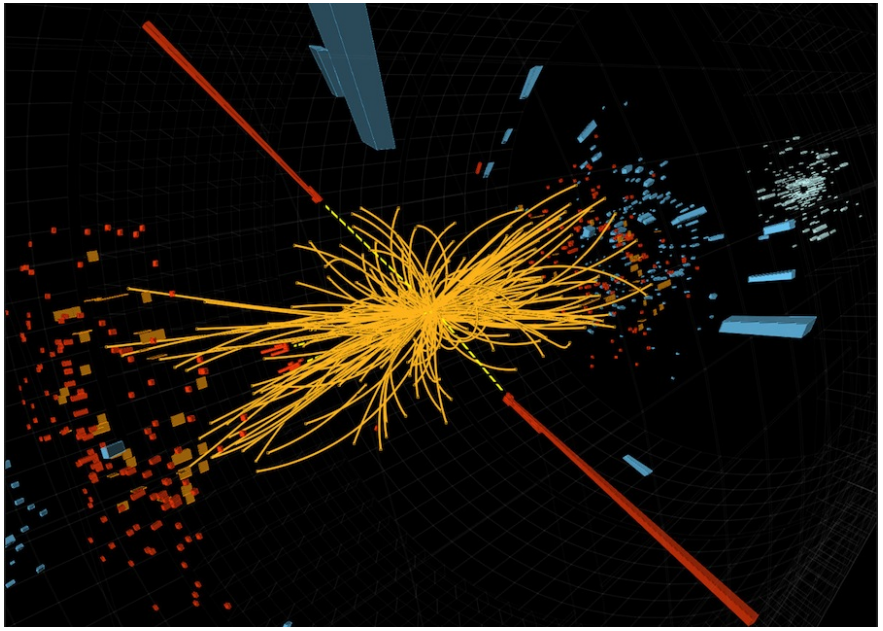
The Search for Dark Matter

Speaker: Daniel Abercrombie, Undergraduate in Physics and Nuclear Engineering at the Pennsylvania State University

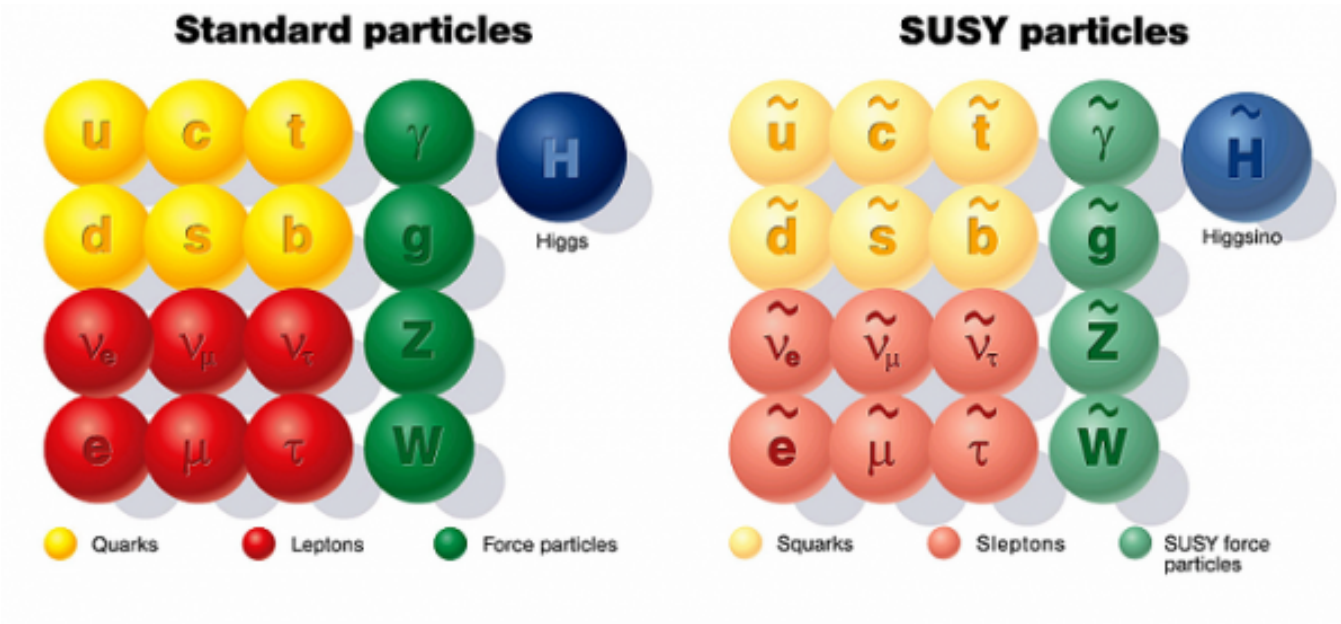
Abstract: Now that scientists at CERN have most likely discovered the Higgs Boson, many researchers are changing focus to search for dark matter during the upcoming run at the LHC. This talk will focus on the basic techniques used to search for the Higgs decaying into dark matter using quark jet substructure.



Outline

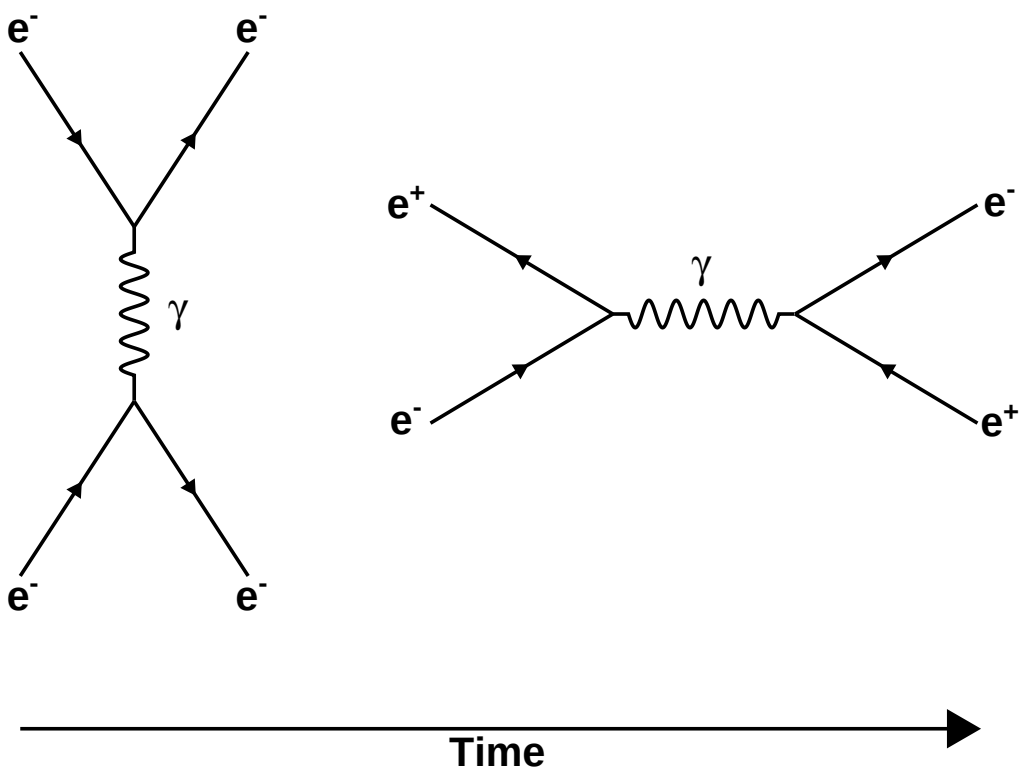
- A little bit of physics
- Some Experimental Apparatuses (AMS, LHC, and CMS)
- Characterizing the $Z \to \nu\bar{\nu}$ background for dark matter
- Using quark jets to identify Higgs events
- Optimizing the W kinematics
- Some tentative conclusions

The Particle Zoo



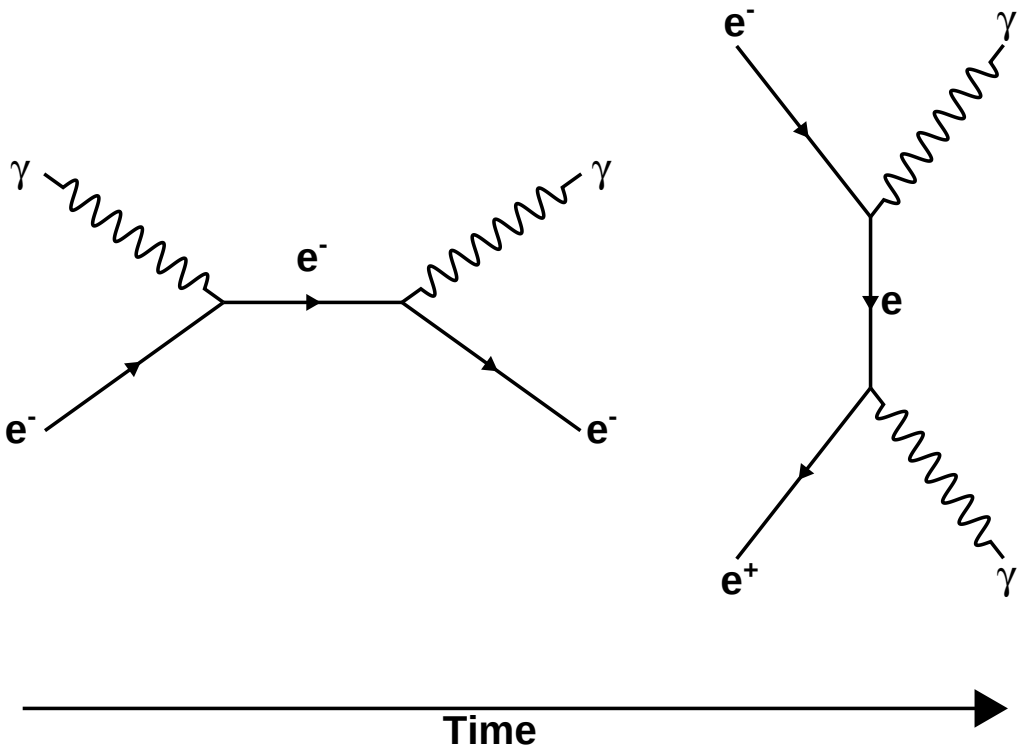
- There are fermions, gauge bosons, and the Higgs
- Dark matter is believed to be "supersymmetric" particles, by some

Anti-matter in Feynman Diagrams



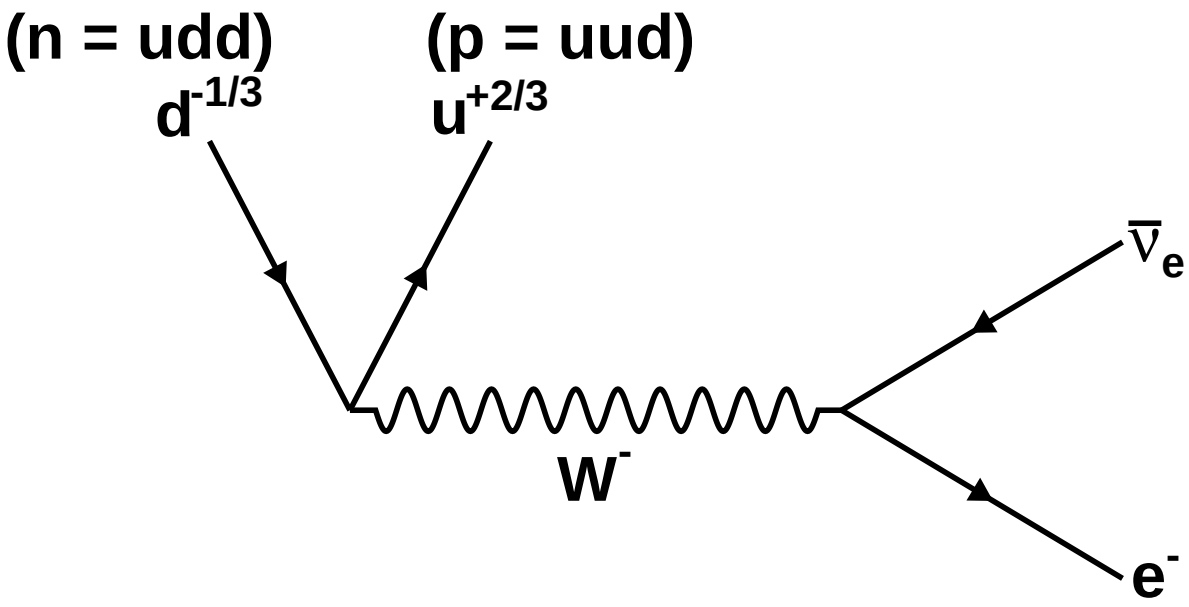
- An equal number of particles and anti-particles must come into each interaction
- Feynman diagrams can be rotated and twisted to show another physical process

An Exciting Example



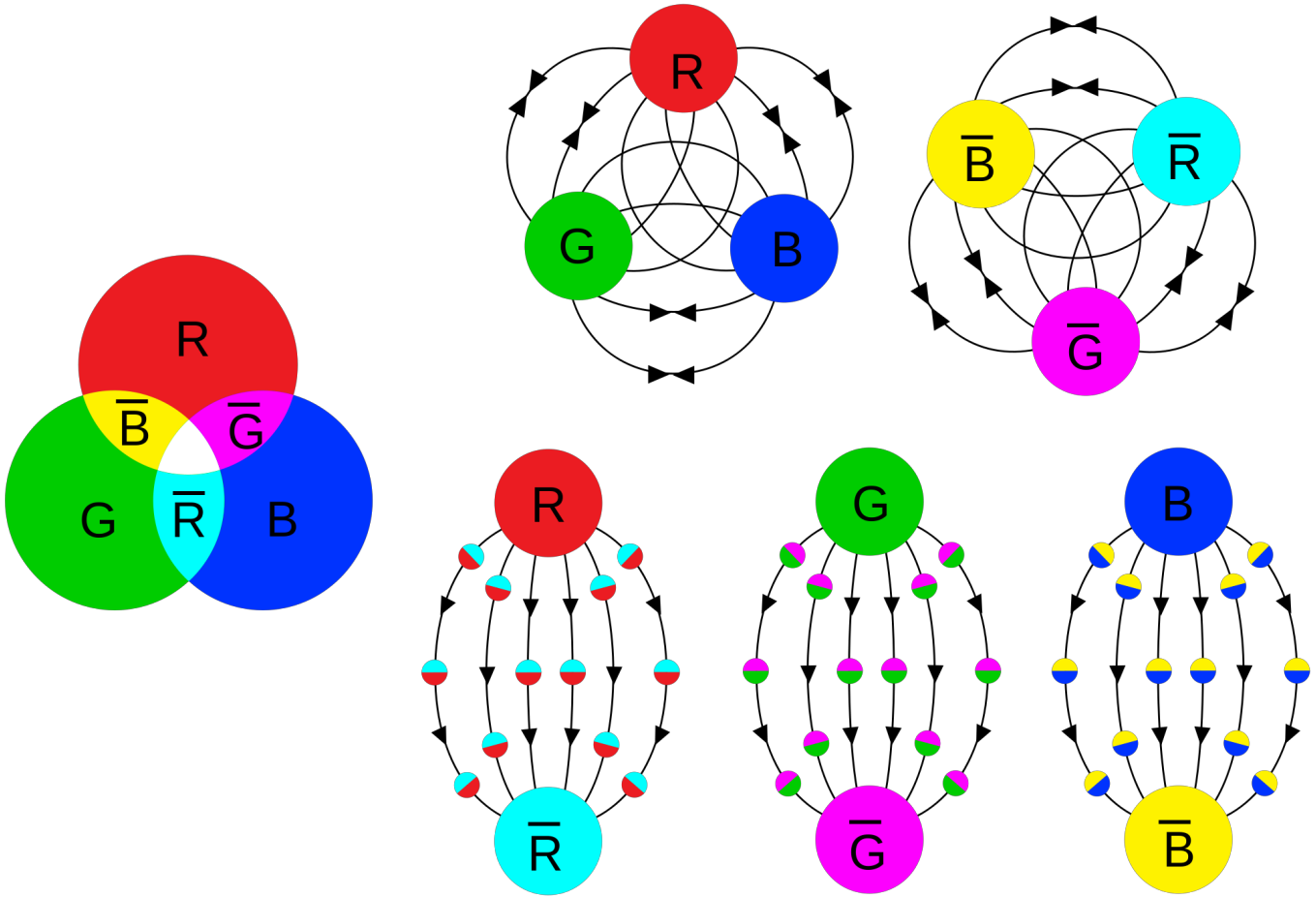
- Compton scattering is related to matter and anti-matter annihilating

Beta Decay



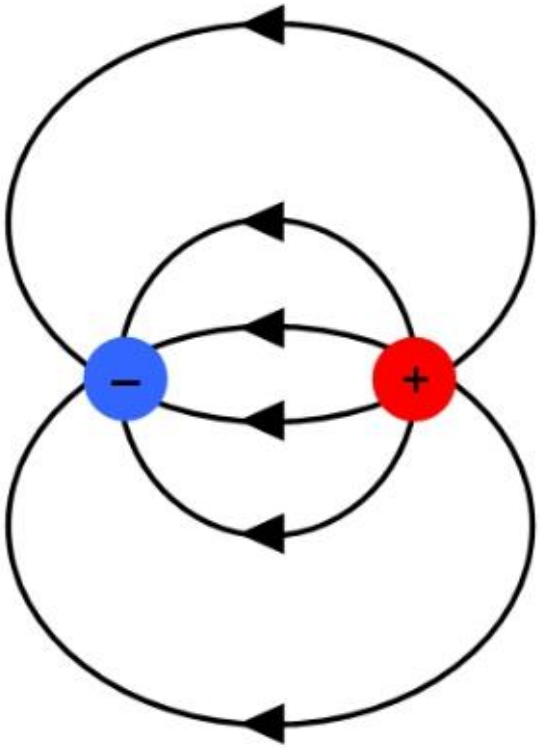
- Another well-known example would be β decay

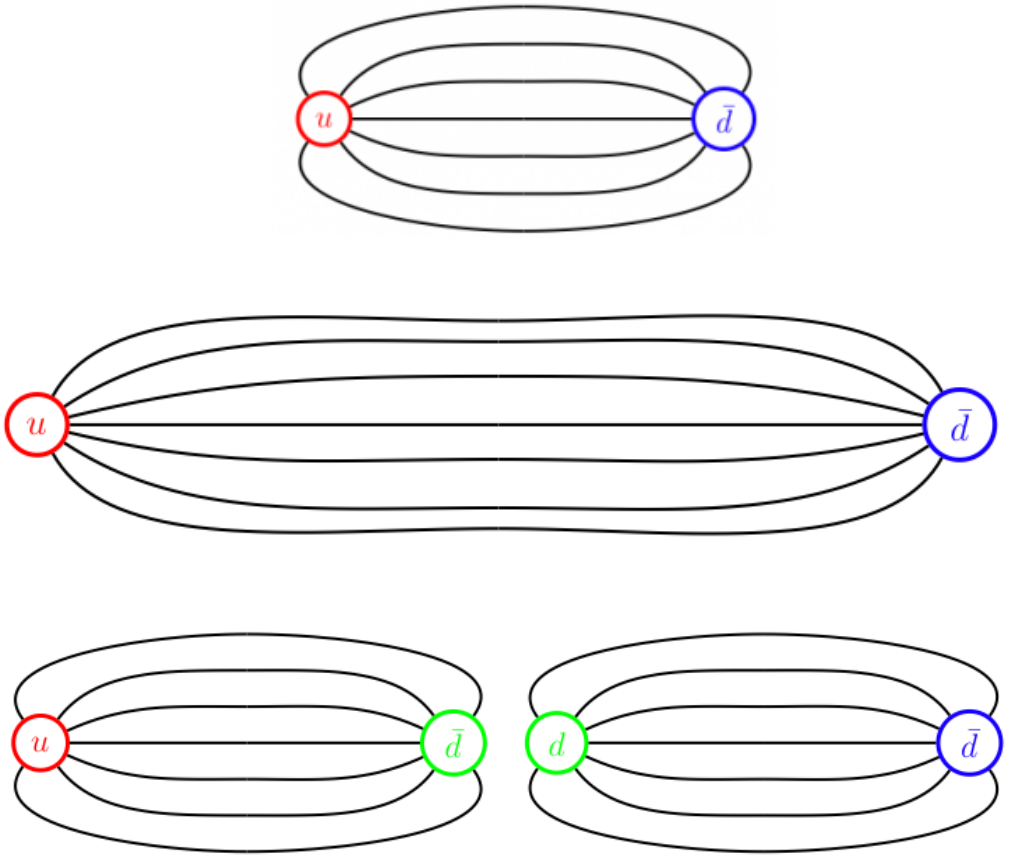
Quantum Chromodynamics



- There are three colors and three anti-colors
- All observable particles are "colorless"

Trying to Separate Quarks

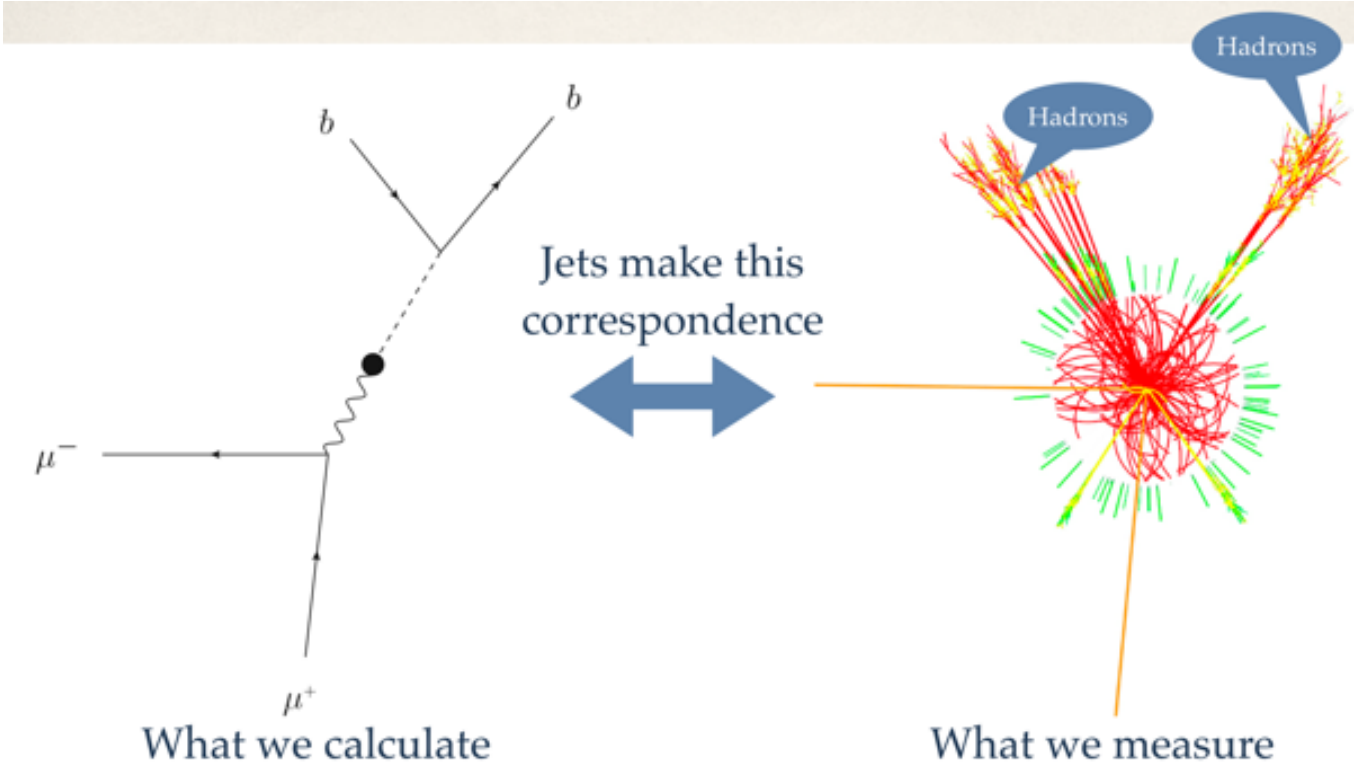




- Electric fields weaken farther from charged particles
- The strong force "gluon fields" becomes constant when color is unshielded
- It becomes energetically favorable to create particles

Isolated Quarks Make Jets

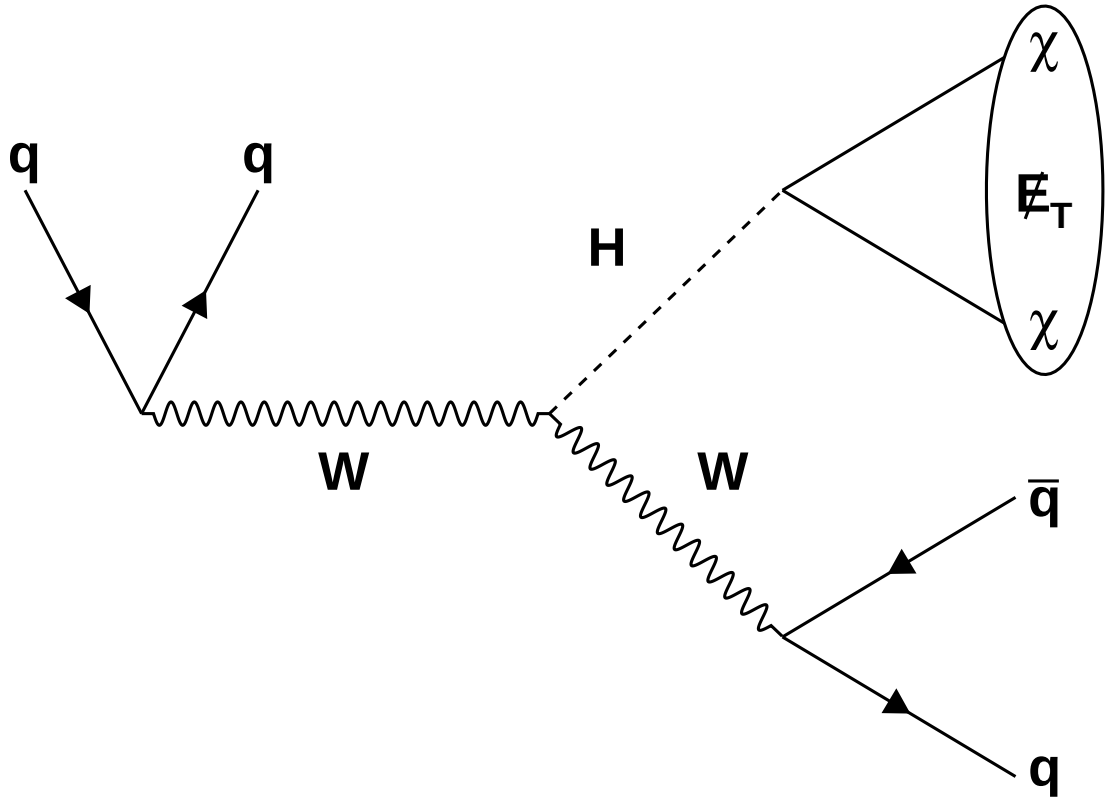
quantumdiaries.org



- Cannot measure isolated quarks, but we have bunches of particles called jets
- Jet reconstruction will be covered later

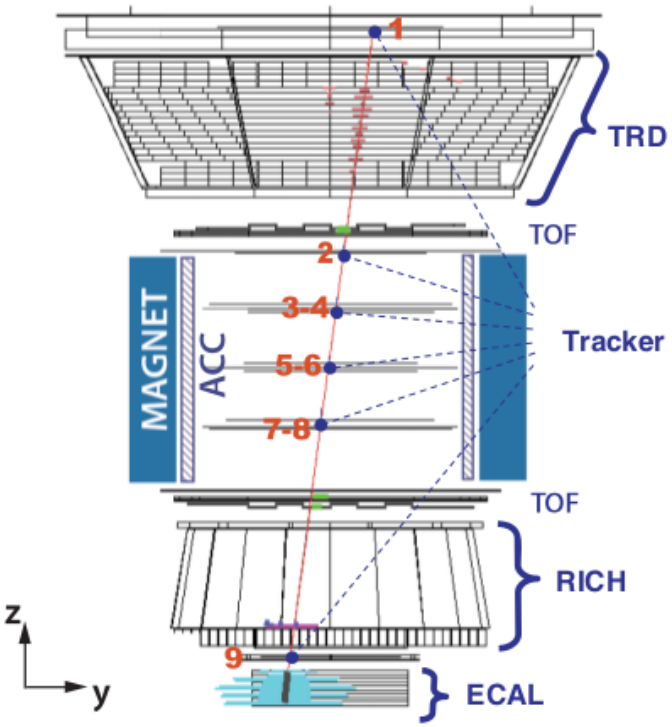
The Desired Process

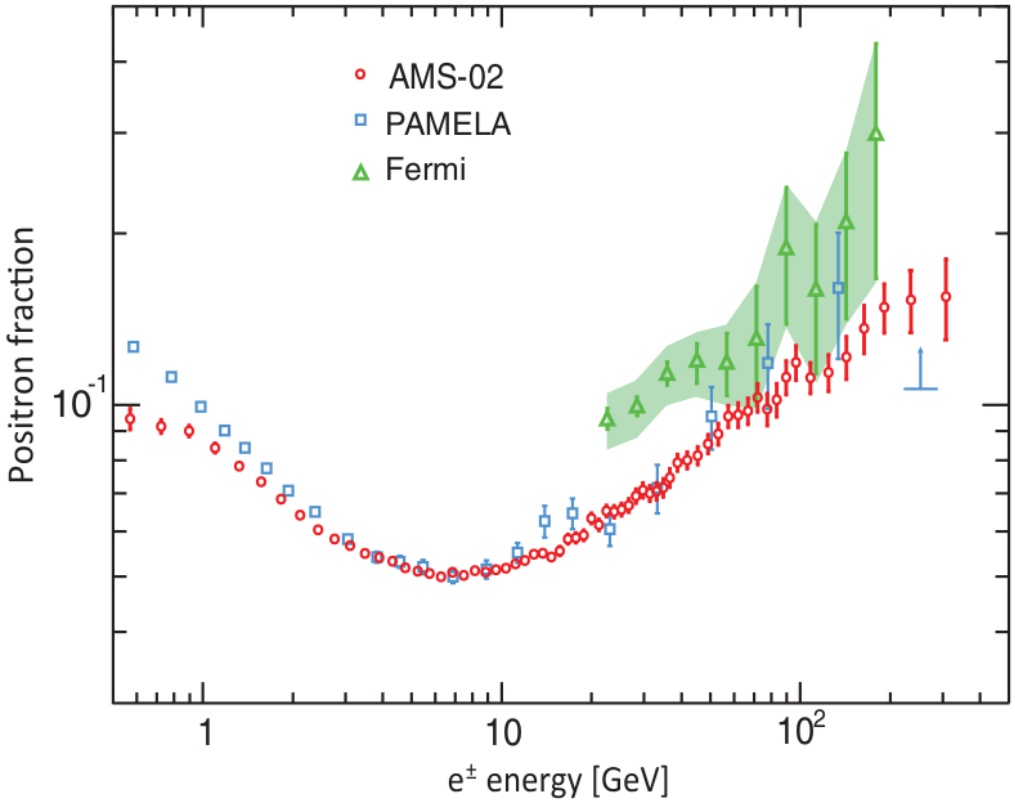
- The Higgs couples to massive particles



- The Higgs decaying into dark matter will be visible as missing transverse energy (MET, $\not{E}_T$, or E_T^{miss}).

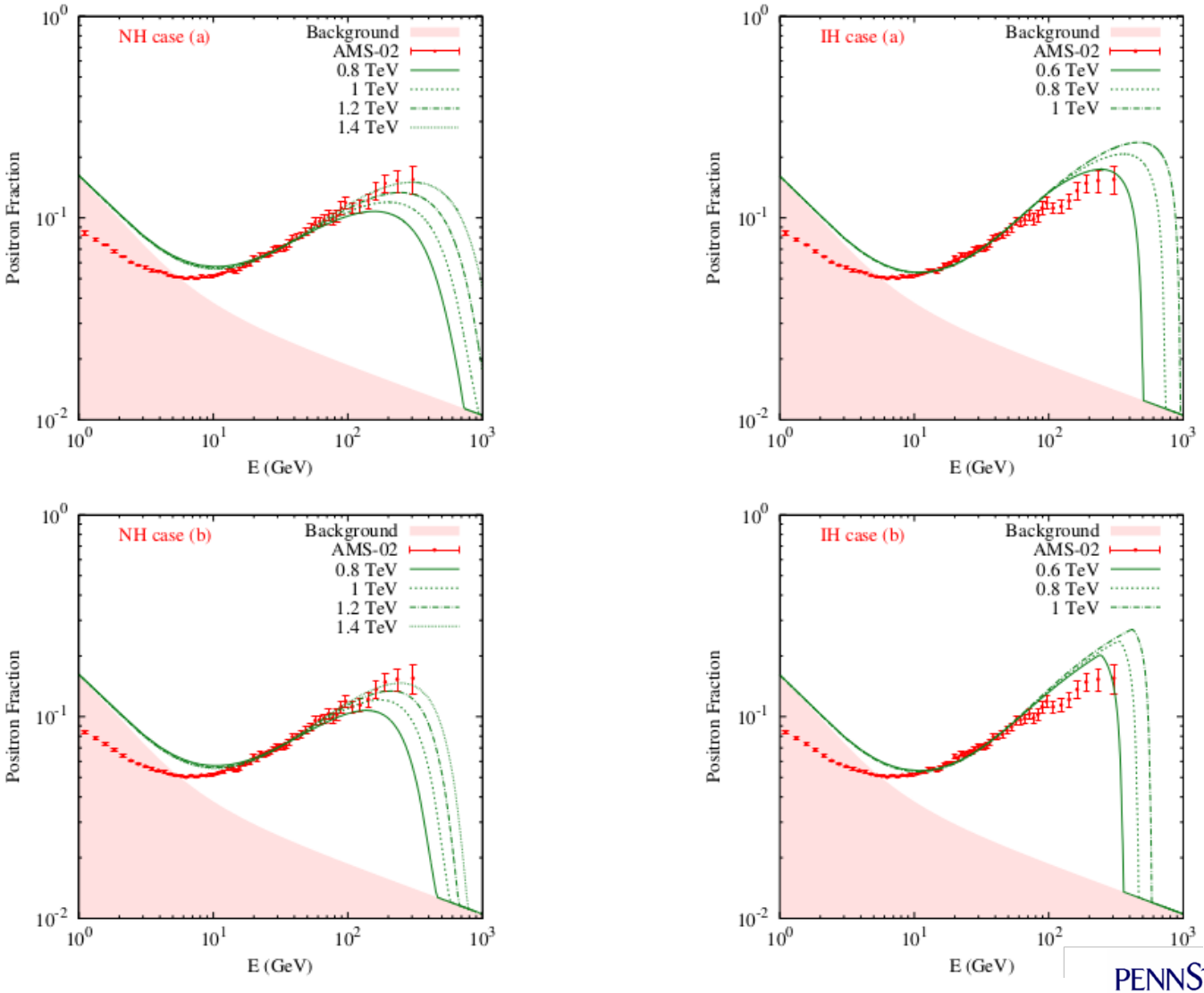
The Alpha Magnetic Spectrometer





- The AMS experiment confirms high e^+ fractions at energies indicating new physics

Interpretations of AMS

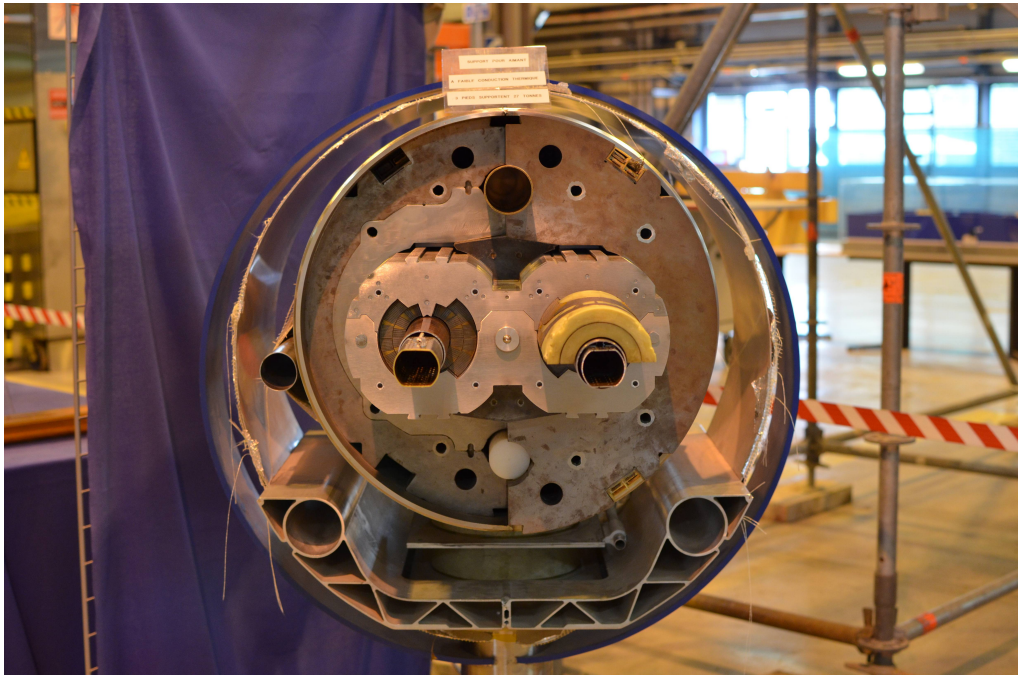


- Some models use dark matter to match the data

The Large Hadron Collider

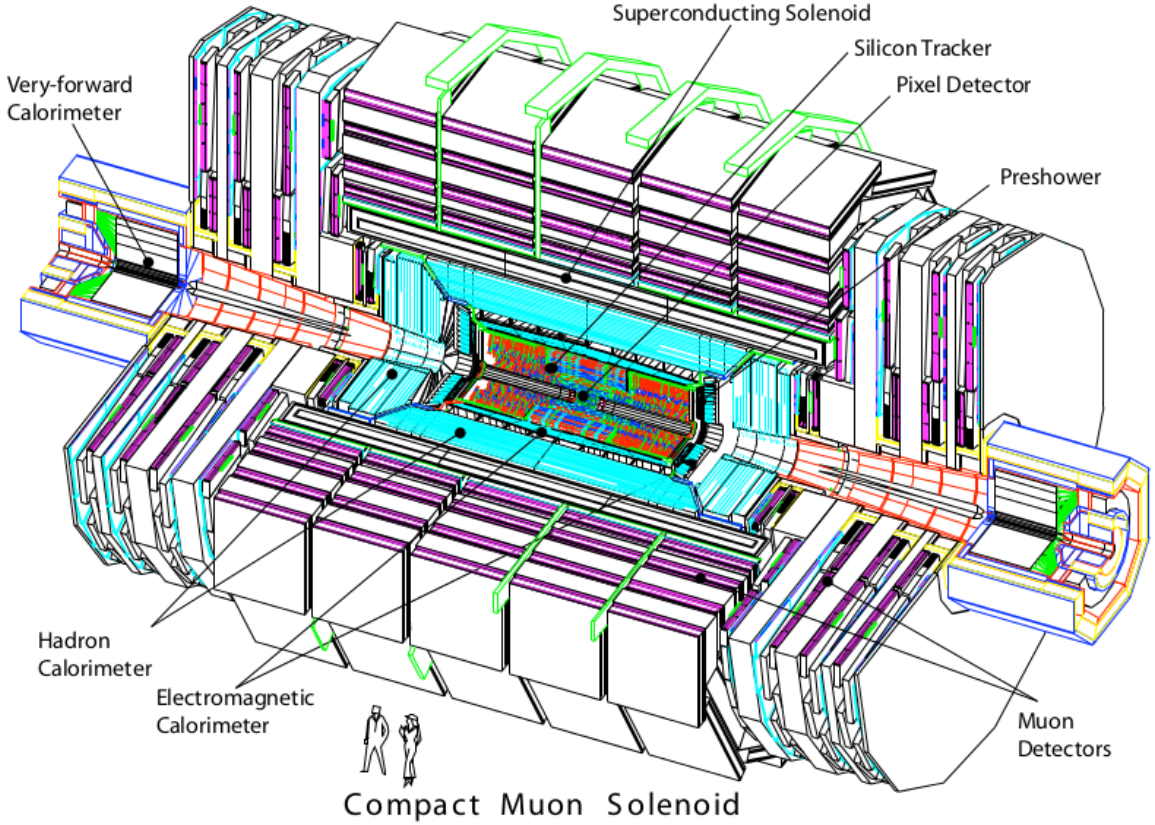
- Circumference of 27 km
- Designed to collide at 14 TeV

Collision Characteristics



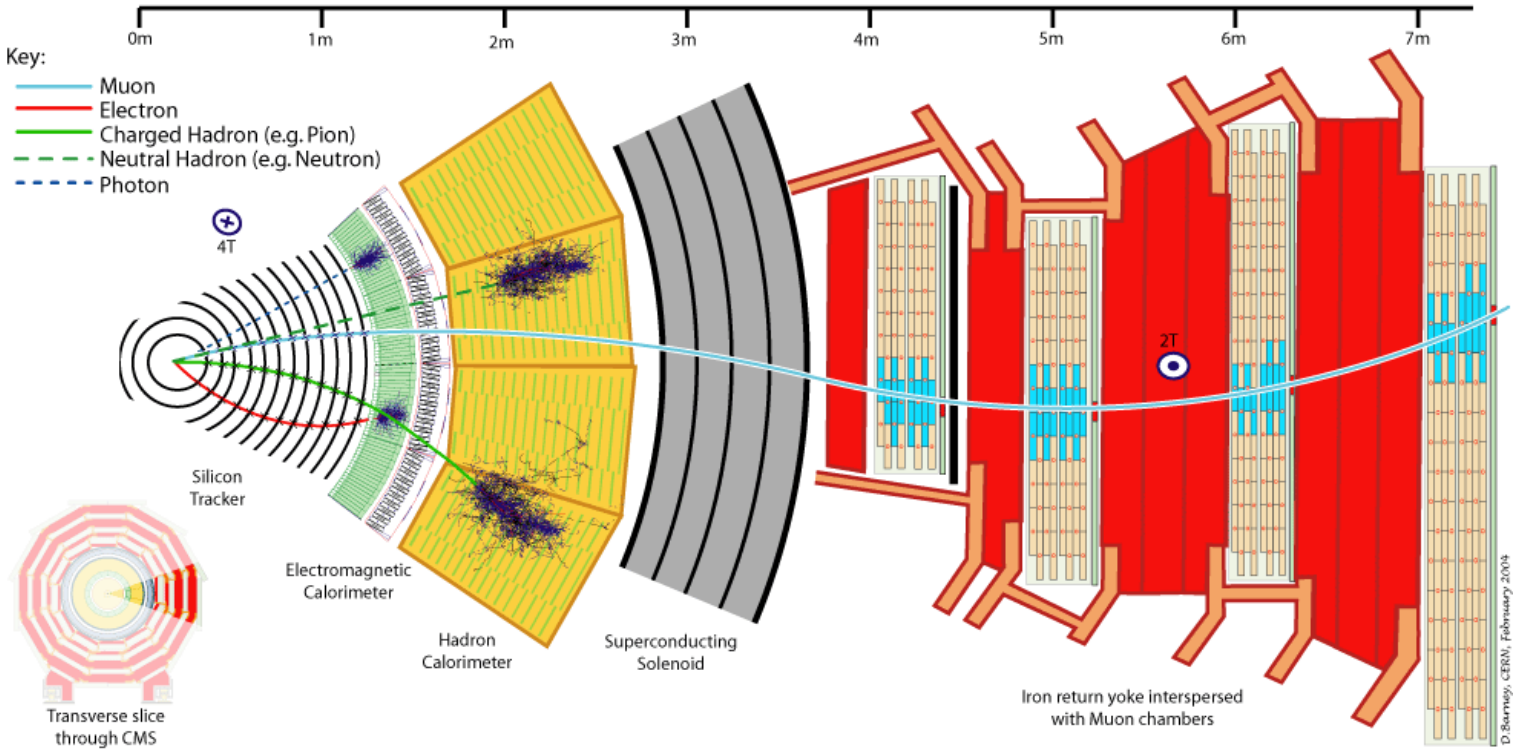
- Uses a magnetic field at 8.3 T from a superconductor cooled to 1.9 K
- Protons come in bunches every 50 ns (will be 25 ns)
- There are about 20 collisions per crossing (will be close to 100)

The CMS Detector



- Length of 21.6 m
- Diameter of 14.6 m
- weight of 12 500 t

A Cross Section

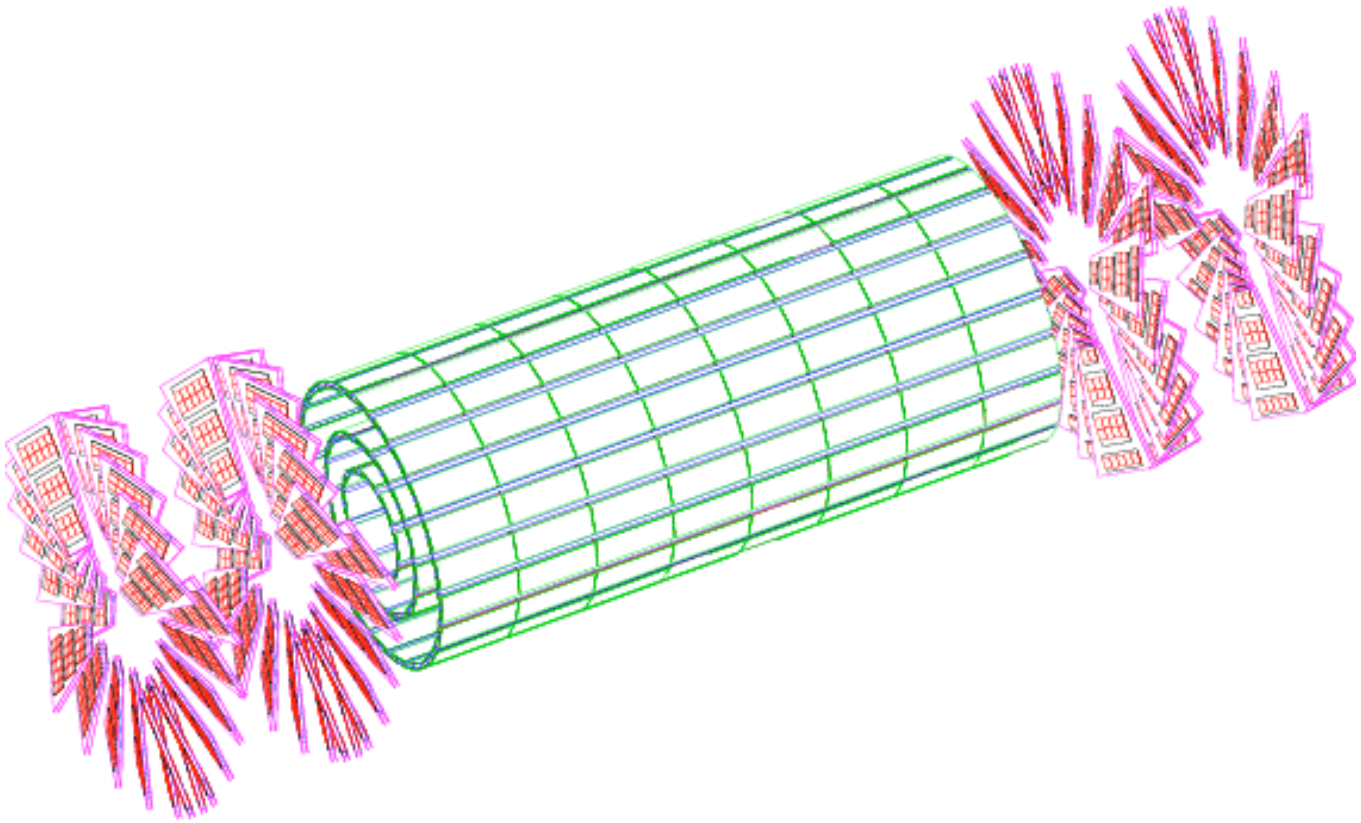


- There are five main detector components that are part of the Compact Muon Solenoid (CMS).
  - Superconducting Solenoid
  - Silicon Tracker
  - Electromagnetic Calorimeter
  - Hadron Calorimeter
  - Muon Chambers

Superconducting Solenoid

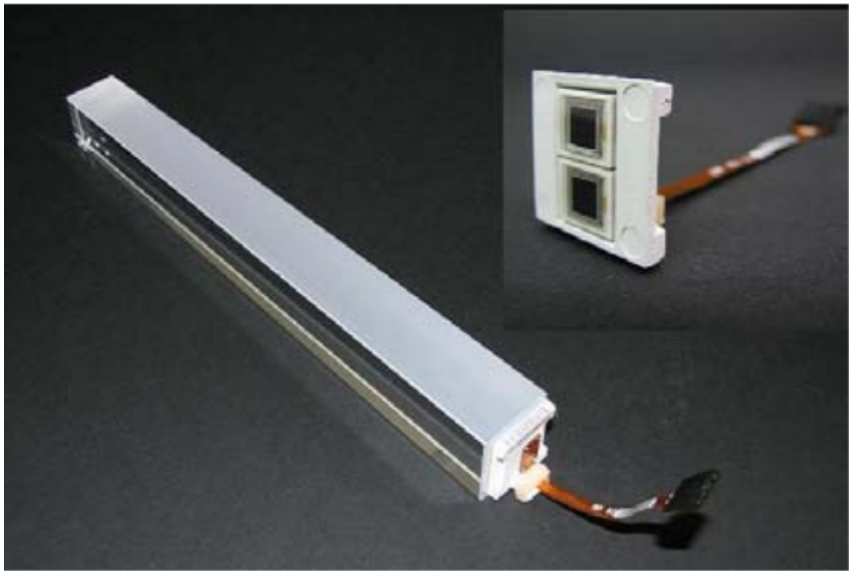
- A magnetic field of 4 T
- Niobium-titanium (NbTi) alloy
  - $T_c = 7.30\,\mathrm{K}$ during operation
  - During running, $T \approx 6.44\,\mathrm{K}$
- Causes charged particles to curve
- Distinguishes μ^- from μ^+ and helps find their momentum

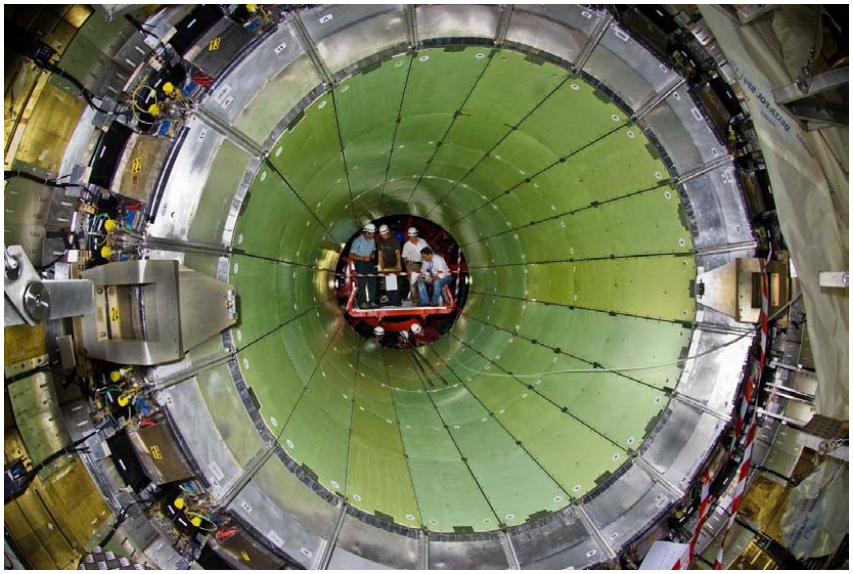
Silicon Tracker



- Inner pixel detector has a resolution of 10 μm by 20 μm
- Locates primary vertex of each particle, which is important for pileup

Electromagnetic Calorimeter

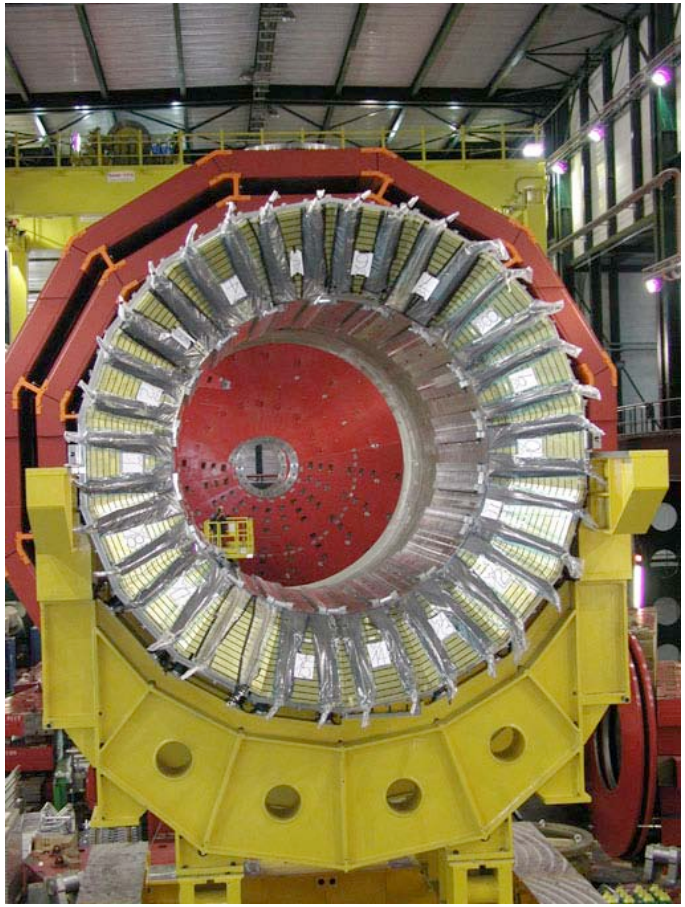




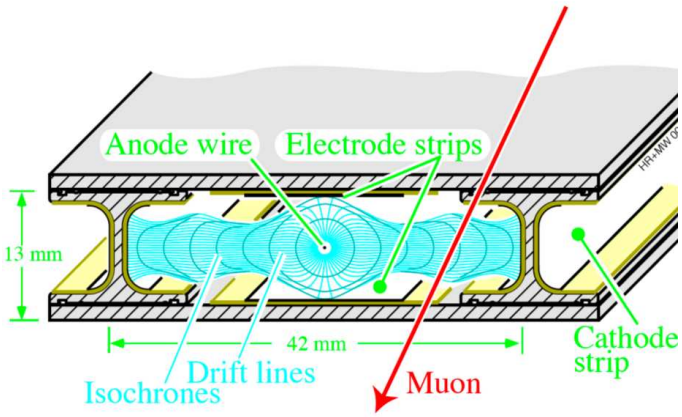
- Crystals of $PbWO_4$ have a density of $8.28\,\mathrm{g/cm^3}$
- Stops electrons and photons quickly
- Produces about 4.5 photons/MeV
- 85% of light produced in 25 ns

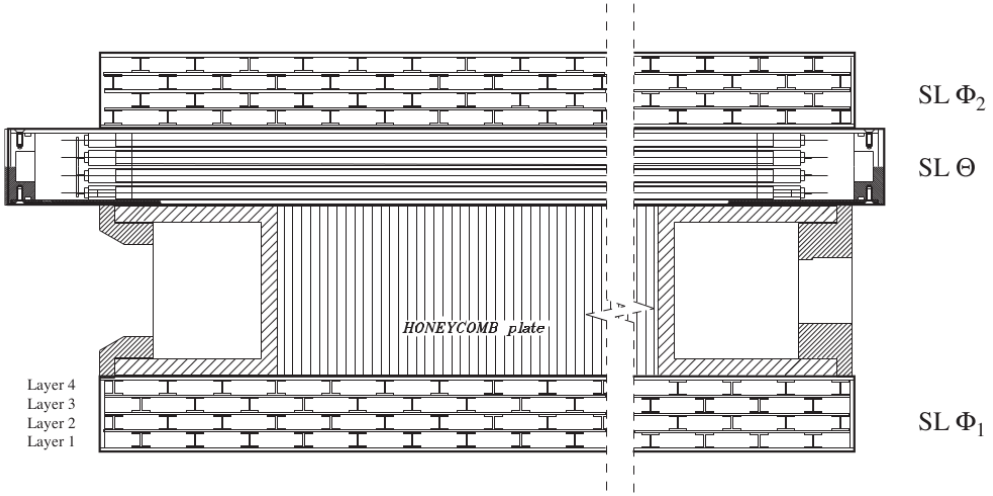
Hadron Calorimeter

- A mixture of steel and brass absorbs energy from hadrons
- Plastic scintillators measure radiated energy
  - Bicron BC408
  - Kuraray SCSN81



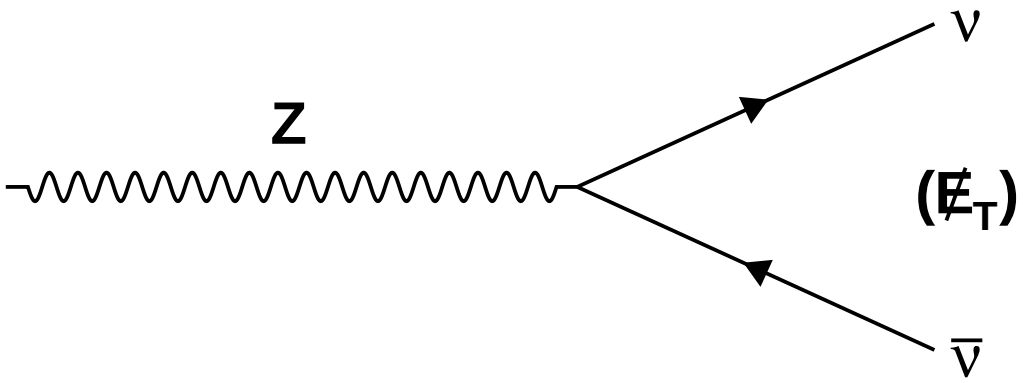
Muon Chambers



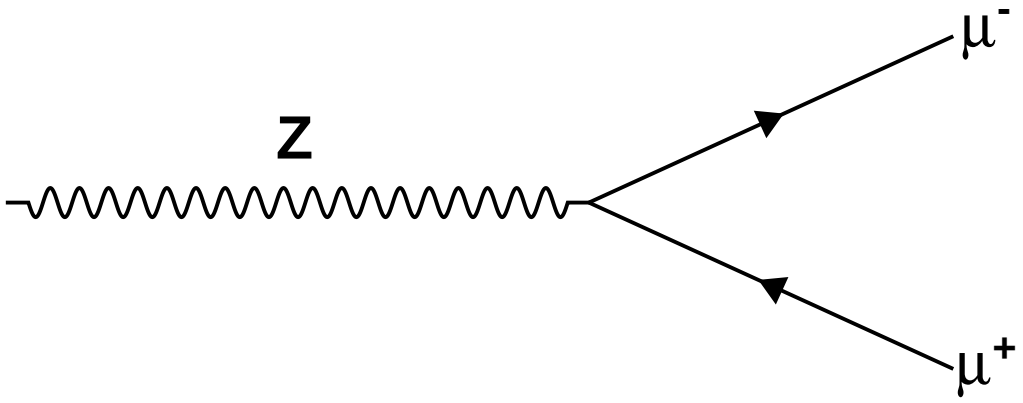


- Muon detectors are made of various drift tubes
- Gas is ionized and ions cause a discharge
  - In barrel, 15% Ar and 85% CO_2
  - There are also cathode strip chambers
  - Finally, resistive plate chambers made of bakelite

The Dominant $Z \to \nu\bar{\nu}$ Background



- Most of the background will be missing energy from neutrinos
- Z events can be characterized using decay into muons



Getting Mass with Four Vectors

- Energy and momentum are conserved

$$E^2 = p^2c^2 + m^2c^4$$

- We can ignore the c, and just use it to adjust our units.

$$E^2 = p^2 + m^2 = p_x^2 + p_y^2 + p_z^2 + m^2$$

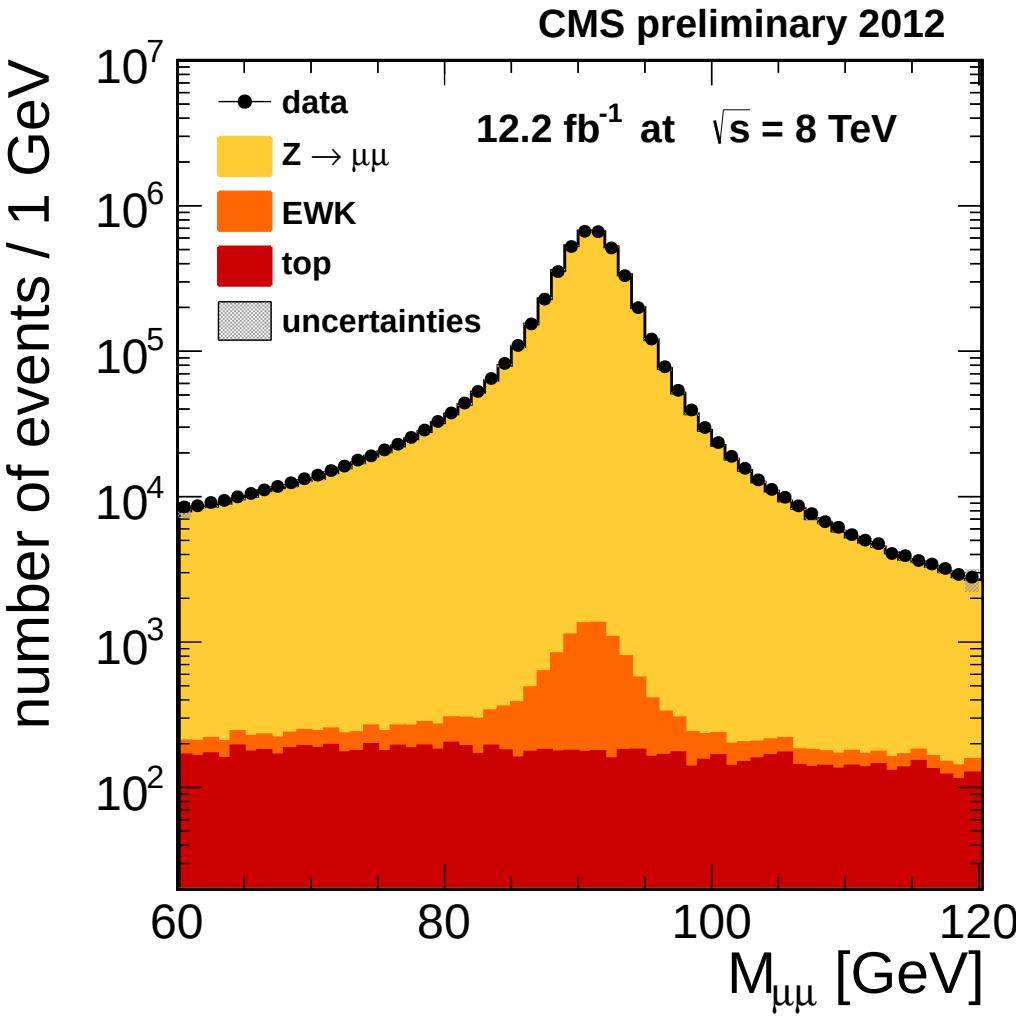
- $\mathbf{p}_Z = \mathbf{p}_{\mu_1} + \mathbf{p}_{\mu_2}$ is written as: $\begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}_Z = \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}_{\mu_1} + \begin{pmatrix} E \\ p_x \\ p_y \\ p_z \end{pmatrix}_{\mu_2}$
- Add each element

$$e.g.\ E_Z = E_{\mu_1} + E_{\mu_2}$$

- Calculate the new mass

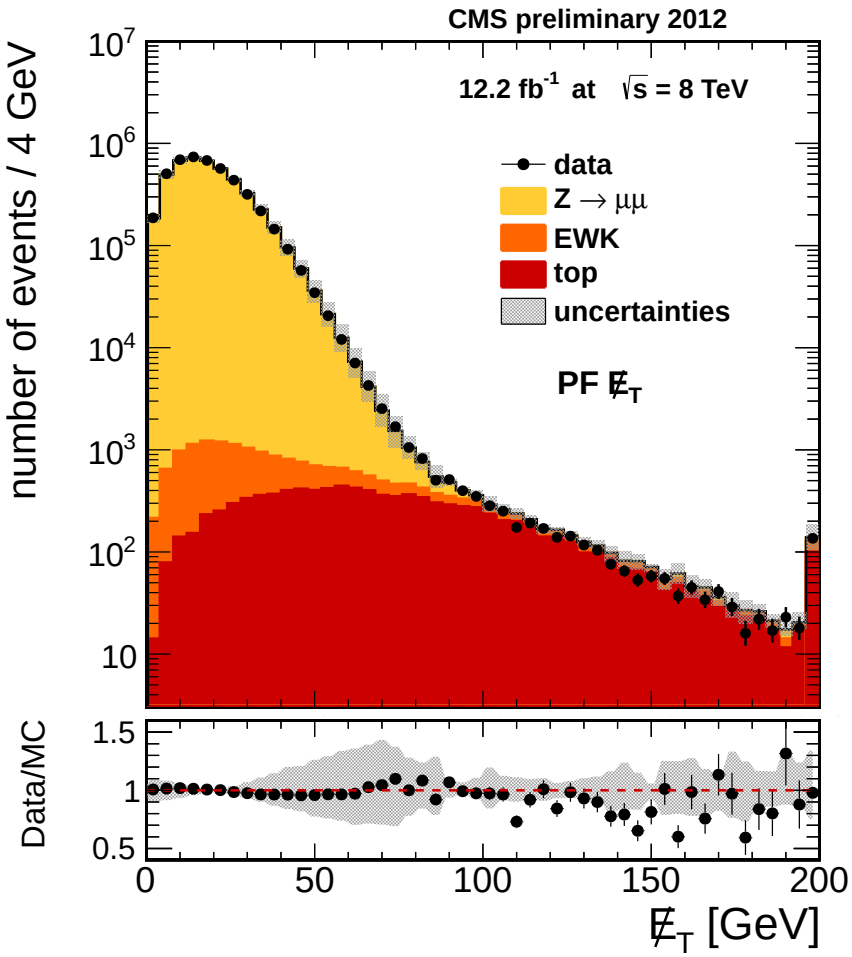
$$m = \sqrt{E^2 - (p_x^2 + p_y^2 + p_z^2)}$$

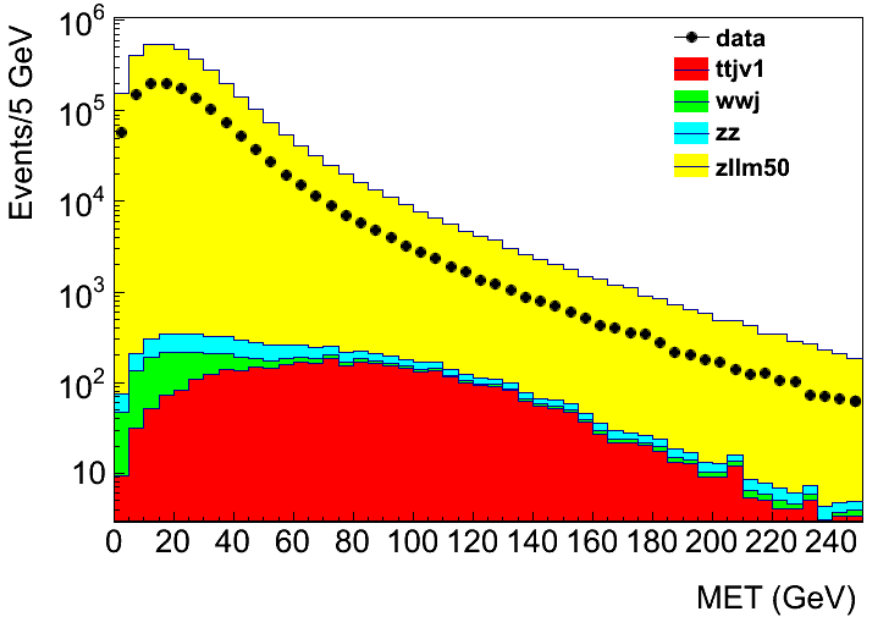
The Z Mass Peak



- Analysis is first done on simulation, which is then compared to data.

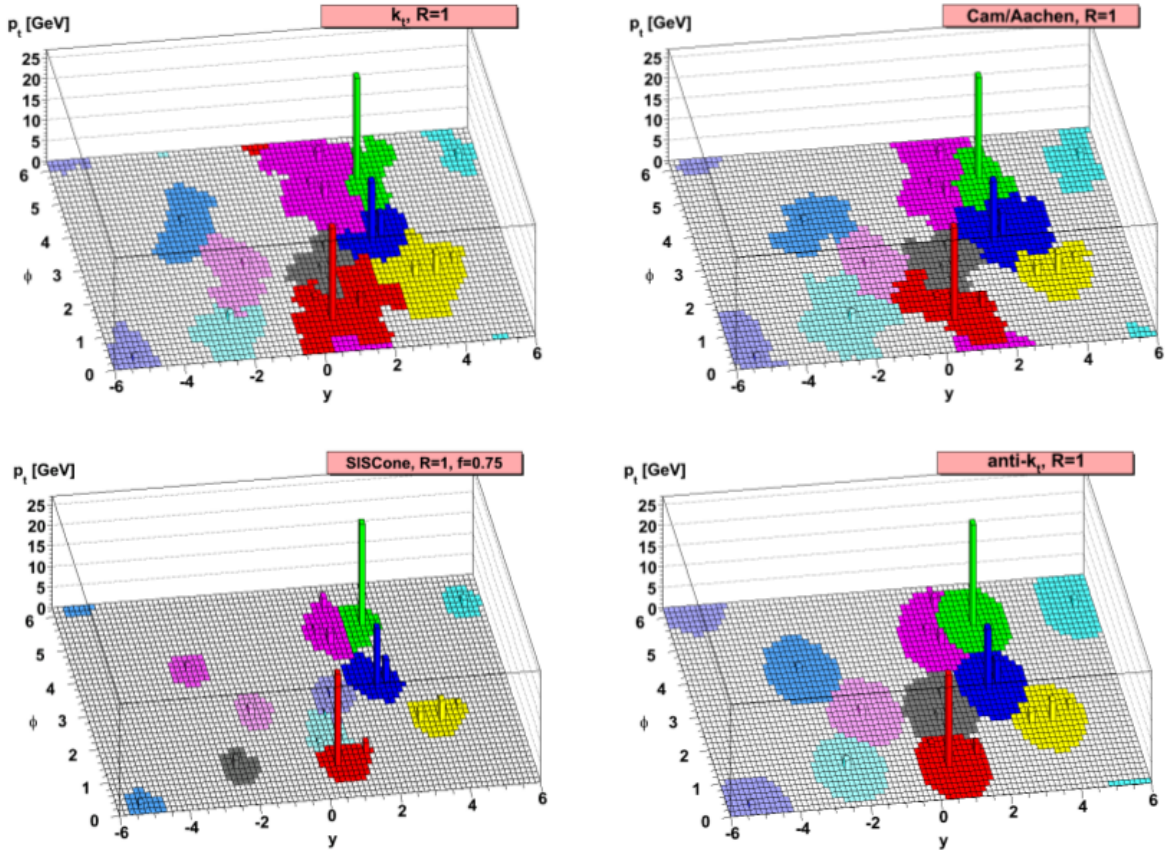
Excepted MET Distribution





- Then we pretend the muons were missing to see what the MET distribution looks like.

Jet Reconstruction



$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- The Anti-k_T algorithm is used to gather quarks
- High energy jets get most conical shape

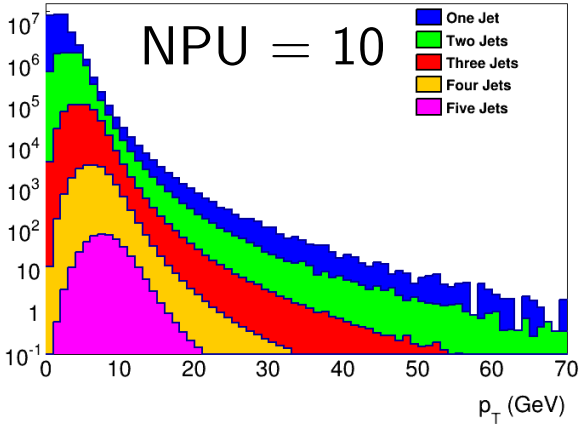
Simulation of Pileup Jets

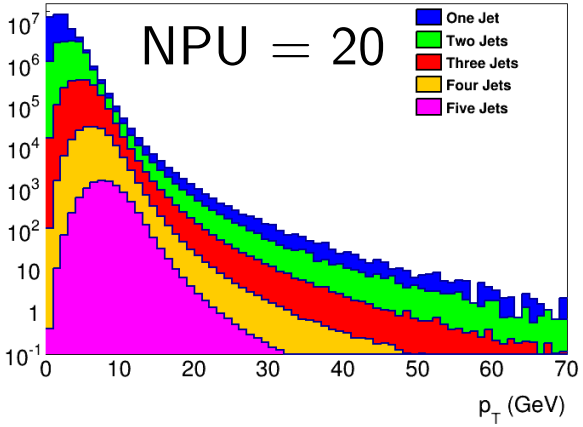
$$\frac{d\sigma}{dp_T} = \begin{cases} Cp_T^{-5}, & \text{if } p_T > 3\,\text{GeV} \\ mp_T + b, & \text{otherwise} \end{cases}$$

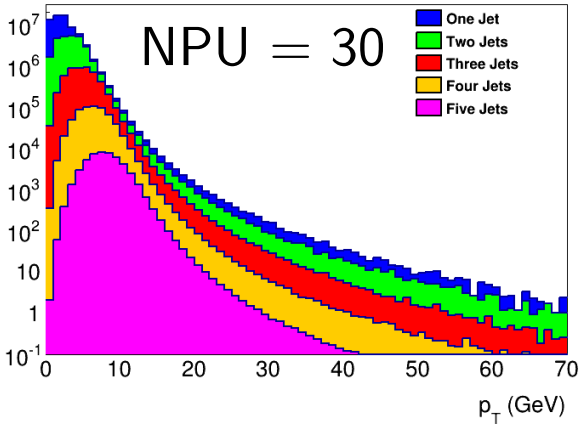
$$\frac{A_{jet}}{A_{CMS}} \approx 0.0125$$

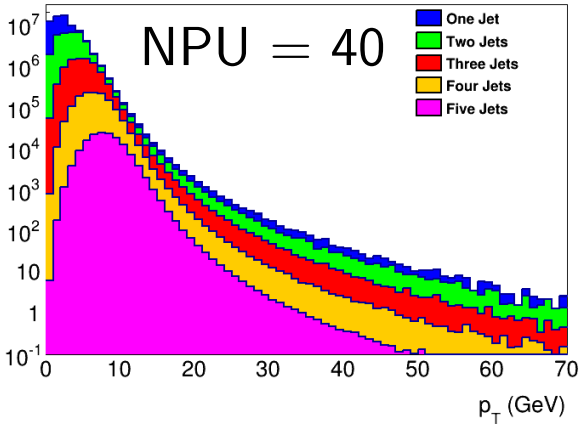
$$w(NPU, n_{jets}) = \frac{NPU!}{(NPU - n_{jets})!\,n_{jets}!}(0.0125)^{n_{jets}}(0.9875)^{NPU-n_{jets}}$$

Results of Simulation



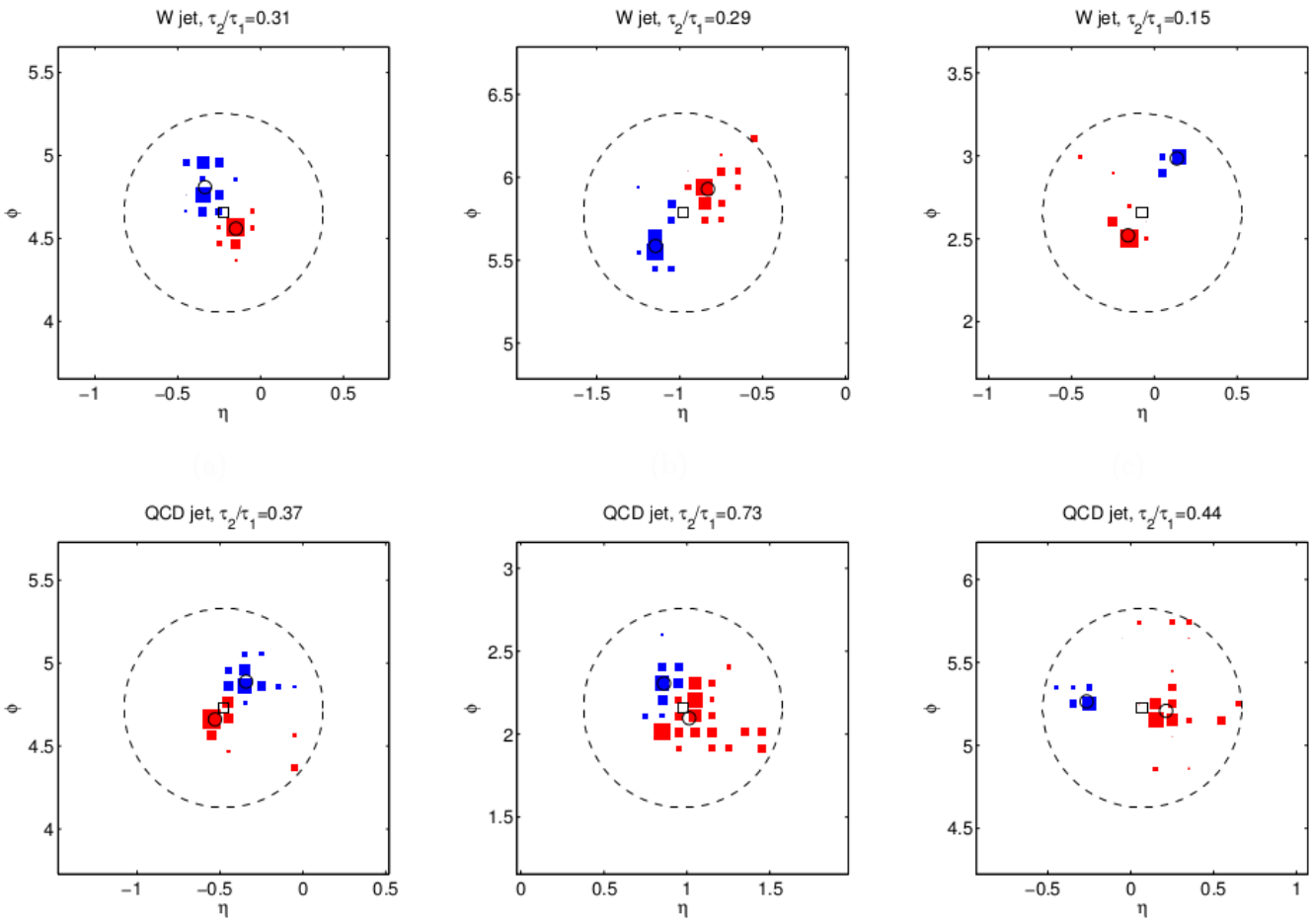






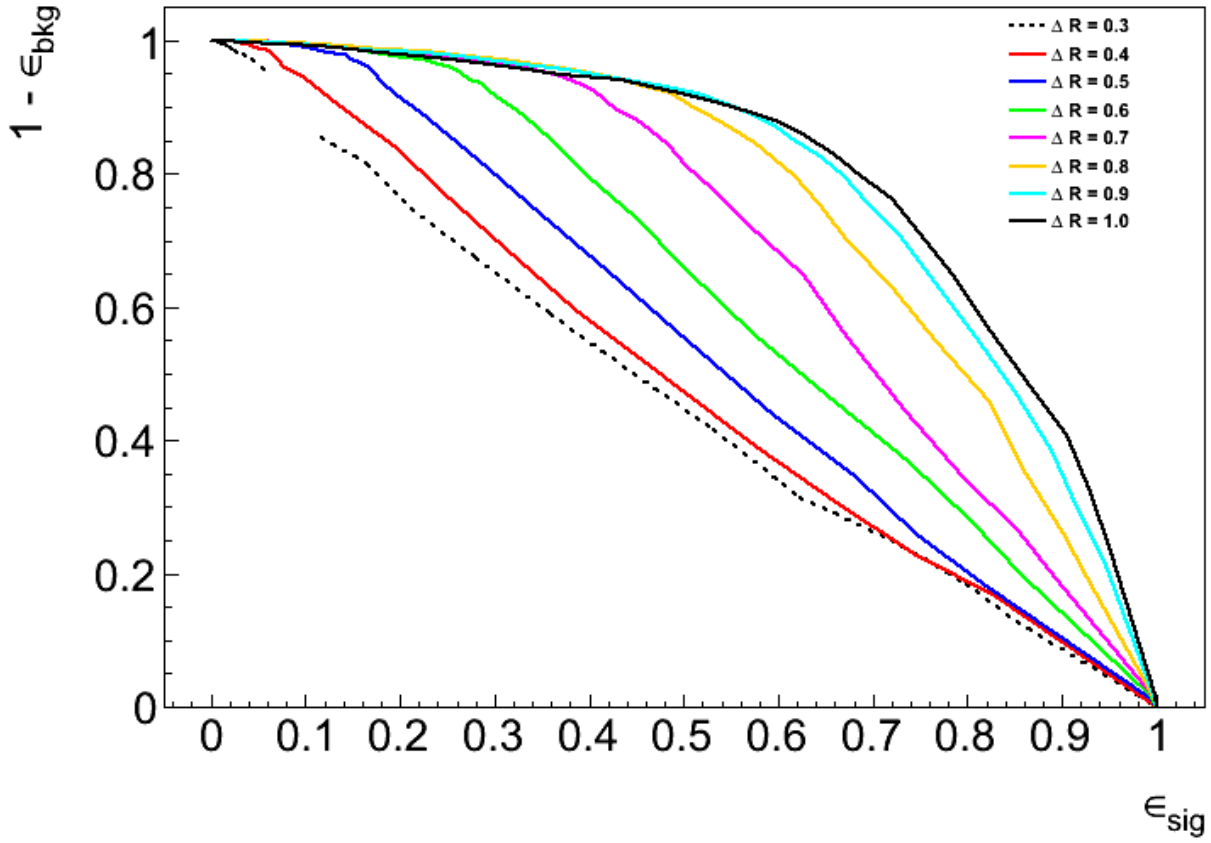
- PU jets pass p_T cuts frequently at high pileup

Substructure Using N-Subjettiness



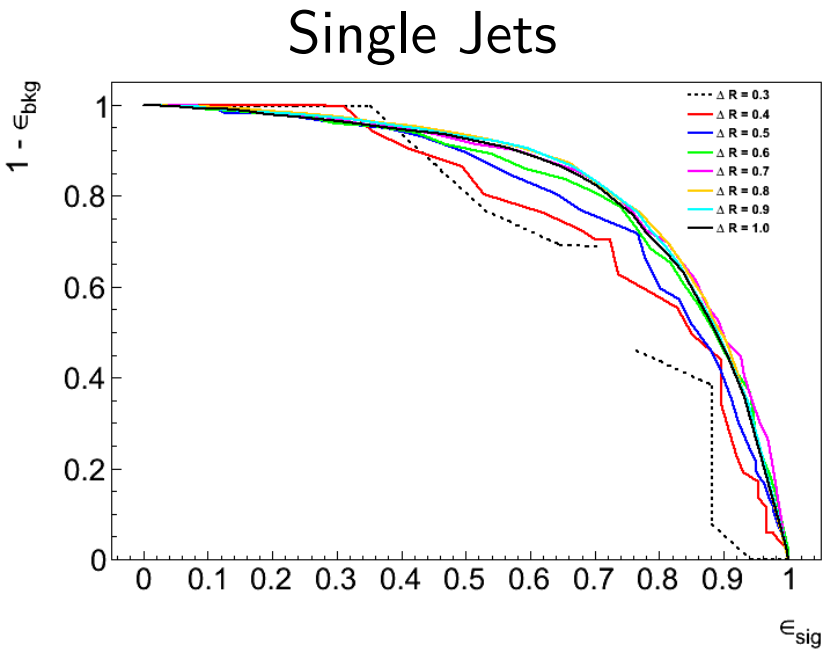
- Using ratios of τ_2/τ_1, W jets are distinguished from gluon jets

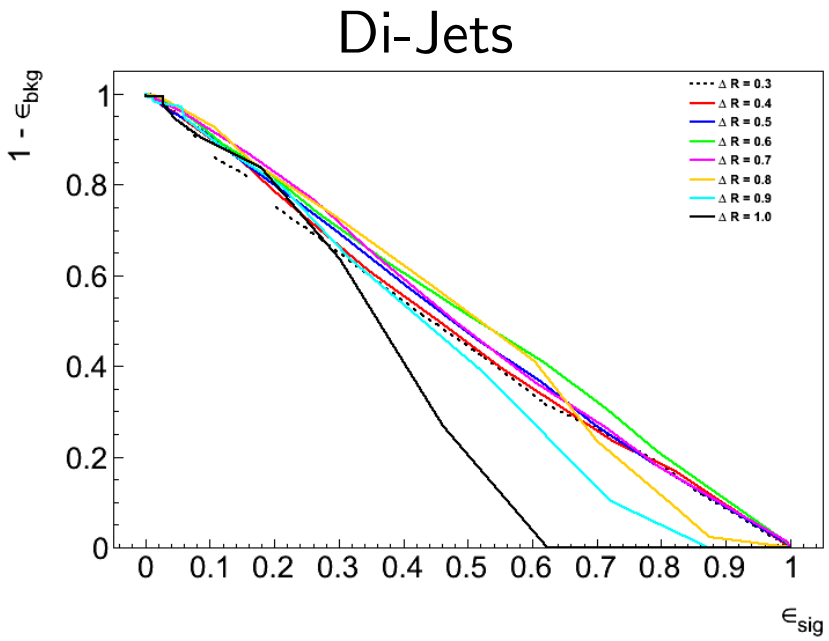
ROC Curve Over Various N-Subjettiness Cuts



- The ROC curve for various cone sizes

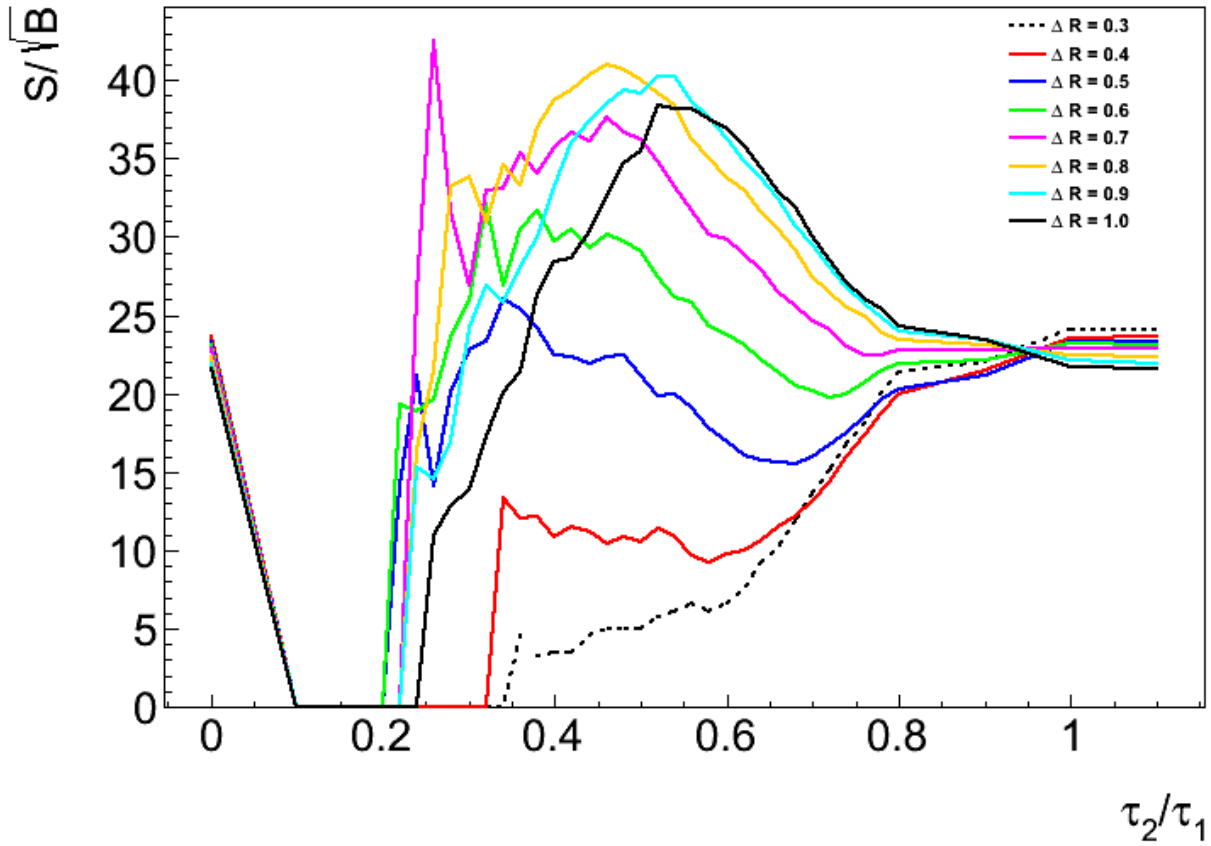
ROC Curve Over Various N-Subjettiness Cuts





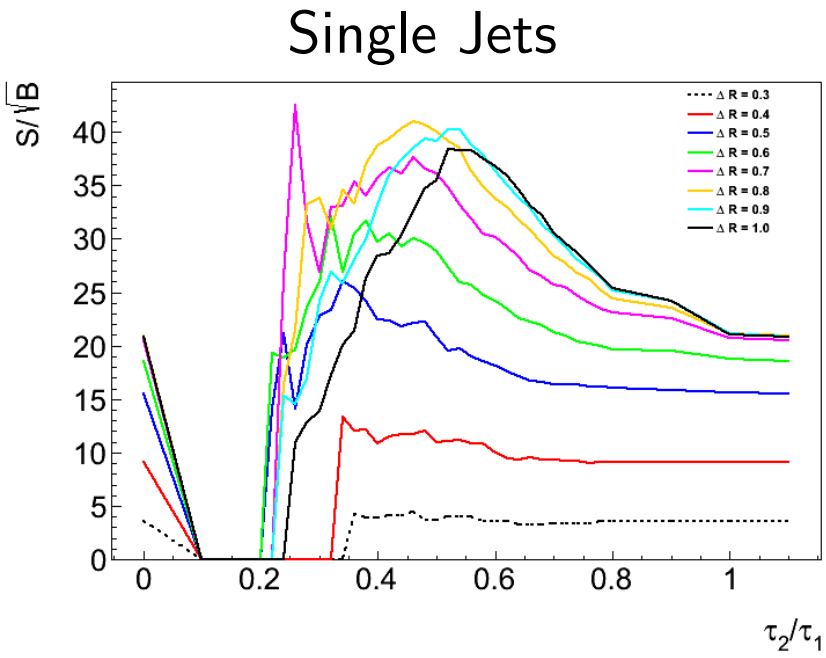
- Considering single jets works much better

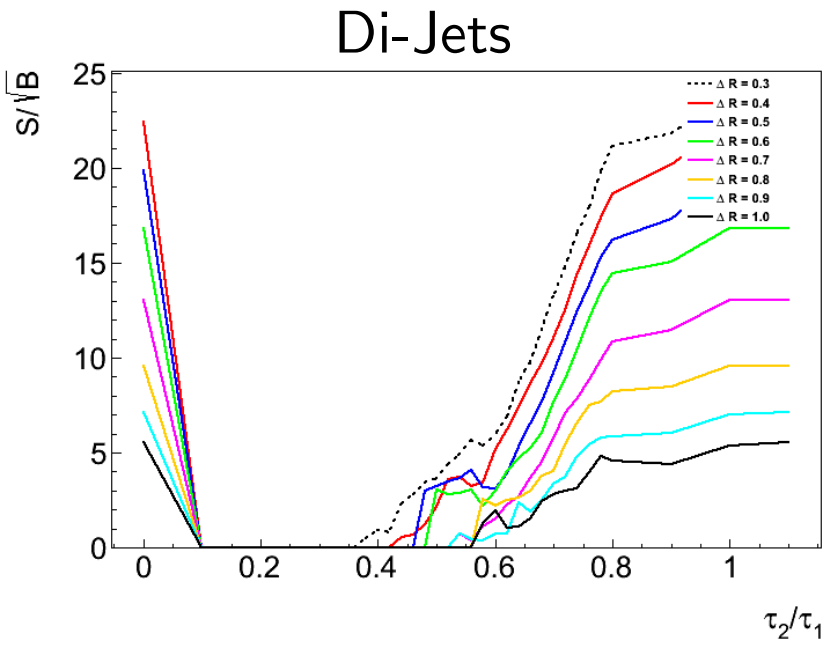
Signal Significance Over N-Subjettiness Cuts



- The signal significance for various τ_1/τ_2

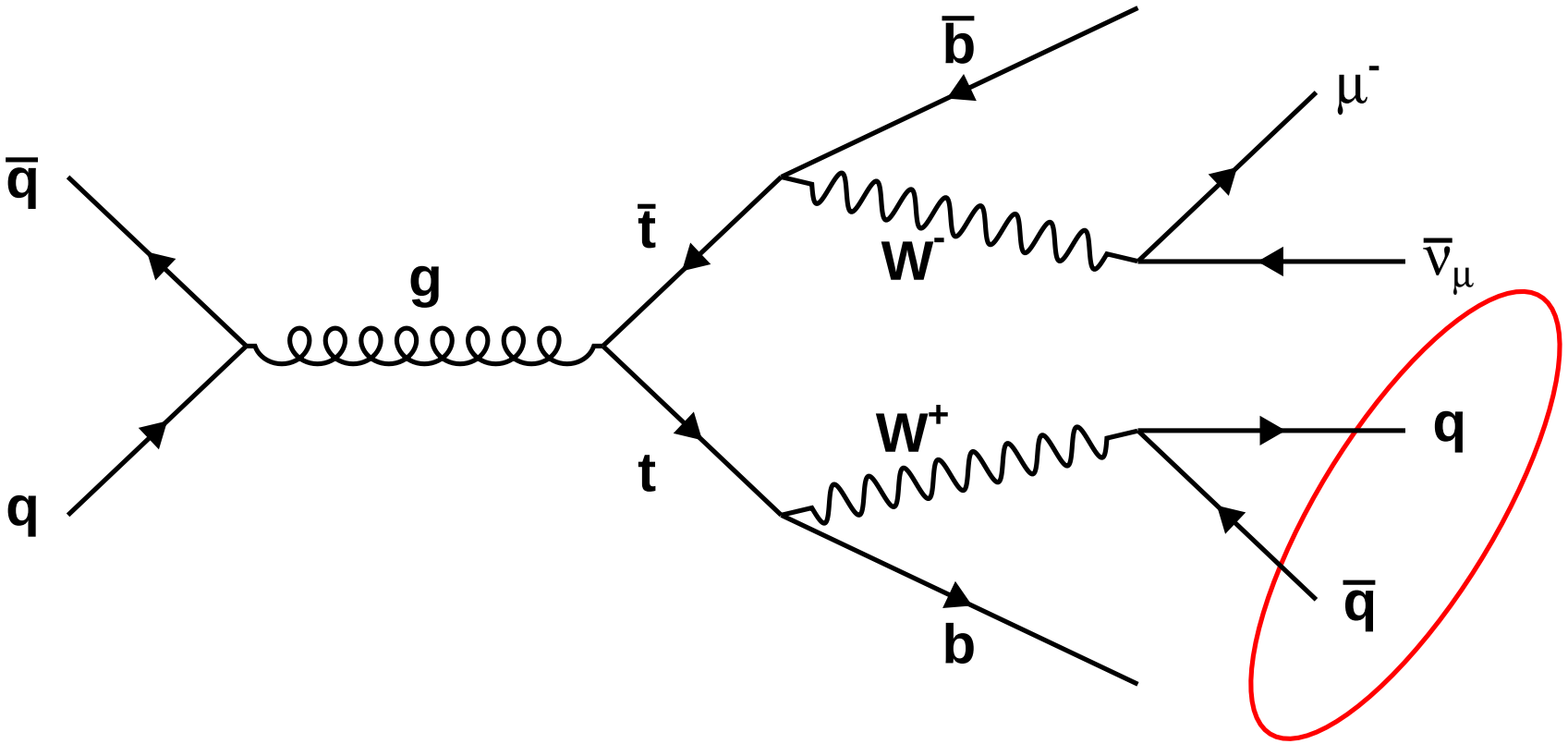
Signal Significance Over N-Subjettiness Cuts





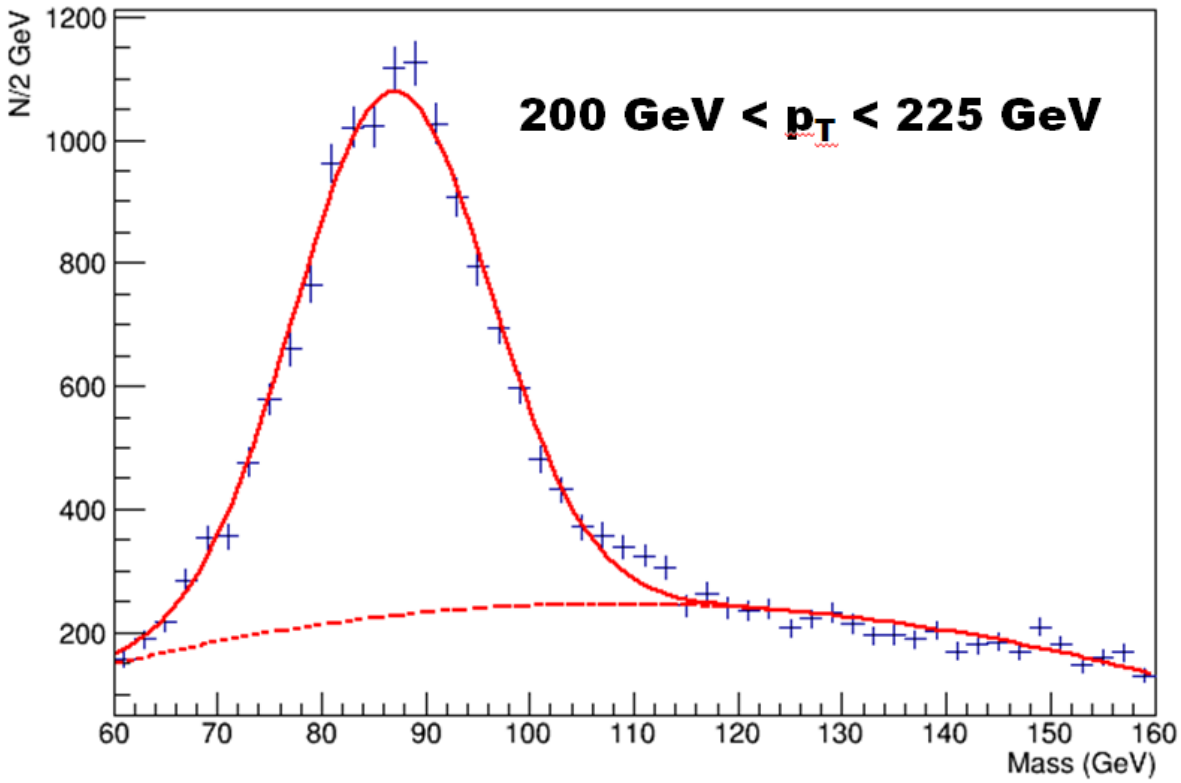
- Again, single jets are better for optimizing signal

A Benchmark for W Bosons



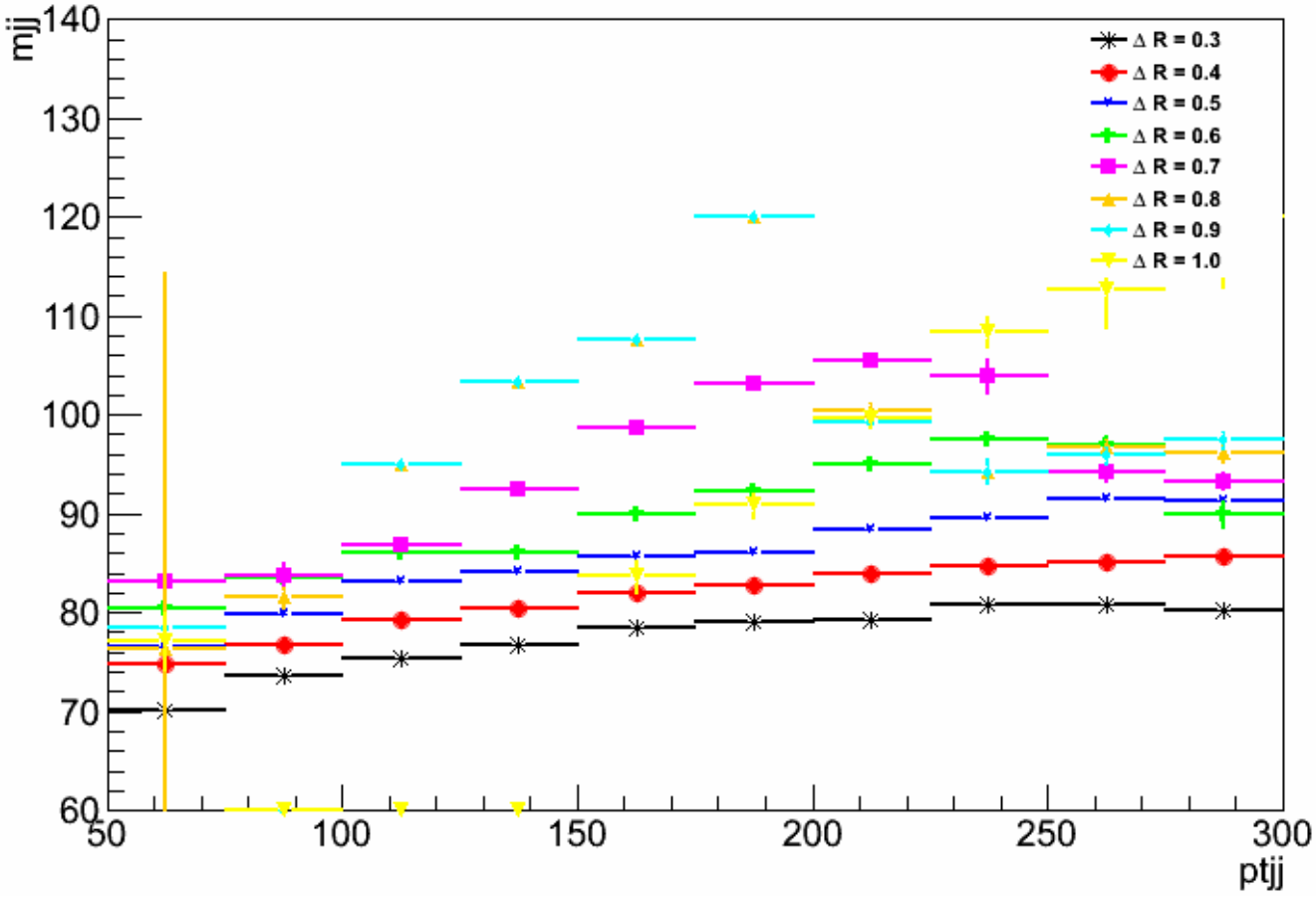
- Ws are always produced by a top quark, which can be spotted through b-tagging

Characterizing the W Peak



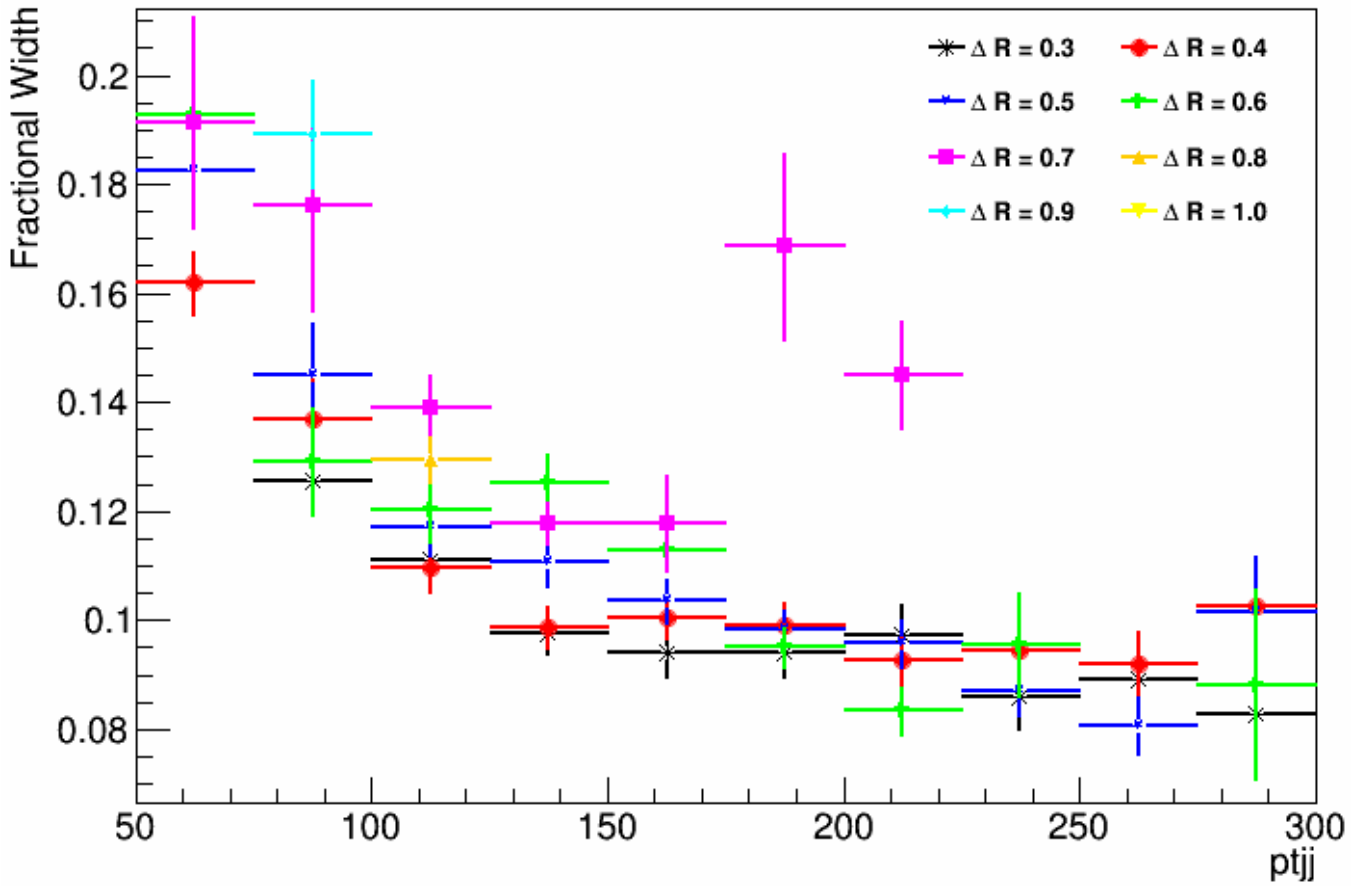
- Gaussian peak on a quadratic background
- We want a constant Gaussian mean and narrow width

Effect of Cone Size for Varying p_T



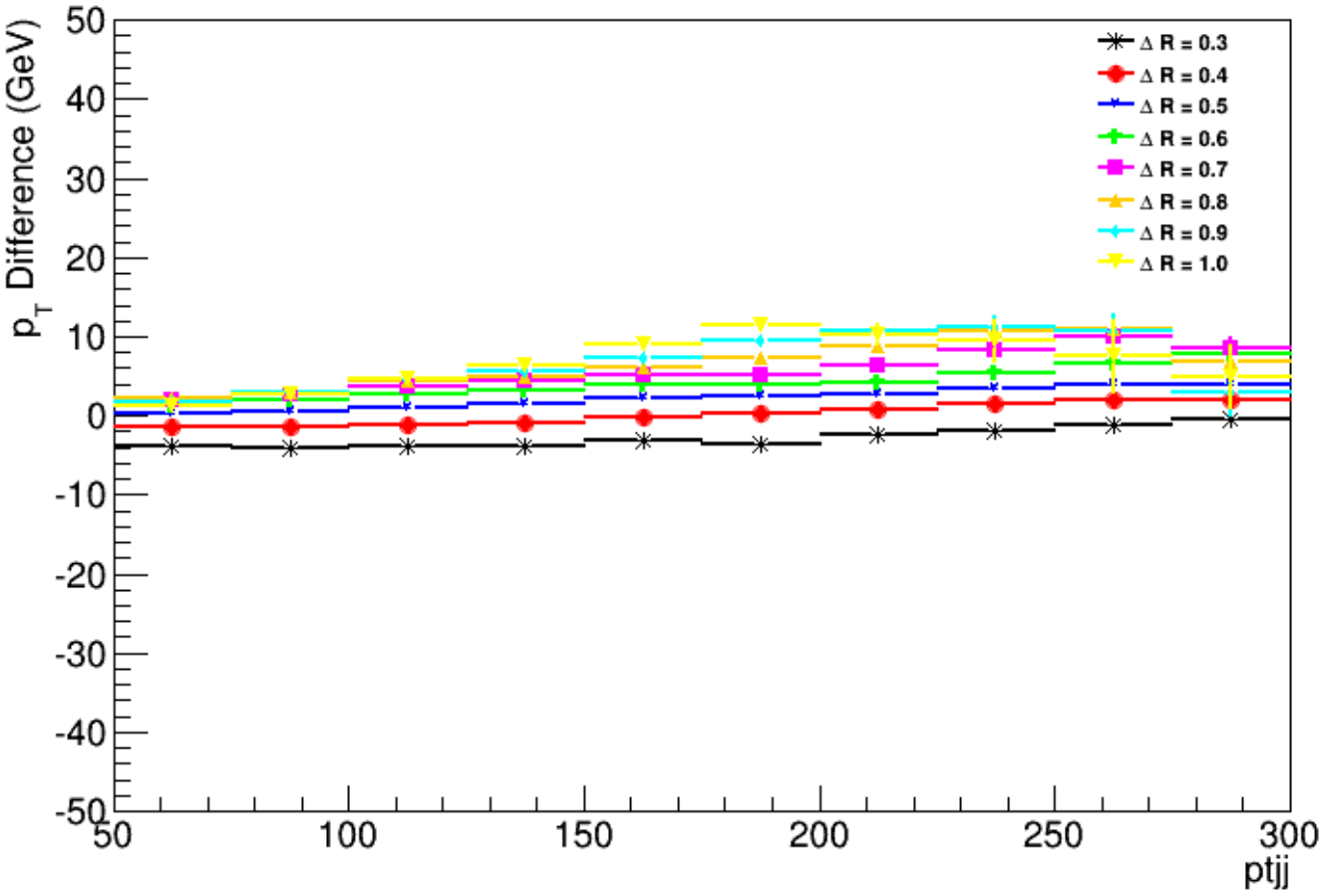
- Jet mass corrections were done for $\Delta R = 0.5$

Effect of Cone Size for Varying p_T



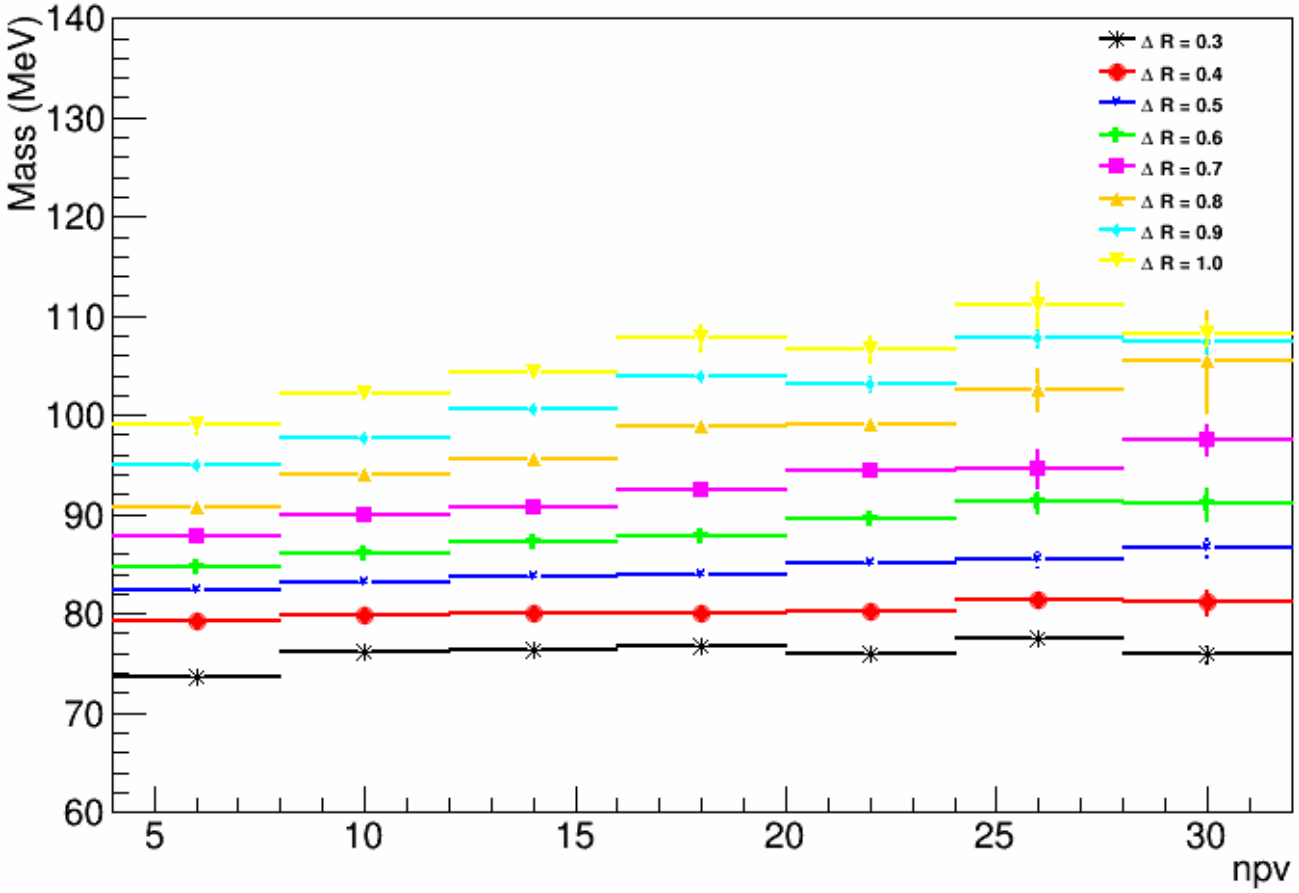
- Smaller cone sizes give the best resolution

Effect of Cone Size for Varying p_T



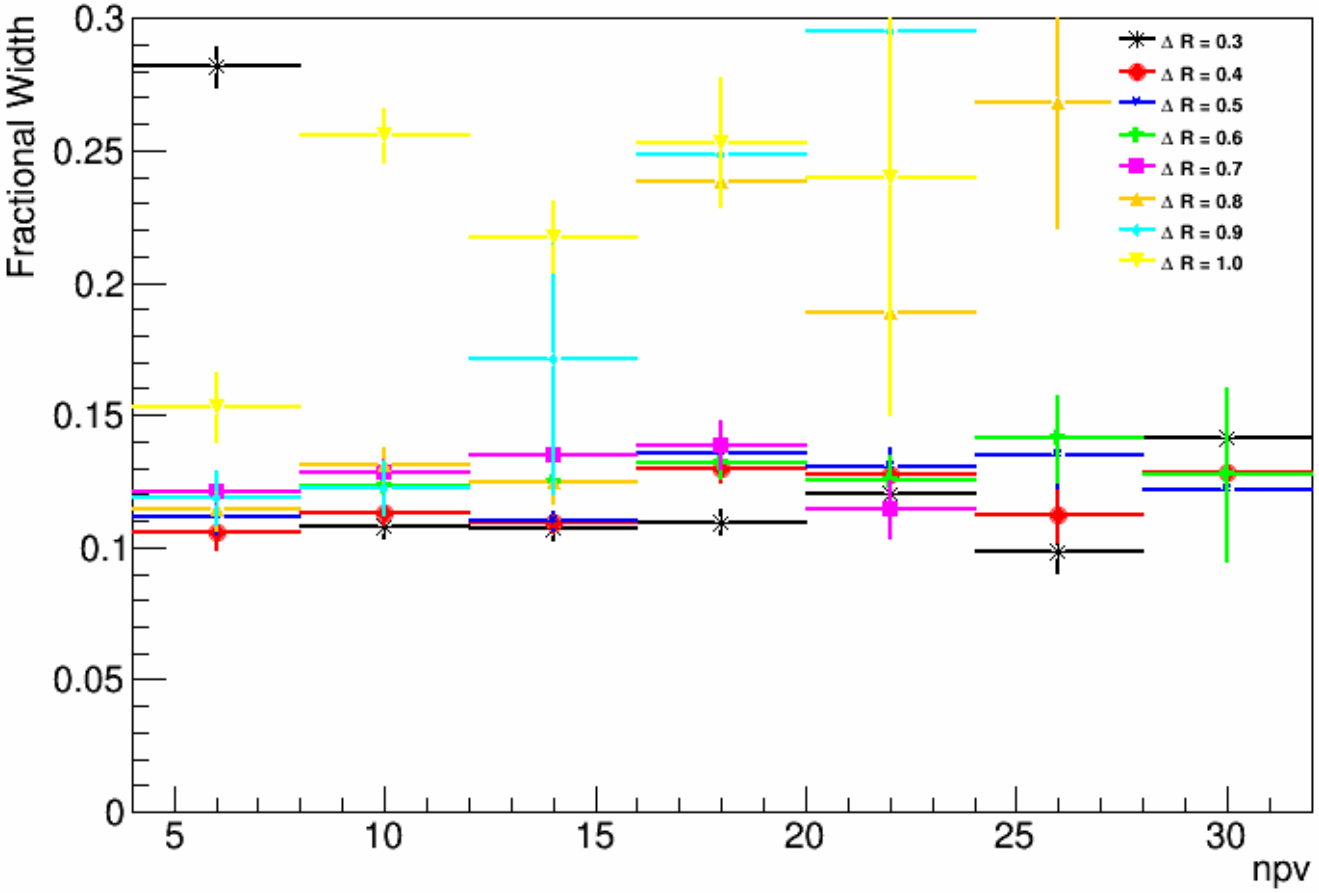
- Smaller cone sizes loss the most p_T

Effect of Cone Size for Varying NPV



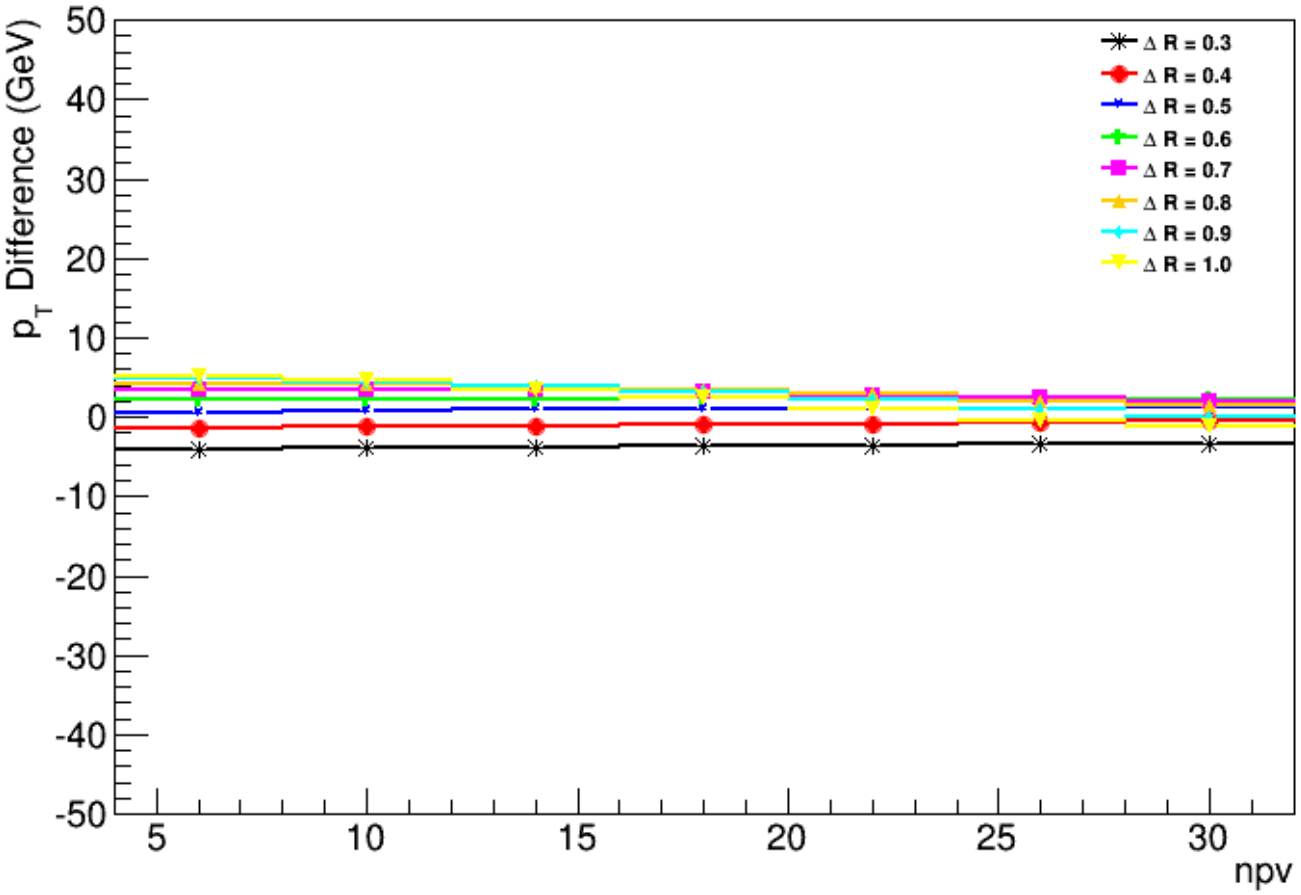
- Constant response over NPV

Effect of Cone Size for Varying NPV



- Smaller cone sizes give the best resolution

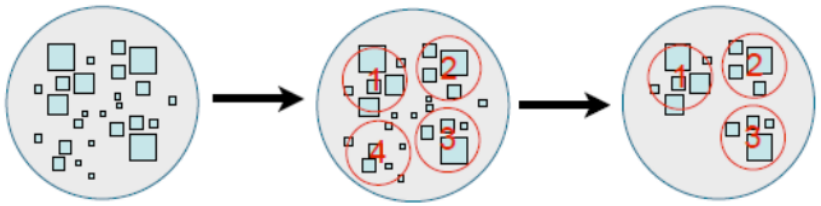
Effect of Cone Size for Varying NPV



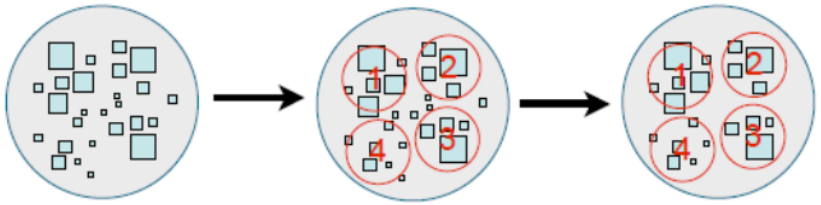
- Smaller cone sizes loss the most p_T

Grooming Algorithms

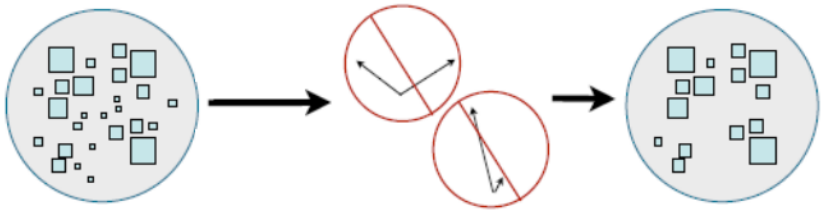
- Filtering
  - Smaller clusters gathered
  - Set number is kept



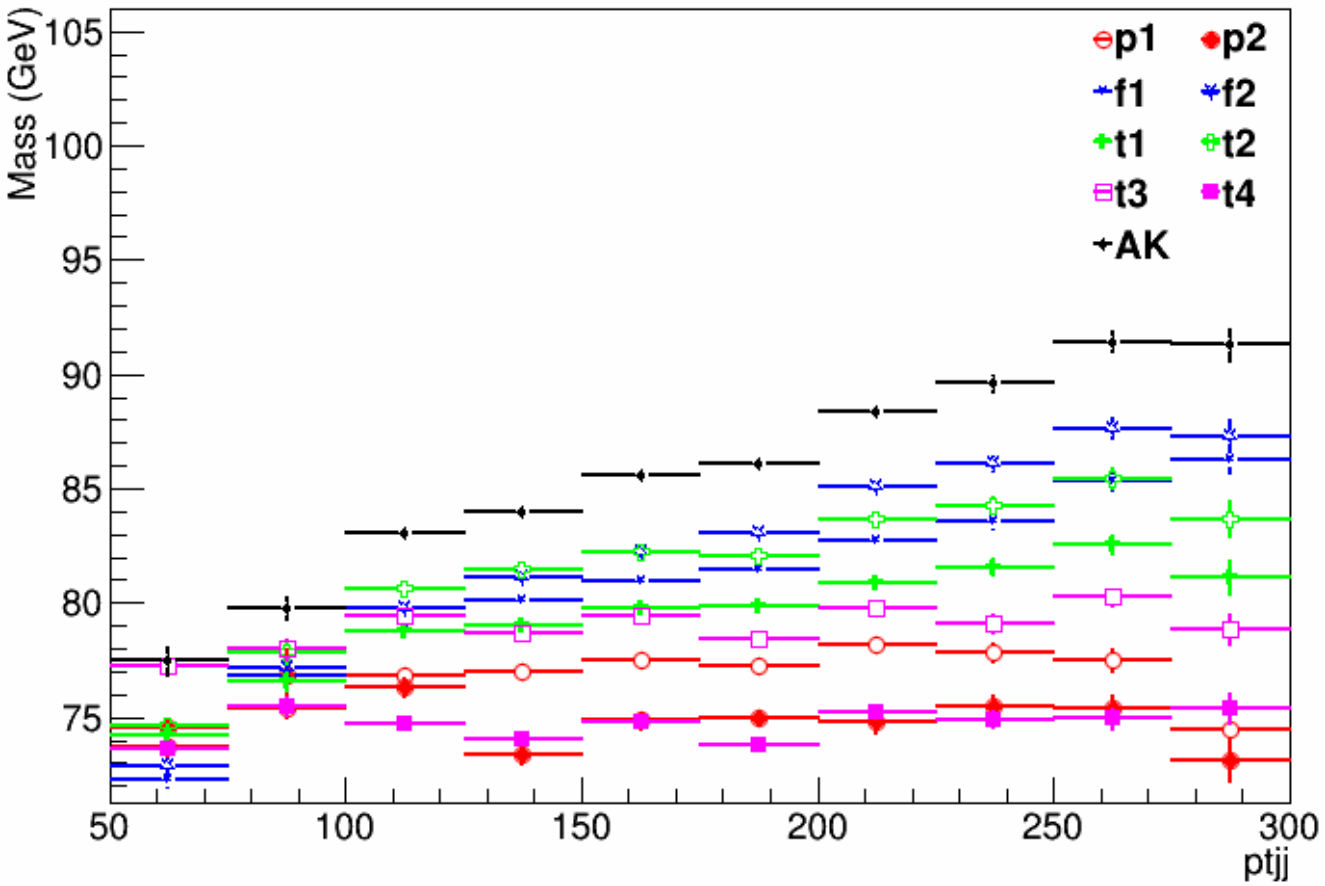
- Trimming
  - Smaller clusters gathered
  - Low fractional p_T is cut



- Pruning
  - Each vertex is considered
  - Large angles or extreme p_T ratios cut

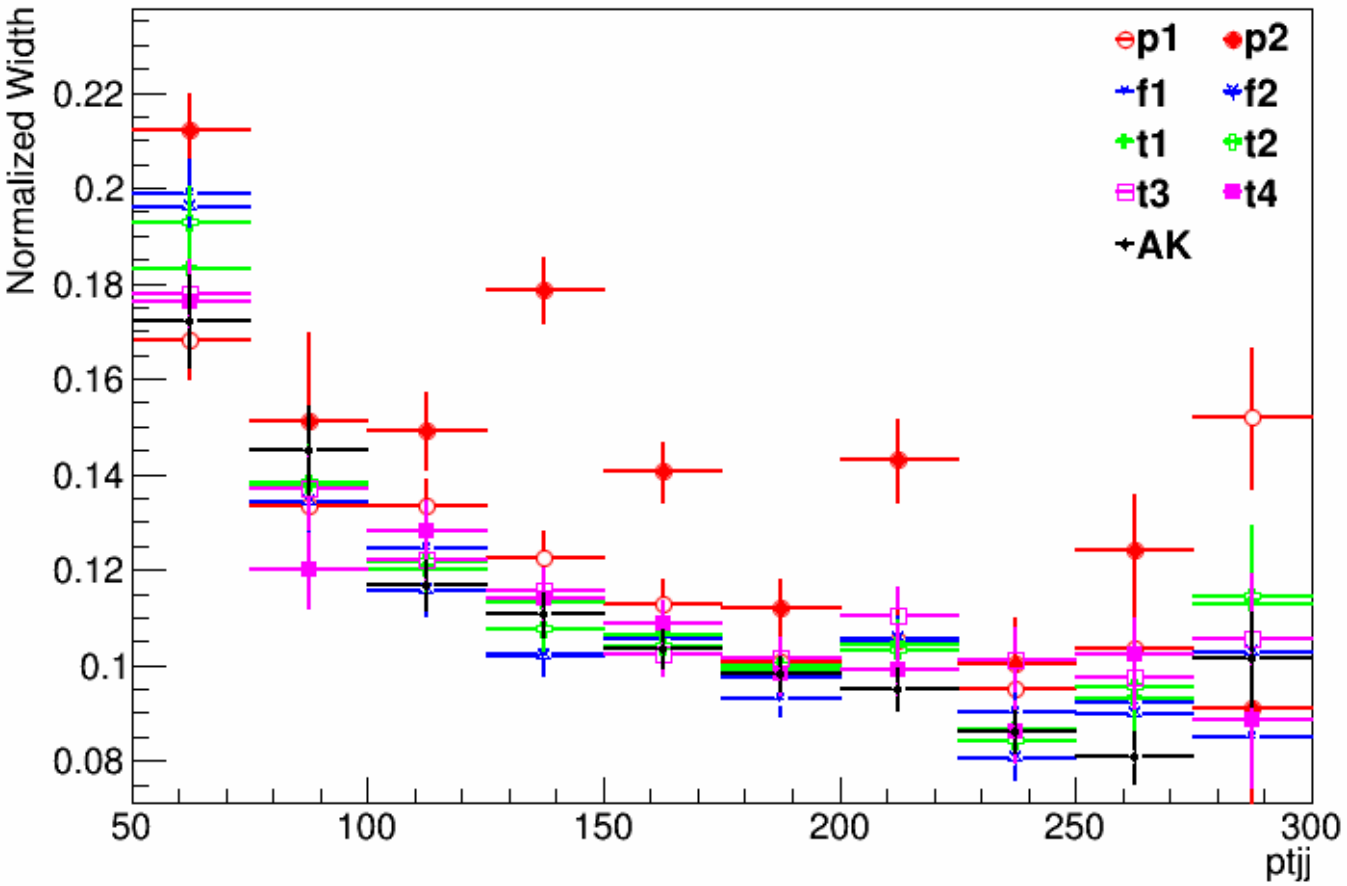


Effect of Grooming for Varying p_T



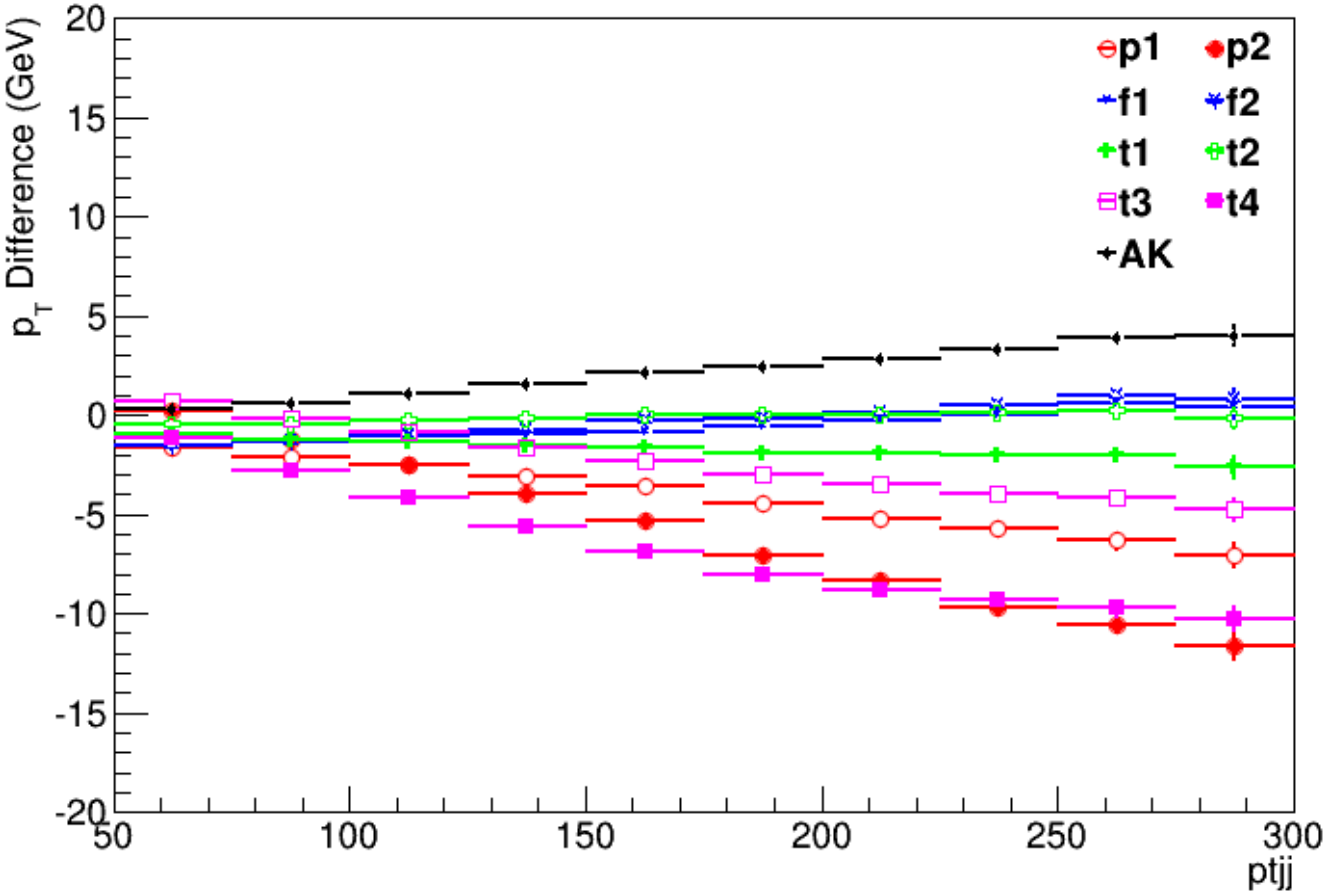
- Trimming and pruning stay constant

Effect of Grooming for Varying p_T



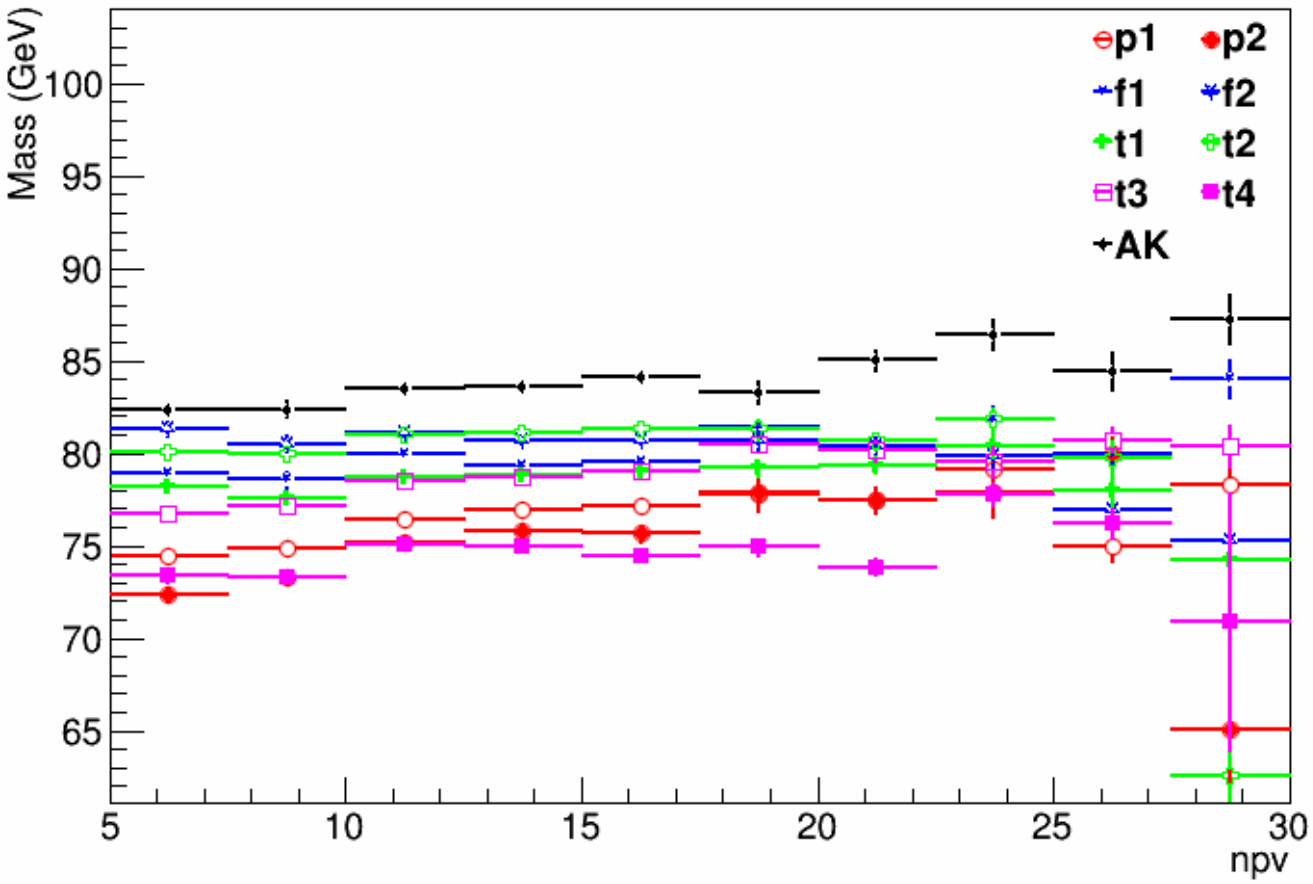
- Pruning gives poor mass resolution

Effect of Grooming for Varying p_T



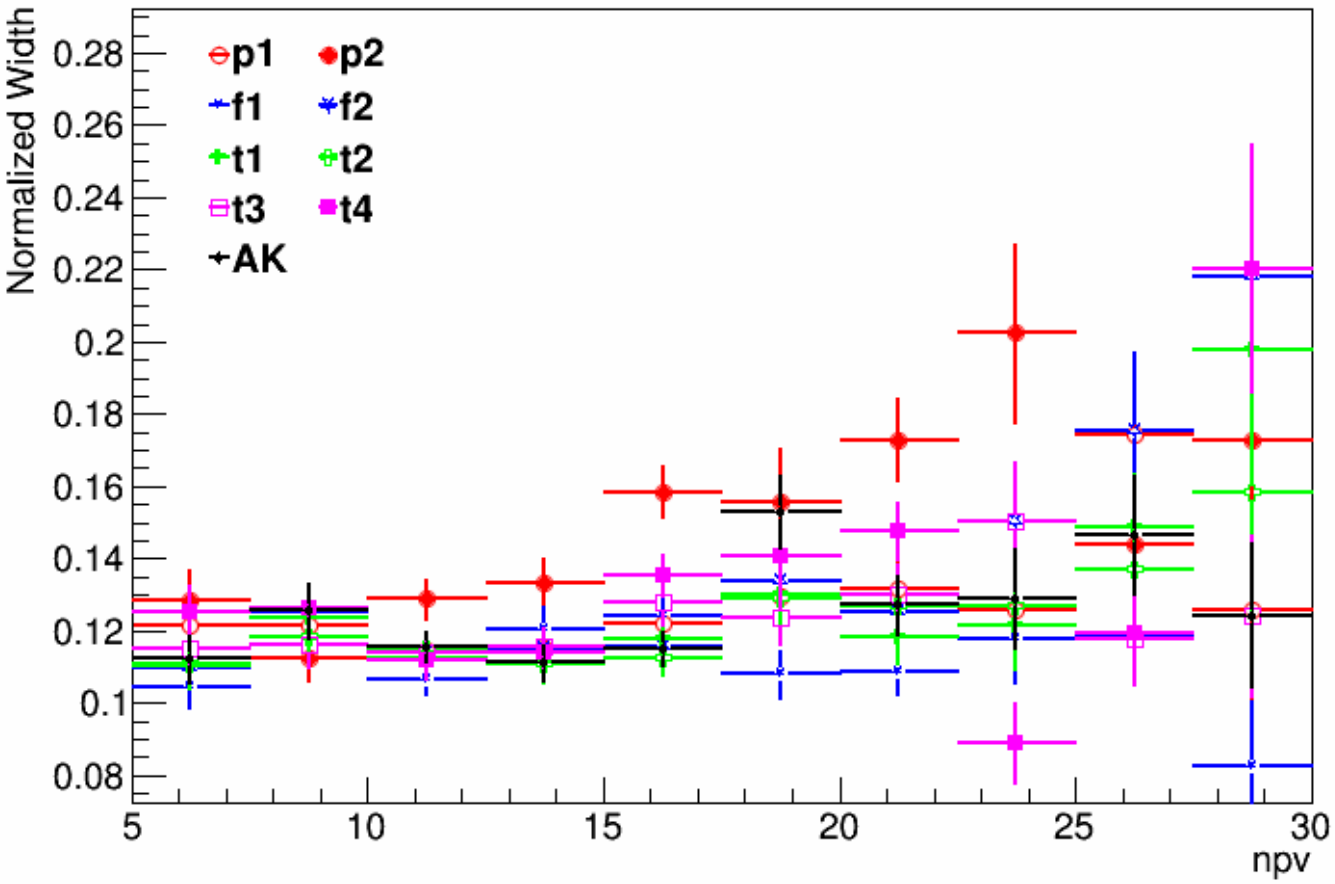
- Pruning and tight trimming also lose a lot of p_T

Effect of Grooming for Varying NPV



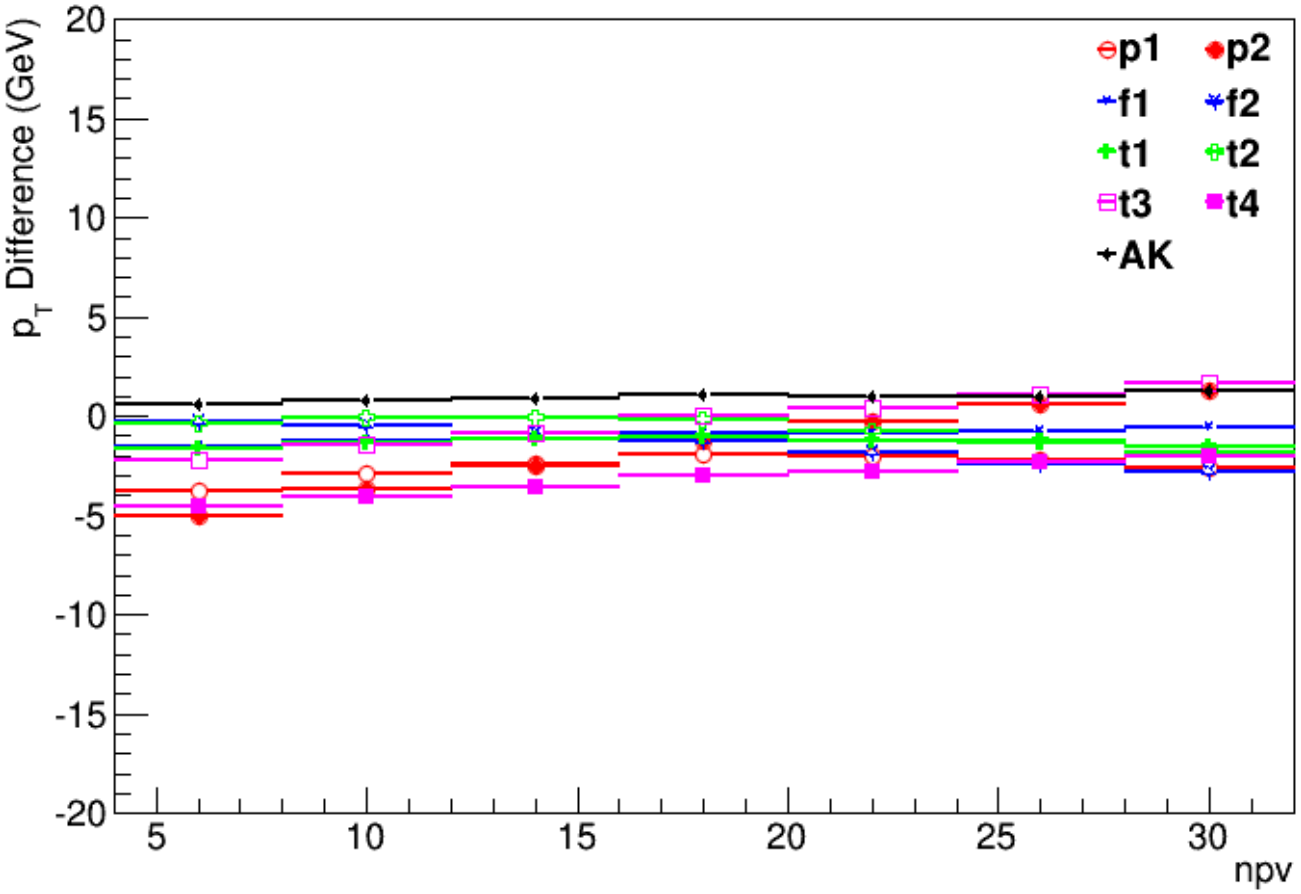
- Relatively constant response for NPV again

Effect of Grooming for Varying NPV



- Pruning again gives poor resolution

Effect of Grooming for Varying NPV



- No particular algorithm is best at retaining p_T for all NPV

Some Tentative Conclusions

- To separate Higgs events from Z events, a cone size of $\Delta R = 0.9$ with an N-Subjettiness cut of $\tau_2/\tau_1 < 0.55$ is recommended
- A smaller jet cone size of $\Delta R = 0.4$ will more accurately reconstruct the W boson
- Either filtering or trimming with larger cones should replace the CMS default of pruning
- These current conclusions should be confirmed (or not) within the next month