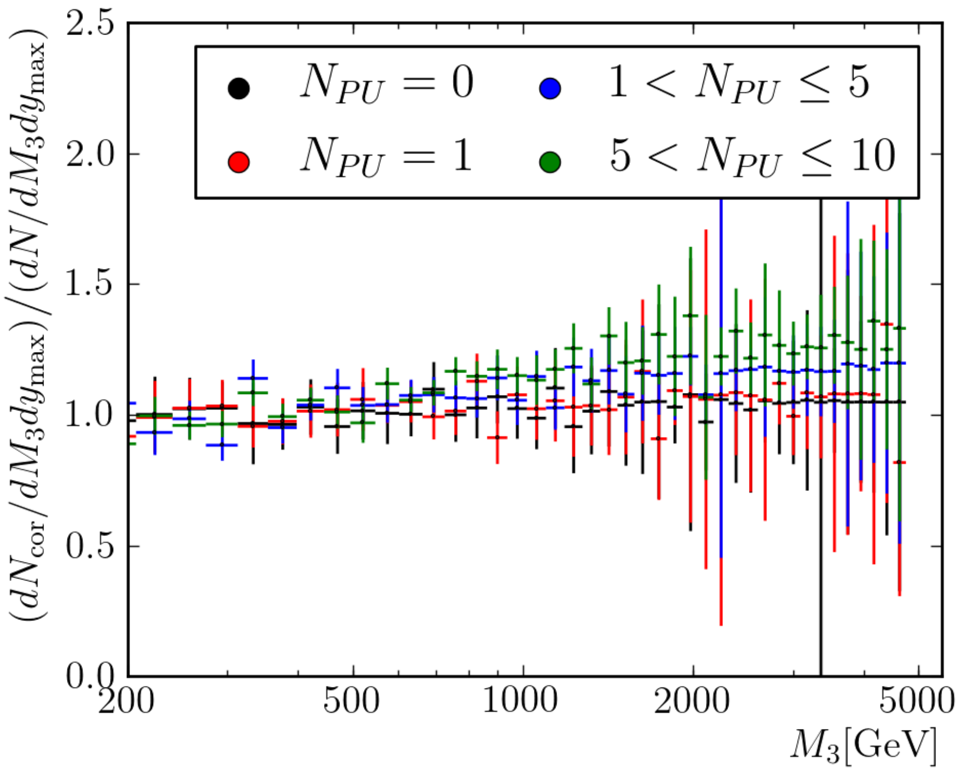
Three-jet mass resolution

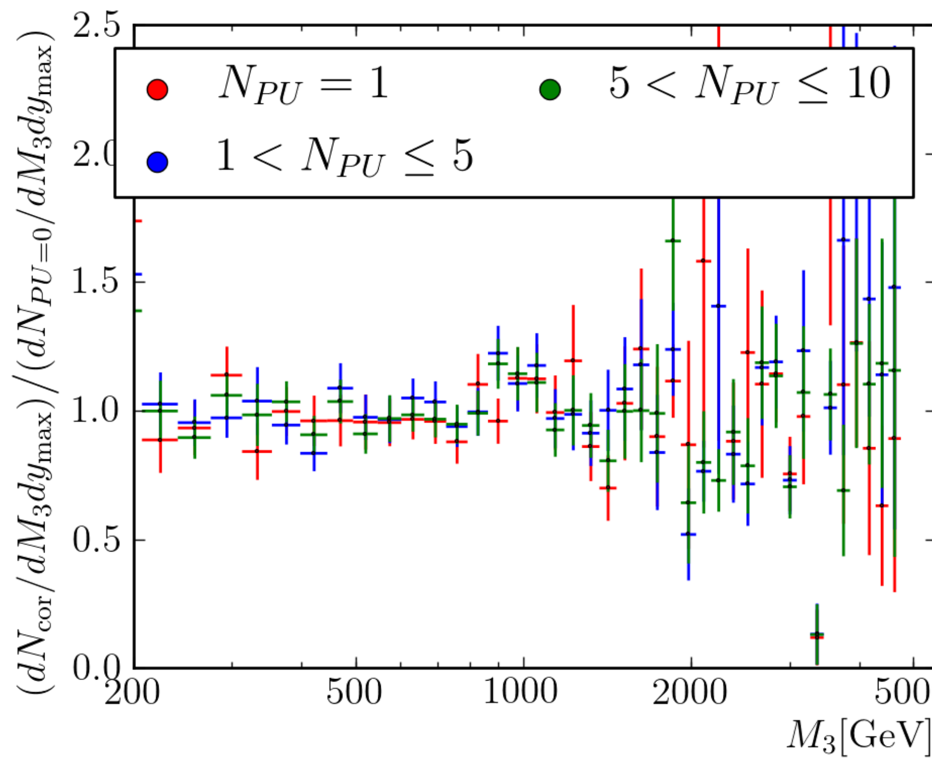


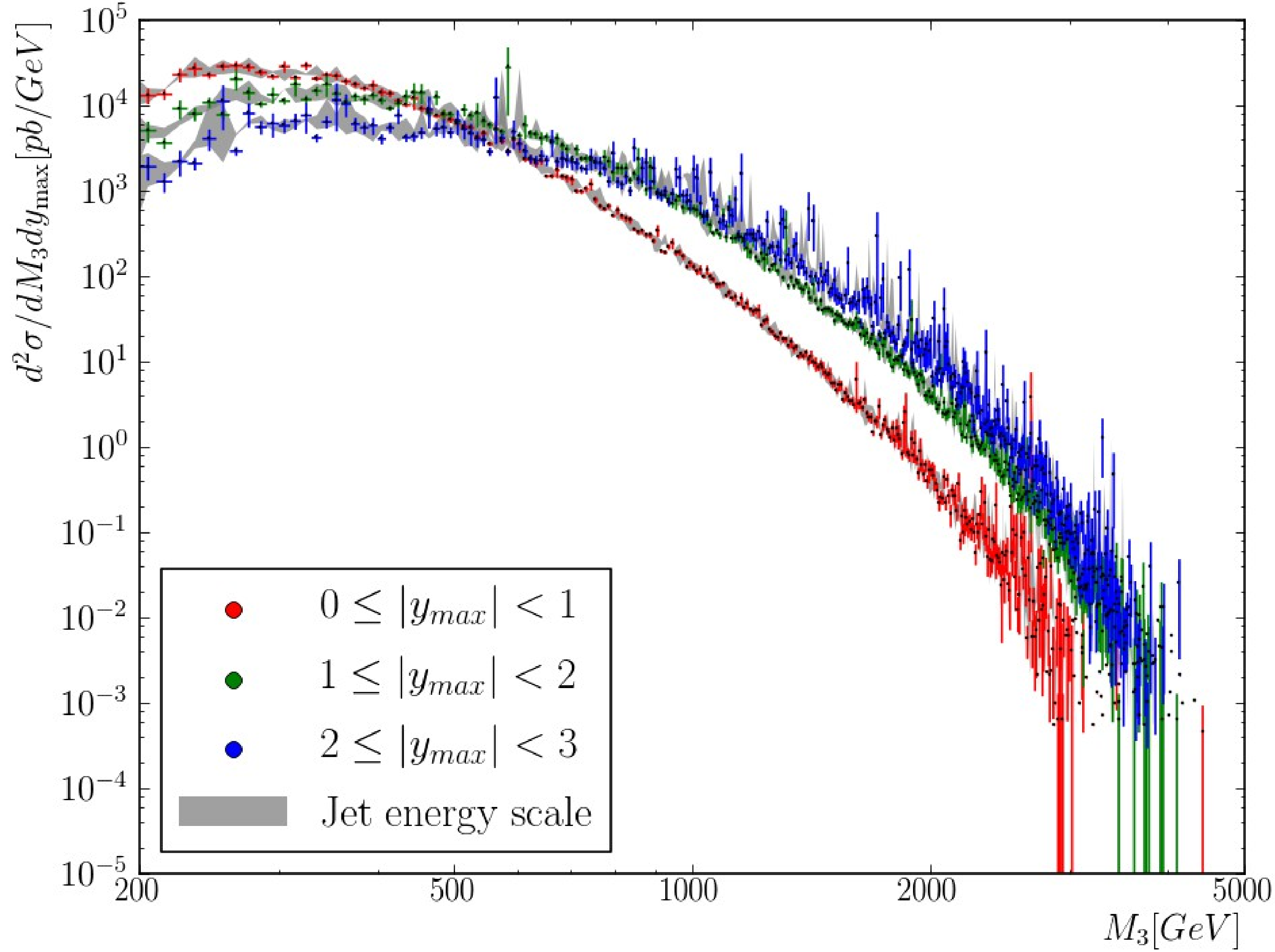
L1 jet corrections



Closure of PU correction

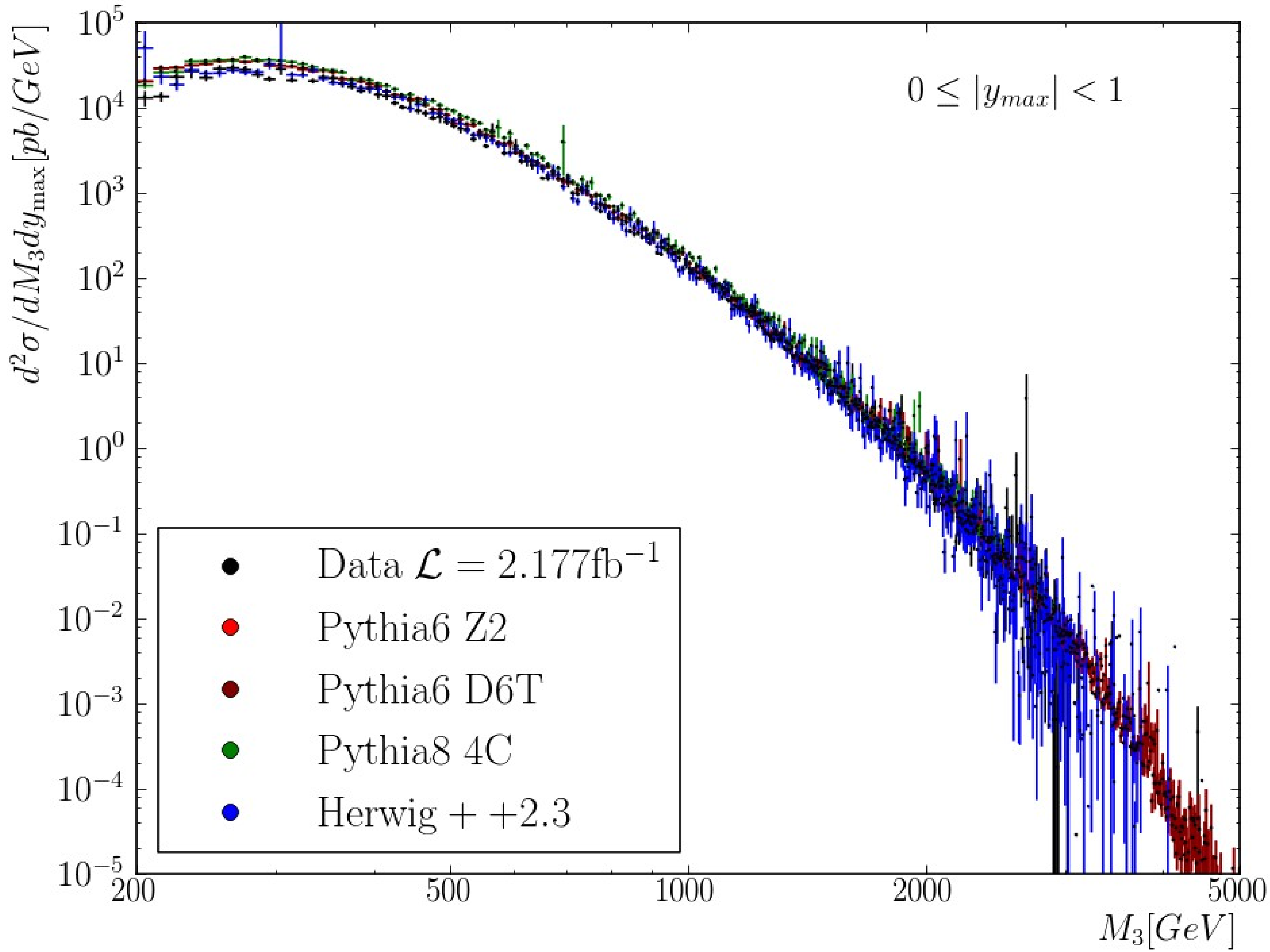


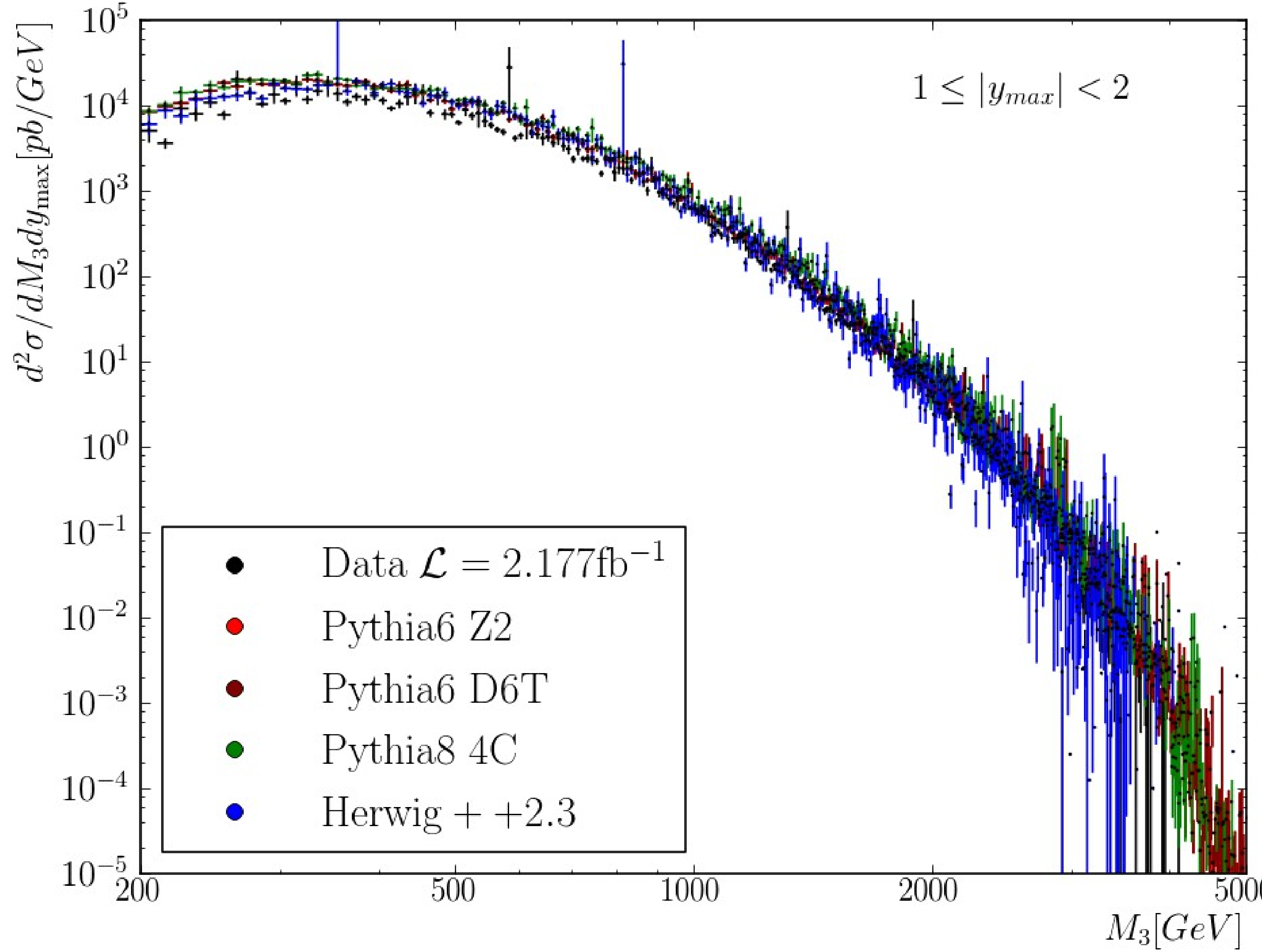




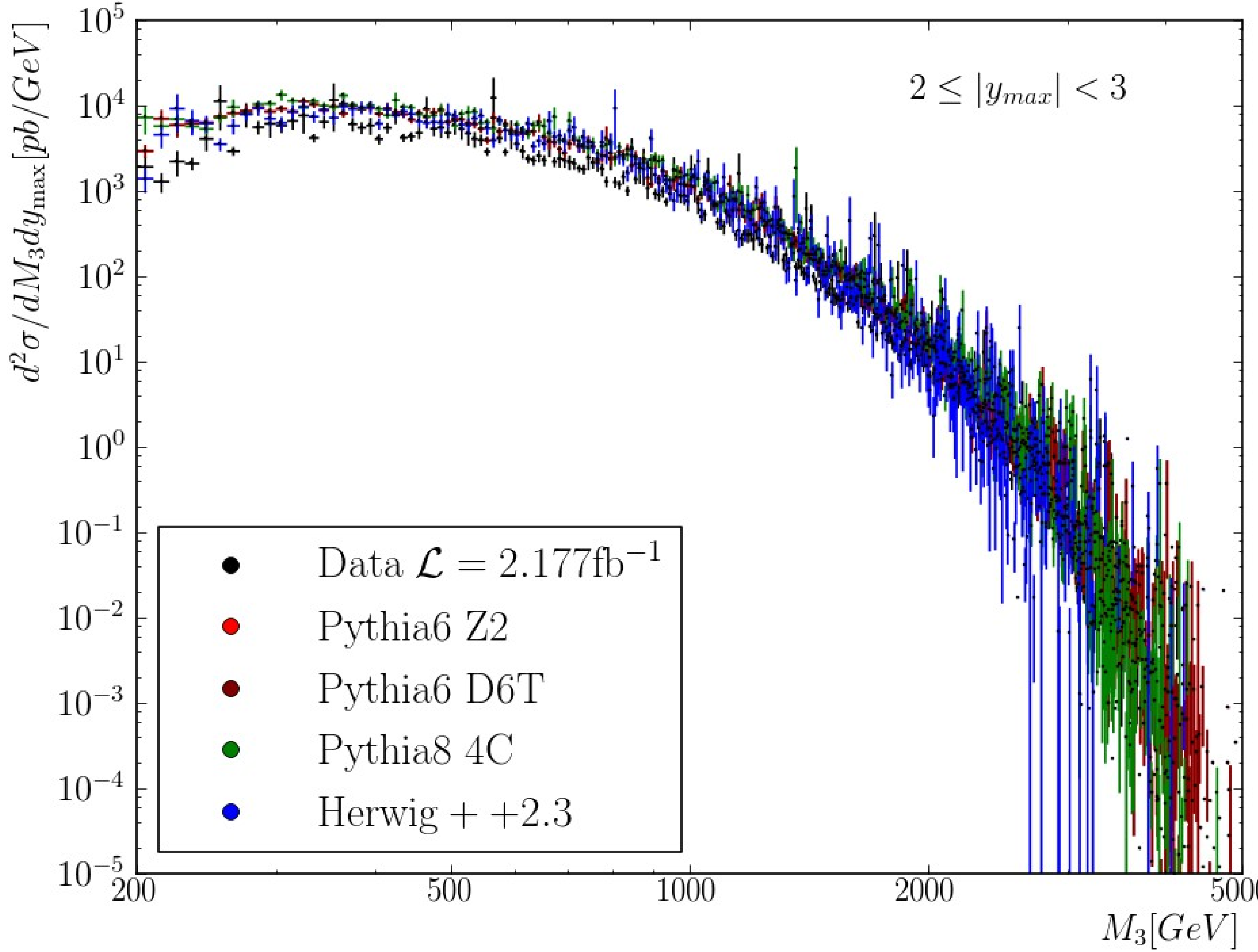
$d^2\sigma/dM_3dy_{\max}[pb/GeV]$
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
200
500
1000
2000
5000
$M_3[GeV]$
$0 \leq |y_{max}| < 1$
$1 \leq |y_{max}| < 2$
$2 \leq |y_{max}| < 3$
Jet energy scale

LO generators





$1 \leq |y_{max}| < 2$
Data $\mathcal{L} = 2.177\text{fb}^{-1}$
Pythia6 Z2
Pythia6 D6T
Pythia8 4C
Herwig + +2.3
$d^2\sigma/dM_3dy_{\max}[pb/GeV]$
$M_3[GeV]$


$d^2\sigma/dM_3dy_{\max}[pb/GeV]$
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$2 \leq |y_{max}| < 3$
Data $\mathcal{L} = 2.177\text{fb}^{-1}$
Pythia6 Z2
Pythia6 D6T
Pythia8 4C
Herwig + +2.3
200
500
1000
2000
5000
$M_3[GeV]$