Lecture 4: Particle ID and Early LHC physics measurements

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TASI Summer School 2009
Boulder, CO

Addressing some questions from last time

- Typical resolutions for:
  - Gas/Wire Drift Chambers: 100-200μm
  - Silicon Strip Detectors:
    - e.g. for CMS it's 8-64μm
  - Silicon Pixel Detectors:
    - e.g. For CMS it's 15-30μm

- Calorimeters: Two types: sampling and homogeneous
  - X_0 important for EM Cal
    - Transverse (lateral) development of EM showers scale with the Moliere radius

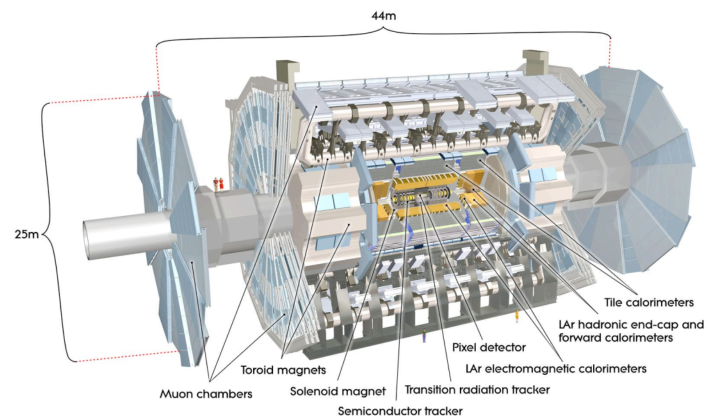
      R_M=21MeV X_0/E_c

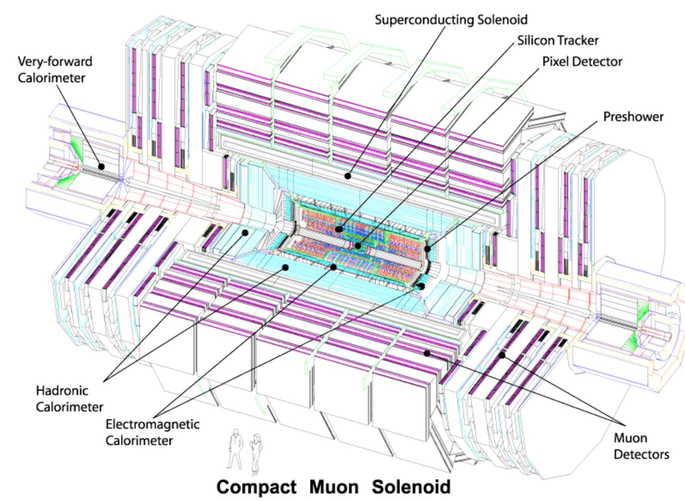
      (multiple scattering of non-radiation electrons)
  - λ_n important for Hadronic Cal

ATLAS and CMS Detectors Revisited

- Two different approaches for detectors
- Both need to be very radiation hard

	ATLAS	CMS
tracking	silicon/gas	silicon
em cal	liquid Ar	PbWO
had cal	steel/scint.	brass/scint.
muon	RPCs/drift	RPCs/drift
Magnet	Solenoid (inner) /Toroid (outer)	Solenoid
B Field	~2 Tesla /4Tesla	~4 Tesla

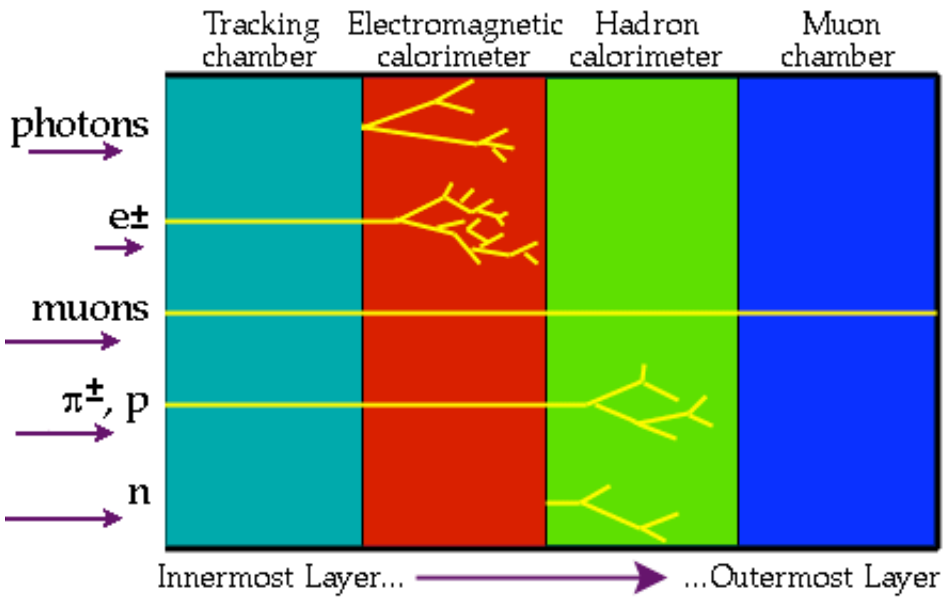


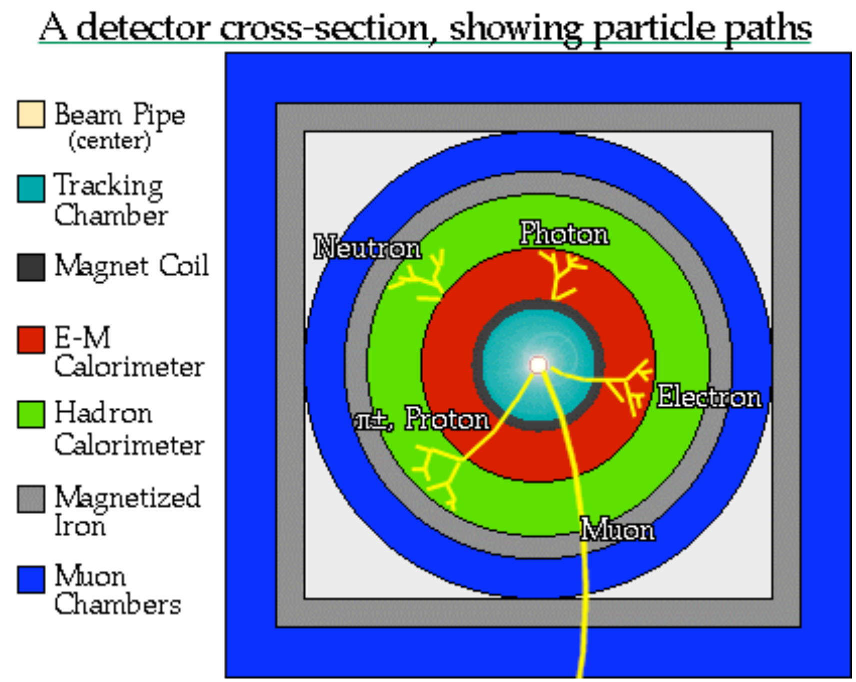


Particle ID

- Now let's see in more detail how these detectors are used for particle identification

How do experimentalists ID particles?

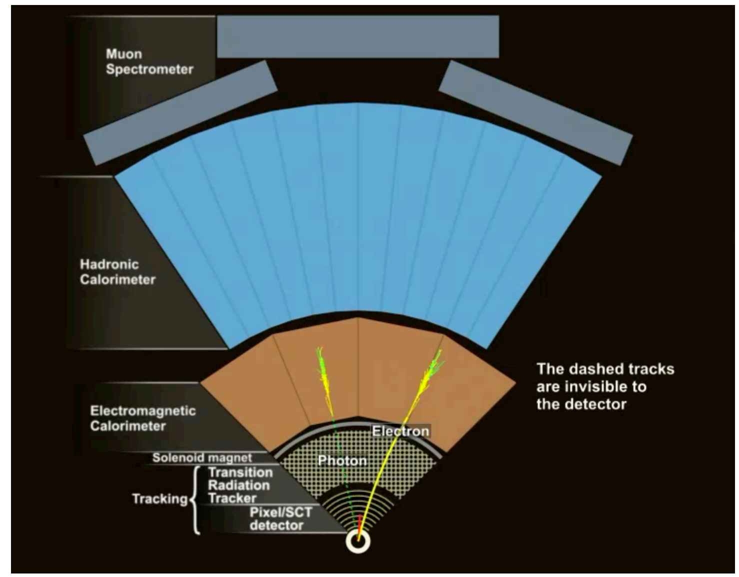


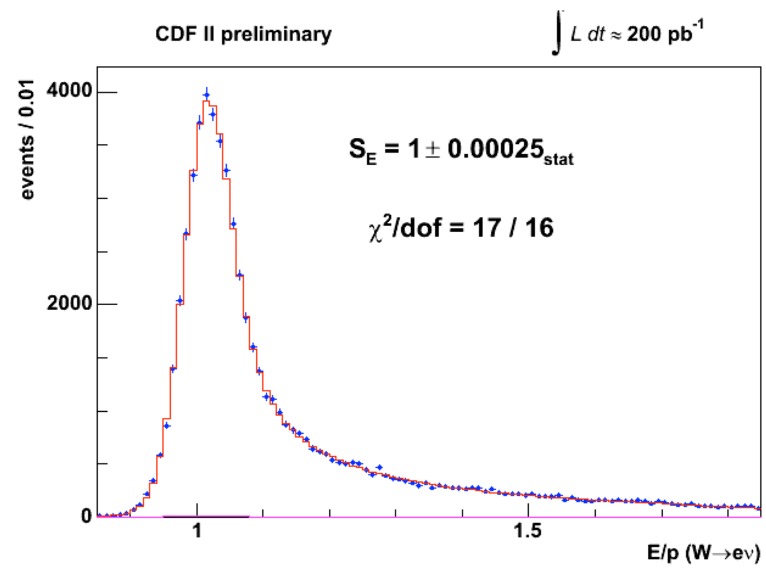


Electrons:	Deposit all their energy in the electromagnetic calorimeter, matched to a track
Photons:	Same as above but no track
Muons:	Match signal in muon chambers to track
"Jets":	Quarks fragment into many particles – energy in both calorimeters matched to track(s)
Neutrinos:	Pass through all material - measured *indirectly* by imbalance of energy in calorimeters

Electrons and Photons

- Energy deposit in calorimeter
  - Shower shape consistent with EM shower
  - Energy loss consistent with EM particle
  - Little or no energy in had calorimeter (leakage)
- If associated with track
  - Electron
  - Additional requirements such as:
    - matching requirements on positions from track and EM cluster
    - ratio of energy (calorimeter) and momentum (track) close to unity
- If not
  - Photon





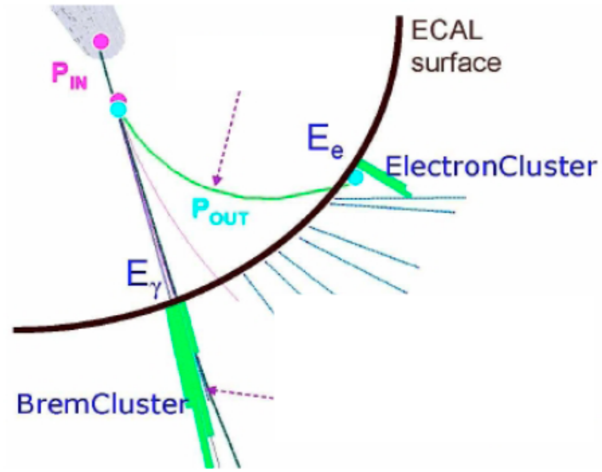
Bremstrahlung and Conversions

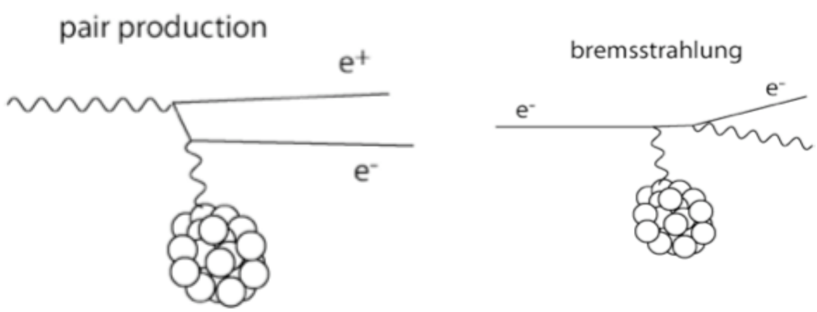
Complications:

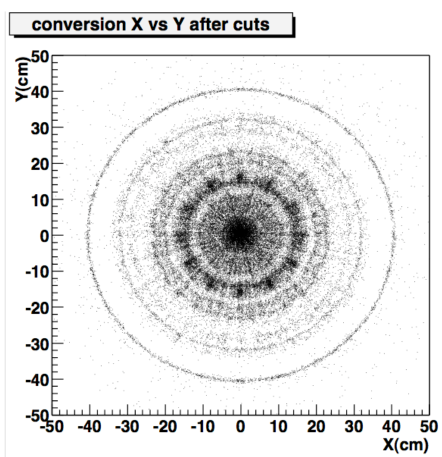
- Electrons radiate photons
- Photons pair produce electrons (conversions)

However, can be useful:

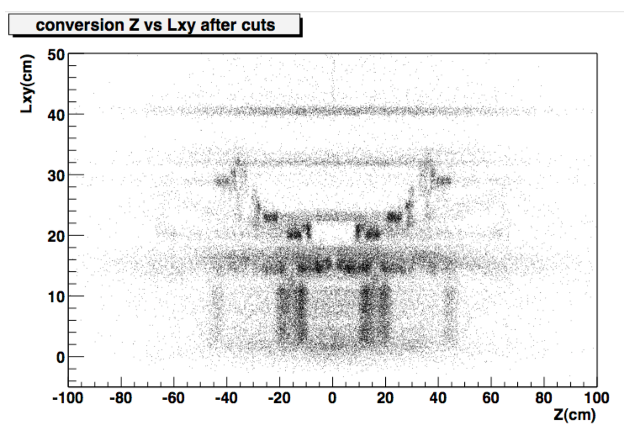
- Can use photon conversions to *x-ray* the detector and determine material before calorimeter (i.e. tracker)





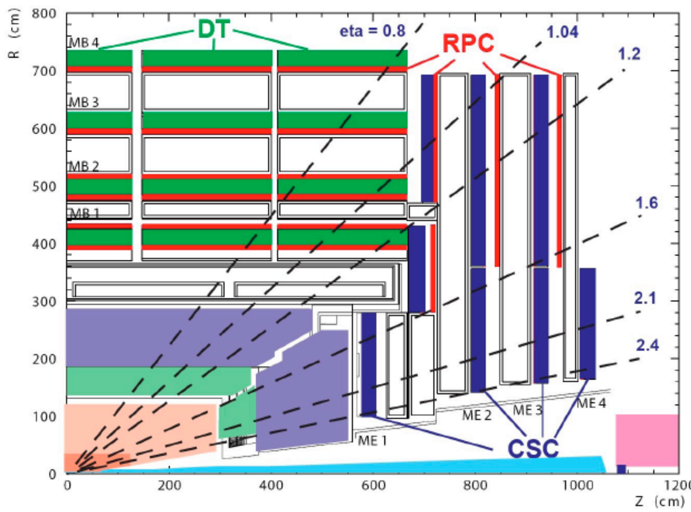


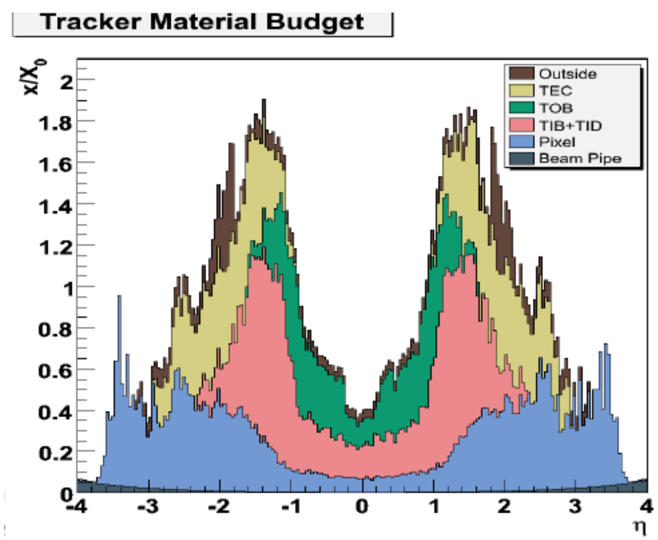
@CDF



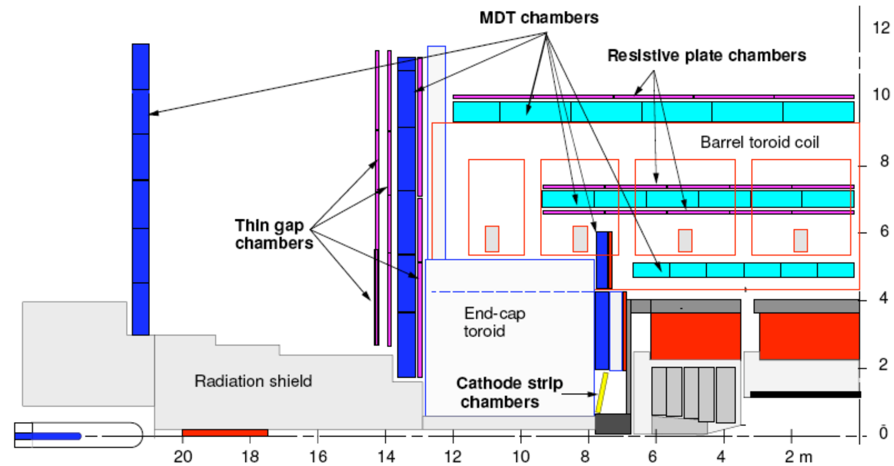
Tracker Material Budget

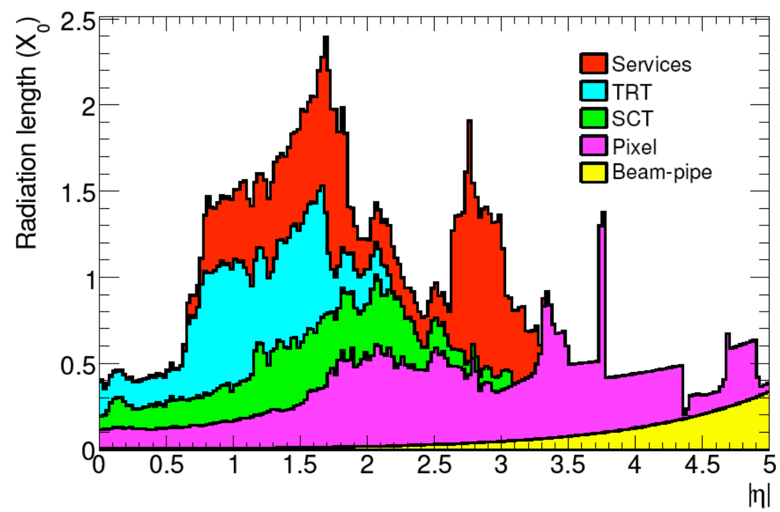
CMS





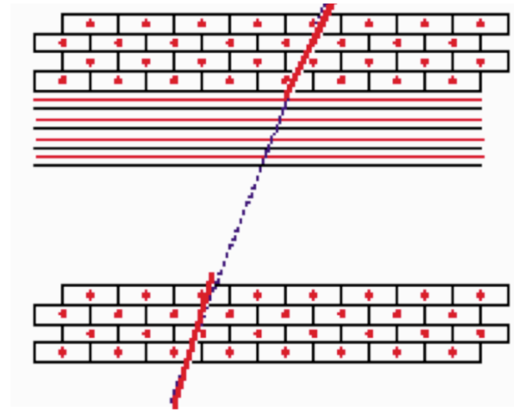
ATLAS

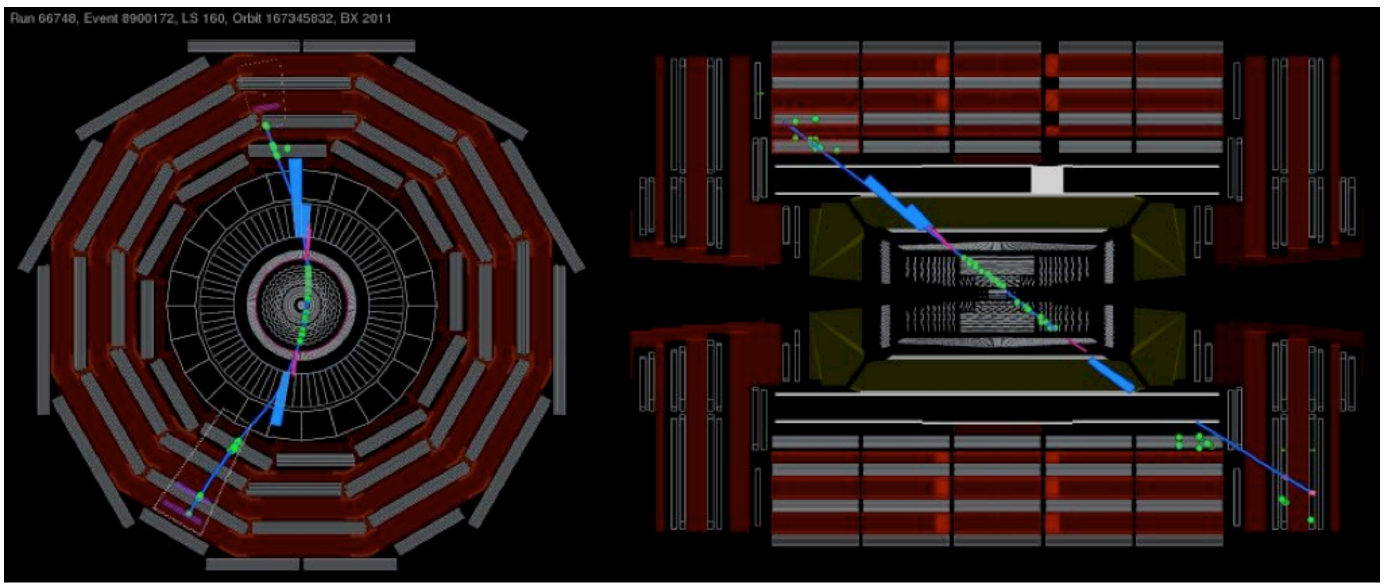




Muons

- Find tracks in the muon system
- Match with track in inner tracker
- Consistent with MIP
  - Little or no energy in calorimeters



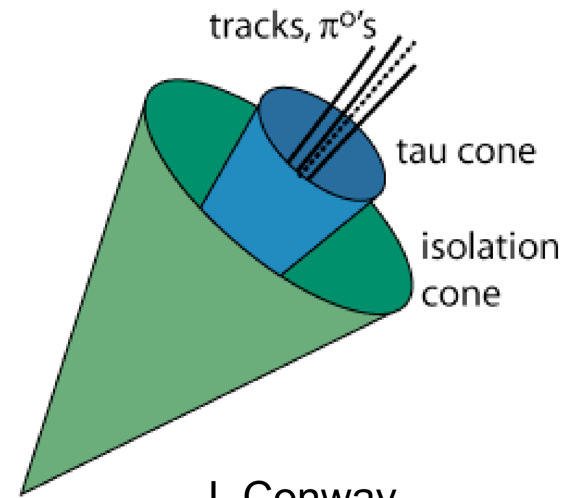


Real cosmic ray muon event in CMS detector!

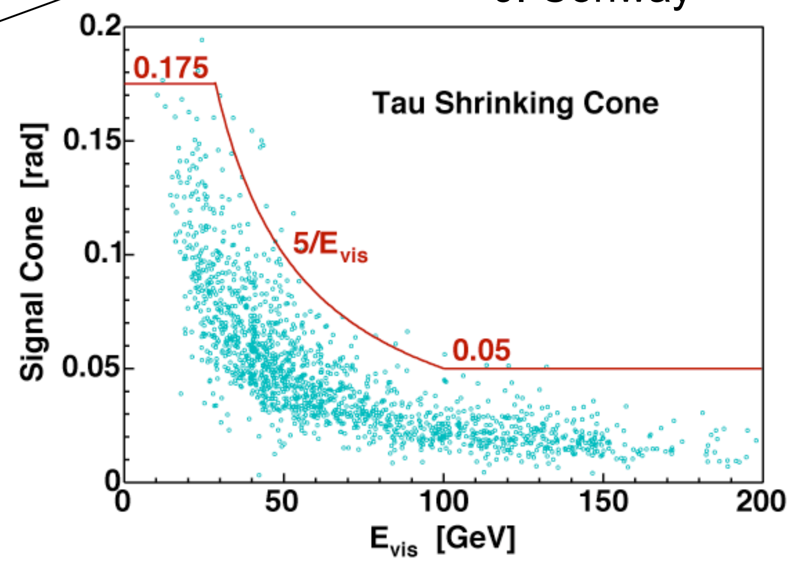
Taus

- A tau lepton decays weakly
  - Always get a neutrino (i.e. MET)
- Experimentalist's jargon:
  - A "lepton" means an e or μ
  - A "tau" means a hadronically decaying tau
- Tau reconstruction
  - narrow "jets" in calorimeter
  - Form ΔR cones around tracks
    - tau cone
    - isolation cone
  - demand tracks (1 or 3) and neutral particles are within cone
- Tau ID is challenging but very sophisticated at Tevatron and LHC

$e^- \nu\nu$	**17.8%**
$\mu^- \nu\nu$	**17.4%**
$h^- \nu$	**49%**
$\pi^- \nu$	11%
$K^- \nu$	0.7%
$\rho^- \nu$	25.4%
$h^+h^-h^- \nu$	**15%**



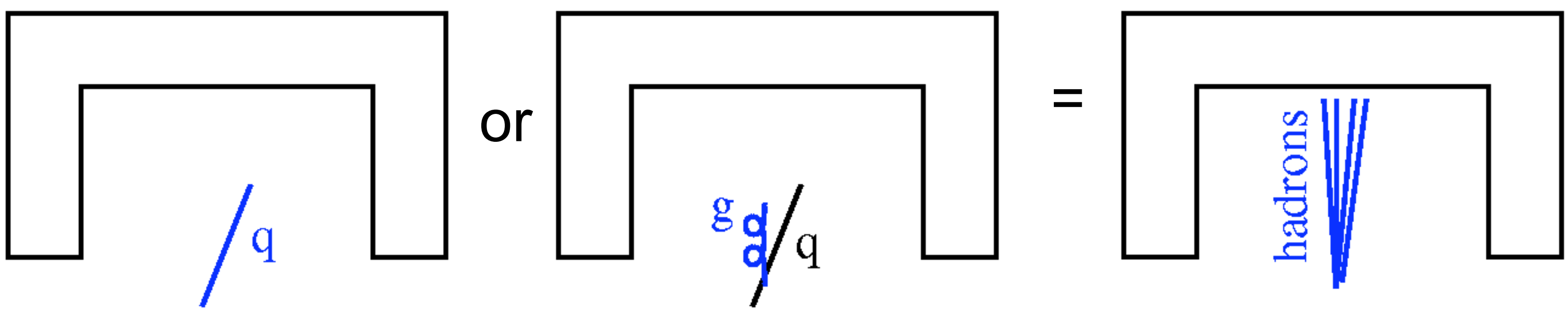
J. Conway



Jets

- What is a jet?
  - A “jet” is created when a q, qbar or gluon is kicked out of the proton
    - A hadron is created and forms a “jet” which is more or less collimated in angle, and again decays to meta-stable hadrons
      - Hadronization
  - It’s the experimentalist’s representation of a parton (more on the next slide)
- Why are they formed?
  - Remember, partons are confined!

So in reality:



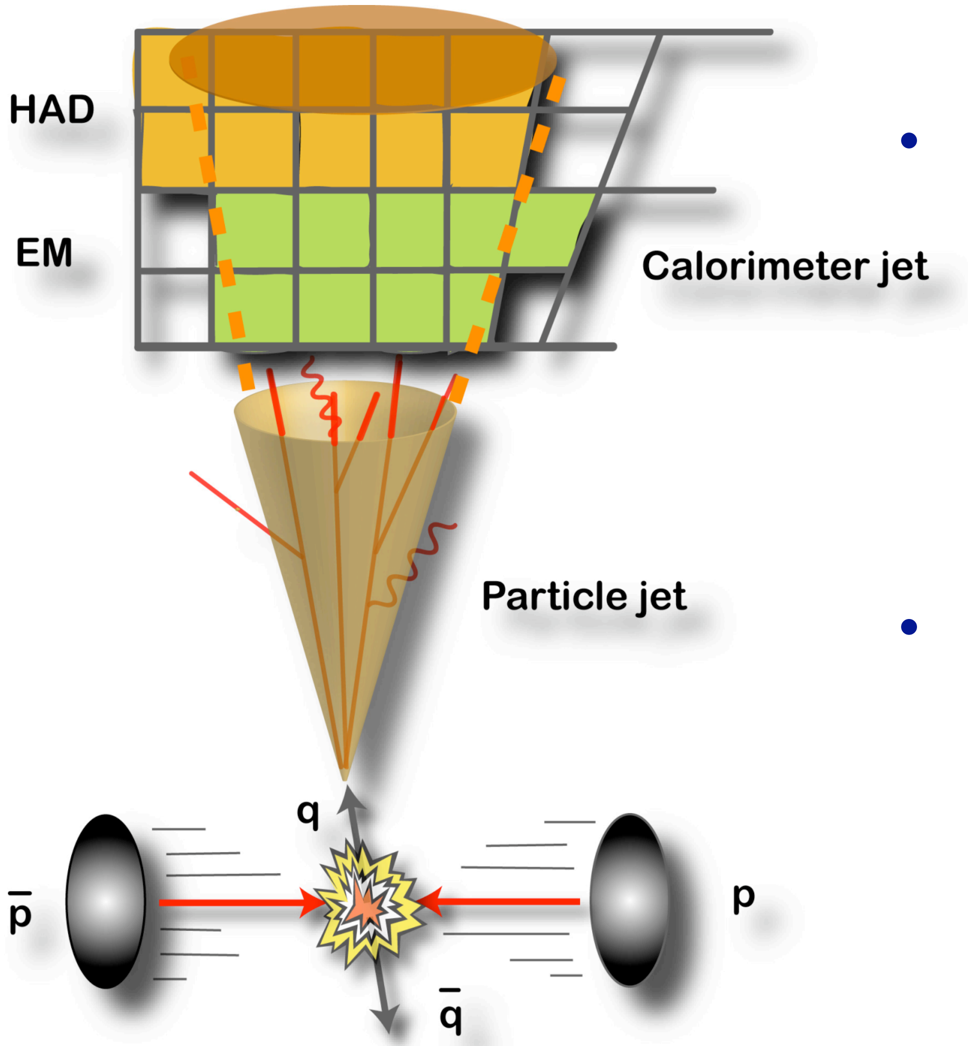
Some Experimentally Important Hadrons of QCD

Name	Mass(MeV)	Lifetime (sec)	Dominant Decay	"Flavor"
π^+	140	3×10^{-8}	$\mu^+ \nu_\mu$	$u\bar{d}$
π^0	135	8×10^{-17}	$\gamma\gamma$	$u\bar{u}, d\bar{d}$
K^+	494	1×10^{-8}	$\mu^+\nu_\mu, \pi^+\pi^0$	$u\bar{s}$
K^0_S	498	9×10^{-11}	$\pi^+\pi^-, \pi^0\pi^0$	$d\bar{s}, s\bar{d}$
K^0_L	498	5×10^{-8}	$\pi\pi\pi, \pi\ell\nu$	$d\bar{s}, s\bar{d}$
η	548	6×10^{-19}	$\gamma\gamma$,$3\pi^0$	$u\bar{u}, d\bar{d}, s\bar{s}$
ρ^+	770	4×10^{-24}	$\pi^+\pi^0$	$u\bar{d}$
ρ^0	770	4×10^{-24}	$\pi^+\pi^-$	$u\bar{u}, d\bar{d}$
ω	782	8×10^{-23}	$\pi^+\pi^-\pi^0$	$u\bar{u}, d\bar{d}$
K^{*+}	892	1×10^{-23}	$K^+\pi^0, K^0\pi^+$	$u\bar{s}$
K^{*0}	896	1×10^{-23}	$K^+\pi^-, K^0\pi^0$	$d\bar{s}$
η'	958	3×10^{-21}	$\pi^+\pi^-\eta, \ldots$	$u\bar{u}, d\bar{d}, s\bar{s}$
p	938	$> 10^{42}$	–	uud
n	940	887	$pe^-\bar{\nu}$	udd
ϕ^0	1020	1×10^{-22}	$K^+K^-, K^0_L K^0_S$	$s\bar{s}$
Λ	1115	2×10^{-10}	$p\pi^-, n\pi^0$	uds
Σ^+	1189	8×10^{-11}	$p\pi^0, n\pi^+$	uus
Σ^0	1193	7×10^{-20}	$\Lambda\gamma$	uds
Ξ^0	1314	3×10^{-10}	$\Lambda\pi^0$	uss
Ξ^-	1321	2×10^{-10}	$\Lambda\pi^-$	dss
Ω^-	1672	8×10^{-11}	$\Lambda K^-, \Xi^0\pi^-$	sss
D^+	1869	1×10^{-12}	$K + \cdots$	$c\bar{d}$
D^0	1864	4×10^{-13}	$K + \cdots$	$c\bar{u}$
B^+	5279	2×10^{-12}	$D + \cdots$	$b\bar{u}$
B^0	5279	2×10^{-12}	$D + \cdots$	$b\bar{d}$

M.Strassler

- Note this is by no means an exhaustive list!

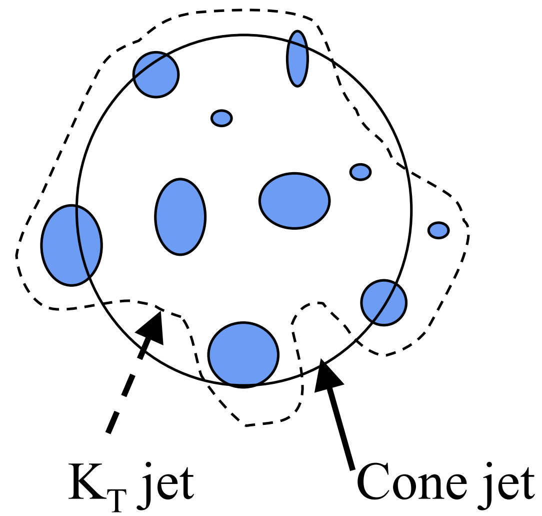
Jet Reconstruction I



- How to reconstruct the jet?
  - Group together the particles from hadronization
  - Attempt to measure the energy of the parton (whatever that means - this is also not precisely defined)
- This sounds easy but in reality is very hard!

Jet Reconstruction II

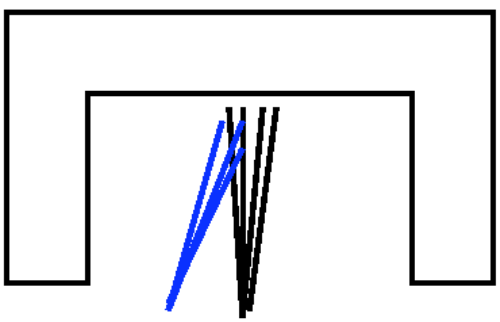
- Experimentalists and theorists form jets using an arbitrary algorithm.
  - Two main types
    - Draw circles around clusters of energy according to some rule
      - e.g. “cone” algorithms (various forms)
    - Make recursive clusters according to some rule
      - e.g. k_T,Cambridge-Aachen,...
- Also, for theory predictions and experimental measurements to agree, their jet definitions must agree!



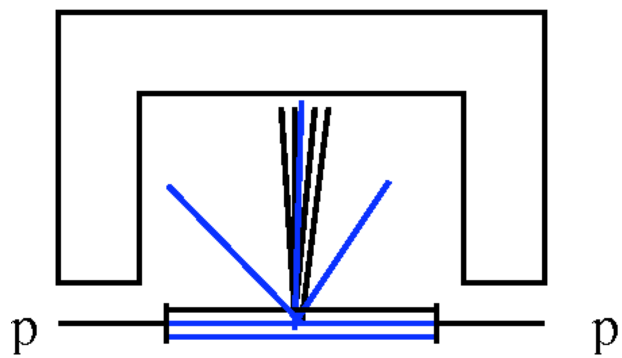
Challenges of measuring jets

- When measuring the jet energy, how can we decide which particles come from which hadronization process?
- We have lots of effects that can complicate the jet energy measurement, such as

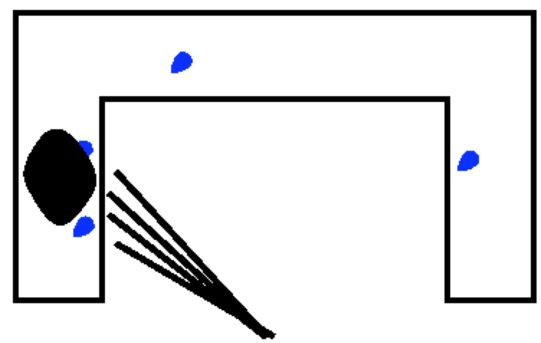
Mulitple p-p interactions:



Multiple partons in proton (spectator) interacting:



Noise in the calorimeter:

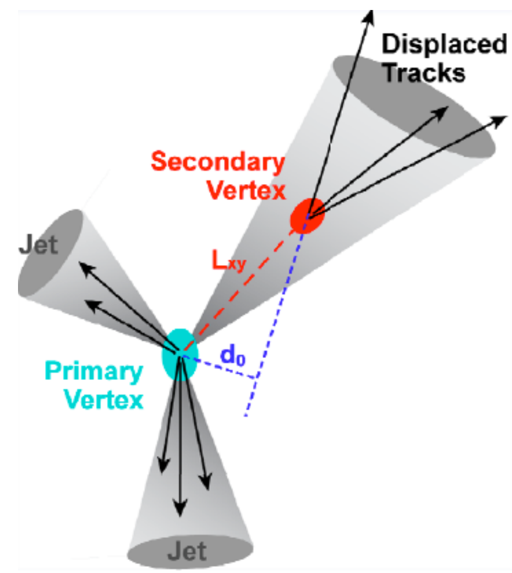


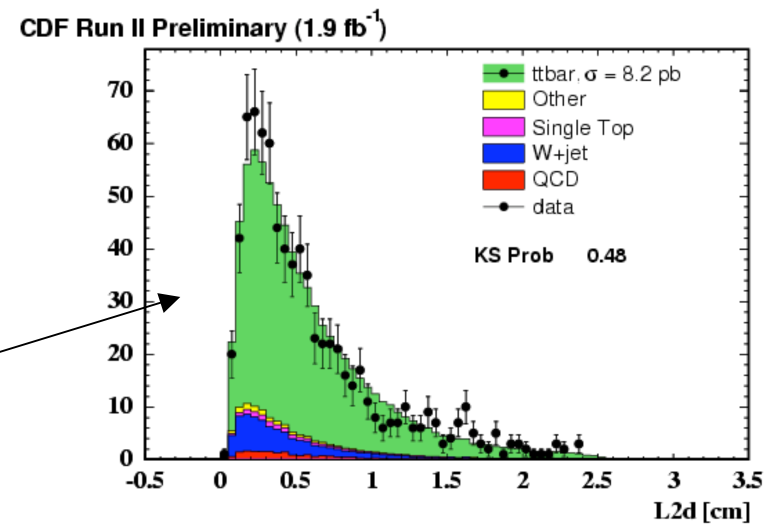
B. Heinemann

- But we have ways of correcting for such effects
  - *This calibration of the jet energy is generally called the "Jet Energy Scale" (JES)*
    - Depends on the p_T and the η of the jet (calorimeter response)

B-tagging

- b hadrons are
  - long-lived (cτ~450 μm)
  - massive
- Signature of a b decay:
  - Displaced vertex
    - Important parameters are
      - d_0 = impact parameter
      - L_{xy} = distance between primary and secondary vertices
  - Or look for e or μ inside jet
    - Decays of B hadrons with leptons





L_{xy} distribution from ttbar events at CDF

Missing Energy (I)

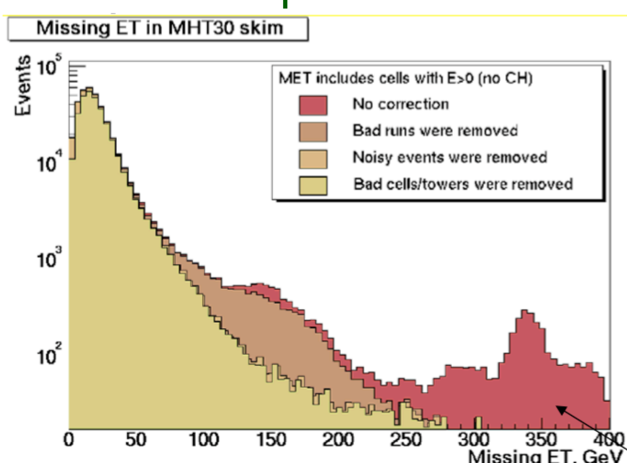
- Recall that MET, is defined as

$$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ \mathrm{visible}} \vec{\mathrm{E}}_\mathrm{T}$$

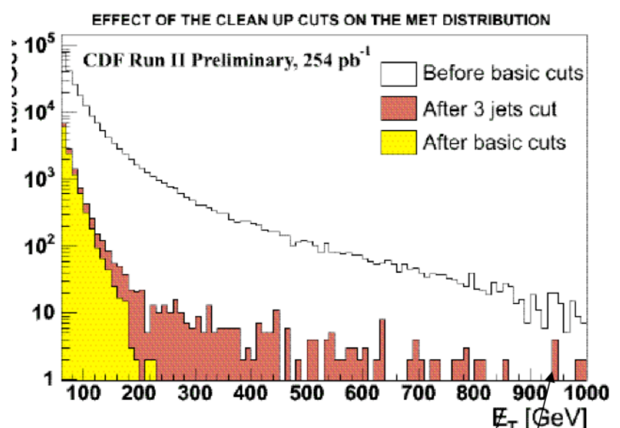
  - where nhat$_i$ is the component in the transverse plane of a unit vector that points from the interaction point to the ith calorimeter detector tower.
  - This includes all clustered and unclustered energy
- It's one of the most interesting and most difficult quantities for experimentalists
  - **Whenever anything goes wrong you have MET!** Examples:
    - dead calorimeter cells
    - jet whose hardest hadron enters a crack in the calorimeter
    - "beam halo"
    - a very rare (but not rare enough) high-pT , high-η jet (QCD jet cross sections dominate hadron collisions)
    - forward calorimeter (not working or not calibrated)
- Therefore, we need to carefully understand this quantity
  - Very important for new physics searches

Missing Energy (II)

- Examples of corrections we apply to MET before we use in analysis
  - Correction for for muons
    - Recall that muons are MIPs and therefore not absorbed in the calorimeter
  - Correction for calorimeter energy scale
    - Once calorimeter calibration determined with jets described before, need to apply this to MET as well
  - Correct for known leakage effects (cracks etc)
- Remember these plots?



MET, before corrections (Do)

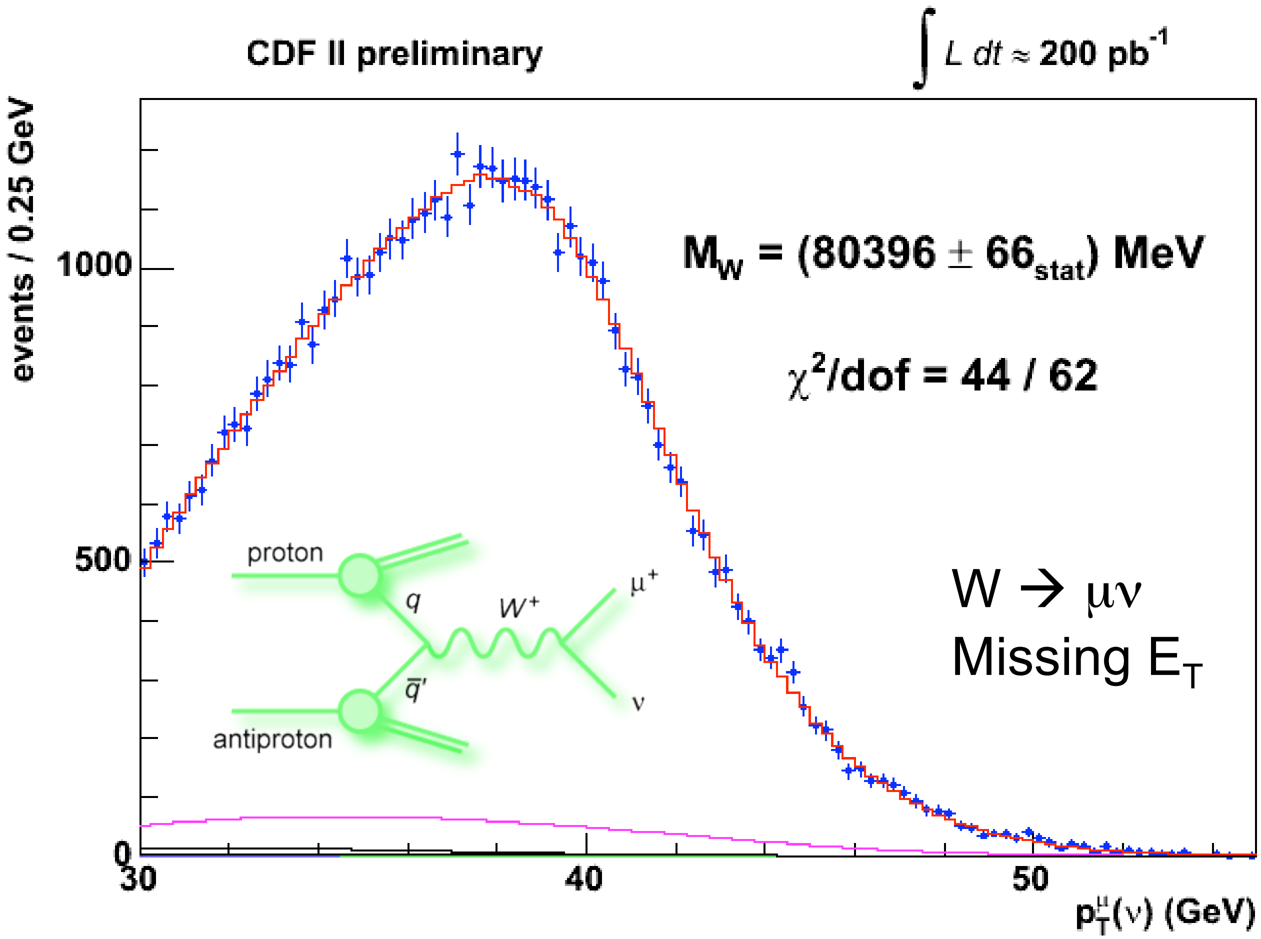


MET, after corrections (CDF)

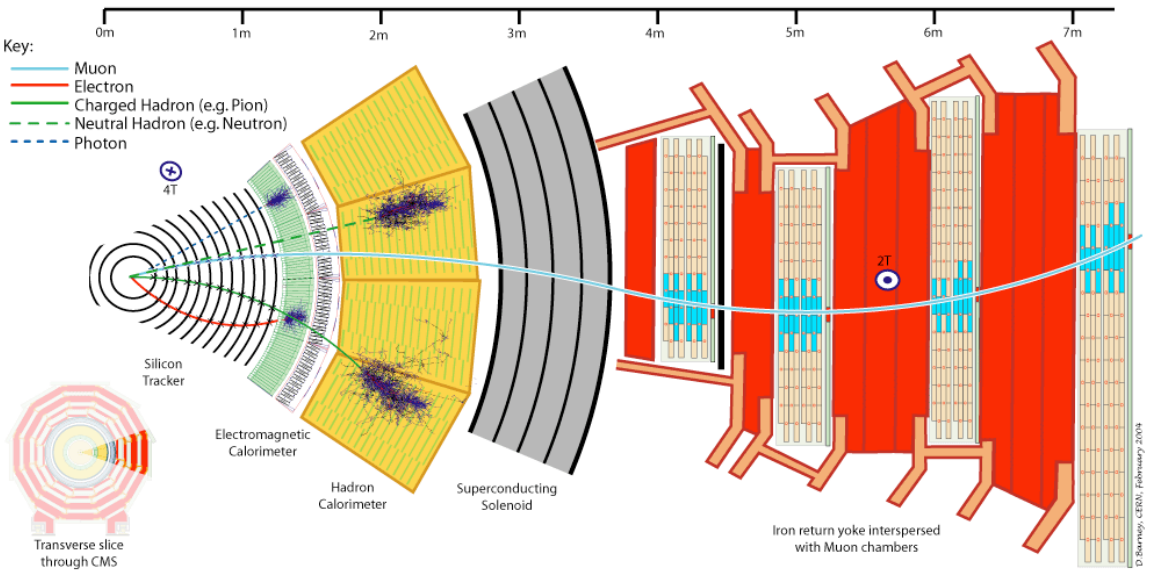
This is where new physics may sit

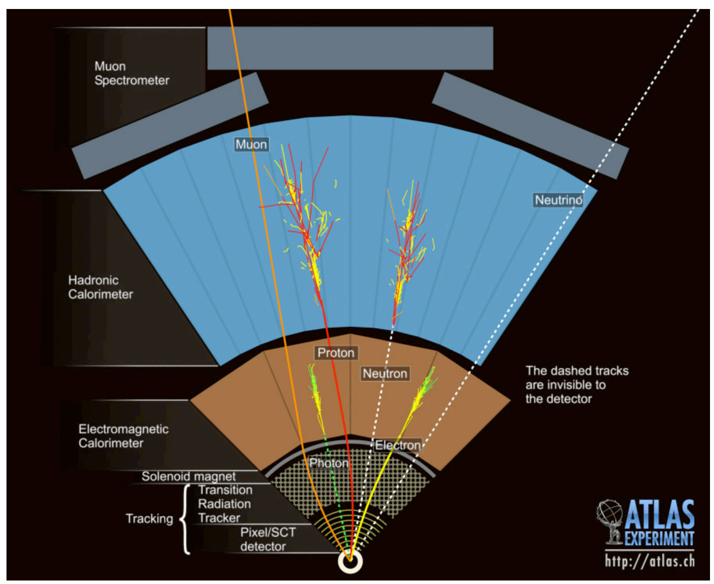
Missing Energy (III)

- An understanding of MET to the level shown below takes a long time!
- Many early analyses at the LHC will avoid using MET initially (e.g. try using H_T instead)



Putting it all together

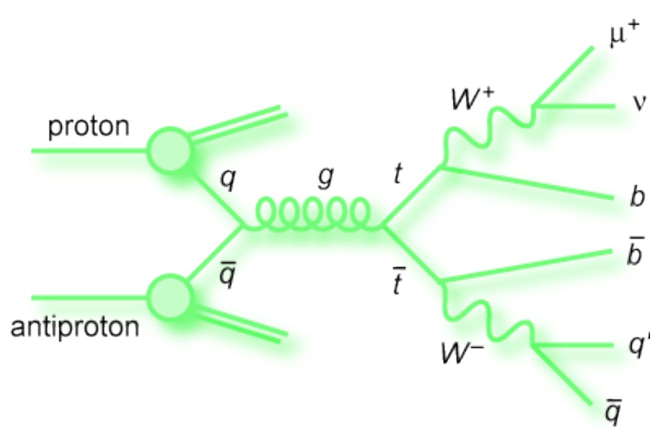




A CDF Event Display

This shows many of the objects we just covered

- leptons (e,μ and τ)
- ν (missing E_T)
- quarks (jets)
- b-quarks (“b-tag” jet)



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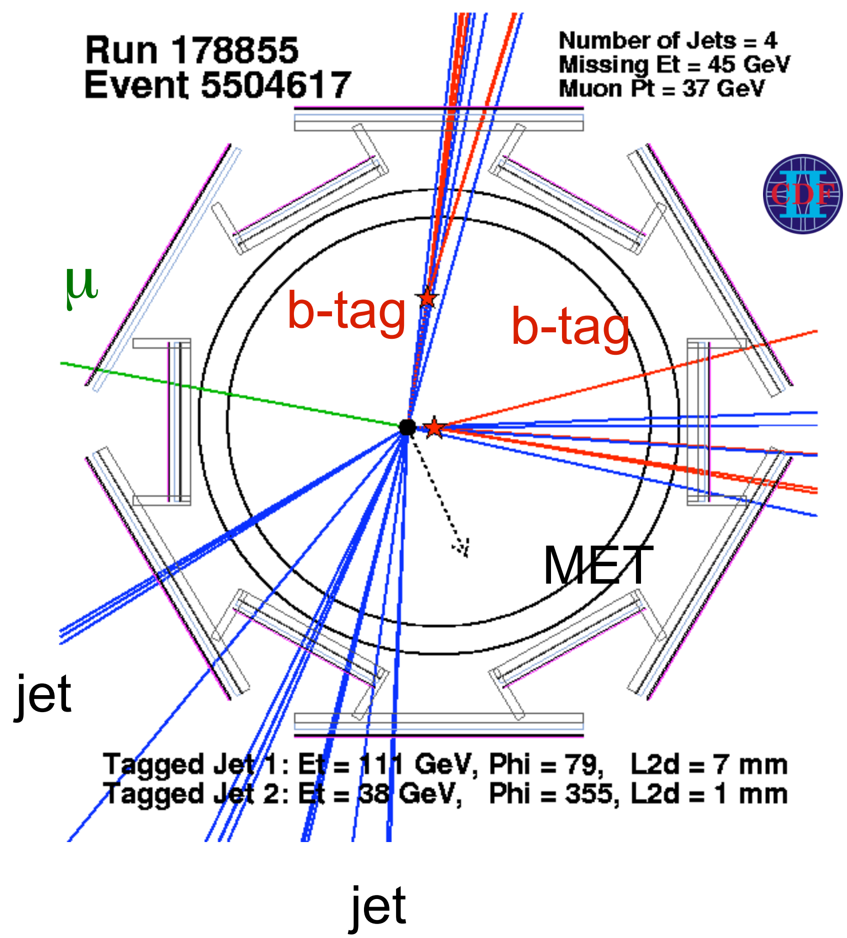
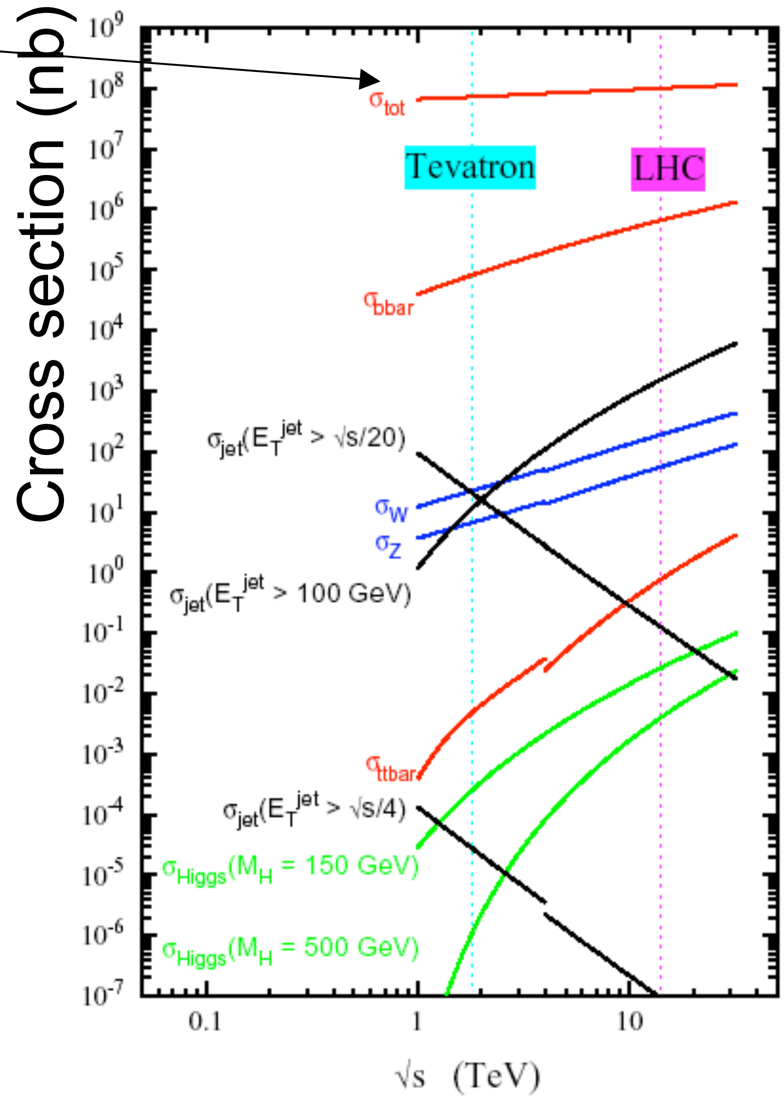


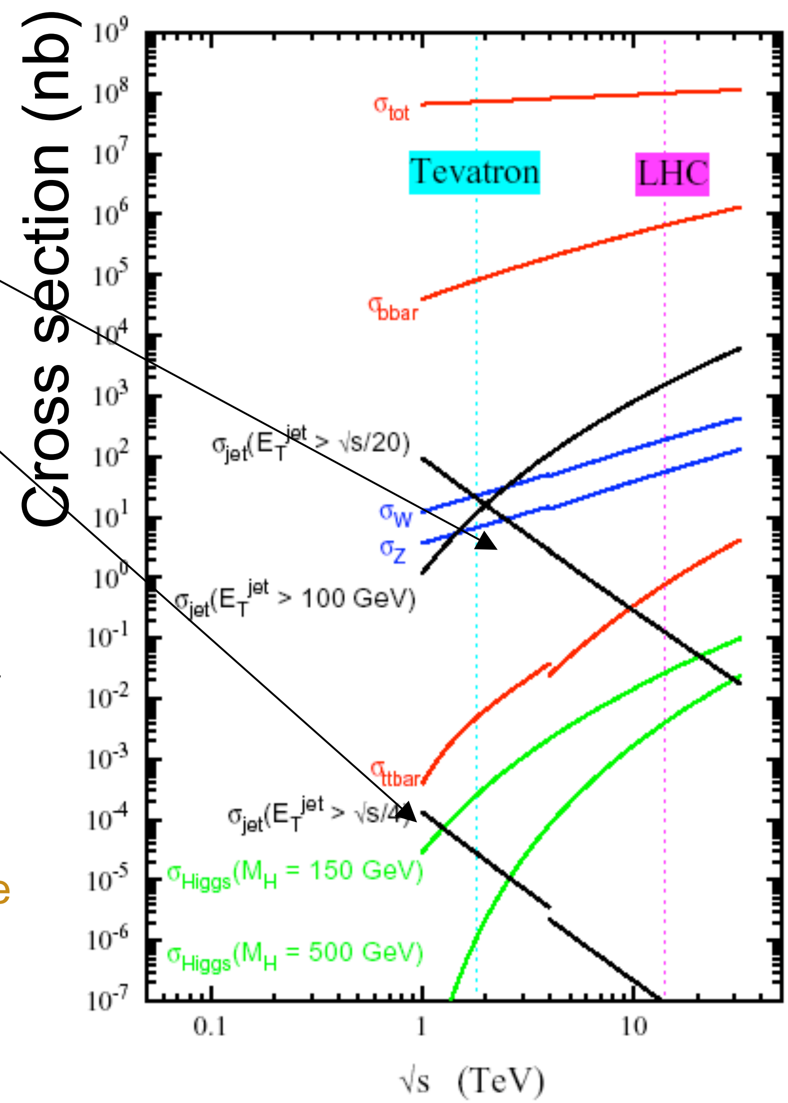
Trigger: Selecting the interesting events (I)

- Our starting point is here
  - At the LHC the rate for all collisions is 40MHz!
  - Although ideal, it's impossible to keep all the events
- Need to decide a priori which are the "interesting" events to keep/filter
- Need to be selective
  - enhance rare processes
  - reduce common ones
- If we make bad/unwise choices we will throw away the new physics!
  - If you don't trigger on it, it's gone forever!
- Theory plays a role in guiding these choices
  - Important to have good communication between theorists and experimentalists for coming up with new triggers



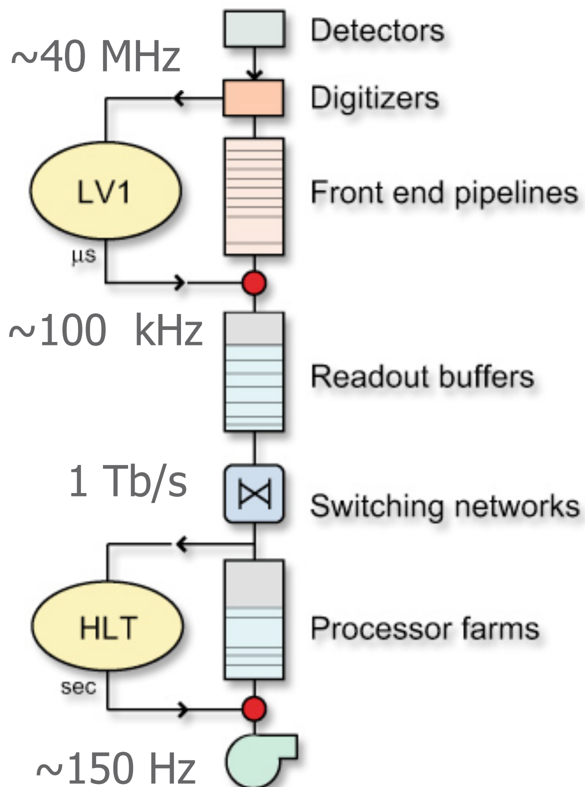
Trigger: Selecting the interesting events (II)

- We want to trigger on things that are rare in the SM
- But also want to keep "less" interesting events (at least initially) for standard-candle measurements, calibrations, etc.
- Your "run-of-the-mill" trigger table will contain triggers on:
  - electroweak particles: γ , e, τ at as low an energy as possible
  - very high-energy partons (jets)
  - apparent invisible particles (MET)
- Beware!
  - All measurements are distorted by the trigger
  - Any measurement must account for the efficiency of the trigger and the resulting distortion (eta, phi pt dependence?)
- Therefore, we must measure the efficiencies of the interesting triggers
  - "Backup" triggers are often needed

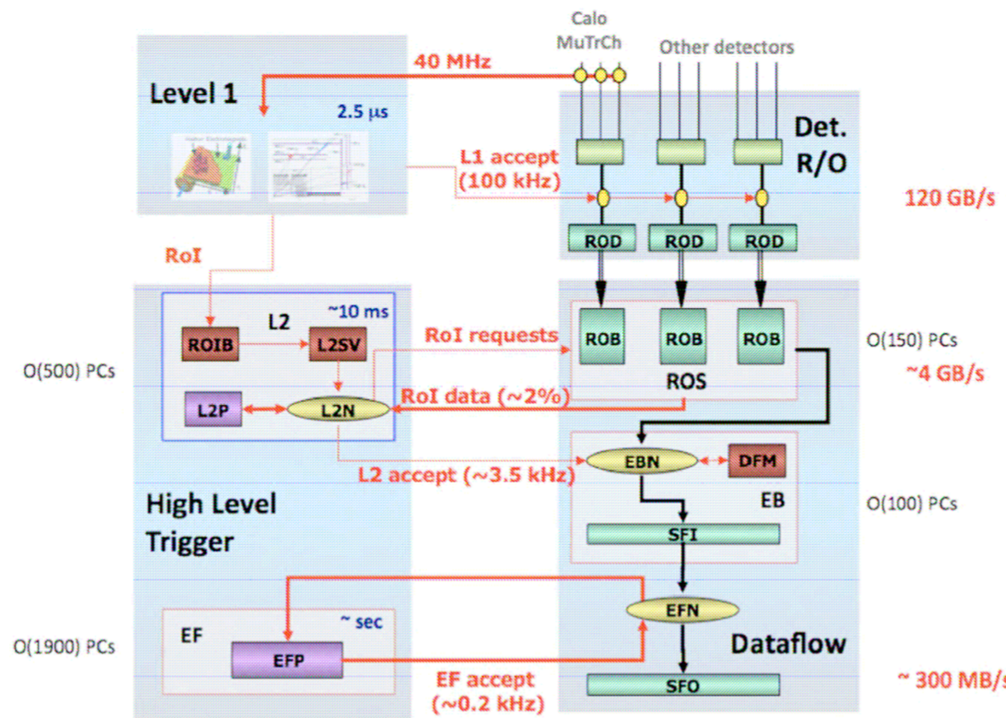


CMS and ATLAS Triggers

CMS



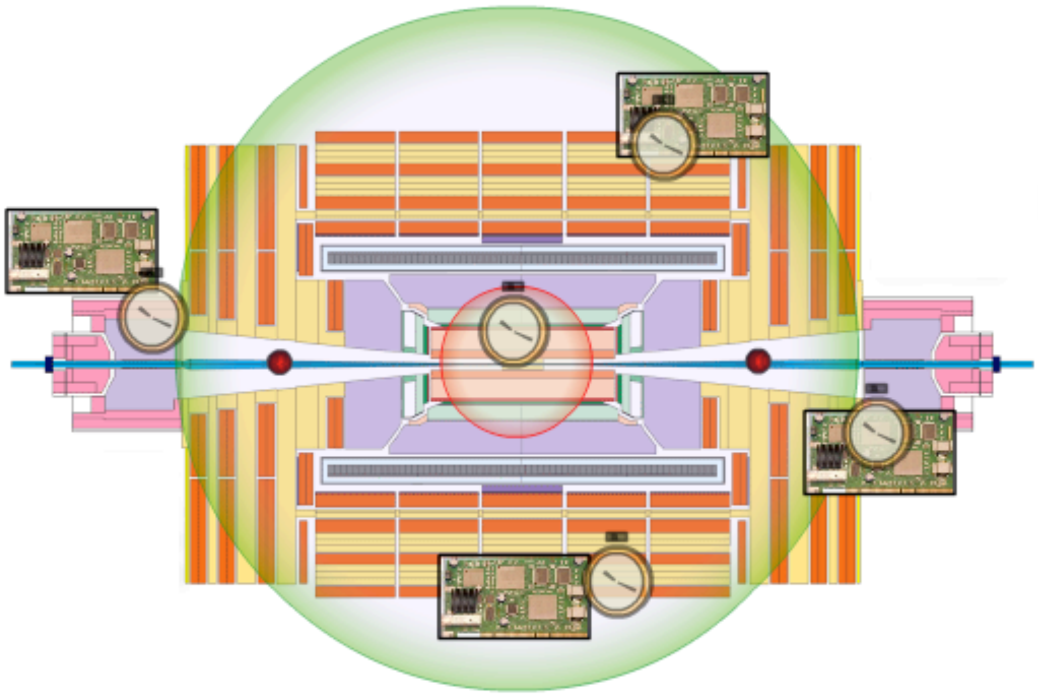
ATLAS



Level 1: Hardware based (electronics)
Level 2: Software based

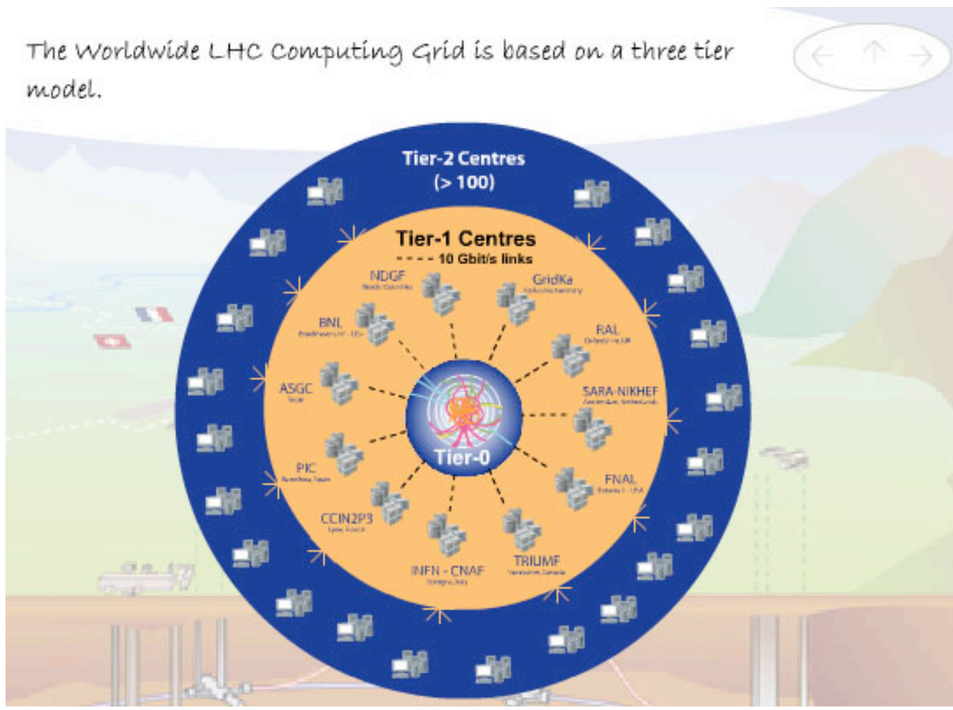
The decision to keep ~1/200,000 events happens every second.
No room for mistakes!

Animation



How do we get to analyze the data?

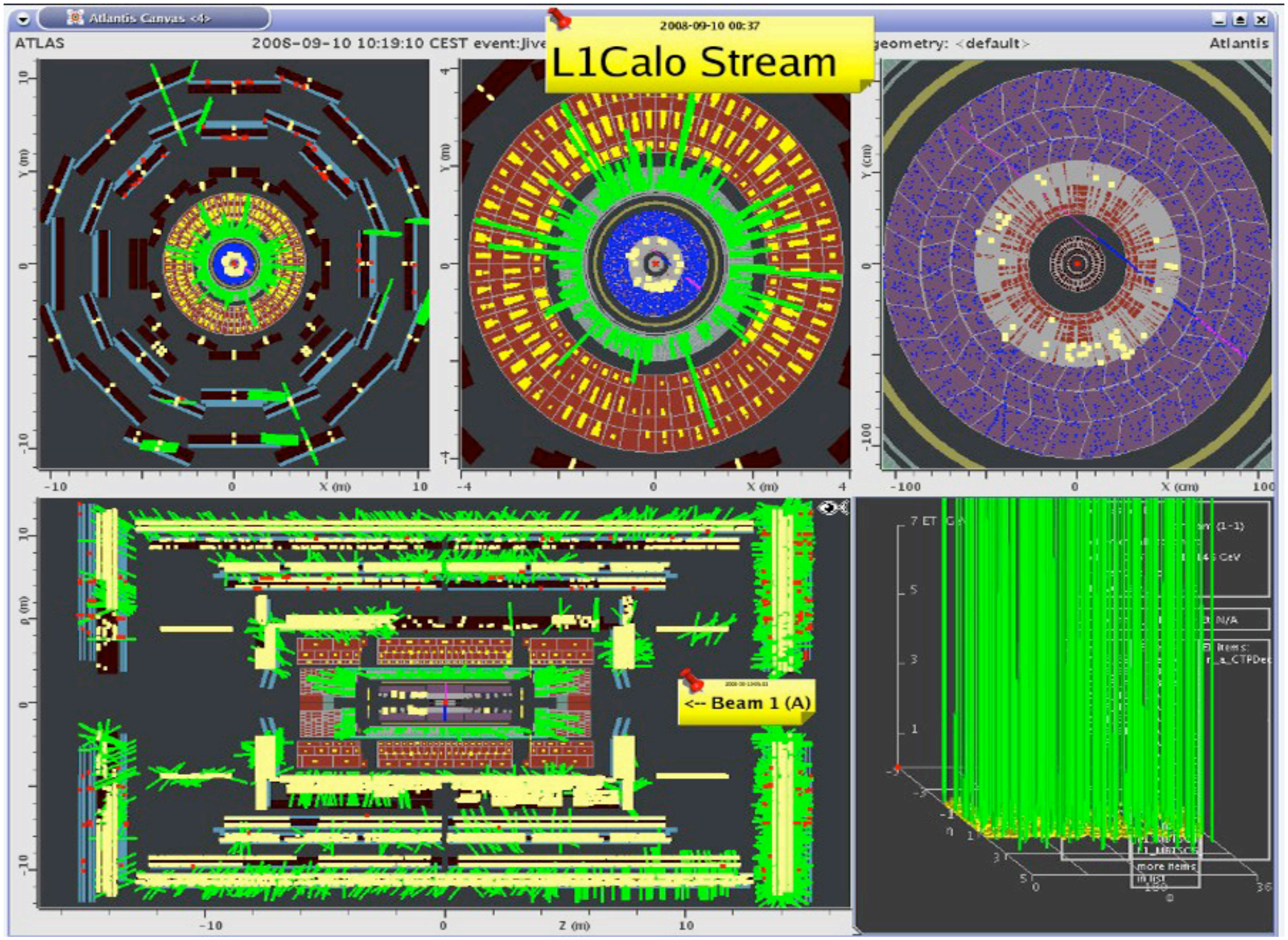
- Once the data has been triggered and recorded, how do I get it at my home institution for analysis?
- Challenging task since the LHC will produce roughly 15 petabytes (15 million gigabytes) of data annually
- The LHC has a tiered computing model to distribute data around the world a.ka. The GRID



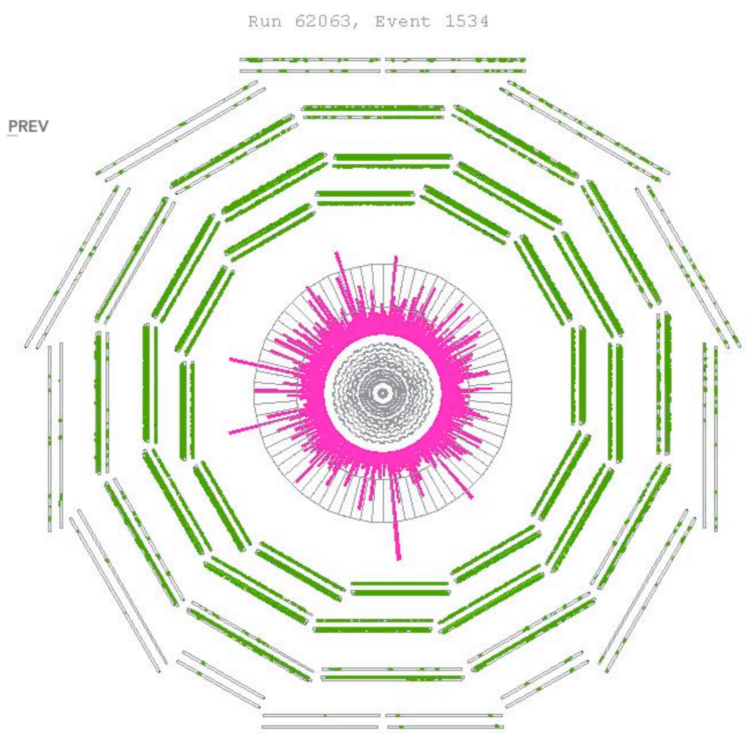
LHC First Beam September 2008

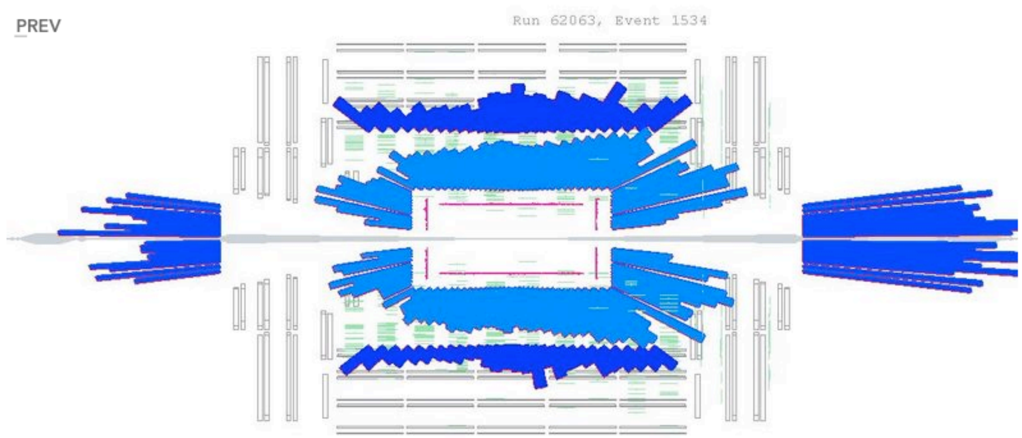
- First beam circulated
  - 450GeV, ~2x10^9 protons
- Beam was steered into collimators (tungsten blocks)
- Detectors picked up debris, or "splash", of particles
- Lots of anticipation, followed by celebration
  - Followed by … well, let's focus on the positive …

Splash events in ATLAS



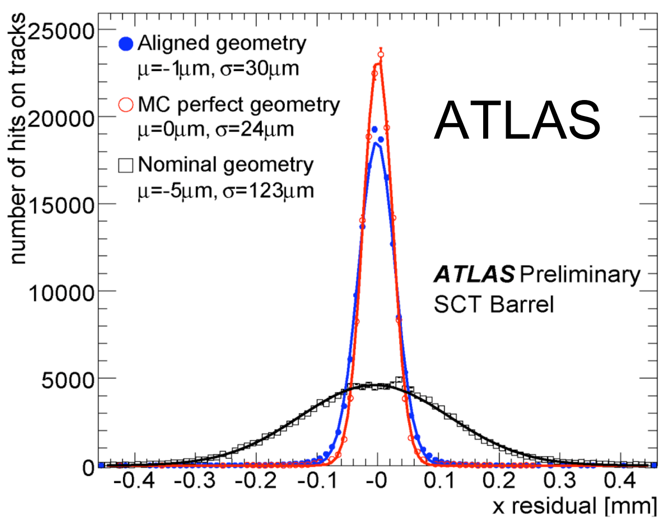
Splash events in CMS

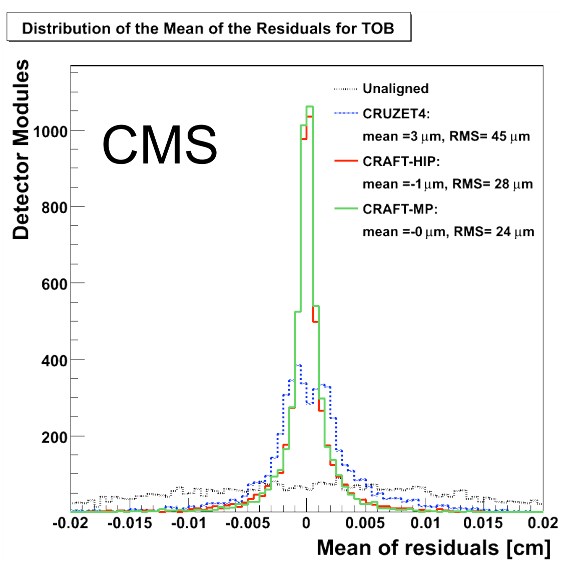


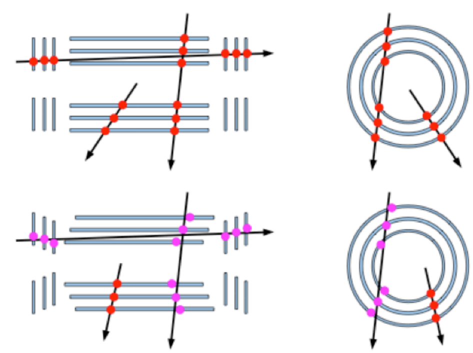


Using Cosmic Ray Muons

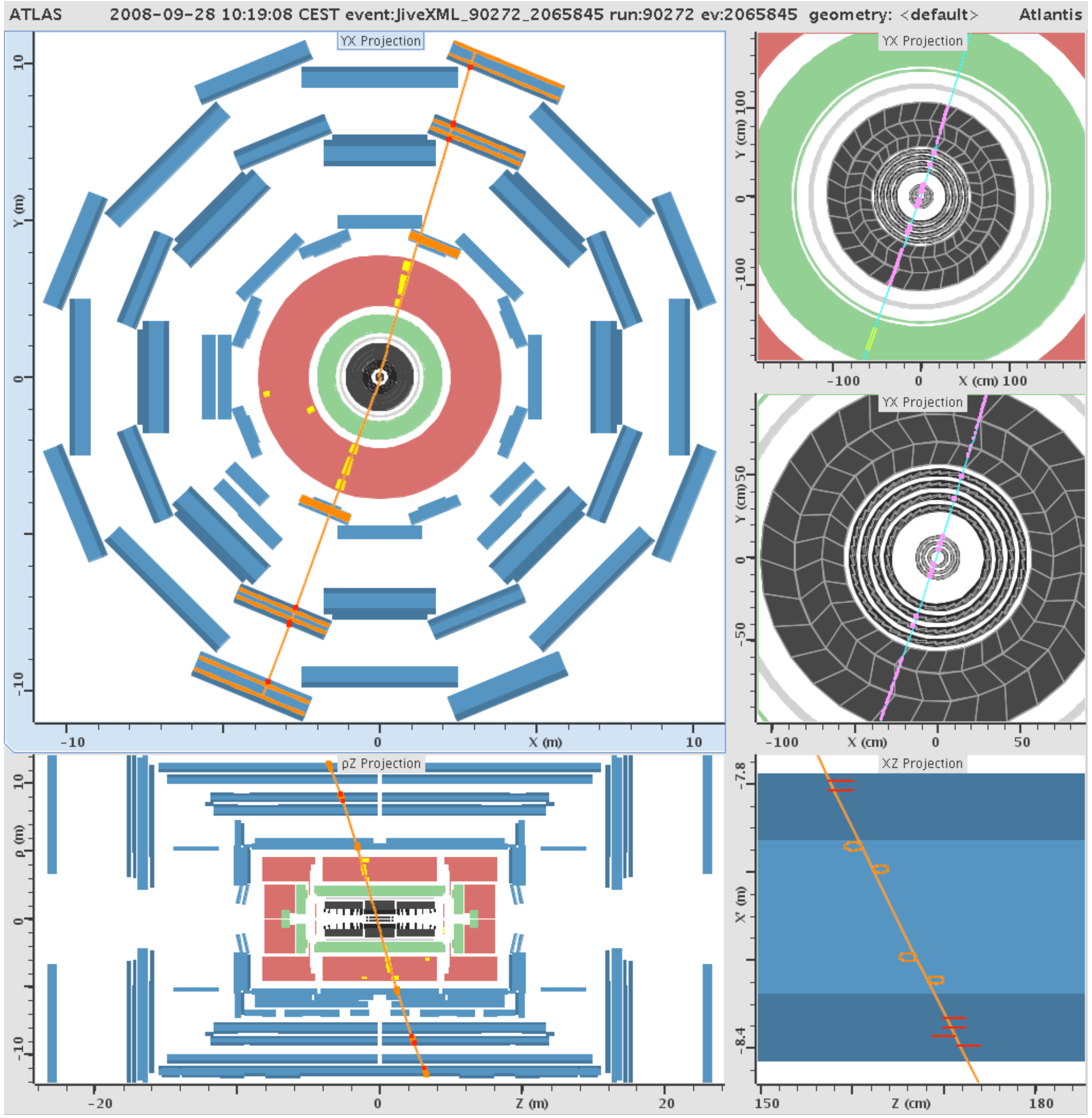
- Since then, the LHC experiments have been preparing for beam by looking at cosmic ray muon events in the detector.
- Tremendously valuable source for detector & software commissioning!
- Can also be used to begin alignment of detector!



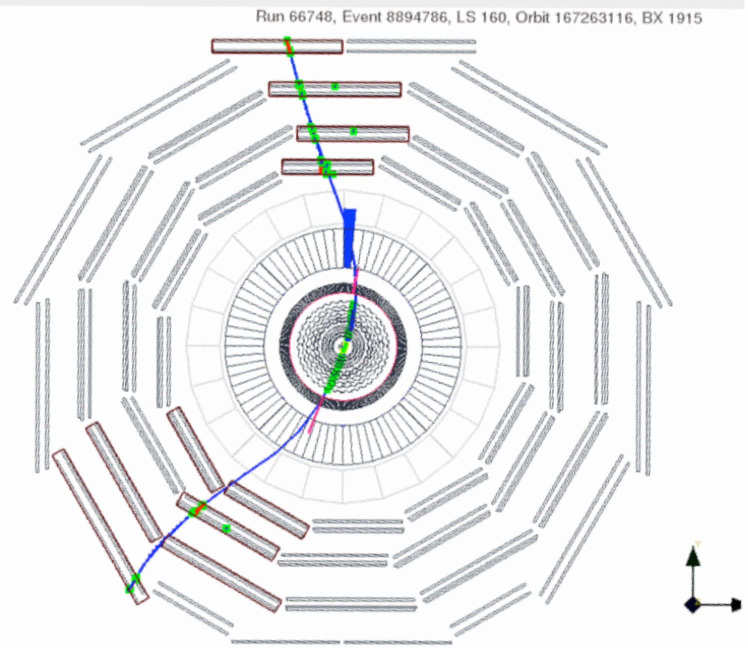




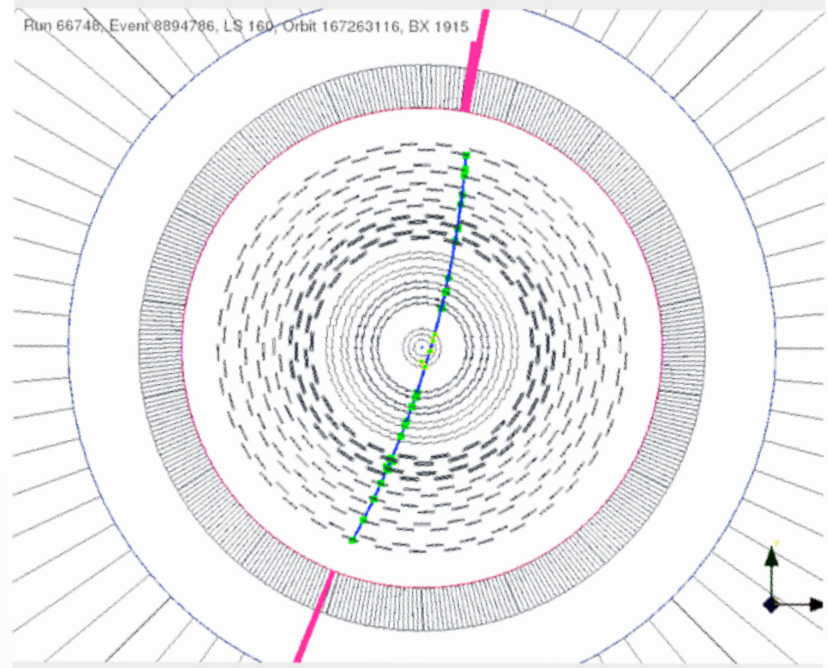
Cosmics in ATLAS



Cosmics in CMS



Muon through tracker…



…including pixel hits

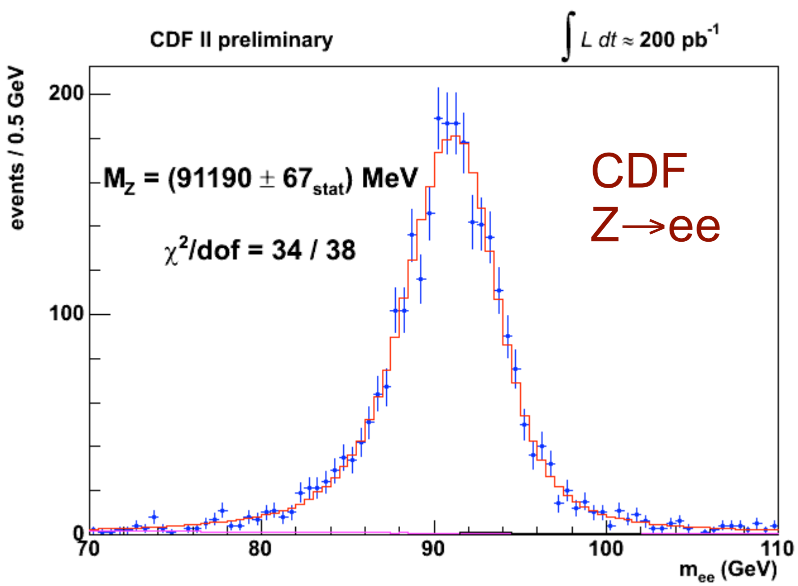
Early Measurements @ LHC

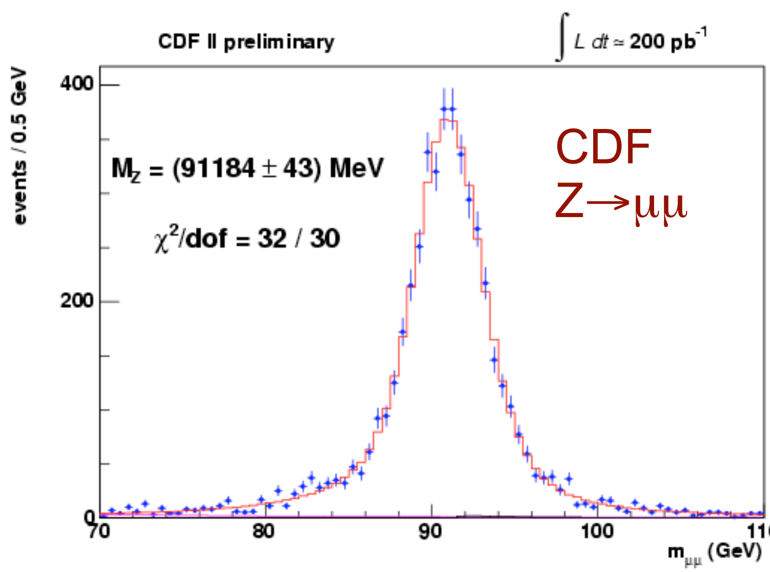
- First job is to understand the detector!
  - Calibrations, alignment, “fake rates”, etc.
- First measurements will be to rediscover the Standard Model
  - Examples:
    - Charged track track multiplicity
    - Inclusive jet cross section
    - Z and W cross sections
    - ttbar cross section

    (Z and W cross sections, ttbar cross section: “standard candles”)
- Without this, no one will believe any claims of discovery
- Unfortunately, it’s impossible for me to cover all of this so I will just give you a flavor

Z's as Standard Candles

- Z→ee and Z→μμ are clean and provide an excellent calibration signal for many purposes!
  - EM energy scale (electrons)
  - Track momentum scale (muons)
  - Lepton ID and trigger efficiencies
  - Luminosity





Measuring a Cross Section

Number of observed events: counted

Background: Measured from data / calculated from theory

$$\sigma = \frac{N_{obs} - N_{bkg}}{\int \mathcal{L} dt \times \varepsilon}$$

Cross section σ

Efficiency: optimized by experimentalist

Luminosity: Determined by accelerator, trigger prescale, …

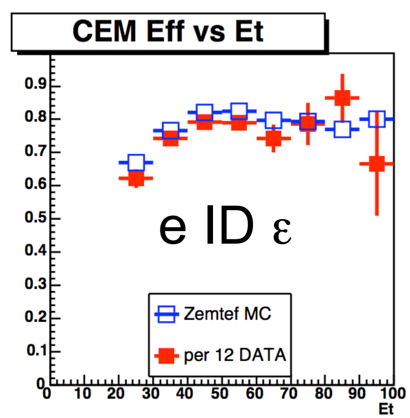
Efficiency/Acceptance

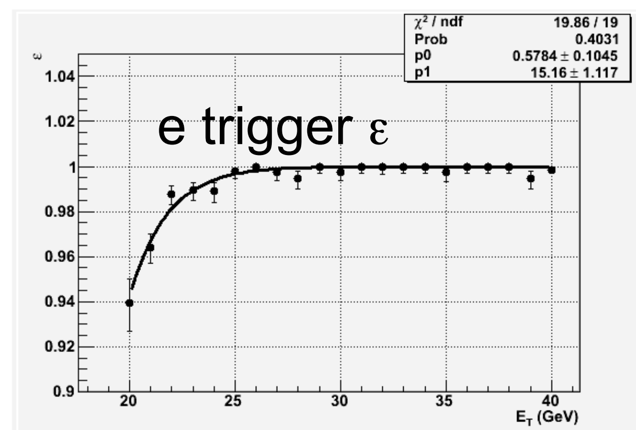
$$\varepsilon_{total} = \frac{\text{Number of events used in analysis}}{\text{Number of events produced}}$$

- Actually rather complex:
  - Many ingredients enter here
    - Trigger efficiency (from data)
    - Identification efficiency (from data, for example using Z's! - tag and probe)
    - Kinematic *acceptance* (from Monte Carlo)
    - Cut efficiencies (from data and/or Monte Carlo)
  - Efficiencies could depend on p_T, η, ϕ, N_{vtx}, etc.
- For example, the total efficiency could look like this:

$$\varepsilon_{total} = \varepsilon_{trigger}\varepsilon_{reconstruction}\varepsilon_{ID}\varepsilon_{kinematic}\varepsilon_{track}$$

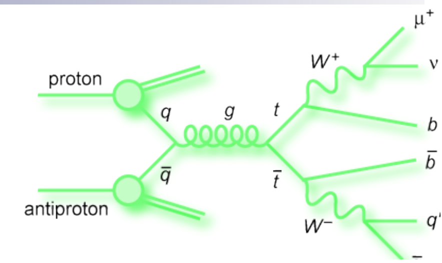
Examples: →
CDF electron ID and trigger efficiencies vs. electron E_T

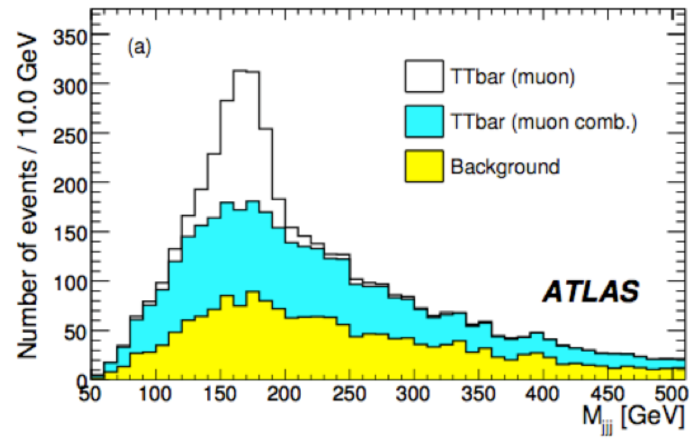




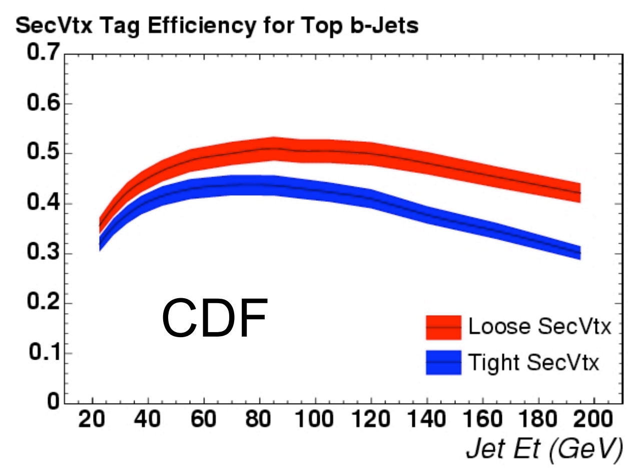
Top

- Interesting signature!
  - Background to a lot of new physics (like SUSY)
- More complex final state
  - Need to understand backgrounds!
    - Data driven methods (esp. QCD)
    - Examples: “ABCD” methods or jet “fake” rates
      - Note:often a “fake” is still a real lepton (inside jets!)
- In early days of LHC, tops can give us
  - Alternative Jet energy scale measurement (primarily from photon+jet, di-jet, Z+jet balancing)
  - b-jet tagging efficiencies



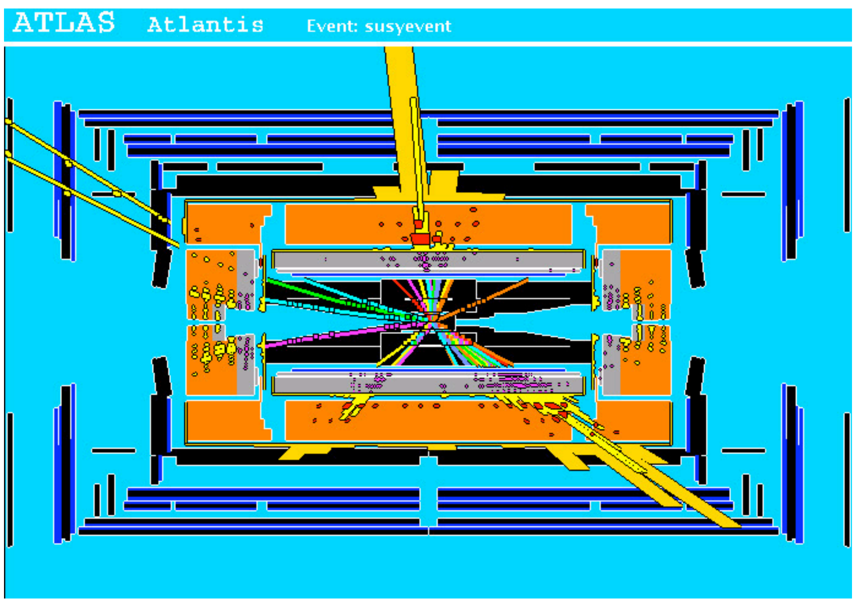


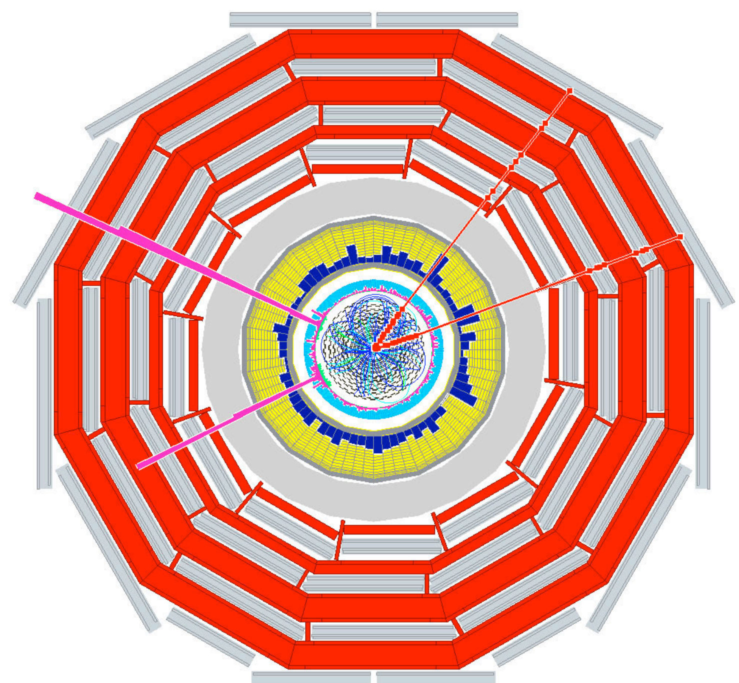
M_{jjj}



New Physics

- Looking forward to discovery at the LHC!





Concluding Remarks

- I only touched the surface!
  - A lot I didn't cover!
- Getting to the level of understanding the data to the point of confidently making a discovery will take time
  - Data analysis is like detective work
  - We need to try to not jump to conclusions too fast!
- I hope you now have a better understanding of
  - detectors and how they work
  - how experimentalists think
- Talk to your experimental colleagues!

- Thank you!
  - It's been a pleasure!