Higgs and Standard Model Experimental Measurements at the LHC
Part 2

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Outline

- Previously:
  - Z as a standard candle
  - Some background on object reconstruction and identification
  - Some background on detector simulation and Monte Carlo
  - Tag and probe for efficiency measurements
  - Precision electroweak measurements with W and Z: m_W, $\sin^2\theta_W$
  - Precision measurements of W and Z cross sections and constraints on PDFs
- **Today:**
  - Jet reconstruction and Jet energy corrections
  - Measurements with jets
  - Multiboson Production
  - Top physics
- Friday:
  - Higgs measurements

Digression: Object Reconstruction, Identification and Mis-identification

- **Main "high level" objects:**
  - **Jets** (+b or c tagging)
  - **Missing transverse momentum** (aka Missing Energy aka MET), e.g. from neutrinos in final state
  - (Isolated high p_T) photons
  - (Isolated high p_T) electrons
  - (Isolated high p_T) muons
  - (Isolated high p_T) taus

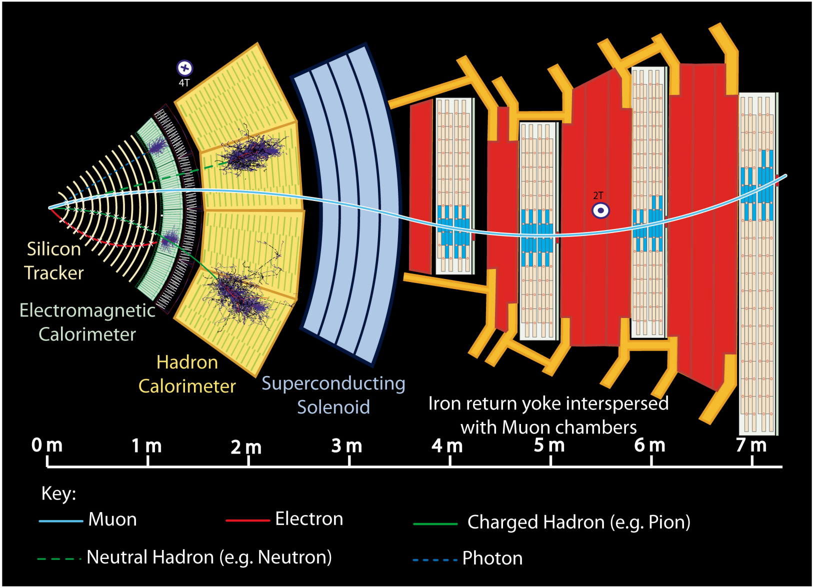
Digression: Object Reconstruction, Identification and Mis-identification

- **What is actually measured in the detector: Stable* particles**

  *given relativistic boost and size of the detector

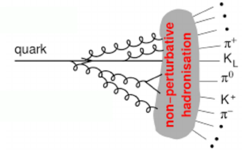
  - Charged hadrons
  - Stable neutral hadrons (e.g. neutral Kaons)
  - Photons
  - Electrons
  - Muons
- **Important special cases:**
  - π^0 is the lightest and most copiously produced neutral hadron, but promptly decays to $\gamma\gamma$ (99%) or $e^+e^-\gamma$(1%)
  - τ has a short but measurable lifetime (decay length 87μm) $\rightarrow$ decays to slightly displaced electrons or muons + neutrinos ($\sim$ 18% each) or hadrons + neutrino
- Jets are a collection of all of the above, but mostly charged hadrons, photons (mainly from π^0) and neutral hadrons in very roughly 60/30/10 proportions on average (but with large fluctuations from jet to jet)

Particle Identification in General Purpose Detectors



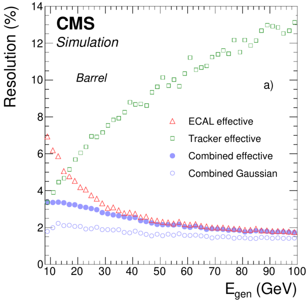
Jet and Missing Energy Reconstruction

- Jets originate from fragmentation of a quark or gluon produced by the hard interaction and tend to be collimated in the detector $\rightarrow$ define (and reconstruct) jets based on clustering of final state particles and/or energy deposits
- Simplest possible clustering would be based on ΔR cones, but e.g. anti-kT is usually preferred for theoretical considerations
- Experimentally a few possibilities:
    - Cluster calorimeter deposits (typically jet clustering of smaller calorimeter clusters)
    - Cluster tracks (this is generally not a good idea, since only charged hadron component can be included, with large fluctuations from jet to jet $\rightarrow$ poor resolution)
    - Cluster Particle Flow candidates
    - Missing energy can be constructed from the same constituents as jets in general

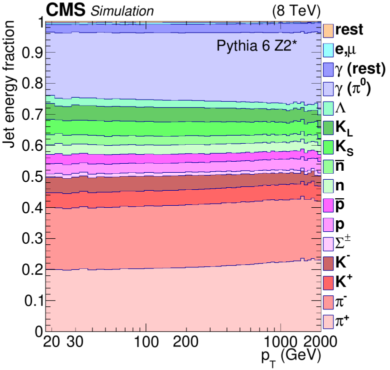


Particle Flow

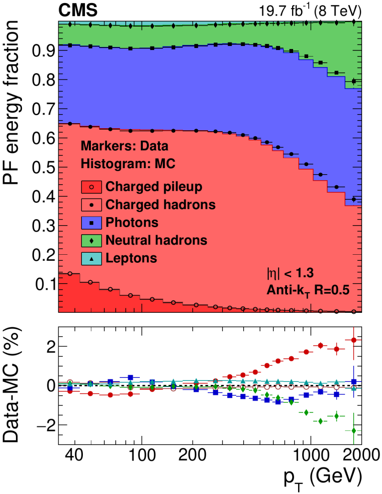
- In a nutshell: **Match tracks to calorimeter deposits** and assign energy based on (resolution-weighted) **combination of track momentum and calorimeter energy**
- This can greatly improve the energy and angular resolution for charged hadrons (and electrons), especially at low energies, and depending on the relative performance of the inner tracker with respect to the calorimeters
- Per-particle pileup subtraction becomes natural in this approach
- Accurately matching calorimeter energy deposits to individual tracks can be challenging depending on calorimeter granularity, density of tracks, etc



Jet Composition Example



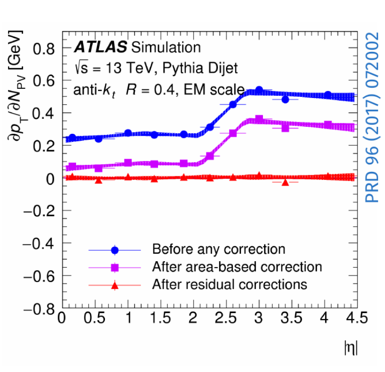
(a) Generator

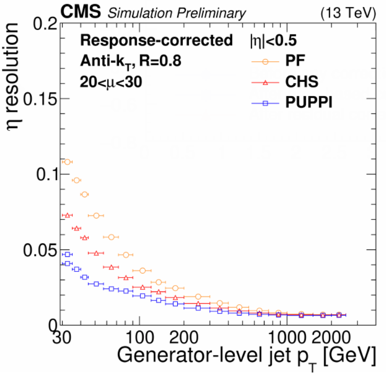


(b) Reconstruction

Pileup Subtraction

- Additional energy/particles from pileup interactions can contaminate reconstructed jets (especially relevant at lower energies)
- Subtraction can be done on average (depending on size of jet and median pileup density) or per particle using track association to primary vertex

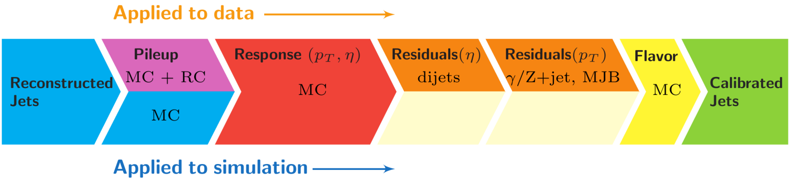




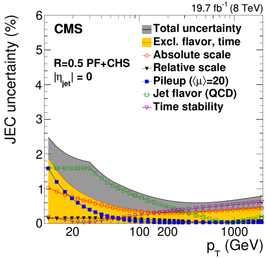
Jet Energy Corrections

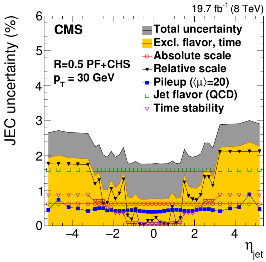
- Ideally, the energy of the reconstructed jet should match as close as possible the energy which would be measured by clustering the stable particles (at generator level in the MC, or from a hypothetical detector which could perfectly separate particles and measure their energy)
- In practice this is not the case out of the box due to a number of reasons
  - Imperfect calibration of calorimeters (and/or biases in track momentum reconstruction)
  - Calorimeter gaps/cracks (and/or tracking inefficiencies)
  - Misidentification of particles in case particle-dependent corrections are used
  - Zero suppression thresholds
  - Noise
  - Pileup
  - etc

Jet Energy Corrections

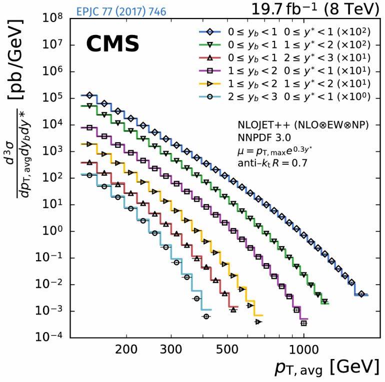


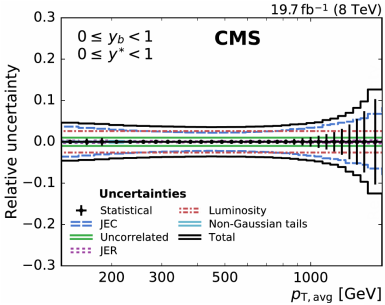
- Derive and apply a sequence of corrections to the jet energy, based on MC to start with, and with residual corrections to account for Data vs MC differences



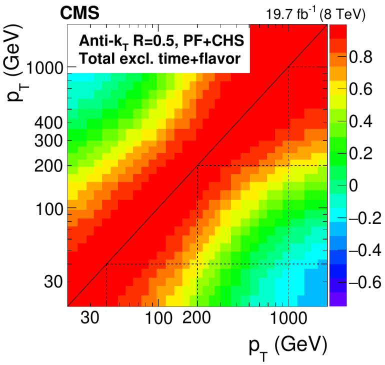


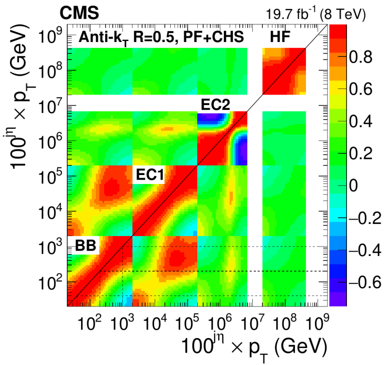
- Measurements of jet production relevant for e.g. PDF constraints, determination of strong coupling constant α_S





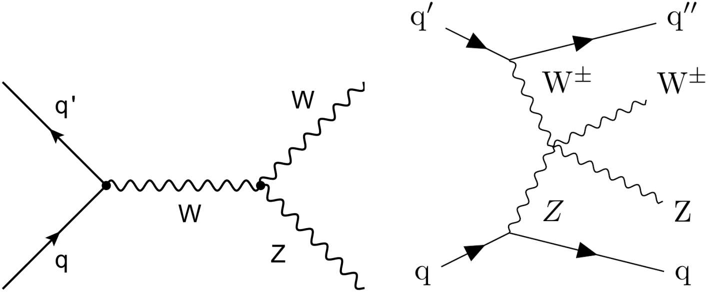
Correlations of Jet Energy Scale Uncertainties





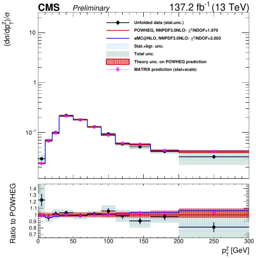
- Consistent determination and propagation of correlations of uncertainties is crucial to the (re)-interpretability of the result, its use in PDF fits, etc
- Accurate assessment of correlations across phase space can be challenging, especially for uncertainty sources related to MC modelling

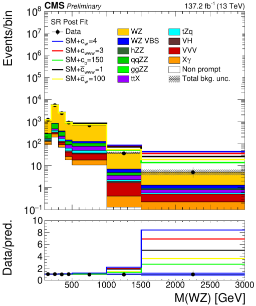
Multiboson Production

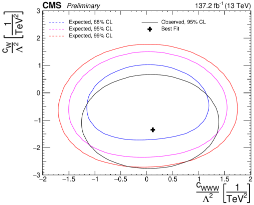


- Multiboson production at the LHC can test SM triple and quartic gauge couplings, search for anomalous gauge couplings (EFT interpretations), etc
- Special importance to vector boson scattering production modes with forward jets

Example: WZ Production: Cross Section and anomalous coupling limits

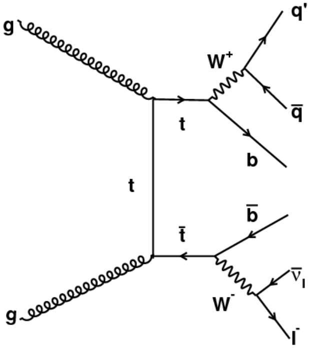






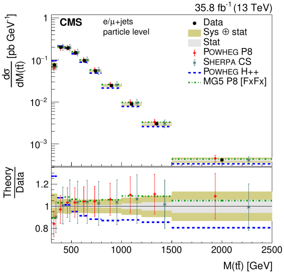
- Typical case, measure cross sections (polarization states), etc, but also use tails of distributions to set limits on anomalous couplings/EFT operators

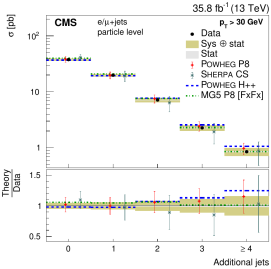
$t\bar{t}$ production at the LHC

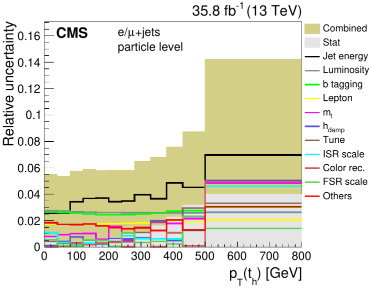


- large $t\bar{t}$ production cross section at the LHC
- Heavy final state, gluon induced production $\rightarrow$ large rate of additional jets
- Complex final states with b-jets, leptons and/or additional jets from W decays
- Possibility of colour reconnection complicates modelling, mass measurement, etc
- Study QCD, top couplings, PDF constraints, m_t, α_S determination, understand backgrounds to other measurements and searches, etc

$t\bar{t}$ Differential Cross Sections

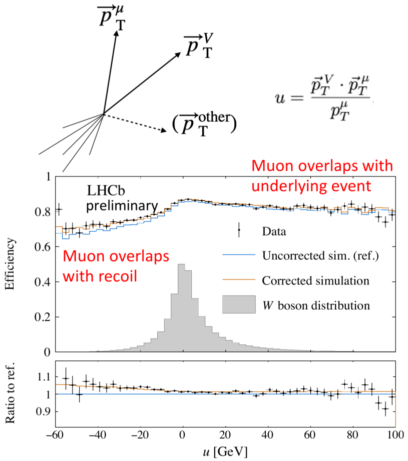






Lepton Efficiencies: Tag and Probe: Caveats

- Lepton efficiency may be **dependent on event topology**
  - Must control associated extrapolation/variation of efficiencies when measuring in one process/phase space and applying to another
  - Example shown here concerns orientation of muon with respect to hadronic recoil in drell-yan events, but the effect may be even larger e.g. in $t\bar{t}$ events with more additional jet activity



Conclusions

- Tomorrow: Higgs physics