Bearing Standard Model Benchmarks to the LHC

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and

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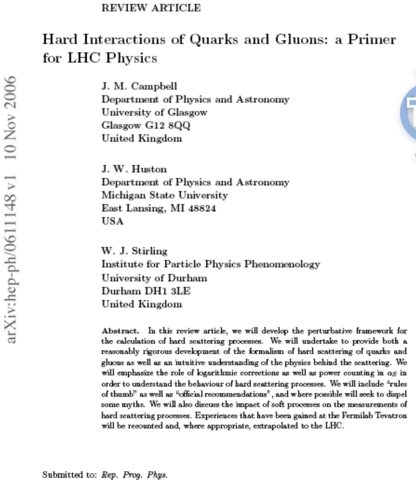
Epiphany Workshop
Krakow Jan. 2007

References

- Also online at ROP



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.*

arXiv:hep-ph/0611148 v1 10 Nov 2006

Standard Model benchmarks

LES HOUCHES
centre de physique

See www.pa.msu.edu/~huston/Les_Houches_2005/Les_Houches_SM.html

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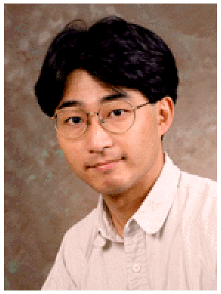
Some background: what to expect at the LHC

…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

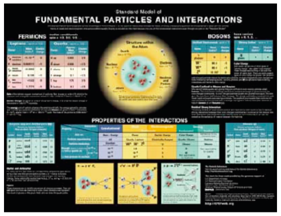
What to expect at the LHC

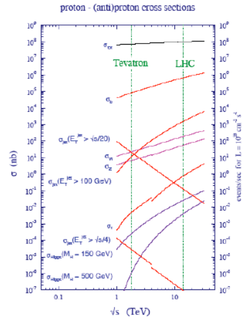
…according to a theorist

- According to a former Secretary of Defense
  - known knowns
    - SM at the Tevatron
    - (most of) SM at the LHC
  - known unknowns
    - some aspects of SM at the LHC
  - unknown unknowns
    - ???

Discovering the SM at the LHC

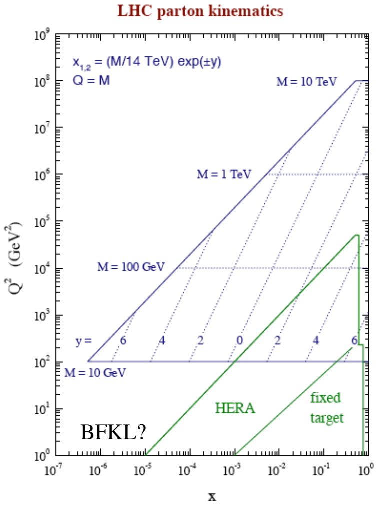
- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM physics understood properly
  - SM backgrounds to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



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-><u>MRST2004</u>
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1-><u>CTEQ6.5</u> *(->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

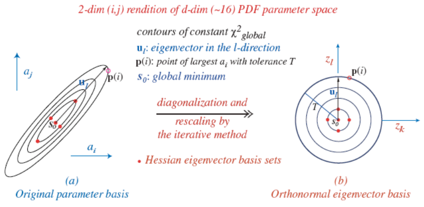


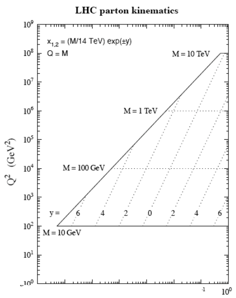
Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

- 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

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
- 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



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

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

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

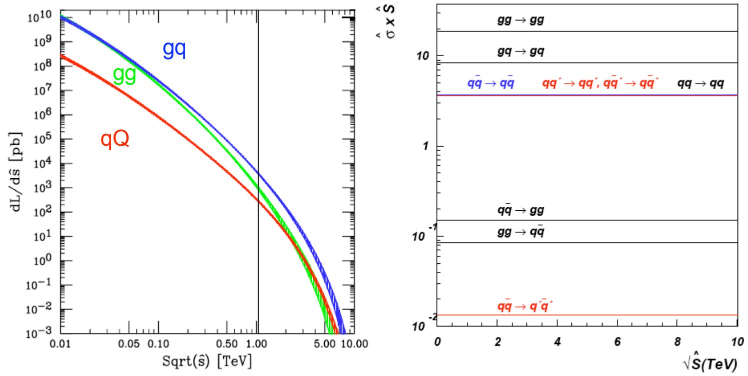
can then be written as

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

Cross section estimates

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

for the gluon pair production rate for $\hat{s}$=1 TeV and $\Delta\hat{s} = 0.01\hat{s}$, we have $\frac{dL_{gg}}{d\hat{s}} \simeq 10^3$ pb and $\hat{s}\,\hat{\sigma}_{gg} \simeq 20$ leading to $\sigma \simeq 200$ pb



for
p_T=0.1*
sqrt(s-hat)

Fig. 2: Left: luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

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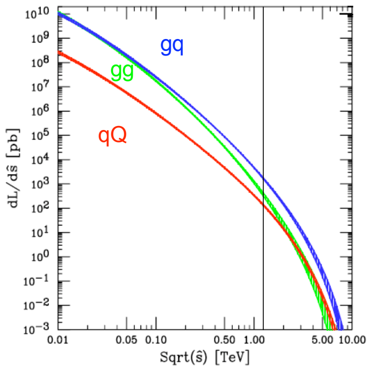
Heavy quark production

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

threshold effects evident



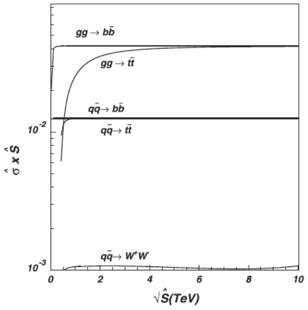


Figure 71. Parton level cross sections $(\hat{s}\hat{\sigma}_{ij})$ for various processes involving massive partons in the final state.

$\sqrt{S}$(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

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PDF luminosities as a function of y

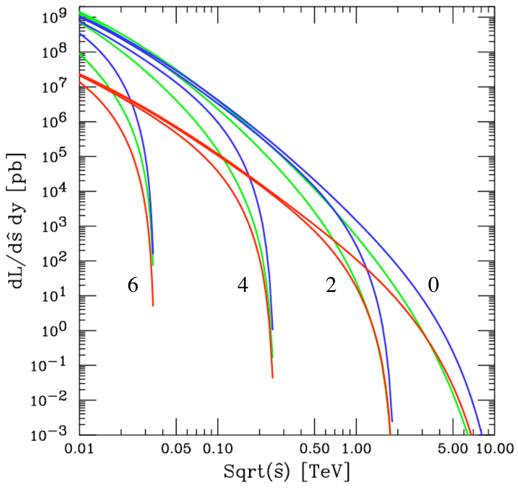


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

PDF uncertainties at the LHC

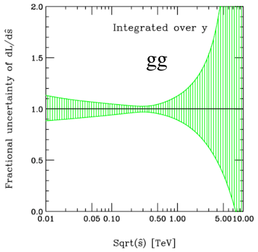


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

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

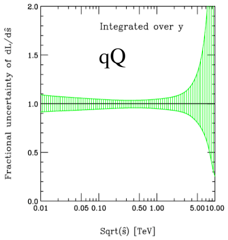


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

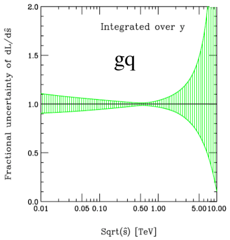


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

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

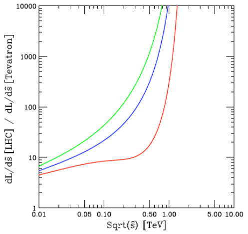


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

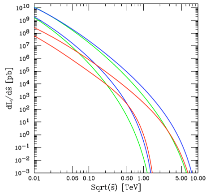


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

Jet rates at the LHC

- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c
- $\sigma_{W+3\ jets} > \sigma_{W+2\ jets}$

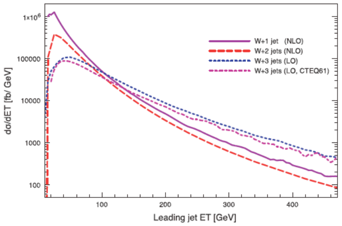


Figure 91. Predictions for the production of $W+\geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- Indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- Also can be understood from point-of-view of Sudakov form factors

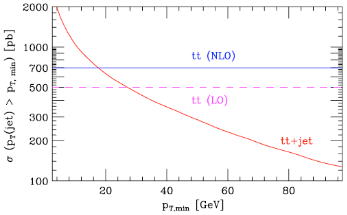


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

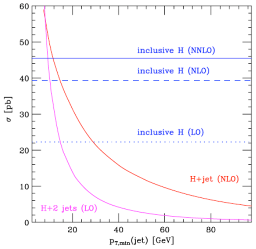


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

Known knowns: Sudakov form factors

- Sudakov form factor gives the probability for a gluon **not** to be emitted; basis of parton shower Monte Carlos
- Curves from top to bottom correspond to initial state Sudakov form factors for gluon x values of 0.3,0.1, 0.03, 0.01, 0.001, 0.0001 at a scale of 500 GeV
- For example, probability for an initial state gluon of x=0.01 not to emit a gluon of >=20 GeV when starting from an initial scale of 500 GeV is ~35%, i.e. there is a 65% probability for such an emission
- Sudakov form factors for q->qg are shown on bottom right; note for x<0.03 form factors are similar to form factor for x=0.03 (and so are not shown)
- Sudakov form factors for g->gg continue to drop with decreasing x
    - g->gg splitting function P(z) has singularities both as z->0 and as z->1
    - q->qg has only z->1 singularity
- **There is a large probability for hard gluon emission if gluons are involved, the value of x is small and the value of the hard scattering scale is large, i.e. the LHC**
    - another known known

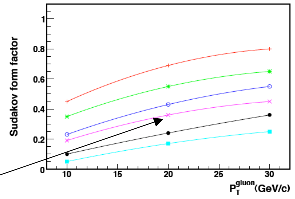


Figure 19. The Sudakov form factors for initial state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

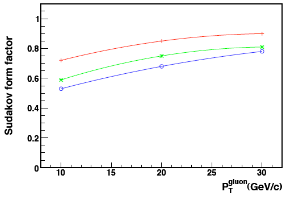
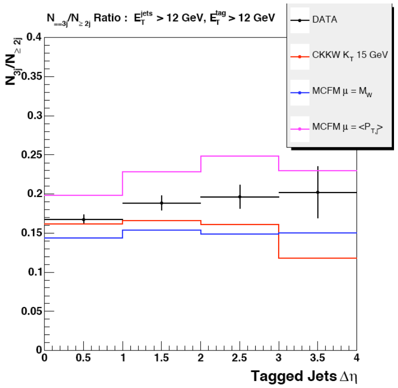


Figure 21. The Sudakov form factors for initial state quarks at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

Benchmark: W/Z + jets at LHC

- Look at probability for 3rd jet to be emitted as a function of the rapidity separation of the tagging jets (VBF Higgs)
- At LHC, ratio (p_T^{jet}>15 GeV/c) much higher than at Tevatron
    - if BFKL logs important, than ratio will be even larger



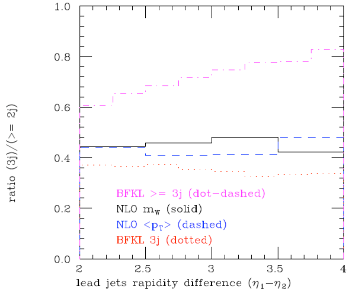


Figure 92. The rate for production of a third (or more) jet in $W+\geq 2$ jet events as a function of the rapidity separation of the two leading jets. A cut of 20 GeV has been placed on all jets. Predictions are shown from MCFM using two values for the renormalization and factorization scale, and using the BFKL formalism, requiring either that there be exactly 3 jets or 3 or more jets.

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

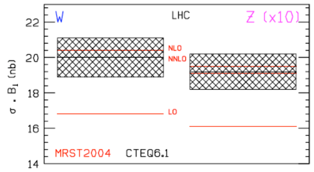
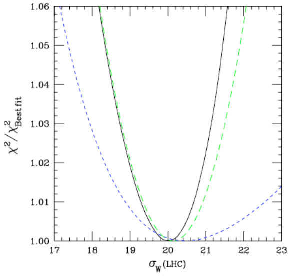
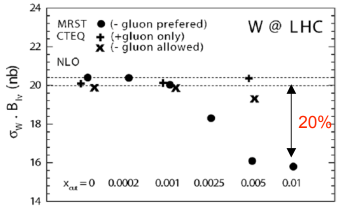


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.



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

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.



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

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.

Rapidity distributions and NNLO

- 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

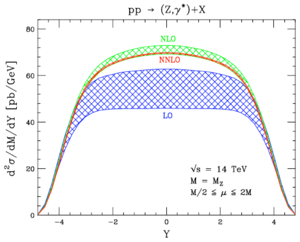


Figure 87. The rapidity distributions for Z production at the LHC at LO, NLO and NNLO.

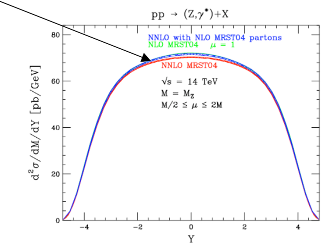


Figure 88. The rapidity distributions for Z production at the LHC at NNLO calculated with NNLO and with NLO pdfs.

Correlations

- As expected, W and Z cross sections are highly correlated
- Anti-correlation between tT and W cross sections
    - more glue for tT production (at higher x) means fewer anti-quarks (at lower x) for W production
    - mostly no correlation for H and W cross sections

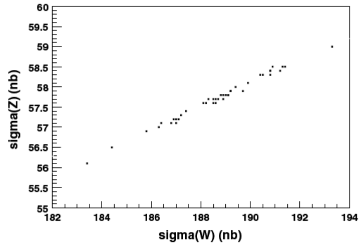


Figure 85. The cross section predictions for Z production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

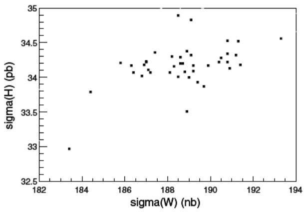


Figure 99. The cross section predictions for Higgs production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

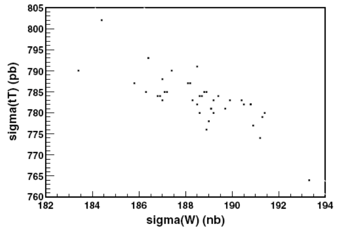
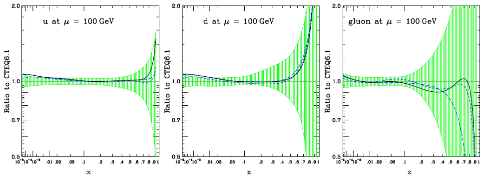


Figure 93. The cross section predictions for $t\bar{t}$ production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

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



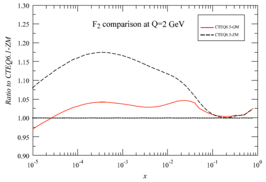
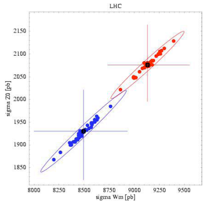


Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

CTEQ6.5

Conclusions on CTEQ6.5

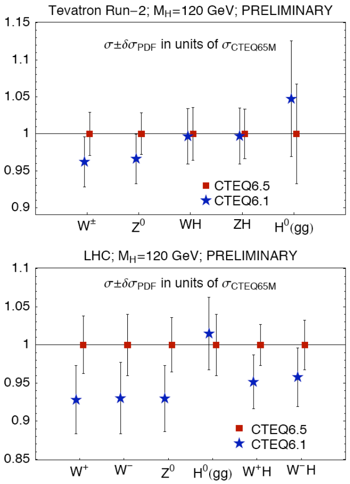
1. Improved Input
   - HQ formalism implemented
   - Use HERA measured cross sections directly
   - Include HERA CC data and NuTeV dimuon data (weight=2.0)
2. Gives better fit (χ^2 lower by ~ 200), suggesting that the physics is better! :)
3. CTEQ6.1 uncertainties were not unreasonable
4. Little or no 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.



W/Z p_T distributions

- p_T-distributions will be shifted (slightly) upwards due to larger phase space for gluon emission
- BFKL logs may become important and have a noticeable effect
- One of early benchmarks; range of importance for BFKL physics

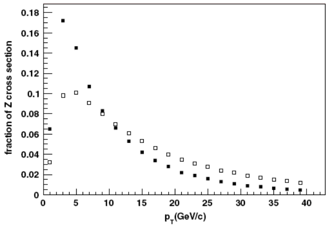


Figure 89. Predictions for the transverse momentum distributions for Z production at the Tevatron (solid squares) and LHC (open squares).

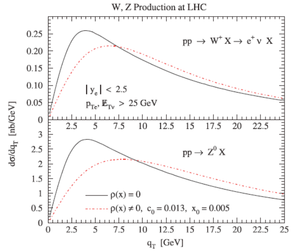


Figure 90. The predictions for the transverse momentum distributions for W and Z production with and without the p_T-broadening effects.

NLO corrections

Shapes of distributions may be different at NLO than at LO, but sometimes it is still useful to define a K-factor. Note the value of the K-factor depends critically on its definition. K-factors at LHC similar to those at Tevatron in most cases

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

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

→ we'll use this later

Counterexample

- Inclusive jet production probes very wide x,Q^2 range along with varying mixture of gg,gq,and qq subprocesses
- Over limited range of p_T and y, can approximate effect of NLO corrections by K-factor but not in general
    - in particular note that for forward rapidities, K-factor <<1
    - LO predictions will be large overestimates
- Need NNLO predictions for jet cross section
    - for precision measurements
    - for use in NNLO pdf fits
- Need inclusive jet in MC@NLO
    - to understand effects of jet algorithms on observables

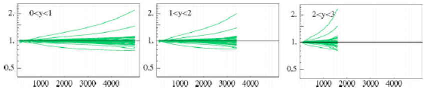


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

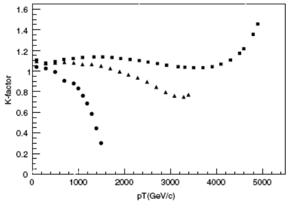
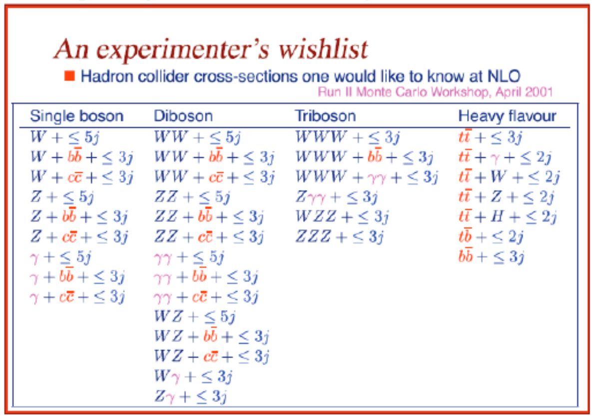


Figure 106. The ratios of the NLO to LO jet cross section predictions for the LHC using the CTEQ6.1 pdfs for the three different rapidity regions (0–1 (squares), 1–2 (triangles), 2–3 (circles)).

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

process ($V \in \{Z,W,\gamma\}$)	relevant for
1. $pp \to V\,V+\text{jet}$	$t\bar{t}H$, new physics
2. $pp \to H+2\,\text{jets}$	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t}+2\,\text{jets}$	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V+2\,\text{jets}$	VBF$\to H \to VV$
7. $pp \to V+3\,\text{jets}$	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

completed since list

- $pp \to$ VV + jet: One of the most promising channels for Higgs production in the low mass range is through the $H \to WW^*$ channel, with the W's decaying semi-leptonically. It is useful to look both in the $H \to WW$ exclusive channel, along with the $H \to WW$+jet channel. The calculation of $pp \to WW$+jet will be especially important in understanding the background to the latter.
- $pp \to H$+2 jets: A measurement of vector boson fusion (VBF) production of the Higgs boson will allow the determination of the Higgs coupling to vector bosons. One of the key signatures for this process is the presence of forward-backward tagging jets. Thus, QCD production of H + 2 jets must be understood, especially as the rates for the two are comparable in the kinematic regions of interest.
- $pp \to t\bar{t}b\bar{b}$ and $pp \to t\bar{t}$ + 2 jets: Both of these processes serve as background to $t\bar{t}H$, where the Higgs decays into a $b\bar{b}$ pair. The rate for $t\bar{t}jj$ is much greater than that for $t\bar{t}b\bar{b}$ and thus, even if 3 b-tags are required, there may be a significant chance for the heavy flavour mistag of a $t\bar{t}jj$ event to contribute to the background.
- $pp \to VVb\bar{b}$: Such a signature serves as non-resonant background to $t\bar{t}$ production as well as to possible new physics.
- $pp \to$ VV + 2 jets: The process serves as a background to VBF production of Higgs.
- $pp \to$ V + 3 jets: The process serves as background for $t\bar{t}$ production where one of the jets may not be reconstructed, as well as for various new physics signatures involving leptons, jets and missing transverse momentum.
- $pp \to VVV$: The process serves as a background for various new physics subprocesses such as SUSY tri-lepton production.

can we develop rules-of-thumb
about size of HO corrections?

What about time lag in going from availability of matrix elements and having a parton level Monte Carlo available? See e.g. H + 2 jets.

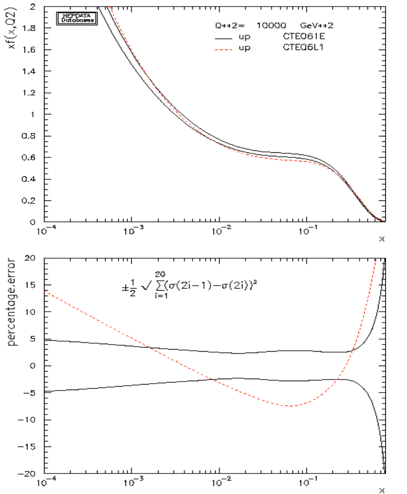
From LHC theory initiative white paper

- time ordered LHC shopping list
    - need for 10 – 30 fb^{-1} (2008-2010):
        - full NLO QCD corrections to $pp \to t\bar{t} \to b\bar{b}+4f$
        - NLO QCD corrections to $t\bar{t}j$, $t\bar{t}\gamma$, $W/Z+\geq 3$ jets production
        - NNLO QCD corrections to PDF's, 2-jet production
    - need for 300 fb^{-1} (2012-2013):
        - NLO QCD corrections to $gg \to HH$, $t\bar{t}W$, $t\bar{t}Z$ production
        - NLO EW corrections are needed for all hard scattering processes
    - need for 3000 fb^{-1} (> 2015):
        - NLO QCD corrections to $WWWjj$, $jj\gamma\gamma$, $Q\bar{Q}\gamma j$ production
        - probably many more processes as time and physics knowledge base evolves

Uli Baur Fermilab W&C Aug 18

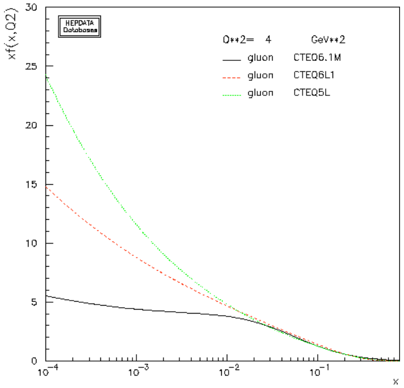
LO vs NLO pdf's for parton shower MC's

- 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

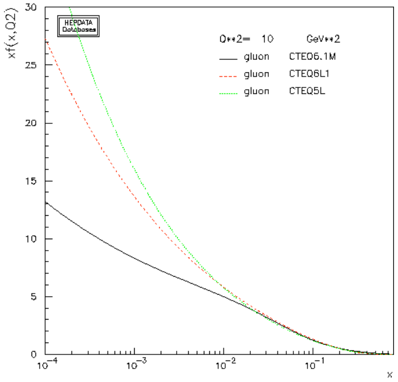


. . .but at the end of the day this is still LO physics; There's no substitute for honest-to-god NLO.

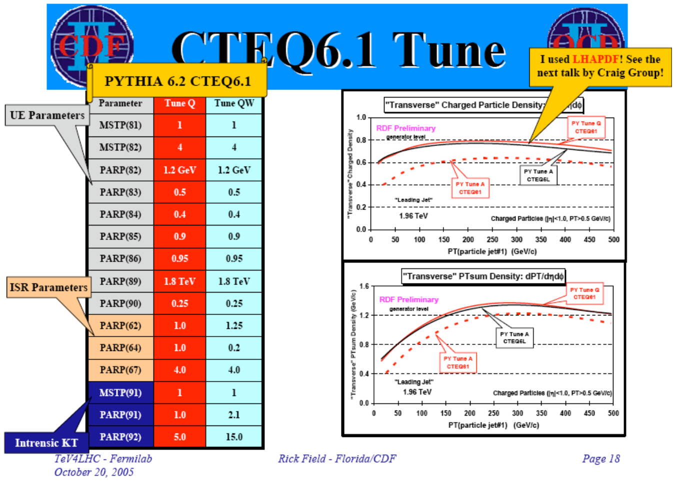
Impact on UE tunes



- 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

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

ISR Parameters

Intrensic KT

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

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

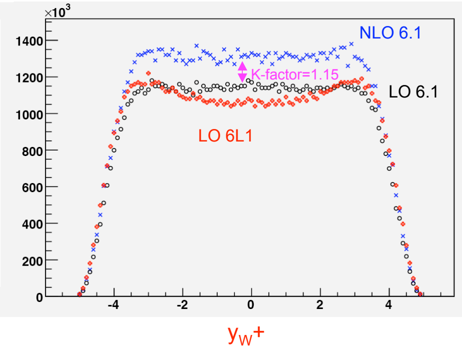
The proof of the pudding . . .

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

Interesting comparisons would then be with the scenarios:
(b) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{LO})$.
(c) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{LO}) \otimes$ showers.
(d) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{NLO})$.
(e) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{NLO}) \otimes$ 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



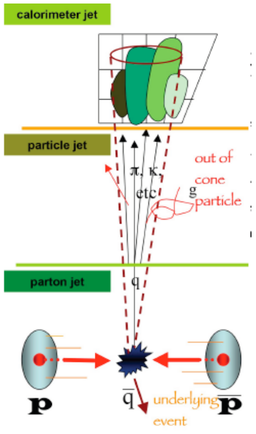
- One possibility
  - use CTEQ5L for UE but NLO pdf's for matrix element evaluation
- Answers by/at Les Houches 2007

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.

Jet algorithms

- To date, emphasis in ATLAS and CMS has been (deservedly so) on jet energy calibration and not on details of jet algorithms
  - at Tevatron, we've been worrying about both for some time
- But some attention to the latter will be necessary for precision physics

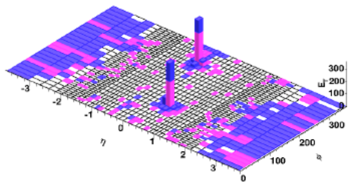
- An understanding of jet algorithms/jet shapes will be crucial early for jet calibration in such processes as γ+jet/Z+jet

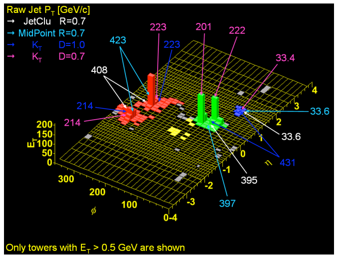


Jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- If comparison is to hadron-level Monte Carlo, then hope is that the Monte Carlo will reproduce all of the physics present in the data and influence of jet algorithms can be understood
  - more difficulty when comparing to parton level calculations

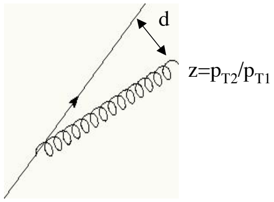
CDF Run II events





Jet algorithms at NLO

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



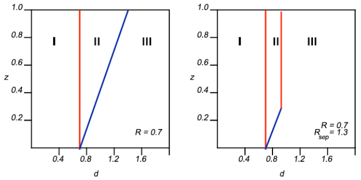


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

Jets at NLO continued

- Construct what is called a Snowmass potential

shown in Figure 50, where the towers unclustered into any jet are shaded black. A simple way of understanding these dark towers begins by defining a "Snowmass potential" in terms of the 2-dimensional vector $\overrightarrow{r} = (y, \phi)$ via

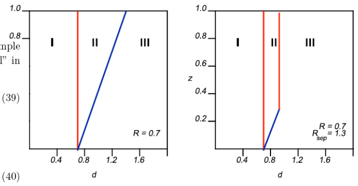
$$V\left(\overrightarrow{r}\right) = -\frac{1}{2}\sum_j p_{T,j}\left(R^2_{cone} - \left(\overrightarrow{r_j} - \overrightarrow{r}\right)^2\right)\Theta\left(R^2_{cone} - \left(\overrightarrow{r_j} - \overrightarrow{r}\right)^2\right) . \quad (39)$$

The flow is then driven by the "force" $\overrightarrow{F}\left(\overrightarrow{r}\right) = -\overrightarrow{\nabla}V\left(\overrightarrow{r}\right)$ which is thus given by,

$$\begin{aligned}\overrightarrow{F}\left(\overrightarrow{r}\right) &= \sum_j p_{T,j}\left(\overrightarrow{r_j} - \overrightarrow{r}\right)\Theta\left(R^2_{cone} - \left(\overrightarrow{r_j} - \overrightarrow{r}\right)^2\right) \\ &= \left(\overline{\overrightarrow{r}}_{C(\overrightarrow{r})} - \overrightarrow{r}\right)\sum_{j\subset C(r)} p_{T,j}, \quad (40)\end{aligned}$$

where $\overline{\overrightarrow{r}}_{C(\overrightarrow{r})} = \left(\overline{y}_{C(\overrightarrow{r})}, \overline{\phi}_{C(\overrightarrow{r})}\right)$ and the sum runs over $j \subset C(\overrightarrow{r})$ such that $\sqrt{(y_j - y)^2 + (\phi_j - \phi)^2} \leq R_{cone}$. As desired, this force pushes the cone to the stable cone position.

- The minima of the potential function indicates the positions of the stable cone solutions
  - the derivative of the potential function is the force that shows the direction of flow of the iterated cone
- The midpoint solution contains both partons



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

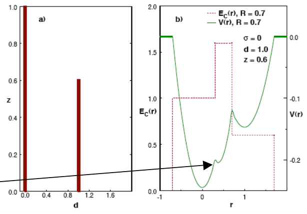


Figure 51. A schematic depiction of a specific parton configuration and the results of applying the midpoint cone jet clustering algorithm. The potential discussed in the text and the resulting energy in the jet are plotted.

Jets in real life

- Thus, jets don't consist of 1 fermi partons but have a spatial distribution
- Can approximate this as a Gaussian smearing of the spatial distribution of the parton energy
  - the effective sigma ranges between around 0.1 and 0.3 depending on the parton type (quark or gluon) and on the parton p_T
- Note that because of the effects of smearing that
  - the midpoint solution is (**almost always**) lost
    - thus region II is effectively truncated to the area shown on the right
  - the solution corresponding to the lower energy parton can also be lost
    - resulting in dark towers

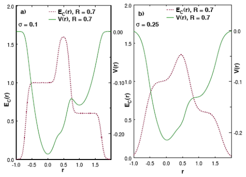


Figure 52. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm.

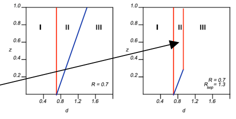


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

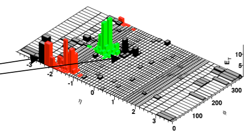


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

Jets in real life

- In NLO theory, can mimic the impact of the truncation of Region II by including a parameter called R_{sep}
  - only merge two partons if they are within $R_{sep}*R_{cone}$ of each other
    - R_{sep}~1.3
  - ~4-5% effect on the theory cross section; effect is smaller with the use of p_T rather than E_T (see extra slides)
  - really upsets the theorists (but there are also disadvantages)
- Dark tower effect is also on order of few (<5)% effect on the (experimental) cross section

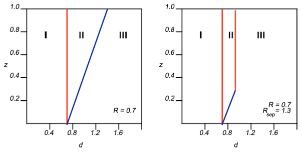
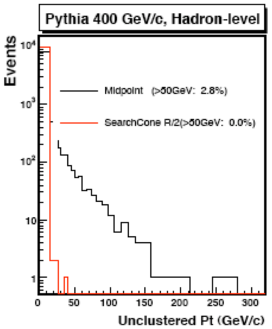


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.



Jets in real life

- Search cone solution
  - use smaller initial search cone (R/2) so that influence of far-away energy not important
  - solution corresponding to smaller parton survives (but not midpoint solution)
  - but some undesireable IR sensitivity effects (~1%), plus larger UE subtraction
- **TeV4LHC consensus**
  - run standard midpoint algorithm
  - remove all towers located in jets
  - run 2nd pass of midpoint algorithm, cluster into jets
  - at this point, can either keep 2nd pass jets as additional jets (recommended for now)
    - use appropriate value of R_{sep}
  - or merge in (d,z) plane
  - correct data for effects of seeds (~1%) so comparisons made to seedless theory

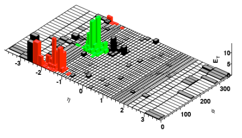


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

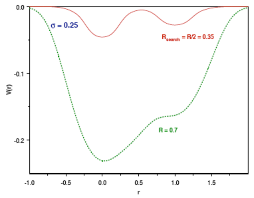
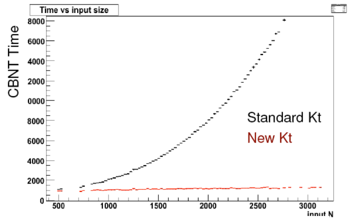
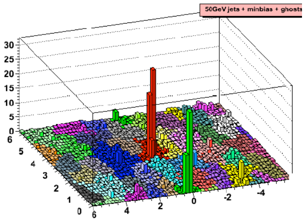


Figure 20. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm and the result of using a smaller initial search cone.

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





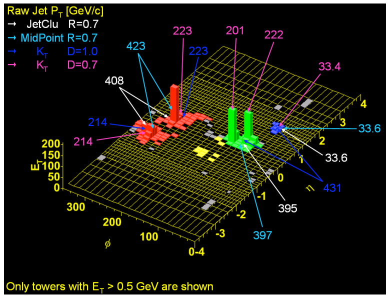
~ 10000 particles

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/index.html

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
```

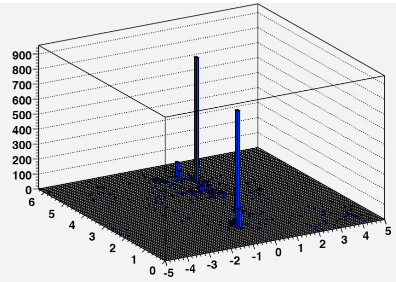
Jets and you

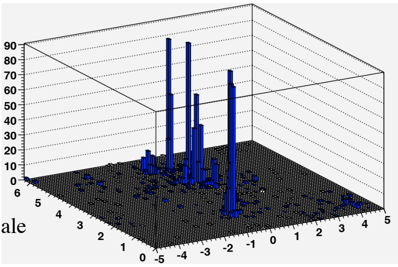
```
// Make Lego plots?
10                 // if any, make lego plots for how many events
         ALL EVENTS
0                  // make lego plots for JETCLU                    0
lego_j
1                  // make lego plots for MIDPOINT                  0
lego_m
1                  // make lego plots for FASTJET KT                0
lego_kt
1                  // make lego plots for FASTJET CAMBRIDGE (AACHEN)  0
lego_kta
0.1                // size of eta division for lego plots           0.05
0.1                // size of phi division for lego plots           0.05
```

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



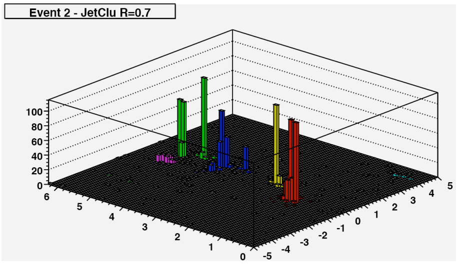


change max scale

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

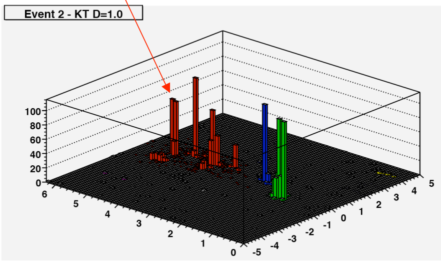
- kT Jets(D=1.0):
- Et=1293., eta=-0.06, phi=4.76, nTowers=268
- Et=1101., eta=-0.36, phi=1.47, nTowers=99
- Et=261., eta =0.50, phi=2.35, nTowers=71
- Et=25.2, eta=0.81, phi=3.98, nTowers = 34



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

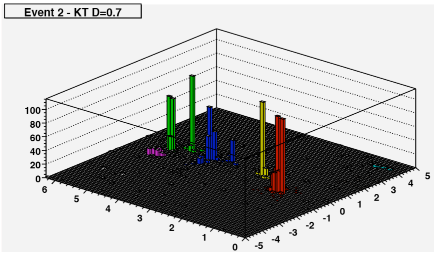
- kT Jets(D=1.0):
- Et=1293., eta=-0.06, phi=4.76, nTowers=268
- Et=1101., eta=-0.36, phi=1.47, nTowers=99
- Et=261., eta =0.50, phi=2.35, nTowers=71
- Et=25.2, eta=0.81, phi=3.98, nTowers = 34



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

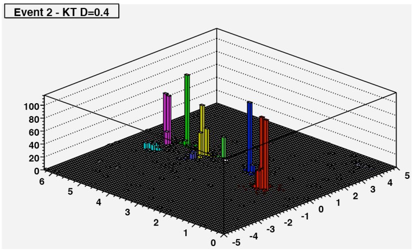
- kT Jets(D=0.7):
- Et=1101., eta=-0.36, phi=1.47, nTowers=98
- Et=1051., eta=0.77, phi=4.90, nTowers=107
- Et=259., eta =0.55, phi=3.98, nTowers=110
- Et=255., eta=0.46, phi=2.35, nTowers = 51
- Et=75., eta=-0.40, phi=5.27, nTowers = 39



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

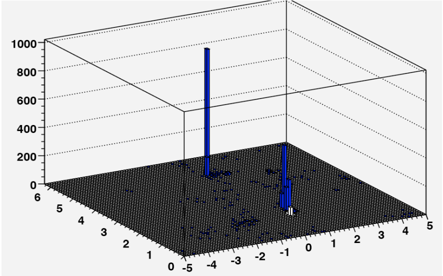


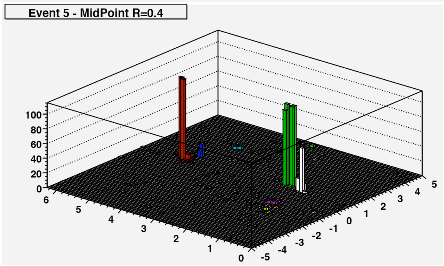
Another example dijet event (5 out of 10)

Input : 520 four vectors

Binned: 209 four vectors

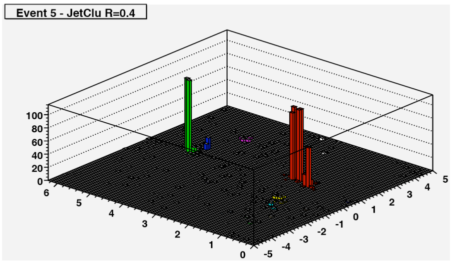
- JetClu Jets (R=0.4)
- Et=1065,eta=1.0,phi=1.94,n=27
- Et=1046,eta=.66,phi=5.08,n=24
- Et=39,eta=1.25,phi=4.87,n=10
- Et=30,eta=-1.06,phi=1.51,n=16
- Et=17.8,eta=2.76,phi=4.53,n=6
- MidPoint Jets (R=0.4)
- Et=1046,eta=0.66,phi= 5.08,n=23
- Et=970,eta=1.01,phi=1.98,n=18
- Et=40,eta=1.25,phi=4.88,n=13
- 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

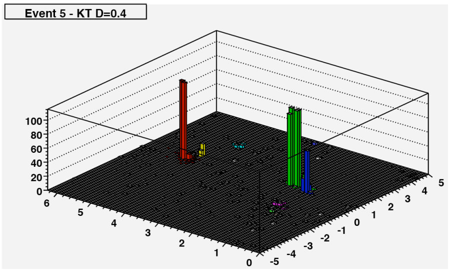




Another example dijet event (5 out of 10)

- Inclusive kT (D=0.4)
- Et=1045,eta=0.66,phi=5.08,n=29,area=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





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/index.html

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

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
- More CTEQ papers coming shortly dealing with strange and charm distributions, and phenomenology implications of CTEQ6.5
  - in future
    - resummation
    - NNLO

Physics at TeV Colliders

Les Houches, 11-29 June 2007

- Note change in dates
- **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 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.

LES HOUCHES - Centre de Physique

Workshop

PHYSICS at TeV COLLIDERS

Les Houches, June 11-29 2007

International Organizing Committee

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- Zvi BERN (UCLA, USA)
- Edward BOOS (Moscow State Univ., Russia)
- Stefano CATANI (Florence, Italy)
- Sally DAWSON (Brookhaven National Laboratory, USA)
- Abdelhak DJOUADI (Orsay, France)
- Manuel DREES (Bonn, Germany)
- Rohini GODBOLE (IISc, Bangalore, India)
- Gian GIUDICE (CERN, Switzerland)
- Rolf-Dieter HEUER (Univ. Hamburg, Germany)
- Wolfgang HOLLIK (MPI, München, Germany)
- Joey HUSTON (Michigan State University, USA)
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LAPP Annecy
- Rémi LAFAYE

LPSC Grenoble
- Sabine KRAML

LAL Orsay
- Dirk ZERWAS

Design - G. Dromby / LAPP

AIM AND FORMAT

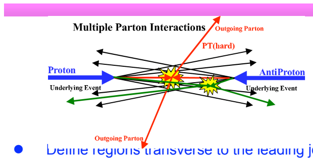
The aim of this Workshop is to bring together theorists and experimentalists working on the phenomenology of the upcoming TeV colliders. The emphasis will be on the physics at the LHC, particularly on progress in new techniques for the simulation of Standard Model processes and on the latest developments concerning new mechanisms of electroweak symmetry breaking and the associated New Physics. Issues ranging from jets and SM candles to Higgs and BSM will be discussed and tools covering these aspects will be critically reviewed and compared. Three Working Groups have been set up to cover these different aspects of physics at the LHC.
The meeting in Les Houches is the central event of this year-long Workshop.

for more information, see: http://lapp.in2p3.fr/conferences/LesHouches/Houches2007/

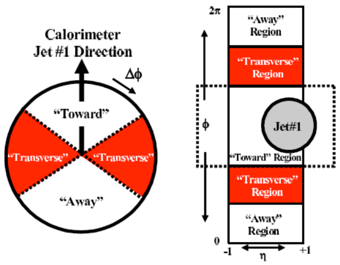
http://lappweb.in2p3.fr/conferences/LesHouches/Houches2007/

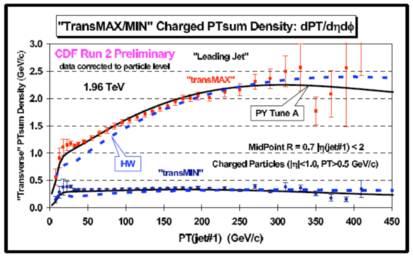
Extra slides

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 is working on some new tunes
  - fixing problems present in Tune A
  - tunes for Jimmy
  - tunes for CTEQ6.1 (NLO)
  - see TeV4LHC writeup for details

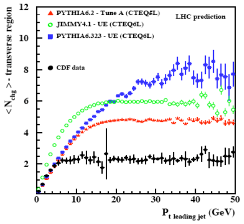
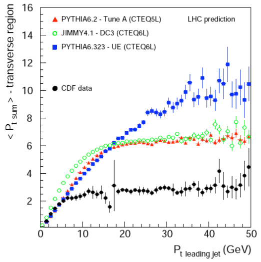


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.



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

LES HOUCHES
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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

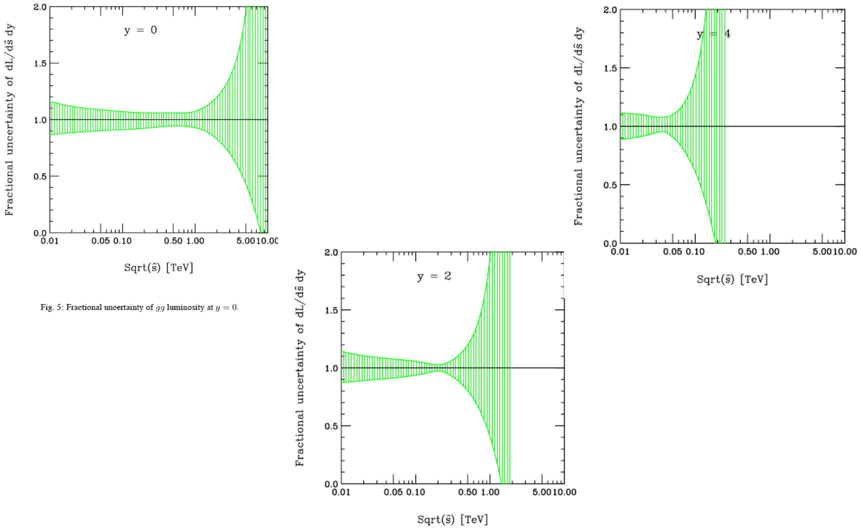

Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

---

gg luminosity uncertainties

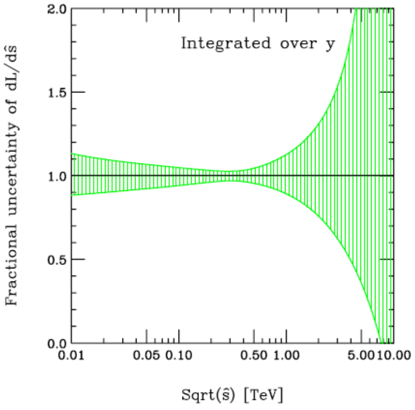

Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

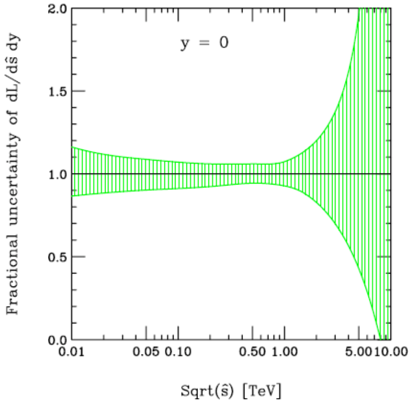

Fig. 5: Fractional uncertainty of gg luminosity at $y = 0$.

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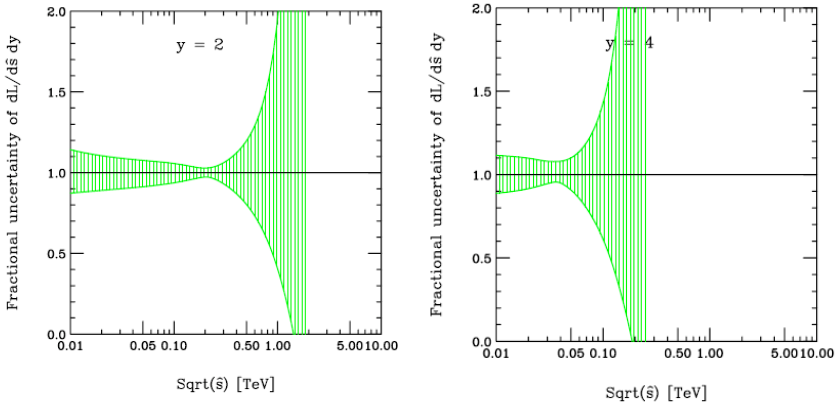
gg luminosity uncertainties



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gq luminosity uncertainties

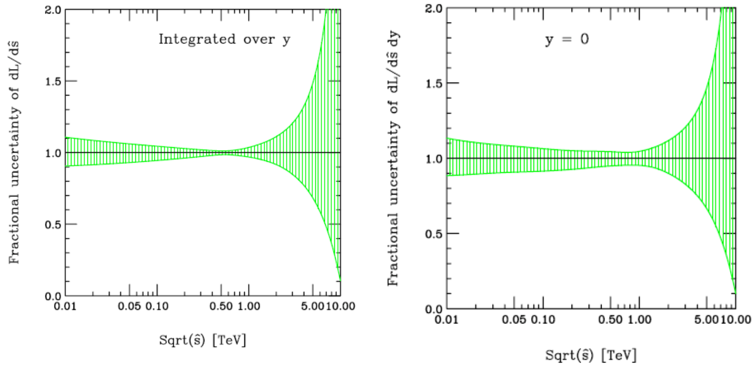
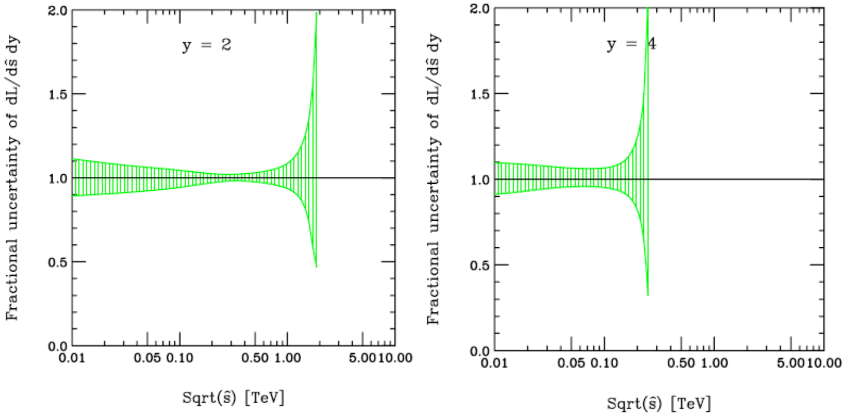


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

gq luminosity uncertainties



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qQ luminosity uncertainties

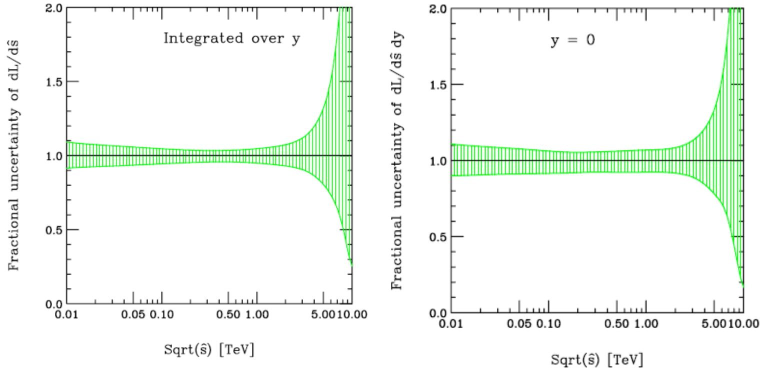

Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

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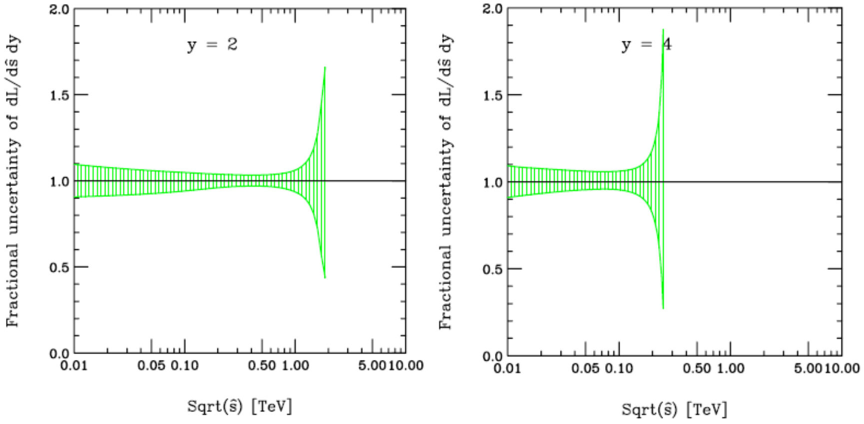
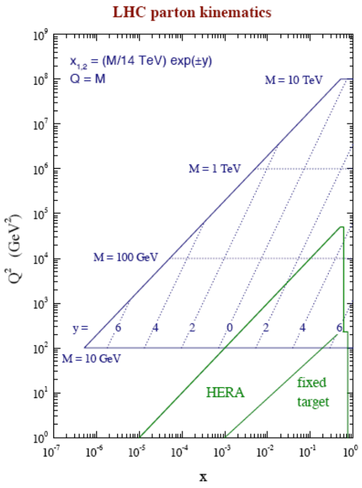
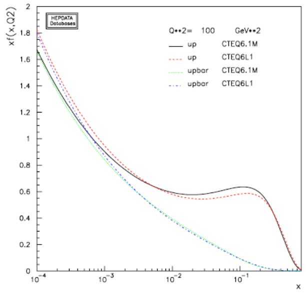
qQ luminosity uncertainties



NLO vs LO pdf's

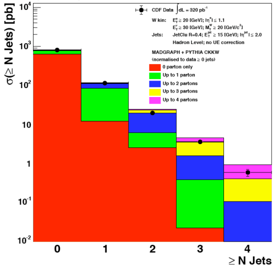




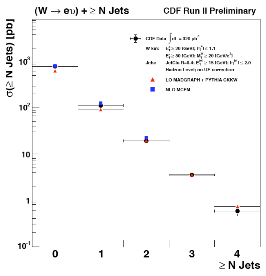
W + jets at the Tevatron

- 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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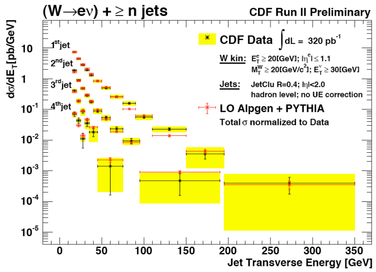
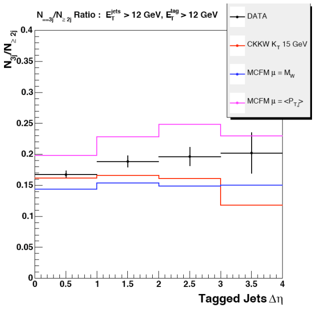
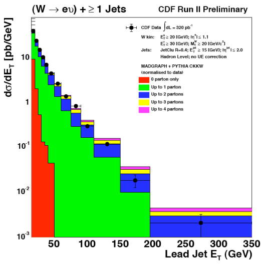




Probability of 3rd jet emission as function of two lead jet rapidity separation in good ageement with theory

At LHC, BFKL logs may become more important for high Δη



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

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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