



Why you should know and love NLO

J. Huston

Michigan State University

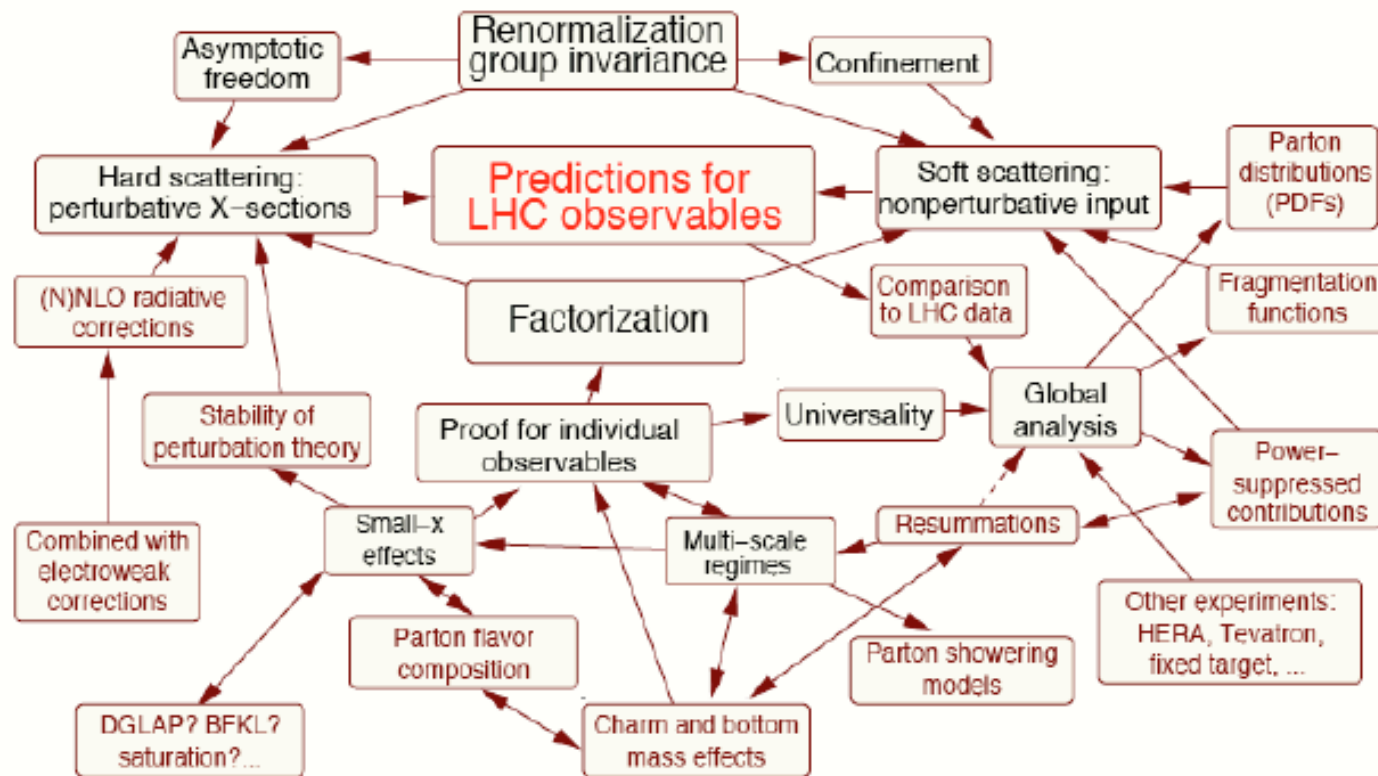


Collider phenomenology

...depends on a large theory framework

Pavel Nadolsky, EFI Mini-Symposium, U. of Chicago, March 14, 2005

Strong interactions at LHC Tevatron



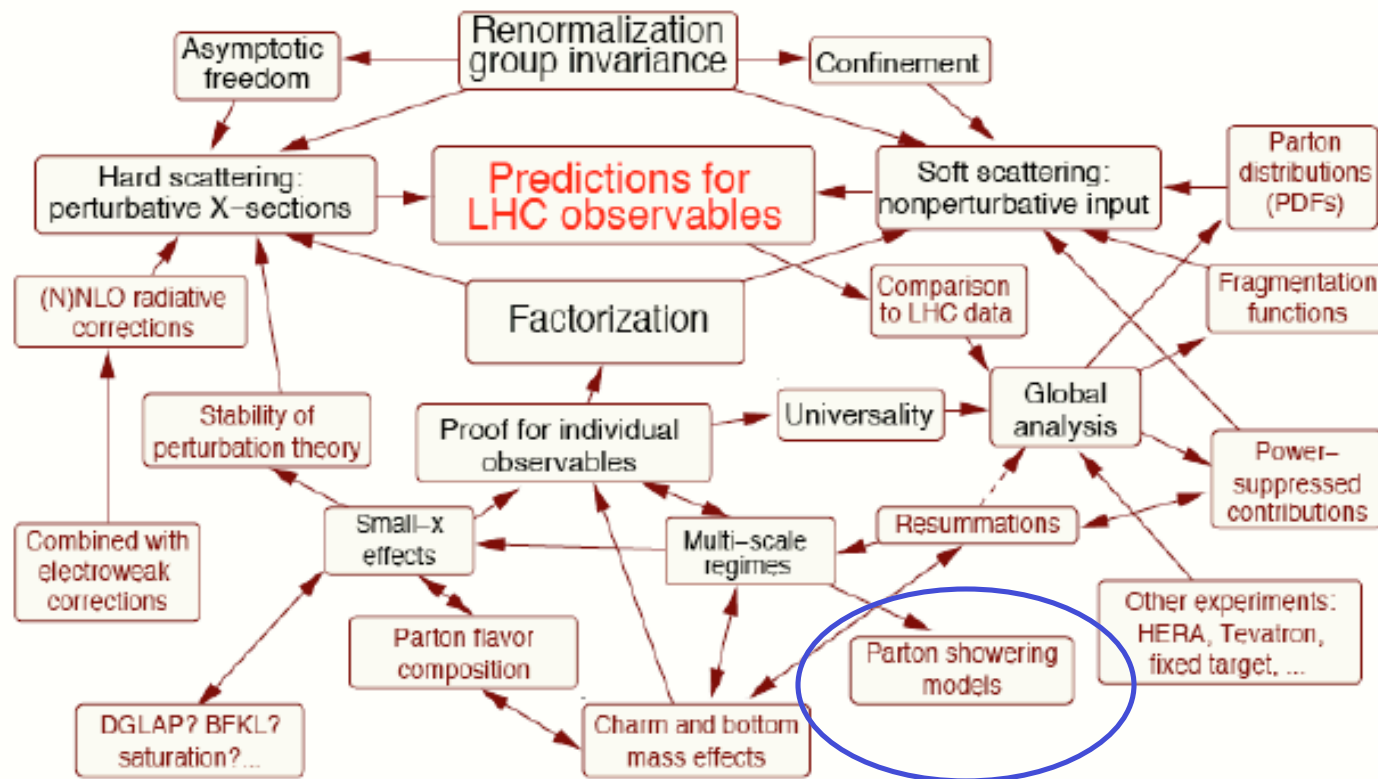


Collider phenomenology

...while experimentalists tend to concentrate only on

Pavel Nadolsky, EFI Mini-Symposium, U. of Chicago, March 14, 2005

Strong interactions at LHC





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 year
 - ▲ 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.): $pp \rightarrow (W, Z) + (W, Z, \gamma)$

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

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

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

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

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

...more about MCFM later



NLO vs LO

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

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

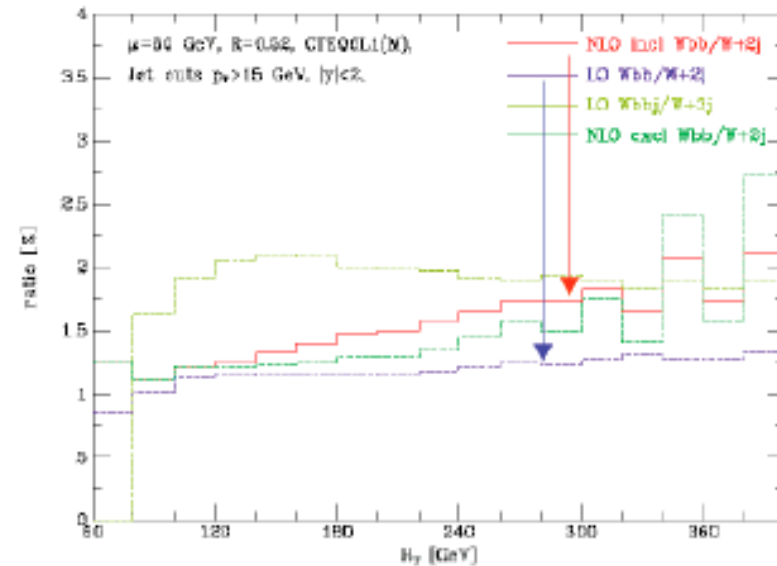
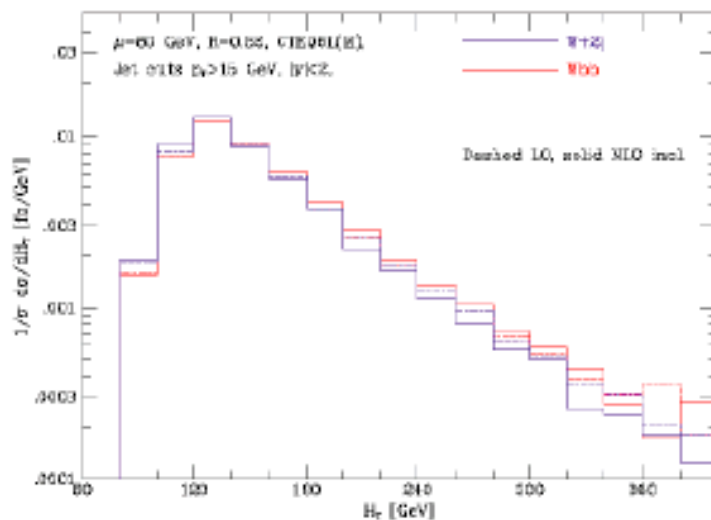


Figure 12: The H_T distributions for $W\bar{W}(j)$ and $Wj(j)$, normalized to the same area.

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



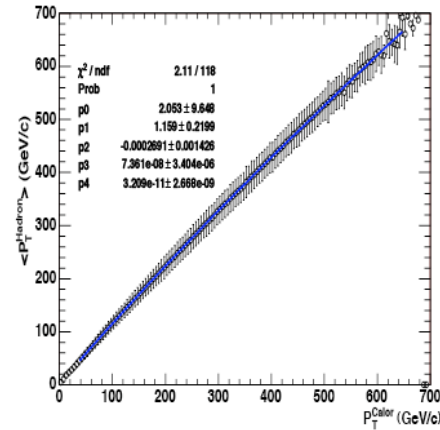
Example NLO analysis: inclusive jet production

- 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)

CDF Run II Preliminary



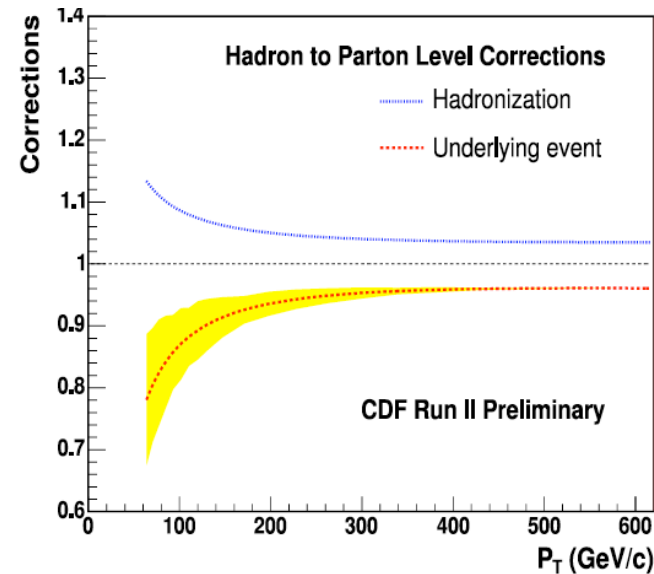
* Match jets at Hadron and calorimeter level by insisting: $\Delta R = \sqrt{(\Delta Y)^2 + (\Delta \phi)^2} < 0.7$

* 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.

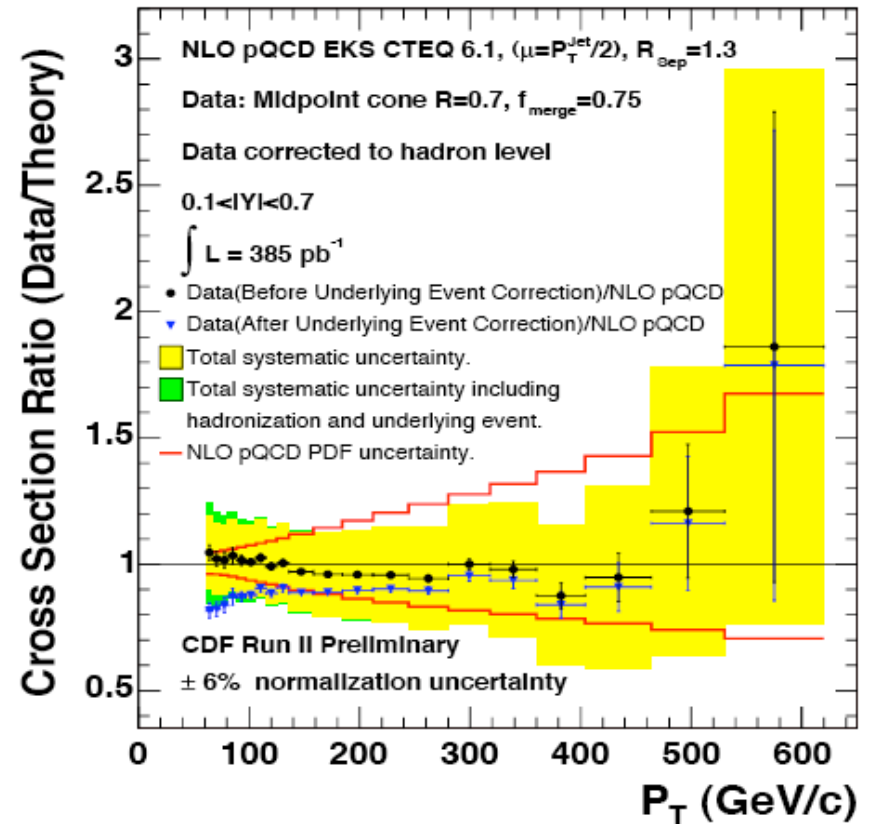
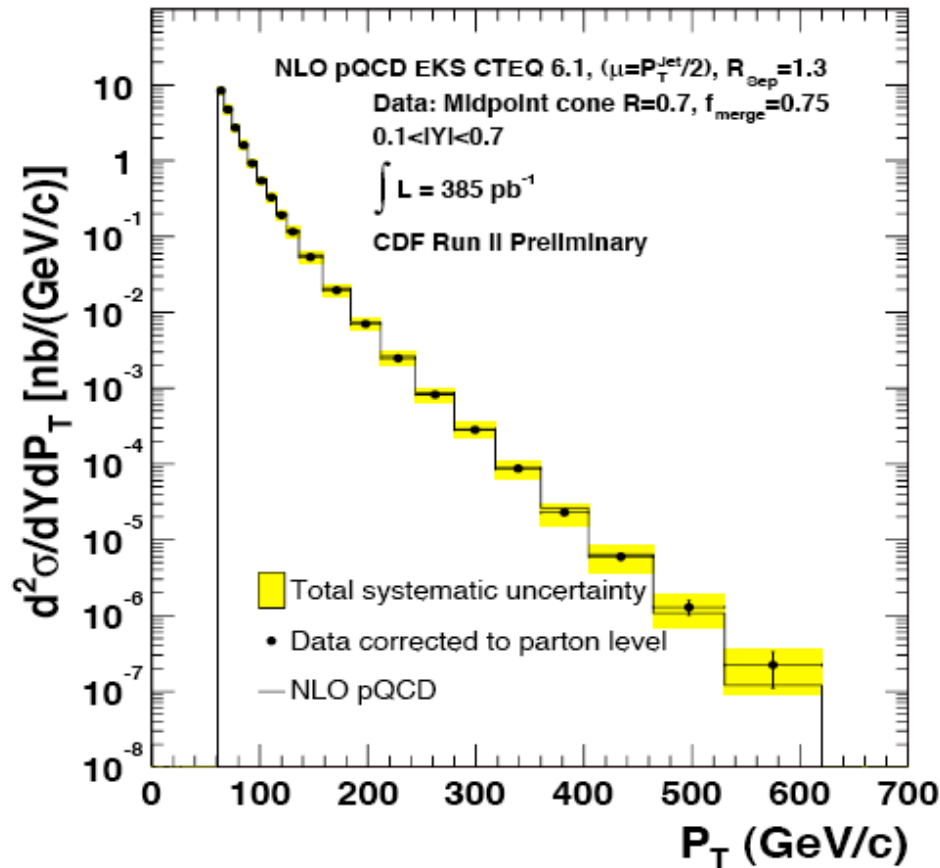
* Fit smooth function to $\langle P_T^{had} \rangle$ vs P_T^{Cal} .

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





Inclusive jet cross section





MCFM

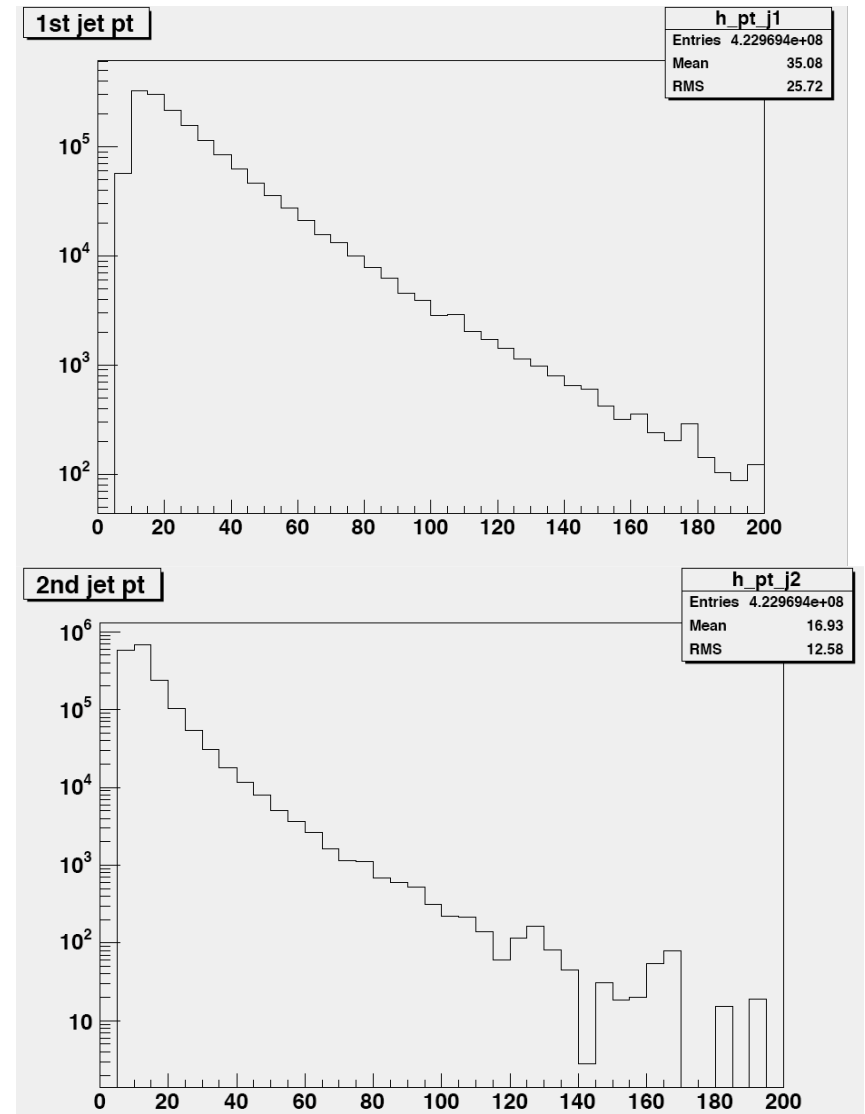
- Handy one-stop shopping for partonic level processes at both LO and NLO
 - ◆ few more pages of processes in addition to what is shown at the right
- I've been using MCFM to make predictions for $W+1,2$ jets and for t - t bar

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



W + jets

- Working with Ben Cooper, Andrea Messina, Jay Dittman and Dave Waters
- Goal is absolutely corrected cross sections for comparison to NLO predictions
- W+2 jets is especially tricky theoretically
 - ◆ because of complexity of phase space, 24 counter-events for each real event
 - ◆ because of - weights, need very high statistics to get meaningful predictions
 - ◆ I've created ROOT ntuples containing 4-vectors for final state particles with >400M events for $W^+, W^- + 2$ jets
 - ◆ easy (4 hours to run through the ntuples) to create any new predictions



happy to generate any requested predictions



Studies for the LHC

- For $W \rightarrow \geq 2$ jets at the Tevatron
 - ◆ look at $|\eta_1 - \eta_2|$ as a function of p_T^{\min}
 - ◆ compare to MCFM, LO and NLO; ALPGEN/MADGRAPH+ Herwig/Pythia (mlm matching and CKKW)
 - ▲ CKKW generated by Steve Mrenna using Madgraph+Pythia
- For $W \rightarrow \geq 3$ jets
 - ◆ η_3^* distribution as a function of p_T^{\min} and $|\eta_1 - \eta_2|$
 - ▲ $\eta_3^* = \eta_3 - (\eta_1 + \eta_2)/2$
 - ◆ 3 jet fraction as a function of $p_T^{\text{jet}3}$

Dieter Zeppenfeld; talk at TeV4LHC

Expected (LO) cross sections for 2,3 jets in W^\pm production; $B(W \rightarrow e\nu, \mu\nu)$ included

$p_{Tj} > 15 \text{ GeV}, |\eta_j| < 3$

	$W+2j$	$W+3j$	σ_3/σ_2
$ \eta_1 - \eta_2 > 2$	15 pb	3 pb	19%
$p_T^{\text{jet}3} > 30 \text{ GeV}$			
$M_R = m_W$	3.2 pb	1.4 pb	44%
$M_R = p_{Tj}$	4.2 pb	2.6 pb	62%
$ \eta_1 - \eta_2 > 3$	0.8 pb	0.37 pb	47%

- No NLO calculation for $W+3j$ available
 - substantial scale dependence
- 3 jet fraction is large
 - fixed order perturbation theory insufficient

More reliable predictions from parton shower programs?



η_3^* for $\Delta\eta > 2$: Zeppenfeld plots

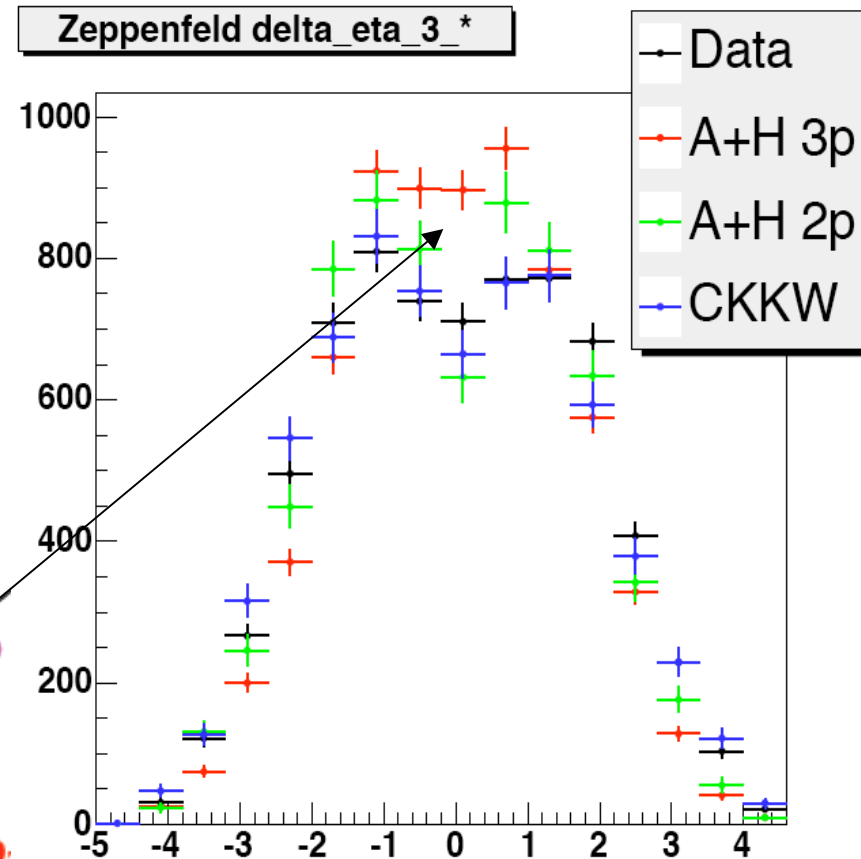
- Look at η_3^* distribution (as defined by Dieter in his talk) for 3 different tagging jet cuts and for 3 different tagging jet $\Delta\eta$ cuts



note peak for A+H 3p
...or dip for other distributions

data has dip for low p.

CKKW has Sudakov suppression where ME does not





t-tbar asymmetry

...working with Dan Amidei, Stephen Miller and Tom Schwarz

- Dominant contribution to charge asymmetry originates from q-qbar annihilation, namely from asymmetric piece in interference between Born amplitude and one loop corrections
- Involving an IR divergence that is cancelled in the sum of virtual and real NLO corrections
- This means that virtual and real corrections to the asymmetry have opposite signs
- In principle, can enhance the asymmetry by setting phase space cuts that separate real radiation
 - ◆ but if cuts are too tight, then large logarithmic corrections

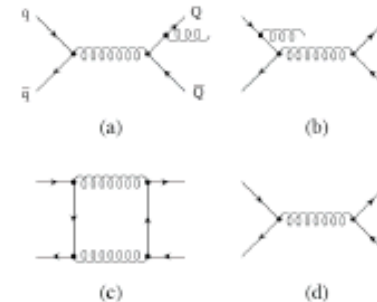


FIG. 1. Origin of the QCD charge asymmetry in hadroproduction of heavy quarks: interference of final-state (a) with initial-state (b) gluon bremsstrahlung plus interference of the box (c) with the Born diagram (d). Only representative diagrams are shown.

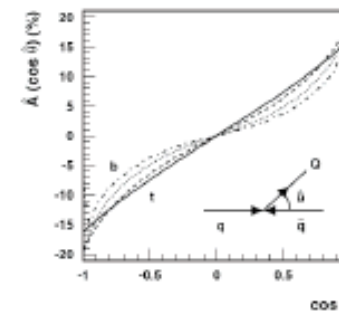


FIG. 4. Differential charge asymmetry in top quark pair production for fixed partonic center of mass energies $\sqrt{\hat{s}} = 400$ GeV (solid), 600 GeV (dashed) and 1 TeV (dotted). We also plot the differential asymmetry for b-quarks with $\sqrt{\hat{s}} = 400$ GeV (dashed-dotted).

can look at asymmetry as a function of top (tbar) rapidity or of $\cos\theta^*$

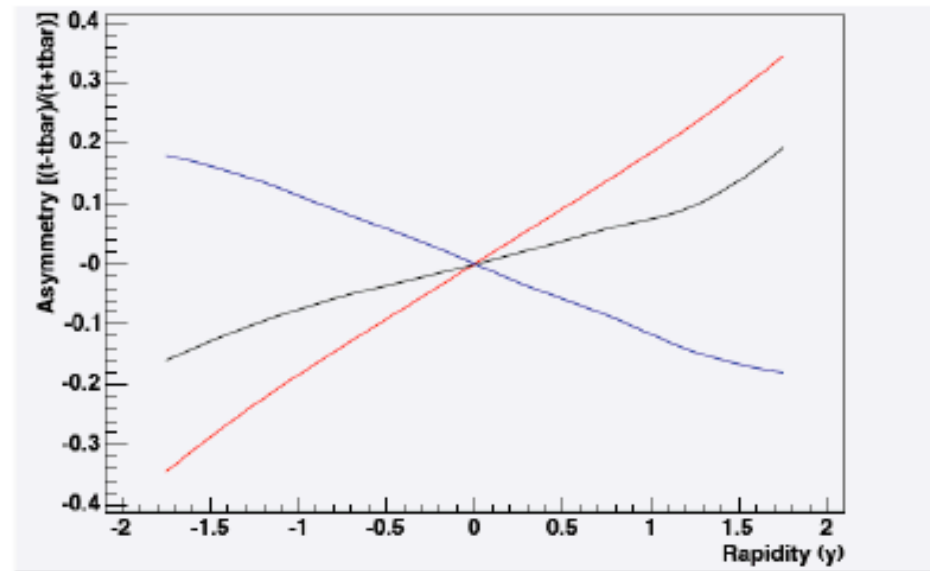
effect not present in LO MC's
use MCFM to study at parton level



MCFM study of asymmetry

- As can be seen in the graph at the right, the asymmetry in the full sample is diluted by the asymmetry for top pairs accompanied by a jet of > 10 GeV
- To check:
 - ◆ scale dependence of asymmetry distributions
 - ▲ note that this scale dependence will be reduced once the NLO $t\bar{t}$ + jet calculation is finished
 - ◆ ability to separate top pairs into the hard ($p_T^{\text{jet}} > 10$ GeV/c) and soft ($p_T^{\text{jet}} < 10$ GeV/c)
 - ◆ effect of soft gluon radiation on above separation

— full asymmetry
— $p_T < 10$ GeV/c
— $p_T > 10$ GeV/c



...see talk at lepton + jets meeting on July 15



Fermilab Samper project

Alternatives seems to be needed giving a systematic calculational procedure:

The Samper project (c++, f95, f77)

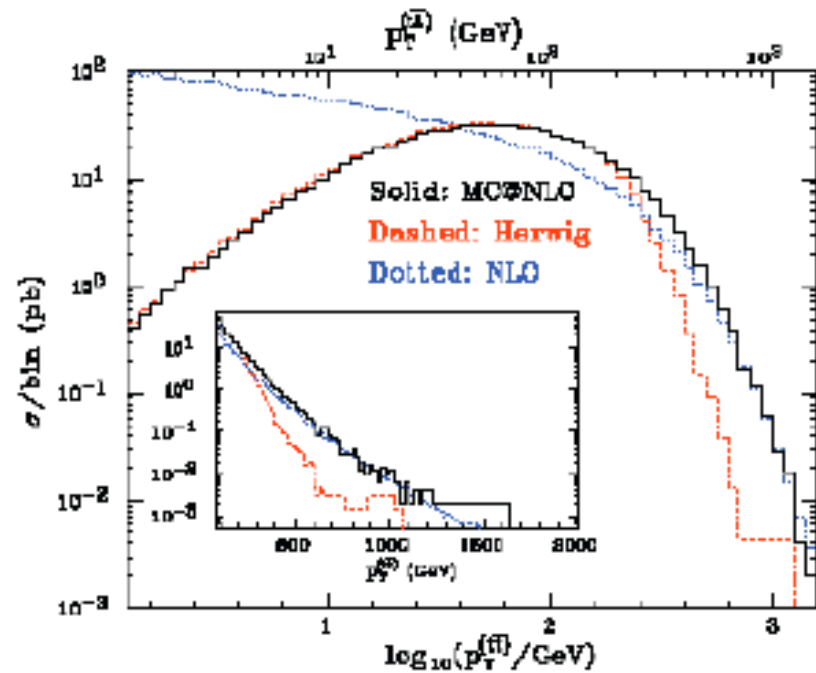
(Semi-numerical **AMPL**itude **EvaluatoR**)

- 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)



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
- Working model has new collaborators coming in to work on favorite process
 - ◆ Eric Laenen: single top production
 - ◆ Vittorio del Duca: WH and WW fusion to Higgs
 - ◆ Bill Kilgore and Steve Ellis: inclusive jet production



- Smoothly matches soft/collinear (MC) and hard (NLO) regions
- Available for $pp \rightarrow W, Z, H, \gamma^*, b\bar{b}, \boxed{t\bar{t}}, WW, ZZ, WZ$
 - no spin correlations yet but minor effect, I believe



t-tbar asymmetry

...naturally included in MC@NLO

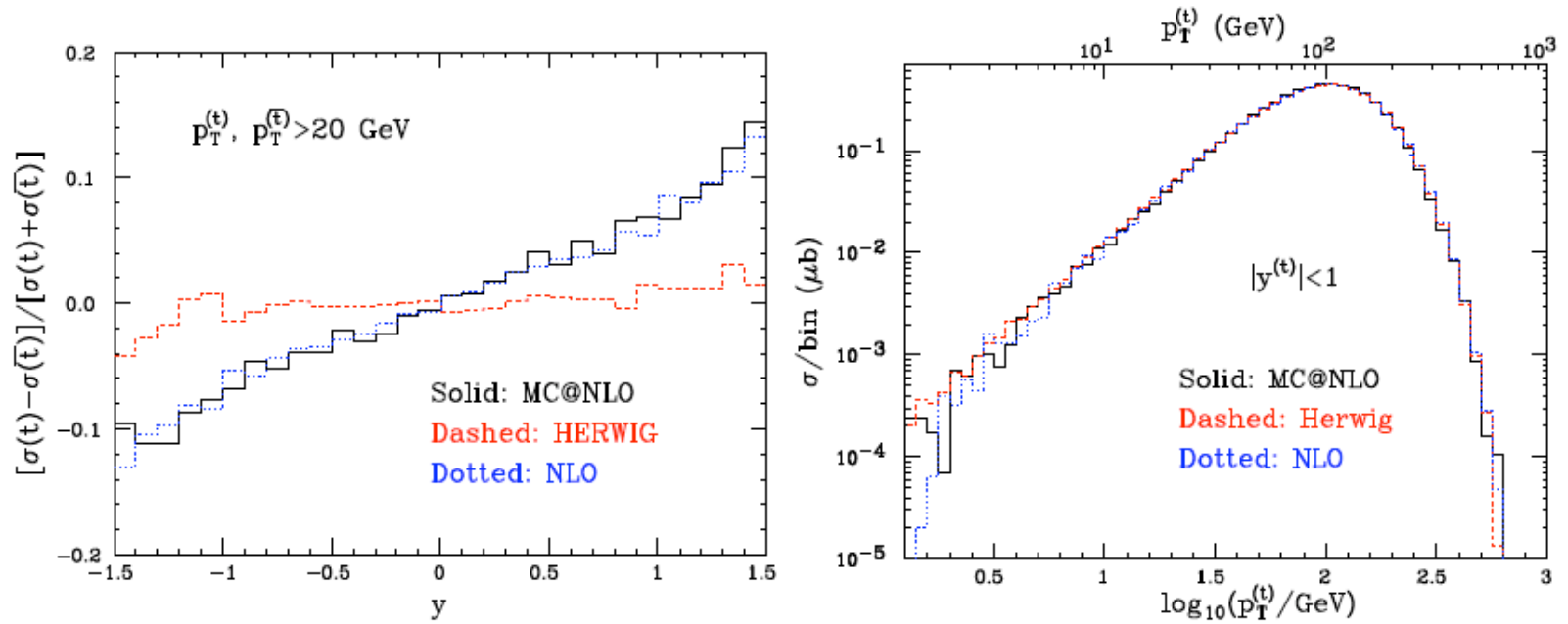


Figure 10: MC@NLO (solid), HERWIG (dashed) and NLO (dotted) results for the rapidity asymmetry (left panel) and the transverse momentum (right panel) of the top quark at the Tevatron. HERWIG results have been normalized as explained in the text.



MC@NLO

MC@NLO vs HERWIG: analysis

If you can run one, you can run the other. The analysis 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

See Un Ki's talk; recent work to make it easier to use MC@NLO in CDF
->top ntuples



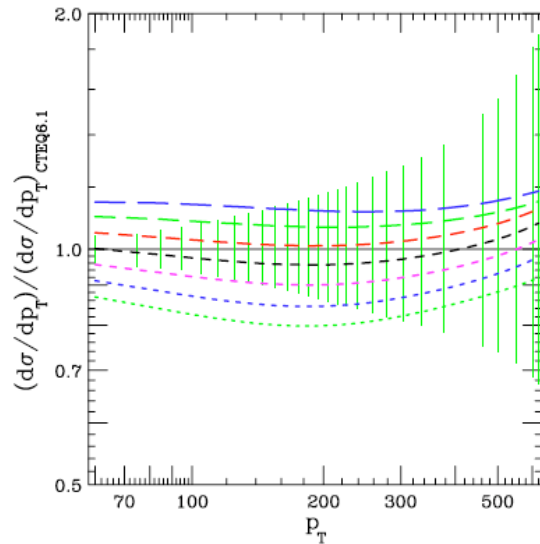
A few uses for MC@NLO ntuples

- Does the acceptance for t-tbar production look any different at NLO than at LO?
- Does the use of the correct (NLO) template change the ME-guided determination of the top mass?
- How well does the t-tbar asymmetry survive soft gluon radiation and hadronization effects? How efficiently can we tag the hard/soft t-tbar events?



Advertisement: CTEQ6.2 α_s series

α_s values of 0.112,
0.114, 0.116, 0.118, 0.
120, 0.122, 0.124



jet production at the
Tevatron

will be distributed through
LHAPDF. something else we should address

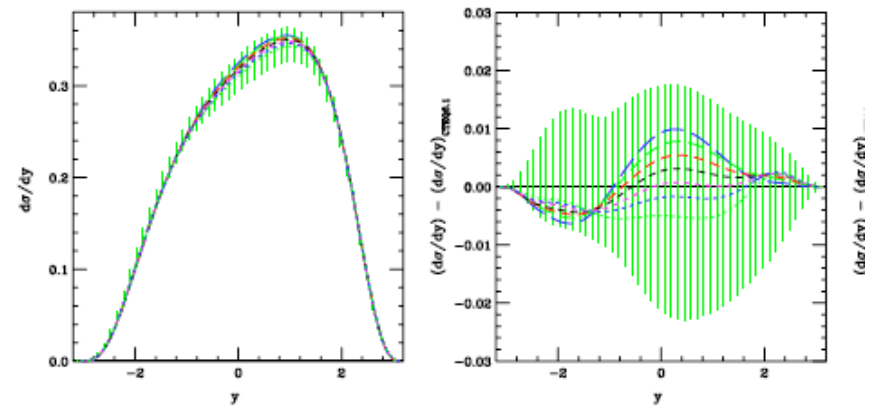


Figure 5: Production of W^- at Tevatron. Center: CTEQ6.1
imode = 1 (QCDNUM) —(((Remove this since it is so similar

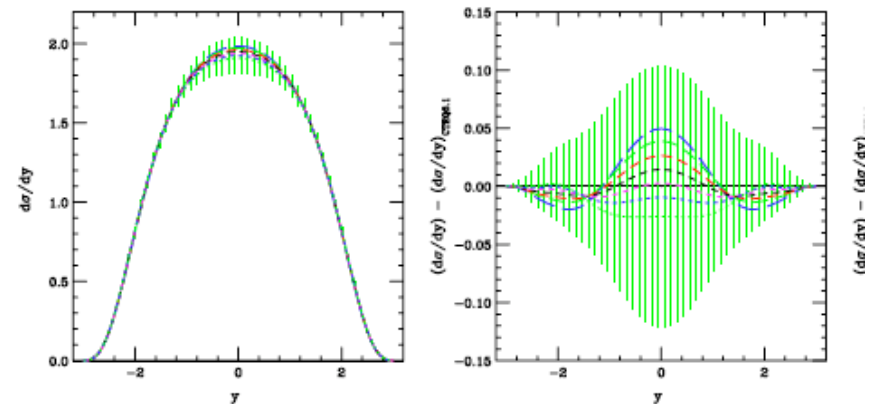


Figure 6: Production of Z^0 at Tevatron. Center: CTEQ6.1