New Developments in LHAPDF/LHAGLUE

and

PDF use from the Tevatron to the LHC

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Outline

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  - Recent developments in LHAPDF/LHAGLUE
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  - Master equations
- Example studies
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  - Gluon fusion to Higgs at LHC
  - High P_T inclusive jet at TeV and LHC
- Summary

Motivation

- Use MC to compare theoretical predictions with experimental results.
- TeV and LHC collide hadrons so every event generated uses PDFs

$$\frac{\mathrm{d}\,\sigma}{\mathrm{d\ variable}}[\mathrm{pp}\to\mathrm{X}] \sim \sum_{\mathrm{ij}} \left(\mathrm{f_{i/p}}(\mathrm{x_1})\mathrm{f_{j/p}}(\mathrm{x_2}) + (\mathrm{i}\leftrightarrow\mathrm{j})\right)\,\hat{\sigma} \qquad (1)$$

$\hat{\sigma}$ - cross section for the partonic subprocess $ij \to X$

$\mathrm{x_1}, \mathrm{x_2}$ - parton momentum fractions,

$\mathrm{f_{i/p}}(\mathrm{x_i})$ - probability to find a parton i with x_i in the proton.

- Standard PDF access is important $\longrightarrow$ LHAPDF
- $\delta\sigma_{th} = \delta\sigma_{PDF} + ...$

TeV/LHC physics affected by PDFs

- UE tunes

  $\longrightarrow$ See talk by R. Field on Pythia tune with CTEQ61

- Luminosity to few percent at LHC using Z/W production

- Heavy flavor PDFs

  $\longrightarrow$ See nice talk by C. Jackson (Brookhaven meeting)

- W+/W- constrain flavor decomposition

- High P_T jet cross section

$\longrightarrow$ See talk "Issues in PDFs" by Wu-Ki Tung from first meeting for nice summary.

LHAPDF/LHAGLUE

- The Les Houches Accord PDF library is replacement for PDFLIB.
- LHAGLUE is a “PDFLIB-like” interface for HERWIG and PYTHIA

→ See talk by J. Huston (Dec.1 2005 QCD working group) for summary of LHAPDF and LHAGLUE.

Recent developments in LHAPDF

- v4 March 2005
  - Photon and pion PDFs from PDFLIB
  - New proton PDFs: MRST2004 and Alekhin's a02m
  - Simplified file structure (All 'source' files in src)
  - Access to $\Lambda^{QCD}_{4/5}$
- v4.1 August 2005
  - New installation method (configure;make;make install)

$\longrightarrow$ See hep-ph/0508110 for more detail and complete history of LHAPDF/LHAGLUE

LHAPDF V5 coming soon!

- Will be possible to keep PDFs from multiple sets stored in memory.
- Feedback from Tevatron experiments implemented
  - pftopdg.f added from PDFLIB.
    - Some CDF and D0 programs use this.
    - pftopdg converts flavor convention of PDFLIB to PDG convention
  - Various generic names changed to be unique to LHAPDF

    These are only internal names which do NOT affect the average user.
- NEW: LHAPDF v5 available ups/upd at FNAL...
  - "lhapdf" "v5_0_0_beta" "Linux+2.4-2.3.2" "GCC3_4_3" "development"
  - "lhapdf_source" "v5_0_0_beta" "NULL" "" "development"

  → Thanks to Lynn Garren!
- Please check v5! Your suggestions/problems can still be dealt with in v5.

→ CDF and D0 use will help validate and develop tools and ideas that will also be useful to the LHC. This is important!

Cross sections and uncertainty checks

Cross sections in [pb] - TEVATRON 2 TeV				
	Drell-Yan		Higgs	
PDF set	PYTHIA	HERWIG	PYTHIA	HERWIG
CTEQ6	198 ± 6.9	195 ± 6.6	0.30 ±0.02	0.31 ± 0.02
CTEQ6l	178	176	0.26	0.26
CTEQ6ll	180	178	0.25	0.26
CTEQ6mE	198 ± 6.9	195 ± 6.6	0.30 ±0.02	0.31 ± 0.02
CTEQ61(one)	198 ± 6.8	195 ± 6.6	0.31 ±0.02	0.31 ± 0.02
CTEQ5m	207	205	0.32	0.33
CTEQ5m1	203	200	0.30	0.30
CTEQ5d	193	190	0.36	0.36
CTEQ5l	185	183	0.25	0.25
CTEQ4m	207	204	0.33	0.33
CTEQ4d	194	191	0.36	0.36
CTEQ4l	184	182	0.27	0.27
MRST2001	202	199	0.32	0.33
MRST2001lo	179	177	0.28	0.28
MRST2001nlo(Standard)	202	200	0.32	0.32
MRST2001nlo(low α_s)	202	200	0.31	0.32
MRST2001nlo(low α_s)	209	206	0.33	0.34
MRST2001nlo(Jet Fit)	201	198	0.33	0.33
MRST2001nnlo	206	203	0.34	0.33
MRST2001E	202 ± 2.2	199 ± 2.2	0.32 ±0.01	0.33 ± 0.01
MRST2002nlo	202	199	0.32	0.33
MRST2002nnlo	205	203	0.34	0.34
MRST98(central)	203	200	0.31	0.28
MRST98(low g)	204	202	0.30	0.27
MRST98(high g)	200	298	0.32	0.28
MRST98(low α)				
MRST98(high α)				
MRSTCNLO	206	204	0.35	0.35
MRSTCNNLO	205	203	0.32	0.32
Fermi2002_100	207 ± 5.1	204 ± 4.9	0.27 ±0.02	0.27 ± 0.02
Fermi2002_1000	209 ± 5.0	206 ± 4.9	0.29 ± ...	0.29 ± ...
Alekhin_100	216 ± 4.0	214 ± 4.0	0.32 ±0.02	0.32 ± 0.02
Alekhin_1000	218 ± 5.1	216 ± 5.2	0.34 ± ...	0.34 ± 0.02

Cross sections in [pb] - LHC 14 TeV				
	Drell-Yan		Higgs	
PDF set	PYTHIA	HERWIG	PYTHIA	HERWIG
CTEQ6	1673 ± 64	1636 ± 63	16.2 ± 0.7	16.0 ± 0.7
CTEQ6m	1673	1636	16.2	16.0
CTEQ6l	1538	1500	18.3	17.6
CTEQ6ll	1647	1608	17.8	17.4
CTEQ6mE	1673 ± 64	1636 ± 62	16.2 ± 0.7	16.0 ± 0.7
CTEQ61(one)	1659 ± 76	1624 ± 78	16.0 ± 0.8	15.8 ± 0.8
CTEQ5m	1802	1756	15.8	15.9
CTEQ5m1	1711	1667	15.7	15.5
CTEQ5d	1684	1647	15.7	15.7
CTEQ5l	1642	1611	17.1	16.8
CTEQ4m	1752	1707	15.4	15.3
CTEQ4d	1653	1615	15.8	15.6
CTEQ4l	1640	1609	16.9	16.5
MRST2001lo	1595	1556	17.0	15.5
MRST2001nlo(Standard)	1699	1657	15.5	15.4
MRST2001nlo(low α_s)	1692	1658	15.8	15.6
MRST2001nlo(high α_s)	1740	1700	15.5	15.6
MRST2001nlo(Jet Fit)	1686	1647	15.1	15.1
MRST2001nnlo	1656	1617	14.6	14.5
MRST2001E	1682 ± 26	1645 ± 28	15.4 ± 0.3	15.3 ± 0.3
MRST2002nlo	1693	1652	15.4	15.3
MRST2002nnlo	1656	1617	14.7	15.2
MRST98(central)	1684	1639	15.4	15.2
MRST98(low g)	1695	1656	15.6	15.4
MRST98(high g)	1665	1618	15.1	14.9
MRST98(low α)				
MRST98(high α)				
MRSTCNLO	1374	1353	15.8	15.5
MRSTCNNLO	1399	1373	14.0	13.8
Fermi2002_100	1391 ± 28	1364 ± 27	14.2 ± 0.5	13.7 ± 0.5
Fermi2002_1000	1418 ± 27	1391 ± 27	14.9 ± ...	14.4 ± 0.5
Alekhin_100	1763 ± 65	1722 ± 64	15.6 ± 0.6	15.4 ± 0.6
Alekhin_1000	1793 ± 64	1744 ± 64	16.2 ± ...	16.1 ± 0.6

Cross sections and uncertainty checks cont..

Cross sections in [pb] - TEVATRON 2 TeV				
	Drell-Yan		Higgs	
PDF set	PYTHIA	HERWIG	PYTHIA	HERWIG
a02_lo_v	216	212	0.28	0.27
a02_nlo_v	229	226	0.32	0.31
a02_nnlo_v	233	230	0.32	0.31
Botje_100	198 ± 1.0	196 ± 1.0	0.27 ±0.01	0.27 ± 0.01
Botje_1000	201 ± 2.1	198 ± 2.0	0.29 ± ...	0.29 ± 0.01
Zeus2002_TR	204	202	0.31	0.32
Zeus2002_ZM	203	200	0.30	0.31
Zeus2002_FF	205	203	0.36	0.34
H12000_ms	205	203	0.32	0.33
H12000_mse	206±4.2	203±3.6	0.32±0.01	0.33 ±0.02
H12000_lo2	198	196	0.37	0.37
H12000_lo2e	197±3.2	195±3.4	0.37±0.01	0.37 ±0.01
H12000_lo	199	196	0.17	0.18
H12000_loE	198±4.5	196±4.6	0.17±0.01	0.18 ±0.01
H12000_dis	196	193	0.34	0.34
H12000_disE	196±3.8	194±3.8	0.34±0.01	0.34 ±0.01
GRV98_lo	190	188		0.31
GRV98_nlo	199	196		0.39

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Cross sections in [pb] - LHC 14 TeV				
	Drell-Yan		Higgs	
PDF set	PYTHIA	HERWIG	PYTHIA	HERWIG
a02_lo_v	1706	1668	17.4	16.4
a02_nlo_v	1841	1792	16.4	15.7
a02_nnlo_v	1864	1813	16.3	15.6
Botje_100	1850 ± 47	1802 ± 46	16.0 ± 0.4	15.6 ± 0.4
Botje_1000	1891 ± 46	1843 ± 45	16.9 ± ...	16.4 ± 0.4
Zeus2002_TR	1732	1696	16.3	16.1
Zeus2002_ZM	1748	1713	16.7	16.6
Zeus2002_FF	1742	1706	16.9	19.1
H12000_ms	1730	1700	17.6	17.2
H12000_mse	1735± 27	1705 ±25	17.5±0.3	17.2 ±0.3
H12000_lo2	1565	1539	15.4	15.3
H12000_lo2e	1561± 19	1534 ±19	15.4±0.2	15.3 ±0.2
H12000_lo	1646	1606	15.4	14.9
H12000_loE	1640± 44	1601 ±39	15.4±0.6	15.0 ±0.6
H12000_dis	1629	1599	18.4	17.7
H12000_disE	1635± 25	1604 ±24	18.4±0.3	17.7 ±0.3
GRV98_lo	1569	1535		17.9
GRV98_nlo	1563	1530		16.9

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PDF Uncertainty:Example CTEQ6

- "The Hessian Method"
  - PDF parameterization
    $F(x,Q) = a_0 x^{a_1}(1-x)^{a_2} P(x; a_3, ..., a_i) i = 1, ...N$
  - Fit to data using N=20 free parameters $\longrightarrow$ central value S_0
  - Increase the global χ^2 by $\Delta\ \chi^2$=100 to form error matrix
    $\rightarrow \Delta\ \chi^2 = \chi^2 - \chi_0^2 = \sum_{i=1}^N \sum_{j=1}^N H_{ij}(a_i - a_i^0)(a_j - a_j^0)$
  - Diagonalize the error matrix $\longrightarrow$ N eigenvectors
  - Vary Up/Down in tolerance along each of the N eigenvector directions to obtain 2N=40 new members of the PDF set $\longrightarrow S_i^{\pm}(i = 1, .., N)$

$$LHAPDF \rightarrow F_i^{\pm} = F(x, Q; S_l^{\pm})$$

$\longrightarrow$ See hep-ph/0101032 for details

4 "Master" equations for uncertainties on observables?

1) $\Delta X_1 = \frac{1}{2}\sqrt{\sum_{i=1}^{N}(X_i^+ - X_i^-)^2}$

What if X_i^+ and X_i^- lie on the same side of X_0?

2) $\Delta X_2 = \frac{1}{2}\sqrt{\sum_{i=1}^{2N} R_i^2}$ ($R_1 = X_1^+ - X_0$,$R_2 = X_1^- - X_0$, $R_3 = X_2^+ - X_0$ ...)

NOTE: For symmetric and asymmetric deviations, ΔX_1 varies from $0 \rightarrow \frac{2}{\sqrt{2}}\Delta X_2$

3) CMS positive and negative variations

$\Delta X_{CMS}^+ = \sqrt{\sum_{i=1}^{N}(X_i^+ - X_0)^2}$, $\Delta X_{CMS}^- = \sqrt{\sum_{i=1}^{N}(X_i^- - X_0)^2}$

4) Consider maximal positive and negative variations separately.*

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

$\longrightarrow$See hep-ph/0110378 (P.M. Nadolsky and Z. Sullivan)*

Techniques for using the "Master" equations

- Brute force
  - Generate MC sample 41 times (once for each PDF in the set)
  - Requires large CPU time! (especially with detector simulation)
  - Need many events to isolate PDF uncertainty over statistical variation.
- PDF weight technique
  - Only one MC sample is generated but 40 PDF weights are stored for each event
    $\rightarrow W_n^0 = 1, W_n^i = \frac{F(x_1,Q;S_i)F(x_2,Q;S_i)}{F(x_1,Q;S_0)F(x_2,Q;S_0)}$
    $n = 1...N_{events}, i = 1..N_{PDF}$
  - Only one run, so kinematics do not change and no residual statistical variation in uncertainty.
  - Must weight the observable (weighted histograms)
- With the above 2 methods use a master equation after you get a result for each PDF.
- One final option is to study which PDFs in the set you are most sensitive to and then just run this subset. Since the contributions add in quadrature this is often good enough.

Implementing the weighting technique for PYTHIA

- Two options for using the weight technique
  - Store 40 weights for each event (we do it this way).
  - Store X_1, X_2, F_1, F_2, and Q^2 and calculate the weights “offline”.
- Momentum fractions for the 2 initial partons from the hard scattering.

$$X_1 = PARI(33) \text{ and } X_2 = PARI(34)$$

- Flavor type of 2 initial partons

$$F_1 = MSTI(15) \text{ and } F_2 = MSTI(16)$$

- Q^2 for the hard scattering

$$Q^2 = PARI(24)$$

This is everything you need to calculate PDF weights using LHAPDF, but we are in the process of writing a general robust code for all users, so you won’t have to.

$\longrightarrow$ Thanks to Torbjörn Sjöstrand for the PYTHIA help!

get_weights SUBROUTINE

- The user passes in the Pythia information.

  W_F1=MSTI(15)

  W_F2=MSTI(16)

  W_X1=PARI(33)

  W_X2=PARI(34)

  W_q2=PARI(24)

- Two arrays are returned; one for the PDF value of each parton.

  LHA_PDFS1(-PDF_ LENGTH:PDF_ LENGTH)

  LHA_PDFS2(-PDF_ LENGTH:PDF_ LENGTH)

  - central value: LHA_PDFS1(0) (member 0)
  - First '+' variation: LHA_PDFS1(1) (member 1)
  - First '-' variation: LHA_PDFS1(-1) (member 2)
  - ...

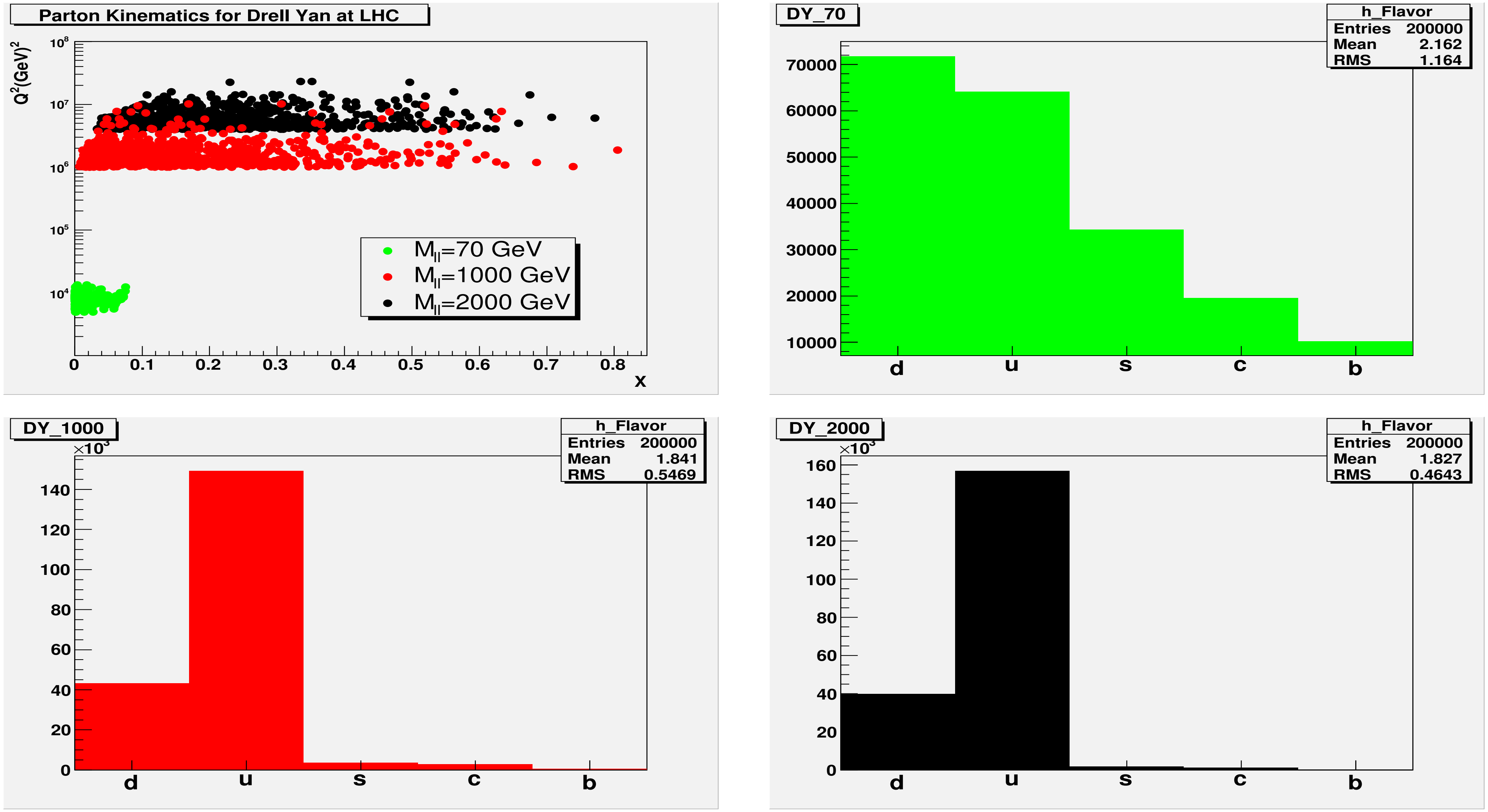
3 example studies

- Drell Yan at the LHC: M=70,1000,2000 ($|\eta| < 2.4$)
- Gluon fusion to Higgs at the LHC
- Dijet500 at TeV and LHC

For all studies PYTHIA v6.324 was used with LHAPDF v4.1.1.

The point of these studies is only to compare the predictions of the weight and "brute force" method as well as the various master equations, not to make predictions for YOUR analysis.

DY Parton kinematics and flavor contributions



TeV2LHC: Drell Yan error results (in pb)

Process (method)	X_0(best fit)	ΔX_1	ΔX_2	$+\Delta X^{+}_{CMS}$	$-\Delta X^{-}_{CMS}$	$+\Delta X^{+}_{max}$	$-\Delta X^{+}_{max}$
70$<$M$<$110 (B.F.)	1086	48	42	+55	-63	+51	-62
70$<$M$<$110 (W)	1086	48	42	+55	-64	+51	-63
M$>$1000 (B.F.)	6.7e-3	3.5e-4	2.6e-4	+ 3.5e-4	-3.8e-4	+3.4e-4	-3.9e-4
M$>$1000 (W)	6.7e-3	5.3e-4.	4.7e-4	+4.5e-4	-8.3e-4	+8.1e-4	-4.6.1e-4
M$>$2000 (B.F.)	2.2e-4	1.8e-5	1.3e-5	+1.9e-5	-1.9e-5	+2.0e-5	-1.7e-5
M$>$2000 (W)	2.2e-4	3.1e-5	2.9e-5	+2.3e-5	-5.3e-5	+5.3e-5	-2.2e-5

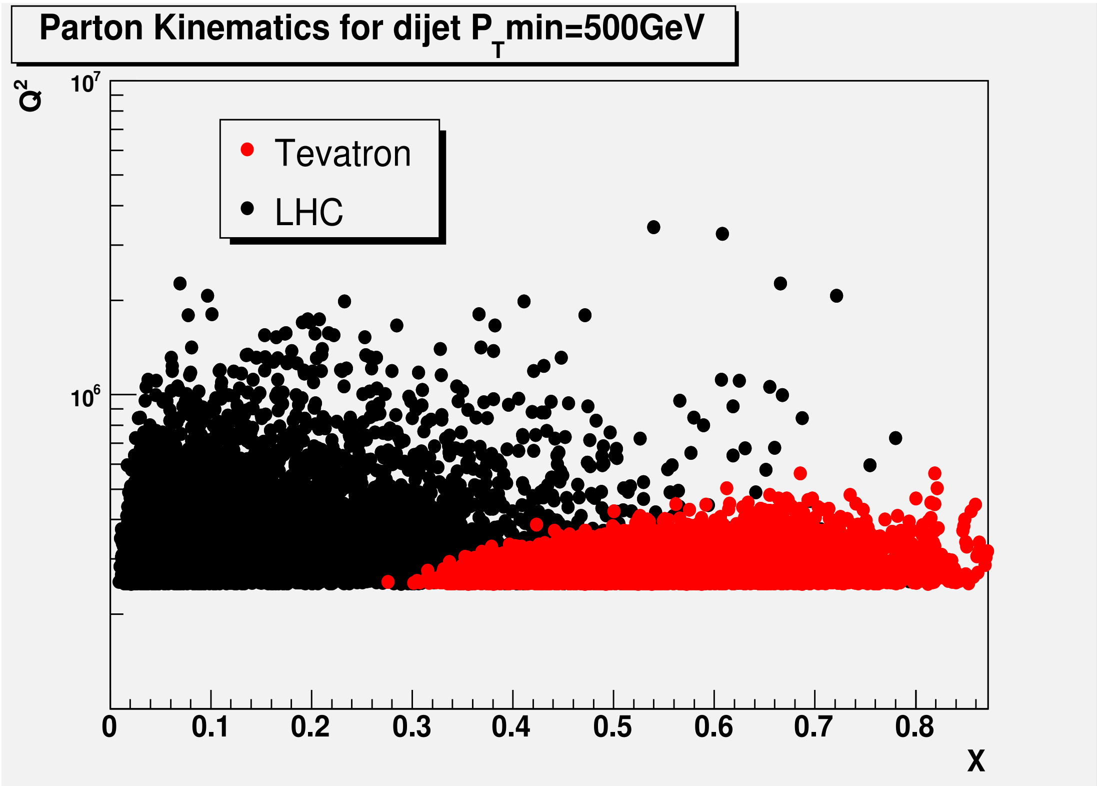
Gluon Fusion to Higgs ($M_H = 120$ GeV)

- No need for kinematics plot here.
  - $Q^2 \sim M_H^2$
  - $x < \frac{M_H}{7000}$
- Results (in pb)

Process (method)	X_0(best fit)	ΔX_1	ΔX_2	$+\Delta X^+_{CMS}$	$-\Delta X^-_{CMS}$	$+\Delta X^+_{max}$	$-\Delta X^+_{max}$
$gg \rightarrow H$ (B.F.)	17	.94	.68	+.82	-1.1	+.8	-1.1
$gg \rightarrow H$ (W)	17	.94	.68	+.82	-1.1	+.8	-1.1

Dijet 500 parton kinematics

- MSEL=1
- CKIN(3)=500



Dijet 500 error results (in pb)

Process (method)	X_0(best fit)	ΔX_1	ΔX_2	$+\Delta X^+_{CMS}$	$-\Delta X^-_{CMS}$	$+\Delta X^+_{max}$	$-\Delta X^+_{max}$
TeV (B.F.)	2.2e-11	6.8e-12	5.74e-12	4.8e-12	1.0e-11	1.1e-11	4.2e-12
TeV (W)	2.2e-11	6.8e-12	5.75e-12	4.8e-12	1.0e-11	1.1e-11	4.2e-12
LHC (B.F.)	8.8e-7	6.3e-8	4.7e-8	5.6e-8	7.4e-8	7.6e-8	5.3e-8
LHC (W)	8.8e-7	6.3e-8	4.7e-8	5.7e-8	7.5e-8	7.7e-8	5.3e-8

No η or P_T cuts applied.

SUMMARY

- Recent developments in LHAPDF/LHAGLUE were discussed as well as changes that will be included in the new v5 code.
- PDF uncertainty techniques were discussed including the “Brute Force” v/s the PDF weights method.
- New code written for the physics community to use the PDF weights techniques was described.
- Results from studies done for this workshop were shown for...
  - There is good agreement between the ’weighting’ and ’brute force’ technique for all processes EXCEPT high mass Drell Yan pairs.
  - The ΔX_1 prediction is consistently larger than ΔX_2. It will underestimate however if the variations have a more “asymmetric” affect on the observable.
  - The two non-symmetric equations have consistent results although it seems that the ’CMS’ version is expecting the ’+’, ’-’ variations to be non-arbitrary

- Thanks to J. Huston, T. Sjstrand, K. Matchev, and R. Field for useful correspondence.

Full error table

Process (method)	X_0(best fit)	ΔX_1	ΔX_2	$+\Delta X^+_{CMS}$	$-\Delta X^-_{CMS}$	$+\Delta X^+_{max}$	$-\Delta X^+_{max}$
70$<$M$<$110 (B.F.)	1086	48	42	+55	-63	+51	-62
70$<$M$<$110 (W)	1086	48	42	+55	-64	+51	-63
M$>$1000 (B.F.)	6.7e-3	3.5e-4	2.6e-4	+ 3.5e-4	-3.8e-4	+3.4e-4	-3.9e-4
M$>$1000 (W)	6.7e-3	5.3e-4.	4.7e-4	+4.5e-4	-8.3e-4	+8.1e-4	-4.6.1e-4
M$>$2000 (B.F.)	2.2e-4	1.8e-5	1.3e-5	+1.9e-5	-1.9e-5	+2.0e-5	-1.7e-5
M$>$2000 (W)	2.2e-4	3.1e-5	2.9e-5	+2.3e-5	-5.3e-5	+5.3e-5	-2.2e-5
$gg \to H$ (B.F.)	17	.94	.68	+.82	-1.1	+.8	-1.1
$gg \to H$ (W)	17	.94	.68	+.82	-1.1	+.8	-1.1
DJ500 TeV (B.F.)	2.2e-11	6.8e-12	5.74e-12	4.8e-12	1.0e-11	1.1e-11	4.2e-12
DJ500 TeV (W)	2.2e-11	6.8e-12	5.75e-12	4.8e-12	1.0e-11	1.1e-11	4.2e-12
DJ500 LHC (B.F.)	8.8e-7	6.3e-8	4.7e-8	5.6e-8	7.4e-8	7.6e-8	5.3e-8
DJ500 LHC (W)	8.8e-7	6.3e-8	4.7e-8	5.7e-8	7.5e-8	7.7e-8	5.3e-8