Roadmap for early ATLAS physics

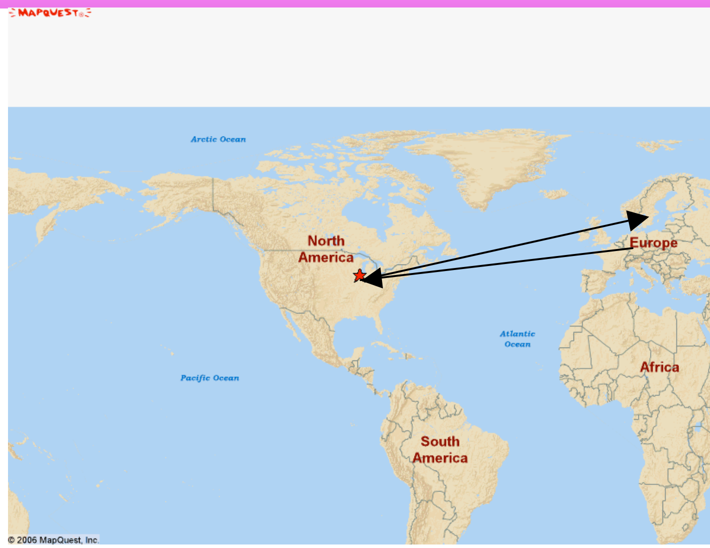
"QCD Benchmarks for the LHC"

Joey Huston
Michigan State University

2nd HERA-LHC Workshop
CERN June 16

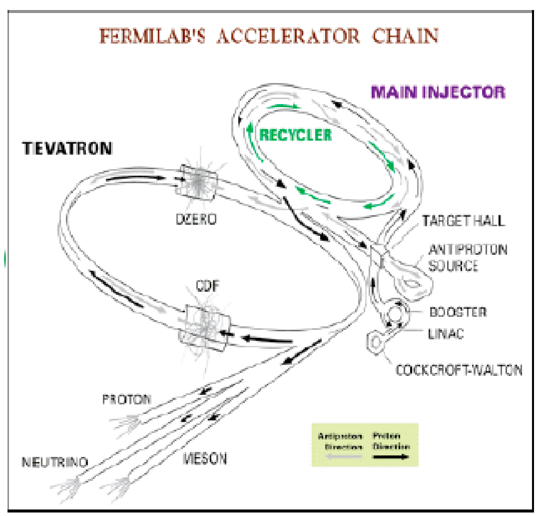
- End at **Stockholm**
- **Total Est. Time:** 18 hours, 50 minutes
- **Total Est. Distance:** 1264.67 miles

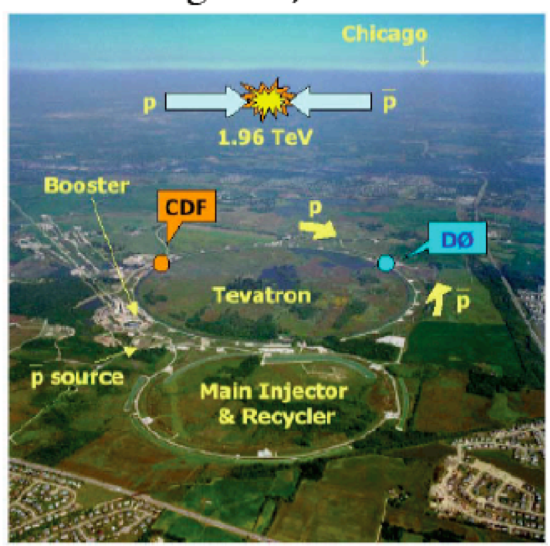
Passing by Fermilab on the way



- I'll be discussing
  - Tevatron results and their usefulness for the LHC (mostly CDF)
  - some QCD benchmarks for the LHC
  - some recent CTEQ pdf results

36 bunches (396 ns crossing time)

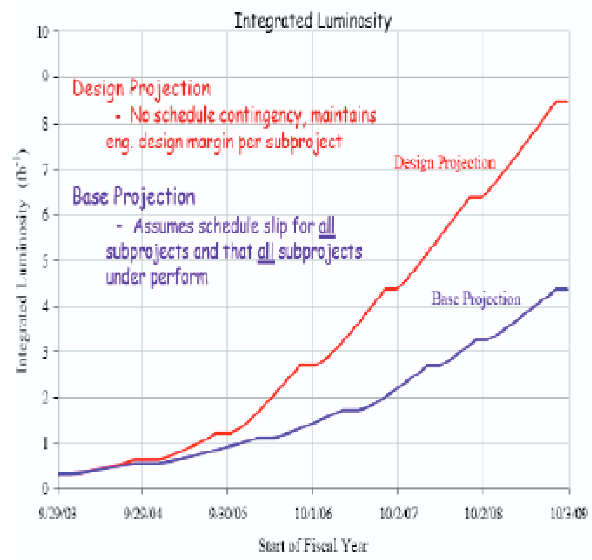


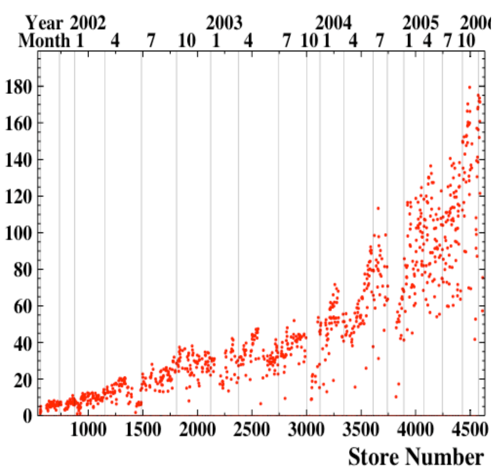


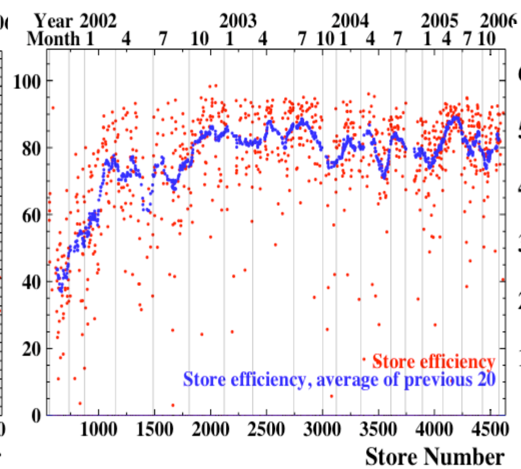
Let me just say

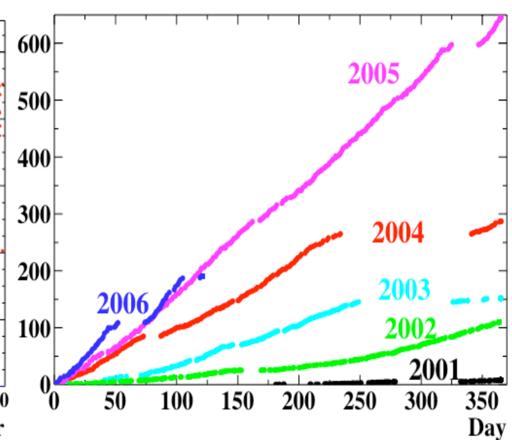
- Tevatron (and CDF and D0) are running well

ultimately 4-9 fb^{-1}





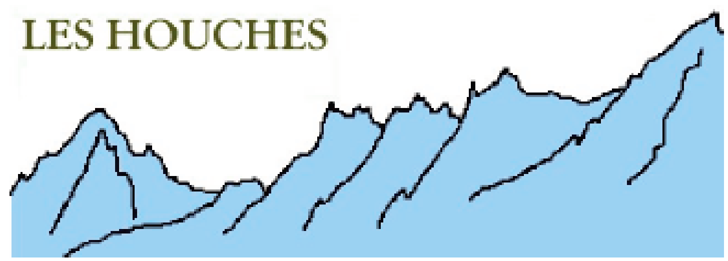




- over 1.2 fb^{-1} on tape
- 1 fb^{-1} analyses presented at Moriond
- coming off of shutdown now
- FY06 design goal = 800 pb^{-1}

Last year's Les Houches well-named

- …or was even a bit pessimistic
- Physics at TeV Colliders
  - From 800 pb^{-1} at the Tevatron to 30 fb^{-1} at the LHC
  - May 2 - 20, 2005
  - proceedings published
  - during Les Houches, I started a benchmark webpage that I will try to maintain through the beginning of the LHC turn-on
  - www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html



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
  - known unknowns
    - SM at the LHC
  - unknown unknowns
    - ???

LHC bandwagon

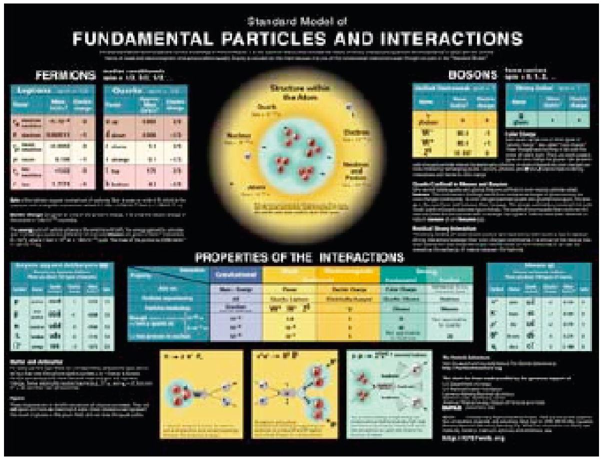
- A lot of useful experience with the Standard Model can be carried forward from Fermilab and HERA and workshops have taken place to summarize that knowledge
  - HERA-LHC TeV4LHC near completion
  - I'm almost finished with a review article for ROP with John Campbell and James Stirling titled "Hard interactions of quarks and gluons: a primer for LHC physics"
    - much of what I will show here is from that article (a few "in-process" copies available for those willing to provide comments)
    - 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

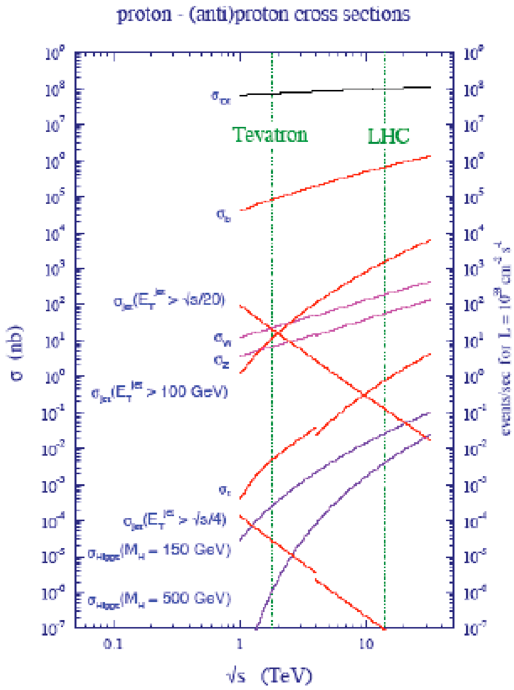
soft and/or collinear logs

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

Discovering the SM at the LHC

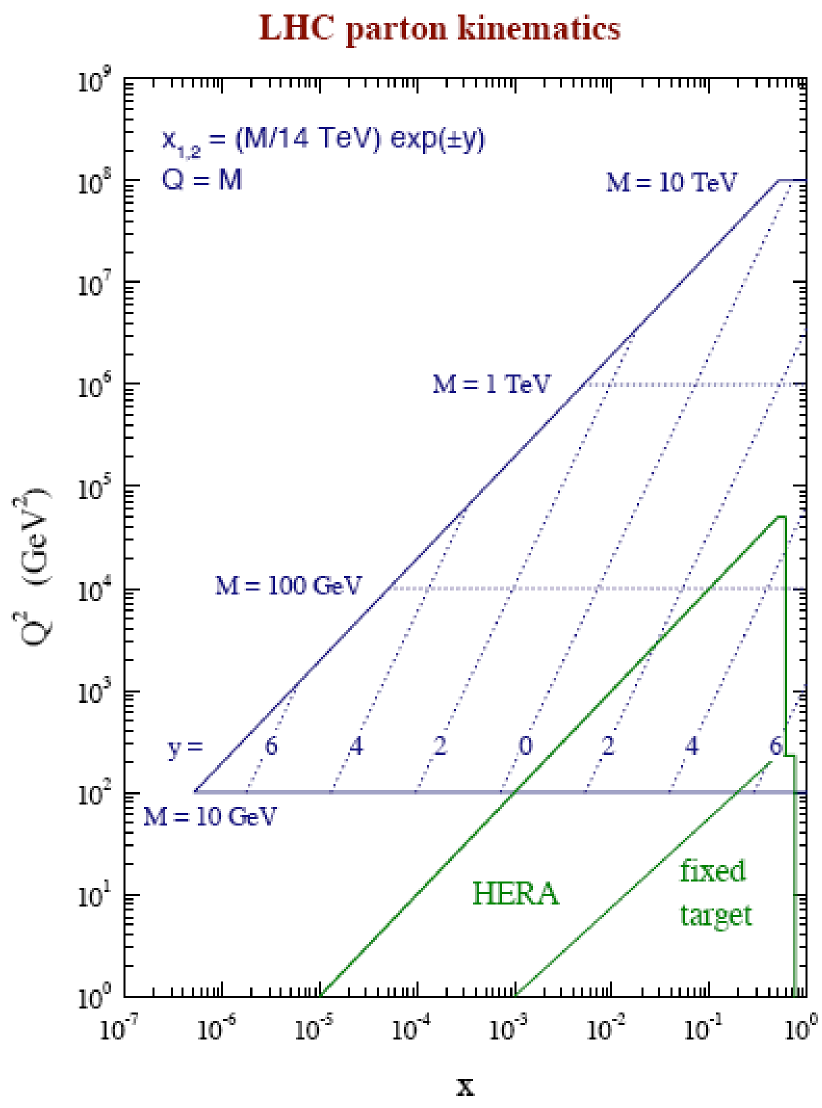
- We’re all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to BSM physics correctly taken into account
- ATLAS 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



"We have a strategery"

Goal # 1 Understand and calibrate detector and trigger in situ using well-known physics samples

e.g. - $Z \to ee, \mu\mu$ tracker, ECAL, Muon chambers calibration and alignment, etc.

- $tt \to bl\nu\, bjj$ 10^3 evts/day after cuts → jet scale from W→jj, b-tag perf., etc.

Understand basic SM physics at $\sqrt{s}$ = 14 TeV → first checks of Monte Carlos

(hopefully well understood at Tevatron and HERA)

e.g. - measure cross-sections for e.g. minimum bias, W, Z, tt, QCD jets (to ~ 10-20 %), look at basic event features, first constraints of PDFs, etc.

- measure top mass (to 5-7 GeV) → give feedback on detector performance

Note : statistical error negligible after few weeks run

Goal # 2 Prepare the road to discovery:

-- measure backgrounds to New Physics : e.g. tt and W/Z+ jets (omnipresent ...)

-- look at specific "control samples" for the individual channels:

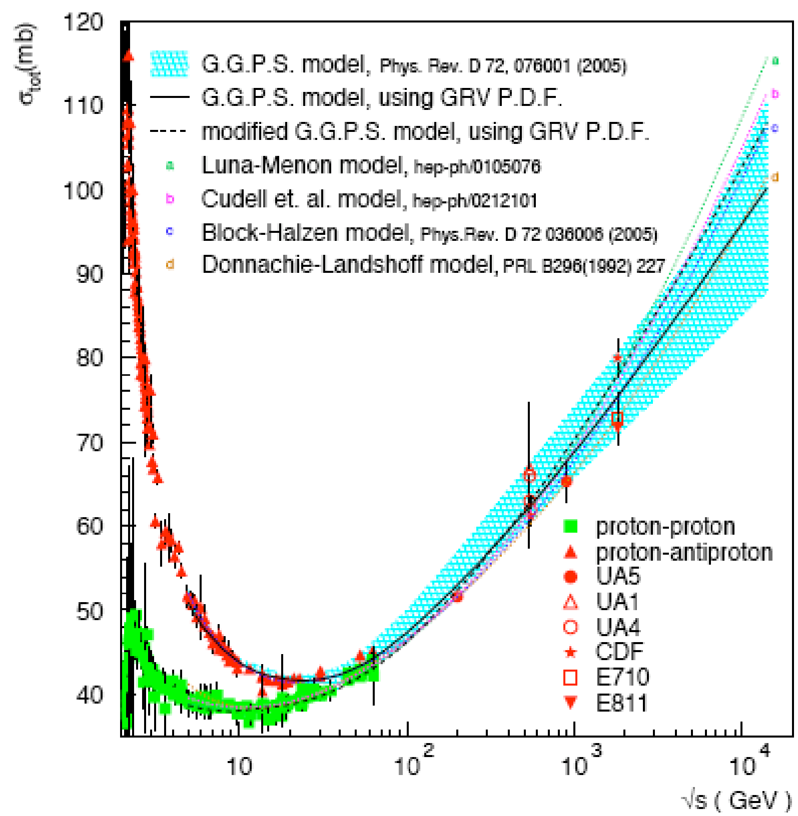
e.g. ttjj with $j \neq b$ "calibrates" ttbb irreducible background to ttH → ttbb

Goal # 3 Look for New Physics potentially accessible in first year (e.g. Z', SUSY, some Higgs ? ...)

…from Mangianotti talks

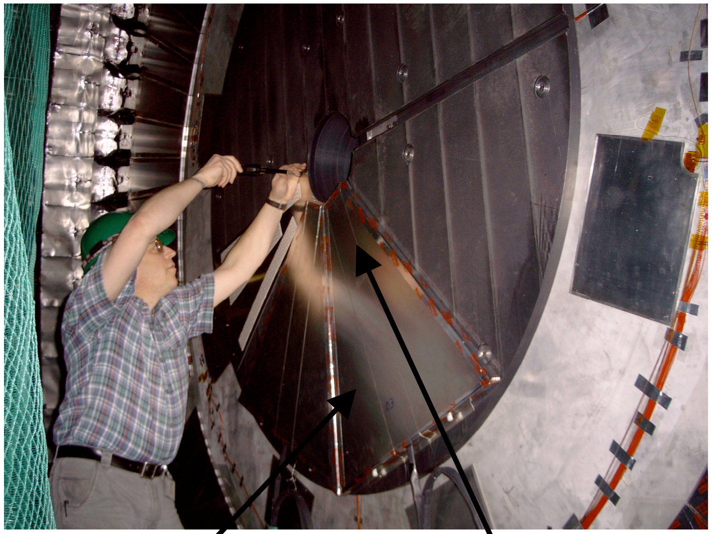
Total cross section at LHC

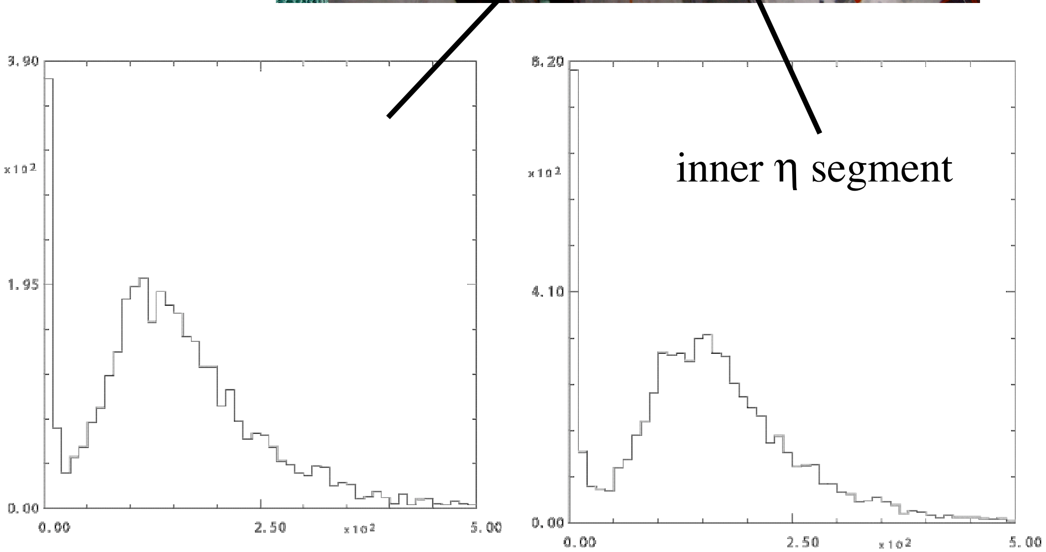
- Fair amount of uncertainty on extrapolation to LHC
  - ln(s) or ln²(s) behavior
- Also uncertainty on $dN_{charged}/d\eta$ and $dN_{charged}/dp_T$
  - role of semi-hard multiple parton interactions
  - reasonable expectation is 7-8 particles per unit rapidity and $<p_T>\sim0.65$ GeV/c
- Both can be measured using the early data, although extrapolating measured cross section to full inelastic cross section will still have large uncertainties



Early triggering in ATLAS

- Beam pickups will indicate which bunches are filled
- Need a fast signal from detector that an interaction has occurred
- This is the role of the MBTS counters
  - mounted on LAr cryostats and cover an η region from ~2 to 3.8
  - 8 segments in ϕ on each side; 2 segments in η
  - good signal to noise offline, but trigger efficiency <100%



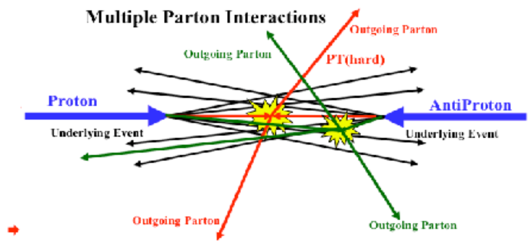


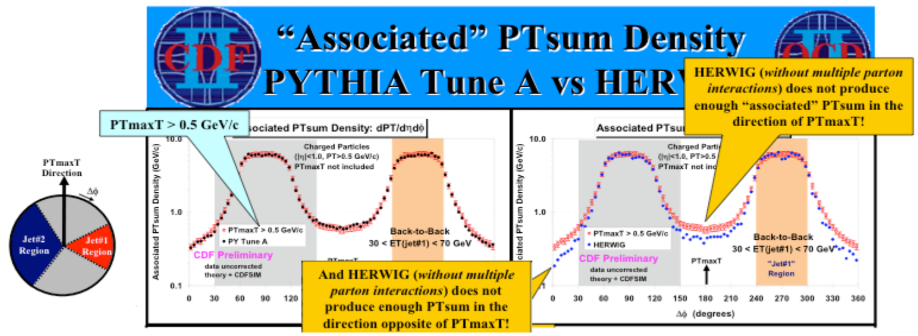
Underlying event at the LHC

- 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
- Should be able to establish reasonably well with the first collisions in 2007
- Rick Field is working on some new tunes
  - some problems with Tune A
  - tunes for Jimmy
  - tunes for CTEQ6.1 (NLO)

The structure of the underlying event

Mounting experimental evidence (R.Field, CDF) that the UE is the result of **multiple semi-hard (minijet-like) interactions**





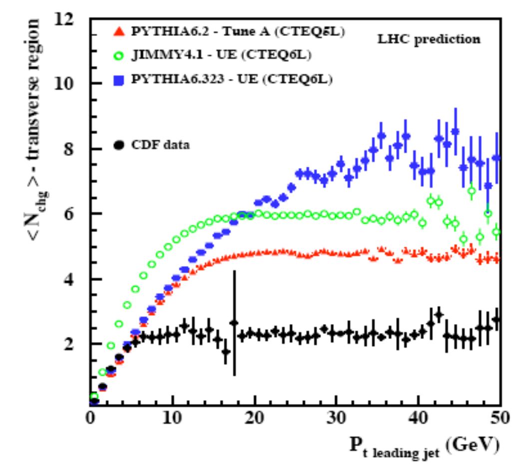
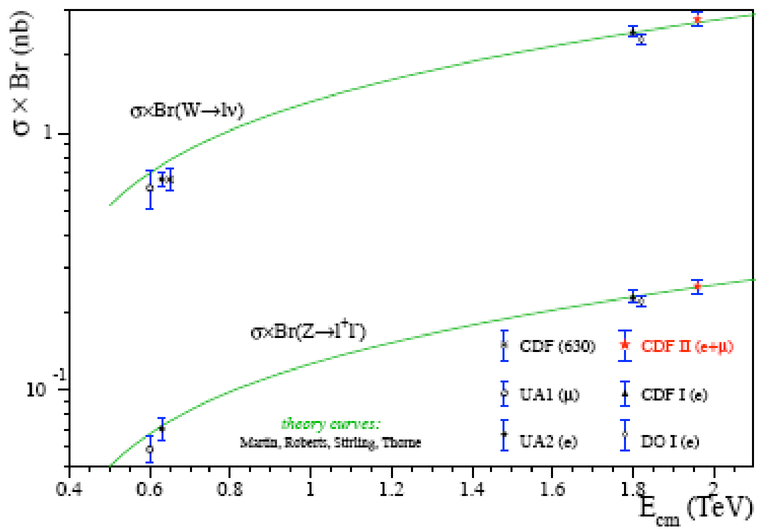
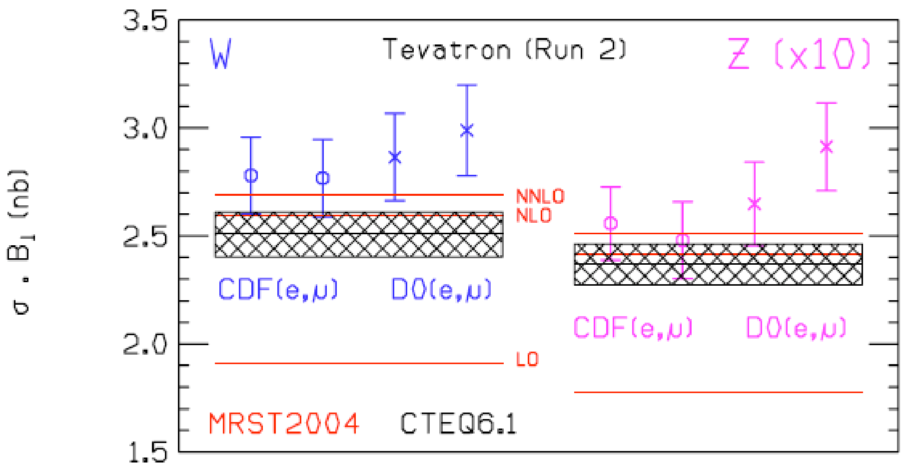


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.

W/Z at the Tevatron

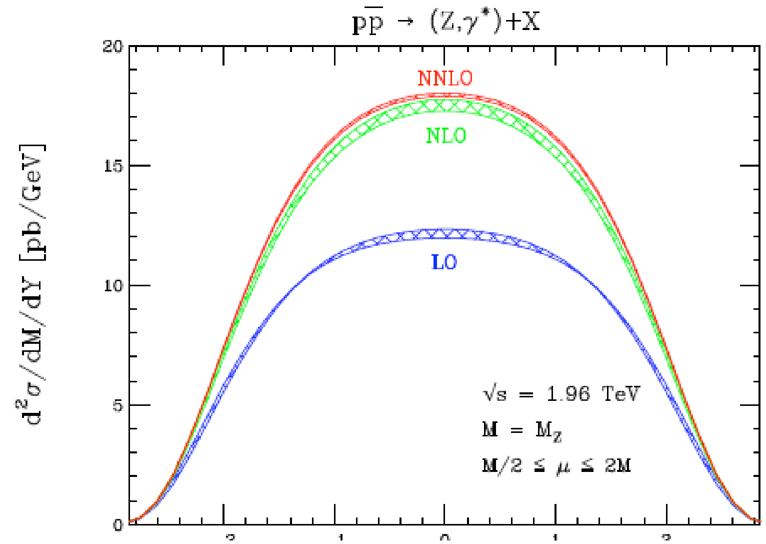
- W/Z cross sections serve as precision physics monitors
  - all cross sections at LHC could be normalized to W/Z
- Both experimental and theoretical errors are under control
  - NNLO a small (positive) correction to NLO
- Note that CTEQ and MRST NLO predictions agree within CTEQ6.1 pdf errors (but MRST at edge of CTEQ6.1 error band)

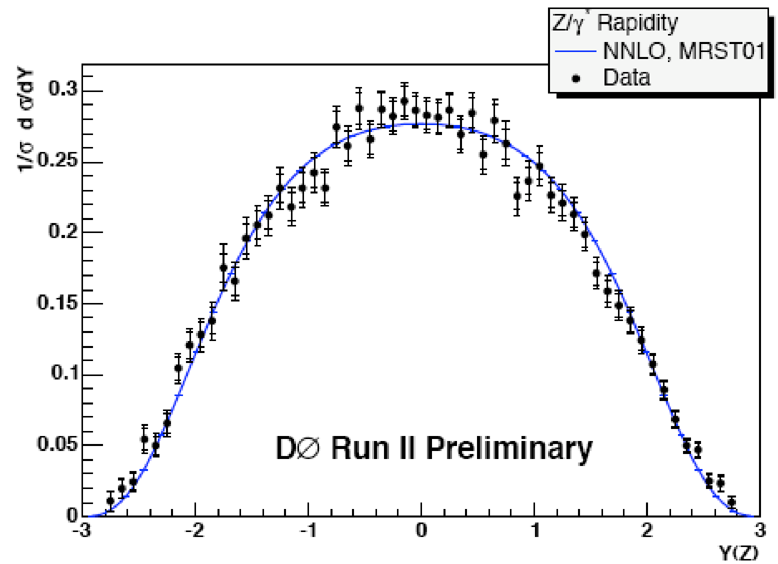




Rapidity distributions

- Little shape difference from NLO to NNLO
  - K-factor should be sufficient
- Z rapidity distributions could/will be used as input for pdf fits





p_T distributions

- Drell-Yan production serves as good benchmark for understanding ISR effects
  - applied in CDF to top mass uncertainty
  - should be extended to LHC

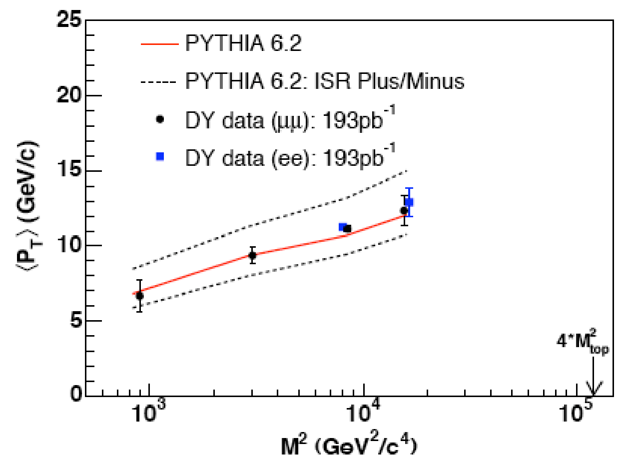


Figure 6. The average transverse momentum for Drell-Yan pairs from CDF in Run 2, along with comparisons to predictions from Pythia.

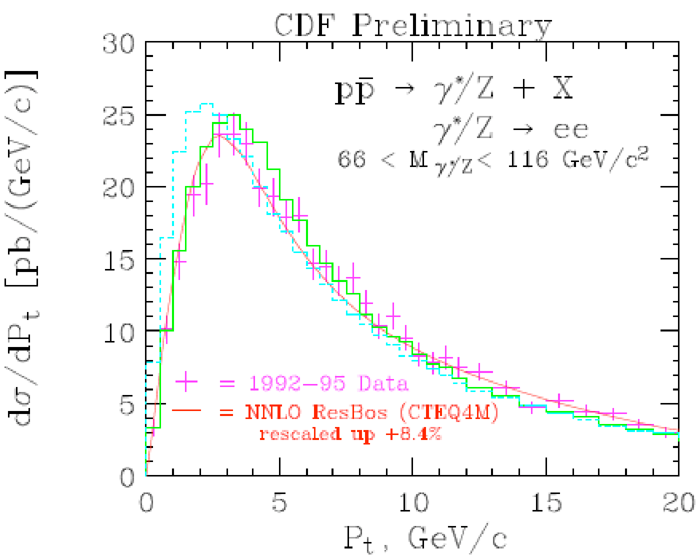


Figure 4. The transverse momentum distribution (low p_T) for $Z \to e^+e^-$ from CDF in Run 1, along with comparisons to predictions from Pythia and ResBos. The Pythia solid-green curve has had an additional 2 GeV/c of k_T added to the parton shower.

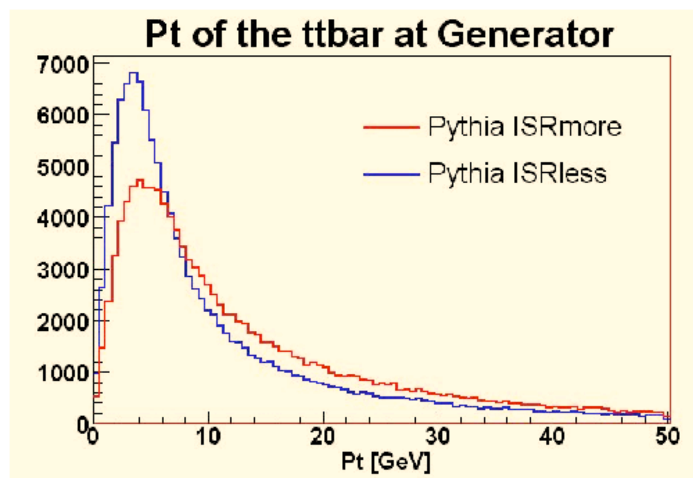
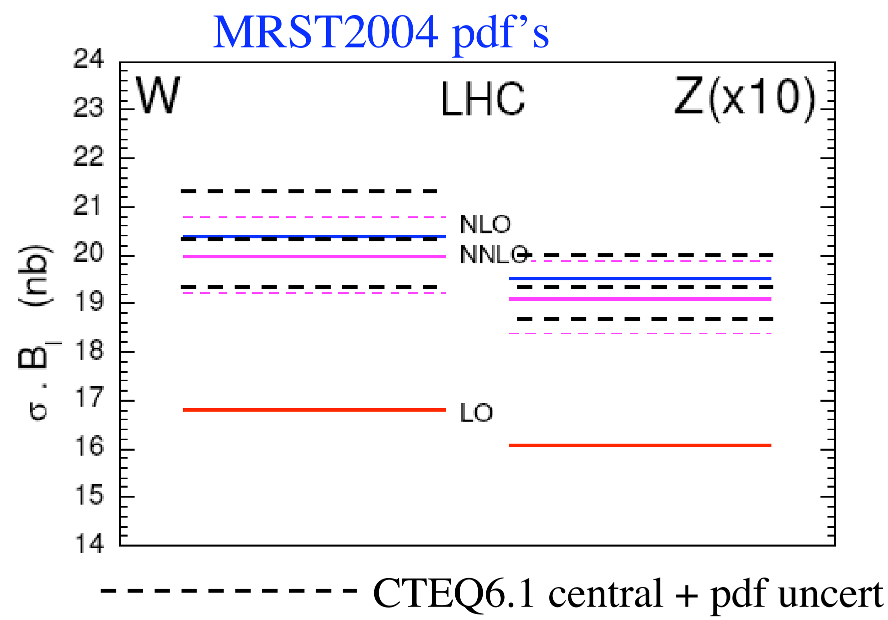
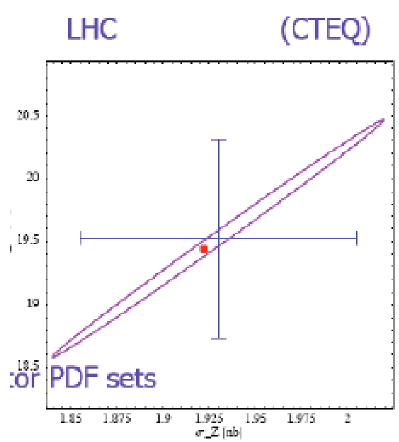


Figure 7. The Pythia predictions for the $t\bar{t}$ transverse momentum using the 'Plus/Minus' tunes.

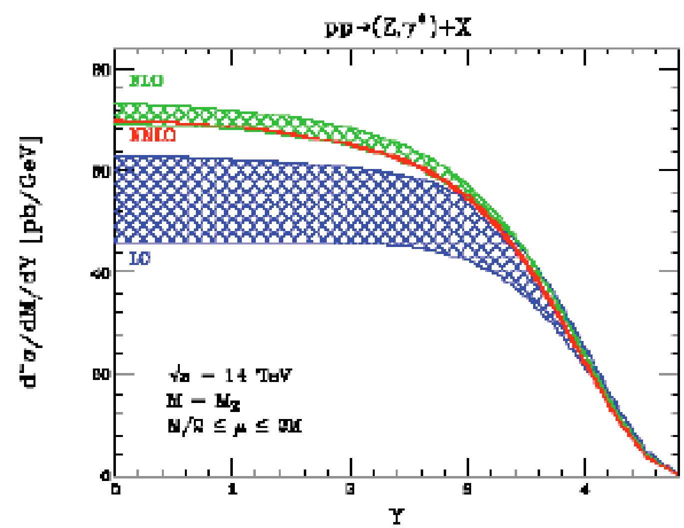
W/Z at the LHC

- Expect similar systematics, both experimental and theoretical, at the LHC for W/Z production as at the Tevatron, plus a huge rate current pdf uncertainties on order of 4-5%; should improve by LHC turn-on
- Very useful to use W/Z cross sections as luminosity monitor/cross section normalization, especially in early days before total inelastic cross section well-determined
  - W/Z cross sections highly correlated vis a vis pdf uncertainties



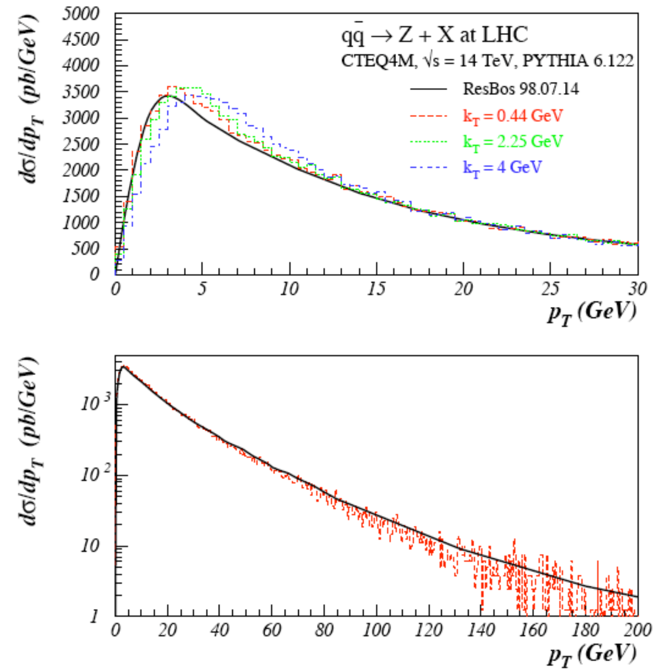


  - W/Z rapidity distributions known to NNLO



W/Z at the LHC

- p_T distribution of W/Z/decay leptons should be well-described by pQCD using DGLAP, as in ResBos, a resummation program
  - should peak at a few GeV, similar to Tevatron
- I've generated a million W->eν and Z->ee events for each of the CTEQ6.1 error pdf's
  - currently ROOT ntuples on CASTOR at CERN for use by ATLAS (castor/cern.ch/atlas/project/smgroup/ResBos
- Note that there may be additional effects for transverse momentum distributions of W/Z at LHC due to low x resummation effects; and also due to photon emission
  - **one of the first steps at the LHC will be to understand the dynamics of W/Z production**



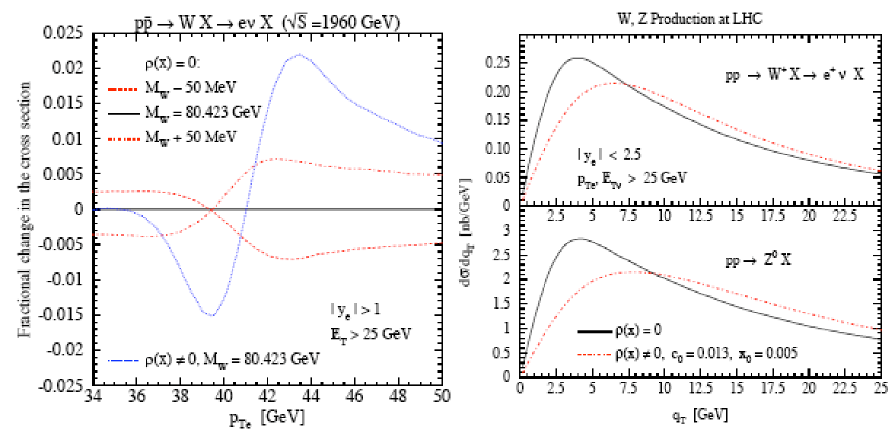
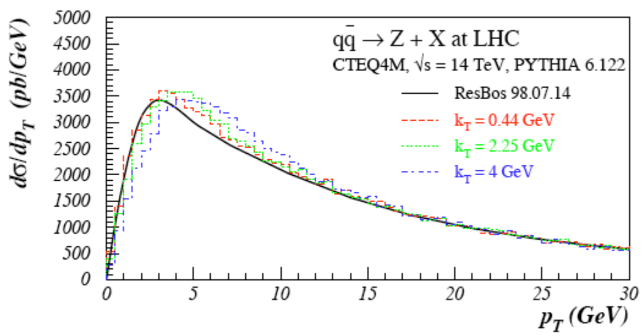


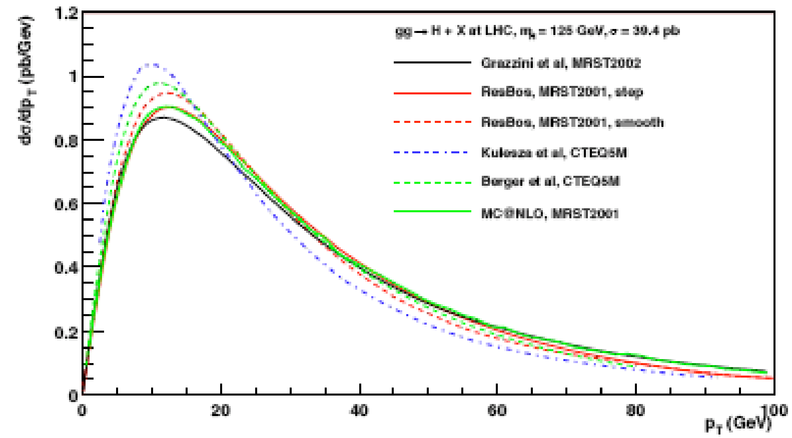
Figure 2. A) The fractional difference in the distribution $d\sigma/dp_{Te}$ for the forward-rapidity sample of electrons ($|y_e| > 1$) at the Tevatron. B) Transverse momentum distributions of (i) W^+ bosons and (ii) Z^0 bosons at the Large Hadron Collider.

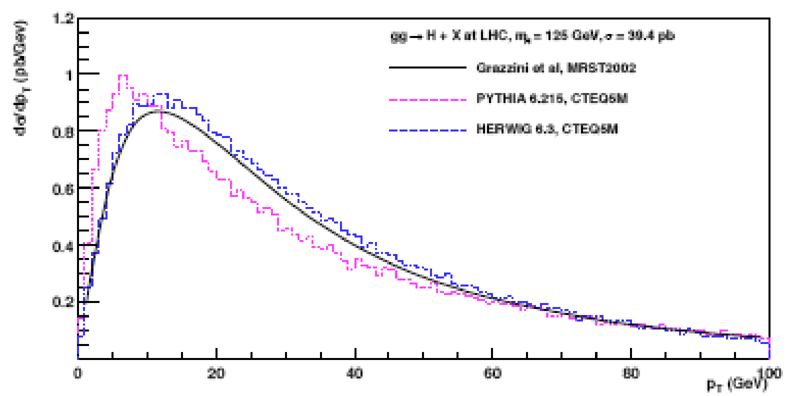
Aside: Higgs p_T at the LHC

- Note:
  - average p_T for Higgs production at the LHC much larger than average p_T for Z



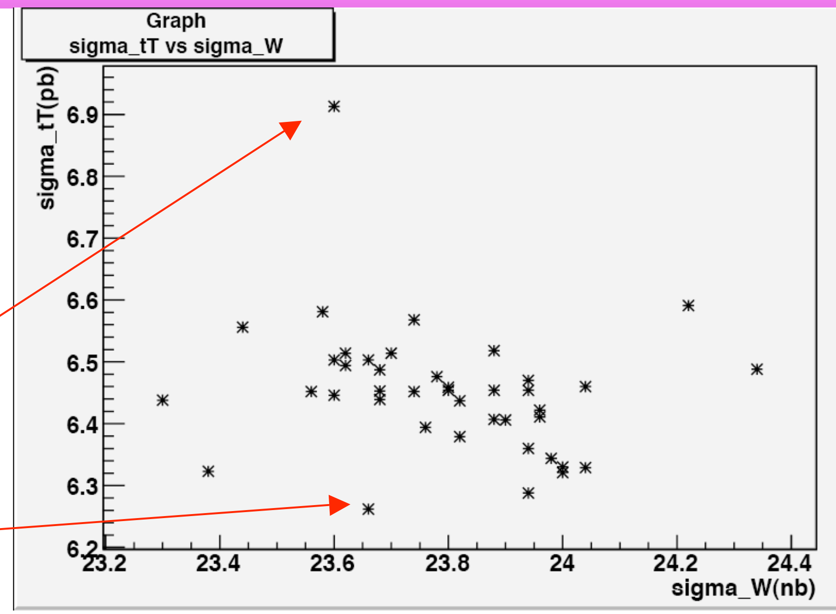
    - color factor of gluon compared to quark
    - z->0 pole in gluon splitting function
  - predictions are in reasonable agreement with each other
  - Pythia with virtuality-ordered shower peaks lower, but the new p_T-ordered shower agrees with the other predictions (comparison to come)

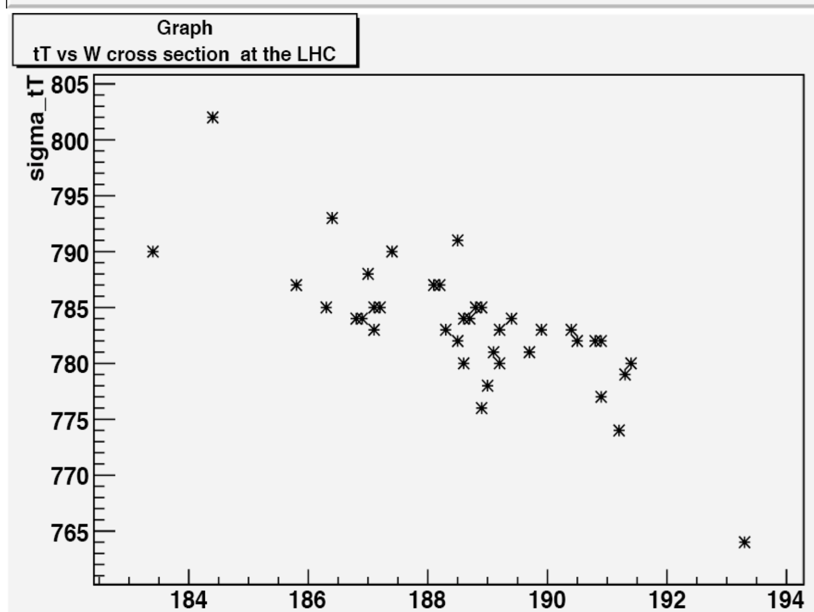




Top vs W cross section

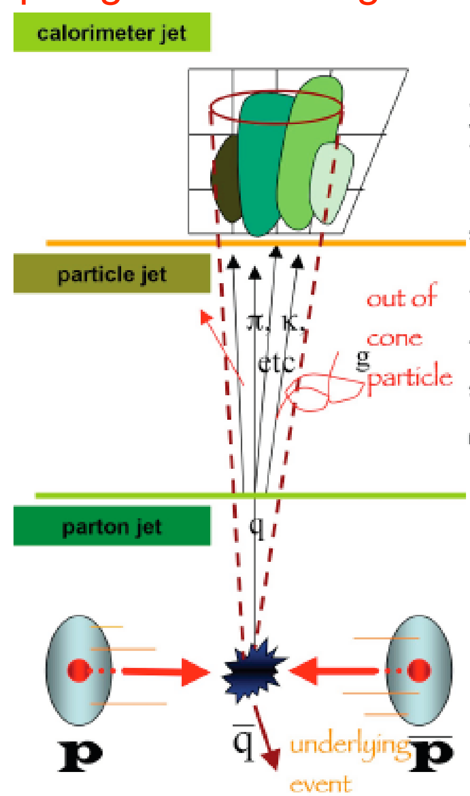
- Plot predictions for 40 error pdf's (CTEQ6.1) for top and W cross sections at the Tevatron and LHC
- Not much correlation at Tevatron
  - big excursions caused by eigenvector 15; high x gluon
- More anti-correlation at LHC; more momentum for gluons, less for sea quarks (at lower x) that produce W's





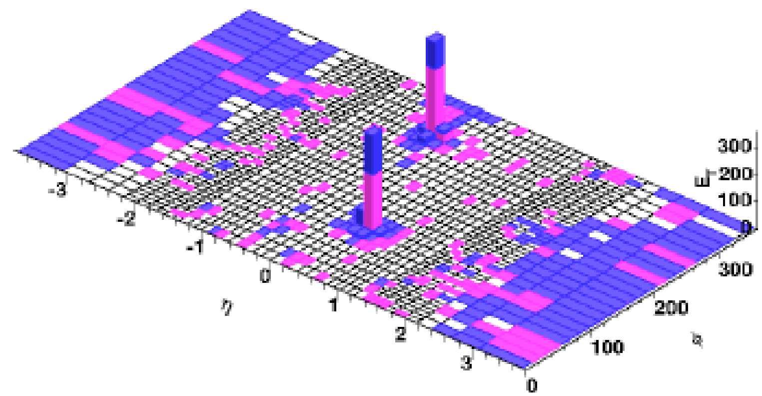
Jet algorithms

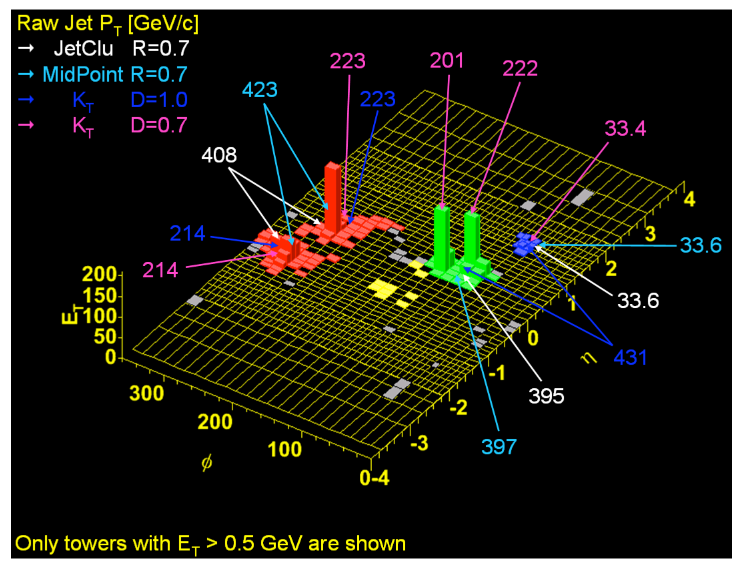
- To date, emphasis in ATLAS and CMS has been (deservedly so) on jet energy calibration and not on details of jet algorithms
- But some attention to the latter will be necessary for precision physics
  - big controversies at Tevatron for example
- Big effort by CMS at Les Houches on this aspect
  - see benchmark webpages
  - www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html
- Some attention to this now at ATLAS, for both cone and k_T algorithms
- An understanding of jet algorithms/jet shapes will be crucial early for jet calibration in such processes as γ+jet/Z+jet
  - especially the interaction with topological clustering



Jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers 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





Midpoint algorithm

* Midpoint algorithm: cone algorithm (R=0.7) (clusters particles whose trajectories/towers are close together). In contrast to JetClu's use of E_T and η, Midpoint uses p_T and ~~ϕ~~ y

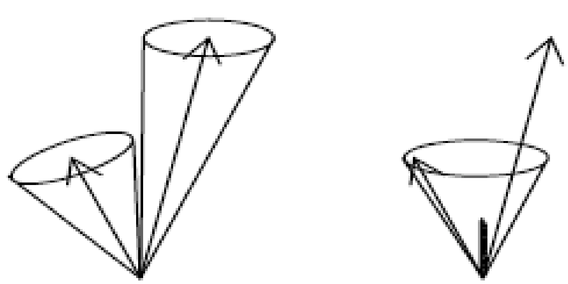
* Need to do this consistently at parton, hadron and calorimeter level.

* Calor Jets: begin with 1 GeV seed towers† $\rightarrow$ cluster towers ($P_T >$ 100MeV) into a centroid if $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta Y)^2} < 0.7$.

* Start new search cones at the midpoints of stable cones‡

* Overlapping jets- merge jets if overlapping energy is $>$ 0.75 the energy of the smaller jet

* Calculate jet quantites from final stable cones: P_T, ~~E_T~~, Y, ϕ etc



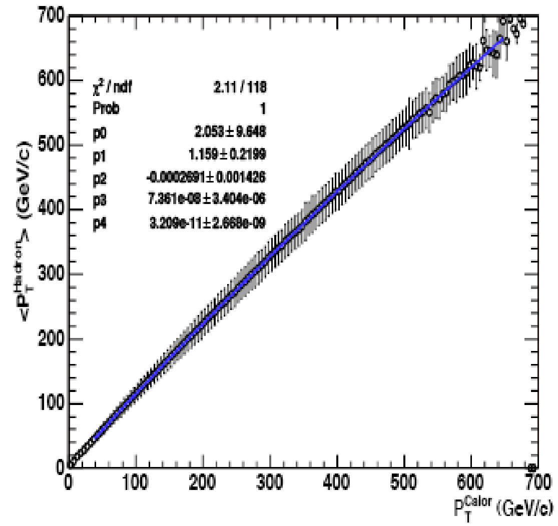
† Clustering begins around seeds, presence of soft radiation can cause merging of jets

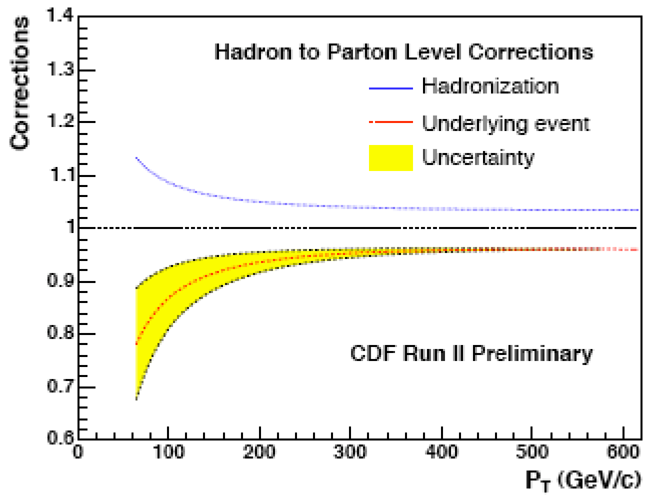
* Ideally algroithm is insensitive to soft radiation.

‡ Addition of midpoints lessens the sensitivity

Jet Corrections

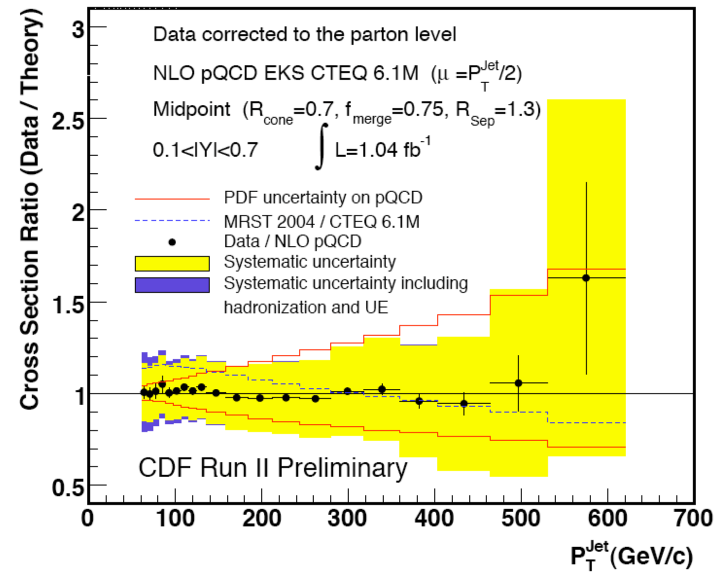
- Need to correct from calorimeter to hadron level
- And for
  - underlying event and out-of-cone for some observables
  - resolution effects
  - hadron to parton level for other observables (such as comparisons to parton level cross sections)
    - can correct data to parton level or theory to hadron 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

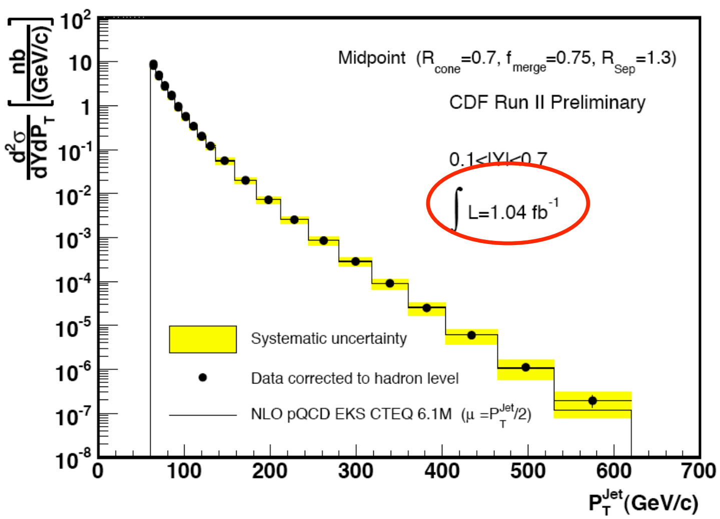


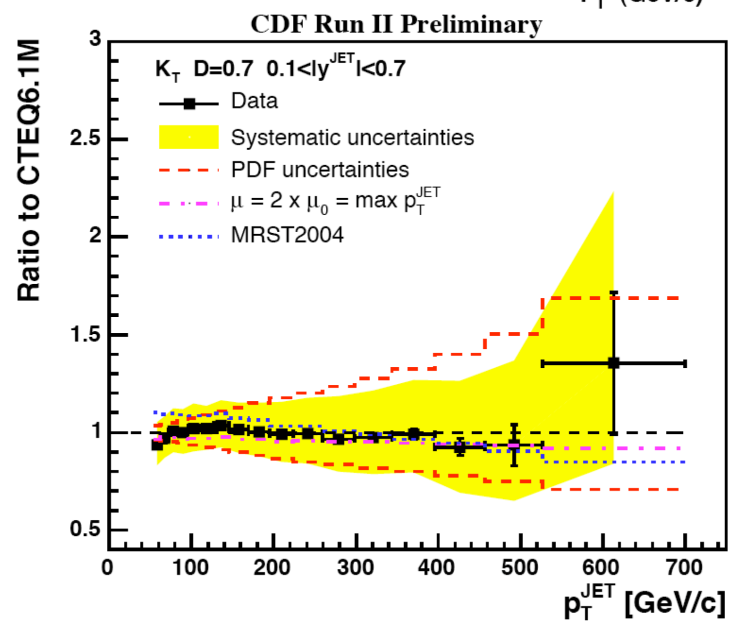


CDF Run 2 results

- CDF Run II result in good agreement with NLO predictions using CTEQ6.1 pdf's
  - enhanced gluon at high x
  - I've included them in some new CTEQ fits leading to new pdf's
- …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

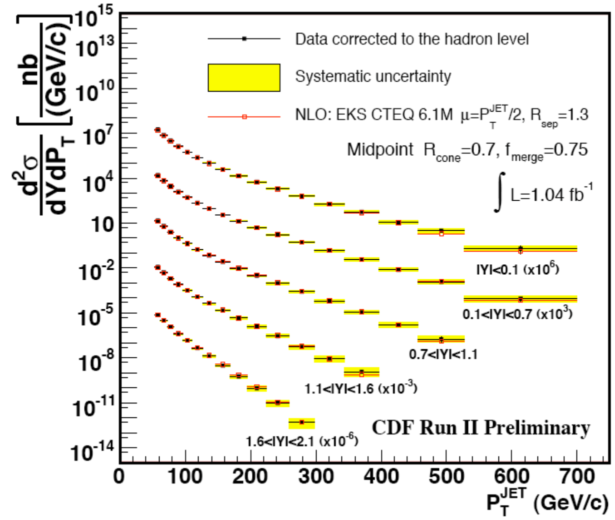


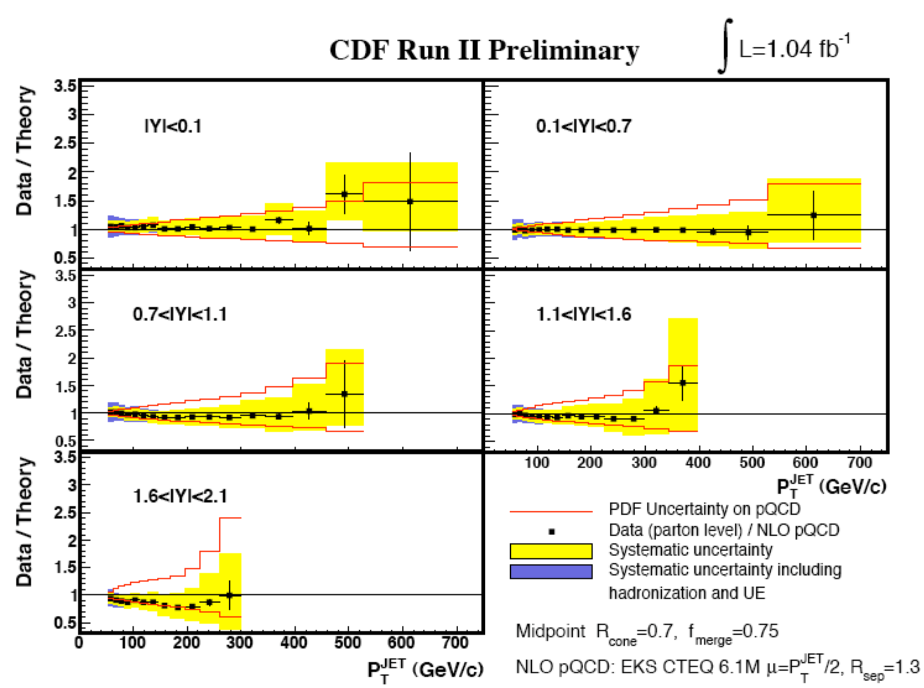




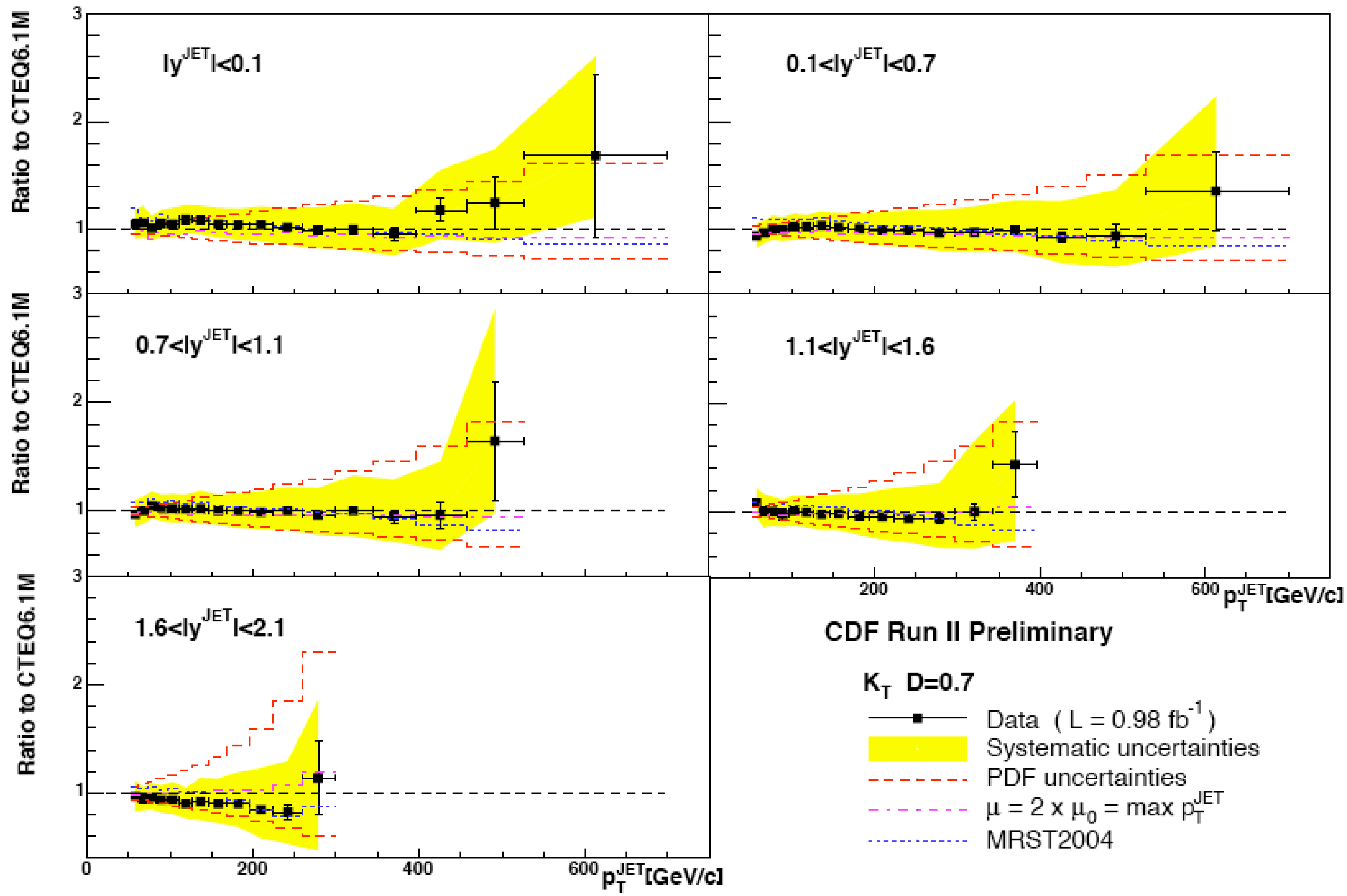
CDF Run 2 cone results

- Precise results over a wide rapidity range
- 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?





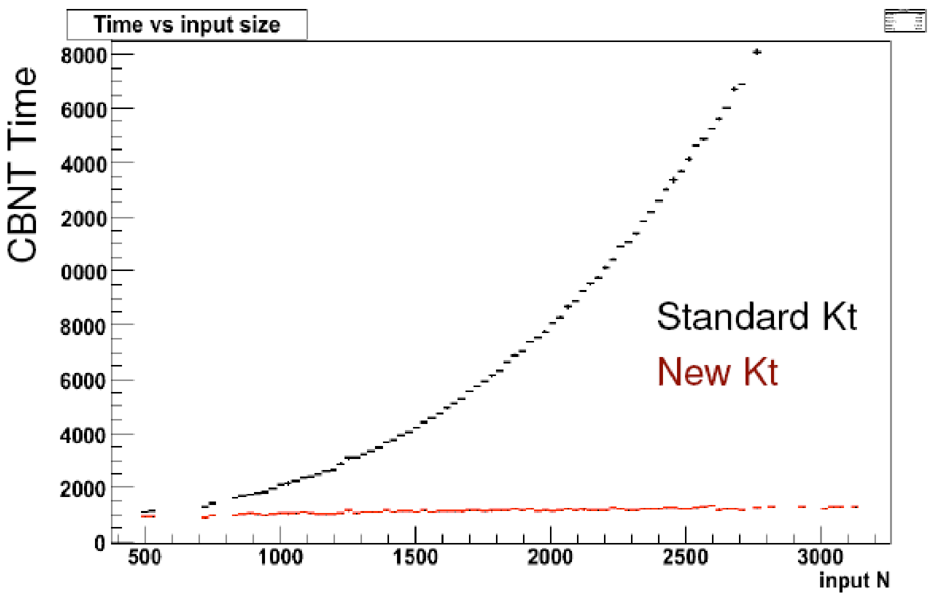
Forward jets with the k_T algorithm



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
  - should be useful for LHC
  - already implemented in ATLAS
- Optimum is if analyses at LHC use **both** cone and k_T algorithms for jet-finding



So what’s the problem(s)

- Matching a cone algorithm at (NLO) parton level and at detector level
- Parton configurations that will be included in a jet at NLO will not be at hadron level due to stochastic smearing because of parton showering/hadronization

•$z = p_T^{jet2}/p_T^{jet1}$; $d = \Delta R$ between partons
•At NLO; two partons within region I or II will be called one jet
•R_{sep} parameter was introduced into the theory because experiment reconstructs separate jets if $\Delta R > R_{sep} * Rcone$

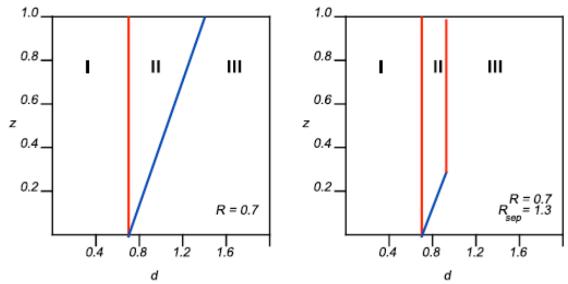


Figure 15. The parameter space (d,Z) for which two partons will be merged into a single jet.

midpoint seed was intended to remove need for R_{sep} …but it’s smearing not seeds

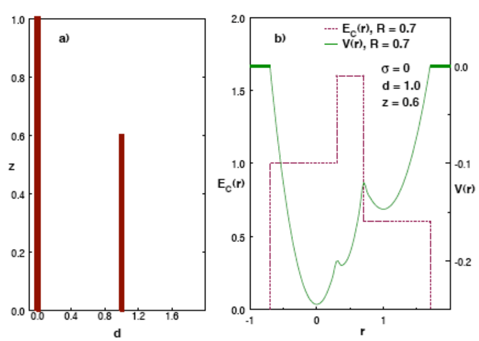


Figure 18. A schematic depiction of a specific parton configuration and the results of applying the midpoint cone jet clustering algorithm. The potential discussed in the text and the resulting energy in the jet are plotted.

have lost central solution (both partons) and right solution… some energy ends up unclustered in any jet

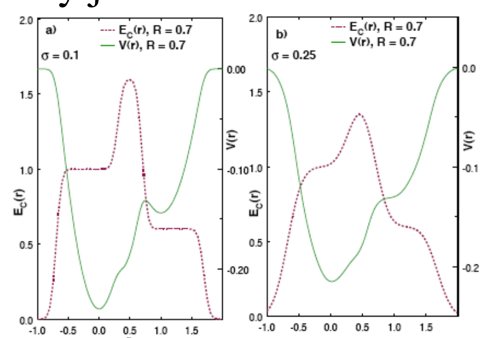
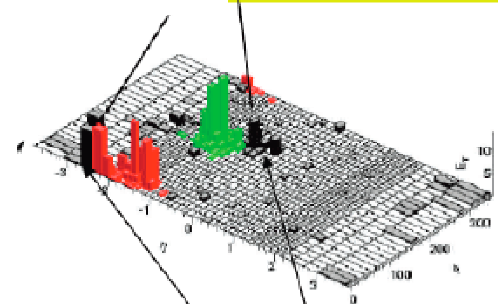
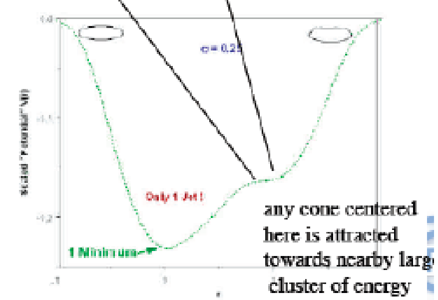


Figure 19. A schematic depiction of the effects of smearing on the midpoint cone j clustering algorithm.





Some major silliness

- Matching a cone algorithm at (NLO) parton level and at detector level
- Parton configurations that will be included in a jet at NLO will not be at hadron level due to stochastic smearing because of parton showering/hadronization
- Modified midpoint algorithm uses smaller initial search cone (R/2), reduces unclustered energy
  - recovers right solution, but in most cases not central
    - i.e. R_{sep} still needed
  - default midpoint algorithm has ~2% of 400 GeV/c dijet events with >50 GeV/c of unclustered energy
- **All cone algorithms are IR-sensitive**
  - D0 version of midpoint algorithm has IR-sensitivity <1%
  - CDF version has IR-sensitivity of ~1%
    - but essentially no unclustered energy
- **Both algorithms are IR-safe**

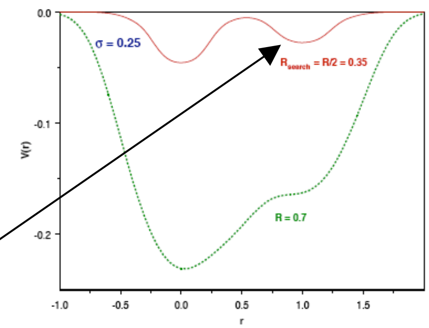
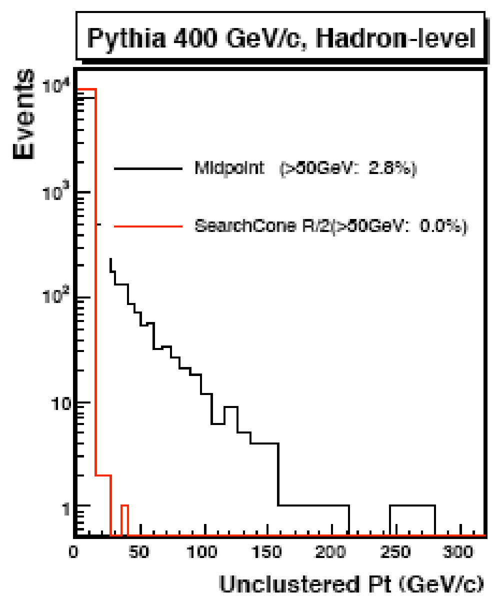
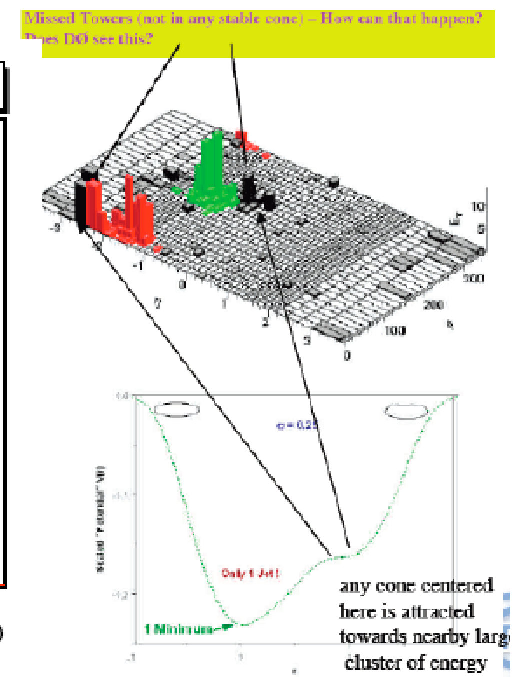


Figure 20. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm and the result of using a smaller initial search cone.





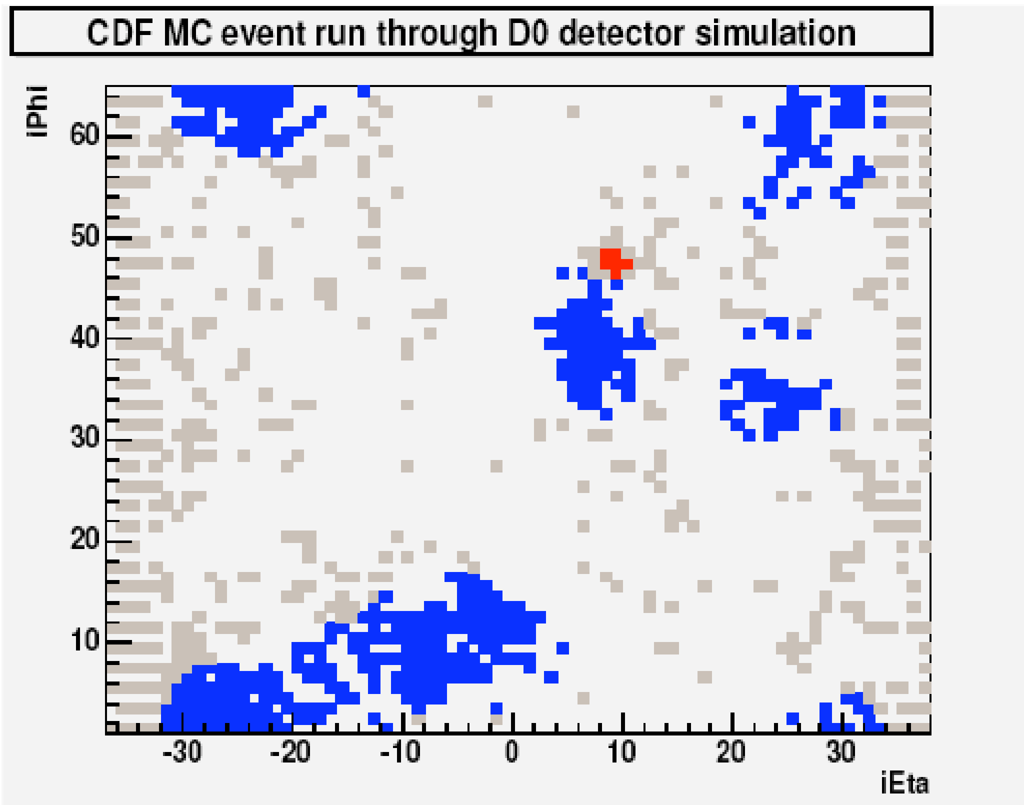
Jet algorithms

- The idea of the mid-point cone algorithm was to
  - provide more perturbative stability for the theoretical calculations
  - provide a jet algorithm common to CDF, D0 and theorists
- But to the strong disappointment of at least one theorist, CDF and D0 are using different implementations of the midpoint algorithm in Run 2
  - CDF is using the smaller initial search cone; D0 is not
    - CDF cross sections will be 5% larger than D0
  - in addition, CDF is using R_{sep} of 1.3; D0 is using 2.0
    - D0 theory will be 5% larger than CDF theory
- So if CDF and D0 were to measure exactly the same events, they would report their relation to NLO theory as being different by 10%

We are planning a meeting(s) between ATLAS, CMS and theorists to try to avoid this for the LHC

D0 report at the TeV4LHC meeting at CERN

- To address CDF observation of unclustered E_T



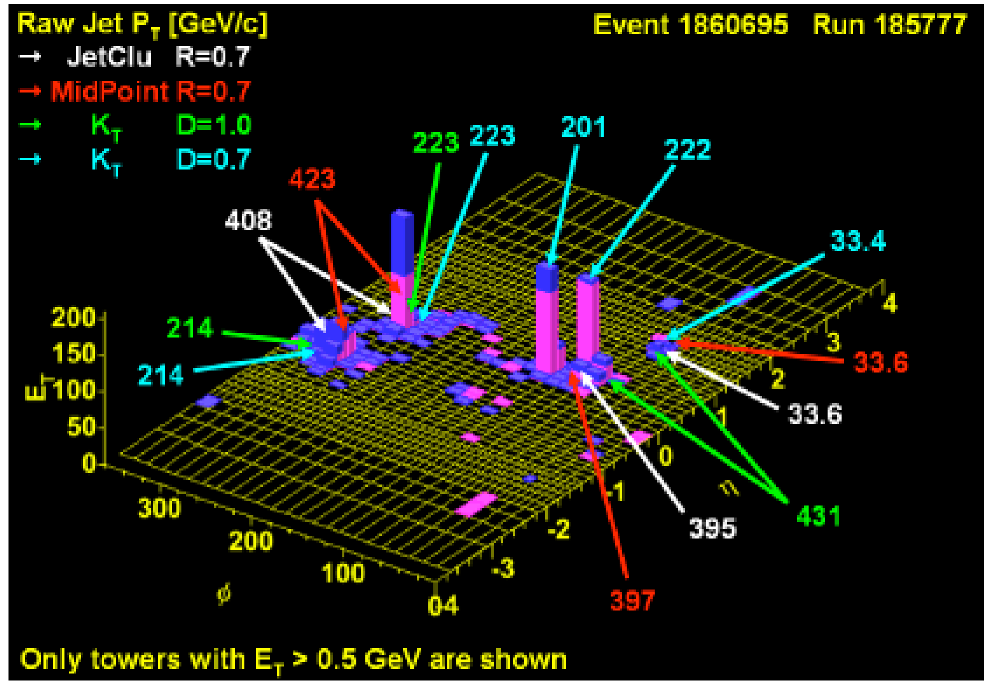
- RunII cone $R = 0.7$
- **Jet** towers
- **Unclustered** towers $pT < 2GeV$
- **Unclustered** towers $pT > 2GeV$

We see it too!

What about ATLAS and CMS? Currently investigating.

Can't we all just get along?

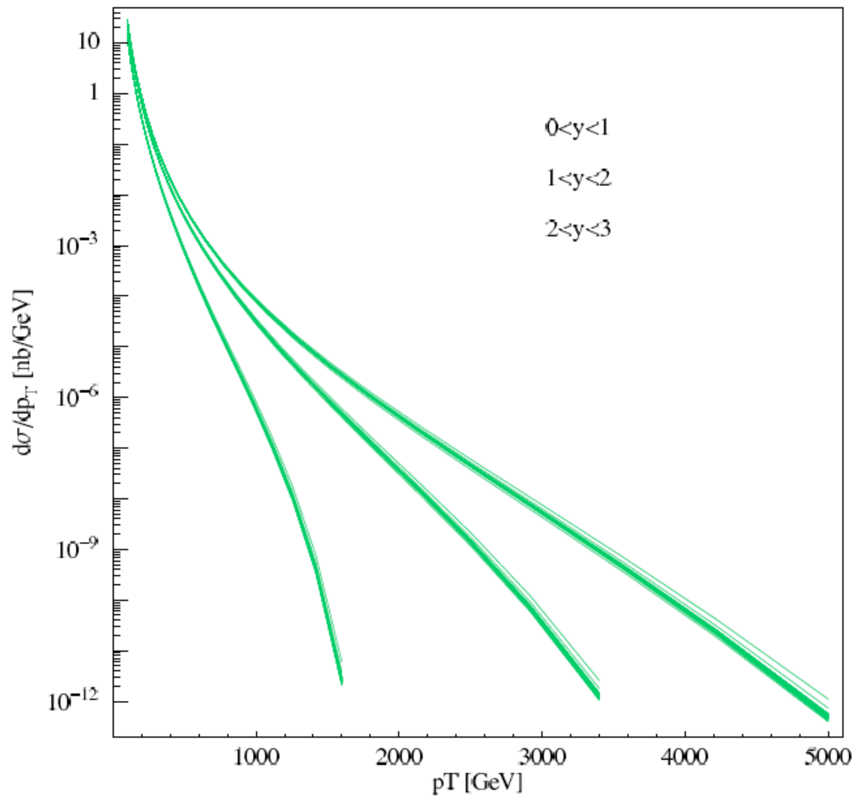
- I still believe that at the LHC, need both k_T and cone jet algorithms
- I'm working now on a version of the jet cone algorithm that matches as closely as possible seedless pQCD
  - trying to bypass both Scylla and Charybdis



- Trying to summarize/think for TeV4LHC writeup
- Further discussion this summer

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.



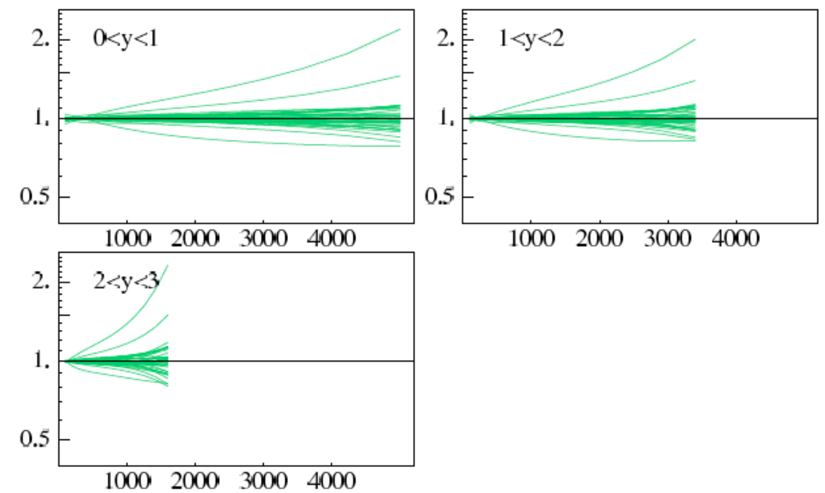


FIG. 31: The uncertainty range of the inclusive jet cross section at the LHC. The curves are graphs of the ratios of the cross sections for the 40 eigenvector basis sets compared to the central (CTEQ6.1M) prediction (ordinate) versus p_T in GeV (ordinate).

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

- γ+jet balancing
- dijet balancing

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

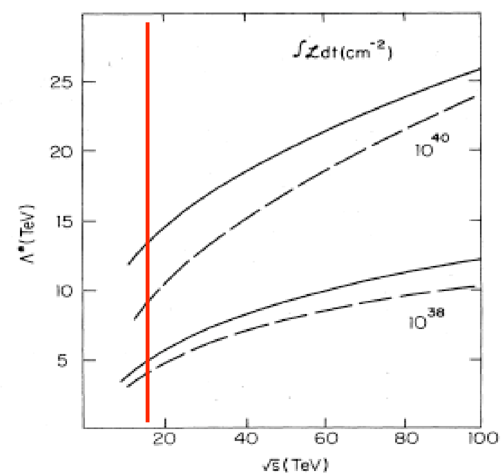
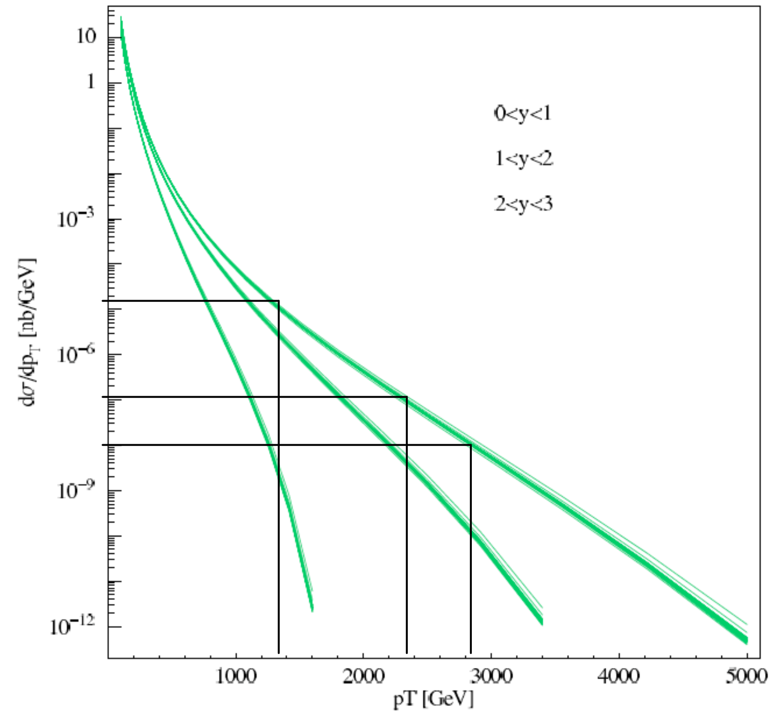
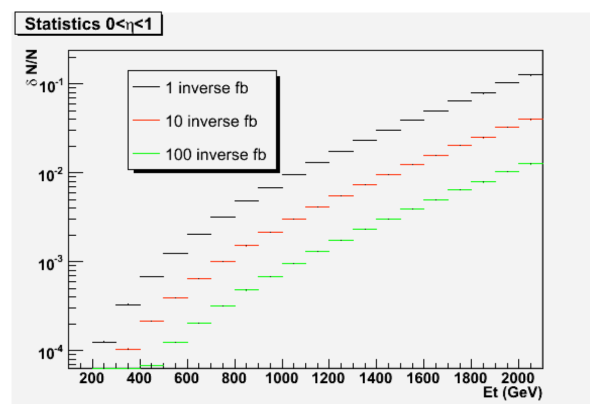


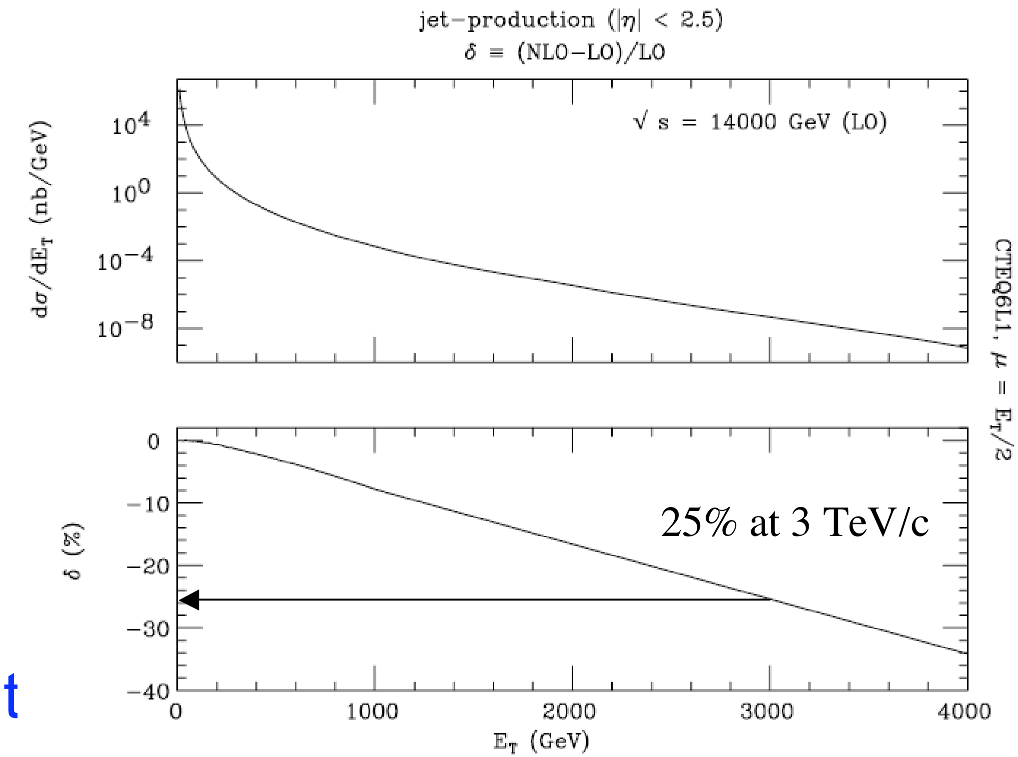
FIG. 236. Maximum compositeness scale Λ^* probed in jet production at $y=0$ in pp collisions as a function of $\sqrt{s}$ for integrated luminosities of 10^{40} and 10^{38} cm^{-2} according to the criterion (8.18). $\eta_0=-1$ (solid lines), $\eta_0=+1$ (dashed lines).





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 $\alpha_W \log^2(E_T^2/M_Z^2)$
- Confirmation is important
- Other (unsuspected) areas where weak corrections are important?



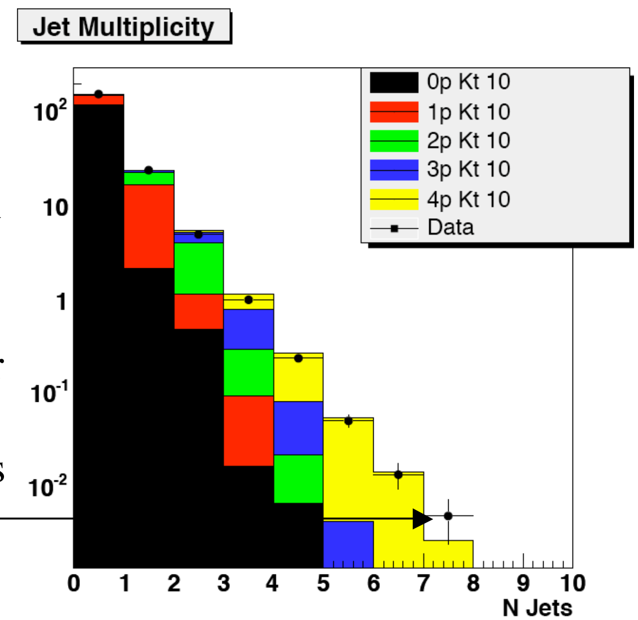
In *Rumsfeldese*, this is now one of the "known unknowns".
What are our unknown unknowns?

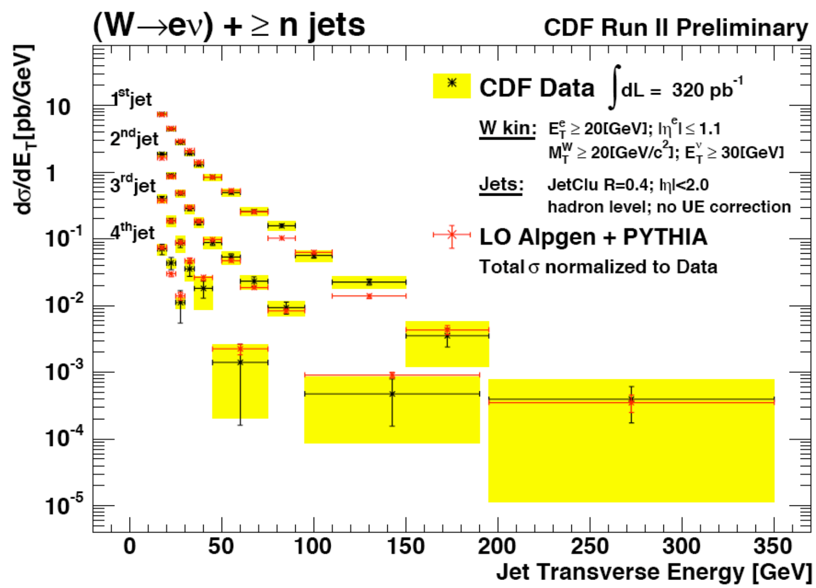
W + jets at the Tevatron

- 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**
  - see www-cdf.fnal.gov QCD webpages
  - in process of comparing to MCFM and CKKW predictions
  - *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





Pop quiz

- What's the difference between the diagrams on the top and bottom?
- Answer: nothing, just a matter of convention
- Myth: ISR is peaked at forward rapidities

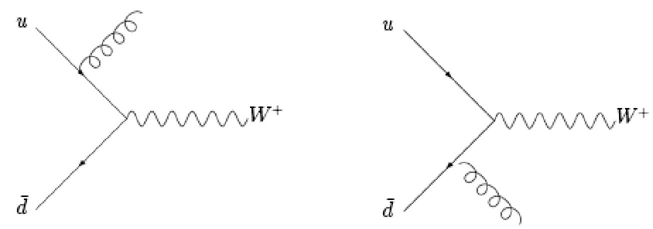


Figure 1. Lowest order diagrams for the production of a W and one jet at hadron colliders.

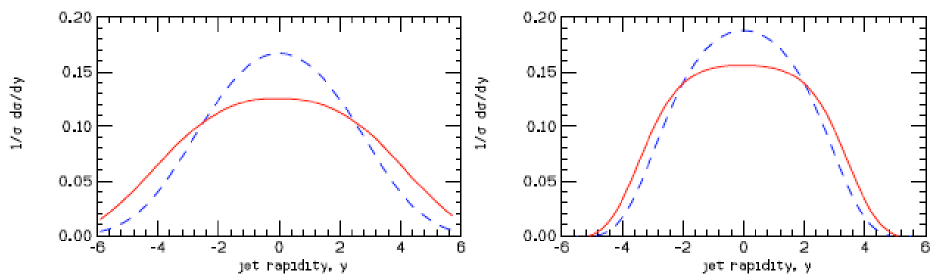


Figure 2. The rapidity distribution of the additional parton found in the real radiation corrections to Drell-Yan production of a W at the LHC. The parton is required to have a p_T larger than 2 GeV (left) or 50 GeV(right). Contributions from $q\bar{q}$ annihilation (solid red line) and the qg process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

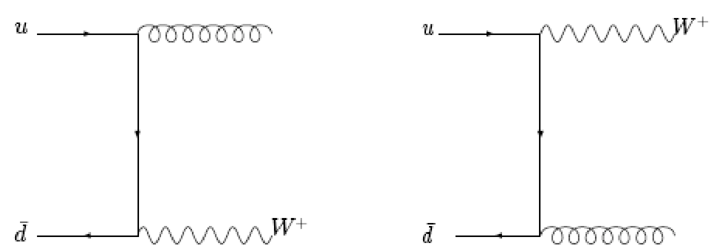


Figure 3. An alternative way of drawing the diagrams of Figure 1.

CKKW/MCFM

- 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)

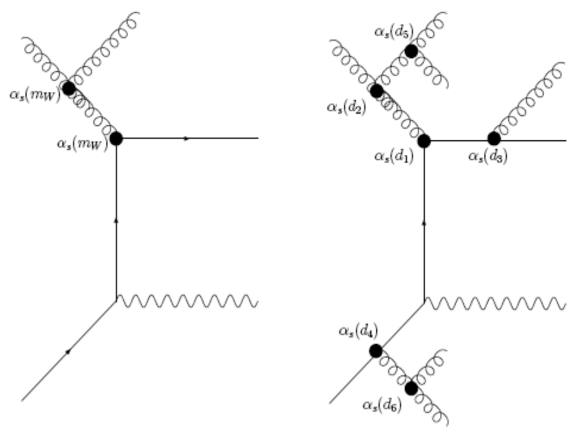
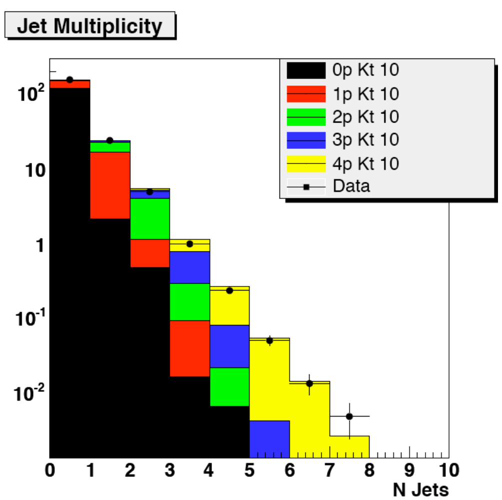


Figure 15. In the NLO formalism, the same scale, proportional to the hardness of the process, is used for each QCD vertex. For the case of the $W+2$ jet diagram shown above to the left, a scale related to the mass of the W boson, or to the average transverse momentum of the produced jets, is typically 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.

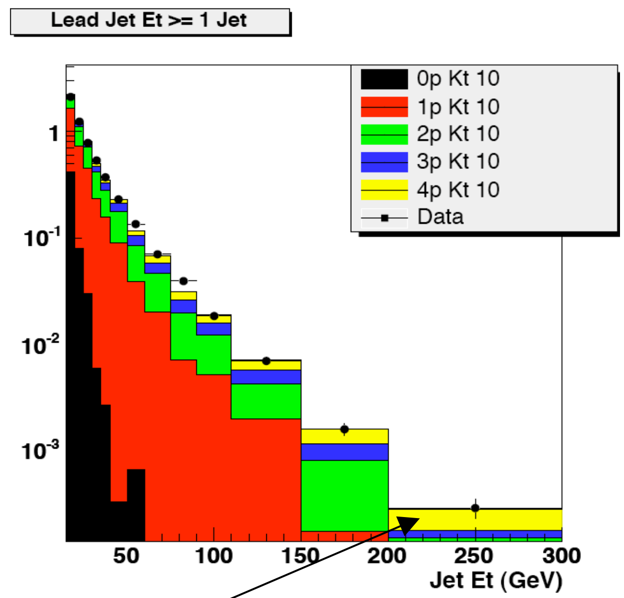
- Steve Mrenna generated a sample of W^+ + n jet events at the Tevatron using Madgraph + Pythia with the CKKW formalism and that's what has been used for a number of CDF studies
  - hep-ph/0312274 with Peter Richardson
  - plan is to compare to ALPGEN and Sherpa predictions

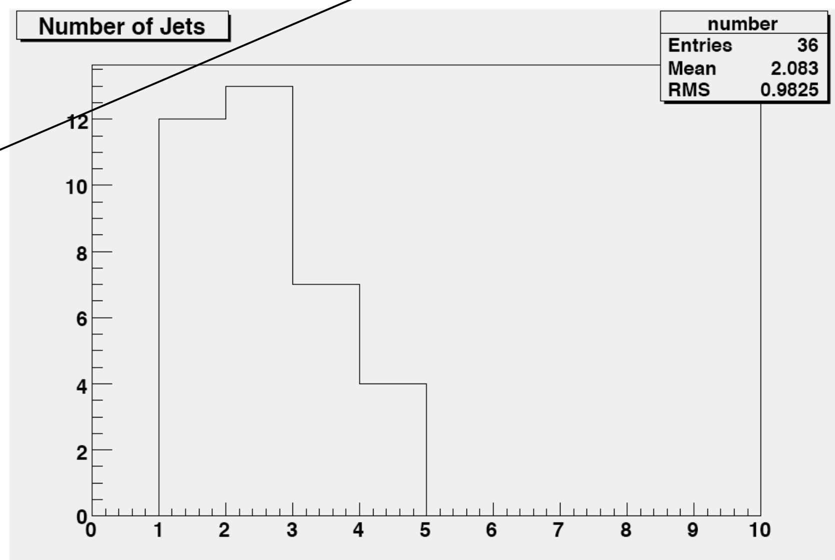


- MCFM calculates cross sections for W/Z/H(VBF) + 2 jets at NLO and the 3 jet cross section at LO (see also later)

(Thou shalt) Listen to the logs

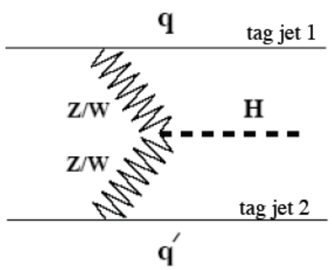
- Look at W + >= 1 jet events and require the lead jet to have >200 GeV/c transverse energy
- What is the average jet multiplicity (>15 GeV/c) for these events?
  - 2.1
- It's not just α_s anymore; there's now also a large log (E_T^{jet1}/15 GeV/c) involved
  - in CKKW formalism, most of cross section 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

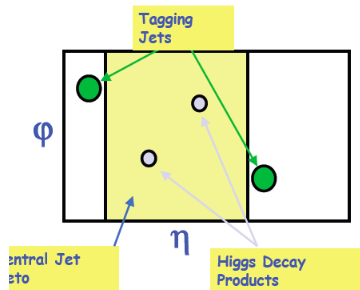




W + jets at the Tevatron and LHC

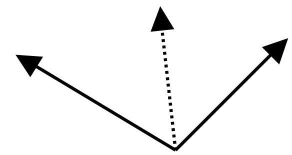
- One of the most promising channels for Higgs production at the LHC is through WW fusion

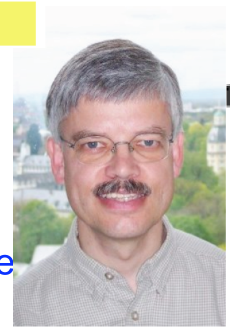




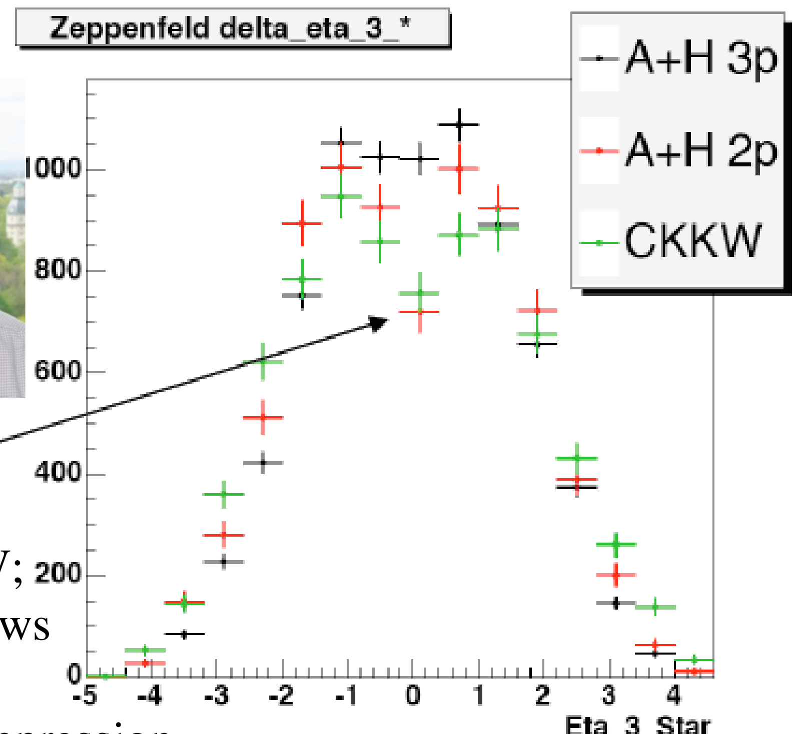
- Plan is to veto on backgrounds from Zjj by requiring no central jets (between tagging jets)
- Look at W + jets at the Tevatron as a way of testing central jet rate and distribution
  - analysis in progress; result will be absolute cross sections
- Extrapolate to LHC using MCFM and CKKW
  - study in progress with Bruce Mellado and Steve Mrenna

2 tagging jets F/B, $\Delta\eta>2$; look at relative rapidity of 3rd jet





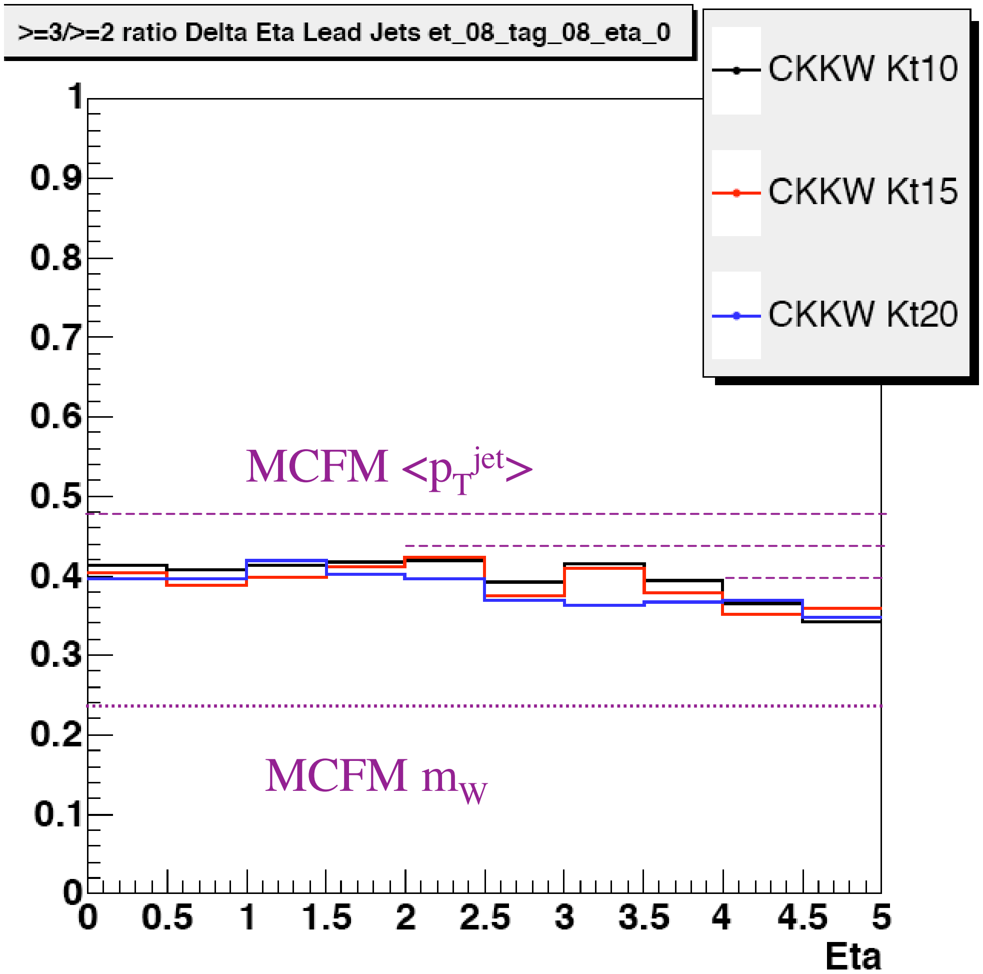
Tag jets > 8 GeV/c; 3rd jet > 8 GeV/c



note central dip with CKKW; CKKW knows about Sudakov suppression for central jet emission (so does data)

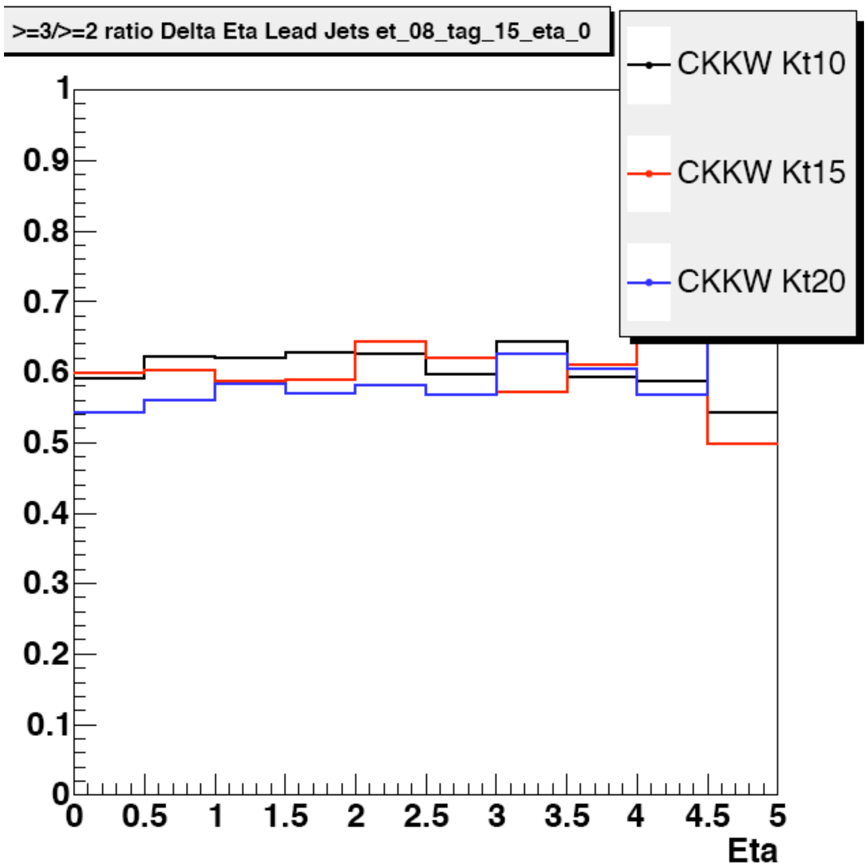
CKKW matching variation

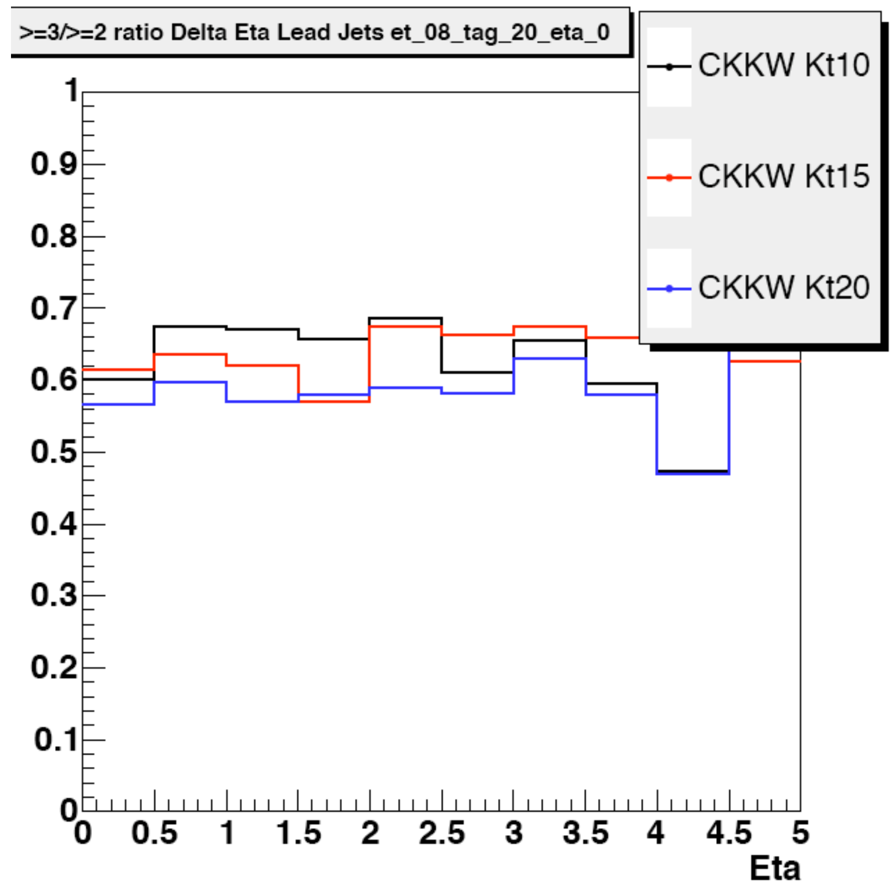
- Look at probability for 3rd jet to be emitted as a function of the rapidity separation of the tagging jets
- Relatively flat probability (although slightly decreasing at low Δη due to kinematic suppression), stable with CKKW scale
- Bracketed by two predictions for MCFM using m_W and $\langle p_T^{jet} \rangle$ as scales
- Data to be blessed soon



CKKW matching variation

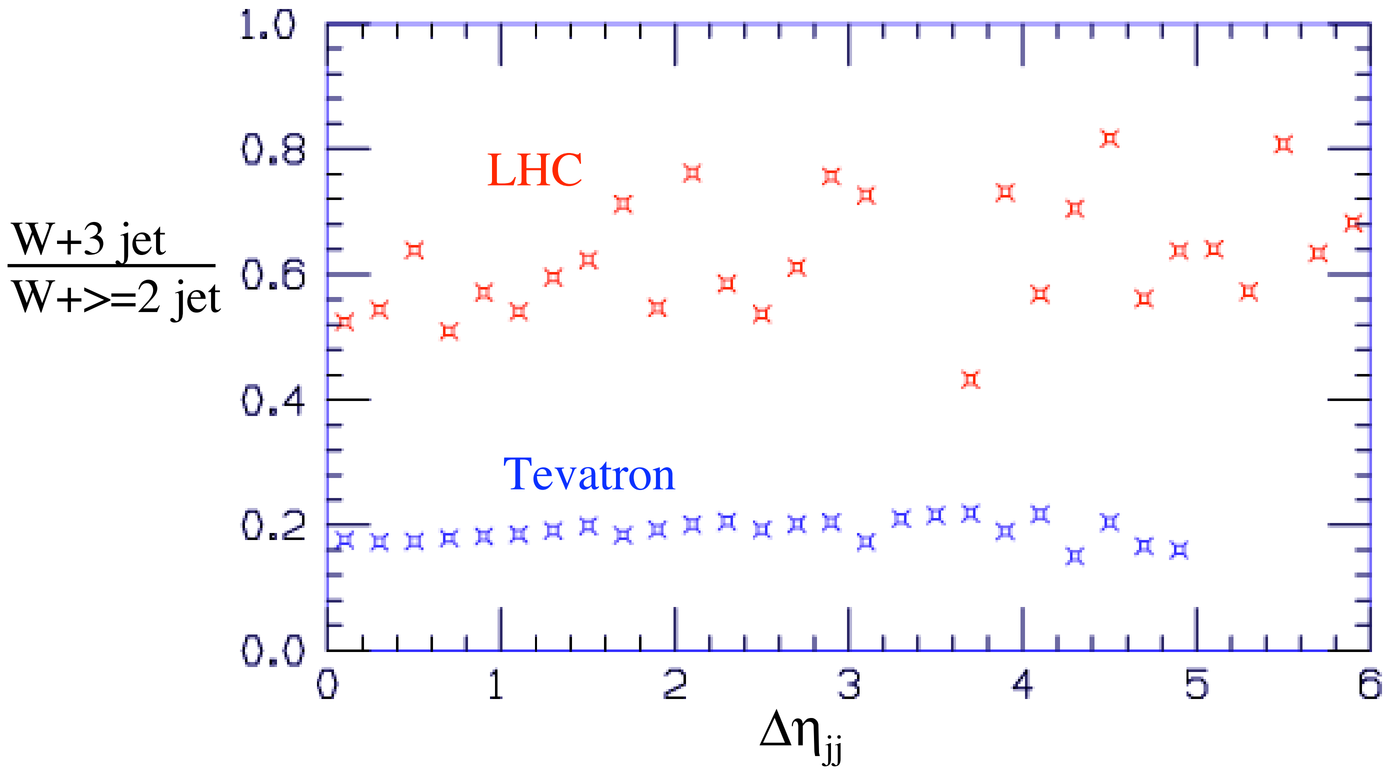
- Increase cut on tagging jet to 15/20 GeV/c
- Probability of jet emission increases





W + jets at LHC

- Look at probability for 3rd jet to be emitted as a function of the rapidity separation of the tagging jets
- At LHC, ratio (p_T^{jet}>15 GeV/c) much higher than at Tevatron
- CKKW comparison underway



Benchmark studies for LHC

- 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

Outline for paper

1. Introduction and Framework

2. 2->1 and 2->2 hard subprocesses at hadron colliders
   a. W/Z/Drell-Yan/Higgs
   b. High pT photon, jet, heavy flavor

3. Adding extra partons, real and virtual; cross sections and jet structures
   a. at LO (tree-level scattering amplitudes)
      i. increasing complexity of 2->n processes as n increases, # of diagrams, color factors
      ii. numerical implementations – Madevent, Alpgen, Sherpa
      iii. new techniques – MHV rules, recursion relations
   b. at NLO (K-factors, singularity cancellations, scheme dependence)
      i. loop and real diagrams, toy model for singularity cancellation
      ii. origin of reduced scale dependence
      iii. complexity of analytical calculations, dependence on # of legs, masses, tensor structure
      iv. new numerical methods (sector decomposition, numerical reduction ...)
      v. new analytical methods (cutting rules, sewing amplitudes)
      vi. examples
   c. at NNLO
      i. different contributions (2-loop, 1-loop/1 unresolved, 2 unresolved)
      ii. 2-loop calculations of 2->2 processes
      iii. bottleneck: generic integration of 2-unresolved contribution; solution for DY is to convert real integrals -> loop integrals
      iv. works for total inclusive, simple cuts on rapidity
      v. example (or already in Sec.2, 5?)
   d. at all orders (parton showers; analytic resummation)
   e. jet algorithms
   f. fragmentation and hadronization
   g. merging fixed order and parton shower predictions
      i. CKKW
      ii. mlm
      iii. connections between parton showers and NLO

general points:
-power counting (in alpha_s)
-where do logs come from? What are LL? NLL? What calculation has what?
-exact, leading pole and eikonal approximations
-color flow: different color flows interfere with each other giving rise to 1/Nc^2 terms that don't correspond to a unique color flow; interference terms not present in parton shower Monte Carlos

4. Parton distribution functions
   a. basics (symmetries, sum rules, small and large x behavior)
   b. global fits (LO, NLO, NNLO)
   c. uncertainties

5. Cross sections and uncertainties
   a. "rules of thumb"
      i. parton-parton luminosities and uncertainties for LHC
         1. effects of evolution
         2. LHAPDF and effective use of pdf uncertainties
      ii. LO vs. NLO vs. parton showers, e.g. regions of applicability
      iii. NLO corrections (K-factors); generalizations; edges of distributions where perturbation theory breaks down
   b. comparisons to Tevatron data
         1. W/Z sigma, y distributions
            a. LO, NLO, NNLO
         2. W/Z + jets
            a. LO+PS, NLO
            b. Zeppenfeld plots
         3. inclusive jet production
            a. jet algorithms revisited
            b. feedback to global fits
            c. fragmentation/UE corrections
   c. SM benchmarks for the LHC – where appropriate, include best theoretical cross sections, error estimates
         1. W/Z/DY as luminosity monitors
         2. UE predictions/uncertainties
         3. inclusive jet production
         4. W/Z + jets
         5. top
         6. Higgs
            a. gg->H
            b. WW->H
   d. new physics signatures and Standard Model backgrounds

6. Outlook: theory and experiment
   a. LHC
   b. NNLO
   c. Samper
   d. twistors

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
    - ongoing work, list of topics (pdf file)

Parton kinematics

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

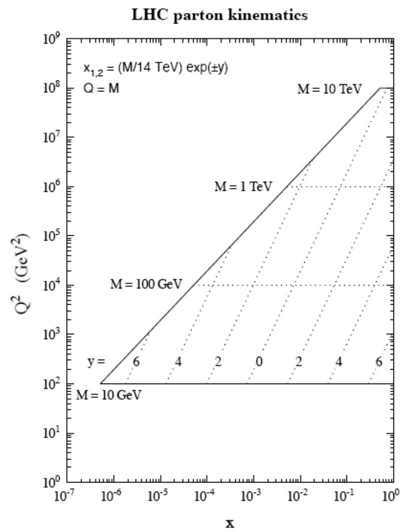


Fig. 1: Parton kinematics for the LHC.

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

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

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

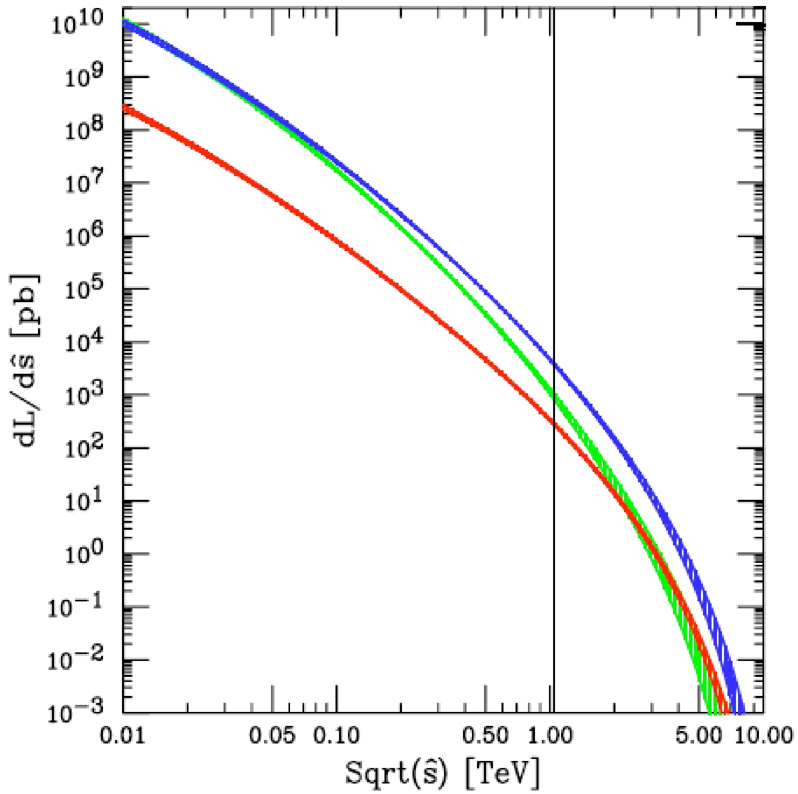
can then be written as

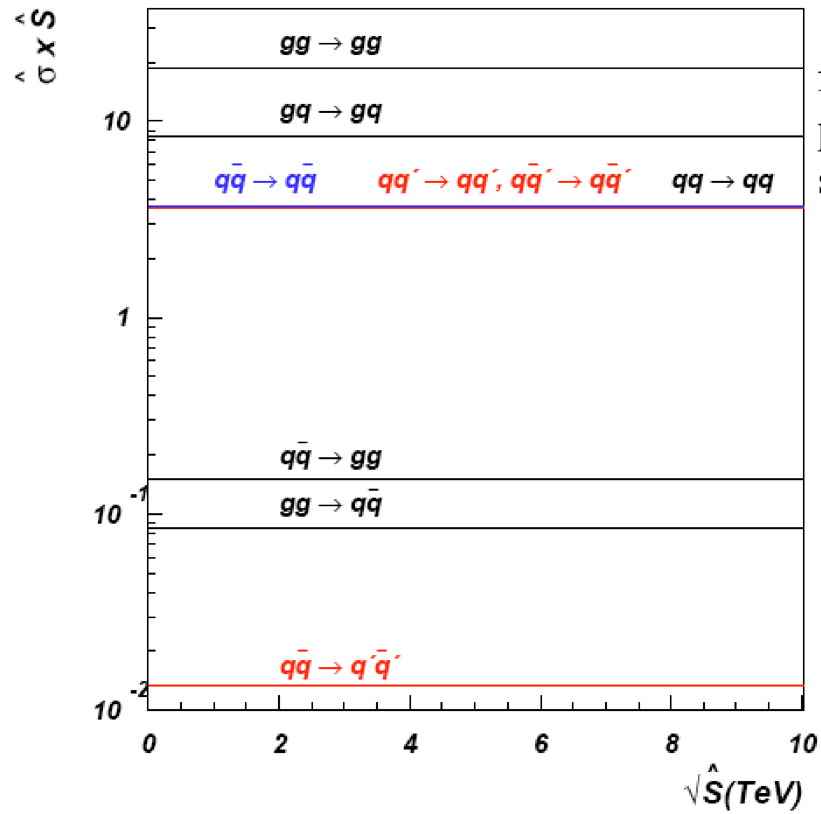
$$\sigma = \sum_{i,j}\int \left(\frac{d\hat{s}}{\hat{s}}\,dy\right)\left(\frac{dL_{ij}}{d\hat{s}\,dy}\right)(\hat{s}\,\hat{\sigma}_{ij}) \; . \tag{3}$$

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

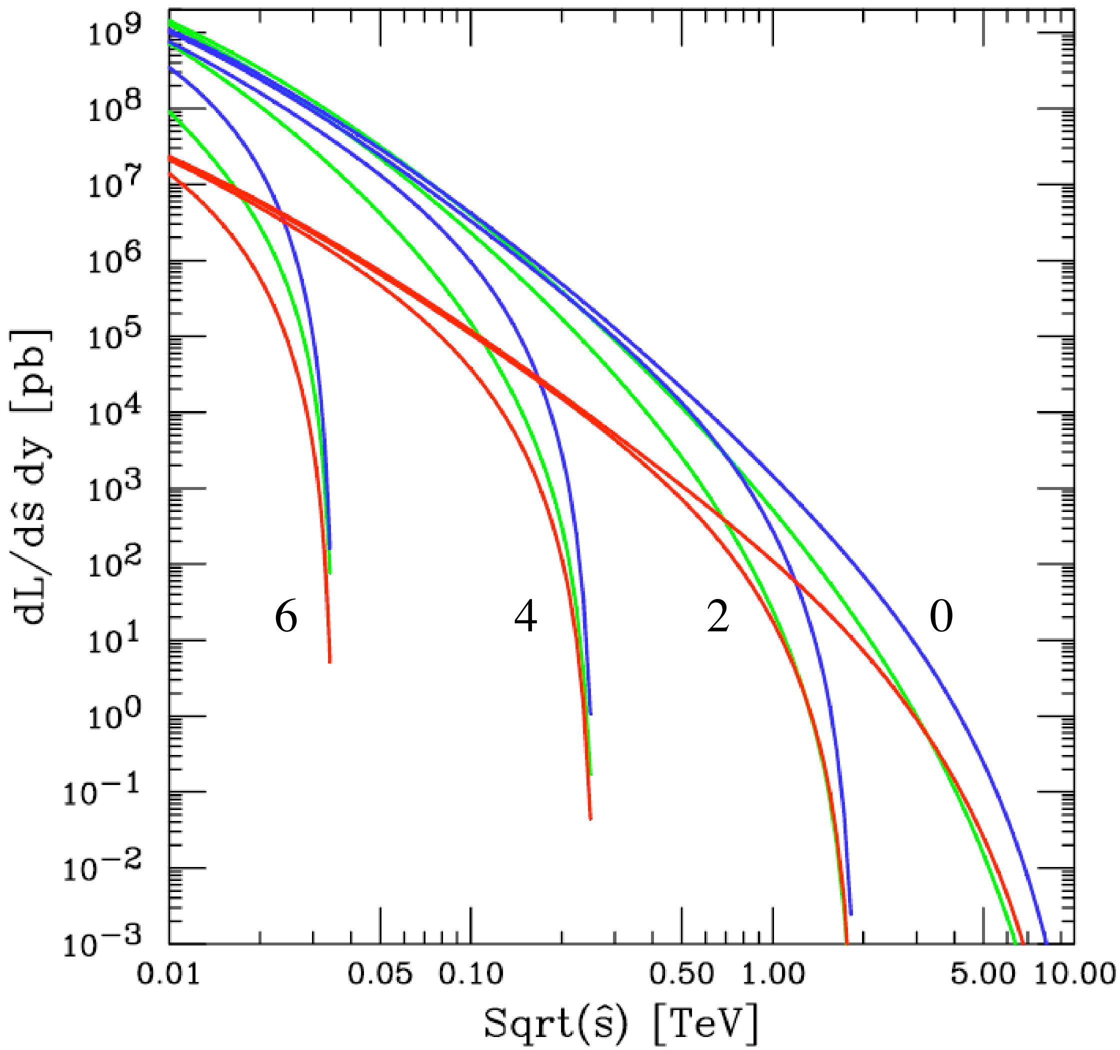


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

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 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

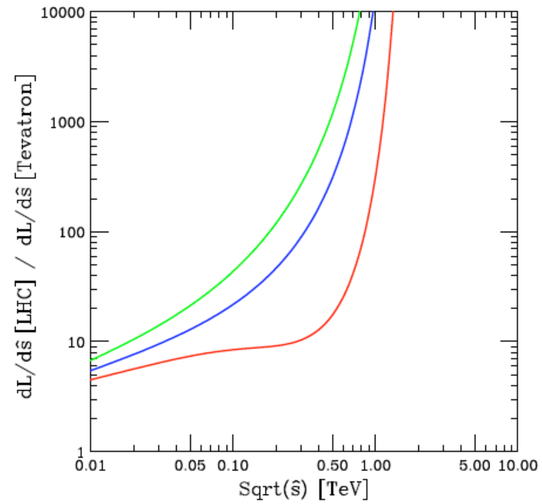


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

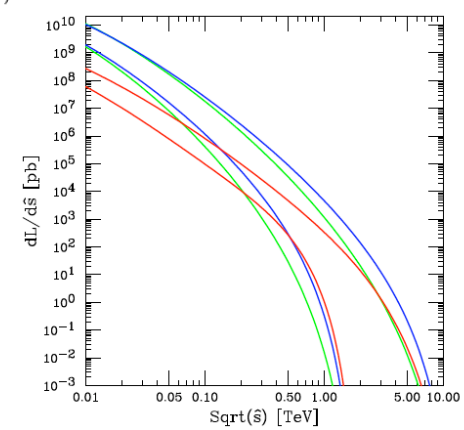


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

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

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?

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
  - still great deal of preparation for early SM analyses needed
- 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
  - longer version of this talk available there
- Review paper should be available soon
  - one of the authors has been honored in advance for his role on the paper
- Once LHC turns on, everything is going to move quickly
- The detector is going to be “as is” and constantly changing
  - “We take data not with the detector we want, but with the detector we have.”

gg luminosity uncertainties

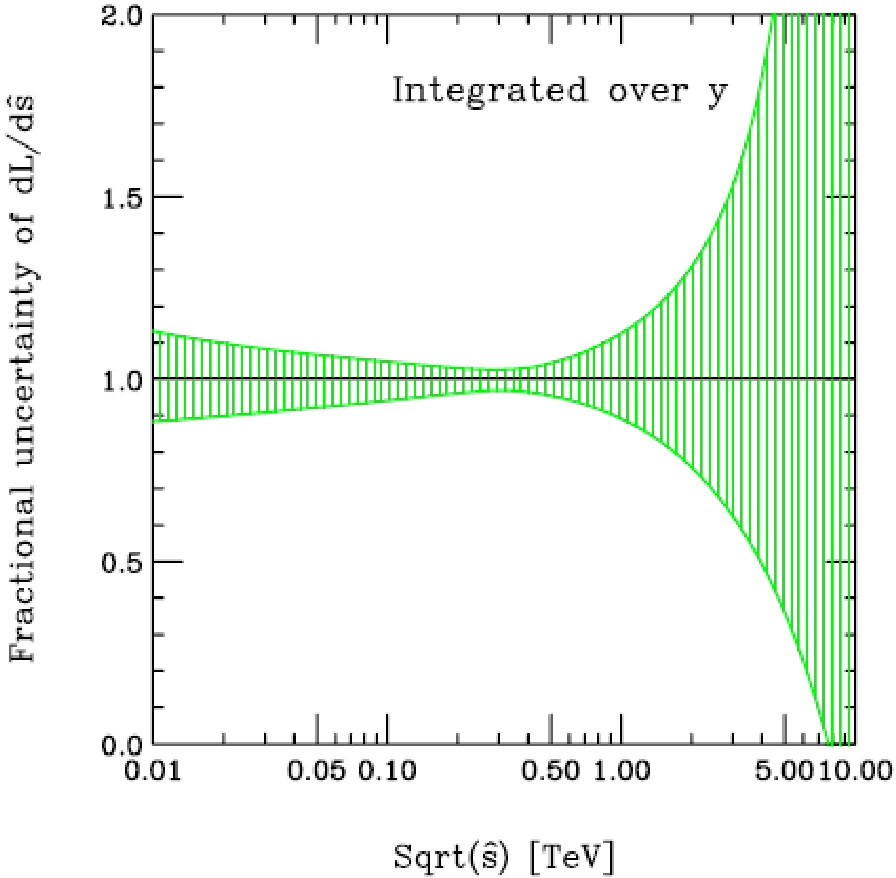


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

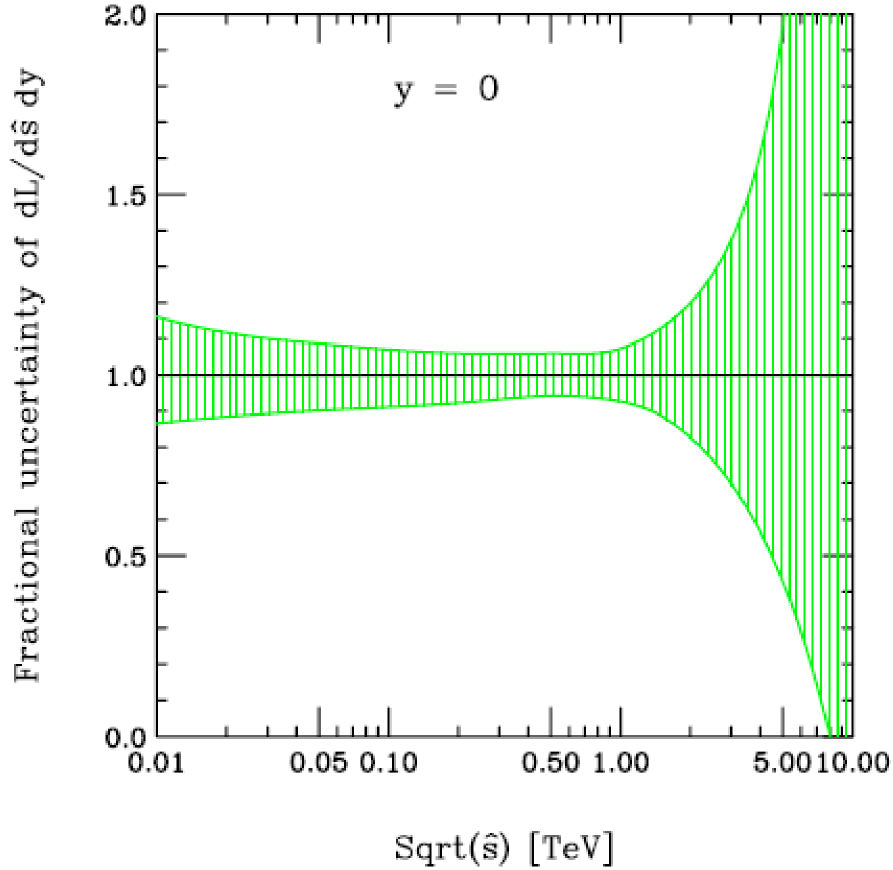
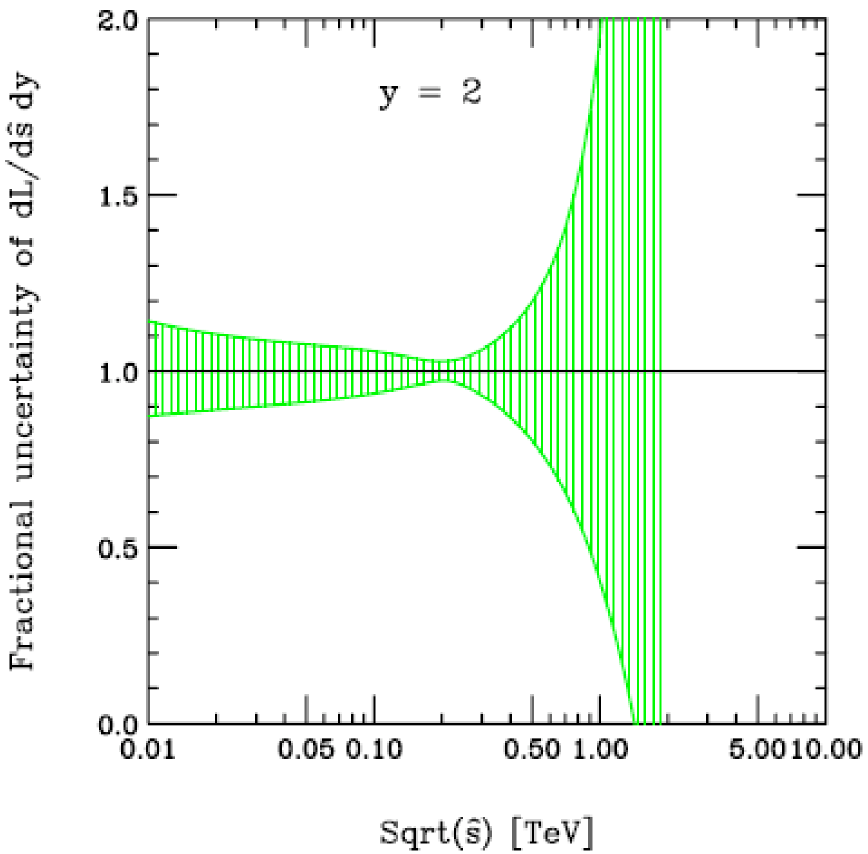
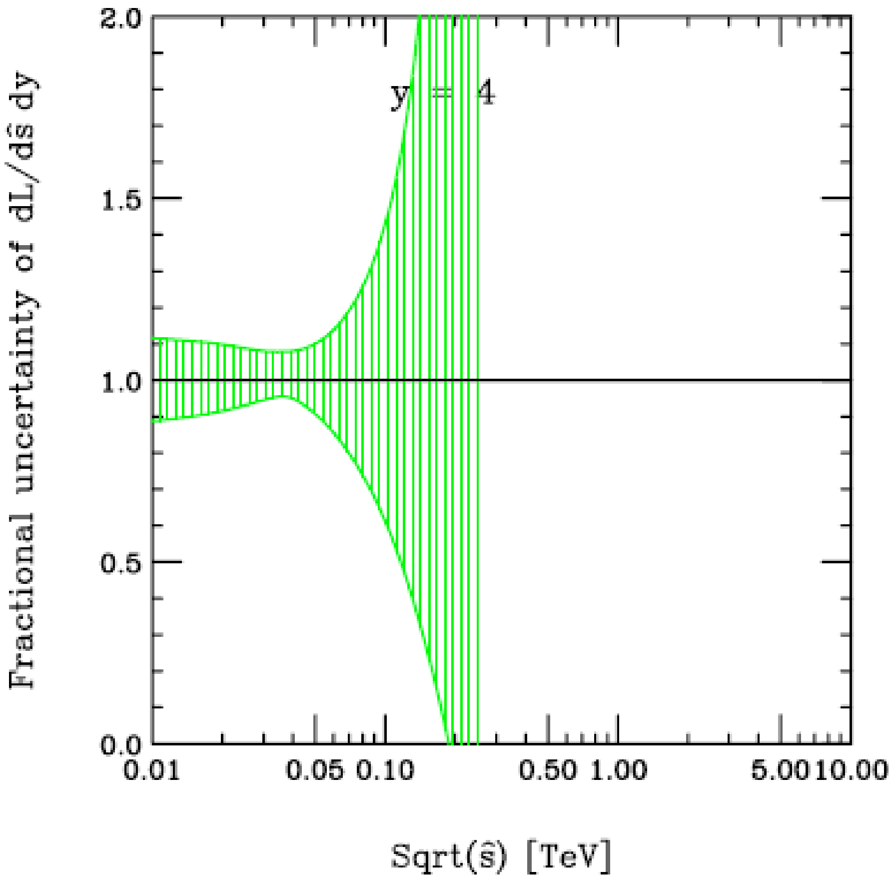


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

gg luminosity uncertainties





gq luminosity uncertainties

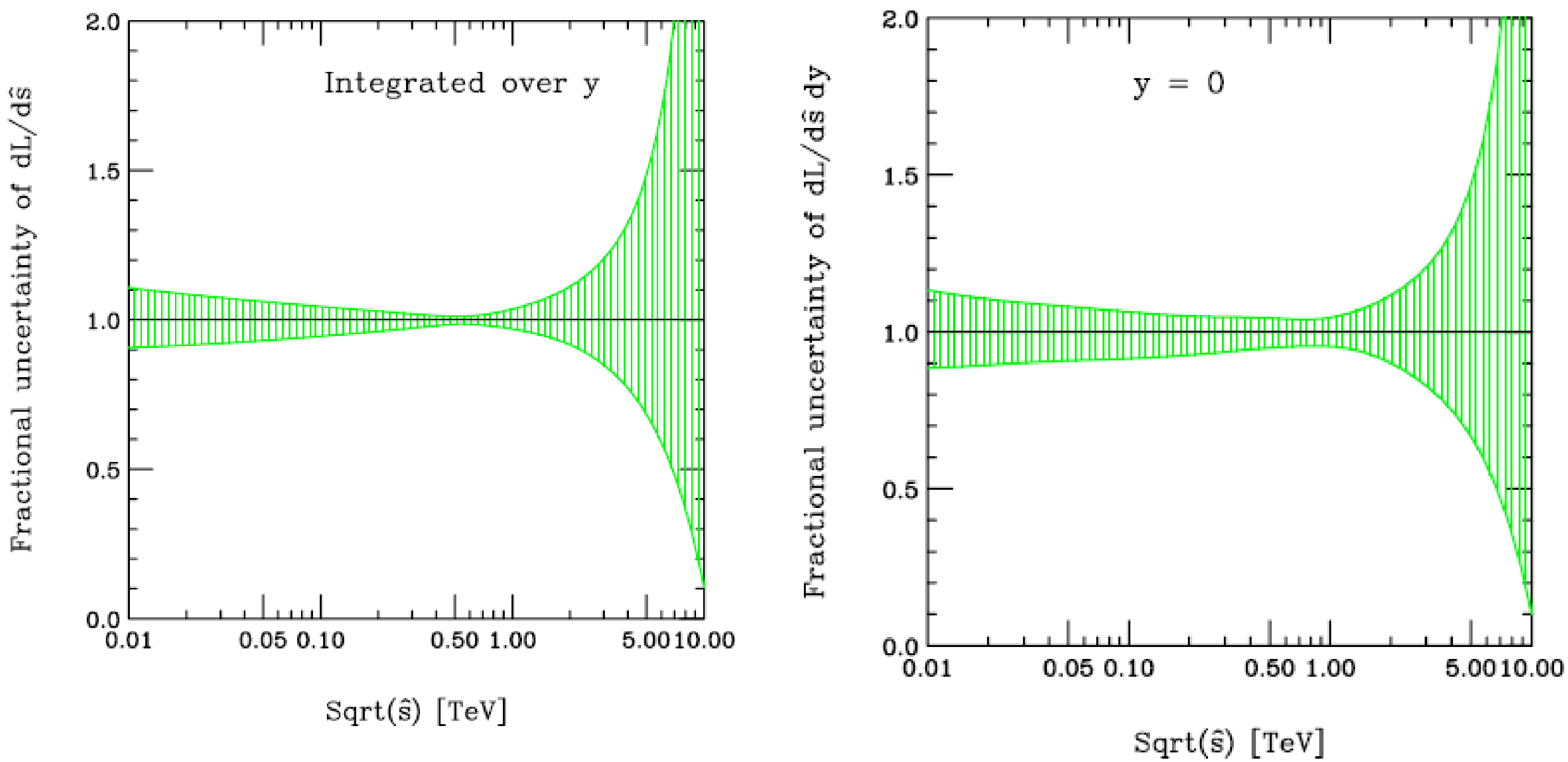
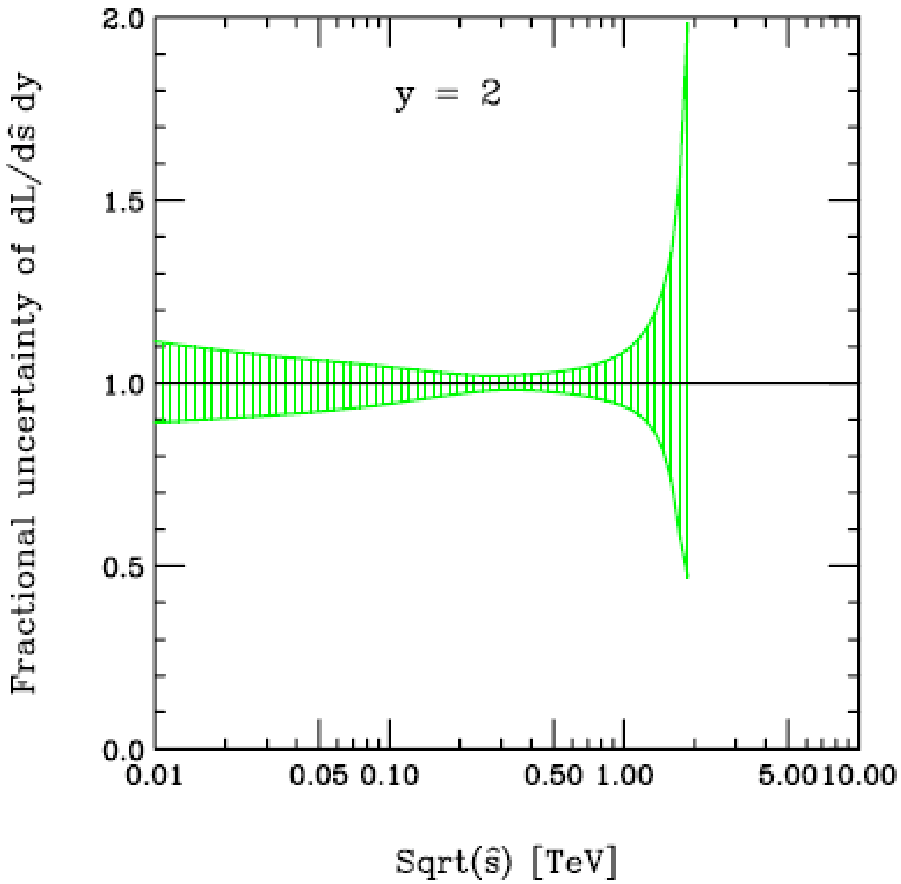
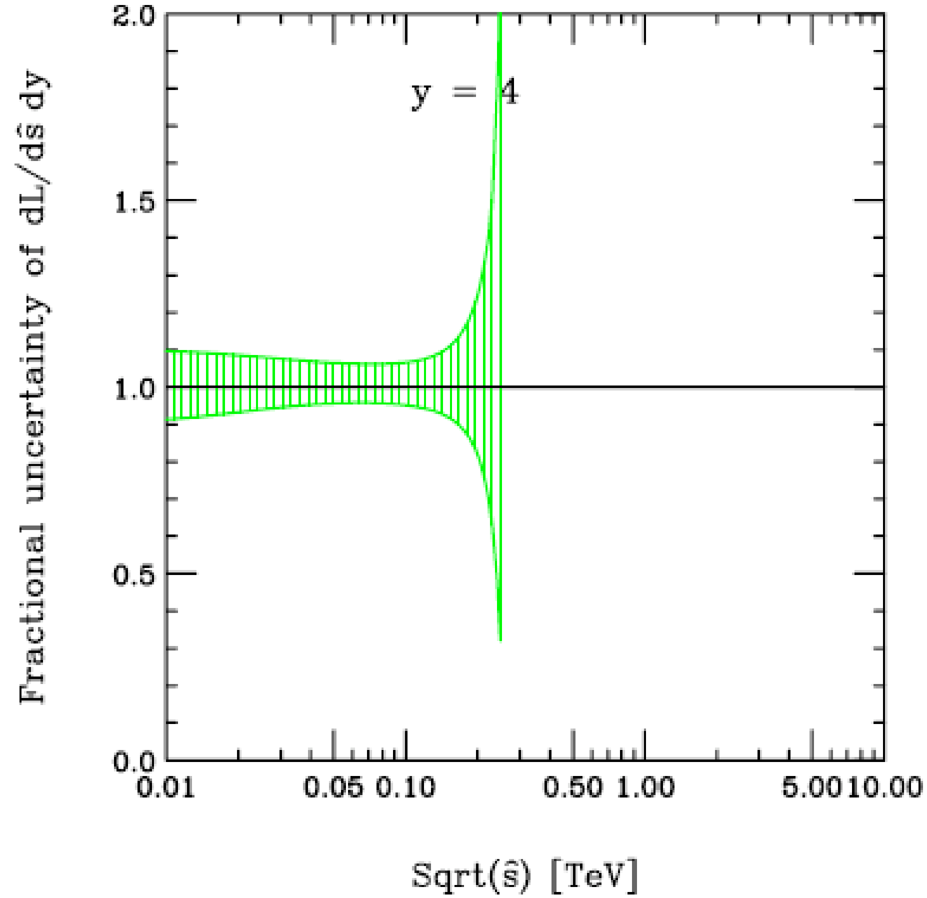


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

gq luminosity uncertainties





qQ luminosity uncertainties

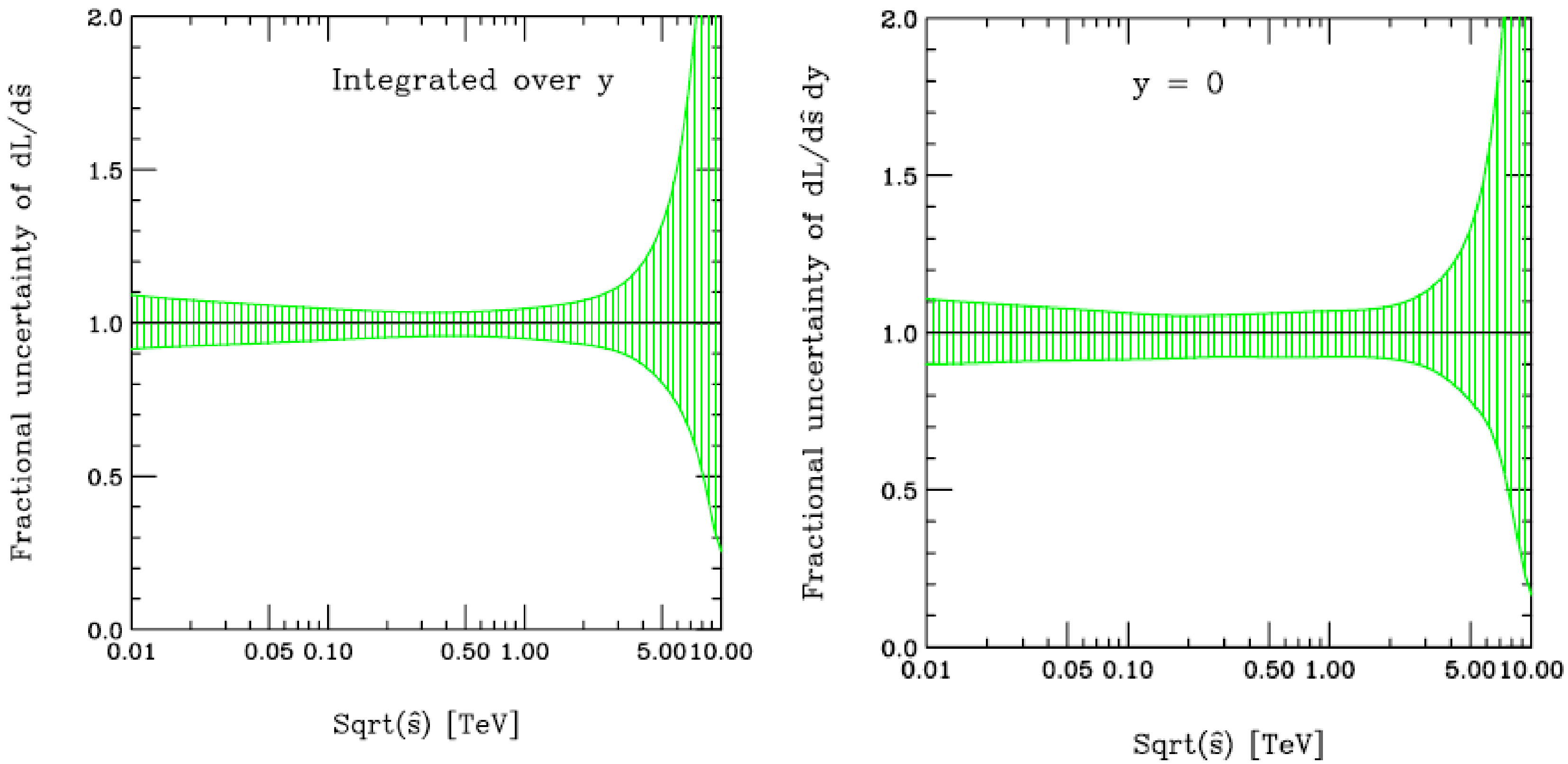
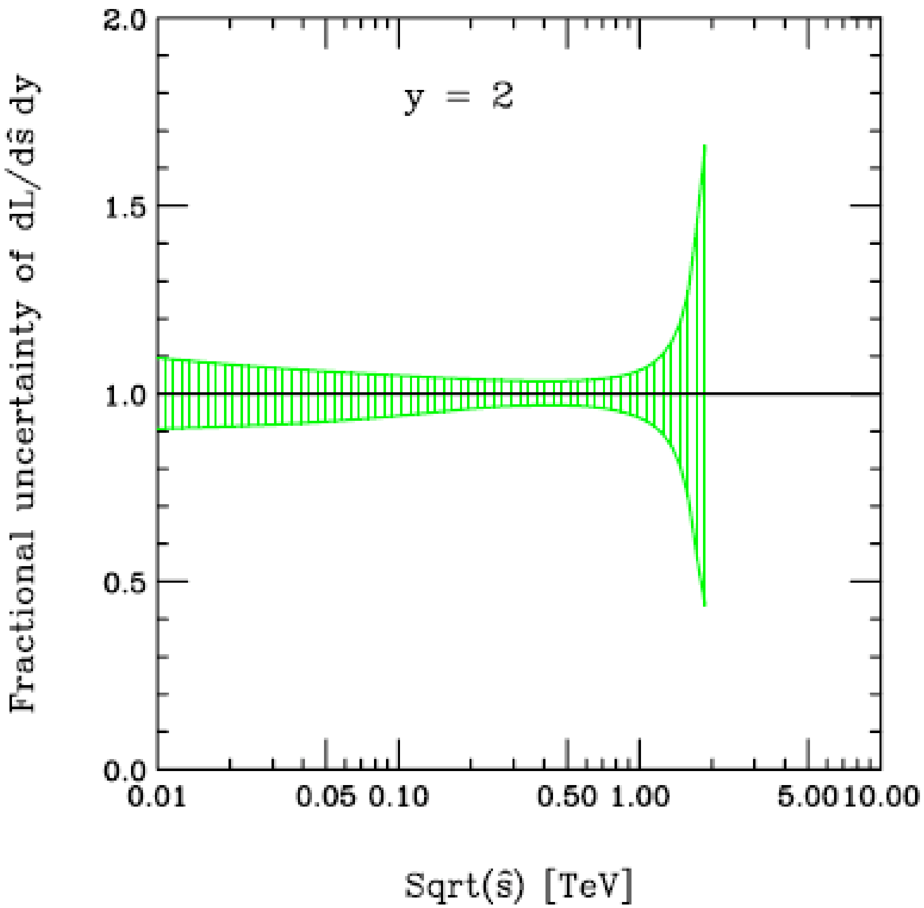
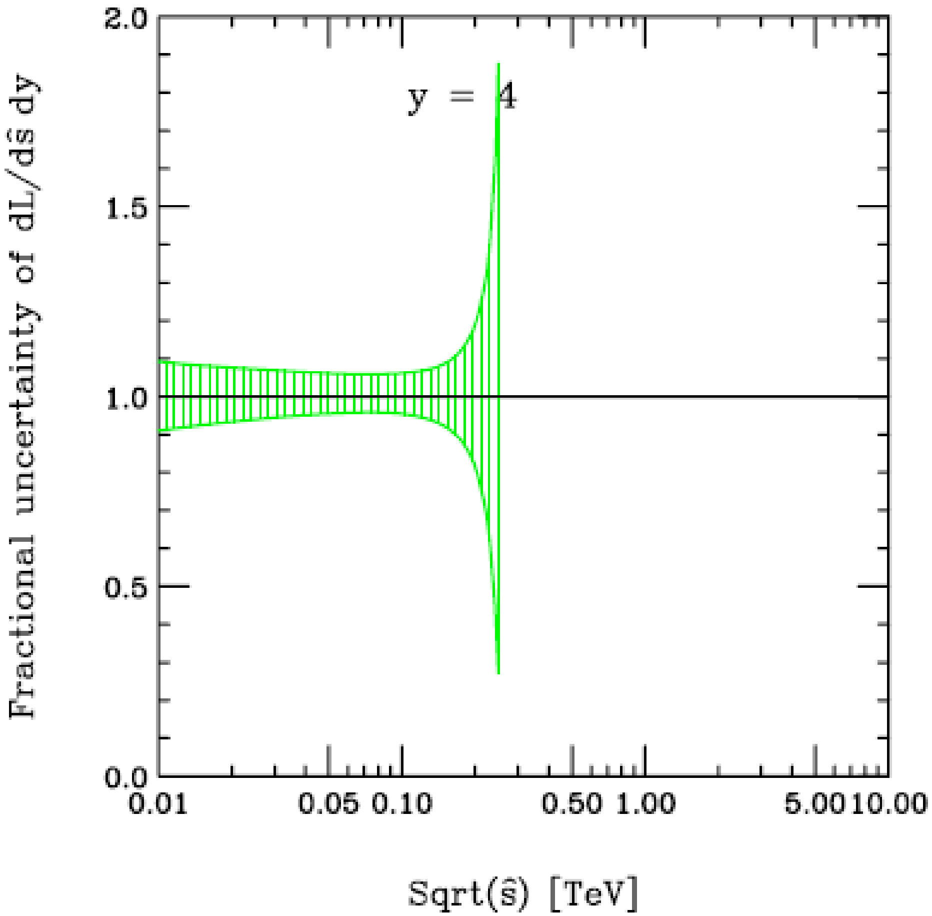


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

qQ luminosity uncertainties



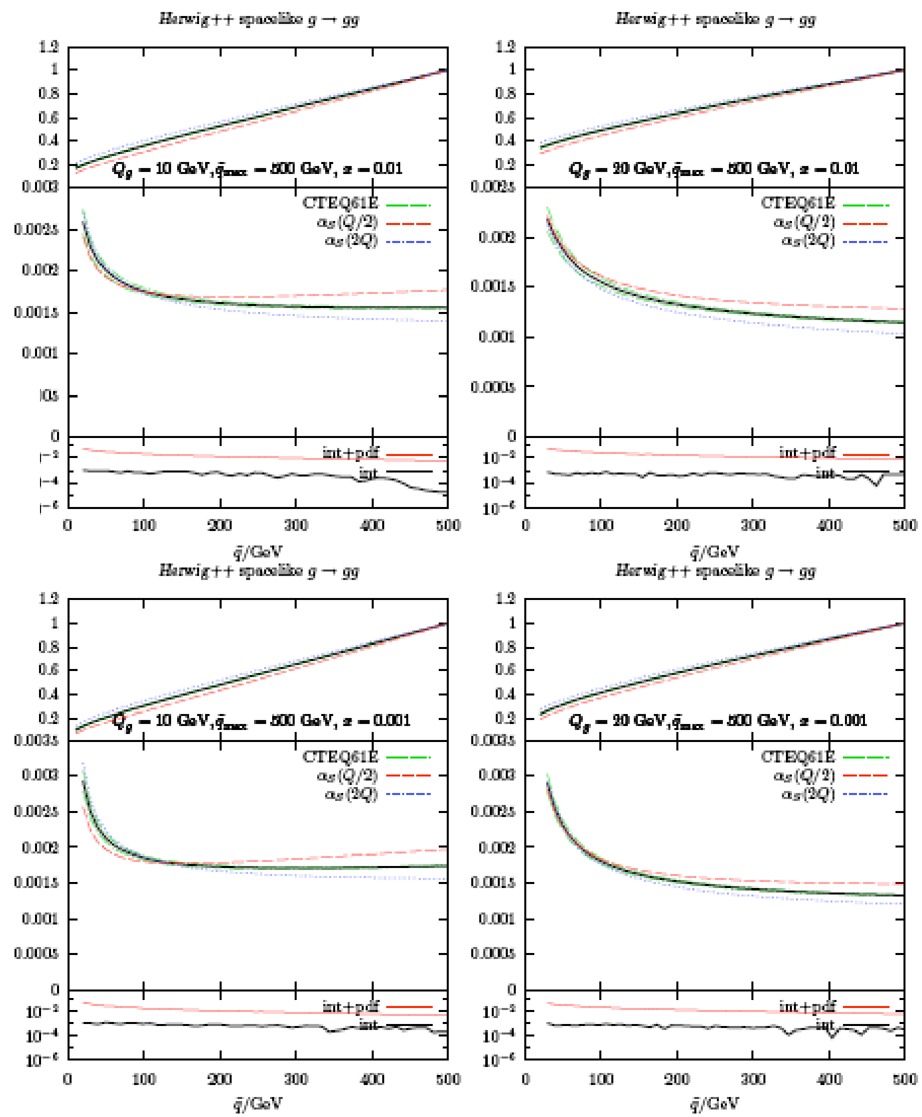


Back to Sudakov form factors

- 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

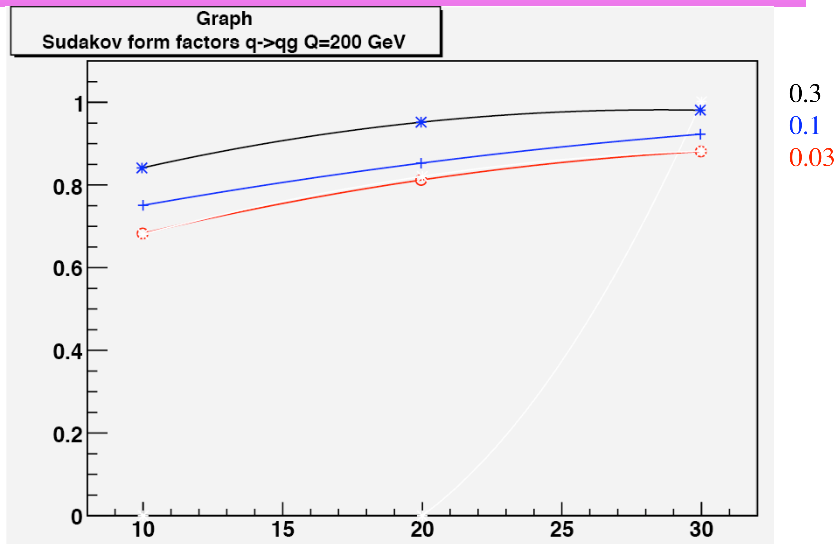
$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int\frac{dz}{z}\frac{\alpha_s}{2\pi}P(z)\,\frac{f(x/z,t)}{f(x,t)}\right]$$

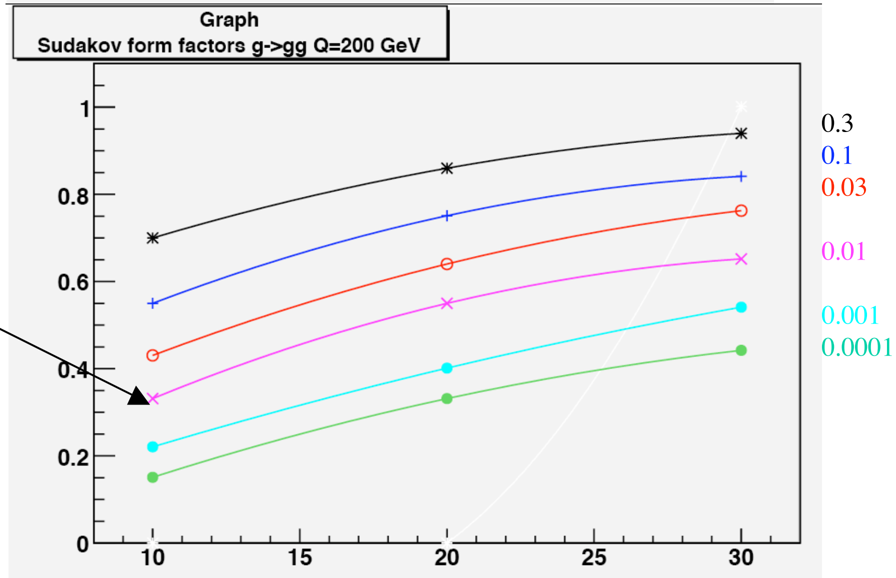
- Probability of emission increases with color charge (gluon vs quark), with larger max scale, with decreasing scale for a resolvable emission and with decreasing parton x



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
  - 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 >=10 GeV when starting from an initial scale of 200 GeV is ~35%, i.e. there is a 65% probability for such an emission

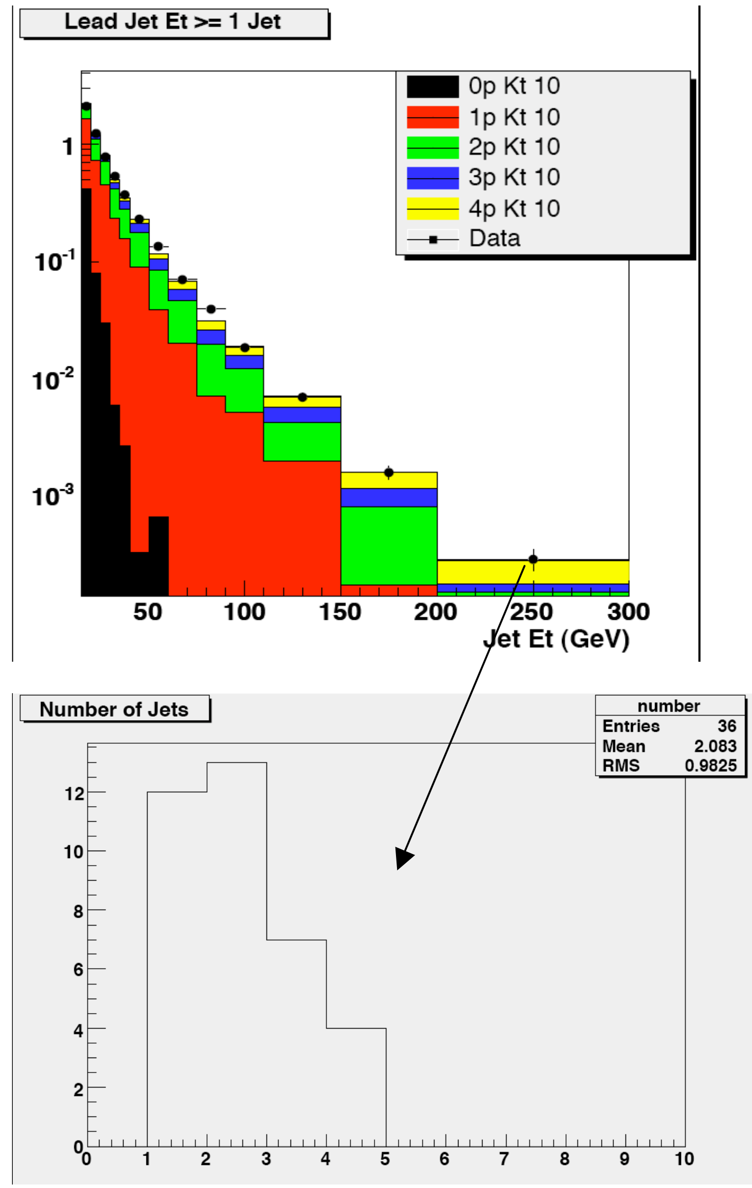




Resolution scale -> ~p_T of gluon

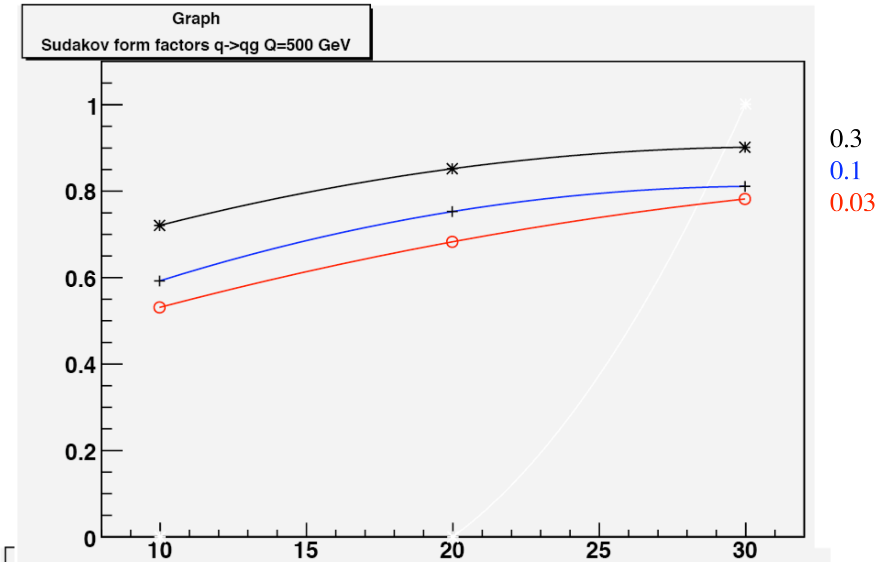
W + jet(s)

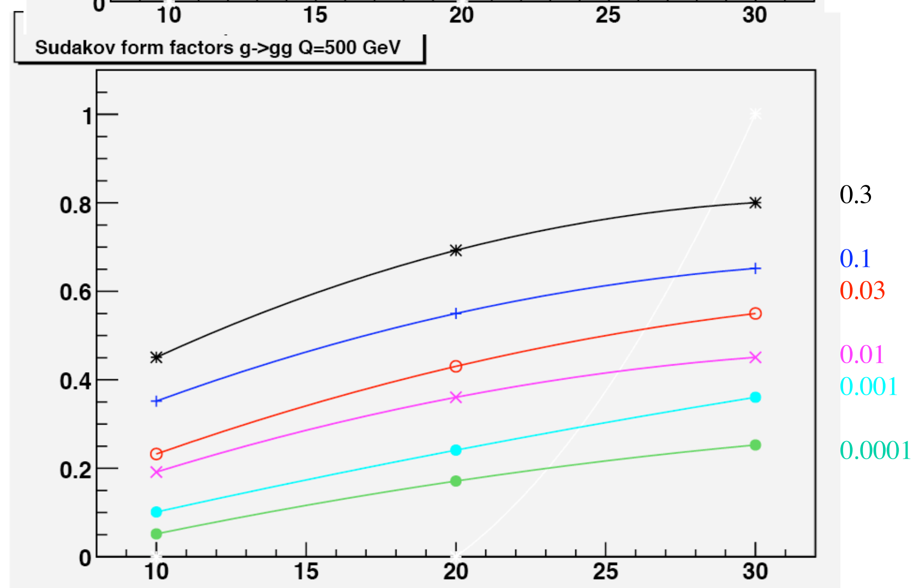
- Consider W + jet at the Tevatron where the jet has a high transverse momentum
- In the CKKW formalism, most of these events will have been produced by W + n parton configurations where n>1
- …or in other words, there is a Sudakov suppression of final states with just the lead jet and no additional (softer) jets
  - I can use the types of curves on the previous page to estimate the rate for ISR jets
  - note I can also get extra jets from final state radiation



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





Consider inclusive jet production

- 500 GeV jets at the Tevatron are produced primarily by qQ scattering (although gq still important)
- For 500 GeV jets at the LHC, scale down by a factor of 7 in x
- Most of the jet events will be produced by at least one gluon in the initial state
- High Q, smaller x, gluon initial states mean more ISR

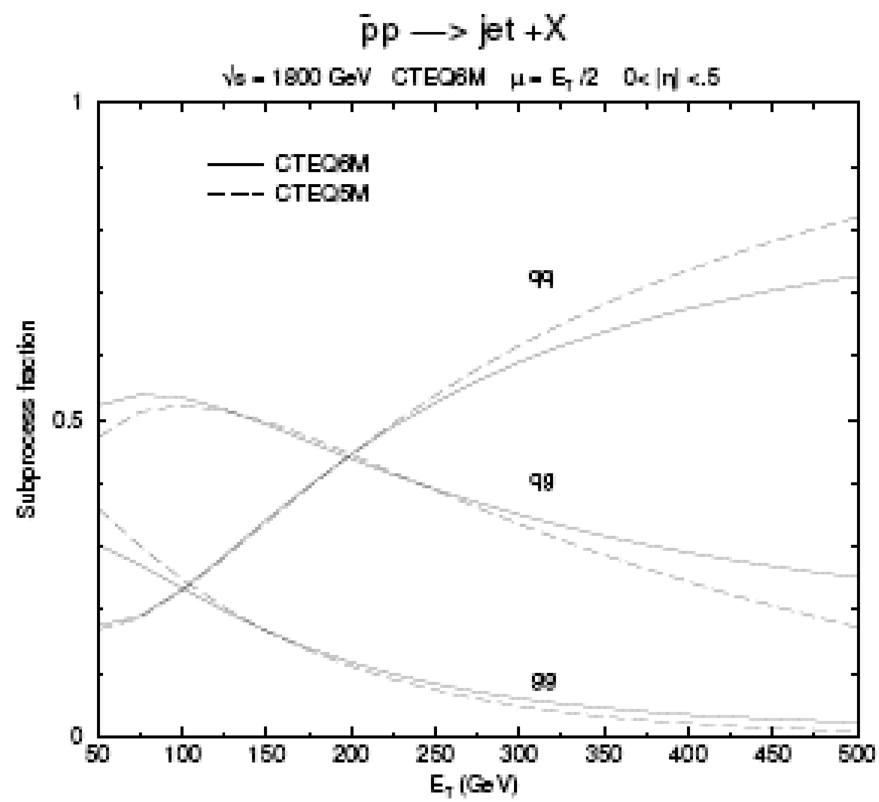
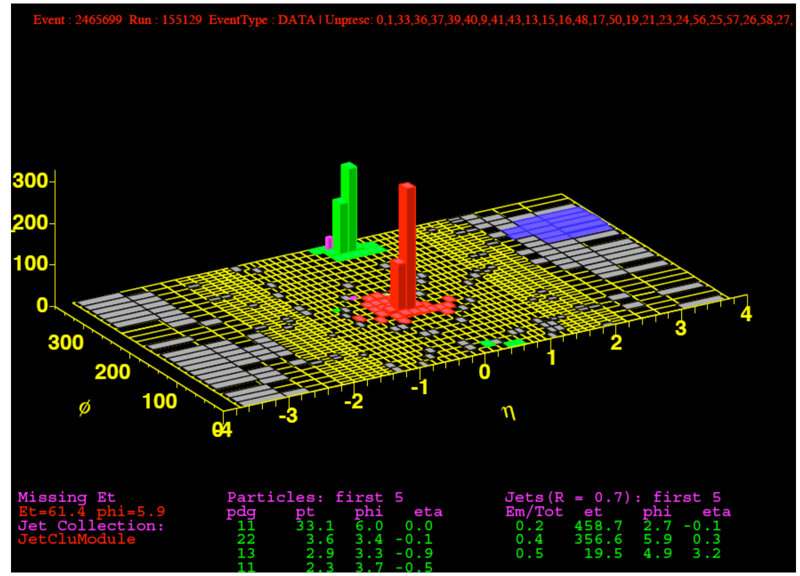
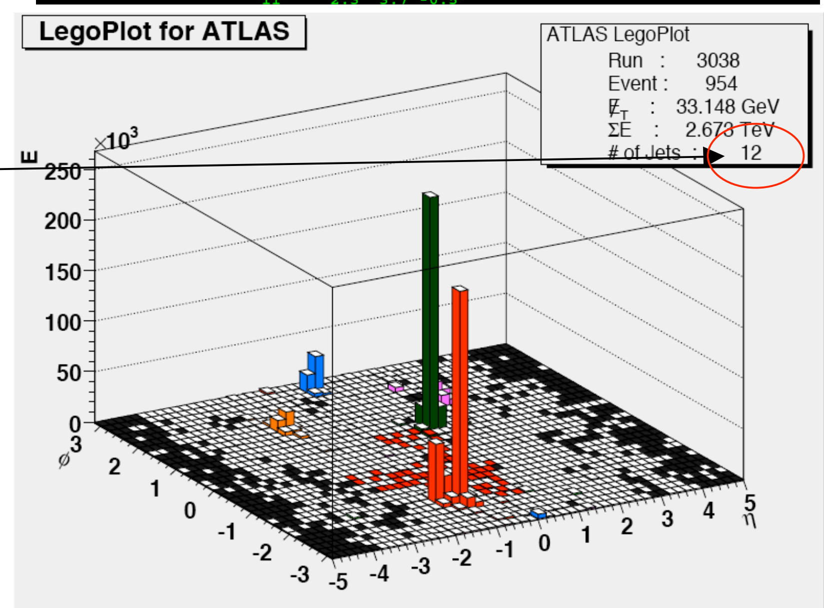


FIG. 3: The subprocess contributions to central jet production.

Jet production

- At the Tevatron, there's a 50% chance of an additional (soft) jet in a high p_T dijet event
  - there's a Sudakov suppression of events without such radiation
- First jet in an ATLAS high p_T dijet MC sample that I looked at has 12 jets (but still clear dijet structure)





More of benchmark webpages

- what are the uncertainties? what are the limitations of the theoretical predictions?
  - indicate scale dependence of cross sections as well as pdf uncertainties
  - how do NLO predictions differ from LO ones?

Table 1. K-factors for various processes at the Tevatron and the LHC, calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements $p_T > 15$ GeV and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). In the $W+2$ jet process the jets are separated by $\Delta R > 0.52$, whilst the weak boson fusion (WBF) calculations are performed for a Higgs of mass 120 GeV.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W+1$ jet	m_W	$\langle p_T^{\rm jet} \rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W+2$ jets	m_W	$\langle p_T^{\rm jet} \rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet} \rangle$	1.07	0.97	1.07	1.23	1.34	1.09

from review paper; in process of adding more processes; any favorites missing?

- to what extent are the predictions validated by current data?
- what measurements could be made at the Tevatron and HERA before then to add further information?

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