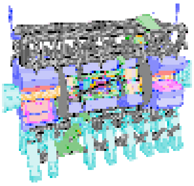
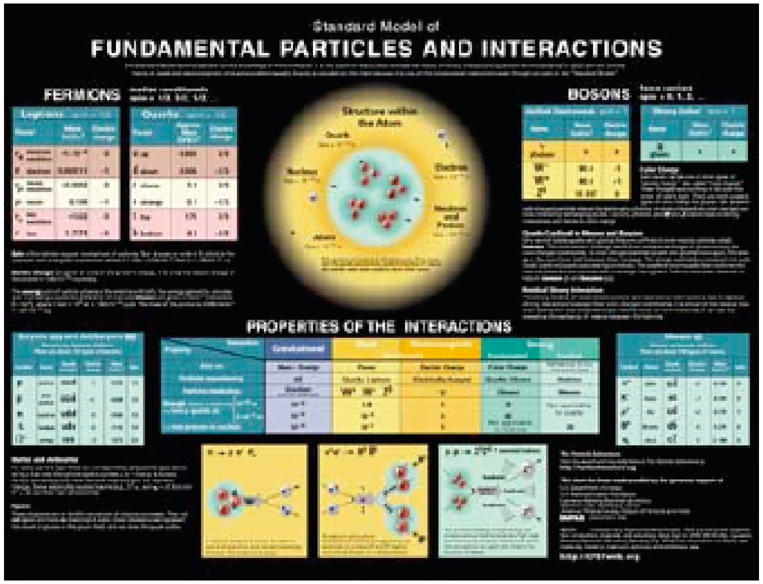


Discovering the Standard Model during the first year(s) of the LHC

…lessons from the Tevatron

…and the benchmarks for the ATLAS early running



Joey Huston
Michigan State University
Aspen 2005 Collider Workshop

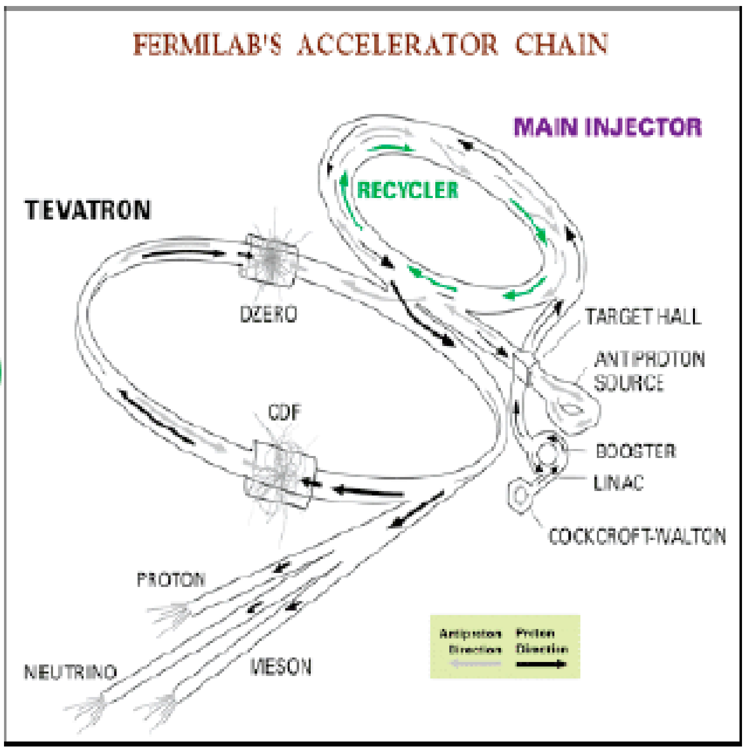
…apologies to those who have heard a similar talk at Les Houches
…or at CERN…or at Toronto

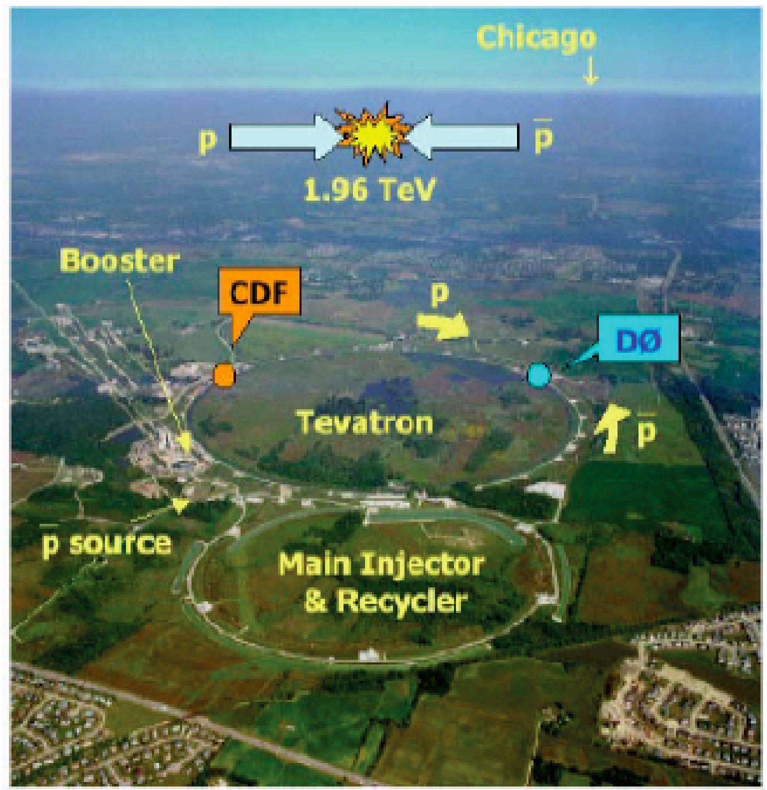
Tevatron

…by this point, you've seen this picture many times and much of the Run 2 results from the Tevatron

I'll be concentrating more on the tools that we'll need for the LHC and the lessons we've learned from the Tevatron

36 bunches (396 ns crossing time)

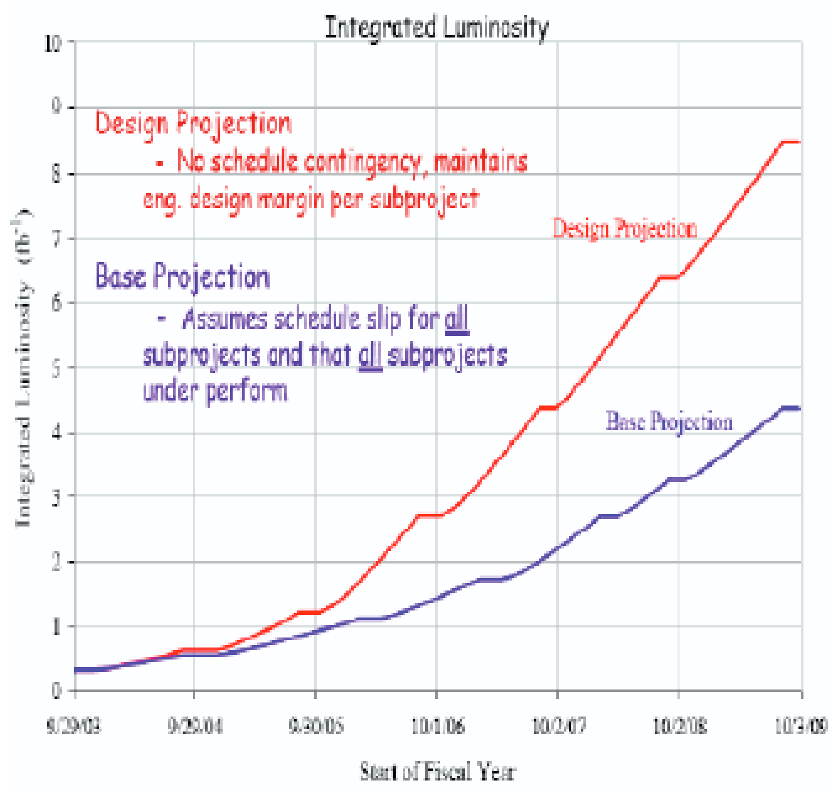


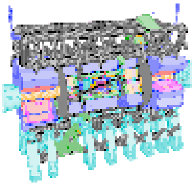


Let me just say

- Tevatron (and CDF and D0) are runnning well

ultimately 4-9 fb^{-1}



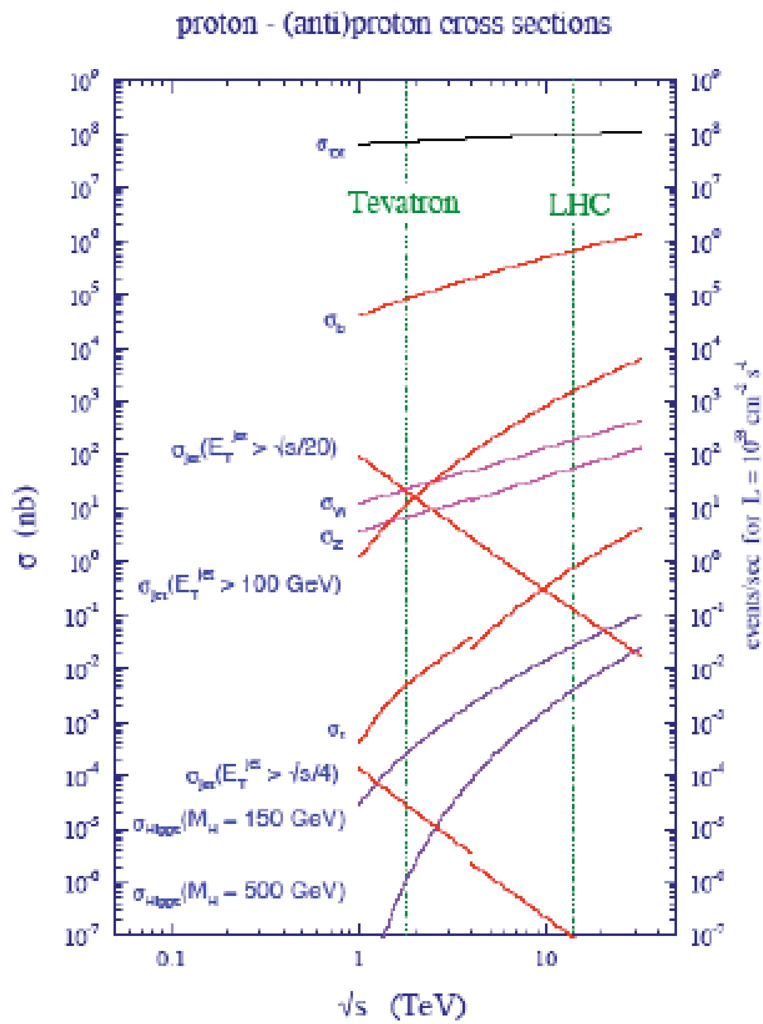


This year's Les Houches well-named

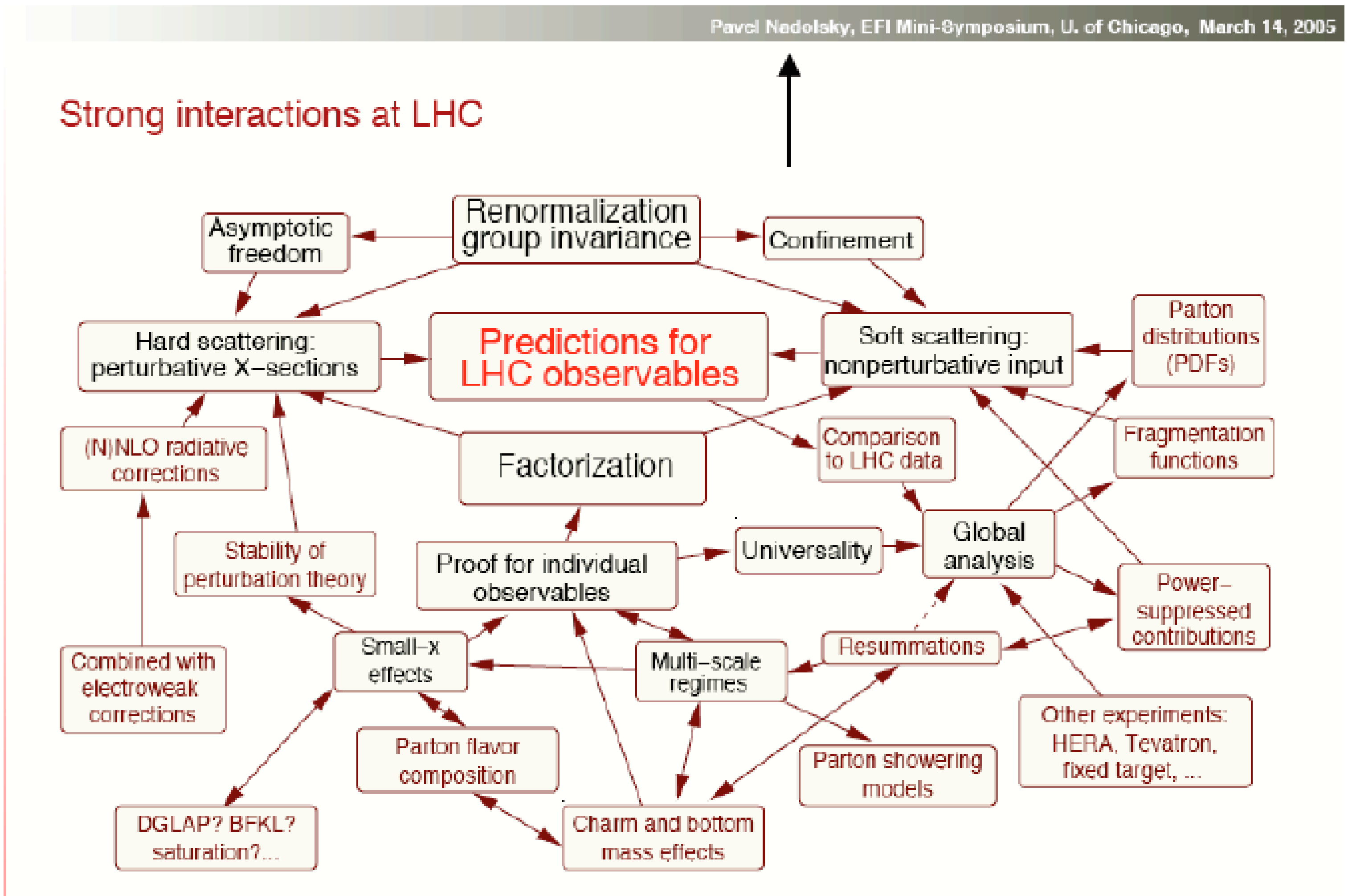
- …or even a bit pessimistic
- Physics at TeV Colliders
  - From 800 pb^{-1} at the Tevatron to 30 fb^{-1} at the LHC
  - May 2 - 20, 2005

Discovering the SM at the LHC

- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to BSM physics correctly taken into account
- ATLAS and CMS will have a program to measure production of SM processes: inclusive jets, W/Z + jets, heavy flavor during first year
  - one advantage is that we've already discovered the SM at the Tevatron so we have useful experience to go with

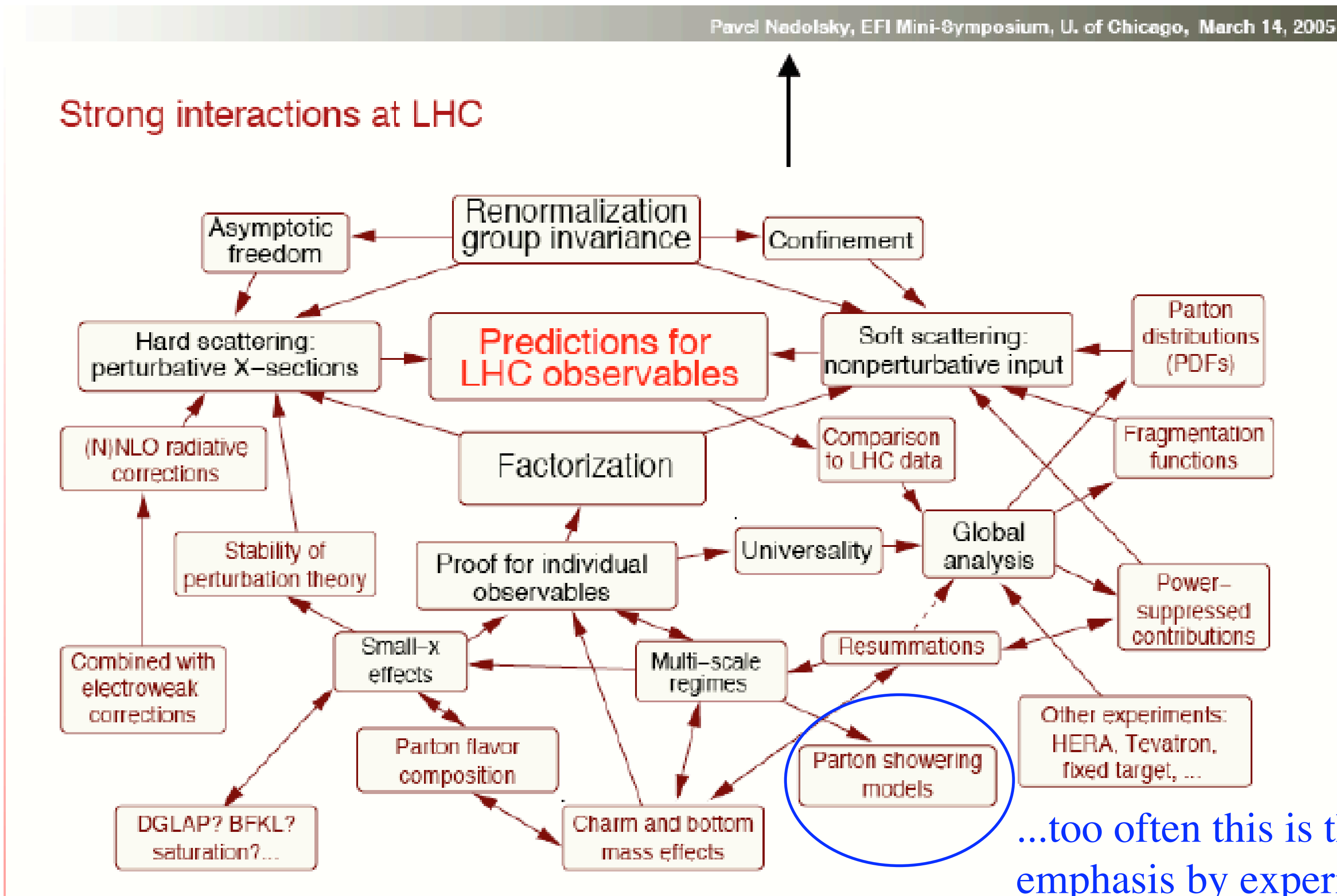


SM predictions



Les Houches 2005

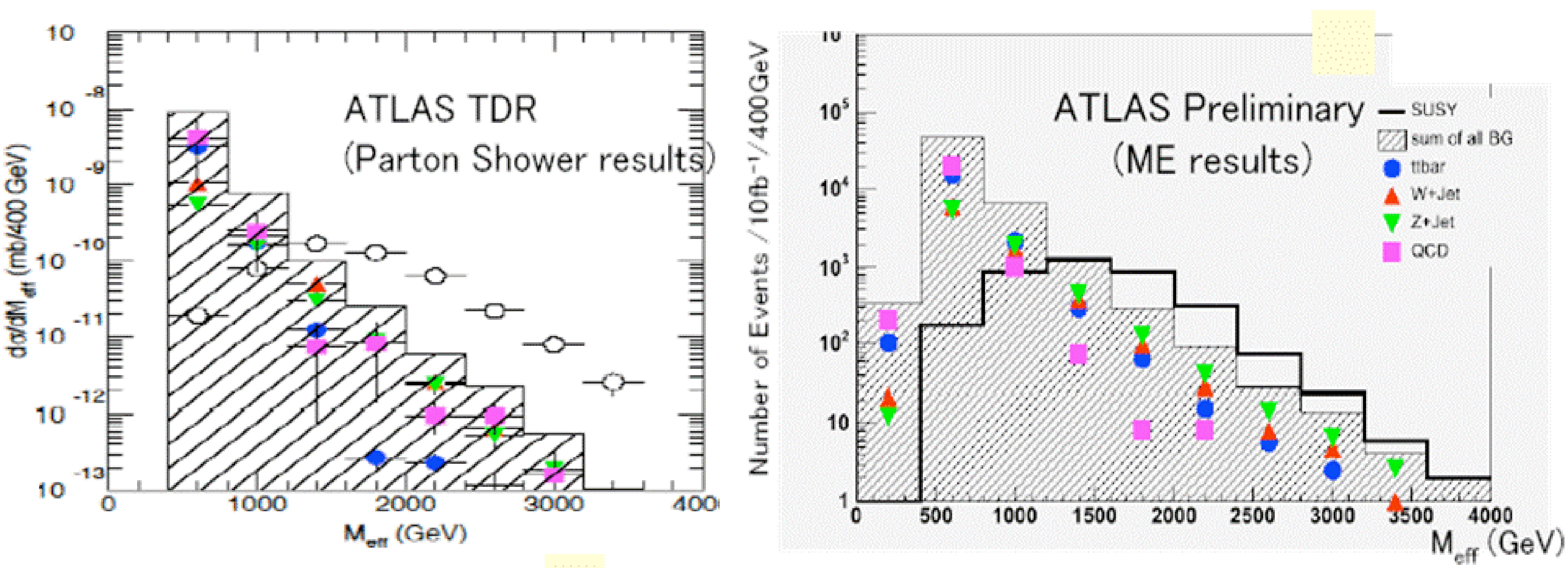
SM predictions



...too often this is the only emphasis by experimenters

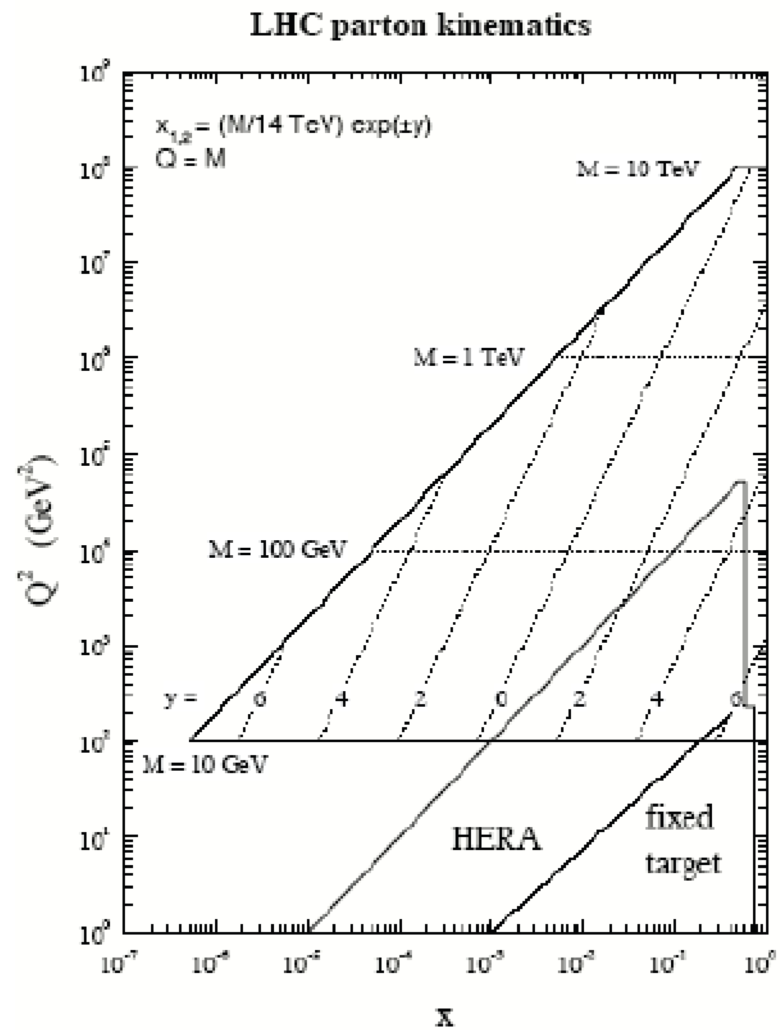
Sometimes a parton shower just isn't enough

Backgrounds to this SUSY search >> if use ME rather than parton shower predictions



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



NLO

- Perturbative calculations have a realistic normalization (and sometimes shape) only at NLO
  - NLO calculations can guide us in our experimental analyses; acceptances, templates, etc…
  - …and in some cases we can make direct comparisons of corrected data to NLO
- Parton level calculations have been performed for all 2->2 hard scattering and some 2->3 hard processes
  - state of the art is W/Z + 2 jets
  - W/Z + 3 jets perhaps in the next few years
    - problem with multi-leg virtual integrations
    - many loop integrals
    - enormous expressions large numerical cancellations

- See www.cedar.ac.uk/hepcode for collection of NLO codes, such as

AYLEN/EMILIA (de Florian et.al.): $pp \to (W,Z) + (W,Z,\gamma)$

DIPHOX (Aurenche et.al.): $pp \to \gamma j, \gamma\gamma, \gamma^* p \to \gamma j$

HQQB (Dawson et.al.): $pp \to t\bar{t}H, b\bar{b}H$

MCFM (Campbell, Ellis): $pp \to (W,Z) + (0,1,2)\,j,\ (W,Z) + b\bar{b}$

NLOJET++ (Nagy): $pp \to (2,3)\,j,\ ep \to (3,4)\,j,\ \gamma^* p \to (2,3)\,j$

VBFNLO (Figy et.al.): $pp \to (W,Z,H) + 2\,j$

MCFM

- Handy one-stop shopping for partonic level processes at both LO and NLO
  - few more pages of processes in addition to what is shown at the right
  - many more will be added in the near future (see next slides)
- I've been generating large ROOT-ntuples for LHC predictions for processes such as W +1,2 jets,t-tbar, WW->H production, etc for use by ATLAS (and CMS)
  - ~400M events per sample
  - ten's of GB's

nproc	$f(p_1) + f(p_2) \to \ldots$	Order
1	$W^+(\to \nu(p_3) + e^+(p_4))$	NLO
6	$W^-(\to e^-(p_3) + \bar\nu(p_4))$	NLO
11	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5)$	NLO
12	$W^+(\to \nu(p_3) + e^+(p_4)) + \gamma(p_5)$	NLO
13	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar c(p_5)$	LO
14	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar c(p_5)$ [massless]	NLO
16	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + f(p_5)$	NLO
17	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + \gamma(p_5)$	NLO
18	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + c(p_5)$	LO
19	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + c(p_5)$ [massless]	NLO
20	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar b(p_6)$ [massive]	LO
21	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar b(p_6)$	NLO
22	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5) + f(p_6)$	NLO
23	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
24	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar b(p_6) + f(p_7)$	LO
25	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + b(p_5) + \bar b(p_6)$ [massive]	LO
26	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + b(p_5) + \bar b(p_6)$	NLO
27	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + f(p_5) + f(p_6)$	NLO
28	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
29	$W^-(\to e^-(p_3) + \bar\nu(p_4)) + b(p_5) + \bar b(p_6) + f(p_7)$	LO
31	$Z^0(\to e^-(p_3) + e^+(p_4))$	NLO
32	$Z^0(\to 3 \times (\nu(p_3) + \bar\nu(p_4)))$	NLO
33	$Z^0(\to b(p_3) + \bar b(p_4))$	NLO
41	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5)$	NLO
42	$Z_0(\to 3 \times (\nu(p_3) + \bar\nu(p_4)))$ – [sum over 3 ν] $+ f(p_5)$	NLO
43	$Z^0(\to b(p_3) + \bar b(p_4)) + f(p_5)$	NLO
44	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5) + f(p_6)$	NLO
45	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
48	$Z^0(\to e^-(p_3) + e^+(p_4)) + \gamma(p_5)$	NLO
49	$Z^0(\to 3 \times (\nu(p_3) + \bar\nu(p_4)))$ – [sum over 3 ν] $+ \gamma(p_5)$	NLO
50	$Z^0(\to e^-(p_3) + e^+(p_4)) + \bar b(p_5) + b(p_6)$ [massive]	LO
51	$Z^0(\to e^-(p_3) + e^+(p_4)) + b(p_5) + \bar b(p_6)$	NLO
52	$Z_0(\to 3 \times (\nu(p_3) + \bar\nu(p_4))) + b(p_5) + \bar b(p_6)$	NLO
53	$Z^0(\to b(p_3) + \bar b(p_4)) + b(p_5) + \bar b(p_6)$	NLO
56	$Z^0(\to e^-(p_3) + e^+(p_4)) + b(p_5) + \bar b(p_6) + f(p_7)$	LO

NLO vs LO: example from the Tevatron

LO->NLO may not be just a K-factor

Don't rely just on LO predictions J. Campbell, J. Huston; hep-ph/0405276

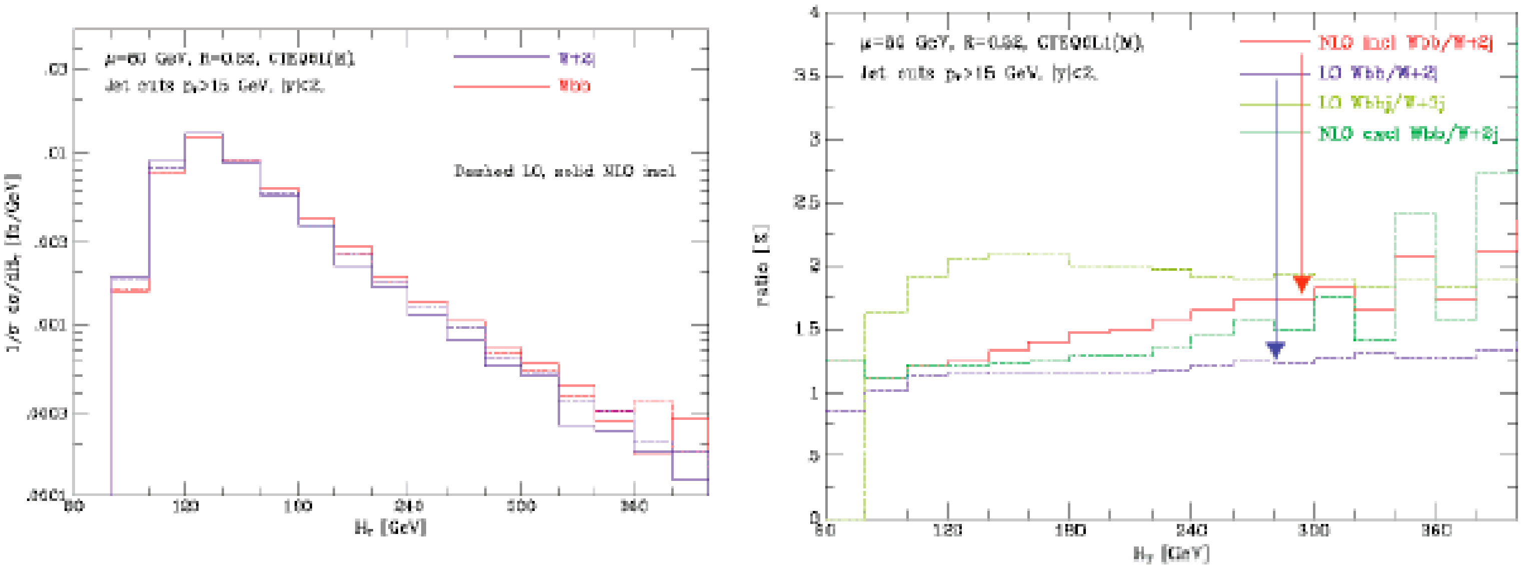


Figure 12: The H_T distributions for $Wb\bar{b}(j)$ and $Wjj(j)$, normalized to the same area.

Wbb and Wjj have similar H_T distribution at LO; different at NLO

Lesson: H_T is a dangerous variable to use for any analysis for which shape discrimination is important

…less inclusive variables have less difference between LO and NLO

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
   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

Stefan Dittmair has promised to finish at least one of these before the LHC turns on (finishing tT + jet now)

Calculation priority list from Les Houches 2005

- 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

1. pp->WW jet
2. pp->H + 2 jets → now been completed by Ellis, Giele, Zanderighi
   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

Walter Giele at the Tevatron Connection meeting

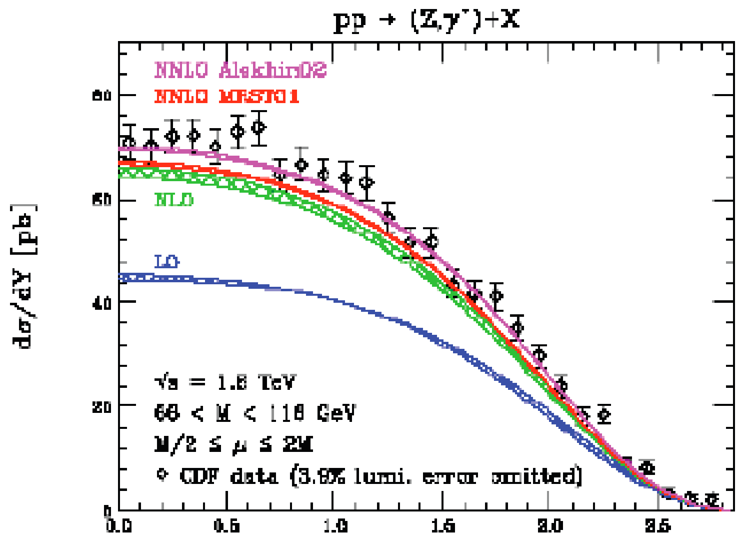
- Alternatives seems to be needed giving a systematic calculational procedure:
  The Samper project (c++, f95, f77)
  (Semi-numerical AMPlitude EvaluatoR)

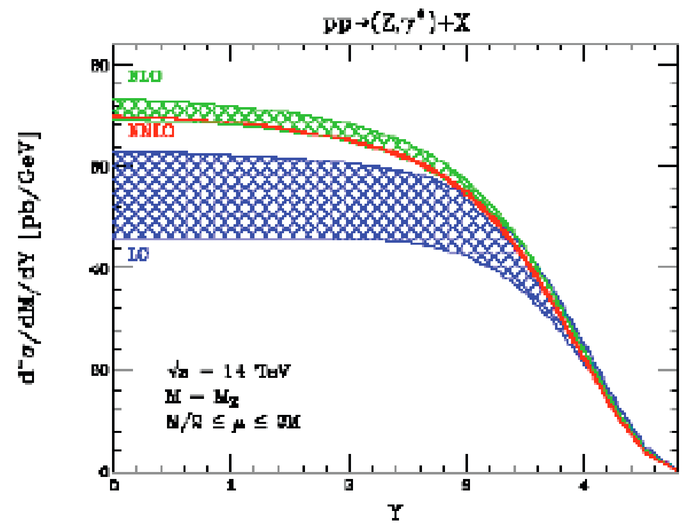
- Development for semi-numerical evaluation of one-loop calculations.
  - Detailed algorithmic method has been developed.
  - Program has been checked and is ready for 2 to 3 processes (no internal masses yet)
  - Will extend MCFM to:
    - Di-boson + 1 jet production
    - Tri-boson production + 0 jet production
    - H + 2 jets (with effective Hgg coupling)

…by late 2007: all 2->3 processes,including heavy quark masses; some 2->4 processes …and interface to parton shower

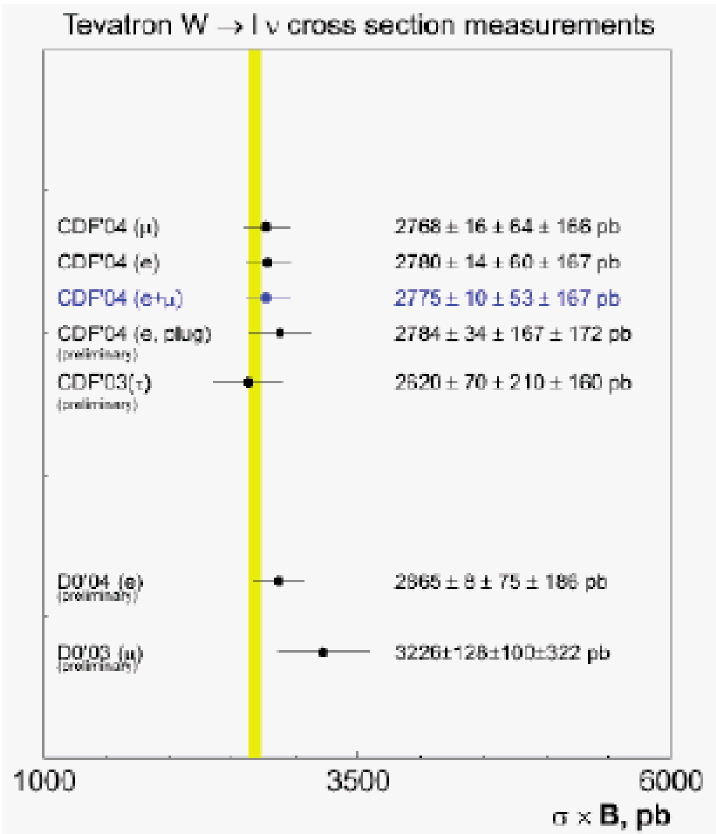
NNLO

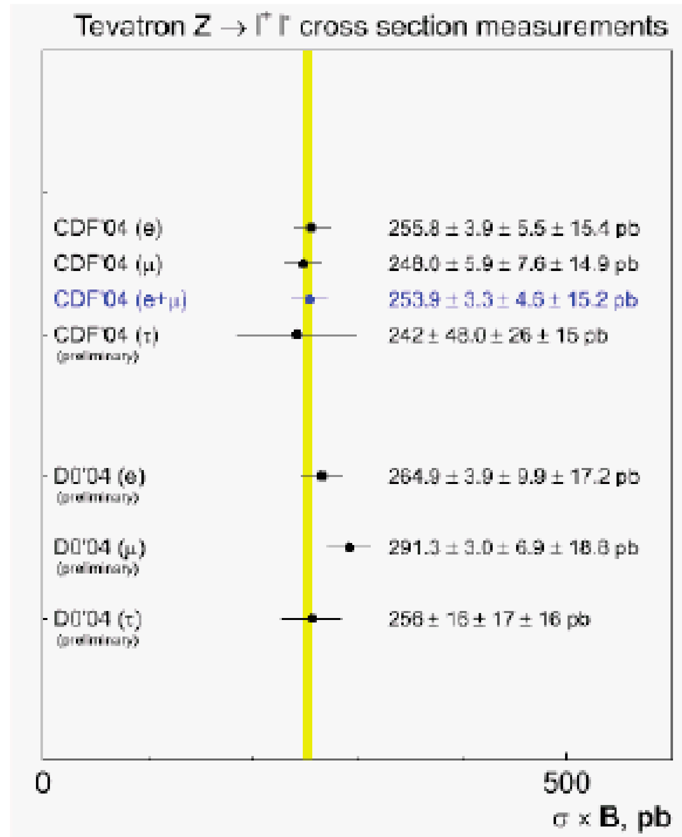
- A few cross sections have been calculated to NNLO
  - inclusive W/Z
  - W/Z/Higgs rapidity
  - inclusive jet still 2? years off; needed for *true* NNLO pdf's
- Often just a K-factor
  - but needed for precision physics such as with W/Z





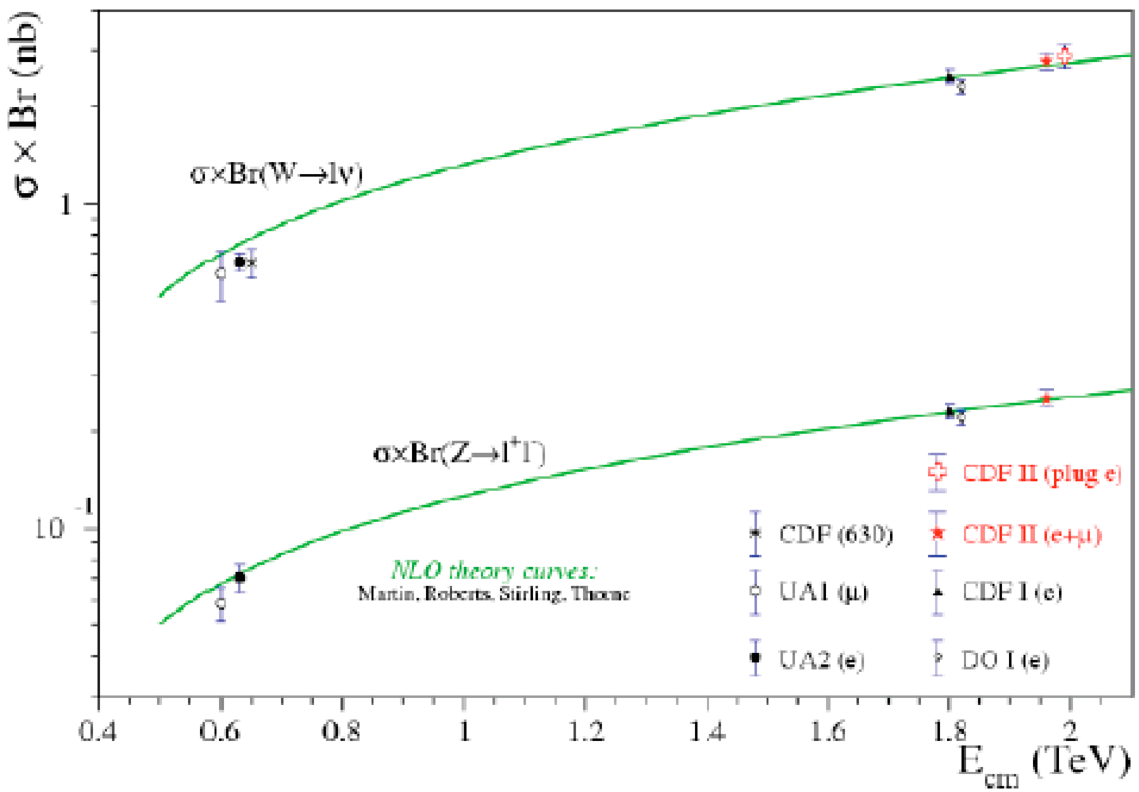
W/Z cross sections at the Tevatron





- good agreement with NNLO predictions
- error dominated by luminosity error (6%)
- 2% systematics (pdf's (acceptance), efficiency) without L error

W/Z cross sections at the Tevatron



$$R = \frac{\sigma_W \times BR(W \to l\nu)}{\sigma_Z \times BR(Z \to l^+ l^-)} = 10.92 \pm 0.15(\text{stat.}) \pm 0.14(\text{syst.})$$

- e, μ combined
- correlated systematics fully taken into account

$W \rightarrow l\,\nu$ as luminosity monitor

- Current method based on σ_{inel}(ppbar)= 61.7±2.4 mb @ 1.96 TeV (4%)
- Can we do better using the cross section for $W \rightarrow l\nu$ measurement?
- Recent paper by Frixione and Mangano (hep-ph/0405130) investigate contributions of uncertainties in acceptance calculation to the $W \rightarrow l\nu$ x-sec measurement (currently ~2%)
- Tevatron and LHC would benefit from experimental and theoretical work

…TeV4LHC project

Aside: PDF's

- Calculation of production cross sections at the Tevatron relies upon knowledge of pdfs in relevant kinematic range
- pdfs 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
  - CTEQ->CTEQ5->CTEQ5(1)->CTEQ6->CTEQ6.1
  - also GKK and Alekhin, but not widely used
- All of the above groups provide a way to estimate the error on the central pdf
  - new methodology enables full characterization of parton parametrization space in neighborhood of global minimum
    - Hessian method
    - Largrange Multiplier
  - both of above techniques used by CTEQ and MRST

Nuts and bolts of fits

- Functional form used in CTEQ fits is:
  - $xf(x,Q_o) = A_o x^{A1} (1-x)^{A2} e^{A3x} (1 + A_4x)^{A5}$
    - Q_o = 1.3 GeV (below any data used in fit)
      - easier to do forward evolution than backward
      - MRST starts at 1 GeV (- gluon distribution)
    - functional form arrived at by adding a 1:1 Pade expansion to quantity d(log xf)/dx
    - more versatile than form used in CTEQ5 or MRST
    - there are 20 free parameters used in the global fit
      - MRST has 15 free parameters
- Light quarks treated as massless; evolution kernels of PDFs are mass-independent
- Zero mass Wilson coefficients used in DIS structure functions
- NB: MRST pdf's not in pure MS-bar scheme; use Roberts-Thorne treatment of heavy quarks at threshold
  - maybe noticeable only at low x

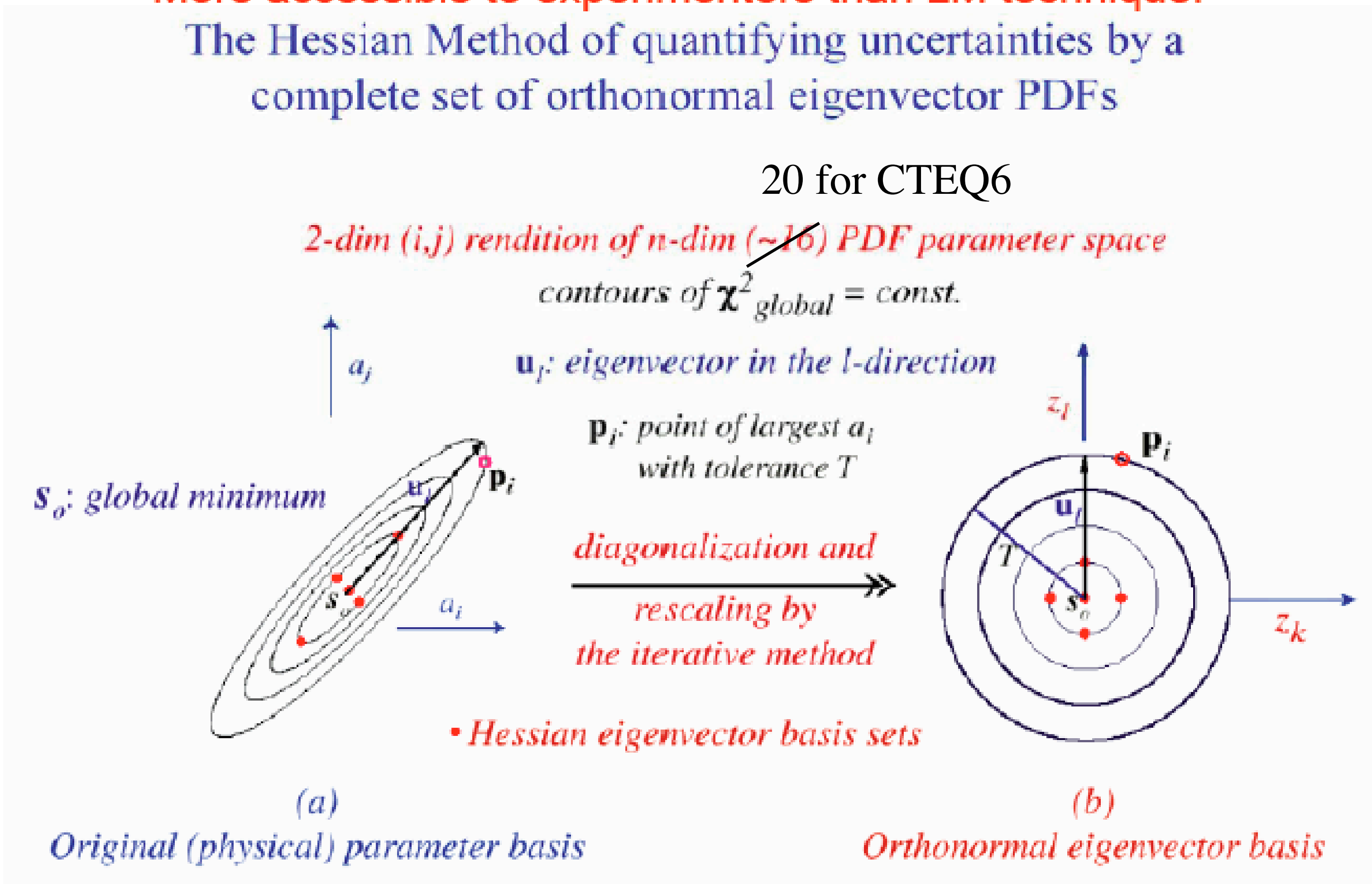
Estimating pdf uncertainties

- Two sources
  - Experimental errors
    - Hessian/Lagrange multiplier techniques designed to address estimate of these effects
      - question is what $\Delta\chi^2$ change best represents estimate of uncertainty (CTEQ uses $\Delta\chi^2$ of 100 (out of 2000) for 90% CL limit; MRST uses $\Delta\chi^2$ of 50); GKK/Alekhin uses 1 (for 1 sigma error)
      - for details on the choice of $\Delta\chi^2$, see the presentation on 2/27/03

  - Theoretical
    - higher twist/non-perturbative effects
      - choose Q^2 and W cuts to try to avoid
    - higher order effects
      - is NNLO necessary yet?
    - edge of phase space effects
      - threshold resummation needed?
    - note that for the most part, CTEQ and MRST make the same cuts/assumptions so theoretical *precision* should be better than theoretical *accuracy*

Hessian method

More accessible to experimenters than LM technique.

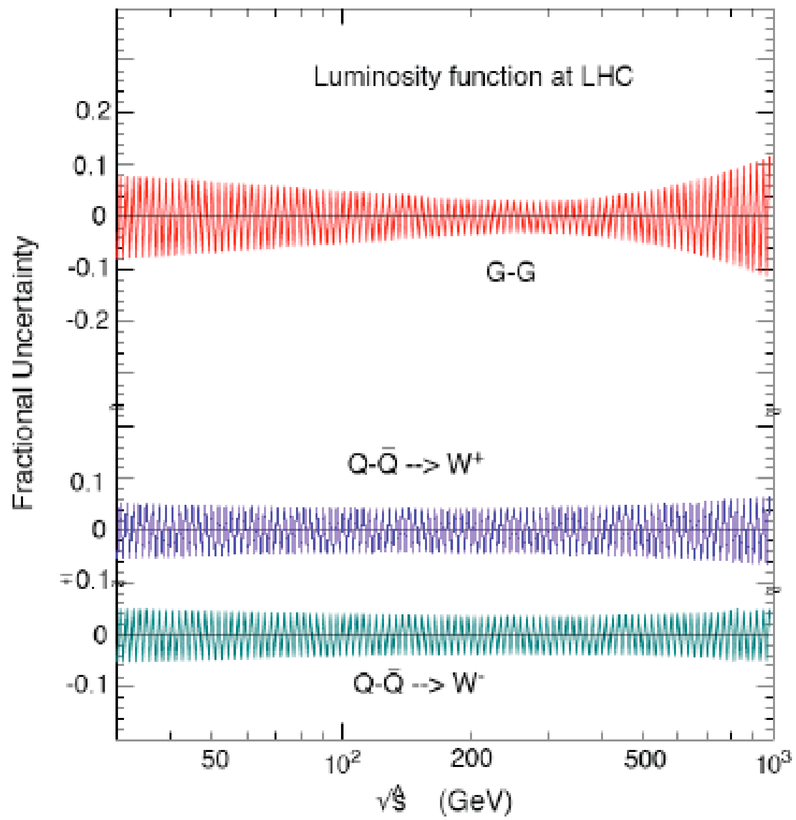


PDF uncertainties

- pdf uncertainties only make sense at NLO (or higher) since this is the first order at which the normalization is believable
- In most kinematic regions of interest at the LHC, pdf uncertainties are small
  - one exception is high E_T jet production
- I've heard people say that the LHC will spend its first year measuring pdf's
- Measuring pdf's is precision physics
- ATLAS will spend its first year being constrained by pdf's

- Using LHAPDF, can easily calculate pdf uncertainties for any observable using pdf weights

Note that you can roughly estimate pdf uncertainties for many processes using plots like the one below. I'll produce more.

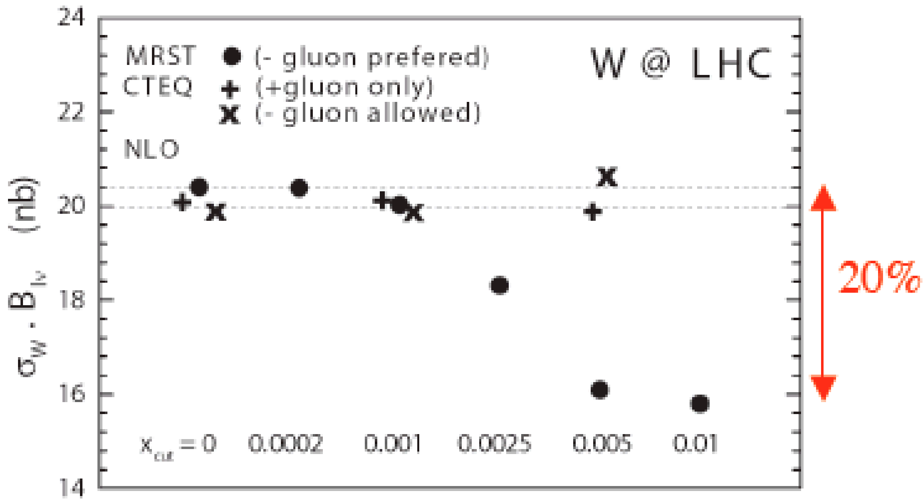


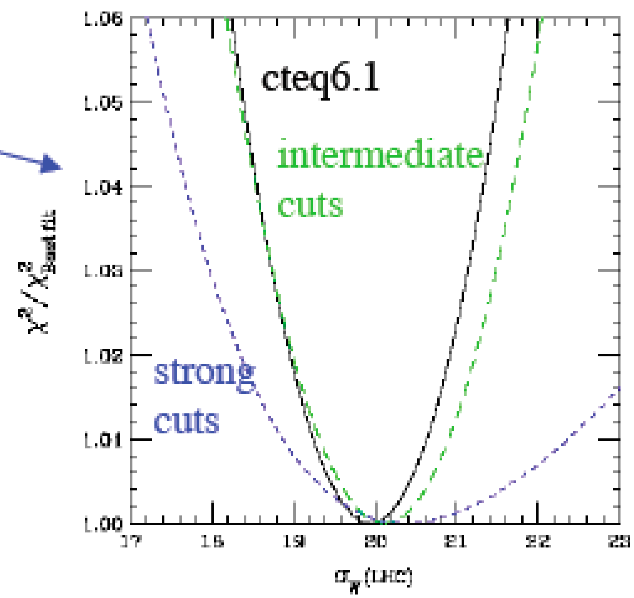
- NLO predictions for LHC under good control if NLO formalism is adequate for LHC

Les Houches 2005

Validity of NLO predictions

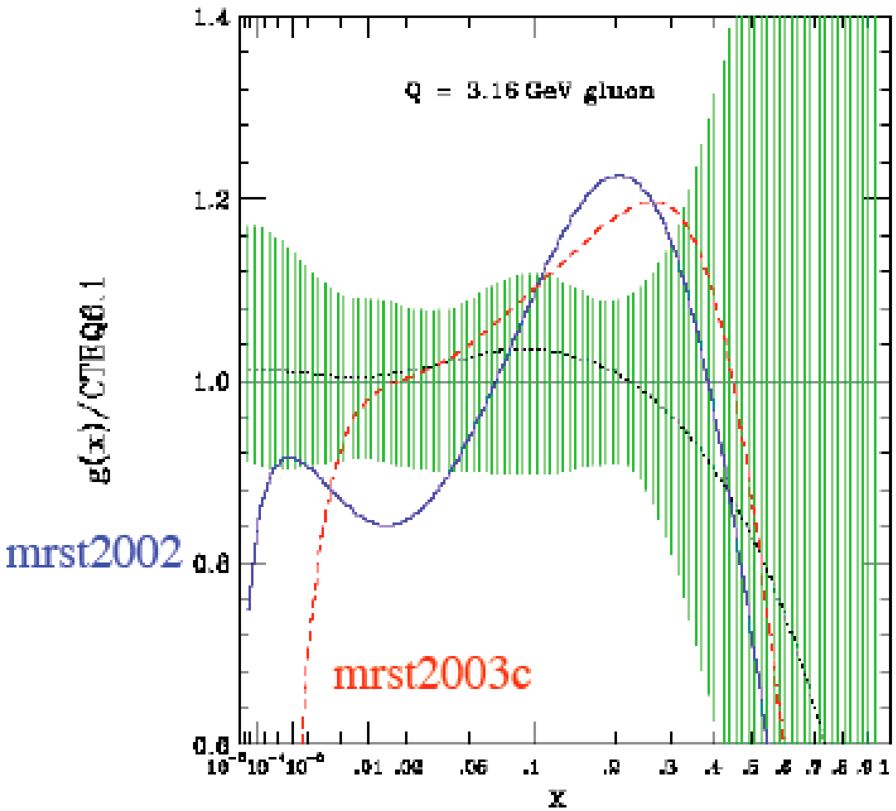
- Is there a *tension* between HERA and Tevatron data requiring NNLO DGLAP to resolve?
  - MRST study: hep-ph/0308087
  - W cross section at LHC drops 20% when data below x=.005 are removed from fit
  - implications for use of W σ as luminosity benchmark
- Recent CTEQ study indicates as more severe cuts are made in x and Q^2 in global analysis, uncertainty on W cross section at the LHC increases but central value remains relatively constant

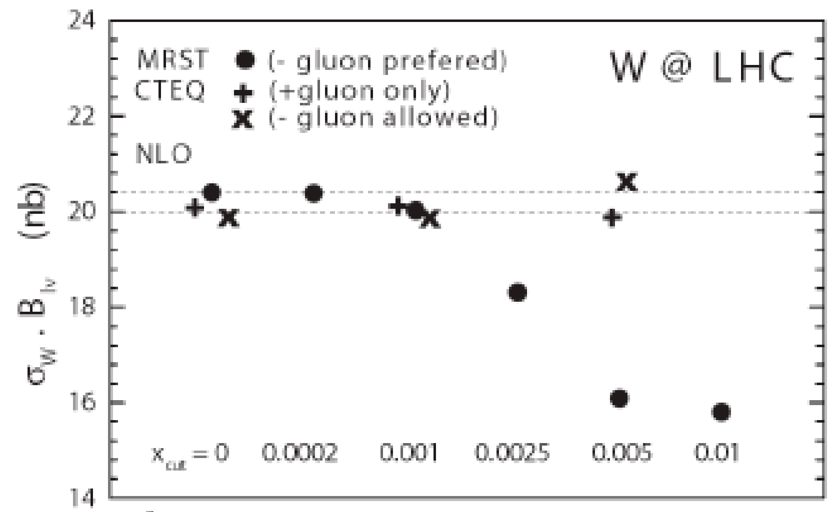


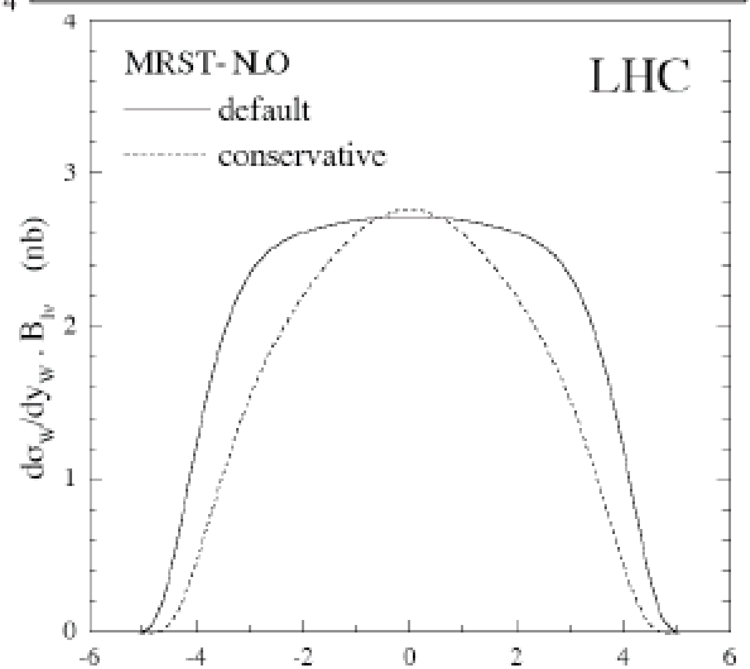


Negative gluon

- Lower cross section in MRST study results from pinched rapidity distribution caused by impact of negative gluon

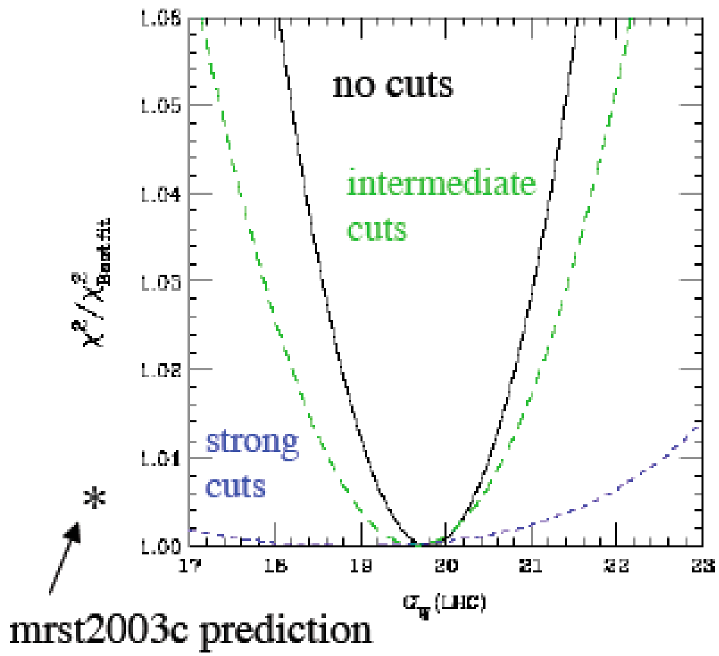






NLO stability

- CTEQ conclusion: if negative gluon allowed, then uncertainty of σ_W increases (dramatically for severe cuts), but again central value remains constant
- No advantage found in fit of allowing negative gluon



hep-ph/0502080

February 3, 2005

MSU-HEP-5
CTEQ-5

Stability of NLO Global Analysis and Implications for Hadron Collider Physics

J. Huston, J. Pumplin, D. Stump, W.K. Tung

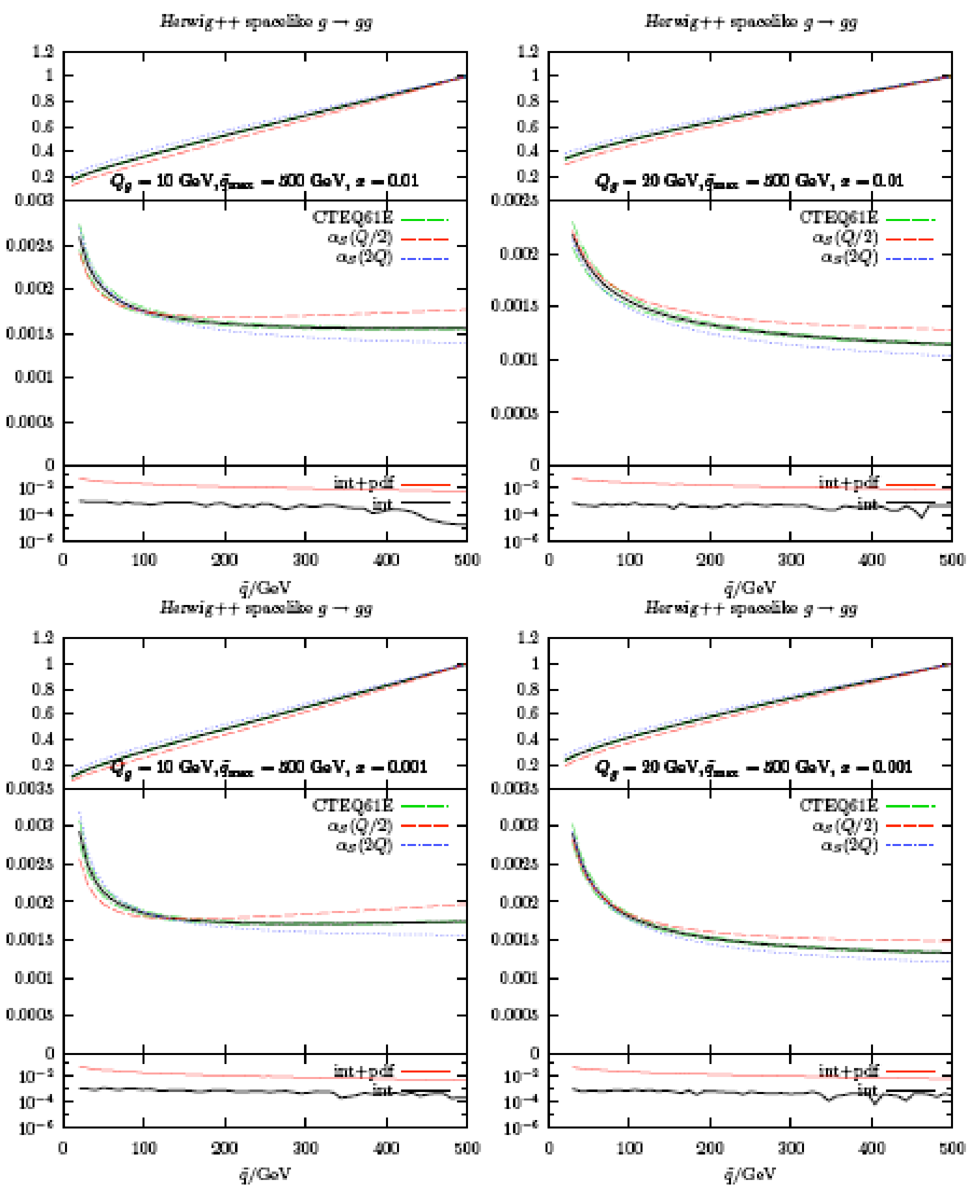
Michigan State University, E. Lansing, MI 48824

Using pdf uncertainties

- PDF uncertainties are important both for precision measurements (W/Z cross sections) as well as for studies of potential new physics (a la jet cross sections at high E_T)
- Most Monte Carlo/matrix element programs have "central" pdf's built in, or can easily interface to PDFLIB
- Determining the pdf uncertainty for a particular cross section/distribution might require the use of many pdf's
- ->LHAPDF
  - a replacement for PDFLIB as the source for up-to-date pdf's
  - originated by Walter Giele; now maintained by Mike Whalley of Durham
- Using the interface is as easy as using PDFLIB (and much easier to update)
- call InitiPDFset(*name*)
  - called once at the beginning of the code; *name* is the file name of external PDF file that defines PDF set
- call InitPDF(*mem*)
  - *mem* specifies individual member of pdf set
- call evolvePDF(*x*,*Q*,*f*)
  - returns pdf momentum densities for flavor *f* at momentum fraction *x* and scale *Q*

In new version, all error pdf's can be kept in memory at same time.
PDF uncertainty for any cross section can be calculated by weights

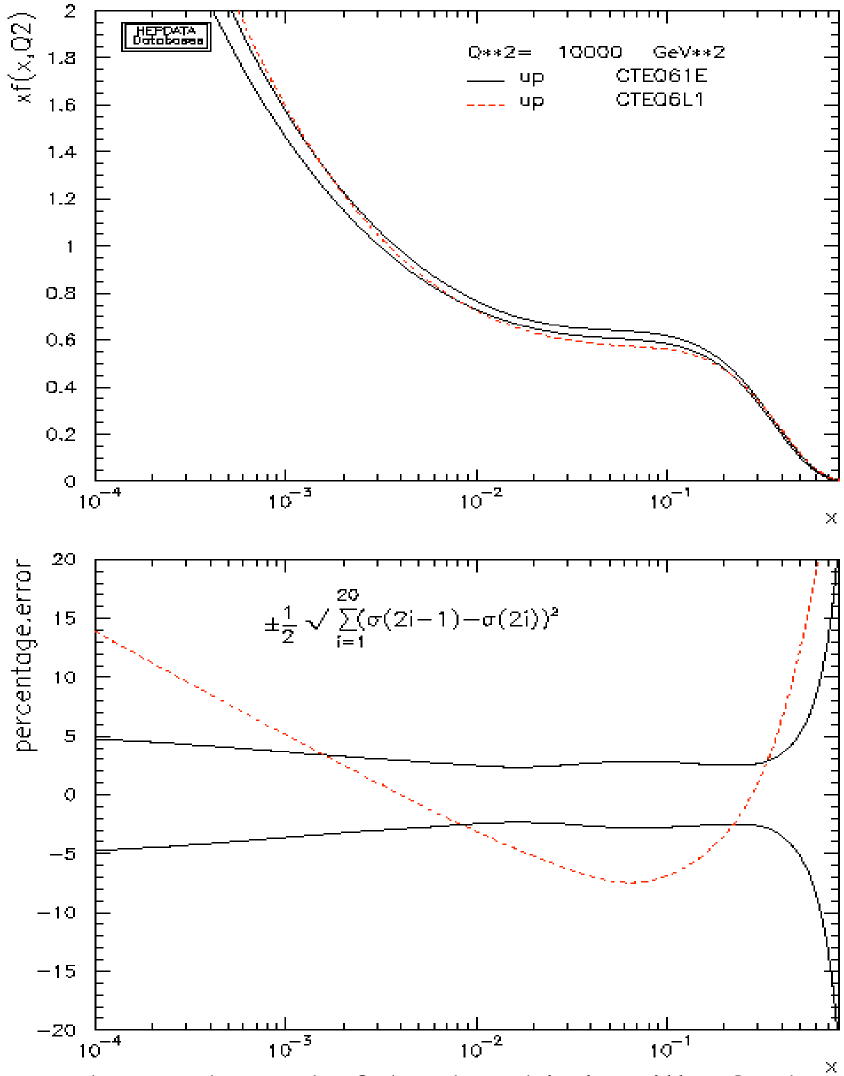
Uncertainties on Sudakov form factors



- Stefan Gieseke showed that the Sudakov form factors have very little dependence on the particular pdf's used
  - hep-ph/0412342
- So pdf weighting works for parton shower Monte Carlos as well as fixed order calculations

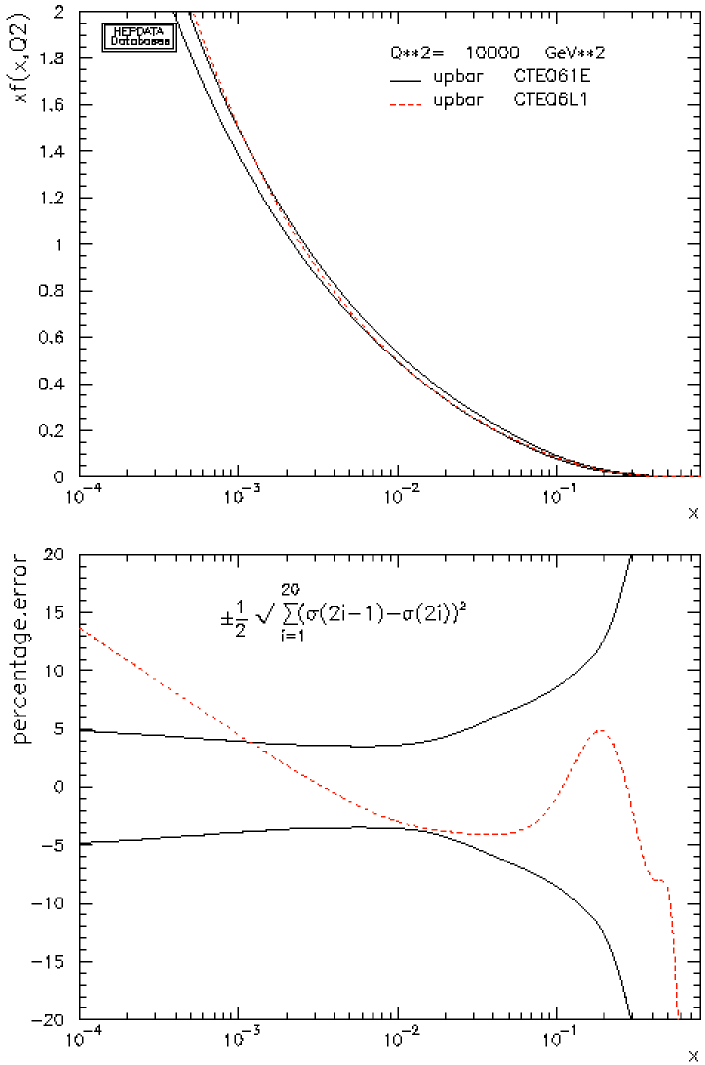
LO vs NLO pdf's for parton shower MC's

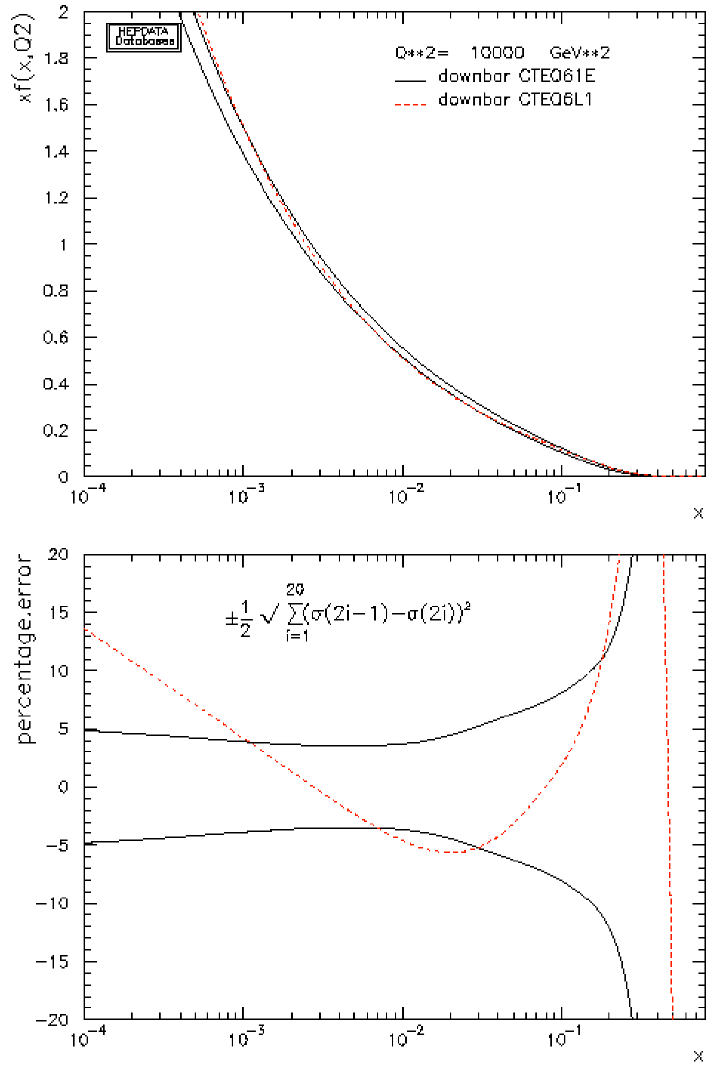
- For NLO calculations, use NLO pdf's (duh)
- What about for parton shower Monte Carlos?
  - somewhat arbitrary assumptions (for example fixing Drell-Yan normalization) have to be made in LO pdf fits
  - DIS data in global fits affect LO pdf's in ways that may not directly transfer to LO hadron collider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



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

upbar/downbar

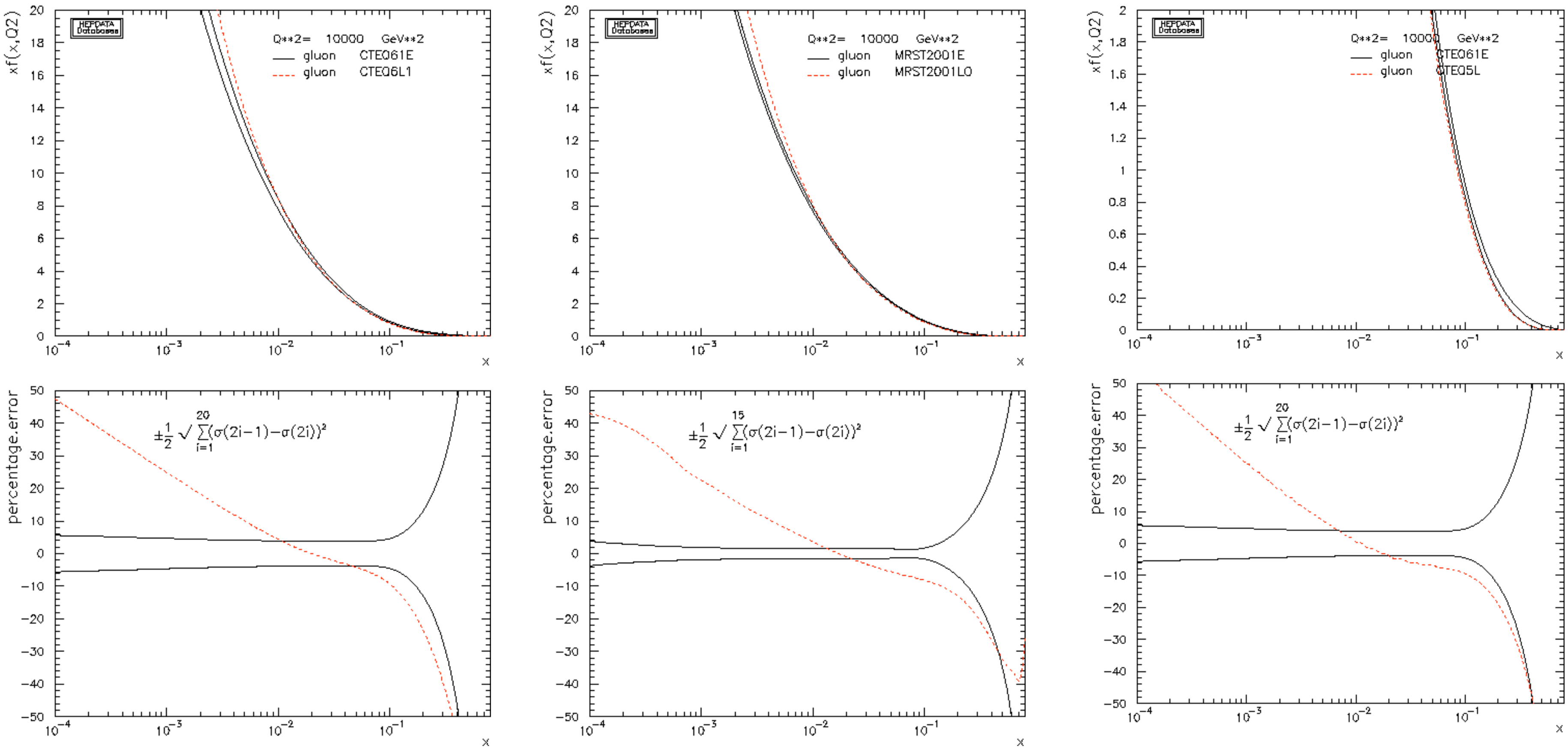




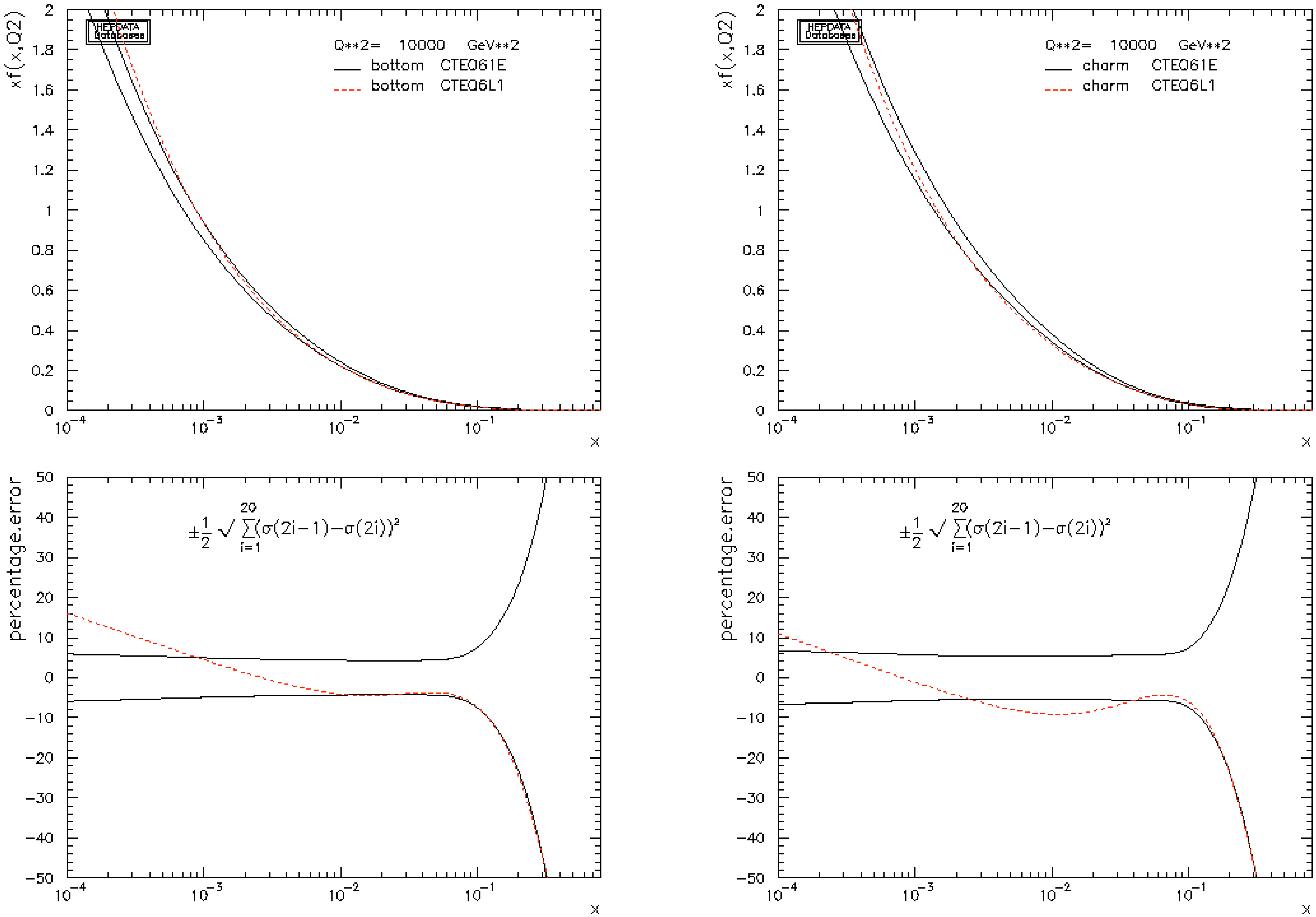
gluon

similar for MRST

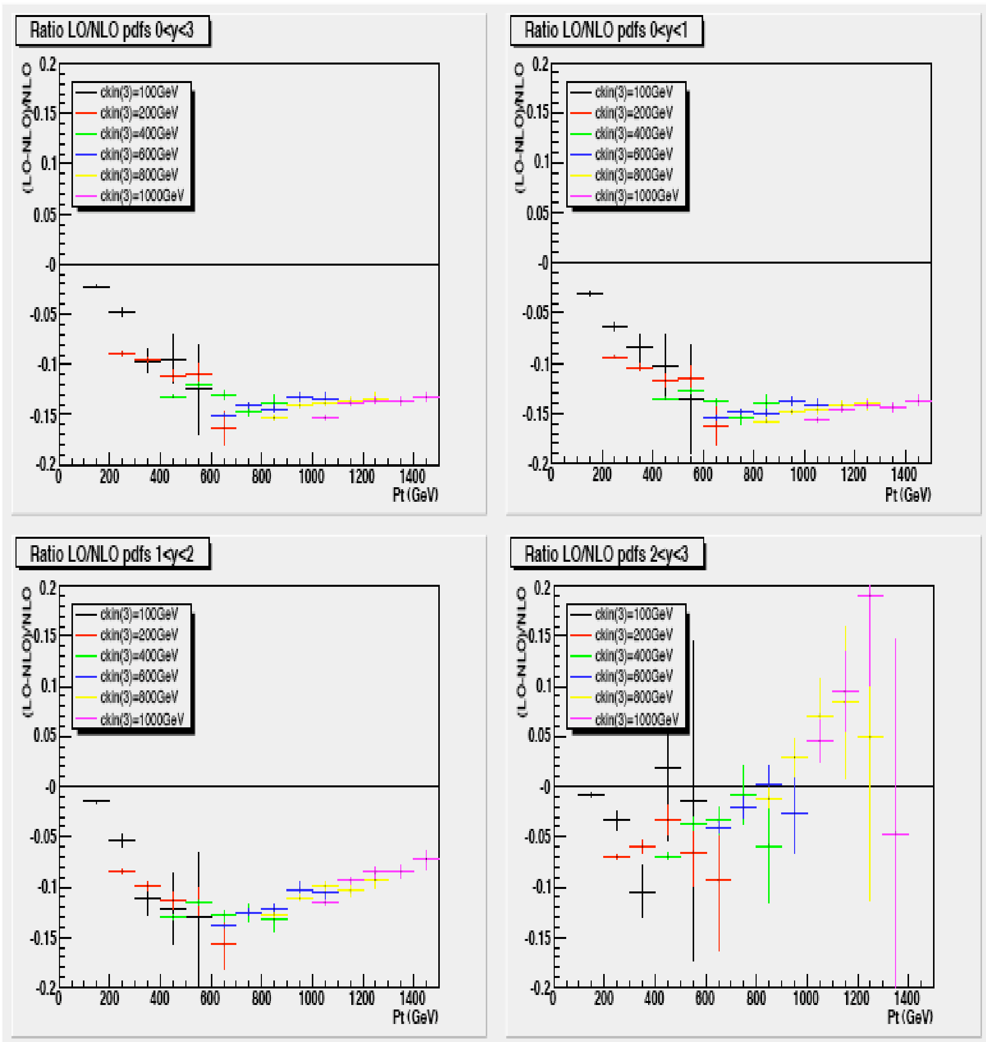
compare to CTEQ5L, used for most MC's



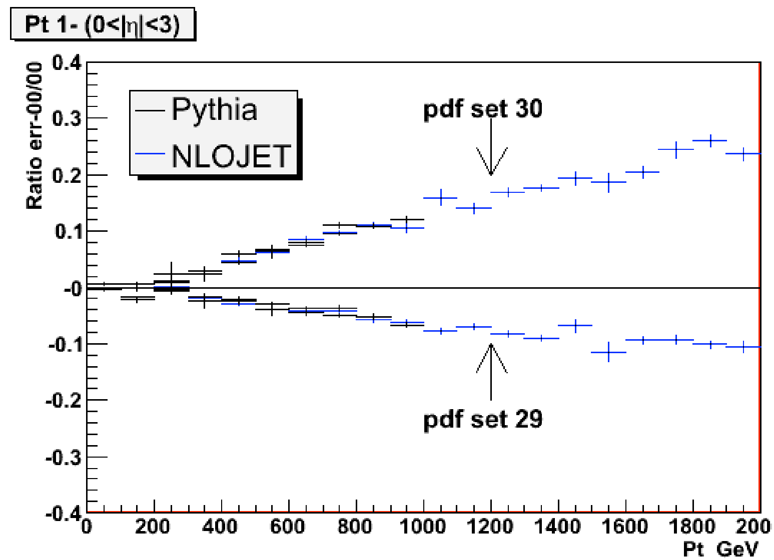
bottom/charm



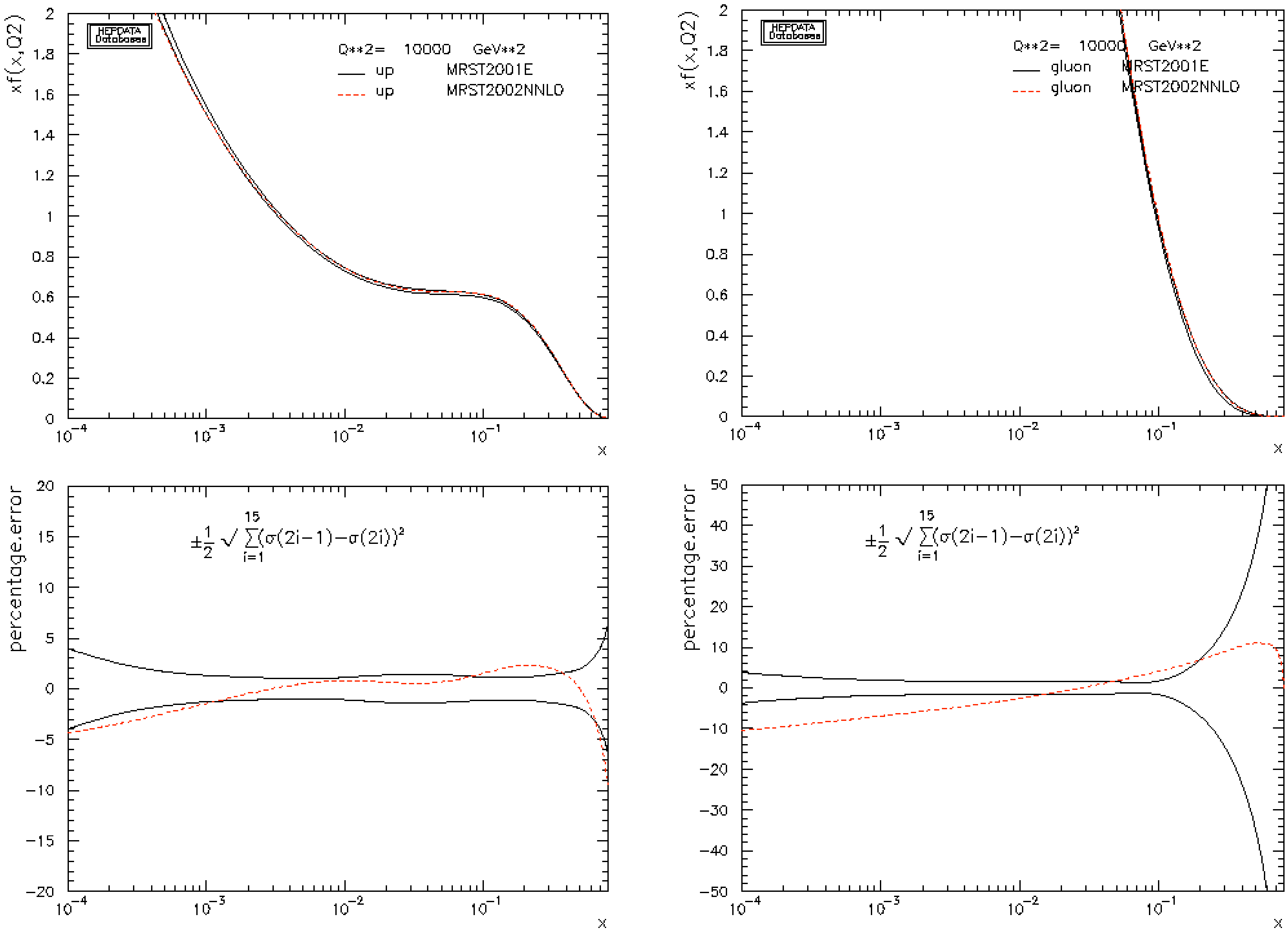
Example: inclusive jet production at the LHC



- Differences between predictions with LO and NLO pdf's larger than pdf uncertainty

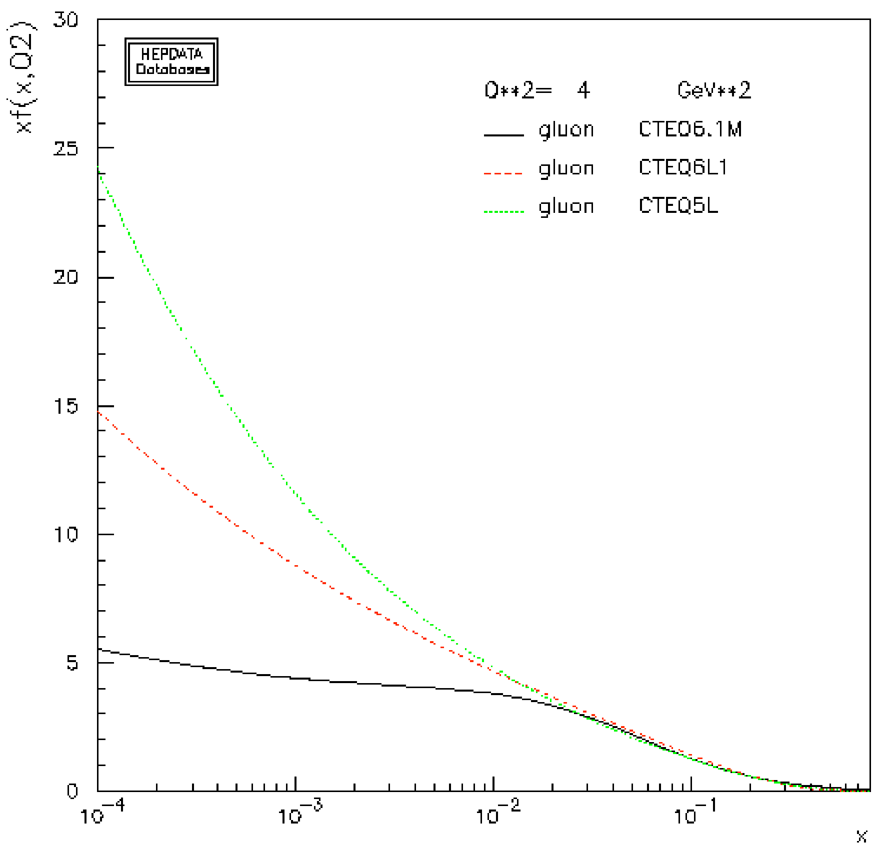


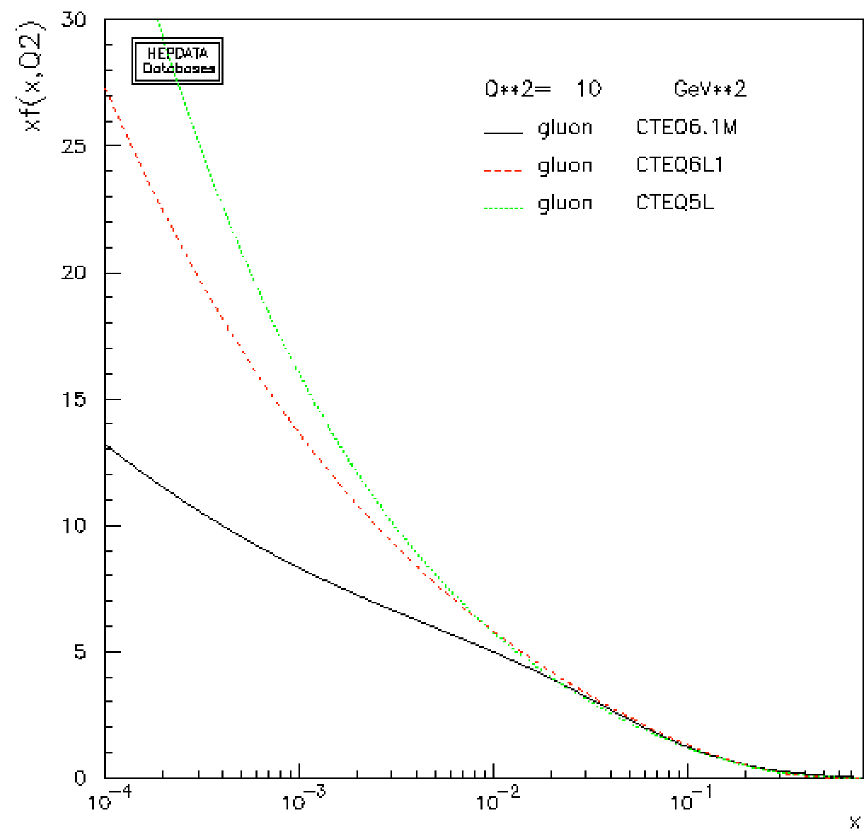
Less difference between NLO and NNLO pdf's



Impact on UE tunes

- 5L significantly steeper at low x and Q^2
- Rick Field working on tunes to CTEQ6.1





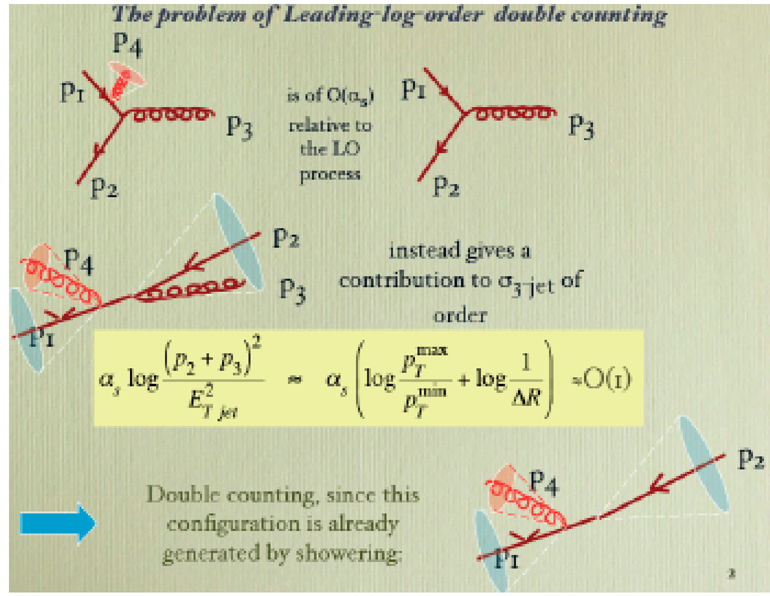
Matrix element and parton shower predictions

- For best (LO) predictions at the LHC, often want to combine matrix element and parton shower predictions
  - matrix elements can describe configurations with hard jets better (see earlier plots)
  - with parton shower programs, you include the effects of multiple gluon radiation and hadronization
- …but need to control size of unwelcome logs when interfacing ME and PS
- mlm and CKKW approaches exist for controlling logs

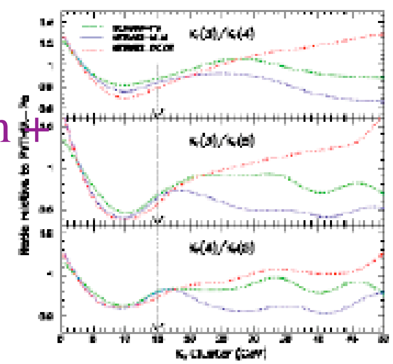
ALPGEN

SHERPA + Mrenna (Madgraph + Pythia)

- Both approaches describe Tevatron W/Z + jets data well
  - hopefully comparisons soon
- Steve Mrenna and Peter Richardson have studied systematic errors for these techniques



hep-ph/0312274



hes 2005

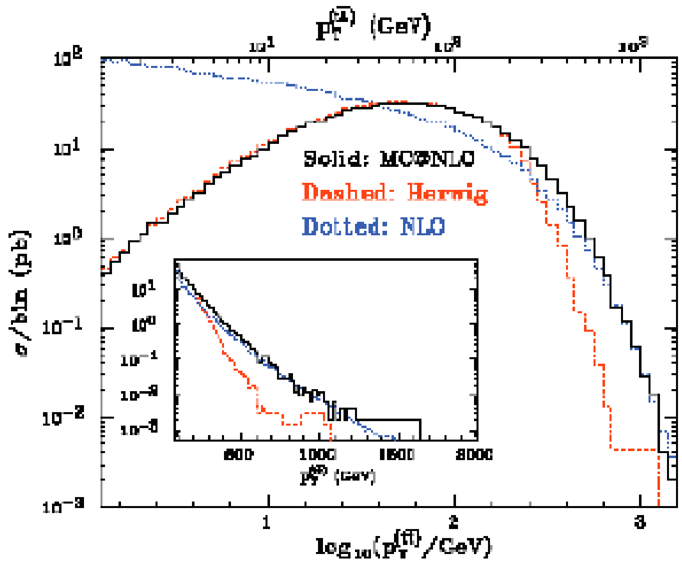
MC@NLO

- 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 has new collaborators 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 $pp \to W, Z, H, \gamma^*, b\bar{b}, t\bar{t}, WW, ZZ, WZ$

MC@NLO in a nutshell

MC@NLO vs HERWIG: analysis

If you can run one, you can run the other. The analisys routines (HWANAL) are unchanged (except perhaps for a few particle codes that are treated in a special way in HERWIG – this mainly concerns vector bosons)

- Unweighted event generation achieved (weights: ± 1)
- Weighted event generation possible (currently not implemented)
- MC@NLO shape identical to HERWIG shape in soft/collinear regions
- MC@NLO/NLO=1 in hard regions
- There are negative-weight events

Negative weights don't mean negative cross sections. They arise from a different mechanism wrt those at the NLO, and their number is fairly limited

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?

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?)

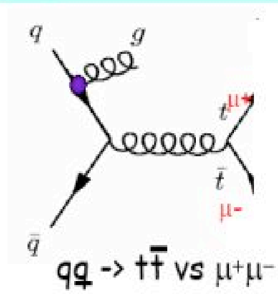
…plus more benchmarks that I have no time to discuss

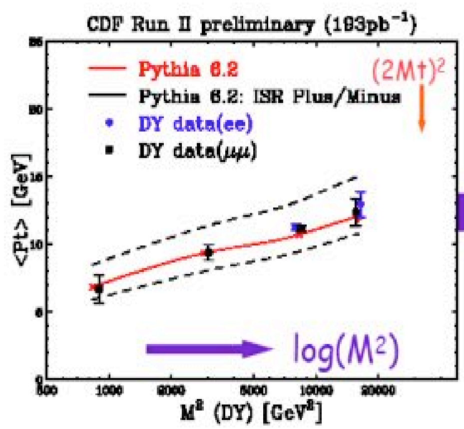
- variation of ISR/FSR a la CDF (study performed by Un-Ki Yang)
  - low ISR/high ISR
  - FSR
  - power showers versus wimpy showers a la Peter Skands
  - number of additional jets expected due to ISR effects (see also Sudakov form factors)
  - impact on top analyses
  - effect on benchmarks such as Drell-Yan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

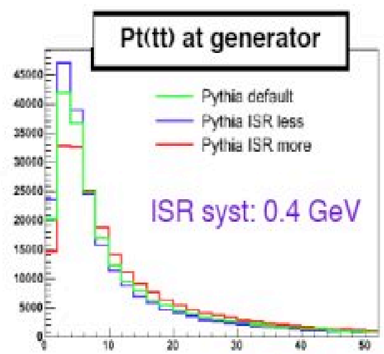
…ok I will discuss the ISR study

How to control ISR?

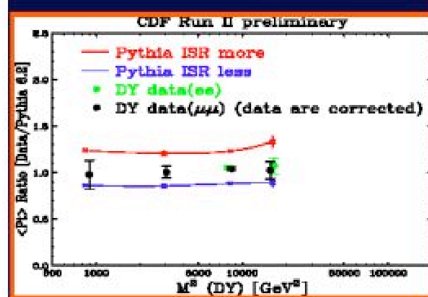
- In Run I, switch ISR on/off using PYTHIA, δMtop = 1.3GeV
- In Run II: systematic approach ISR/FSR effects are governed by DGALP evolution eq.: <Pt> of the DY(ll) as a function of Q^2





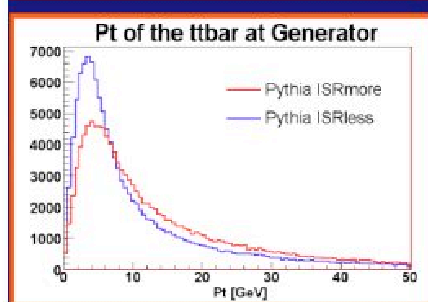


ISR uncertainty



- Non s-channel resonance like ttbar, dijet etc

Pythia	ISR more (Top std)	ISR less (Top std)
PARP(61)	0.292(5fl: LO)	0.073
PARP(64)	0.5	2.0
PARP(67) D=1	4.0(tune-A)	4.0



Pythia	ISR more (Top cntrl)	ISR less (Top cntrl)
PARP(61)	0.292(5fl: LO)	0.073
PARP(64)	1.0	1.0
PARP(67)	8.0	2.0

- s-channel resonance like W/Z (no ISR enhancement fromPARP(67)) set PARP(64)=0.2, vary PARP(61)

Un-Ki Yang at Wine and Cheese seminar at Fermilab

Look in detail at one of the benchmarks

- Inclusive jet production →
  - $d\sigma/dp_T/dy$
  - Δy: 0-1,1-2,2-3
  - wide rapidity range crucial to separate new physics from pdf effects
- Differential dijet production
  - $d\sigma/dp_{T1}dy_1dp_{T2}dy_2$
- W/Z/Drell-Yan production
  - $d\sigma/dy$
  - A_{FB}
  - WW,Wγ(γ)
  - W/Z + jets (1,2,3,4…)
- Single photon production
  - $d\sigma/dp_Tdy$
- Underlying event
  - effects of variations on above analyses

- Look at existing MC samples/generate needed ones to establish jet cross section over full kinematic range of LHC
  - sample of events through full simulation
  - examine results using different jet algorithms
- Re-weight to NLO for use as pseudo-experiments in CTEQ global pdf fits

Inclusive jet production and jet algorithms

- Current range of uncertainty for predictions for ATLAS

see hep-ph/0303013

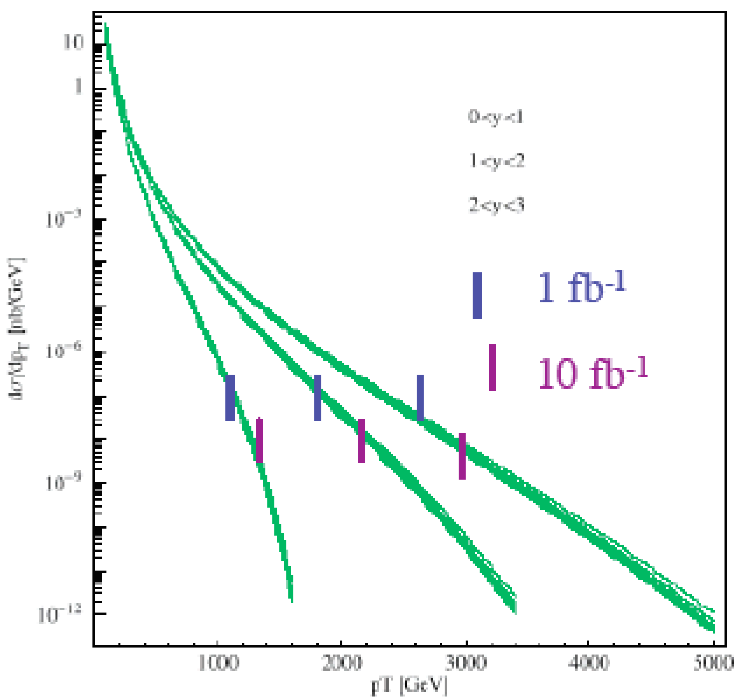


FIG. 30: The inclusive jet cross section as a function of p_T for three rapidity bins at the LHC. The three rapidity ranges are (0,1), (1,2) and (2,3). Predictions of all 40 eigenvector basis sets are superimposed.

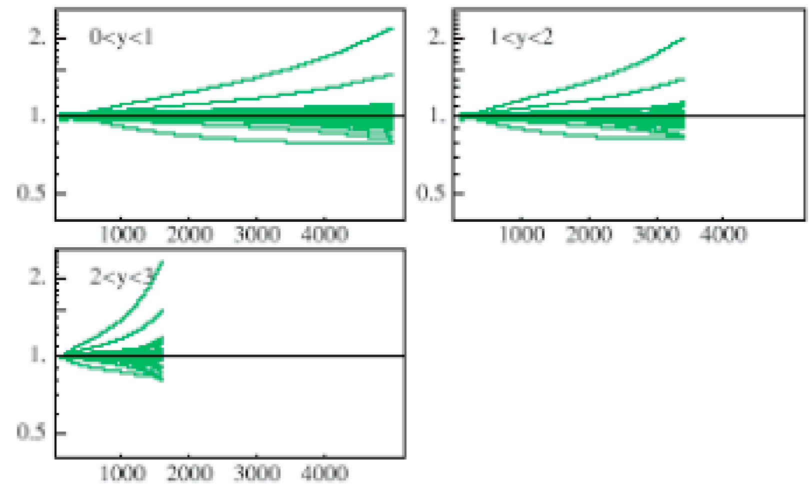


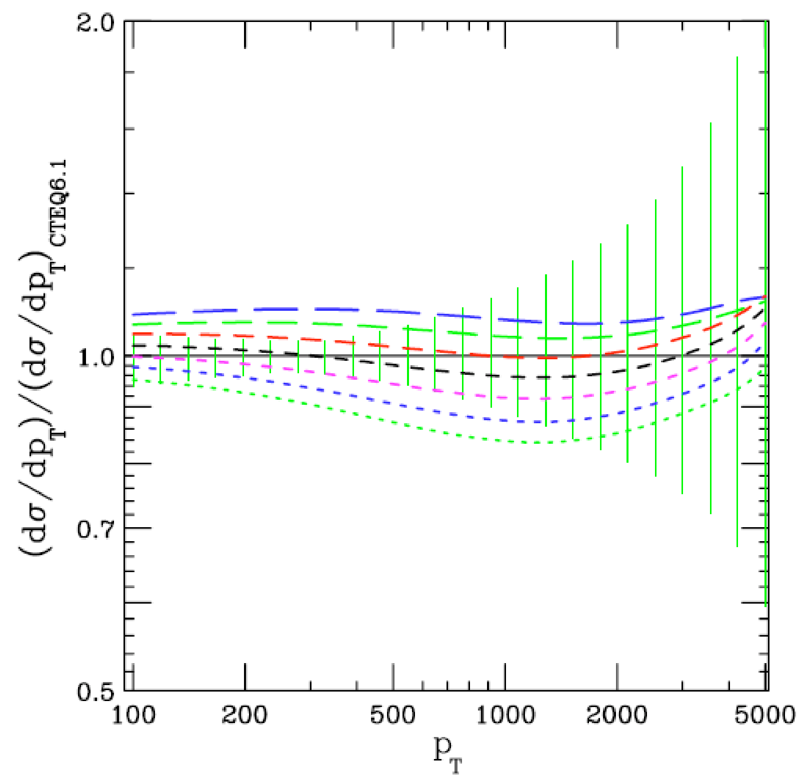
FIG. 31: The uncertainty range of the inclusive jet cross section at the LHC. The curves ar graphs of the ratios of the cross sections for the 40 eigenvector basis sets compared to the centr (CTEQ6.1M) prediction (ordinate) versus p_T in GeV (ordinate).

Will Run II Tevatron jet data be enough to reduce uncertainty? **TeV4LHC exercise**
What will pdf uncertainties look like at the end of HERA? **Related HERALHC exercise**

New pdf's

- By popular demand, an α_s series of pdf's for CTEQ6.**2**
  - data set has some changes wrt CTEQ6.1
- CTEQ7 will be coming out in the near term future
  - LO, NLO and NNLO, along with error sets
  - any other requests?

α_s uncertainty < pdf uncertainty

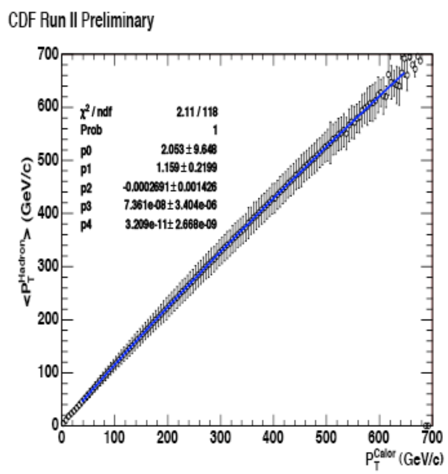


from top to bottom: α_s =0.112, 0.114, 0.116,0.118,0.120,0.122,0.124

Example of a NLO analysis: inclusive jet production in CDF

- Experimental cross section is corrected to parton level and then compared to parton level calculation from EKS
  - correct jets from calorimeter level to hadron level
  - correct for smearing
  - correct for underlying event
    - run Pythia with/without underlying event
  - correct for hadronization
    - correct for energy deposited outside the cone from partons whose trajectories lie inside the cone
    - run Pythia with/wo hadronization

Calorimeter to Hadron Corrections (Pythia tune A)



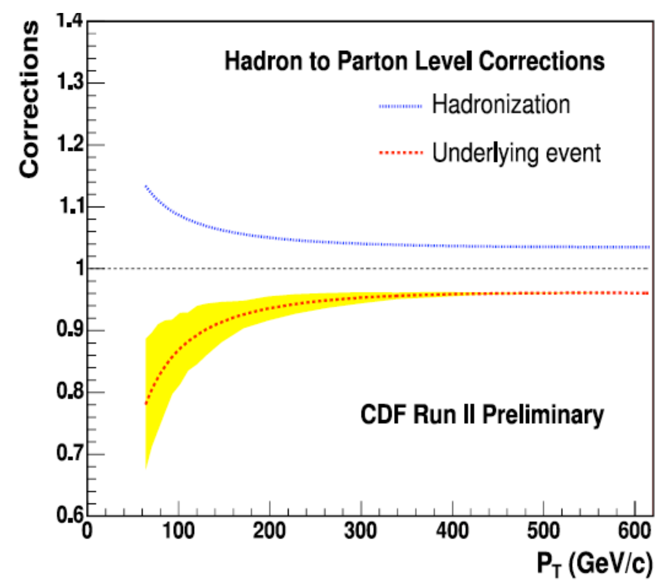
* Match jets at Hadron and calorimeter level by insisting: $\Delta R = \sqrt{(\Delta Y)^2 + (\Delta\phi)^2} < 0.7$

* For fixed calorimeter $P_T \rightarrow$ find a hadron P_T distribution

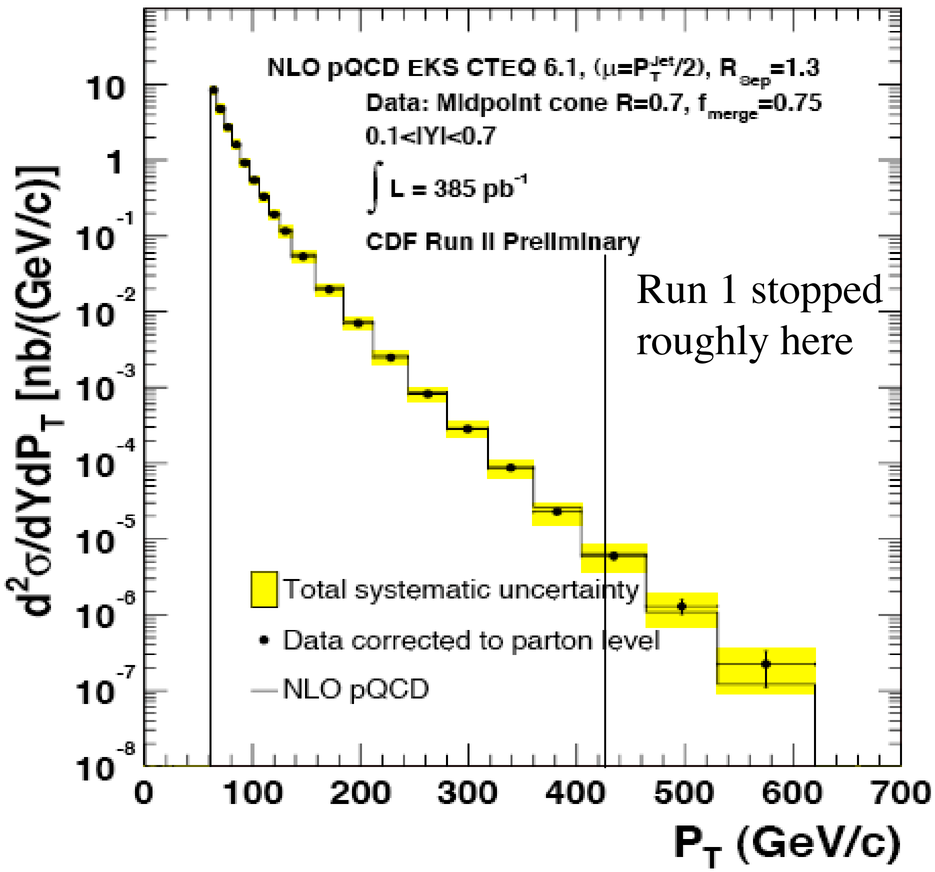
* Using weighted MC, still need to avoid low P_T threshold where sample sees the generator level cut.

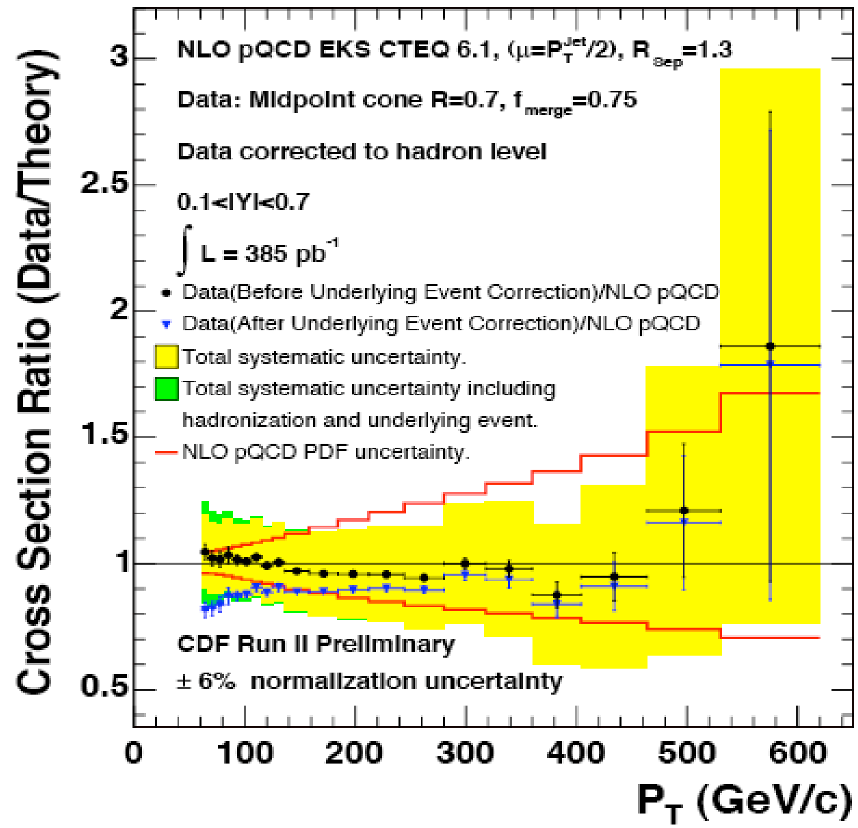
* Fit smooth function to $\langle P_T^{had} \rangle$ vs P_T^{Cal}.

* Use function to make a jet by jet correction to the P_T.



Inclusive jet cross section using cone algorithm



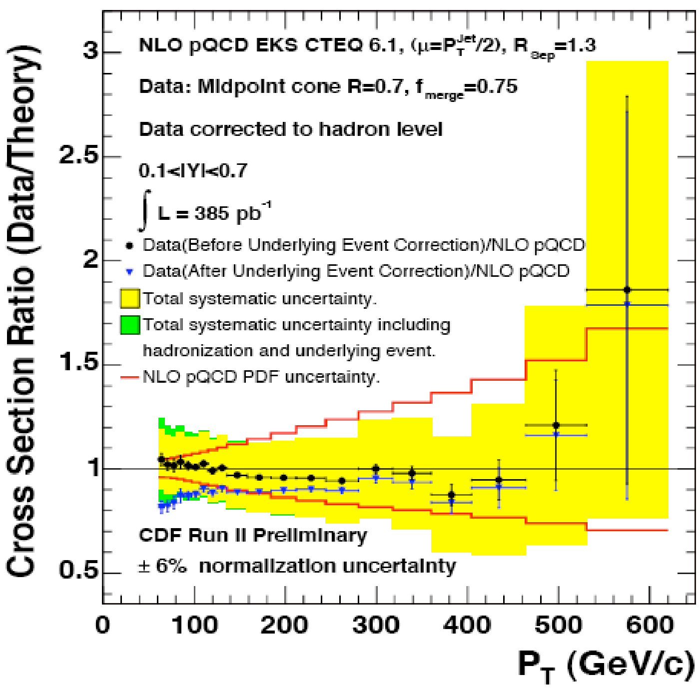


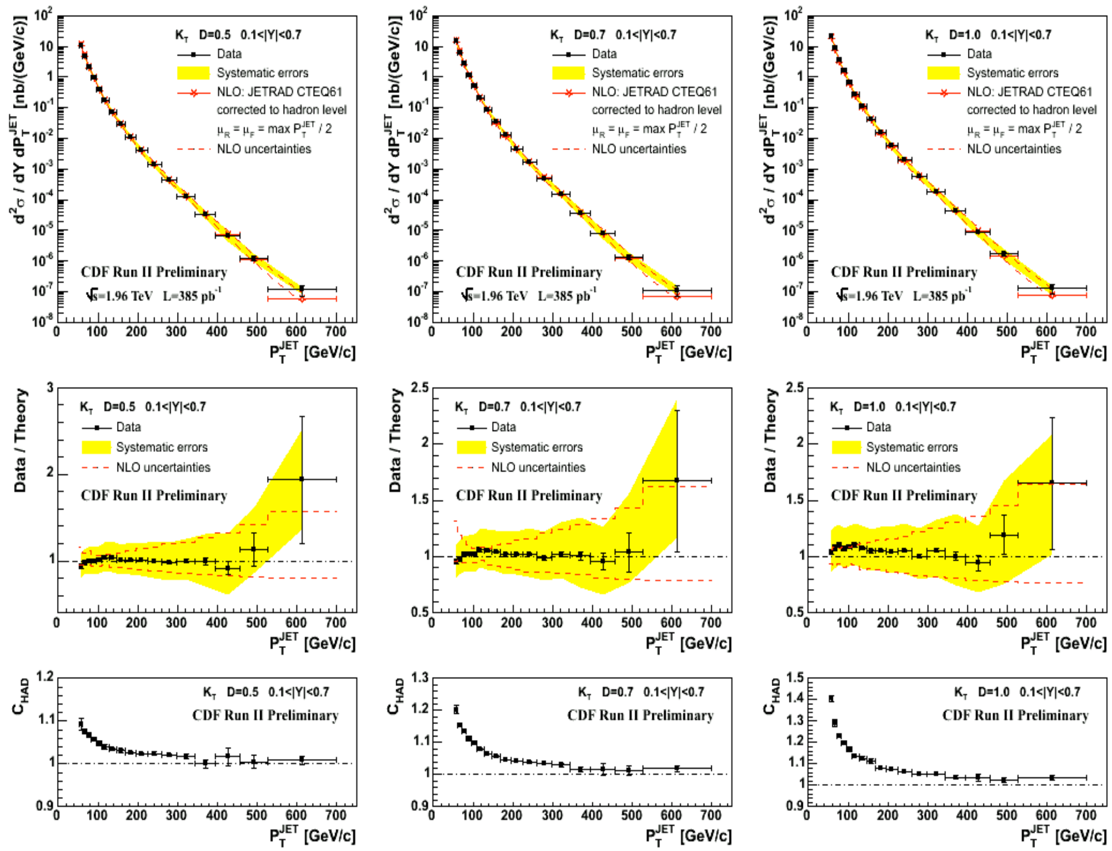
Systematic uncertainty better than Run 1; many man-years (and ~4 physical years) to bring this about

k_T results agree with cone results

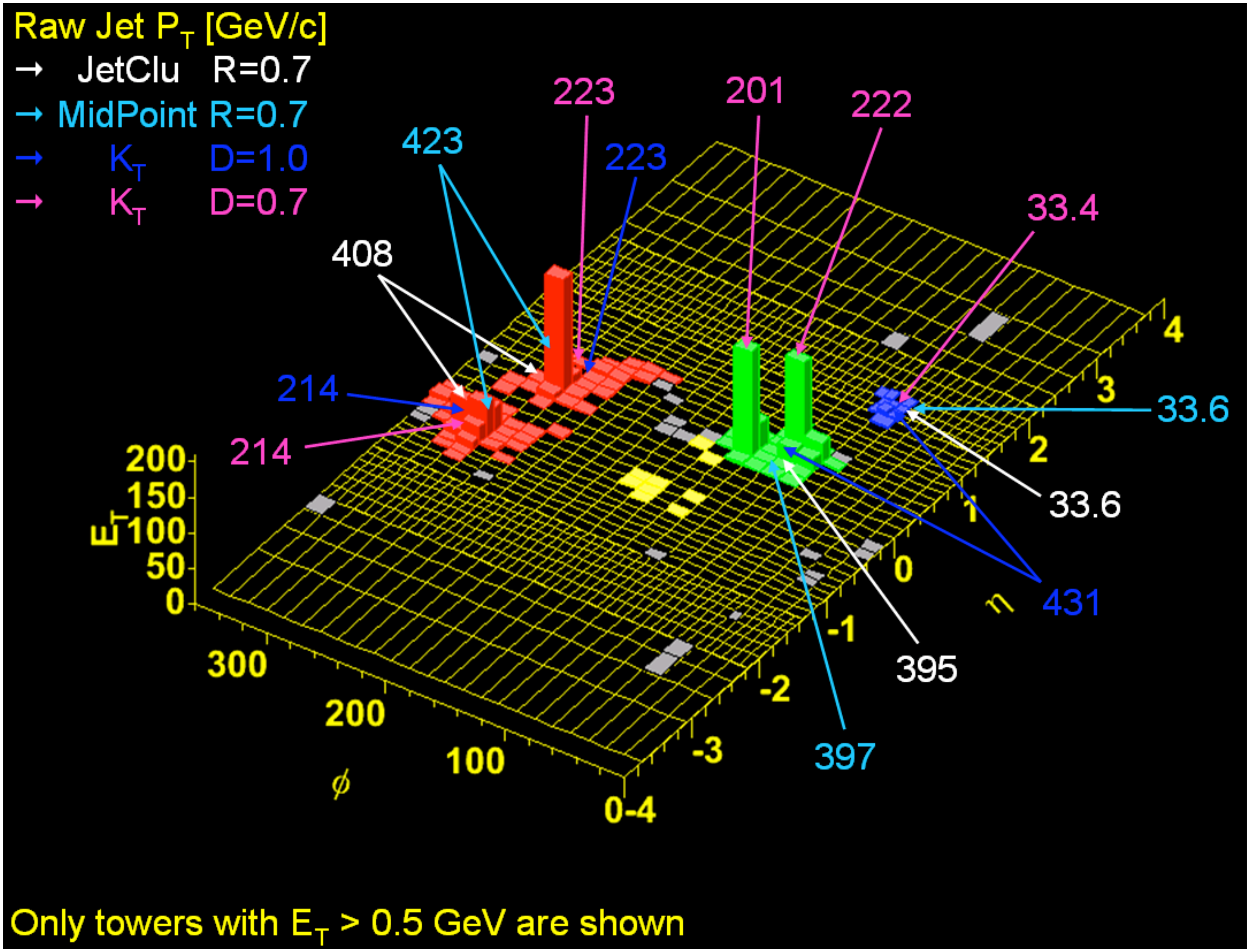
- Both algorithms can (and should) be used in hadron-hadron collider environments

Run 2 results agree with enhanced high x gluon derived from Run 1 data



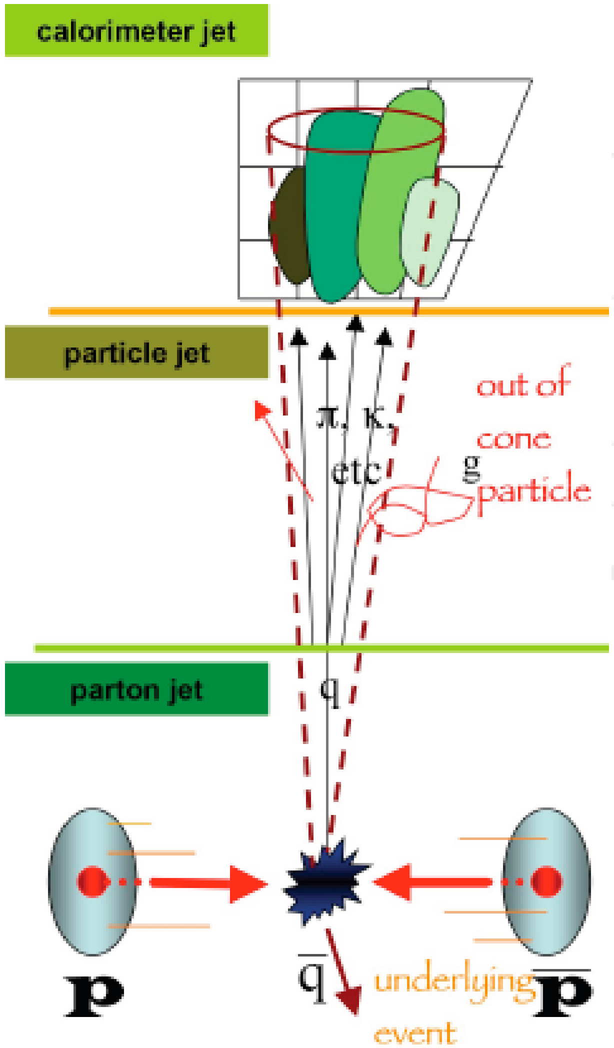


Trying different algorithms on one Run 2 events



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 effort by CMS at Les Houches on this aspect
  - see benchmark webpages



Example: cone algorithms

- Run II analyses in CDF use both cone and k_T jet algorithm
  - CDF has used both JetClu (Run I) and midpoint (Run II) cone algorithms

midpoint improves perturbative behavior

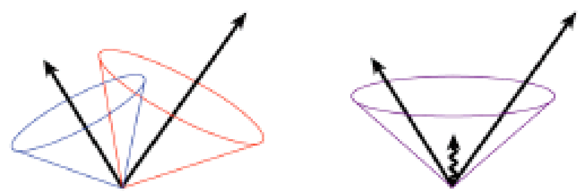
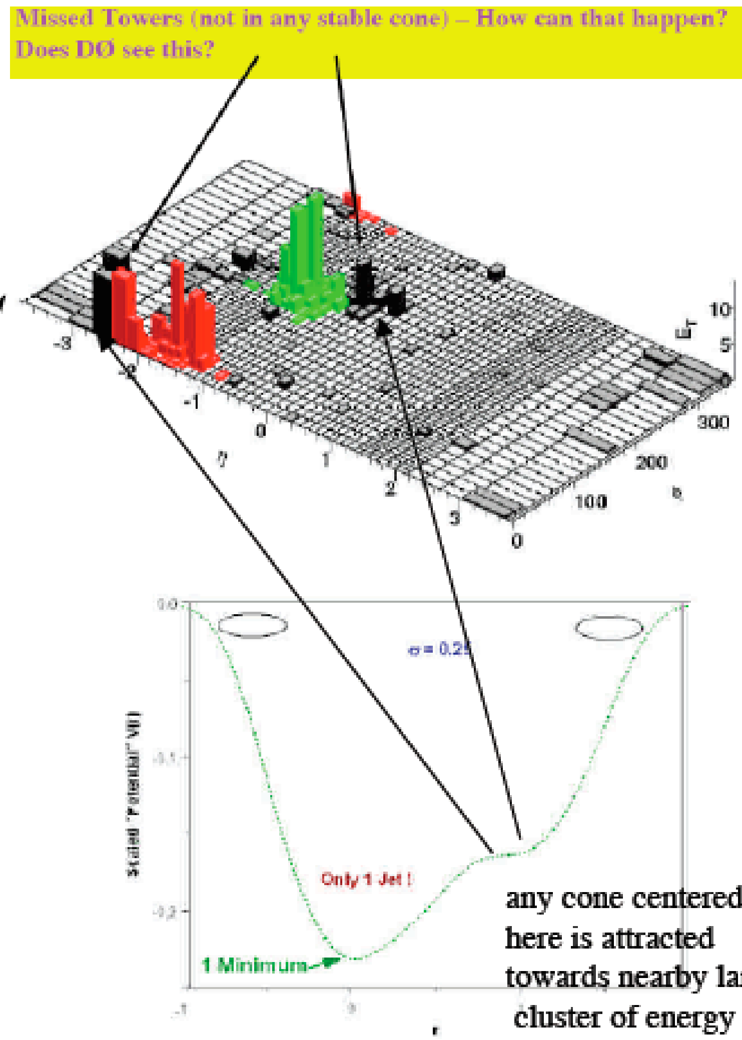


FIG. 1: Two partons in two cones or in one cone with a (soft) seed present.

- subtle issues regarding use of cone algorithms at hadron colliders
  - see hep-ph/0111434, S. Ellis, J. Huston, M. Tonnesmann, *On Building Better Cone Jet Algorithms*
  - under study in both Tevatron and LHC experiments as part of TeV4LHC workshop (and Les Houches)



From TeV4LHC webpage

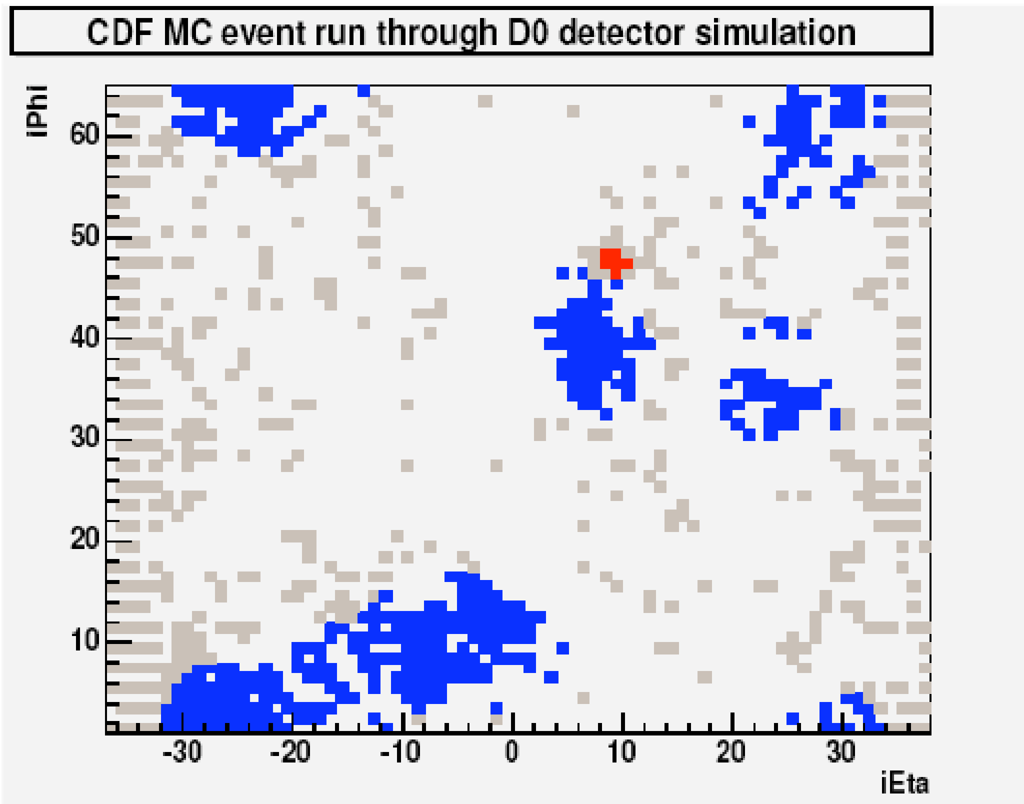
- www.pa.msu.edu/~huston/tev4lhc/wg.htm

- A stand-alone CDF Fortran/C++ jet clustering routine is available here.
- Some descriptive text from Matthias Tonnesmann is available here.

- The Monte Carlo events that resulted in "fat jets" or "dark towers" in the CDF clustering are available here (along with some descriptive text from Matthias).

D0 report at the TeV4LHC meeting at CERN

- To address CDF observation of unclustered E_T



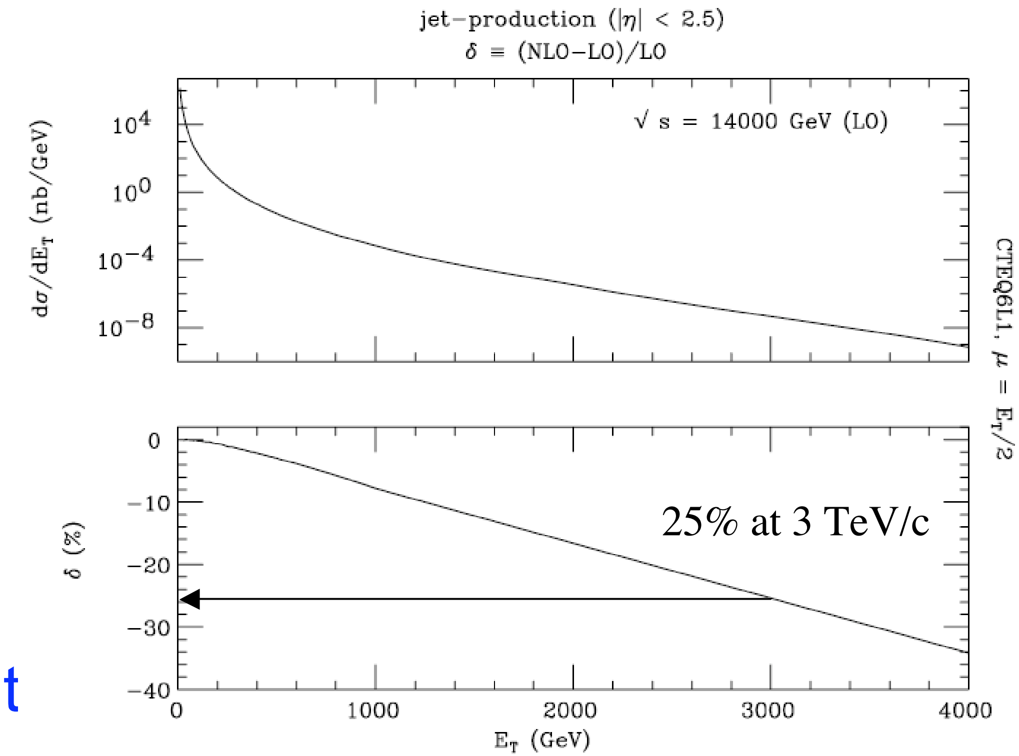
- RunII cone $R = 0.7$
- **Jet** towers
- **Unclustered** towers $pT < 2GeV$
- **Unclustered** towers $pT > 2GeV$

We see it too!

What about ATLAS and CMS?

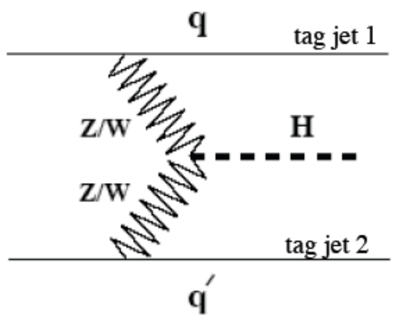
Example: *Unexpected* new SM physics

- 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?

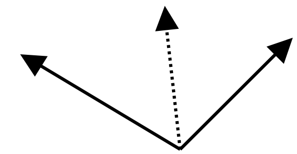


W + jets at the Tevatron and LHC

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

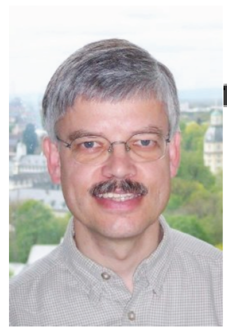


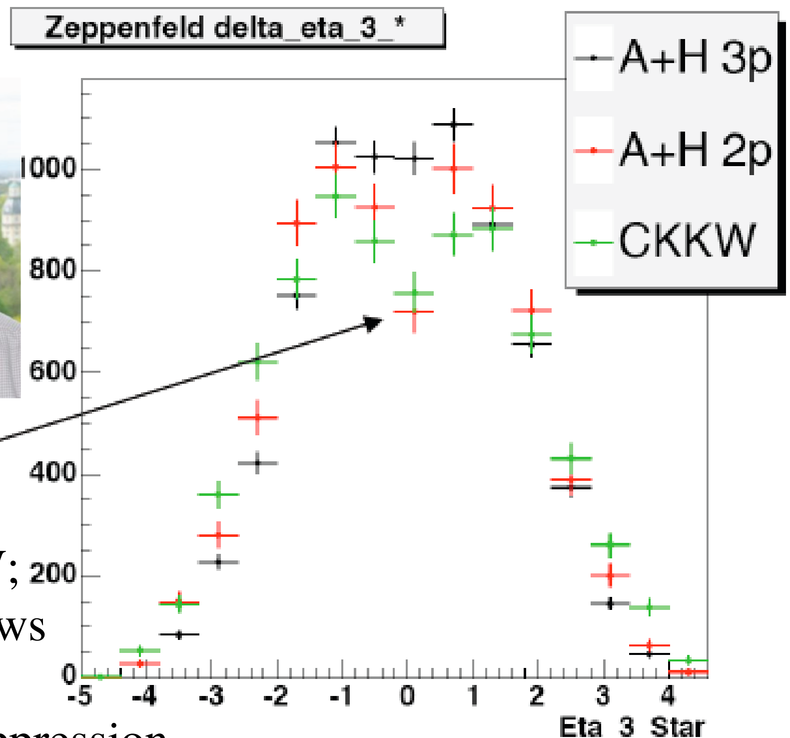
2 tagging jets F/B, Δη>2; look at relative rapidity of 3rd jet



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

- 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 corrected to parton level
- Extrapolate to LHC using MCFM and CKKW
  - paper in progress





note central dip with CKKW; CKKW knows about Sudakov suppression for central jet emission

Summary

- Theoretical program to develop a broad range of tools for LHC
  - up to us 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
  - will go into Les Houches proceedings, summarize in an ATLAS note

TeV4LHC info

- TeV4LHC: conferences.fnal.gov/tev4lhc/
- QCD
  - www.pa.msu.edu/~huston/tev4lhc/wg.htm
- TopEW
  - www.hep.anl.gov/tait/tev4lhc/topew.html
- Higgs
  - www-clued0.fnal.gov/~iashvili/TeV4LHC_higgs/higgs.html
- Landscape

- Final meeting at Fermilab in October