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QCD: The First LHC Measurements

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Outline

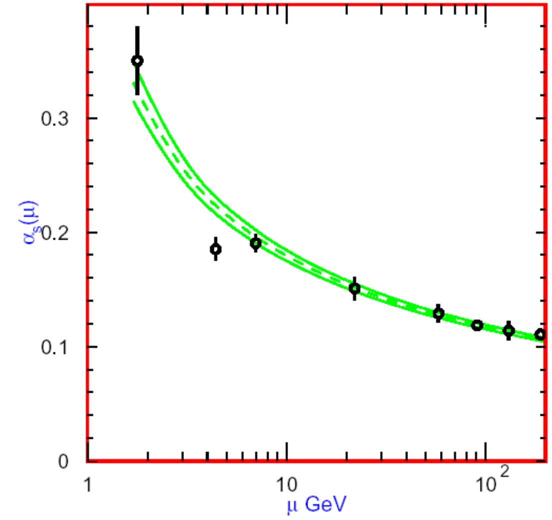
- A six-and-one half minute review of QCD
- Too few slides on early jet measurements
  - I will start with the “what” and “how” of the measurements first, and only later explain “why”
  - Evolution of these measurements
- Way too few slides on early direct photon measurements
- One slide on double parton scattering
- A list of things I didn’t mention at all
- Summary

Thanks to the organizers for inviting me!

QCD vs. QED

	QED	QCD
Symmetry Group	U(1)	SU(3)
Charge	Electric charge	Three kinds of color
Force carrier	1 Photon – neutral	8 Gluons - colored
Coupling strength	1/137 (runs slowly)	~1/6 (runs quickly)

α changes by about 7% from Q=0 to Q=100 GeV. This will change the results of a calculation, but not the character of a calculation.



Perturbative vs. non-Perturbative

Consider the series: $1+\alpha+2\alpha^2+3\alpha^3+4\alpha^4+\ldots$

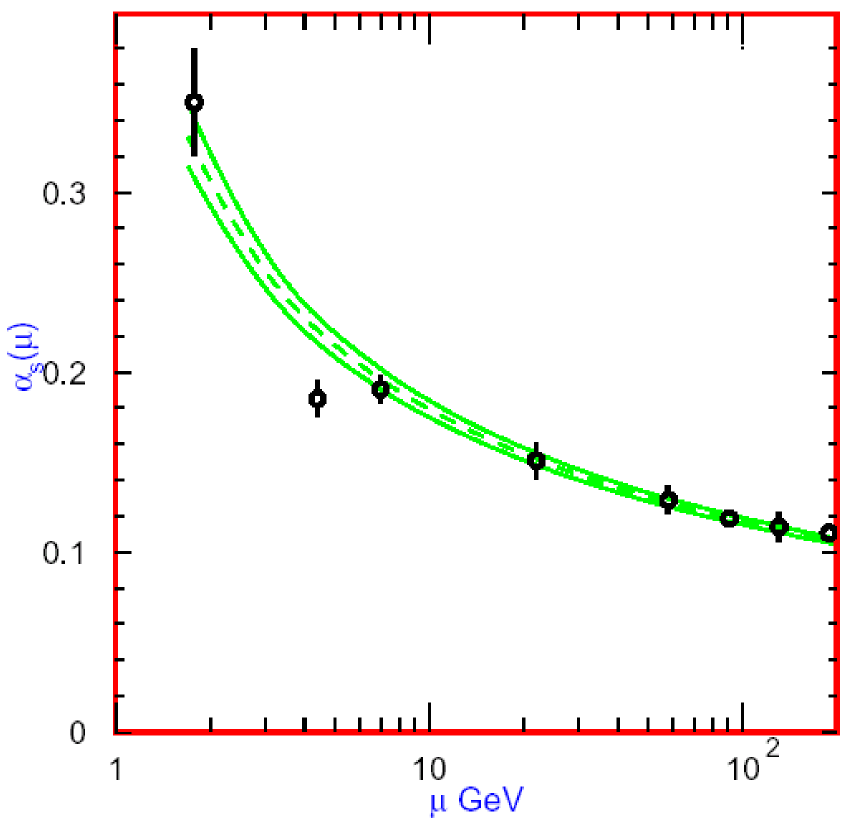
If α is small, the series converges quickly. For example, for $\alpha = 1/10$, the first two terms approximate the sum to within 2%. A **perturbative** expansion is a good approximation.

On the other hand, if α is large, the series converges slowly – so slowly that it may not even seem to converge at all. For example, for $\alpha = 9/10$, it's not until the 12^{th} term that the terms start to decrease. The first two terms alone are a factor 47 smaller than the entire sum. To get within 2% takes 55 terms.

A perturbative expansion is a not good approximation. We call this behavior **non-perturbative**.

So far, this is only mathematics – there is no physics on this slide.

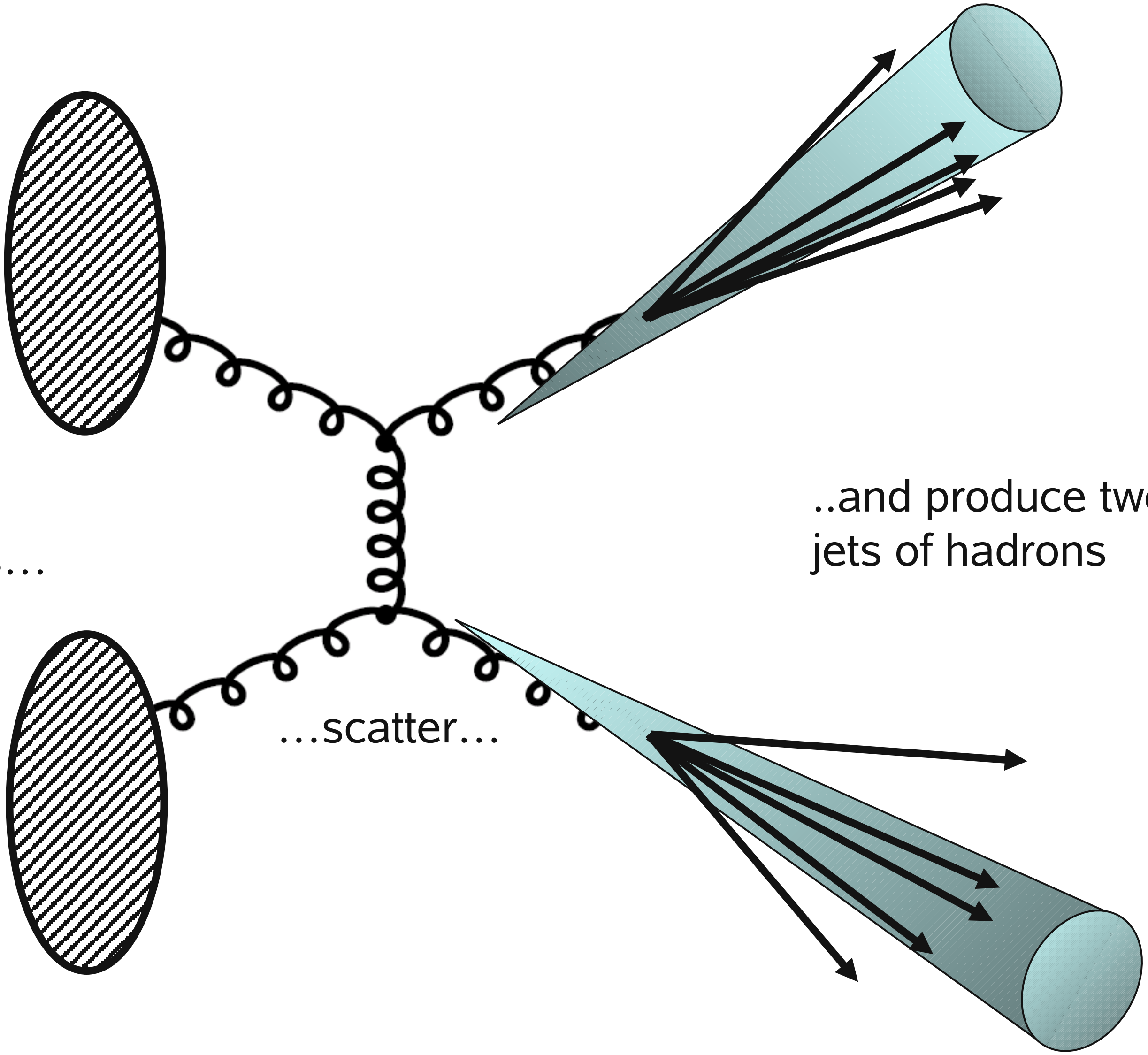
The Running of α_s



From I. Hinchliffe – this contains data from several kinds of experiments: decays, DIS, and event topologies at different center of mass energies.

- At high Q^2, α_s is small, and QCD is in the perturbative region.
  - Calculations are "easy"
- At low Q^2, α_s is large, and QCD is in the non-perturbative region.
  - Calculations are usually impossible
    - *Occasionally, some symmetry principle rescues you*
  - Anything we want to know here must come from measurement

A Simple QCD Calculation: Dijet production



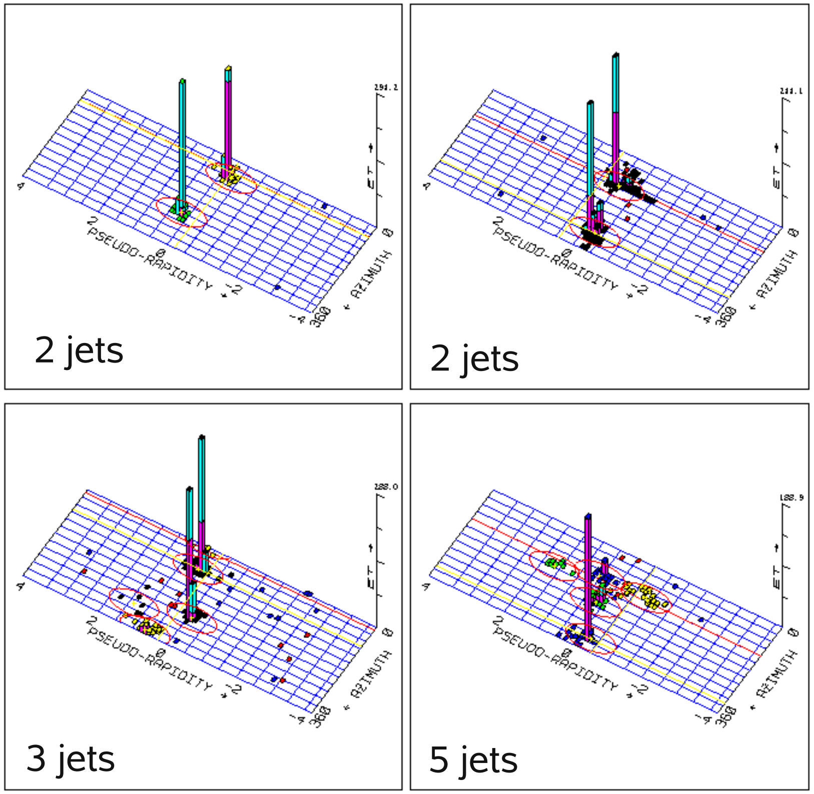
Gluons from
incoming protons…

…scatter…

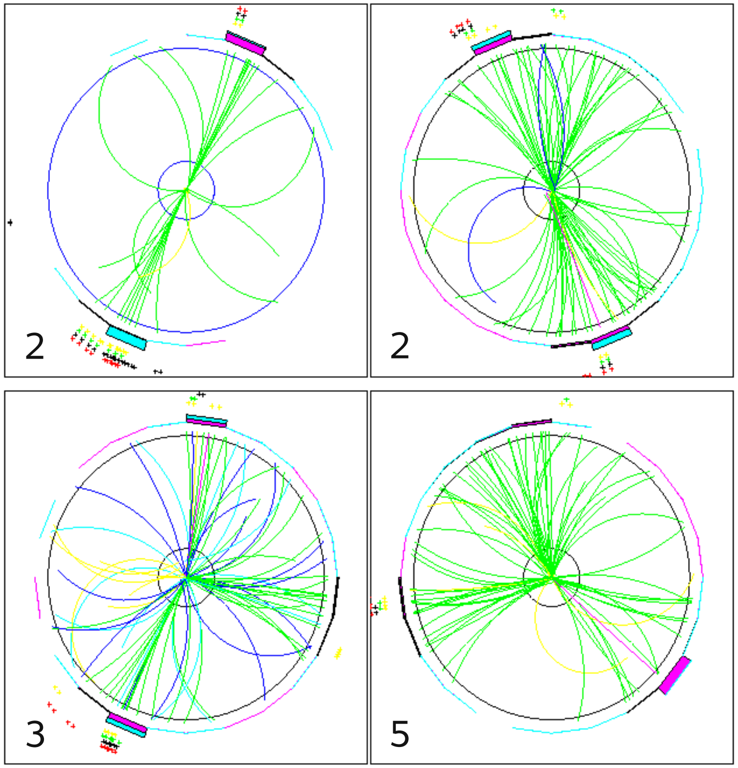
..and produce two
jets of hadrons

What is a Jet Anyway?

A “blast” of particles, all going in roughly the same direction.



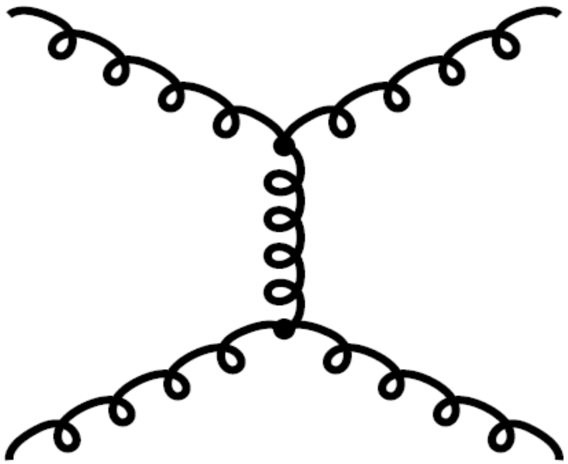
Calorimeter View



Same Events, Tracking View

A Simple QCD Calculation II: Factorization

One part: the
calculation of the
“hard scatter”

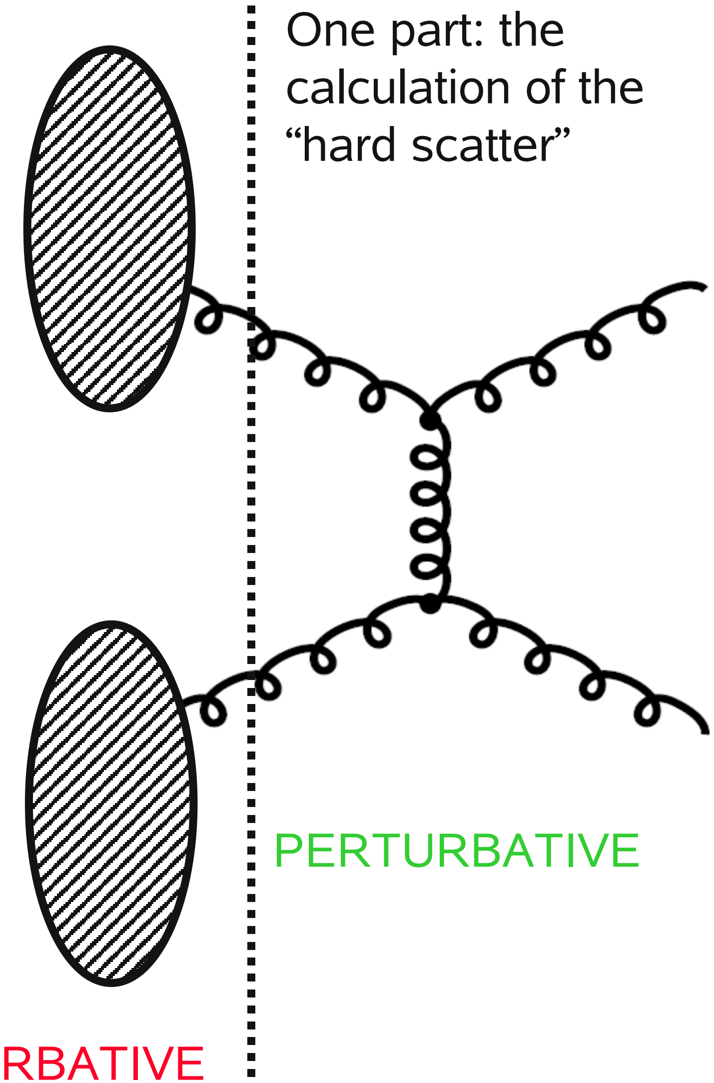


PERTURBATIVE

A Simple QCD Calculation II: Factorization

One part: the calculation of the "hard scatter"

Another part: connecting the calculation (which involves gluons) to protons (which contain gluons)



PERTURBATIVE

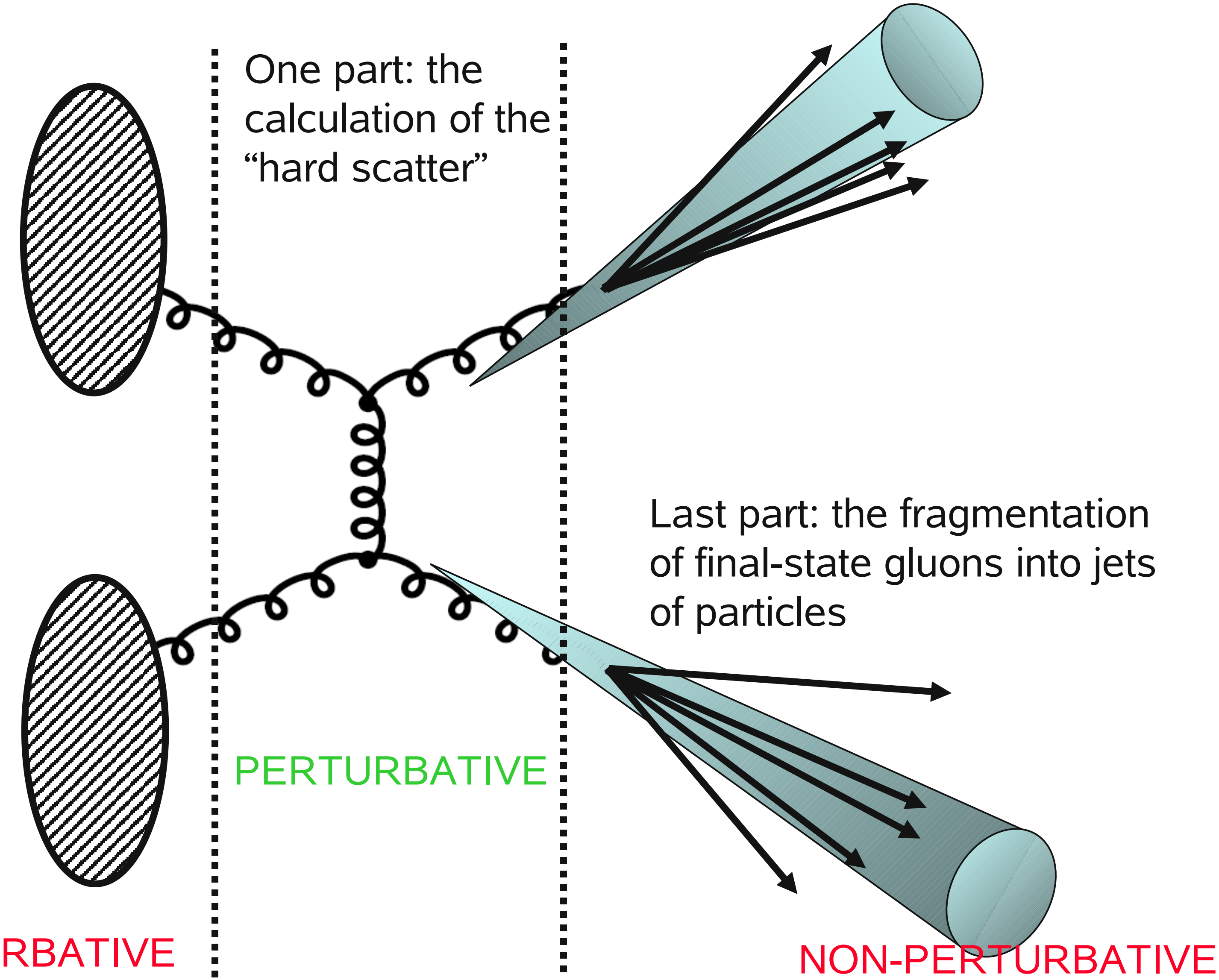
NON-PERTURBATIVE

A Simple QCD Calculation II: Factorization

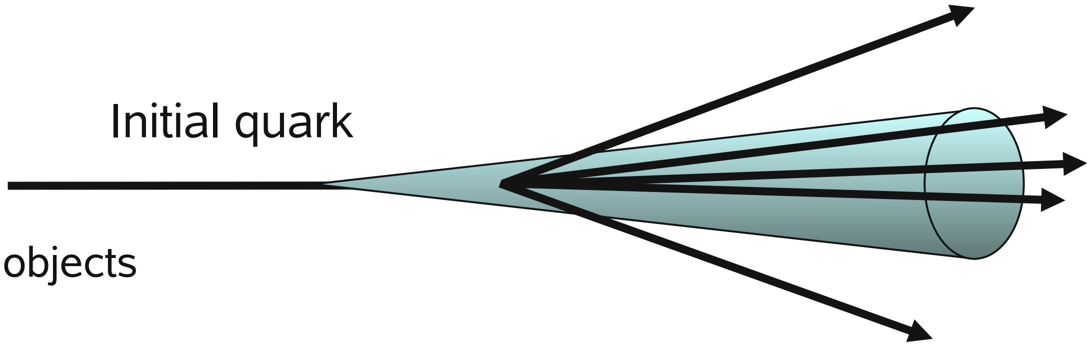
Another part: connecting the calculation (which involves gluons) to protons (which contain gluons)

One part: the calculation of the "hard scatter"

Last part: the fragmentation of final-state gluons into jets of particles



Jet Fragmentation



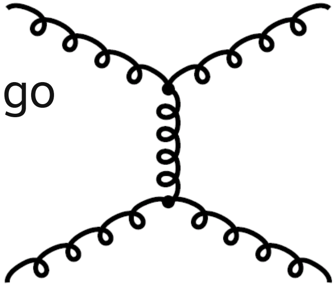
- The force between two colored objects (e.g. quarks) is independent of distance
  - Therefore the potential energy grows linearly with distance
  - When it gets big enough, it pops a quark-antiquark pair out of the vacuum
  - These quarks and antiquarks ultimately end up as a collection of hadrons
- We can't calculate how often a jet's final state is, e.g. ten π's, three K's and a Λ.
  - This is a **non-perturbative** process.
    - The scale is ~m(π) or ~Λ_{QCD}, where α is quite large

- Fortunately, **it doesn't matter**.
  - We're interested in the quark or gluon that produced the jet.
  - Summing over all the details of the jet's composition and evolution is A Good Thing.
    - Two jets of the same energy can look quite different; this lets us treat them the same

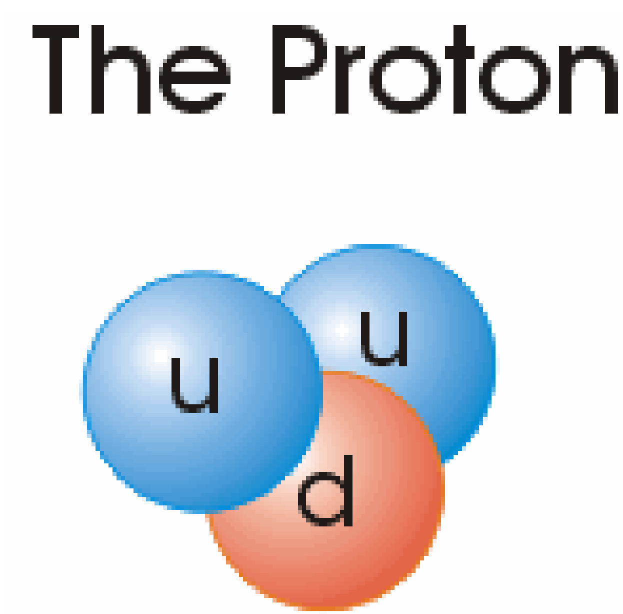
What makes the measurement possible & useful is the conservation of energy & momentum.

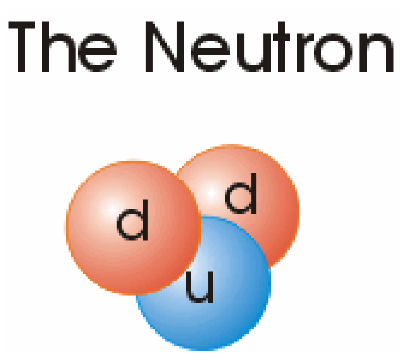
So Why Would You Want To Measure Jets Anyway?

- Reason One: This will be among the earliest physics that the LHC will do
  - The rates are very high (~few % of all events have a jet) – more on this later
- Reason Two: There's a non-perturbative piece to the cross-section that we need to measure if we want to know it:
  - We have beams of protons, not of quarks and gluons
  - Reminder: we can't calculate how to go from one to the other – this must be measured.



An Early Modern, Popular and Wrong View of the Proton





- The proton consists of two up (or *u*) quarks and one down (or *d*) quark.
  - A u-quark has charge +2/3
  - A d-quark has charge –1/3
- The neutron consists of just the opposite: two d's and a u
  - Hence it has charge 0
- The u and d quarks weigh the same, about 1/3 the proton mass
  - That explains the fact that m(n) = m(p) to about 0.1%
- Every hadron in the Particle Zoo has its own quark composition

So what's missing from this picture?

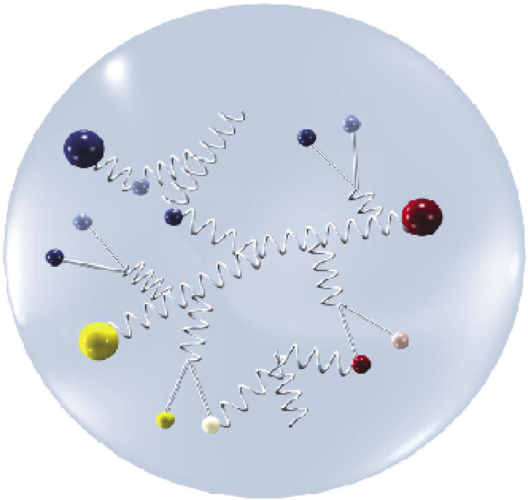
Energy is Stored in Fields

- We know energy is stored in electric & magnetic fields
  - Energy density ~ $E^2 + B^2$
  - The picture to the left shows what happens when the energy stored in the earth's electric field is released
- Energy is also stored in the gluon field in a proton
  - There is an analogous $E^2 + B^2$ that one can write down
  - There's nothing unusual about the idea of energy stored there
    - *What's unusual is the amount:*

	Energy stored in the field
Atom	10^{-8}
Nucleus	1%
Proton	99%

Thunder is good, thunder is impressive; but it is lightning that does the work.
(Mark Twain)

The Modern Proton



The Proton

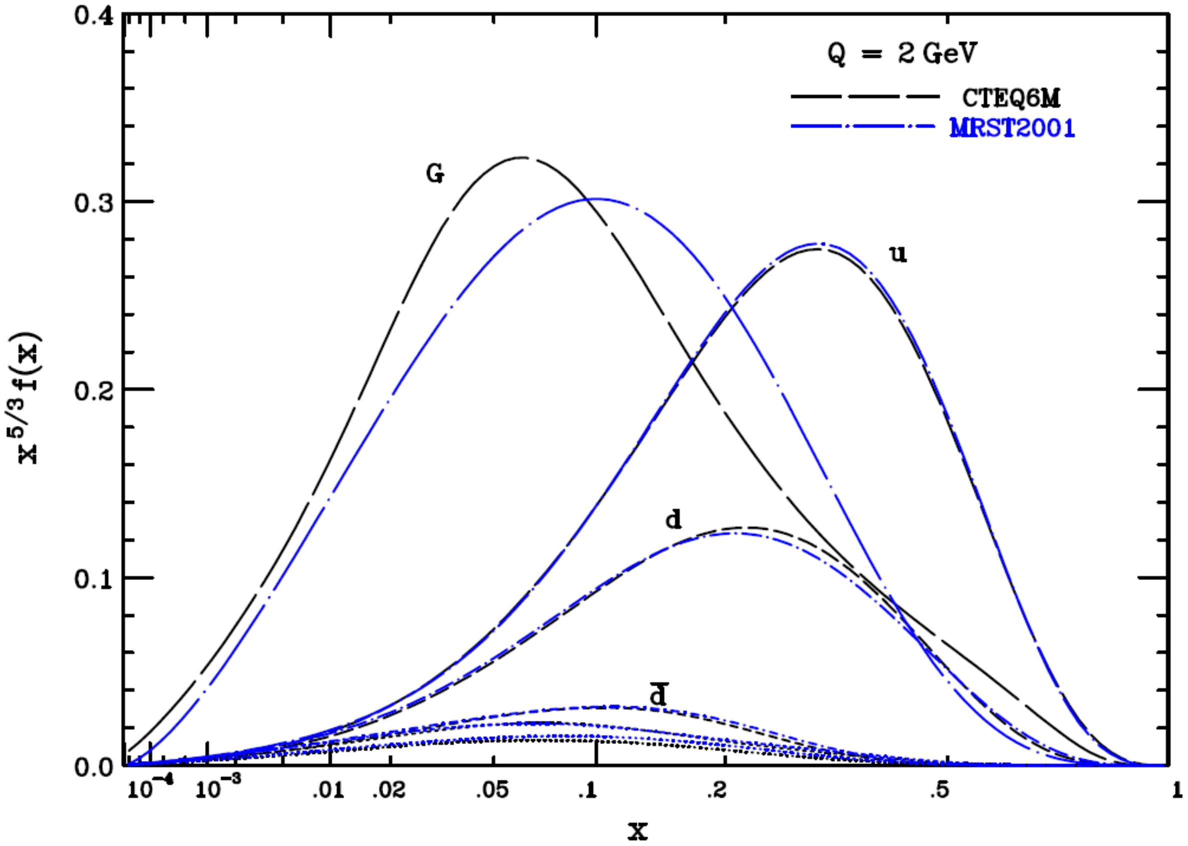
Mostly a very dynamic self-interacting field of gluons, with three quarks embedded.

Like plums in a pudding.

- 99% of the proton's mass/energy is due to this self-generating gluon field
- The two u-quarks and single d-quark
  - 1. Act as boundary conditions on the field (a more accurate view than generators of the field)
  - 2. Determine the electromagnetic properties of the proton
    - *Gluons are electrically neutral, so they can't affect electromagnetic properties*
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Has nothing to do with the quarks
- The most useful description is in terms of parton density functions (pdf's)
  - The probability a parton is carrying a fraction x of the proton's momentum

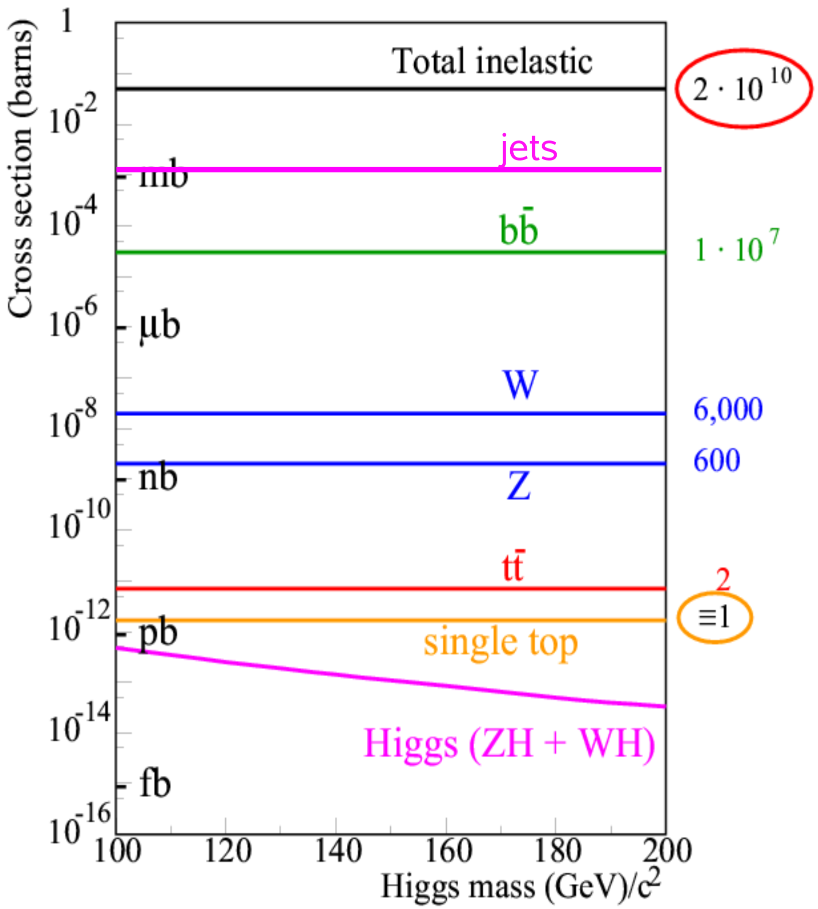
Parton Density Functions

- One fit from CTEQ and one from MRS is shown
  - These are global fits from all the data
- Despite differences in procedure, the conclusions are remarkably similar
  - Lends confidence to the process
- The gluon distribution is enormous:
  - The proton is mostly glue, not mostly quarks

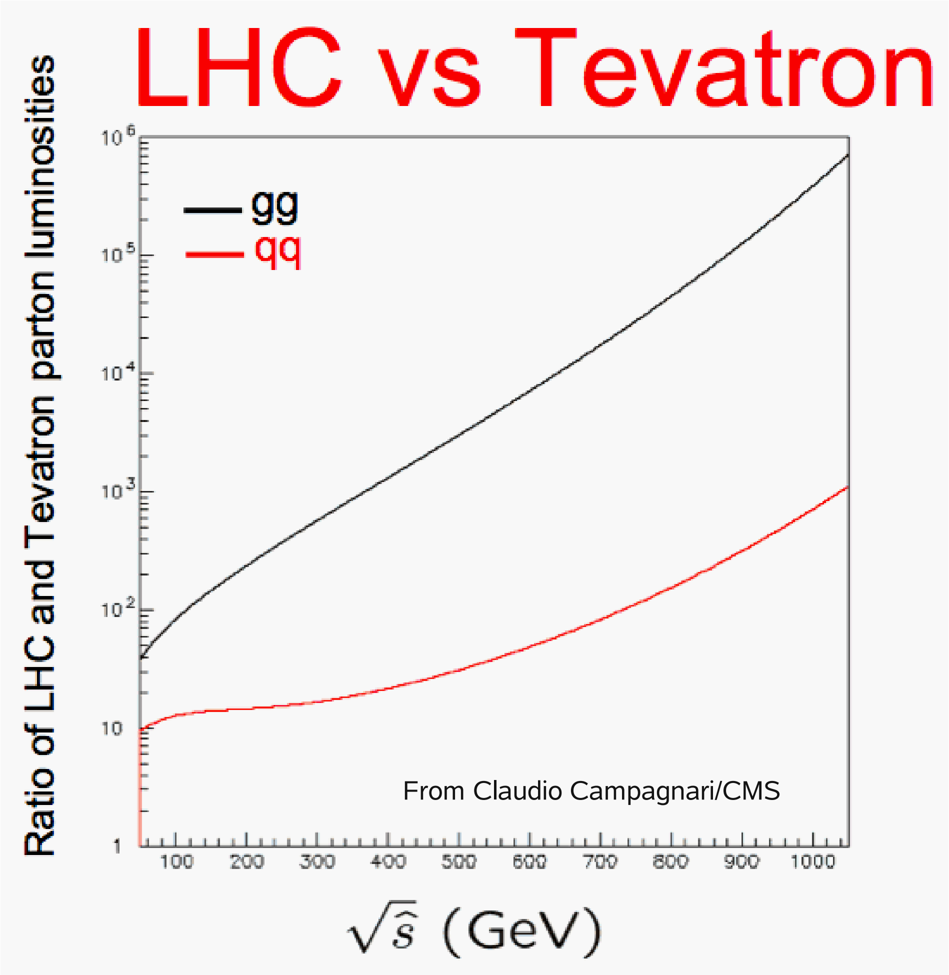


Amazing fact: Parton Density Functions are universal. The same PDFs work across different processes and different experiments.

PDF Consequences at the LHC

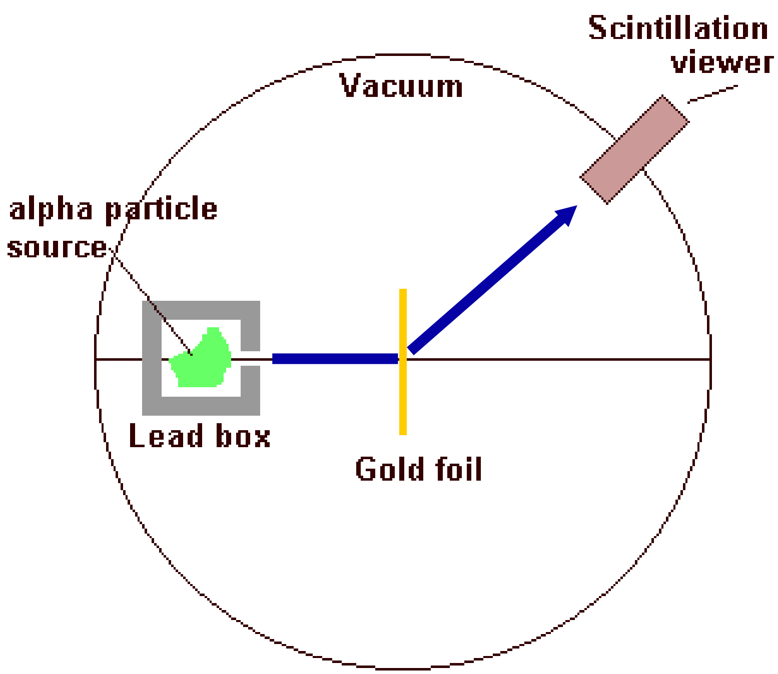


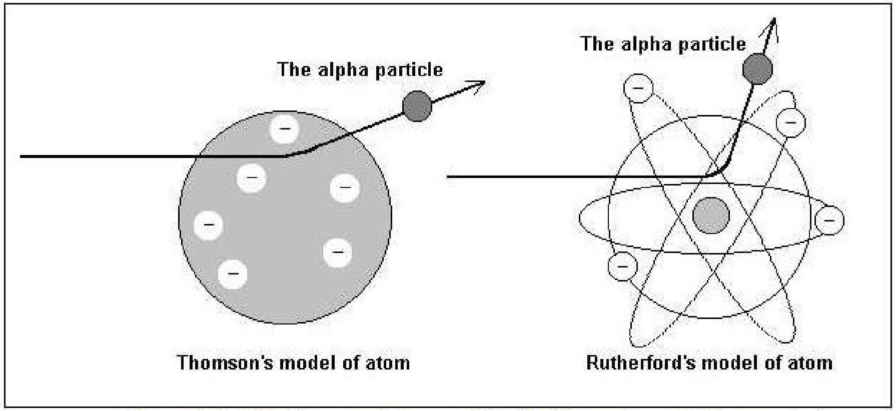
Measured cross-sections (except for Higgs) at the Tevatron



How to extrapolate to the LHC

The “Rutherford Experiment” of Geiger and Marsden





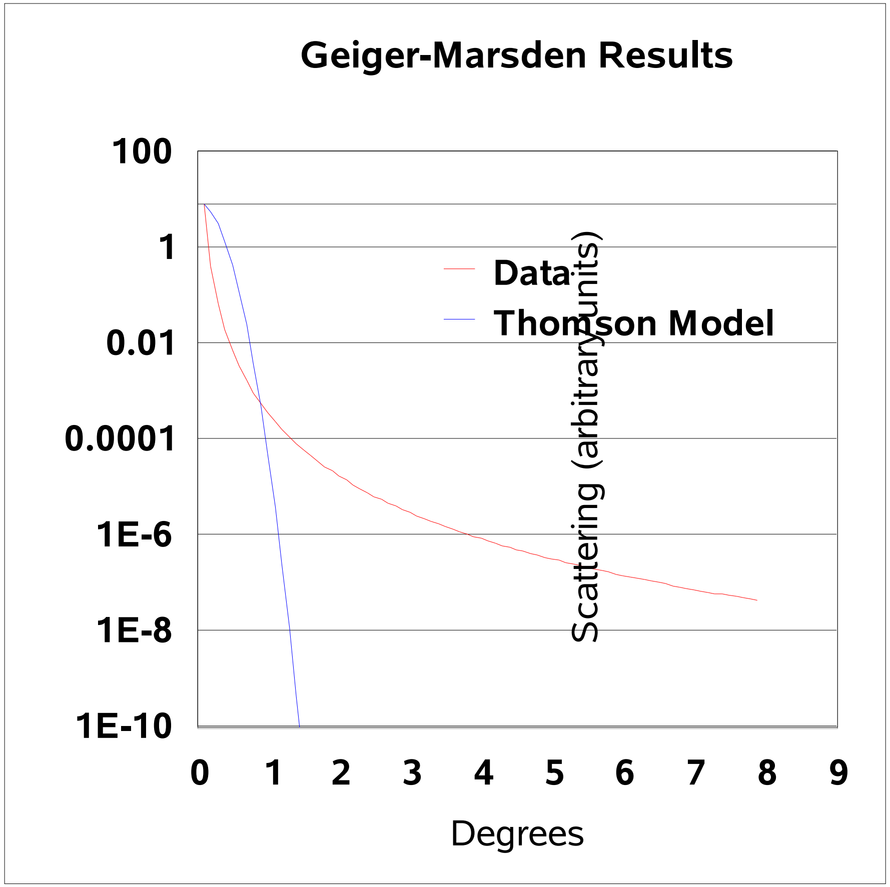
The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

α particle scatters from source, off the gold atom target, and is detected by a detector that can be swept over a range of angles

(n.b.) α particles were the most energetic probes available at the time

The electric field the α experiences gets weaker and weaker as the a enters the Thomson atom, but gets stronger and stronger as enters the Rutherford atom and nears the nucleus

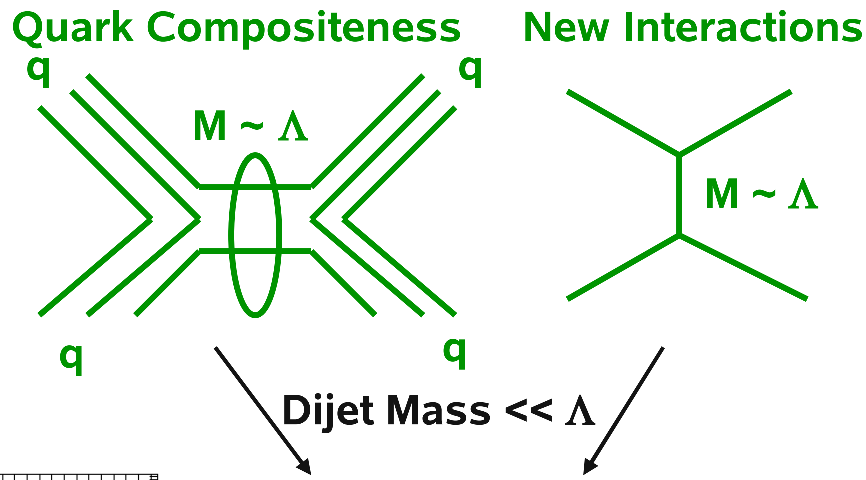
Results of the Experiment



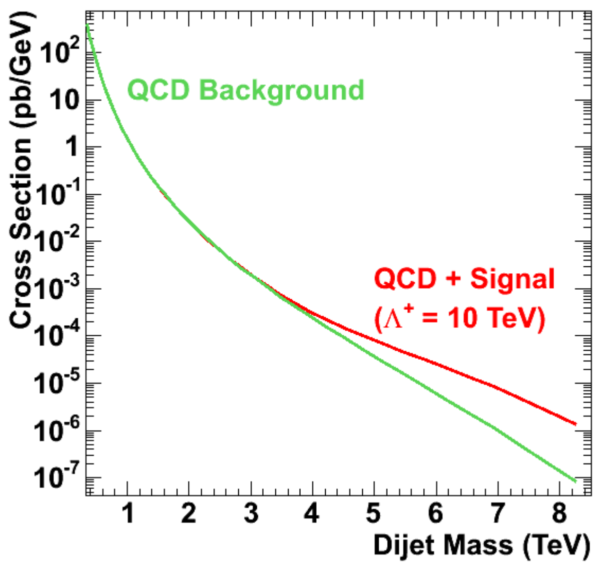
- At angles as low as 3°, the data show a million times as many scatters as predicted by the Thomson model
  - Textbooks often point out that the data disagreed with theory, but they seldom state how bad the disagreement was
- There is an excess of events with a large angle scatter
  - This is a universal signature for substructure
  - It means your probe has penetrated deep into the target and bounced off something hard and heavy
- An excess of large angle scatters is the same as an excess of large transverse momentum scatters

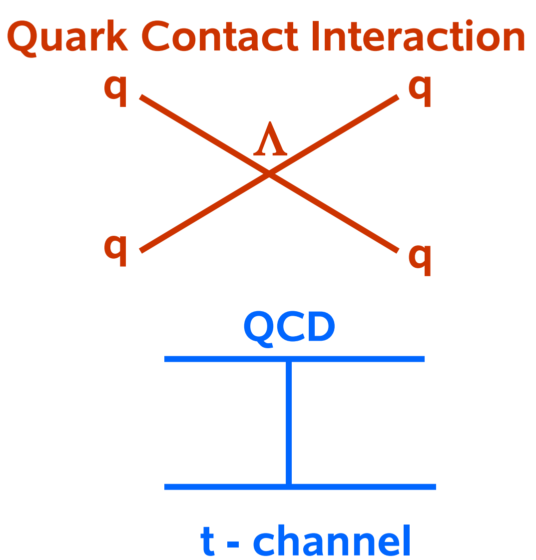
The 3rd Reason to Measure Jets: Quark Contact Interactions (Rutherford Revisited)

- New physics at a scale Λ above the observed dijet mass is modeled as an effective contact interaction.
  - Quark compositeness.
  - New interactions from massive particles exchanged among partons.



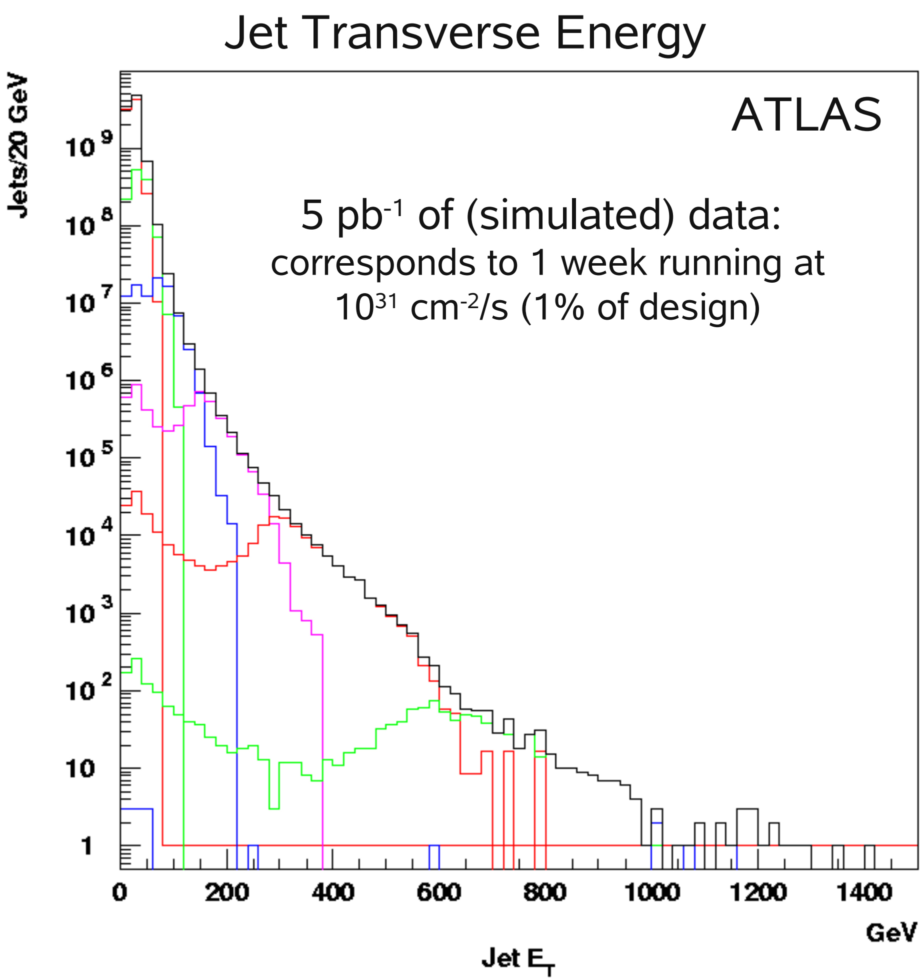
- Contact interactions look different than QCD.
  - QCD is predominantly t-channel gluon exchange.





Diagrams: R. Harris, CMS

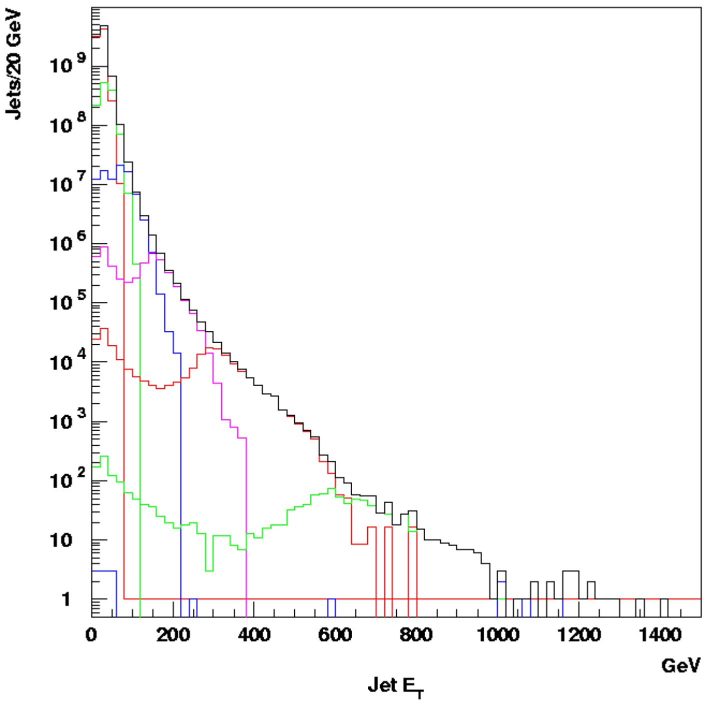
“Week One” Jet Measurements



- Expected limit on contact interaction: Λ(qqqq) > ~6 TeV
  - Rule of thumb: 4x the E_T of the most energetic jet you see
  - Present PDG limit is 2.4-2.7 TeV
  - Ultimate limit: ~20 TeV
  - The LHC measurement is at lower x than the Tevatron: PDF uncertainties are less problematic

Note that after a very short time, LHC will be seeing jets beyond the Tevatron kinematic limit.

Making the Measurement



- There are only two hard things in making this plot:
  - The x-axis
  - The y-axis

- The y-axis has two pieces: counting the events, and measuring the luminosity
  - The first is easy
  - The second is hard, and I won't talk about it

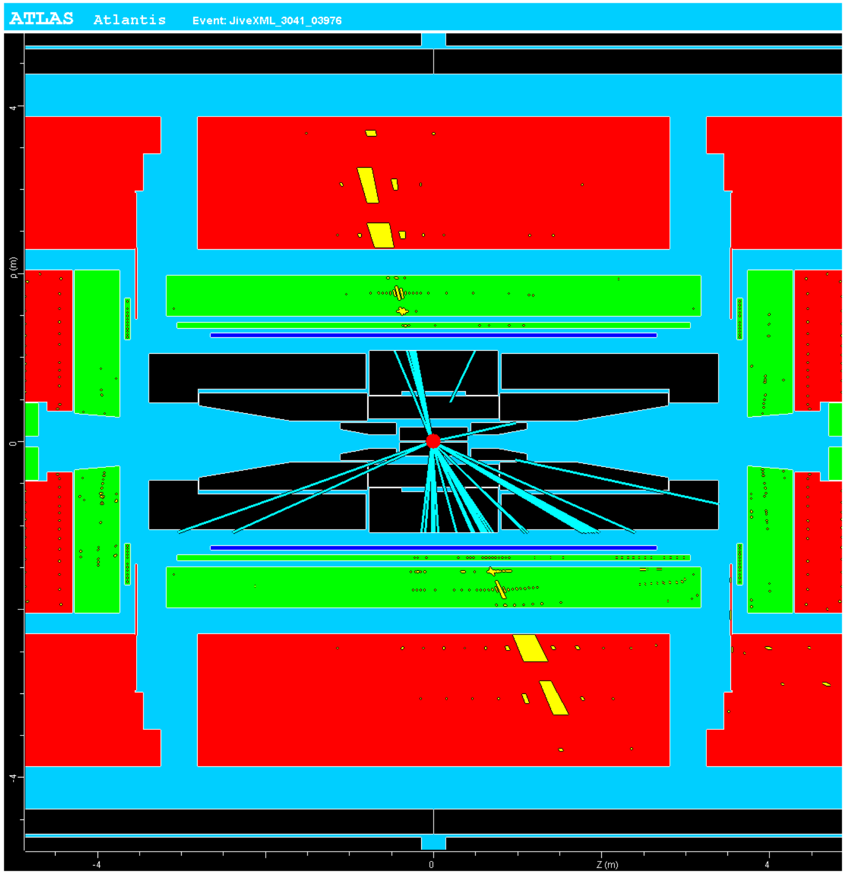
- The key to the x-axis is correctly measuring the jet energy

Balancing Jets

- The problem of setting the jet energy scale can be split into two parts:
  - 1. Establish that all jets share the **same** scale
  - 2. Establish that all jets share the **right** scale.

- A good start to #1 is to look at dijet events and show there is no bias to the jet energy as a function of jet position, jet composition, energy deposition, pile-up, etc.

- A good start to #2 is to use known particles (electrons and Z's) to set the overall scale.



Getting the jet energy scale right to 20% is easy. Getting it right to 2% is hard – and will take time.

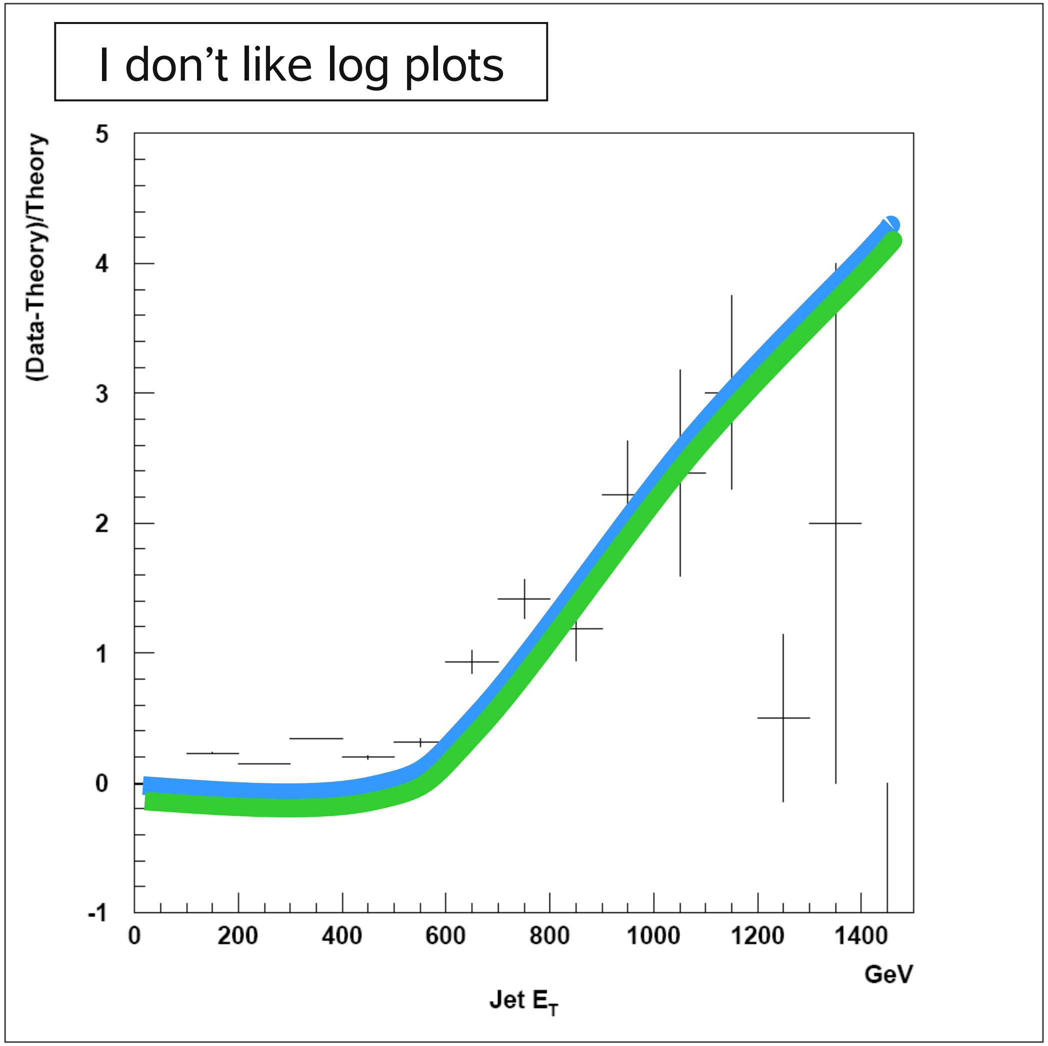
20% in JES = a factor of 2 in data

Jet Energy Scale Job List

- See that the Z decay to electrons ends up in the right spot
  - Demonstrates that the EM calorimeter is calibrated
- Balance jets with high and low EM fractions
  - Demonstrates that the EM and hadronic calorimeters have the same calibration
- Balance one jet against two jets
  - Demonstrates that the calorimeter is linear
- Balance jets against Z's and photons
  - Verifies that the above processes work in an independent sample
  - Demonstrates that we have the same scale for quark and gluon jets
- Use top quark decays as a final check that we have the energy scale right
  - Is m(t) = 175 and m(W) = 80? If not, fix it!

Note that most of the work isn't in getting the jet energy scale right. It's in convincing ourselves that we got the jet energy scale right – and that we have assigned an appropriate and defensible systematic uncertainty to it.

Sensitivity to A Contact Interaction



Black: one week's running at 1% of design luminosity.

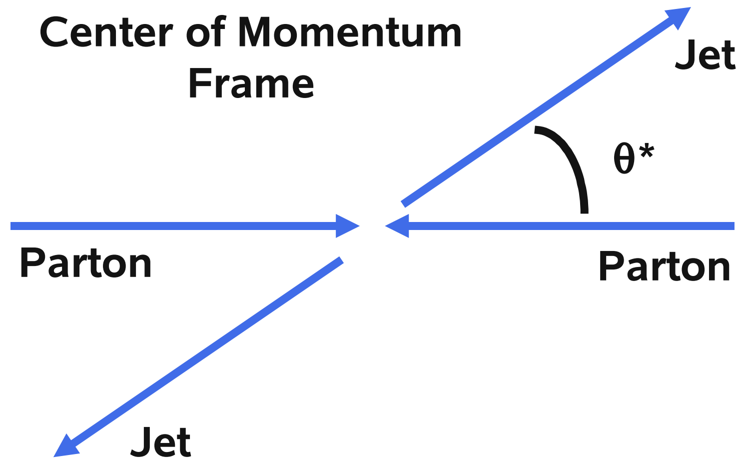
Blue: Expectations for a contact interaction term of ~4 TeV (SM is a line at 0)

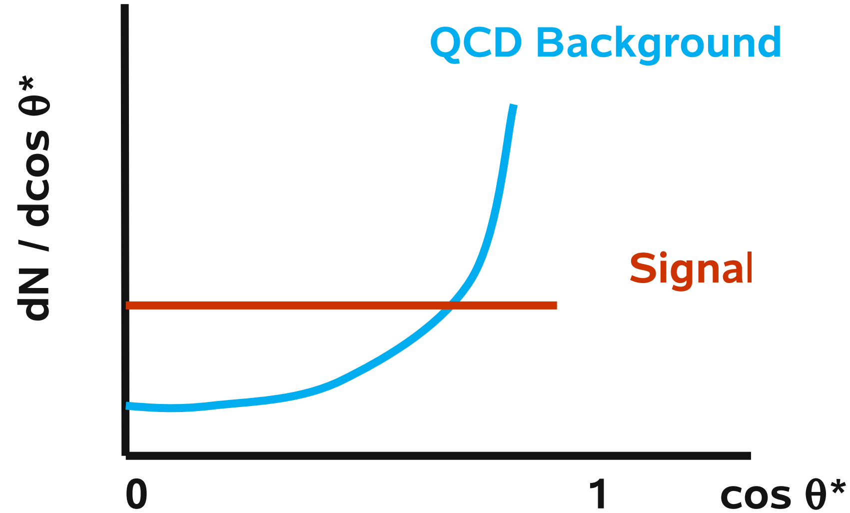
Green: A miscalibration selected to look like a contact interaction

Some care needs to be taken before announcing a major discovery.

Angular Distribution of a Contact Interaction

- It’s harder to grossly mismeasure a jet’s position than its energy.
- Contact interaction is often more isotropic than QCD
  - QCD is dominated by t-channel gluon exchange.
  - c.f. Eichten, Lane and Peskin (Phys. Rev. Lett. 50, 811-814 (1983)) for distributions from a contact interaction
- CMS (and D0) compress this distribution into a single ratio of central-to-forward jets





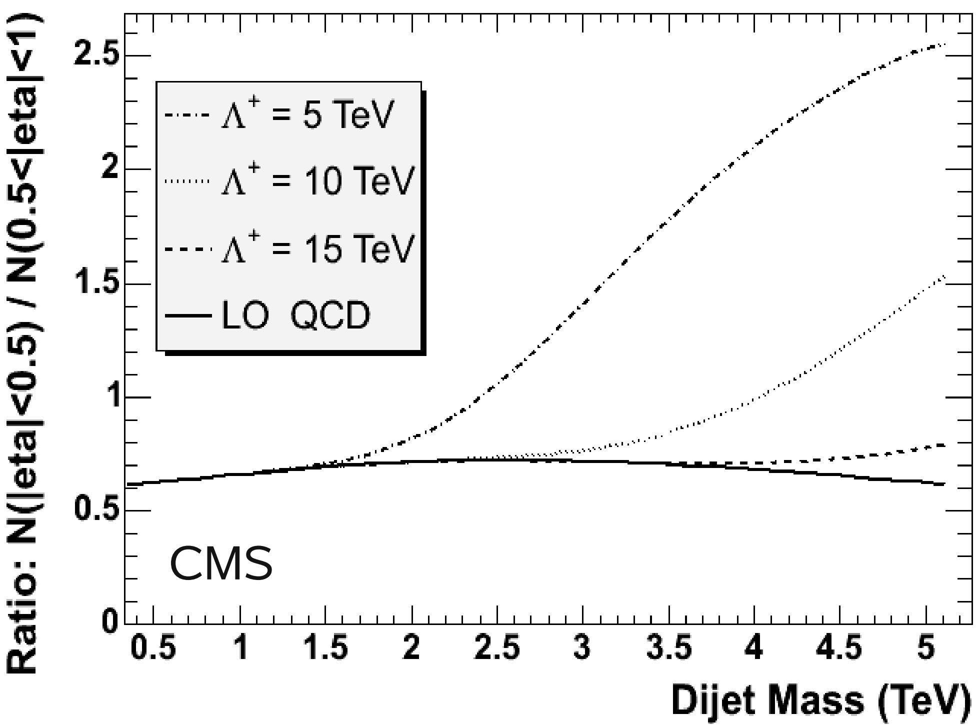
Diagrams: R. Harris, CMS

Angular Distribution of a Contact Interaction II

- The D0 (hep-ex/980714) dijet ratio:
  N(|η| < 0.5)/N(0.5 < | η | < 1)
  - This is essentially a measurement of the position of the *leading* jet.

- CMS plans to do the same thing (see plot)

- ATLAS is leaning more towards a combined fit of energy and angle.
  - Same idea, different mathematics



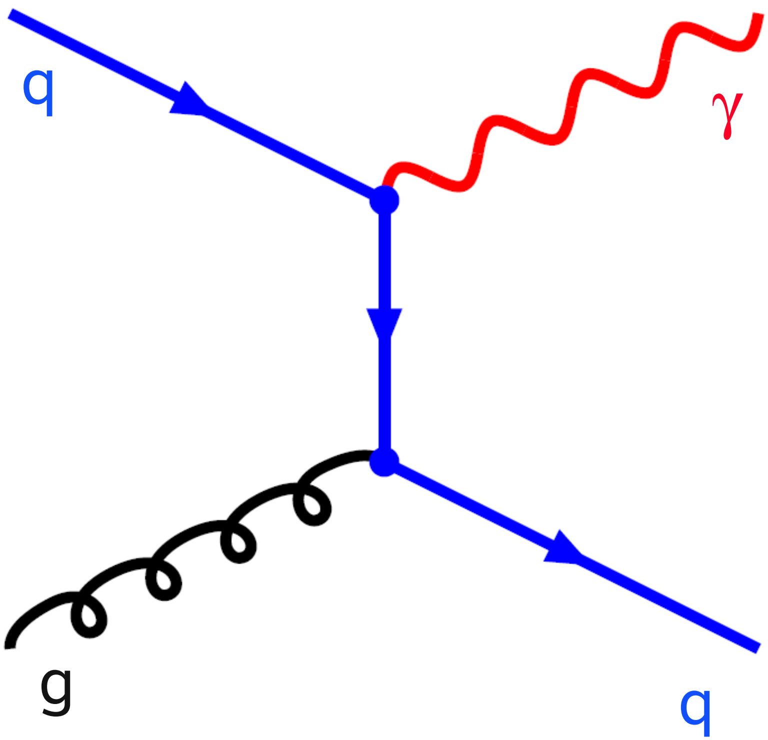
New physics changes the *shape* of this plot. You aren't counting on having a precise prediction of the QCD value.

Variations on a Theme

- Dijets
  - Masses: Also sensitive to compositeness, but also sensitive to new particles decaying to dijets
  - Kinematics: measures x_1 and x_2 simultaneously
- Trijets etc…
  - This measures α_s as a function of Q^2
- Heavy flavor jets
  - Could be identified with a displaced vertex/nearby lepton
  - Probes a different mix of quarks and gluons
  - A new resonance might couple only to bottom
- More advanced kinematic studies
- And so on…

Direct Photons and Gluon PDF History

- DIS and Drell-Yan are sensitive to the quark PDFs.
- Gluon sensitivity is indirect
  - The fraction of momentum not carried by the quarks must be carried by the gluon.
- It would be useful to have a direct measurement of the gluon PDFs
  - Even if it were less sensitive than the indirect measurements, it would lend confidence to the picture that is developing
  - This process depends on the (known) quark distributions and the (unknown) gluon distribution

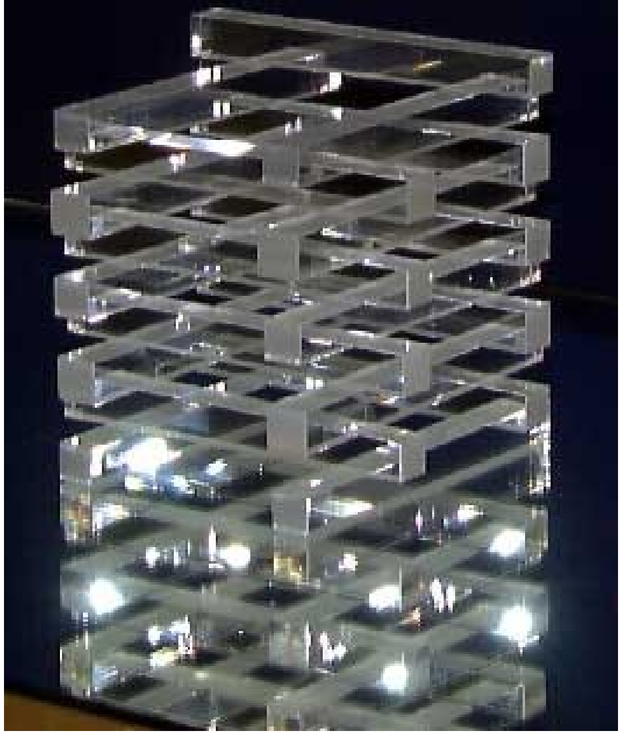


Direct photon "Compton" process.

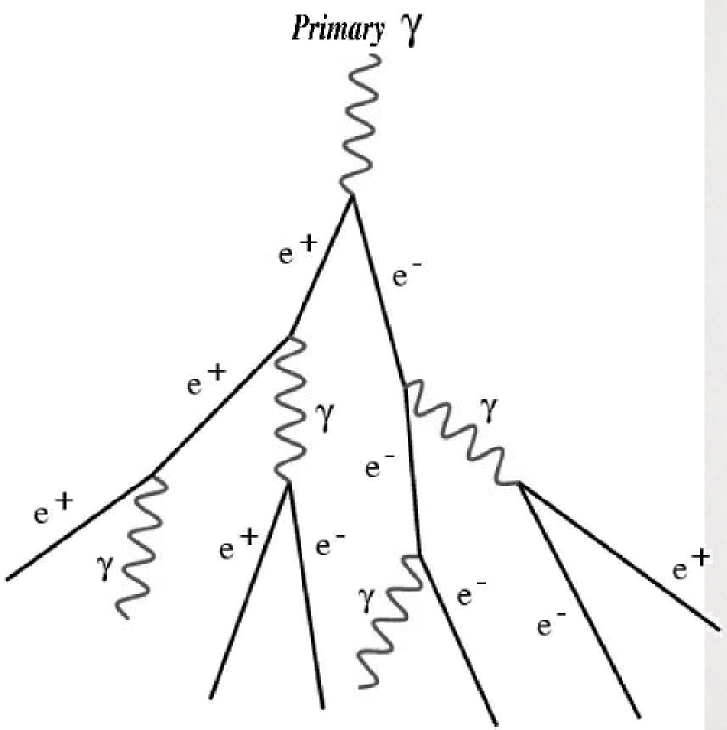
Direct Photons

- In principle, simple: build a calorimeter (right) and measure the energy of photons detected in it
- In practice, tough
  - You need to measure direct photons, not decay photons
  - The background from $\pi^0 \rightarrow \gamma\gamma$ and $\eta^0 \rightarrow \gamma\gamma$ decays is fierce
    - *E-706 reports a factor ~30 over direct γs*
    - *If that weren't bad enough, each background event gives you two photons*
  - E-706's final paper was published 12 years after they took data

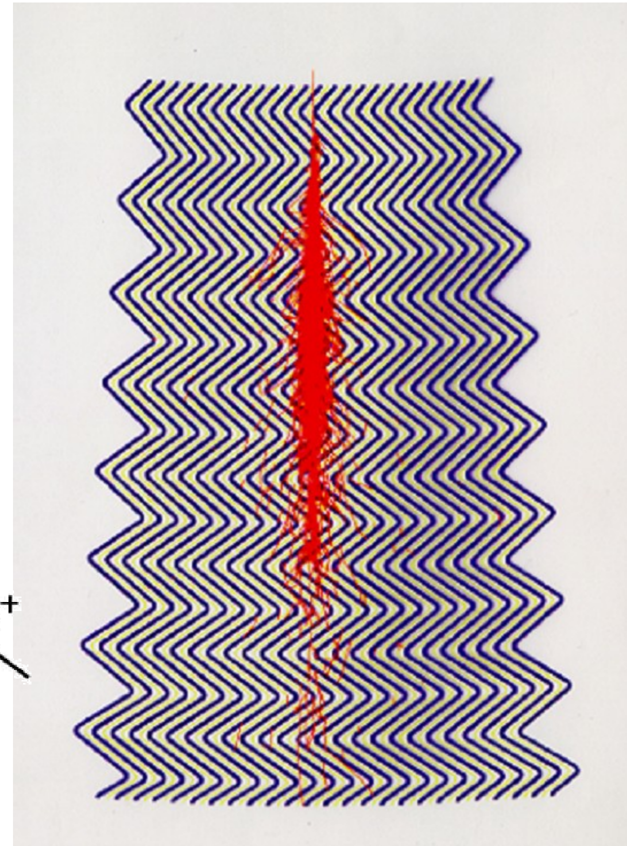
Lead Tungstate crystals used in the CMS calorimeter



Identifying Photons – Basics of Calorimeter Design



A schematic of an electromagnetic shower



A GEANT simulation of an electromagnetic shower

Not too much or too little energy here.

You want exactly one photon – not 0 (a likely hadron) or 2 (likely π^0)

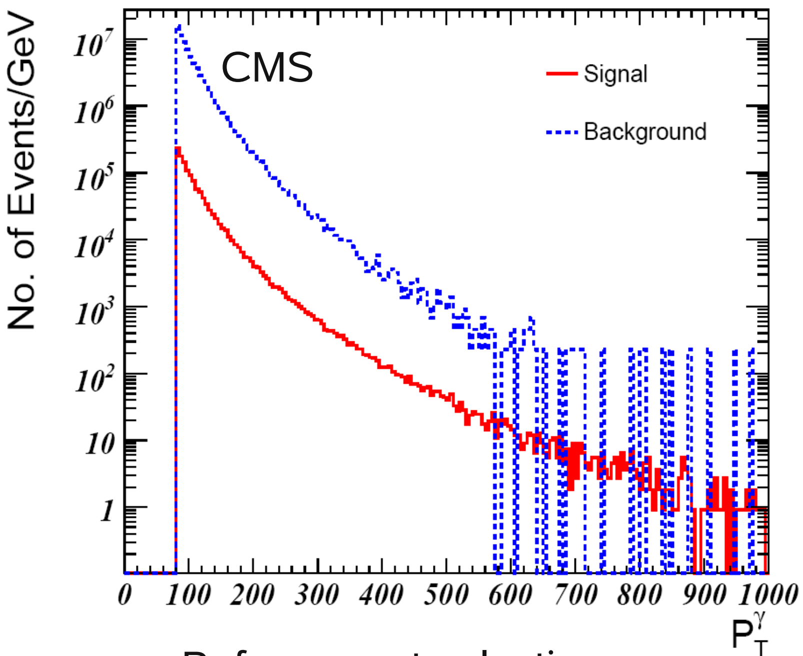
Not too wide here.

One photon and not two nearby ones (again, a likely π^0)

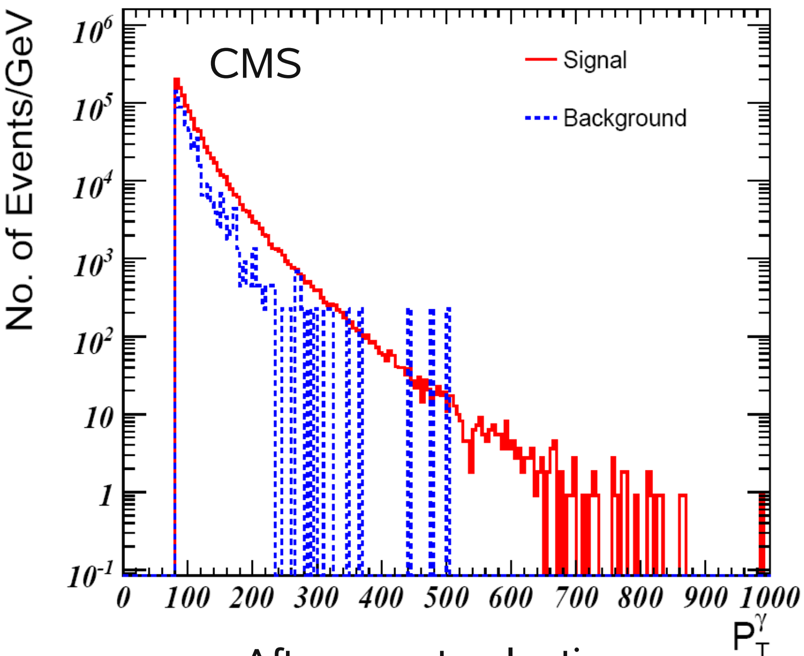
Not too much energy here.

Indicative of a hadronic shower: probably a neutron or K_L.

Direct Photon Backgrounds



Before event selection



After event selection

- There are two "knobs we can turn"
  - Shower shape – does this look like a photon (last slide)
  - Isolation – if it's a fake, it's likely to be from a jet, and there is likely to be some nearby energy
- Different experiments (and analyses in the same experiment) can rely more on one method than the other.

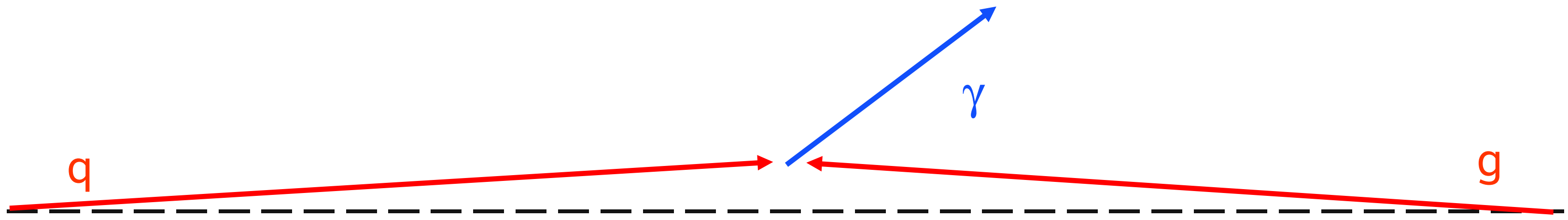
Direct Photon (Partial) Job List

- Decide what kinematic region to look at:
  - We will have a huge range if energies: ~20 to hundreds of GeV
  - Directly influences the trigger strategy

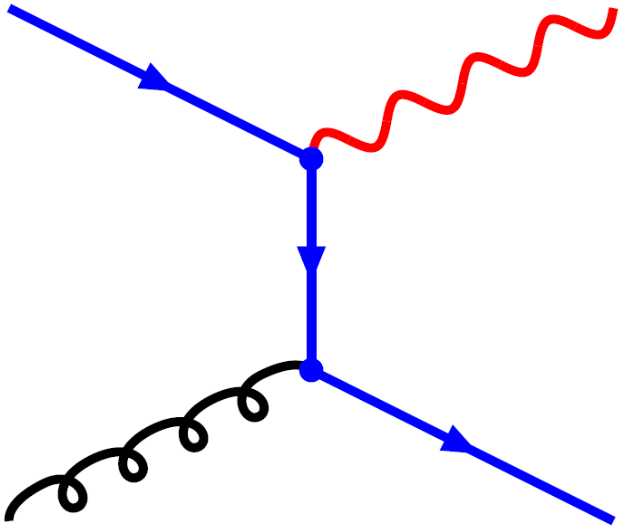
- Understand how to remove (event by event or statistically) the backgrounds

- Understand the photon efficiency and survival probability

- Understand the effect of the "k_T-kick"
  - Traditionally done with diphoton events



More Variations on A Theme



- One can scatter a gluon off of a heavy quark in the proton as well as a light quark
  - This quark can be identified as a bottom or charmed quark by "tagging" the jet
  - This measures how much b (or c) is in the proton
    - *Determines backgrounds to various searches, like Higgs*
    - *Turns out to have a surprisingly large impact on the ability to measure the W mass (ask me about this at the end, if interested)*
- Replace the γ with a Z, and measure the same thing with different kinematics
- Replace the Z with a W and instead of measuring how much charm is in the proton, you measure how much strangeness there is

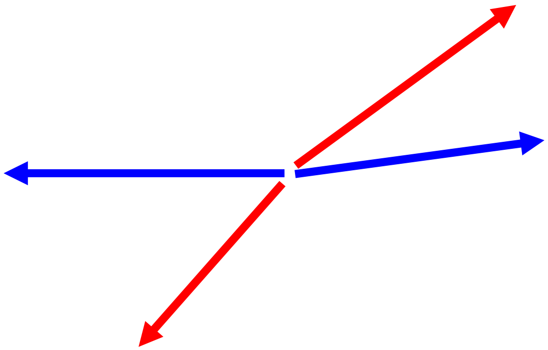
…and so on…

Double Parton Scattering

- Two independent partons in the proton scatter:

$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{Effective}}$$ might be better characterized by $$\sigma_{AB} = A(\hat{s}) \frac{\sigma_A \sigma_B}{\sigma_{Inelastic}}$$

- Searches for complex signatures in the presence of QCD background often rely on the fact that decays of heavy particles are "spherical", but QCD background is "correlated"
  - This breaks down in the case where part of the signature comes from a second scattering.
  - Probability is low, but needed background reduction can be high
- We're thinking about bbjj as a good signature
  - Large rate/large kinematic range
  - Relatively unambiguous which jets go with which other jets.



Some things I shouldn't have ignored

- QCD effects on the W mass
  - Finding **a** Higgs isn't the same as finding **all** of the Higgses
- Diffractive physics
- Double heavy flavor production
- Drell-Yan production
- …and so on…and so on…

There are many areas of QCD the LHC is suited to investigate.

Many of these are, if not exactly prerequisites, are helpful in understanding the "lay of the land" for new physics searches.

Summary

- Our first measurements will be QCD measurements
  - Rates are huge: a very small amount of data allows us to push past some of the Tevatron limits
  - It's less important that our uncertainty be **small** on an absolute scale than that it be **well understood**.

- Many of these measurements can be built upon as we collect more data
  - In many cases, these will strengthen the searches and improve precision measurements as well as being interesting in their own right.

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No matter what physics you want to do in 2011, think about what you want to be doing in 2008.