A few CDF measurements and Standard Model Benchmarks for the LHC

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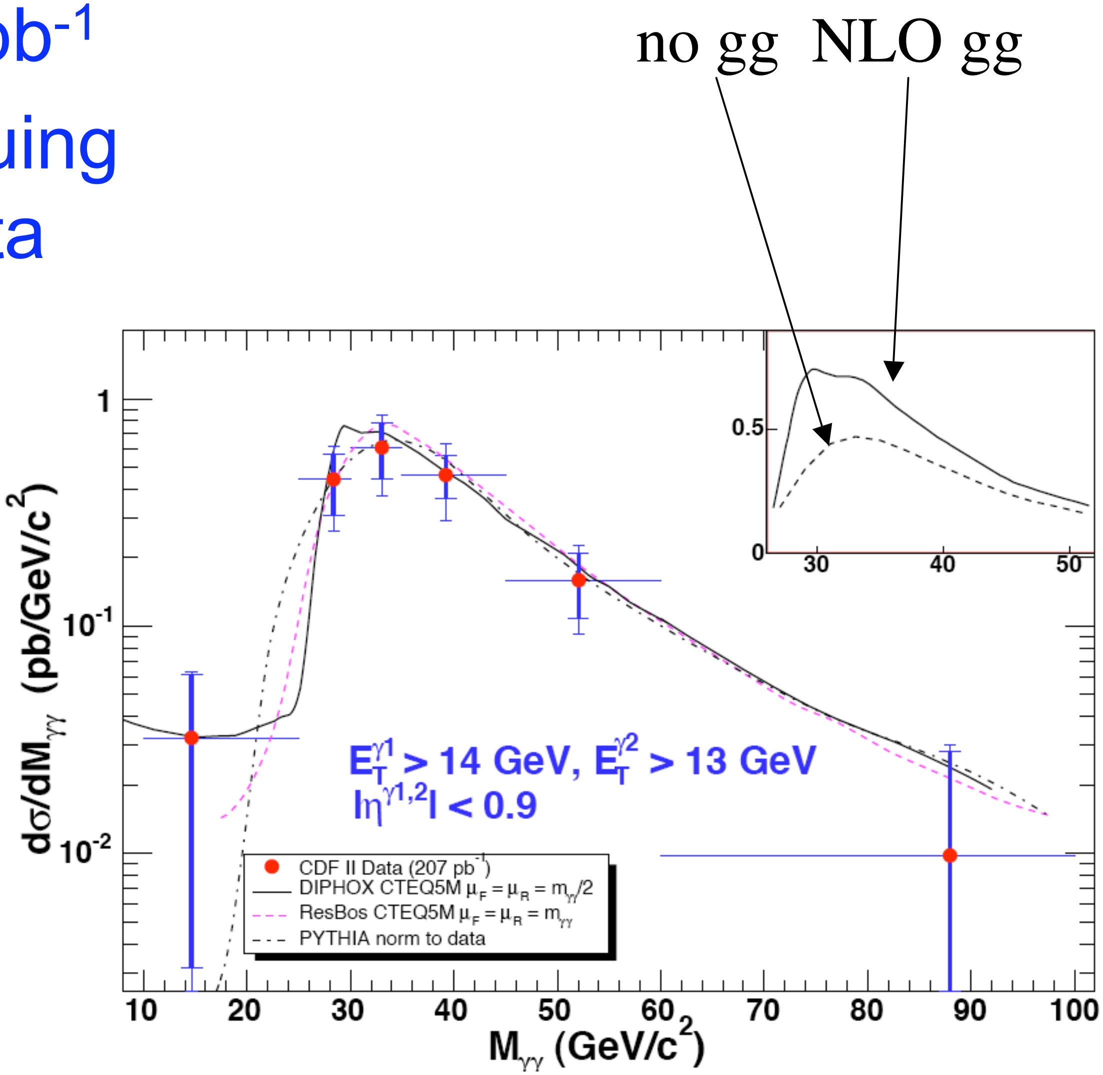
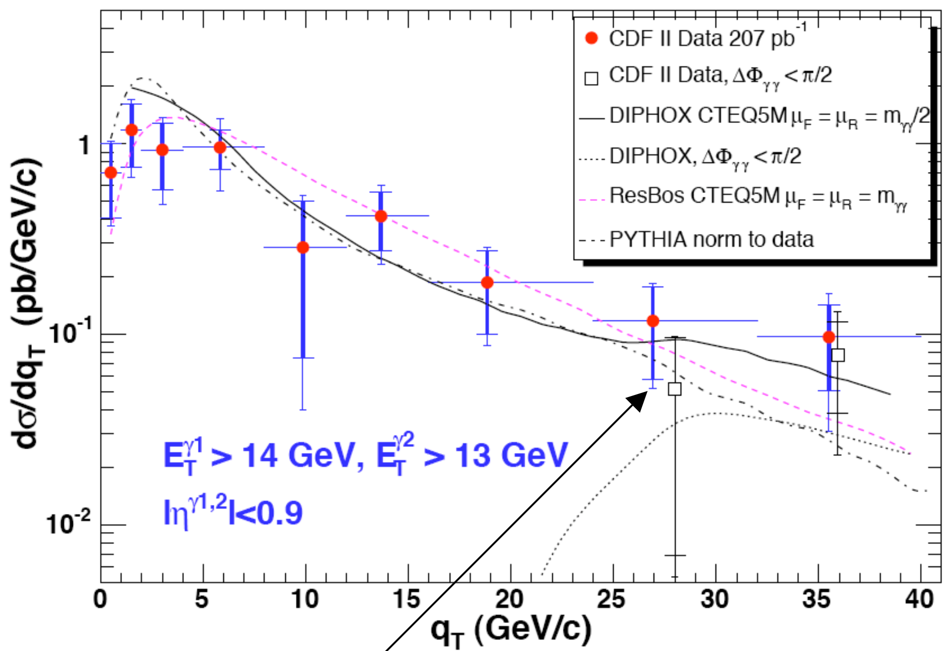
Diphoton measurements

- Based on a data sample of 200 pb^{-1}
- Analysis continuing on >1 fb^{-1} of data
- Isolated: <1 GeV/c in cone of radius 0.4

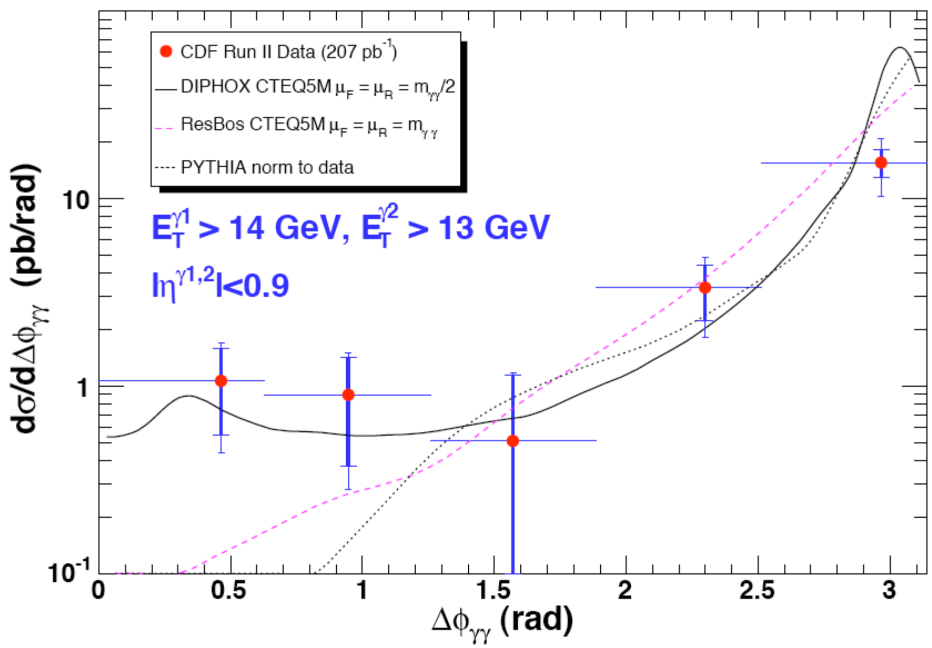


Other distributions

- Need a theory that
  - is NLO for all processes including fragmentation
  - includes soft gluon resummation



Guillet shoulder



CDF Run 2 jet measurements

- Publications being prepared on first 400 pb^{-1} of data
- Combination of larger integrated luminosity and higher center of mass energy allow cross section to be measured ~150 GeV/c further than in Run 1
- Analysis currently underway on a data sample of > 1 fb^{-1}

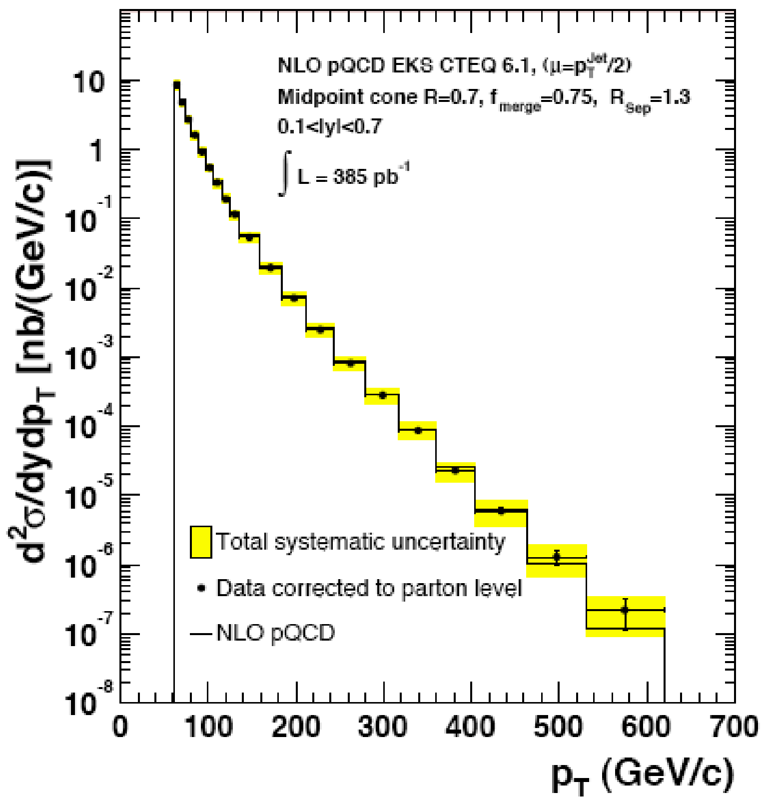


FIG. 1: *The measured inclusive jet differential cross section corrected to the parton level compared to the NLO pQCD prediction of the EKS calculation using CTEQ6.1M.*

Midpoint algorithm

- For the first time, results will be published with the midpoint jet algorithm and with the jet cross section corrected back to the parton level, allowing direct comparison with NLO predictions
- These jet cross sections will be included in next round of CTEQ fits, but probably will not have much impact given as they already agree well with CTEQ6.1 predictions
- Note MRST2004 prediction

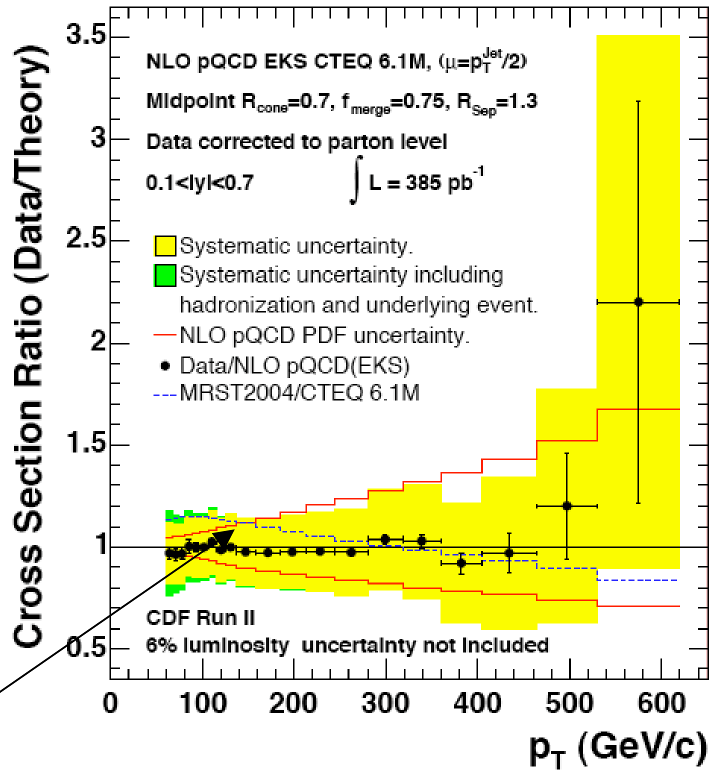
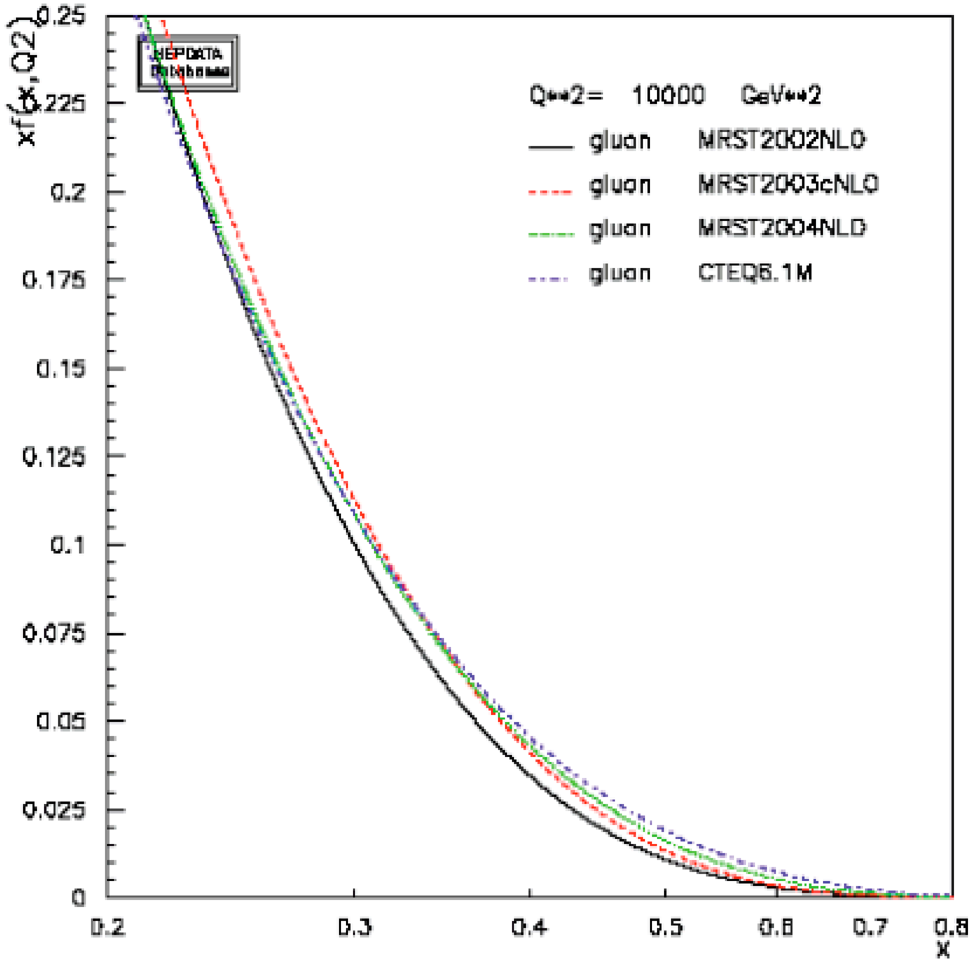


FIG. 2: *The ratio of the data corrected to the parton level over the NLO pQCD prediction of the EKS calculation using CTEQ6.1M. Also shown are the experimental systematic errors and the theoretical errors from the PDF uncertainty. The ratio of MRST2004/CTEQ6.1M is shown as the dashed line. An additional 6% uncertainty on the determination of the luminosity is not shown.*

MRST2004

- New MRST2004 pdf's now have a gluon similar to CTEQ6.1 at high x
- And thus similar predictions for jet cross sections at both the Tevatron and LHC



Hadronization and underlying event corrections

- For comparison to NLO parton level predictions, jet cross sections have to be corrected for underlying event and for hadronization
- Underlying event refers to energy in jet cone not due to the hard interaction
- Hadronization refers to the energy deposited outside the cone by partons whose trajectories lie inside the cone
- The two corrections partially offset each other

cone of 0.7

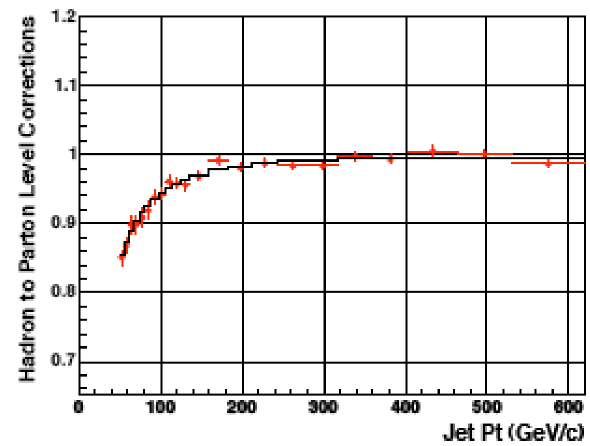


Figure 25: *Hadron to parton level corrections ($C_i^{h\to p}$) derived according to Eq. 16 from Pythia dijet Monte Carlo samples. The fitted values are used in the analysis.*

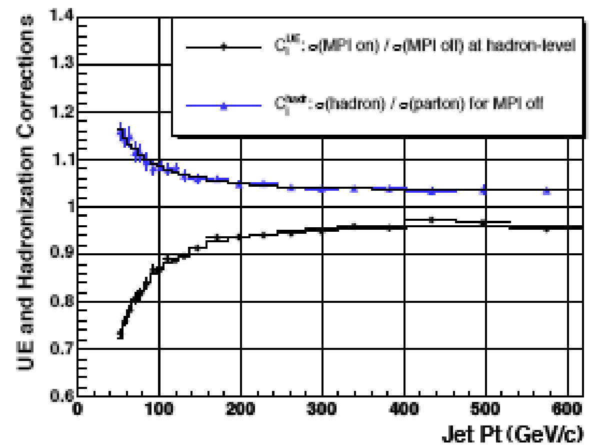
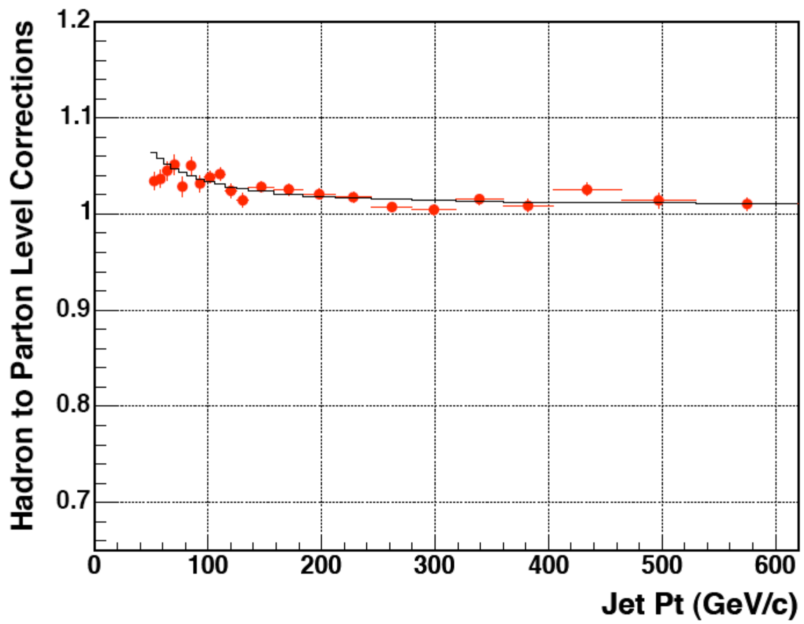


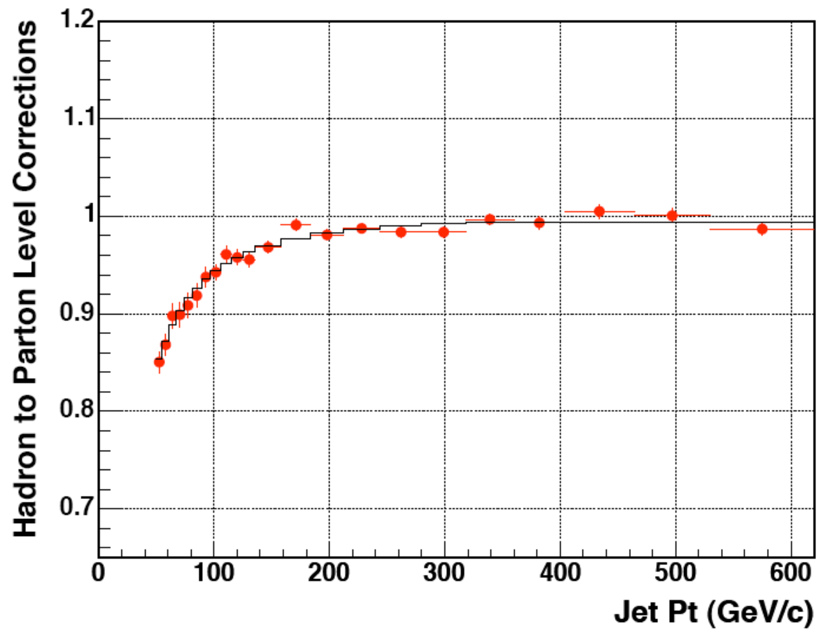
Figure 26: *UE corrections (C_i^{UE}) and hadronization corrections (C_i^{hadr}) derived according to Eq. 18 from Pythia dijet Monte Carlo events. The fitted values are used in the analysis.*

Combined effect is cone-size dependent

R=0.4

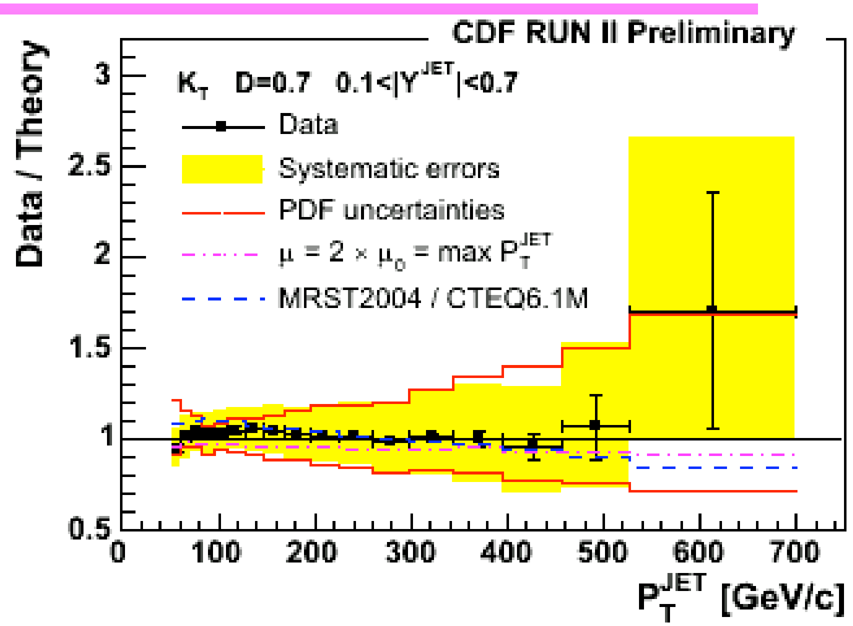


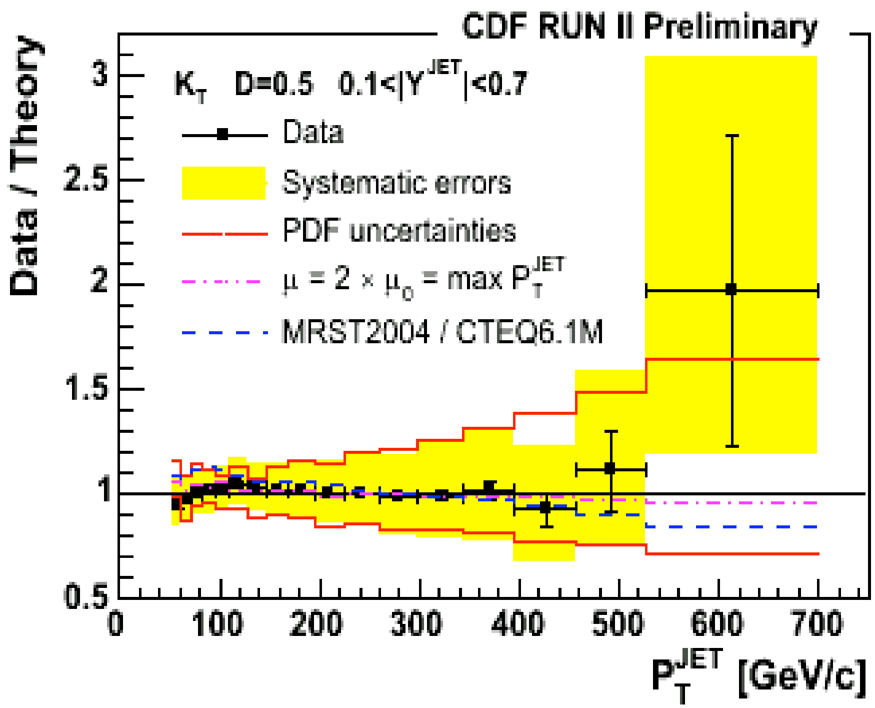
R=0.7

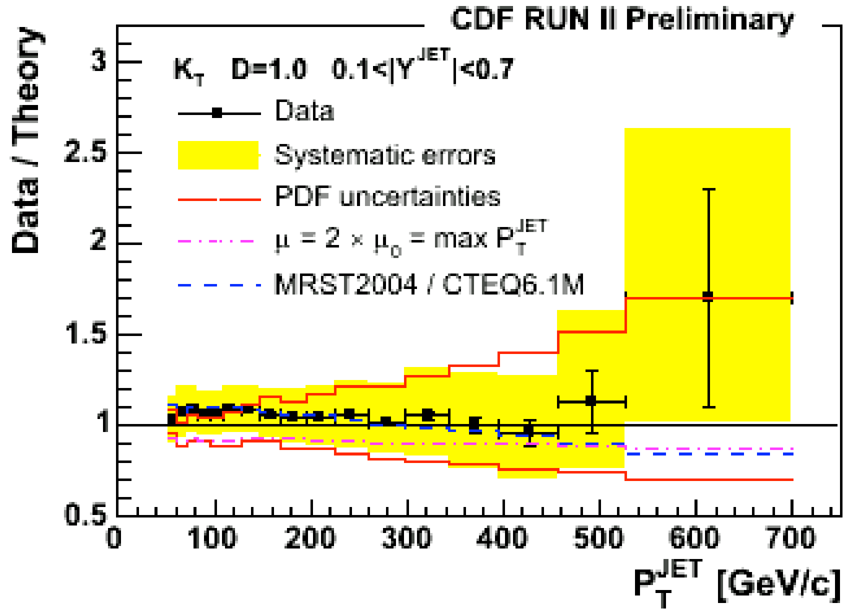


k_T jet results

- k_T results agree well with theory and thus with cone jet results
  - agreement would be even better if “same theory” were used







M. Wobisch: cone jet algorithms

Run II Workshop had proposed the infrared-safe Midpoint Cone Algorithm:

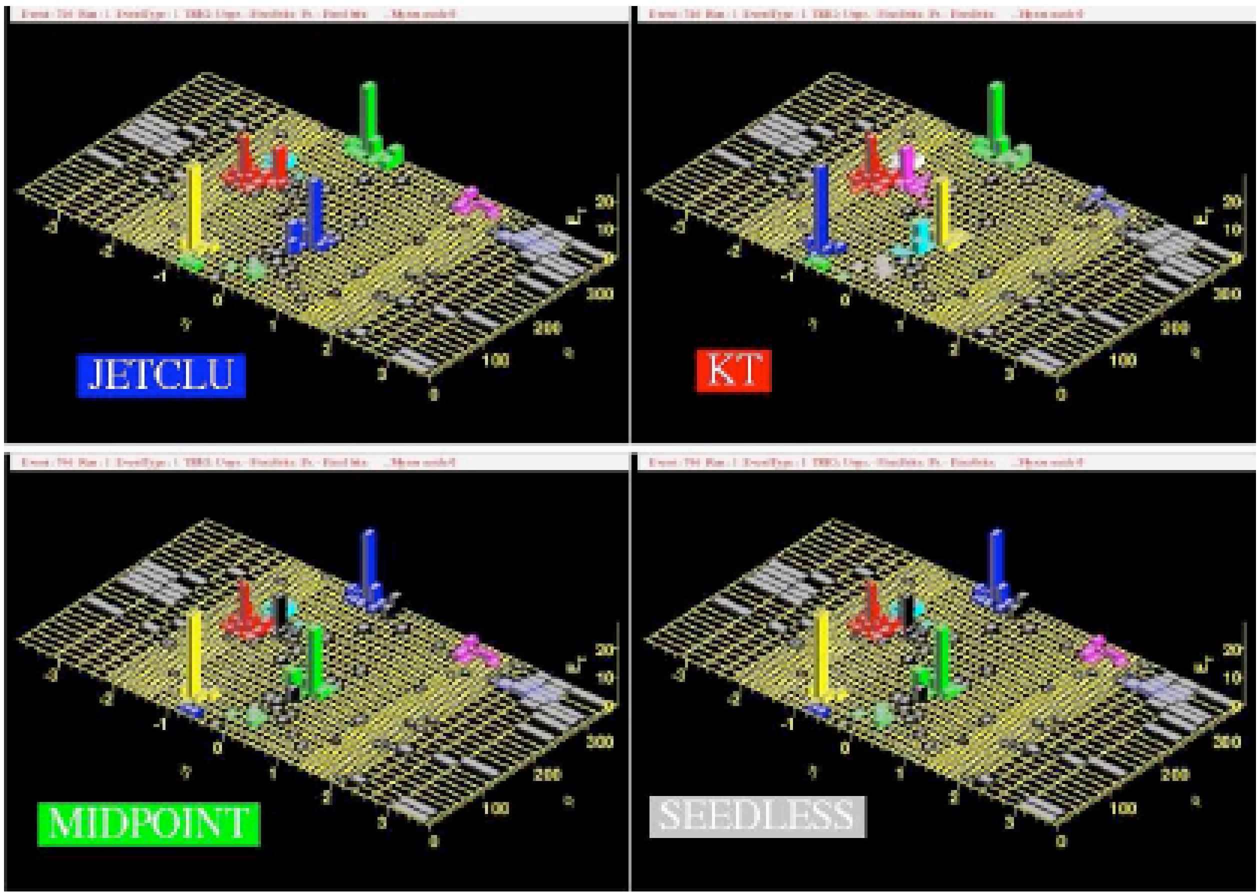
Iterative cone algorithm, using midpoints between jets as additional seeds
three parameters: R_{cone} (jet cone), f_{overlap}, $p_{T\,\text{min}}$ (fractional energy in overlap treatment)

- use every particle as seed:
  – seed specifies cone axis / draw cone with R_{cone} around cone axis
  – define proto-jet fourvector from particle four-vectors (in E-Scheme)
  – use proto-jet axis as new cone axis
  – iterate until jet axis = cone axis
- now use all midpoints between pairs of jets as additional seeds
  $\Rightarrow$ repeat iterative procedure
- Overlap treatment: (only for jets with $p_T > p_{T\,\text{min}}$)
  – if a jet shares more than a fraction f_{overlap} of it's p_T with a higher p_T jet $\longrightarrow$ merge jets
  – if the fractional overlapping p_T is below f_{overlap} $\longrightarrow$ split jets

comments
– usually: jet axis = cone axis — not when overlap treatment is used
– jets are basically defined by iterative procedure – overlap treatment is an exception

Discovery

CDF saw that the midpoint cone algorithm can leave some towers unclustered (“dark towers”)



Solution

solution proposed: S.D. Ellis, J. Huston, M. Tonnesmann, hep-ph/0111434

- introduce smaller "search cone" in iterative procedure to define jet direction
  $\Rightarrow$ stable jet solutions can be closer

- once a stable solution is found, use the **full** cone radius to define the jet
  $\Rightarrow$ consequence: jet axis $\neq$ cone axis

- "midpoint step" uses full cone radius (otherwise not infrared-safe)
  (this is not correctly described in the first CDF Run II jet publication!! hep-ex/0505013)

- Since initial stable solutions can be closer, overlap treatment is more often needed to define the final jet configuration $\longrightarrow$ overlap treament becomes a standard-procedure

- overlap treatment may merge many nearby jets
  $\Rightarrow$ this results in merged jets with huge spacial extension (CDF: "fat jets")
  $\longrightarrow$ way out: increase f_{overlap} parameter from 0.5 to 0.75
  $\Rightarrow$ largely overlapping jets are still counted separately

Problem

... as before in Run I:

CDF and DØ are using different jet algorithms!!!!

- However, for QCD jet cross sections the consequences are very small
  $\Rightarrow$ only 6% difference between the inclusive jet cross sections for both algorithms
- But beware: The effect may be much larger for multi-jet production!!
  3-jet, 4-jet – when the jet-jet separation is more critical – not been studied so far!
- Totally unrealistic to assume that either CDF or DØ would change to the other algorithm during Run II
- The difference of 6% is not a huge effect (same as luminosity uncertainty)
- But important to settle this issue for the LHC experiments!!

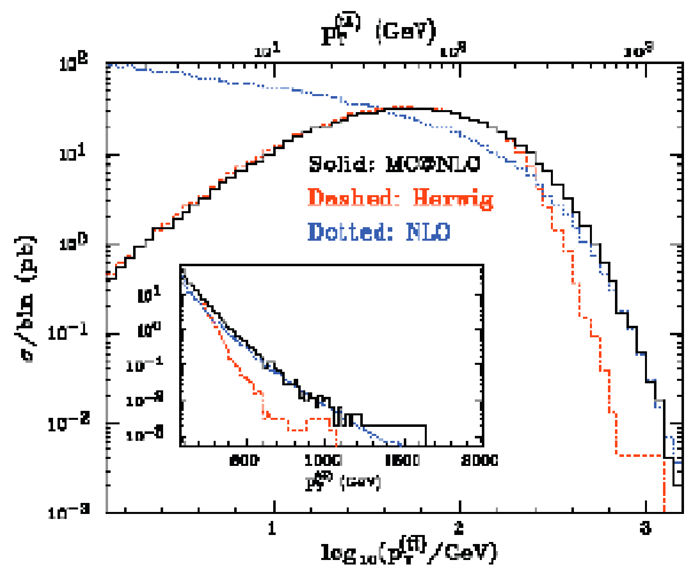
MC@NLO

- Ideally, want NLO normalization and kinematics while retaining the effects of multiple gluon radiation and hadronization
  - many papers written on the subject
- MC@NLO (Frixione/Webber) is only program in use by experimenters

proverbial 2-in-bush

proverbial
NLO MC-in-hand

- Working model h rs coming in to work on favorite process
  - Eric Laenen and student: single top production (now complete)
  - Vittorio del Duca and Carlo Oleari: WH and WW fusion to Higgs
  - Bill Kilgore and Steve Ellis: inclusive jet production (started at Les Houches)



- Smoothly matches **soft/collinear** (MC) and **hard** (NLO) regions
- Available for $pp \to W, Z, H, \gamma^*, b\bar{b}, t\bar{t}, WW, ZZ, WZ$

Mea Culpa @ NLO

What is this about? The title is Joey's attempt to shame the speakers!!

We (Steve Ellis and Bill Kilgore) "promised" Joey we would prepare a JETS@NLO MC calculation (code) by the end of the Workshop.

Unfortunately we have failed miserably, and have no results to report. So here is our *hairshirt*, which we will wear until the calculation is finished.

The interested reader/listener is encouraged to study the results of S. Frixione and B. Webber (and collaborators) plus Eric Laenen and Patrick Motylinski, whose efforts in various arenas (e.g., vector boson production, heavy flavor production) of MC@NLO are further along.

Sorry about that, we are ashamed!!

Steve & Bill

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
- *Companion* review article on hard scattering physics at the LHC by John Campbell, James Stirling and myself

SM benchmarks for the LHC

LES HOUCHES
centre de physique

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

- 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)

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?
- 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?
- What are the highest priority NLO calculations to be done before the LHC turns on?
- Opportunity for CTEQ to contribute

Les Houches priority list

A start of the basic NLO needs for a serious phenomenology program at the LHC (from Les Houches 2005):

1. PP → V V + jet (new physics and Higgs search background)
2. PP → H + 2 jets (Higgs production through vector boson fusion background) ⟶ matrix elements have now been calculated
3. PP → T Tbar + B Bbar (Higgs plus top quark background)
4. PP → V V + B Bbar (new physics and Higgs search background)
5. PP → V V + 2 jets (Higgs search background)
6. PP → V + 3 jets (Generic background)
7. PP → V V V (background to tri-lepton searchs)
8. Rules of thumb for uncalculated NLO processes?

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

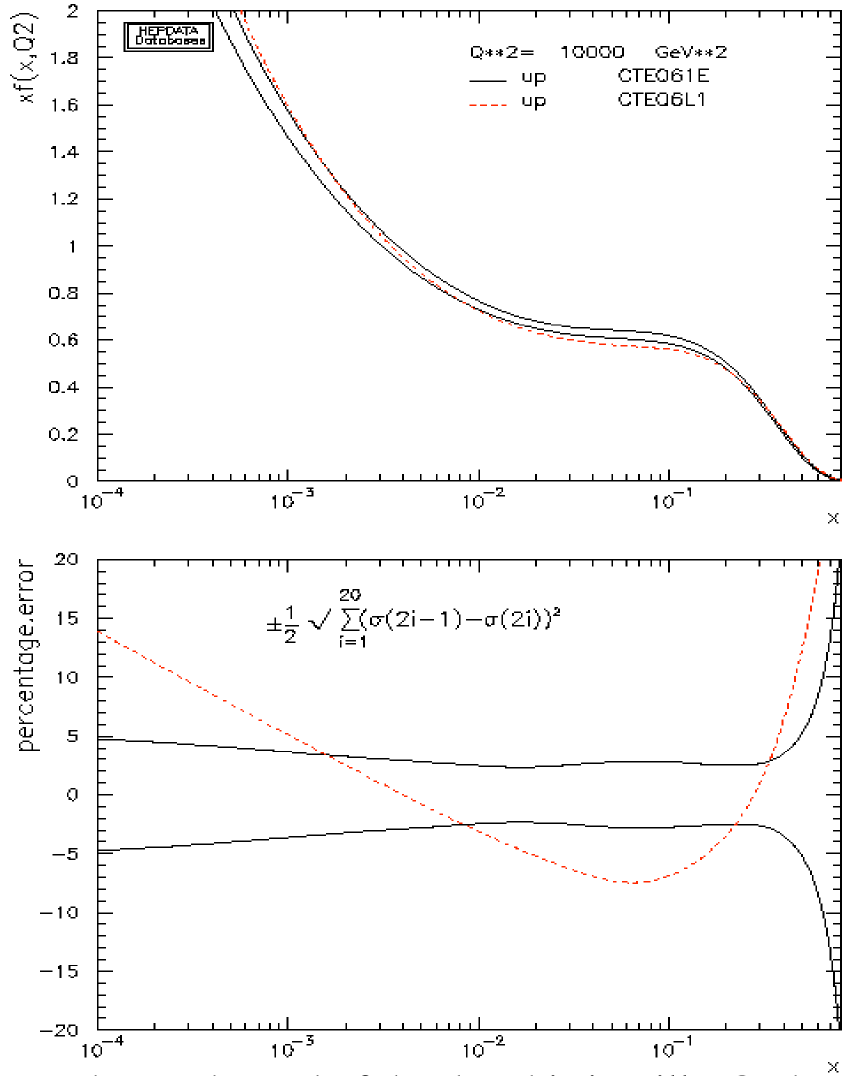
- variation of ISR/FSR a la CDF (study performed by Un-Ki Yang)
  - low ISR/high ISR
  - FSR
  - power showers versus wimpy showers a la Peter Skands
  - number of additional jets expected due to ISR effects (see also Sudakov form factors)
  - impact on top analyses
  - effect on benchmarks such as Drell-Yan 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

Strong overlap with TeV4LHC report

1. Introduction/motivation
2. PDF's:tools and issues
   1. fastNLO
   2. LHAPDF
      1. pdf reweighting techniques
      2. Sudakov FF's
   3. CTEQ α_s series and CTEQ7
   4. use of NLO pdf's (MC's)
3. Monte Carlo parameters
   1. underlying event tuning at the Tevatron
      1. Pythia and Jimmy
      2. CTEQ6.1
   2. extrapolation to the LHC: predictions and uncertainties
5. Matrix element/parton shower tools
   - W+jets: CKKW/MCFM comparisons to data
   - extrapolation to the LHC: backgrounds to VBF
   - Samper case study: Higgs + 2 jets
6. Jet production
   - MC@NLO: inclusive jet production
   - jet algorithms:advice for the LHC
7. Diffraction
8. White paper on remaining measurements at the Tevatron
9. SM Benchmarks for the LHC
   - relation to Tevatron measurements
10. Conclusions

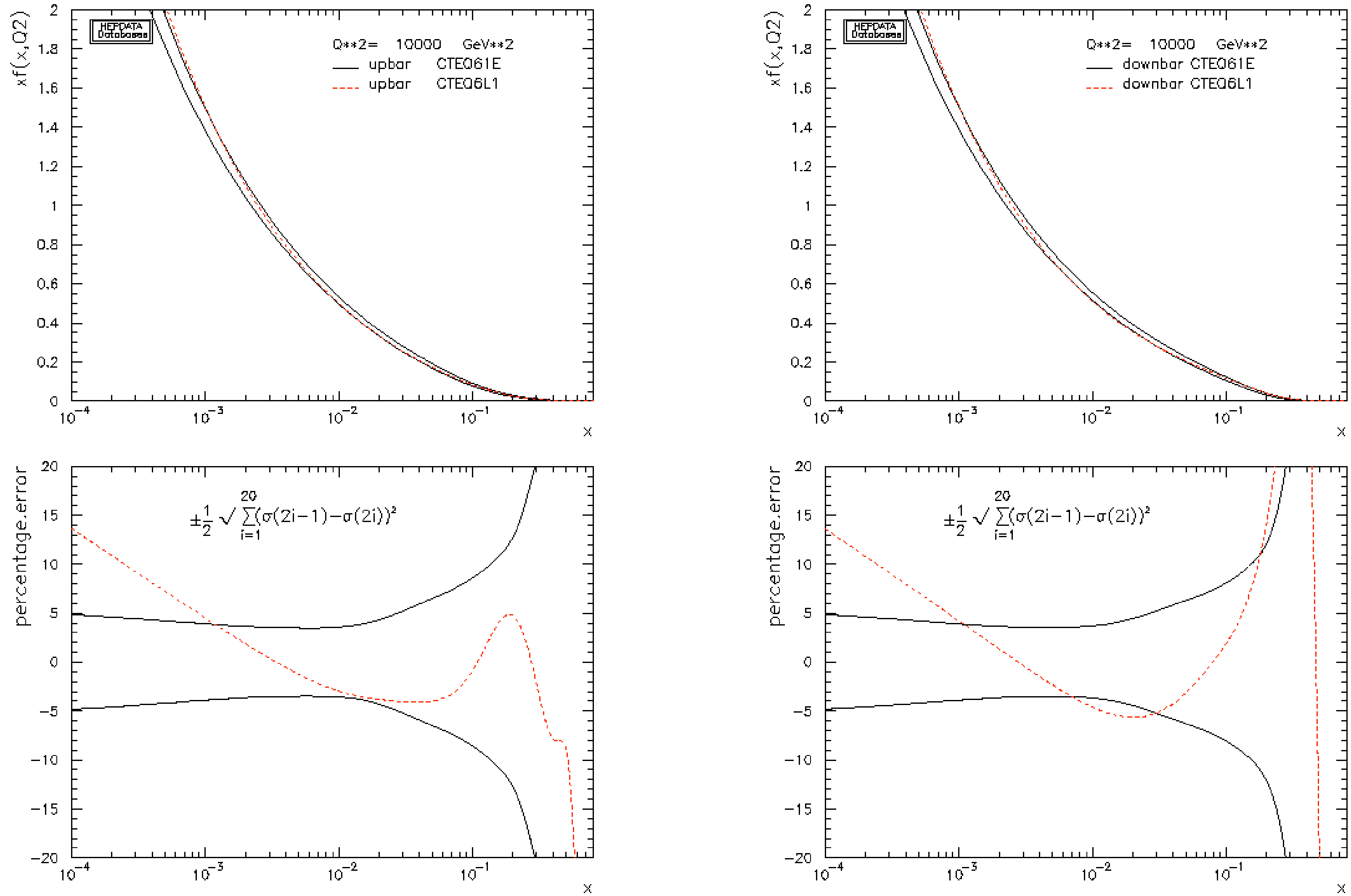
LO vs NLO pdf’s for parton shower MC’s

- 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.

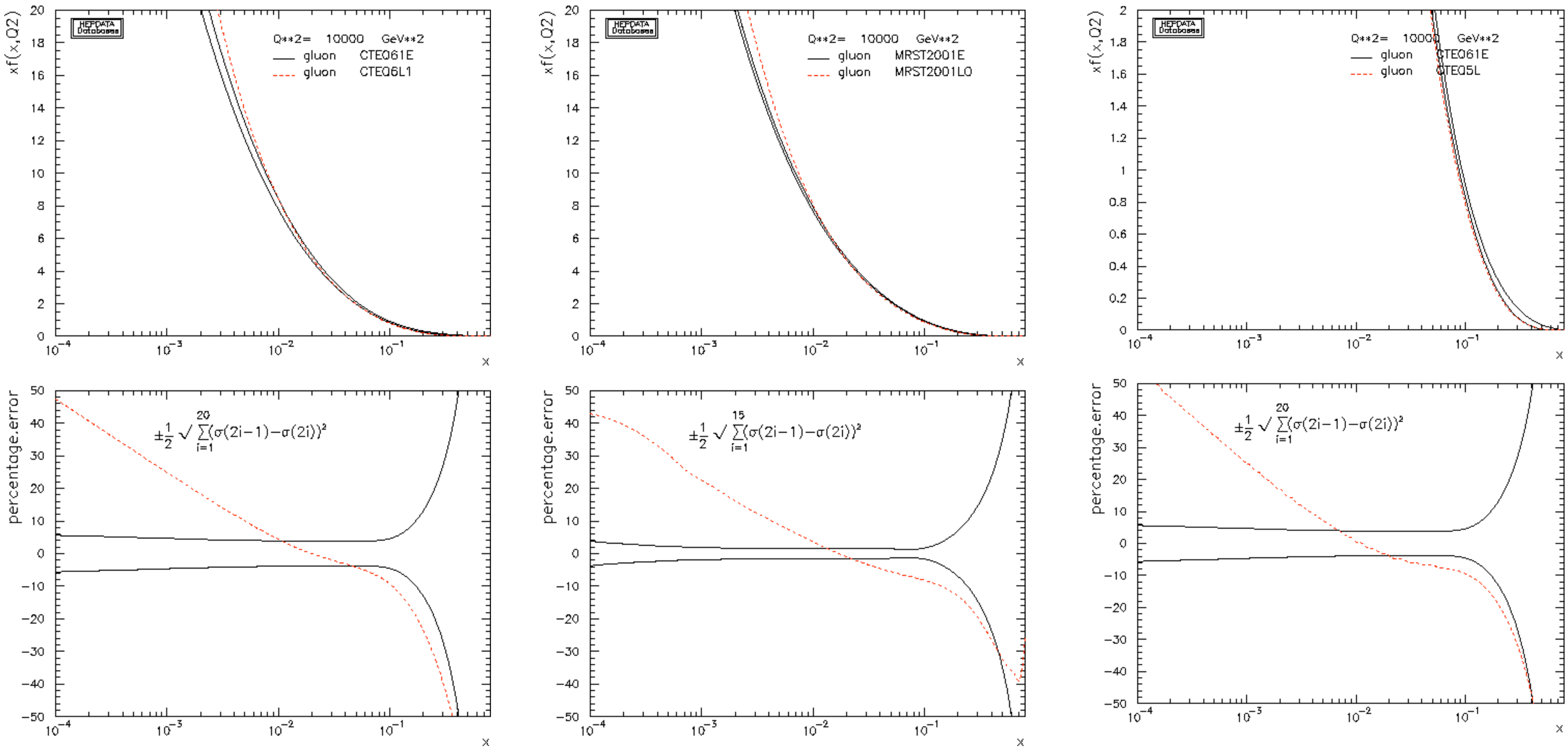
upbar/downbar



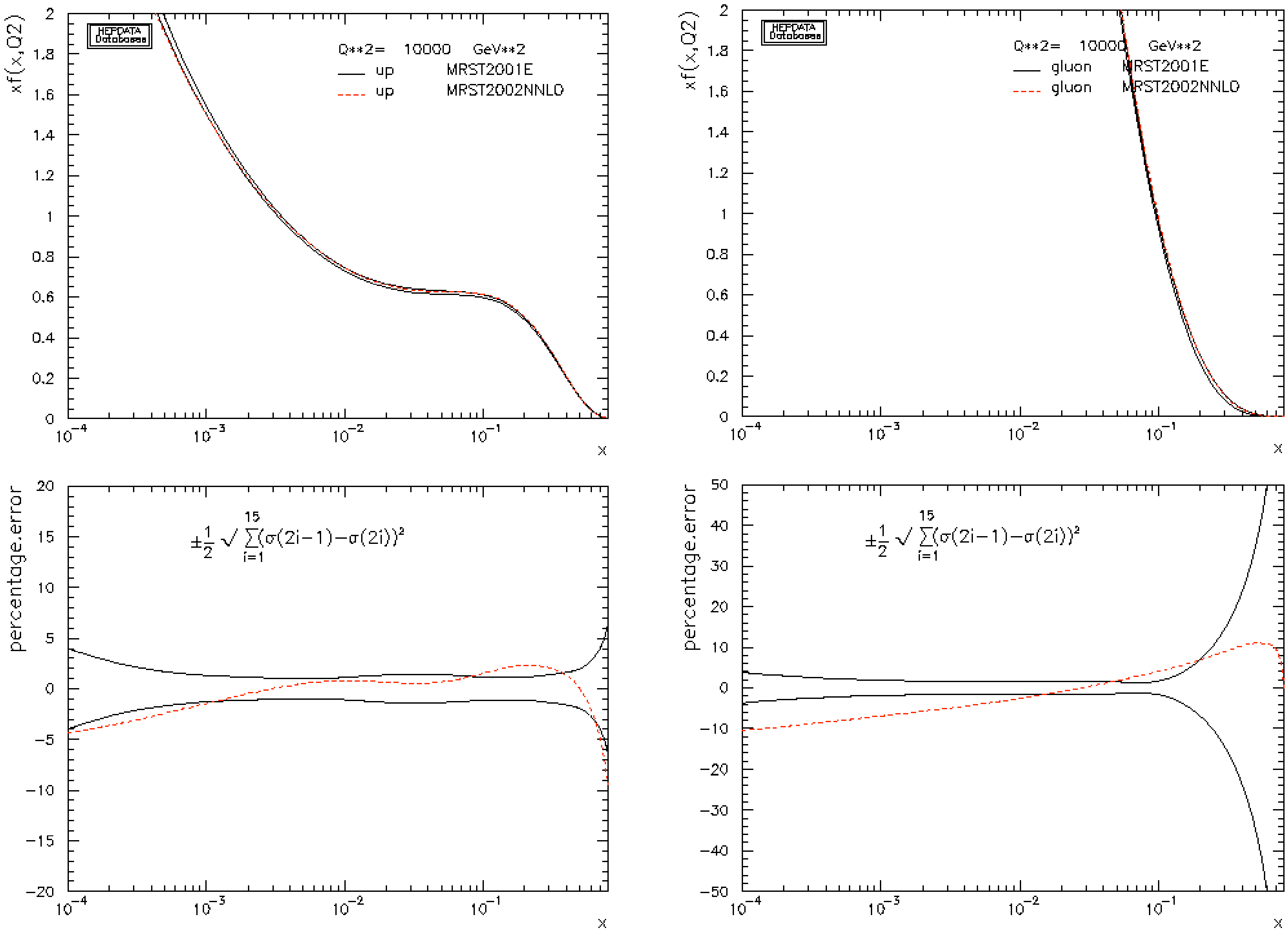
gluon

similar for MRST

compare to CTEQ5L, used for most MC's

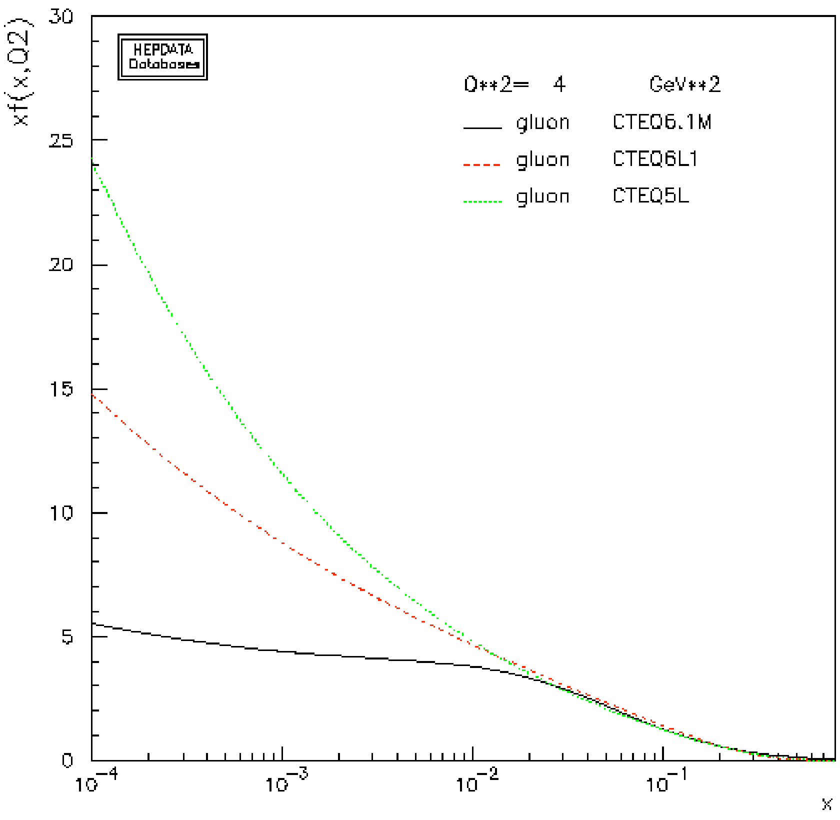


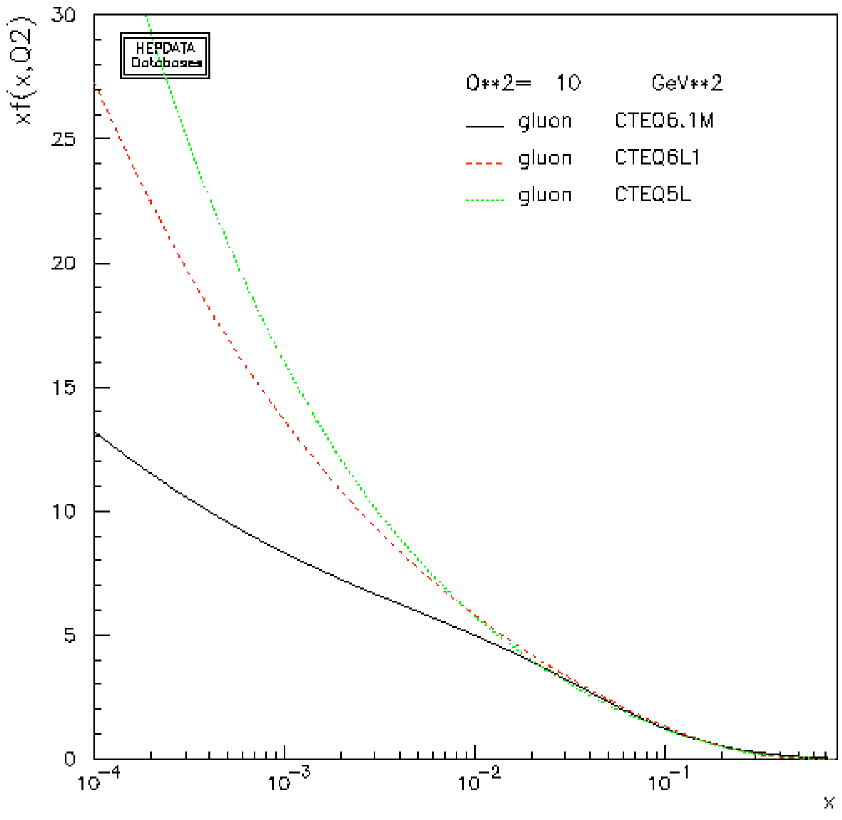
Less difference between NLO and NNLO pdf's



Impact on UE tunes

- 5L significantly steeper at low x and Q^2





CTEQ6.1 Tune

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

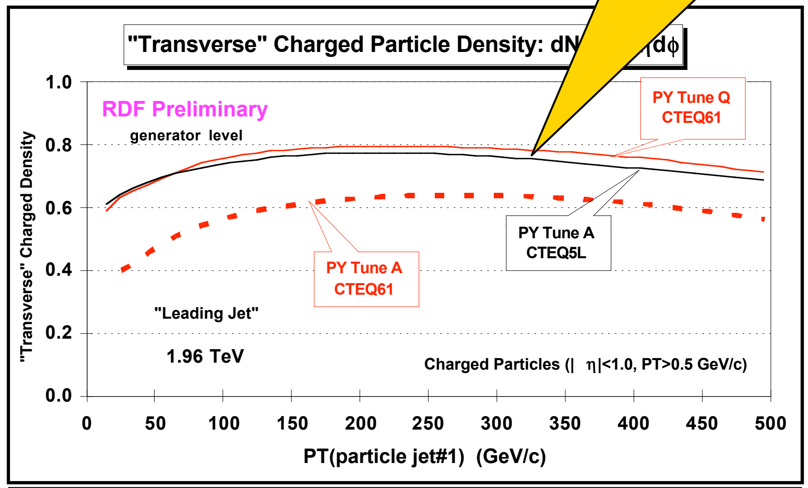
PYTHIA 6.2 CTEQ6.1

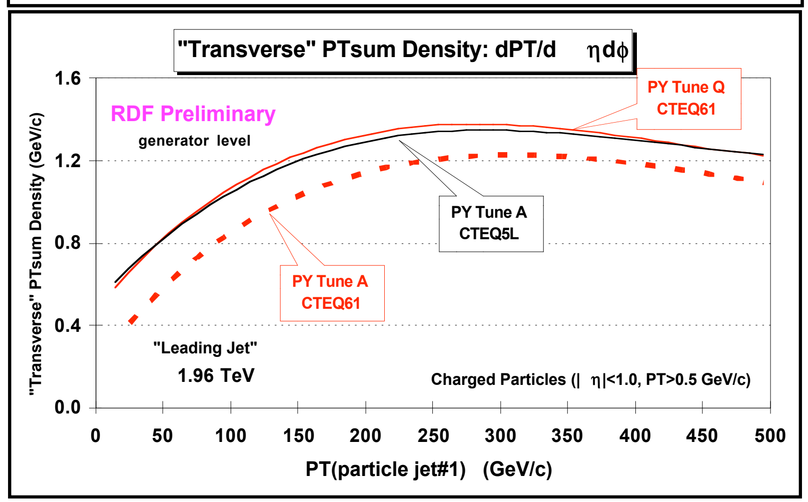
UE Parameters

ISR Parameters

Intrensic KT

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





Extra

Outline for review article

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

Outline, continued

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