Report from the TeV4LHC Workshop
…and some other stuff

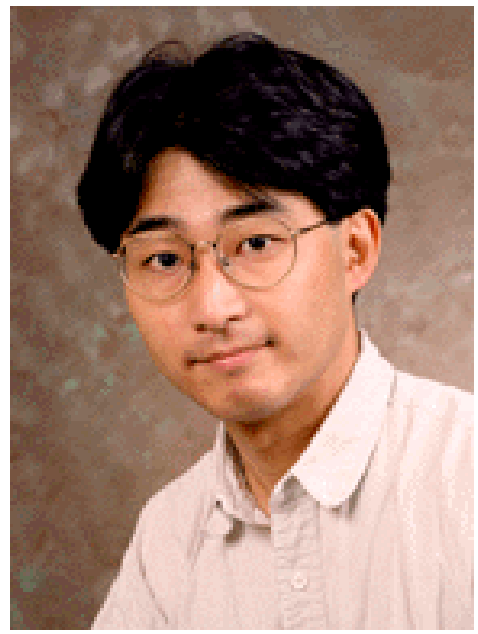
Joey Huston
Michigan State University

…apologies for not being there in person

Some background: 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~~ former Secretary of Defense
  - known knowns
  - known unknowns
  - unknown unknowns

What to expect at the LHC

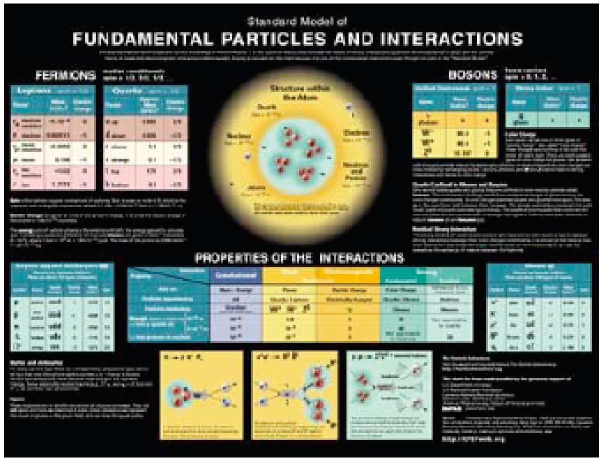
…according to a theorist

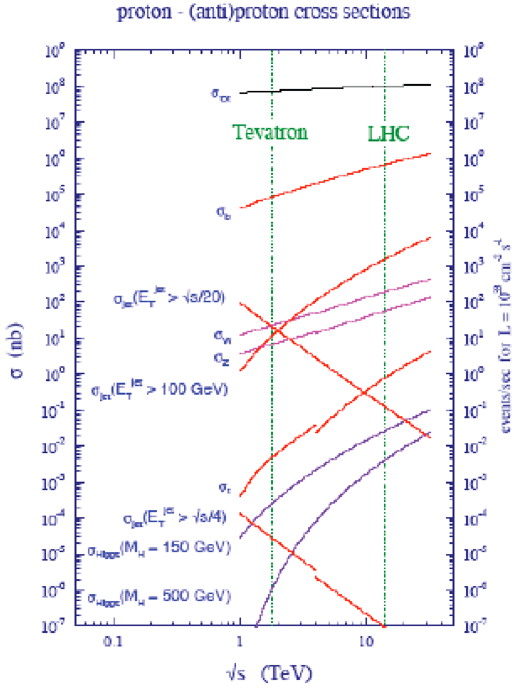
Murayama LP03

- According to a former Secretary of Defense
  - known knowns
    - **SM at the Tevatron**
      - and thus relevant for this talk
    - (most of) SM at the LHC
  - known unknowns
    - some aspects of SM at the LHC
  - unknown unknowns
    - ???

Discovering the SM at the LHC

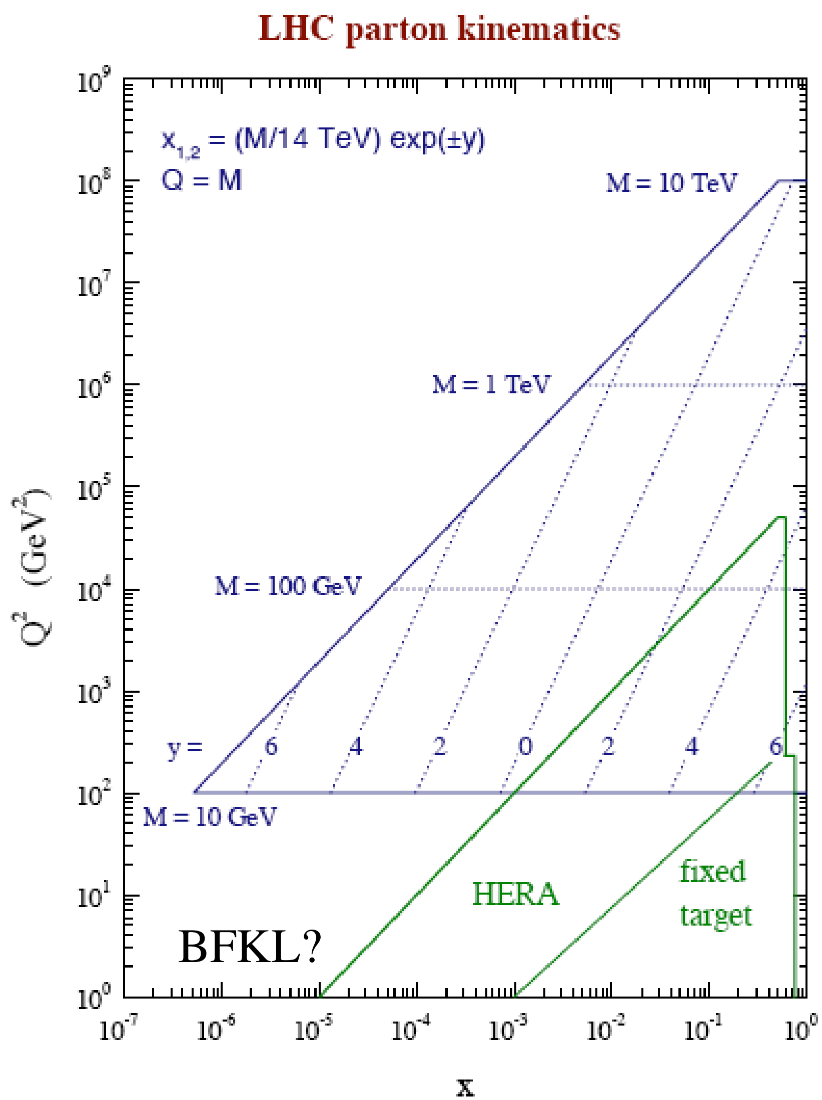
- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
    - detector and reconstruction algorithms operating properly
    - SM physics understood properly
    - SM backgrounds to BSM physics correctly taken into account
- ATLAS/CMS will have a program to measure production of SM processes: inclusive jets, W/Z + jets, heavy flavor during first inverse femtobarn
    - 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 and theoretical prediction 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
    - where HERA experience comes in handy
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



Website + references for TeV4LHC workshop

- See http://conferences.fnal.gov /tev4lhc
- WRITE-UPs
  - Tevatron-for-LHC Report: Higgs Aglietti et al. FERMILAB-CONF-06-467-E-T, Dec 2006e-Print Archive: [http://xxx.lanl.gov/hep-ph/0612172]
  - Tevatron-for-LHC Report of the QCD Working Group.TeV4LHC QCD Working Group et al. FERMILAB-CONF-06-359, Oct 2006.e-Print Archive: [http://xxx.lanl.gov/hep-ph/0610012]
  - Tevatron-for-LHC Report: Preparations for DiscoveriesV. Buescher et al FERMILAB-CONF-06-284-T, Aug 2006e-Print Archive: [http://xxx.lanl.gov/hep-ph/0608322]

- Most of the tools we want to use/develop in the TeV4LHC workshop are QCD-related
  - ME/MC generation
  - NLO
  - jet algorithms
  - pdf's and pdf uncertainties
  - …
- Most of what I'll discuss in this talk is related to the QCD Working Group
  - and given the context of this group, much will be related to pdf's
- Caveat: the workshop ended some time ago so some of the material has been updated in the context of other studies

QCD Report

- QCD conveners
  - M. Albrow, F. Chlebana, A. de Roeck, S. Ellis, W. Giele, J. Huston, W. Kilgore, S. Mrenna, W.K. Tung, M. Wobisch, M. Zielinski
    - goal was to have a large group just by staffing it with conveners
    - but then we had trouble finding anyone to do the work
- Group website
  - www.pa.msu.edu/~huston/tev4lhc/wg.html
- Many presentations over the course of 4 meetings at Fermilab, Brookhaven and CERN as well as in several interim group meetings

- [http://xxx.lanl.gov/hep-ph/0610012]

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Other References

- Also online at ROP

http://stacks.iop.org/0034-4885/70/89

REVIEW ARTICLE

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

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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 behaviour 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.

Submitted to: *Rep. Prog. Phys.*

Standard Model benchmarks

LES HOUCHES
centre de physique

See www.pa.msu.edu/~huston/_Les_Houches_2005/Les_Houches_SM.html

See also the talks of Wu Ki Tung and Steve Mrenna in this workshop

Known known: Parton distribution functions

- Calculation of production cross sections at the LHC relies upon knowledge of pdf's in the relevant kinematic region
- Pdf's are determined by global analyses of data from DIS, DY and jet production
- Two major groups that provide semi-regular updates to parton distributions when new data/theory becomes available
  - MRS->MRST98->MRST99 ->MRST2001->MRST2002 ->MRST2003->MRST2004
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5 *(->CTEQ7)*
- All of the above groups provide ways to estimate the error on the central pdf
  - methodology enables full characterization of parton parametrization space in neighborhood of global minimum

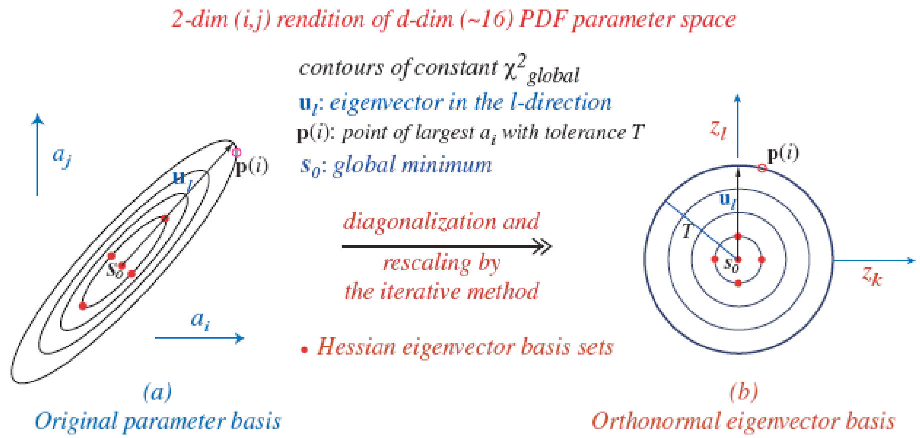


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

▲Hessian method

▲Lagrange Multiplier

◆both of above techniques used by CTEQ and MRST

▲Hessian method accessible to general user

▲NB: the error estimate only covers experimental sources of errors

▲theory uncertainties

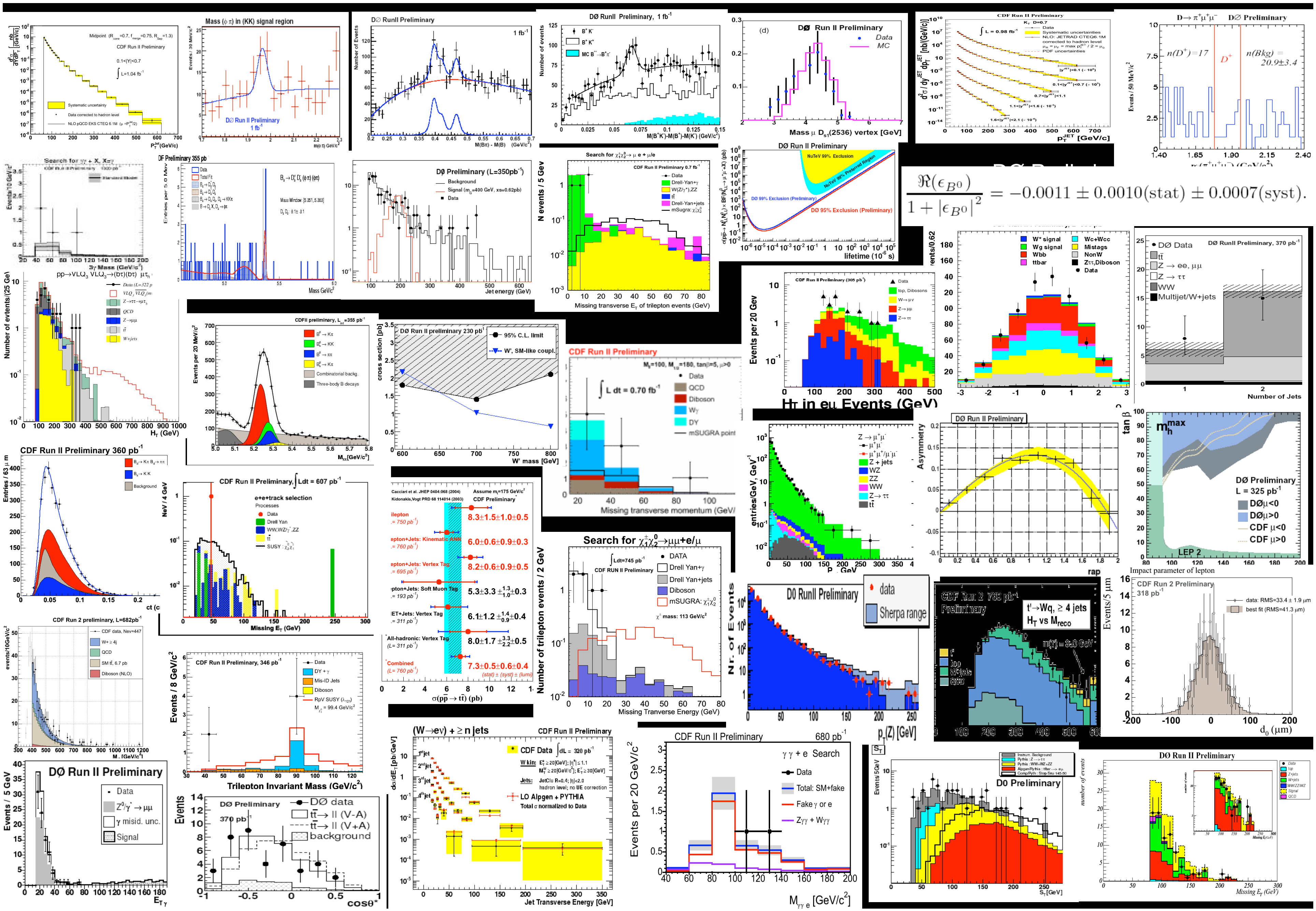
▲higher twist/non-perturbative effects

▲choose Q^2 and W cuts to avoid

▲higher order effects (NNLO)

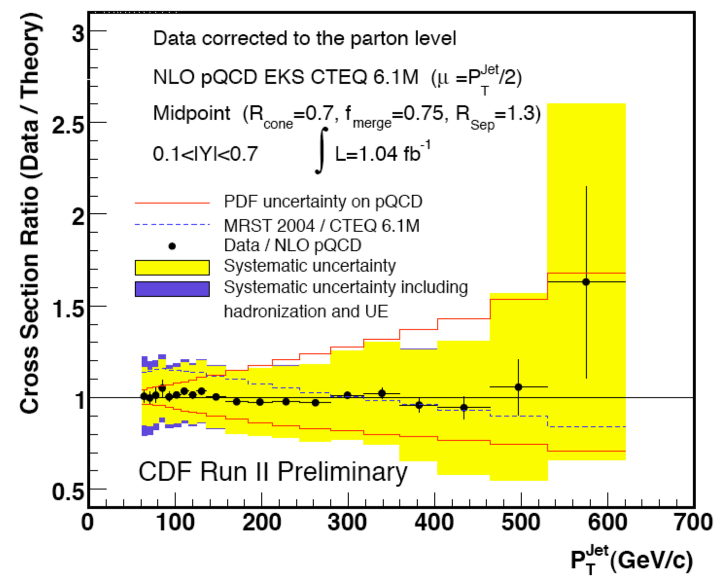
▲heavy quark mass effects

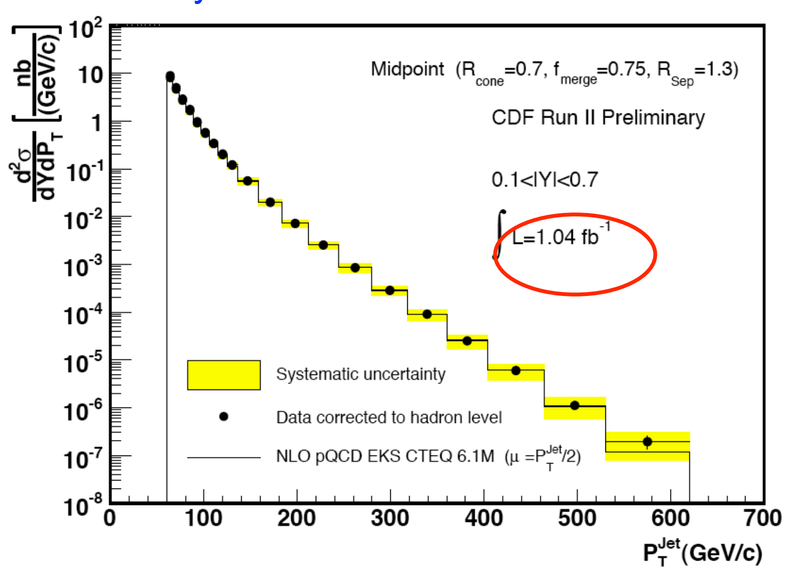
Results from the Tevatron: summary

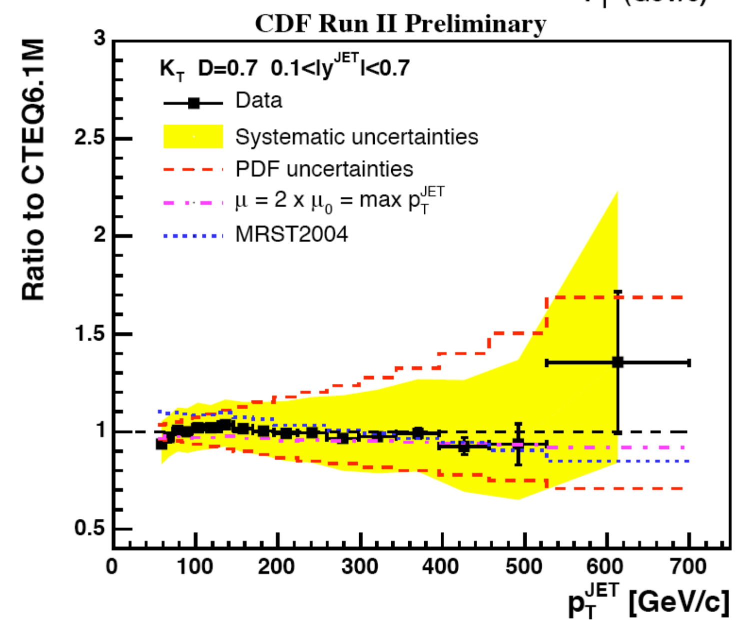


Only a few of these results have been included in global pdf fits

- The most important example is the inclusive jet cross section
- CDF Run II result in good agreement with NLO predictions using CTEQ6.1 pdf's
  - and the implicit 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 $p_T^{max}/2$)
- Theme of workshop: need to have the capability of using different algorithms in analyses as cross-checks

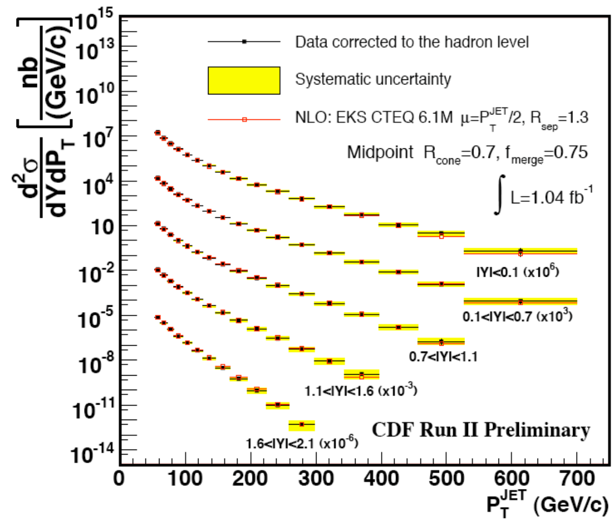


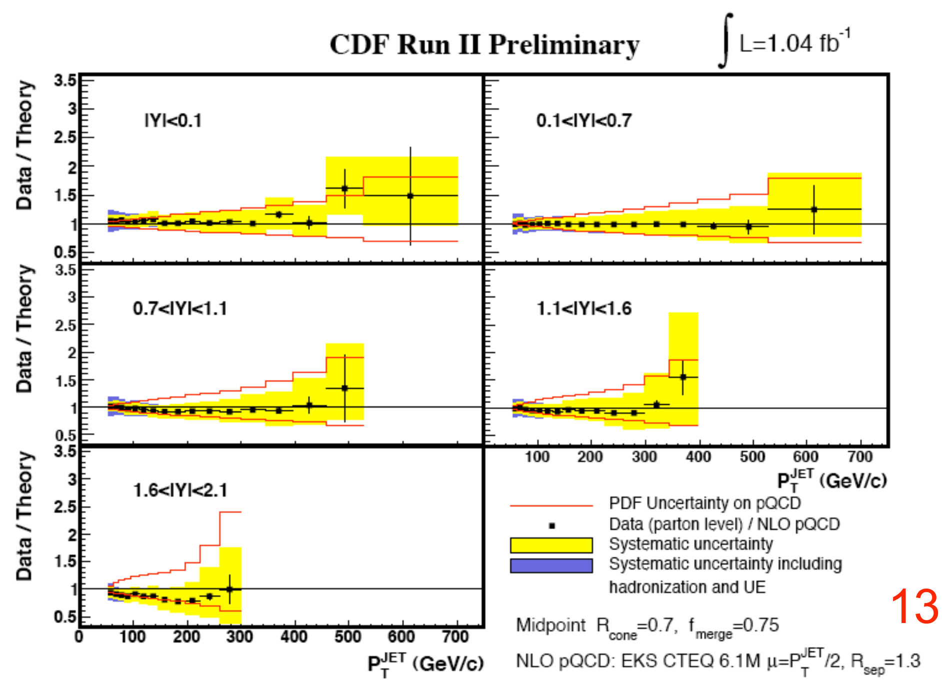




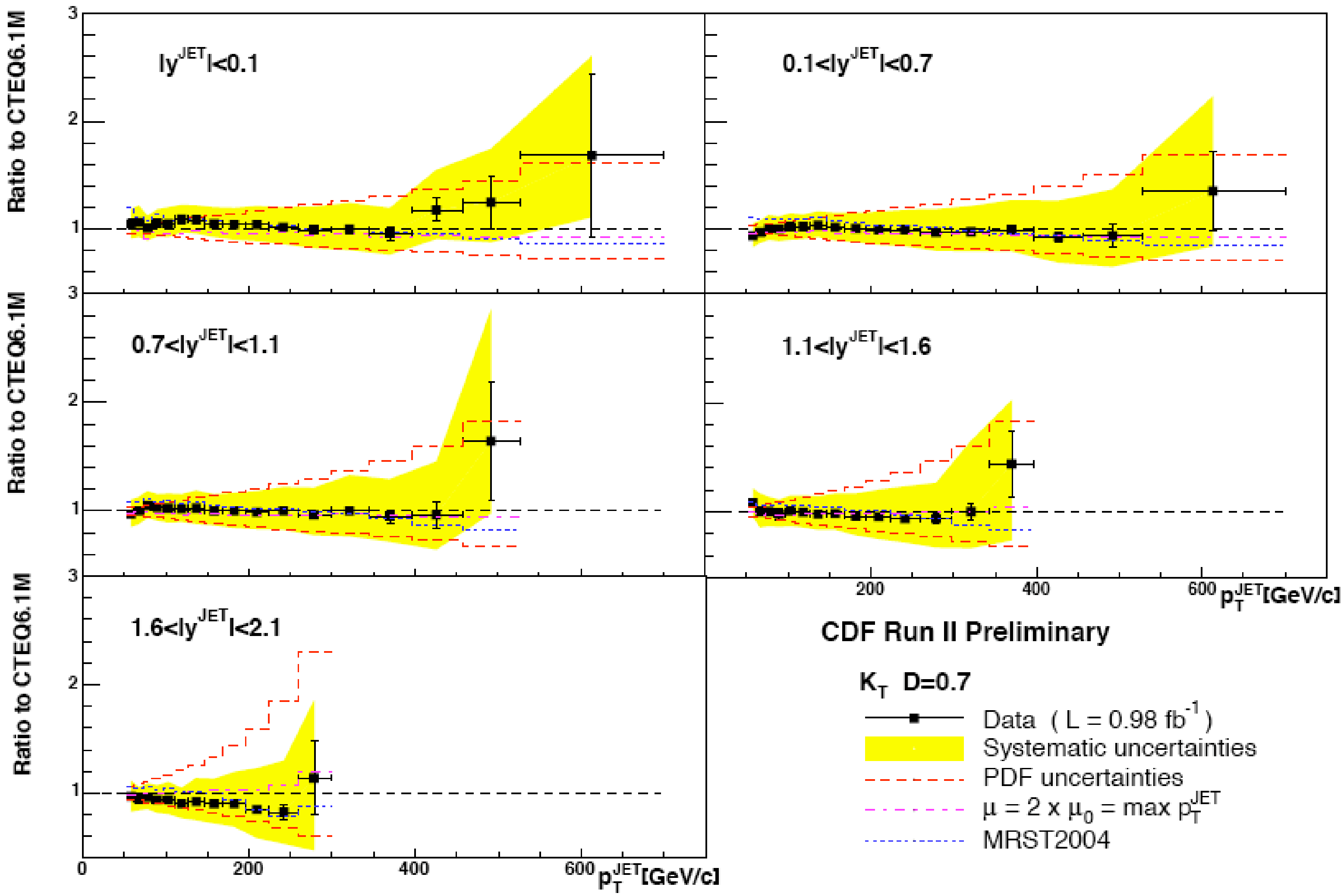
CDF Run 2 cone results

- 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?





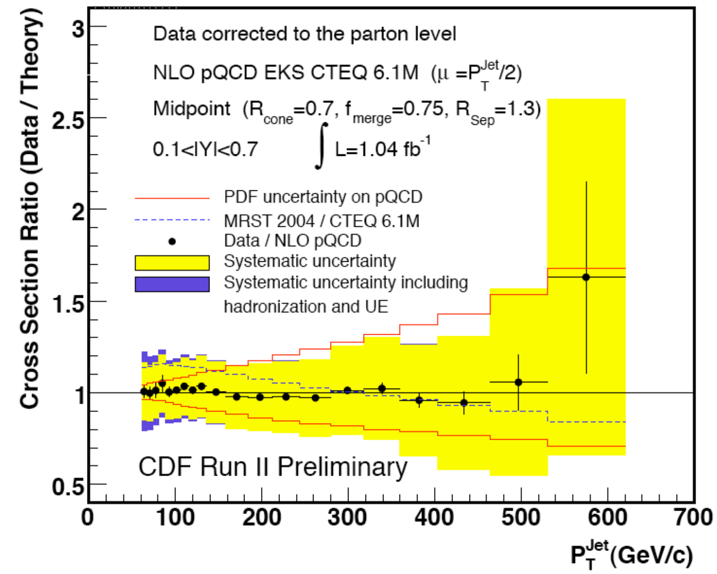
Forward jets with the k_T algorithm

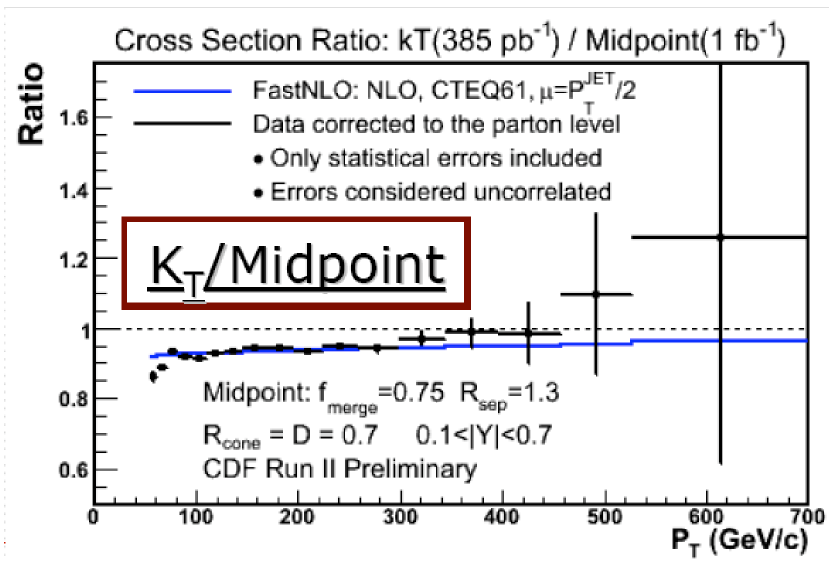


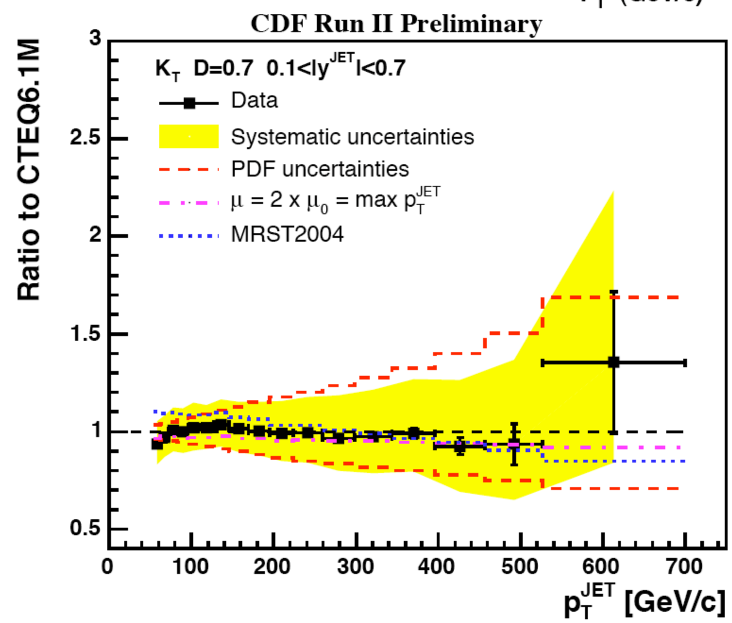
Need to go lower in p_T for comparisons of the two algorithms, apply k_T to other analyses

Consistency of results

- At hadron level, k_T cross section with D of 0.7 tends to be larger than cone with R of 0.7
- But at parton level, k_T<cone as it should be
  - hadronization corrections are different

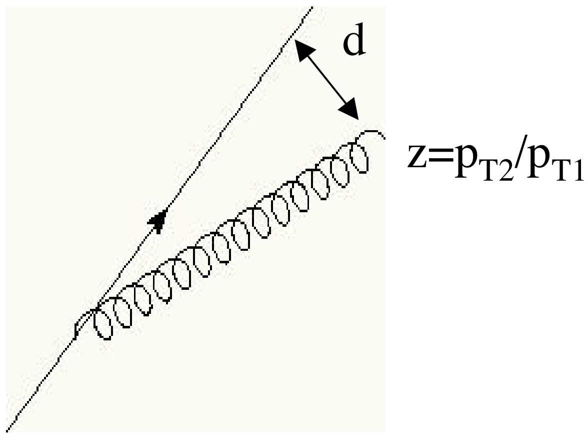






Why should k_T be less than cone at parton level?

- 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); <u>thus at parton level, the cone algorithm is always larger than the k_T algorithm</u>



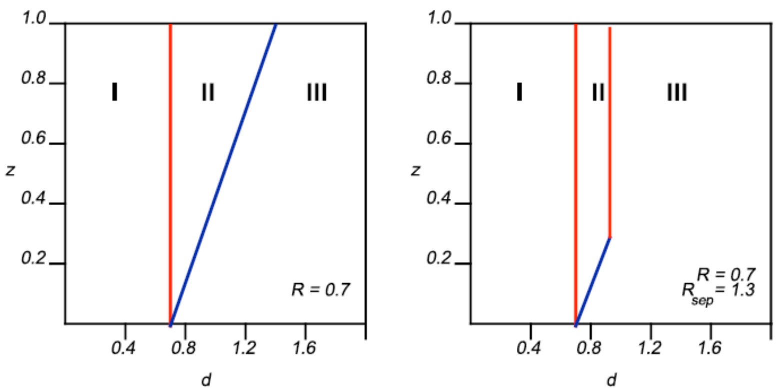
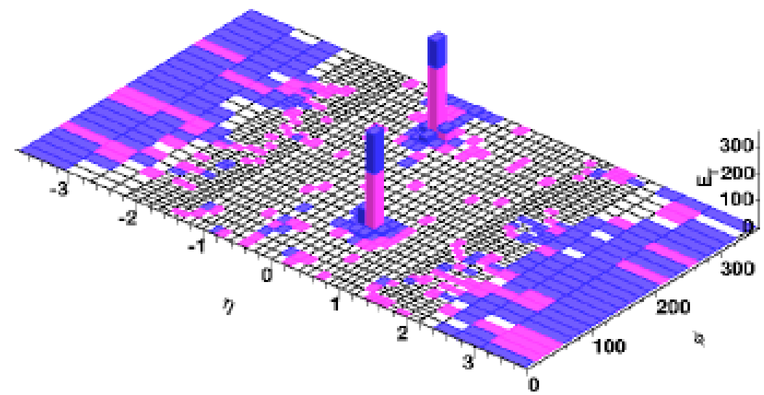


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

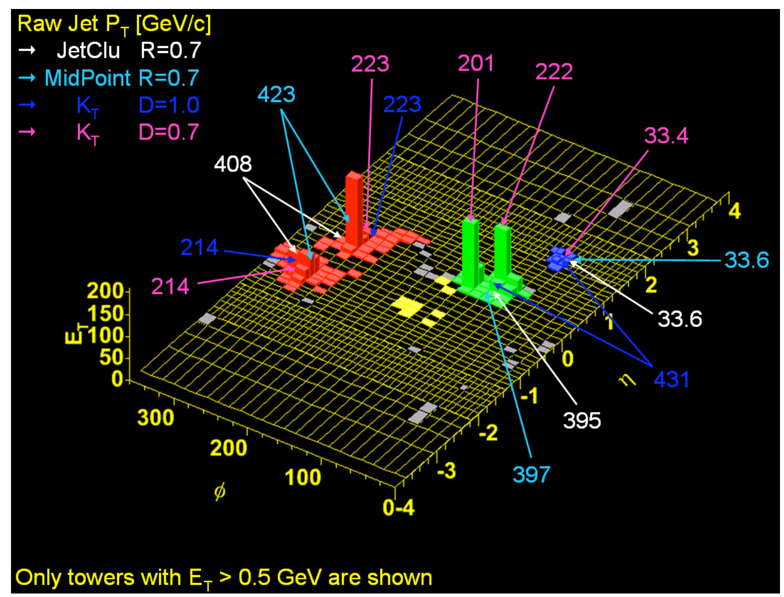
Jets and you

- There is a need/desire to have available the results of more than one jet algorithm when analyzing an event
- A student of mine and I have assembled some jet algorithms together in a routine that runs on 4-vector files
- So far, the routine runs JetClu, Midpoint, k_T (inclusive and exclusive), Cambridge/Aachen algorithm and simple Pythia UA-1 type algorithm (CellJet)
  - the k_T algorithms are run by linking to the FastJet program written by Gavin Salam and Matteo Cacciari
- User specifies the parameters for the jet reconstruction (including whether to pre-cluster the 4-vectors together into towers), whether to add in extra min bias events (pending), and whether to make lego plots (with user-specified tower granularity)
- Interactive output + a ROOT tree
- Available from www.pa.msu.edu /~huston/lhc_jet/lhc_jet.html

simple event structure



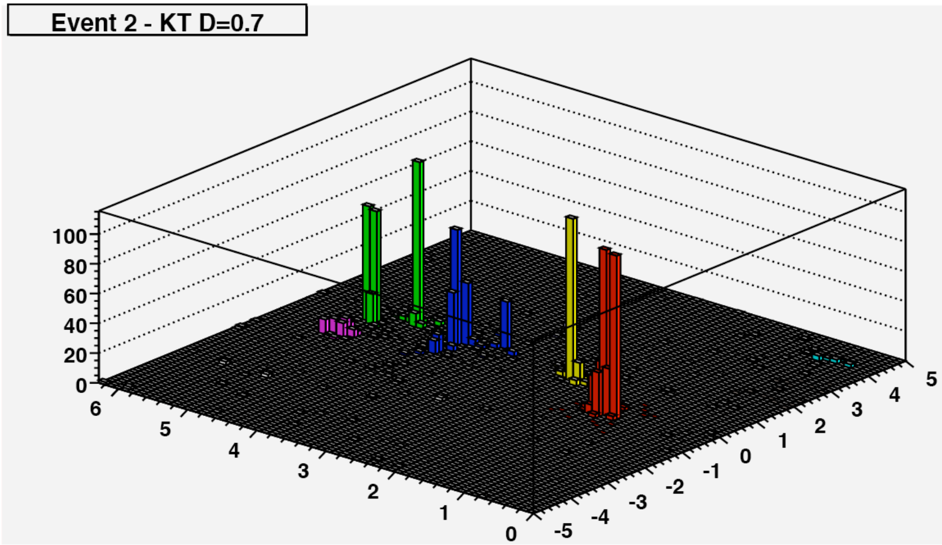
not so simple event structure



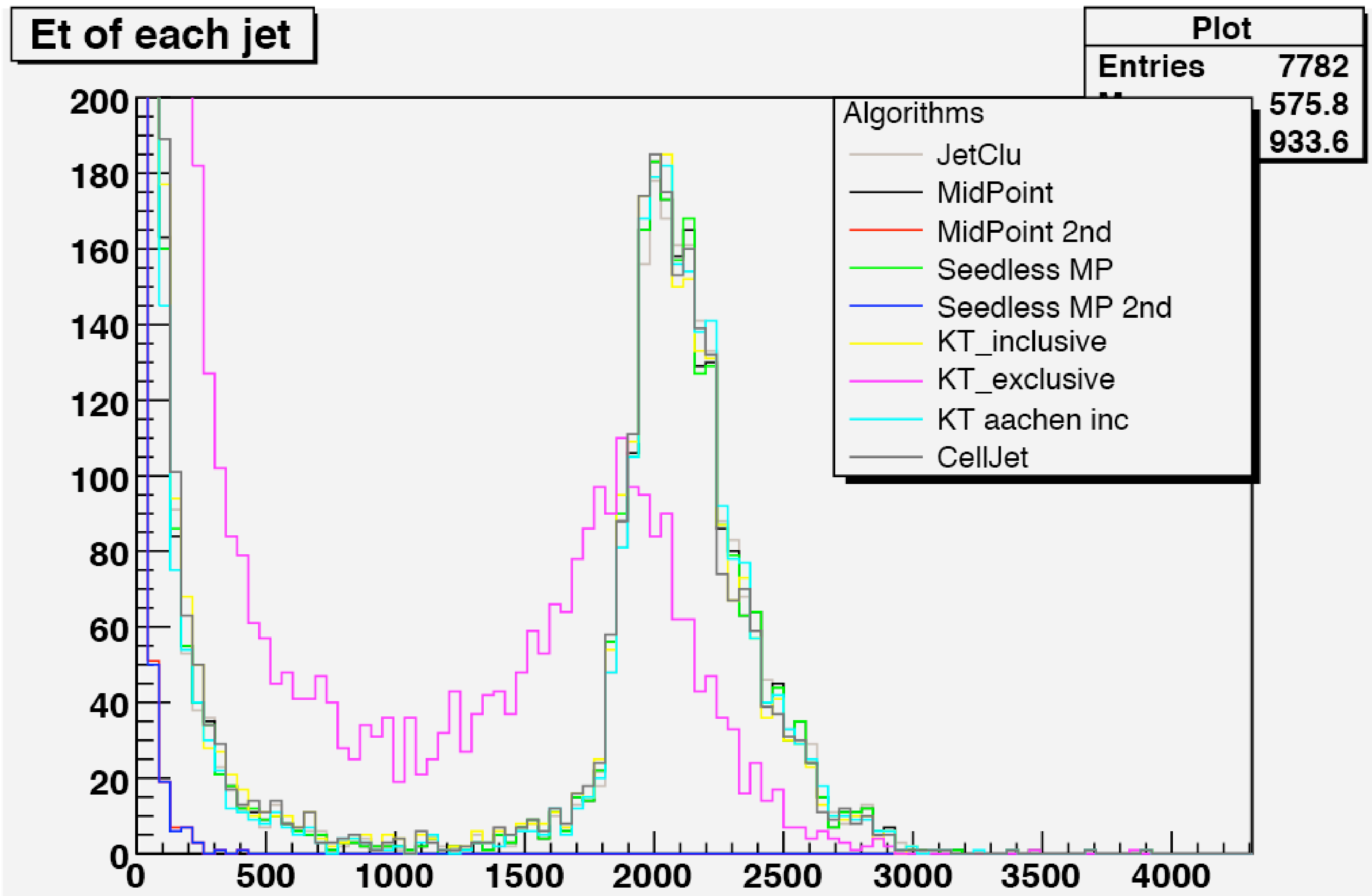
Example dijet event

- MidPoint Jets(R=0.7):
- Et=1109., eta=-0.36, phi=1.47, nTowers=95
- Et=1068, eta=0.80, phi=4.90, nTowers=99
- Et=275., eta =0.59, phi=3.99, nTowers=106
- Et=257., eta=0.47, phi=2.35, nTowers = 52
- Et=78.8, eta=-0.41, phi=5.27241, nTowers = 41
- Et=17.0, eta=4.16, phi=0.63, nTowers=14

- kT Jets(D=0.7):
- Et=1101., eta=-0.36, phi=1.47, nTowers=98
- Et=1051., eta=0.77, phi=4.90, nTowers=107
- Et=259., eta =0.55, phi=3.98, nTowers=110
- Et=255., eta=0.46, phi=2.35, nTowers = 51
- Et=75., eta=-0.40, phi=5.27, nTowers = 39

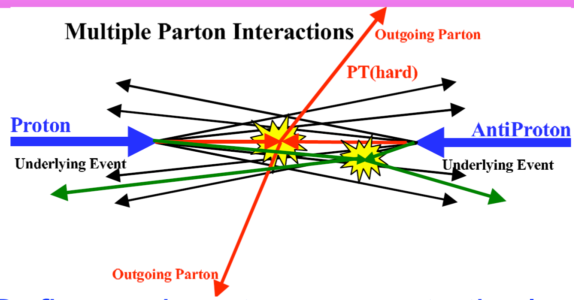


J8 sample

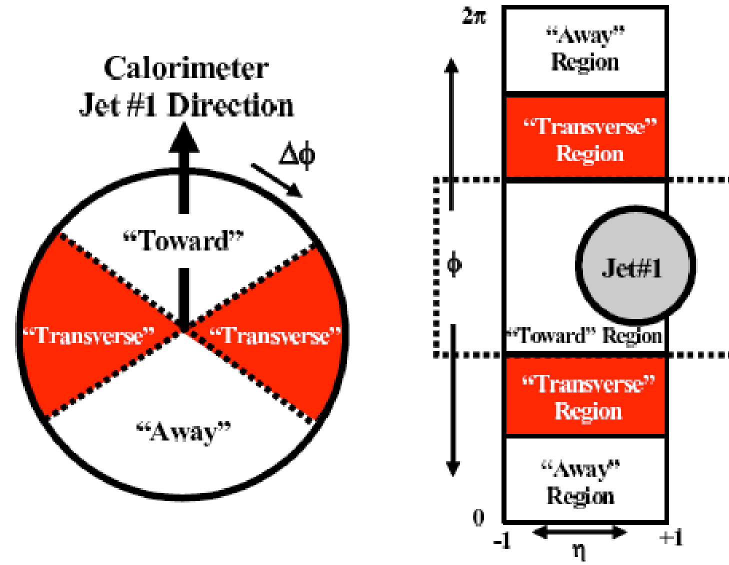


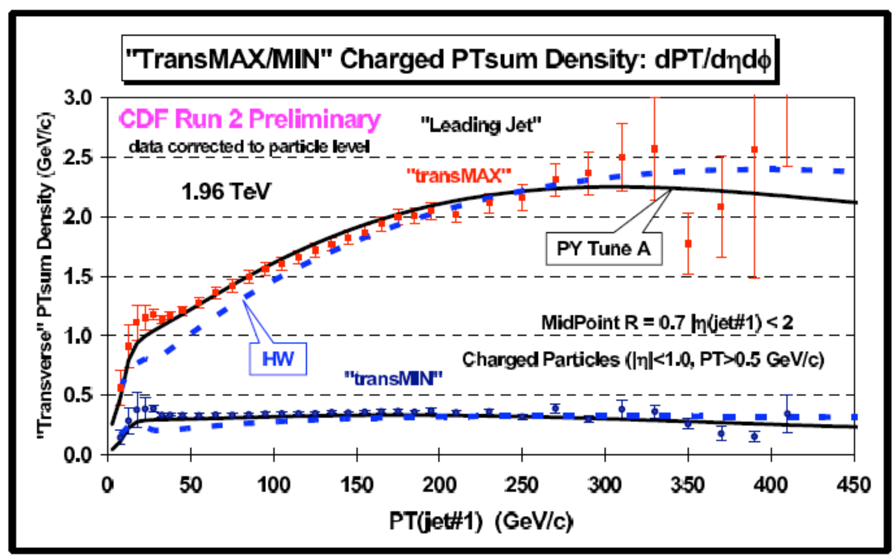
…except for exclusive k_T (where jets are explicitly broken up) high E_T distributions look similar

Known known: 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 reasonably good universal description of the data for inclusive jet production and for other types of events as well
  - multiple interactions among low x gluons





Known unknown: 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 2008
- Rick Field has been working on some new tunes
  - fixing problems present in Tune A
  - tunes for Jimmy
  - **tunes for CTEQ6.1 (NLO)**
  - see TeV4LHC writeup for details

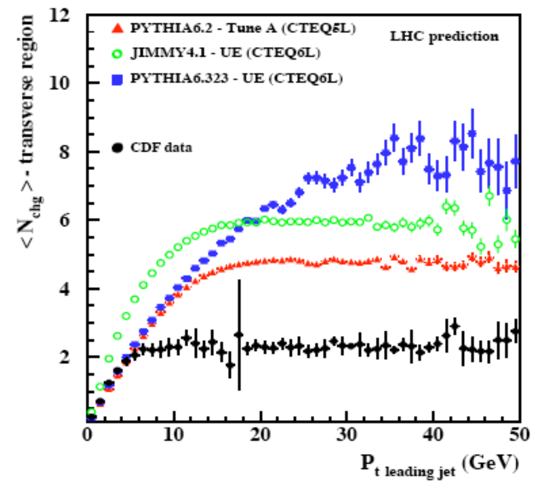
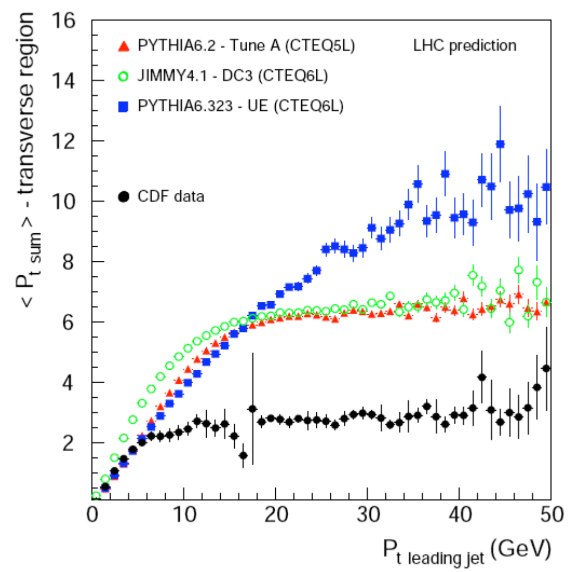
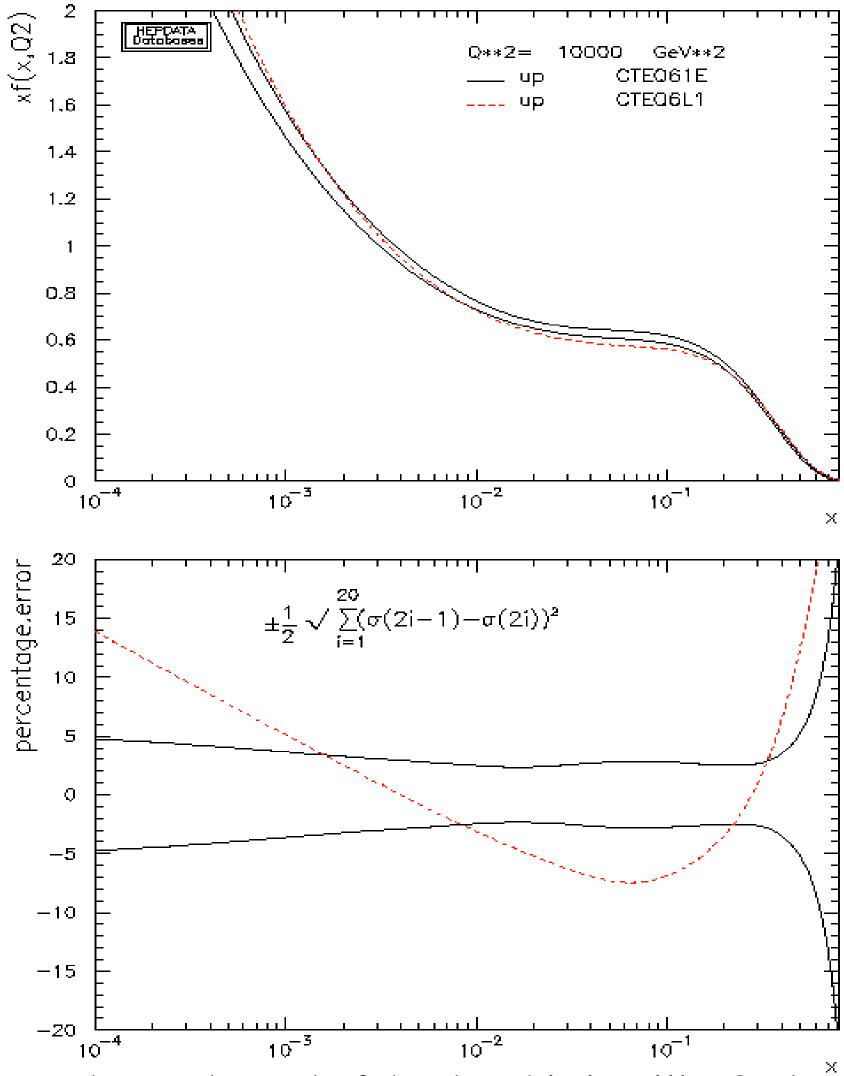


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.



…which brings me to: LO vs NLO pdf's for parton shower MC's

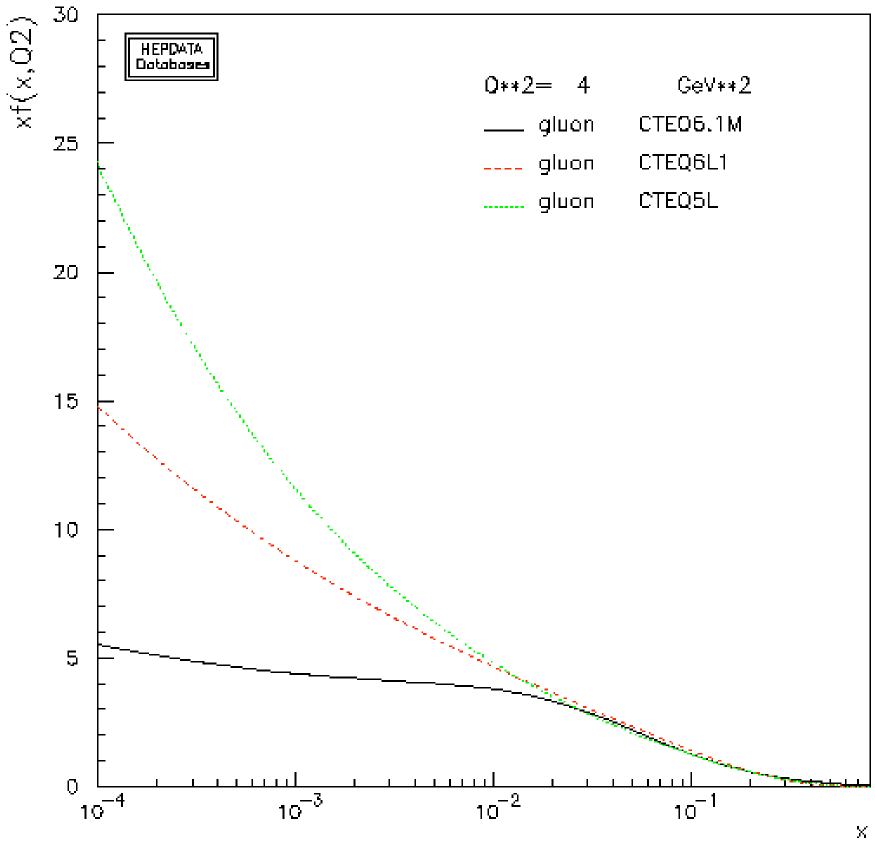
- For NLO calculations, use NLO pdf's (duh)
- What about for parton shower Monte Carlos?
  - somewhat arbitrary assumptions (for example fixing Drell-Yan normalization) have to be made in LO pdf fits
  - DIS data in global fits affect LO pdf's in ways that may not directly transfer to LO hadron collider 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) <u>use NLO pdf's</u>
  - 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

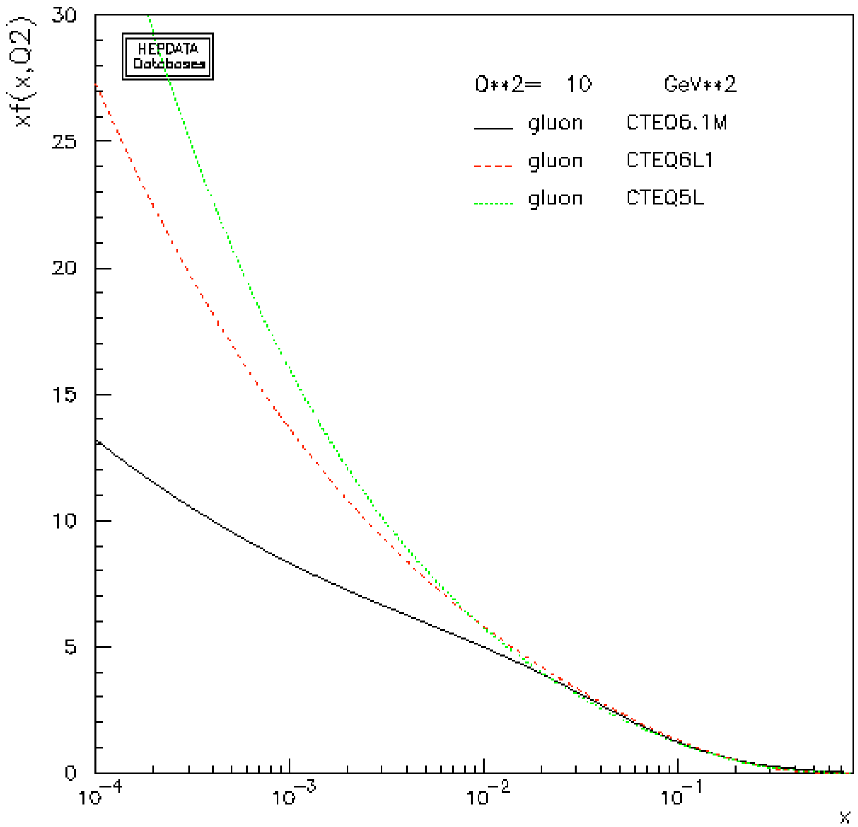


...but at the end of the day this is still LO physics;
There's no substitute for honest-to-god NLO.

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

CTEQ6.1 Tune

PYTHIA 6.2 CTEQ6.1

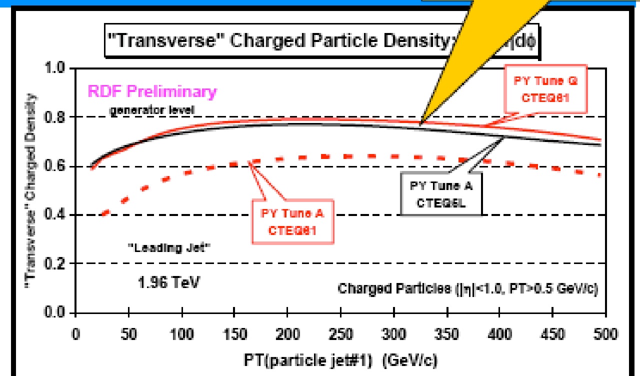
I used **LHAPDF**! See the next talk by Craig Group!

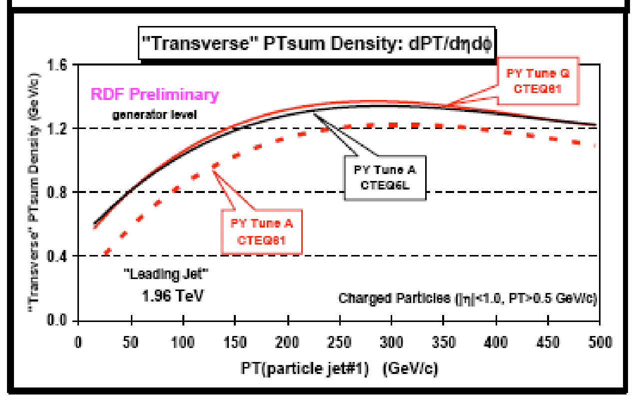
Parameter	Tune Q	Tune QW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.2 GeV	1.2 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	0.9	0.9
PARP(86)	0.95	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.0	1.25
PARP(64)	1.0	0.2
PARP(67)	4.0	4.0
MSTP(91)	1	1
PARP(91)	1.0	2.1
PARP(92)	5.0	15.0

UE Parameters: MSTP(81) – PARP(90)

ISR Parameters: PARP(62) – PARP(67)

Intrensic KT: MSTP(91) – PARP(92)





TeV4LHC - Fermilab October 20, 2005 *Rick Field - Florida/CDF* *Page 18*

…discussed in detail in TeV4LHC writeup

Study

- We are carrying out a systematic study of the impact of the use of NLO pdf's for LO parton shower predictions

Torbjorn Sjostrand

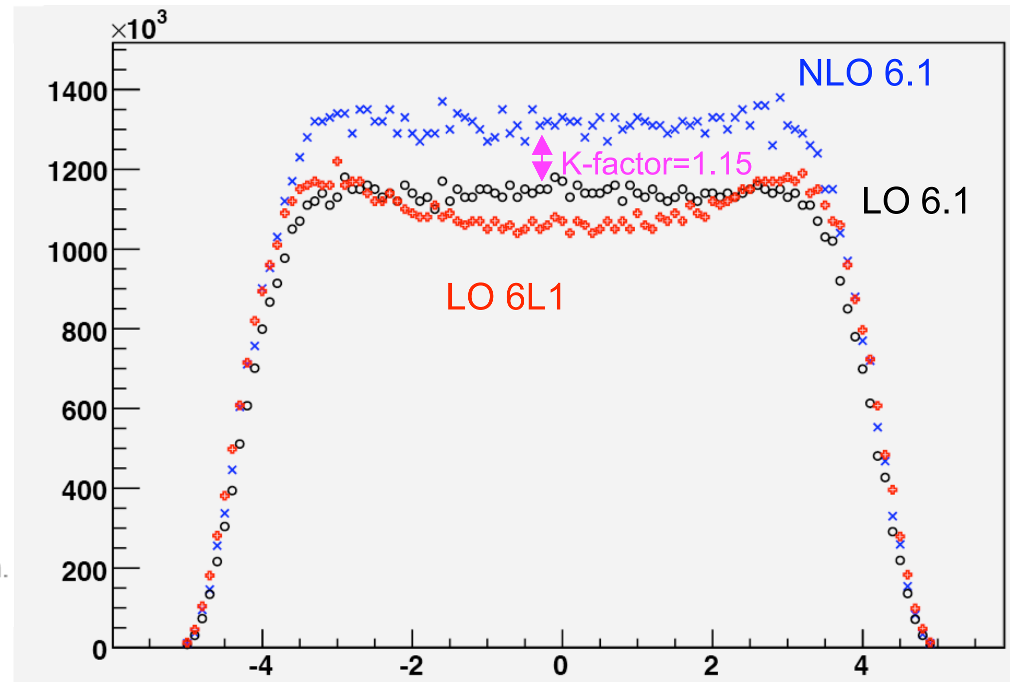
The proof of the pudding . . .

Assume the best description of physics is obtained with
(a) $\hat{\sigma}(\mathrm{NLO}) \otimes \mathrm{PDF(NLO)}$.

Interesting comparisons would then be with the scenarios:
(b) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(LO)}$.
(c) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(LO)} \otimes$ showers.
(d) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(NLO)}$.
(e) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF(NLO)} \otimes$ showers.
Only if (e) is a better approximation to (a) than is (c) would the use of NLO PDF's be motivated in a general-purpose generator.

Technical aside:
(a) = external NLO program.
(c), (e) = PYTHIA/HERWIG/. . . without primordial $k_{\perp}$, MI or hadronization.
(b), (d) = ditto, also without ISR and FSR showers.

W^+ rapidity distribution at LHC



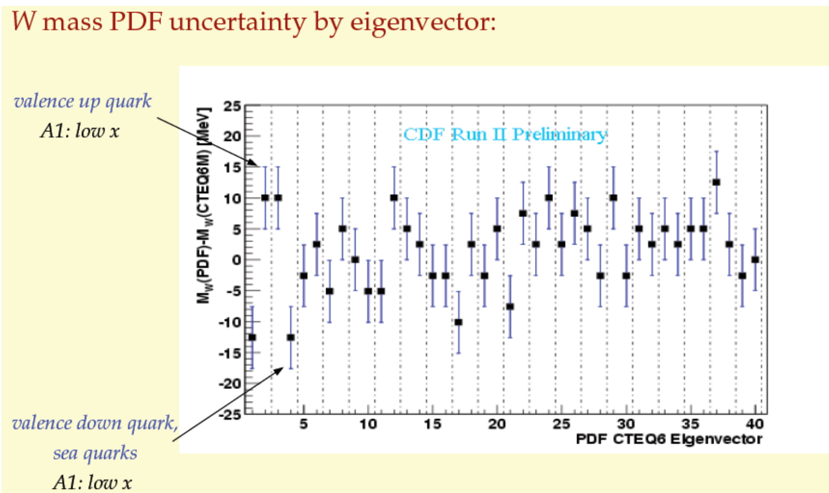
y_{W^+}

- One possibility
  - use CTEQ5L for UE but NLO pdf's for matrix element evaluation
- Answers by/at Les Houches 2007

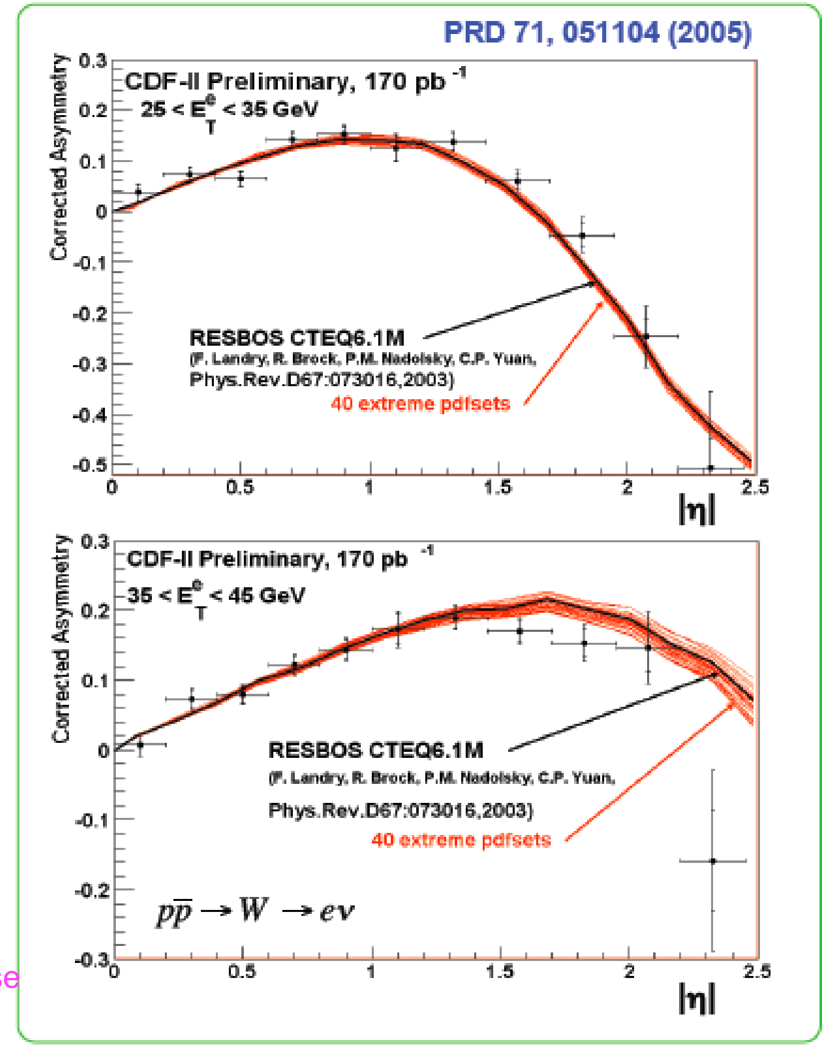
For example, the shape of the W^+ rapidity distribution is significantly different than the NLO result if the LO pdf is used, but very similar if the NLO pdf is used.

Another useful Tevatron data set: W asymmetry

- •CDF Run 1 asymmetry measurement included in both CTEQ and MRST fits
- •CDF and D0 Run 2 measurements currently being included in new round of fits
- •Separation into two bins of lepton E_T allows for more discrimination

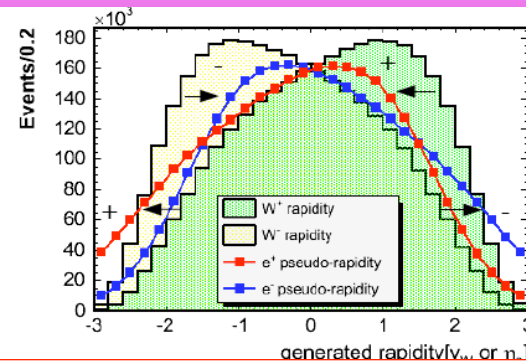


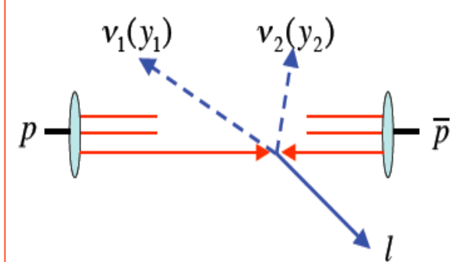
eigenvectors 1 and 2 also cause the extremes for the W asymmetry



New technique

- What was measured before was really lepton asymmetry
- A new technique is being applied to directly measure the W asymmetry
- This should be more powerful from the point-of-view of pdf determination





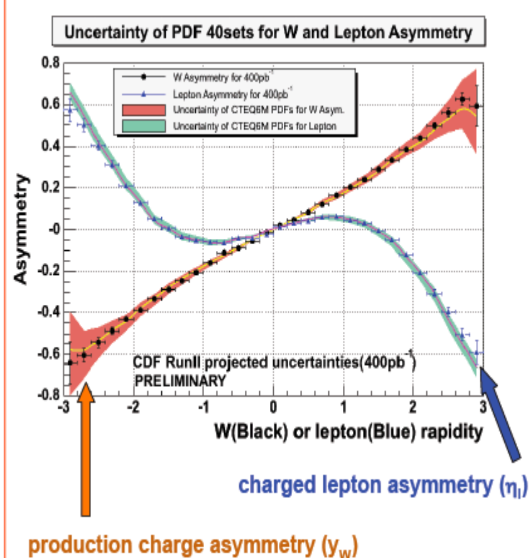
- Reconstruct the production asymmetry distribution $A(y_W)$ directly ?

1. Find 2 solutions using M_W constraint.
2. Weight each by a factor taking into account production & decay :

$$P_{1,2}(\pm\cos\theta^*, y_W, p_T^W)$$

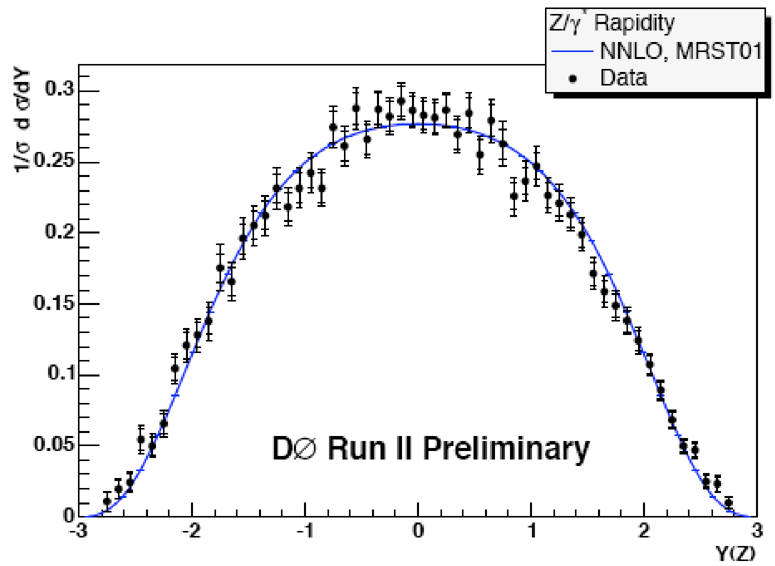
3. Resolve dependence on y_W iteratively to yield $A(y_W)$.

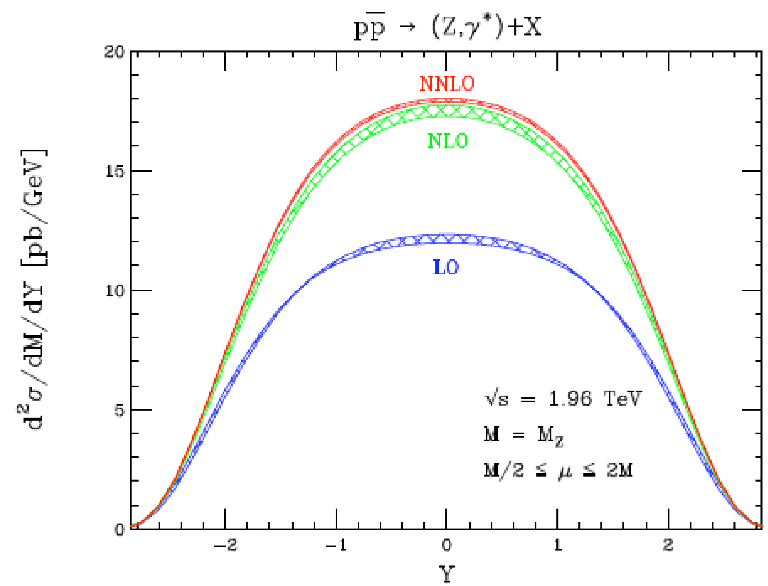
- Preliminary CDF Monte Carlo analysis shows significantly increased sensitivity :



Other data: Z Rapidity distributions

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





Known known: W/Z at the Tevatron

- W/Z cross sections serve as precision physics monitors
  - all cross sections at Tevatron/LHC could be normalized to W/Z
  - Tevatron is a *W factory*

W Factory

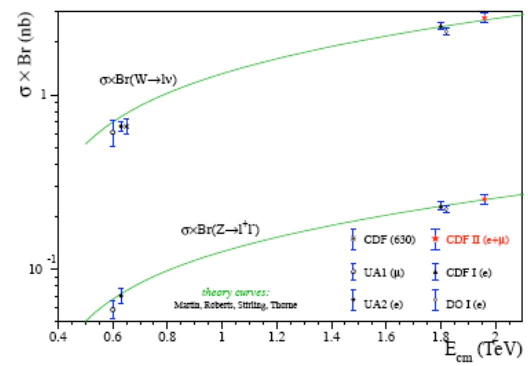
Mode	Events/Week/Exp. (after trigger & cuts)
$W \to e\nu$	~ 15,000
$Z \to ee$	~ 1,500

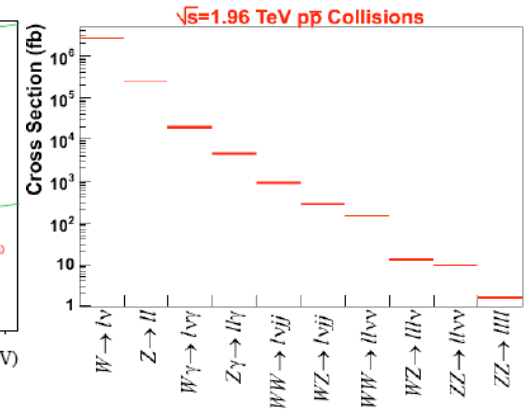
- Both experimental and theoretical errors are under control
  - NNLO a small (positive) correction to NLO

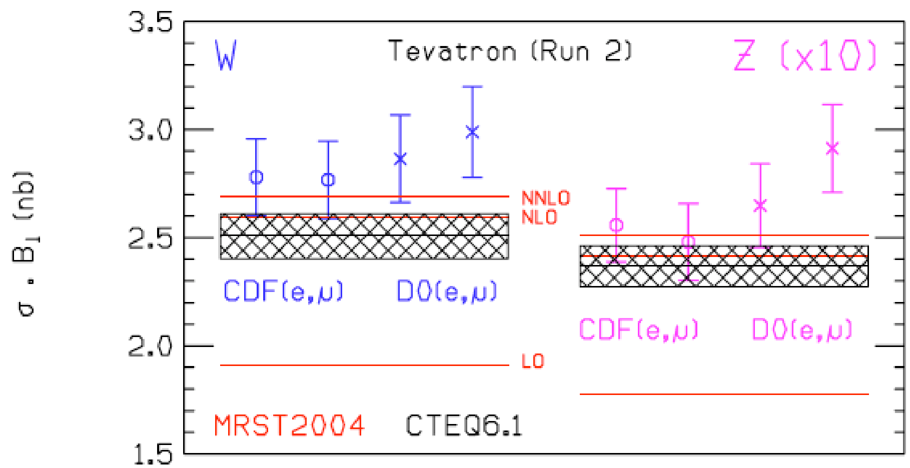
$$\frac{\sigma(L)}{L} = 2.5\% \oplus 5.5\%$$

dominated by experimental uncertainty

$\sigma_{TOT}(p\bar{p})$ σ_{EXP} (lumi detector acceptance)







- Note that CTEQ and MRST NLO predictions agree within CTEQ6.1 pdf errors (but MRST at edge of CTEQ6.1 error band)

Precision benchmarks: W/Z cross sections at the LHC

- CTEQ and MRST NLO predictions in good agreement with each other
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC

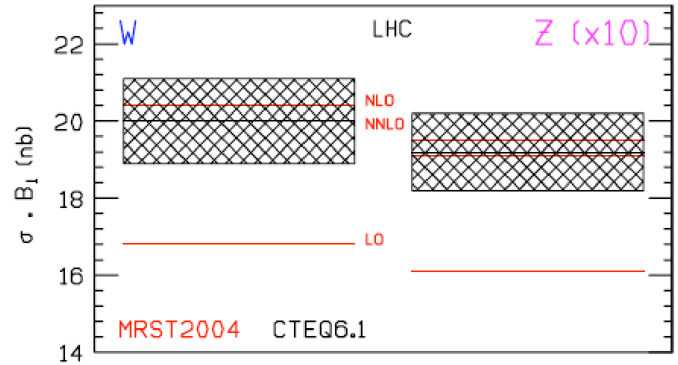


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

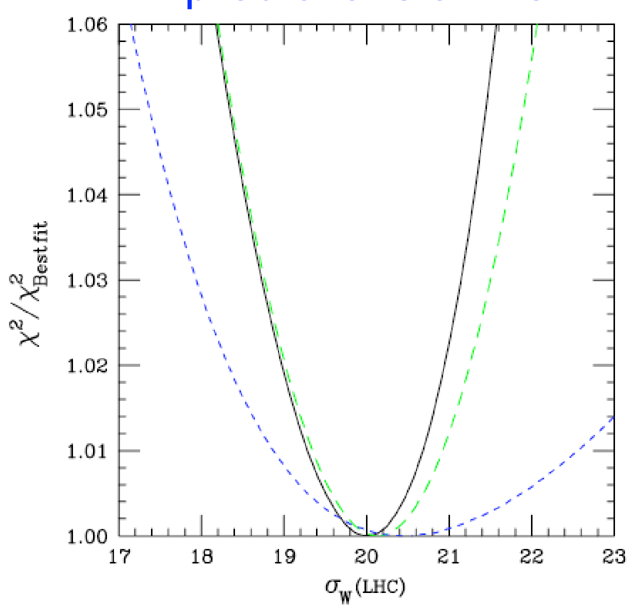


Figure 82. Lagrange multiplier results for the W cross section (in nb) at the LHC using a positive–definite gluon. The three curves, in order of decreasing steepness, correspond to three sets of kinematic cuts, standard/intermediate/strong.

removing low x data from global fits increases uncertainty but does not significantly move central answer

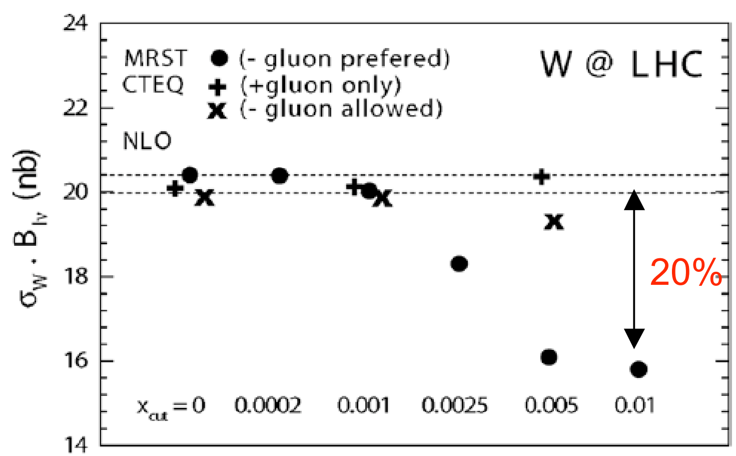


Figure 81. Predicted total cross section of $W^+ + W^-$ production at the LHC for the fits obtained in the CTEQ stability study, compared with the MRST results. The overall pdf uncertainty of the prediction is ~5%, as observed in figure 77.

MRST found a tension between low x and high x data; not present in CTEQ analysis

Rapidity distributions and NNLO

- As at Tevatron, effect of NNLO just a small normalization factor over the full rapidity range
- NNLO predictions using NLO pdf’s are close to full NNLO results, but outside of (very small) NNLO error band

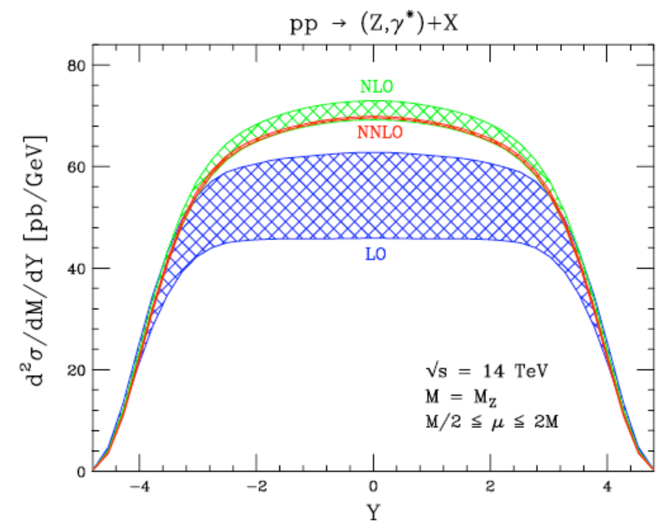


Figure 87. The rapidity distributions for Z production at the LHC at LO, NLO and NNLO.

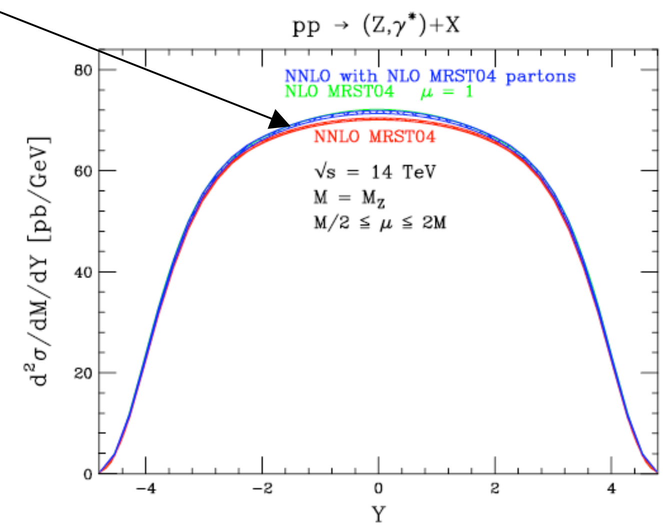
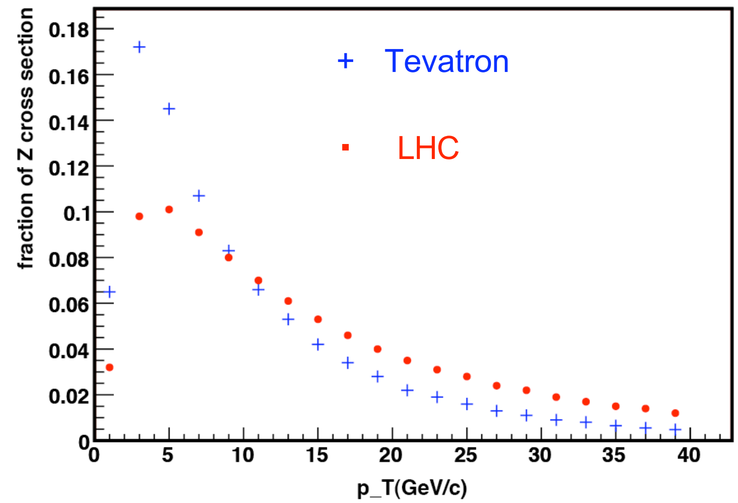


Figure 88. The rapidity distributions for Z production at the LHC at NNLO calculated with NNLO and with NLO pdfs.

W/Z p_T distributions at the Tevatron/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
  - but distribution is broadened at higher p_T
- 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**



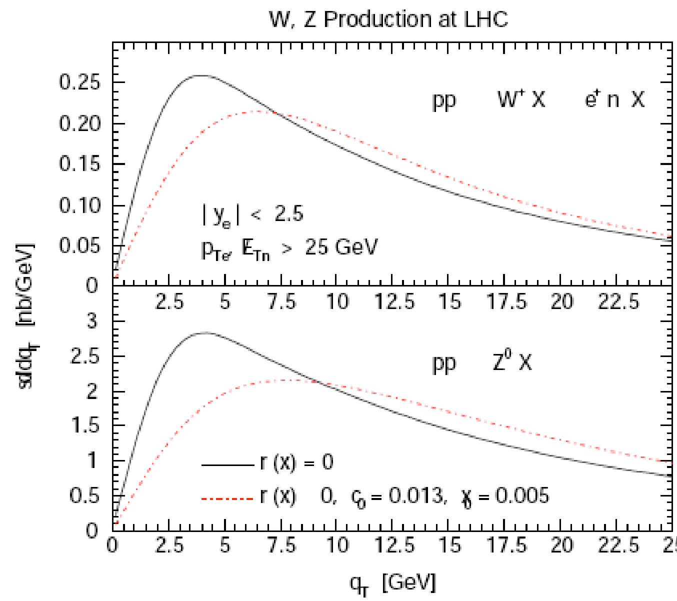
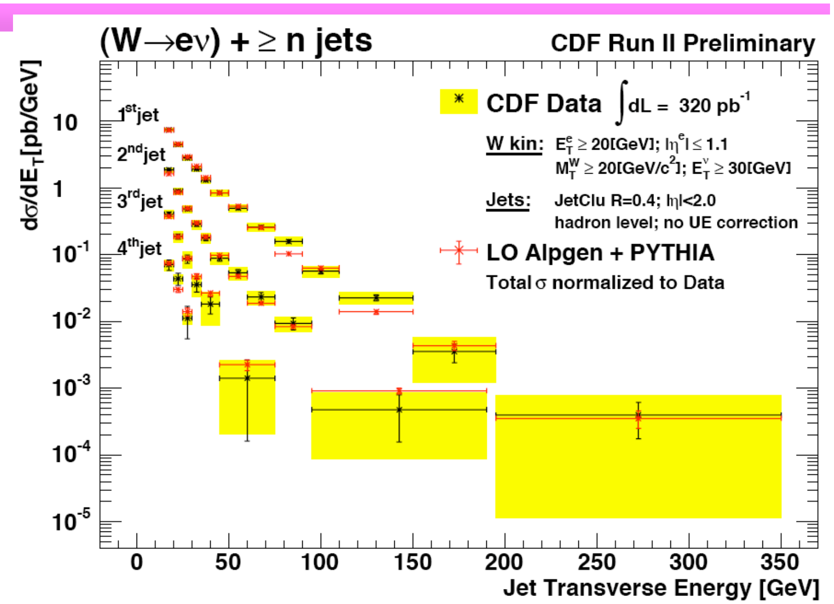


Figure 88. The predictions for the transverse momentum distributions for W and Z production with and without the q_T-broadening effects.

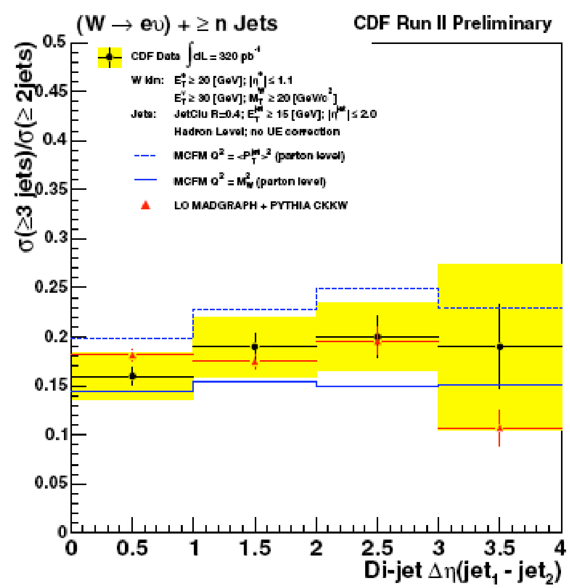
W + jets at the Tevatron

- Interesting for tests of perturbative QCD formalisms
    - matrix element calculations
    - parton showers
    - …or both
- Results from Tevatron to the right are in **a form that can be easily compared to theoretical predictions (hadron level)**



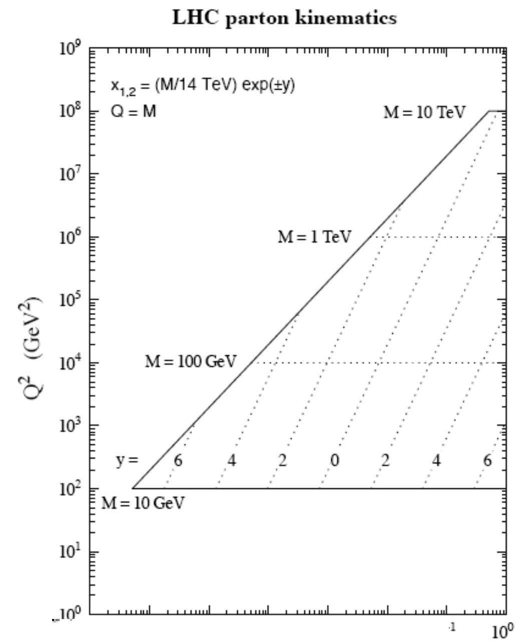
Probability of 3rd jet emission as function of two lead jet rapidity separation in good ageement with theory

At LHC, BFKL logs may become more important for high $\Delta\eta$



Using pdf information: parton kinematics

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity
  - this is from the review paper cited on previous slide (using CTEQ6.1 pdf's)
- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element



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

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

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

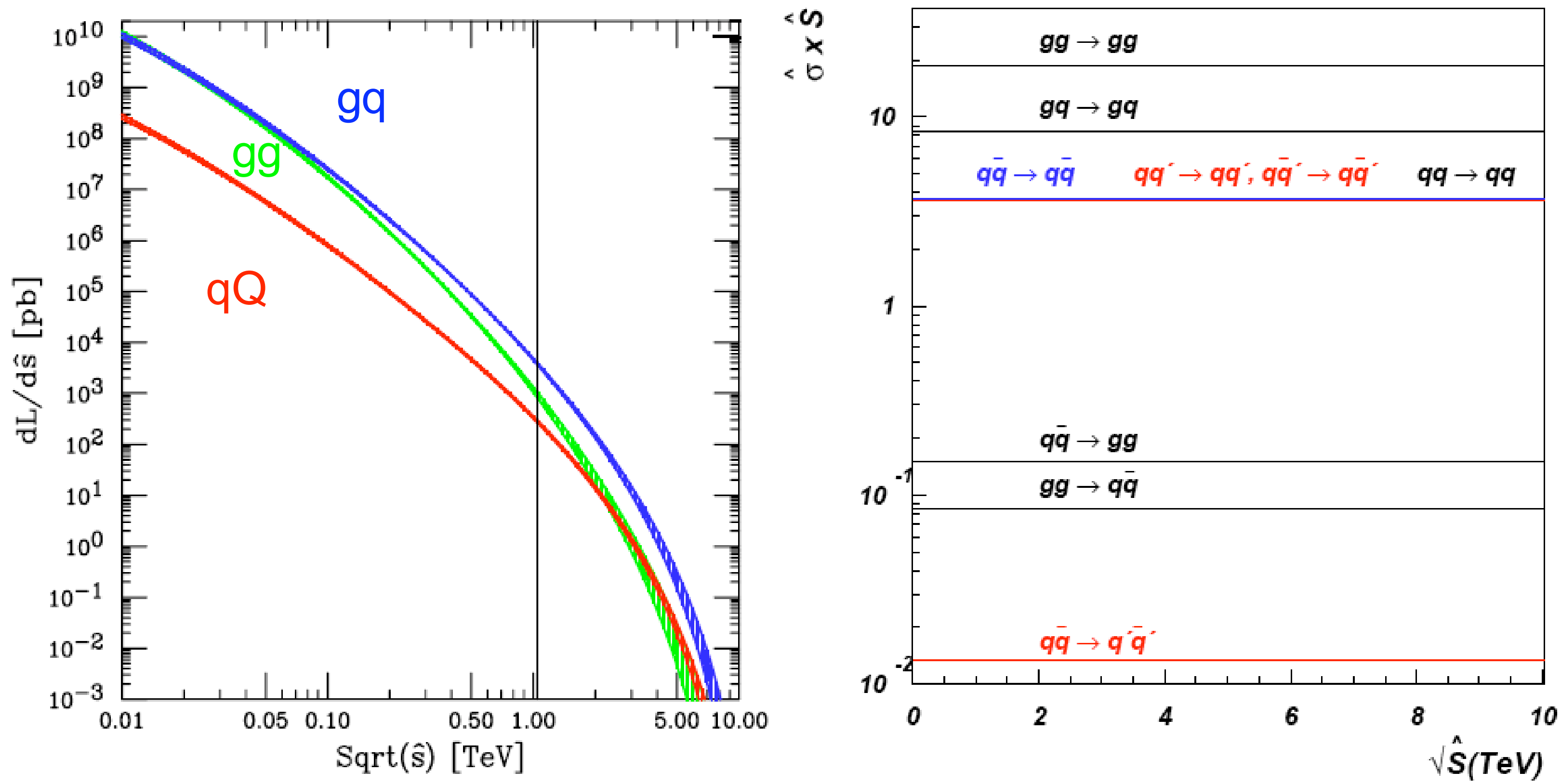
can then be written as

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

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



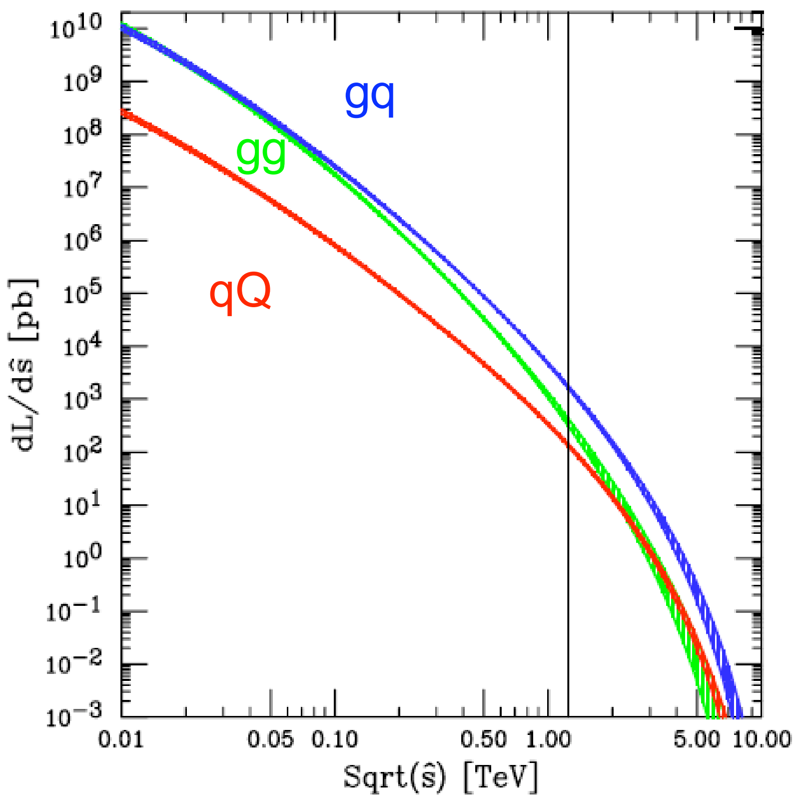
for p_T=0.1* sqrt(s-hat)

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

Heavy quark production

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

threshold effects evident



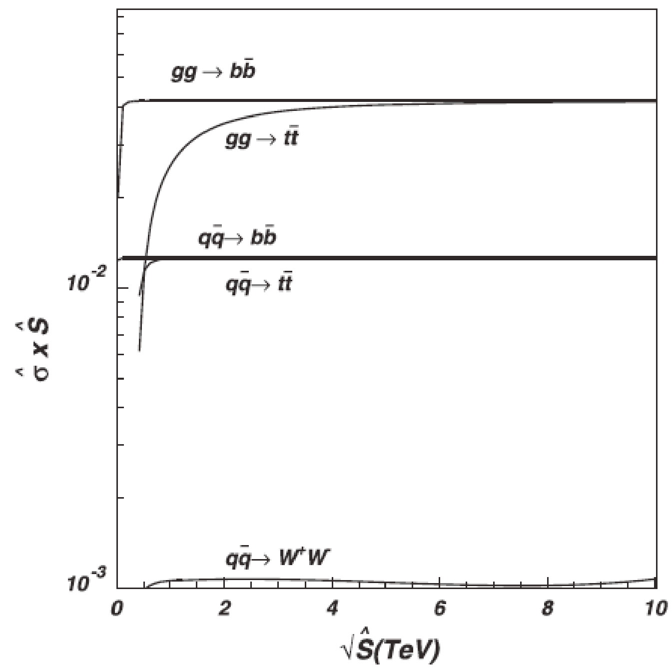


Figure 71. Parton level cross sections $(\hat{s}\hat{\sigma}_{ij})$ for various processes involving massive partons in the final state.

$\sqrt{S}$(TeV)

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

PDF luminosities as a function of y

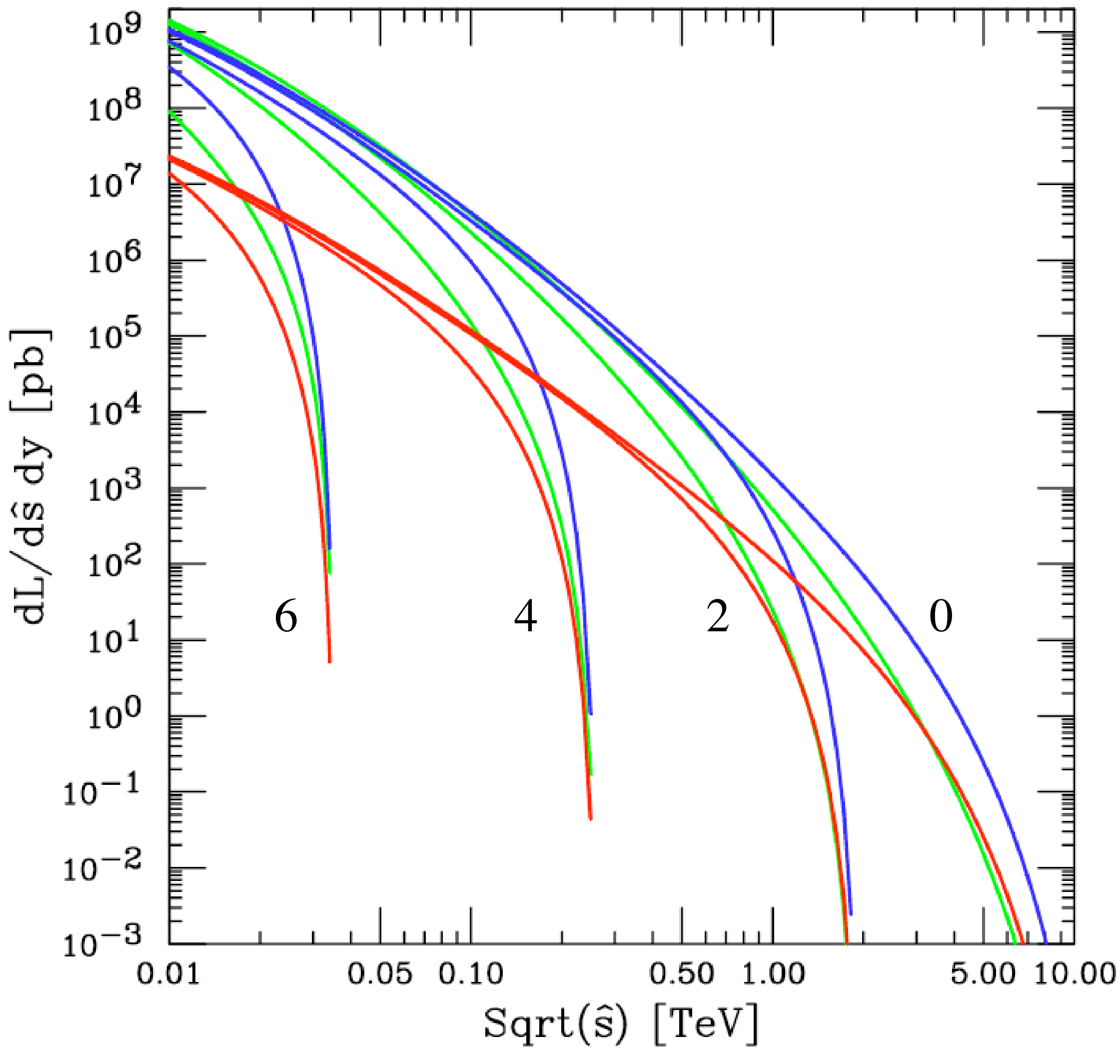


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

PDF uncertainties at the LHC

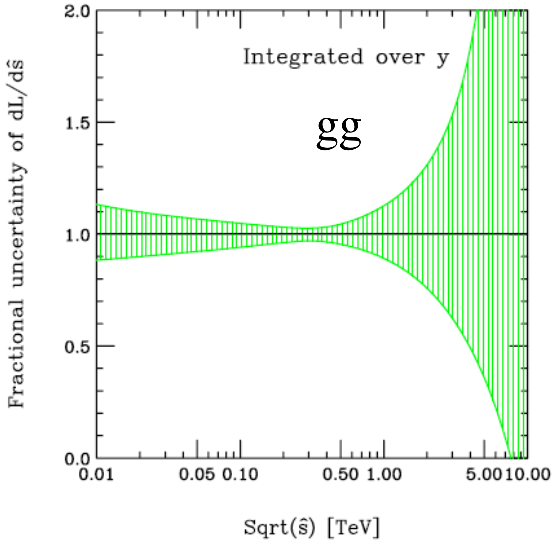


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

Note that for much of the SM/discovery range, the pdf luminosity uncertainty is small

It will be a while, i.e. not in the first fb^{-1}, before the LHC data starts to constrain pdf's

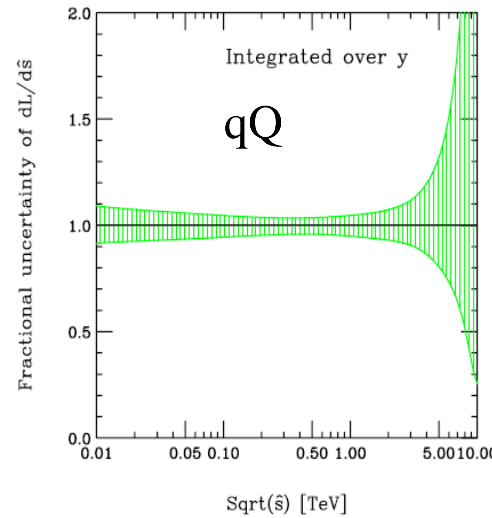


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

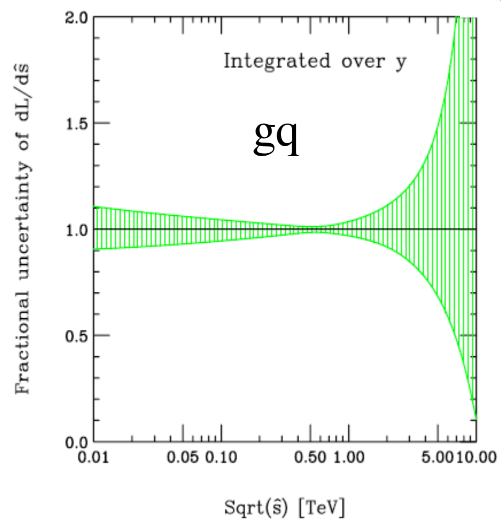


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

NB: the errors are determined using the Hessian method for a $\Delta\chi^2$ of 100 using only experimental uncertainties

Ratios:LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (e.g. 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
- W+4 jets is a background to tT production both at the Tevatron and at the LHC
- tT production at the Tevatron is largely through a qQ initial states and so qQ->tT has an enhancement factor at the LHC of ~10
- 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
  - known known: jet cuts have to be higher at LHC than at Tevatron

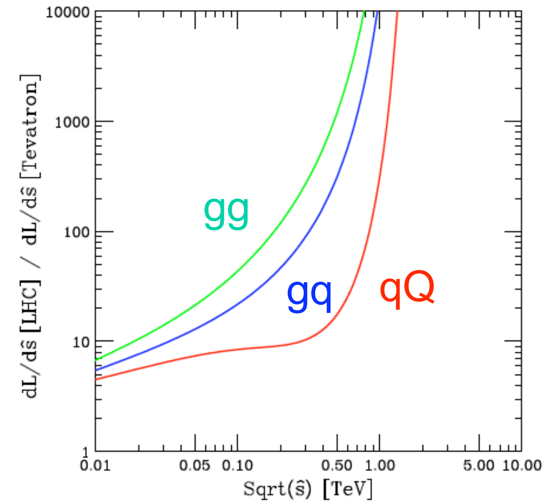


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

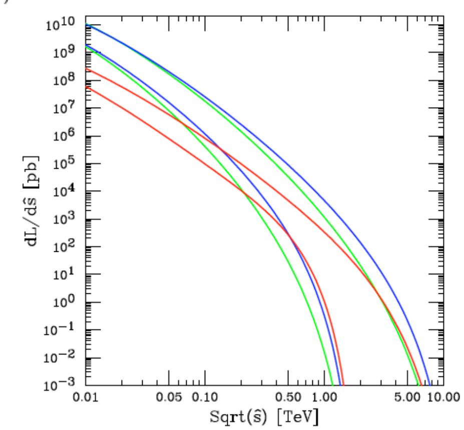
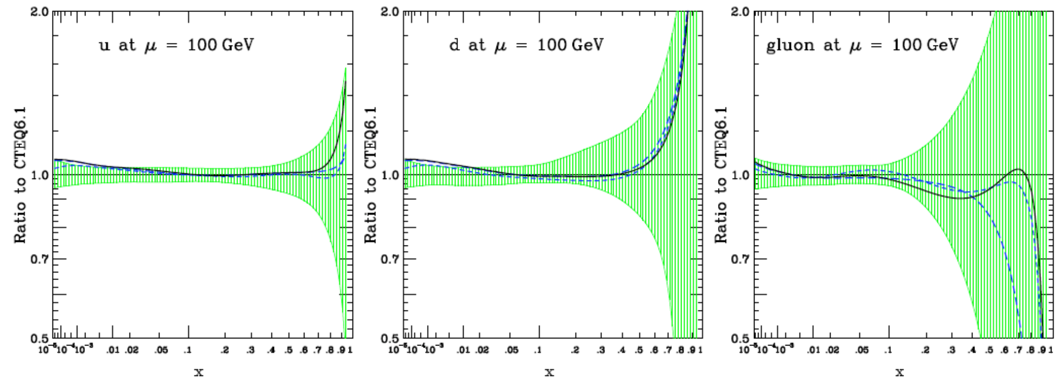


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

Known known: heavy quark mass effects in global fits

- CTEQ6.1 (and previous generations of global fits) used zero-mass VFNS scheme
- With new sets of pdf's (CTEQ6.5), heavy quark mass effects consistently taken into account in global fitting cross sections and in pdf evolution
- In most cases, resulting pdf's are within CTEQ6.1 pdf error bands
- But not at low x (in range of W and Z production at LHC)
- Heavy quark mass effects only appreciable near threshold
  - ex: prediction for F_2 at low x,Q at HERA smaller if mass of c,b quarks taken into account
  - thus, quark pdf's have to be bigger in this region to have an equivalent fit to the HERA data → implications for LHC phenomenology



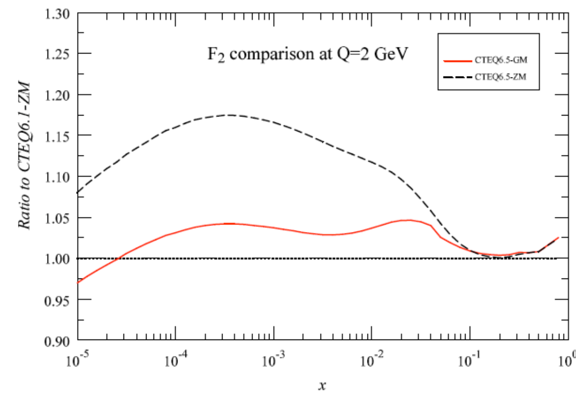


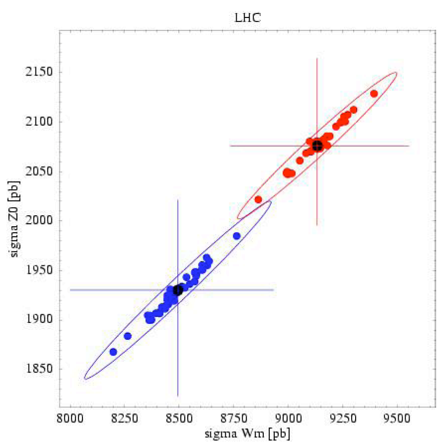
Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

See Wu Ki's talk.

CTEQ6.5

Conclusions on CTEQ6.5

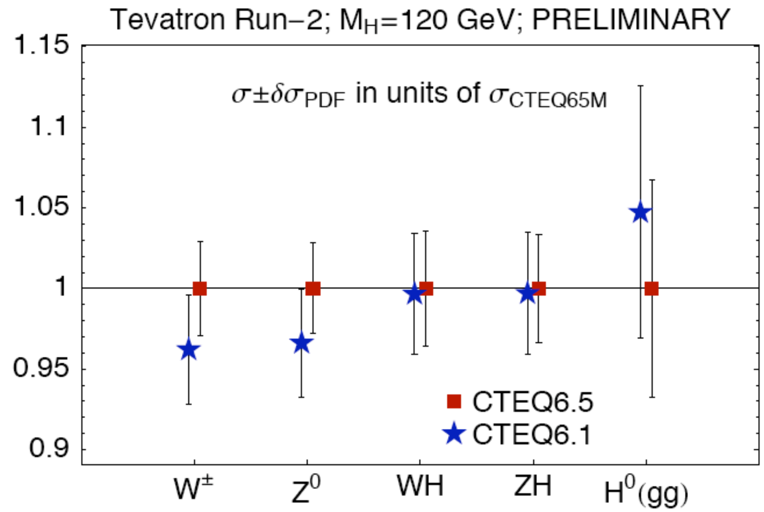
1. Improved Input
   - HQ formalism implemented
   - Use HERA measured cross sections directly
   - Include HERA CC data and NuTeV dimuon data (weight=2.0)
2. Gives better fit (χ^2 lower by ~ 200), suggesting that the physics is better! :)
3. CTEQ6.1 uncertainties were not unreasonable
4. Little or no decrease in estimated uncertainty – though the agreement with CTEQ6.1 (except where difference is expected) inspires increased confidence.
5. Larger q and $\bar{q}$ distributions at $x \sim 10^{-3}$ from correcting the former ZM approximation implies larger cross sections at LHC.

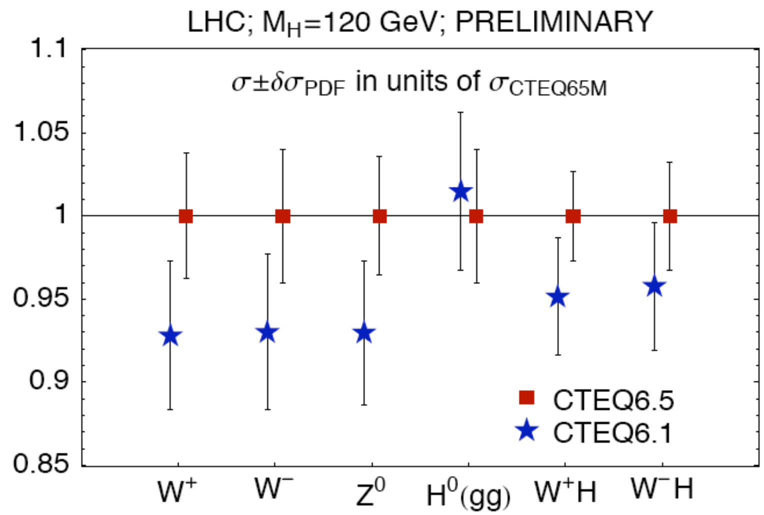


LHC

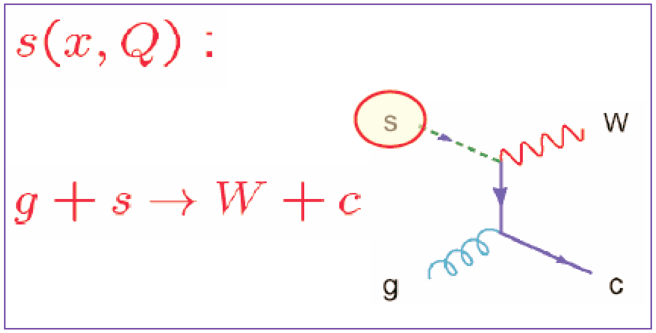
W- and Z0 cross sections for CTEQ6.1 (Blue) and CTEQ6.5 (Red)

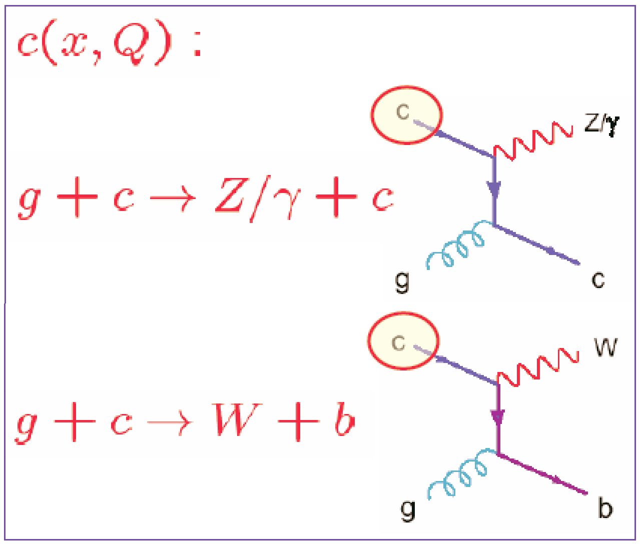
Uncorrelated uncertainties and correlated error ellipses.

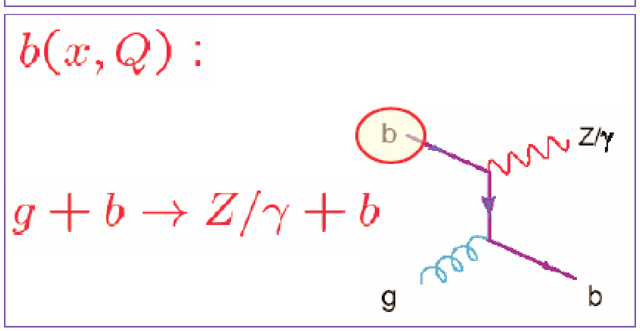


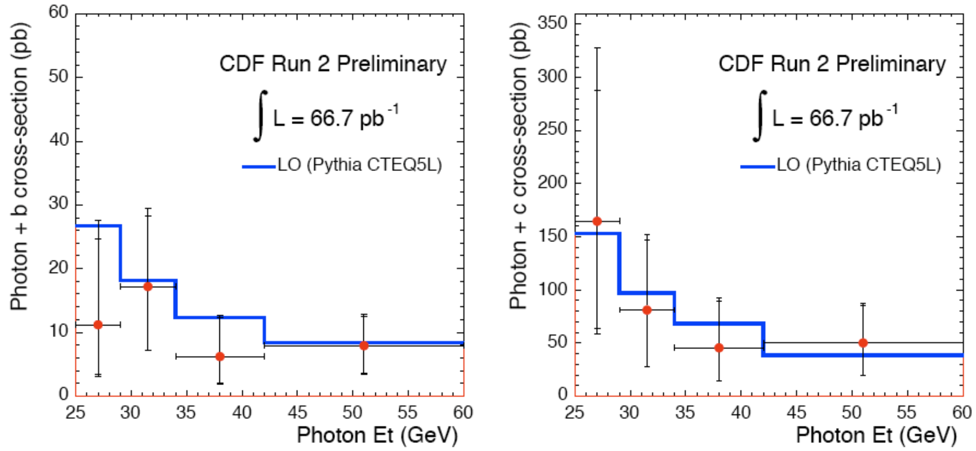


Measuring heavy quark pdf's at the Tevatron



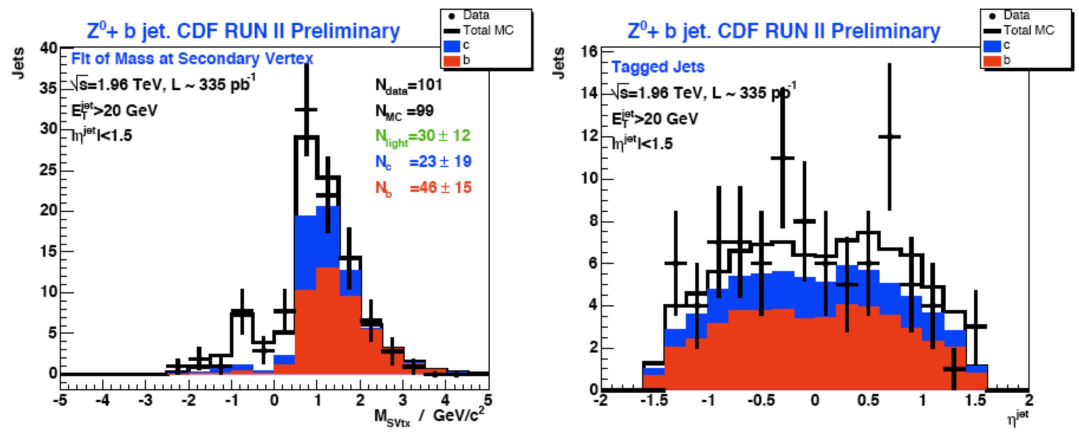






(a) Photon+charm (b) Photon+bottom

Fig. 3.2.21: Transverse energy distribution for photons in events with a tagged heavy quark. The data is compared to PYTHIA.



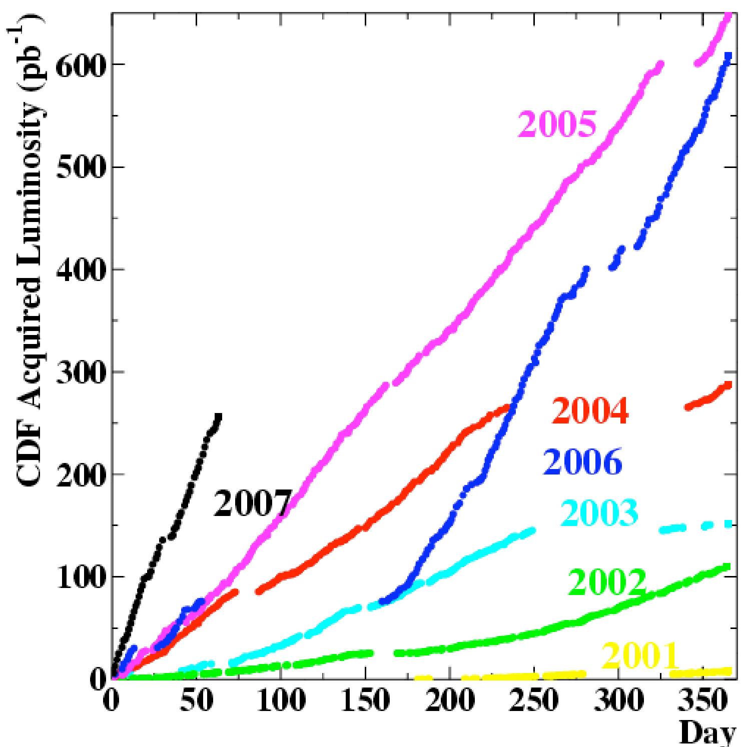
(a) Invariant mass of the tracks composing the secondary vertex

(b) η distribution of the tagged jets

Fig. 3.2.22: Distributions for Zb events

Summary

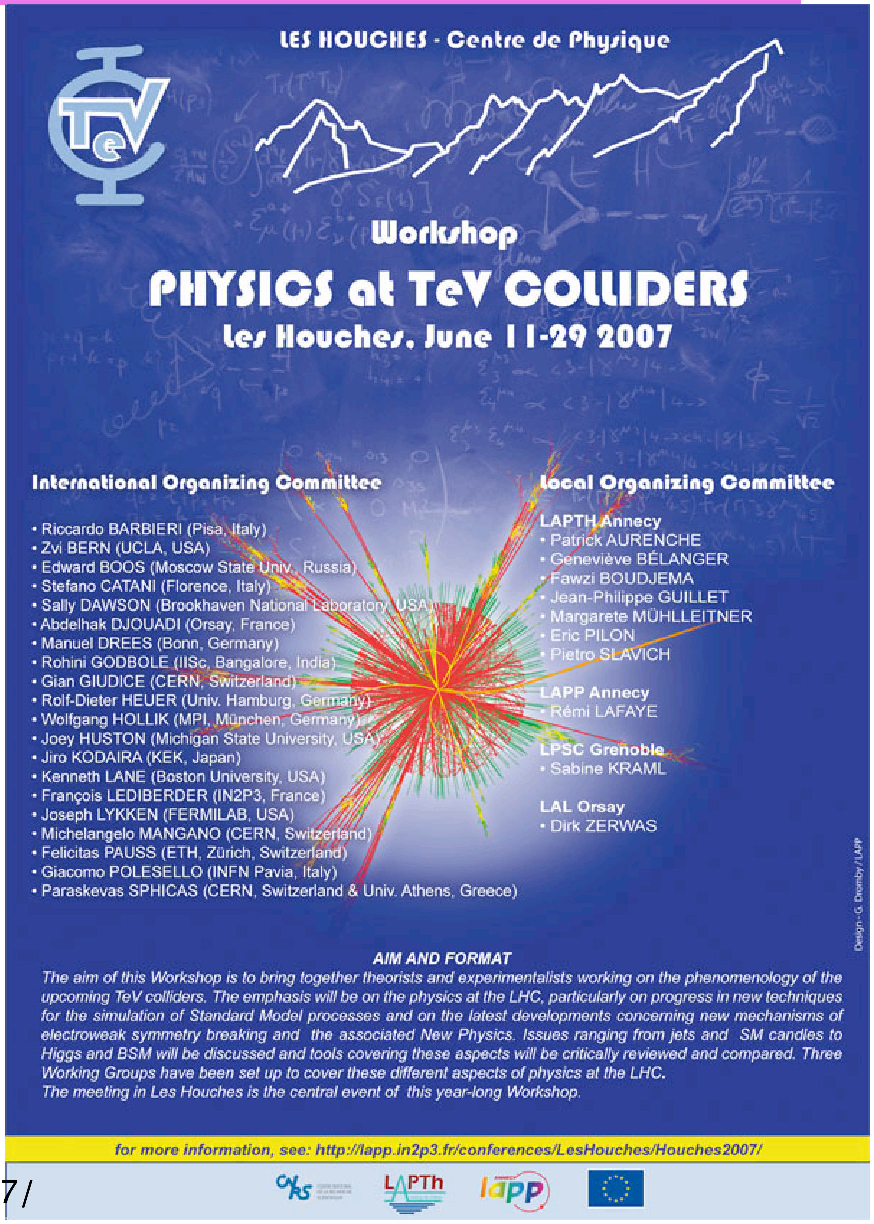
- Physics will come flying hot and heavy when LHC turns on at full energy in 2008
- Important to establish both the SM benchmarks and the tools we will need to properly understand this flood of data
  - and in particular, those dealing with jet reconstruction
  - and to make the best use of existing/future data from both the Tevatron and HERA
- More CTEQ papers coming shortly dealing with phenomenology implications of CTEQ6.5
  - in future
    - resummation
    - NNLO



Physics at TeV Colliders

Les Houches, 11-29 June 2007

- **WG NLO Multi-leg** will address the issue of the theoretical predictions for **multileg processes**, in particular beyond leading order, and the possibility of implementing these calculations in Monte Carlos. This working group aims at a cross breeding between novel approaches (twistors, bootstraps,..) and improvements in standard techniques.
  - Dave Soper, Borut Kersevan and I are leading a group dealing with NLO calculations and their use
- **WG SM Handles and Candles** will review and critically compare existing tools for **SM processes**, covering issues in pdf, jets and Higgs physics.
- **WG New Physics** is a **beyond SM** group, subdivided into SUSY and new models of symmetry breaking. It will also address the issue of model reconstruction and model independent searches based on topologies.
- There will also be an **intergroup** dedicated to **Tools and Monte Carlos**. This intergroup will liaise with **all** WG with the task of incorporating some of the issues and new techniques developed in these groups in view of improving Monte Carlos and setting **standards and *accords*** among the simulation codes to better meet the experimental needs.

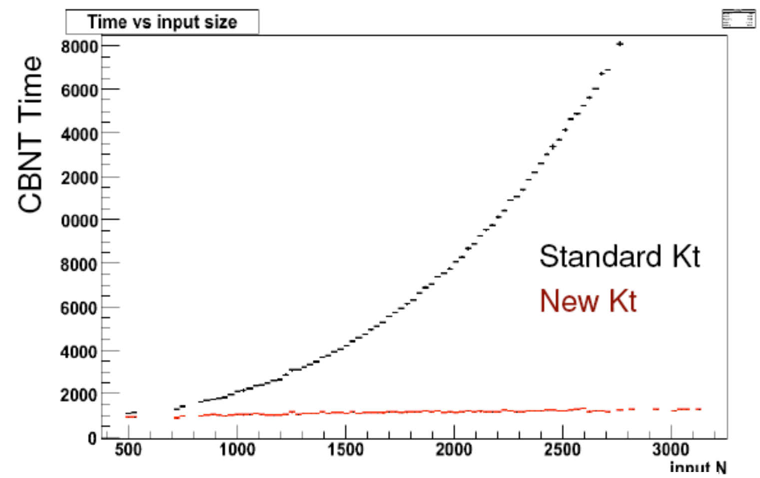


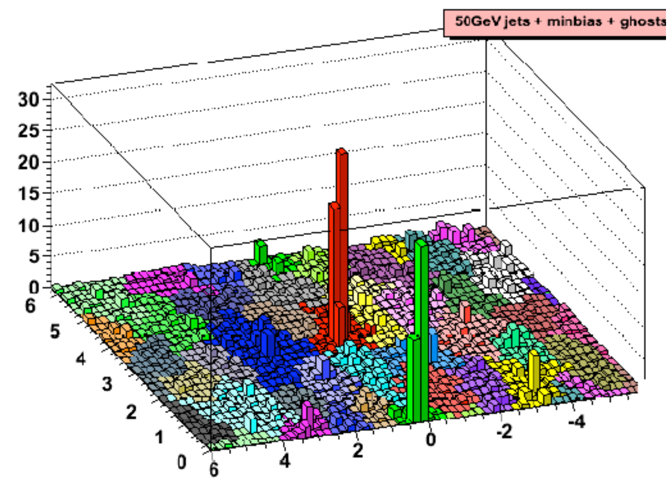
http://lappweb.in2p3.fr/conferences/LesHouches/Houches2007/

Extra slides

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 and CMS
- Optimum is if analyses at LHC use **both** cone and k_T algorithms for jet-finding
  - universal benchmark
  - need experience now from the Tevatron





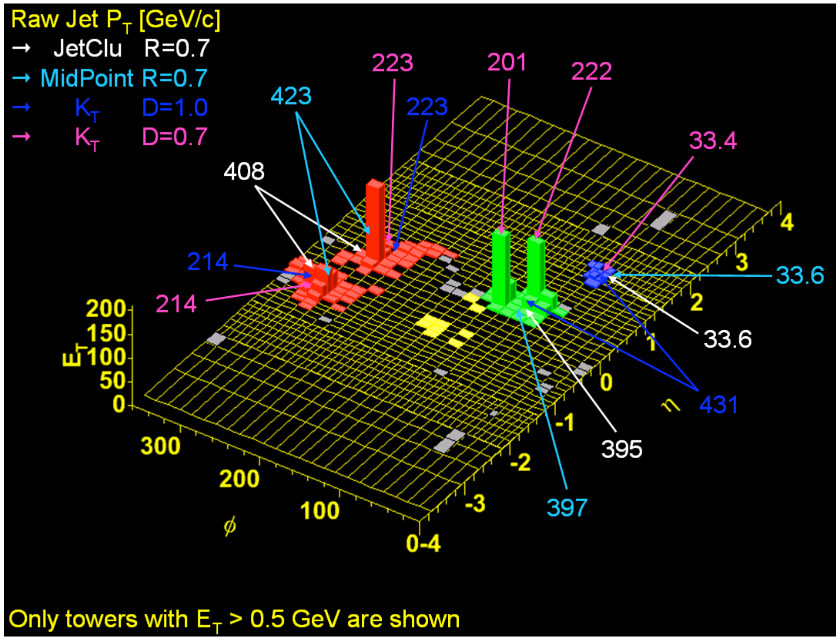
~ 10000 particles

Clustering takes ~ 20 minutes with old methods.

0.6s with `FastJet`.

Jets and you

- There is a need/desire to have available the results of more than one jet algorithm when analyzing an event
- A student of mine and I have assembled some jet algorithms together in a routine that runs on 4-vector files
- So far, the routine runs JetClu, Midpoint, k_T (inclusive and exclusive), Cambridge/Aachen algorithm and simple Pythia UA-1 type algorithm (CellJet)
  - in a UA-1 type algorithm, the center of the jet is taken as the location of the highest pT tower; a cone is drawn around the jet and those towers are eliminated from the remaining jet clustering
- User specifies the parameters for the jet reconstruction (including whether to pre-cluster the 4-vectors together into towers), whether to add in extra min bias events (pending), and whether to make lego plots (with user-specified tower granularity)



- Available from www.pa.msu.edu /~huston/lhc_jet/lhc_jet.html

LHC jet webpage

- This webpage is intended to store some reference materials for the common study of jet algorithms at the LHC to be carried out by ATLAS and CMS. One of the main tools for this exercise is a collection of jet routines that is intended to run on files of 4-vectors. These 4-vectors can be partons, particles or calorimeter towers.
- At MSU, we are proceeding on two paths.
  - A version of the program that runs in stand-alone fashion can be found here. Instructions on how to use it can be found in the README files.
  - A development version that runs within the ROOT framework can be found here. Instructions can also be found in its README file. This version seems reasonably stable as of Feb. 15. Please report any bugs or "features.
- "As of Feb. 7, both versions contains the JetClu, Midpoint, seedless and CellJet (a UA-1 type of algorithm found in Pythia). We have also included the routines for the inclusive and exclusive kT algorithms and for the Cambridge/Aachen algorithm provided by Matteo Cacciari and Gavin Salam in their FastJet program.
- The programs provide a number of options for running the algorithms, such as cone size/R parameter, seed thresholds, split/merge fraction etc. An ascii output file is generated as well as optional lego plots and ROOT ntuples. The program runs inside the example sub-directory. The input is controlled from the input.txt file and the program to run is called main. In the subdirectory scripts are several useful scripts. In particular, in the ROOT version the script analysis.c should be run on the ROOT output file created by the main program. This script will enable you to interactively make lego plots, plot jet ET distributions, etc. In addition, you can directly access the tree in the ROOT file created by running the main program.

Jets and you

```
// Any value set to -1 will be read in as the default
data/Pythia-PtMin1000-LHC-10ev.dat
output/output_file.dat
                          DEFAULT
1                 // QUIET mode (minimalist console output)          0
0                 // WRITE events to files (next line = file prefix)  0
event
10                // TOTAl events to process                  ALL EVENTS
0.1               // group 4-vectors into bins of this size (eta) -1   (no
                  binning)
0.1               //(same, but for phi)                   -1   (no binning)

1                 // do jetclu                                        0
                  // JetClu Parameters
-1                // seed Threshold                                   1
0.4               // cone radius                                     0.7
-1                // adjacency cut                                    2
-1                // max iterations                                  100
-1                // iratch                                          1
-1                // overlap threshold                               0.75
```

Jets and you

```
1                  // do midpoint                                        0
// MidPoint Parameters
-1                 // seed Threshold                                     1
0.4                // cone radius                                        0.7
1                  // cone area fraction (search cone area)              0.25
-1                 // max pair size                                      2
-1                 // max iterations                                     100
-1                 // overlap threshold                                  0.75

1                  // do midpoint second pass or not?                    0

1                  // do kt fastjet                                      0
//kt fastjet Parameters
0.4                // Rparam                                             1.0
-1                 // min pt                                             5.0
-1                 // dcut                                               25.0

1                  // do kt cambridge (aachen algorithm)                 0
//kt cambridge Parameters
0.4                // Rparam                                             1.0
-1                 // min pt                                             5.0
-1                 // dcut                                               25.0
```

Jets and you

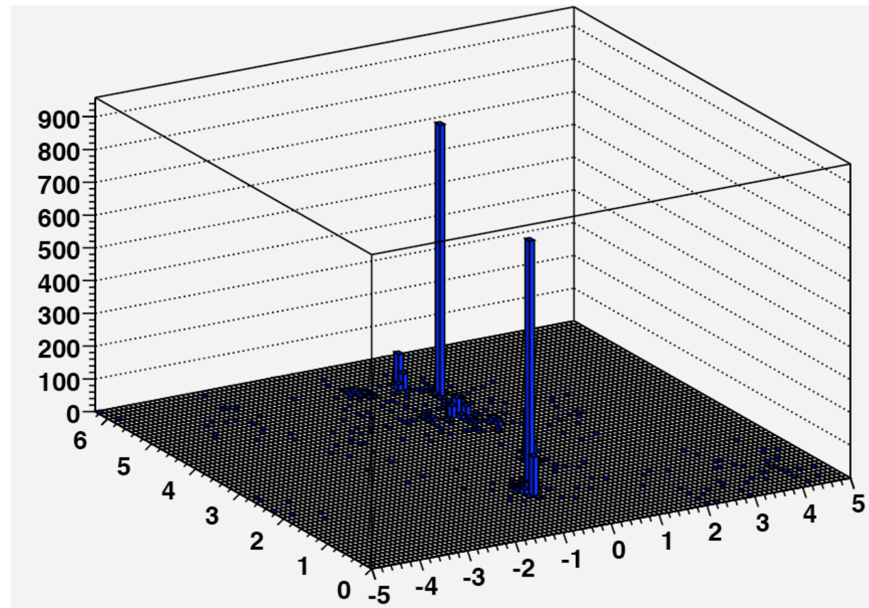
```
//area Parameters
-1              // ghost_etamax                    6.0
-1              // repeat                          5
-1              // ghost_area                      0.01
-1              // grid_scatter                    1E-4
-1              // kt_scatter                      0.1
-1              // mean_ghost_kt                   1E-100

1               // do CellJet                      0
//CellJet Parameters
1               // min jet Et                       5
0.4             // cone Radius                     0.7
-1              // eTseedIn                        1.5
```

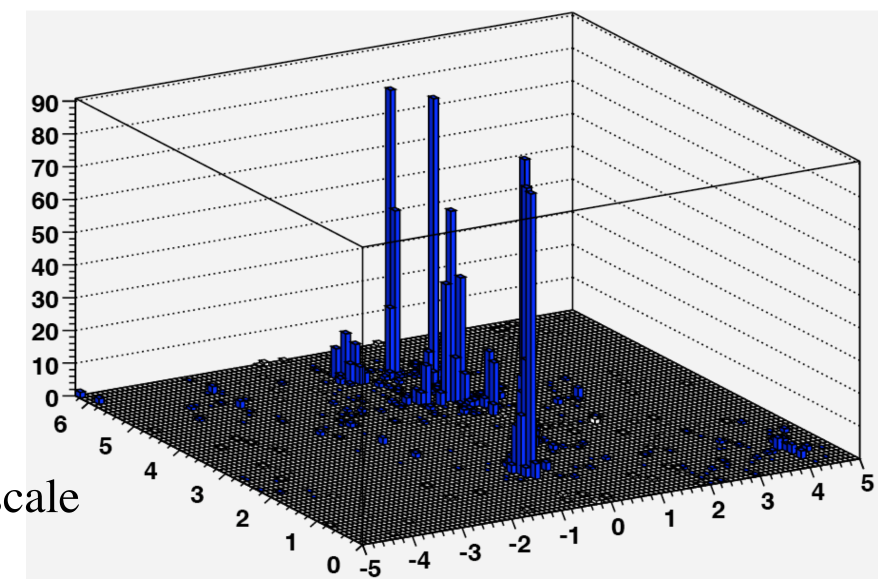
Example dijet event (2 of 10) for p_T^{min} of 1 TeV/c

Input : 713 four vectors

Binned: 300 four vectors

- MidPoint Jets(R=0.7):
- Et=1109., eta=-0.36, phi=1.47, nTowers=95
- Et=1068., eta=0.80, phi=4.90, nTowers=99
- Et=275., eta =0.59, phi=3.9906, nTowers=106
- Et=257.334, eta=0.468712, phi=2.35006, nTowers = 52
- Et=78.8206, eta=-0.407128, phi=5.27241, nTowers = 41
- Et=17.0014, eta=4.16126, phi=0.625633, nTowers=14



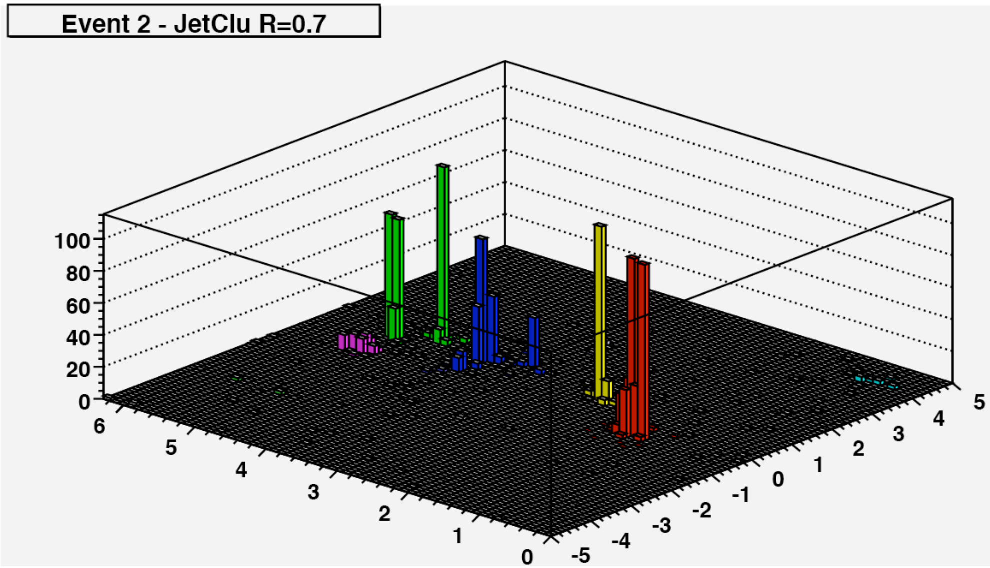


change max scale

Example dijet event

- MidPoint Jets(R=0.7):
- Et=1109., eta=-0.36, phi=1.47, nTowers=95
- Et=1068, eta=0.80, phi=4.90, nTowers=99
- Et=275., eta =0.59, phi=3.99, nTowers=106
- Et=257., eta=0.47, phi=2.35, nTowers = 52
- Et=78.8, eta=-0.41, phi=5.27241, nTowers = 41
- Et=17.0, eta=4.16, phi=0.63, nTowers=14

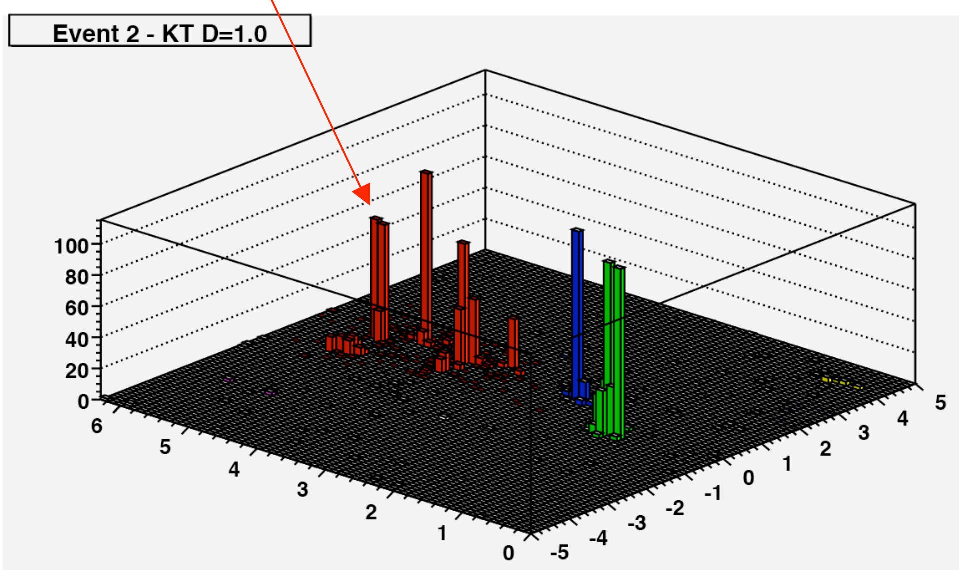
- kT Jets(D=1.0):
- Et=1293., eta=-0.06, phi=4.76, nTowers=268
- Et=1101., eta=-0.36, phi=1.47, nTowers=99
- Et=261., eta =0.50, phi=2.35, nTowers=71
- Et=25.2, eta=0.81, phi=3.98, nTowers = 34



Example dijet event

- MidPoint Jets(R=0.7):
- Et=1109., eta=-0.36, phi=1.47, nTowers=95
- Et=1068, eta=0.80, phi=4.90, nTowers=99
- Et=275., eta =0.59, phi=3.99, nTowers=106
- Et=257., eta=0.47, phi=2.35, nTowers = 52
- Et=78.8, eta=-0.41, phi=5.27241, nTowers = 41
- Et=17.0, eta=4.16, phi=0.63, nTowers=14

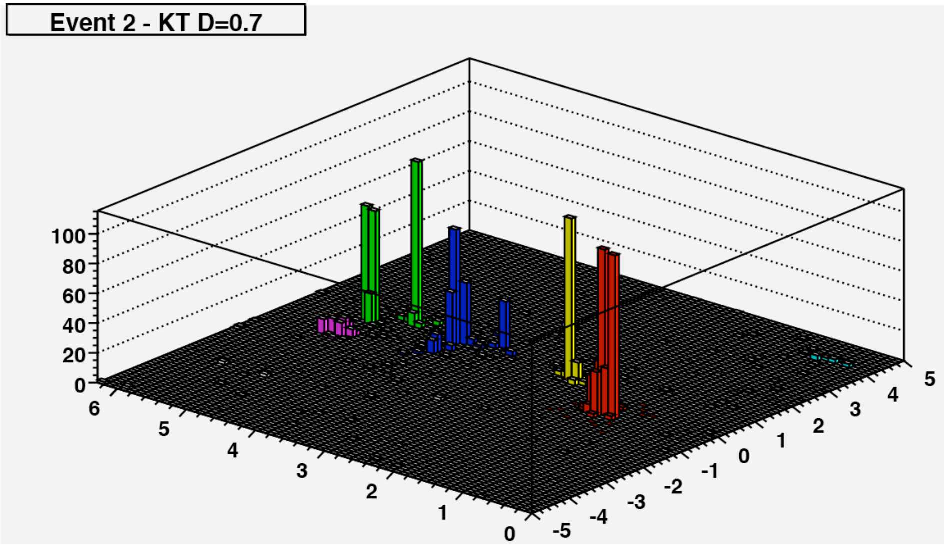
- kT Jets(D=1.0):
- Et=1293., eta=-0.06, phi=4.76, nTowers=268
- Et=1101., eta=-0.36, phi=1.47, nTowers=99
- Et=261., eta =0.50, phi=2.35, nTowers=71
- Et=25.2, eta=0.81, phi=3.98, nTowers = 34



Example dijet event

- MidPoint Jets(R=0.7):
- Et=1109., eta=-0.36, phi=1.47, nTowers=95
- Et=1068, eta=0.80, phi=4.90, nTowers=99
- Et=275., eta =0.59, phi=3.99, nTowers=106
- Et=257., eta=0.47, phi=2.35, nTowers = 52
- Et=78.8, eta=-0.41, phi=5.27241, nTowers = 41
- Et=17.0, eta=4.16, phi=0.63, nTowers=14

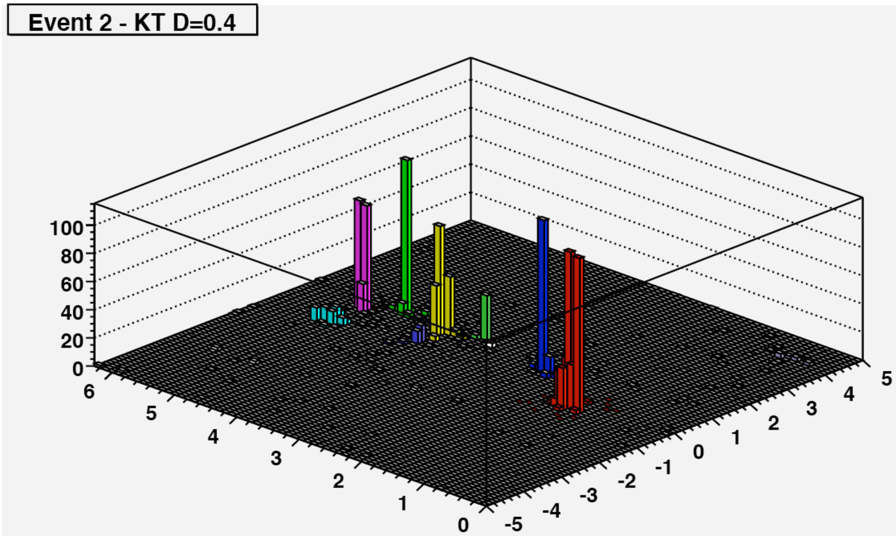
- kT Jets(D=0.7):
- Et=1101., eta=-0.36, phi=1.47, nTowers=98
- Et=1051., eta=0.77, phi=4.90, nTowers=107
- Et=259., eta =0.55, phi=3.98, nTowers=110
- Et=255., eta=0.46, phi=2.35, nTowers = 51
- Et=75., eta=-0.40, phi=5.27, nTowers = 39



Example dijet event

- MidPoint Jets(R=0.4):
- Et=1108., eta=-0.36, phi=1.47, nTowers=89
- Et=881, eta=0.85, phi=4.82, nTowers=62
- Et=257., eta =0.47, phi=2.35, nTowers=52
- Et=216., eta=0.48, phi=4.06, nTowers = 72
- Et=186., eta=0.42, phi=5.28, nTowers=32
- Et=75., eta=-0.40, phi=5.26, nTowers=32
- Et=49.9, eta=0.91, phi=3.65, nTowers=24

- kT Jets(D=0.4):
- Et=1101., eta=-0.36, phi=1.47, nTowers=97
- Et=881., eta=0.46, phi=2.34, nTowers=47
- Et=250., eta =0.46, phi=2.34, nTowers=47
- Et=184., eta=0.56, phi=4.04, nTowers = 58
- Et=184., eta=0.42, phi=5.28, nTowers = 30
- Et=70.9., eta=-0.40, phi=5.29, nTowers=30

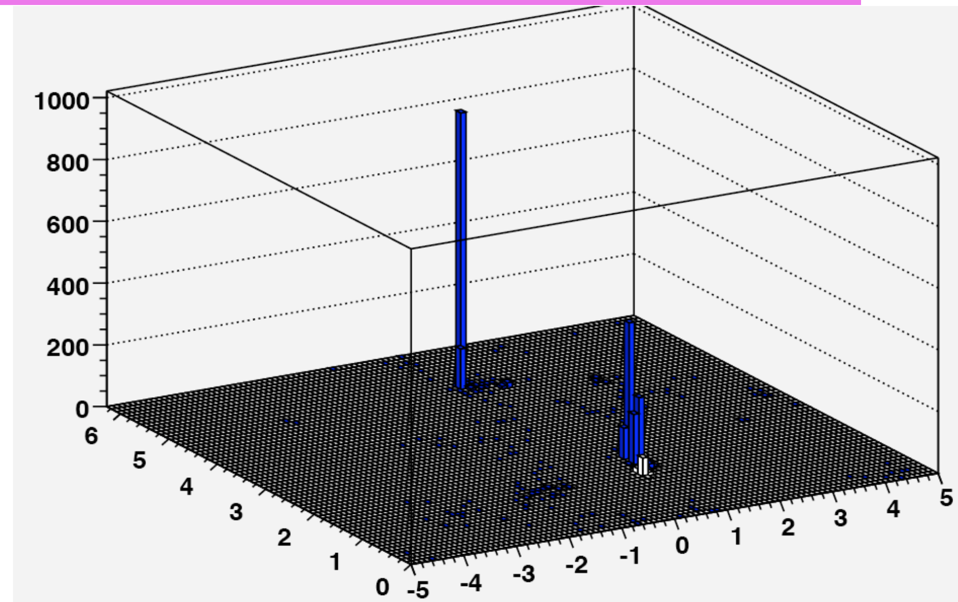


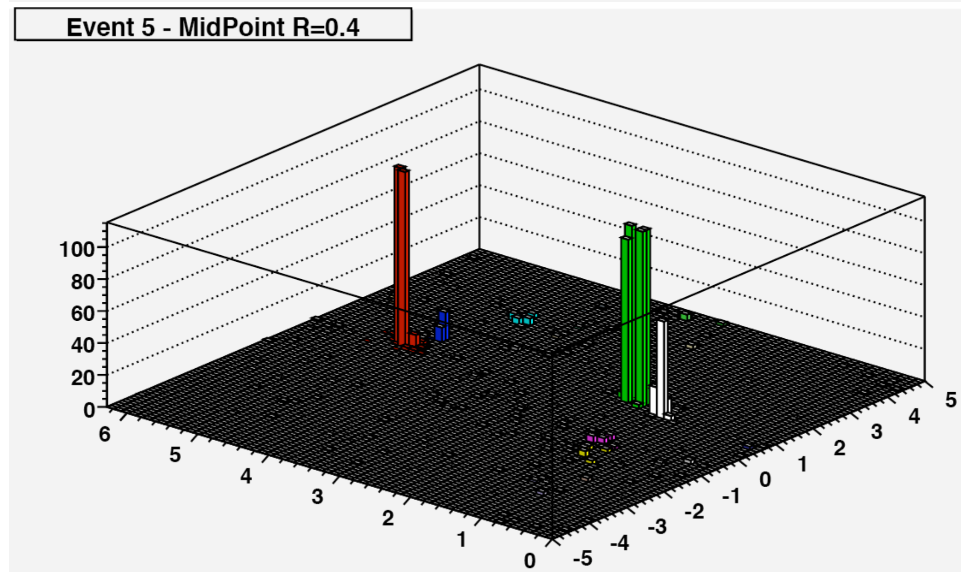
Another example dijet event (5 out of 10)

Input : 520 four vectors

Binned: 209 four vectors

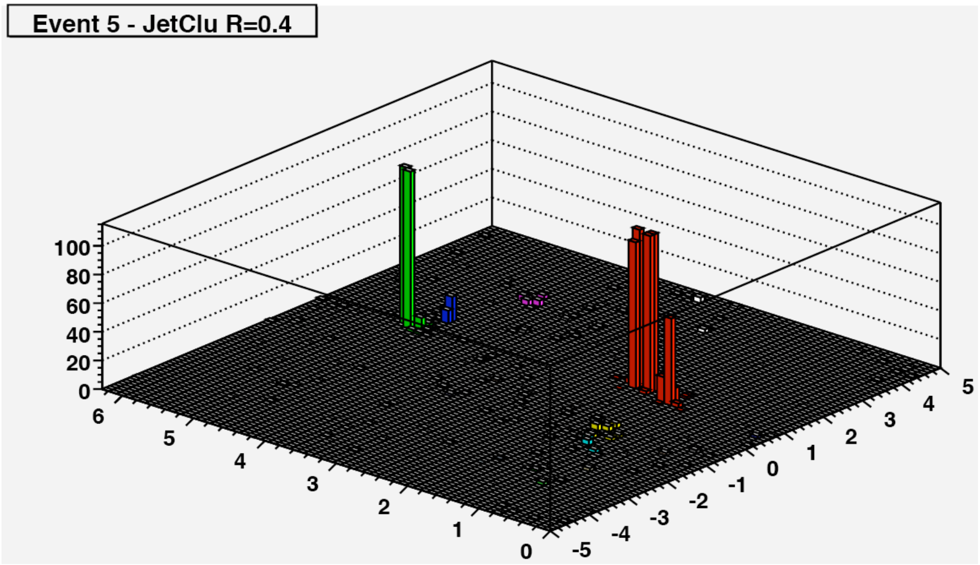
- JetClu Jets (R=0.4)
- Et=1065,eta=1.0,phi=1.94,n=27
- Et=1046,eta=.66,phi=5.08,n=24
- Et=39,eta=1.25,phi=4.87,n=10
- Et=30,eta=-1.06,phi=1.51,n=16
- Et=17.8,eta=2.76,phi=4.53,n=6
- MidPoint Jets (R=0.4)
- Et=1046,eta=0.66,phi= 5.08,n=23
- Et=970,eta=1.01,phi=1.98,n=18
- Et=40,eta=1.25,phi=4.88,n=13
- Et=19.7,eta=-1.46,phi=1.38,n=13
- Et=19.6,eta= -0.88,phi=1.49,n=9
- MidPoint Jets Second Pass
- Et=99.6,eta=0.77,phi=1.48,n=11
- Et=2.09,eta=-1.97,phi=1.21,n=3
- Et=1.82,eta=-1.80,phi=1.80,n=2
- Et=1.60,eta=-1.32,phi=2.05,n=2
- because of presence of nearby larger energy cluster, 100 GeV jet is missed by midpoint algorithm, but caught by 2nd pass

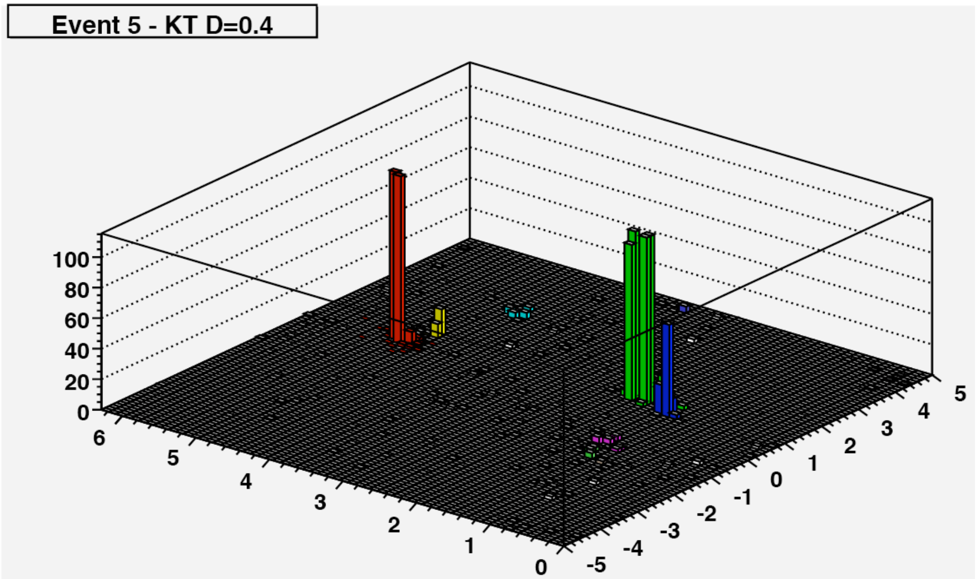




Another example dijet event (5 out of 10)

- Inclusive kT (D=0.4)
- Et=1045,eta=0.66,phi=5.08,n=29,a rea=1.21
- Et=971,eta=1.01,phi=1.98, n=21,area=1.24
- Et=97.4,eta=0.76,phi=1.48, n=10,area=0.35
- Et=39.8,eta=1.25,phi=4.88, 12,area=0.59
- Et=22.2,eta=-0.85,phi=1.46, n=10,area=0.79
- CellJet R=0.4
- Et=1048,eta=0.7,phi=5.00,n=58
- Et=965,eta=1.1,phi=2.06,n=59
- Et=107,eta=0.7,phi=1.47,n=31
- Et=35,eta=1.3,phi=4.81,n=10
- Et=21.3,eta= -1.3,phi=1.47,n=14
- Kt with D parameter of 0.4 clusters 100 GeV jet as separate jet; so does CellJet with R of 0.4

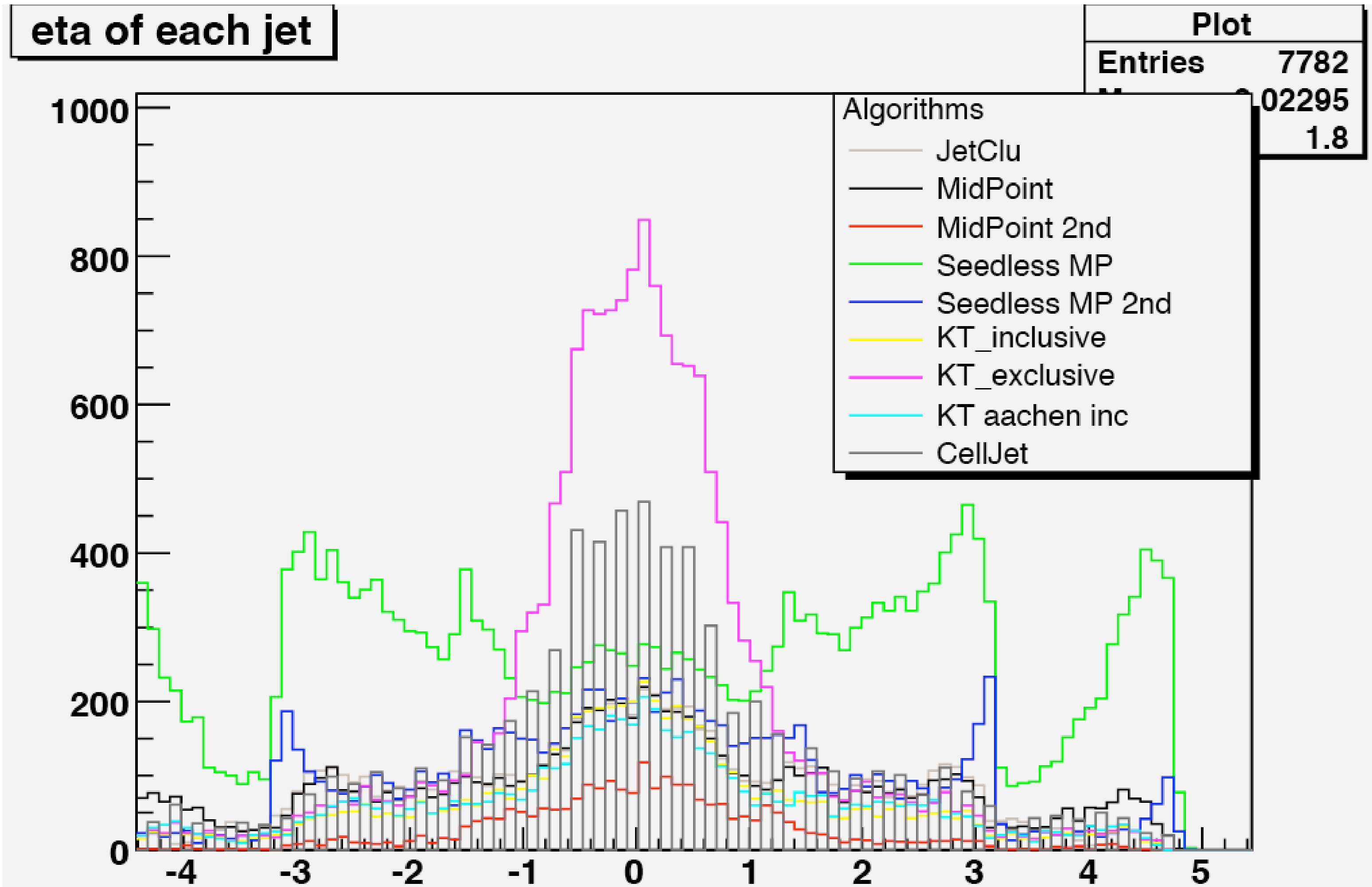




J* files included on website

- Some sample event files have been included in the data subdirectory of the programs. Additional LHC data files (J*.dat) can be found below. They consist of 1000 dijet events (and min bias) with varying values of pT_min from ~10 GeV/c up to 2 TeV/c. The files were provided by Peter Loch and Walter Lampl and the 4-vectors are ATLAS topological clusters, i.e. groups of calibrated calorimeter cells roughly of size 0.1X0.1.
    - min bias
    - J3
    - J4
    - J5
    - J6
    - J8
- Future upgrades will include the ability to add an arbitrary number of LHC min bias events. If you download these routines, please send an email to huston@msu.edu so we can keep you up to date on any further improvements.

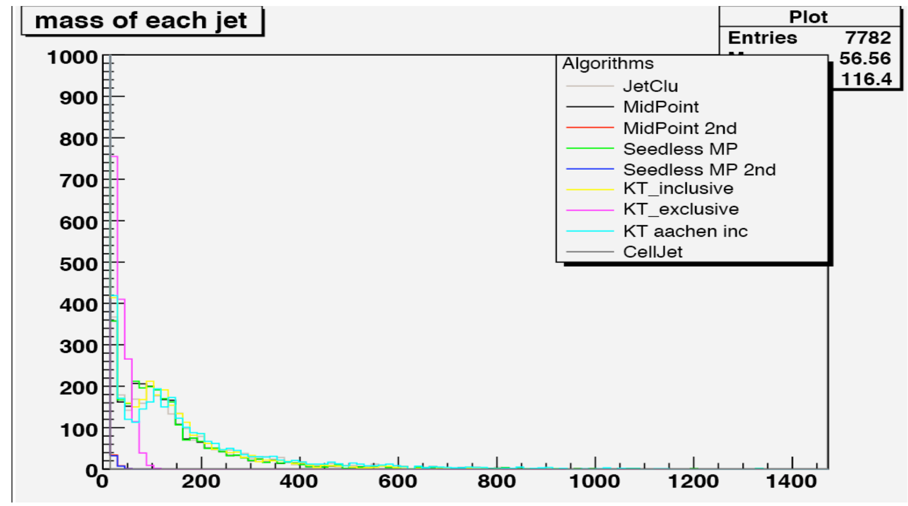
η distributions: low E_T cutoff

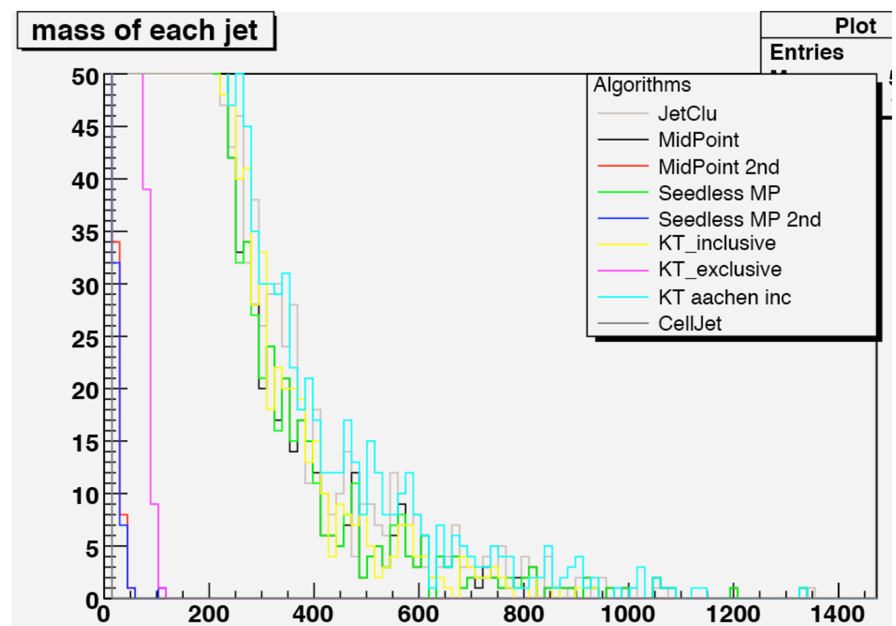


Note seedless finds many forward jets. Gavin Salam and Gregory Soyez is working on fast version of seedless algorithm.

J8 jet masses

- It's often useful to examine jet masses, especially if the jet might be some composite object, say a W/Z or even a top quark
  - very popular in recent literature, LHC Olympics
- For 2 TeV jets, peak mass (from dynamical sources) is on order of 125 GeV/c^2, but with long tail
  - Sudakov suppression for low jet masses
  - fall-off as $1/m^2$ due to hard gluon emission
  - algorithm suppression at high masses
    - jet algorithms tend to split high mass jets in two

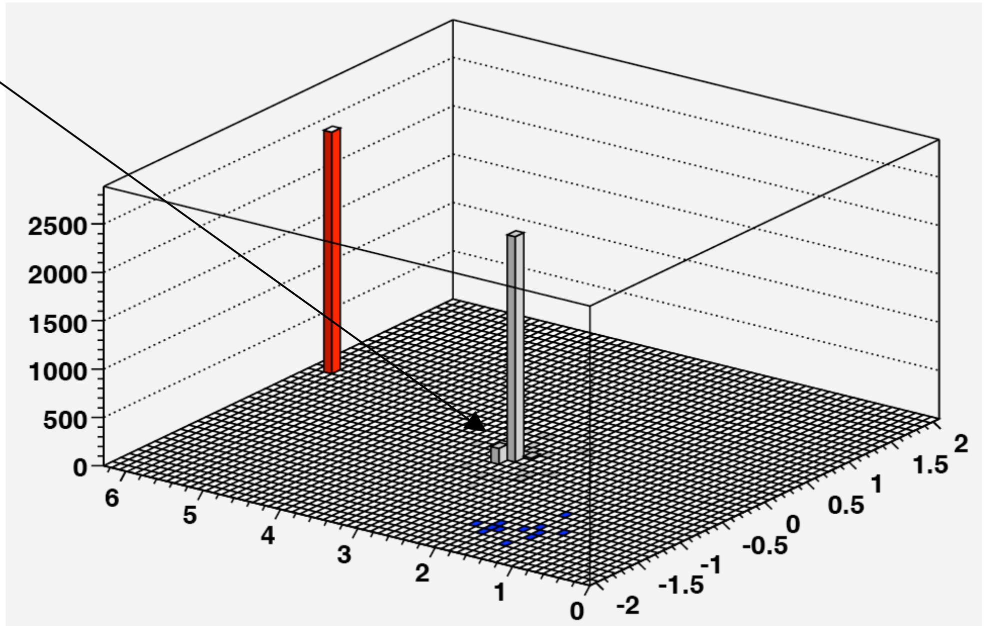




Event from J8 file (5017, 49120)

- MidPoint Jets

Et	eta	phi	n	mass
2622	-0.348	2.92	26	**174.5**
2509	0.442	6.05	14	59.8
15.5	-0.033	0.40	9	4.7
9.03	-1.55	1.53	13	2.79



- A 2.6 TeV/c jet with the mass of a top quark
- But a real top quark would probably have jet energy distributed differently
  - separate W and b clusters
- Need to be able to look inside structure of jet as well

Event from J8 file (5017, 49125)

- JetClu Jets

Et	eta	phi	n	mass
2479.73	-0.0440902	0.224169	21	128.884
1408.92	-0.739588	3.60445	30	179.484
1323.23	-0.243806	3.0665	29	258.7
8.04726	1.65128	1.37153	10	1.94272

- MidPoint Jets

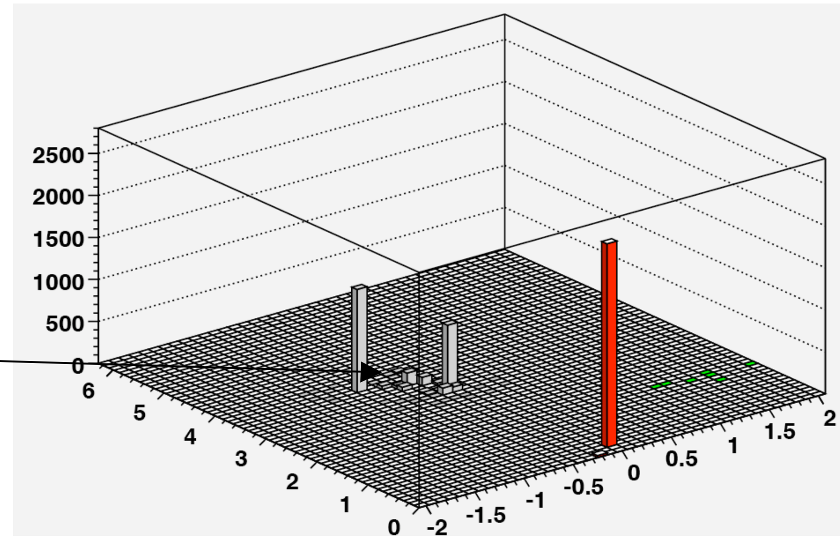
Et	eta	phi	n	mass
2766.22	-0.53164	3.34472	55	**1078.71**
2479.73	-0.0440902	0.224169	21	128.884
8.04726	1.65128	1.37153	10	1.94272

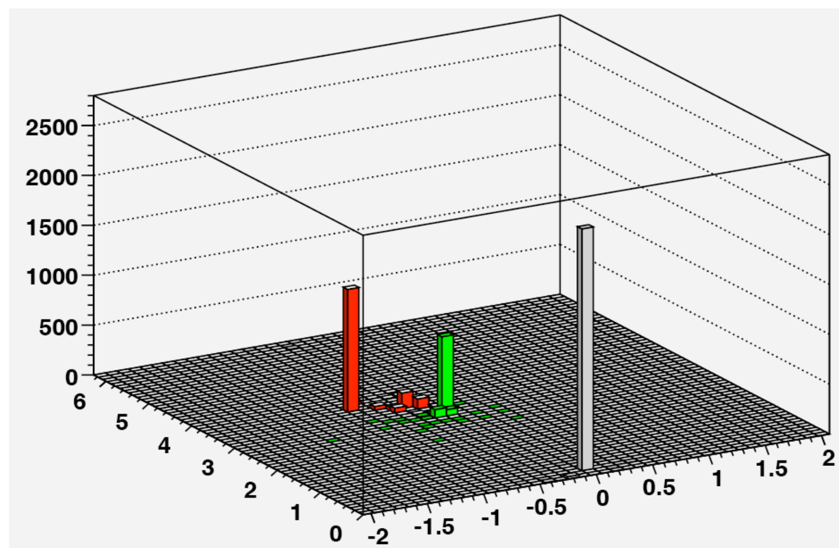
- Seedless MidPoint Jets

Et	eta	phi	n	mass
2766.22	-0.53164	3.34472	55	1078.71
2479.73	-0.0440902	0.224169	21	128.884
7.72652	1.62055	1.38142	8	1.60524

- KT_Fastjet Algorithm

Et	eta	phi	n	area	mass
2476.67	-0.0440619	0.224077	22	3.12364	130.575
1707.38	-0.671143	3.56067	41	4.40222	354.245
1005.65	-0.193714	2.97766	30	3.60834	89.0489
8.02993	1.62637	1.37074	11	1.74732	1.96888





LHC jet study

- We've started an LHC working group on jets, with the intent to have ATLAS and CMS (and interested theorists) work on
  - commonality of jet algorithms
  - jet benchmarks
    - we're running common events through the ATLAS/CMS machinery to note any differences
  - continuing the work begun at the MC4LHC workshop last summer
    - http://mc4lhc06.web.cern.ch/mc4lhc06/
    - to be continued at Les Houches 2007
- See www.pa.msu.edu/~huston/lhc_jet/lhc_jet.html

- Steve Ellis and I are also working on a review article on jet production for Prog. Part. Nucl. Phys.

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

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)

gg luminosity uncertainties

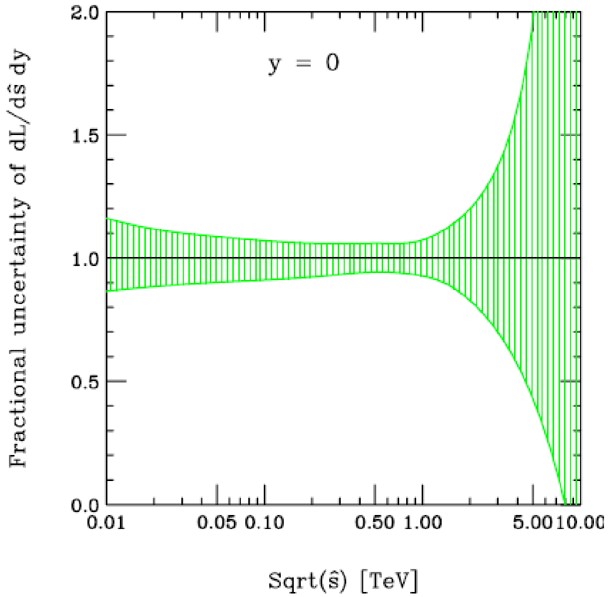
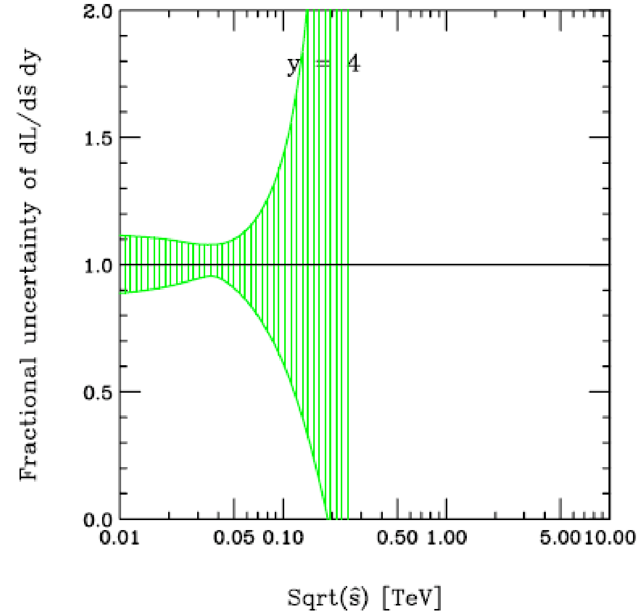
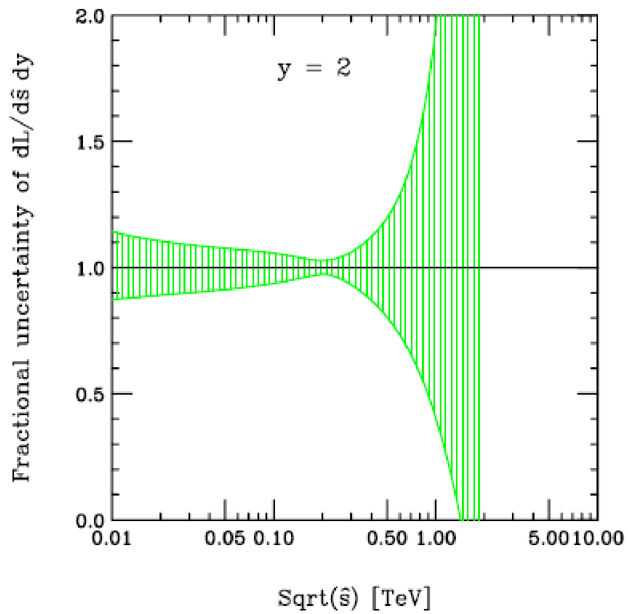


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.





gg luminosity uncertainties

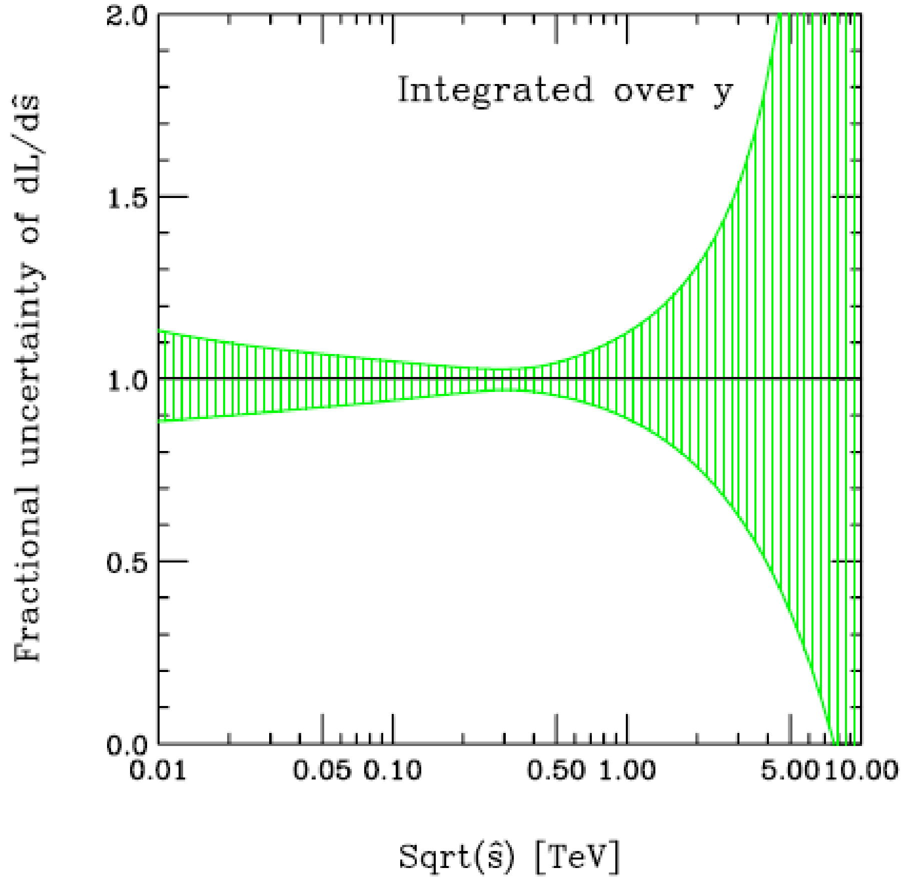


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

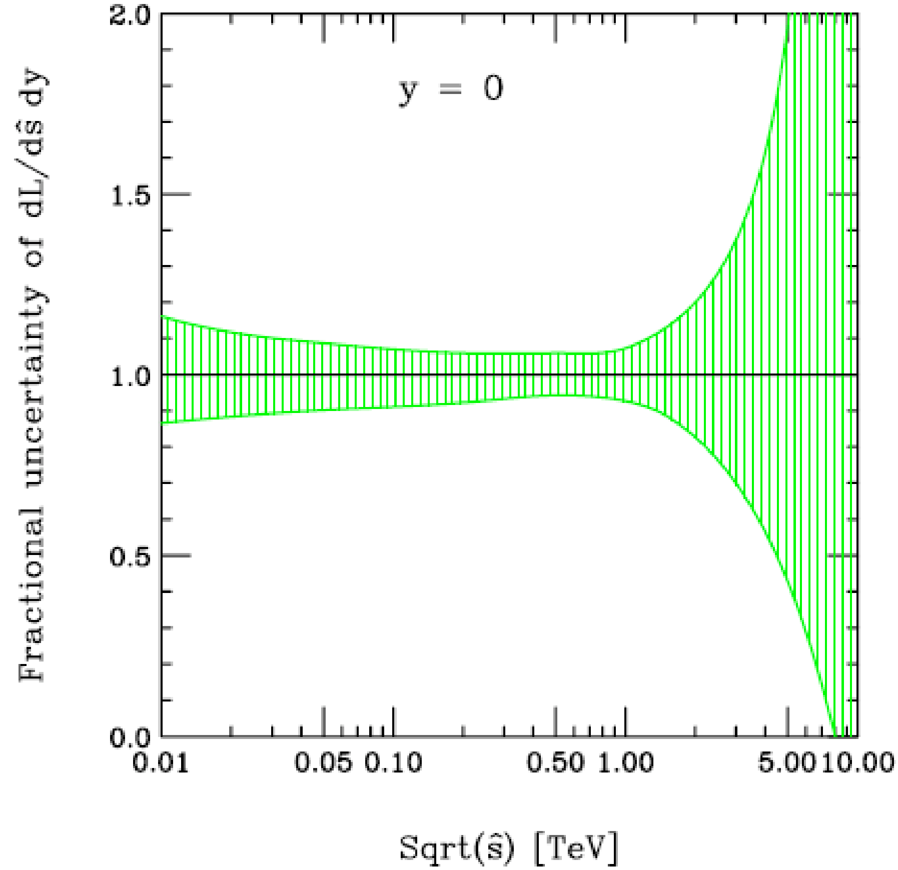
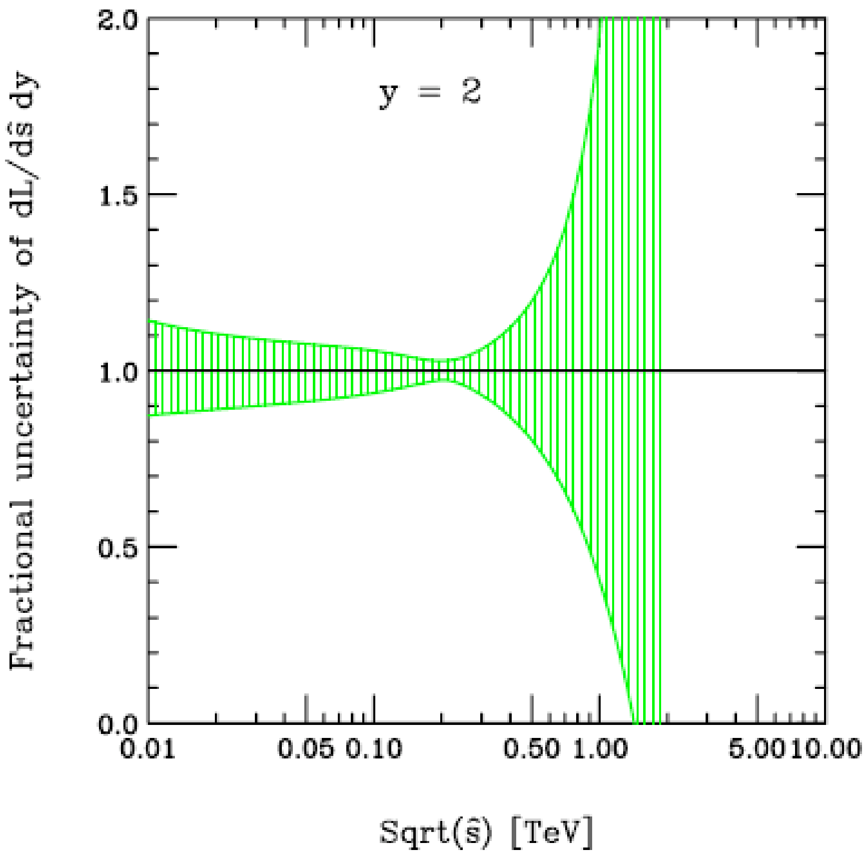
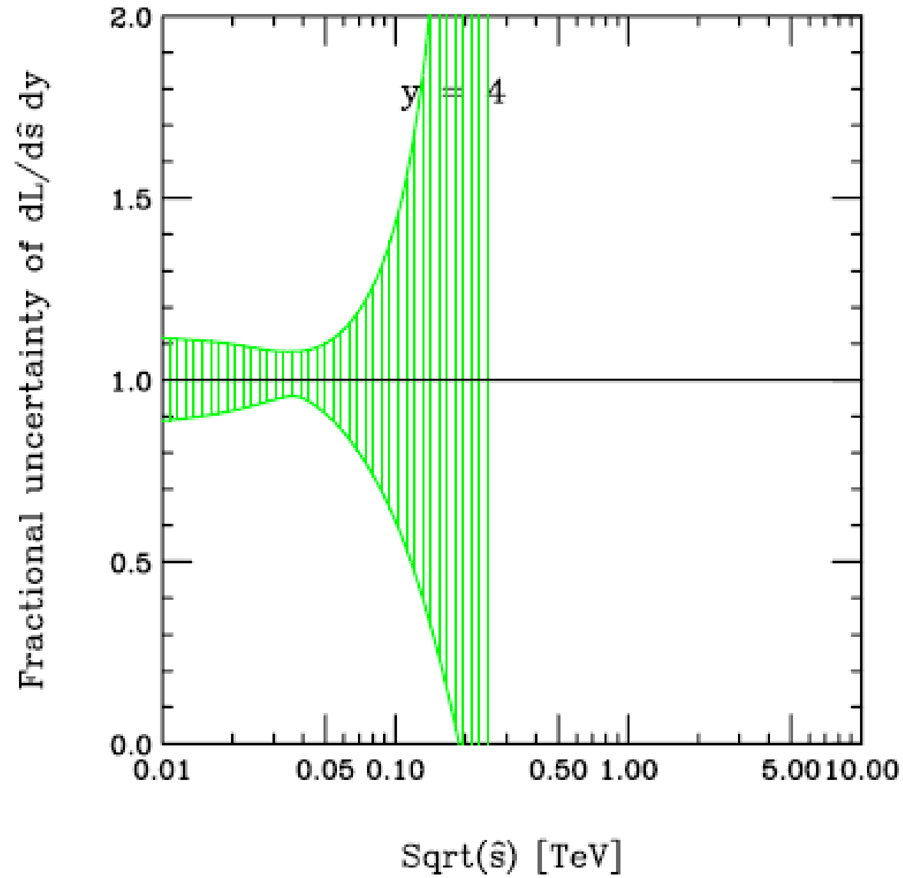


Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

gg luminosity uncertainties





gq luminosity uncertainties

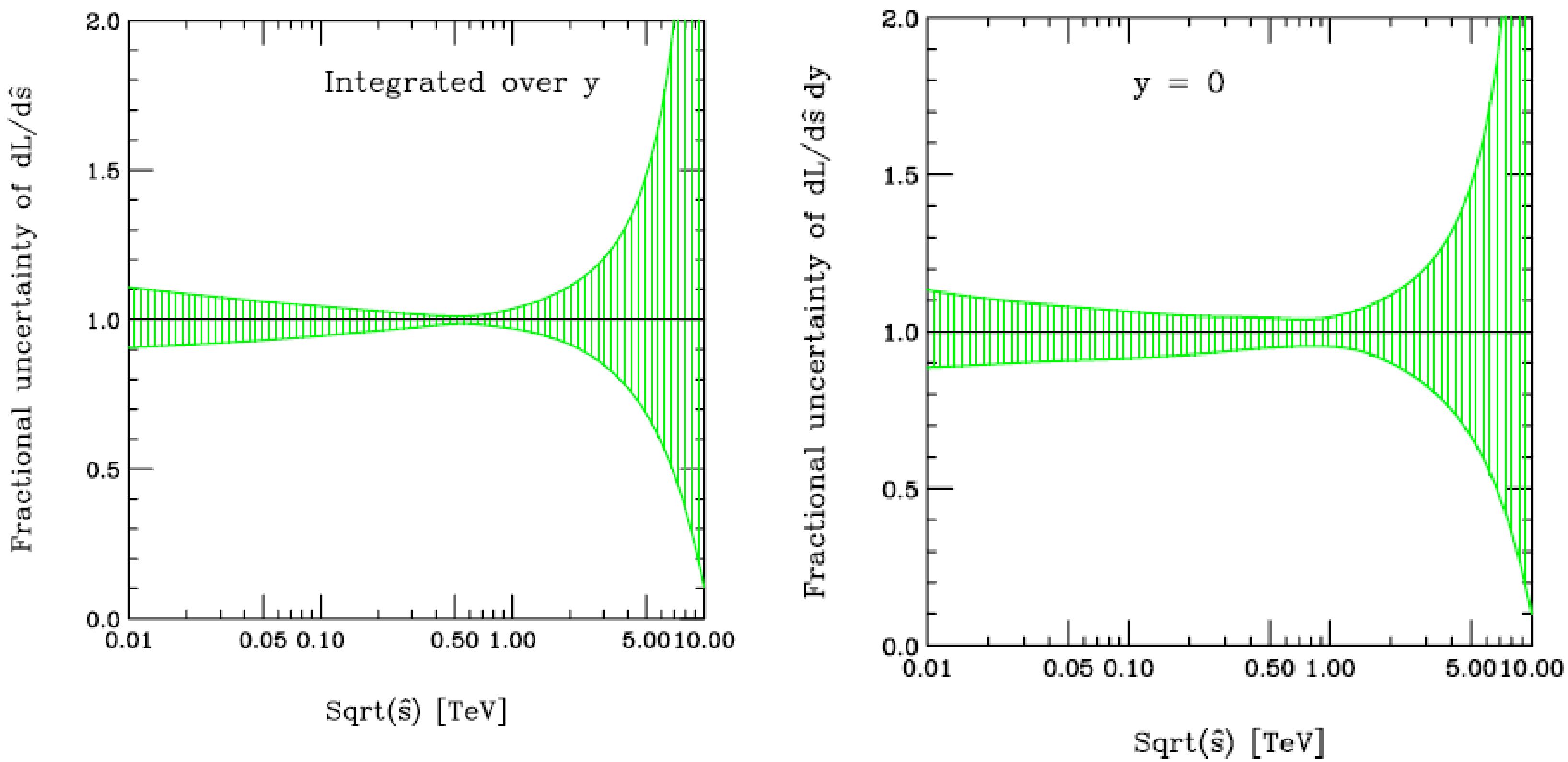
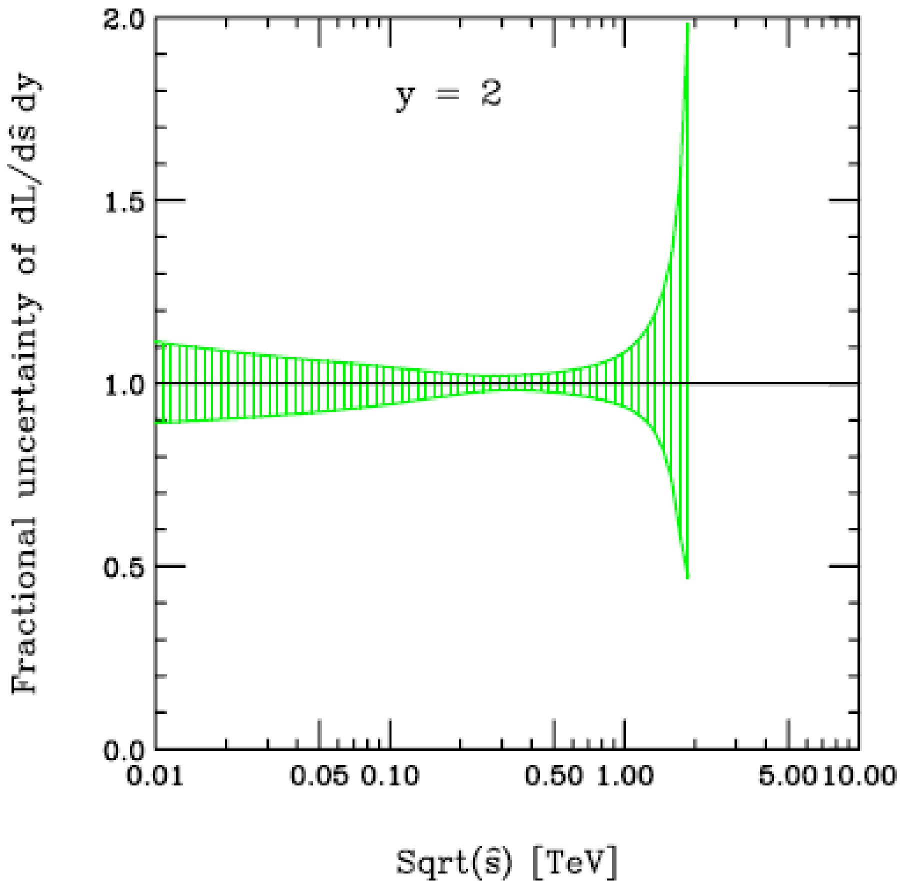
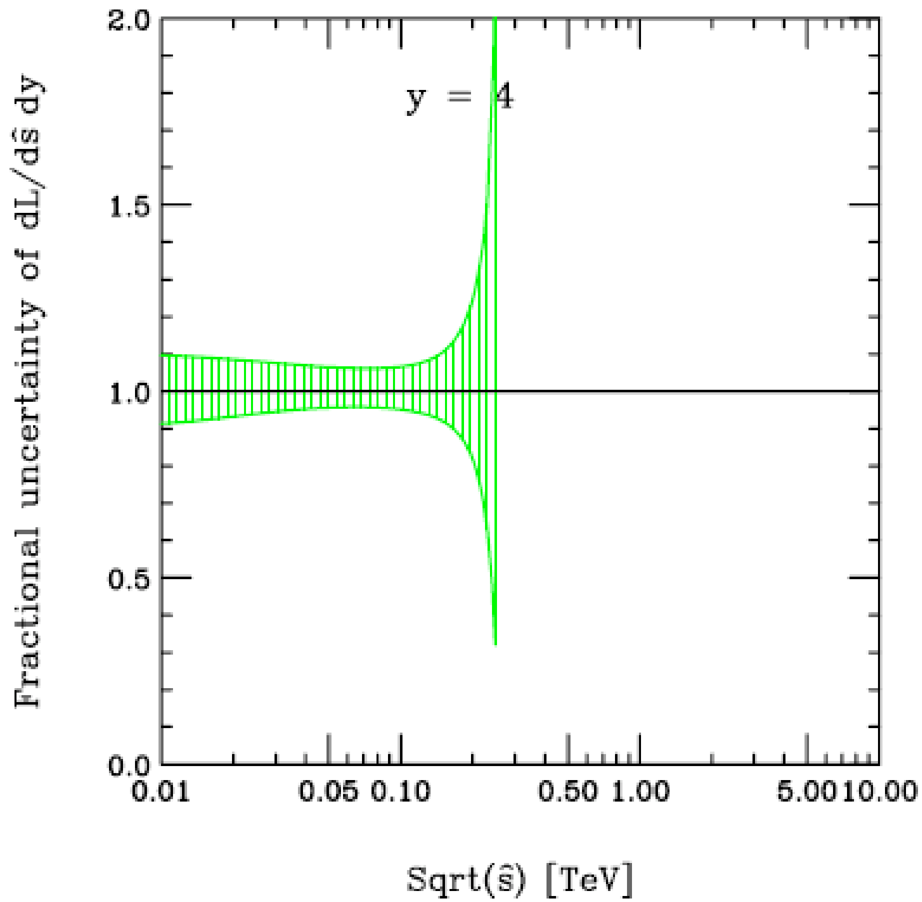


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

gq luminosity uncertainties





qQ luminosity uncertainties

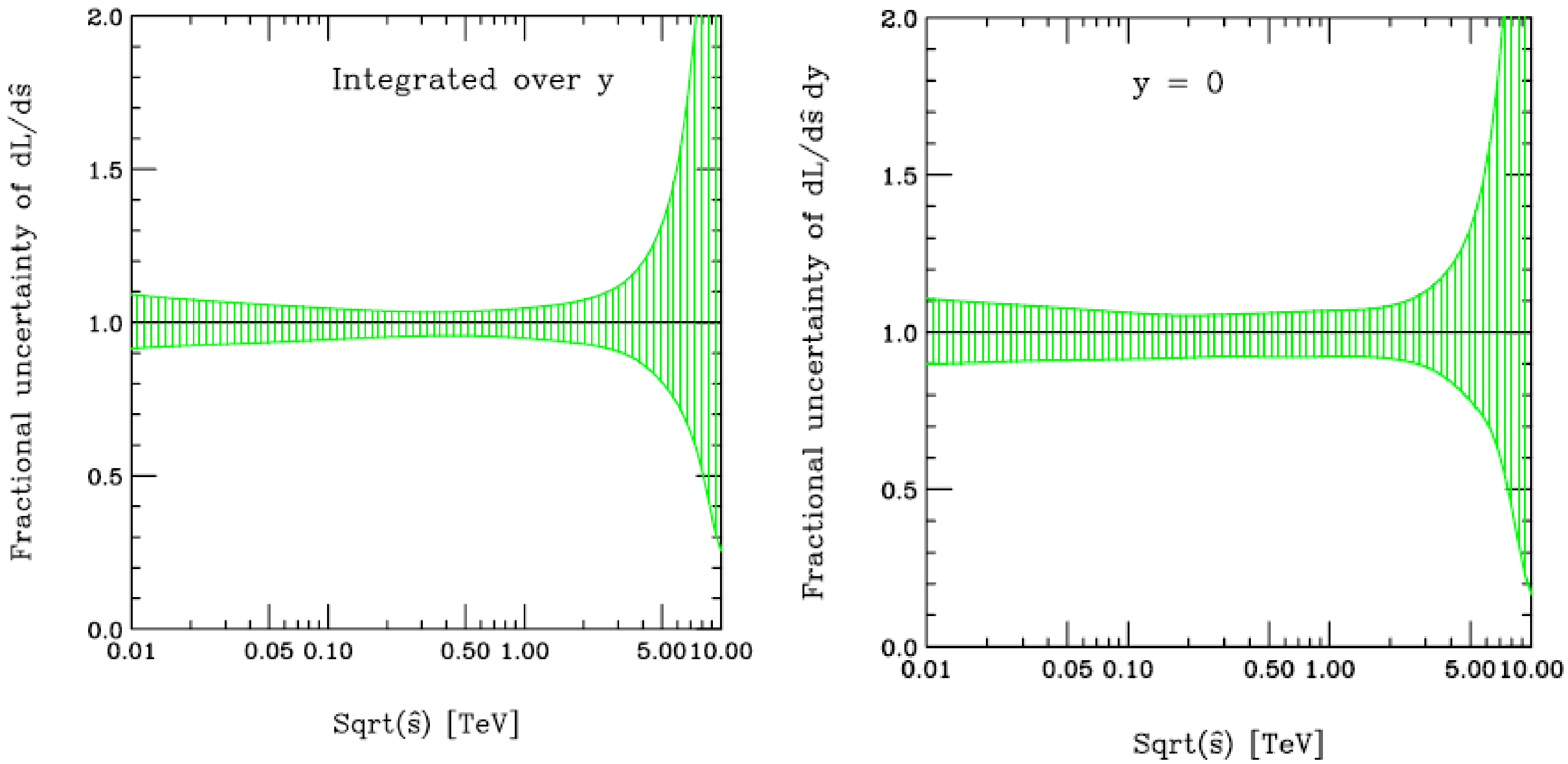
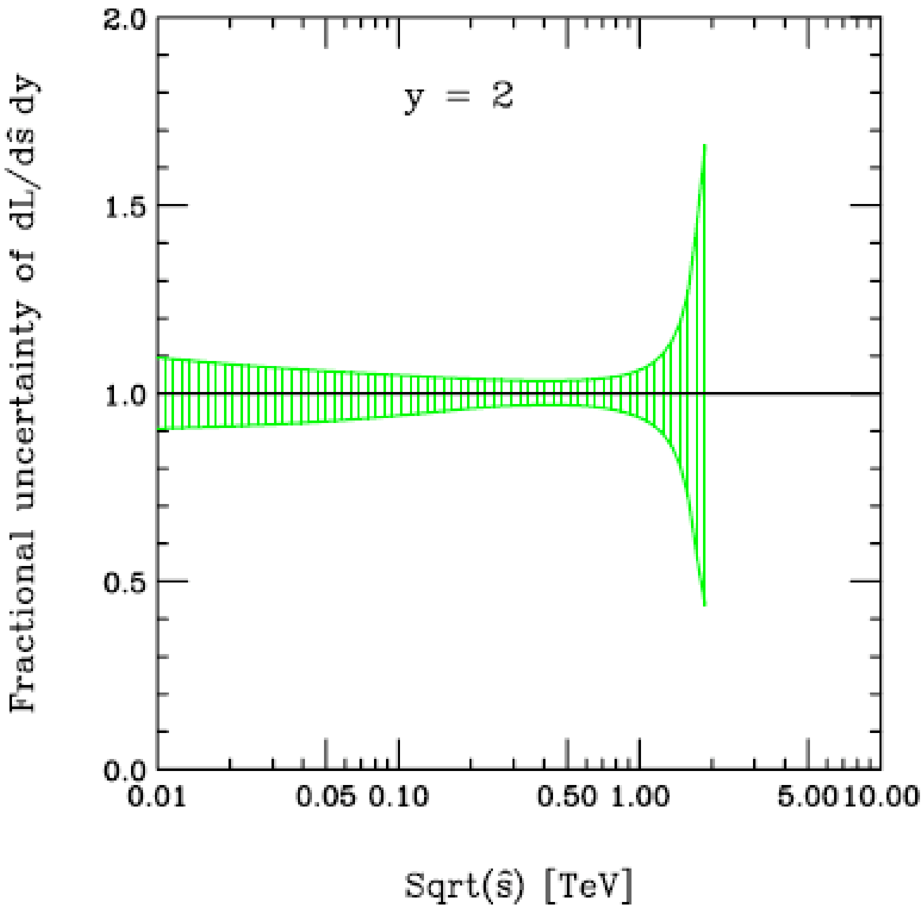
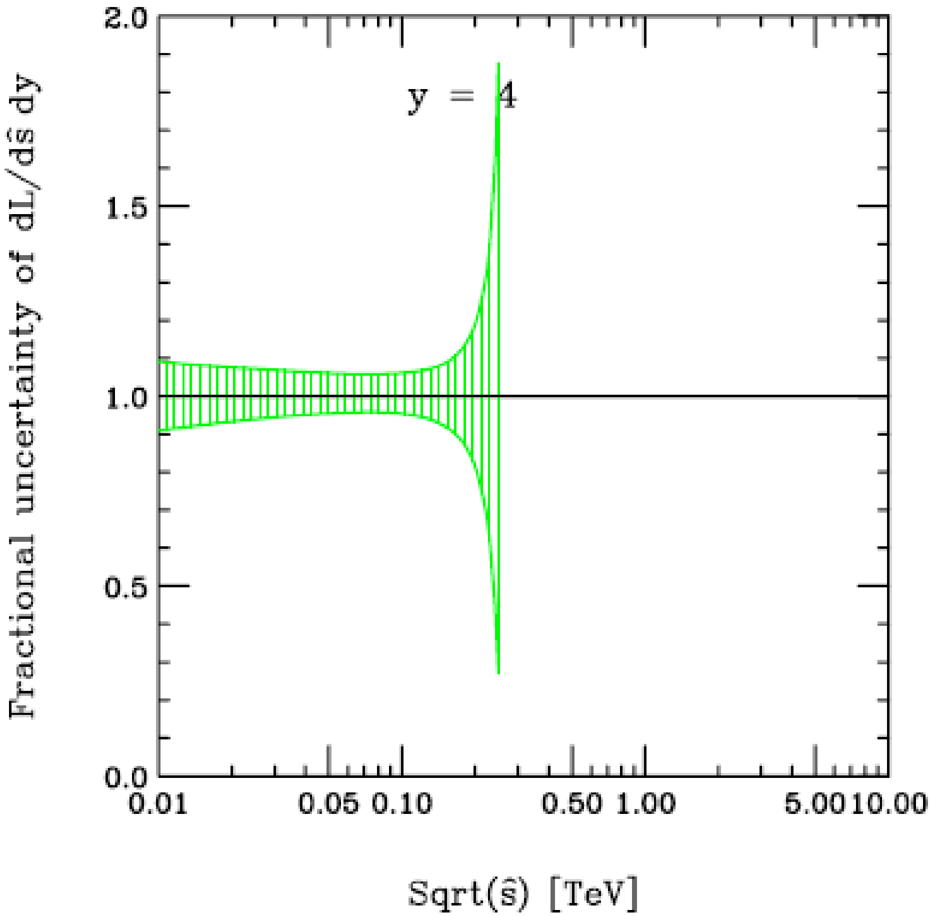


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

qQ luminosity uncertainties

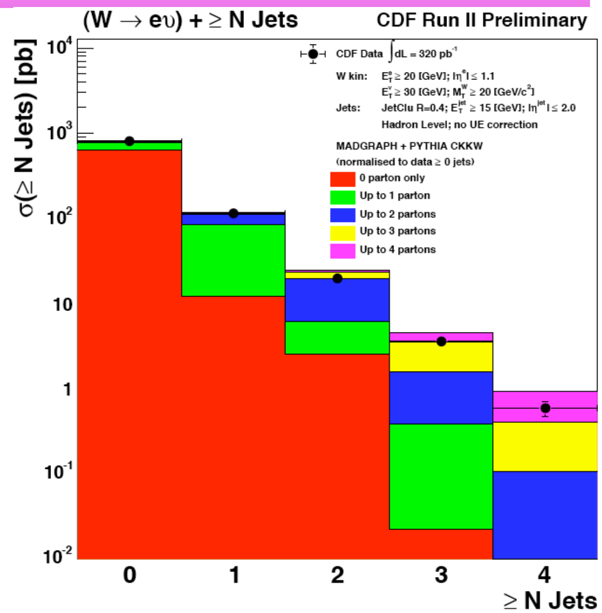




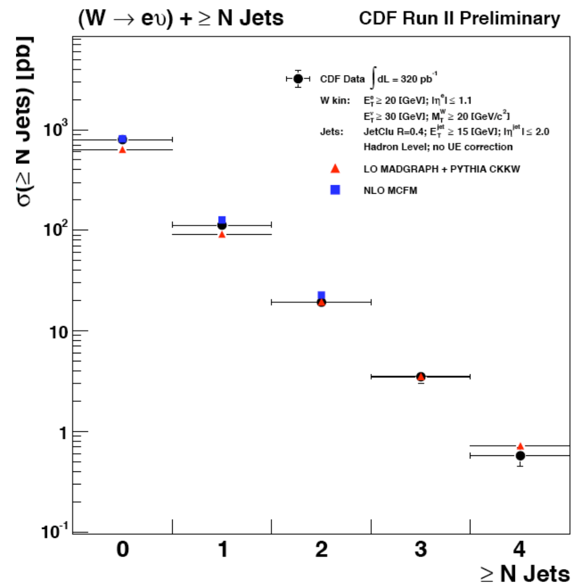
W + jets at the Tevatron

- 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 (at hadron level)**
    - 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



agreement with MCFM for low jet multiplicity



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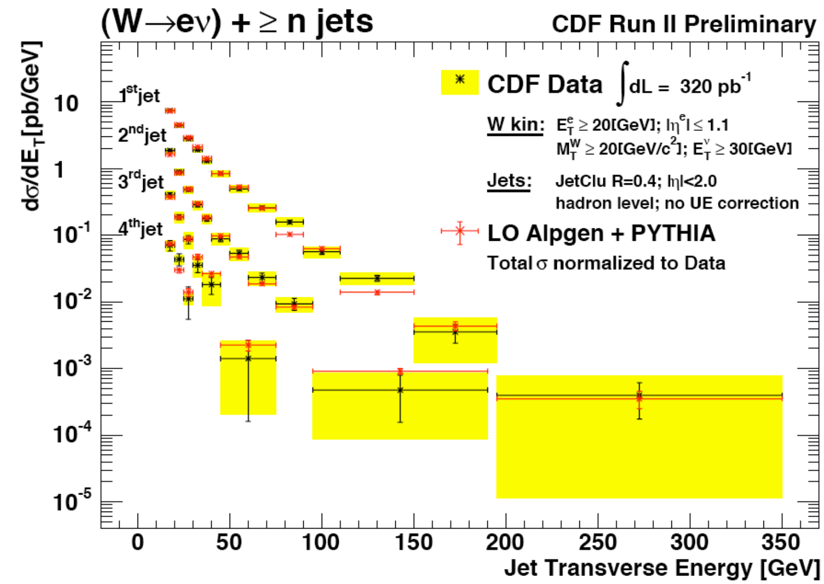
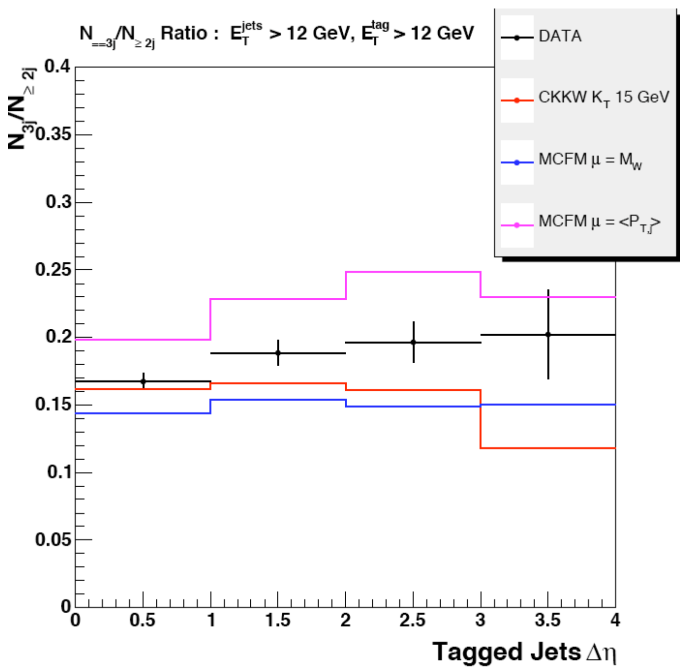
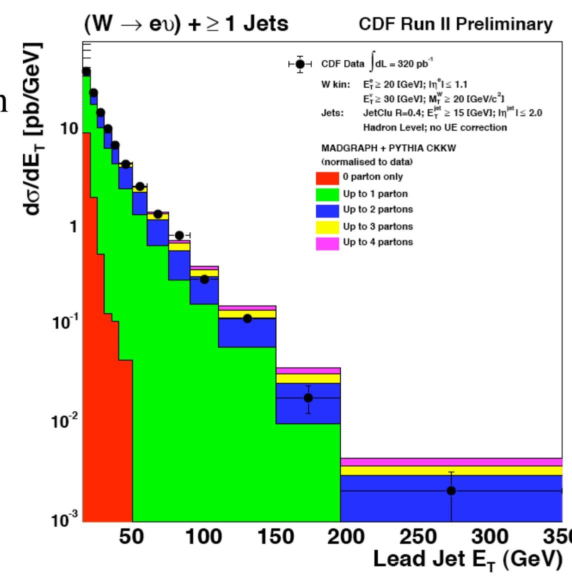




Probability of 3rd jet emission as function of two lead jet rapidity separation in good ageement with theory

At LHC, BFKL logs may become more important for high $\Delta\eta$



Sudakov logs: for high lead jet E_T, probability of additional (lower energy) jet is high

High p_T tops

- At the LHC, there are many interesting physics signatures for BSM that involve highly boosted top pairs
- This will be an interesting/challenging environment for trying to optimize jet algorithms
  - each top will be a single jet
- Even at the Tevatron have tops with up to 300 GeV/c of transverse momentum