Introduction to Hadron Collider Physics (I)

April 3, 2021

Outline: Introduction to Hadron Collider Physics

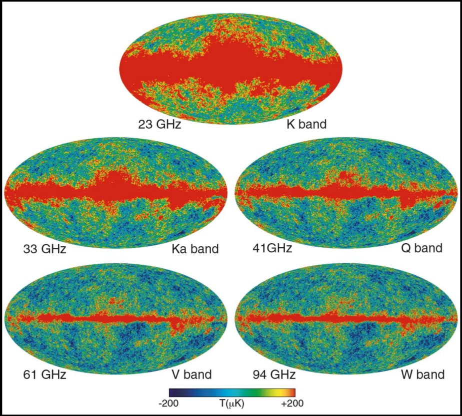
Today

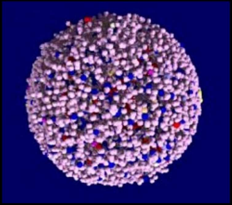
- Introduction and overview
- Cross section calculations: The basics
- Soft Physics: min bias and underlying evenet
- Jet Physics
- What we have learned so far

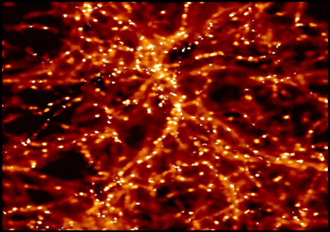
Tomorrow

- W and Z production
- Top physics
- Dibosons
- The Higgs
- Conclusions

The Universe is a Laboratory for Understanding Fundamental Physics



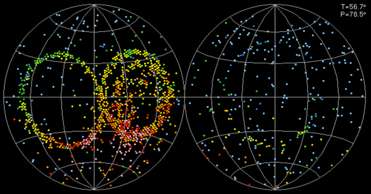


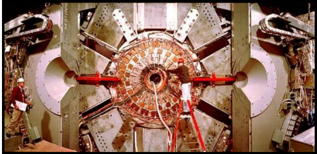


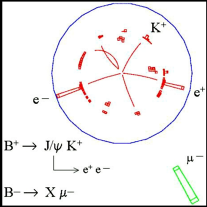
Pictures of the early Universe

But Laboratory Measurements Can Also Teach Us About the Universe

Neutrino interaction from
SuperKamioKande
(from sun)

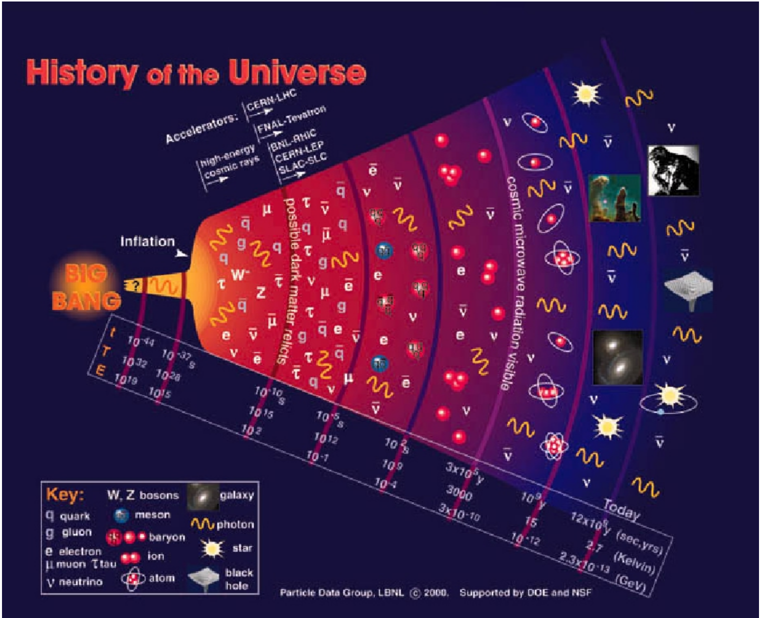




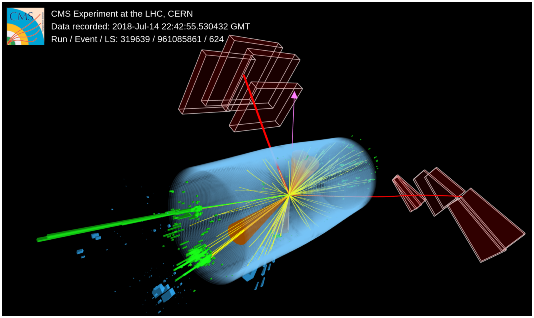


Matter-antimatter
asymmetry from
Babar
(accelerator based)

Description of early universe requires knowledge of particles that existed and interactions between them



LHC can play an especially critical role



- Highest Achievable Energy
  - Reproduce conditions of the early Universe
- TeV energy scale
  - Where fundamental particles obtain their mass
- Many theoretical possibilities
  - But need data to distinguish between them

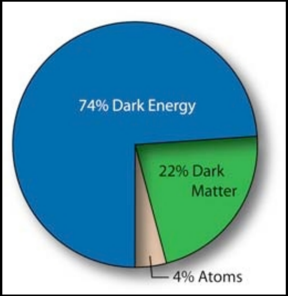
The Large Hadron Collider (LHC)

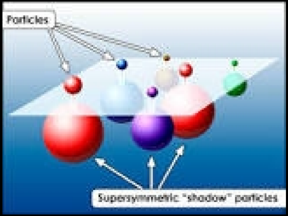
13 TeV now, 14 TeV in future, $\mathcal{L} > 10^{34}$ cm^{-2}s-1

What might we find at the LHC?

Answers to very fundamental questions:

- What is Dark Matter?
  - Supersymmetric particles?
  - Other weakly interacting particles?
- Why is gravity so weak?
  - Supersymmetry?
  - Extra spatial dimensions?
- Why do particles have mass?
  - A single Higgs boson?
  - A more complicated EWSB sector?



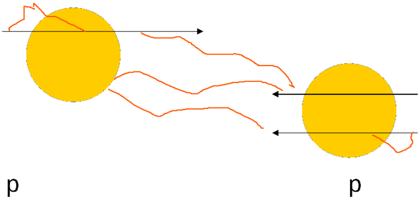


Strategies for exploring new physics with hadron colliders

- Direct searches for new particles and new interactions through
  - Bumps in invariant mass spectra
  - Excesses in rate for processes with missing mometum
  - Unexpected production of long lived particles
- Searches for decays predicted to be forbidden or highly suppressed
  - Lepton flavor violation
  - Flavor changing neutral currents
- Precision measurements of fundamental properties sensitive to new particles through loop corrections
  - W mass
  - Higgs couplings
  - Anomolous couplings in 3 and 4 boson final states

All these strategies depend on our ability to model SM processes accurately and precisely

Begin with the largest cross sections: Soft Physics



- Bulk of inelastic cross section: Large impact parameters, soft collisions
- Low momentum transfer ⇒ cannot use perturbative QCD
- Rely on phenomenological models fit to data
  - Fireballs
  - Strings
  - Multiple parton interactions
- Qualitative features:
  - Limited p_T wrt beamline
  - Longitudinal momentum distribution dominated by phase space

$$\frac{d^3p}{dE} = d\phi \frac{dp_T^2}{2} \frac{dp_{||}}{E}$$

$$E\frac{d\sigma}{d^3p} = \frac{1}{\pi} \frac{d\sigma}{dp_T^2 dy}$$

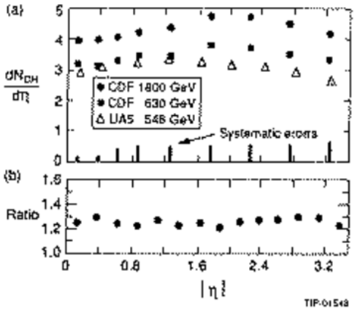
$$\text{where} \quad y = \frac{1}{2}\ln\left(\frac{E+p_{||}}{E-p_{||}}\right) \quad \leftarrow \text{“rapidity”}$$

$$dy = \frac{dp_{||}}{E}$$

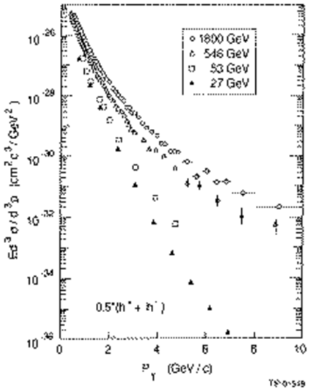
$$\text{massless particles :} \quad y \approx -\ln\left(\tan\frac{\theta}{2}\right) \equiv \eta \quad \leftarrow \text{pseudo} - \text{rapidity}$$

Natural variables to describe particle production are: p_T, η, ϕ

Particle Production in randomly triggered events



- Particle production flat in η
- Small rise in $dN/d\eta$ with $\sqrt{s}$

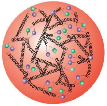


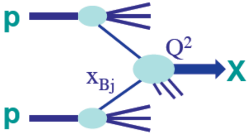
- dN/dpT falls exponentially for low $\sqrt{s}$
- As $\sqrt{s}$ increase, high tail develops

Onset of hard scattering!

The physics of hard collisions

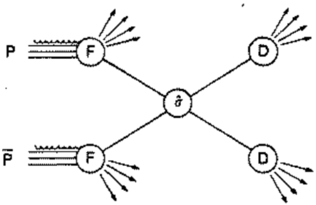
$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$





- Protons are made of partons
  - Energy in hard scatter depends on x_1 and x_2: the fraction of the proton's momentum carried by the initial state partons
- Like Rutherford, identify high momentum transfer scatters by looking at large angles
  - Large transverse momentum (p_T)
- Highest energy collisions are rare
  - Requires high intensity beams (large luminosity)

Factorizing the calculation



$$d\sigma(a+b \to c+d) = \sum_{ij} F_i^{(a)(x_a)} F_j^{(b)}(x_b) d\hat{\sigma}(i+j \to c+d+X') D_{c/C}(z_c) D_{d/D}(z_d)$$

- $\hat{\sigma}$ calculated using Feynman diagrams (QFT)
- Initial and final state interactions described using
  - $F(x)$: the parton distributions
  - $D(z)$: the fragmentation functions

  measured in reference processes;
- Both exhibit scaling violations: $F(x, \mu)$, $D(z, \mu')$
- Note: example here is $2 \to 2$ scattering; $2 \to 1$ and $2 \to N$ also possible

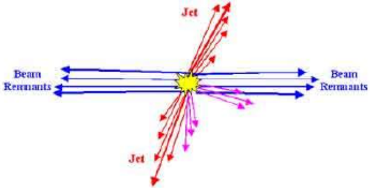
The topology of hard scattering events

Two "beam jets" plus high p_T objects

- Beam Jets: "Underlying Event"
  - Limited p_T wrt beamline
  - Looks alot like soft events
  - Presence of hard scatter $\longrightarrow$ larger $p\overline{p}$ overlap, so mean p_T and multiplicity somewhat higher
- Hard Scattering
  - $\hat{s} = x_a x_b s$ where x's are the fraction of the hadron momenta carried by the iteracting partons
  - p_T in general is well measured
  - p_Z can be large. Often <u>not</u> well measured directly (losses down the beampipe) but can use angle and p_T
  - Cross sections for hard scattering can be calculated using perturbative QCD

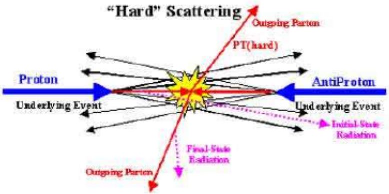
Beam Jets and Underlying Event

- Hard Collision leaves remnants of incoming p's moving in Beam Direction

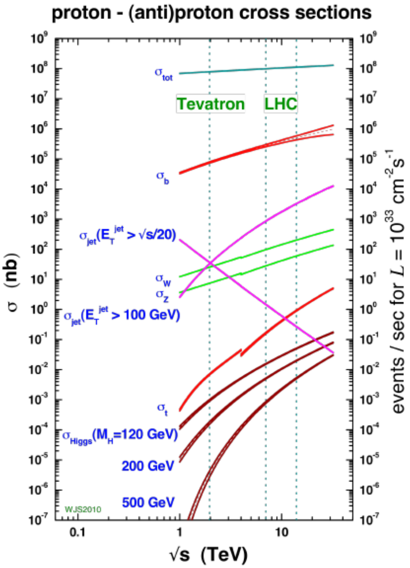


- "Initial State" gluon radiation largely co-linear with incoming partons: same basic structure

Soft particles distributed uniformly in η

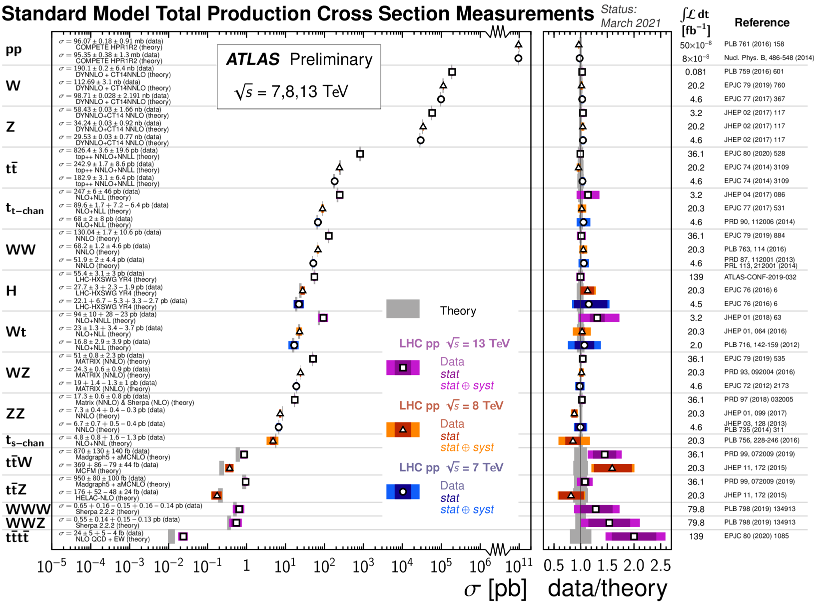


Predicted Cross Sections at Hadron Colliders



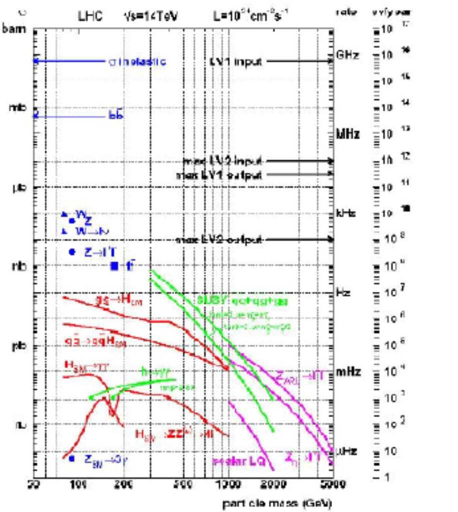
- Rates determined by
  - Hard Scattering Cross Section
  - Parton luminosity
- QCD processes dominate
  - EW rates lower by α/α_S
- For given s, cross sections decrease rapidity with $\hat{s}$
  - Heavy particles difficult to produce

How well do these calculations do?



Practical Details

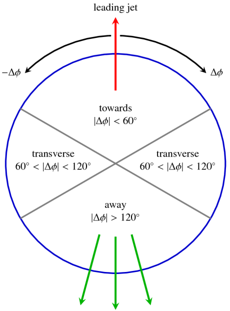
- Something happens every beam crossing
  - 24 inelastic events/crossing at 10^{34} cm$^{-2}s^{-1}$ "Pile-up"
- Must select events of interest: Trigger
  - Must know what you throw out
  - Analysis must be trigger-aware
- Jets dominate hard scattering rate
  - Can isolate EW processes only if they have something besides jets, eg leptons
  - Jets are a potential source of background to leptons "fakes"
  - Detector mis-measurements can induce false signals
- W, Z: Background for Top, Higgs, SUSY
- Top: Background for many SUSY and exotica signals

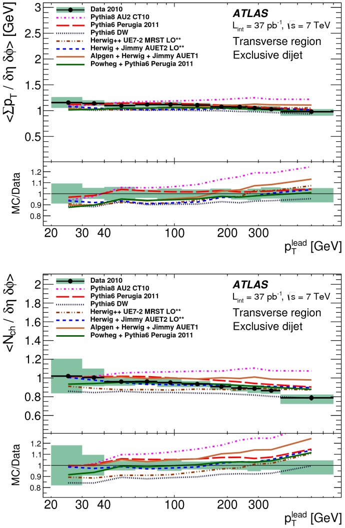


Analysis Strategy: Begin with the largest cross section and work down

- Characterize bulk of cross section "soft physics"
  - Tracks
- Identify dominant $2 \to 2$ QCD processes
  - Jets
- Develop strategies for selecting EW processes
  - e, μ, ν, γ
- Reconstruct heavy objects produced strongly
  - Top
- Understand discovery potential for low rate EW processes
  - Dibosons
  - Higgs
- Develop strategies to look for new physics (BSM)

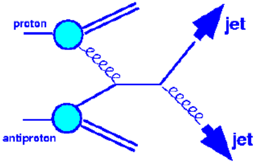
Track distributions from underlying event

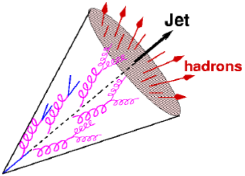




- Look away from the hard scattering products (jets or leptons)
  - Eg, 90° from jets in a dijet event
- Particle multiplicity almost independent of jet p_T
- Remnants of the inital hadrons moving down beamline with limited p_T with respect to beam direction

QCD Jets





- Need an algorithm to decide how many jets we have and to associate particles with the jets
  - Algorithm will have some parameter to handle the infrared divergence (eg a cut-off)
- Two basic types of algorithm:
  - Geometric cluster algorithms:
    - Cluster based on angular separation. Define in terms of a cone-size (eg the δ of Sterman-Weinberg)
  - Recombination cluster algorithm
    - Find particles close together in a momentum-based metric and replace them with the sum of their four-momenta

What is important in a jet-finding algorithm?

- Should combine particles (or energy clusters) into jets in a way that agrees with what we see "by eye" in straightforward cases
  - Avoid pathologies (turns out this isn't easy)
- Should be insenstive to details of the hadronization
  - If a particle decays, calculation using parent and daughters should give nearly the same answer
- Should be possible to apply same algorithm to the quarks and gluons that are the outgoing "particles" in a QCD calculation (before hadronization)
  - Should not have divergences for colinear or soft emission: "Colinear and Infra-red safe"

The Basics of Recombination Cluster Algorithms

- Can start with any objects where we can define a 4-momentum, eg
  - Particles
  - Energy clusters

  Label them $i = 1 \ldots n$
- Loop over all these objects, calculating the distance between them according to a metric
- Combine the two that are closest together in that metric, if the distance is below a fixed cut
- Iterate until all pairs satisfy $y_{ij} > y_{cut}$
- Two common metrics:
  - k_T:

$$M_{ij}^2 = \min\left(E_i^2, E_j^2\right)\frac{R_{ij}}{D}$$

  - anti-k_T:

$$D_{ij} = \min\left(E_i^{-2}, E_j^{-2}\right)\frac{R_{ij}}{D}$$

where R_{ij} is essentially θ_{ij} and D is a parameter of the algorithm indicating how big we allow jets to be

First Evidence for Jets in Hadron Colliders (UA2, 1982)

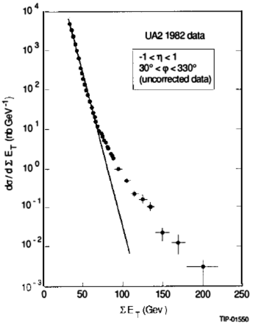


Figure 3 The observed distribution of $d\sigma/d\Sigma E_t$ as a function of ΣE_t as measured by the UA2 experiment. The solid line shows the exponential falloff at low ΣE_t.

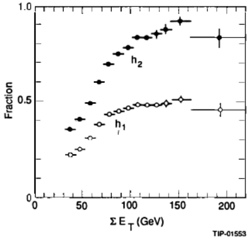


Figure 4 The fraction of the total transverse energy observed in the highest (h_1) and two highest (h_2) clusters as a function of the total transverse energy of the event, as measured by the UA2 experiment.

$p\bar{p}$ interactions at 546 GeV ($Sp\bar{p}S$ collider at CERN)

- High tail in $\sum E_T$ indicates onset of hard scattering
- Use simple nearest-neighbor clustering algorithm
- Majority of transverse energy in two clusters, back-to-back in ϕ
- Dijet system boosted in z: two intial partons carry different fractions of inital hadron energies

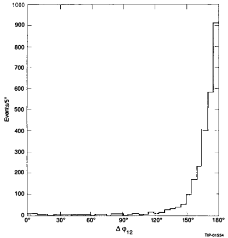
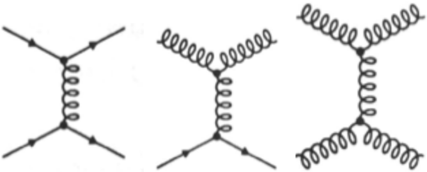


Figure 5 The distribution of the difference in azimuth between the two highest E_t clusters in events with ($\Sigma E_t \geq 60$ GeV), as measured by the UA2 experiment.

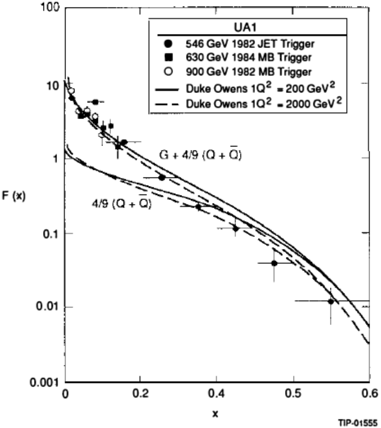
Early evidence for the non-abelian nature of the gluon



- Elastic parton-parton scattering
- t-channel exchange of a gluon
- All 3 processes have similar Feynman diagrams
  - Different quark and gluon n color charge
  - Different quark and gluon PDFs
  - Define an "single effective subprocess" PDF

$$F(x) = G(x) + \frac{4}{9}\left(Q(x) + \overline{Q}(x)\right)$$

- Clear evidence for gluon scattering



Dijet Angular Distribution

- t-channel pole leads to angular distribtion

$$\frac{d\sigma}{d\cos\theta^*} = \alpha_s^2 \hat{s} \frac{1}{1-\cos^2\theta^*}$$

- Rutherford-like shape with divergence in beam direction
- Change variables

$$\chi \equiv \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

Distribution is approximately constant for $\chi > 2$

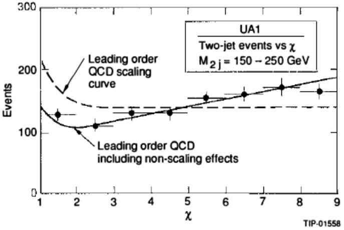
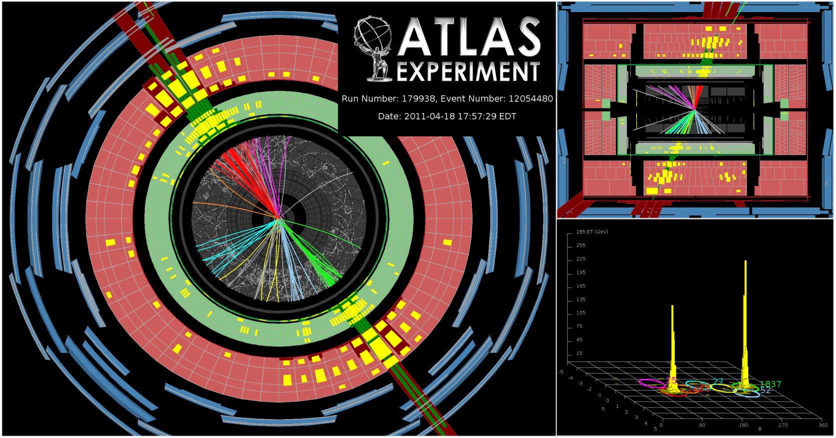


Figure 9 The distribution of χ for two-jet events as measured by the UA1 collaboration. The curve shows the predictions of a lowest-order two-parton scattering QCD calculation, with and without contributions due to QCD scaling violations.

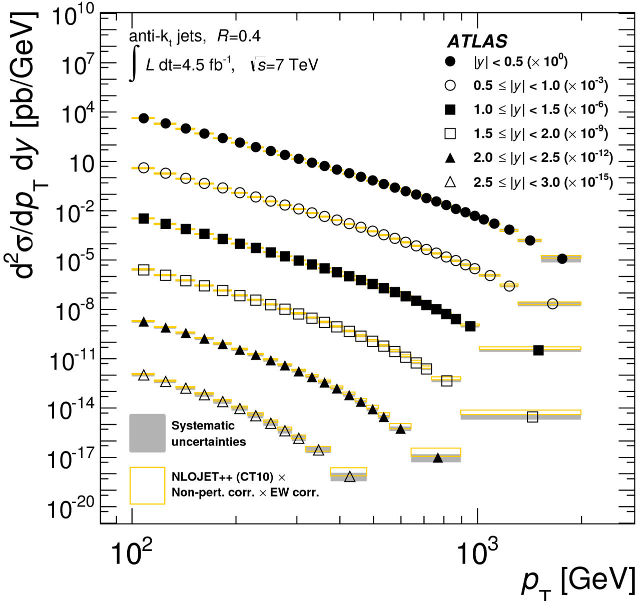
What do jets look like at the LHC?



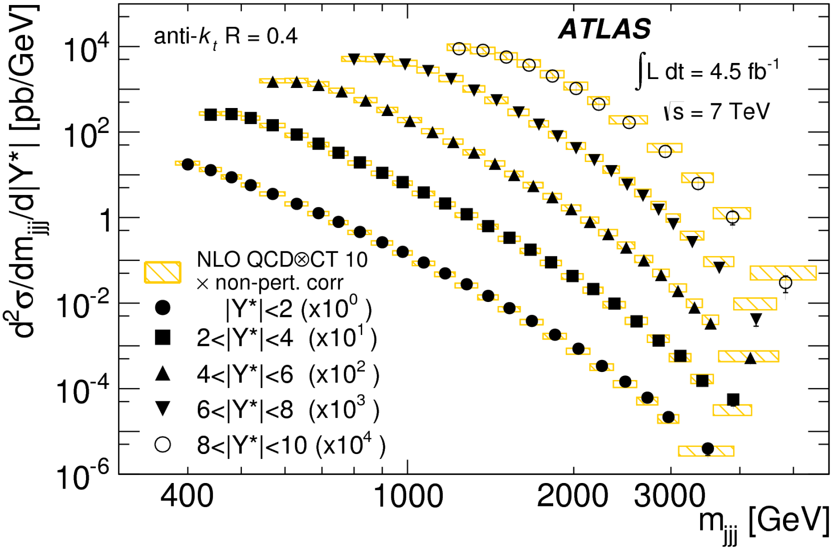
State of the Art: Theory and Experiment

- Hard scattering cross section at NLO or multileg (your choice)
  - Estimate uncertainties by evaluating dependence of calculation on choice of scale
- Well measured PDFs
- Jet finding algorithms that are infra-red and colinear safe
- Evaluation of non-perturbative effects through the use of Monte Carlo generators
  - Independent generators and generator tunes to assess systematic uncertainties
- Careful in-situ calibration of jet energy
- Corrections for pileup (multiple collisions in one beam crossing)

Can the theorists predict the cross section?

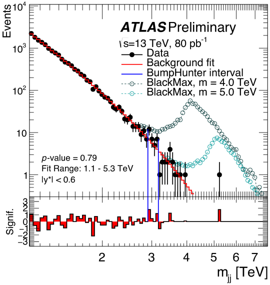


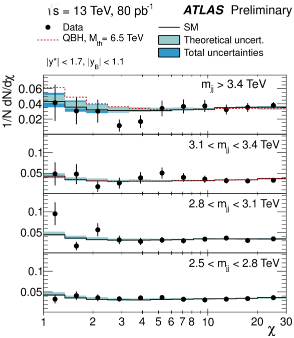
How about 3 jets?



Using dijet angular distribution to look for new physics

- Look for new resonance that decays to jets
  - Signal is a peak in dijet invariant mass
- In addition, new heavy resonance would decay with spherical angular distribution
  - Can distinguish from QCD background, which is peaked at large $\cos\theta^*$
  - Bin in dijet mass and plot χ
  - Signal would manifest as peak in low χ region
- Analysis requires good understanding of QCD background





What we have learned so far

- High energy and luminosity available at hadron colliders make the an essential tool to search for new physics
- Such searches only possible if Standard Model physics well modelled using precise and accurate calculations
- Calculations factorize into
  - Initial parton luminosities determined from parton distribution function measured in reference processes (eg ep)
  - Hard scattering cross section calculated using perturative QCD
  - For quarks and gluons: Fragmentation functions again measured in reference processes
- Quarks and gluons cloth themselves as jets of hadrons
  - Jet finding algorithms necessary both for particles and partons
- With model calculational techniques both experimental and theoretical, agreement between predictions and measurements is excellent
- Tomorrow:
  - Extend the picture to electroweak bosons (W and Z), top and Higgs
  - Look forward towards the next frontiers in measurement and calculations