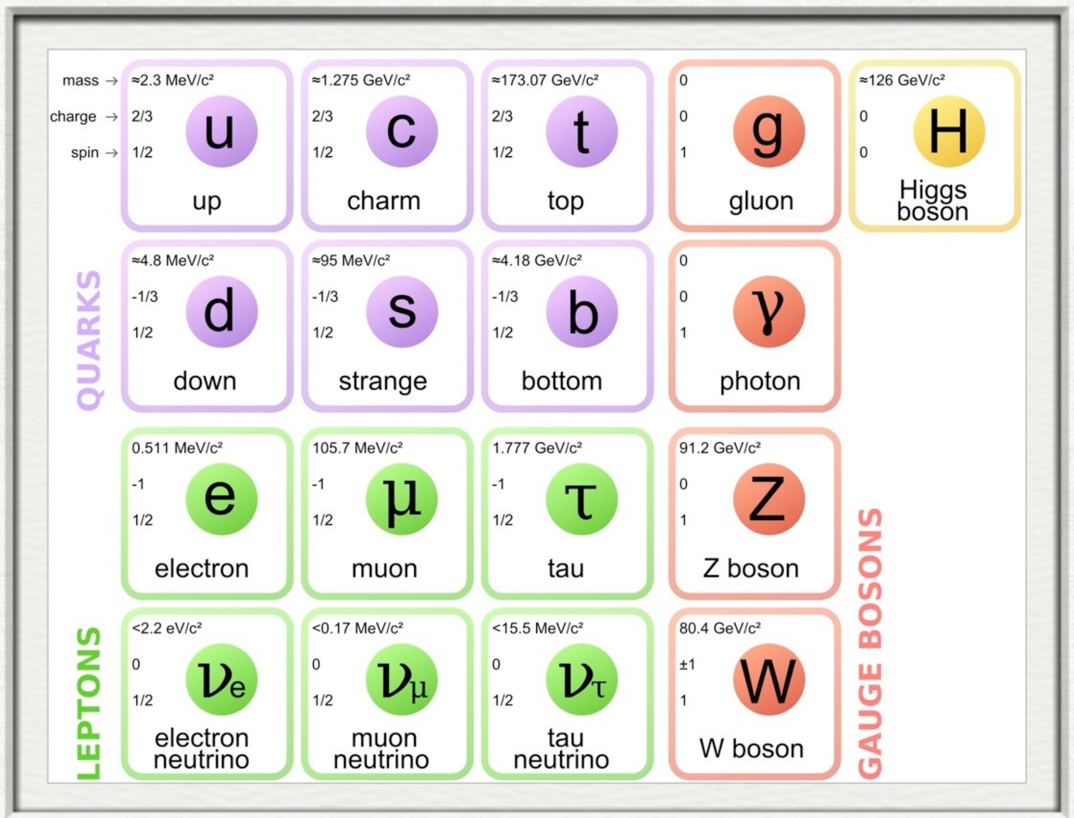
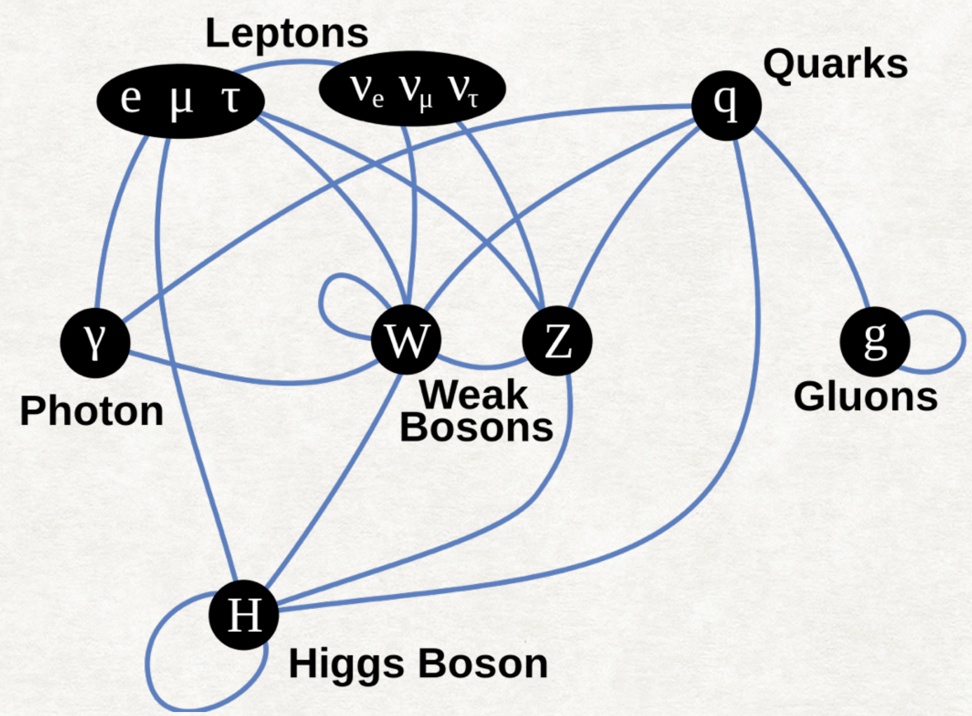
Object Reconstructions and Corrections in Analyses at the LHC

Tulin Varol

The Standard Model

- Describes the fundamental particles and interactions between them





- Three generations leptons and quarks

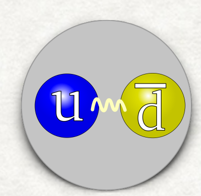
Particle Classification

Leptons

Hadrons

Mesons

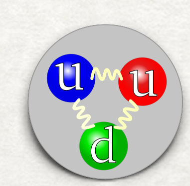
quark | anti quark

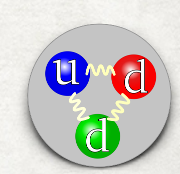


Baryons

quark | quark | quark

anti quark | anti quark | anti quark





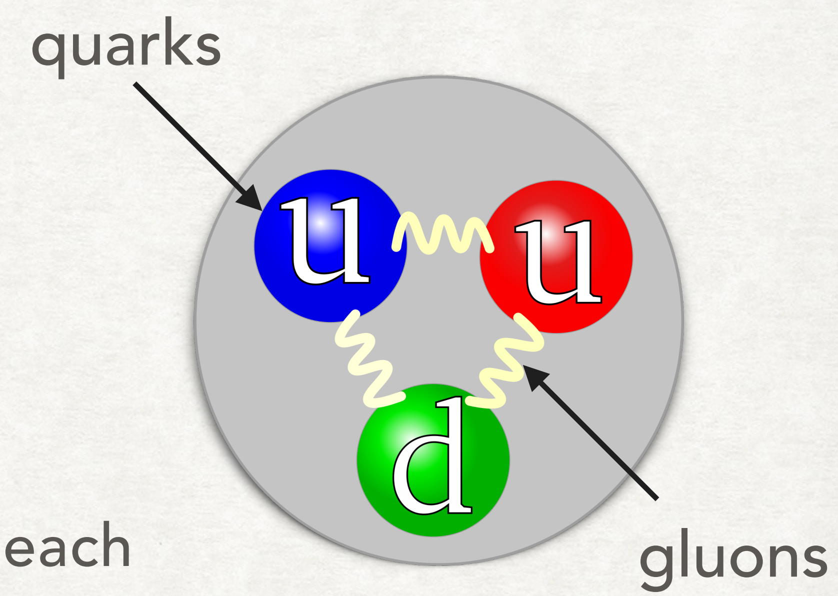
QCD in a Nutshell

- **QCD - Theory of Strong Interactions**

- Point-like fermions called **quarks**
  - Six different flavours (u,d,c,s,t,b)

Free particles (hadrons) are colourless

- **Quarks carry colour - analogous to electric charge**
  - There are three types of colour (red,blue,green)



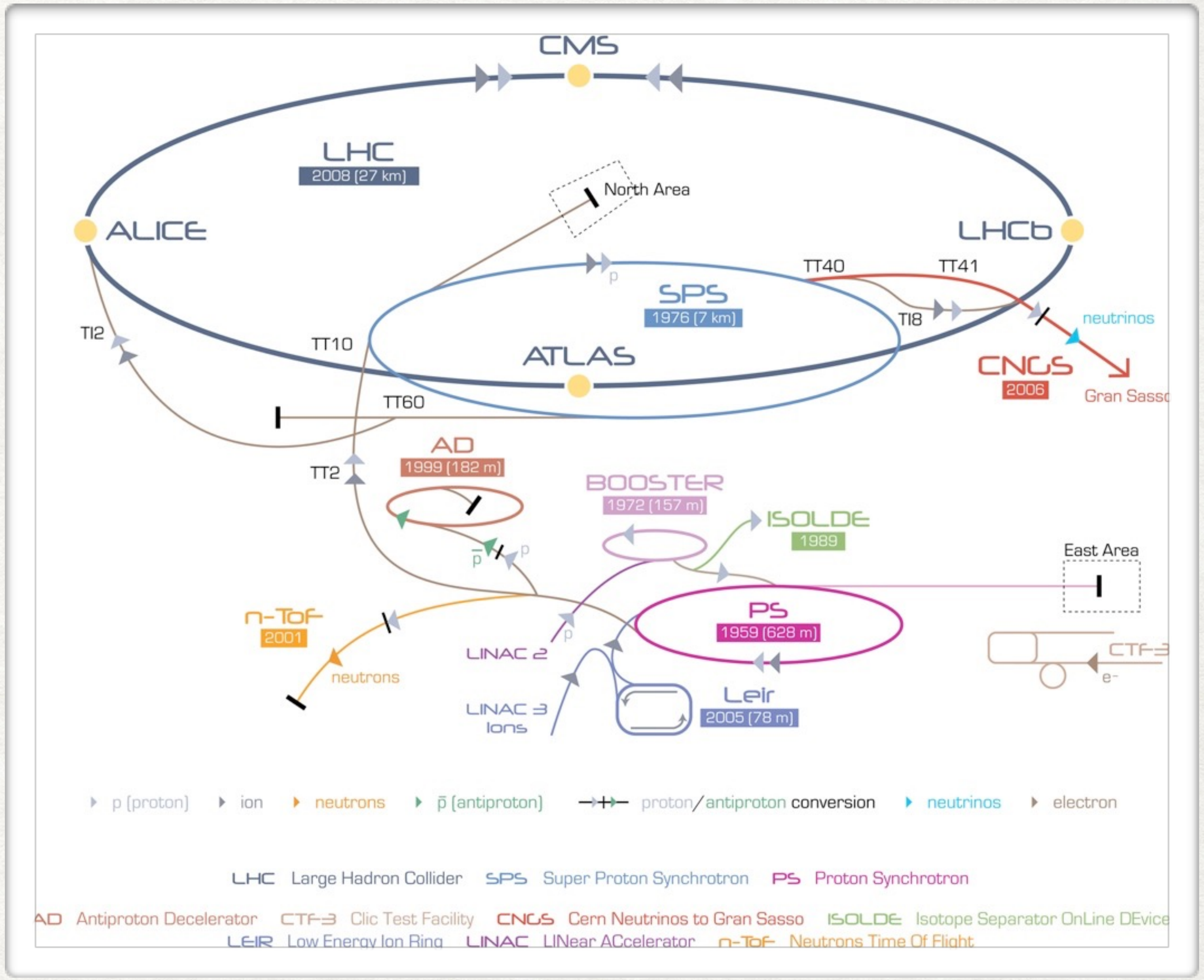
- Mediating boson is called **gluon**

- **Gluons have color "charges"** and hence can interact with each other

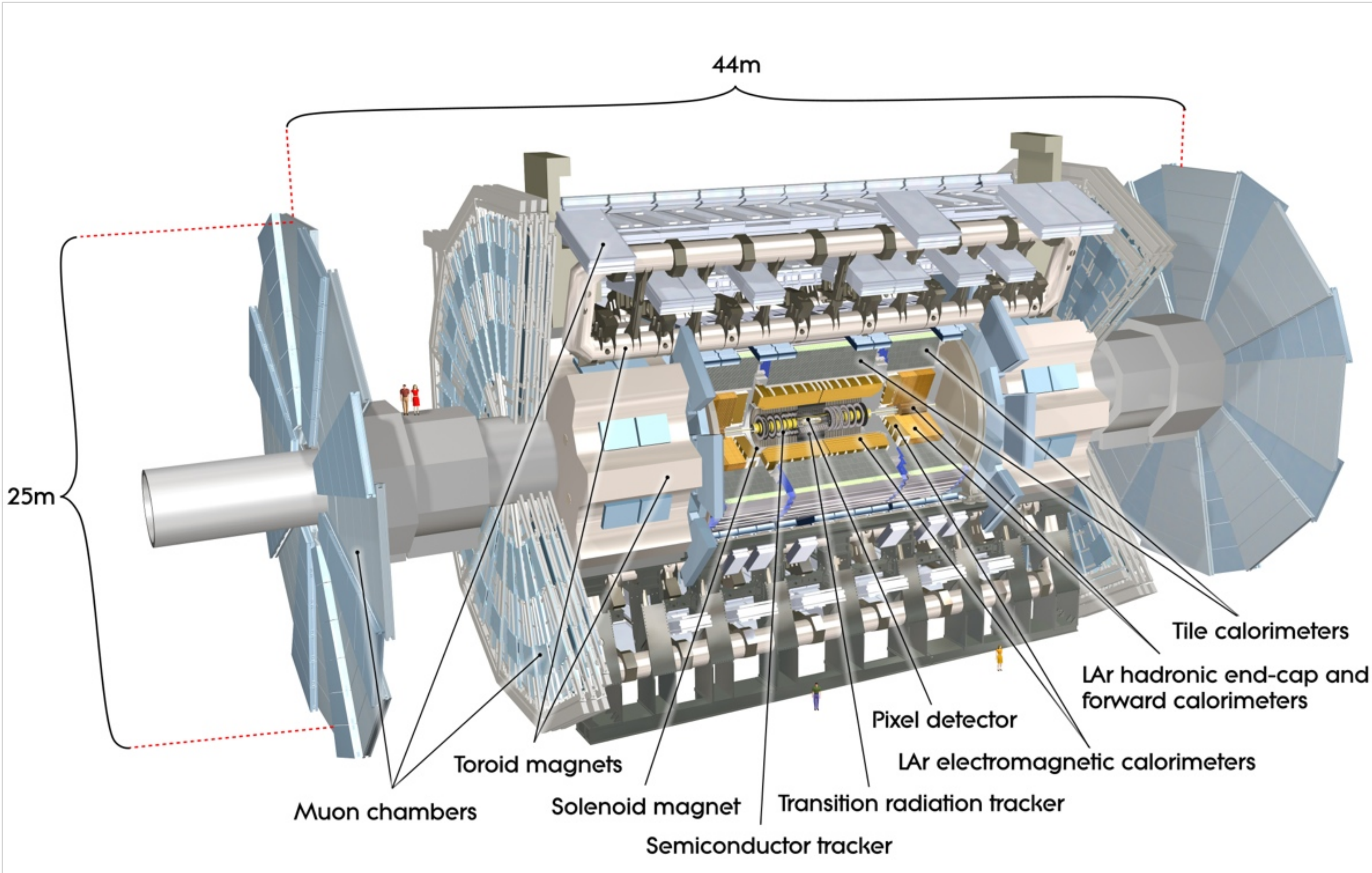
- At large distances: parton interactions become large (**confinement**)
- At small distances: parton interactions become small (**asymptotic freedom**)

The Large Hadron Collider

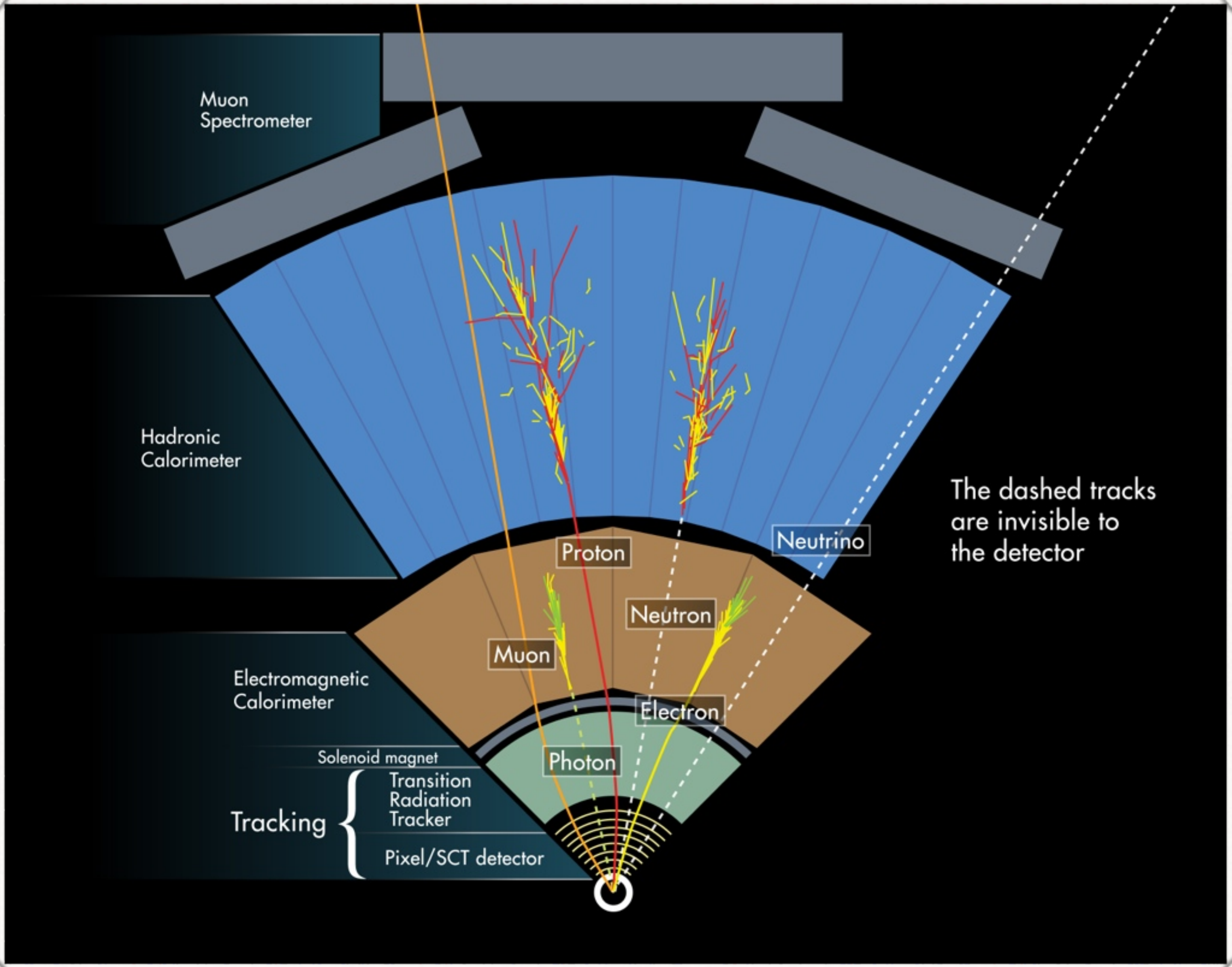
- **Highest energy collider in the world**
  - 27 km in circumference
  - Collides protons (p-p), lead ions (Pb-Pb) or both (p-Pb)
- **4 collision points:**
  - **ATLAS**, CMS, ALICE, LHCb
- **pp collision energy:**
  - 7 TeV in 2011
  - 8 TeV in 2012
  - 13 TeV in 2015



The ATLAS Detector

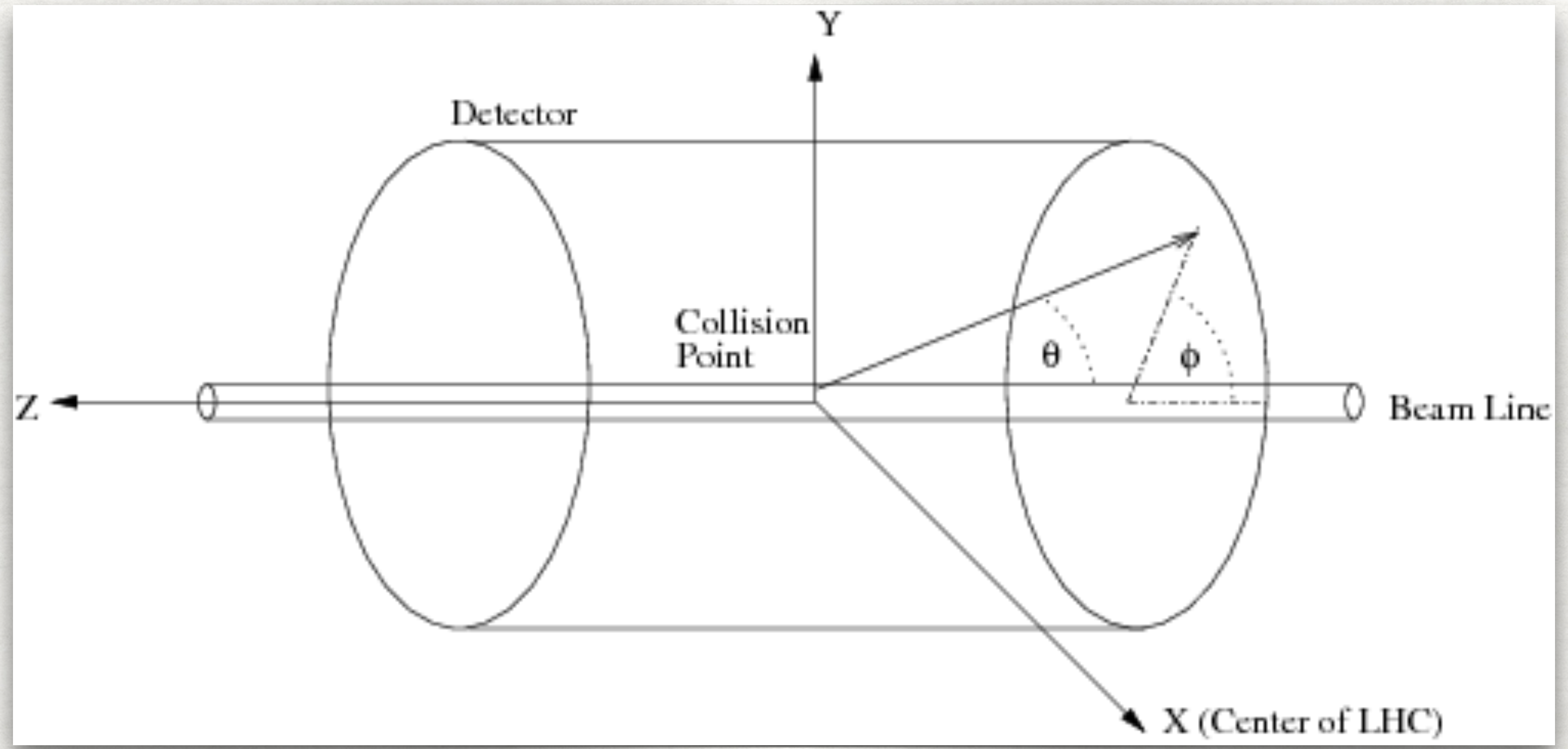


Particle Identification in the ATLAS



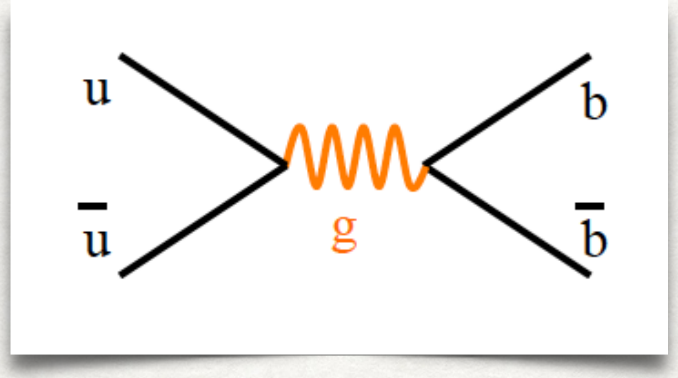
ATLAS Coordinate System

- A right-handed coordinate system with z along the beam line

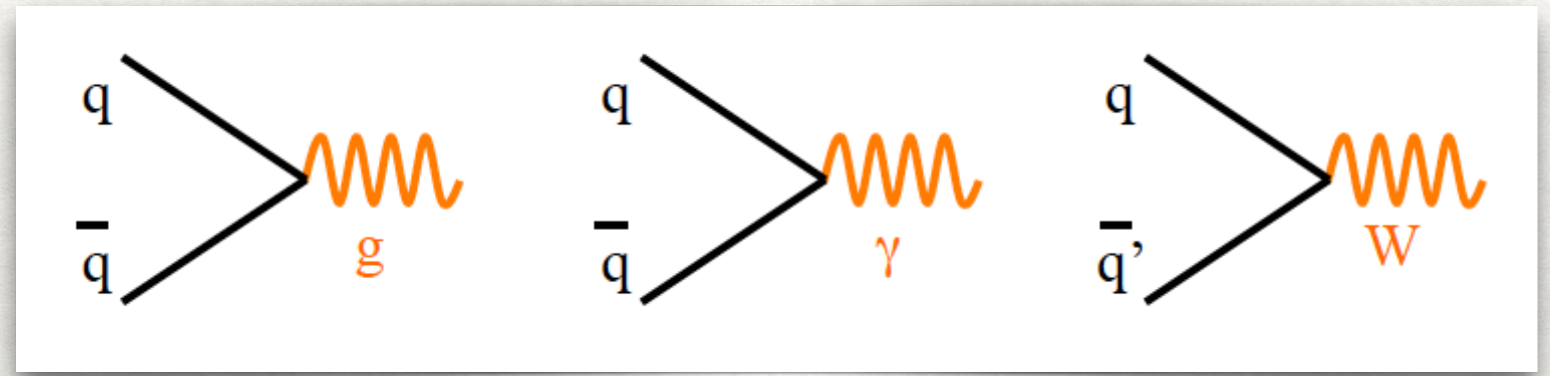


Hadronic Collisions

- Most interested in **the interactions between the constituent partons** and not between the protons themselves



- Quarks participate in **strong, weak, and electromagnetic interactions**



Analysis at a Hadron Collider

- SM precision measurements
- New physics searches (BSM models)

- To perform an analysis, one needs
  - Object Reconstruction/Selection
  - Event Selection

- Need to apply corrections to the objects and events

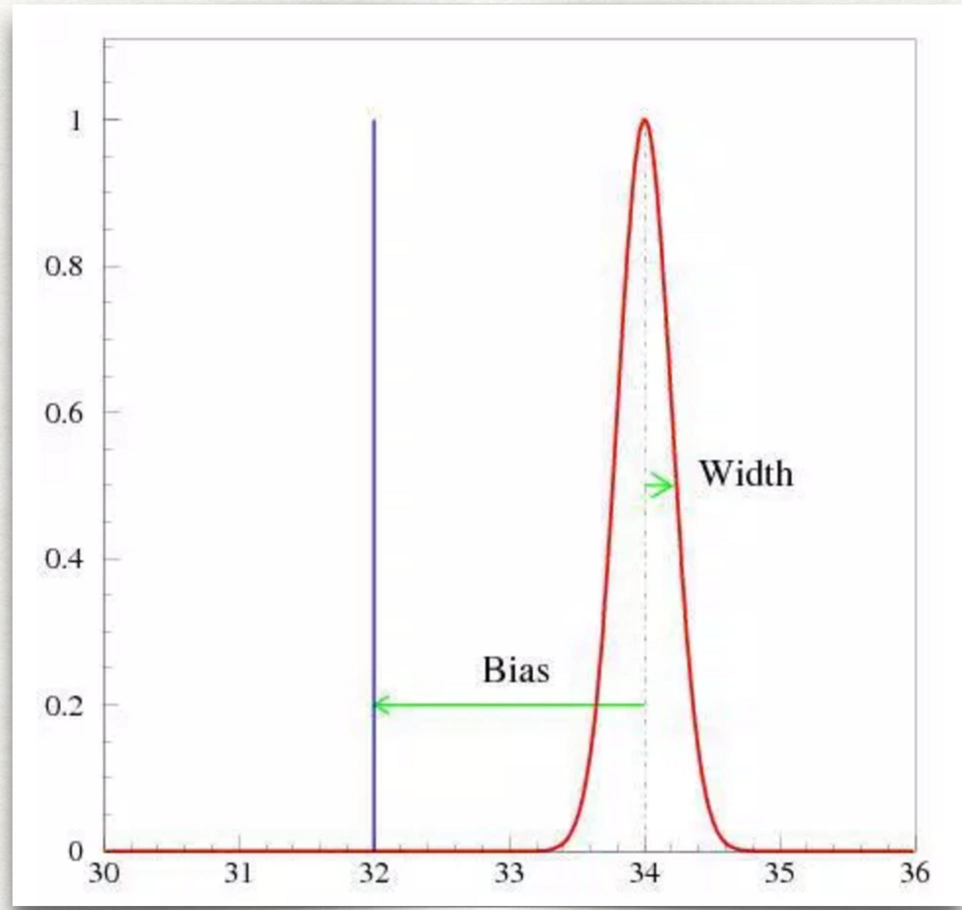
- Academic training lecture programme on "Analysis at a Hadron Collider" :
  - https://indico.cern.ch/event/77805/

Why Corrections?

- No such thing as perfect measurement:
  - Particles hit parts of the device which are un-instrumented or malfunctioning
  - i.e. The part of the calorimeter measuring the jet may be hit by additional particles not belonging to the jet originated from the quark, affecting our measurement
- All these effects are modelled with a detailed simulation program
  - The program knows in detail how the detector is made, knows the physics of the interaction of energetic particles with matter
  - We can thus study how a measurement is degraded by all the known effects

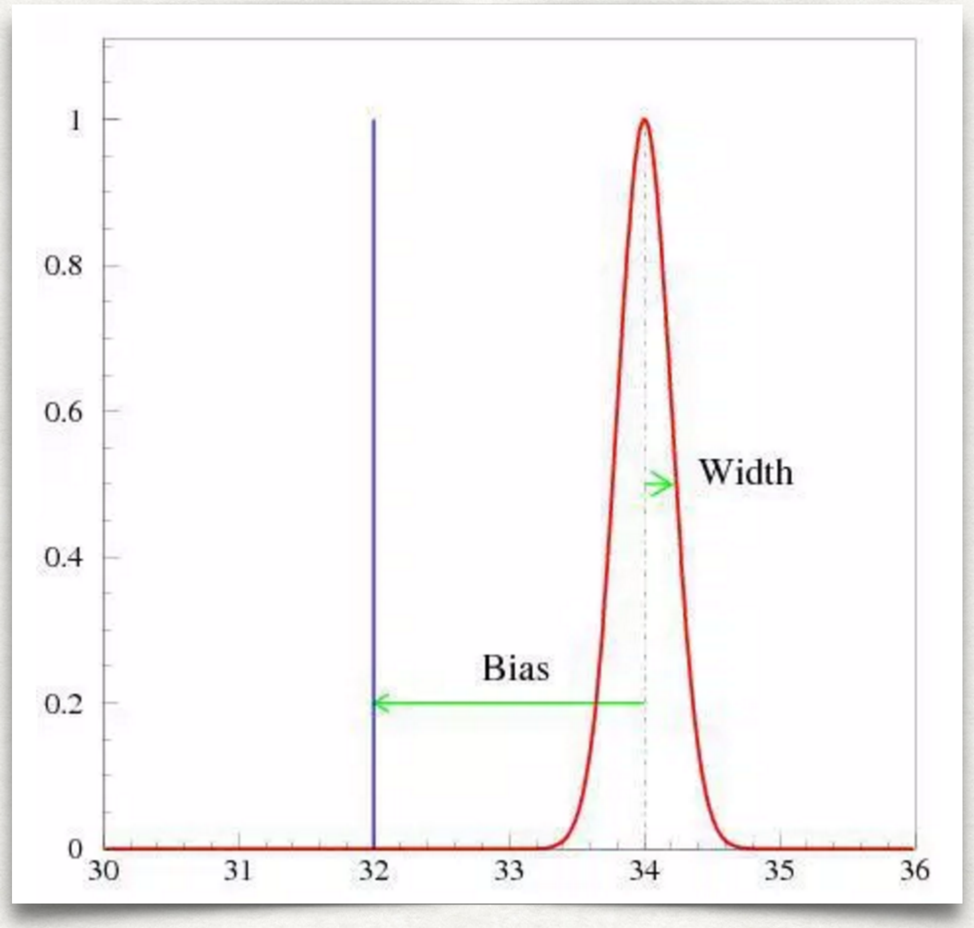
Example: Scale

- Start with a quantity we are all more familiar with: **temperature**, rather than particles' energy
- A biased measurement of temperature?
- Insert the **thermometer in melting ice** (32°F)
- **Note the reading**
- **Do it a hundred times**, with different containers, at different hours of the day, different weather conditions
- The deviation of the peak of the distribution from the true value (2°F) is called **a scale error**
- The shift indicates that the thermometer is indeed **biased**
- **Every instrument has a scale error of some magnitude**
  - Ours will measure 2°F more, on average.



Example: Resolution

- You also see what **the typical error of any individual measurement of water+ice is**
- **The width of the distribution** of measured temperatures (0.2°F in our case).
- The width tells you **how much you are going to err, on average, on any single measurement** – if the distribution was centered on the true value
- **The width is the resolution** of your instrument, folded with the variation expected from the measuring conditions
- **A calibration point is a great thing!** It allows you to tune your measurement:
    - From now on, when you read 64°F with your device, you know the true measurement is roughly 62±0.2°F.



Example: Simulation

- The computer does not provide you with real melting ice - no calibration point

- A simulation of the measuring process, and of the melting ice system
  - Possible with the information of the basic physics of melting ice and of mercury expansion inside a glass tube
  - Provide a set of simulated measurements
  - Get a measurement of the expected scale and resolution of your temperature measurement

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  - i.e. The part of the calorimeter measuring the jet may be hit by additional particles not belonging to the jet originated from the quark, affecting our measurement

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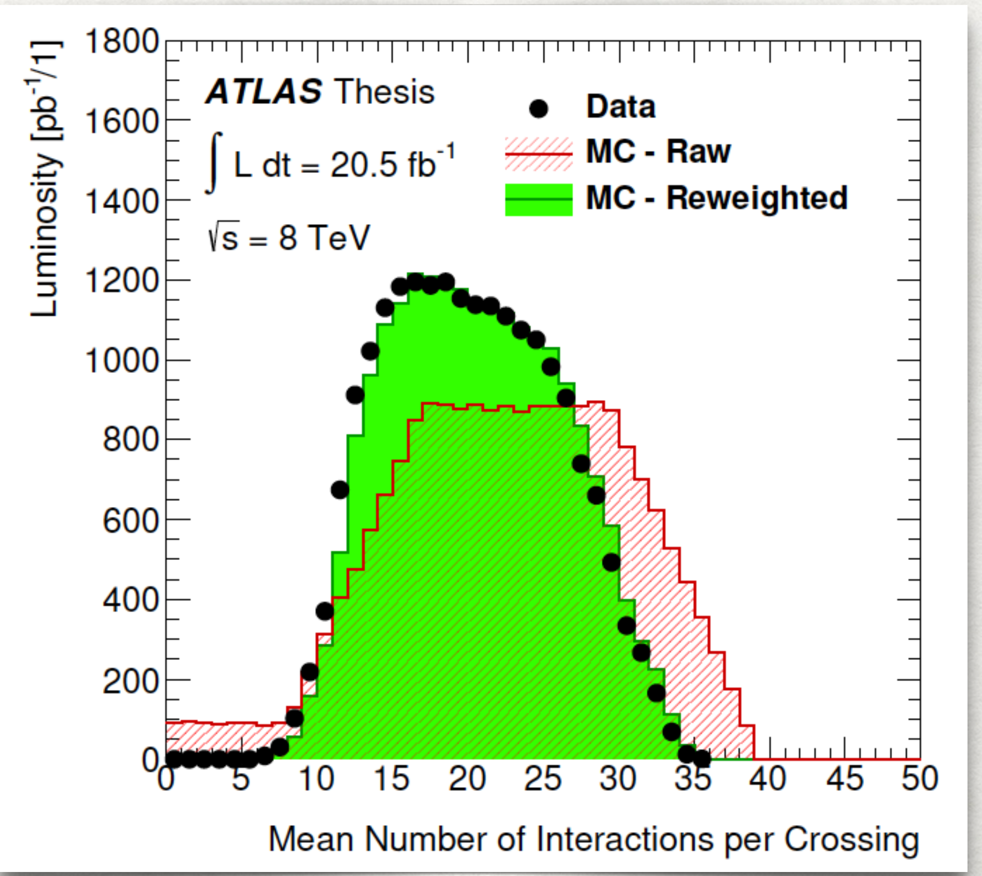
Event Correction

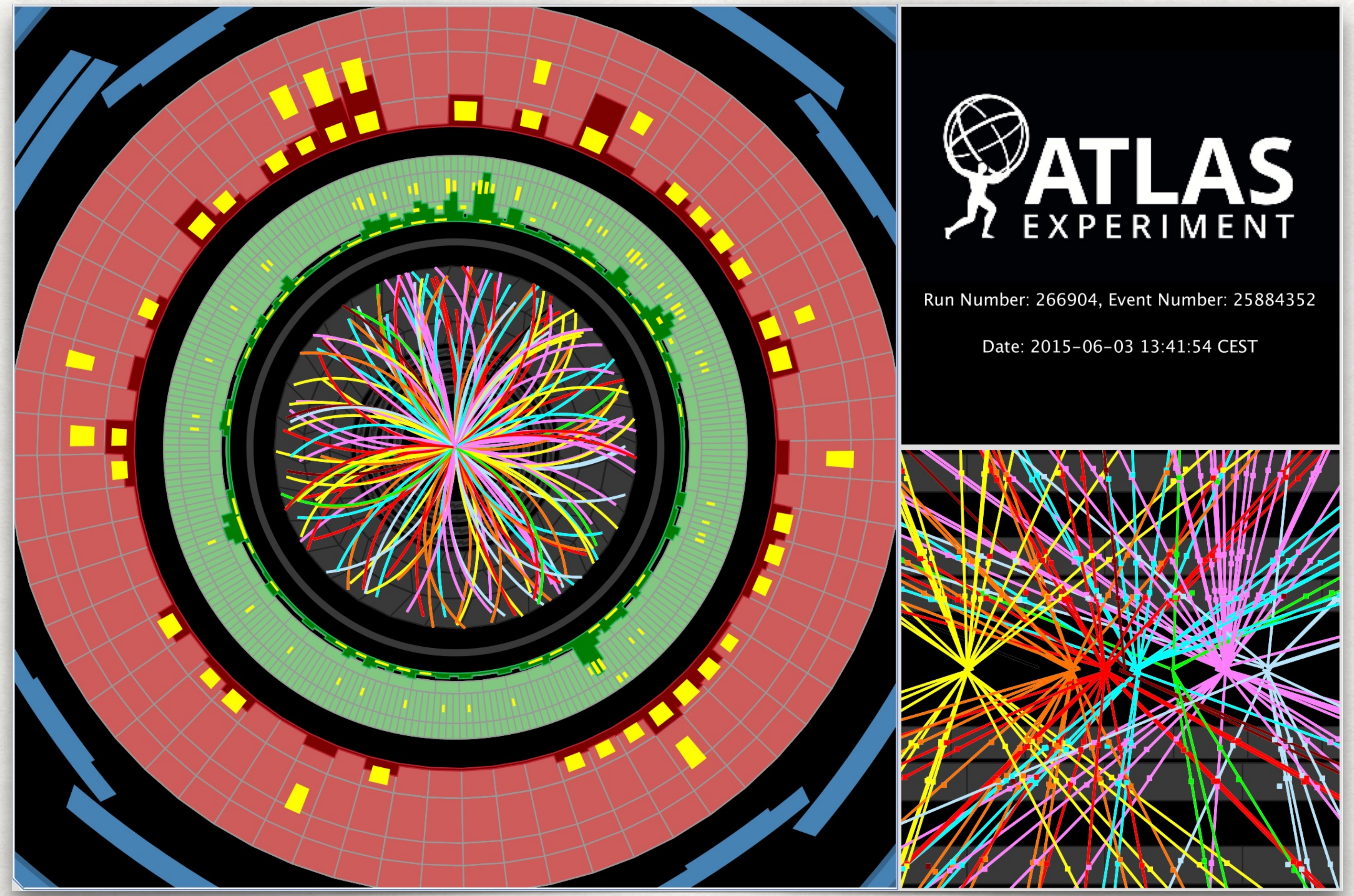
Pile-Up Corrections

- Multiple interactions per event, called **"pile-up"**
- **Correlated with the instantaneous luminosity** (a measure of number of particles in the beam, i.e protons, that pass through a surface of unit area per unit time)
- The parameter is defined as **the average number of particle interactions per bunch crossing μ**
- Multiple interactions i**n the same bunch crossing**, the pile-up is referred to as **"in-time"**
  - Correlated to the number of reconstructed vertices
- There are also **overlapping signals in the detector from other neighbouring bunch crossings**, so called **"out-of-time"** pile-up
- In order to account for that, it is **averaged over all bunches in the collider in a given lbn (<μ>)** and used as a measure of pile-up
- To account for pile-up, **MC samples are also simulated with these conditions**
- However, **μ in MC samples is not exactly the same as in data**
  - Events from the simulation need to be corrected to data
- **The pile-up reweighting is done by comparing μ as measured in the collected data, to that in the generated MC sample**



Pile-Up in Event Display

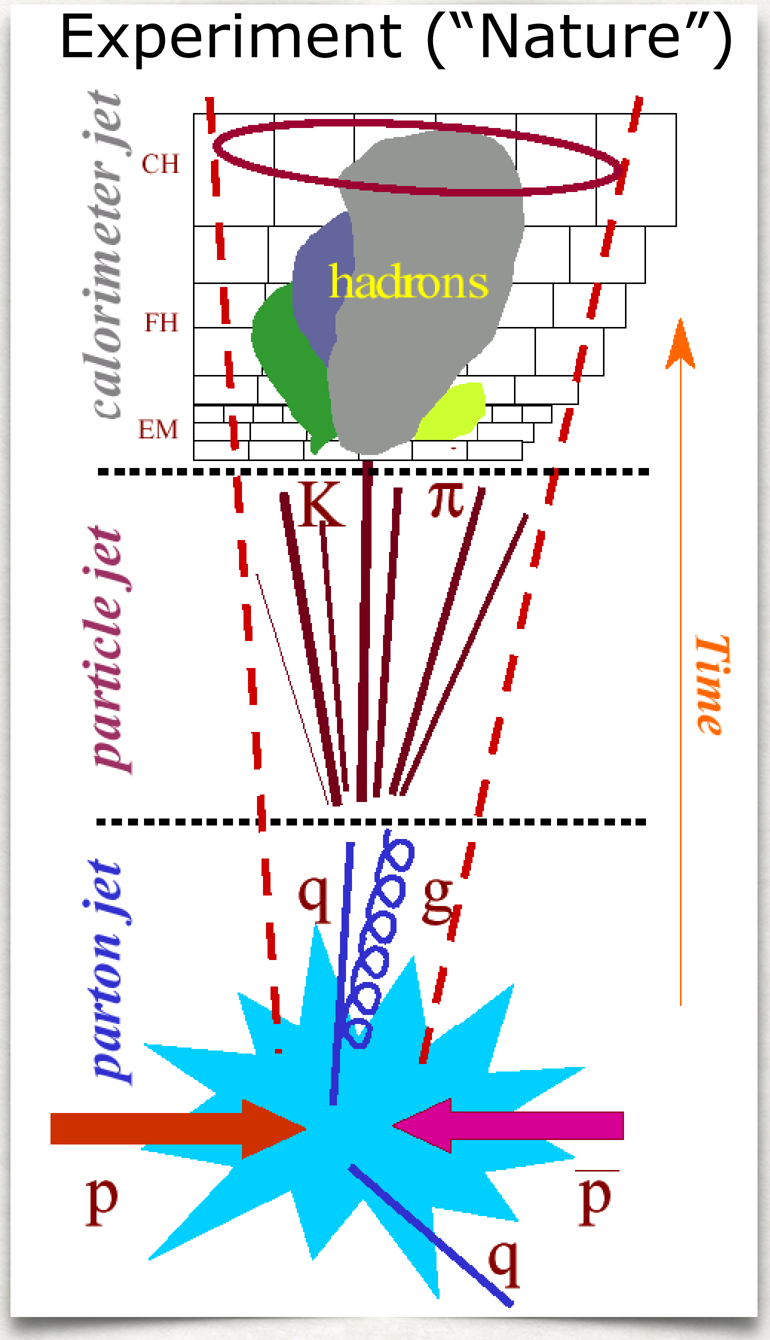
- Display of a proton-proton collision event recorded by ATLAS on **3 June 2015**, with the first LHC stable beams at a collision energy of 13 TeV
- Tracks originate from several vertices, indicating **multiple proton-proton interactions (also known as pile-up) recorded in one event**



Object Correction

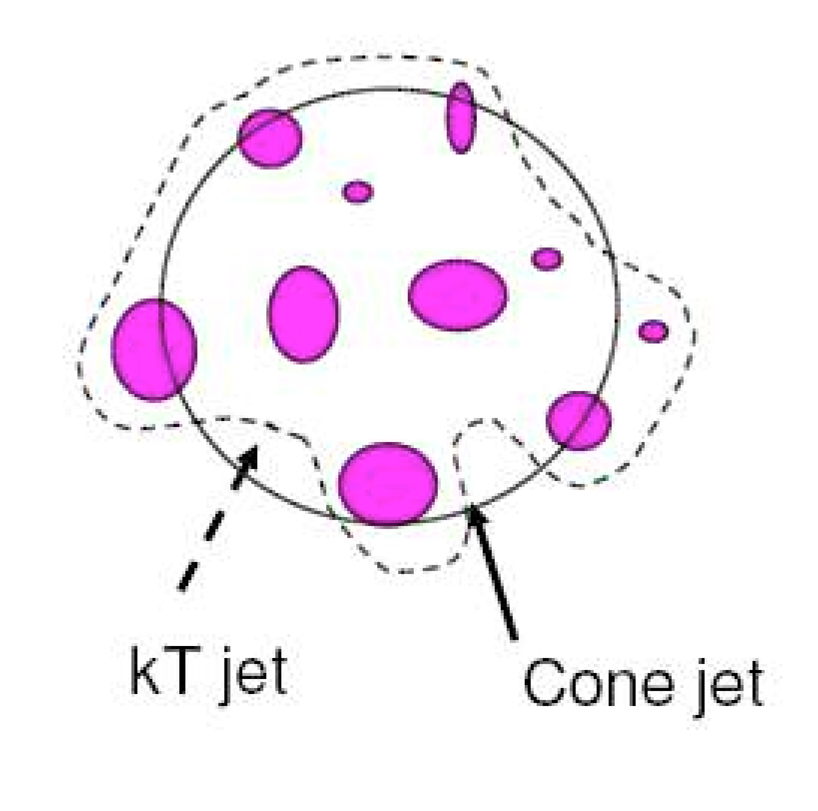
Jet Definition

- What are **jets**?
  - **Footprints of partons that cannot be observed directly:**
    - Color confinement → hadrons → detector signals
- Measuring **the total energy of the particles in order to determine the energy of the original quark**
- Identifying jets accurately is **an important issue in collider physics**, many physics topologies involve jets
  - Allows us to make important measurements and discoveries
    - Our knowledge on QCD is based on jet measurements: **gluon was discovered in 3-jet event**
    - The signal of **the Higgs boson**, a particle which may **decay to a pair of jets**



Jet Finding Algorithms

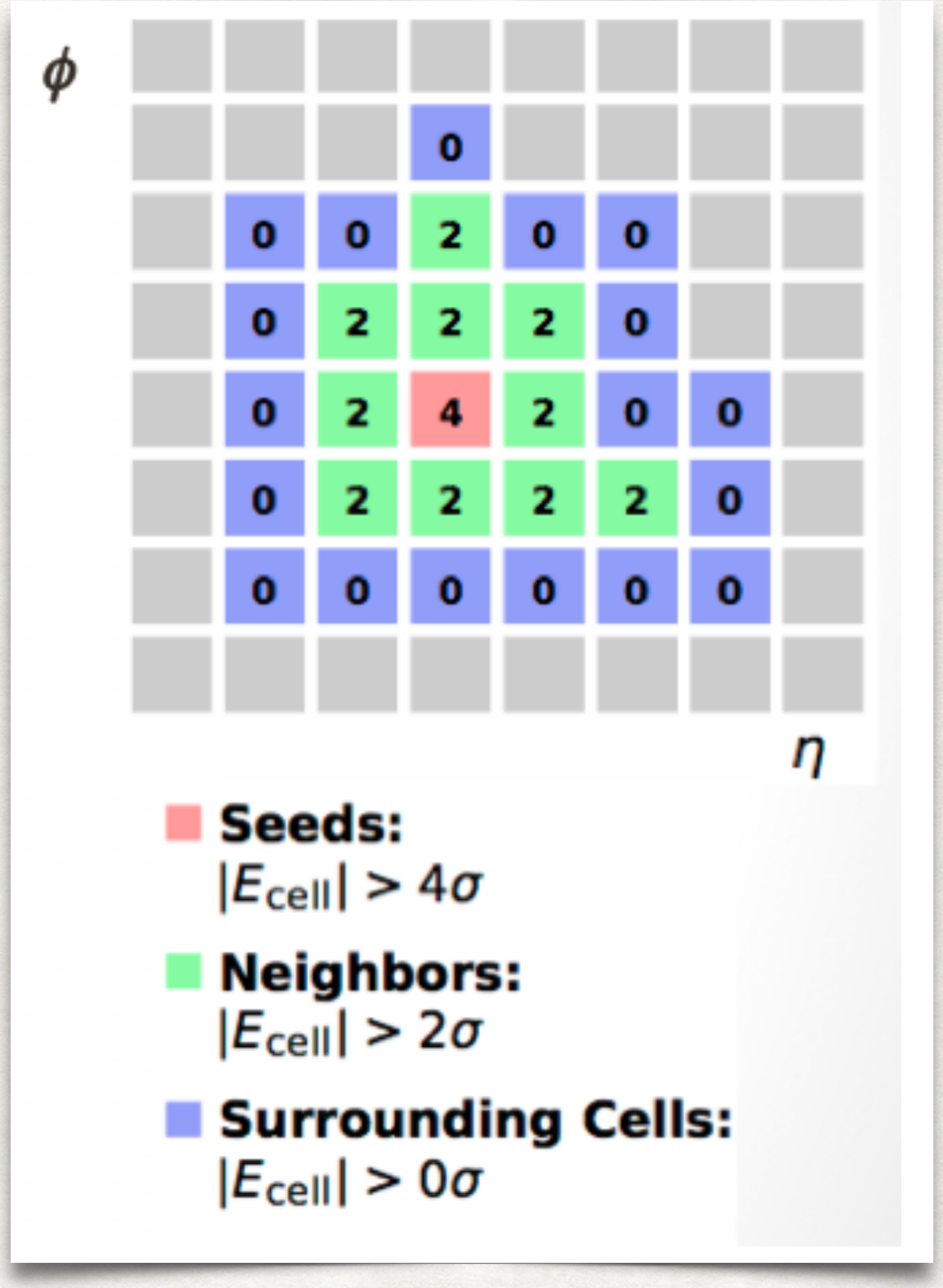
- Jet finding algorithms are used to associate particles to a particular jet
- Major classes of jet algorithms:
  - **Cone Algorithms:**
    - Cluster objects close in angle
    - Simple shape, unless jets overlap
  - **k_T Algorithms:**
    - Cluster objects close in relative p_T
    - Irregular shape



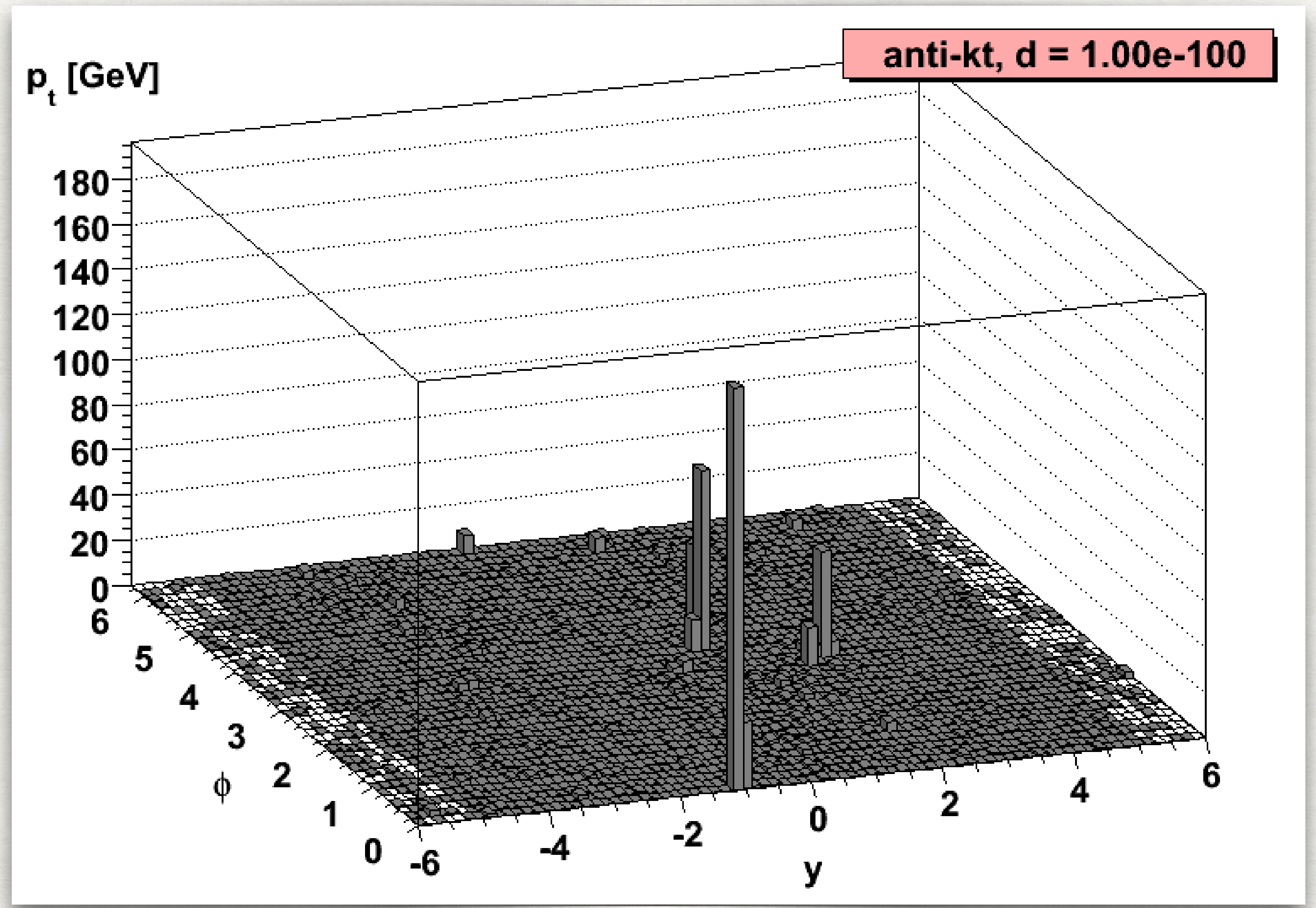
Jet Reconstruction

- Use anti-k_T algorithms ($R = 0.4$) starting from topological clusters (EM scale)

- Cells selected based on energy significance ($|E|/\sigma_{noise}$), where σ_{noise} is the cell noise



Anti-k_T in Action



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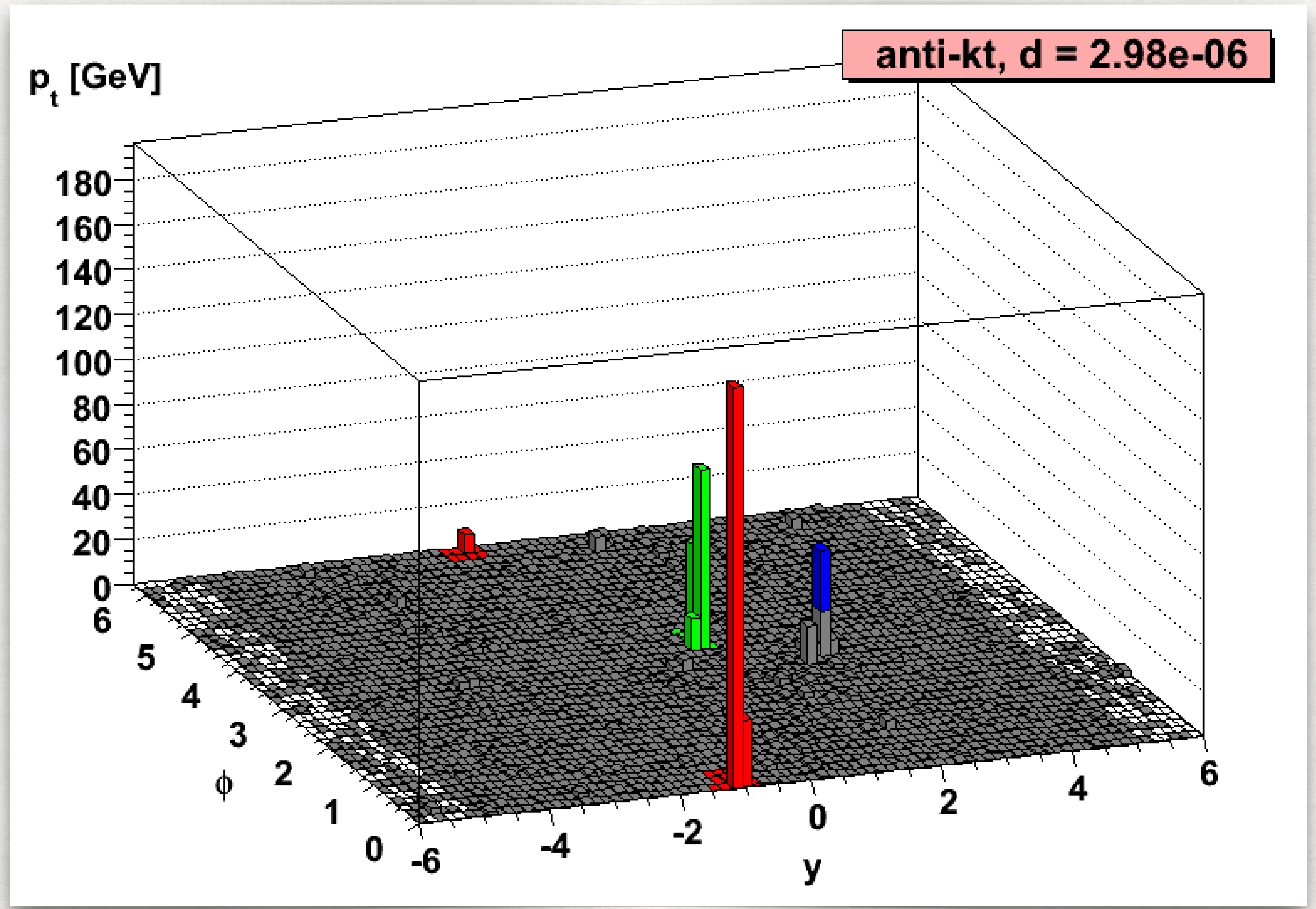

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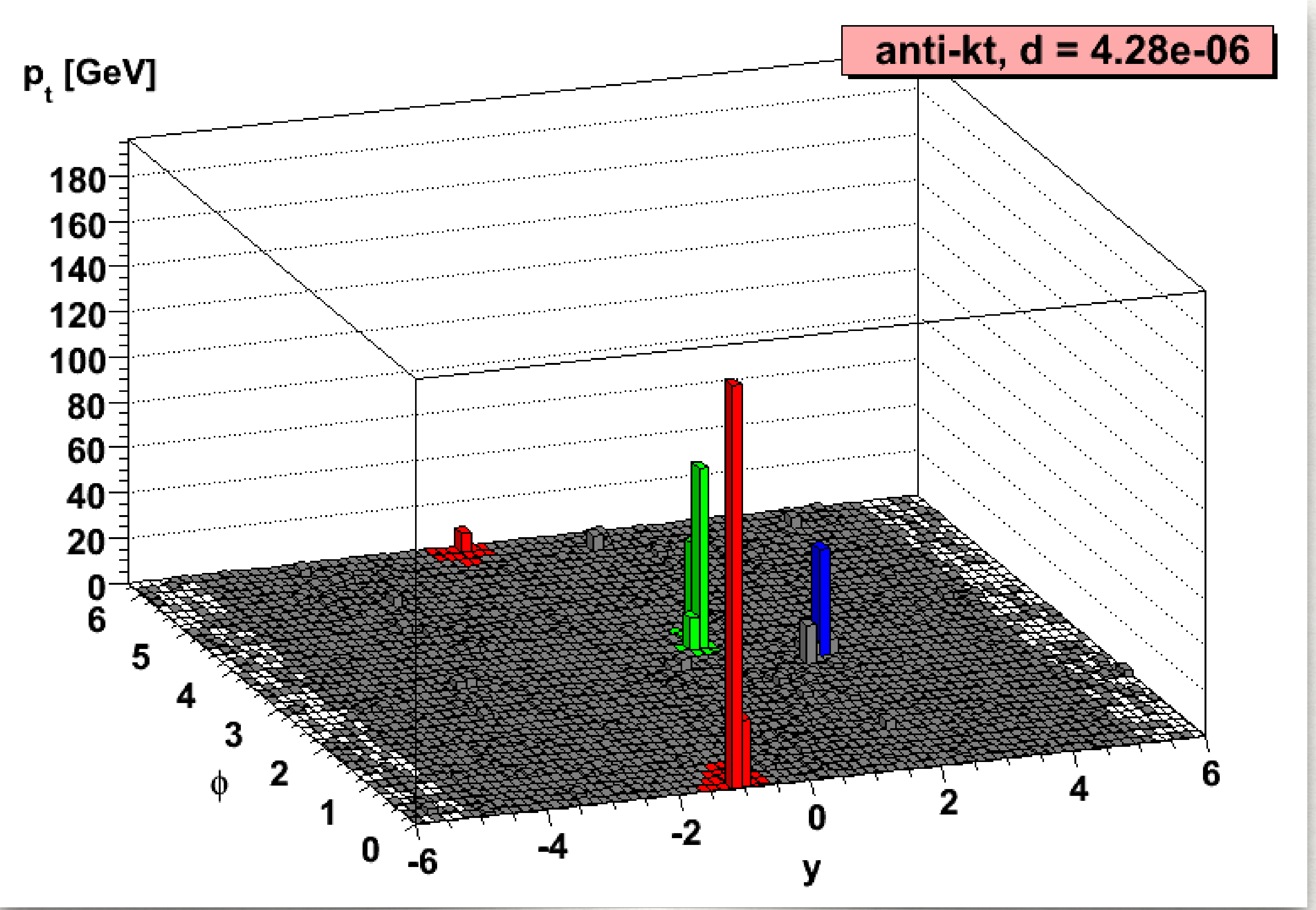

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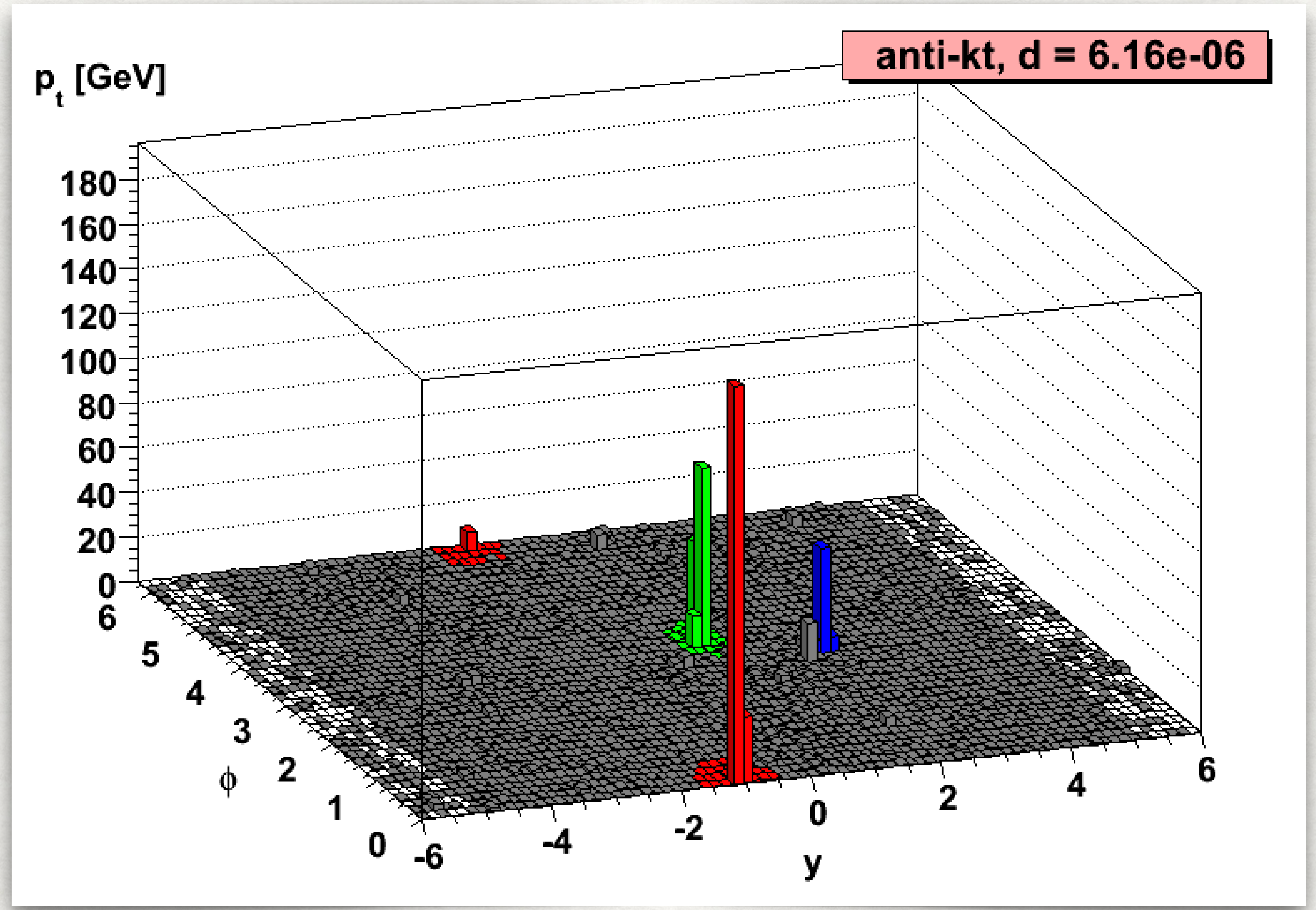

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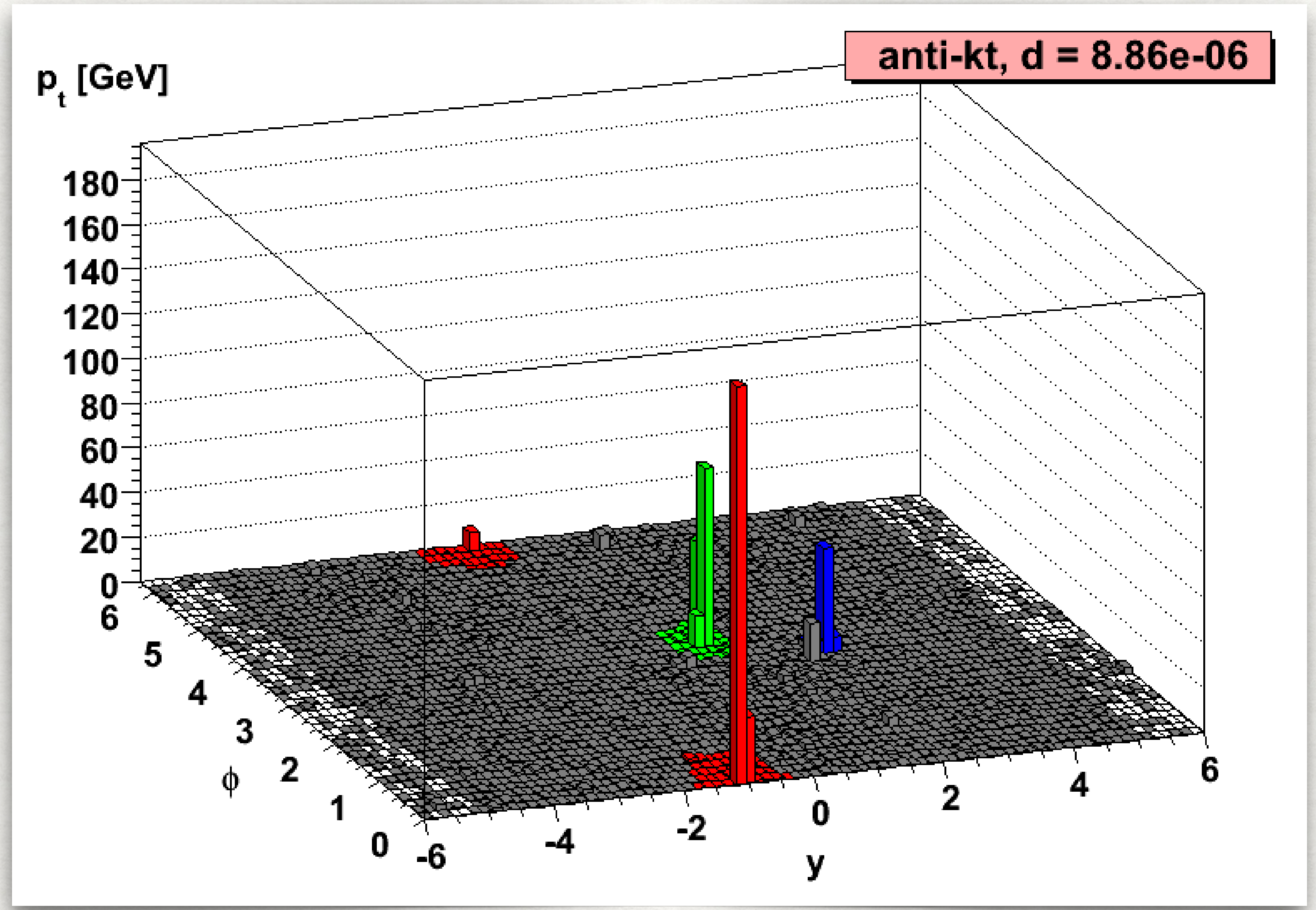

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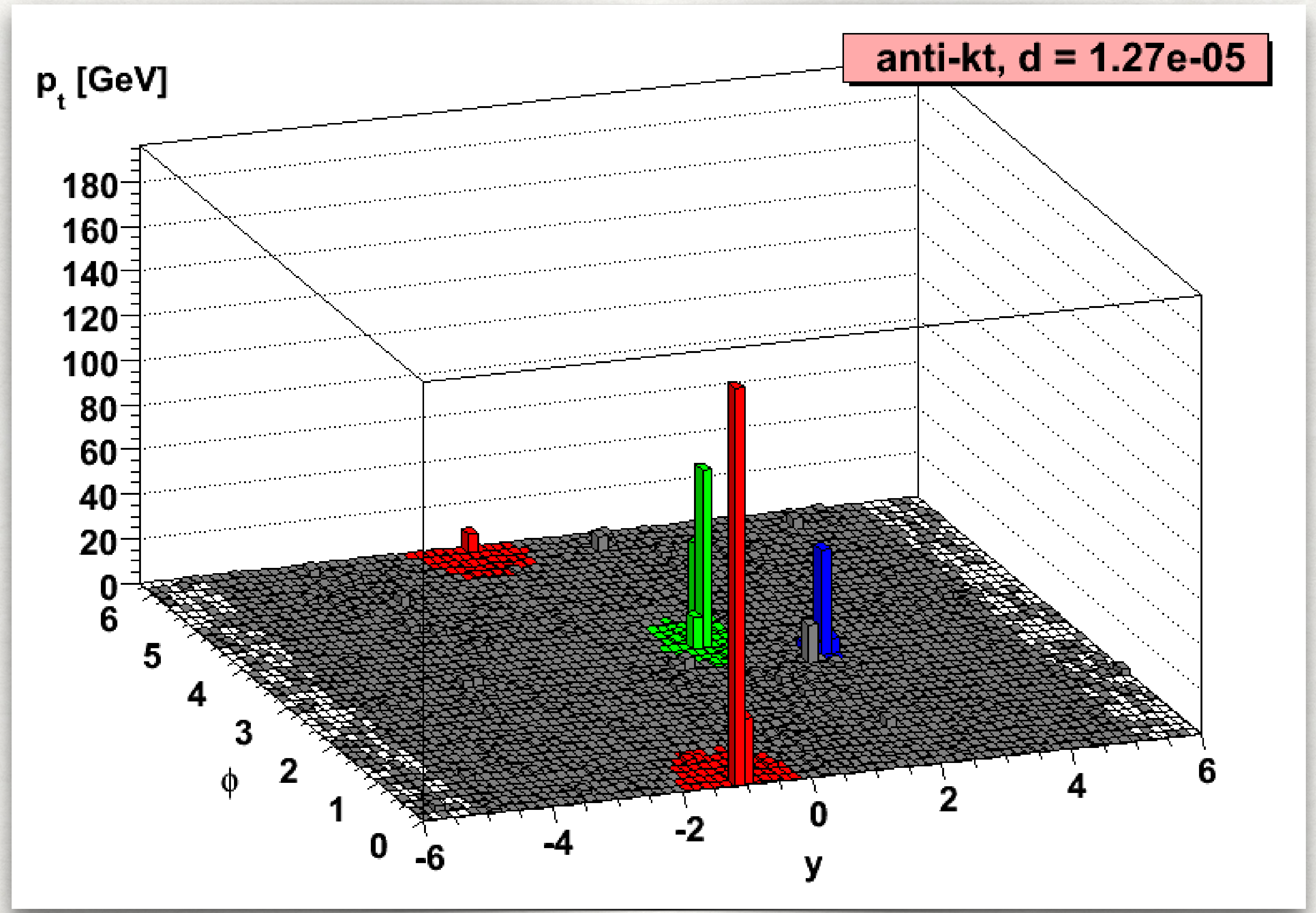

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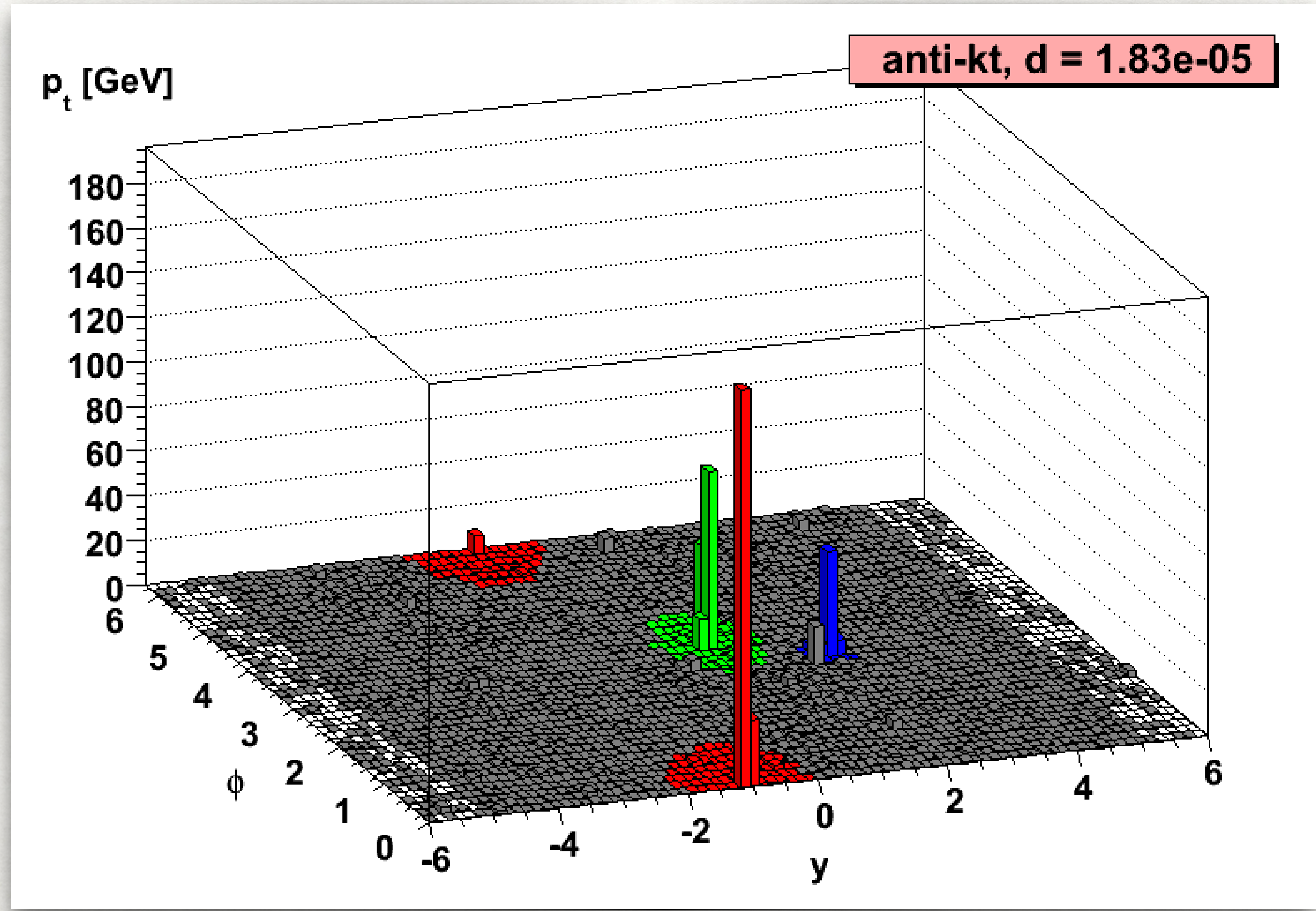

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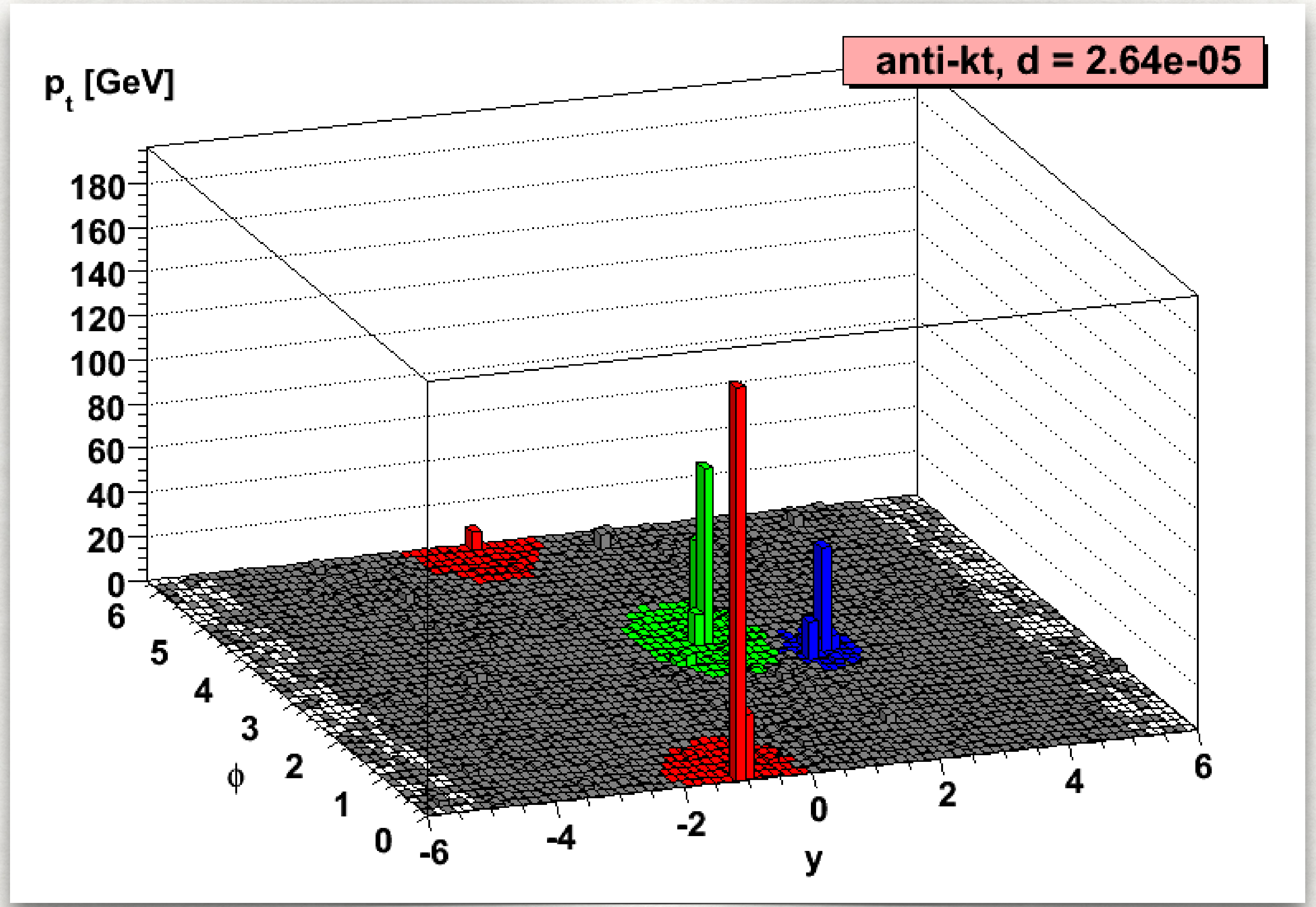

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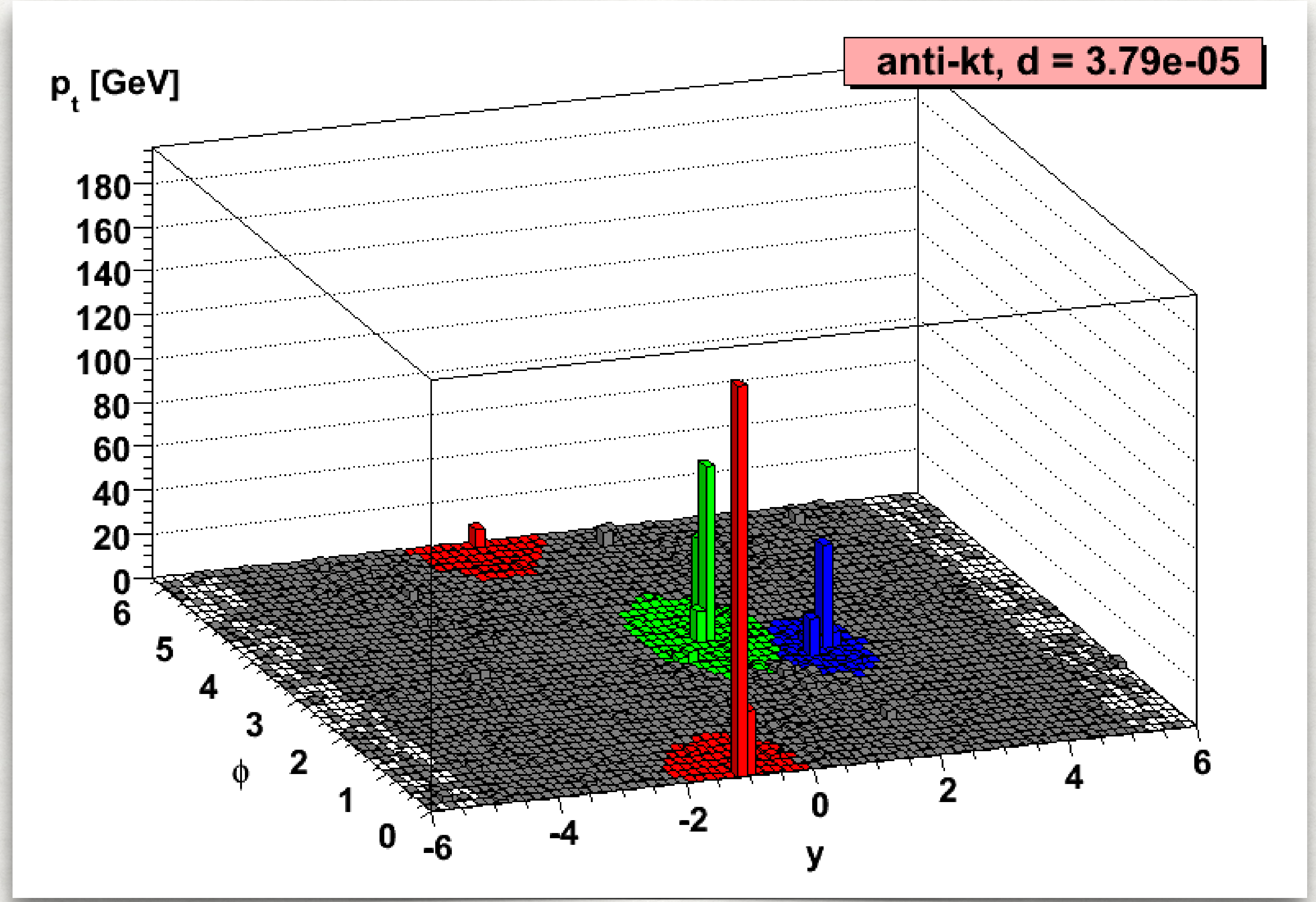

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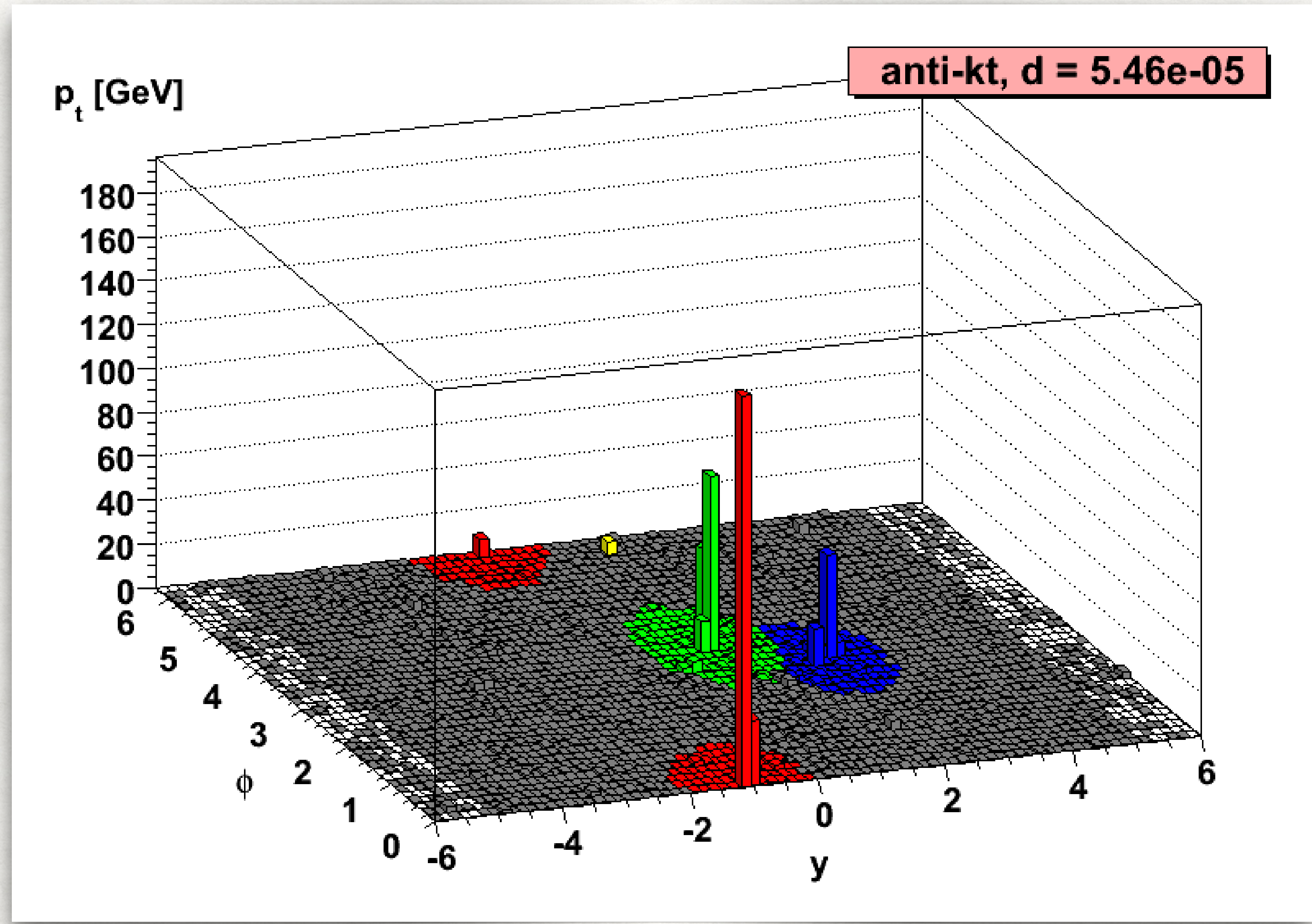

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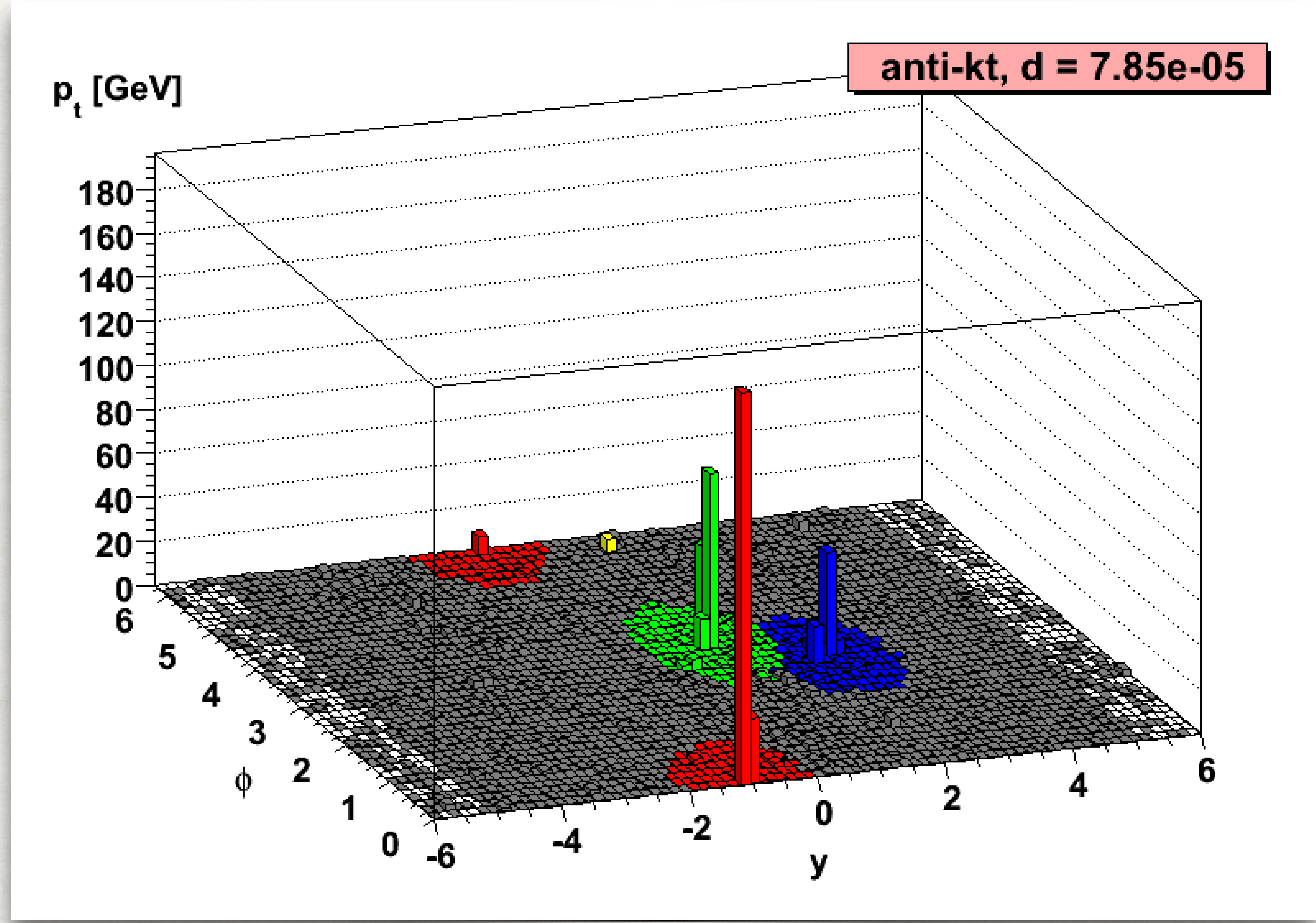

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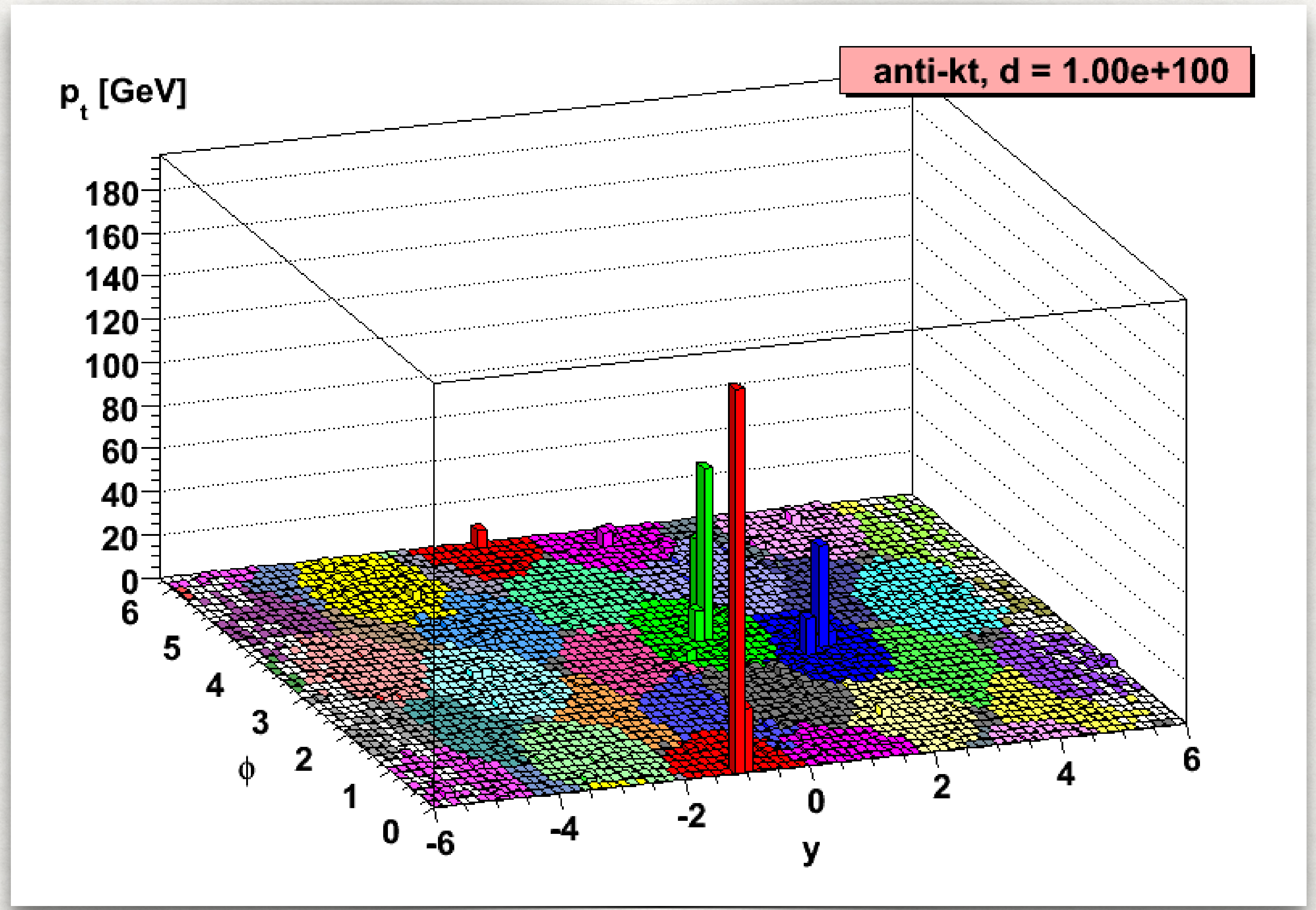
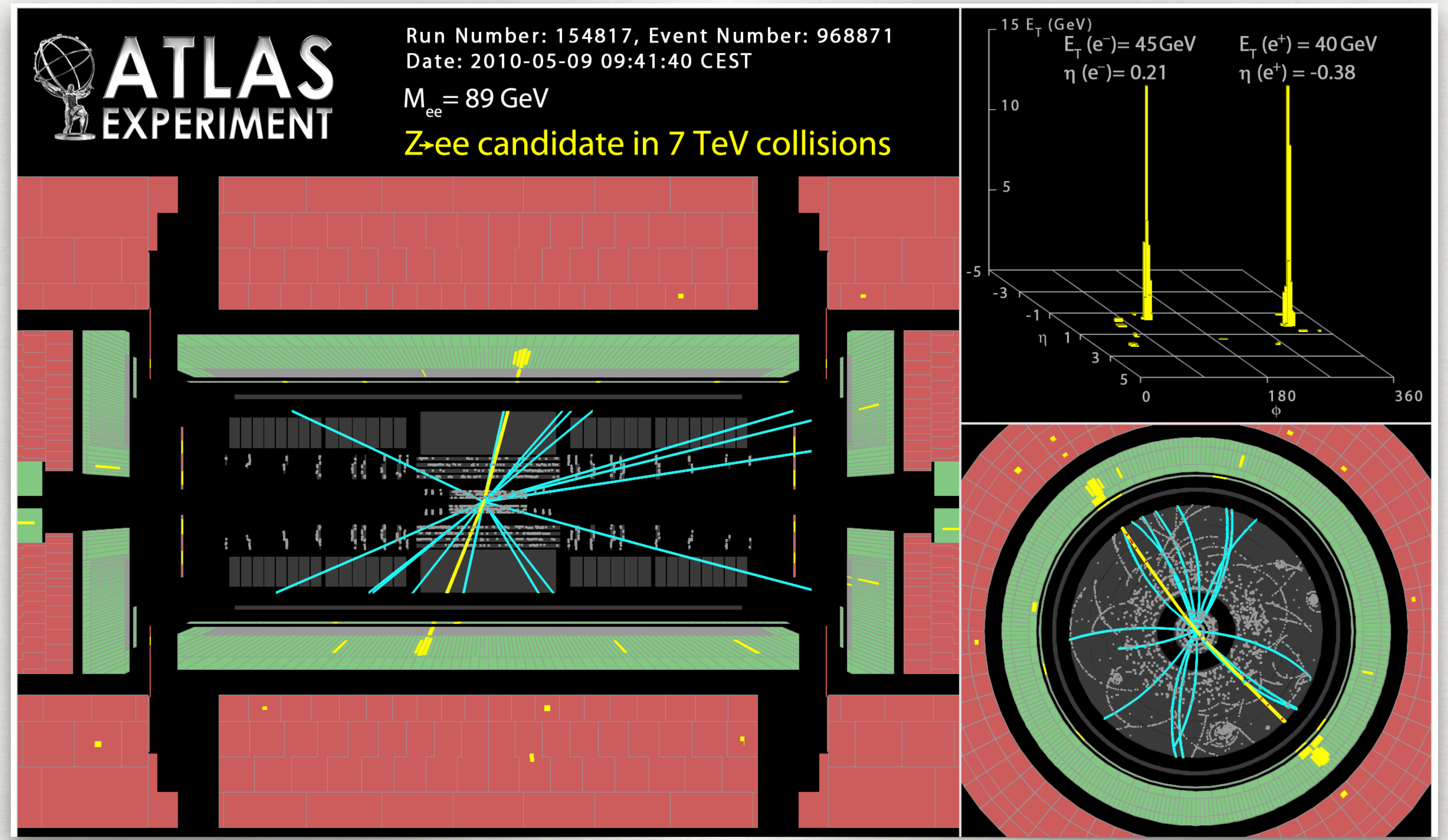
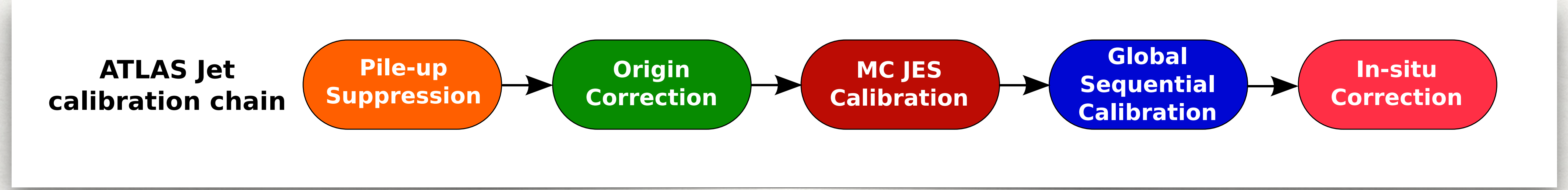


Jets in Event Display



Jet Calibration



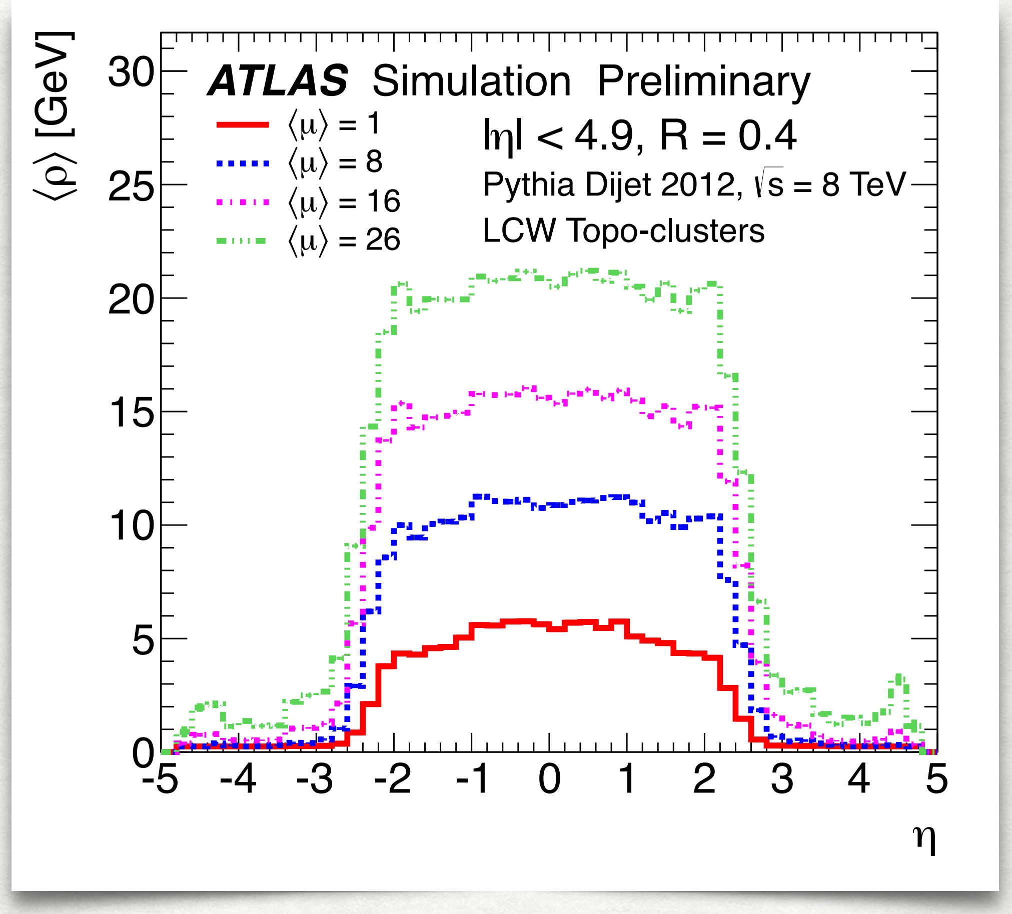
- Measurements from the calorimeter are inherently incomplete
  - ATLAS calorimetry is sampling and non-compensating: **energy will be missed!**

- **Calibrations bring the energy of jets (on average) to the particle scale**
  - Goal is **to recover the total energy of the spray**, so that jets are "comparable" to electrons/muons/etc.
  - Need to both **remove energy** (due to pileup) and **add energy** (due to sampling and non-compensation)

- **Pileup suppression is the first component— and perhaps the most critical in the coming years!**

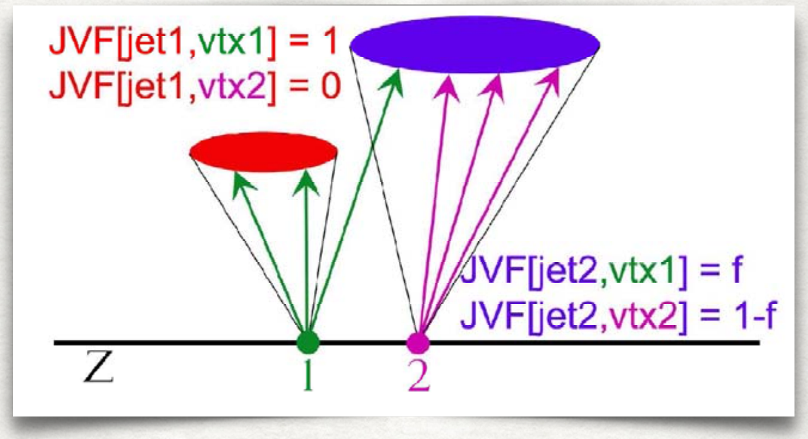
Pile-up Correction With ρ x A

- **Measure ρ:**
  - The "ambient" pileup energy in the event
- **Correct the jet p_T** with: $p_T^{corr} = p_T^{jet} - \rho \times A$
- Effectively **corrects for the soft, diffuse element of pileup in jets**
- **How do you measure the energy density?**
  - Current ATLAS procedure:
    - cluster R = 0.4 k_T jets, take median of p_T /A
- **Changing granularity of ATLAS detector means that ρ changes with η**
  - Forward regions have lower **ρ**, fewer pileup clusters over threshold
  - **ρ** calculated in central region and applied everywhere: can be improved!



Hard Pileup: Jet Vertex Tagger

- Pile-up also has **a hard component** which can **create new QCD jets**

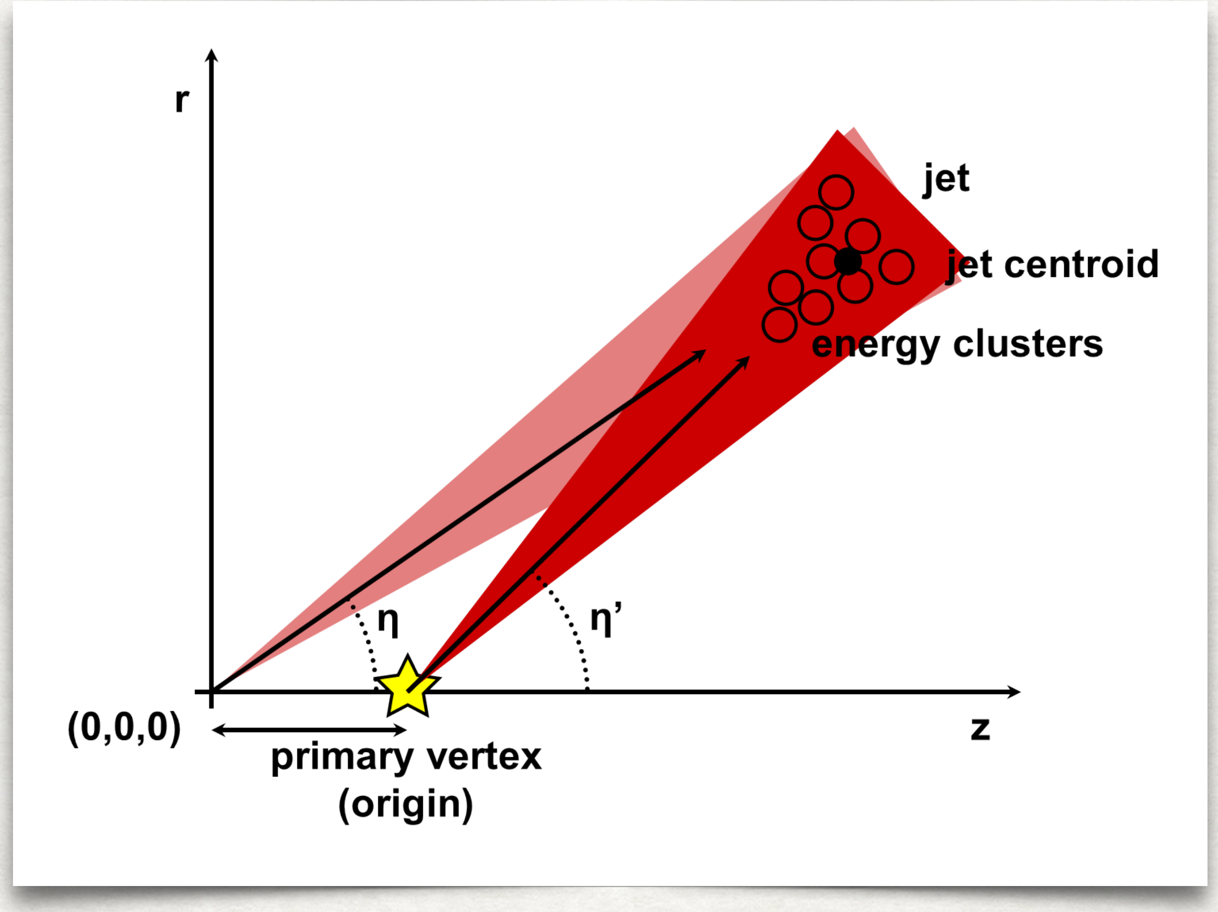


- **Jet Vertex Fraction (JVF):**
  - Match tracks in track jet with calorimeter jet
  - Calculate p_T fraction coming from each vertex for given jet
  - Jets with little p_T from primary vertex are likely from multiple interactions (e.g. more likely from multiple interactions)

- A new extension of Jet Vertex Fraction, called **Jet Vertex Tagger** (JVT), tags these jets very effectively!
  - Upgraded version of JVF, more sophisticated

Back to Calibrations: Origin Correction

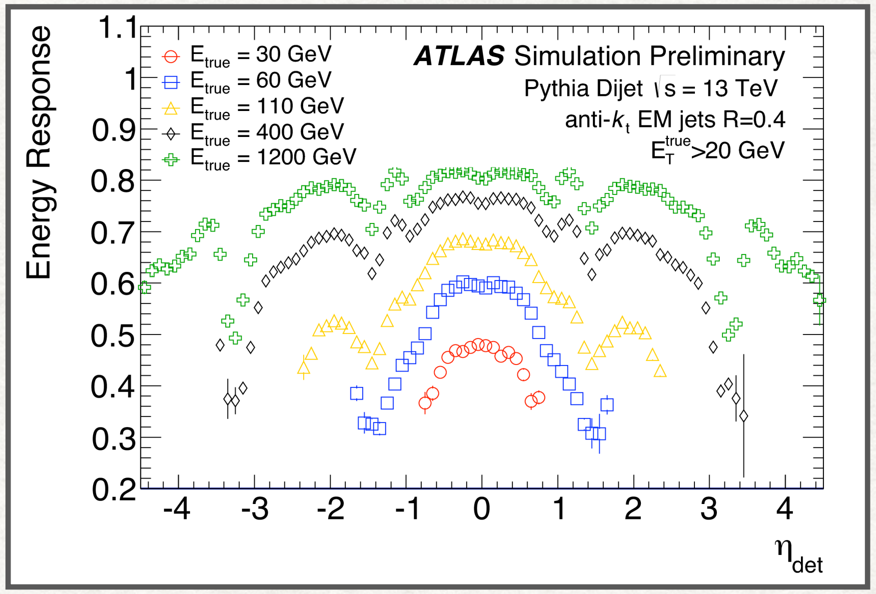
- Point back to the identified hard-scatter
- Changes the jet angle
- Calculate four-momentum again with new angle



Back to Calibrations: Jet Energy Scale (JES)

- The JES is the heart of the calibration chain
  - Account for **changing jet response as a function of energy and detector location**

- Simple **correction based on MC** relating the reconstructed jet energy to the truth jet energy
  - Correction factor
    - **$R = \langle E_{jet}^{EM} / E_{jet}^{Truth} \rangle$**
    - Used inclusive di-jet MC

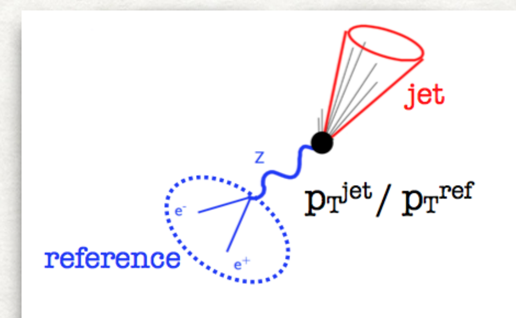


- In some specific regions of the detector there is a **bias in the jet η** distribution with respect to the truth jet
  - An additional correction in jet **η** is applied to resolve this bias

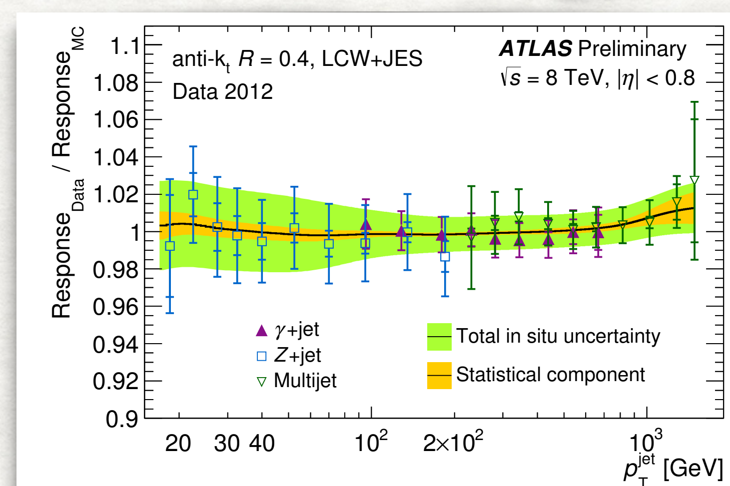
Back to Calibrations: In-situ Correction

- In-situ corrections **account for differences between data and MC** in p_T jet measurements.

- In-situ measurements **using a well-calibrated object** as a reference, recoiling against jet



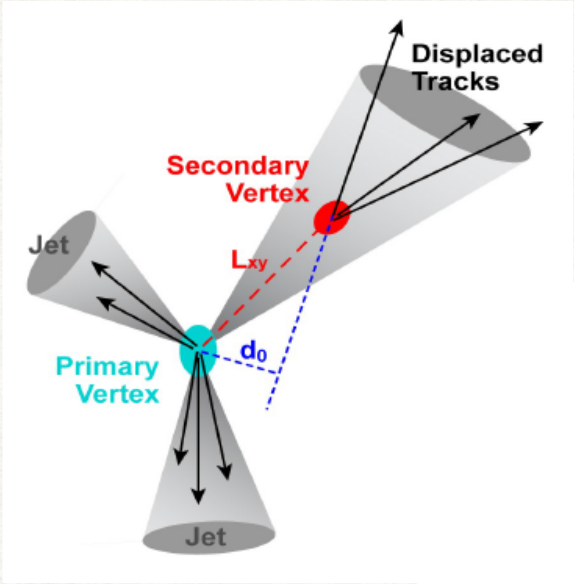
- Different reference objects depending on jet p_T:
  - **Z+jet** 17 < p_T < 260 GeV
  - **γ+jet** 25 < p_T < 800 GeV
  - **Multijet** 300 < p_T < 1900 GeV



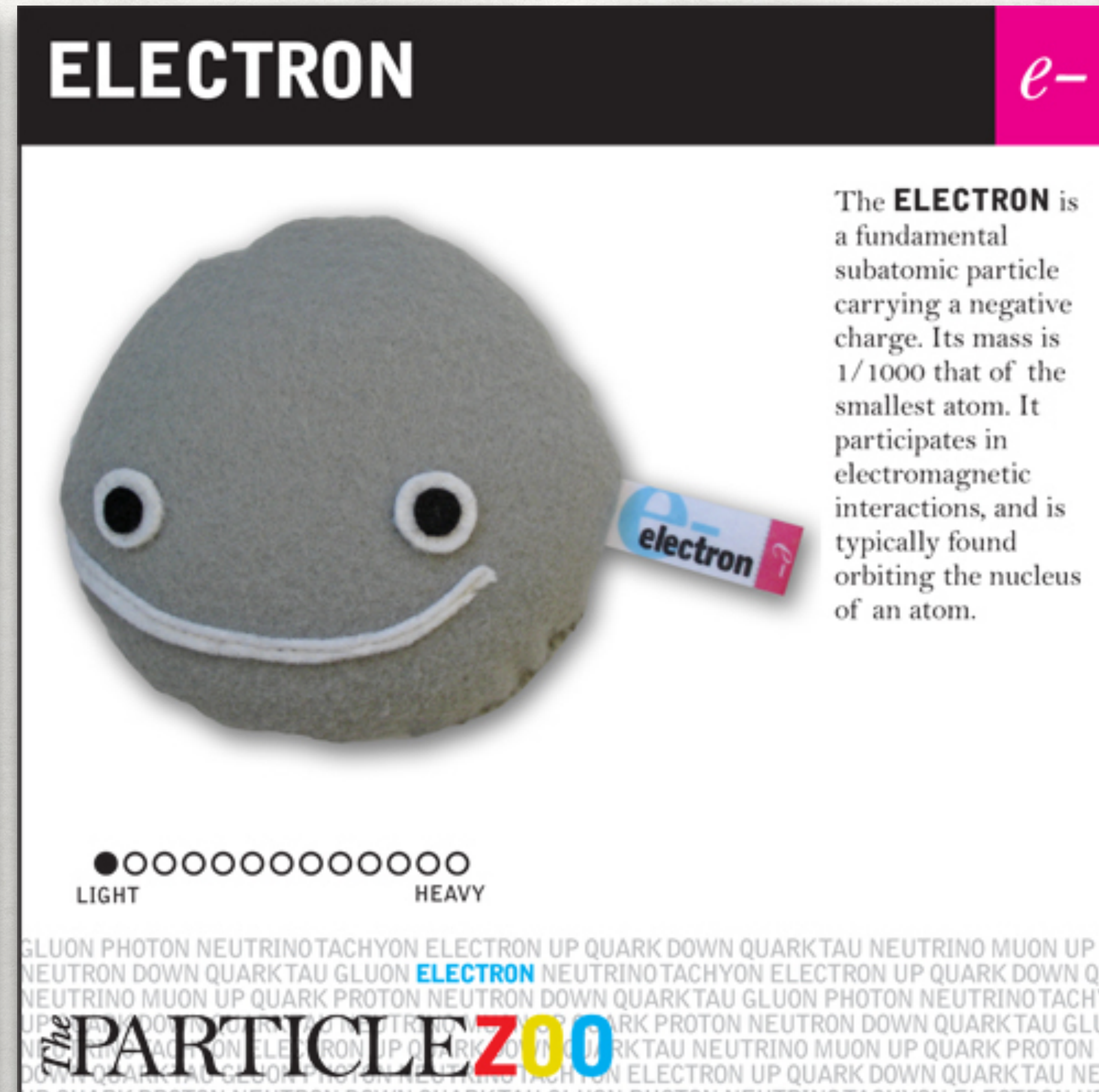
- **In-situ calibration:** Standard combining technique of the 3 measurements of the p_T, binned in **η**

b-tagging

- **The goal of b-tagging is to identify jets containing b-hadrons**
- B-tagging is used in analyses with **high-p_T b-jets in final state**:
  - Top physics
  - Higgs physics
  - Beyond Standard Model physics
- The main handle is the **long lifetime of b-hadrons**
- On average tracks from long lived b-decay
  - **Have higher p_T**
  - **Have larger d_0**
  - Vertex to **a point displaced from the beam line** relative to tracks from light-flavored (udsg) jets
- Basically, b-tag algorithms
  - Identify **tracks likely to originate from b-decays** using (p_T, d_0) information
  - Constrain those tracks to **a common vertex**
  - **Remove backgrounds** from $\gamma \to ee$, $V \to hh$ decays
  - **Require the "secondary vertex"** to be significant displaced from the primary interaction vertex



Photon and Electron Objects

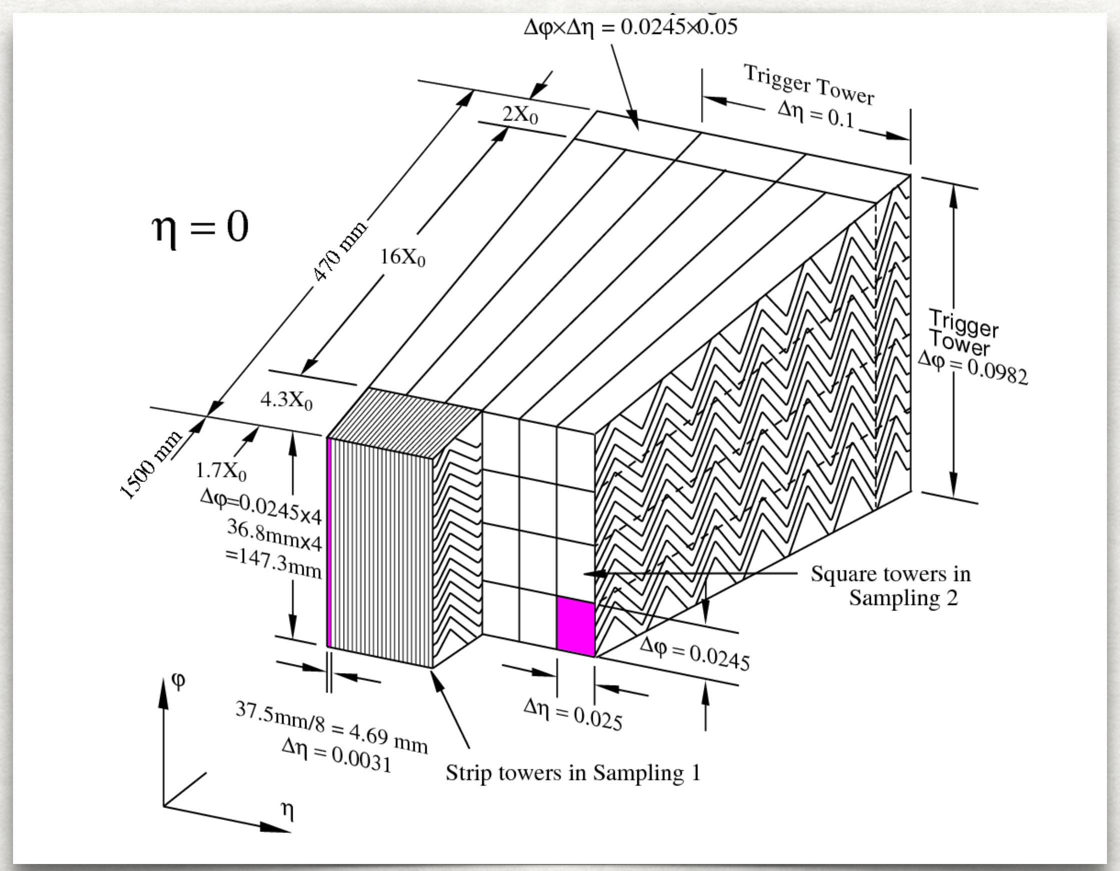


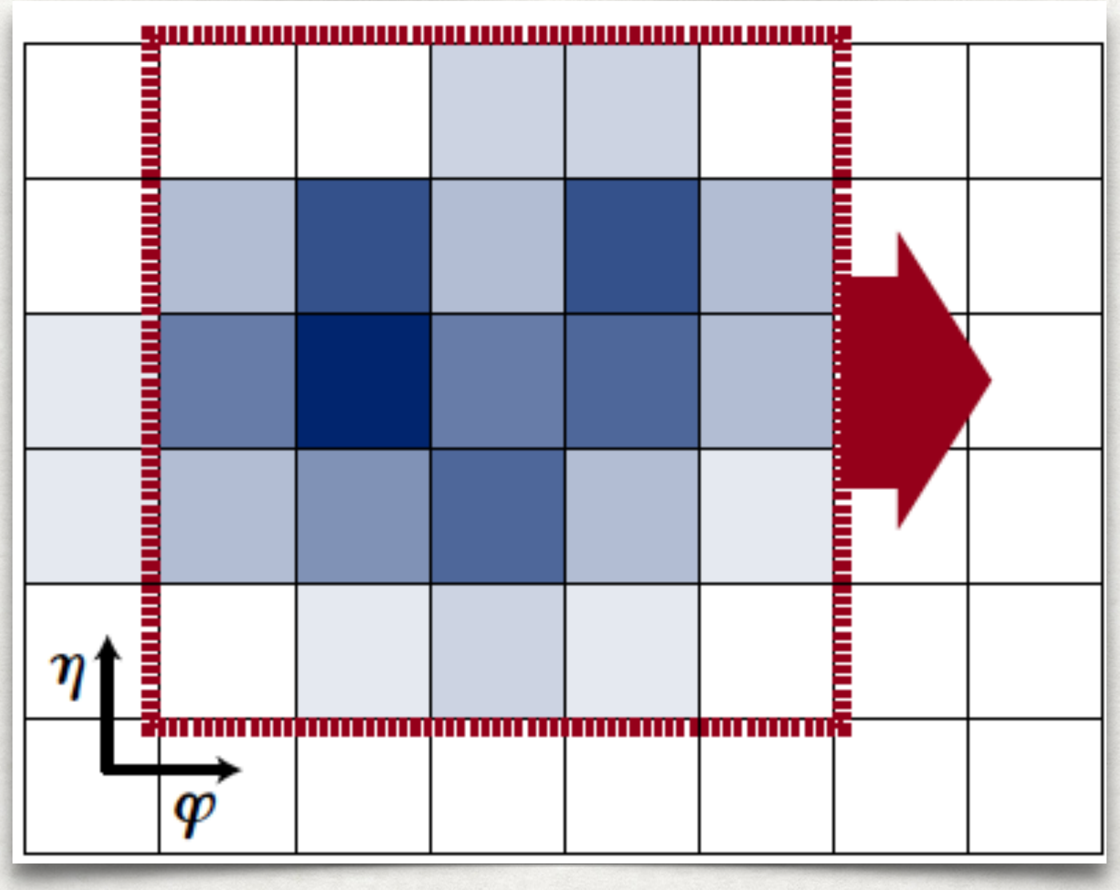
Electron and Photon Reconstruction

- **Reconstructed at ATLAS based on clusters**
  - Energy deposits in the EM calorimeter

Electron and Photon Reconstruction

- Reconstructed at ATLAS based on clusters
    - Energy deposits in the EM calorimeter
- **Use sliding window algorithm**
    - Find seed cluster with energy greater than 2.5 GeV





Electron and Photon Reconstruction

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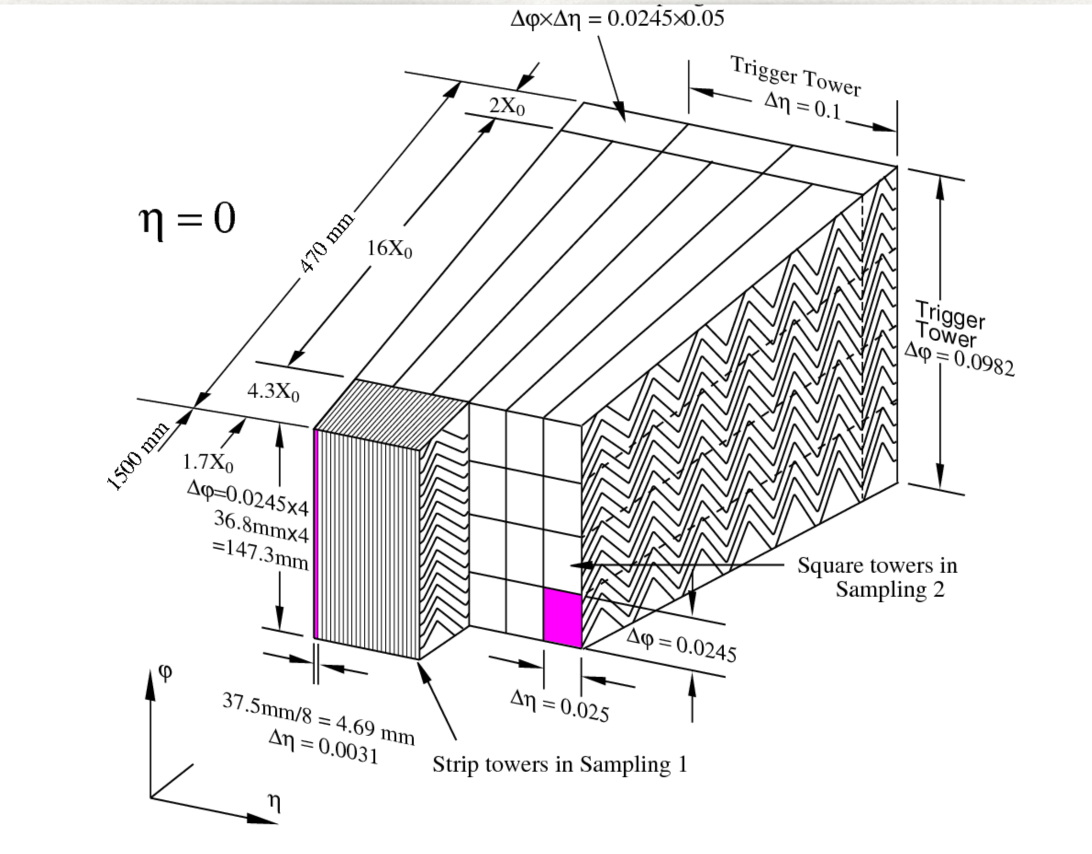
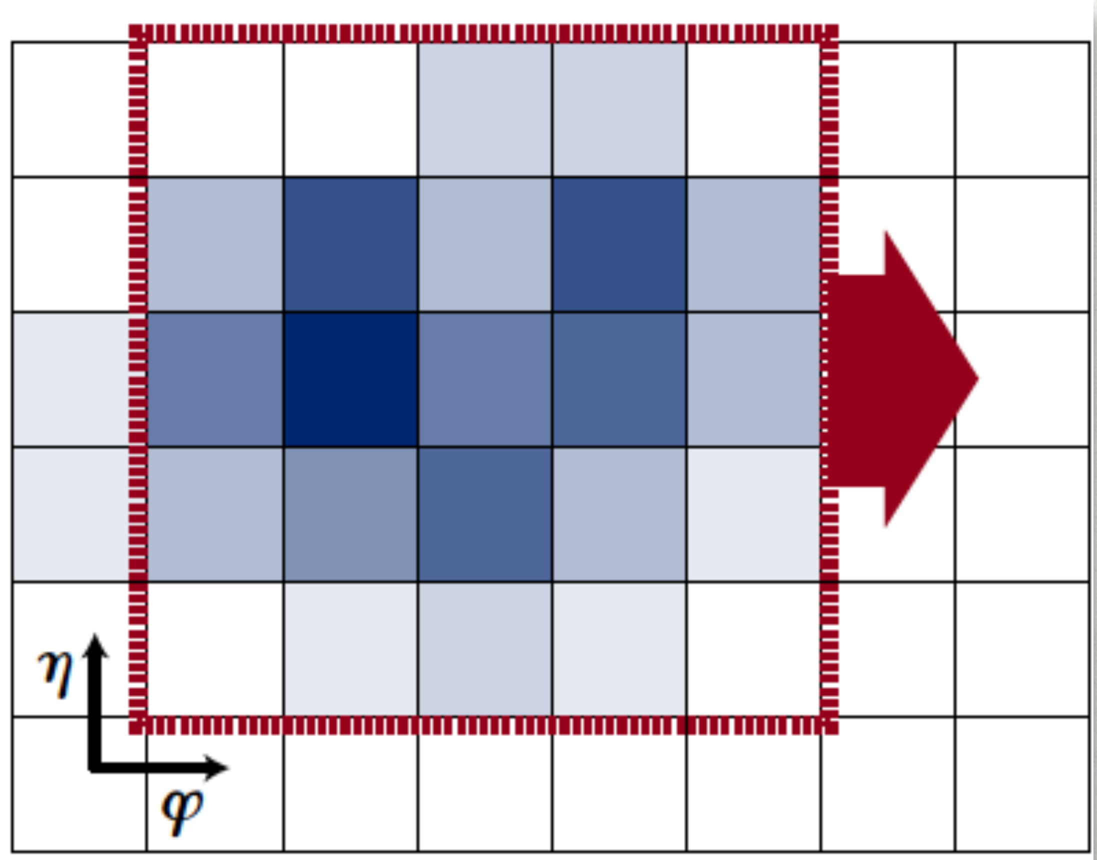
    - Energy deposits in the EM calorimeter
- Use sliding window algorithm
    - Find seed cluster with energy greater than 2.5 GeV
- **Form clusters Δη x ΔΦ**





Electron and Photon Reconstruction

- Reconstructed at ATLAS based on clusters (energy deposits) in the EM calorimeter
- Use sliding window algorithm
  - Find seed cluster with energy greater than 2.5 GeV
- Form clusters $\Delta\eta \times \Delta\Phi$
- **Match cluster to an Inner Detector (ID) track**
  - Electron - photon separation
  - Measure and calibrate cluster energy

Electron and Photon Reconstruction

- Reconstructed at ATLAS based on clusters (energy deposits) in the EM calorimeter
- Use sliding window algorithm
  - Find seed cluster with energy greater than 3 GeV
- Form clusters $\Delta\eta \times \Delta\Phi$
- **Match cluster to an ID track**
  - Electron - photon separation
  - Measure and calibrate cluster energy

- Tracks reconstructed in the inner detector are extrapolated into the calorimeter
- Well-reconstructed tracks matched to clusters are classified as ELECTRONS
- Clusters with no matching tracks are classified as UNCONVERTED PHOTON CANDIDATES
- Clusters matched to tracks consistent with the hypothesis of a $\gamma \rightarrow e^+e^-$ pair production are classified as CONVERTED PHOTON CANDIDATES

- The cluster energy is corrected for detector inhomogeneities and energy losses by applying simulation-based corrections
- Scale corrections and intercalibration
- The clusters associated with electron and photon candidates must satisfy a set of identification criteria

Photon-Electron Energy Calibration

- **Scale Corrections:**
  - Apply simulation-based corrections
  - Different for electrons, converted and unconverted photons
  - The detector geometry and the interactions of particles with matter must be accurately described in the simulation

- **η-Intercalibration:**
  - Example for electron calibration:
    - $Z \rightarrow ee$ events used
      - The Z mass is known to exquisite precision
    - Reconstructing the Z mass in data and simulation, and setting the observation to the known value, absorbs any remaining offset
    - The scale choices are allowed to vary with |**η**| which results in **η**-intercalibration
    - Finally the Z lineshape in Monte Carlo is fixed to better match data, by broadening the momentum resolution through a “smearing”

Photon-Electron Identification

- The majority of the objects reconstructed are **jets**

- **Need aggressive algorithms to select photons/electrons and reject jets**
  - Backgrounds: QCD dijet and photon-jet production

- **Identification relies on two things:**
  - The **shape of an EM shower** in the calorimeter
    - Photons and electrons have narrow showers
    - **Quark- and gluon- induced showers are broader**, and a significant fraction of their energy is typically deposited in the hadronic calorimeter
  - **The fraction of energy deposited in the hadronic calorimeter**

- **Additional checks for electron identification**
  - Properties of the tracks in the inner detector
  - Matching between track and energy cluster

Loose, tight photons

Loose, medium, tight electrons

Muon Objects

Muon Reconstruction

- **Combined Muon:**
  - Combining tracks of the Inner Detector and Muon Spectrometer
  - Muons reconstructed at $|\eta| < 2.5$
  - Energy losses in the calorimeter are taken into account
  - Most precise measurement of the momentum and position of a muon
  - Different selection categories are defined: loose, medium, tight

- In order to determine muon momentum resolution and scale, $Z \to \mu\mu$ decays are used
- Imperfect modelling of the muon momentum resolution and scale in MC, needs to corrected to data
- The reconstructed simulated muon momenta must be smeared and shifted

Simulation Corrections

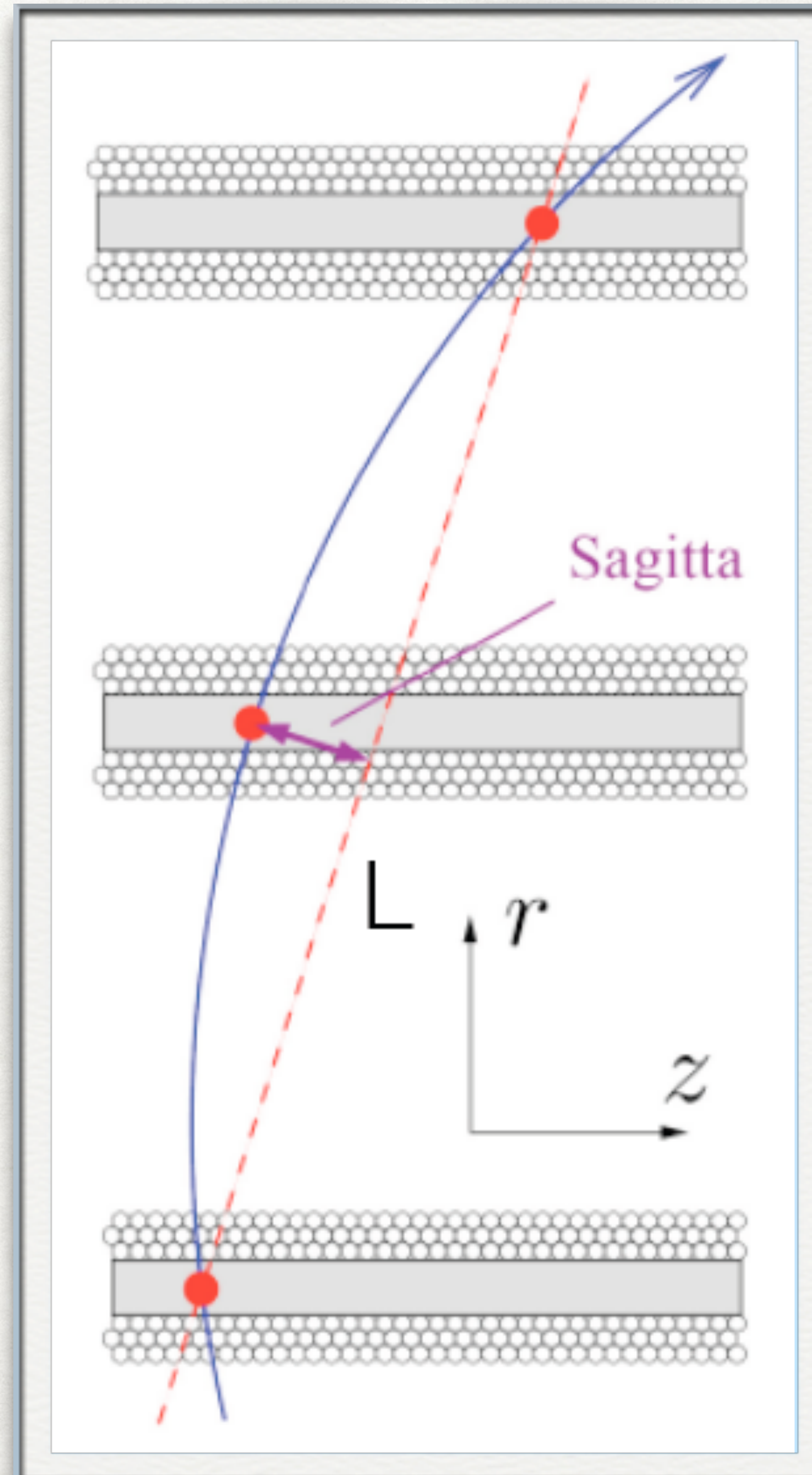
- **The smearing constants are determined by computing the quadratic differences in the resolution parameters between data and simulations**
- Inverse momentum proportional to the sagitta

$$\frac{1}{p} = \frac{8S}{BL^2}$$

- Main contributions to the muon momentum resolution for high-p_T muons come from **muon chamber misalignments**
- Optimistic in simulation
- q/p_T of each muon is "**smeared**" by a factor of:

$$\delta\left(\frac{q}{p_T}\right) = S_1 \cdot g_1 \cdot \left(\frac{q}{p_T}\right) + S_2 \cdot g_2$$

- **S_1, S_2** are coefficients related to **multiple scattering** and **the intrinsic resolution terms**, respectively - S_2 dominates at high-p_T



Muon Momentum Scale and Resolution Corrections

- In order to determine muon momentum resolution and scale, Z→μμ decays are used
- Events are required to include two isolated CB muons of opposite charge, with pT > 25 GeV
- To select muons from Z decay, the μμ mass is required to be within 15 GeV of the Z boson mass
- The resolution is the width of the Gaussian which is convoluted with the Breit-Wigner shape in Z decays at generator level

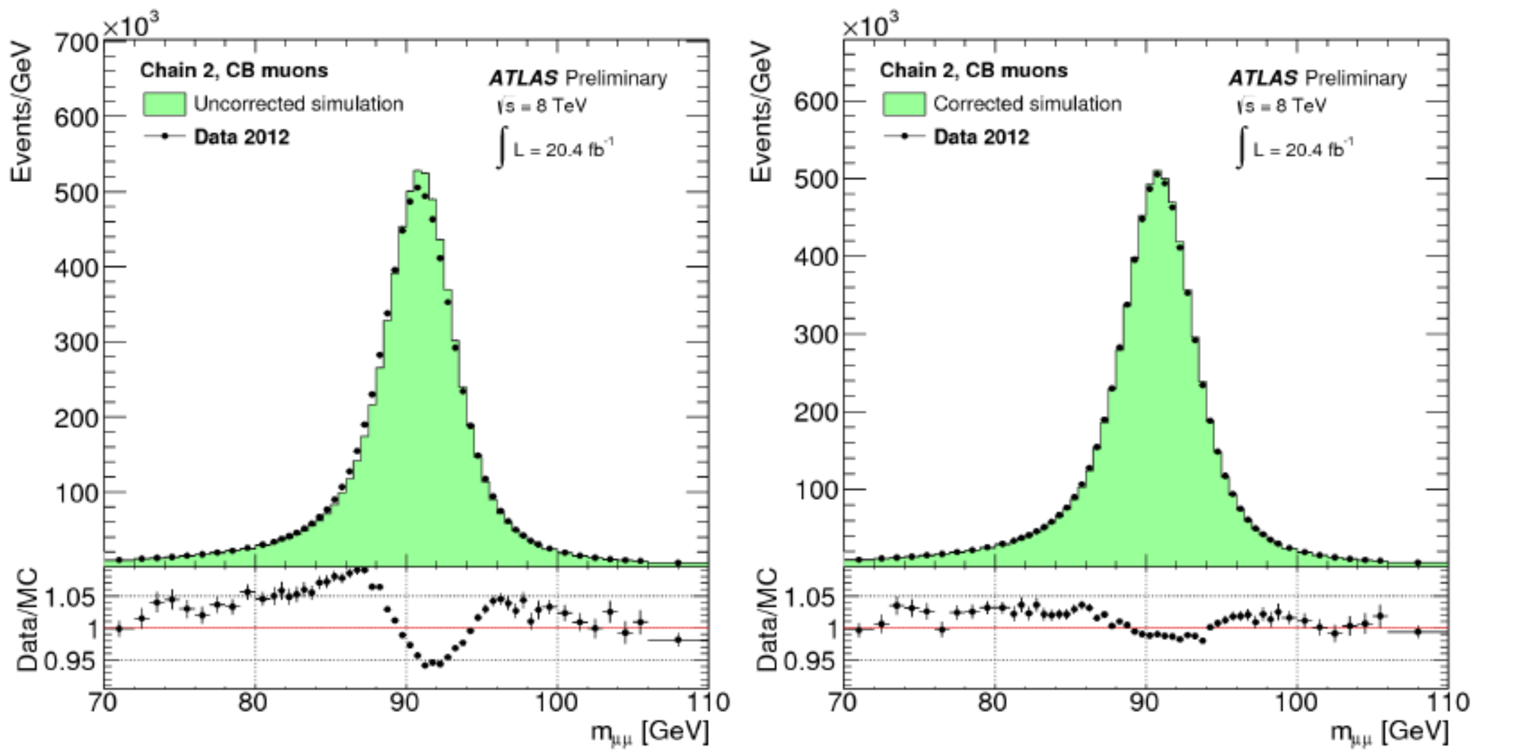
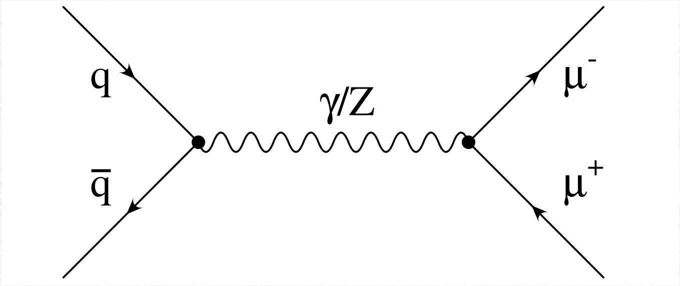
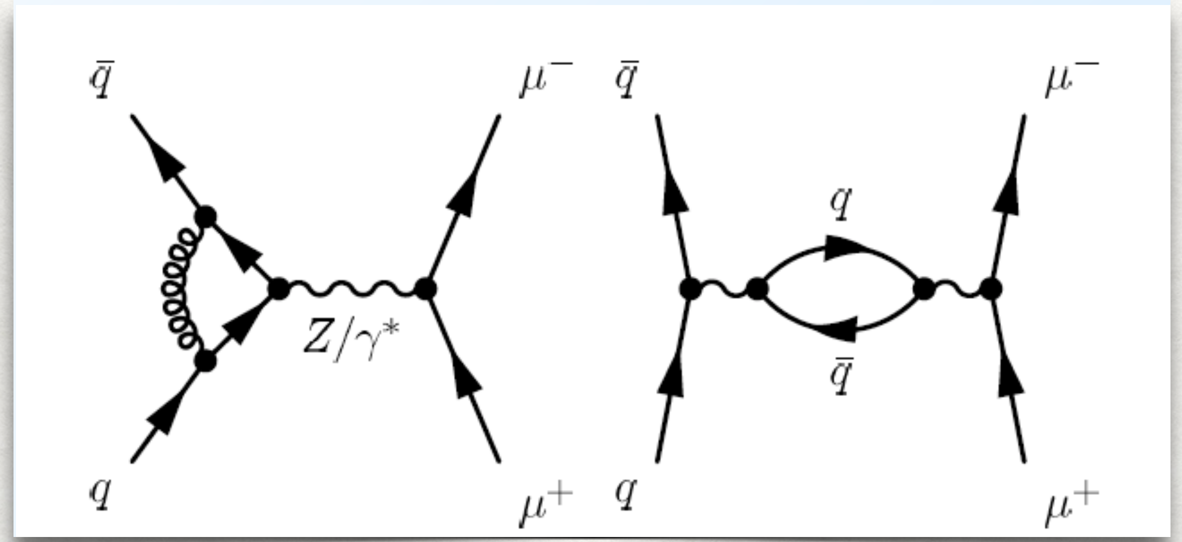


Figure 3.11: Dimuon mass distribution for Chain 2 (Muid Chain), CB muons, isolated and with p_T > 25 GeV [90]. **Left:** No smearing and scale corrections are applied on the plot. **Right:** Smearing and scale corrections are applied to the MC simulation.

Theoretical Corrections - kFactor

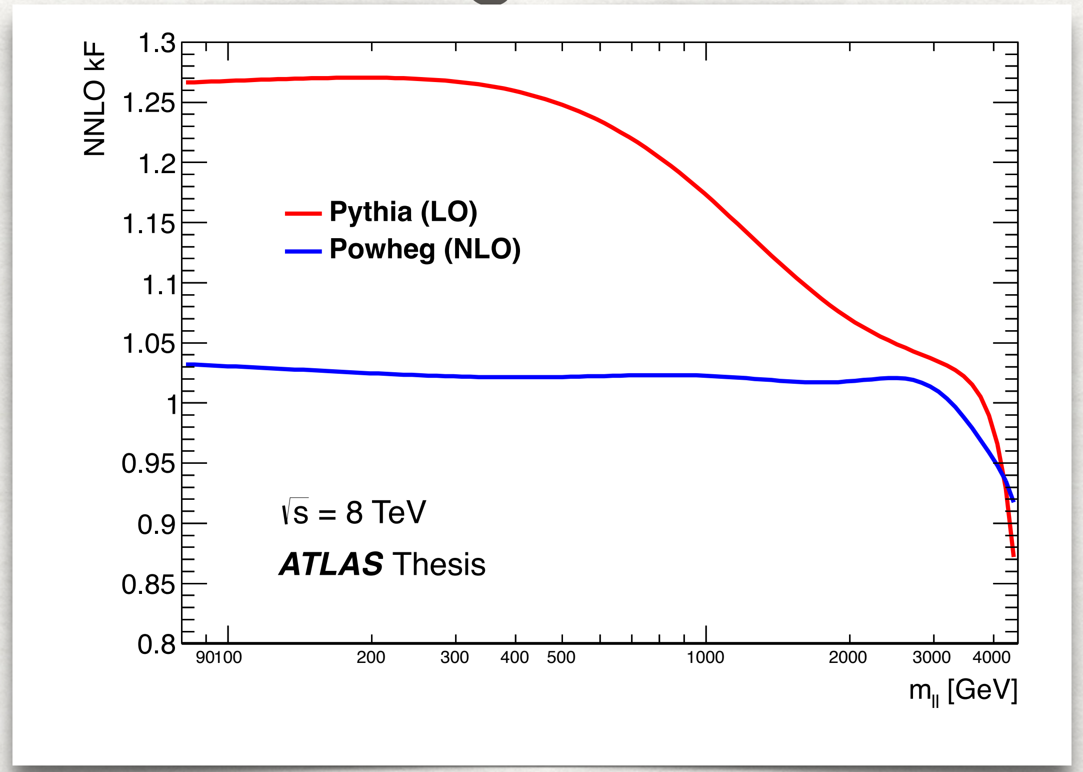
- Due to imperfect modeling of some characteristics of data in simulation, MC samples need to be corrected
- Data derived corrections
- Applied event-by event basis
- Higher order cross section corrections; "K-factors"
- QCD and EW K-factors applied to DY and signal





QCD higher order process

EW higher order process



What did we discuss?

- The Standard Model
- Particle classification
- The LHC
- The ATLAS experiment
- Corrections are needed to account for energy loss, inhomogeneities in detector regions, un-instrumented parts of the detector etc..
- Object reconstructions for jets, electrons, photons, muons
- Jet, electron, photon calibrations
- Muon momentum resolution and scale corrections
- Theory corrections

- Let me know if you have any questions!!!!
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