Reweighting and PDF Systematics from CDF

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Introduction

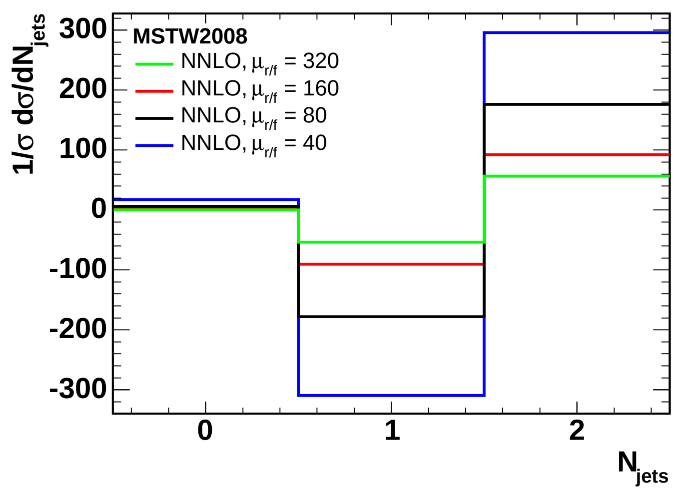
- Theoretical uncertainties on $gg \to H$ are a challenge experimentally
  - Given our selection, how to properly determine the size of scale and PDF uncertainties?
  - Should there be correlations between cross section and acceptance systematics?
  - Can theoretical uncertainties cause shape changes in our discriminants?
- We do rely on theoreticians' tools and advice when estimating these uncertainties
- In this talk:
  - Discuss the theory programs we use
  - Show how we reweight our $gg \to H$ Pythia samples
  - Show how we estimate scale and PDF uncertainties on the $gg \to H$ cross section and acceptance

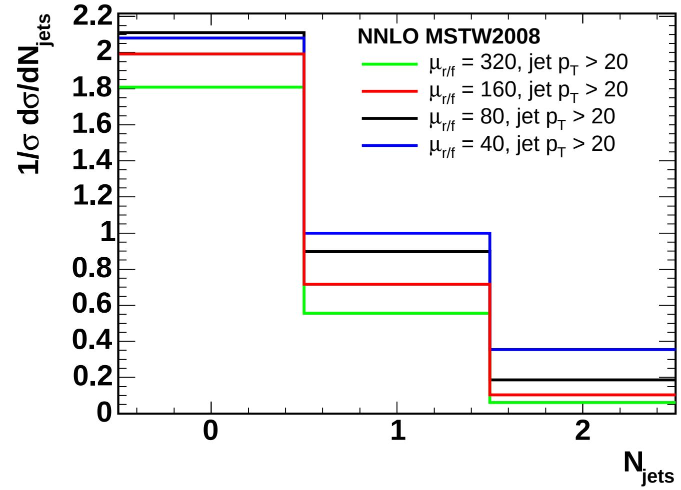
Theory programs in use at CDF

- We use the latest versions of HqT and HNNLO programs
  - Both available on Massimiliano Grazzini's webpage: http://theory.fi.infn.it/grazzini/codes.html
- HqT
  - Computes transverse momentum distribution for $gg \longrightarrow H$ production in $p\overline{p}$ collisions at NNLL+NLO accuracy
  - Cannot apply experimental-like cuts
- HNNLO
  - Computes cross sections for $gg \longrightarrow H$ production in $p\overline{p}$ collisions up to NNLO in QCD perturbation theory
  - Allows applying arbitrary cuts on the momenta of the partons and/or leptons produced in the final state
  - Obtain desired distributions in the form of binned histograms

HNNLO Examples

- Some distributions don't make sense without applying cuts
  - Numerical instabilities at low Higgs/jet p_T





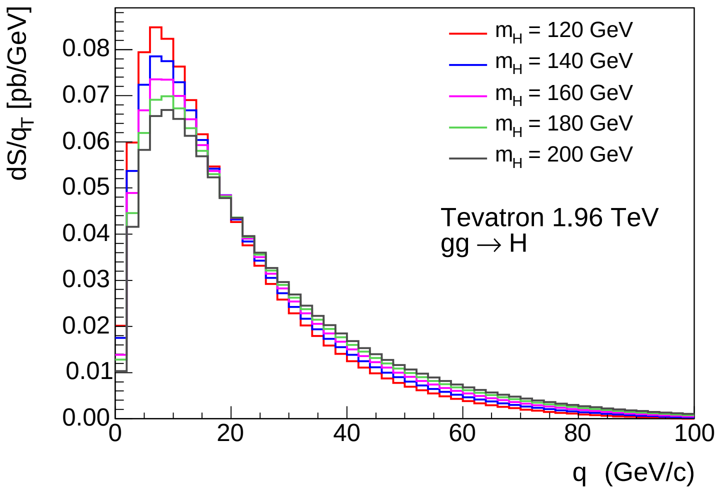
- To study variations in the differential N_{jets} cross section, apply these cuts:
  - $p_T(\mathrm{jet}) > 20$ GeV/c, $|\eta(\mathrm{jet})| < 2.5$
  - $p_T(\ell_1) > 20$ GeV/c, $p_T(\ell_2) > 10$ GeV/c, $|\eta(\ell)| < 2$

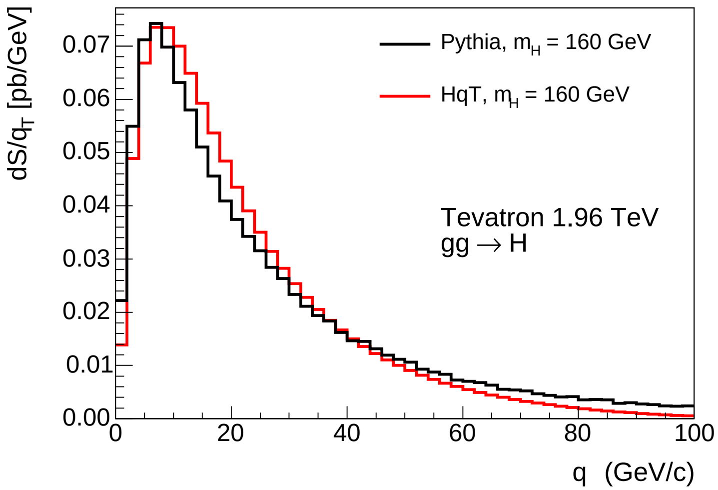
Reweighting Procedure

- Assumption: since the Higgs is a scalar particle, all that matters are boost and rapidity
  - For our acceptance studies, we modify the generator-level Higgs p_T or y distribution
  - Then run the reweighted Pythia MC through our analysis selection to find the change in Higgs acceptance
- If we could modify both p_T and y simultaneously (2D reweighting histogram), we would
  - But neither HqT nor HNNLO can produce 2D histograms
  - So we treat p_T and y as uncorrelated
  - We find that y has a small effect
- Use MSTW2008 NNLO PDFs for everything

Reweighting Pythia $gg \to H$ samples

- We want our central prediction to be as accurate as possible
  - Reweight Pythia Higgs p_T spectrum to HqT prediction
  - Calculate HqT spectrum for each mass (scale set to m_H)





- HqT shows less of a high-p_T tail than Pythia
  - Effect of reweighting is to move a few percent of Higgs acceptance from higher jet bins into 0-jet bin

Determining $gg \to H$ systematic uncertainties

- Currently consider cross section and acceptance uncertainties to be uncorrelated
  - Both have two components: scale and PDF
  - Acceptance uncertainties calculated for reweighting Higgs p_T and y separately
- For all studies shown here today, considered three different Higgs mass points
  - $m_H = 135$, 165, and 195
  - Found uncertainties did not vary by Higgs mass

$\longrightarrow$ Use the uncertainties determined for $m_H = 165$ for all Higgs mass points

Cross section uncertainties

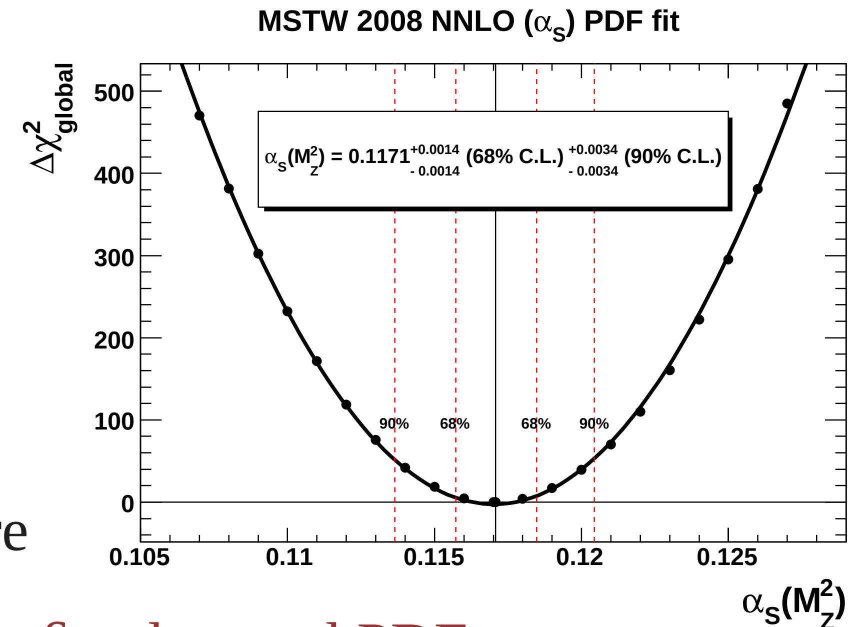
- Scale uncertainties
  - Calculated separately for 0, 1, and 2+ jet bins
  - Take the values from 0905.3529, but also cross-checked with HNNLO:

Channel:	0 Jets	1 Jet	2+ Jets
Cross Section Scale	7.0%	23.5%	67.5%

- PDF uncertainties
  - Previously used inclusive cross section PDF uncertainty of 7.7% for all jet bins
  - This comes from de Florian and Grazzini's paper (0901.2427) and does not include α_s uncertainty...

MSTW2008 α_s + PDF eigenvectors

- Default MSTW2008 NNLO PDF allows α_s to vary in the fit
  - Result: $\alpha_s = 0.1171^{+0.0014}_{-0.0014}$ (68% C.L.) $^{+0.0034}_{-0.0034}$ (90% C.L.)
  - α_s stays at the central value for the 20 up and down variations that give the PDF error eigenvectors



- Now: move α_s out to $\pm$90% C.L.
  - Refit central PDF values
  - Perform 20 up/down variations here
- Many ($\sim$16 out of 40) identical to the refitted central PDF
  - Contacted the authors; this is expected (moving α_s to such an extreme value leaves nowhere for the fit to go when varying some parameters)

CDF Procedure for PDF Uncertainties

- Generate reweighting spectrum for each eigenvector
  - For acceptance, we take Higgs p_T spectrum from HqT, Higgs y spectrum from HNNLO (no cuts applied)
- Calculate weighted acceptance after reweighting
  - We reweight twice, once for p_T and once for y
- Add in quadrature the differences in acceptance (between default and reweighted) for each eigenvector
  - Calculated asymmetrically, adding in quadrature those that increase/decrease the acceptance separately
  - Finally, take the average of the $\pm$ uncertainties as a symmetric uncertainty

Cross section: α_s + PDF uncertainties

- Use HNNLO to calculate cross section in 0, 1, and 2+ jet bins for each α_s + PDF eigenvector
  - Dual purpose: update PDF uncertainty to include α_s variation, and calculate uncertainty by jet bin
- As expected, α_s + PDF uncertainty is larger than PDF alone:
  - Sum in quadrature gives total cross section uncertainty of -10.1% (-90% C.L. α_s), +12.3% ($+90\%$ C.L. α_s)
- Change is correlated but *not* constant across jet bins

Channel:	0 Jets	1 Jet	2+ Jets
-90% C.L. α_s Uncertainty:	-9.6%	-15.0%	-19.4%
$+90\%$ C.L. α_s Uncertainty:	+5.6%	+19.5%	+40.0%
Average Uncertainty:	7.6%	17.3%	29.7%

Acceptance: Higgs p_T α_s + PDF Reweighting

- Reweighting Higgs p_T moves events between jet bins
  - 0-jet anticorrelated with 1-jet and 2+ jets
  - Call it the "Acceptance α_s + PDF (jets)" uncertainty
- Change in acceptance from α_s-varied eigenvectors is much larger than using normal eigenvectors
  - Example: 0-jet bin on next slide
- In 0-jet bin, +90% C.L. α_s decreases acceptance while -90% C.L. α_s increases acceptance:

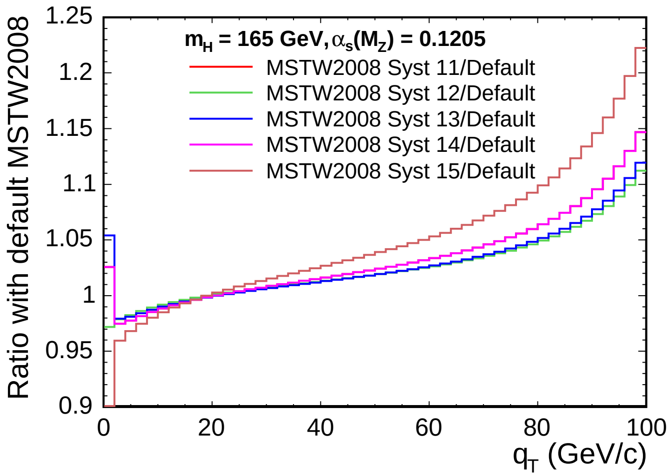
Channel:	0 Jets	1 Jet	2+ Jets
−90% C.L. α_s Uncertainty:	-4.5%	+5.0%	+8.7%
+90% C.L. α_s Uncertainty:	+6.5%	-7.5%	-15.9%
Average:	+5.5%	-6.3%	-12.3%

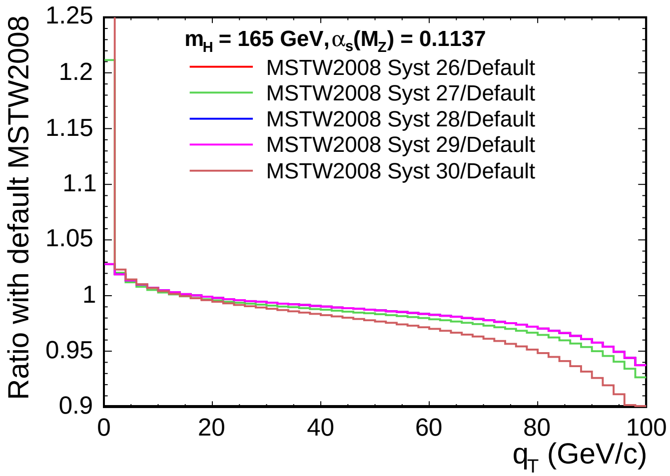
Acceptance change example (absolute differences), 0-jets

Eigenvector	Default α_s	+90% C.L. α_s	-90% C.L. α_s	Eigenvector	Default α_s	+90% C.L. α_s	-90% C.L. α_s
1	0.024	-0.149	0.114	21	0.001	-0.157	0.106
2	0.014	-0.144	0.091	22	0.035	-0.151	0.091
3	-0.05	-0.160	0.079	23	0.043	-0.151	0.091
4	0.042	-0.151	0.091	24	0.004	-0.162	0.106
5	0.028	-0.151	0.091	25	0.009	-0.163	0.150
6	0.007	-0.153	0.098	26	0.003	-0.151	0.091
7	0.024	-0.138	0.138	27	0.002	-0.151	0.125
8	-0.01	-0.181	0.091	28	0.049	-0.167	0.091
9	-0.006	-0.136	0.107	29	0.075	-0.151	0.091
10	0.014	-0.151	0.091	30	-0.01	-0.180	0.174
11	0.002	-0.151	0.116	31	0.057	-0.151	0.125
12	0.042	-0.126	0.091	32	-0.01	-0.153	0.092
13	-0.08	-0.119	0.086	33	0.013	-0.145	0.111
14	0.1	-0.151	0.091	34	-0.007	-0.151	0.091
15	0.039	-0.256	0.091	35	0.021	-0.151	0.103
16	-0.05	-0.151	0.114	36	-0.00	-0.154	0.131
17	0.054	-0.108	0.121	37	-0.04	-0.151	0.107
18	-0.008	-0.151	0.091	38	-0.007	-0.195	0.113
19	0.041	-0.151	0.093	39	0.015	-0.144	0.095
20	0.005	-0.144	0.091	40	0.010	-0.151	0.135

Acceptance: Higgs p_T α_s + PDF Shape Uncertainties

- Does changing the Higgs p_T spectrum affect the final shape of the discriminant?
- Take the two eigenvectors with the largest shape difference:





- Run these reweighted $gg \to H$ samples through the trained NN
  - See if the final template shape changes
  - No change observed for combination of 0 and 1 jet bins!

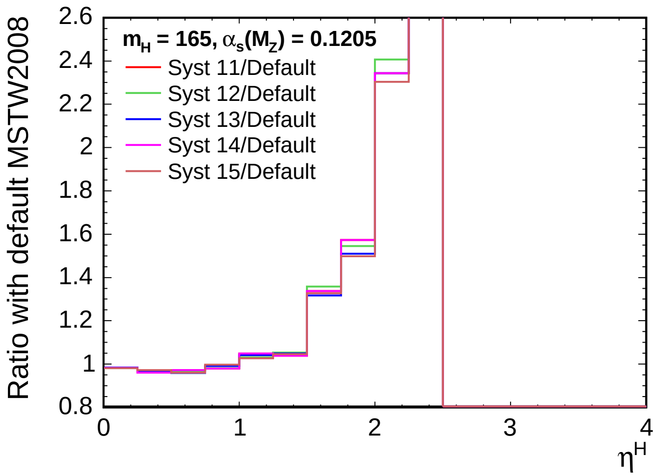
Acceptance: Higgs y α_s + PDF Reweighting

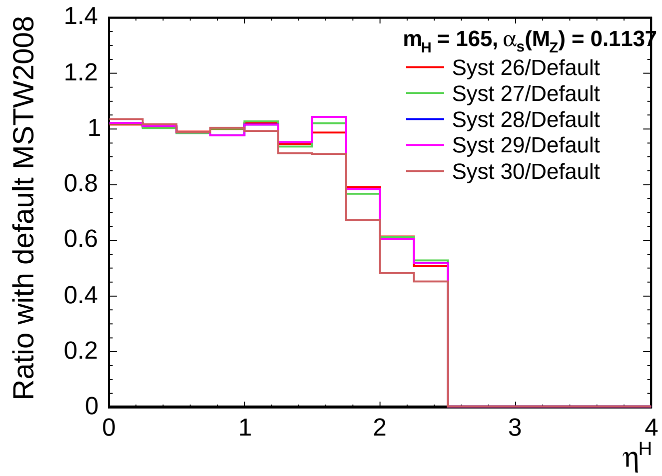
- Reweighting Higgs y moves events into/out of acceptance
  - Change is correlated across all jet bins
  - Call it the "Acceptance α_s + PDF (lepton)" uncertainty
- Difference from p_T reweighting: our default sample has not been reweighted for y
  - Discuss this in a few slides (scale reweighting)
- For all jet bins, +90% C.L. α_s decreases acceptance while -90% C.L. α_s increases acceptance:

Channel:	0 Jets	1 Jet	2+ Jets
$-$90% C.L. α_s Uncertainty:	+1.1%	+1.6%	+2.1%
$+$90% C.L. α_s Uncertainty:	-4.2%	-5.7%	-7.4%
Average:	2.7%	3.6%	4.8%

Acceptance: Higgs y α_s + PDF Shape Uncertainties

- Look at the two eigenvectors with the largest shape difference in p_T
  - Find shape difference in y is much less than in p_T:



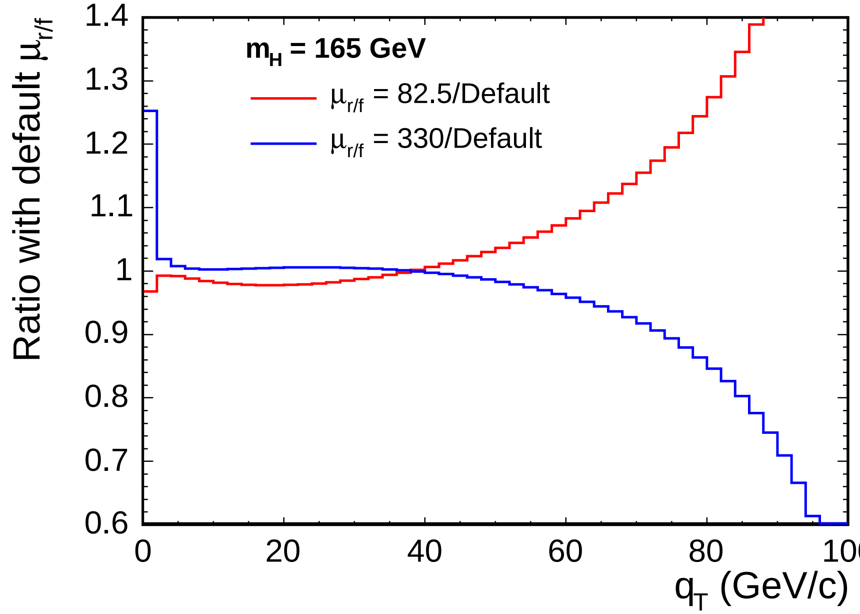


- As we saw no change for p_T reweighting, have not tried with y reweighting for a shape uncertainty
  - Very few events in the tail where we see changes

Acceptance: Higgs p_T Scale Reweighting

- As for cross section, use $m_H/2$ and $m_H \cdot 2$ as our scale variations
  - Only 2 reweightings, one up and down!
  - Call it the “Acceptance Scale (jets)” uncertainty

Channel:	0 Jets	1 Jet	2+ Jets
$m_H/2$:	-1.6%	+2.3%	+8.6%
$m_H \cdot 2$:	+1.1%	-1.6%	-5.0%
Average:	+1.3%	-1.9%	-6.8%



- Again check for shape uncertainties
  - No effect seen in 0 and 1 jet bins

Acceptance: Higgs y Scale Reweighting

- Default $gg \to H$ acceptance does not include Higgs y reweighting
  - Reweight with NNLO MSTW2008 PDF y distribution before assessing scale and PDF uncertainties:

Channel:	0 Jets	1 Jet	2+ Jets
Pythia with p_T reweighting	15.1	7.10	2.36
With y reweighting	14.9 (-1.7%)	6.94 (-2.2%)	2.29 (-3.1%)

- Then do the reweighting for scale and PDF
  - Scale uncertainties are negligible ($< 1\%$) $\to$ take difference between default and y reweighting as scale uncertainties
  - Call it the “Acceptance Scale (lepton)” uncertainty
  - PDF uncertainties (shown earlier) determined relative to sample with y reweighting

Summary

- $gg \longrightarrow H$ uncertainties as we calculate them:

Channel:	0 Jets	1 Jet	2+ Jets
Cross Section Scale	7.0%	23.5%	67.5%
Cross Section α_s+PDF	7.6%	17.3%	29.7%
Acceptance Scale (leptons)	1.7%	2.2%	3.1%
Acceptance Scale (jets)	1.3%	-1.9%	-6.8%
Acceptance α_s + PDF (leptons)	2.7%	3.6%	4.8%
Acceptance α_s + PDF (jets)	5.5%	-6.3%	-12.3%

- Shape uncertainties found to be negligible

Backup slides…

Total cross section change with α_s and PDF variations

PDF	+90% C.L. α_s		-90% C.L. α_s		PDF	+90% C.L. α_s		-90% C.L. α_s	
	x-sec (fb)	% Change	x-sec (fb)	% Change		x-sec (fb)	% Change	x-sec (fb)	% Change
1	2.638	1.46	2.582	0.69	21	2.632	1.23	2.547	2.03
2	2.678	3.00	2.560	1.53	22	2.644	1.69	2.567	1.26
3	2.658	2.23	2.552	1.84	23	2.644	1.69	2.567	1.26
4	2.644	1.69	2.567	1.26	24	2.669	2.65	2.526	2.84
5	2.644	1.69	2.560	1.53	25	2.664	2.46	2.622	0.84
6	2.648	1.84	2.550	1.92	26	2.651	1.96	2.567	1.26
7	2.647	1.80	2.563	1.42	27	2.644	1.69	2.595	0.19
8	2.660	2.30	2.560	1.53	28	2.651	1.96	2.567	1.26
9	2.657	2.19	2.563	1.42	29	2.644	1.69	2.567	1.26
10	2.644	1.69	2.567	1.26	30	2.658	2.23	2.539	2.34
11	2.644	1.69	2.570	1.15	31	2.644	1.69	2.546	2.07
12	2.659	2.26	2.567	1.26	32	2.659	2.26	2.561	1.49
13	2.670	2.69	2.547	2.03	33	2.638	1.46	2.551	1.88
14	2.651	1.96	2.567	1.26	34	2.644	1.69	2.567	1.26
15	2.629	1.11	2.567	1.26	35	2.644	1.69	2.590	0.38
16	2.651	1.96	2.574	1.00	36	2.672	2.76	2.538	2.38
17	2.552	1.84	2.509	3.49	37	2.644	1.69	2.567	1.26
18	2.651	1.96	2.560	1.53	38	2.631	1.19	2.566	1.30
19	2.651	1.96	2.567	1.26	39	2.663	2.42	2.565	1.34
20	2.639	1.50	2.567	1.26	40	2.644	1.69	2.558	1.61

0-jet cross section change with α_s and PDF variations

PDF	+90% C.L. α_s		-90% C.L. α_s		PDF	+90% C.L. α_s		-90% C.L. α_s	
	x-sec (fb)	% Change	x-sec (fb)	% Change		x-sec (fb)	% Change	x-sec (fb)	% Change
1	1.841	0.32	1.825	0.55	21	1.845	0.51	1.805	1.65
2	1.869	1.82	1.811	1.34	22	1.832	0.16	1.816	1.05
3	1.859	1.27	1.800	1.92	23	1.832	0.16	1.816	1.05
4	1.832	0.16	1.816	1.05	24	1.866	1.64	1.781	2.94
5	1.832	0.16	1.811	1.34	25	1.862	1.45	1.846	0.60
6	1.851	0.84	1.801	1.84	26	1.848	0.66	1.816	1.05
7	1.849	0.76	1.811	1.34	27	1.832	0.16	1.836	0.02
8	1.862	1.43	1.811	1.34	28	1.852	0.93	1.816	1.05
9	1.860	1.33	1.810	1.38	29	1.832	0.16	1.816	1.05
10	1.832	0.16	1.816	1.05	30	1.858	1.21	1.800	1.91
11	1.832	0.16	1.817	0.97	31	1.832	0.16	1.802	1.79
12	1.855	1.06	1.816	1.05	32	1.859	1.31	1.803	1.73
13	1.871	1.92	1.792	2.35	33	1.837	0.09	1.803	1.75
14	1.848	0.66	1.816	1.05	34	1.832	0.16	1.816	1.05
15	1.828	0.40	1.816	1.05	35	1.832	0.16	1.830	0.26
16	1.848	0.66	1.826	0.49	36	1.866	1.65	1.792	2.33
17	1.782	2.92	1.767	3.70	37	1.832	0.16	1.816	1.05
18	1.848	0.66	1.811	1.34	38	1.825	0.55	1.805	1.63
19	1.848	0.66	1.812	1.26	39	1.860	1.36	1.807	1.56
20	1.845	0.54	1.816	1.05	40	1.832	0.16	1.806	1.59

1-jet cross section change with α_s and PDF variations

PDF	+90% C.L. α_s		-90% C.L. α_s		PDF	+90% C.L. α_s		-90% C.L. α_s	
	x-sec (fb)	% Change	x-sec (fb)	% Change		x-sec (fb)	% Change	x-sec (fb)	% Change
1	0.689	2.68	0.661	1.43	21	0.689	2.69	0.652	2.85
2	0.702	4.63	0.655	2.35	22	0.684	2.00	0.655	2.32
3	0.695	3.57	0.655	2.40	23	0.684	2.00	0.655	2.32
4	0.684	2.00	0.655	2.32	24	0.699	4.14	0.648	3.38
5	0.684	2.00	0.655	2.35	25	0.698	4.10	0.671	0.06
6	0.693	3.26	0.654	2.44	26	0.695	3.60	0.655	2.32
7	0.694	3.41	0.656	2.18	27	0.684	2.00	0.663	1.18
8	0.694	3.49	0.655	2.35	28	0.694	3.52	0.655	2.32
9	0.694	3.53	0.657	2.01	29	0.684	2.00	0.655	2.32
10	0.684	2.00	0.655	2.32	30	0.697	3.96	0.647	3.47
11	0.684	2.00	0.659	1.75	31	0.684	2.00	0.651	3.00
12	0.692	3.17	0.655	2.32	32	0.694	3.48	0.659	1.71
13	0.696	3.74	0.654	2.50	33	0.690	2.85	0.652	2.83
14	0.695	3.60	0.655	2.32	34	0.684	2.00	0.655	2.32
15	0.693	3.26	0.655	2.32	35	0.684	2.00	0.662	1.35
16	0.695	3.60	0.655	2.31	36	0.696	3.75	0.651	2.95
17	0.672	0.15	0.642	4.23	37	0.684	2.00	0.655	2.32
18	0.695	3.60	0.655	2.35	38	0.694	3.49	0.658	1.93
19	0.695	3.60	0.658	1.91	39	0.697	3.91	0.658	1.83
20	0.689	2.74	0.655	2.32	40	0.684	2.00	0.657	2.04

2-jet cross section change with α_s and PDF variations

PDF	+90% C.L. α_s		-90% C.L. α_s		PDF	+90% C.L. α_s		-90% C.L. α_s	
	x-sec (fb)	% Change	x-sec (fb)	% Change		x-sec (fb)	% Change	x-sec (fb)	% Change
1	0.103	5.52	0.095	2.18	21	0.102	5.18	0.094	3.62
2	0.104	7.35	0.094	2.95	22	0.103	6.32	0.094	2.93
3	0.104	6.52	0.095	2.57	23	0.103	6.32	0.094	2.93
4	0.103	6.32	0.094	2.93	24	0.104	7.10	0.093	4.29
5	0.103	6.32	0.094	2.95	25	0.104	6.83	0.097	0.53
6	0.103	6.36	0.094	2.94	26	0.103	6.37	0.094	2.93
7	0.103	6.36	0.094	3.21	27	0.103	6.32	0.095	1.98
8	0.103	6.41	0.094	2.95	28	0.103	6.35	0.094	2.93
9	0.103	6.26	0.094	3.03	29	0.103	6.32	0.094	2.93
10	0.103	6.32	0.094	2.93	30	0.105	7.47	0.092	5.01
11	0.103	6.32	0.095	2.70	31	0.103	6.32	0.094	3.80
12	0.103	5.53	0.094	2.93	32	0.104	6.47	0.095	2.37
13	0.103	6.36	0.095	2.76	33	0.103	5.62	0.094	3.48
14	0.103	6.37	0.094	2.93	34	0.103	6.32	0.094	2.93
15	0.104	6.72	0.094	2.93	35	0.103	6.32	0.096	1.75
16	0.103	6.37	0.094	3.15	36	0.104	6.89	0.094	3.62
17	0.099	1.87	0.092	5.08	37	0.103	6.32	0.094	2.93
18	0.103	6.37	0.094	2.95	38	0.104	7.10	0.094	3.05
19	0.103	6.37	0.095	2.40	39	0.104	6.80	0.095	2.36
20	0.103	5.48	0.094	2.93	40	0.103	6.32	0.094	3.06