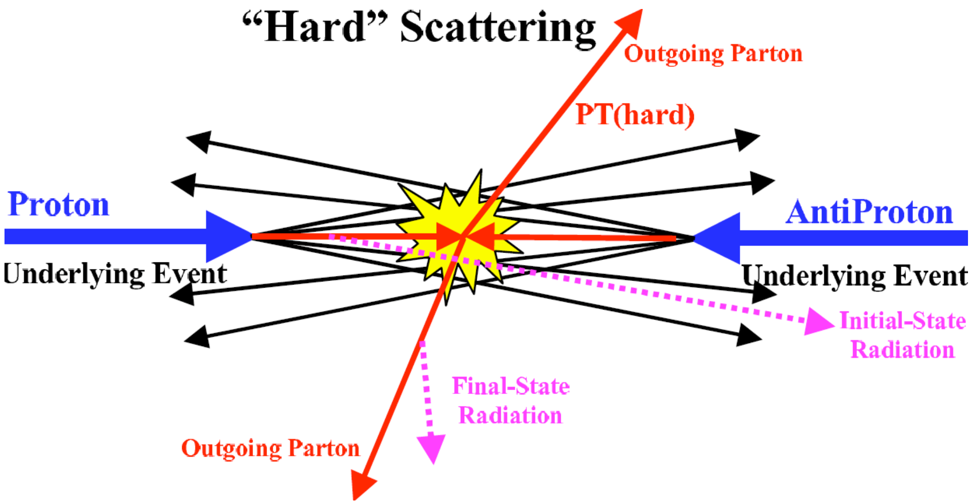
Hadrons and jets at hadron-hadron colliders

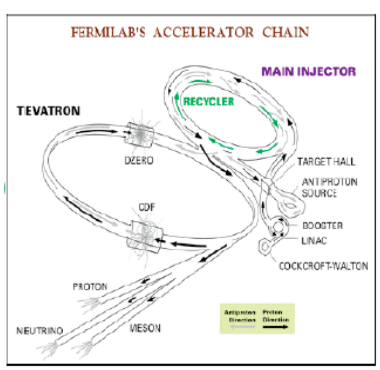
…and related physics stuff for the Tevatron and LHC

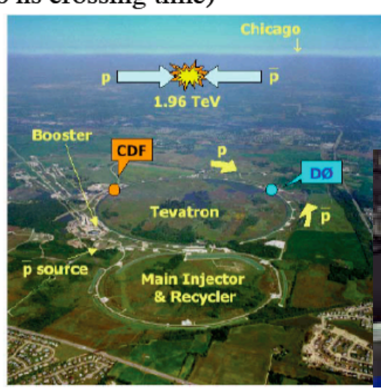


Joey Huston
Michigan State University
HCPSS2006
huston@msu.edu

- lessons from the Tevatron
- rules-of-thumb for the LHC
- using the language of American politics
- not much about τ's though

36 bunches (396 ns crossing time)





How lucky you are!

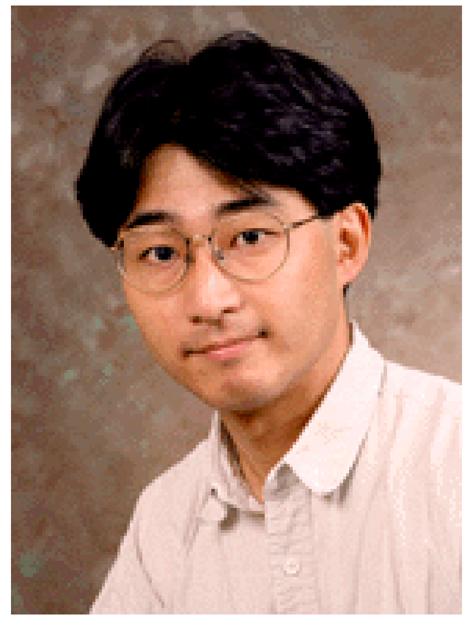
- …to be at Fermilab for this summer school
- Other students had to go to Rodos for the CTEQ summer school
- …with all of those distractions

view from SS 4-star hotel

What to expect at the LHC

…according to a theorist

Murayama LP03



What to expect at the LHC

…according to a theorist

Murayama LP03

- According to a current Secretary of Defense
  - known knowns
  - known unknowns
  - unknown unknowns

What to expect at the LHC

…according to a theorist

Murayama LP03

- According to a current Secretary of Defense
  - known knowns
    - SM at the Tevatron
      - signatures of W/Z/γ/leptons/jets/$\not{E}_T$
  - known unknowns
    - SM at the LHC
      - same as above but in a new kinematic environment, with perhaps a few surprises
  - unknown unknowns
    - ???

LHC bandwagon

- A lot of useful experience with the Standard Model can be carried forward from Fermilab and HERA and workshops have taken place to summarize that knowledge
  - HERA-LHC published
  - TeV4LHC near completion
  - I'm finished with a review article for ROP with John Campbell and James Stirling titled "Hard interactions of quarks and gluons: a primer for LHC physics"
    - much of what I will show here is from that article I'm trying to include as many "rules-of-thumb" for LHC physics as possible, including the importance of large logarithmic corrections
    - …and to dispel some myths
    - www.pa.msu.edu/~huston/seminars/Main.pdf

REVIEW ARTICLE

Hard Interactions of Quarks and Gluons: a Primer for LHC Physics

J. M. Campbell
Department of Physics and Astronomy
University of Glasgow
Glasgow G12 8QQ
United Kingdom

J. W. Huston
Department of Physics and Astronomy
Michigan State University
East Lansing, MI 48840
USA

W. J. Stirling
Institute for Particle Physics Phenomenology
University of Durham
Durham DH1 3LE
United Kingdom

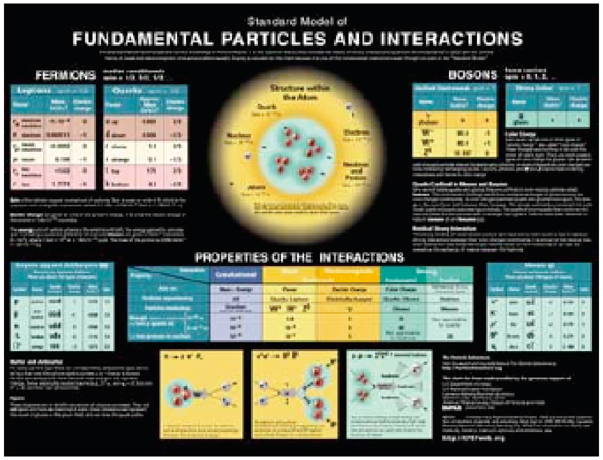
Abstract. In this review article, we will develop the perturbative framework for the calculation of hard scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_s in order to understand the behaviors of hard scattering processes. We will include "rules of thumb" as well as "official recommendations", and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

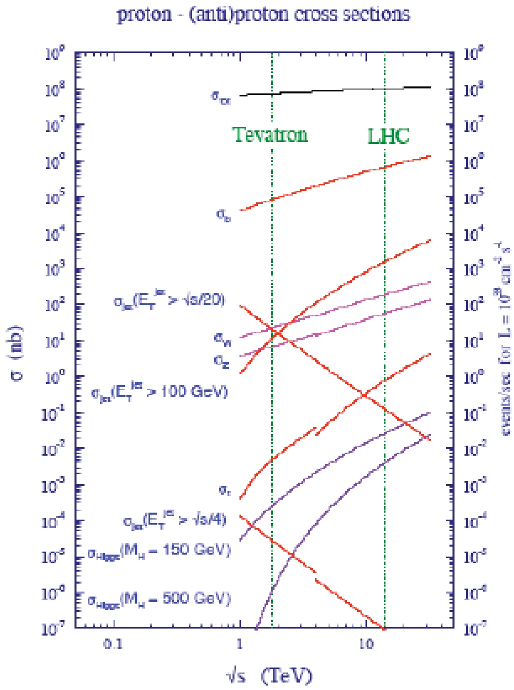
soft and/or collinear logs

$$d\sigma = \sigma_0(W{+}1\,\text{jet})\left[1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots\right]$$

Discovering the SM at the LHC

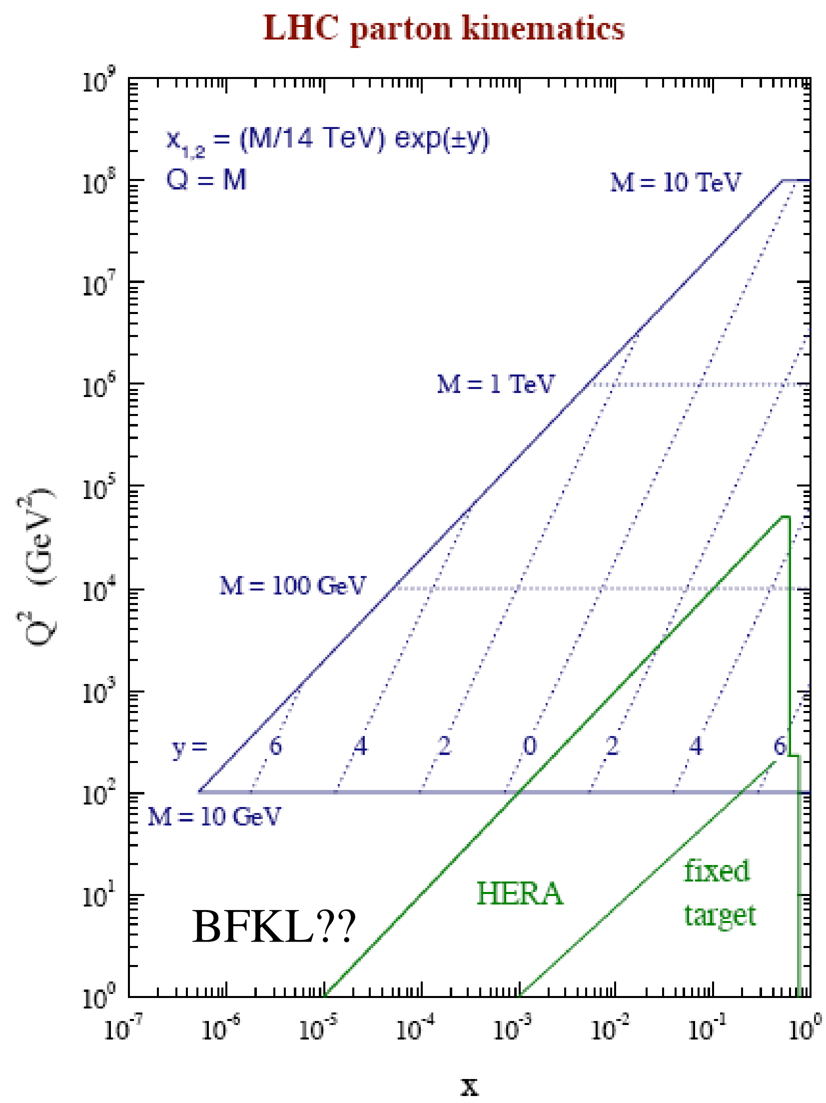
- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to BSM physics correctly taken into account
- ATLAS and CMS will have a program to measure production of SM processes: inclusive jets, W/Z + jets, heavy flavor during first year
  - so we need/have a program now of Monte Carlo production and studies to make sure that we understand what issues are important
  - and of tool and algorithm development





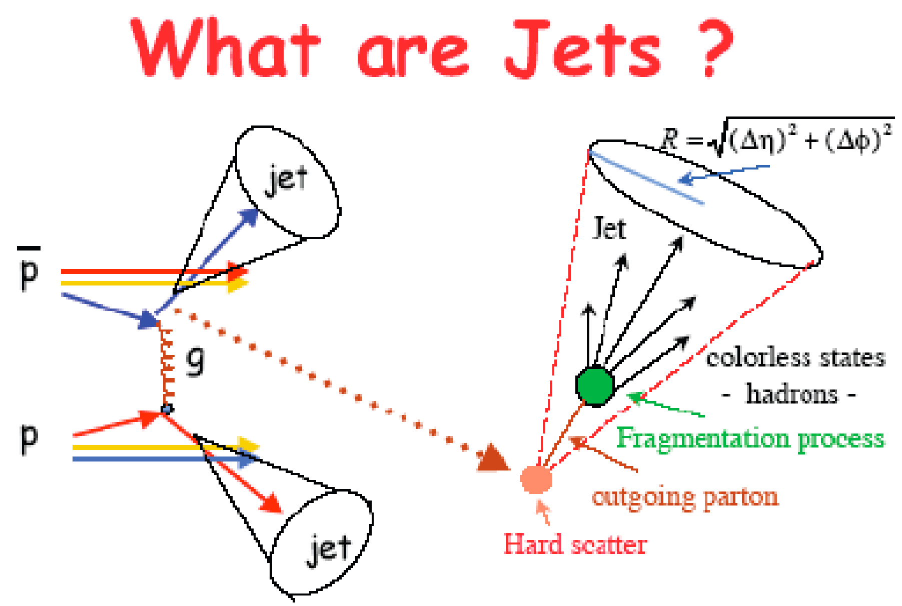
Cross sections at the LHC

- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just "rescaled" scattering at the Tevatron
- Small typical momentum fractions x in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



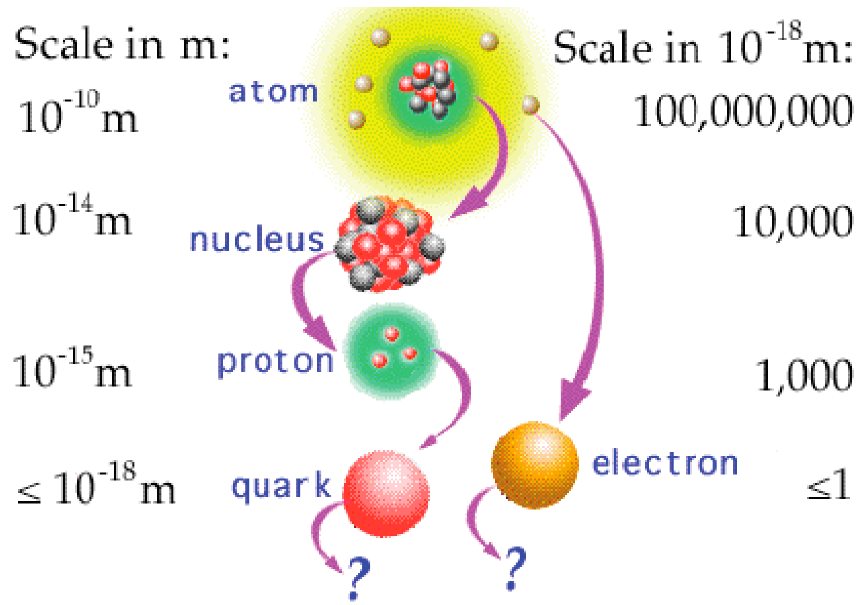
Now finally to jets

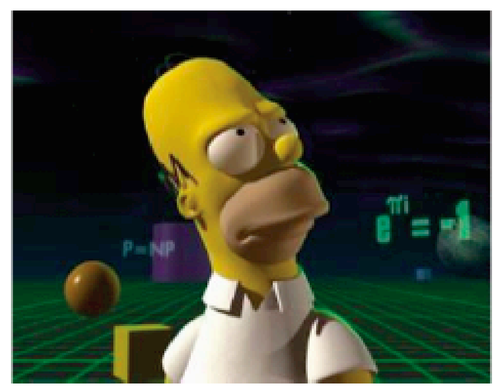
- One of the most useful and ubiquitous signatures, for both SM and BSM physics, at either the Tevatron or the LHC is a jet
- One can either measure inclusive jet production or jets in combination with other objects, W/Z/…



Inclusive jet production

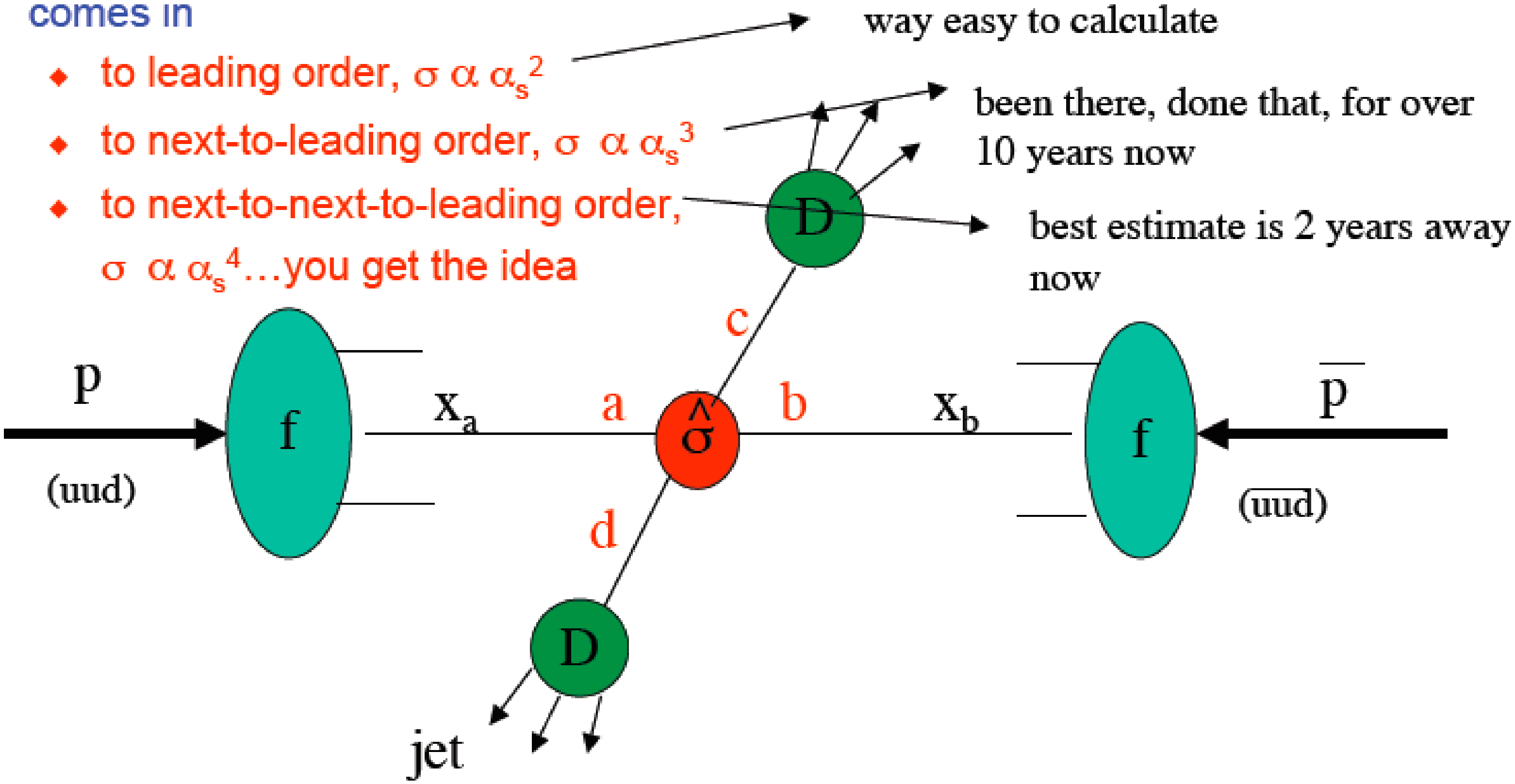
- Consider inclusive jet production at the Tevatron; it probes the most violent collisions currently achievable
  - smallest distance scales (10^{-17} m)
  - some of greatest sensitivity to new physics (quark compositeness)
- New version of Rutherford scattering
  - production of jets at high transverse momentum indicates that there must be point-like constituents within protons, i.e. quarks
  - If we observe a deviation from the expected jet cross sections at the highest jet p_T's, this may be an indication of something inside the quarks





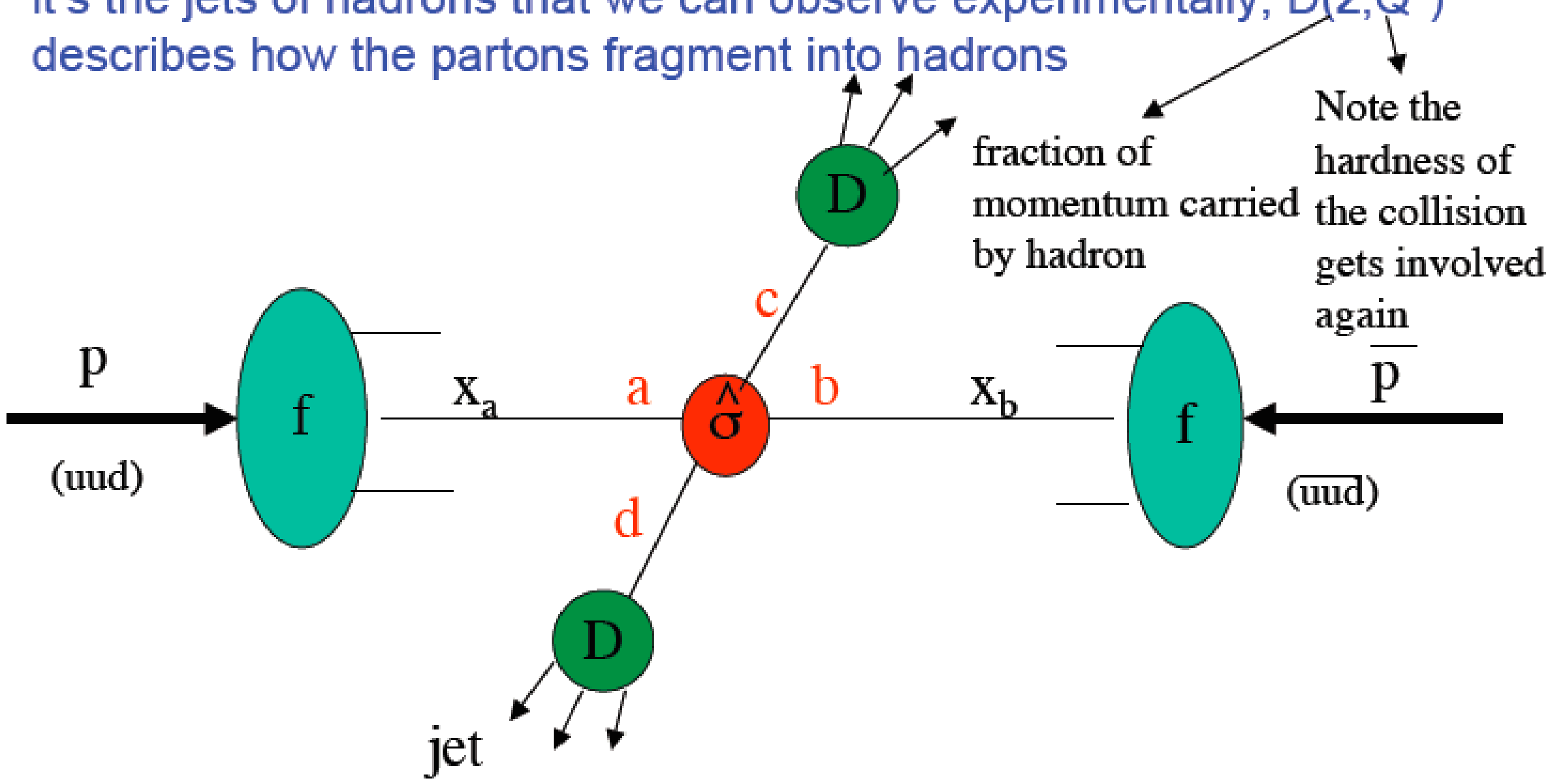
2->2 hard scattering

- So one parton carrying a momentum fraction x_a collides with another parton carrying a momentum fraction x_b
  - •distribution of parton momenta given by parton distribution functions $f(x,Q^2)$
- The collision is given by the red blob; that's where most of the hard QCD comes in
  - to leading order, $\sigma \propto \alpha_s^2$
  - to next-to-leading order, $\sigma \propto \alpha_s^3$
  - to next-to-next-to-leading order, $\sigma \propto \alpha_s^4$…you get the idea



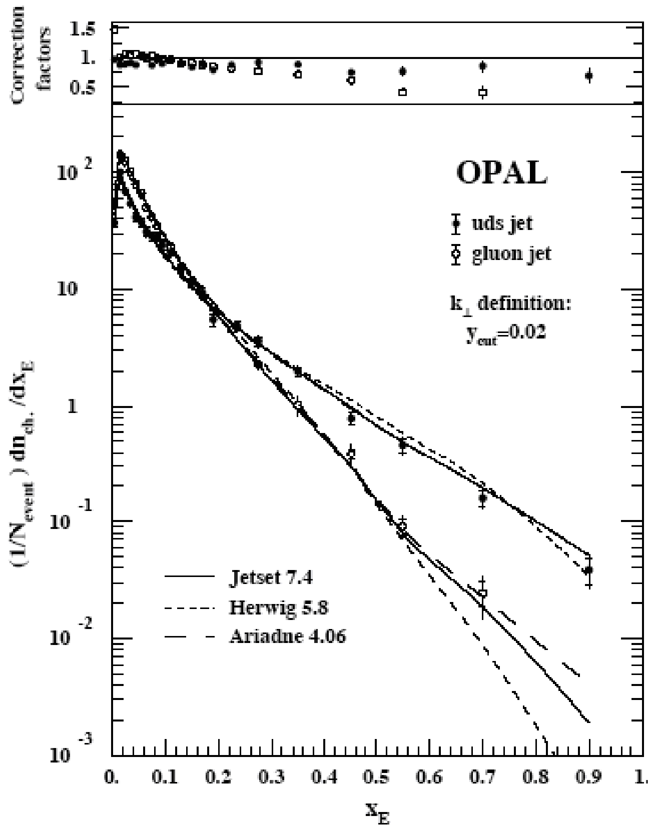
2->2 hard scattering

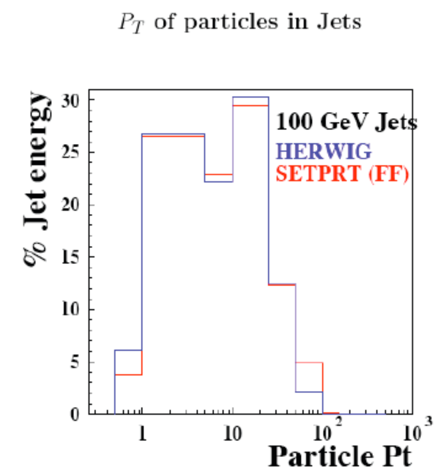
- c and d are the outgoing partons, but problem: they carry color; we don't observe the quarks or gluons themselves (don't see naked color) but instead the partons fragment into jets of hadrons (pions, kaons, and protons)
- it's the jets of hadrons that we can observe experimentally; $D(z,Q^2)$ describes how the partons fragment into hadrons



Jet fragmentation

- The parton that gives rise to the jet fragments into a fairly large number of particles (increasing as the jet E_T increases)
  - say 20 particles for a jet with E_T of 100 GeV
- Most of the jet particles have a small fraction (z) of the total jet momentum
  - and the gluon fragmentation is softer than the quark fragmentation
- We can't calculate the fragmentation functions perturbatively; have to measure them
  - mosly at LEP
  - we can calculate how they change with Q, though



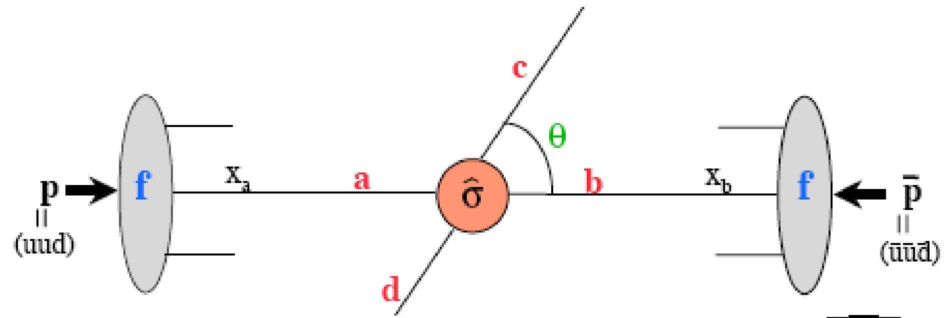


100 GeV Jets are primarily (90%) particles with P_T < 50 GeV.

Note that the fragmentation for gluon jets is much softer than for quark jets; thus it is more unlikely for a gluon jet to fragment into a high z particle

Jets (at LO) and the kinematics of jets

- 2->2 hard scattering
- 1 (outgoing) parton = 1 jet



We use the following definitions for Run II jet quantities. For a jet 4-vector (E, p_x, p_y, p_z):

$$p = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\theta = \cos^{-1}(p_z/p) \qquad (0 \leq \theta \leq \pi)$$

$$\phi = \tan^{-1}(p_y/p_x) \qquad (0 \leq \phi < 2\pi)$$

$$y = \frac{1}{2}\ln\left[\frac{E+p_z}{E-p_z}\right]$$

which lead to

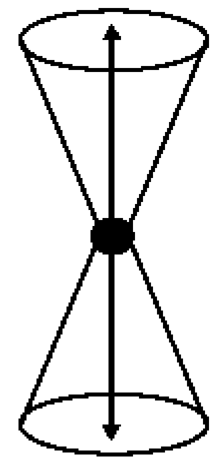
$$E_x = E\cos\phi\sin\theta$$

$$E_y = E\sin\phi\sin\theta$$

$$E_z = E\cos\theta$$

$$E_T = \sqrt{E_x^2 + E_y^2} = E\sin\theta$$

By definition, $E = \sqrt{E_x^2 + E_y^2 + E_z^2}$.



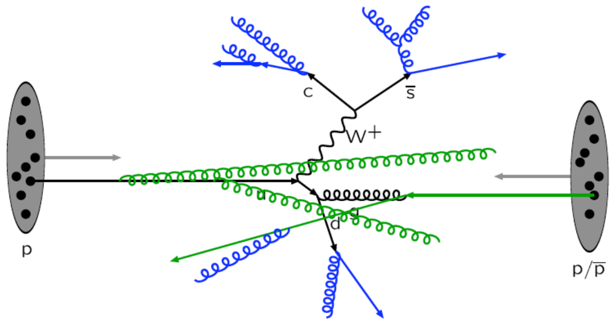
- Jet has no size (except for ~1 fermi)

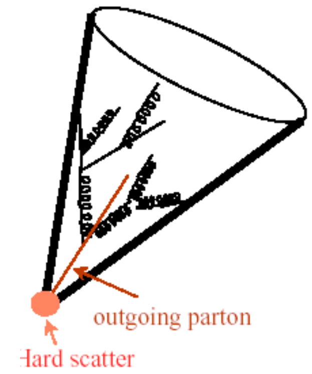
In general, $E_T \neq p_T$, and they should not be used interchangeably. The use of p_T is preferred!

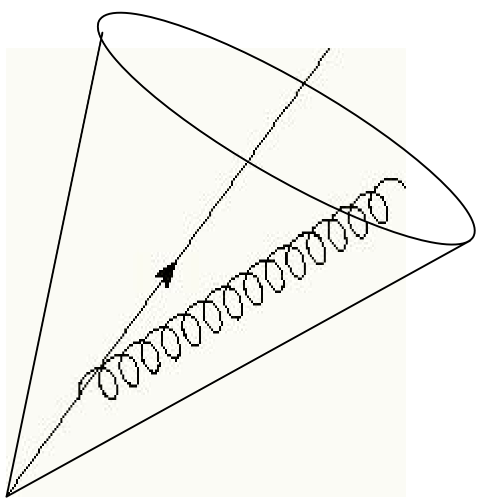
although when the jet is 1 outgoing massless parton, $E_T = p_T$

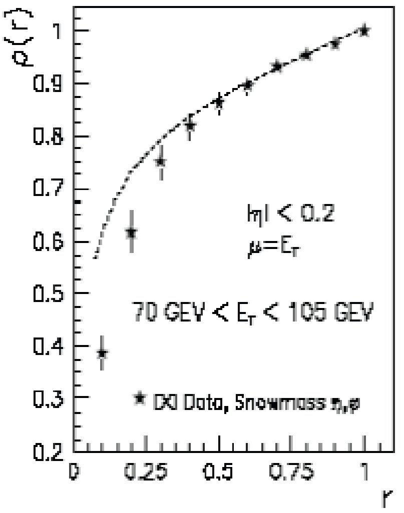
Jets (at higher orders)

- As you've seen in Torbjorn's lectures, there is a parton shower that results from a hard collision so that one parton becomes many partons (and eventually hadrons) and the jet acquires a lateral size
    - or in the words of the previous transparency, the fragmentation function $D(z,Q^2)$ is built up
- Many of the important properties of the jet such as the lateral shape/mass don't require the full parton shower but can be well-described by one (hard) gluon emission (NLO)



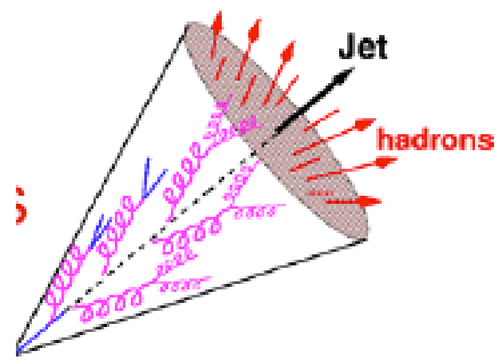


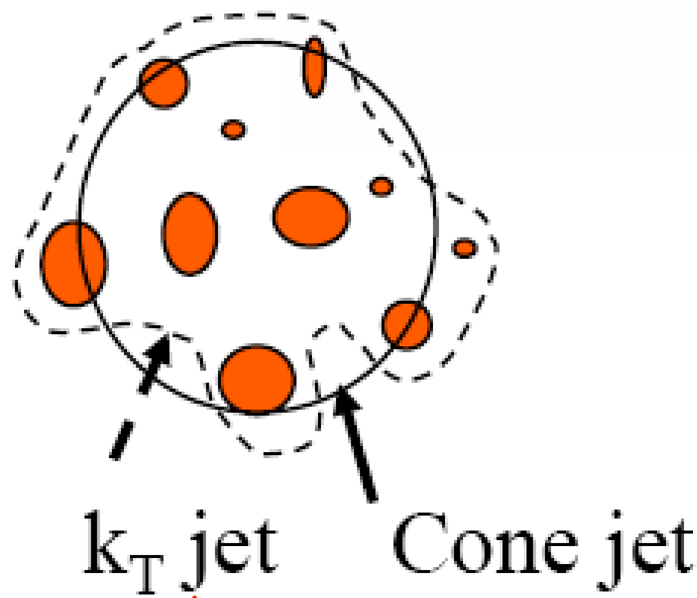




What is a jet?

- Jets are the experimental signatures of quarks and gluons
- Jets manifest themselves as localized clusters of energy
- It is the role of the jet algorithm to identify and measure the properties of a jet
- A jet algorithm can either measure
  - closeness in momentum space: k_T algorithm
    - most often used at LEP and HERA
  - closeness in coordinate space: cone algorithm
    - most often used at the Tevatron
  - at the LHC, hopefully both will be equally used
- Can apply these jet algorithms to calorimeter towers or particles or partons…and would like to get a similar answers, as much as possible

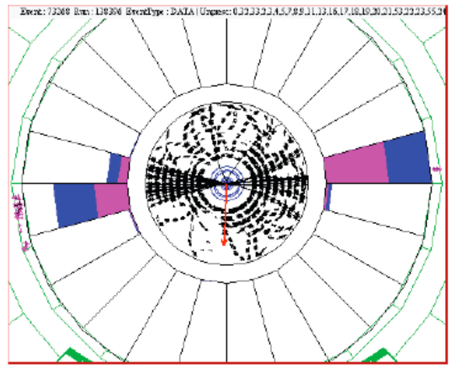


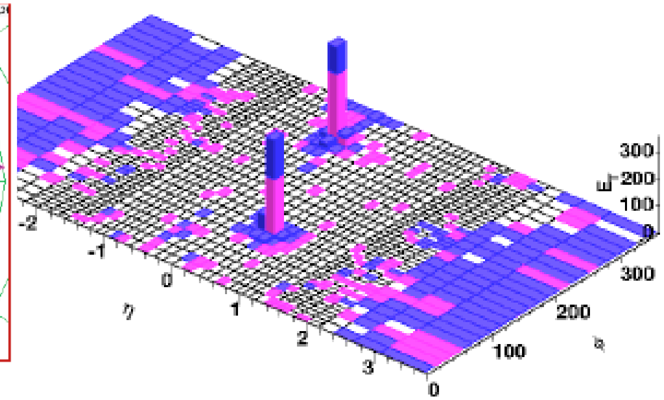


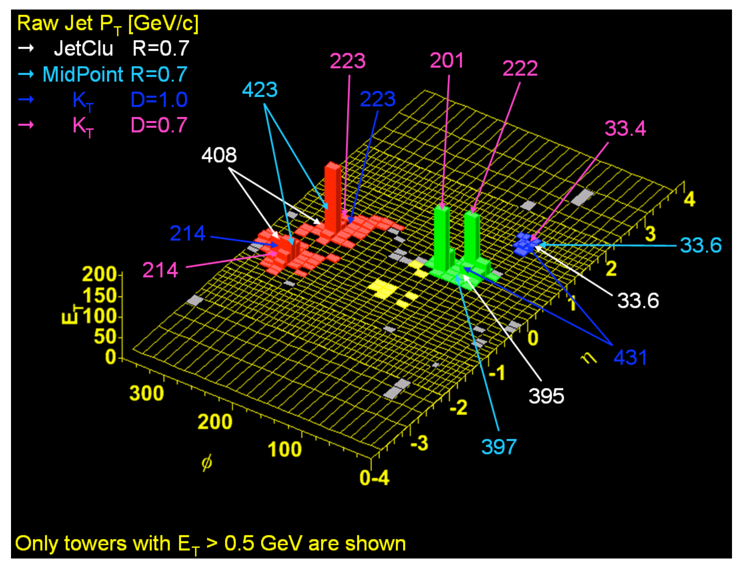
…a cone jet on a bad hair day

Jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers/particles to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- If comparison is to hadron-level Monte Carlo, then hope is that the Monte Carlo will reproduce all of the physics present in the data and influence of jet algorithms can be understood
  - more difficulty when comparing to parton level calculations





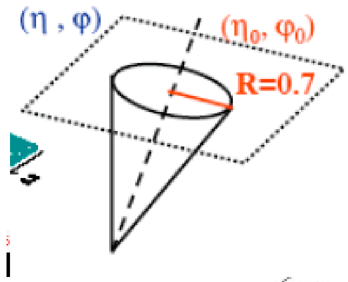


Desired features of jet algorithms

- From theoretical point-of-view
  - infrared safety: insensitive to soft gluon radiation
  - collinear safety: insensitive to collinear splitting of gluon radiation
  - boost invariance: algorithm should find the same jets independent of any boosts along the beam axis
  - boundary stability: the kinematics that define the jet should be insensitive to the details of the final state
  - order independence: the algorithm should give similar results at the particle, parton and detector levels
  - straightforward implementation: the algorithm should be straightforward to implement in perturbative calculations
- From experimental point-of-view
  - detector independence: there should be little or no dependence on detector segmentation, energy response or resolution
  - minimization of resolution smearing:The algorithm should not amplify the inevitable effects of resolution smearing and angle biases
  - stability with luminosity: jet finding should not be strongly affected by multiple interactions at high luminosities
  - resource efficiency: the jet algorithm should identify jets using a minimum of computer time
  - reconstruction efficiency: the jet algorithm should identify all jets associated with partons
  - ease of calibration: the algorithm should not present obstacles to the reliable calibration of the jet
  - fully specified: all of the details of the algorithm must be fully specified including specifications for clustering, energy and angles, and splitting/merging

Midpoint cone algorithm

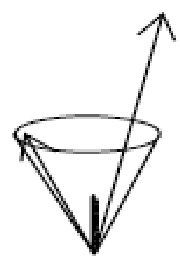
- Generate p_T ordered list of towers (or particles/partons)
- Find proto-jets around seed towers (typically 1 GeV) with p_T>threshold (typically 100 MeV)
  - include tower k in cone if

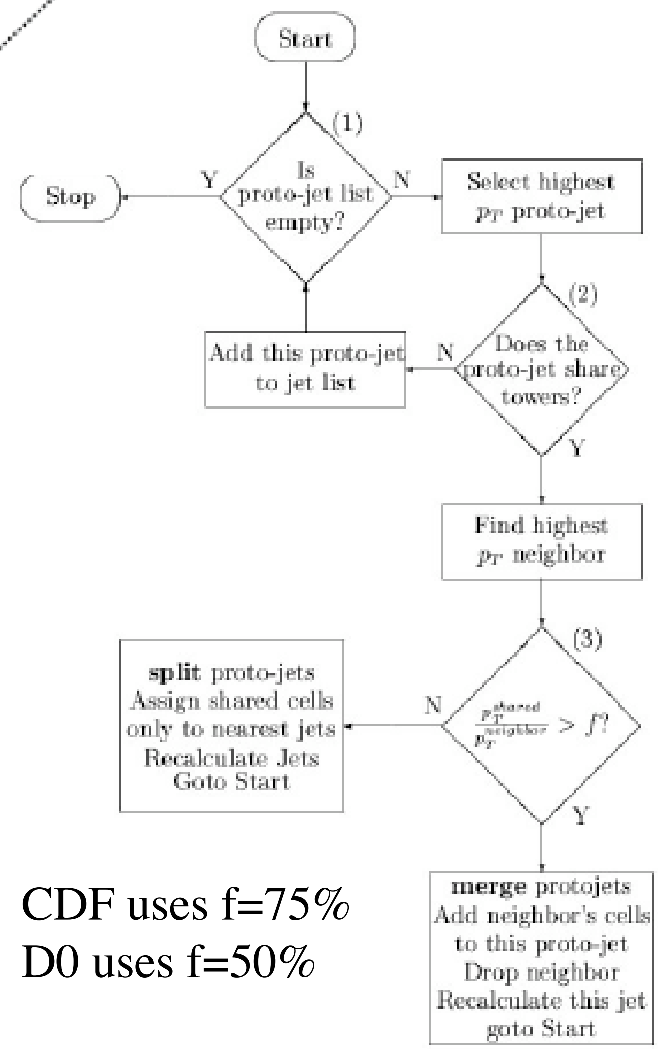


$$k \subset C \text{ iff } \sqrt{(y_k - y_C)^2 + (\phi_k - \phi_C)^2} \leq R_{cone},$$

$$p_C = (E_C, \vec{p}_C) = \sum_{k \subset C} (E_k, \vec{p_k}), \quad \bar{y}_C \equiv \frac{1}{2} \ln \frac{E_C + p_{z,C}}{E_C - p_{z,C}}, \quad \bar{\phi}_C \equiv \tan^{-1} \frac{p_{y,C}}{p_{x,C}}$$

  - iterate if $(\bar{y}_C,\bar{\phi}_C) \neq (y_C,\phi_C)$
  - NB: use of seeds creates IR-sensitivity
- Generate midpoint list from proto-jets
  - using midpoints as seed positions reduces IR-sensitivity
- Find proto-jets around midpoints
- Go to splitting/merging stage
  - real jets have spatial extent and can overlap; have to decide whether to merge the jets or to split them
- Calculate kinematics (p_T,y,ϕ) from final stable cones

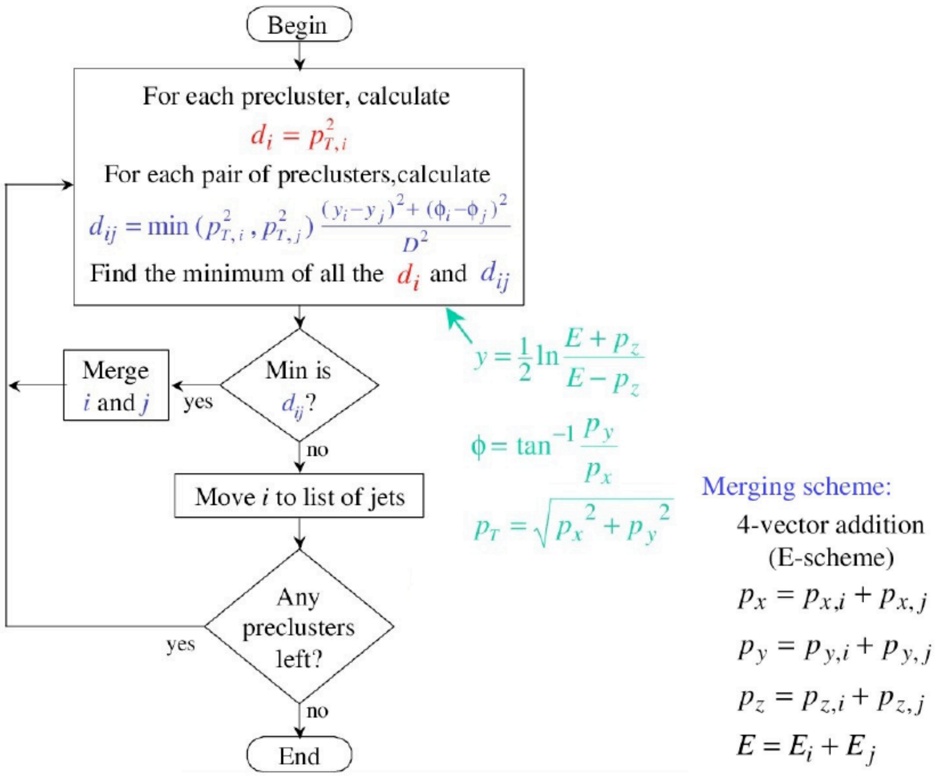




CDF uses f=75%
D0 uses f=50%

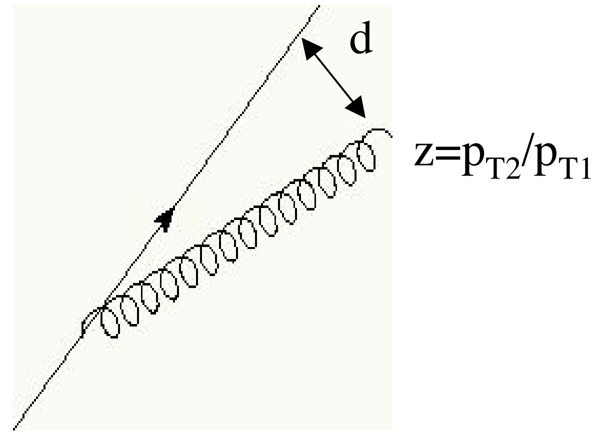
k_T algorithm

- The k_T jet algorithm successively merges pairs of partons, particles or calorimeter towers in order of increasing relative transverse momentum
- The algorithm typically contains a parameter D that controls the termination of the merging and characterizes the approximate size of the resulting jets
- Since the k_T algorithm fundamentally merges nearby particles,there is a correspondence of jets reconstructed in a calorimeter to jets reconstructed from individual hadrons, leptons, and photons
- As the jet does not have a fixed area, the underlying event subtraction is more problematic



Jet algorithms at NLO

- Remember at LO, 1 parton = 1 jet
- At NLO, there can be two partons in a jet and life becomes more interesting
- Let's set the p_T of the second parton = z that of the first parton and let them be separated by a distance d (=ΔR)
- Then in regions I and II (on the left), the two partons will be within R_{cone} of the jet centroid and so will be contained in the same jet
  - ~10% of the jet cross section is in Region II; this will decrease as the jet p_T increases (and α_s decreases)
  - at NLO the k_T algorithm corresponds to Region I (for D=R); thus at parton level, the cone algorithm is always larger than the k_T algorithm



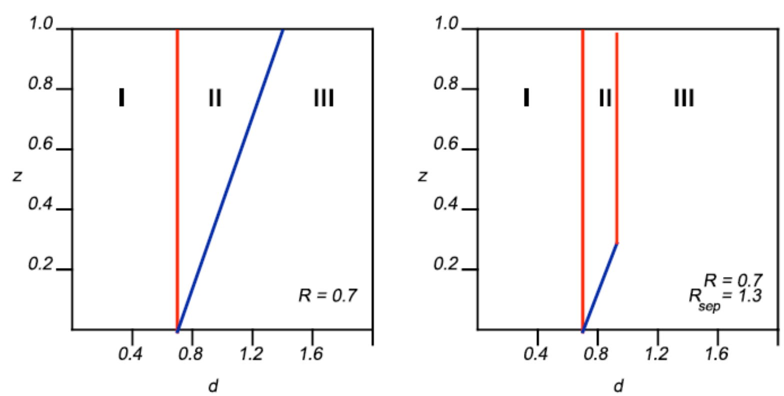


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

Jets at NLO continued

- Construct what is called a Snowmass potential

shown in Figure 50, where the towers unclustered into any jet are shaded black. A simple way of understanding these dark towers begins by defining a "Snowmass potential" in terms of the 2-dimensional vector $\overrightarrow{r} = (y, \phi)$ via

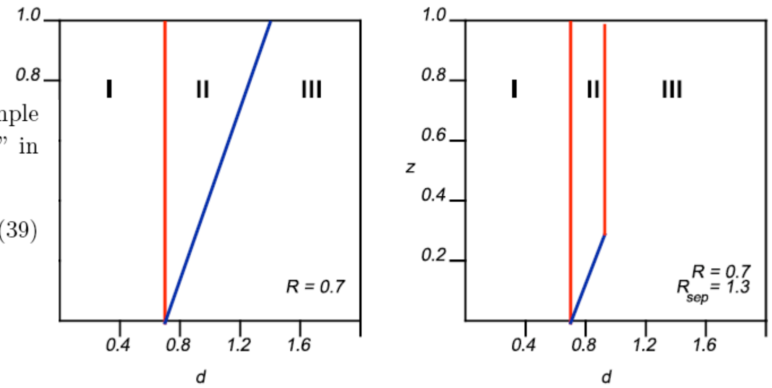
$$V(\overrightarrow{r}) = -\frac{1}{2}\sum_j p_{T,j}\left(R_{cone}^2 - (\overrightarrow{r_j} - \overrightarrow{r})^2\right)\Theta\left(R_{cone}^2 - (\overrightarrow{r_j} - \overrightarrow{r})^2\right) . \quad (39)$$

The flow is then driven by the "force" $\overrightarrow{F}(\overrightarrow{r}) = -\overrightarrow{\nabla}V(\overrightarrow{r})$ which is thus given by,

$$\begin{aligned}\overrightarrow{F}(\overrightarrow{r}) &= \sum_j p_{T,j}\left(\overrightarrow{r_j} - \overrightarrow{r}\right)\Theta\left(R_{cone}^2 - (\overrightarrow{r_j} - \overrightarrow{r})^2\right) \\ &= \left(\overrightarrow{r}_{C(\overrightarrow{r})} - \overrightarrow{r}\right)\sum_{j \subset C(r)} p_{T,j}, \end{aligned} \quad (40)$$

where $\overrightarrow{r}_{C(\overrightarrow{r})} = \left(\overline{y}_{C(\overrightarrow{r})}, \overline{\phi}_{C(\overrightarrow{r})}\right)$ and the sum runs over $j \subset C(\overrightarrow{r})$ such that $\sqrt{(y_j - y)^2 + (\phi_j - \phi)^2} \le R_{cone}$. As desired, this force pushes the cone to the stable cone position.

- The minima of the potential function indicates the positions of the stable cone solutions
  - the derivative of the potential function is the force that shows the direction of flow of the iterated cone
- The midpoint solution contains both partons



igure 22. The parameter space (d,Z) for which two partons will be merged into a ngle jet.

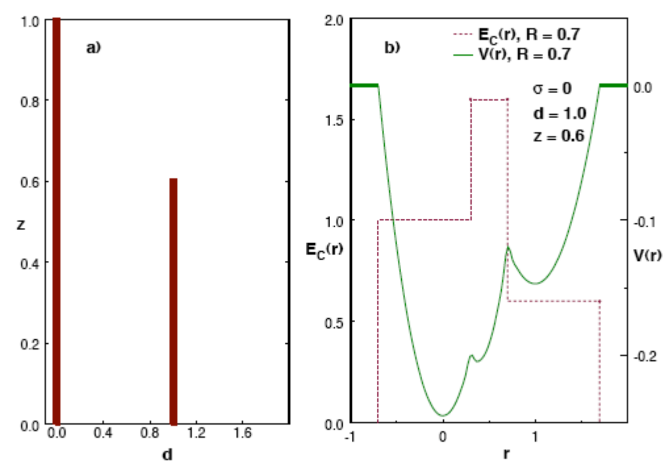
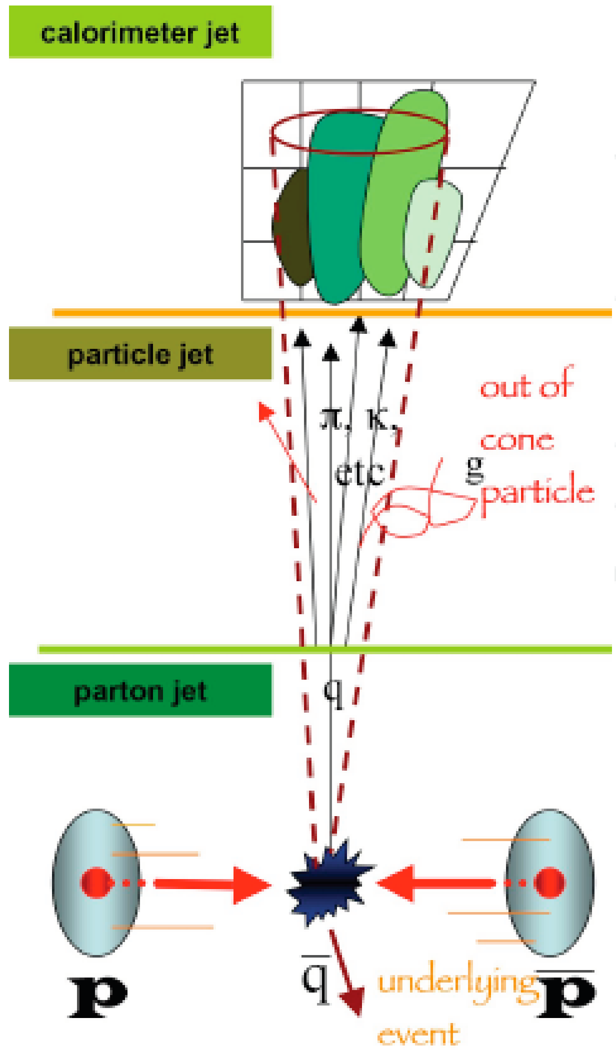


Figure 51. A schematic depiction of a specific parton configuration and the results of applying the midpoint cone jet clustering algorithm. The potential discussed in the text and the resulting energy in the jet are plotted.

Jet at all orders (real life)

- A high energy hard collision produces outgoing partons
- These are highly virtual and can emit further gluons (parton showers)
- Once the shower reaches a low scale, color is neutralized and the final state particles are produced
  - first resonances such as $A_1, A_2, \rho \ldots$
  - eventually $\pi, K, p, \gamma, \ldots$
- These particles deposit energy in the calorimeters and it's based on this energy (in most cases) that the jet reconstruction is based



Jets in real life

- Thus, jets don't consist of 1 fermi partons but have a spatial distribution
- Can approximate this as a Gaussian smearing of the parton energy
  - The effective sigma ranges between around 0.1 and 0.3 depending on the parton type (quark or gluon) and on the parton p_T
- Note that because of the effects of smearing that
  - the midpoint solution is (almost always) lost
    - thus region II is effectively truncated to the area shown on the right
  - The solution corresponding to the lower energy parton can also be lost
    - resulting in dark towers

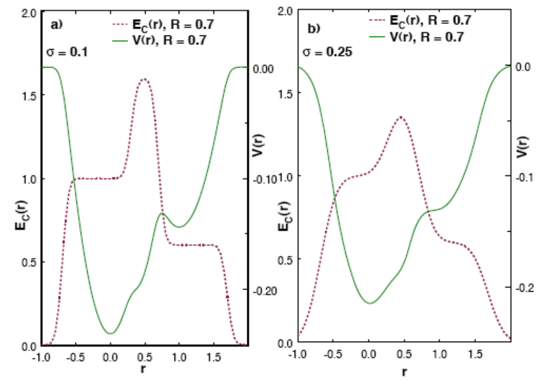


Figure 52. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm.

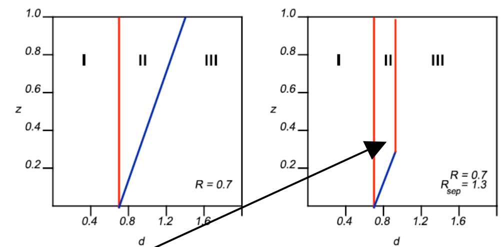


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

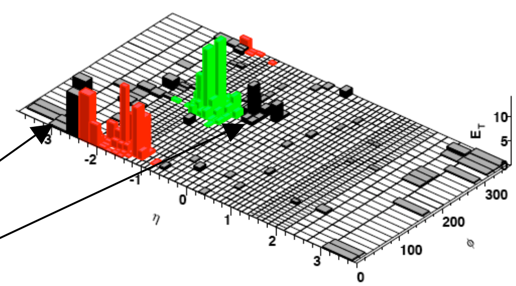


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

Jets in real life

- In NLO theory, can mimic the impact of the truncation of Region II can including a parameter called R_{sep}
  - only merge two partons if they are within $R_{sep}*R_{cone}$ of each other
    - R_{sep}~1.3
  - ~5% effect on the theory cross section
  - really upsets the theorists (but there are also disadvantages)
- Dark tower effect is also ~5% effect on the (experimental) cross section

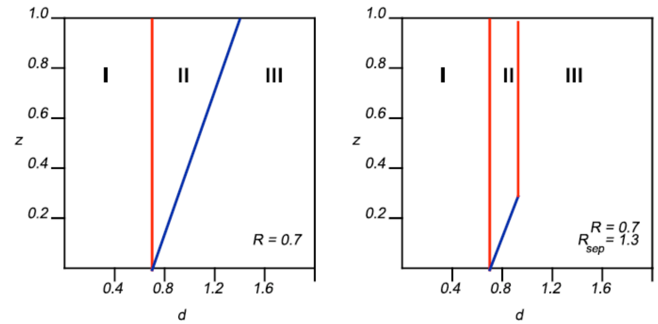
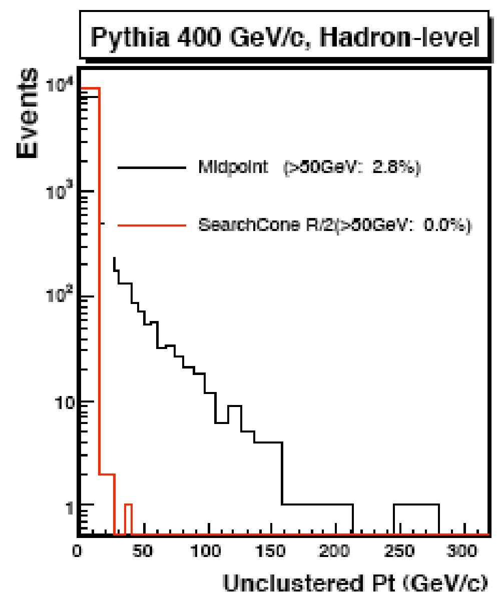


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.



Jets in real life

- Search cone solution
  - use smaller initial search cone (R/2) so that influence of far-away energy not important
  - solution corresponding to smaller parton survives (but not midpoint solution)
  - but some undesireable IR sensitivity effects (~1%)
- Another possibility
  - run standard midpoint algorithm
  - remove all towers located in jets
  - run 2nd pass of midpoint algorithm, cluster into jets
  - either merge in (d,z) plane or use effective value of R_{sep}
  - recommended solution?; see TeV4LHC writeup

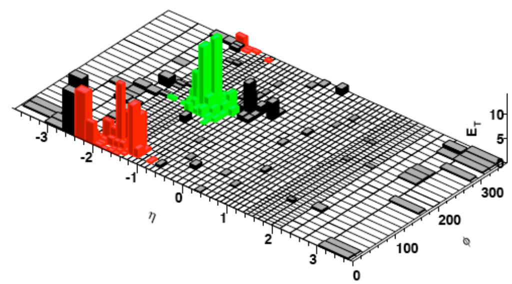


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

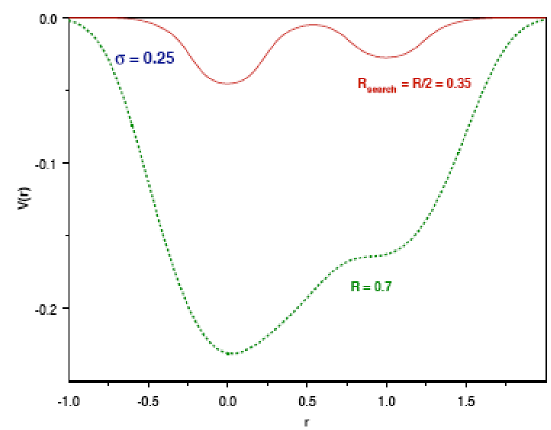
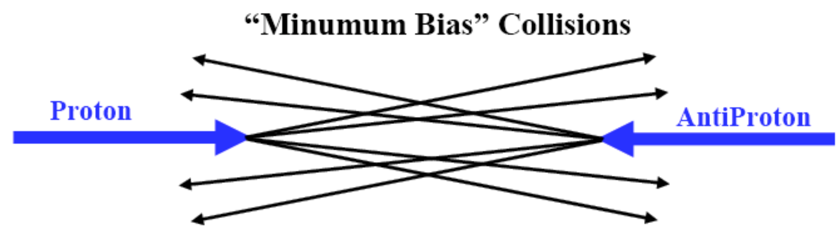
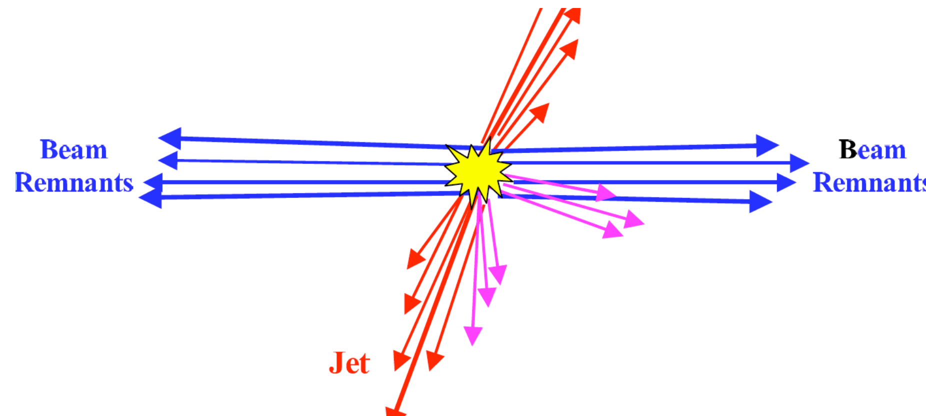


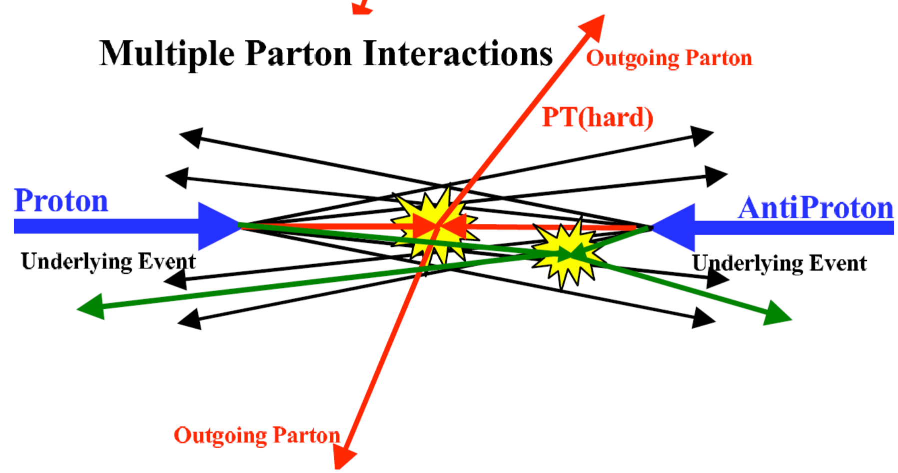
Figure 20. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm and the result of using a smaller initial search cone.

Another complication in real life: the underlying event

- Most proton-(anti)proton collisions are boring, with a peripheral or glancing collision producing a handful of particles with low transverse momentum in the final state
  - so-called minimum bias events
- More interesting are the collisions where there is a hard interaction of a parton from one proton with a parton from the other, for example producing two jets
- Of course, this hard collision takes place on top of the interactions of the other partons in the two hadrons
- This may include the soft beam remnants as well as semi-hard multiple parton interactions
  - which become more important the higher the center-of-mass energy
- The underlying event and pile-up from extra minimum bias events need to be taken into account in most analyses in order to understand the hard scattering

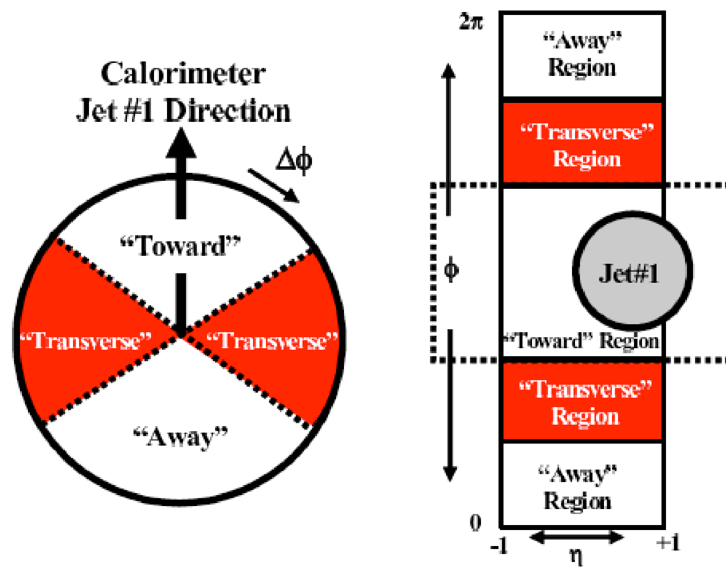


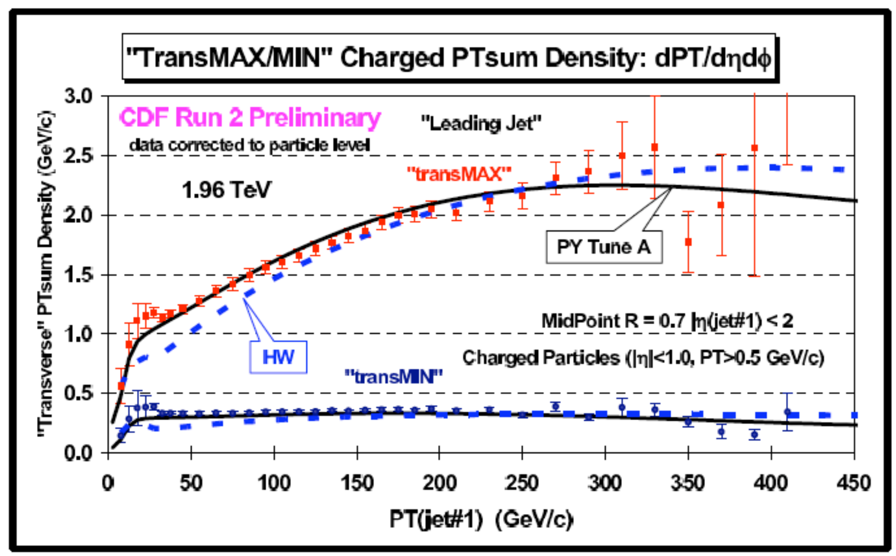




Underlying event at the Tevatron

- Define regions transverse to the leading jet in the event
- Label the one with the most transverse momentum the MAX region and that with the least the MIN region
- The transverse momentum in the MAX region grows as the momentum of the lead jet increases
  - receives contribution from higher order perturbative contributions
- The transverse momentum in the MIN region stays basically flat, at a level consistent with minimum bias events
  - no substantial higher order contributions
- Monte Carlos can be tuned to provide a good description of the data and the appropriate level of underlying event can then be subtracted

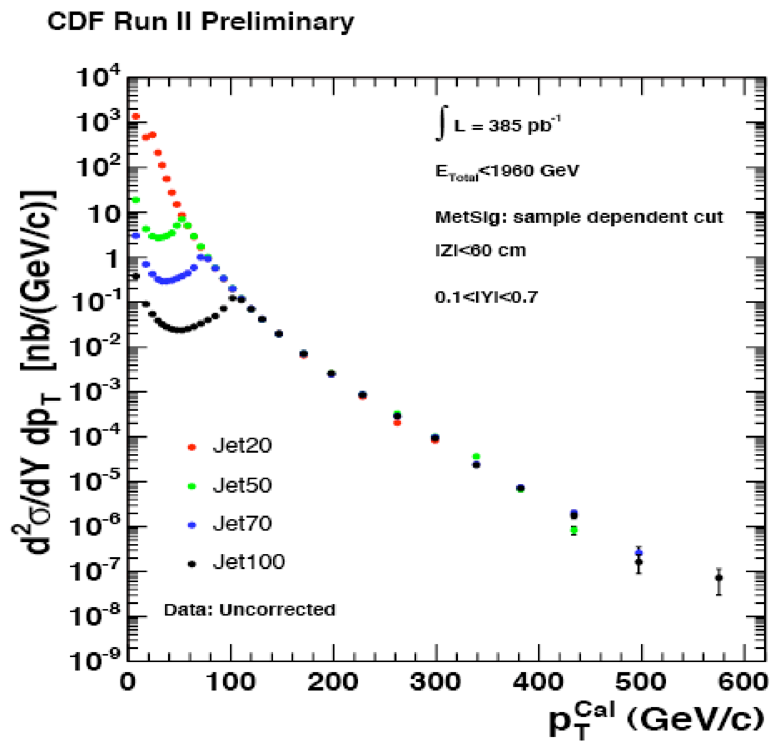




Example: inclusive jet cross section in CDF using midpoint cone algorithm

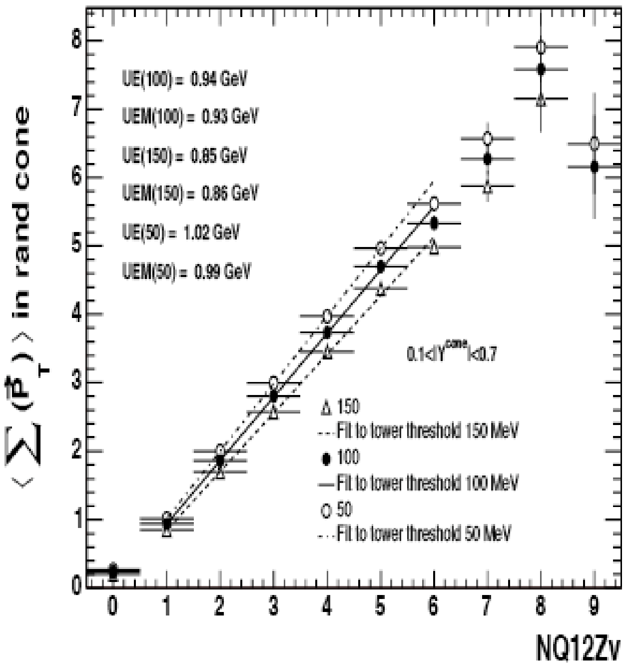
- Collect data from 4 trigger thresholds, Jet20,Jet50,Jet70, Jet100
  - only last is not prescaled
- Piece together (require trigger efficiency to be >0.99) to form inclusive jet cross section from ~60 GeV/c to >600 GeV/c

$$\frac{d^2\sigma}{dY\,dP_T} = \frac{N^{Jets}}{\Delta P_T \Delta Y \int L}$$



Corrections: multiple interactions

Multiple Interactions (Data Based Correction).



* In minimum bias sample, sum the transverse momentum in a random cone (R=0.7) in the rapidity region corresponding to the analysis. (cone size == jet cone size)

* We plot the average momentum in the random cone as a function of vertices in the event.

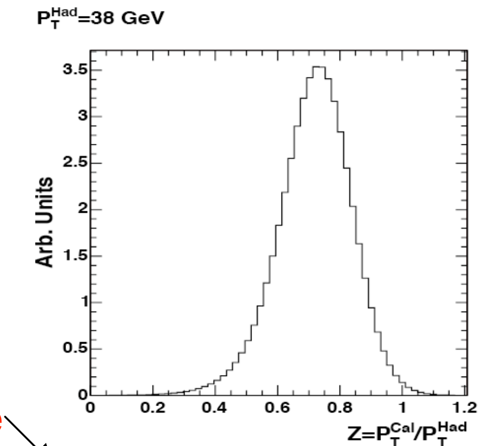
$\rightarrow$ vertices $\propto$ luminosity and characterise the number of interactions per crossing.

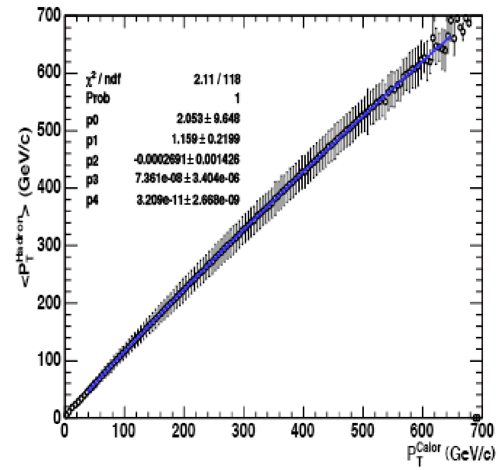
* Correction to each jet:

$$P_T = P_T - ((NQ12Zv - 1) \times 0.93)$$

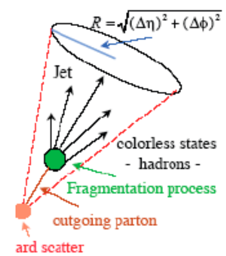
Jet Corrections

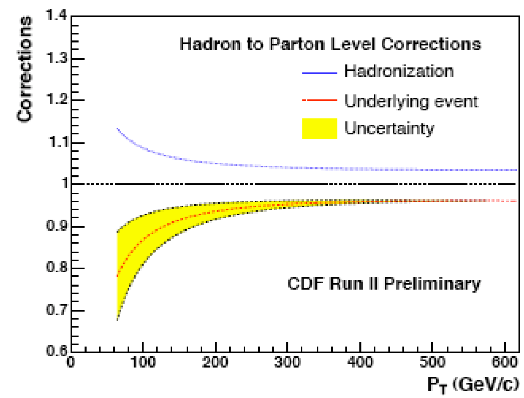
- Need to correct from calorimeter to hadron level (different response of calorimeter to EM and HAD energy)
    - and for resolution effects
- And from hadron to parton level for other observables (such as comparisons to parton level cross sections)
    - underlying event and out-of-cone
        - can correct data to parton level or theory to hadron level…or both and be specific about what the corrections are
    - note that loss due to hadronization is basically constant at 1 GeV/c for all jet p_T values at the Tevatron (for a cone of radius 0.7)
        - for a cone radius of 0.4, the two effects cancel to within a few percent
    - interesting to check over the jet range at the LHC

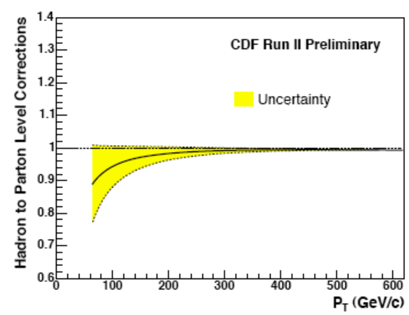




partons in cone give rise to hadrons outside the cone



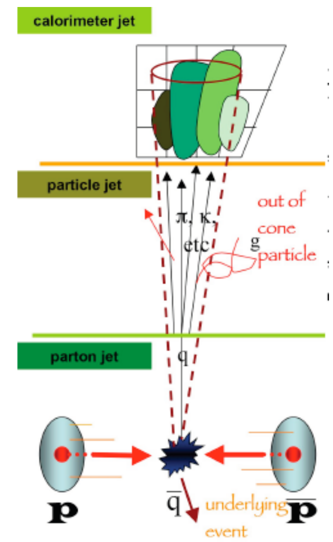


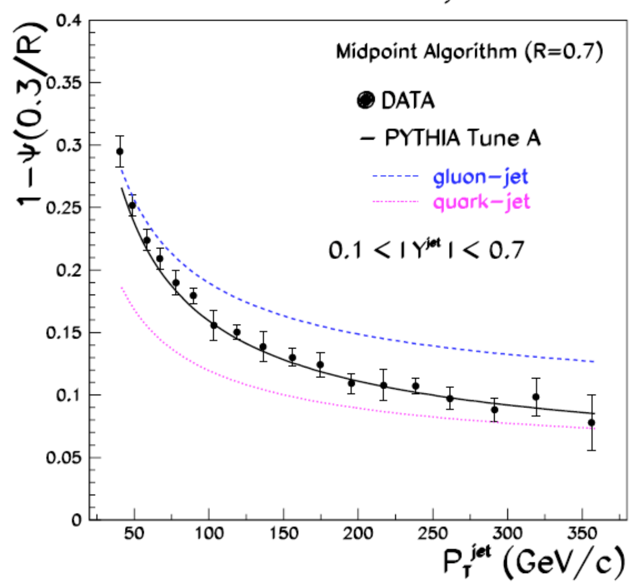


for cone of 0.7, UE correction wins

Aside: jet shape

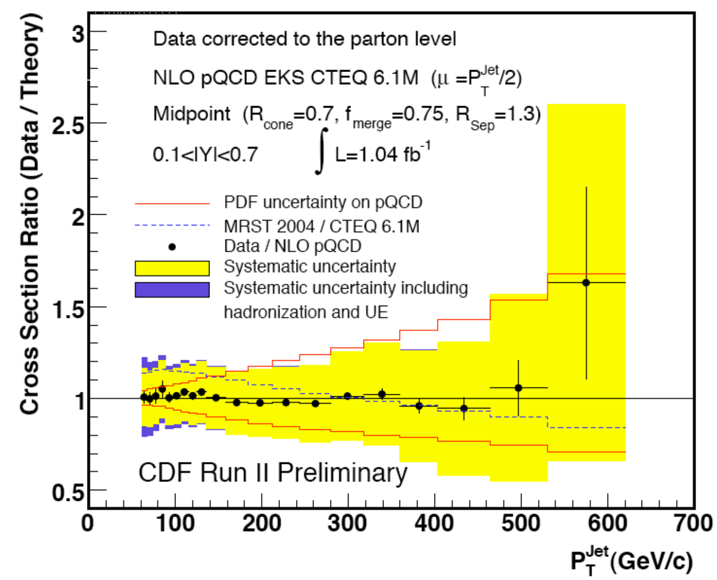
- Why is there a roughly constant amount of energy (1 GeV/c) deposited outside the jet cone due to the non-perturbative hadronization process, independent of jet p_T?
- As the transverse momentum of the jet increases, the jet becomes more collimated, leaving a roughly constant amount of energy near the perimeter of the jet
  - it's the partons near the perimeter that give rise to the resonances (A_1's,ρ's,..) that kick pions out of the cone
  - part of the collimation is due to the increased boost; part to the larger percentage of quark jets

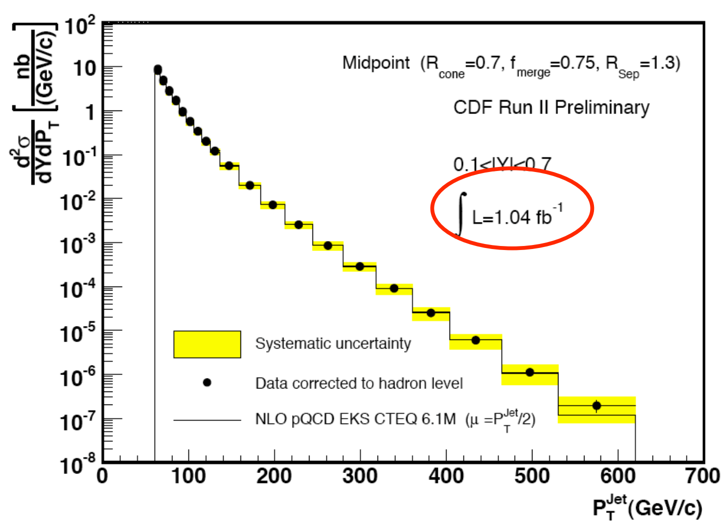


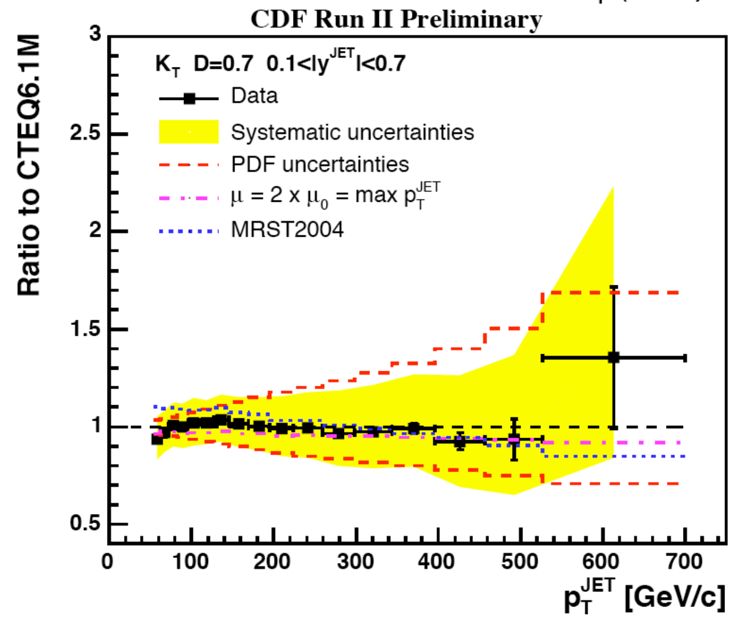


CDF Run 2 results

- CDF Run II result in good agreement with NLO predictions using CTEQ6.1 pdf's
  - enhanced gluon at high x
- …and with results using k_T algorithm
  - the agreement would appear even better if the same scale were used in the theory (k_T uses $p_T^{max}/2$)
- need to have the capability of using different algorithms in analyses as cross-checks







Systematic uncertainties

*Jet Energy Scale: Uncertainty on Jet energy: $\leq 3\%$.

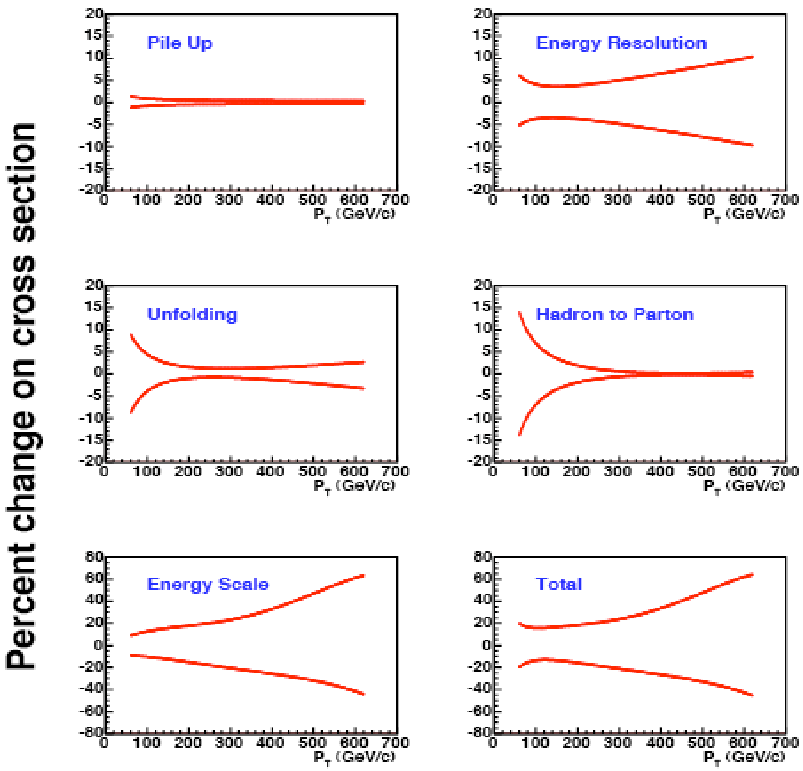
*Unfolding: Herwig vs Pythia, different fragmentation/spectrum models

*Pile-up: 30% covers luminosity dependence, changes in tower threshold and measurement made in other samples (not significant when pile-up is small)

*Resolution: 8%: deviation in jet resolution between Data and Pythia (measured using bisector method).

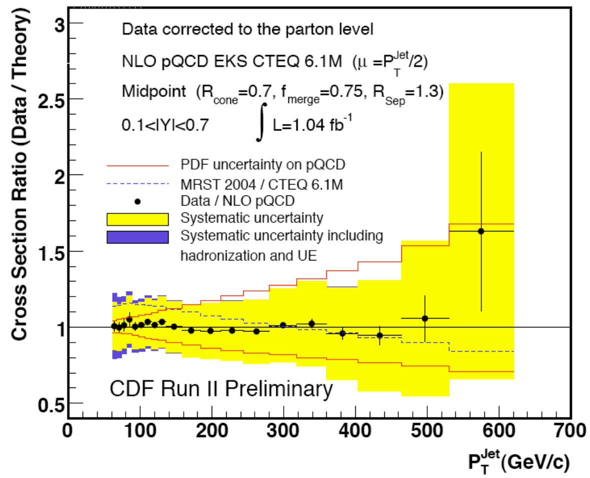
*Luminosity: 6% uncertainty has no shape$\rightarrow$ normalisation (not included in systematic band in final plots)

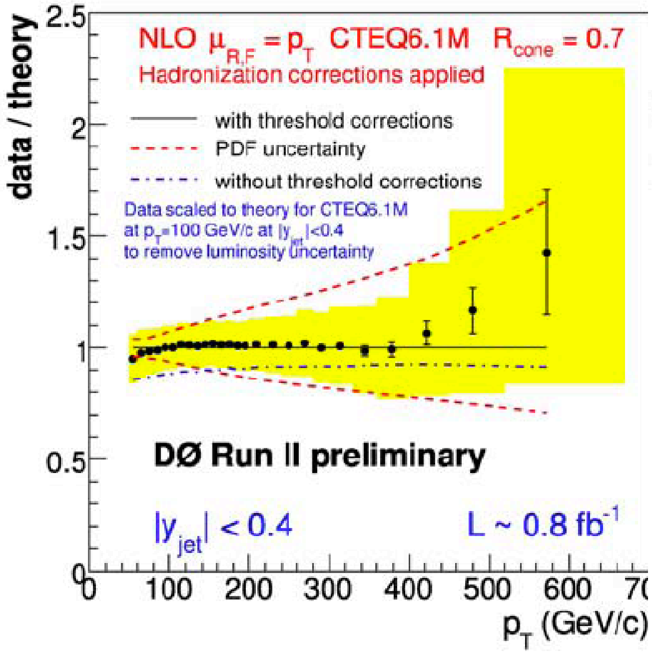
*Hadron to Parton: Use difference between Pythia and Herwig hadron to parton corrections, this comes almost exclusively from the underlying event component $\sim 10\%$ only effects low p_T region.

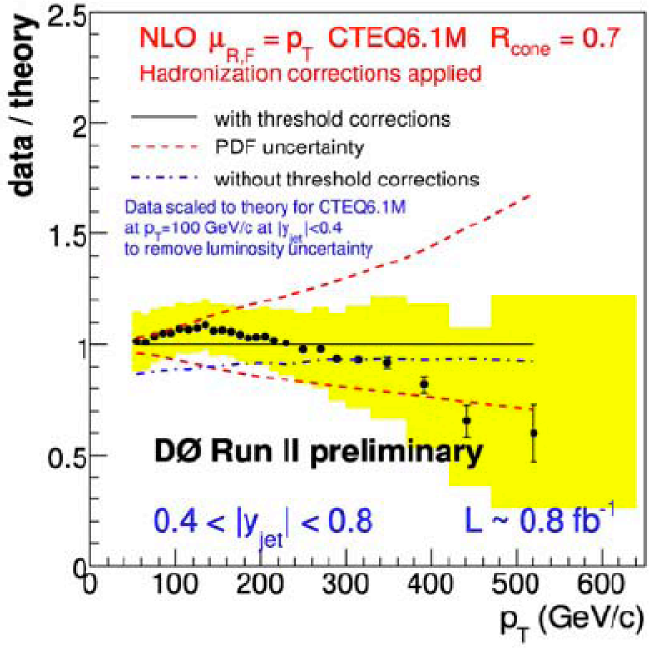


D0 Run 2 results

- Preliminary D0 results qualitatively similar to CDF
  - more detailed comparisons can be made later when results are finalized

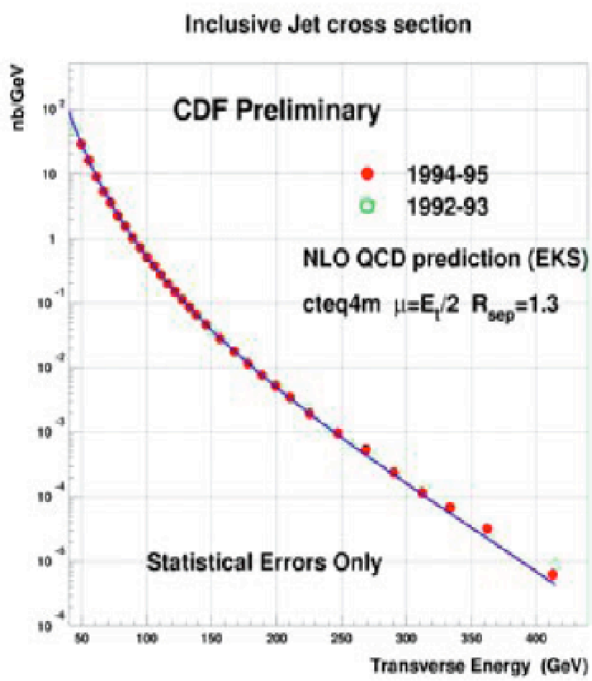


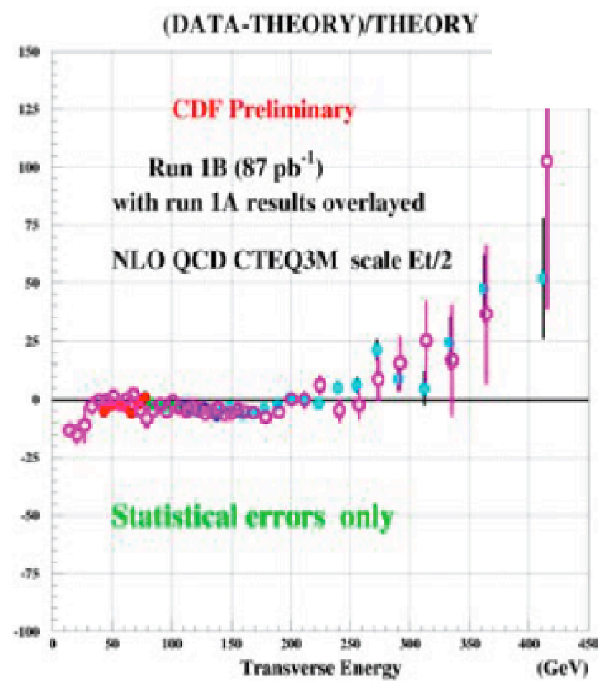


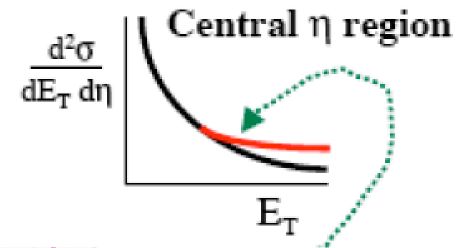


Historical interlude

An excess at high E_T was observed by CDF in Run 1 when comparing to NLO predictions using the topical pdf's



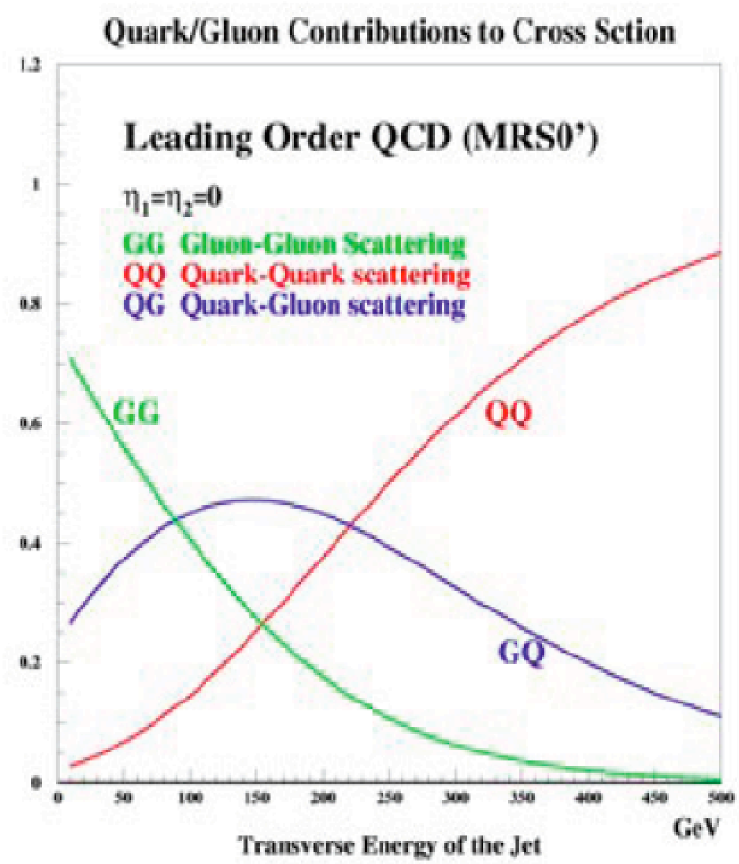


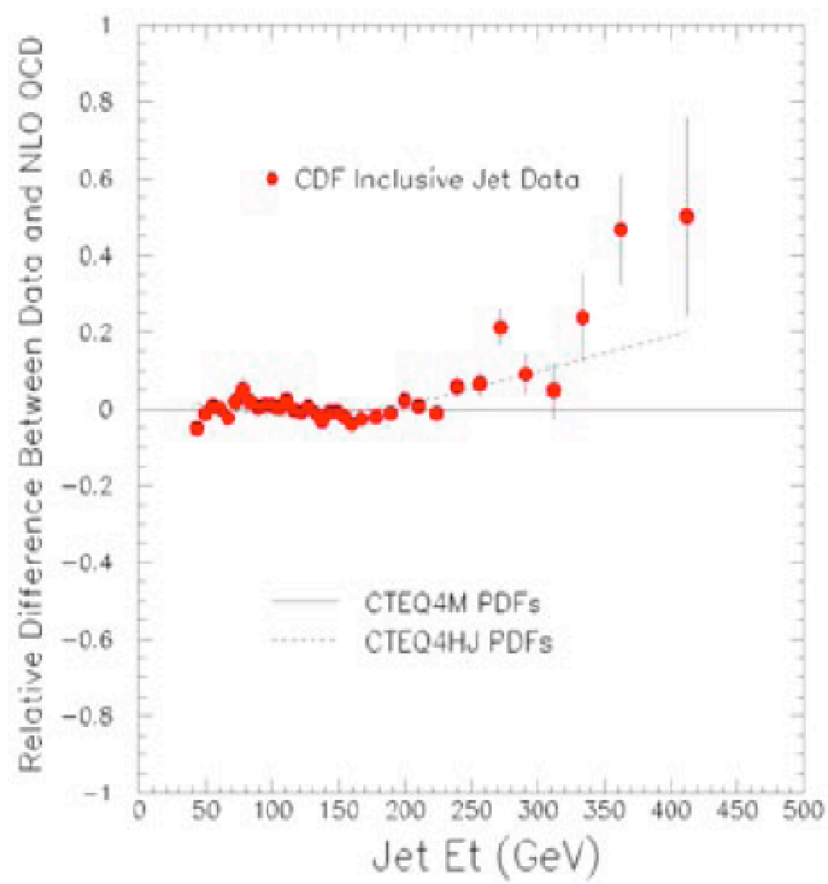


Rutherford scattering all over again

New physics or just old?

Modify the gluon distribution at high x



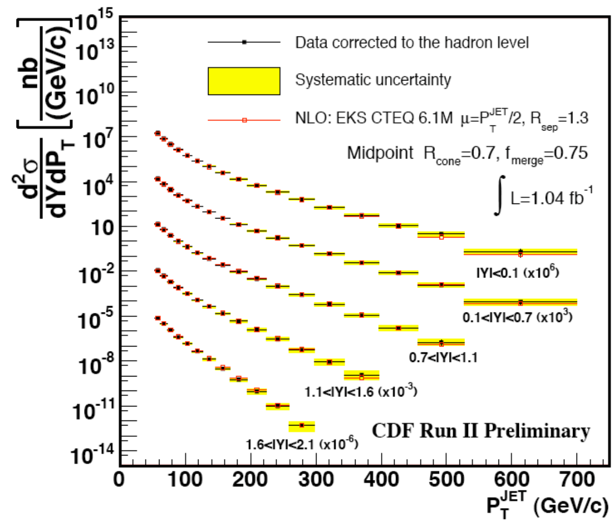


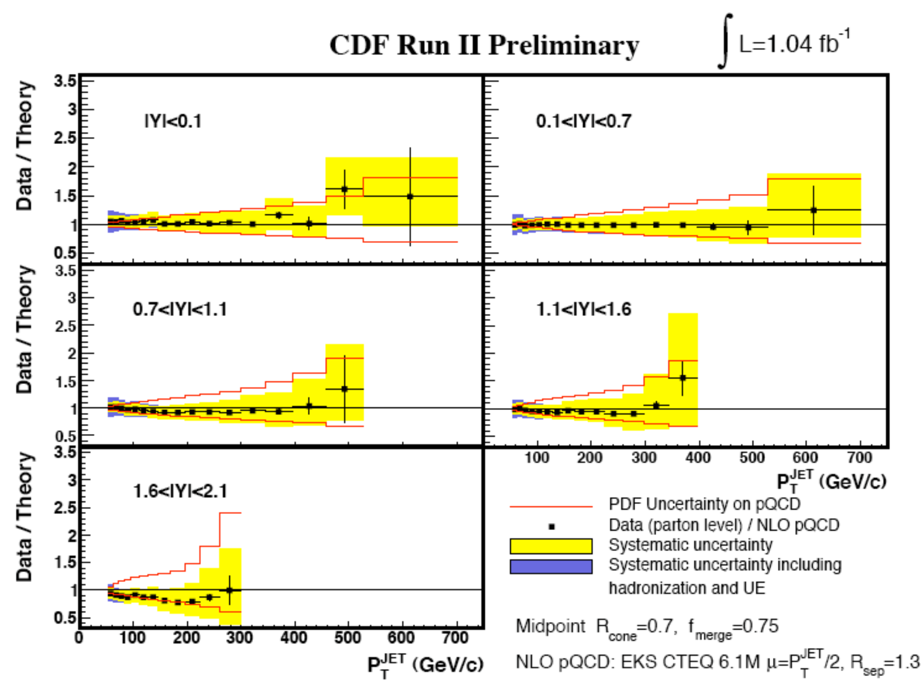
Which is now the accepted explanation

…and has effectively been incorporated into modern pdf's such as CTEQ6.1

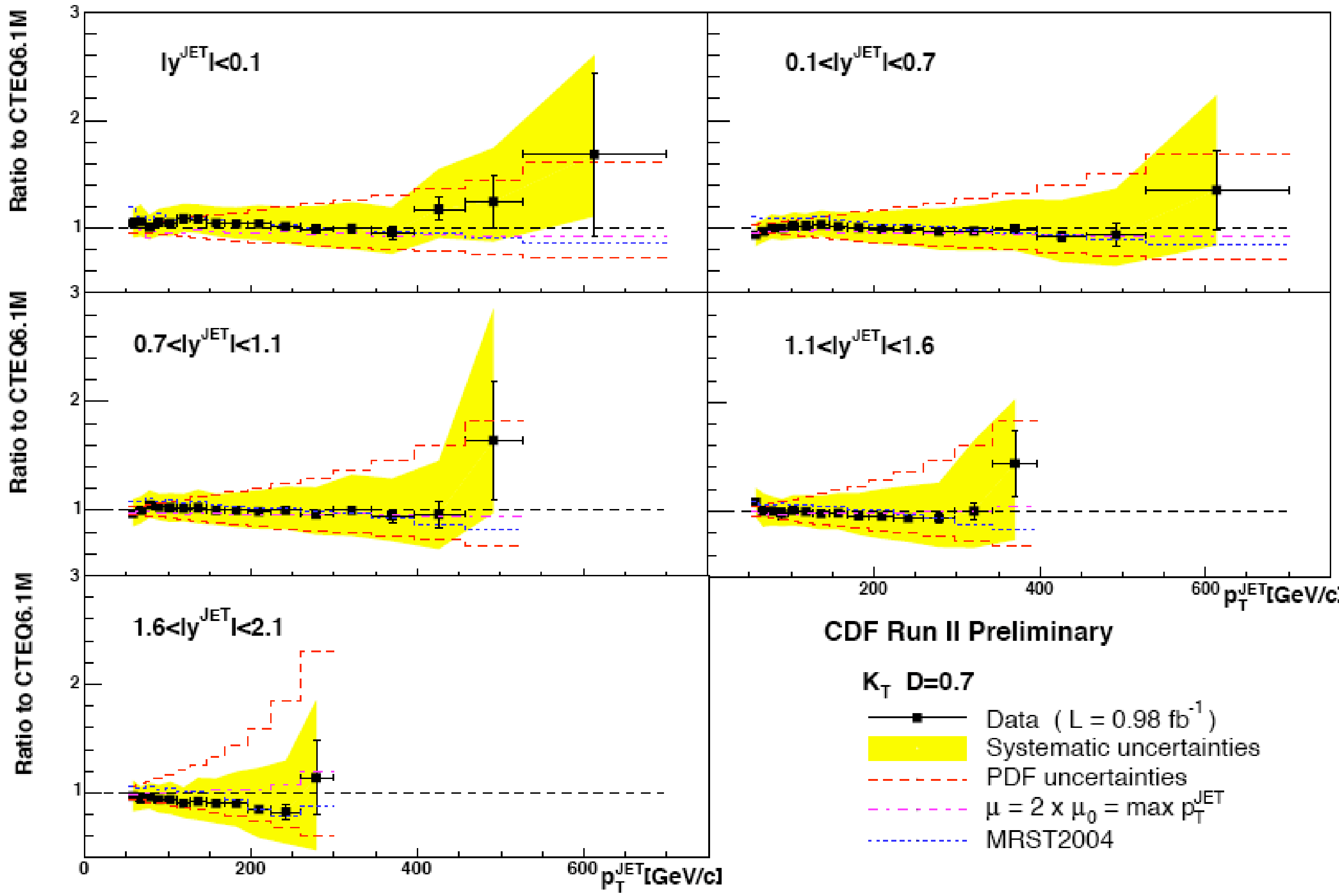
More CDF Run 2 cone results

- Precise results over a wide rapidity range
  - new physics will be central; a pdf explanation is universal over rapidity
  - in Run 1, it was the D0 measurement of the jet cross section over a wide rapidity range that led to the understanding of the high x gluon
- Good agreement with CTEQ6.1 predictions using CDF midpoint algorithm
- PDF uncertainties are on the same order or less than systematic errors
- Should reduce uncertainties for next round of CTEQ fits
  - so long to eigenvector 15?





Forward jets with the k_T algorithm



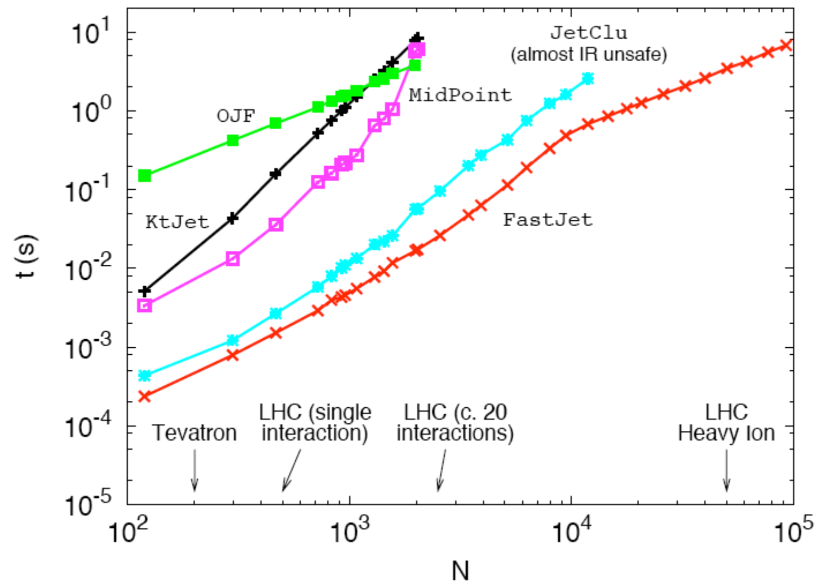
Note that for D=R, k_T jet cross section is no longer < cone jet cross section

k_T algorithm tends to reach out and grab hadrons that "splash-out" with cone algorithm

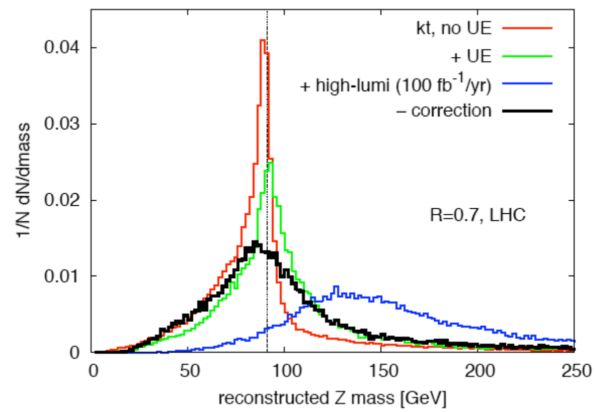
Need to go lower in p_T for comparisons of the two algorithms, apply k_T to other analyses

New k_T algorithm

- k_T algorithms are typically slow because speed goes as $O(N^3)$, where N is the number of inputs (towers, particles,…)
- Cacciari and Salam (hep-ph/0512210) have shown that complexity can be reduced and speed increased to O(N) by using information relating to geometric nearest neighbors
  - i.e. towers, particles that are nearby in momentum space also tend to be nearby in coordinate space
  - should be useful for LHC
- Optimum is if analyses at LHC (and Tevatron) use **both** cone and k_T algorithms for jet-finding



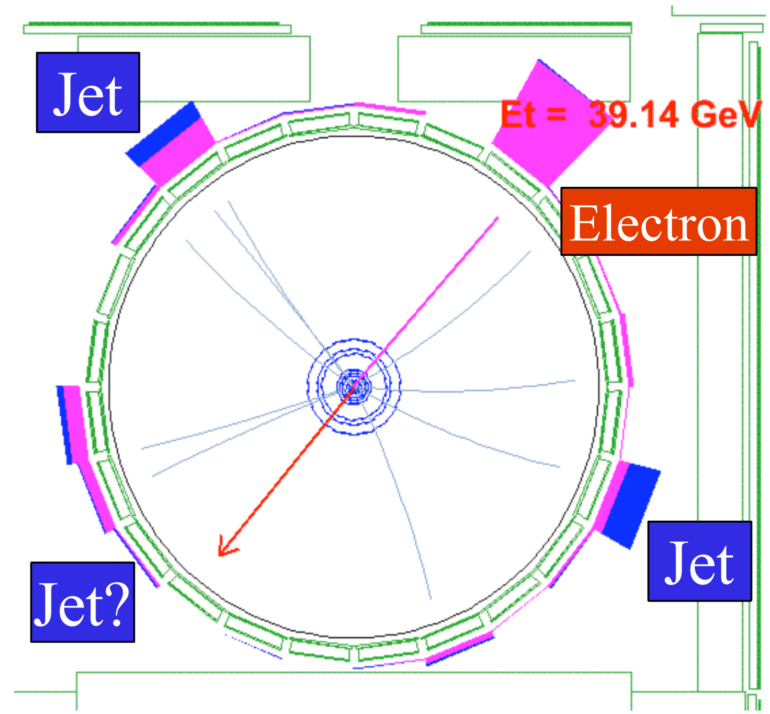
Try reconstructing M_Z from $Z \to 2$ jets, with subtraction of UE/MB



Some loss in resolution, but good value for the Z mass

W + jets at the Tevatron

- Interesting for tests of perturbative QCD formalisms
  - matrix element calculations
  - parton showers
  - …or both
- Backgrounds to tT production and other potential new physics
- Define W->eν
  - high p_T track, large EM shower deposition, E/p near 1, lateral shower profile consistent with electron, electron candidate is relatively isolated, plus subtantial missing transverse energy
  - define jet using a cone algorithm with a radius of 0.4
    - use smaller cone size for events that may be complicated

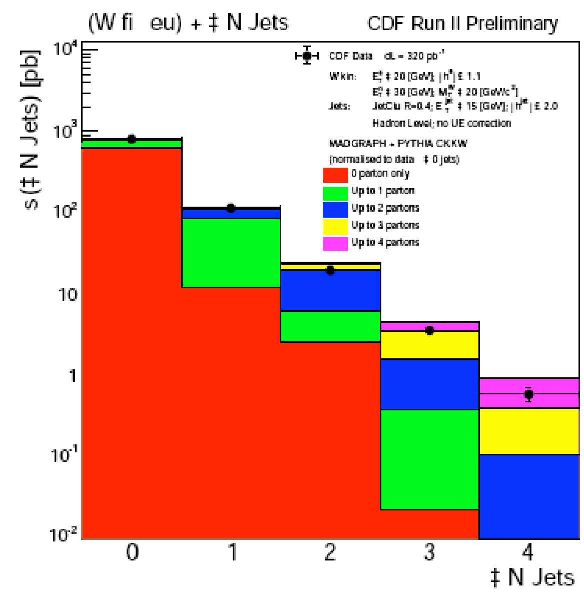


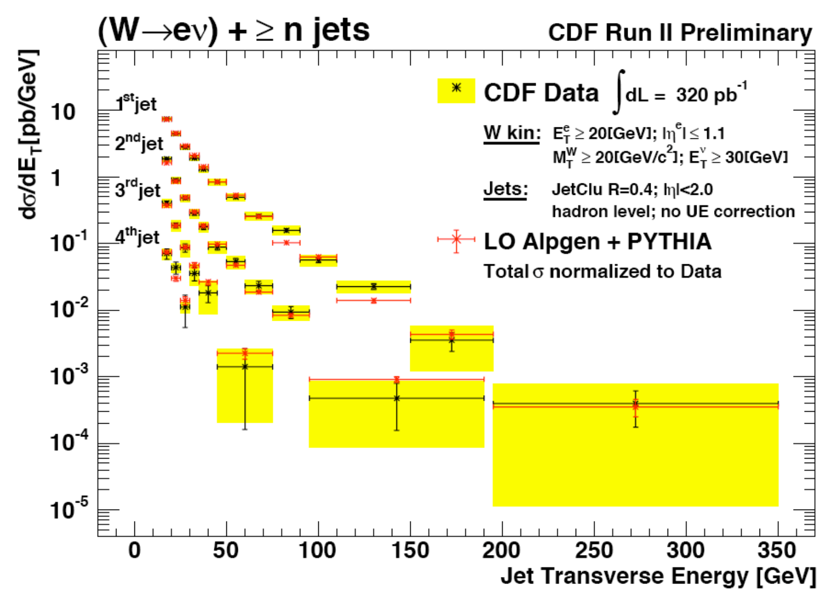
W + jets at the Tevatron

- Interesting for tests of perturbative QCD formalisms
  - matrix element calculations
  - parton showers
  - …or both
- Backgrounds to tT production and other potential new physics
- Observe up to 7 jets at the Tevatron
- Results from Tevatron to the right are in **a form that can be easily compared to theoretical predictions, corrected to hadron level**
  - see www-cdf.fnal.gov QCD webpages
  - *remember for a cone of 0.4, hadron level ~ parton level*

note emission of each jet suppressed by ~factor of α_s

parton shower can produce 1 or 2 extra jets but not more





CKKW

- CKKW procedure combines best of exact (LO) matrix element and parton shower description of multijet events
- Currently implemented in Sherpa Monte Carlo and approximately implemented in ALPGEN (mlm procedure)
- ME-PS matching scheme: vetos events at the PS stage that infringe on the phase space already covered by ME
- W+n parton samples can then be combined without double counting

See Tjorborn's lectures for more detail

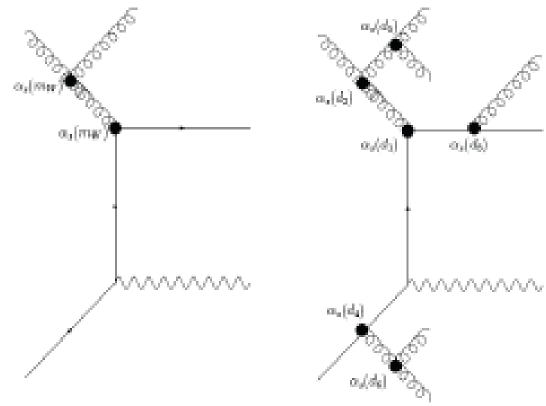
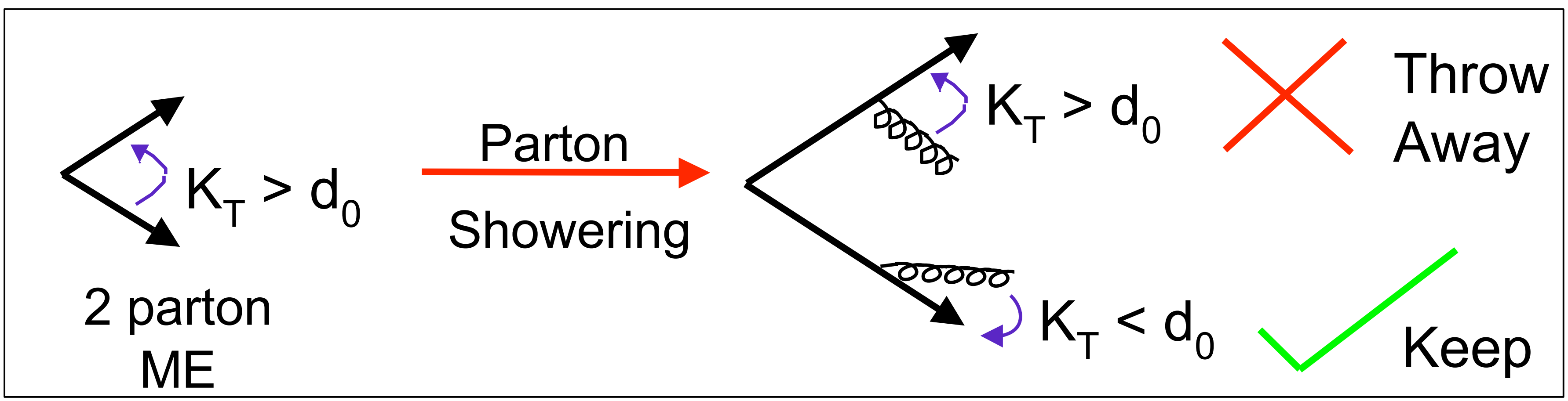
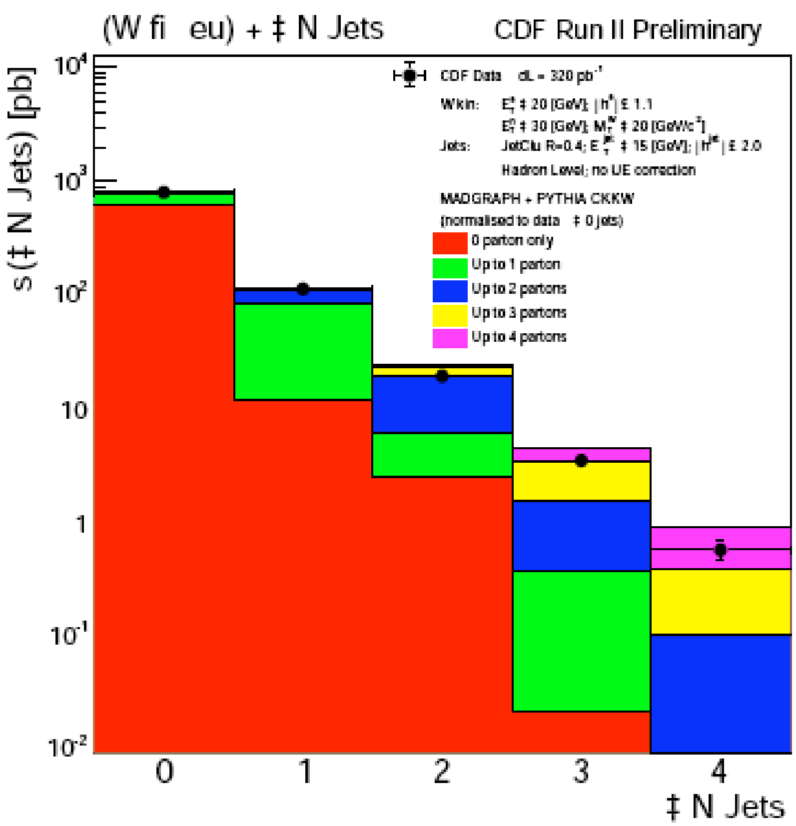


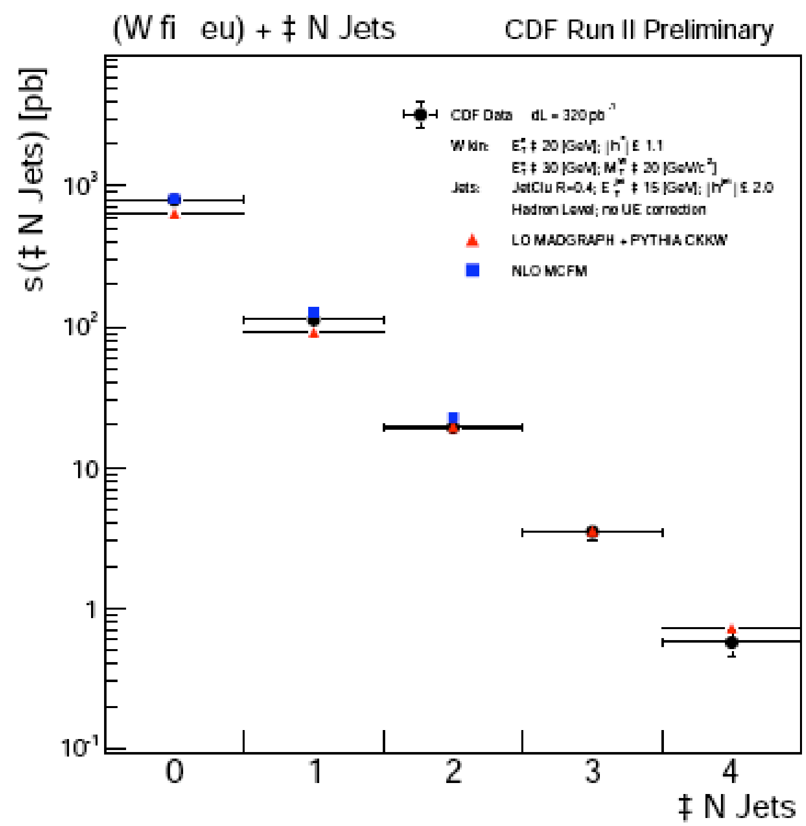
Figure 15. In the NLO formalism, the same scale, proportional to the hardness of the process, is used for each QCD vertex. For the case of the $W+$ 2 jet diagram shown above to the left, a scale related to the mass of the W boson, or to the average transverse momentum of the produced jets, is typically used. The figure to the right shows the results of a simulation using the CKKW formalism. Branchings occur at the vertices with resolution parameters d_i, where $d_1 > d_2 > d_3 > d_4 > d_5 > d_6$ Branchings at the vertices 1-3 are produced with matrix element information while the branchings at vertices 4-6 are produced by the parton shower.



W + jets at the Tevatron

N jet multiplicity: compared on the left to a combined matrix element + parton shower description using the CKKW formalism for matching, and on the right to the CKKW and NLO predictions





Pop quiz

- What's the difference between the diagrams on the top and bottom?

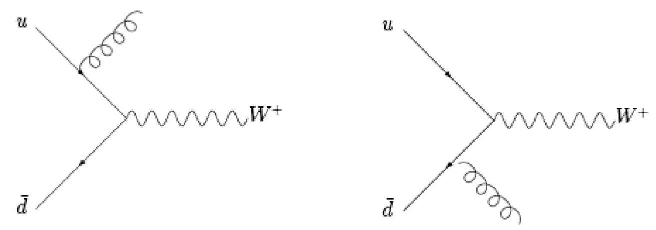


Figure 1. Lowest order diagrams for the production of a W and one jet at hadron colliders.

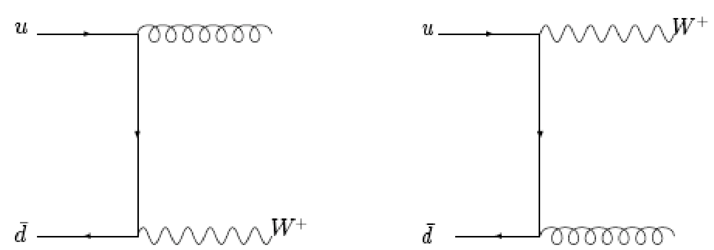
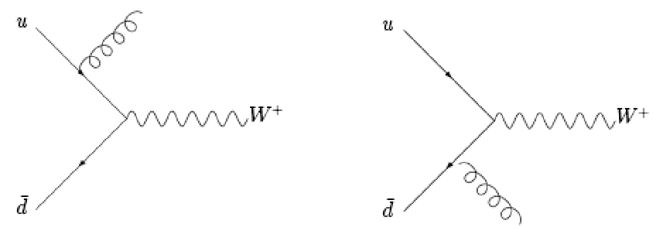


Figure 3. An alternative way of drawing the diagrams of Figure 1.

Pop quiz

- What's the difference between the diagrams on the top and bottom?
- Possible answers:
  a) the top is initial state radiation, the bottom are 2->2 processes



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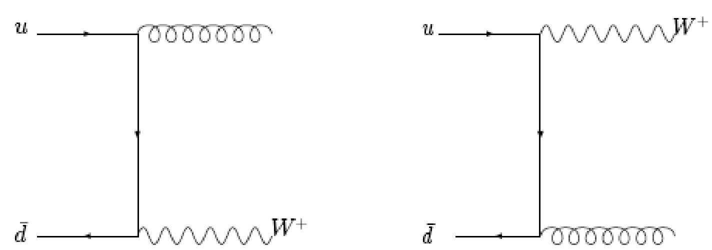
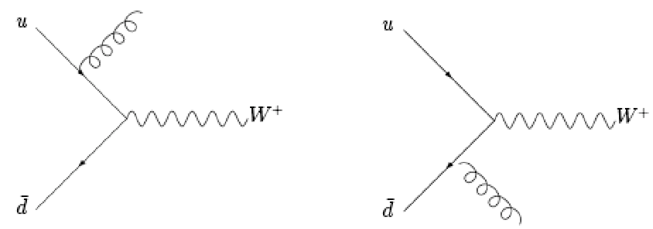


Figure 3. An alternative way of drawing the diagrams of Figure 1.

Pop quiz

- What's the difference between the diagrams on the top and bottom?
- Possible answers:
  a) the top is initial state radiation, the bottom are 2->2 processes
  b) nothing, they both represent the same physics



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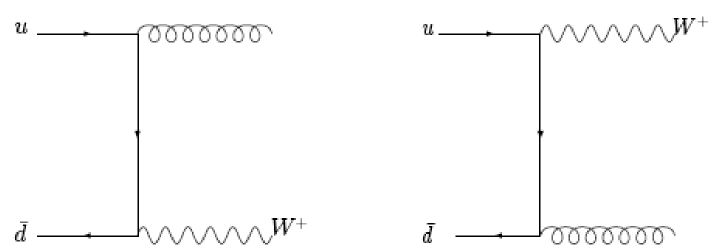
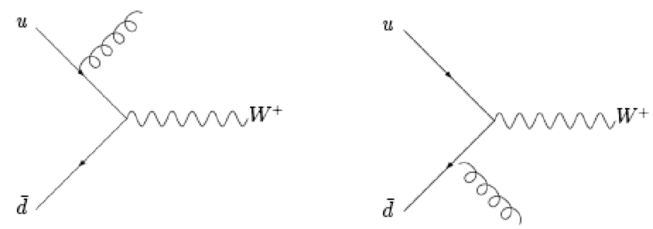


Figure 3. An alternative way of drawing the diagrams of Figure 1.

Pop quiz

- What's the difference between the diagrams on the top and bottom?
- Possible answers:
  a) the top is initial state radiation, the bottom are 2->2 processes
  b) nothing, they both represent the same physics
  c) quiz, no one said anything about a quiz



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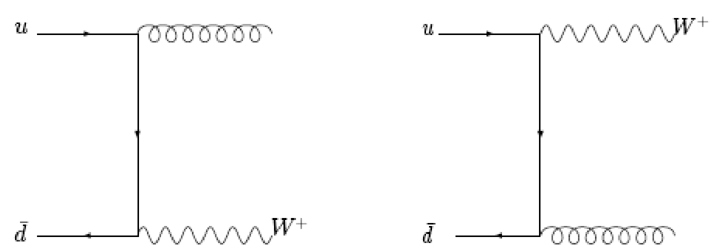

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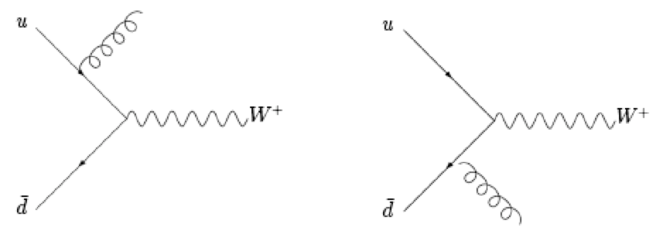

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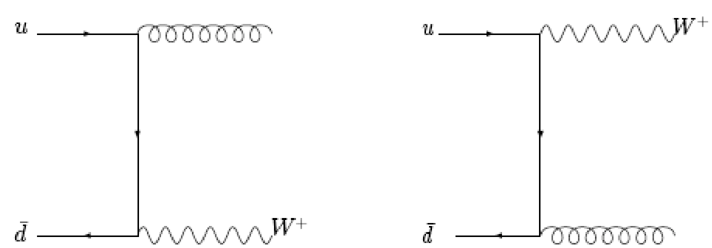

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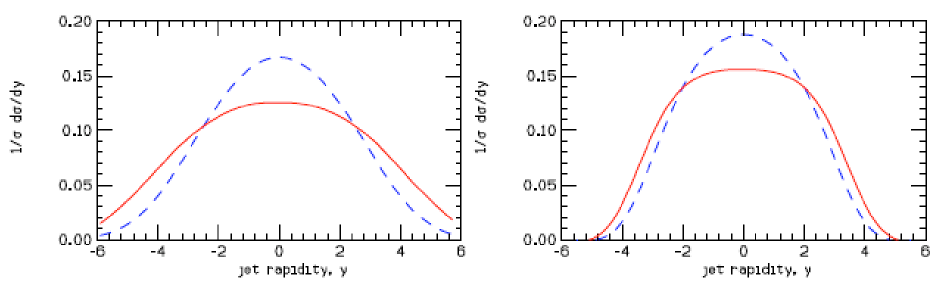
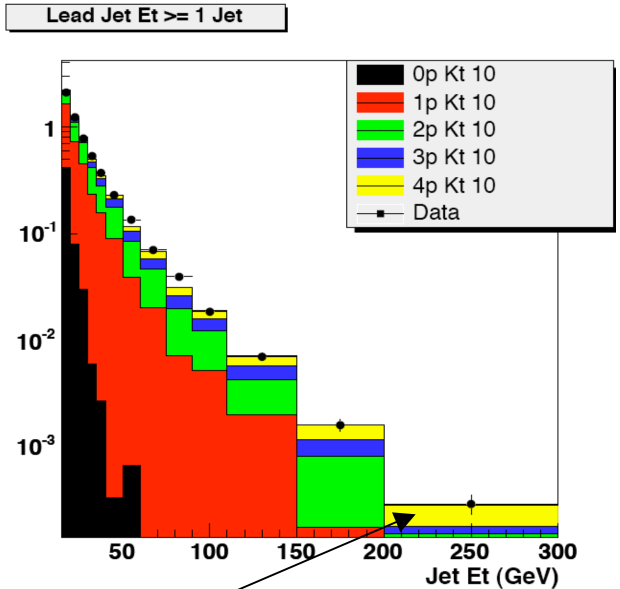


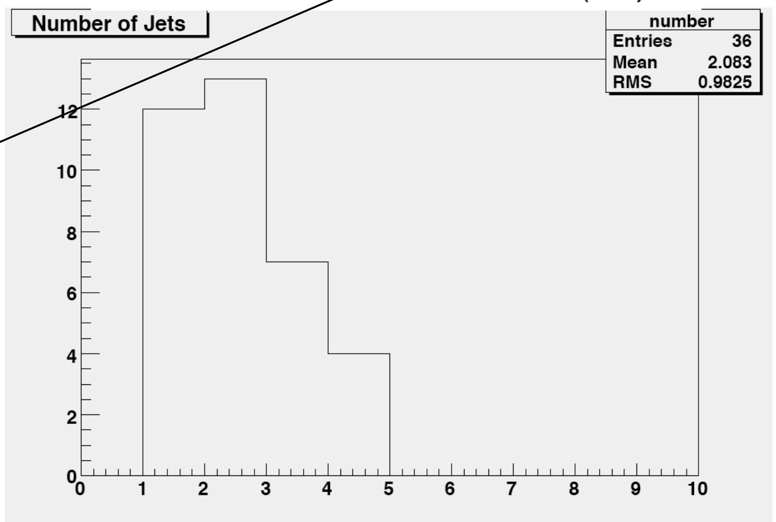
Figure 2. The rapidity distribution of the additional parton found in the real radiation corrections to Drell-Yan production of a W at the LHC. The parton is required to have a p_T larger than 2 GeV (left) or 50 GeV(right). Contributions from $q\bar{q}$ annihilation (solid red line) and the qg process (dashed blue line) are shown separately.

Myth: ISR is peaked in the forward direction. Not if you bin by p_T.

(Thou shalt) Listen to the logs[1]

- Look at W + >= 1 jet events and require the lead jet to have >200 GeV/c transverse energy
- What is the average jet multiplicity (>15 GeV/c) for these events?
  - 2.1
- It's not just α_s anymore; there's now also a large log (E_T^{jet1}/15 GeV/c) involved
  - in CKKW formalism, most of cross section for bin created by W + 4 parton matrix element
  - or another way of saying it is that there's a Sudakov suppression for any events that don't emit such additional hard gluons

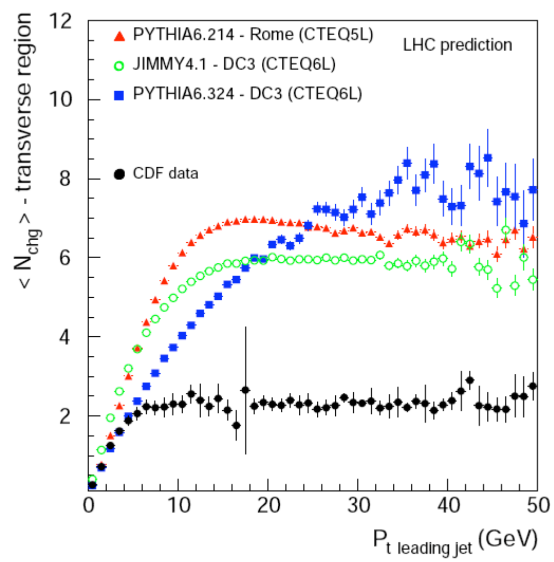


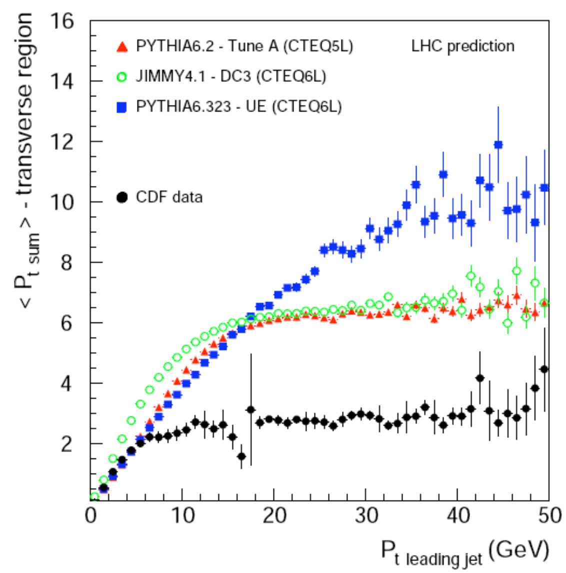


[1] an 11th commandment

Looking forward to the LHC: underlying event

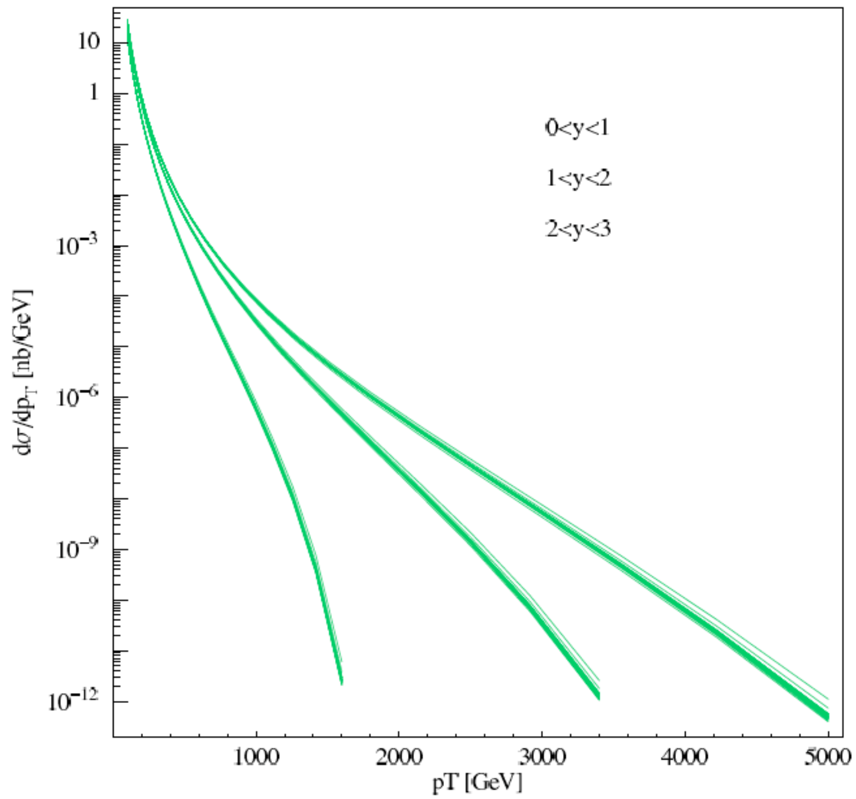
- We can project the size of the underlying event for the LHC
- There's a great deal of uncertainty regarding the level of underlying event at 14 TeV, but it's clear that the UE is larger at the LHC than at the Tevatron
  - and will be harder (more mini-jets from multiple parton scattering)
  - thus, some jets will in the event will come from the underlying event and may be forced to use a higher jet p_T threshold in analyses
- Should be able to establish reasonably well with the first collisions in 2008





Predictions for LHC

These are predictions for ATLAS based on the CTEQ6.1 central pdf and the 40 error pdf's using the midpoint jet algorithm.



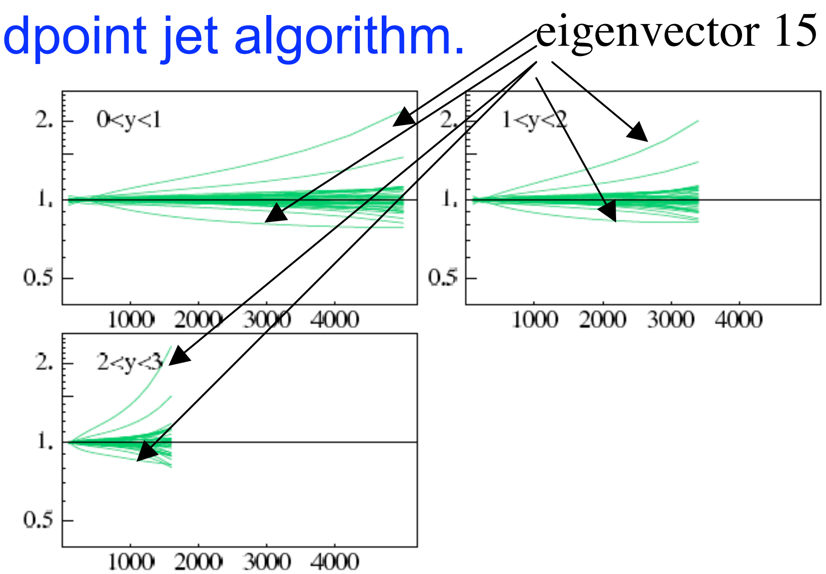


FIG. 31: The uncertainty range of the inclusive jet cross section at the LHC. The curves are graphs of the ratios of the cross sections for the 40 eigenvector basis sets compared to the central (CTEQ6.1M) prediction (ordinate) versus p_T in GeV (ordinate).

Need to have jet measurements over full rapidity range and good control over rapidity variations of jet systematics.

Predictions for LHC:K-factors

These are predictions for ATLAS based on the CTEQ6.1 central pdf and the 40 error pdf's using the midpoint jet algorithm.

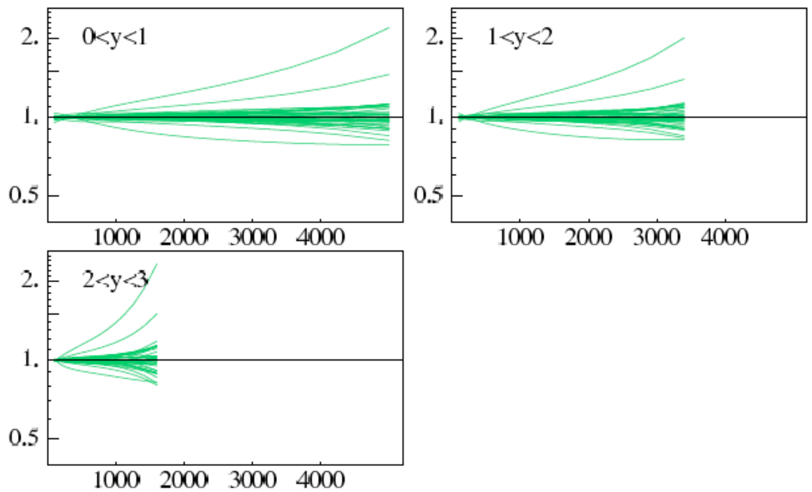


FIG. 31: The uncertainty range of the inclusive jet cross section at the LHC. The curves are graphs of the ratios of the cross sections for the 40 eigenvector basis sets compared to the central (CTEQ6.1M) prediction (ordinate) versus p_T in GeV (ordinate).

K-factor = NLO/LO

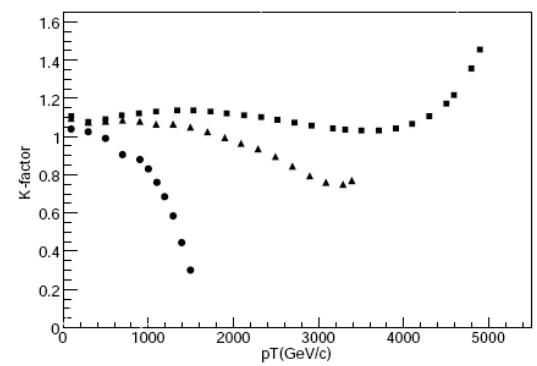
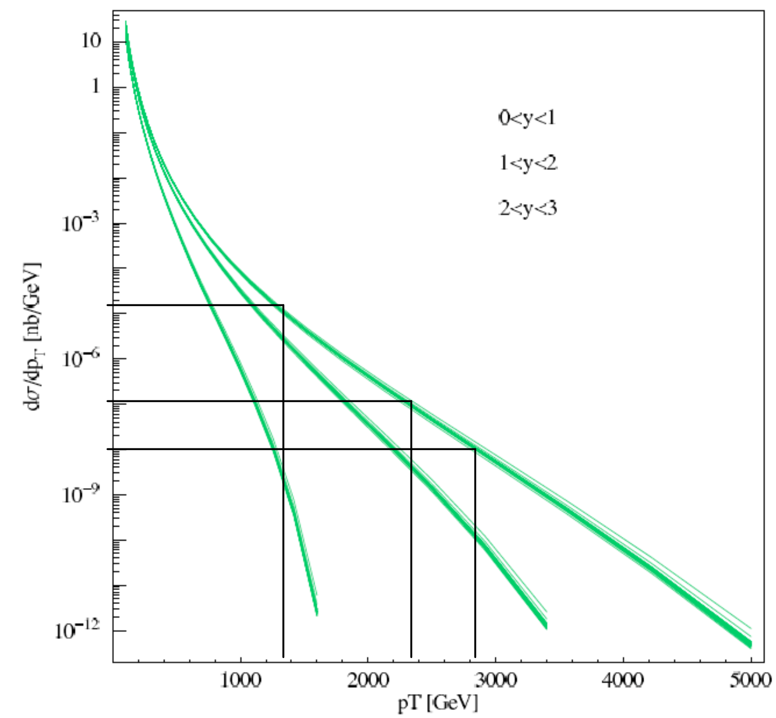


Figure 93. The ratios of the NLO to LO jet cross section predictions for the LHC using the CTEQ6.1 pdf's for the three different rapidity regions (0–1 (squares), 1–2 (triangles), 2–3 (circles)).

Statistical reach

- Reach is ~
  - 1.4 TeV/c for 100 pb^{-1}
    - basically no constraints on pdf's
  - 2.4 TeV/c for 10 fb^{-1}
  - 2.8 TeV/c for 100 fb^{-1}
- For sensitive to compositeness scales of~
  - 4-5 TeV/c
  - 10-13 TeV/c
  - 13-16 TeV/c



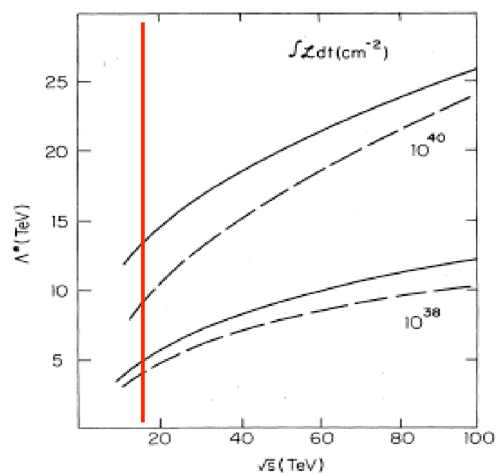
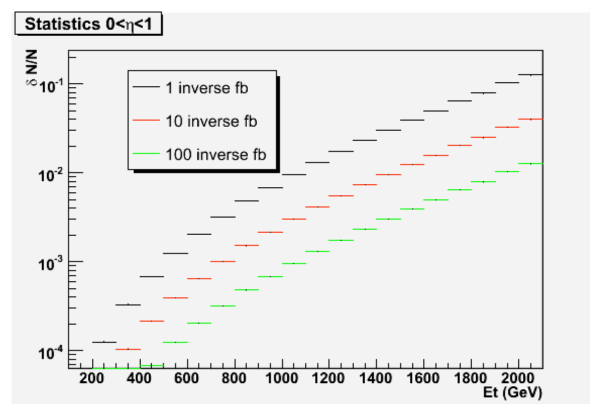
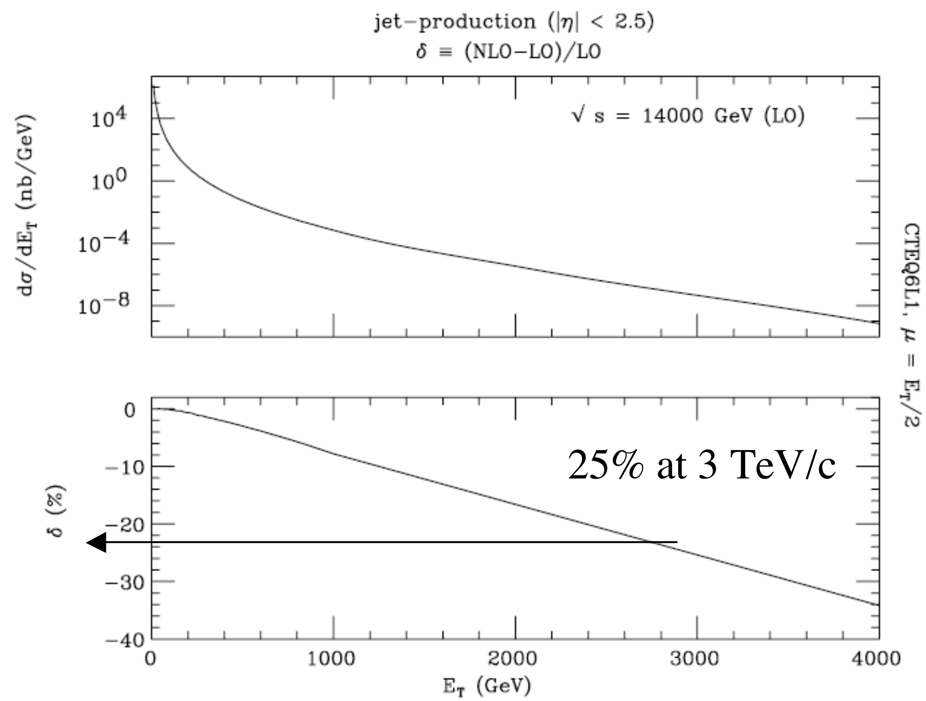


FIG. 236. Maximum compositeness scale Λ^* probed in jet production at $y=0$ in pp collisions as a function of $\sqrt{s}$ for integrated luminosities of 10^{40} and 10^{38} cm^{-2} according to the criterion (8.18). $\eta_0=-1$ (solid lines), $\eta_0=+1$ (dashed lines).



Example: *Unexpected* new SM physics

- In a recent paper (hep-ph/0503152), Stefano Moretti and Douglas Ross have shown large 1-loop weak corrections to the inclusive jet cross section at the LHC
- Effect goes as $\alpha_W \log^2(E_T^2/M_Z^2)$
  - at the LHC, this log can get large
  - no cancellation with real W emission since W is massive and phase space is restricted
- Confirmation is important
- Other (unsuspected) areas where weak corrections are important?

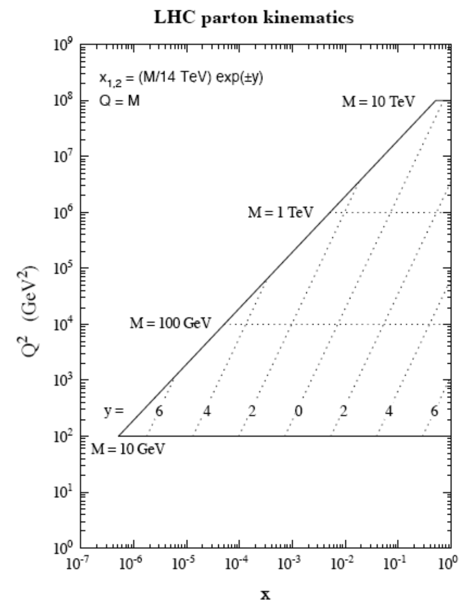


In *Rumsfeldese*, this is now one of the "known unknowns".

What are our unknown unknowns?

Parton kinematics at the LHC

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity
- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC



$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\,[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)]\ . \tag{1}$$

The prefactor with the Kronecker delta avoids double-counting in case the partons are identical. The generic parton-model formula

$$\sigma = \sum_{i,j}\int_0^1 dx_1\,dx_2\,f_i(x_1,\mu)\,f_j(x_2,\mu)\,\hat{\sigma}_{ij} \tag{2}$$

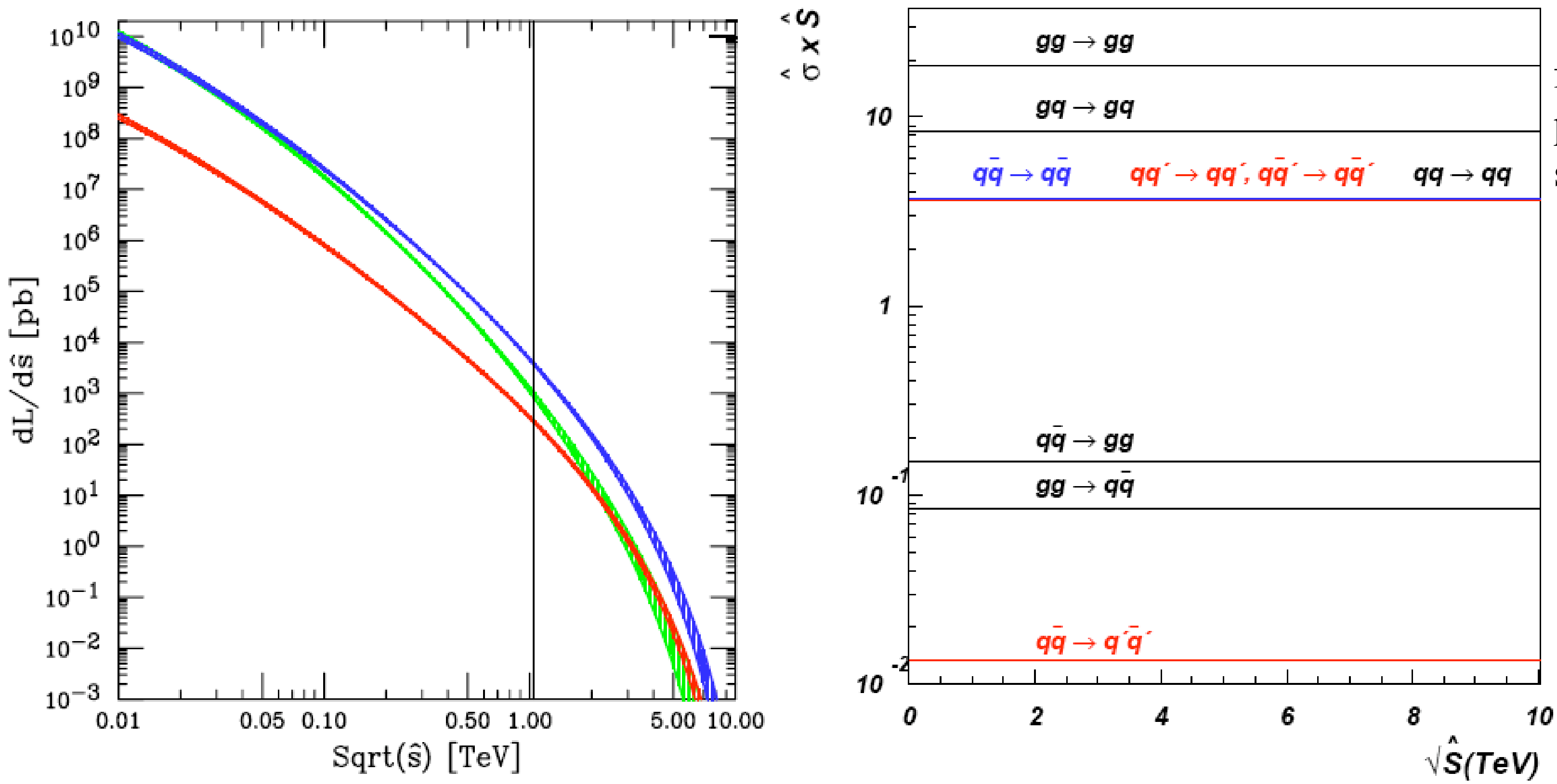
can then be written as

$$\sigma = \sum_{i,j}\int\left(\frac{d\hat{s}}{\hat{s}}\,dy\right)\left(\frac{dL_{ij}}{d\hat{s}\,dy}\right)(\hat{s}\,\hat{\sigma}_{ij})\ . \tag{3}$$

Cross section estimates

$$\sigma = \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\,\hat{\sigma}_{ij})$$

for the gluon pair production rate for $\hat{s}$=1 TeV and $\Delta\hat{s} = 0.01\hat{s}$, we have $\frac{dL_{gg}}{d\hat{s}} \simeq 10^3$ pb and $\hat{s}\,\hat{\sigma}_{gg} \simeq 20$ leading to $\sigma \simeq 200$ pb



for p_T=0.1* sqrt(s-hat)

Fig. 2: Left: luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

Luminosities as a function of y

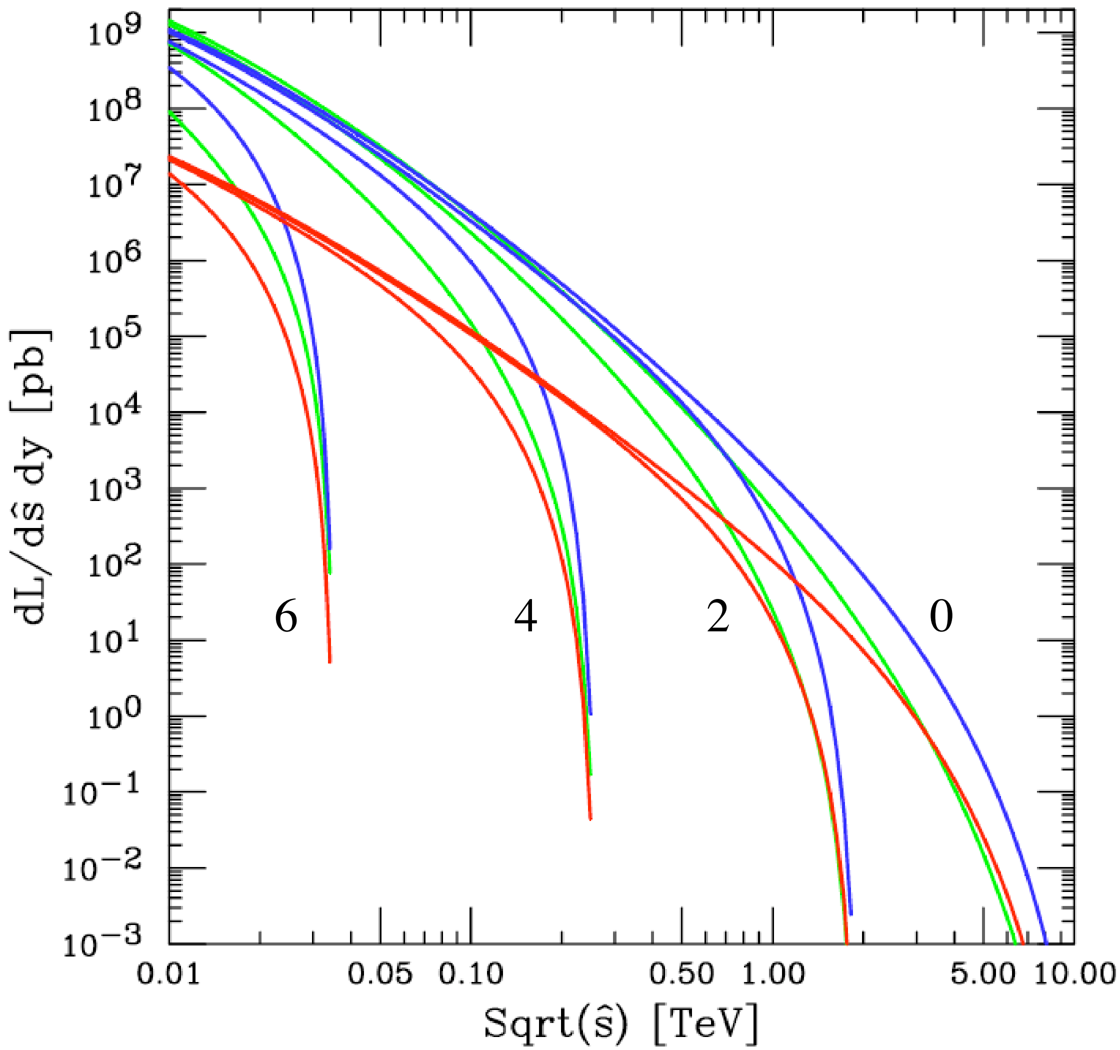


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (chargino pair production) have small enchancements
- Most backgrounds have gg or gq initial states and thus large enhancement factors (500 for W + 4 jets for example, which is primarily gq) at the LHC
- Luckily tT has a gg initial state as well as qQ so total enhancement at the LHC is a factor of 100
    - but increased W + jets background means that a higher jet cut is necessary at the LHC (30-40 GeV/c rather than 15 GeV/c)

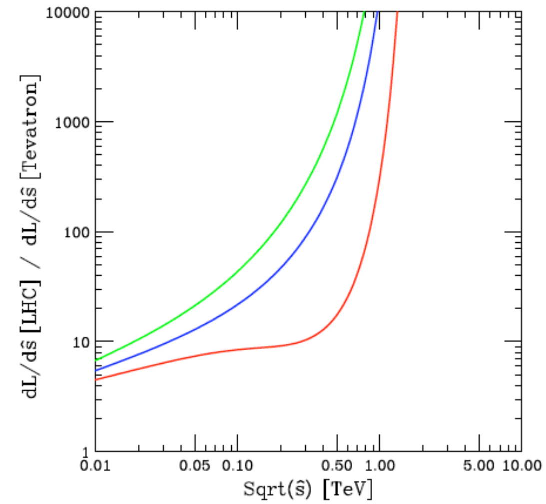


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$ (bottom).

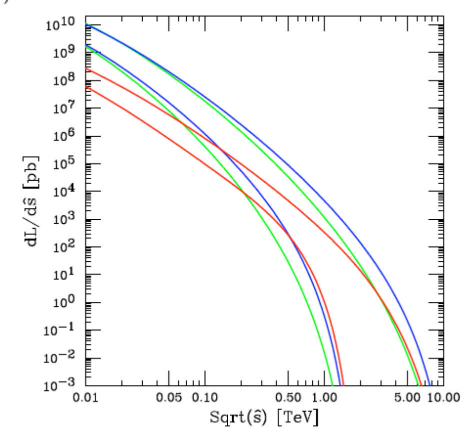


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. The top family of curves are for the LHC and the bottom for the Tevatron.

gg luminosity uncertainties

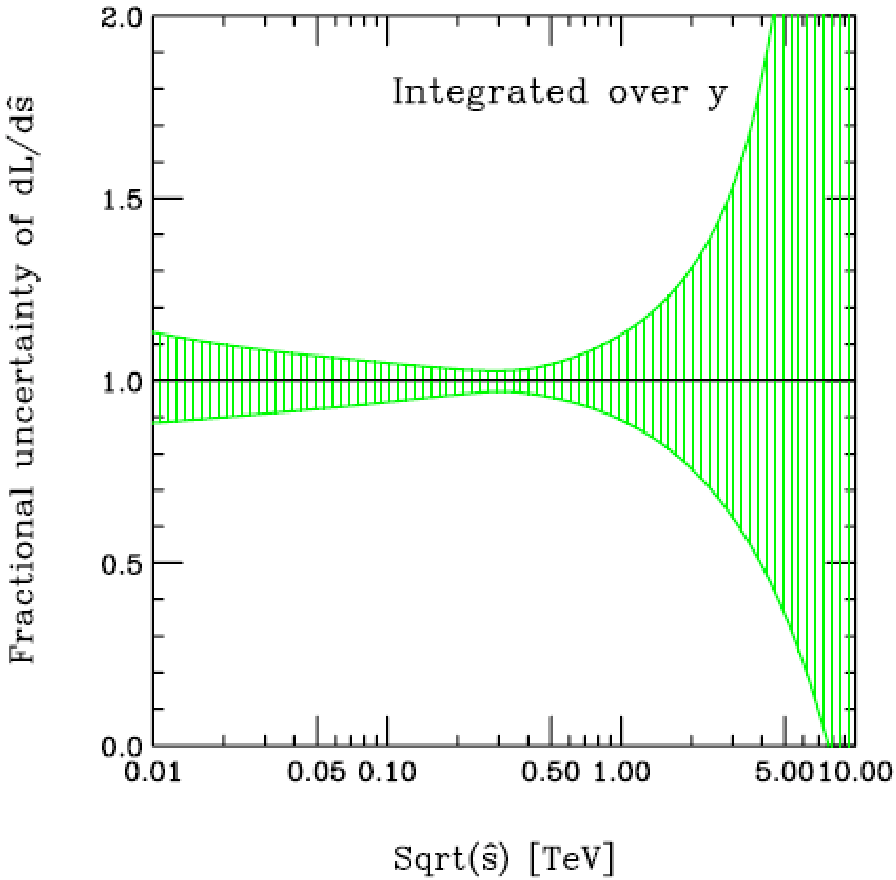


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

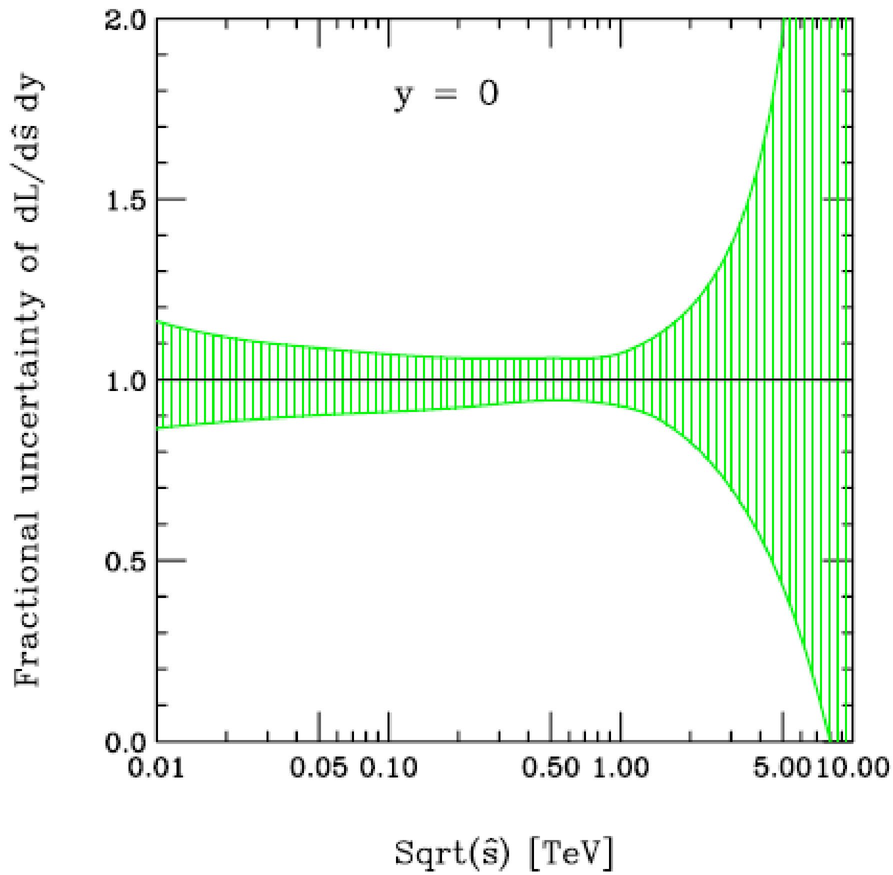


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

…more in extra slides at end of talk

Benchmark studies for LHC (from Les Houches 2005)

- Goal: produce predictions/event samples corresponding to 1 and 10 fb^{-1}
- Cross sections will serve as
  - benchmarks/guidebook for SM expectations in the early running
    - are systems performing nominally? are our calorimeters calibrated?
    - are we seeing signs of “unexpected” SM physics in our data?
    - how many of the signs of new physics that we undoubtedly will see do we really believe?
  - feedback for impact of ATLAS data on reducing uncertainty on relevant pdf’s and theoretical predictions
  - venue for understanding some of the subtleties of physics issues
- Has gone (partially) into Les Houches proceedings; hope to expand on it later
- *Companion* review article on hard scattering physics at the LHC by John Campbell, James Stirling and myself

SM benchmarks for the LHC

See www.pa.msu.edu/~huston/
Les_Houches_2005/Les_Houches_SM.html
(includes CMS as well as ATLAS)

- pdf luminosities and uncertainties
- expected cross sections for useful processes
  - inclusive jet production
    - simulated jet events at the LHC
    - jet production at the Tevatron
      - a link to a CDF thesis on inclusive jet production in Run 2
      - CDF results from Run II using the kT algorithm
  - photon/diphoton
  - Drell-Yan cross sections
  - W/Z/Drell Yan rapidity distributions
  - W/Z as luminosity benchmarks
  - W/Z+jets, especially the *Zeppenfeld* plots
  - top pairs

Summary

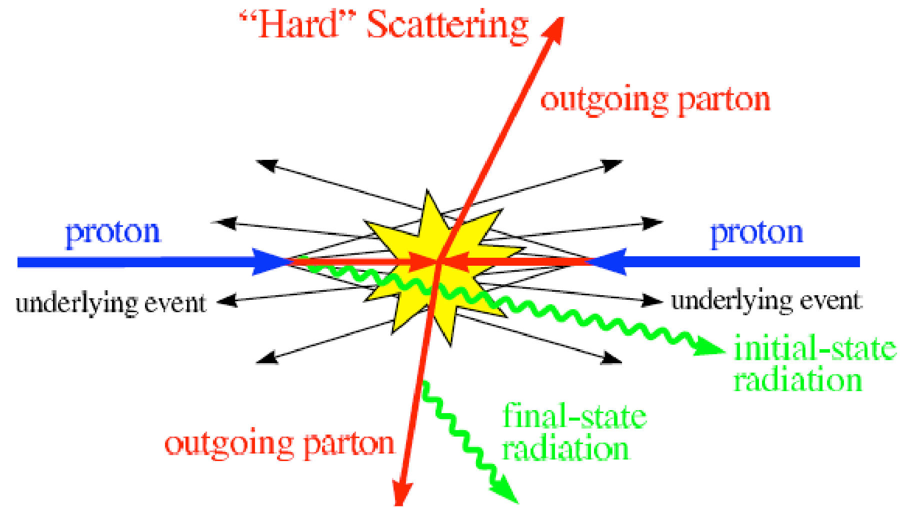
- Now is the time to set up the SM tools and measurement program we need for the first few years of the LHC running
  - jets will continue to be one of the most important tools both at the Tevatron and at the LHC
  - where possible, analyses should use both cone and k_T algorithms
- Theoretical program to develop a broad range of tools for LHC
  - up to us (experimentalists) to make use of them/drive the development of what we need
- Program for SM benchmarks for LHC underway
  - www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html
- Review paper available
  - www.pa.msu.edu/~huston/seminars/Main.pdf

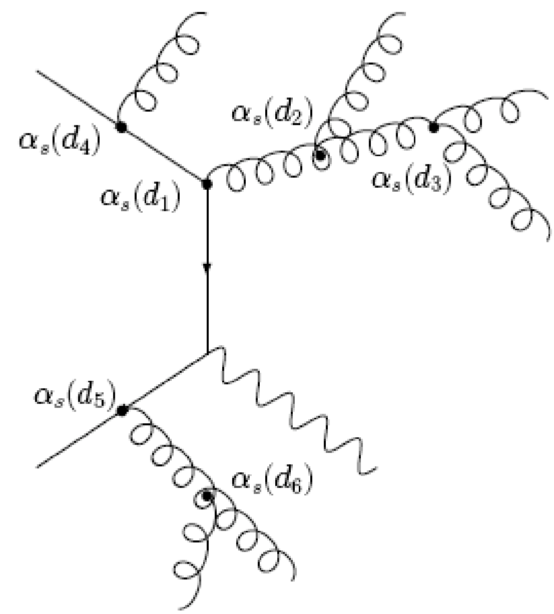
- Once LHC turns on, everything is going to move quickly
- The ATLAS and CMS detectors are going to be "as is" and constantly changing
  - "We take data not with the detector we want, but with the detector we have."

Extras

Gluon radiation

- In addition to the hard scatter, there can be additional emissions from the initial and/or final state partons
  - included in higher multiplicity tree level/NLO calculations and as well in parton shower Monte Carlos
    - these additional emissions give rise to the jet shapes as well as creating additional jets
  - some information can also be summarized in terms of Sudakov form factors
    - a “rule-of-thumb”





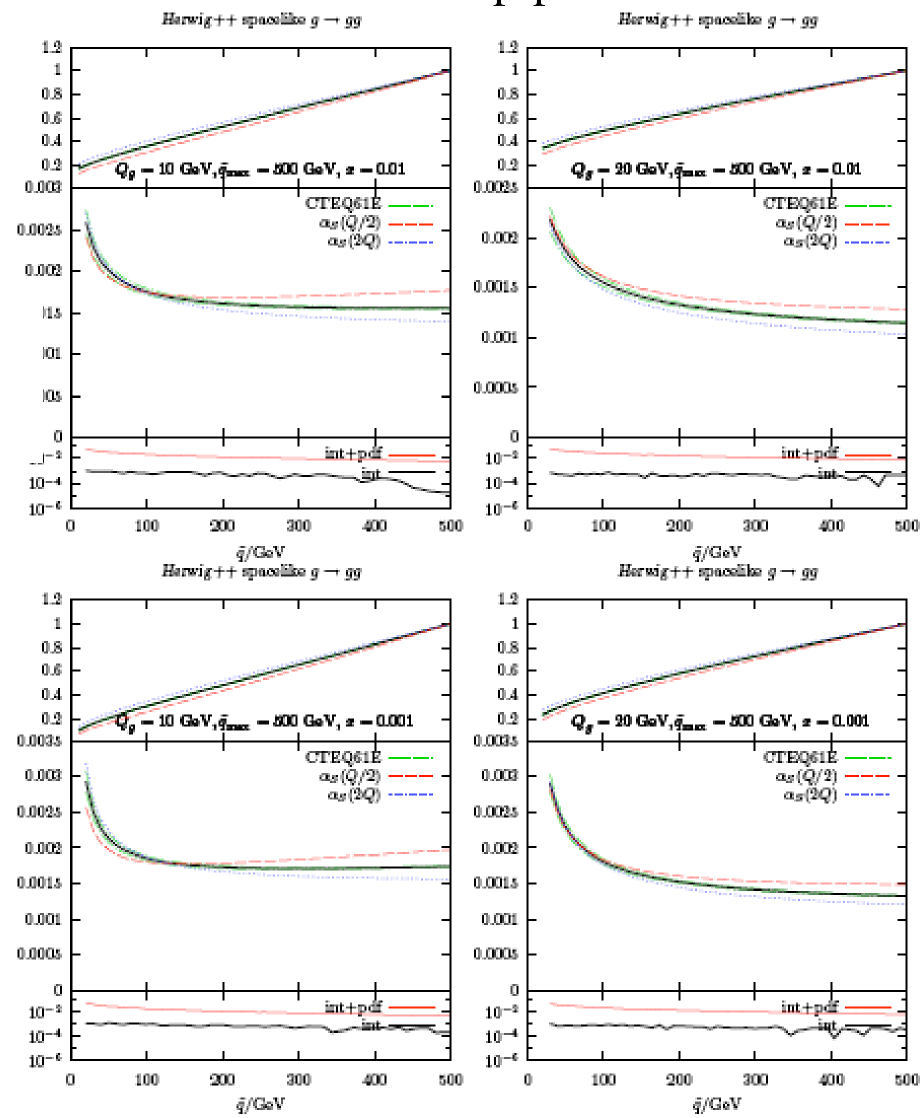
Initial state Sudakov form factors

- The Sudakov form factor gives the probability for a parton not to radiate, with a given resolution scale, when evolving from a large scale down to a small scale
  - below Sudakov form factor for initial state radiation is shown

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int\frac{dz}{z}\frac{\alpha_s}{2\pi}\,P(z)\,\frac{f(x/z,t)}{f(x,t)}\right]$$

- Probability of emission increases with color charge (gluon vs quark), with larger max scale, with decreasing scale for a resolvable emission and with decreasing parton x
  - NB: Sudakovs do not depend strongly on initial state pdf's; thus p_T distribution of final state should not depend on initial pdf's (to first order)

Stefan Gieseke hep-ph/0412342



Sudakov form factors

- Curves from top to bottom correspond to x values of 0.3,0.1, 0.03, 0.01, 0.001, 0.0001
  - Sudakov form factors for q->qg for x<0.03 are similar to form factor for x=0.03 (and so are not shown)
- Sudakov form factors for g->gg continue to drop with decreasing x
  - g->gg splitting function P(z) has singularities both as z->0 and as z->1 (as Peter said)
  - q->qg has only z->1 singularity
- For example, probability for an initial state gluon of x=0.01 not to emit a gluon of >=20 GeV when starting from an initial scale of 500 GeV is ~70%, i.e. there is a 30% probability for such an emission

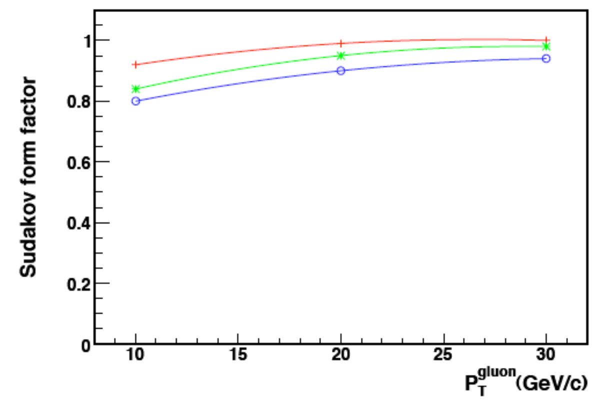


Figure 20. The Sudakov form factors for initial state quarks at a hard scale of 100 GeV/c as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3,0.1 and 0.03.

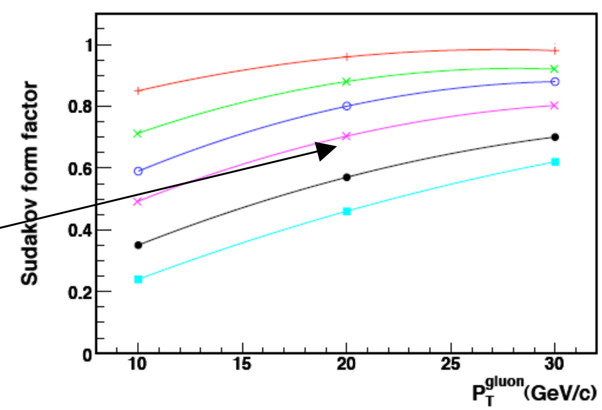


Figure 18. The Sudakov form factors for initial state gluons at a hard scale of 100 GeV/c as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3,0.1,0.03,0.01,0.001 and 0.0001.

Resolution scale -> ~p_T of gluon

Sudakov form factors

- If I go to small x, or high scale or a gluon initial state, then probability of a ISR gluon emission approaches unity
- The above sentence basically describes the LHC

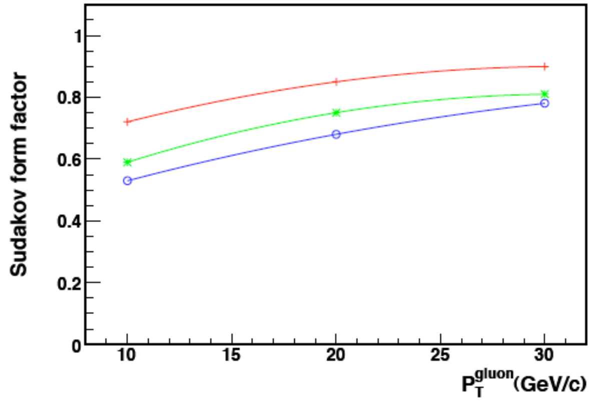


Figure 21. The Sudakov form factors for initial state quarks at a hard scale of 500 GeV/c as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3,0.1 and 0.03.

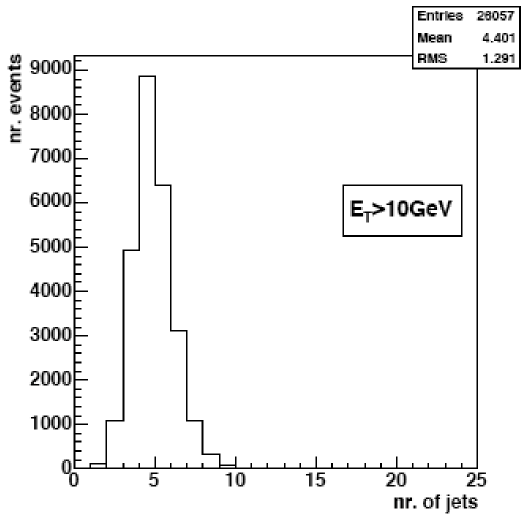


Figure 75. The jet multiplicity in $t\bar{t}$ events with a lepton + jets final state at the LHC. A cut of 10 GeV has been applied to the jets.

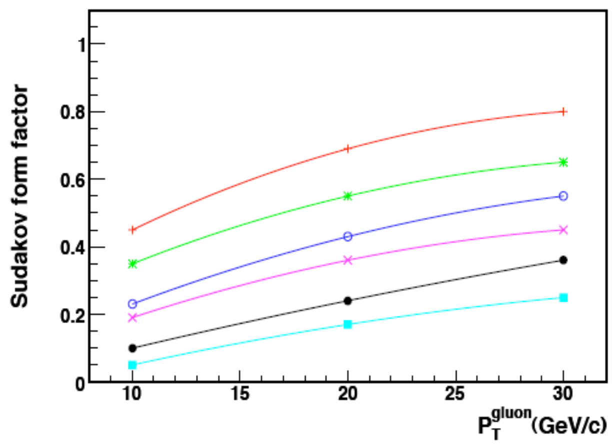
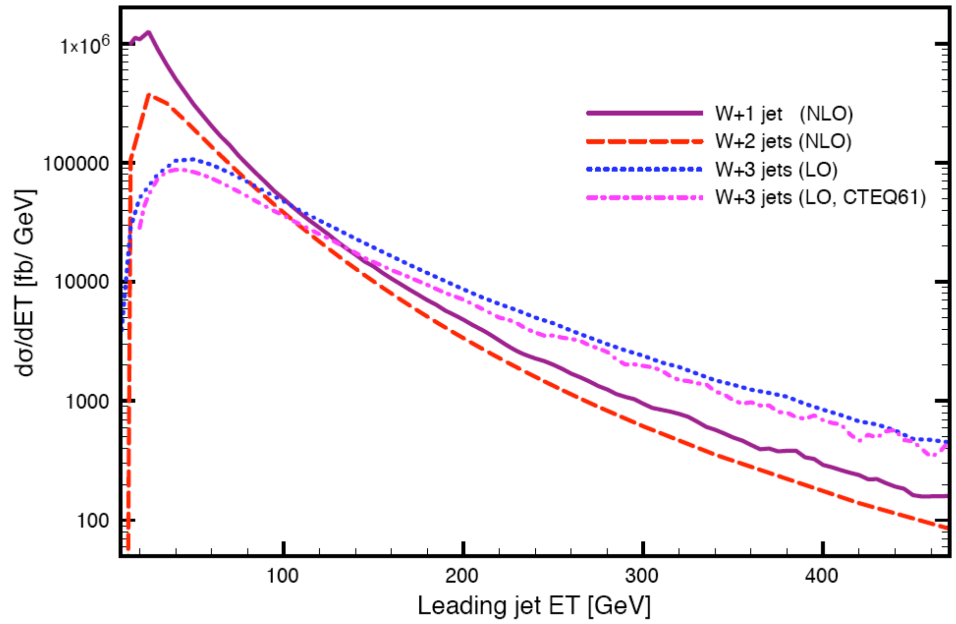


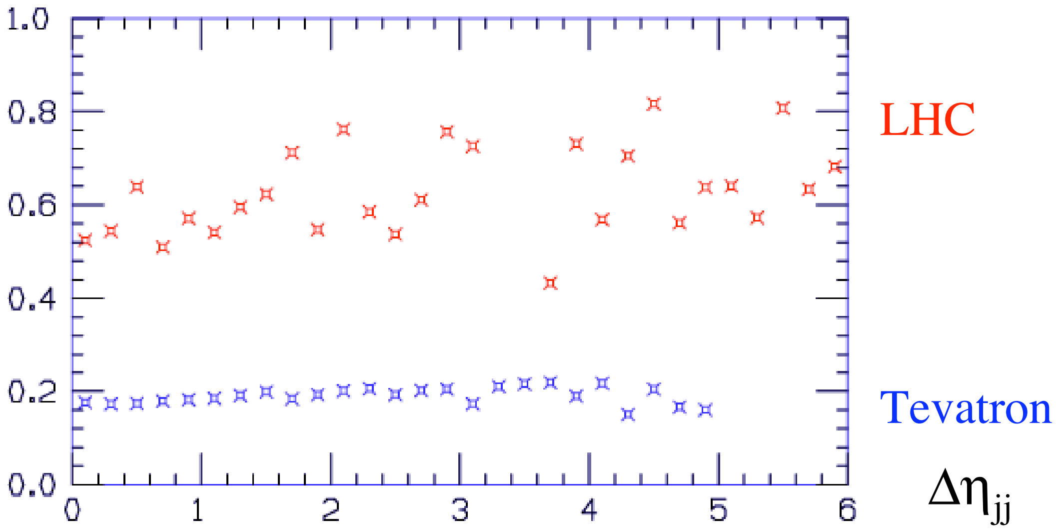
Figure 19. The Sudakov form factors for initial state gluons at a hard scale of 500 GeV/c as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3,0.1,0.03,0.01,0.001 and 0.0001.

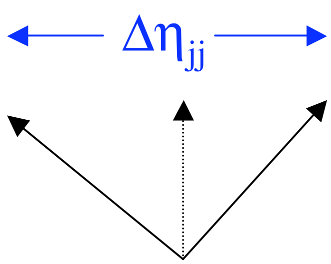
W + jets at LHC

- For high leading jet E_T, W + 3 jet is larger than W+ 2 jet
  - Sudakov suppression again
- Look at probability for 3rd jet to be emitted as a function of the rapidity separation of the tagging jets
  - relevant for VBF Higgs searches
- At LHC, ratio (p_T^{jet}>15 GeV/c) much higher than at Tevatron

$$\frac{\text{W+3 jet}}{\text{W+>=2 jet}}$$







The “maligned” experimenter’s wishlist

- Missing many needed NLO computations — Campbell

An experimenter’s wishlist

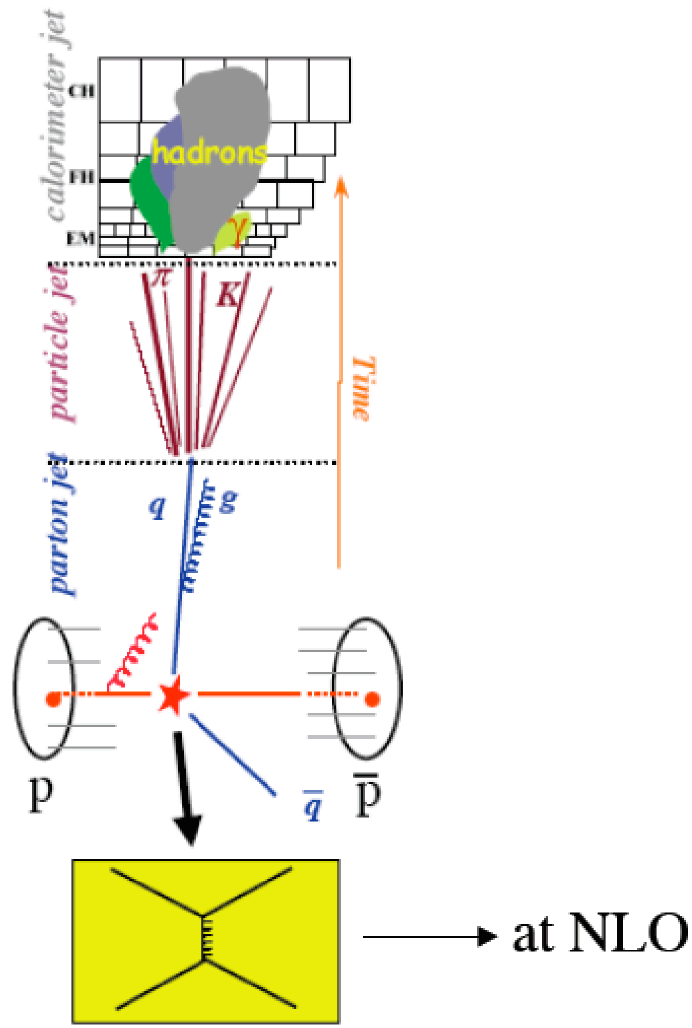
- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

MC@NLO

- MC @ NLO combines the best features of parton shower Monte Carlos and NLO calculations
- The hard cross section is calculated to NLO and then passed on to Herwig for additional gluon radiation and hadronization
- Inclusive jet production will be included by this fall



NLO calculation priority list from Les Houches 2005: theory benchmarks

- Note have to specify how inclusive final state is
  - what cuts will be made?
  - how important is b mass for the observables?
- How uncertain is the final state?
  - what does scale uncertainty look like at tree level?
  - new processes coming in at NLO?
- Some information may be available from current processes
  - pp->tT j may tell us something about pp->tTbB?
    - j=g->bB
  - CKKW may tell us something about higher multiplicity final states

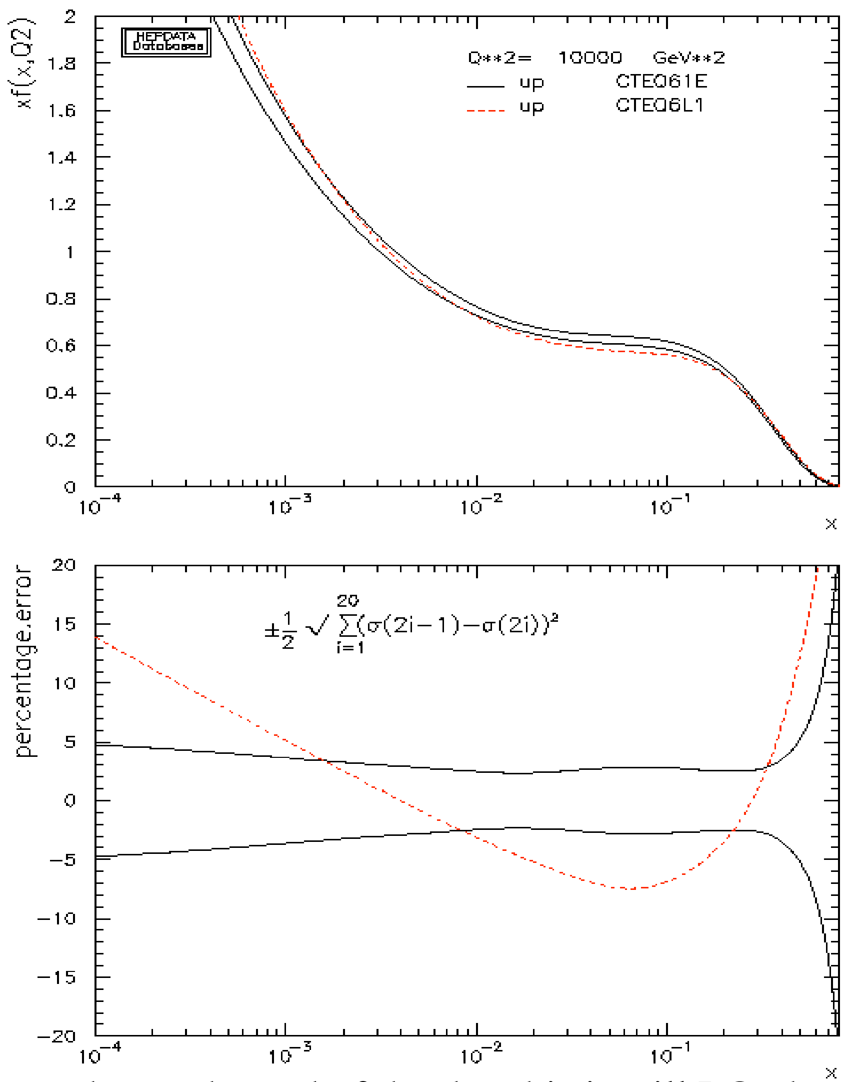
can we develop rules-of-thumb about size of HO corrections?

1. pp->WW jet
2. pp->H + 2 jets now complete
   1. background to VBF production of Higgs
3. pp->tT bB
   1. background to tTH
4. pp->tT + 2 jets
   1. background to tTH
5. pp->WWbB
6. pp->V V + 2 jets
   1. background to WW->H->WW
7. pp->V + 3 jets
   1. beneral background to new physics
8. pp->V V V
   1. background to SUSY trilepton

Are there any other cross sections that should be on this list?

LO vs NLO pdf's for parton shower MC's

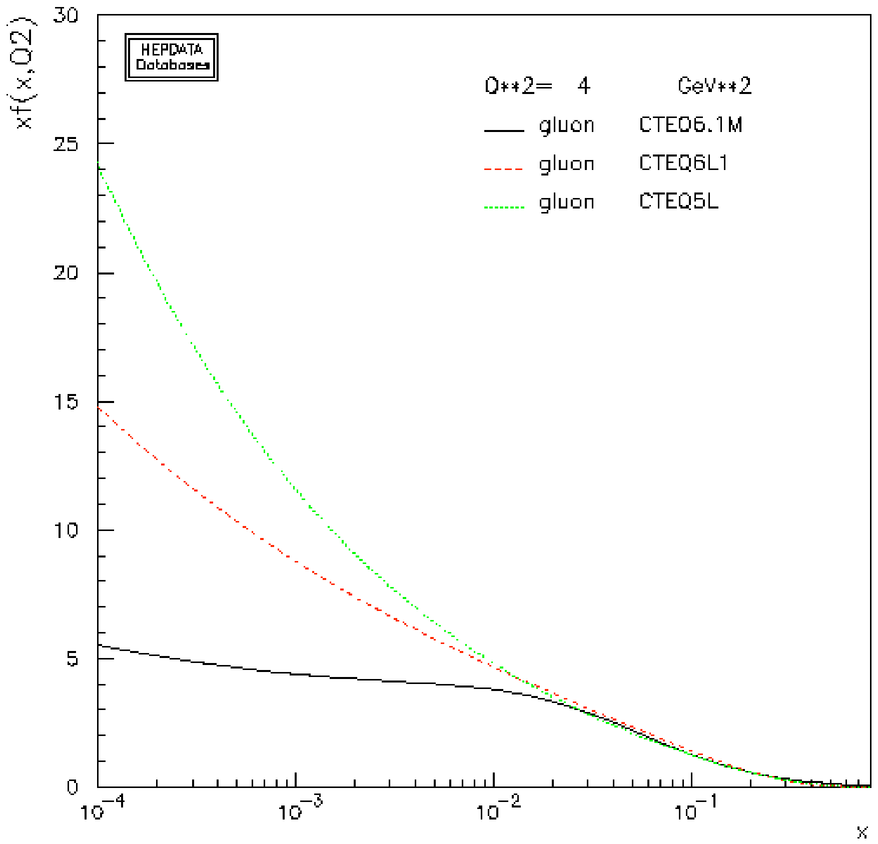
- For NLO calculations, use NLO pdf's (duh)
- What about for parton shower Monte Carlos?
  - somewhat arbitrary assumptions (for example fixing Drell-Yan normalization) have to be made in LO pdf fits
  - DIS data in global fits affect LO pdf's in ways that may not directly transfer to LO hadron collider predictions
  - LO pdf's for the most part are outside the NLO pdf error band
  - LO matrix elements for many of the processes that we want to calculate are not so different from NLO matrix elements
  - by adding parton showers, we are partway towards NLO anyway
  - any error is formally of NLO
- (my recommendation) use NLO pdf's
  - pdf's must be + definite in regions of application (CTEQ is so by def'n)
- Note that this has implications for MC tuning, i.e. Tune A uses CTEQ5L
  - need tunes for NLO pdf's

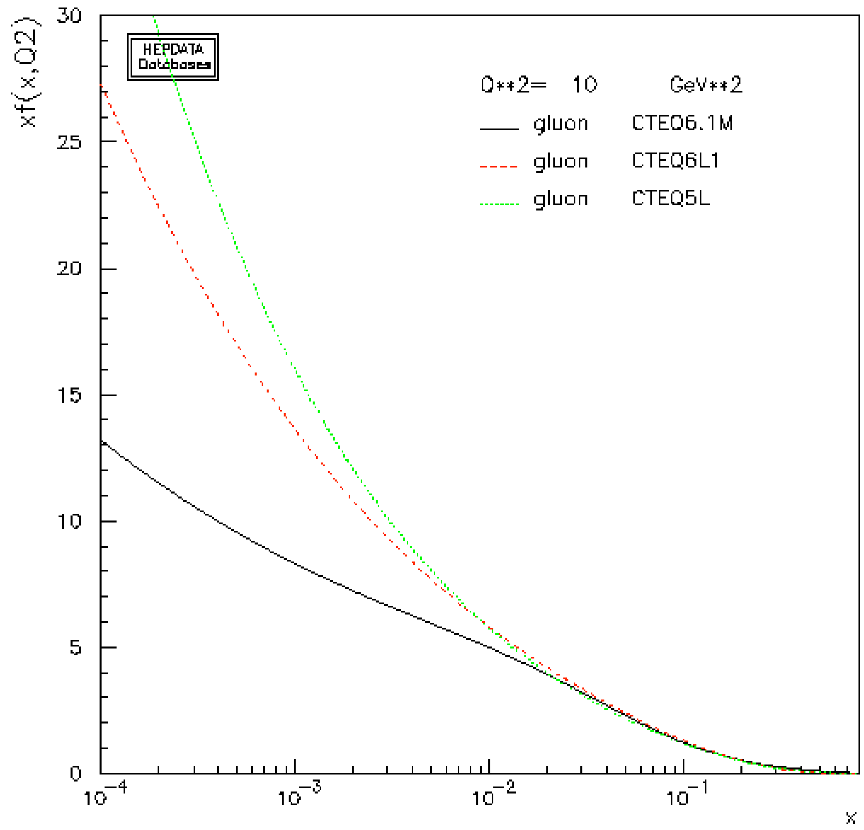


. . .but at the end of the day this is still LO physics;
There's no substitute for honest-to-god NLO.

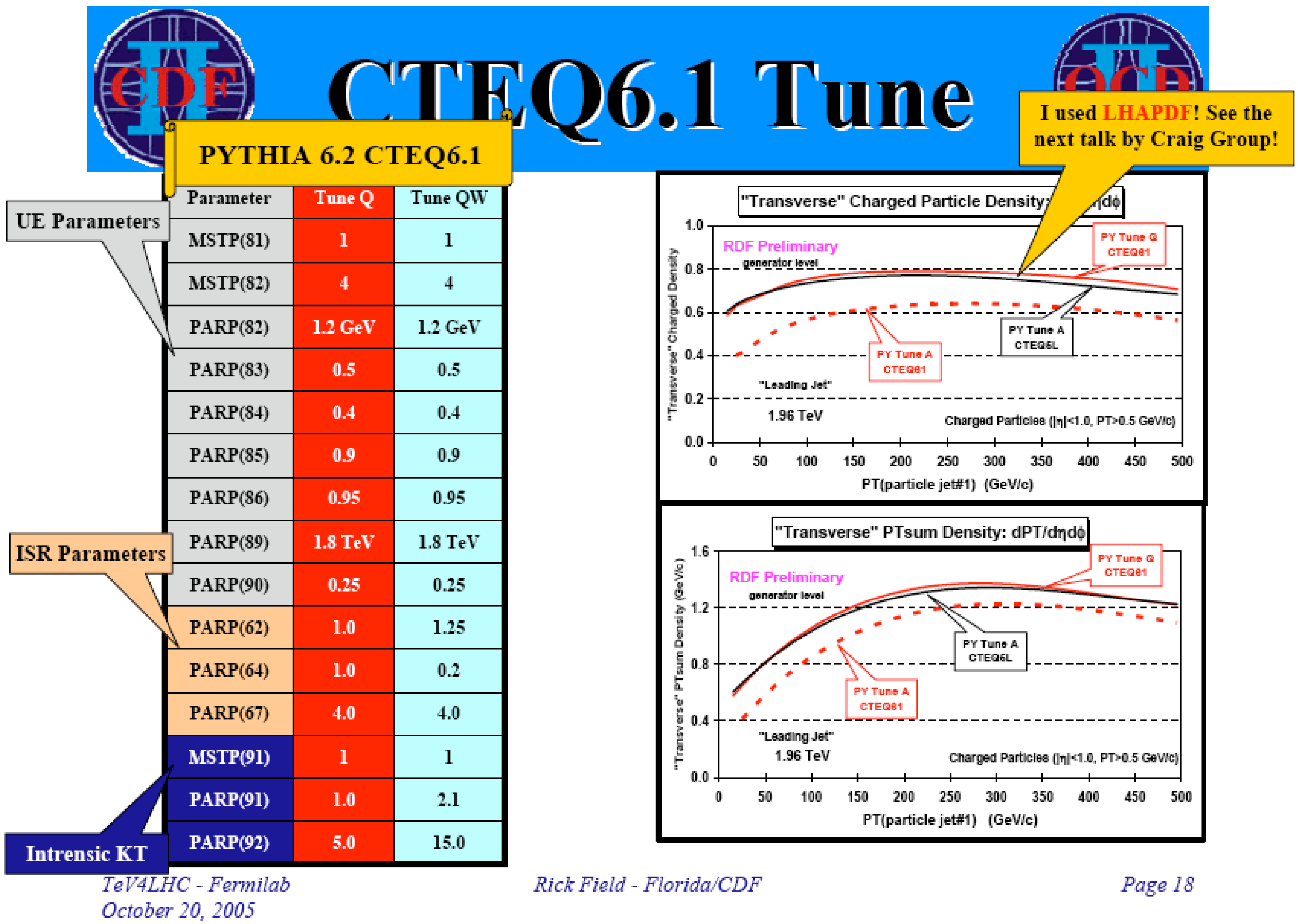
Impact on UE tunes

- 5L significantly steeper at low x and Q^2
- Rick Field has produced a tune based on CTEQ6.1





Rick’s tune



Parameter	Tune Q	Tune QW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.2 GeV	1.2 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	0.9	0.9
PARP(86)	0.95	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.0	1.25
PARP(64)	1.0	0.2
PARP(67)	4.0	4.0
MSTP(91)	1	1
PARP(91)	1.0	2.1
PARP(92)	5.0	15.0

…will be discussed in detail in TeV4LHC writeup

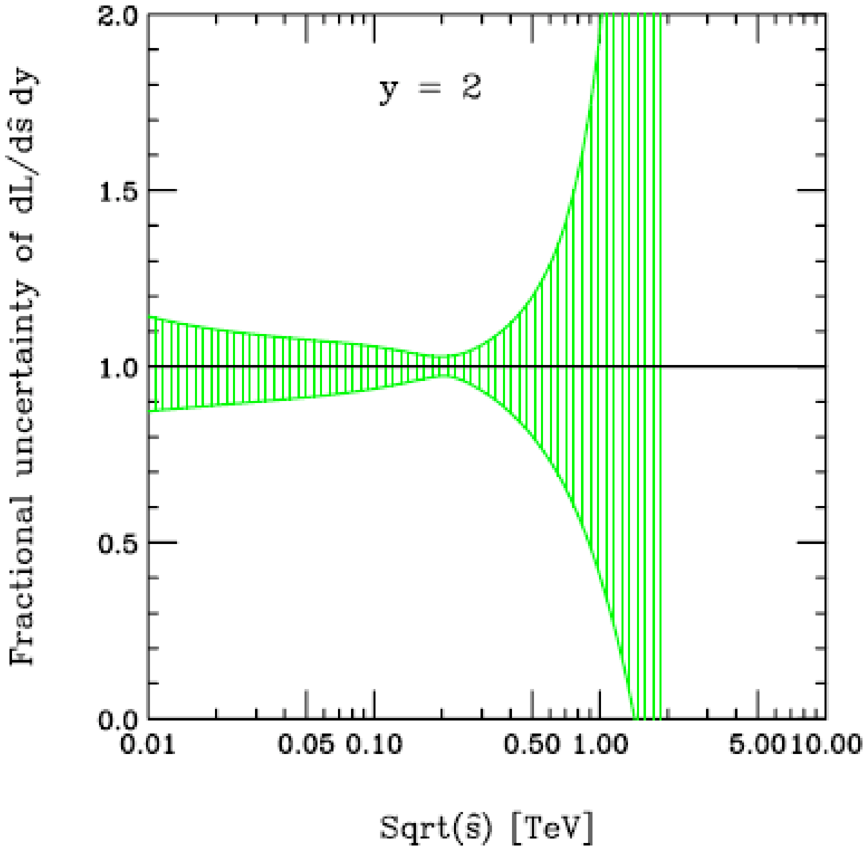
More…

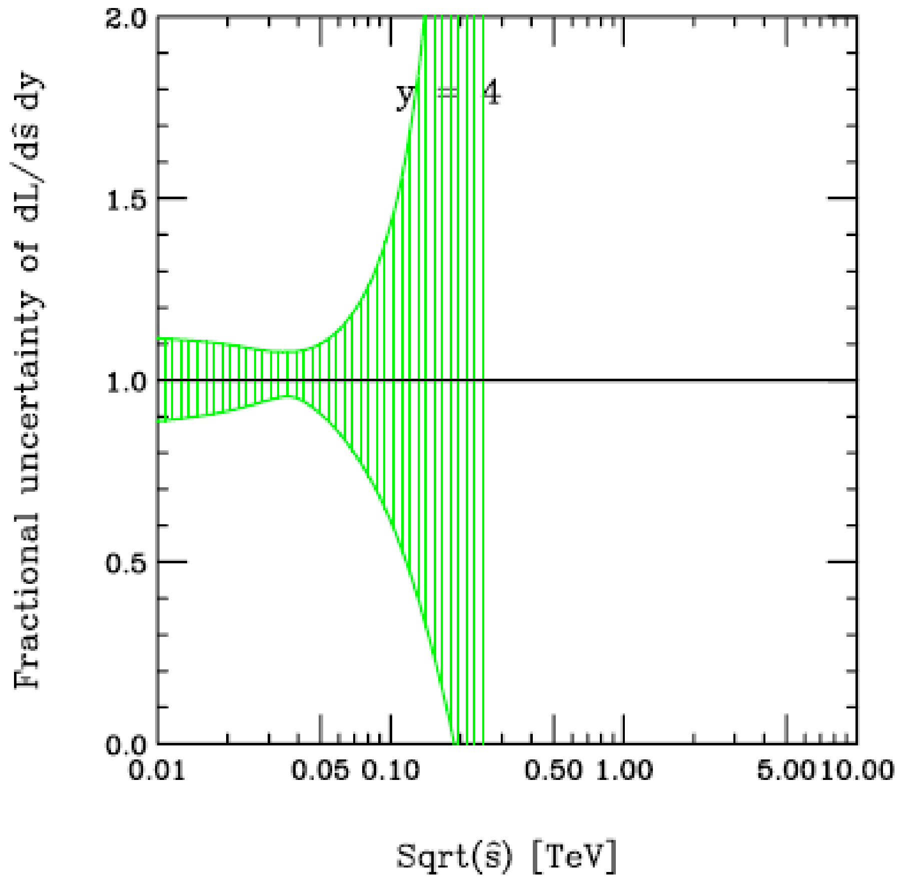
- technical benchmarks
  - jet algorithm comparisons
    - midpoint vs simple iterative cone vs kT
      - top studies at the LHC
      - an interesting data event at the Tevatron that examines different algorithms
    - Building Better Cone Jet Algorithms
      - one of the key aspects for a jet algorithm is how well it can match to perturbative calculations; here is a 2-D plot for example that shows some results for the midpoint algorithm and the CDF Run 1 algorithm (JetClu)
      - here is a link to Fortran/C++ versions of the CDF jet code
  - fits to underlying event for 200 540, 630, 1800, 1960 GeV data
    - interplay with ISR in Pythia 6.3
    - establish lower/upper variations
    - extrapolate to LHC
    - effect on target analyses (central jet veto, lepton/photon isolation, top mass?)

…plus more benchmarks that I have no time to discuss

- variation of ISR/FSR a la CDF (study performed by Un-Ki Yang)
    - low ISR/high ISR
    - FSR
  - power showers versus wimpy showers a la Peter Skands
  - number of additional jets expected due to ISR effects (see also Sudakov form factors)
  - impact on top analyses
  - effect on benchmarks such as Drell-Yan and diphoton production
    - goal is to produce a range for ISR predictions that can then be compared at the LHC to Drell-Yan and to diphoton data
- Sudakov form factor compilation
  - probability for emission of 10, 20, 30 GeV gluon in initial state for hard scales of 100, 200, 500, 1000, 5000 GeV for quark and gluon initial legs
  - see for example, similar plots for quarks and gluons for the Tevatron from Stefan Gieseke
- predictions for W/Z/Higgs p_T and rapidity at the LHC
  - compare ResBos(-A), joint-resummation and Berger-Qiu for W and Z

gg luminosity uncertainties





gq luminosity uncertainties

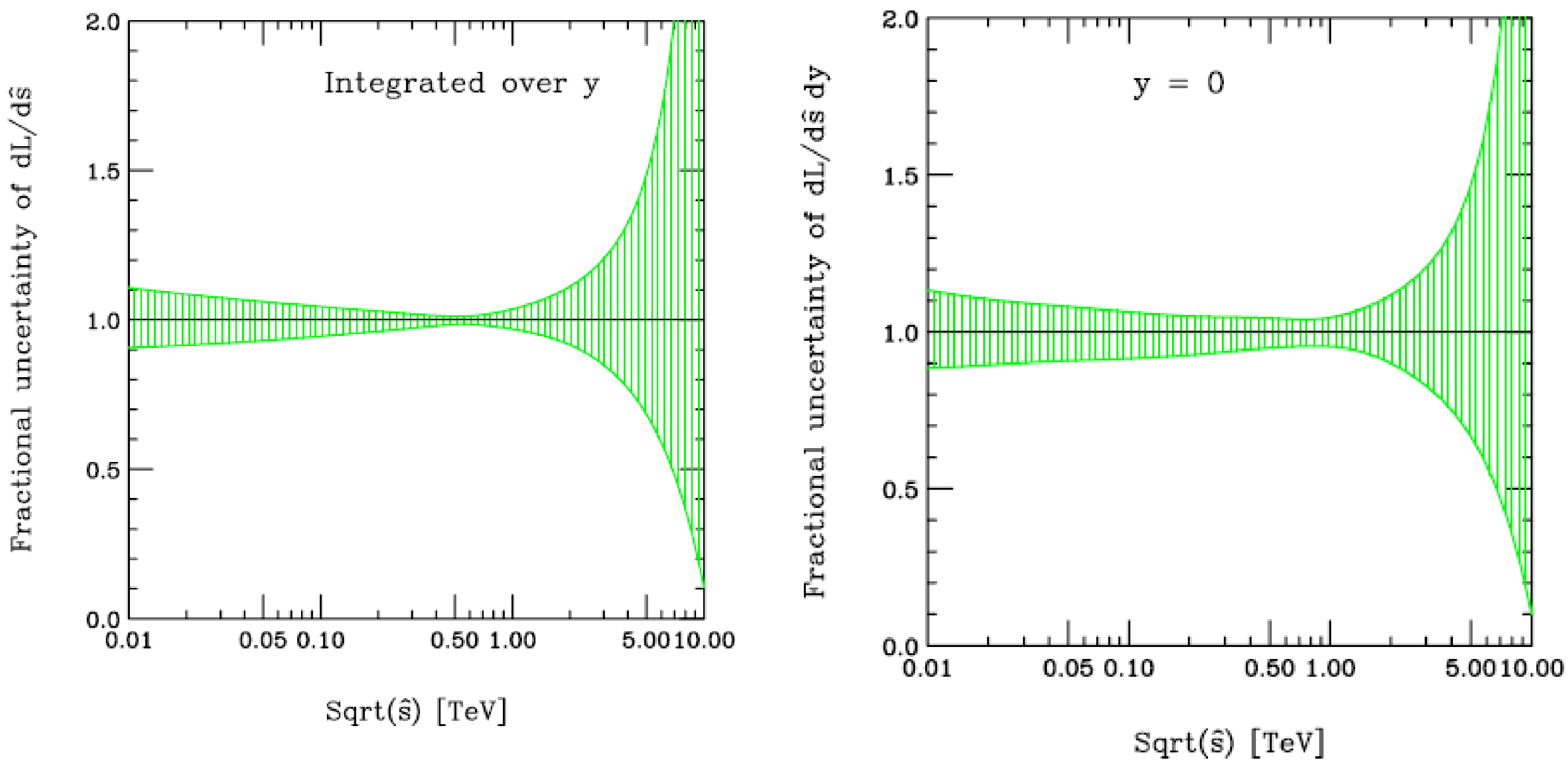
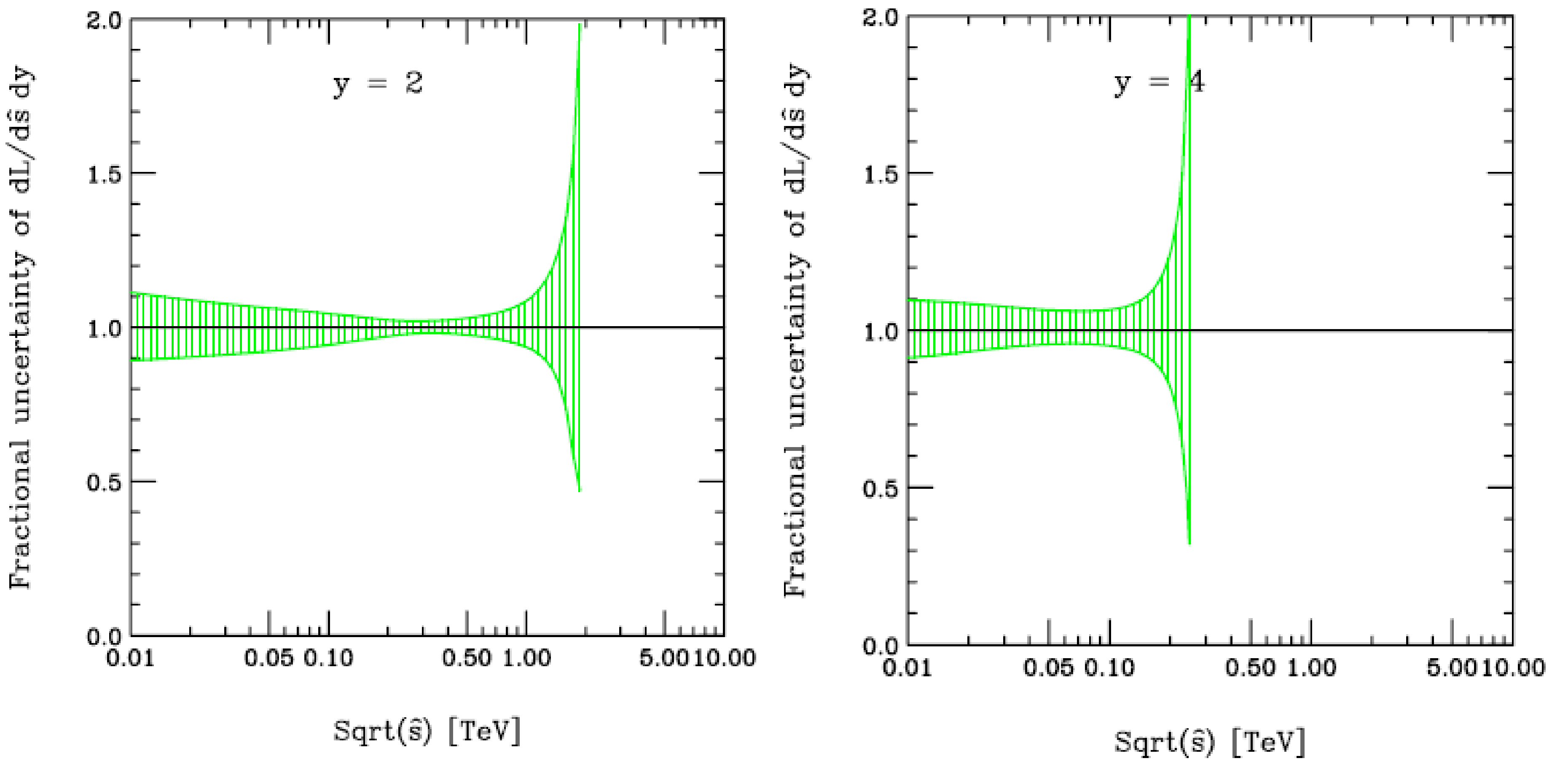


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

gq luminosity uncertainties



qQ luminosity uncertainties

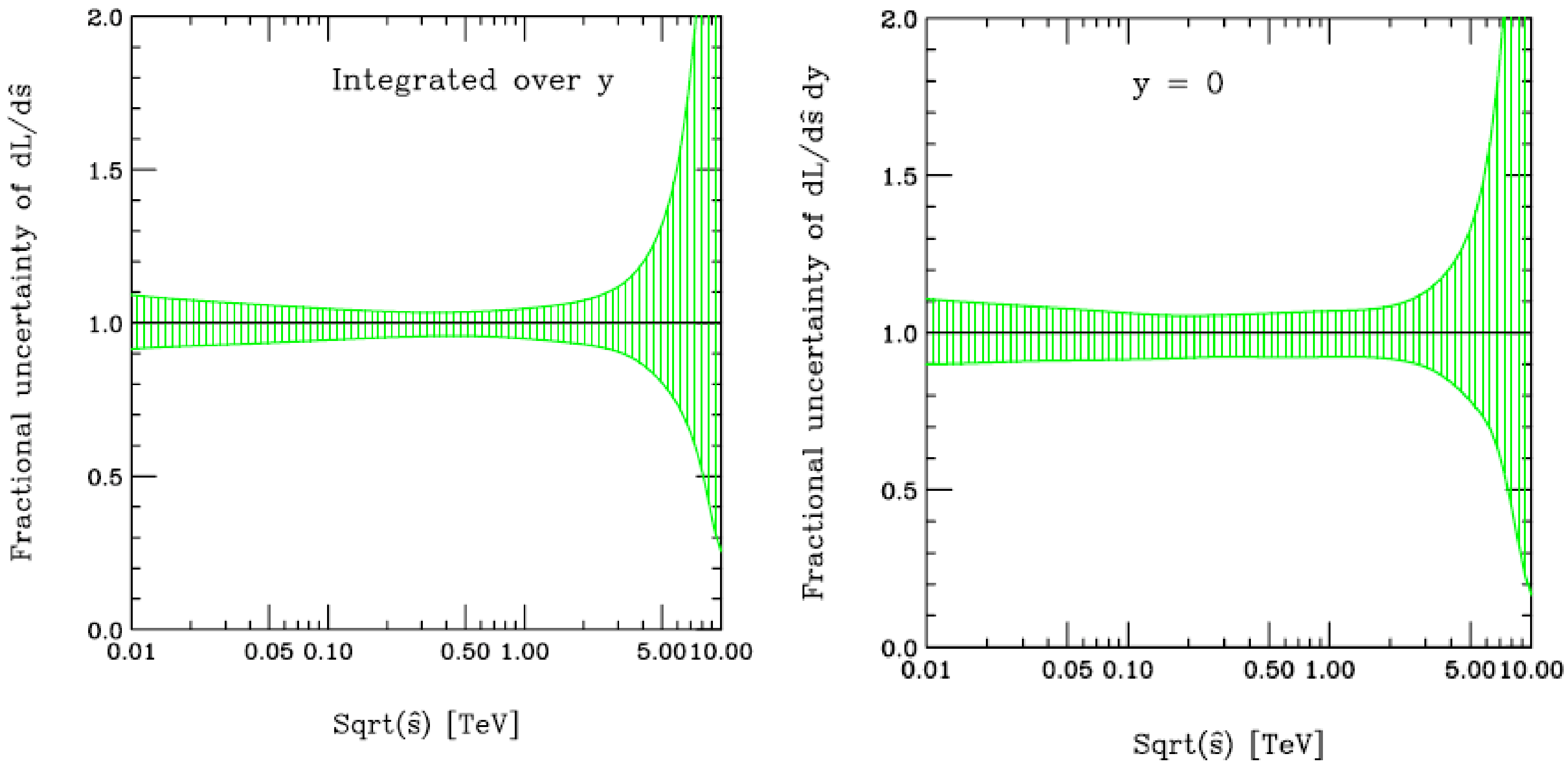


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

qQ luminosity uncertainties