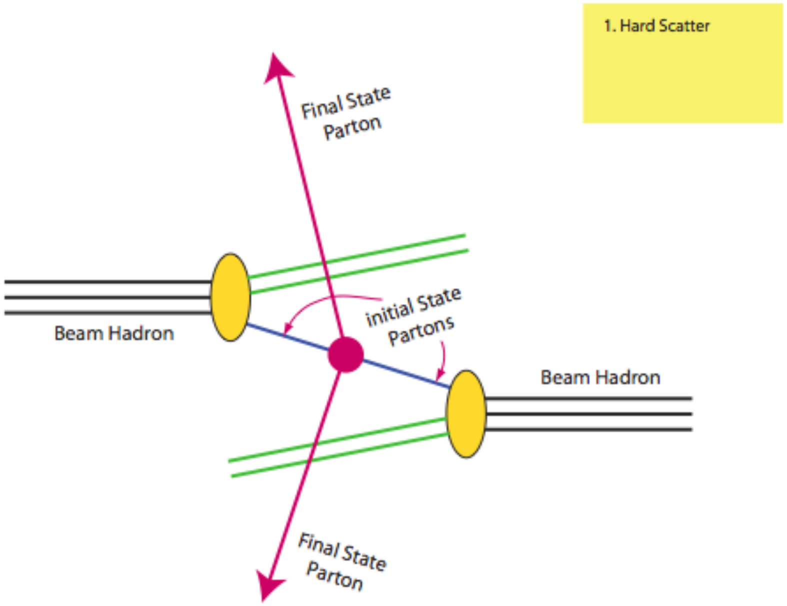
Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

Section 2: Basic Phenomenology of Hard Scattering

1. **Proton Structure (PDFs and all that)**
2. **Hard Scattering SubProcess**
3. **Calculational Strategies**
4. **Example: Drell-Yan W Boson Production**

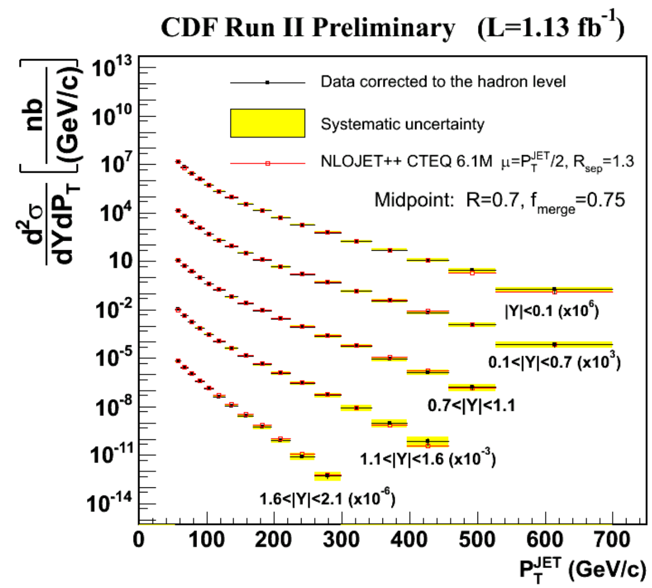
Hard Scattering SubProcess

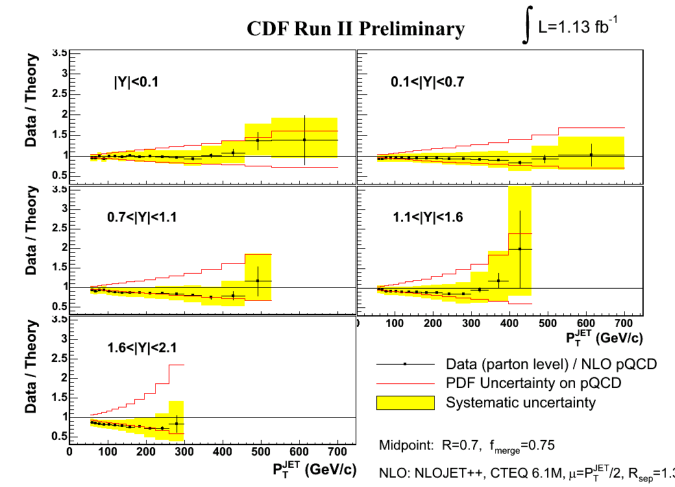
- Key element of a hadron-hadron collision is hard-scattering process
  - Accesses highest possible energies
  - Where the "light is brightest"
- Immediately have to confront
  - What process are we really interested in?
  - Dealing with higher-order effects
  - Taking ISR/FSR effects into account
  - Estimating uncertainties in calculation



Setting Up the Problem

- **Basic theoretical elements**
  - **Time of interaction << timescale of any other process**
    - Treat hadron as a “bag” of free partons
  - **Two partons interact**
    - Treat the process perturbatively (typically to some order)
      - **Introduce a renormalization scheme and scale**
      - **Introduce uncertainties from (neglected) HO processes**
  - **Have to perform an integration over initial state variables**
    - Most important being averaging over hadron structure
  - **Why should you believe in this?**
    - Extraordinary consistency arising from PDF analysis
    - Look at inclusive jet production at Tevatron





Production Cross Section

- **Start with parton model**
  - **Each parton has momentum fraction x_1, x_2 of hadron**
    - Given by parton distribution function (PDFs)
    - Either gluons, valence (u,d) or sea quarks $\rightarrow$ u, d, s, s, b, ,$\bar{u}$, $\bar{d}$, $\bar{c}$, $\bar{s}$, $\bar{b}$
  - **Gives subprocess centre of mass energy** $\sqrt{\hat{s}} = \sqrt{s x_1 x_2}$
  - **Cross section given by**

$$\sigma = \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \hat{\sigma}(\tau s)$$

$\hat{\sigma}$ is partonic cross section

$\tau = x_1 x_2$

- **Need to introduce a few other variables**
  - **Q^2 of process**
    - $(4\text{-momentum transfer})^2$ between incoming partons
      - **E.g. s-channel process**
        - **4-momentum of produced object**
    - Don't confuse
      - **with q^2 scale of hadronization**
      - **With renormalization scale used in perturbative calculation**
  - **Rapidity** $y \equiv \frac{1}{2} \log\left(\frac{E + p_z}{E - p_z} \right) = \tanh^{-1}\left(\frac{p_z}{E} \right)$
  - **Pseudorapidity** $\eta \equiv -\log\left(\tan\frac{\theta}{2} \right)$
    - **Rapidity assuming massless particle**

Exercise: Derive pseudorapidity from rapidity

Partonic Luminosities

- **The form of the cross section leads to following**

$$\sigma = \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \hat{\sigma}(\tau s)$$

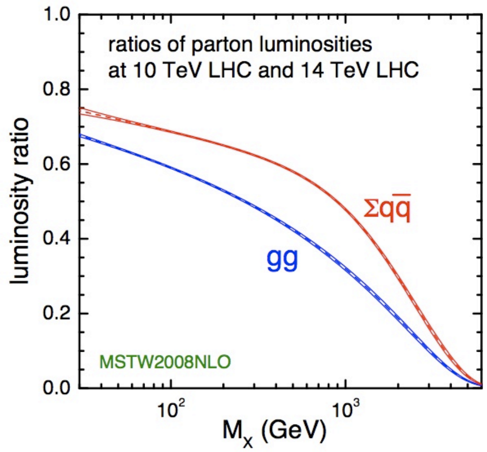
$$\Rightarrow \frac{d\sigma}{d\tau} = \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right] \hat{\sigma}(\tau s)$$

$$= \frac{d\mathcal{L}_{12}}{d\tau} \hat{\sigma}(\tau s)$$

$$where\ \frac{d\mathcal{L}_{12}}{d\tau} \equiv \sum_{\substack{partons\ i \\ colour\ j}} C_{ij} \int_\tau^1 \frac{dx_1}{\tau} \left[f_1(x_1) f_2(\tau / x_1) \right]$$

  - **Motivates the concept of "partonic luminosity"**
  - **Useful to keep in mind to improve intuition**

$$M_X \sim \sqrt{s}\sqrt{\tau}$$



Courtesy of J. Stirling

- **Parton distribution functions are determined by**
  - **Taking all "relevant" data, eg**
    - Deep inelastic lepton-proton scattering
    - Drell-Yan production
  - **Fitting the collection to theoretically motivated parameterizations**
    - Scheme-dependence
    - Physical assumptions
    - Attempt to use a consistent set of inputs
      - **Order of calculations**
      - **Coupling constants**
- **Produce a set of PDFs that are used to generate random x_i in Monte Carlo calculations with appropriate distributions**

Formal Definition of PDF

- **Proton PDFs are defined by**
  - **The perturbative calculations for the hard-scattering processes**
    - LO, NLO, NNLO
    - Scheme & factorization scale
  - **Parametrization of the PDFs**
  - **Assumptions for the heavy quark contributions**
  - **Which datasets to employ**

$$xu_v\left(x,Q_0^2\right) = A_u x^{\eta_1}(1-x)^{\eta_2}\left(1+\varepsilon_u\sqrt{x}+\gamma_u x\right), u_v \equiv (u-\bar{u})$$

$$xd_v\left(x,Q_0^2\right) = A_d x^{\eta_3}(1-x)^{\eta_4}\left(1+\varepsilon_d\sqrt{x}+\gamma_d x\right), d_v \equiv (d-\bar{d})$$

$$xS\left(x,Q_0^2\right) = A_S x^{\delta_S}(1-x)^{\eta_S}\left(1+\varepsilon_S\sqrt{x}+\gamma_S x\right), S \equiv 2\left(\bar{u}+\bar{d}\right)+s+\bar{s}$$

$$x\Delta\left(x,Q_0^2\right) = A_\Delta x^{\eta_\Delta}(1-x)^{\eta_S+2}\left(1+\gamma_\Delta x+\delta_\Delta x^2\right), \Delta \equiv \bar{d}-\bar{u}$$

$$xg\left(x,Q_0^2\right) = A_g x^{\eta\delta_g}(1-x)^{\eta_g}\left(1+\varepsilon_g\sqrt{x}+\gamma_g x\right)+A_{g'}x^{\delta_{g'}}(1-x)^{\eta_{g'}},$$

$$x(s+\bar{s})\left(x,Q_0^2\right) = A_+ x^{\delta_S}(1-x)^{\eta_+}\left(1+\varepsilon_S\sqrt{x}+\gamma_S x\right),$$

$$x(s-\bar{s})\left(x,Q_0^2\right) = A_- x^{\delta_-}(1-x)^{\eta_-}\left(1-x/x_0\right)$$

- **Fitting data to**
  - **28 free parameters**
  - $\alpha_s\left(Q_0^2\right)$, where $Q_0^2 = 1\,(\mathrm{GeV/c})^2$
  - **20 normalisations & corrections**

Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})\, N \to \mu^-(\mu^+)\, X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu\, N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu}\, N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \to \bar{\nu} X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \to e^\pm c\bar{c} X$	$\gamma^* c \to c$, $\gamma^* g \to c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^\pm \to \ell^\pm\nu)\, X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-)\, X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

Table 1: The main processes included in the current global PDF analysis ordered in three groups: fixed-target experiments, HERA and the Tevatron. For each process we give an indication of their dominant partonic subprocesses, the primary partons which are probed and the approximate range of x constrained by the data.

MSTW, hep-ph/0901.0002

MRS Parametrization

$$xu_v\left(x,Q_0^2\right) = A_u x^{\eta_1}\left(1-x\right)^{\eta_2}\left(1+\varepsilon_u\sqrt{x}+\gamma_u x\right),\ u_v \equiv \left(u-\bar{u}\right)$$

$$xd_v\left(x,Q_0^2\right) = A_d x^{\eta_3}\left(1-x\right)^{\eta_4}\left(1+\varepsilon_d\sqrt{x}+\gamma_d x\right), d_v \equiv \left(d-\bar{d}\right)$$

$$xS\left(x,Q_0^2\right) = A_S x^{\delta_S}\left(1-x\right)^{\eta_S}\left(1+\varepsilon_S\sqrt{x}+\gamma_S x\right),\ S \equiv 2\left(\bar{u}+\bar{d}\right)+s+\bar{s}$$

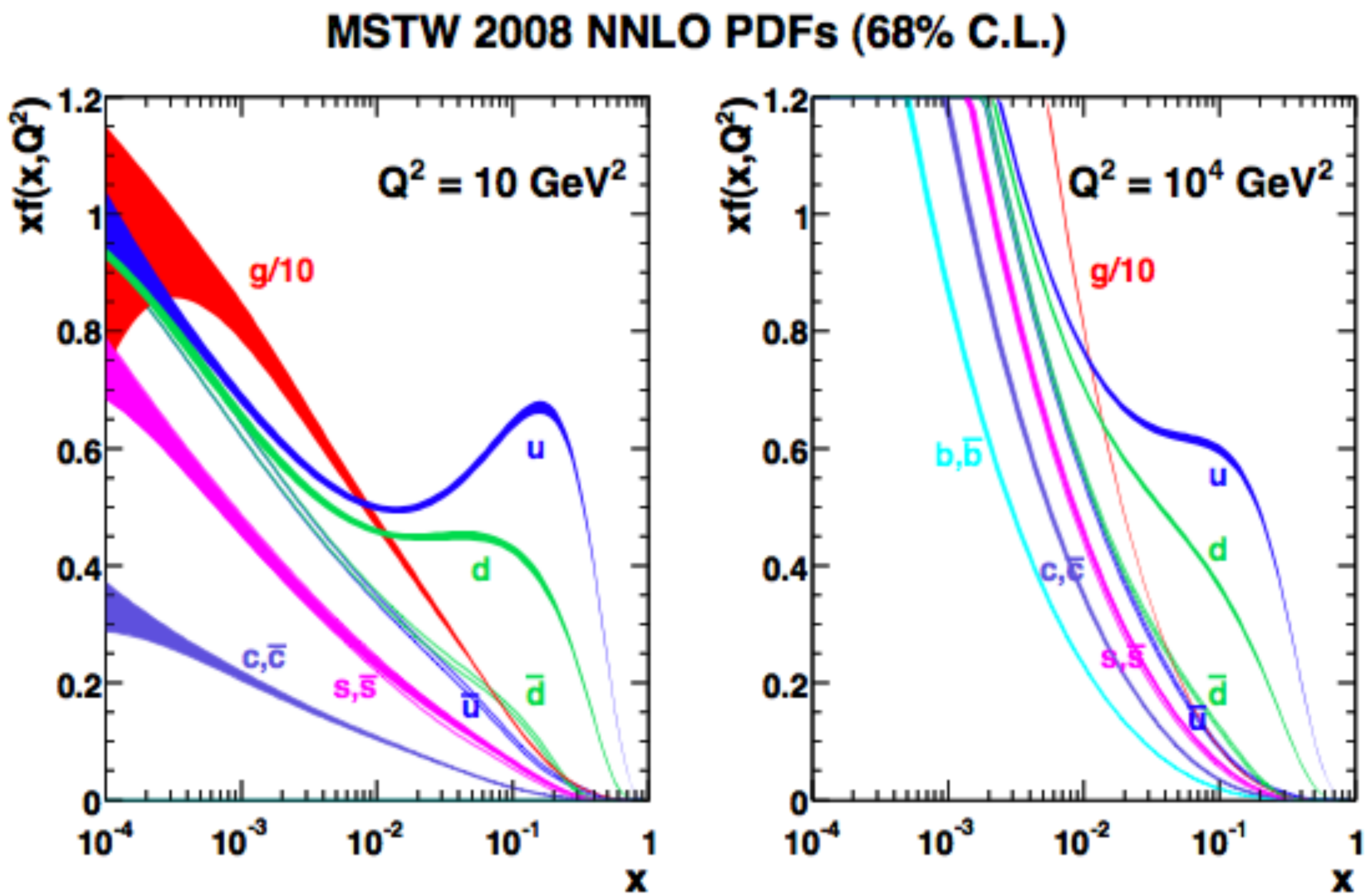
$$x\Delta\left(x,Q_0^2\right) = A_\Delta x^{\eta_\Delta}\left(1-x\right)^{\eta_S+2}\left(1+\gamma_\Delta x+\delta_\Delta x^2\right),\ \Delta \equiv \bar{d}-\bar{u}$$

$$xg\left(x,Q_0^2\right) = A_g x^{\eta\delta_g}\left(1-x\right)^{\eta_g}\left(1+\varepsilon_g\sqrt{x}+\gamma_g x\right)+A_{g'}x^{\delta_{g'}}\left(1-x\right)^{\eta_{g'}},$$

$$x\left(s+\bar{s}\right)\left(x,Q_0^2\right) = A_+ x^{\delta_S}\left(1-x\right)^{\eta_+}\left(1+\varepsilon_S\sqrt{x}+\gamma_S x\right),$$

$$x\left(s-\bar{s}\right)\left(x,Q_0^2\right) = A_- x^{\delta_-}\left(1-x\right)^{\eta_-}\left(1-x/x_0\right)$$

“LHC” MSTW PDFs



MSTW, hep-ph/0901.0002

Courtesy of J. Stirling

PDFs in Use

- The "marketplace" has two sets of broadly-based PDFs (my term):
  - CTEQ (now CT10)
    - Coordinated Theoretical and Experimental Project on QCD
    - CTEQ6.6
  - MRST -- recently MSTW
    - MSTW2008LO/NLO/NNLO
    - A.D.Martin, W.J.Stirling, R.S.Thorne & G. Watt
- Other approaches continue to be investigated
  - A large industry here, eg,
    - NNPDF
    - DGLAP
  - Some of these are specific to certain physics processes
  - Have to appreciate the relevance
- Some issues to worry about:
  - Make sure you have the right order, scheme and scale
    - PDFs and perturbative calculation should be consistent!
  - Recognize the possibility of sensitivities to PDFs
    - Getting less important in many cases at Tevatron, but still problematic
    - Think of ways of reducing uncertainties
      - W'/W search -- use relative normalization of cross section
  - Keep up-to-date with what is happening!

The Low-Down on PDFs

- **The PDFs differ (and have uncertainties) arising from:**
  - **Choice of scheme and scale**
  - **Which data were used (and how to constrain)**
  - **What is the form of the parametrization**
  - **Statistical uncertainties on input**
- **Often hard to get a totally consistent picture**
  - **Each group has developed schemes to determine how input data uncertainties propogate into MC calculations**
    - Don’t really address all the issues (IMHO), and probably can’t
- **Current issues:**
  - **Behaviour of g(x) at small x**
  - **Handling of heavy quarks**
    - No intrinsic c/b in proton
    - All comes from g evolution
  - **Behaviour of g(x) at large x**
  - **Treatment of uncertainties**
    - Both CTEQ and MSTW use a Hessian matrix approach
      - **Diagonalize it and define eigenvectors**
      - **Use ±1 sigma change in eigenvectors**
  - **Data not well-reconciled**
    - NuTeV EWK measurement
    - Tevatron High E_T jets
    - W boson asymmetry

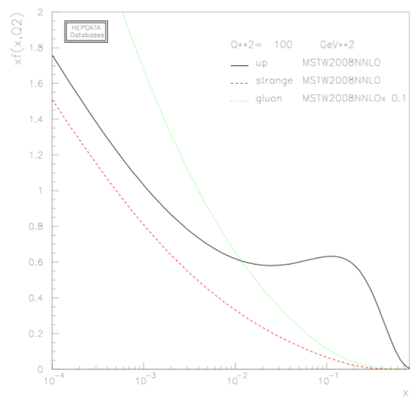
Accessing PDFs

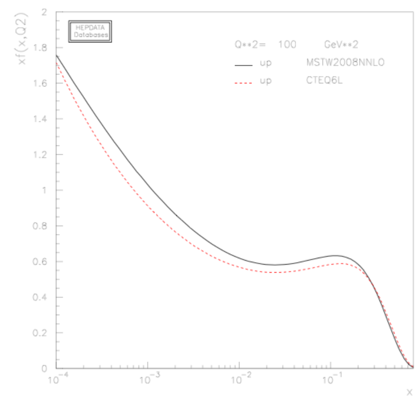
- **A standard interface has been developed**
  - **Allows for selection of different PDFs painlessly -- “Les Houches Accord”**
    - Boos et al., hep-ph/0109068
  - **Makes inclusion of new PDFs straightforward**
- **Also have web-based tools to access them**
  - **Theory Institute at Durham**

http://durpdg.dur.ac.uk/hepdata/pdf3.html

  - **CTEQ group**

http://hep.pa.msu.edu/cteq/public/cteq6.html





CTEQ6 parton distribution functions

CTEQ6 parton distribution functions are publicly available as a part of the **LHAPDF Fortran library**

Here you can download a **standalone Fortran interface and demonstration program**, as well as the tables with interpolated PDF values for the latest general-purpose set (CTEQ6.6M and 44 eigenvector sets for computation of PDF uncertainties) and other CTEQ6.XX sets.

An alternative interface for simultaneous interpolation of several CTEQ PDF tables has been developed by Zoltan Nagy. It is written in C and can be linked to C/C++/Fortran modules using gcc and other compilers.

Available PDF sets

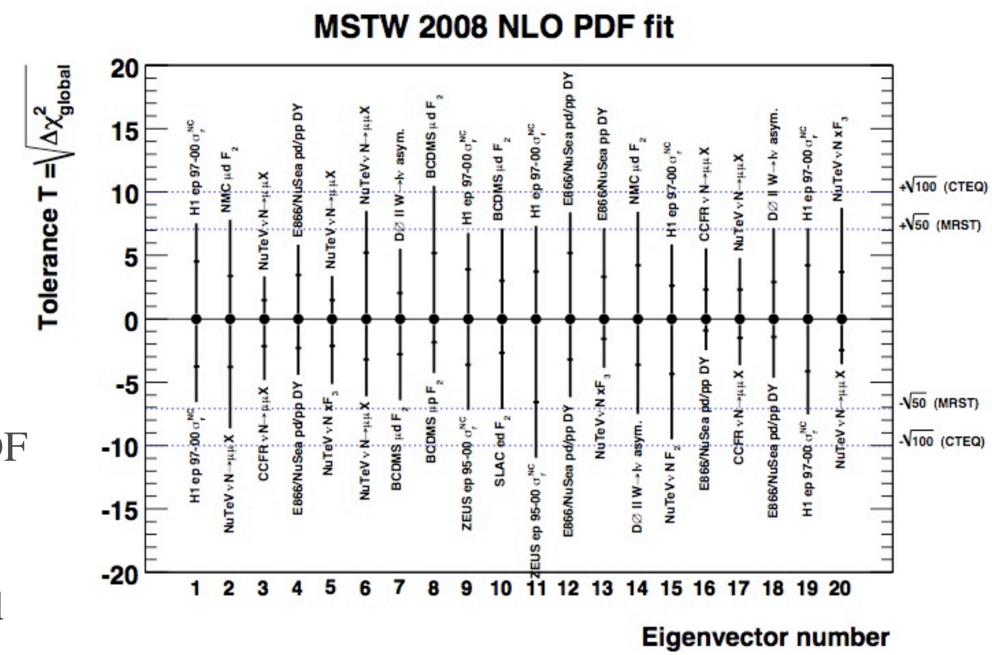
Further explanations of the implemented PDF sets can be found in this **summary**

PDF set	Description	Authors or main contact	References	Date	Tables	Additional resources
CTEQ6.6A	6.6 series with a varied strong coupling alpha_s (M_Z)=0.125, 0.122, 0.114, 0.112 for n = 0...3	J. Pumplin	arXiv: 0802.0007	02/2008	ctq66a.pds.zip	
CTEQ6.6C	6.6 intrinsic charm series (n = 0...3)	J. Pumplin	arXiv: 0802.0007	02/2008	ctq66c.pds.zip	
CTEQ6.6	general-purpose CTEQ6.6M + 44 eigenvector sets	P. Nadolsky et al.	arXiv: 0802.0007	02/2008	ctq66m.pds.zip	Extra figures, cross sections
CTEQ6.5.snn	6.5 symmetric (nn=+0...+4) and asymmetric (nn=-2...-0) strangeness series	H.L. Lai et. al.	hep-ph/0702268	02/2007	ctq65s.pds.zip	
CTEQ6.5.cn	6.5 intrinsic charm series (n = 0...6)	J. Pumplin et.al	hep-ph/0701220	01/2007	ctq65c.pds.zip	
CTEQ6.5	general-purpose CTEQ6.5M + 40 eigenvector sets	W.-K. Tung et.al.	hep-ph/0611254	12/2006	ctq65m.pds.zip	
CTEQ6AB	Alpha-series (for two definitions of Alpha)	J. Pumplin et al.	hep-ph/0512167	12/2005	LHAPDF	
CTEQ6.1	general-purpose CTEQ6.1M + 40 eigenvector sets	D. Stump et al.	hep-ph/0303013	03/2003	cteq61.xx.zip	
CTEQ6HQ, CTEQ6S	CTEQ6 series in the general-mass scheme (HQ) and for alternative strangeness parametrizations (S)	S. Kretzer et al. F. Olness et al.	hep-ph/0307022 hep-ph/0312323	07/2003 12/2003	cteq6.pds.zip	
CTEQ6	general-purpose CTEQ6M + 40 eigenvector sets CTEQ6M, CTEQ6D, CTEQ6L, CTEQ6L1	J. Pumplin et al.	hep-ph/0201195	01/2002	cteq6m.xx.zip cteq6std.zip	

Previous versions of this webpage: 2007 2002

Propagating PDF Uncertainties

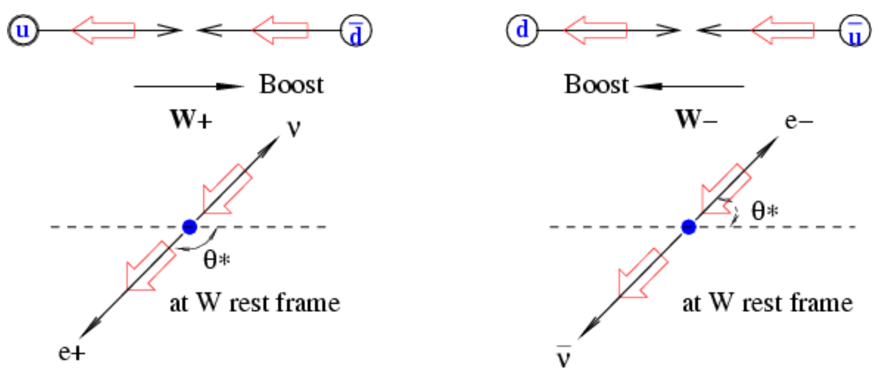
- **General formalism now in use**
  - **Separate out uncertainties from**
    - Choice of scale (or strong coupling)
    - Shape of PDFs
  - **Vary scale within uncertainties to determine sensitivity**
  - **For PDF shapes:**
    - Create sample with standard PDF
    - Use this to measure physics observable, eg., acceptance
    - Reweight MC with PDFs varied by displacement in parameter space along an "eigenvector"
    - Do this for all independent eigenvectors
  - **Use variation in observable between displacements in pairs of eigenvectors as measure**
    - Histogram this uncertainty and use it to gauge sensitivity



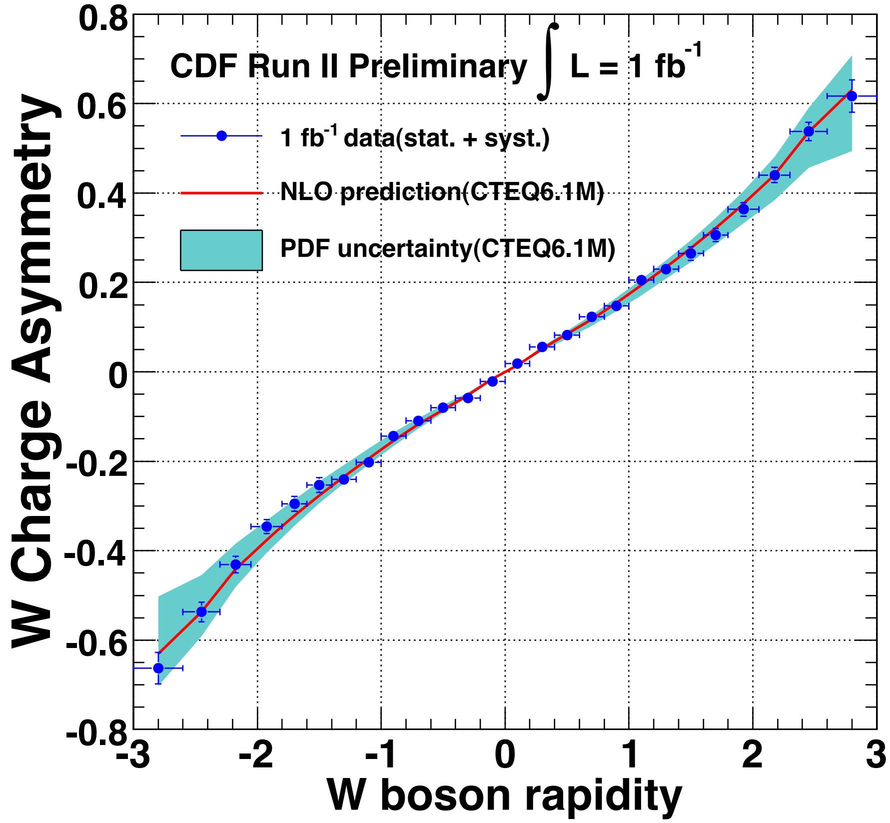
- **Both CTEQ/MSTW have specific prescriptions**
  - **Reasonable approaches**
  - **However, note that:**
    - No theory uncertainties
    - No uncertainties from choice of data sets

Example: W Charge Asymmetry

- Measured at Tevatron
  - Use left-handed nature of W coupling
  - Creates charge asymmetry versus y



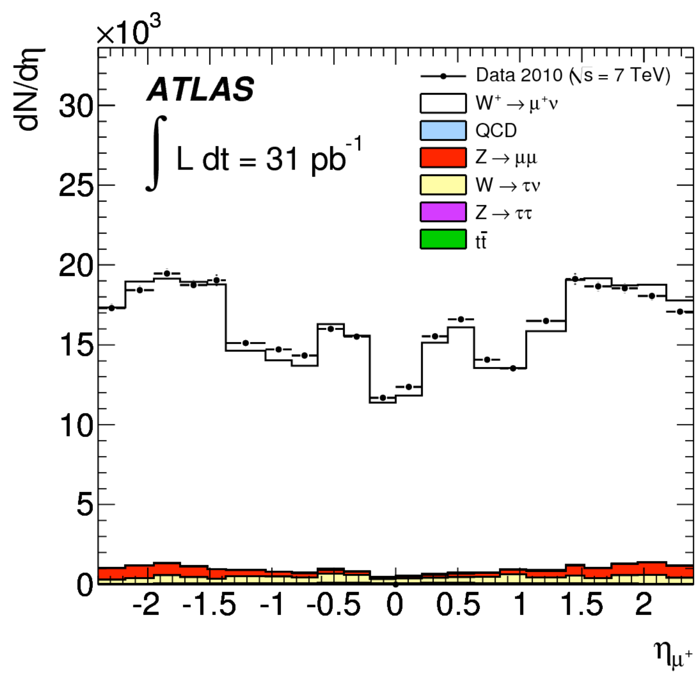
$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W} \approx \frac{u(x1)d(x2) - d(x1)u(x2)}{u(x1)d(x2) + d(x1)u(x2)}$$

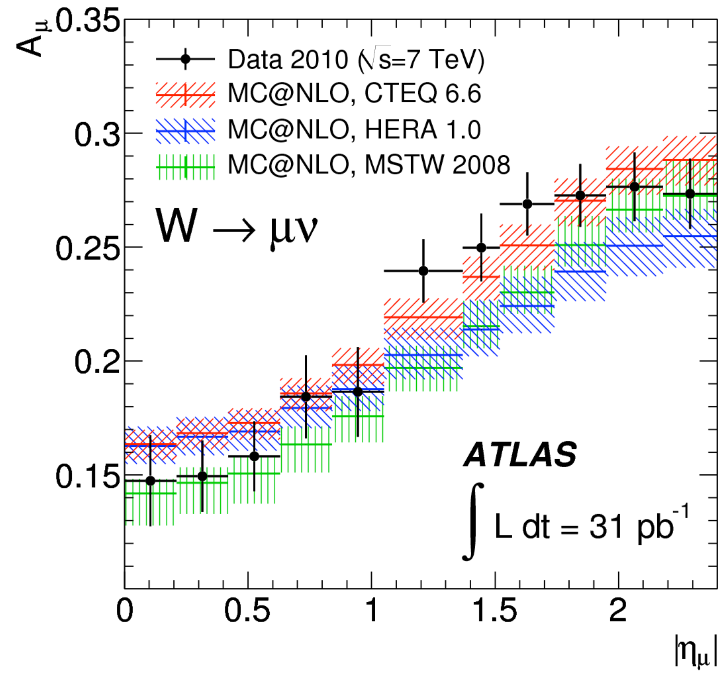


← p̄ direction p direction →

Example: W Charge Asymmetry

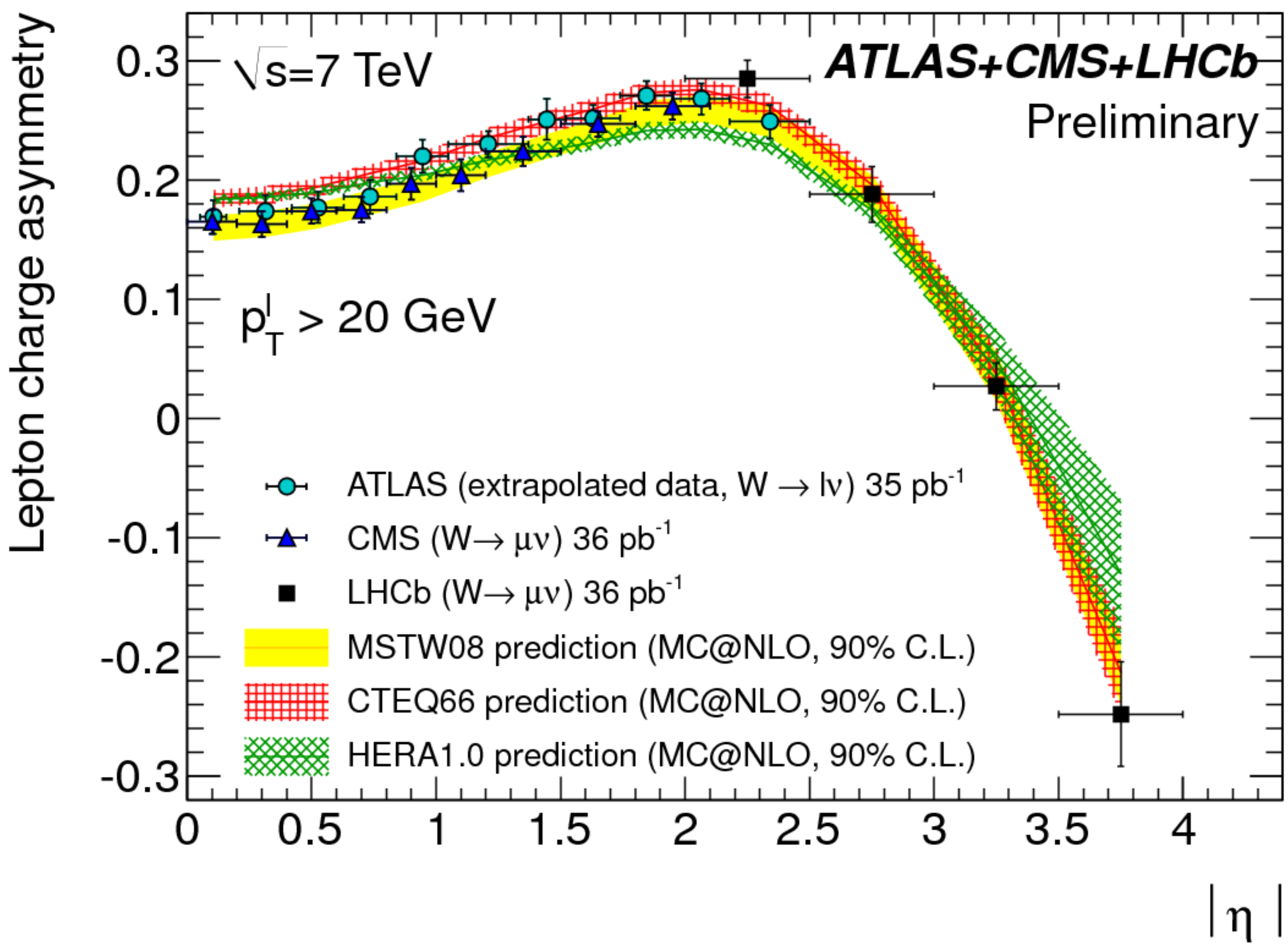
- Measured at LHC
  - Complicated by the intrinsic asymmetry in W+/W- production
  - But detector effects cancel





$$\chi^2 / NDF = 9.6/11 \text{ (CTEQ 6.6)}$$
$$\chi^2 / NDF = 35.8/11 \text{ (HERA 1.0)}$$
$$\chi^2 / NDF = 27.3/11 \text{ (MSTW 2008)}$$

Example: W Charge Asymmetry



Sub-Process Calculations

- **Perturbative QCD/EWK approach is used**
  - **Characterized by "choices" that define the MATRIX ELEMENT (ME):**
    - Order of calculation
      - **LO, NLO, NNLO,…**
      - **Renormalization scheme and scale ([illegible])**
    - Initial and final-states that are included
    - How transition to non-perturbative regime is handled
      - **Essentially blending of ME and "shower MC" through matching/merging process**
    - Choice of model for "hadronization"
    - Model for ISR and FSR
    - How integration over phase space is performed
      - **Weighting events or sampling?**
  - **Some of these are hardwired in specific MC generators**
  - **Others take a general approach**
    - You specify final state, generator "writes" the relevant code

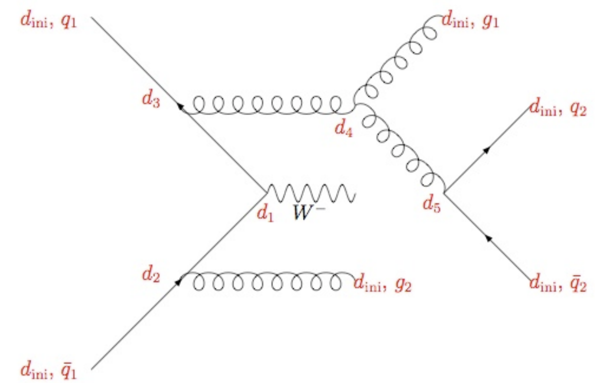
- **Impressive list of MC codes on the market, including:**
  - **PYTHIA**
  - **HERWIG**
  - **MC@NLO**
  - **POWHEG**
  - **SHERPA**
  - **ALPGEN**
  - **MADGRAPH**

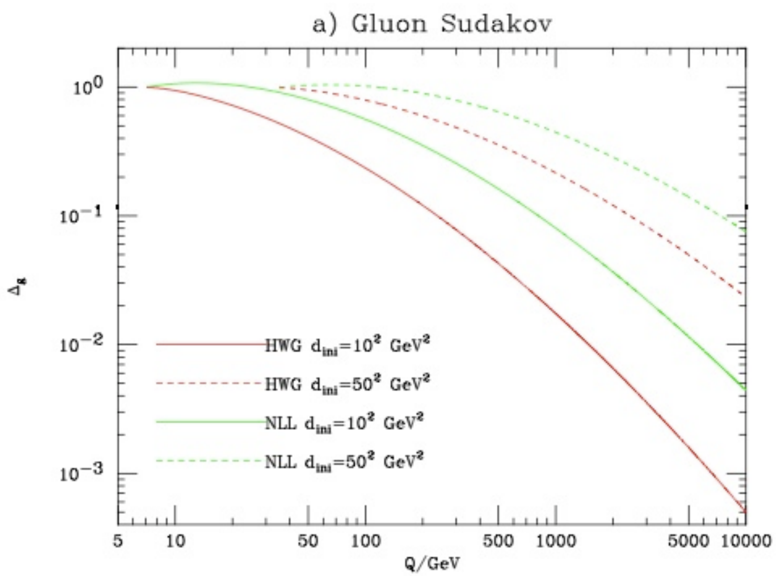
- **Many differences in detail**
  - **Optimized & tuned against different processes**
  - **As an example, will look at recent work on "merging schemes"**
    - W+n jet processes
    - Five different algorithms!
  - **Gives a flavour for the challenges**

Mangana & Stelzer, Ann. Rev. Nucl. Part. Scii. 2005, 555 (2005).

Jet Merging Schemes

- **Fundamental issue**
  - **W+n jet is at LO Drell-Yan process**
    - Higher orders produce additional partons
      - **Are they observable as jets?**
    - Early approaches treated these as ISR/FSR
      - **Not treated as part of the ME**
      - **Not a consistent QCD calculation**
    - Also introduced the concept of "K factor"
      - **Ratio of full cross section to cross section at LO**
        - **Could be large (1.4 for W production at Tevatron)**
  - **Recognize this as arising from higher-order QCD diagrams AND non-perturbative processes**
    - Probability of not giving off gluon given by the "Sudakov Factor"
    - General formalism comes from Altarelli-Parisi evolution
      - **Basis for most (all?) ISR/FSR codes**
    - Key is to avoid "double counting"

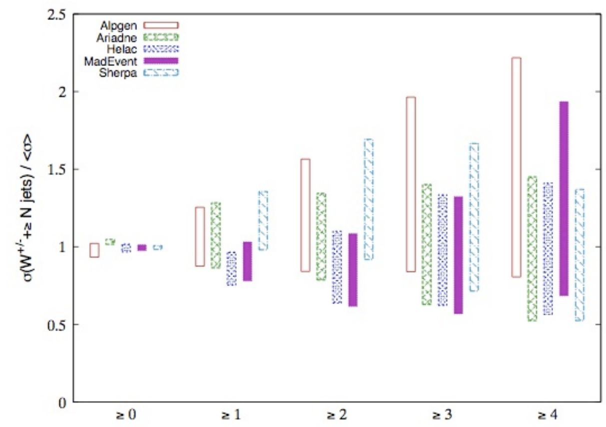


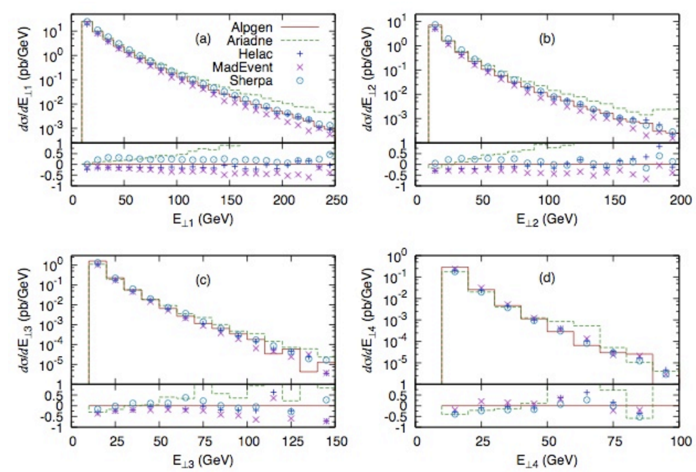


Mrenna & Richardson, JHEP 05, 040 (2004)
Alwall et al., Eur. Phys. J. C53, 473 (2008)

Tevatron Results for Merging

- General strategy
  - Generate hard parton final states in proportion to ME
  - Accept/reject based on Sudakov factors, etc.
    - Varies by algorithm
  - Create hadron showers, rejecting some that produce extra-hard partons
    - Varies by algorithm
  - Process accepted events through detector simulation, clustering algorithms
- Compare results of different algorithms (and internal variations)

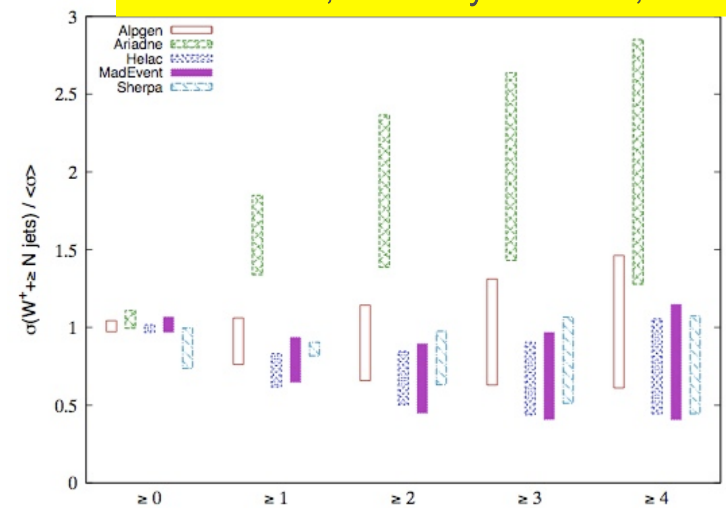


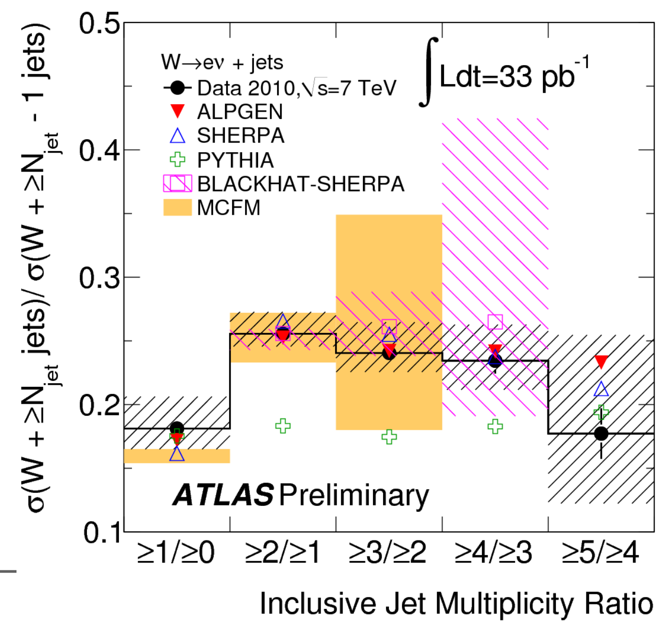


Merging Results for LHC

- **Much greater variations for LHC predictions**
  - **As expected—**
    - Without data to constrain, have large variation
    - Greater sensitivity given higher energy scale
  - **Key is to be consistent in approach**
    - Feeds into jet algorithm development, at least for QCD physics

Alwall et al., Eur. Phys. J. C53, 473 (2008)





ATLAS-CONF-2011-060

Key Issues to Keep in Mind

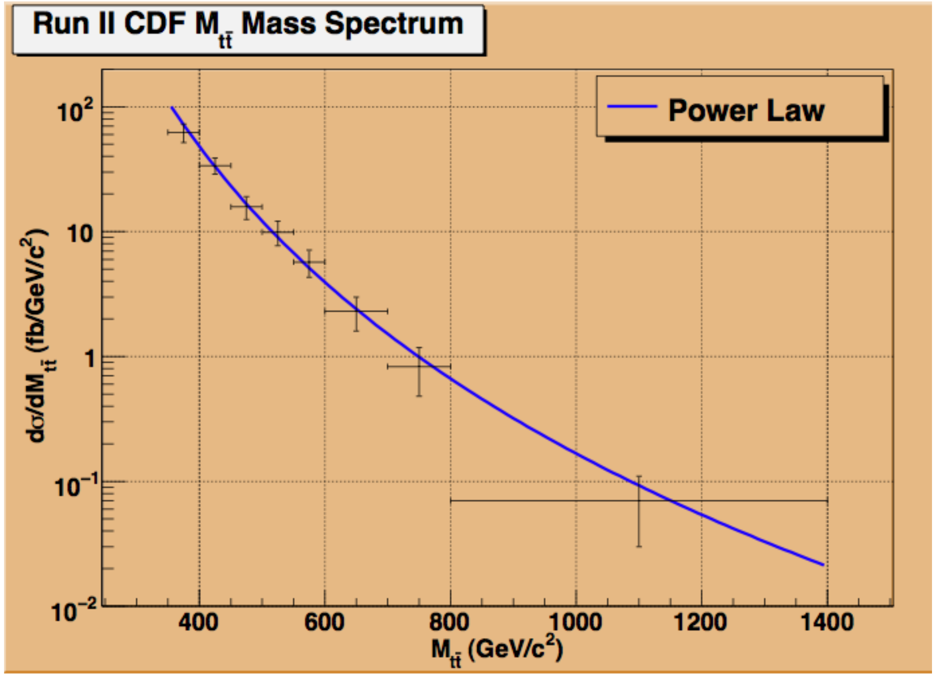
- **Understand limitations of the ME calculation**
  - **Don't treat it as a black box -- read the relevant documentation and/or literature**
- **Spend time in validating the MC at the parton level**
  - **If it doesn't make sense at particle level, it certainly won't be sensible after simulation & selection**
- **Careful that you remain as consistent as possible in choices**
  - **Order of ME, renormalization scheme, Q^2 scales all are important**
- **Understand relationship between MC generation and analysis strategy**
  - **Eg., jet clustering algorithms**
- **Comment: Weighted vs unweighted events:**
  - **Sampling of phase space is a problem when large # of partons**
  - **In some MCs, events are given weights**
    - OK in principle
    - In practice, not efficient if large weight variation
  - **Can ALWAYS deweight the MC sample**
    - Use weight as probability of keeping the event
    - Use random sampling to generate unweighted events
  - **Benefits:**
    - More readily see how events distributed
    - Don't spend CPU/disk space on events with low weights

Does this Picture Work?

- Sometimes people seem to be skeptical about how well this model works
  - Take a very simple case, where uncertainties from other effects are small
  - Top quark pair production at the Tevatron
    - Invariant mass of top quark pairs, after unfolding resolution effects

- Top quark pair invariant mass

$$\frac{d\sigma}{dM_{t\bar{t}}} \propto \left(M_{t\bar{t}}\right)^{(-6.1\pm0.9)}$$



Exercise: Repeat this calculation for ATLAS data

Example: Drell-Yan Production

- **Drell-Yan production seems like a simple process to calculate**
  - **Need to choose MC that**
    - Has correct P_T and eta dependence
    - Make sure it has correct K factor?
    - What does it do with higher-order processes
- **PYTHIA has been “tuned” and generally seen as OK**
  - **Still have to check that everything works**
  - **Make sure that kinematics agree with observed data**
  - **If selection sensitive to jet physics, need to worry about matching/ merging at parton level**

- **Most recent measurements**
  - **Focus on W & Z production**
  - **Precision limited by systematic uncertainties, not statistics**

Abulencia et al., J. Phys. G. 34, 2457 (2007)

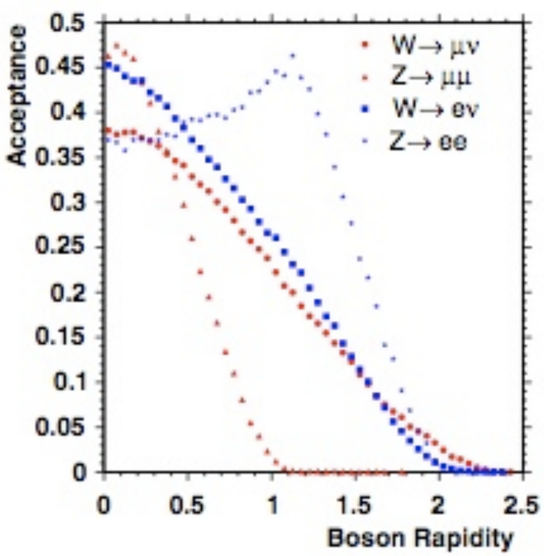
$$q + \bar{q} \rightarrow V$$

$$\begin{gathered} q + \bar{q} \rightarrow V \\ q + \bar{q} \rightarrow V + g \\ q(\bar{q}) + g \rightarrow V + q(\bar{q}) \end{gathered}$$

$$\begin{gathered} q + \bar{q} \rightarrow V \\ q + \bar{q} \rightarrow V + g \\ q + \bar{q} \rightarrow V + g + g \\ q(\bar{q}) + g \rightarrow V + q(\bar{q}) \\ q(\bar{q}) + g \rightarrow V + q(\bar{q}) + g \\ q + \bar{q} \rightarrow V + q + \bar{q} \\ q(\bar{q}) + q(\bar{q}) \rightarrow V + q(\bar{q}) + q(\bar{q}) \\ g + g \rightarrow V + q + \bar{q} \end{gathered}$$

W/Z Selection & Acceptance

- **Selected events**
  - **One lepton (e/γ) + MET**
    - E_T>25 GeV, P_T>20 GeV/c
    - MET>25/20 GeV
  - **Two leptons**
- **Used PYTHIA with NNLO**
  - **"Tuned" boson recoil model and UE event model**



- **Single largest source of uncertainty is PDFs**
  - **CTEQ5L and MRST2001NNLO**
  - **Used CTEQ uncertainties**
    - Larger, but not clear whose uncertainties are more realistic
  - **Also checked difference between NLO and NNLO calculations**
    - 0.2-0.7% difference

Table 16. PDF model acceptance uncertainties based on the CTEQ and MRST error PDF sets.

Acceptance	CTEQ +Uncertainty (%)	CTEQ −Uncertainty (%)	MRST +Uncertainty (%)	MRST −Uncertainty (%)
$A_{W\to\mu\nu}$	1.13	1.47	0.46	0.57
$A_{W\to e\nu}$	1.16	1.50	0.48	0.58
$A_{Z\to\mu\mu}$	1.72	2.26	0.67	0.87
$A_{Z\to ee}$	0.69	0.84	0.27	0.33
$A_{Z\to\mu\mu}/A_{W\to\mu\nu}$	0.67	0.86	0.26	0.31
$A_{Z\to ee}/A_{W\to e\nu}$	0.74	0.56	0.29	0.23

Tevatron DY Results

- **Much work to reduce systematic uncertainties**
  - **Most interesting result is ratio of cross sections**

	$W \to e\nu$	$W \to \mu\nu$
N_W^{obs}	37584	31722
N_W^{bck}	1762 ± 300	3469 ± 151
A_W	$0.2397\,^{+0.0035}_{-0.0042}$	$0.1970\,^{+0.0024}_{-0.0031}$
ϵ_W	0.749 ± 0.009	0.732 ± 0.013
$\int \mathcal{L}\,dt$ (pb^{-1})	72.0 ± 4.3	72.0 ± 4.3

	$\gamma^*/Z \to ee$	$\gamma^*/Z \to \mu\mu$
N_Z^{obs}	4242	1785
N_Z^{bck}	62 ± 18	13 ± 13
A_Z	$0.3182\,^{+0.0039}_{-0.0041}$	$0.1392\,^{+0.0027}_{-0.0033}$
ϵ_Z	0.713 ± 0.012	0.713 ± 0.015
$\int \mathcal{L}\,dt$ (pb^{-1})	72.0 ± 4.3	72.0 ± 4.3

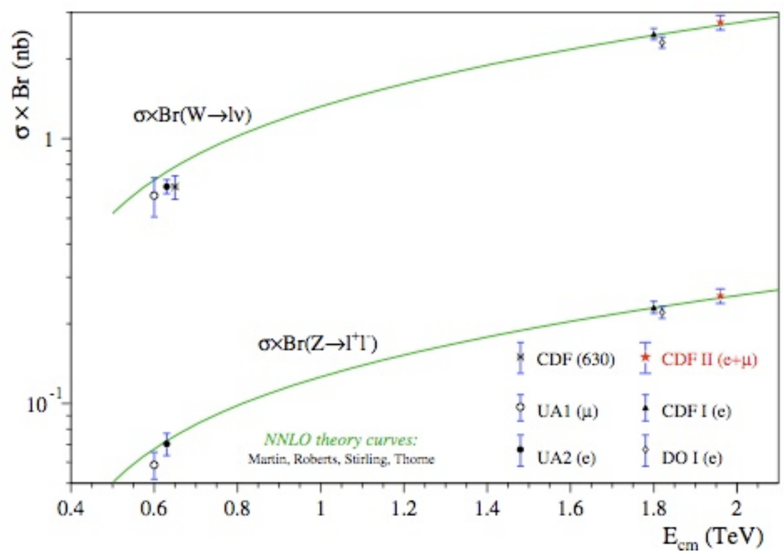
$$\sigma_W = 2.775 \pm 0.010\,(\text{stat}) \pm 0.053\,(\text{syst}) \pm 0.167\,(\text{lum})\ \text{nb}$$

$$\sigma_Z = 0.255 \pm 0.003\,(\text{stat}) \pm 0.005\,(\text{syst}) \pm 0.015\,(\text{lum})\ \text{nb}$$

$$R \equiv \frac{\sigma_W}{\sigma_Z} = 10.92 \pm 0.15\,(\text{stat}) \pm 0.14\,(\text{syst})$$

Table 22. Summary of estimated uncertainties on the measured acceptances for our four candidate samples.

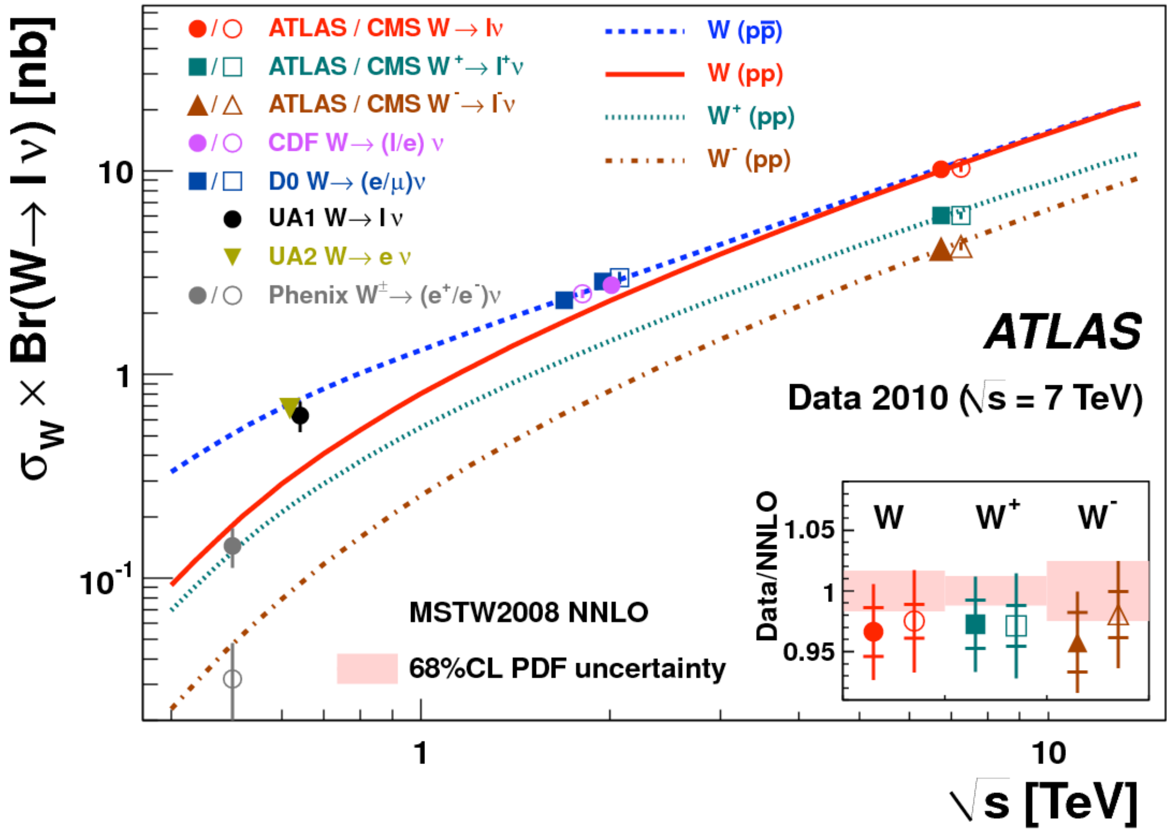
Uncertainty category	$\Delta A_{W\to e\nu}$ (%)	$\Delta A_{W\to \mu\nu}$ (%)	$\Delta A_{Z\to ee}$ (%)	$\Delta A_{Z\to \mu\mu}$ (%)
NNLO $d\sigma/dy$ calculation	0.29	0.25	0.06	0.72
PDF model (positive)	1.16	1.13	0.69	1.72
PDF model (negative)	1.50	1.47	0.84	2.26
Boson p_T model	0.04	0.04	0.06	0.08
Recoil energy model	0.25	0.35	0.00	0.00
Track p_T scale/resolution	0.03	0.21	0.04	0.05
Cluster E_T scale/resolution	0.34	0.00	0.26	0.00
Detector material model	0.73	0.00	0.96	0.00
Simulated event statistics	0.13	0.14	0.24	0.41
Total (positive)	1.46	1.22	1.23	1.94
Total (negative)	1.75	1.57	1.26	2.44



LHC DY Results

- **First ATLAS/CMS measurements are now published**

	$\sigma_W^{tot} \cdot \mathrm{BR}(W \to \ell\nu)$ [nb]				
		sta	sys	lum	acc
W^+	6.048	± 0.016	± 0.072	± 0.206	± 0.096
W^-	4.160	± 0.014	± 0.057	± 0.141	± 0.083
$W^\pm$	10.207	± 0.021	± 0.121	± 0.347	± 0.164
	$\sigma_{Z/\gamma^*}^{tot} \cdot \mathrm{BR}(Z/\gamma^* \to \ell\ell)$ [nb] $66 < m_{\ell\ell} < 116$ GeV				
		sta	sys	lum	acc
Z/γ^*	0.937	± 0.006	± 0.009	± 0.032	± 0.016



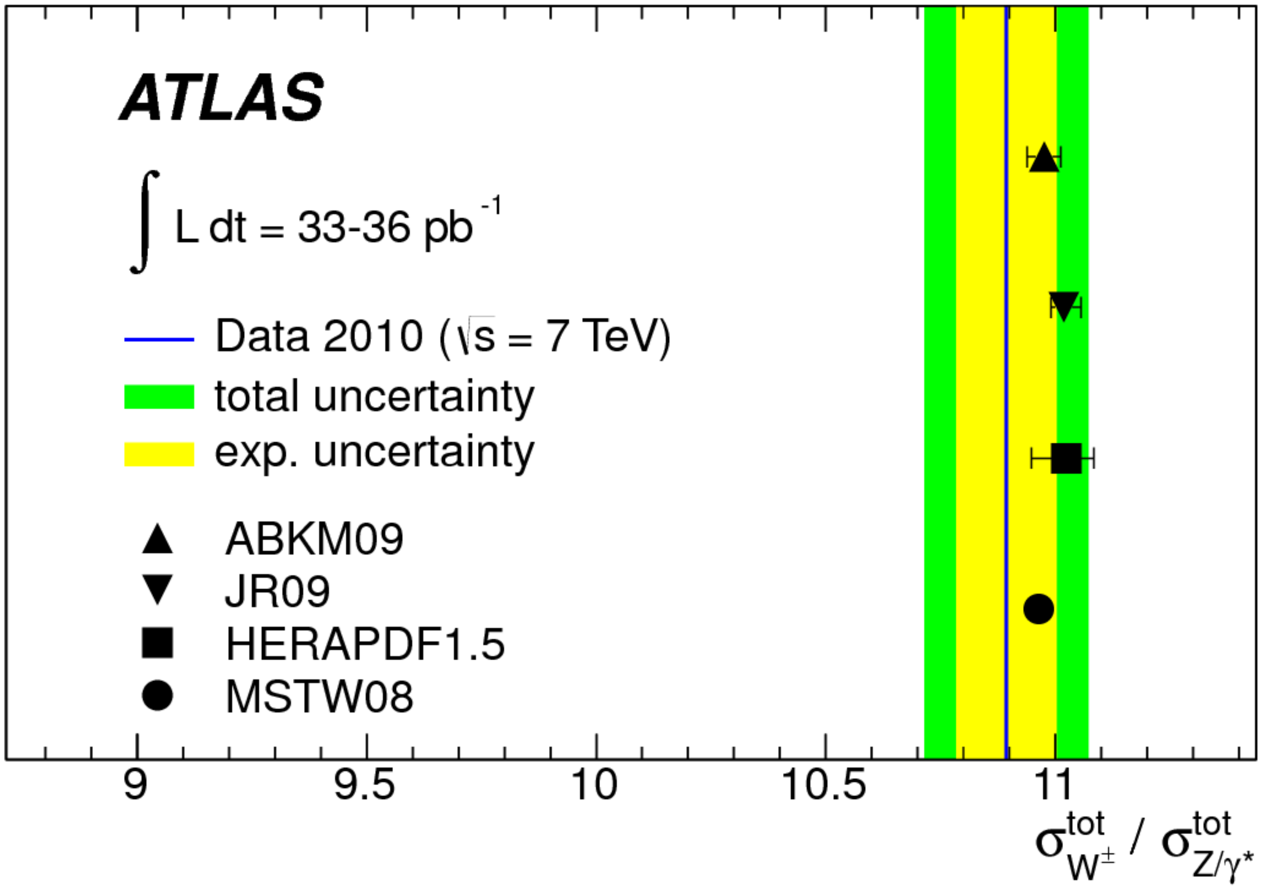
ATLAS Collaboration, Phys. Rev. D85 (2012) 072004

$$\sigma_W = 10.207 \pm 0.021\,(\mathrm{stat}) \pm 0.121\,(\mathrm{syst}) \pm 0.347\,(\mathrm{lum}) \pm 0.164\,(\mathrm{acc})\ \mathrm{nb}$$

$$\sigma_Z = 0.937 \pm 0.006\,(\mathrm{stat}) \pm 0.009\,(\mathrm{syst}) \pm 0.032\,(\mathrm{lum}) \pm 0.016\,(\mathrm{acc})\ \mathrm{nb}$$

$$R \equiv \frac{\sigma_W}{\sigma_Z} = 10.893 \pm 0.079\,(\mathrm{stat}) \pm 0.110\,(\mathrm{syst}) \pm 0.116\,(\mathrm{acc})$$

Cross Section Ratios



ATLAS Collaboration, Phys. Rev. D85 (2012) 072004

$$R \equiv \frac{\sigma_W}{\sigma_Z} = 10.893 \pm 0.079\,(\text{stat}) \pm 0.110\,(\text{syst}) \pm 0.116\,(\text{acc})$$