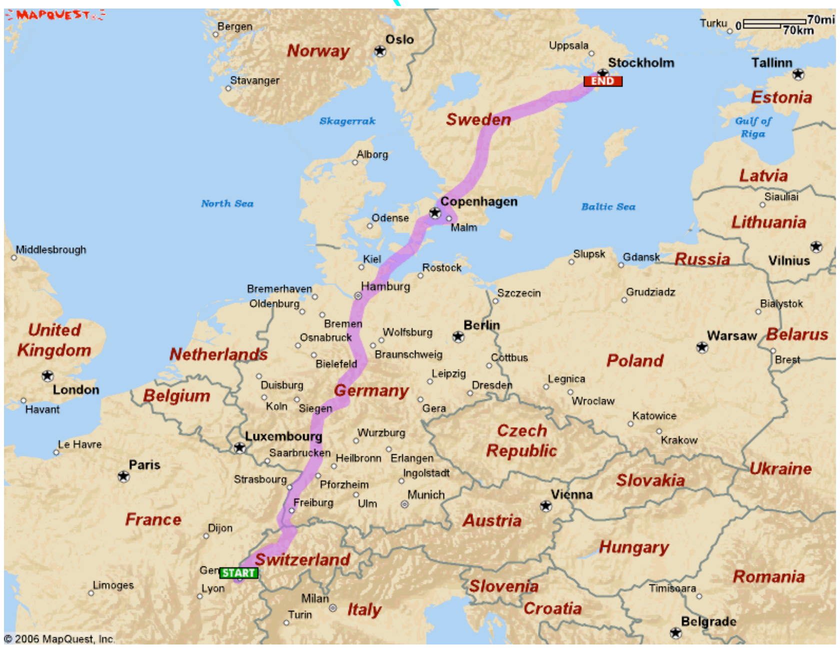
First we discover the Standard Model

Roadmap for the first few fb^{-1}

(more on tools than analysis strategies)

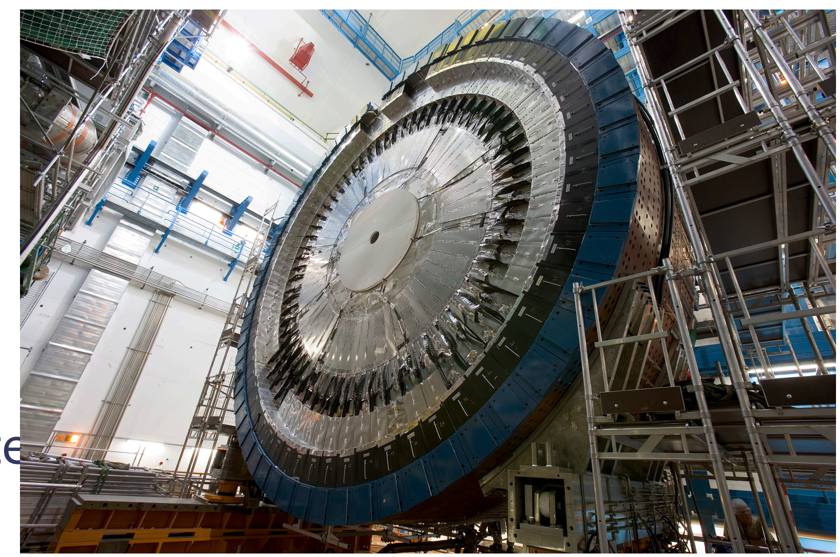


J. Huston

Michigan State University *and*

IPPP, University of Durham

- End at **Stockholm**
- **Total Est. Time:** 18 hours, 50 minute
- **Total Est. Distance:** 1264.67 miles



Some references

- Also online at ROP

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

REVIEW ARTICLE CHS

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

arXiv:hep-ph/0611148 v1 10 Nov 2006

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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.*

Some lecture notes based on review article can be found at www.pa.msu.edu/~huston/seignosse

LES HOUCHES
centre de physique

Standard Model benchmarks

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

More references

Jets in Hadron-Hadron Collisions

S. D. Ellis,[1] J. Huston,[2] K. Hatakeyama,[3] P. Loch,[4] M. Tönnesmann,[5]

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December 14, 2007

Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.

Contents

Symmetry
A joint Fermilab/SLAC publication
PO Box 500
MS 206
Batavia Illinois 60510
USA

symmetry

Some background: what to expect at the LHC

…according to a theorist, perhaps like many of you

Murayama LP03

What to expect at the LHC

…according to a theorist

Murayama LP03

- According to a ~~current~~ former Secretary of Defense
  - known knowns
  - known unknowns
  - unknown unknowns

What to expect at the LHC

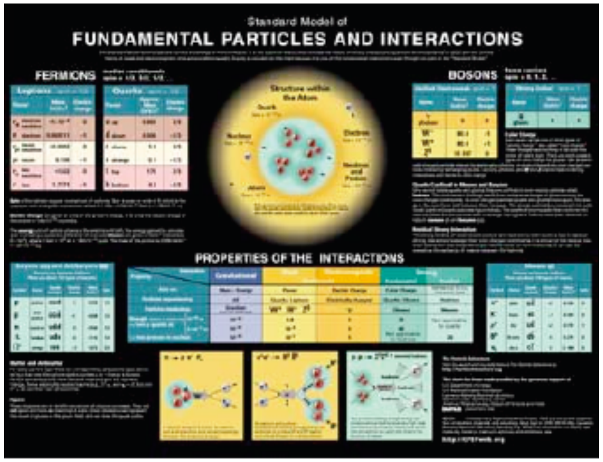
…according to a theorist

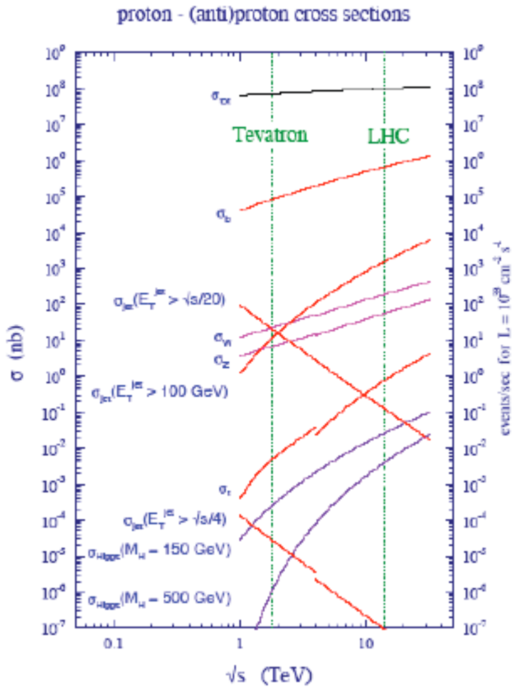
Murayama LP03

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

Discovering the SM at the LHC

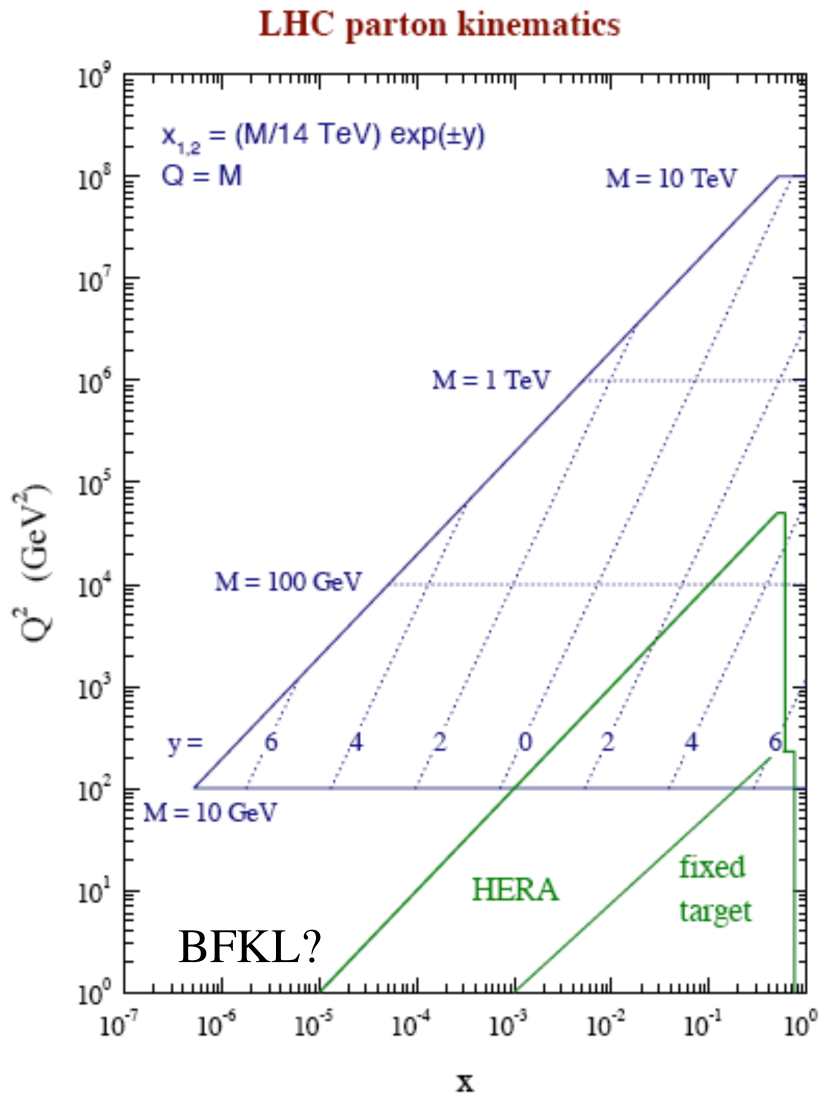
- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/ understand SM cross sections
    - detector and reconstruction algorithms operating properly
    - SM physics understood properly
    - SM backgrounds to BSM physics correctly taken into account
- ATLAS will have a program to measure production of SM processes: inclusive jets, W/Z + jets, heavy flavor during first inverse femtobarn
    - so experimenters need/have a program now of Monte Carlo production and studies to make sure that we understand what issues are important
    - **and we also need tool and algorithm and theoretical prediction developments**





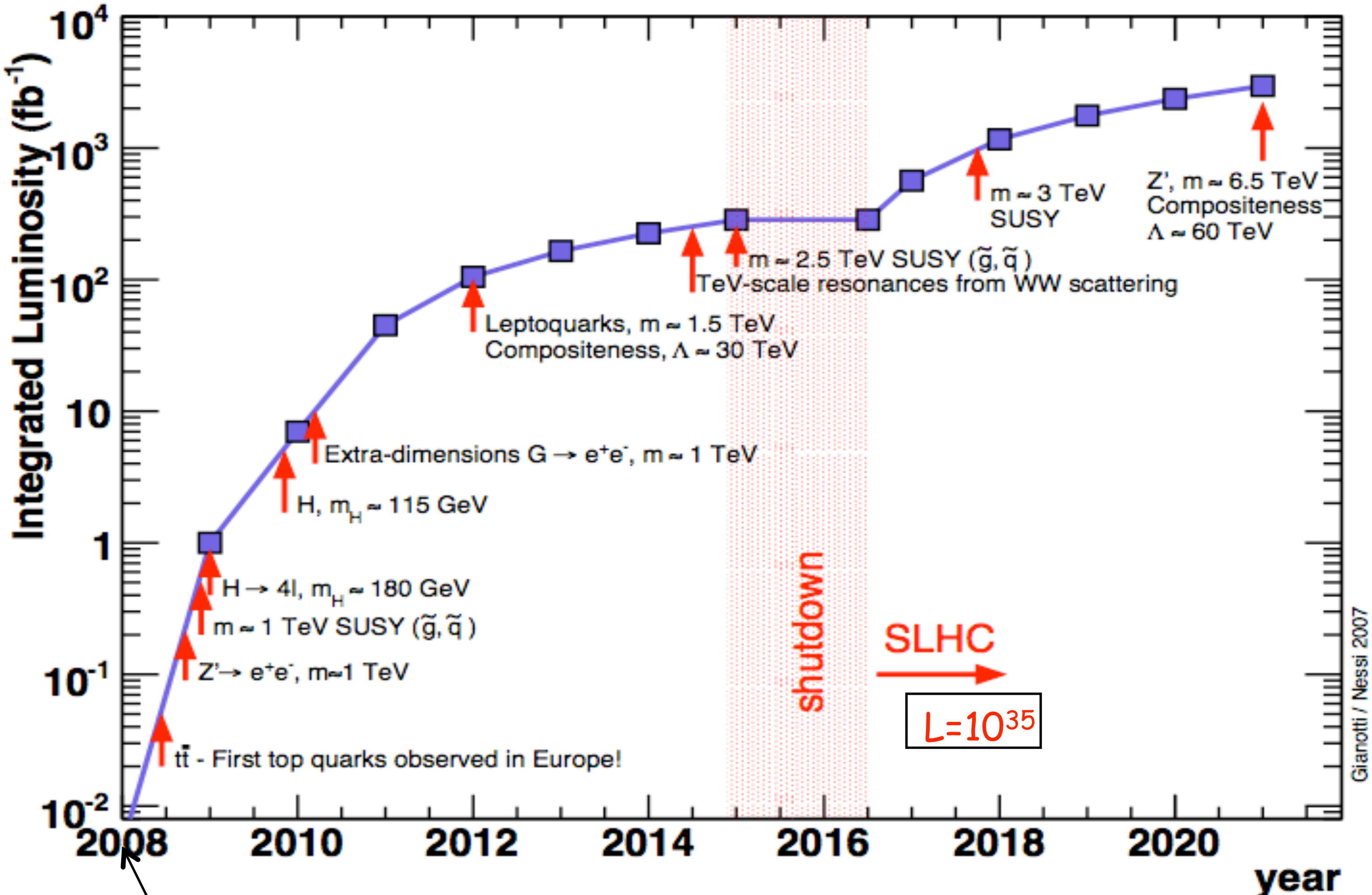
Cross sections at the LHC

- 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



Looking back in 15 years

LHC vs time: a wild guess …



you are here

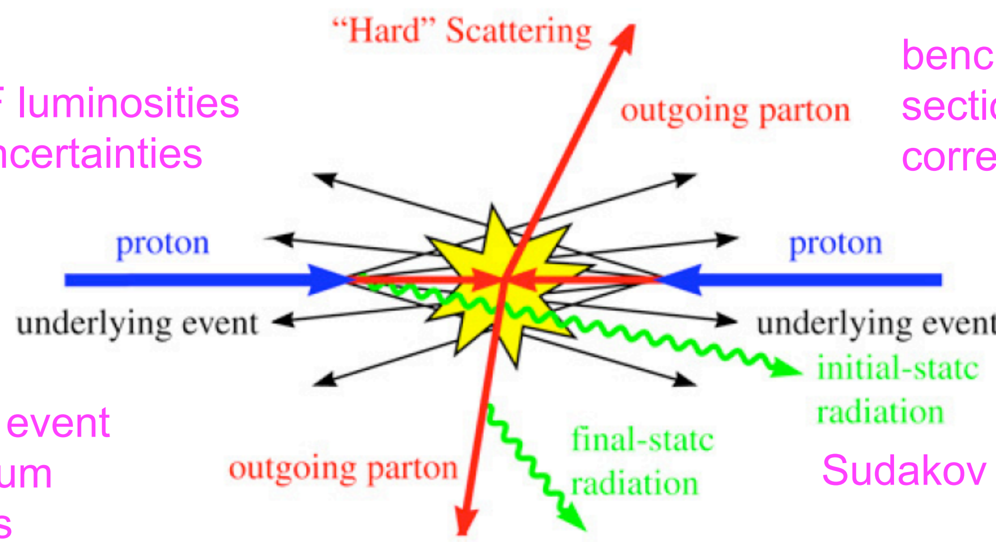
…but before looking back

Understanding SM predictions at the LHC

LO, NLO and NNLO calculations
K-factors

PDF’s, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



underlying event
and minimum
bias events

Sudakov form factors

jet algorithms and jet reconstruction

Parton distribution functions

- Calculation of production cross sections at the LHC relies upon knowledge of pdf's in the relevant kinematic region
- Pdf's are determined by global analyses of data from DIS, DY and jet production
- Two major groups that provide semi-regular updates to parton distributions when new data/theory becomes available
  - MRS->MRST98->MRST99 ->MRST2001->MRST2002 ->MRST2003->MRST2004->MSTW2008
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5/6
  - All global analyses use a generic form for the parametrization of both the quark and gluon distributions at some reference value Q_o, where Q_o is usually in the range of 1-2 GeV
- Pdf's are available at LO, NLO and NNLO
- NB: currently working on *modified LO* pdf's for use with parton shower Monte Carlos

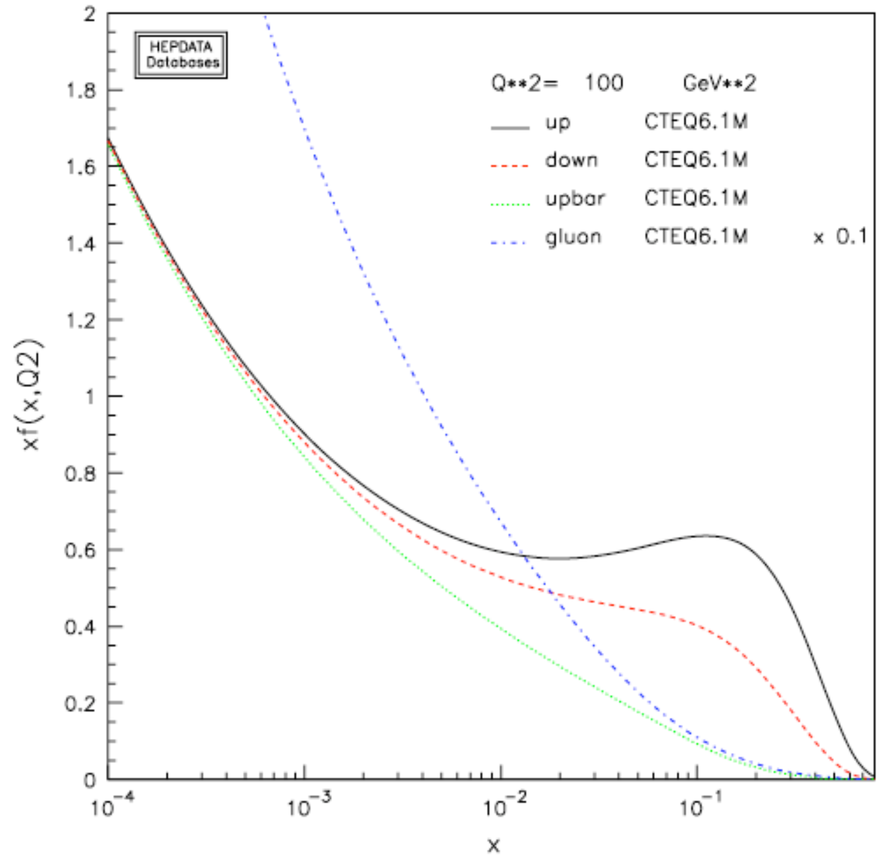


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

$$F(x, Q_0) = A_0 x^{A_1} (1-x)^{A_2} P(x; A_3, \ldots).$$

Parton distribution functions

- All of the above groups provide ways to estimate the error on the central pdf
  - Hessian methodology enables full characterization of parton parametrization space in neighborhood of global minimum

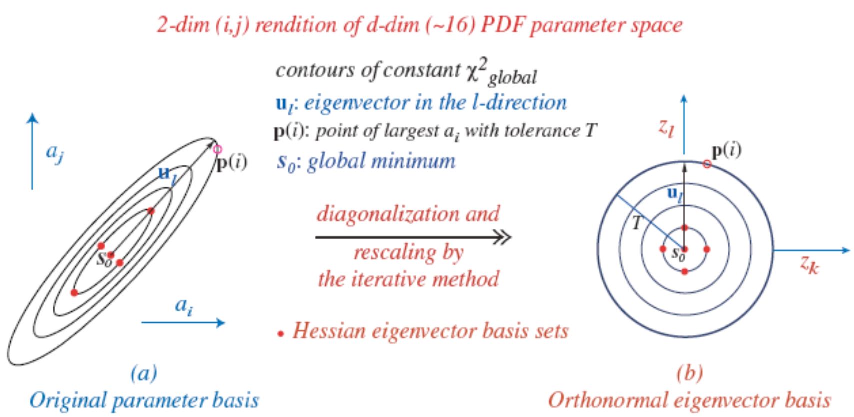


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

Inclusive jets at the Tevatron

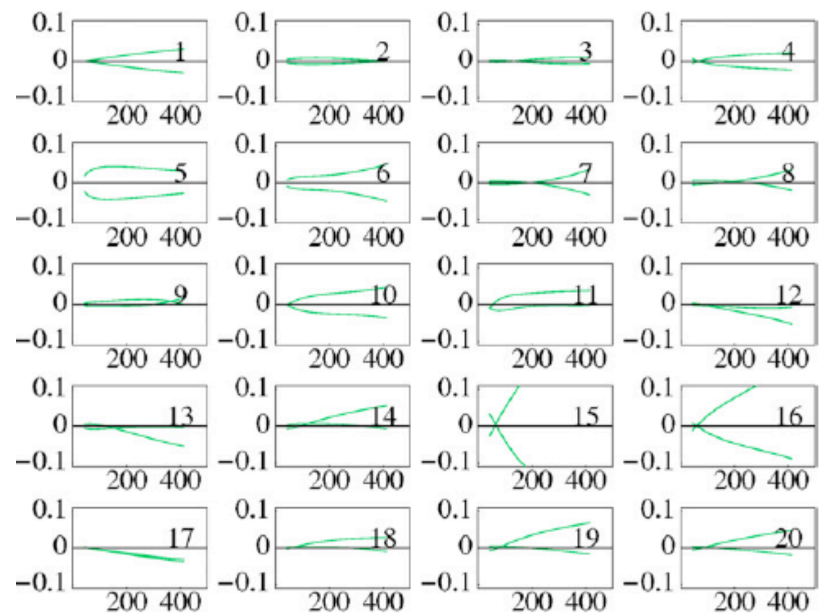


Figure 29. The pdf errors for the CDF inclusive jet cross section in Run 1 for the 20 different eigenvector directions. The vertical axes show the fractional deviation from the central prediction and the horizontal axes the jet transverse momentum in GeV.

  - CTEQ6.1 has 20 free parameters so 20 directions in eigenvector space

40 error pdfs

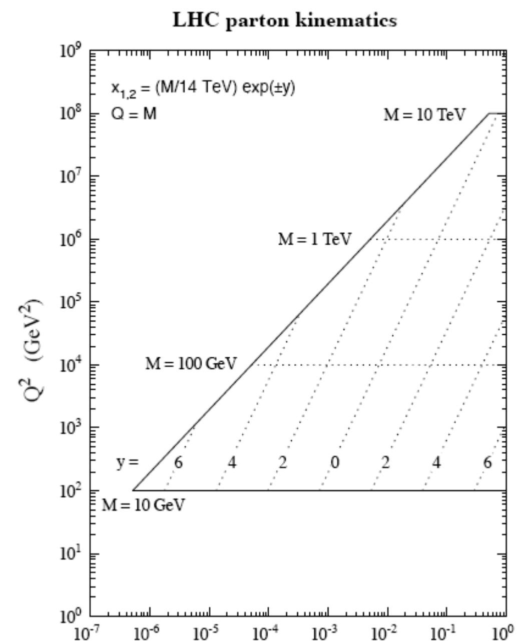
$$\Delta X^{+}_{\max} = \sqrt{\sum_{i=1}^{N} [\max(X^{+}_i - X_0, X^{-}_i - X_0, 0)]^2},$$

$$\Delta X^{-}_{\max} = \sqrt{\sum_{i=1}^{N} [\max(X_0 - X^{+}_i, X_0 - X^{-}_i, 0)]^2}.$$

- theory uncertainties
  - higher twist/non-perturbative effects
    - choose Q^2 and W cuts to avoid
  - higher order effects (NNLO)
  - **heavy quark mass effects (see later)**

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 (CHS) and the Les Houches 2005 writeup
- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element



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

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

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

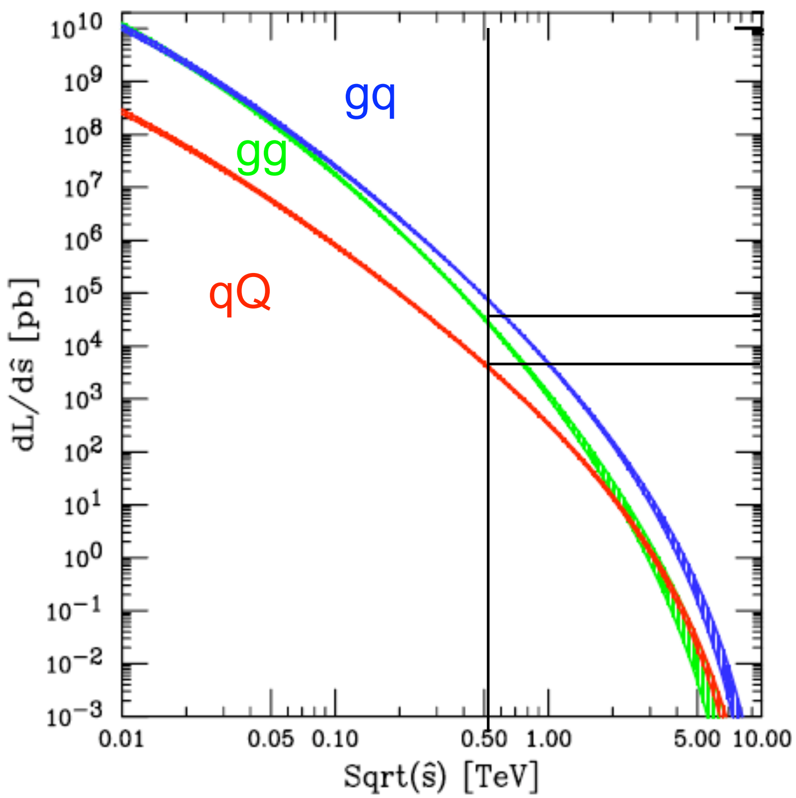
can then be written as

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

Cross section estimates

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

@500 GeV tT mass, gg factor of 10 larger than qQ; σxs factors ~ same;
~1 * 4E4 pb * 0.012 = order of 500 pb (LO)



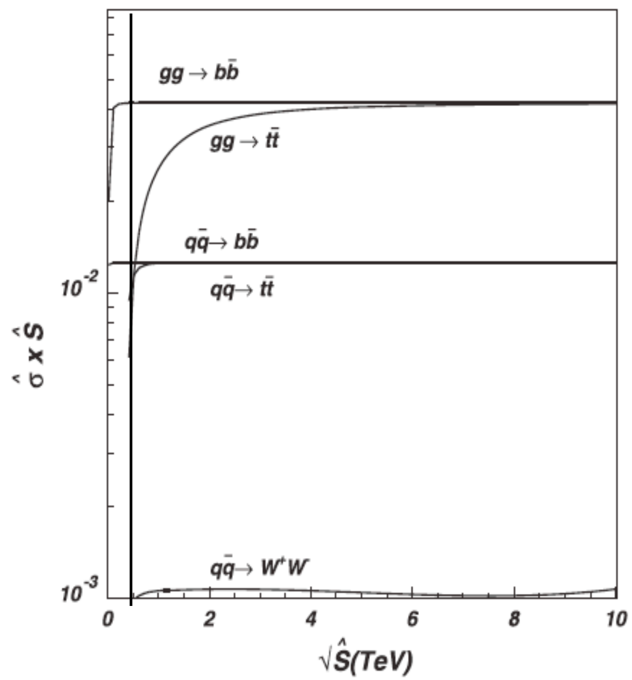


Figure 71. Parton level cross sections $(\hat{s}\hat{\sigma}_{ij})$ for various processes involving massive partons in the final state.

Note threshold behavior for gg more complex than for qQ

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

PDF uncertainties at the LHC

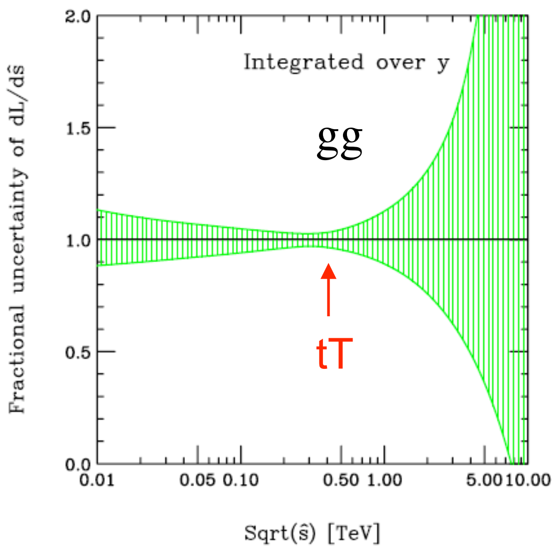


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

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

Need similar level of precision in theory calculations

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

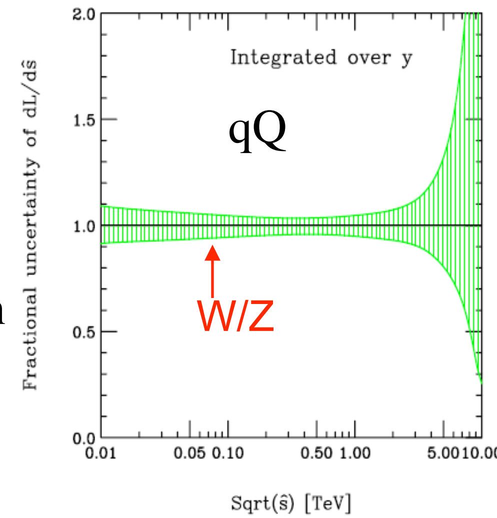


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

NBIII: tT uncertainty is of the same order as W/Z production

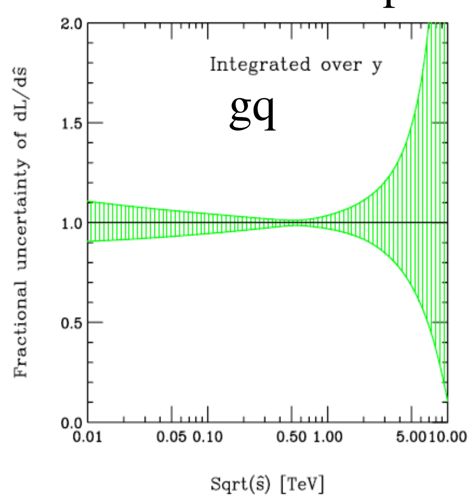


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b) + g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b}) + (d+u+s+c+b)g + (\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

NB I: the errors are determined using the Hessian method for a $\Delta\chi^2$ of 100 using only experimental uncertainties,i.e. no theory uncertainties

NB II: the pdf uncertainties for W/Z cross sections are not the smallest

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

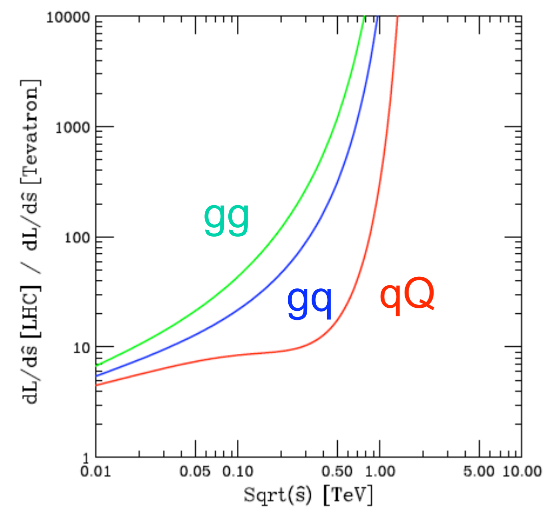


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

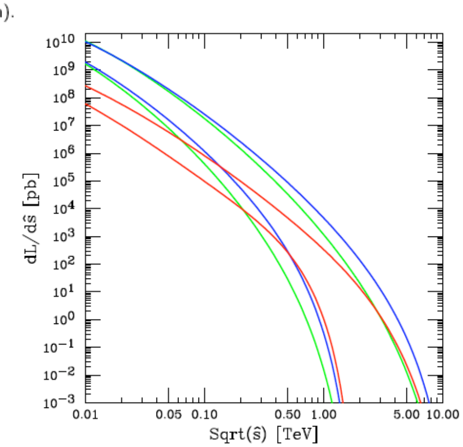
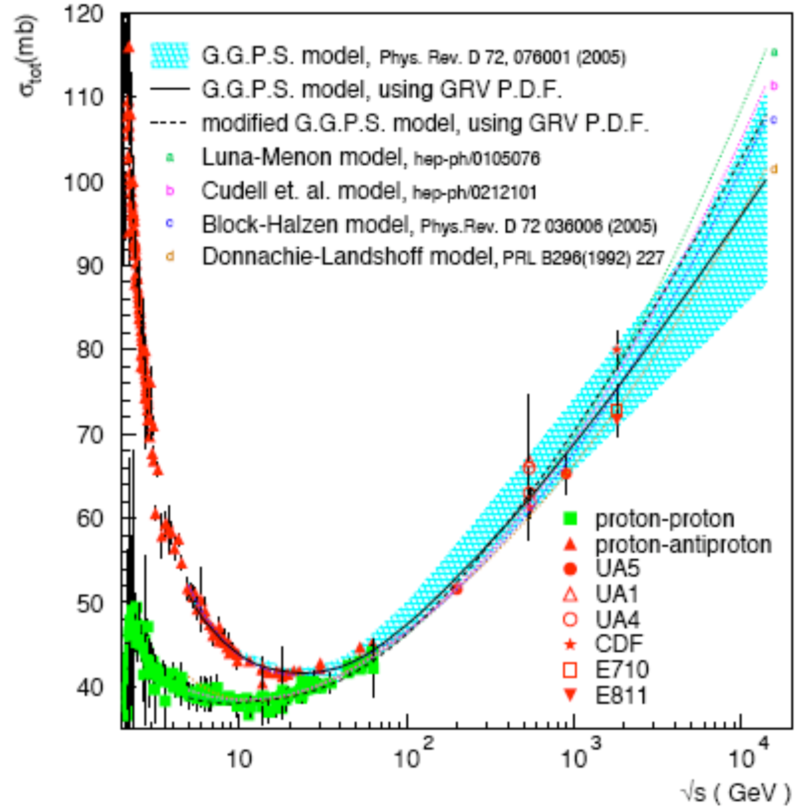


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

The LHC Environment

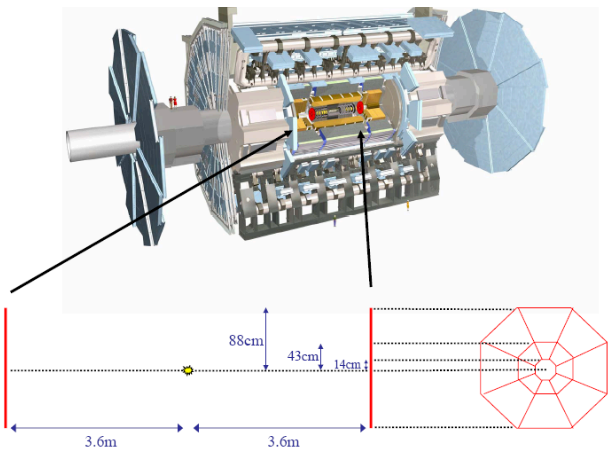
Known unknowns: total cross section at LHC (14 TeV)

- Fair amount of uncertainty on extrapolation to LHC
  - $\ln(s)$ or $\ln^2(s)$ behavior
  - rely on Roman pot measurements
    - need 90 m optics run; sometime in 2009?
  - extrapolating measured cross section to full inelastic cross section will still have uncertainties (and may take time/analysis)
  - we'll need benchmark cross sections for normalization
- Also uncertainty on $dN_{charged}/d\eta$ and $dN_{charged}/dp_T$
  - role of semi-hard multiple parton interactions
  - reasonable expectation is 7-8 particles per unit rapidity and $\langle p_T \rangle \sim 0.65$ GeV/c
  - 10K events should be enough

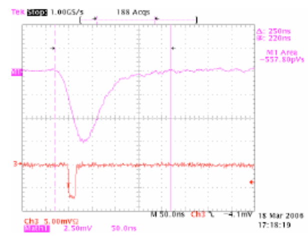


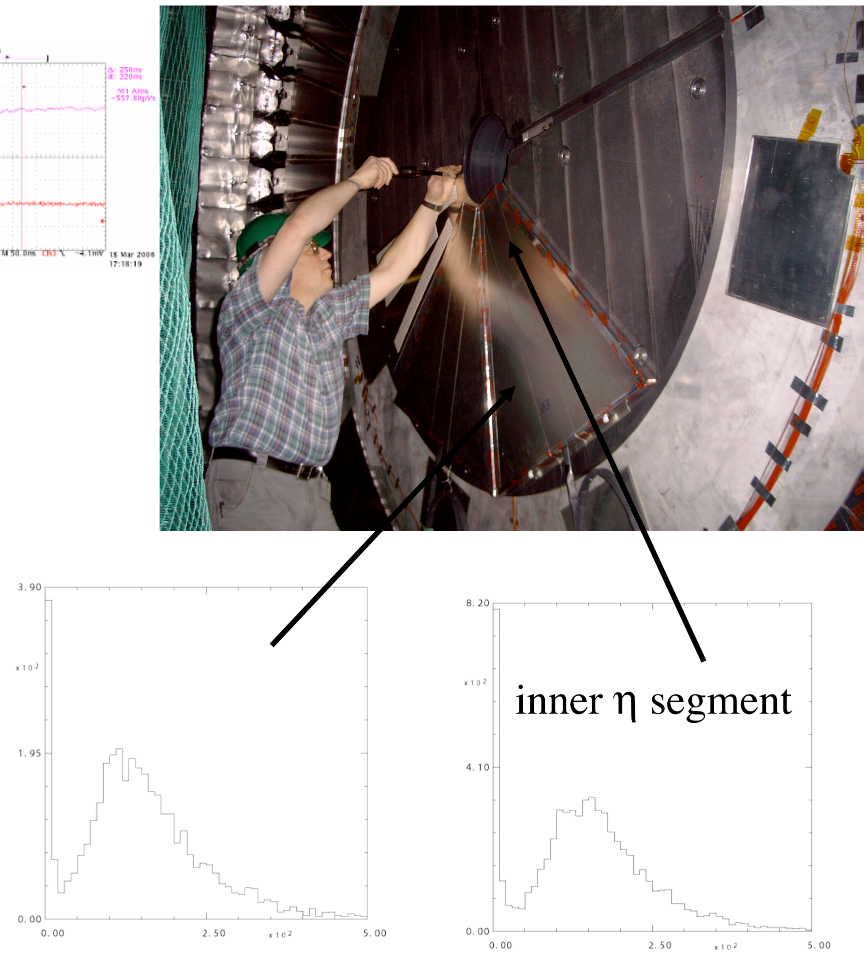
Early triggering in ATLAS

- Beam pickups will indicate which bunches are filled
- Need a fast signal from detector that an interaction has occurred
- This is the role of the MBTS counters
  - mounted on LAr cryostats and cover an η region from ~2 to 3.8



  - 8 segments in ϕ on each side; 2 segments in η
  - good signal to noise offline
  - signal to noise online is being improved by mods to drawers





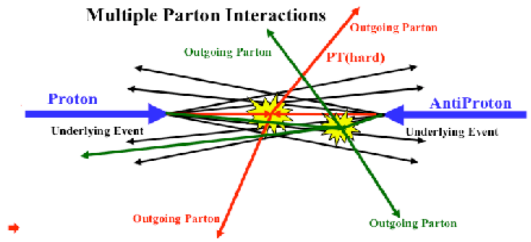
•trigger logic still being determined
•forward/backward coincidence, multiplicity at L1
•more info at L2, if needed
•will be first detector in ATLAS to die (but ok for year)

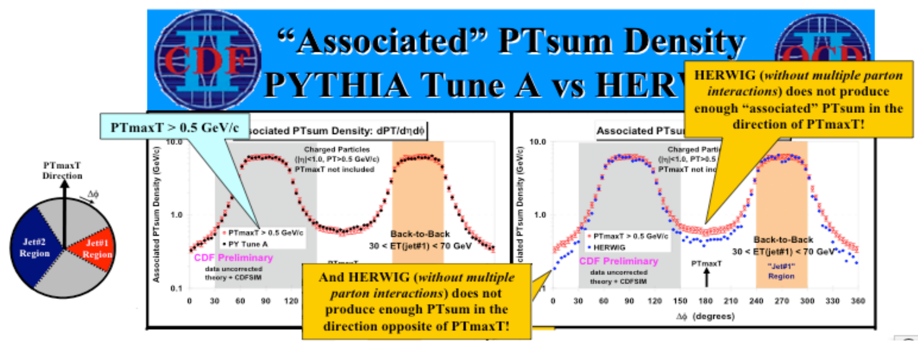
Known unknown: underlying event at the LHC

- There's also 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
  - ~20M MB events will allow overlap with hard scatter regime (~30 GeV/c)

The structure of the underlying event

Mounting experimental evidence (R.Field, CDF) that the UE is the result of **multiple semi-hard (minijet-like) interactions**





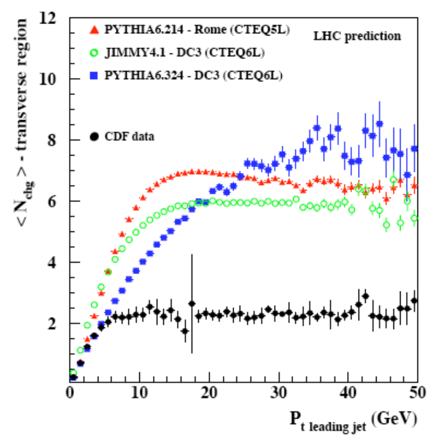


Figure 89. Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the transverse region in the underlying event for LHC *pp* collisions.

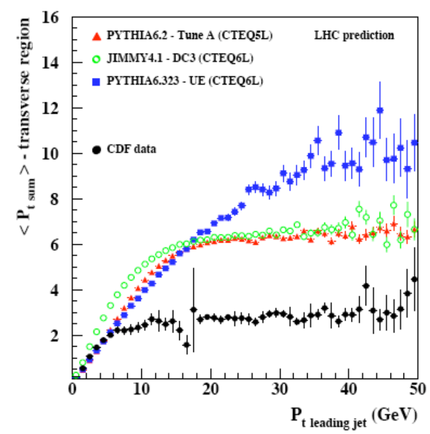


Figure 90. Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average sum of the transverse momenta of charged particles in the transverse region in the underlying event for LHC *pp* collisions.

Known known: the LHC will be a very *jetty* place

- 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
- $\sigma_{W+3\ jets} > \sigma_{W+2\ jets}$

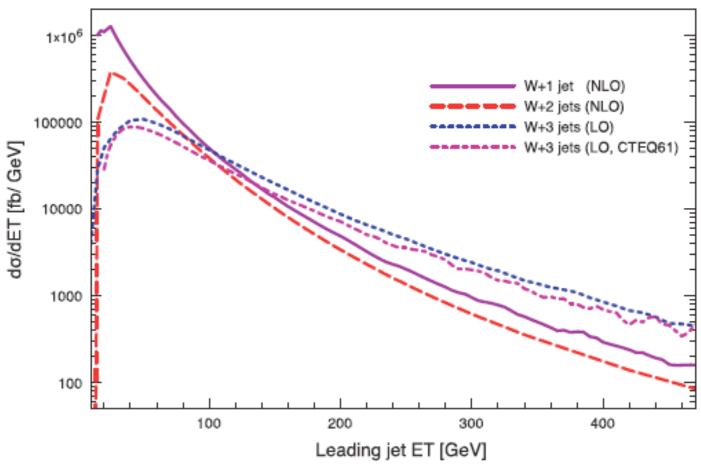


Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- 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

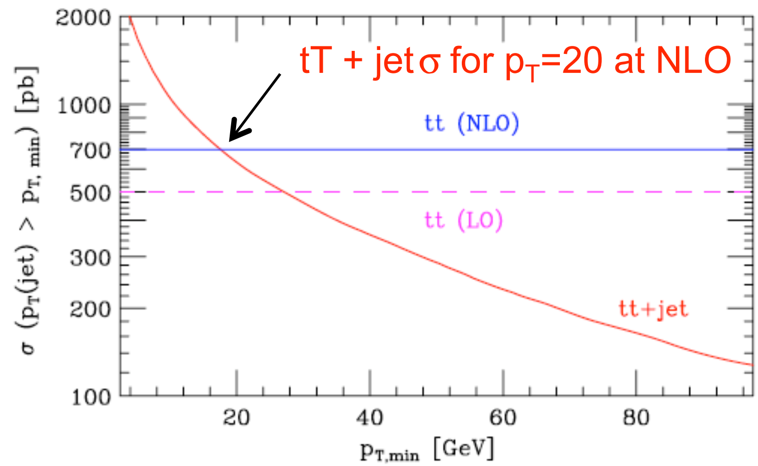


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

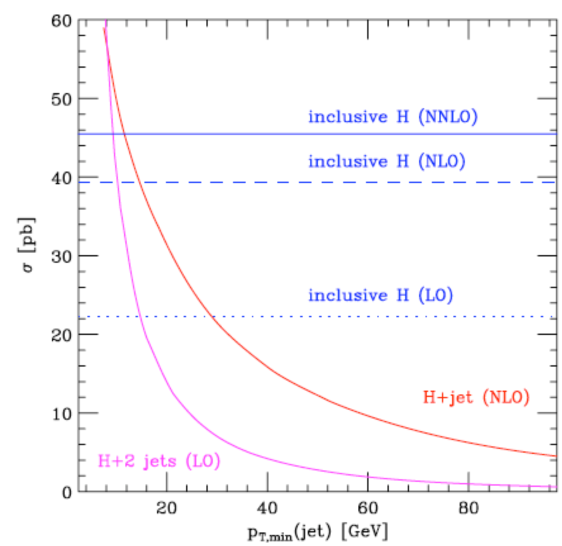


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\mathrm{min}}$, together with the top pair production cross sections at LO and NLO.

Sudakov form factors

- Sudakov form factor gives the probability for a gluon **not** to be emitted; basis of parton shower Monte Carlos
- Consider tT production
- In going from the Tevatron to the LHC, you are moving from primarily qQ initial states to gg initial states
- …and to smaller values of parton x
  - so there's more phase space for gluon emission
- So significantly more *extra* jets associated with the tT final state

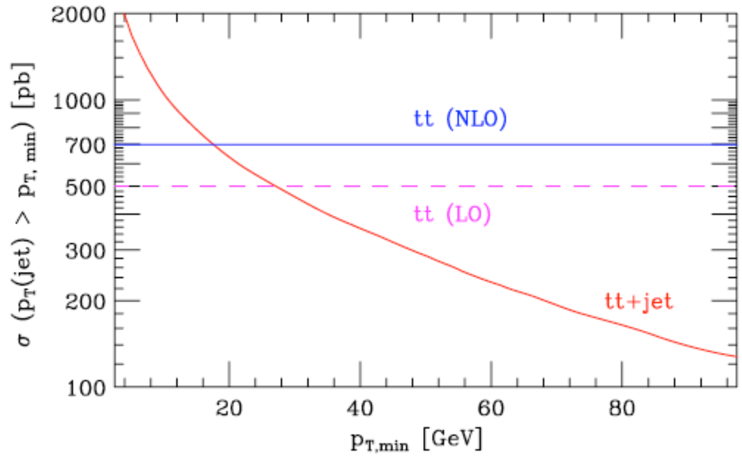


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\rm min}$, together with the top pair production cross sections at LO and NLO.

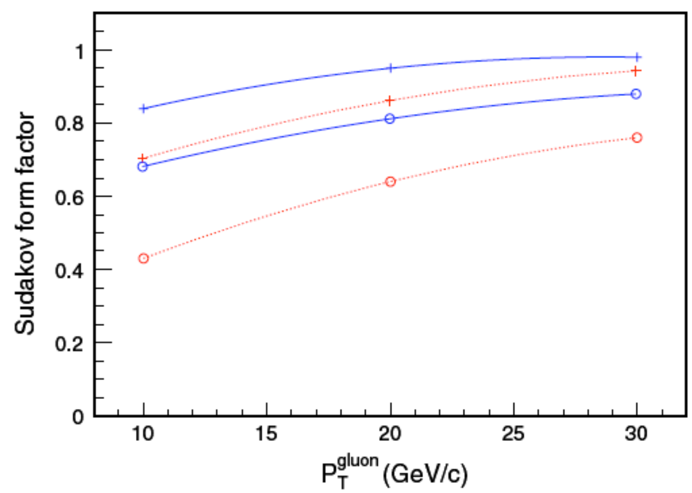


Figure 96. The Sudakov form factors for initial-state quarks and gluons at a hard scale of 200 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for quarks (blue-solid) and gluons (red-dashed) at parton x values of 0.3 (crosses) and 0.03 (open circles).

NLO corrections

- NLO is the first order for which the normalization, and sometimes the shape, is believable
- NLO is necessary for precision comparisons of data to theory
- Sometimes backgrounds to new physics can be extrapolated from non-signal regions, but this is difficult to do for low cross section final states and/or final states where a clear separation of a signal and background region is difficult

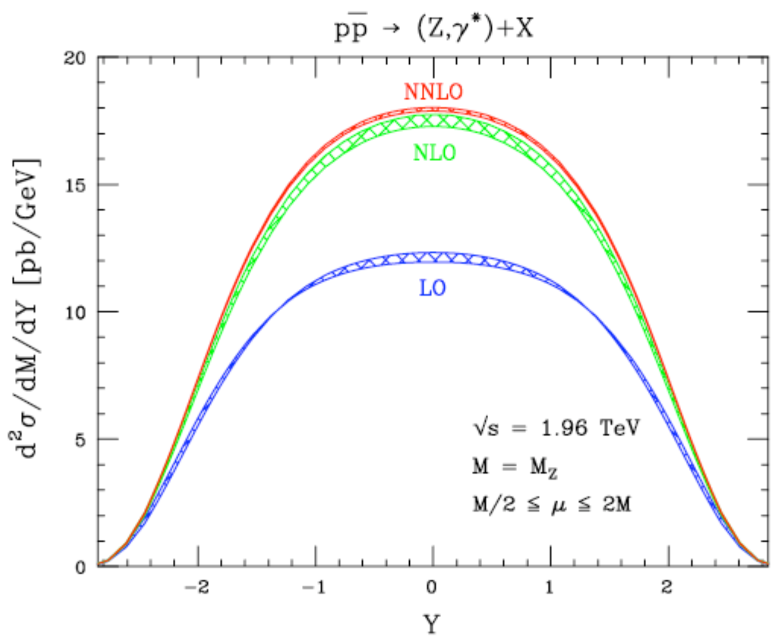


Figure 38. Predictions for the rapidity distribution of an on-shell Z boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$.

NLO corrections

Sometimes it is useful to define a K-factor (NLO/LO). Note the value of the K-factor depends critically on its definition. K-factors at LHC (mostly) similar to those at Tevatron.

CHS

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	1.15
$W+1$ jet	m_W	$\langle p_T^{\text{jet}} \rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W+2$ jets	m_W	$\langle p_T^{\text{jet}} \rangle$	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	$\langle p_T^{\text{jet}} \rangle$	1.07	0.97	1.07	1.23	1.34	1.09
Higgs + 1 jet						1.42		
Higgs + 2 jets						1.15		
tT + 1 jet			1.19	1.37	1.26	0.97	1.29	1.10

K-factors may differ from unity because of new subprocesses/ contributions at higher order **and/or differences between LO and NLO pdf's**

Now we come to the "maligned" experimenter's NLO 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
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$		$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

→ 7 years later and yet not a single calculation finished! Shame

NLO calculation priority list from Les Houches 2005: theory benchmarks

G. Heinrich and J. Huston

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.

pp->bBbB
pp->4 jets
gg->W*W*

added in 2007

*completed since list
+people are working

- $pp \to$ 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.

[23] Process 2 has been calculated since the first version of this list was formulated [138].

What about time lag in going from availability of matrix elements to having a parton level Monte Carlo available? See e.g. H + 2 jets. Other processes are going to be just as complex. What about other processes for which we are theorist/time-limited?

Go back to K-factor table

- Some rules-of-thumb
- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - gg->Higgs
  - gg->γγ
  - *K*(gg->tT) > *K*(qQ -> tT)
- NLO corrections decrease as more final-state legs are added
  - *K*(gg->Higgs + 2 jets) < *K*(gg->Higgs + 1 jet) < *K*(gg->Higgs)
  - unless can access new initial state gluon channel
- Can we generalize for uncalculated HO processes?
  - so expect K factor for W + 3 jets or Higgs + 3 jets to be reasonably close to 1

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.

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Higgs via WBF	m_H	$\langle p_T^{\text{jet}}\rangle$	1.07	0.97	1.07	1.23	1.34	1.09

Casimir for biggest color representation final state can be in

Simplistic rule

$C_{i1} + C_{i2} - C_{f,max}$

Casimir color factors for initial state

Don't forget

- NNLO: we need to know some processes (such as inclusive jet production) at NNLO
- Resummation effects: affect important physics signatures
  - mostly taken into account if NLO calculations can be linked with parton showering Monte Carlos

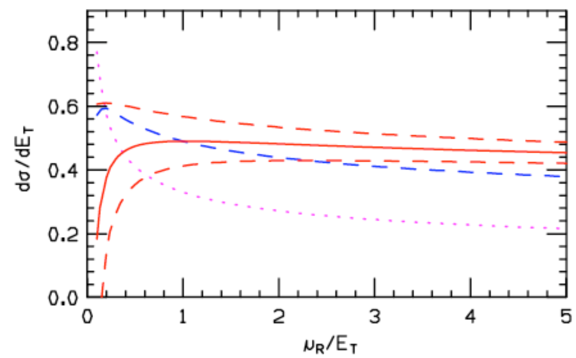


Figure 16. The single jet inclusive distribution at $E_T = 100$ GeV, appropriate for Run I of the Tevatron. Theoretical predictions are shown at LO (dotted magenta), NLO (dashed blue) and NNLO (red). Since the full NNLO calculation is not complete, three plausible possibilities are shown.

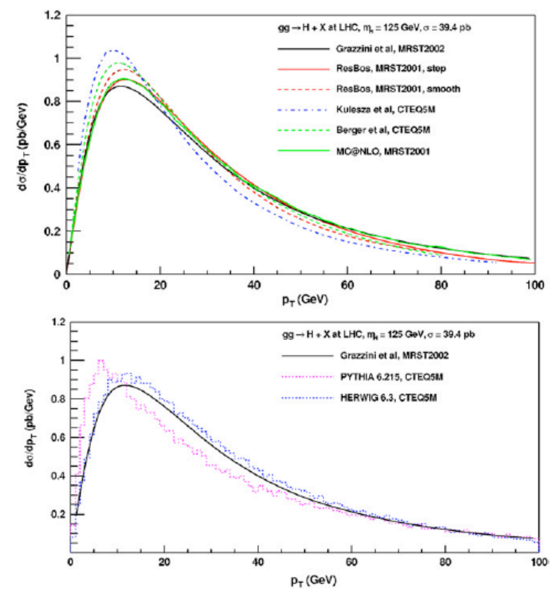


Figure 102. The predictions for the transverse momentum distribution for a 125 GeV mass Higgs boson at the LHC from a number of theoretical predictions. The predictions have all been normalized to the same cross section for shape comparisons. This figure can also be viewed in colour on the benchmark website.

…and

- BFKL logs: will we finally see them at the LHC?

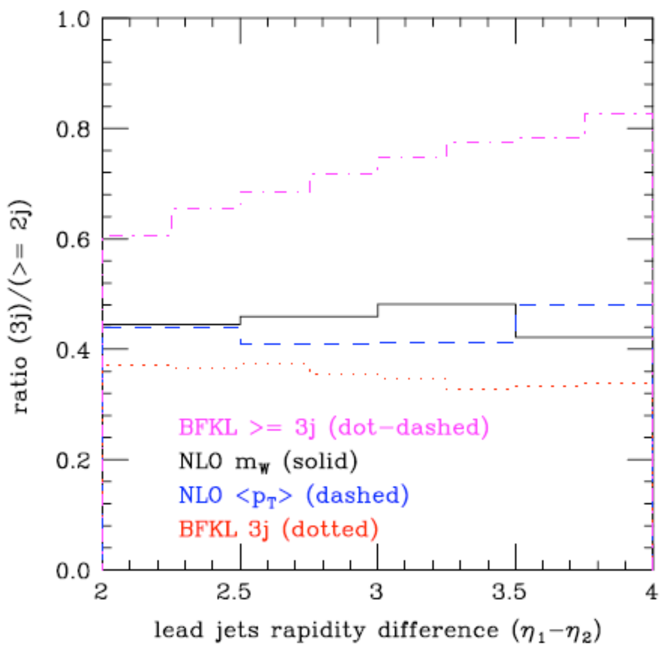
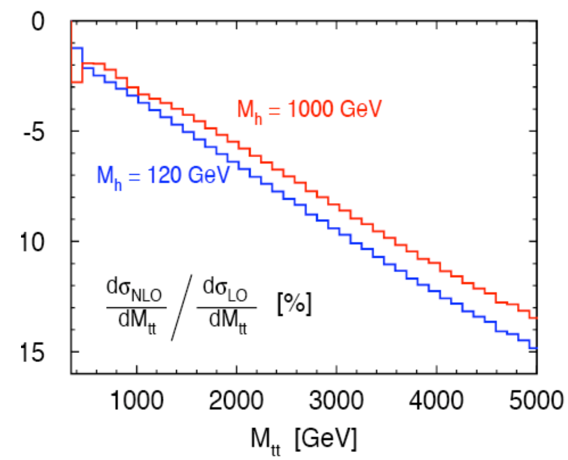


Figure 92. The rate for production of a third (or more) jet in $W + \geqslant 2$ jet events as a function of the rapidity separation of the two leading jets. A cut of 20 GeV has been placed on all jets. Predictions are shown from MCFM using two values for the renormalization and factorization scale,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

- EW logs: $\alpha_W \log^2(p_T^2/m_W^2)$ can be a big number at the LHC



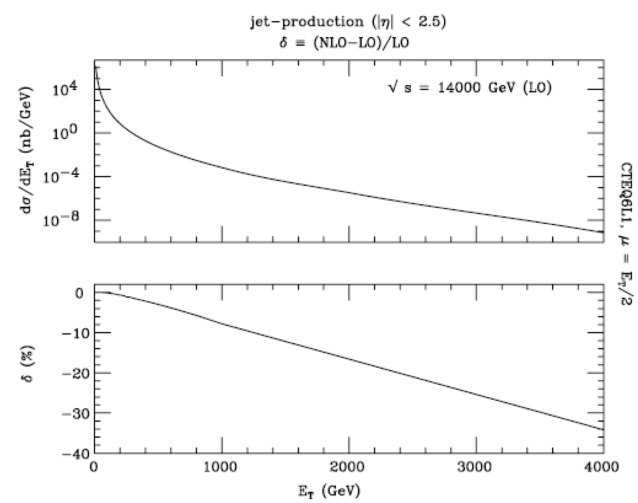


Figure 107. The effect of electroweak logarithms on jet cross sections at the LHC.

Precision benchmarks: W/Z cross sections at the LHC

- CTEQ6.1 and MRST NLO predictions in good agreement with each other →
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC

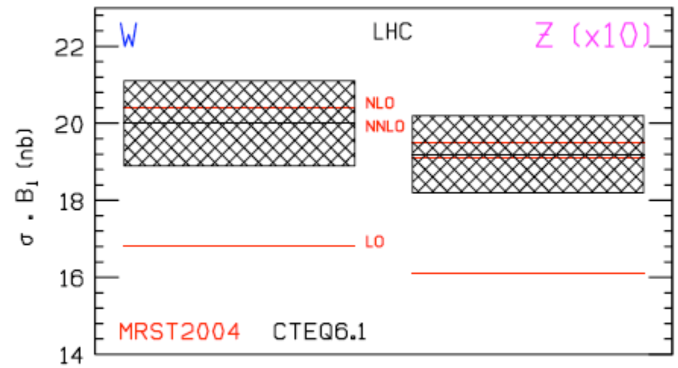


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

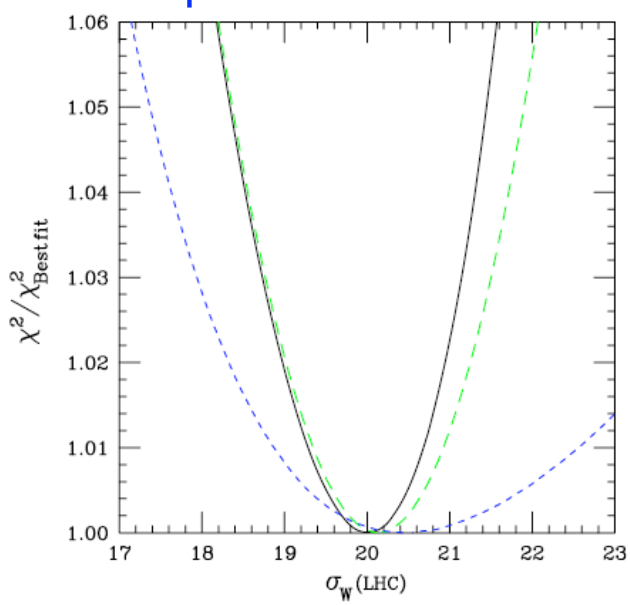
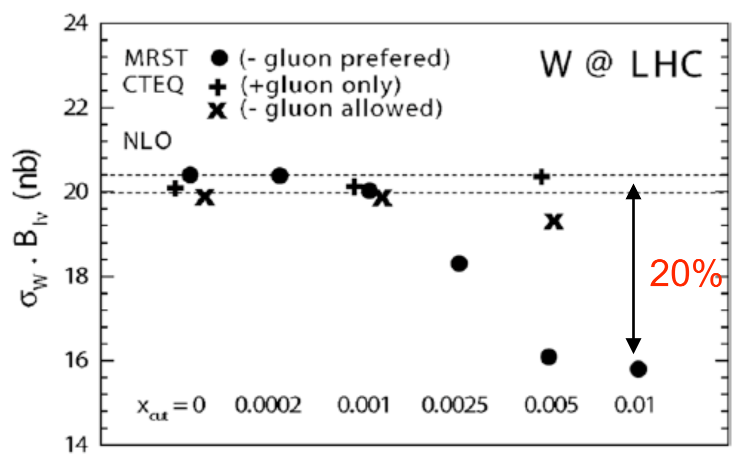


Figure 82. Lagrange multiplier results for the W cross section (in nb) at the LHC using a positive–definite gluon. The three curves, in order of decreasing steepness, correspond to three sets of kinematic cuts, standard/intermediate/strong.

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



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

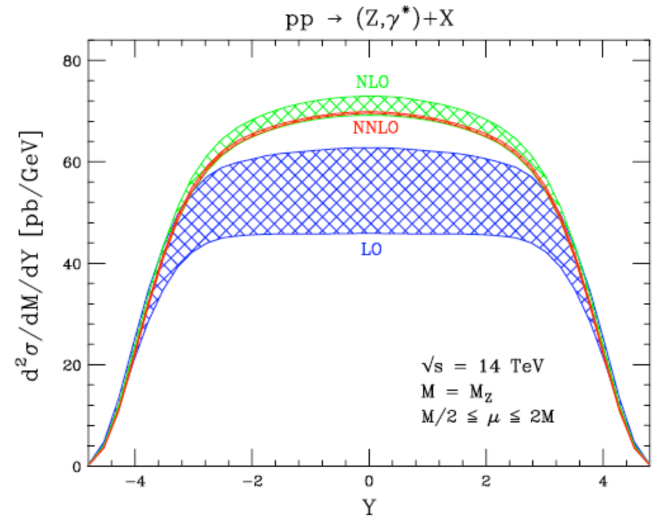


Figure 87. The rapidity distributions for *Z* production at the LHC at LO, NLO and NNLO.

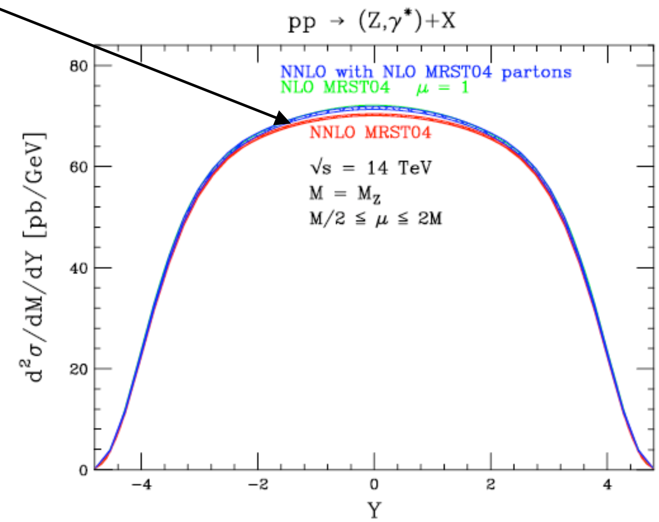


Figure 88. The rapidity distributions for *Z* production at the LHC at NNLO calculated with NNLO and with NLO pdfs.

W/Z p_T distributions

- p_T distributions will be shifted (slightly) upwards due to larger phase space for gluon emission
- I've generated a million W->eν and Z->ee events for each of the CTEQ6.1 error pdf's using ResBos
  - currently ROOT ntuples on CASTOR at CERN for use by ATLAS (castor/cern.ch/atlas/project/smgroup/ResBos
- BFKL logs may become important and have a noticeable effect
  - **one of the first steps at the LHC will be to understand the dynamics of W/Z production**
  - **can be done with first 100 pb^{-1}**

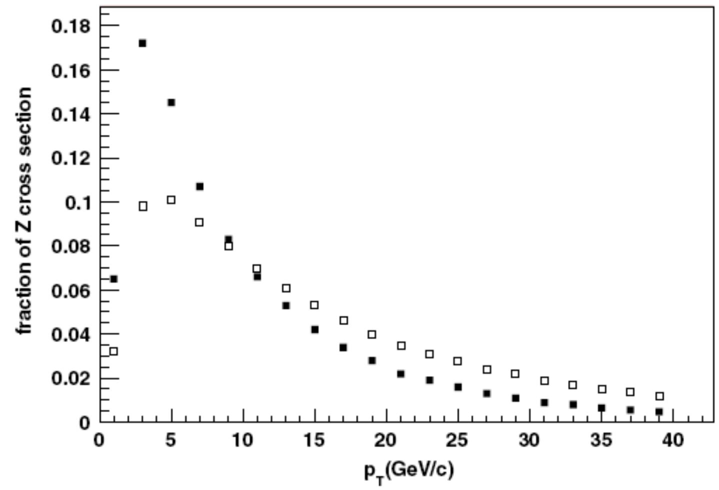


Figure 89. Predictions for the transverse momentum distributions for *Z* production at the Tevatron (solid squares) and LHC (open squares).

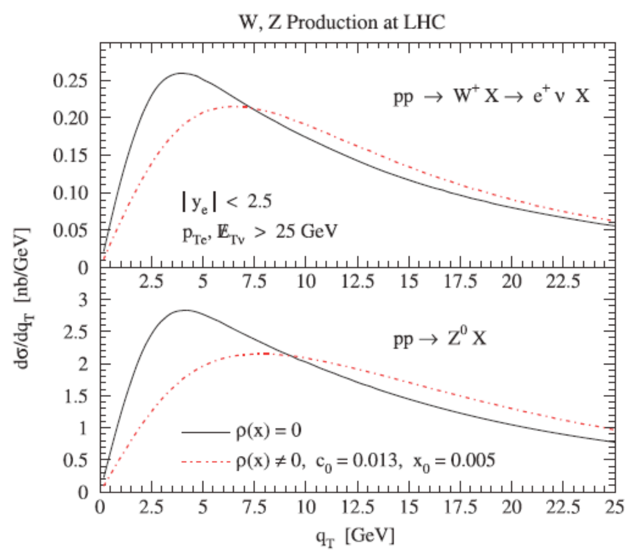


Figure 90. The predictions for the transverse momentum distributions for *W* and *Z* production with and without the p_T-broadening effects.

Correlations using CTEQ6.1 error pdf's

- 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 (low mass) H and W cross sections
  - see more later

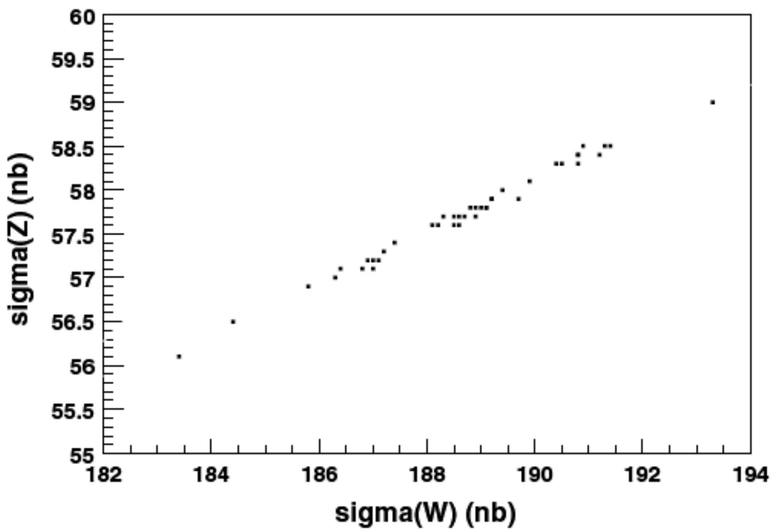


Figure 85. The cross section predictions for Z production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

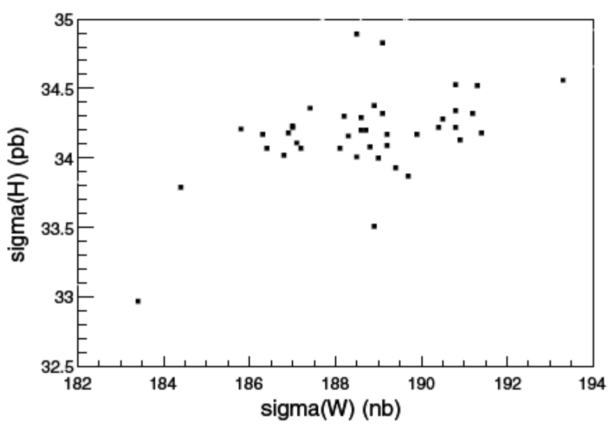


Figure 99. The cross section predictions for Higgs production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

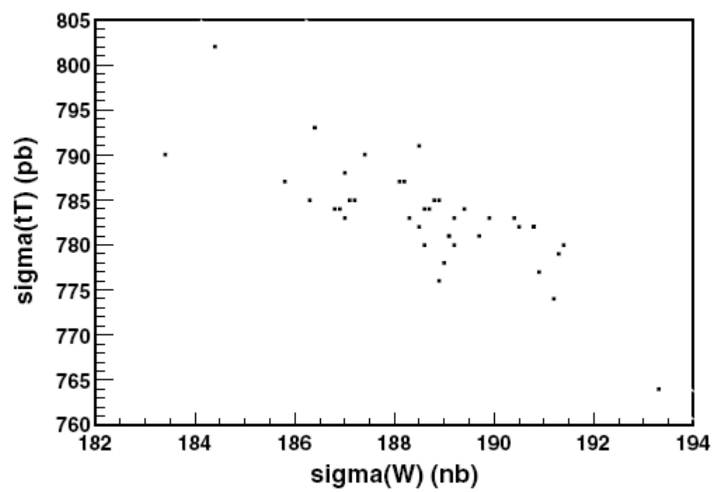
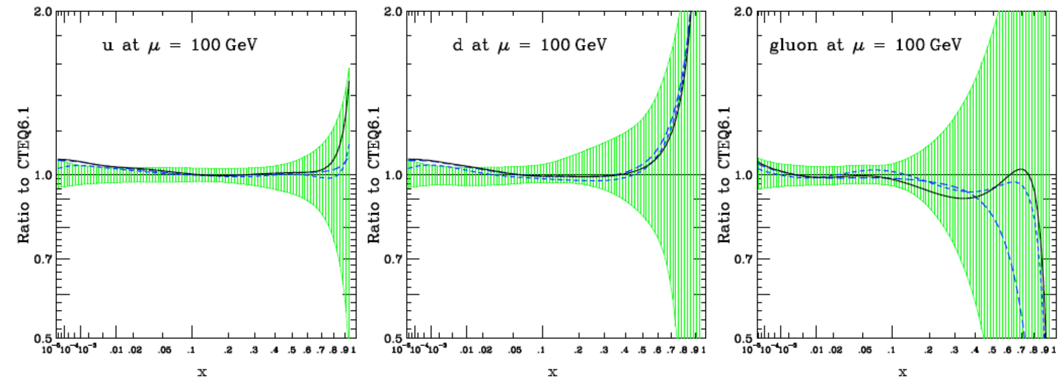


Figure 93. The cross section predictions for $t\bar{t}$ production versus the cross section predictions for W production at the LHC plotted using the 41 CTEQ6.1 pdfs.

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 (CTEQ6.5/6.6), 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



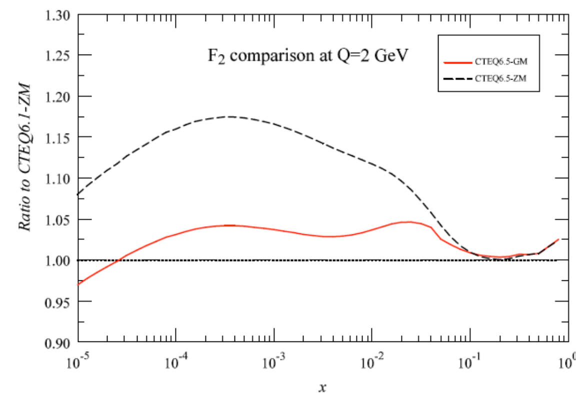
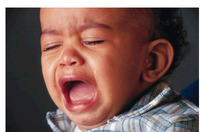


Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

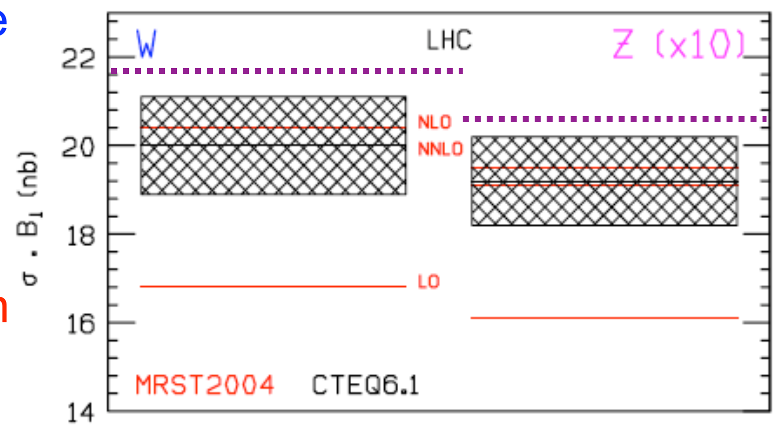
→ implications for LHC phenomenology

CTEQ6.5(6)

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- Cross sections for W/Z increase by 7-8%
  - now CTEQ and MRST2004 in disagreement

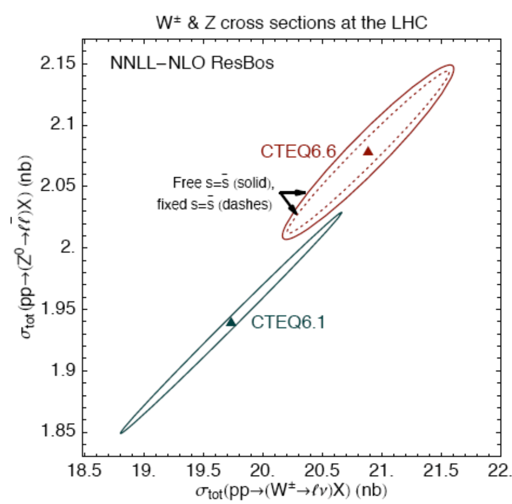


  - and relative uncertainties of W/Z increase
  - although individual uncertainties of W and Z decrease
- Two new free parameters in fit dealing with strangeness degrees of freedom so now have 44 error pdf's rather than 40



CTEQ6.5(6)

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.

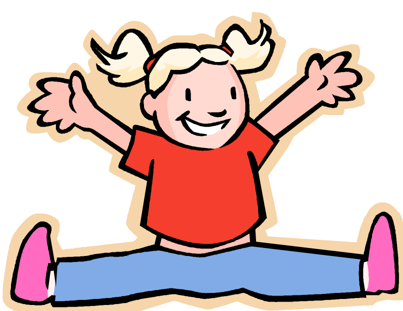


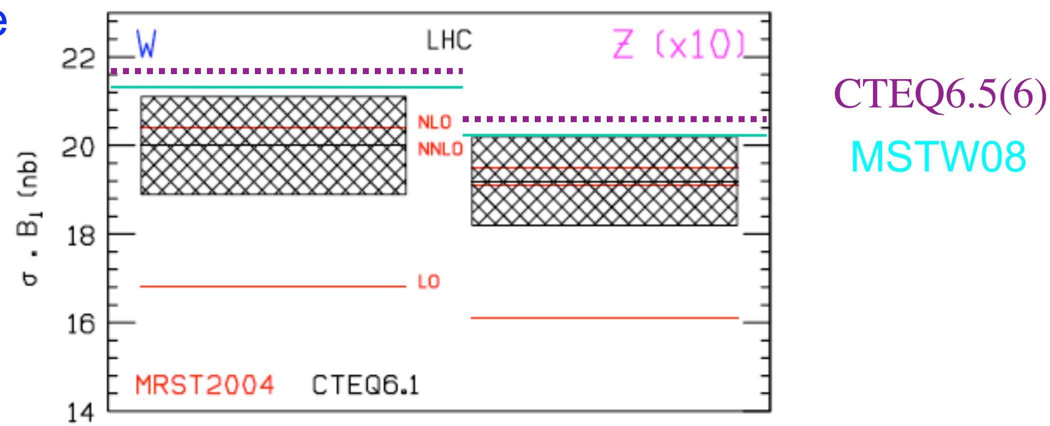
Note importance of strange quark uncertainty for ratio

Figure 8: W & Z correlation ellipses at the LHC obtained in the fits with free and fixed strangeness.

CTEQ6.5(6)

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- …but MSTW2008 has also lead to increased W/Z cross sections at the LHC
    - now CTEQ6.6 and MSTW2008 in agreement





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Now some technical stuff

- Consider a cross section X(a)
- i^{th} component of gradient of X is

$$\frac{\partial X}{\partial a_i} \equiv \partial_i X = \frac{1}{2}(X_i^{(+)} - X_i^{(-)})$$

- Now take 2 cross sections X and Y
  - or one or both can be pdf's
- Consider the projection of gradients of X and Y onto a circle of radius 1 in the plane of the gradients in the parton parameter space
- The circle maps onto an ellipse in the XY plane
- The angle ϕ between the gradients of X and Y is given by

$$\cos\varphi = \frac{\vec{\nabla} X \cdot \vec{\nabla} Y}{\Delta X \Delta Y} = \frac{1}{4 \Delta X \, \Delta Y} \sum_{i=1}^{N} \left(X_i^{(+)} - X_i^{(-)} \right) \left(Y_i^{(+)} - Y_i^{(-)} \right)$$

- The ellipse itself is given by

$$\left(\frac{\delta X}{\Delta X}\right)^2 + \left(\frac{\delta Y}{\Delta Y}\right)^2 - 2\left(\frac{\delta X}{\Delta X}\right)\left(\frac{\delta Y}{\Delta Y}\right)\cos\varphi = \sin^2\varphi$$

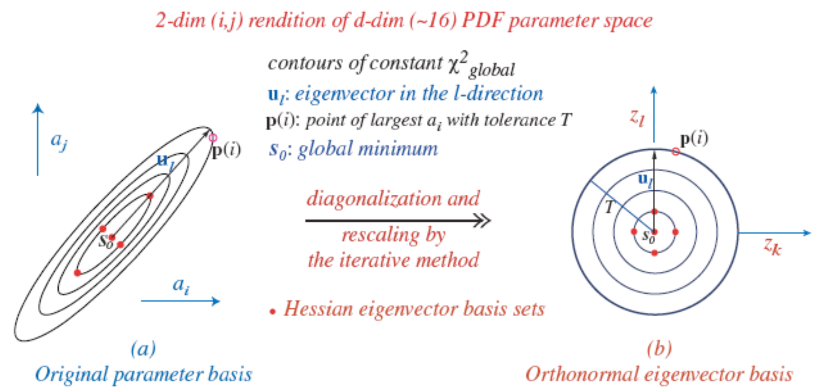


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

- If two cross sections are very correlated, then $\cos\phi \sim 1$
- …uncorrelated, then $\cos\phi \sim 0$
- …anti-correlated, then $\cos\phi \sim -1$

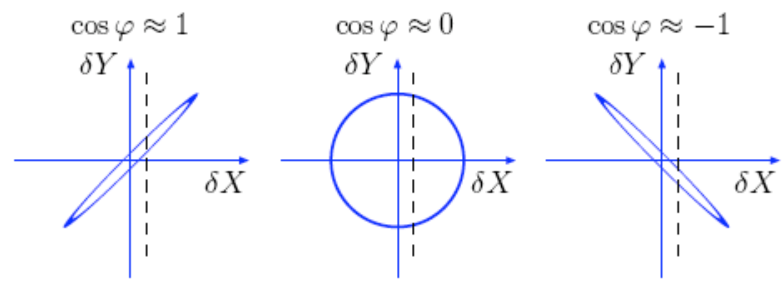


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

Correlations: W/Z and pdf's

- At the Tevatron, W and Z cross sections most correlated with u,U,d,D pdf's
- At the LHC, W and Z cross sections most correlated with charm, bottom and gluon distributions
- A large correlation with the gluon for x values ~0.005 is accompanied by a large anti-correlation with the gluon at larger x
- This implies a strong anti-correlation of W and Z with heavy states produced by gg

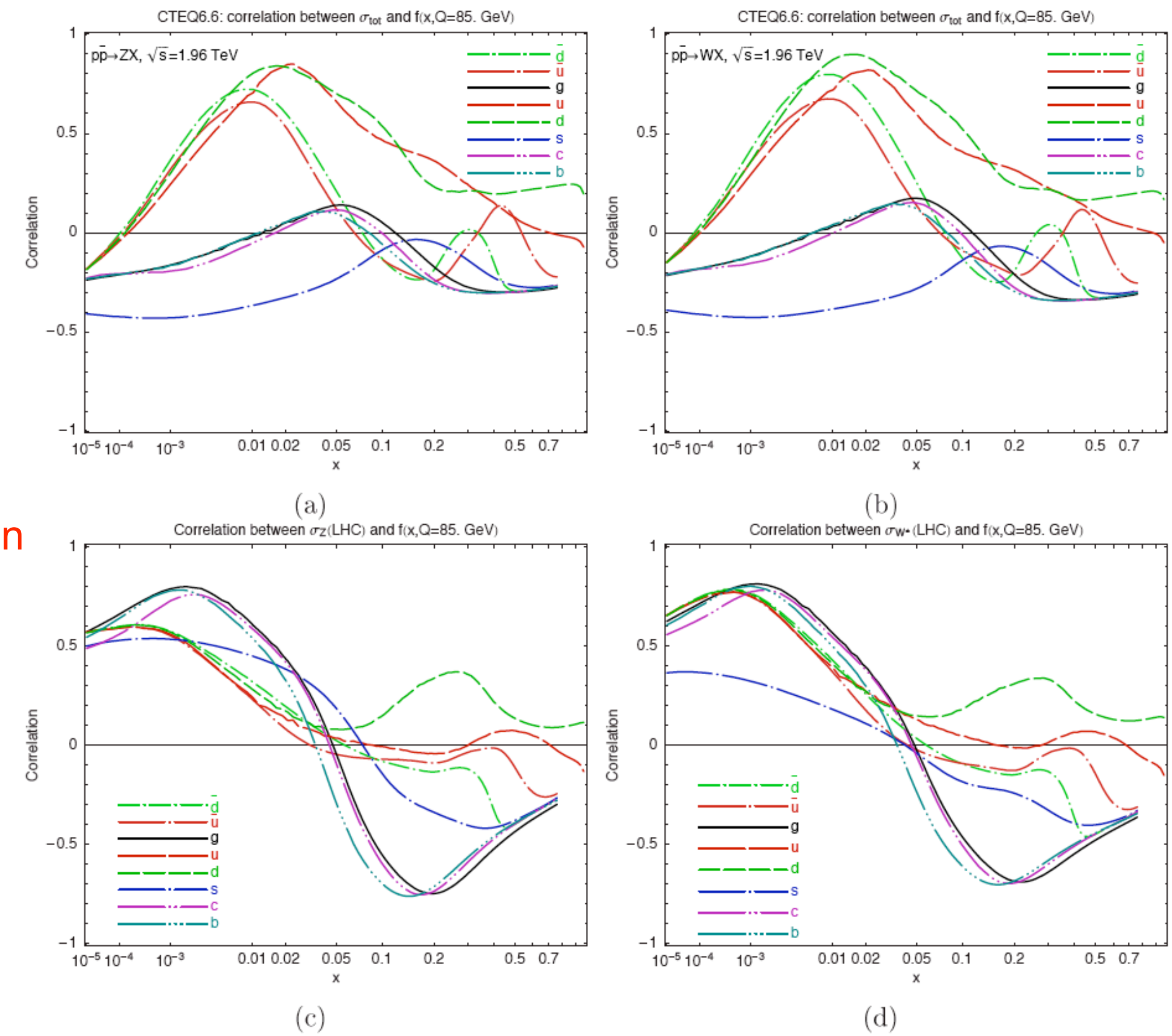
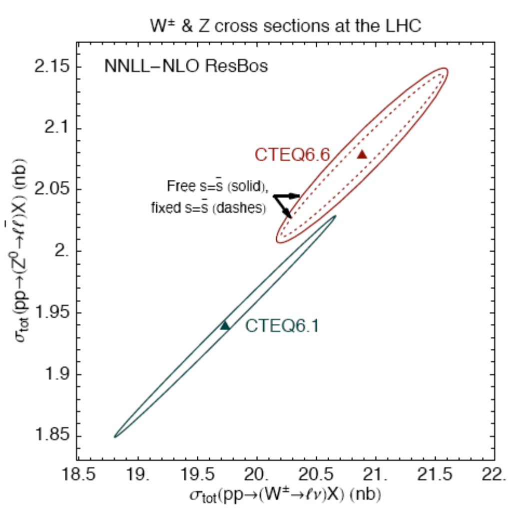


Figure 10: (a,b) Correlation between the total cross sections for Z^0 and $W^\pm$ production at the Tevatron and PDF's of various flavors, plotted as a function of x for $Q = 85$ GeV; (c,d) the same for the LHC

Correlations: Z to W ratio

- The ratio of the Z to W cross section is most strongly correlated with the strange quark distribution



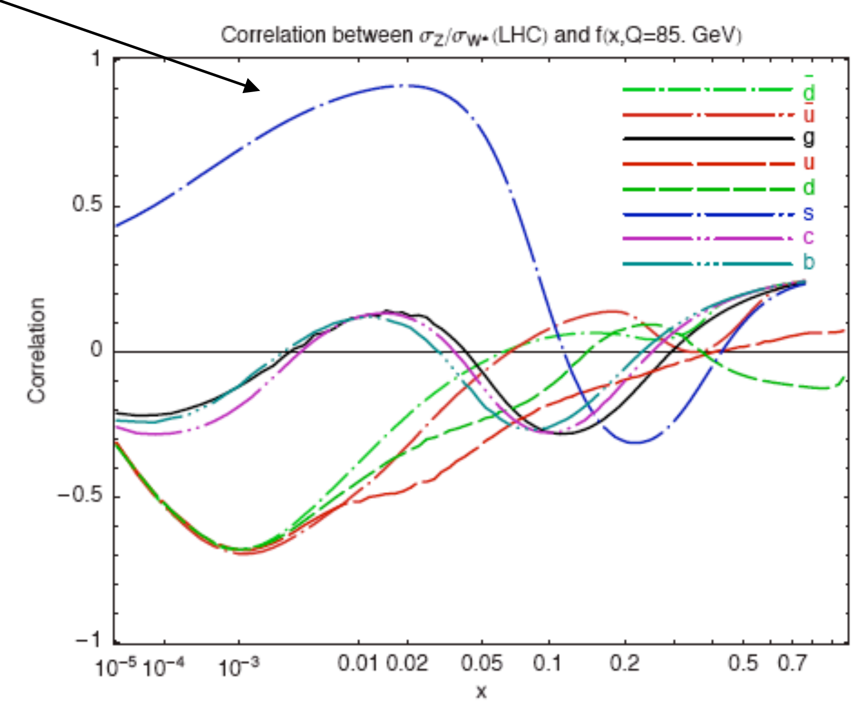


Figure 11: Correlation between the ratio σ_Z/σ_W of LHC total cross sections for Z^0 and $W^\pm$ production at PDF's of various flavors, plotted as a function of x for $Q = 85$ GeV.

Re-visit correlations with Z, tT

Define a correlation cosine between two quantities

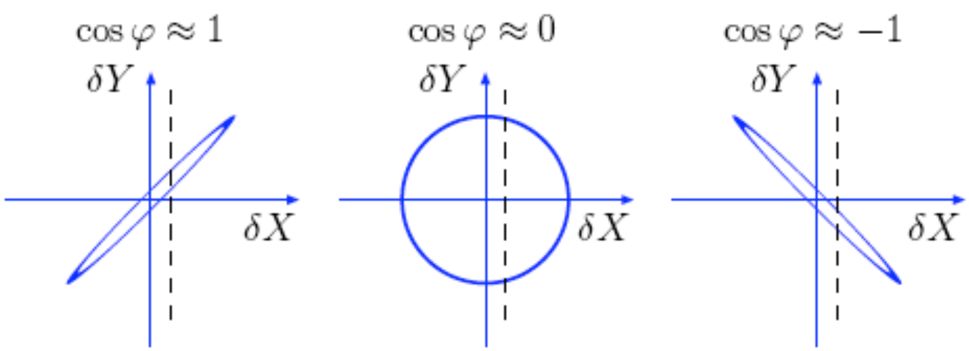
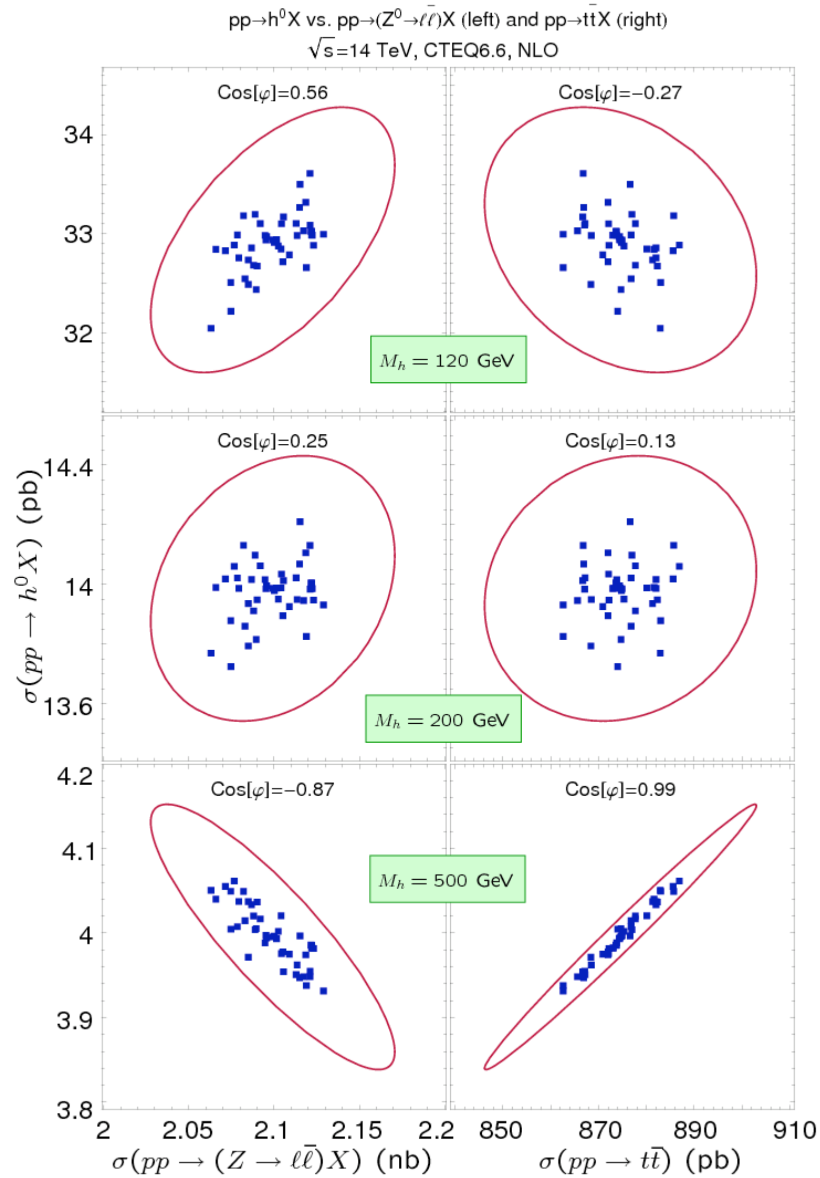


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.



- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1

Re-visit correlations with Z, tT

Define a correlation cosine between two quantities

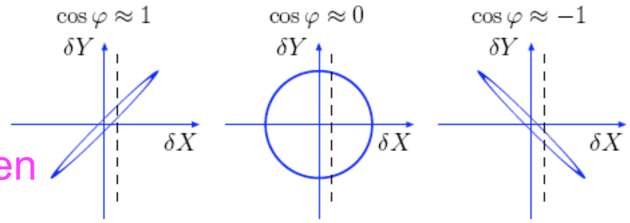


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosϕ~1
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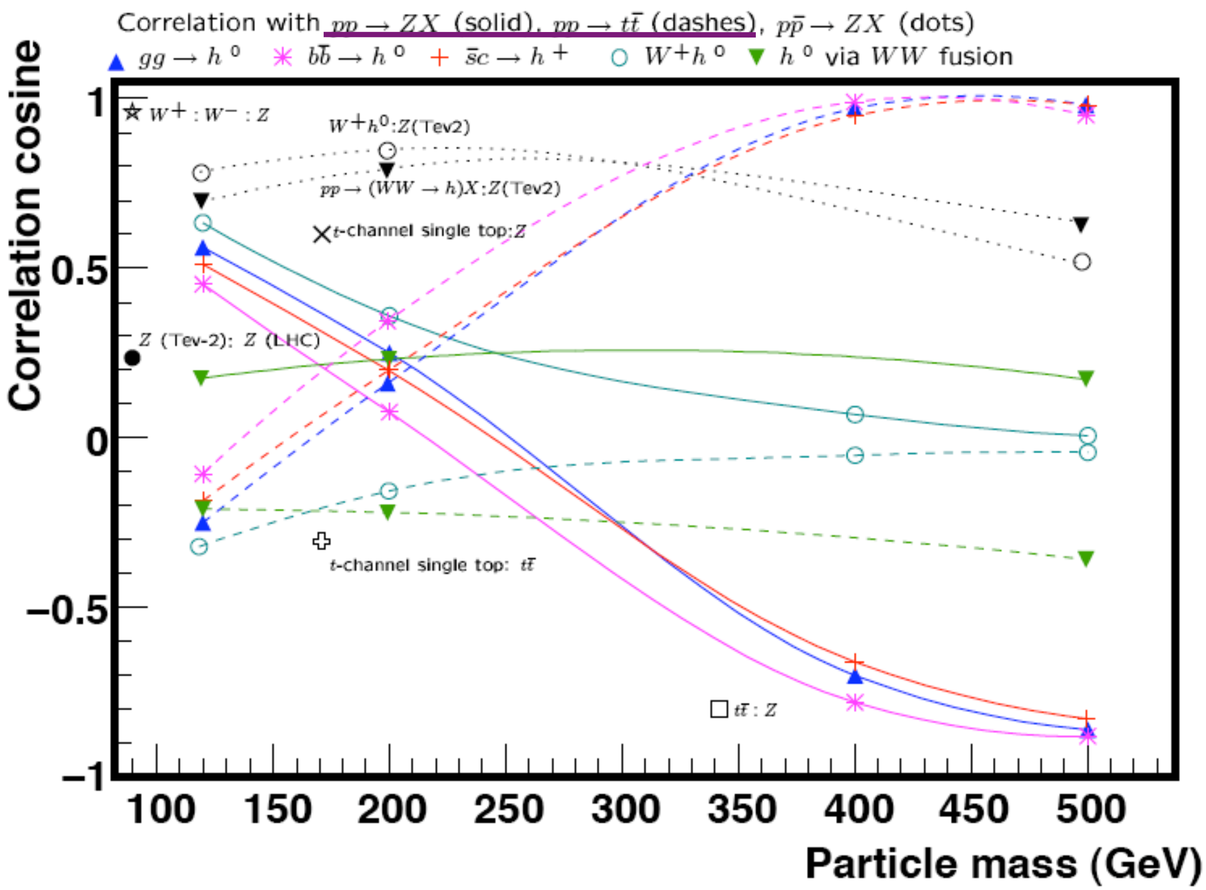


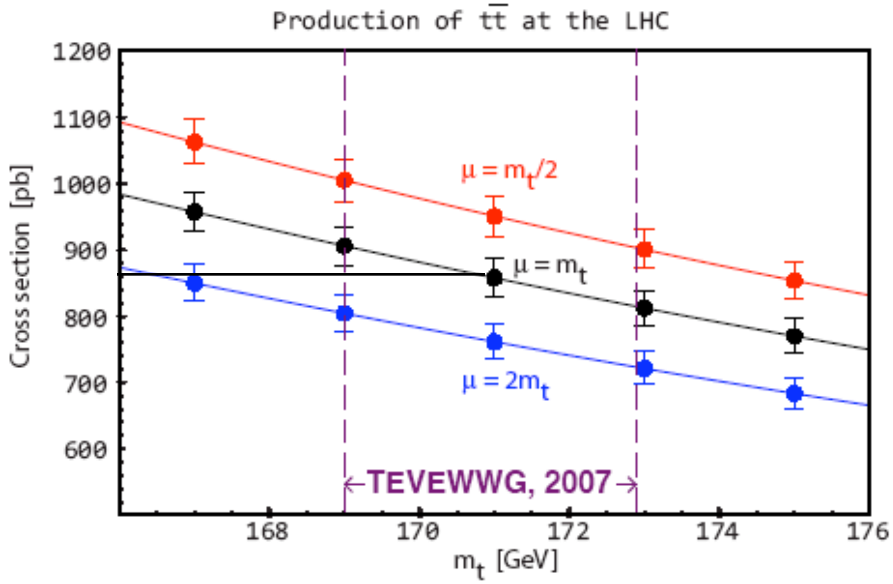
- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_{W^+}/\sigma_Z)$~1%
- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger
- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

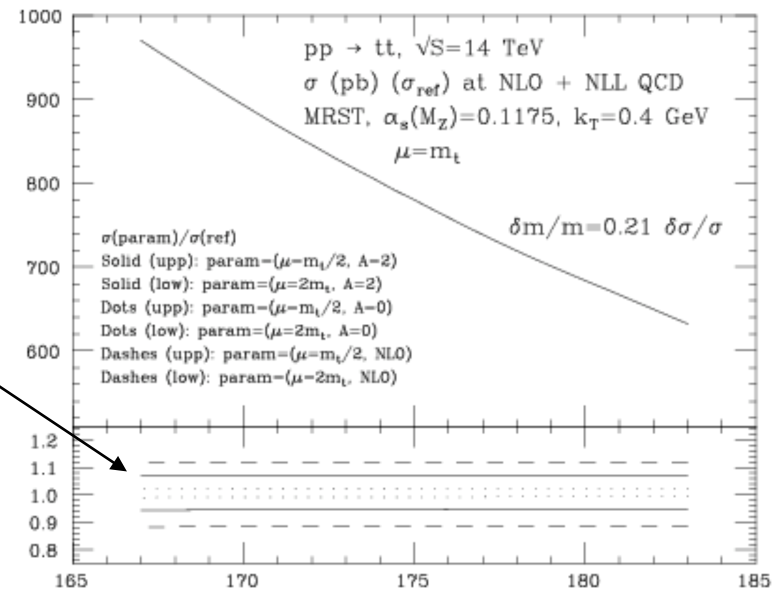
W/Z summary so far

- We will use W and Z cross sections as luminosity normalizations in early running and perhaps always
  - because integrated luminosity is not going to be known much better than 15-20% at first and maybe never better than 5-10%
- The pdf uncertainty for the ratio of a cross section that proceeds with a qQ initial state to the W/Z cross section is significantly reduced
- The pdf uncertainty for the ratio of a cross section that proceeds with a gg initial state to the W/Z cross section is significantly increased
- Would it be reasonable to use tT production as an additional normalization tool?

Theory uncertainties for tT at LHC

- Note that at NLO with CTEQ6.6 pdf's the central prediction for the tT cross section for $\mu=m_t$ is ~850 pb (not 800 pb, which it would be if the top mass were 175 GeV); ~880 pb if use effect of threshold resummation
- The scale dependence is around +/-11% and mass dependence is around +/-6%
- Tevatron plans to measure top mass to 1 GeV
  - mass dependence goes to ~+/-3%
- NNLO tT cross section will be finished this year (Czakon et al)
  - scale dependence will drop (how far?)
  - threshold resummation reduces scale dependence to <6%; may hope for 3% with full NNLO
- tT still in worse shape than W/Z, but not by too much
  - and pdf uncertainty is (a bit) smaller





New tool from John Campbell: MCFM with pdf errors

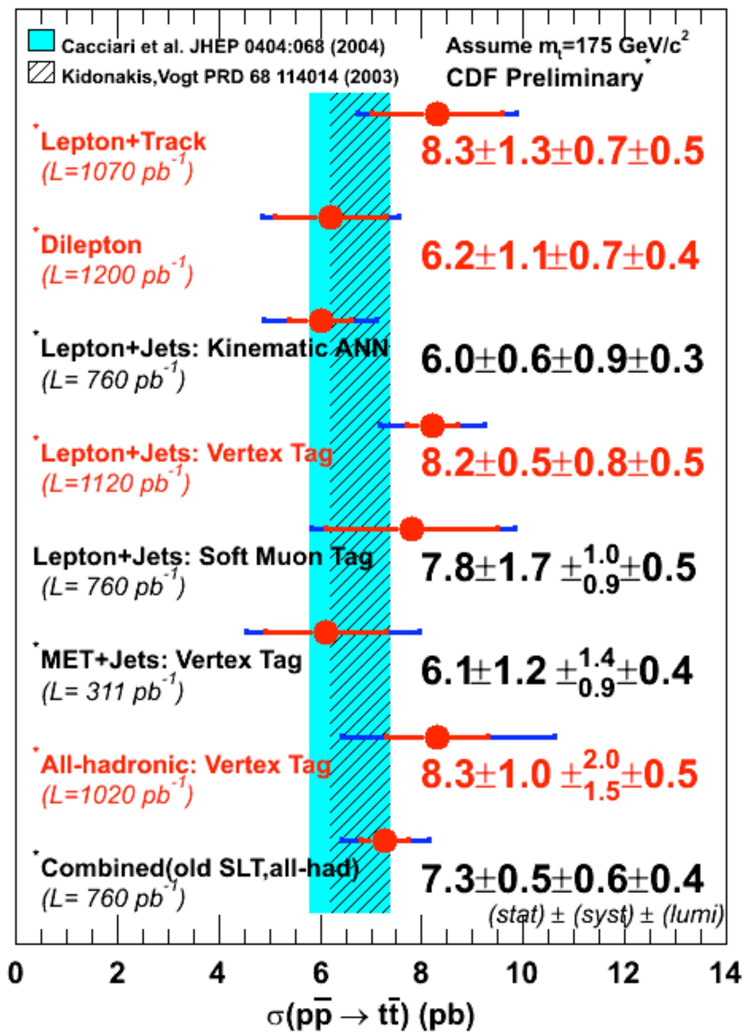
- Error pdf parton luminosities stored along with other event information; tremendous time-saving for MCFM
- Example output below from tT at LHC with CTEQ6.1(virtual diagrams only)

```
PDF error set  0 --->  922503.705 fb
PDF error set  1 --->  924901.729 fb
PDF error set  2 --->  920106.561 fb
PDF error set  3 --->  926873.142 fb
PDF error set  4 --->  918314.821 fb
PDF error set  5 --->  924319.039 fb
PDF error set  6 --->  920737.988 fb
PDF error set  7 --->  930912.022 fb
PDF error set  8 --->  914120.978 fb
PDF error set  9 --->  944892.019 fb
PDF error set 10 --->  899134.509 fb
PDF error set 11 --->  910661.311 fb
PDF error set 12 --->  933849.973 fb
PDF error set 13 --->  918037.641 fb
PDF error set 14 --->  926658.411 fb
PDF error set 15 --->  929544.061 fb
PDF error set 16 --->  916165.078 fb
PDF error set 17 --->  926807.189 fb
PDF error set 18 --->  918520.852 fb
PDF error set 19 --->  914185.317 fb
PDF error set 20 --->  928791.454 fb
PDF error set 21 --->  916124.098 fb
PDF error set 22 --->  919646.351 fb
PDF error set 23 --->  922102.562 fb
PDF error set 24 --->  920512.494 fb
PDF error set 25 --->  923791.211 fb
PDF error set 26 --->  919567.536 fb
PDF error set 27 --->  924333.235 fb
PDF error set 28 --->  922540.280 fb
PDF error set 29 --->  917348.784 fb
PDF error set 30 --->  933489.451 fb
PDF error set 31 --->  921711.144 fb
PDF error set 32 --->  920739.212 fb
PDF error set 33 --->  919592.767 fb
PDF error set 34 --->  923451.843 fb
PDF error set 35 --->  923859.904 fb
PDF error set 36 --->  923632.556 fb
PDF error set 37 --->  923740.945 fb
PDF error set 38 --->  921204.429 fb
PDF error set 39 --->  922465.341 fb
PDF error set 40 --->  922560.436 fb
* --------------- SUMMARY -------------
*      Minimum value     899134.509 fb
*      Central value     922503.705 fb
*      Maximum value     944892.019 fb
*      Err estimate +/-  31131.272 fb
*      +ve direction     31383.680 fb
*      -ve direction     32098.504 fb
****************************************
```

real diagrams contribute -70000 fb, so central NLO is ~850 pb; threshold resum->880 pb

What about experimental uncertainties?

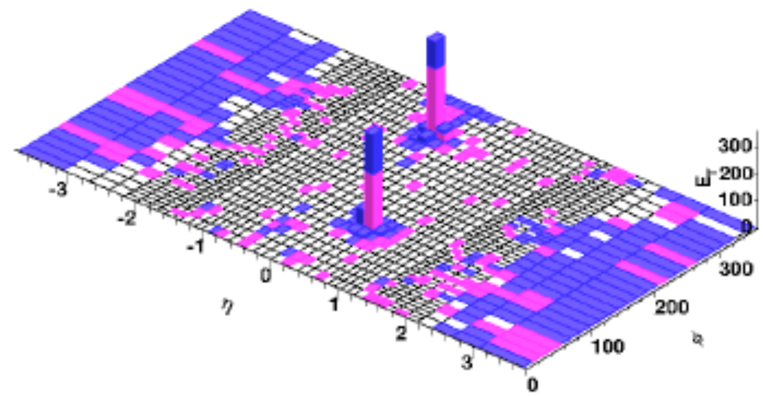
- 10-15% in first year
  - unfortunately, which is where we would most like to have a precise value
- Ultimately, ~5%?
  - dominated by b-tagging uncertainty?
  - systematic errors in common with other complex final states, which may cancel in a ratio?
- Tevatron now does 8% (non-lum)

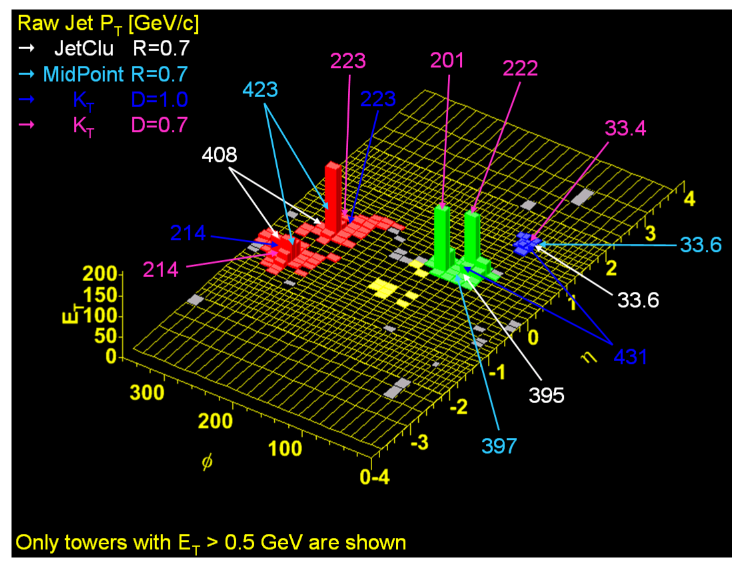


Last but not least: Jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers/ particles to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- There is the tendency to treat jet algorithms as one would electron or photon algorithms
- There's a much more dynamic structure in jet formation that is affected by the decisions made by the jet algorithms and which we can tap in ATLAS
- ATLAS, with its fine segmentation and the ability to make topoclusters, has perhaps the most powerful jet capabilities in any hadron collider experiment to date…if we take full advantage of what the experiment offers

CDF Run II events





Entrez Le SpartyJet

LAPP

SpartyJet

What is SpartyJet?

- "a framework intended to allow for the easy use of multiple jet algorithms in collider analyses"
  - **Fast** to run, no need for heavy framework
  - **Easy** to use, basic operation is very simple
  - **Flexible**
    - ROOT-script or standalone execution
      - "on-the-fly" execution for event-by-event results
    - many different input types
    - different algorithms
    - output format

Available Algorithms

CDF - JetClu
- MidPoint (with optional second pass)

D0 - D0RunIICone
(from Lars Sonnenschein)

ATLAS - Cone
- FastKt

FastJet (from Gavin Salam and Matteo Cacciari)
- FastKt
- Seedless Infrared Safe Cone (SISCone)

Pythia 8 - CellJet

all algorithms are fully parameterizable

JetBuilder

- basically a frontend to handle most of the details of running SpartyJet
- not necessary, but makes running SpartyJet **much** simpler
- Allows options that are not otherwise accessible
  - text output
  - add minimum bias events

with JetBuilder

```
gSystem->Load("libTree.so") ;
gSystem->Load("libs/libJetCore.so");
gSystem->Load("libs/libCDFJet.

StdTextInput textinput("data/J1_Clusters.dat");

JetBuilder builder;
builder.configure_input((InputMaker*)&textinput);

builder.add_default_alg( new cdf::JetClustFinder("myJetClu"));
builder.set_default_cut(0,1*textinput.getGeV);

builder.configure_output
("SpartyJet_Tree","data/output/simple.root");
builder.process_events(10);
```

without JetBuilder

```
TFile f("/home/delsart/SpartyJet_vwithSISCone/example/data/small.root");
TTree * tree = (TTree*) f.Get("CollectionTree");

atlas::CBNTInput input;
input.init(tree);

JetAlgorithm * alg = new JetAlgorithm("MidPointJets");

JetPtSelectorTool *selec = new JetPtSelectorTool(1*GeV);
MidPoint * midpoint = new MidPoint("TOTO");

alg->addTool((JetTool*)midpoint);
alg->addTool((JetTool*)selec);

alg->init();

NtupleMaker ntp;
ntp.addJetVar("MidPointJets");
ntp.init("JetTree","out.root");

Jet::jet_list_t injets;
Jet::jet_list_t outjets;

input->fillInput(2,injets);
alg->execute(injets, outjets);

ntp.set_data("MidPointJets", outjets);
ntp.fillJets() ;

clear_jetlist(injets);
clear_jetlist(outjets);

 input->fillInput(5,injets);
alg->execute(injets, outjets);

ntp.set_data("MidPointJets", outjets);
ntp.fillJets() ;

ntp.finalize();
```

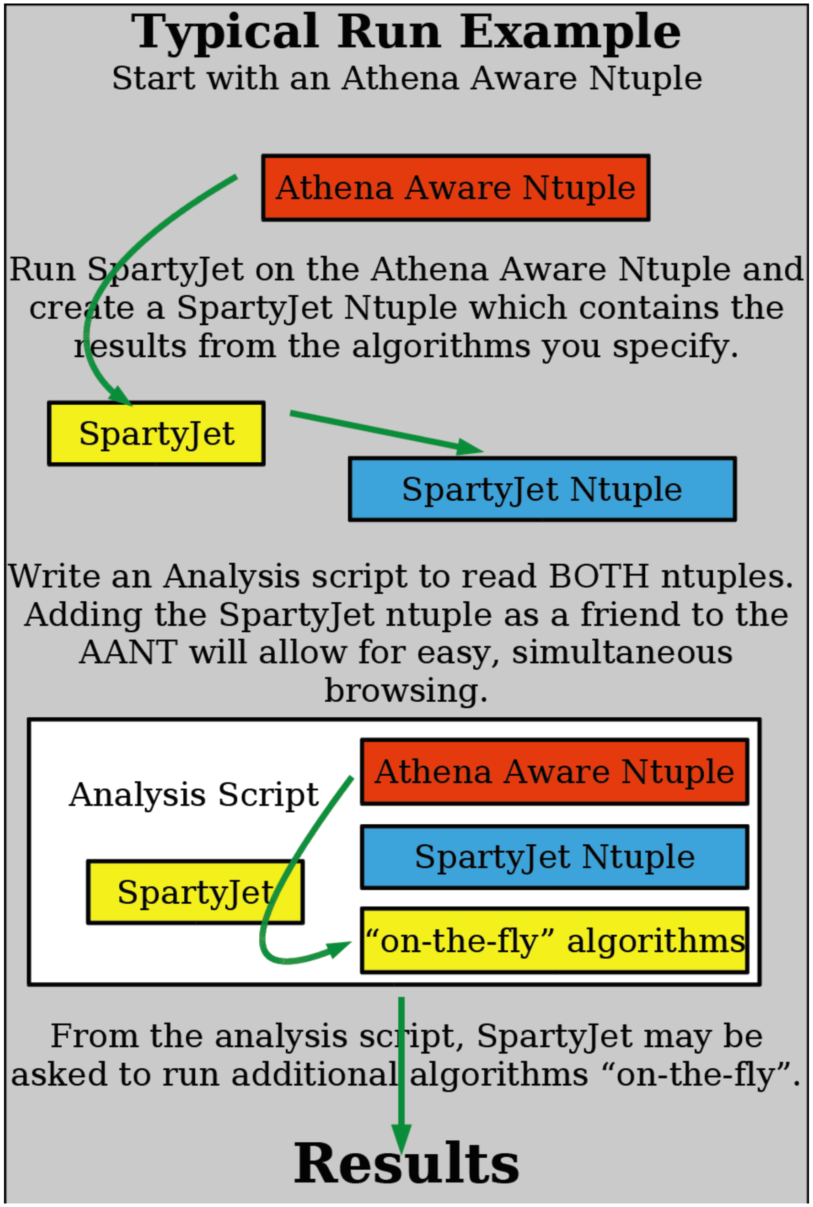
"on-the-fly" method

- no input data file, no output data file
- from other C++ programs, call a variant of
  `jets = SpartyJet::getjets(JetTool*,data)`
- Currently supported data types:

```
Jet::jet_list_t&                      SpartyJet::getjets( JetTool* tool,
                                          Jet::jet_list_t& inputJets);

std::vector<TLorentzVector>&          SpartyJet::getjets( JetTool* tool,
                                          std::vector<TLorentzVector>& input);

std::vector<TLorentzVector>&          SpartyJet::getjets( JetTool* tool,
                                          std::vector<TLorentzVector>& input,
                                          std::vector<std::vector<int> >& constituents);

std::vector<SpartyJet::simplejet>     SpartyJet::getjets( JetTool* tool,
                                          std::vector<simplejet>& input);
```

reconstruct individual jets with new parameters in context of analysis

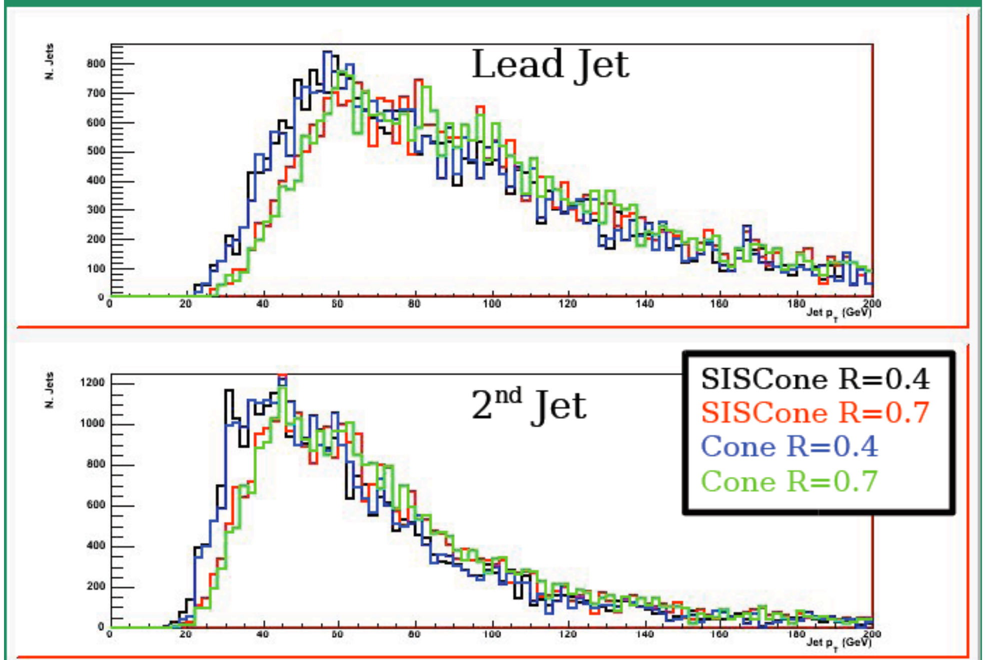
SpartyJet ntuples for ATLAS



- SpartyJet ntuples produced for W/Z + jets analysis for 0,1,2,3,4,5 parton samples
- VBF Higgs production
- tT

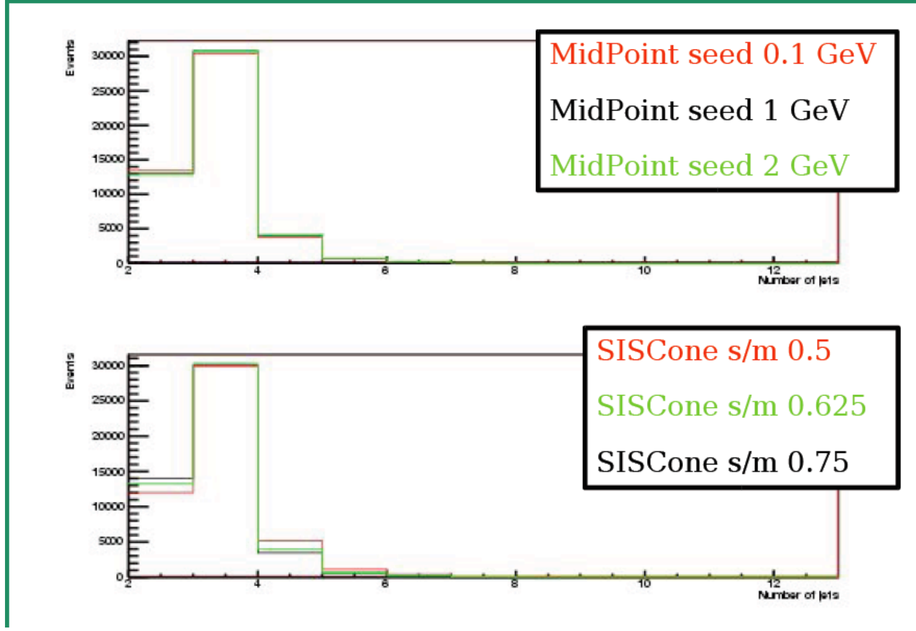
SpartyJet

W + 4parton
Jet pT distributions



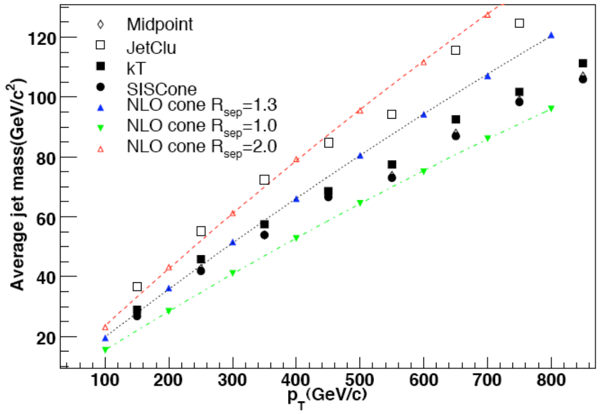
Cone uses split/merge = 0.5
SISCone uses split/merge = 0.75

Changing jet parameters: Number of jets



Jet masses

- It's often useful to examine jet masses, especially if the jet might be some composite object, say a W/Z or even a top quark



- For 2 TeV jets (J8 sample), peak mass (from dynamical sources) is on order of 125 GeV/c^2, but with long tail
  - Sudakov suppression for low jet masses
  - fall-off as 1/m^2 due to hard gluon emission
  - algorithm suppression at high masses
    - jet algorithms tend to split high mass jets in two

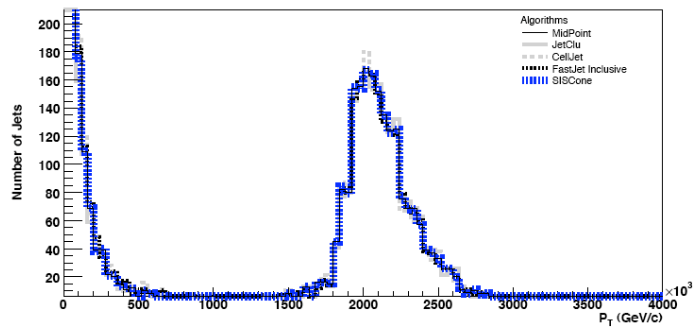


Figure 50: The inclusive jet cross section for the LHC with a $p_{T,min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{cone}$) of 0.7. The first bin has been suppressed.

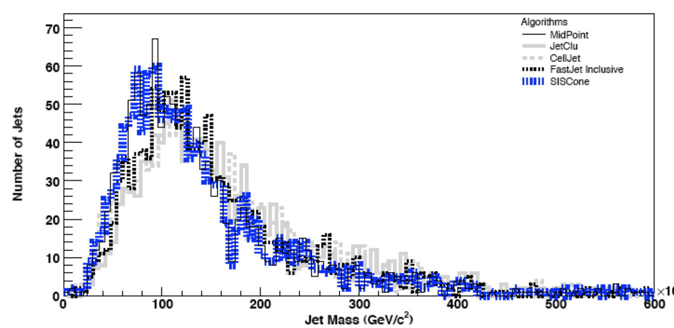
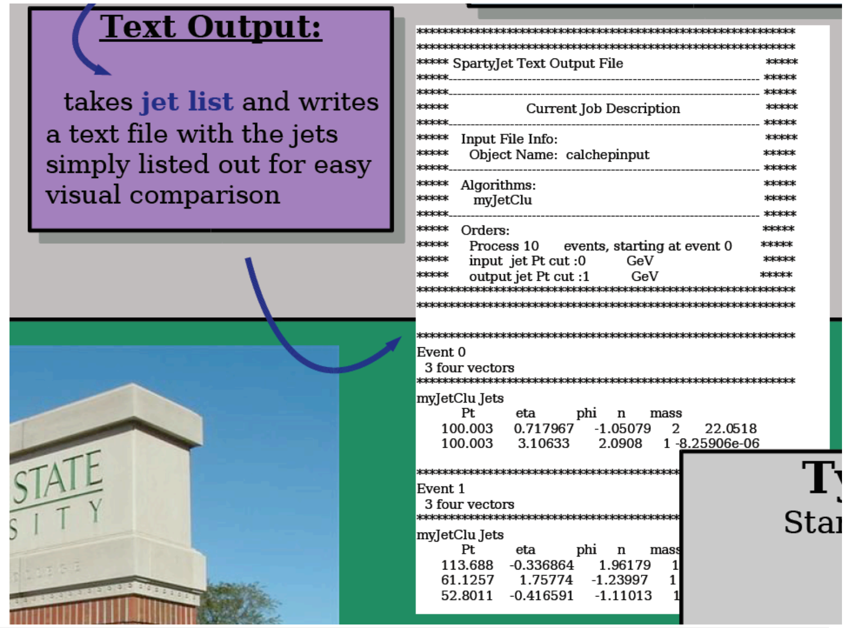
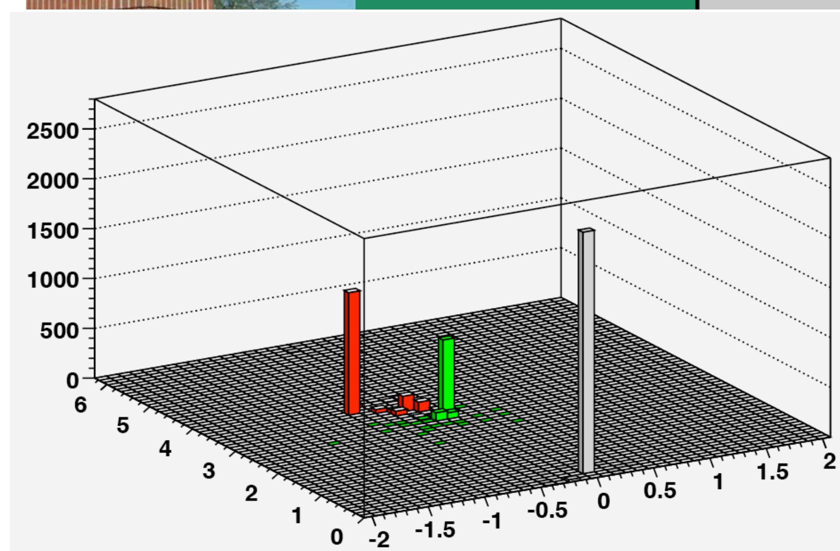


Figure 51: The jet mass distributions for an inclusive jet sample generated for the LHC with a $p_{T,min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{cone}$) of 0.7. The first bin has been suppressed.

Other features

- Access to jet constituents
- Y-splitter, to determine scale at which jet can be resolved into n sub-jets (pending)
- Ability to add n min bias events
- Event visualization
- gui interface (coming soon)





Some recommendations from jet paper

- 4-vector kinematics (p_T,y and not E_T,η) should be used to specify jets
- Where possible, analyses should be performed with multiple jet algorithms
- For cone algorithms, split/merge of 0.75 preferred to 0.50

Summary

- Physics will come flying hot and heavy when LHC turns on in 2008
  - most likely 10-11 TeV, in August, with a running period of 2-3 months
- Important to establish both the SM benchmarks and the tools we will need to properly understand this flood of data
- So we can have confidence that any BSM signals that we see are really BSM

- "We have to live with the Standard Model we have, not the Standard Model we want."

New CTEQ project: CTEQ4LHC

- Collate/create cross section predictions for LHC
  - processes such as W/Z/Higgs(both SM and BSM)/diboson/ tT/single top/photons/jets…
  - at LO, NLO, NNLO (where available)
    - new: W/Z production to NNLO QCD and NLO EW
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation (q_T and threshold)
- As prelude towards comparison with actual data
- Using programs such as:
  - MCFM
  - ResBos
  - EKS
  - Pythia/Herwig/Sherpa
  - …numerous private codes with CTEQ
- First on webpage and later as a report

2008 CTEQ summer school

…in conjunction with MCNET

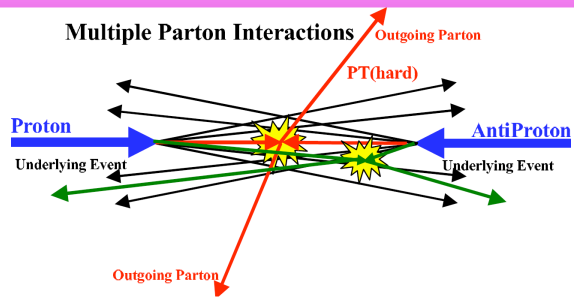
A combination of broad lectures on QCD theory, phenomenology and analysis and a practical approach to event generator physics and techniques, with hands-on sessions and talks on using them in real analyses

Debrecen, Hungary
Aug 8-16

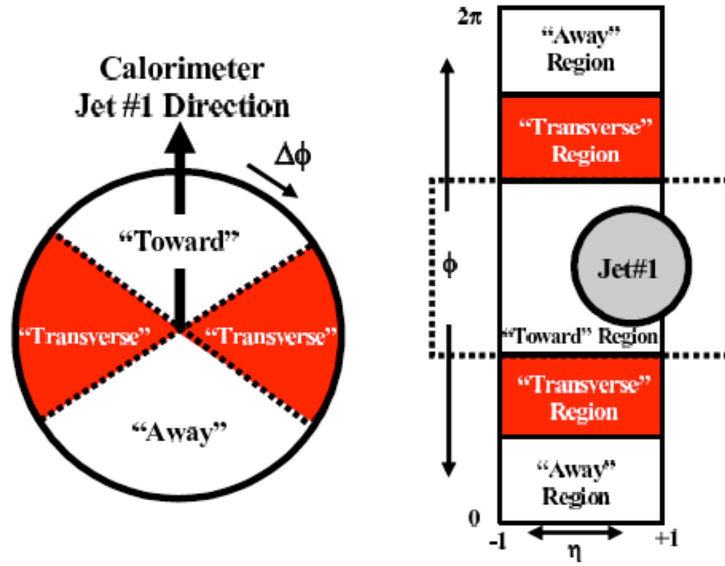
http://cteq-mcnet.org/

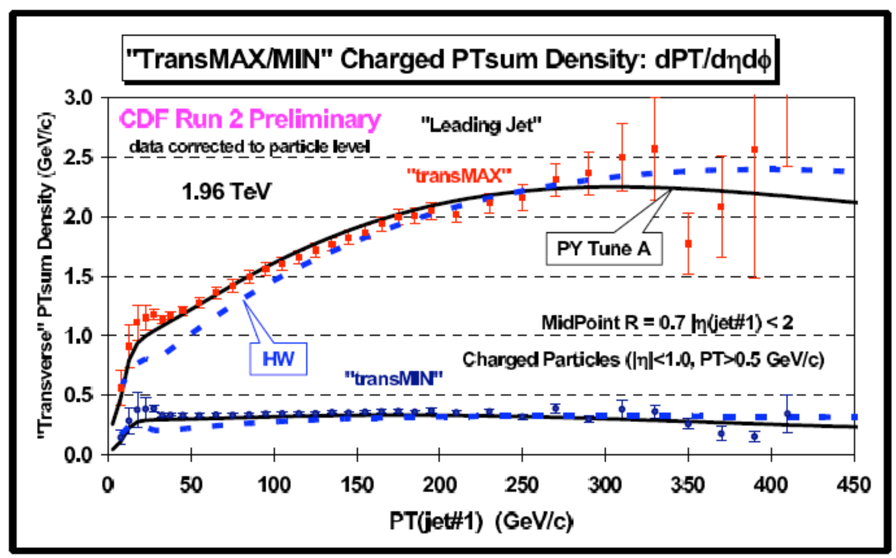
Extra slides

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





Aside: Why K-factors < 1 for inclusive jet production?

- Write cross section indicating explicit scale-dependent terms
- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases
- Second term is negative for $\mu<p_T$, positive for $\mu>p_T$
- Third term is negative for factorization scale $M < p_T$
- Fourth term has same dependence as lowest order term
- Thus, lines one and four give contributions which decrease monotonically with increasing scale while lines two and three start out negative, reach zero when the scales are equal to p_T, and are positive for larger scales
- At NLO, result is a roughly parabolic behavior

Consider a large transverse momentum process such as the single jet inclusive cross section involving only massless partons. Furthermore, in order to simplify the notation, suppose that the transverse momentum is sufficiently large that only the quark distributions need be considered. In the following, a sum over quark flavors is implied. Schematically, one can write the lowest order cross section as

$$E\frac{d^3\sigma}{dp^3} \equiv \sigma = a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \qquad (1)$$

where $a(\mu) = \alpha_s(\mu)/2\pi$ and the lowest order parton-parton scattering cross section is denoted by $\hat{\sigma}_B$. The renormalization and factorization scales are denoted by μ *and* M, respectively. In addition, various overall factors have been absorbed into the definition of $\hat{\sigma}_B$. The symbol $\otimes$ denotes a convolution defined as

$$f \otimes g = \int_x^1 \frac{dy}{y}\, f(\frac{x}{y})\, g(y). \qquad (2)$$

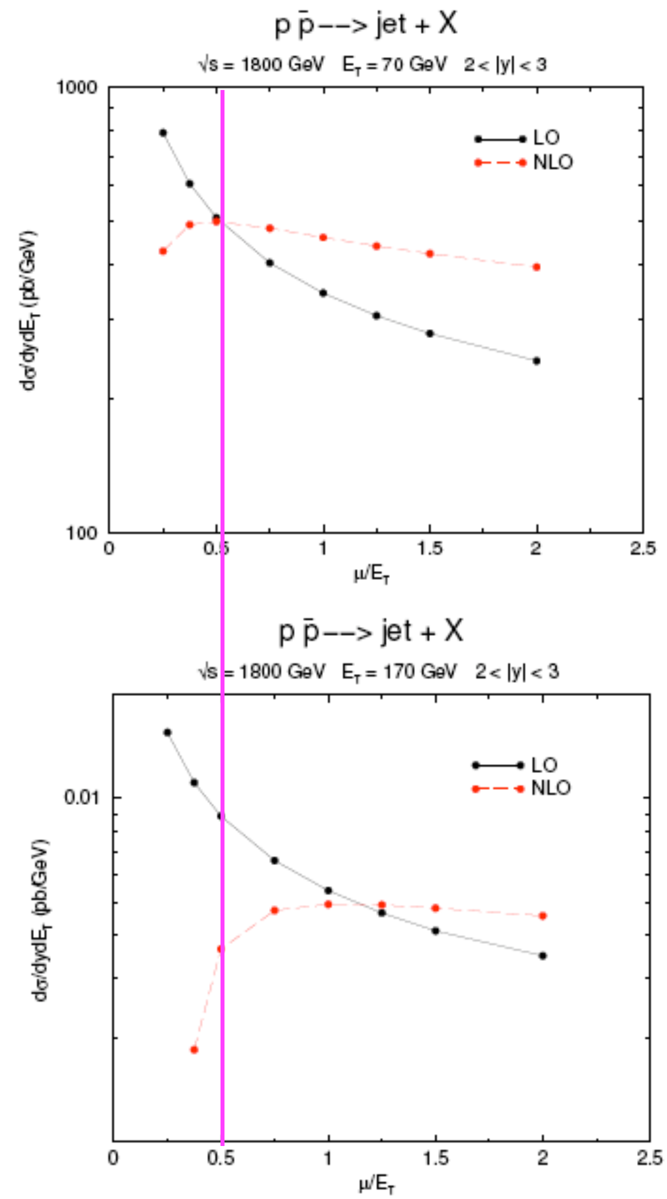
When one calculates the $\mathcal{O}(\alpha_s^3)$ contributions to the inclusive cross section, the result can be written as

$$\begin{aligned}
(1)\quad \sigma &= a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M)\\
(2)\quad &+ 2a^3(\mu)\,b\ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M)\\
(3)\quad &+ 2a^3(\mu)\,\ln(p_T/M)P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M)\\
(4)\quad &+ a^3(\mu)\,K \otimes q(M) \otimes q(M). \qquad (3)
\end{aligned}$$

In writing Eq. (3), specific logarithms associated with the running coupling and the scale dependence of the parton distributions have been explicitly displayed; the remaining higher order corrections have been collected in the function K in the last line of Eq. (3). The μ

Why K-factors < 1?

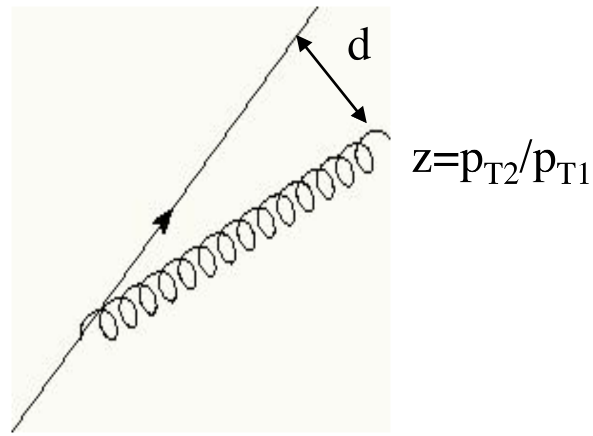
- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases
- Second term is negative for $\mu<p_T$, positive for $\mu>p_T$
- Third term is negative for factorization scale $M < p_T$
- Fourth term has same dependence as lowest order term
- Thus, lines one and four give contributions which decrease monotonically with increasing scale while lines two and three start out negative, reach zero when the scales are equal to p_T, and are positive for larger scales
- NLO parabola moves out towards higher scales for forward region
- Scale of $E_T/2$ results in a K-factor of ~1 for low E_T, <<1 for high E_T for forward rapidities at Tevatron



Aside: Jet algorithms at NLO

- 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

- Remember at LO, 1 parton = 1 jet
- At NLO, there can be two (or more) partons in a jet and life becomes more interesting
- Let's set the p_T of the second parton = z that of the first parton and let them be separated by a distance d (=ΔR)
- Then in regions I and II (on the left), the two partons will be within R_{cone} of the jet centroid and so will be contained in the same jet
  - ~10% of the jet cross section is in Region II; this will decrease as the jet p_T increases (and α_s decreases)
  - at NLO the k_T algorithm corresponds to Region I (for D=R); <u>thus at parton level, the cone algorithm is always larger than the k_T algorithm</u>



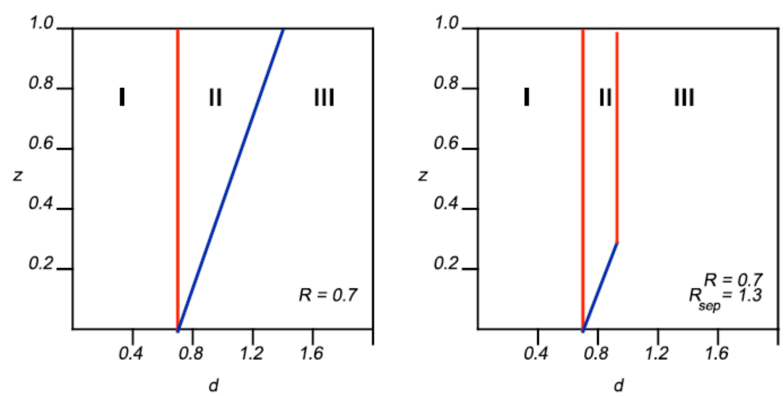
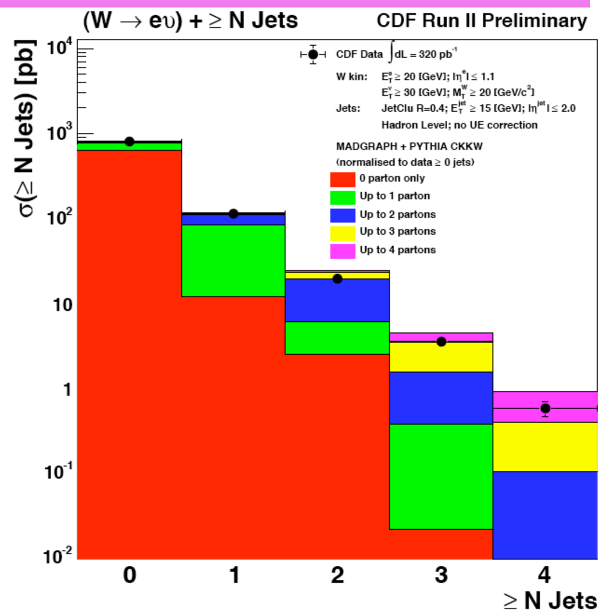


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

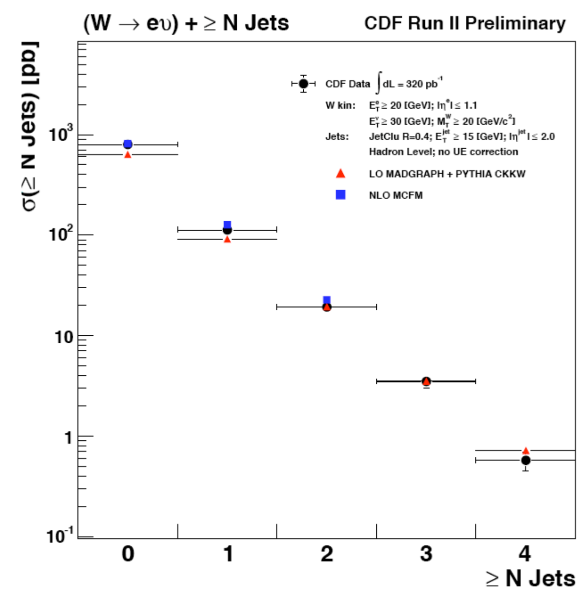
W + jets at the Tevatron

- 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



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