Recent developments in MCFM

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MCFM summary

- MCFM represents a unified approach to NLO corrections.

  http://mcfm.fnal.gov (v5.8, April 2010)

  J. M. Campbell, R. K. Ellis (main authors)
  R. Frederix, F. Maltoni, F. Tramontano, S. Willenbrock

- Next-to-leading order parton-level predictions.
- Cross sections and differential distributions.
- Standard Model processes involving vector boson+jets, top quarks, Higgs.
- Decays of unstable particles are included, maintaining spin correlations.
- Helicity amplitudes calculated from scratch or taken from the literature.
- Slightly-modified implementation of Catani-Seymour dipole subtraction.

Overview: W/Z+jets

Final state	Notes	Reference
W/Z		
diboson	anomalous couplings	hep-ph/9905386
Wbb	massless b-quark	hep-ph/9810489
Zbb	massless b-quark	hep-ph/0006304
W/Z+1 jet		
W/Z+2 jets		hep-ph/0202176, hep-ph/0308195
Wc	massive c-quark	hep-ph/0506289
Zb	5-flavour scheme	hep-ph/0312024
Zb+jet	5-flavour scheme	hep-ph/0510362

Overview: Higgs and top

Final state	Notes	Reference
H (g.f.)	effective coupling	
H+1 jet (g.f.)	effective coupling	
H+2 jets (g.f.)	☆ effective coupling	hep-ph/0608194, arXiv:1001.4495
WH/ZH		
H via WBF		hep-ph/0403194
Hb	5-flavour scheme	hep-ph/0204093
t	s- and t-channel (5F), top decay included	hep-ph/0408158
t	t-channel (4F)	arXiv:0903.0005, arXiv:0907.3933
Wt	5-flavour scheme	hep-ph/0506289
top pairs	☆ with top decay	

Overview: other calculations

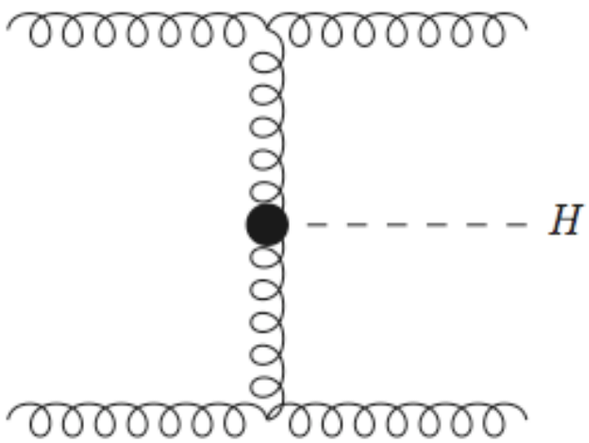
Final state	Notes	Reference
Wb+jet	complicated procedure, private version only	hep-ph/0611348, arXiv:0809.3003
WW+jet	semi-numerical virtual amplitudes; private	arXiv:0710.1832
J/ψ and Υ(singlet)	private version only, could be made available	hep-ph/0703113, arXiv:0806.3282
J/ψ (photo-prod. in DIS)	private version only, could be made available	arXiv:0901.4352

- Private versions either not sufficiently polished for a general audience, or of only limited interest.
- Leading order calculations of related processes also available.
- Select other processes also at LO (e.g. ttH with decays).

Higgs + 2 jets

- A new inclusion in the most recent versions of the code has been production of H+2 jets from parton-parton fusion.

not just gluon fusion, also channels with one or two quark pairs



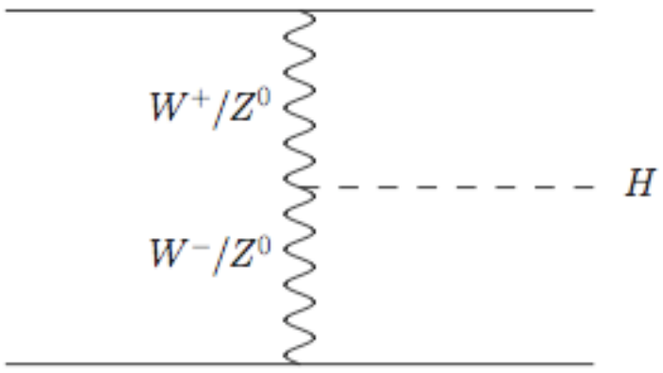
Effective coupling of Higgs to two gluons:

$$\mathcal{L}_{\text{eff}} = \frac{1}{4}\left(\frac{g^2}{12\pi^2 v}\right)(1+\Delta) H G^a_{\mu\nu} G^{a\,\mu\nu}$$

Valid as long as m_H, p_T(jet) $\lesssim m_t$

Del Duca et al., hep-ph/0108030

- Interest in this process is high:
  - a 2→3 calculation amenable to a number of calculational techniques;
  - "Every little helps" for the Higgs search at the Tevatron;
  - this is the same final state as for vector boson fusion, relevant for extraction of Higgs couplings @ LHC.



vector boson fusion

First iteration

- This interest led to a first calculation of the relevant matrix elements in 2005.

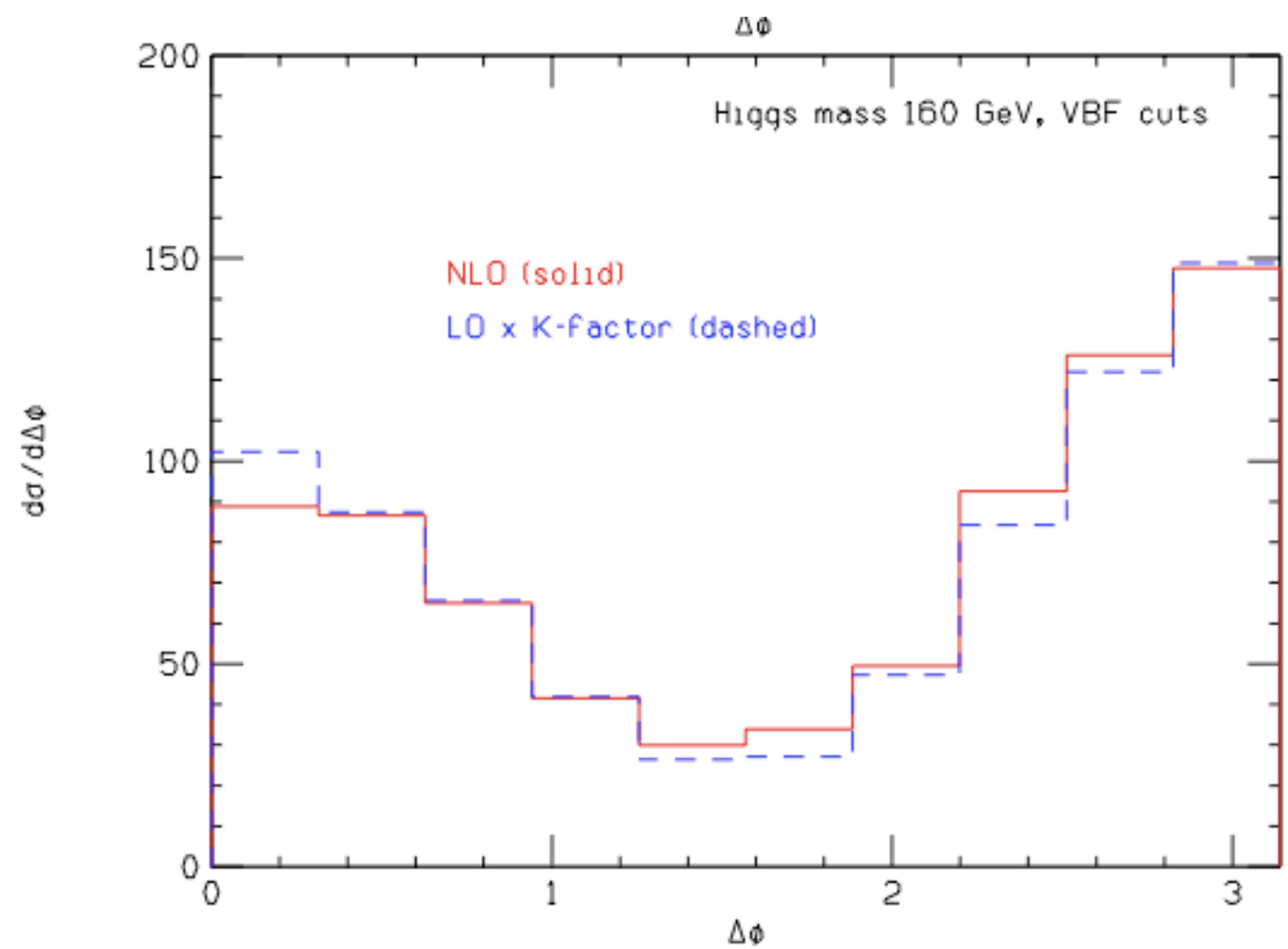
  Ellis, Giele and Zanderighi, hep-ph/0506196

  - 4-quark matrix elements (spin-summed) in analytic form;
  - the remainder (bulk of the calculation) using a semi-numerical method in which tensor integrals are reduced numerically to a known set of scalars.

- A phenomenological study followed shortly after, with limited results due to the intense computational effort required at each phase space point.

  JC, Ellis and Zanderighi, hep-ph/0608194

- As a result, the code was never released.



The bag of tricks

- All of the relevant amplitudes are now known in analytic form, thanks to calculations performed using analytic unitarity.
- These are greatly simplified by a deft decomposition of the effective Lagrangian: Dixon, Glover and Khoze, hep-th/0411092

$$\mathcal{L}^{\rm int}_{H,A} = \frac{C}{2}\Big[H\ {\rm tr}\, G_{\mu\nu}\, G^{\mu\nu} + iA\ {\rm tr}\, G_{\mu\nu}\, {}^*G^{\mu\nu}\Big]$$
$$= C\Big[\phi\ {\rm tr}\, G_{SD\ \mu\nu}\, G^{\mu\nu}_{SD} + \phi^\dagger\ {\rm tr}\, G_{ASD\ \mu\nu}\, G^{\mu\nu}_{ASD}\Big]$$

complex scalar field: $\phi = \frac{1}{2}(H + iA)\,, \quad \phi^\dagger = \frac{1}{2}(H - iA)$

self-dual and anti-self-dual field strengths: $G^{\mu\nu}_{SD} = \frac{1}{2}(G^{\mu\nu} + {}^*G^{\mu\nu})\,, \quad G^{\mu\nu}_{ASD} = \frac{1}{2}(G^{\mu\nu} - {}^*G^{\mu\nu})\,, \quad {}^*G^{\mu\nu} \equiv \frac{i}{2}\epsilon^{\mu\nu\rho\sigma}G_{\rho\sigma}$

- This neatly explains the observed structure of Higgs amplitudes:

$$A(H, \{p_k\}) = A(\phi, \{p_k\}) + A(\phi^\dagger, \{p_k\})$$

$$A(1_g^-, 2_g^-, 3_g^+, 4_g^+) \sim C\left(\frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 41\rangle} + \frac{[34]^4}{[12][23][34][41]}\right)$$

Analytic results

- Only calculate a restricted set of amplitudes since $\varphi, \varphi^\dagger$ are related by parity.

all gluons

H amplitude	ϕ amplitude	$\phi^\dagger$ amplitude
$A(H,1^+,2^+,3^+,4^+)$	$A(\phi,1^+,2^+,3^+,4^+)$ [1]	$A(\phi^\dagger,1^+,2^+,3^+,4^+)$ [4]
$A(H,1^-,2^+,3^+,4^+)$	$A(\phi,1^-,2^+,3^+,4^+)$ [1]	$A(\phi^\dagger,1^-,2^+,3^+,4^+)$ [5]
$A(H,1^-,2^-,3^+,4^+)$	$A(\phi,1^-,2^-,3^+,4^+)$ [2]	$A(\phi^\dagger,1^-,2^-,3^+,4^+)$ [2]
$A(H,1^-,2^+,3^-,4^+)$	$A(\phi,1^-,2^+,3^-,4^+)$ [3]	$A(\phi^\dagger,1^-,2^+,3^-,4^+)$ [3]

one quark line

H amplitude	ϕ amplitude	$\phi^\dagger$ amplitude
$A(H,1^-_{\bar{q}},2^+_q,3^+,4^+)$	$A(\phi,1^-_{\bar{q}},2^+_q,3^+,4^+)$ [1]	$A(\phi^\dagger,1^-_{\bar{q}},2^+_q,3^+,4^+)$ [6]
$A(H,1^-_{\bar{q}},2^+_q,3^-,4^-)$	$A(\phi,1^-_{\bar{q}},2^+_q,3^-,4^-)$ [6]	$A(\phi^\dagger,1^-_{\bar{q}},2^+_q,3^-,4^-)$ [1]
$A(H,1^-_{\bar{q}},2^+_q,3^+,4^-)$	$A(\phi,1^-_{\bar{q}},2^+_q,3^+,4^-)$ [7]	$A(\phi^\dagger,1^-_{\bar{q}},2^+_q,3^+,4^-)$ [7]
$A(H,1^-_{\bar{q}},2^+_q,3^-,4^+)$	$A(\phi,1^-_{\bar{q}},2^+_q,3^-,4^+)$ [7]	$A(\phi^\dagger,1^-_{\bar{q}},2^+_q,3^-,4^+)$ [7]

two quark lines

[1] C. F. Berger, V. Del Duca and L. J. Dixon, arXiv:hep-ph/0608180.

[2] S. D. Badger, E. W. N. Glover and K. Risager, arXiv:0704.3914 [hep-ph].

[3] E. W. N. Glover, P. Mastrolia and C. Williams, arXiv:0804.4149 [hep-ph].

[4] S. D. Badger and E. W. N. Glover, arXiv:hep-ph/0607139.

[5] S. Badger, E. W. N. Glover, P. Mastrolia and C. Williams, arXiv:0909.4475 [hep-ph].

[6] S. Badger, J. M. Campbell, R. K. Ellis and C. Williams, arXiv:0910.4481 [hep-ph].

[7] L. J. Dixon and Y. Sofianatos, arXiv:0906.0008 [hep-ph].

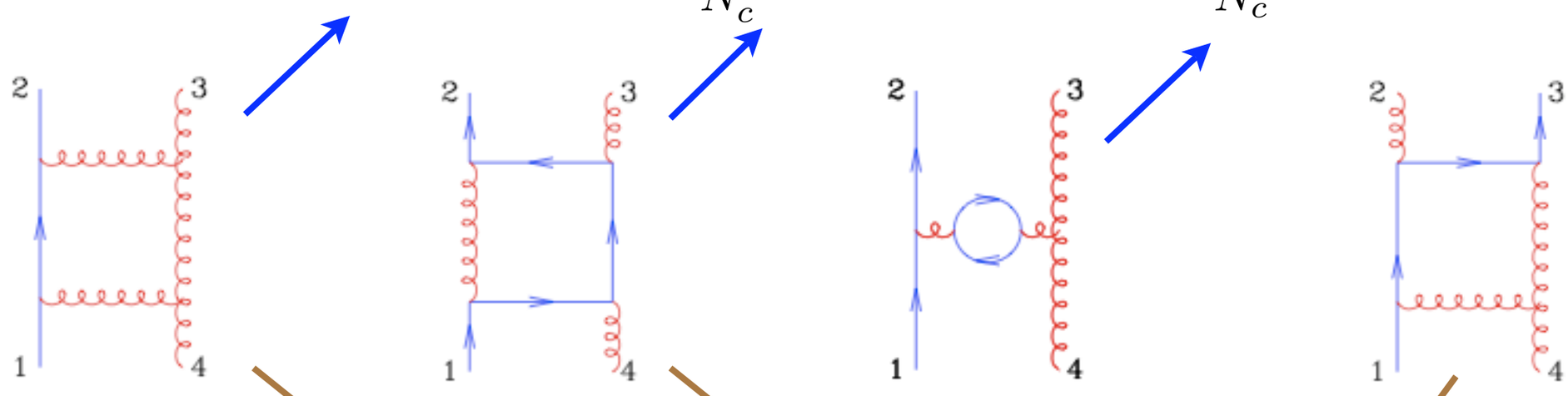
The NMHV HQQgg amplitude

- Work performed in collaboration with S. Badger, K. Ellis and C. Williams.
- Can decompose amplitudes into two colour structures:

$$\mathcal{A}_4^{(1)}(\phi,1_{\bar{q}},2_q,3_g,4_g) = Cg^4\, c_\Gamma \left[N_c \sum_{\sigma\in S_2} \left(T^{a_{\sigma(3)}}T^{a_{\sigma(4)}}\right)_{i_2}^{\ \bar{\imath}_1} A_{4;1}(\phi,1_{\bar{q}},2_q,\sigma(3),\sigma(4)) + \delta^{a_3a_4}\,\delta_{i_2}^{\ \bar{\imath}_1} A_{4;3}(\phi,1_{\bar{q}},2_q;3_g,4_g)\right].$$

- These are further broken down into gauge-invariant primitive amplitudes:

$$A_{4;1}(\phi,1_{\bar{q}},2_q,3_g,4_g) = A_4^L(\phi,1_{\bar{q}},2_q,3_g,4_g) - \frac{1}{N_c^2}A_4^R(\phi,1_{\bar{q}},2_q,3_g,4_g) + \frac{n_f}{N_c}A_4^{\rm f}(\phi,1_{\bar{q}},2_q,3_g,4_g)$$



$$\begin{aligned} A_{4;3}(\phi,1_{\bar{q}},2_q;3_g,4_g) &= A_4^L(\phi,1_{\bar{q}},2_q,3_g,4_g) + A_4^R(\phi,1_{\bar{q}},2_q,3_g,4_g) + A_4^L(\phi,1_{\bar{q}},3_g,2_q,4_g) \\ &+ A_4^L(\phi,1_{\bar{q}},2_q,4_g,3_g) + A_4^R(\phi,1_{\bar{q}},2_q,4_g,3_g) + A_4^L(\phi,1_{\bar{q}},4_g,2_q,3_g) \end{aligned}$$

Method

- Use various unitarity techniques to extract the coefficients of all integrals.

box: Britto, Cachazo, Feng, hep-th/0412103

triangle: Forde, arXiv:0704.1835

bubble: Mastrolia, arXiv:0905.2909

  - algebra controlled using Mathematica package S@M. Maitre and Mastrolia, arXiv:0710.5559
  - compact form for all coefficients.

- Rational pieces computed using separate PV reduction of diagrams.
  - diagrams generated using QGRAF and manipulated using Form.
- Additional check of integral coefficients via numerical evaluation of PV reduction at a specific phase space point.
  - powerful book-keeping tool.

Right-moving amplitude

- The simplest of the primitive amplitudes is proportional to n_f (no boxes).
- The right-moving amplitude only contains 4 boxes.
- The left-moving is marginally more complicated than this one.
- Rational piece (not shown here) is ~10 terms.

$$
\begin{aligned}
-iA_4^R\left(\phi,1_{\bar q}^-,2_q^+,3_g^-,4_g^-\right) &= -iA_4^{(0)}\left(\phi,1_{\bar q}^-,2_q^+,3_g^-,4_g^-\right)\times V^R \quad \longleftarrow \text{poles} \\
&+ \frac{[1\,2]^2\langle 4|(1+2)|3]^2}{[1\,3]^3[2\,3]s_{123}}\,\mathrm{Ls}_{-1}\left(s_{12},s_{23};s_{123}\right)+\frac{\langle 3|(1+4)|2]^2}{[1\,4]\,[2\,4]\,s_{124}}\,\mathrm{Ls}_{-1}\left(s_{14},s_{12};s_{124}\right) \\
&- \frac{\langle 1|(3+4)|2]^2}{[2\,3][3\,4]\langle 1|(2+3)|4]}\,\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{14},s_{234};s_{23},m_\phi^2\right) \\
&+ \frac{s_{134}^2}{[1\,4][3\,4]\langle 2|(1+4)|3]}\,\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{23},s_{134};s_{14},m_\phi^2\right) \quad \Big\}\ \text{boxes} \\
&- C_{3;\phi|41|23}\left(\phi,1_{\bar q}^-,2_q^+,3_g^-,4_g^-\right)\mathrm{I}_3^{3\mathrm{m}}\left(s_{23},s_{14},m_\phi^2\right)-\frac{1}{2}\frac{\langle 1\,4\rangle^2[1\,2]^2\langle 3|(1+2)|4]^2}{[1\,4]\,[2\,4]\,s_{124}}\,\widehat{\mathrm{L}}_2\left(s_{124},s_{12}\right) \\
&+ 2\frac{\langle 3\,4\rangle\,\langle 3|(1+4)|2]}{[1\,4]}\,\widehat{\mathrm{L}}_1\left(s_{124},s_{12}\right)+\frac{1}{2}\frac{\langle 3|(1+4)|2]^2}{[1\,4]\,[2\,4]\,s_{124}}\,\widehat{\mathrm{L}}_0\left(s_{124},s_{12}\right) \\
&- \frac{1}{2}\frac{\langle 1\,4\rangle^2[2\,4]^2s_{234}^2}{[2\,3]\,[3\,4]\,\langle 1|(2+3)|4]}\,\widehat{\mathrm{L}}_2\left(s_{234},s_{23}\right)-2\frac{\langle 3\,4\rangle\,\langle 1|(3+4)|2]}{[3\,4]}\,\widehat{\mathrm{L}}_1\left(s_{234},s_{23}\right) \\
&+ \frac{1}{2}\frac{\langle 1|(3+4)|2]^2}{[2\,3]\,[3\,4]\,\langle 1|(2+3)|4]}\,\widehat{\mathrm{L}}_0\left(s_{234},s_{23}\right)-\frac{1}{2}\frac{\left(\langle 1\,2\rangle\,[1\,2]\,\langle 4|(2+3)|1]\right)^2[2\,3]}{[1\,3]^3s_{123}}\,\widehat{\mathrm{L}}_2\left(s_{123},s_{23}\right) \\
&+ 2\frac{\langle 1\,3\rangle\,[1\,2]\,\langle 4|(1+2)|3]\langle 4|(2+3)|1]}{\langle 2\,3\rangle\,[1\,3]^2\,[2\,3]}\,\widehat{\mathrm{L}}_1\left(s_{123},s_{23}\right) \\
&+ \left[-2\frac{\langle 1\,3\rangle\,[1\,2]\,\langle 4|(1+2)|3]\langle 4|(2+3)|1]}{s_{123}[1\,3]^2\,\langle 2\,3\rangle\,[2\,3]}+\frac{1}{2}\frac{\langle 4|(2+3)|1]^2\,[2\,3]}{[1\,3]^3s_{123}}\right]\widehat{\mathrm{L}}_0\left(s_{123},s_{23}\right) \\
&- \frac{1}{2}\frac{\left(\langle 1\,3\rangle\,[1\,2]\,\langle 4|(1+2)|3]\right)^2}{[1\,3]\,[2\,3]\,s_{123}}\,\widehat{\mathrm{L}}_2\left(s_{123},s_{12}\right) \\
&+ \langle 3\,4\rangle\,[1\,2]\,\langle 4|(1+2)|3]\frac{\left(-2\,\langle 1\,3\rangle\,[1\,3]-\langle 2\,3\rangle\,[2\,3]\right)}{\langle 2\,3\rangle\,[1\,3]^2\,[2\,3]}\,\widehat{\mathrm{L}}_1\left(s_{123},s_{12}\right) \\
&+ [1\,2]\,\langle 4|(1+2)|3]\frac{\langle 2\,3\rangle\,\langle 4|(1+3)|2]+2\,\langle 1\,3\rangle\,\langle 4|(2+3)|1]}{[1\,3]^2\,\langle 2\,3\rangle\,[2\,3]\,s_{123}}\,\widehat{\mathrm{L}}_0\left(s_{123},s_{12}\right) \\
&+ R^R\left(\phi,1_{\bar q}^-,2_q^+,3_g^-,4_g^-\right) \quad \longleftarrow \text{rational}
\end{aligned}
$$

Rational terms

- In pure QCD, supersymmetric decompositions of amplitudes can be used to relate different primitives. Bern, Dixon and Kosower, hep-ph/9409393
- A similar relation applies to the rational parts of the amplitudes here:

extracts full rational part

$$\mathcal{R}\Big\{ A_4^L(\phi, 1_{\bar{q}}, 2_q, 3_g, 4_g) + A_4^R(\phi, 1_{\bar{q}}, 2_q, 3_g, 4_g) + A_4^{\mathrm{f}}(\phi, 1_{\bar{q}}, 2_q, 3_g, 4_g) \Big\}$$
$$+2A_4^{(0)}\left(\phi^\dagger, 1_{\bar{q}}, 2_q, 3_g, 4_g\right) - 2A_4^{(0)}(\phi, 1_{\bar{q}}, 2_q, 3_g, 4_g) = 0\,,$$

- True in the four-dimensional helicity scheme only.
- This is derived empirically, but presumably has a supersymmetric origin.
  - used to greatly simplify the rational part of the left-moving amplitude.
- Also applies to previously-calculated MHV amplitudes.
- The equivalent relation for the Higgs amplitudes is even simpler since the last two terms on the LHS cancel in the combination.

The other colour structure

$$
\begin{aligned}
-iA_{4;3}\left(\phi,1_{\bar{q}}^{-},2_{q}^{+},3_{g}^{-},4_{g}^{-}\right) &= -iA_{4}^{(0)}\left(\phi,1_{\bar{q}}^{-},2_{q}^{+},3_{g}^{-},4_{g}^{-}\right)\times V_{5}(s_{12},s_{34},s_{13},s_{24})\\
&+\frac{1}{s_{123}}\left[\frac{\langle 4|(1+2)|3]^{2}\,[1\,2]^{2}}{[1\,3]^{3}\,[2\,3]}+\frac{[2\,3]^{2}\,\langle 4|(2+3)|1]^{3}}{[1\,3]^{3}\,[1\,2]\,\langle 4|(1+2)|3]}-\frac{m_{\phi}^{4}\,\langle 1\,3\rangle^{3}}{\langle 1\,2\rangle\,\langle 1|(2+3)|4]\langle 3|(1+2)|4]}\right]\\
&\times \mathrm{Ls}_{-1}\left(s_{12},s_{23};s_{123}\right)\\
&+\frac{1}{s_{124}}\left[\frac{m_{\phi}^{4}\,\langle 1\,4\rangle^{2}\,\langle 2\,4\rangle}{\langle 1\,2\rangle\,\langle 2|(1+4)|3]\langle 4|(1+2)|3]}-\frac{\langle 3|(1+4)|2]^{2}\langle 3|(2+4)|1]}{[1\,4]\,\langle 3|(1+2)|4]\,[1\,2]}\right]\mathrm{Ls}_{-1}\left(s_{12},s_{14};s_{124}\right)\\
&+\frac{1}{s_{123}}\left[\frac{m_{\phi}^{4}\,\langle 1\,3\rangle^{2}}{\langle 1|(2+3)|4]\langle 2|(1+3)|4]}-\frac{\langle 4|(1+3)|2]^{2}}{[1\,3]\,[2\,3]}\right]\mathrm{Ls}_{-1}\left(s_{13},s_{23};s_{123}\right)\\
&+\frac{s_{341}^{2}}{[1\,3]\,[3\,4]\,\langle 2|(1+3)|4]}\left[\mathrm{Ls}_{-1}\left(s_{13},s_{14};s_{341}\right)+\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{23},s_{341},s_{14},m_{\phi}^{2}\right)\right]\\
&+\frac{s_{341}^{2}}{[1\,4]\,[3\,4]\,\langle 2|(1+4)|3]}\left[\mathrm{Ls}_{-1}\left(s_{14},s_{34};s_{341}\right)+\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{12},s_{341},s_{34},m_{\phi}^{2}\right)\right]\\
&-\frac{\langle 1|(3+4)|2]^{2}}{[2\,3]\,[3\,4]\,\langle 1|(2+3)|4]}\left[\mathrm{Ls}_{-1}\left(s_{23},s_{34};s_{234}\right)+\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{12},s_{234},s_{34},m_{\phi}^{2}\right)\right]\\
&+\frac{[2\,4]^{2}\,\langle 1|(2+4)|3]^{2}}{[2\,3]\,[3\,4]^{3}\,\langle 1|(2+3)|4]}\mathrm{Ls}_{-1}\left(s_{23},s_{24};s_{234}\right)\\
&-\frac{\langle 1|(3+4)|2]^{2}}{\langle 1|(2+4)|3]\,[2\,4]\,[3\,4]}\,\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{14},s_{234},s_{23},m_{\phi}^{2}\right)\\
&+\frac{1}{s_{123}}\left[-\frac{m_{\phi}^{4}\,\langle 1\,3\rangle^{2}\,\langle 2\,3\rangle}{\langle 1\,2\rangle\,\langle 2|(1+3)|4]\langle 3|(1+2)|4]}+\frac{\langle 4|(1+3)|2]^{2}}{\langle 4|(1+2)|3]}\frac{\langle 4|(2+3)|1]}{[1\,2]\,[1\,3]}\right]\\
&\quad\times\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{14},s_{123},s_{23},m_{\phi}^{2}\right)\\
&+\frac{1}{s_{123}}\left[\frac{m_{\phi}^{4}\,\langle 1\,3\rangle^{3}}{\langle 1\,2\rangle\,\langle 3|(1+2)|4]\langle 1|(2+3)|4]}-\frac{\langle 4|(1+3)|2]^{3}}{\langle 4|(1+2)|3]\,[1\,2]\,[2\,3]}\right]\\
&\quad\times\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{24},s_{123},s_{13},m_{\phi}^{2}\right)\\
&+\frac{1}{s_{123}}\left[-\frac{m_{\phi}^{4}\,\langle 1\,3\rangle^{2}}{\langle 2|(1+3)|4]\langle 1|(2+3)|4]}+\frac{\langle 4|(1+3)|2]^{2}}{[1\,3]\,[2\,3]}\right]\widetilde{\mathrm{Ls}}_{-1}^{2\mathrm{m}h}\left(s_{34},s_{123},s_{12},m_{\phi}^{2}\right)\\
&+\left\{3\leftrightarrow 4\right\},
\end{aligned}
$$

- The other colour structure is a combination of the primitive amplitudes, A^L, A^R and an entirely new primitive.
- Rather than writing down the form of this new primitive, simplest just to construct this combination.
- Particularly simple form since there's no corresponding tree level colour structure
  - no rational terms;
  - only box integrals.

New implementation

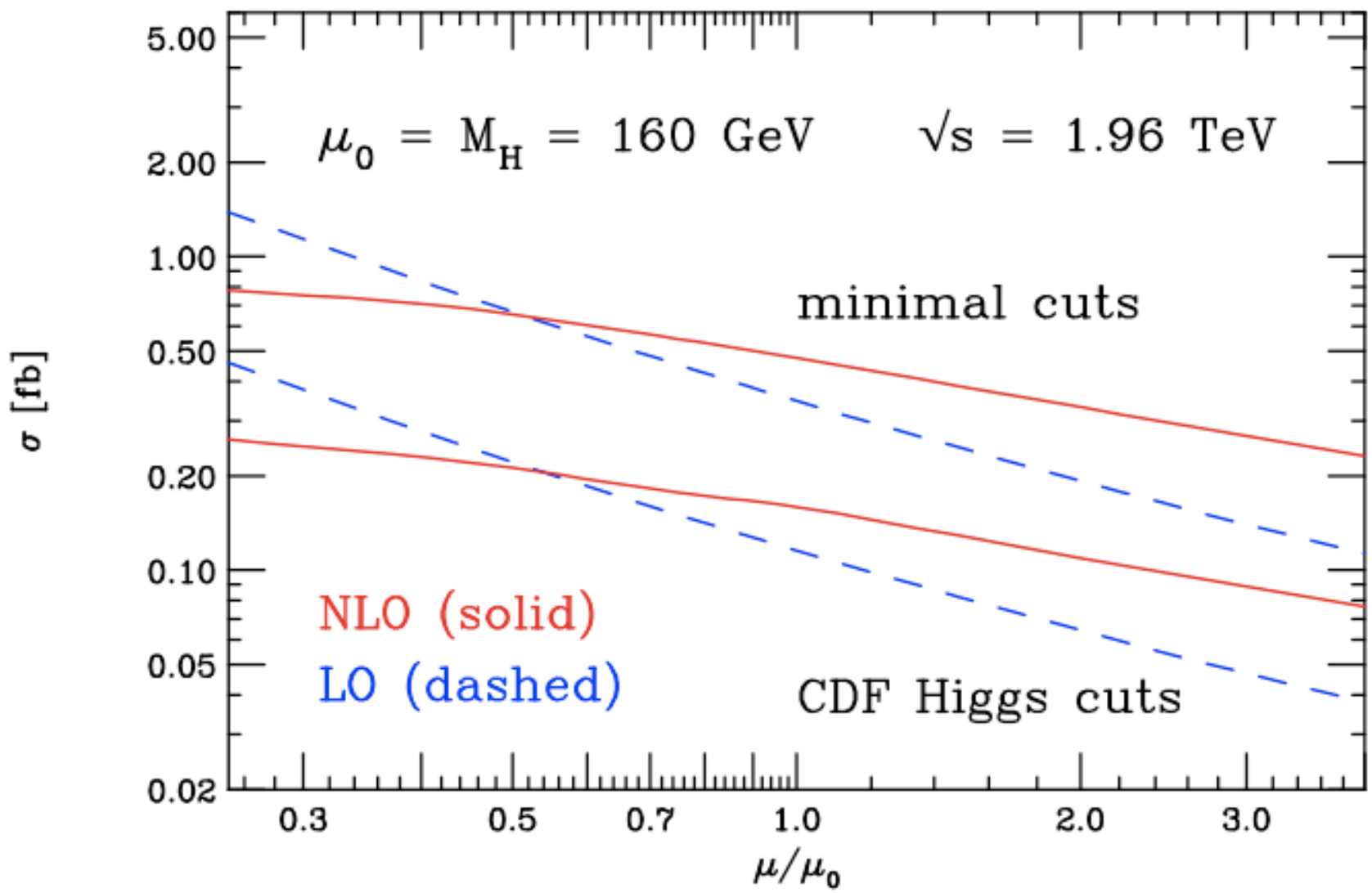
- All helicity amplitudes implemented in MCFM v.5.7 and onwards.
- Fully checked against the previous semi-numerical implementation.
  - much faster: ~5ms per virtual point (2.66GHz iMac, no optimization)
    (squared and summed, all crossings, normal MCFM overhead, e.g. PDFs)
  - squared matrix elements for 2 quark-antiquark pairs faster than amplitudes
  - evaluation of virtual contribution no longer an issue, so full decays of the Higgs into W pairs can be straightforwardly included.

$$h_1 + h_2 \to H + j_1 + j_2 \to W^- + W^+ + j_1 + j_2$$
$$W^+ \to \nu + e^+$$
$$W^- \to e^- + \bar{\nu}$$

- New phenomenological study: JC, Ellis, Williams, arXiv: 1001.4495.

Scale dependence

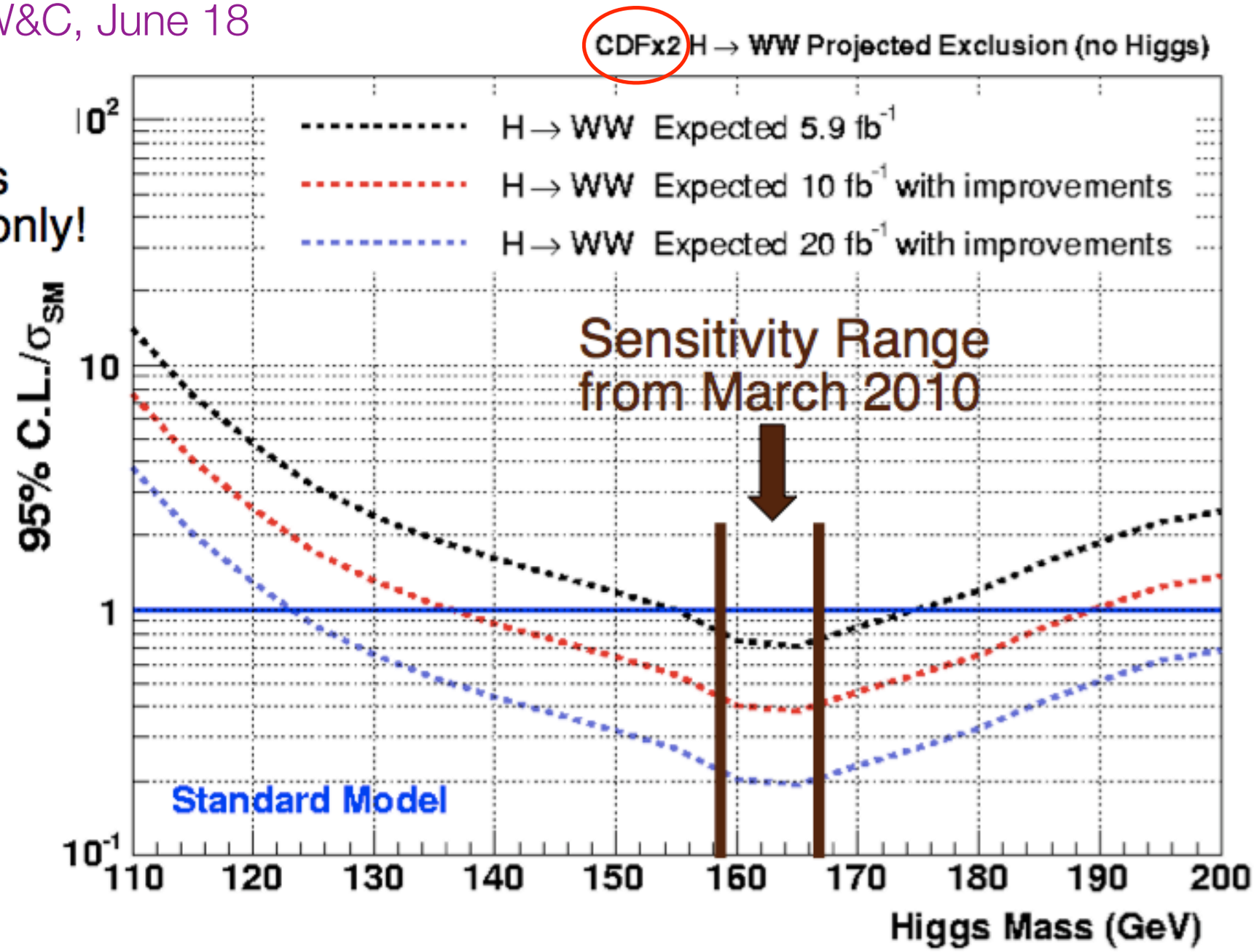
- Can easily investigate the effect of NLO corrections in a particular phase space region, e.g. the particular set of cuts used in a typical CDF H→WW* search:
  - usual lepton cuts, dilepton invariant mass, missing E_T and isolation



Latest projection from CDF

Jennifer Pursley
Fermilab W&C, June 18

High Mass analyses only!



- Impressive reach - “High Mass” means analyses of H→WW* only.

Tevatron Higgs search

- The search strategy at the Tevatron divides events into bins according to the number of jets observed.
  - understanding the expected theoretical cross section and uncertainty in each bin is essential for imposing the best limits.
- A detailed theoretical analysis, using the NNLO calculation of the inclusive Higgs cross section, was given a year ago.

Anastasiou, Dissertori, Grazzini, Stöckli and Webber, arXiv:0905.3529

0-jet 1-jet 2-jet overall

$$\frac{\Delta N_{\rm signal}(\text{scale})}{N_{\rm signal}} = 60\% \cdot \left(^{+5\%}_{-9\%}\right) + 29\% \cdot \left(^{+24\%}_{-23\%}\right) + 11\% \cdot \left(^{+91\%}_{-44\%}\right) = \left(^{+20.0\%}_{-16.9\%}\right)$$

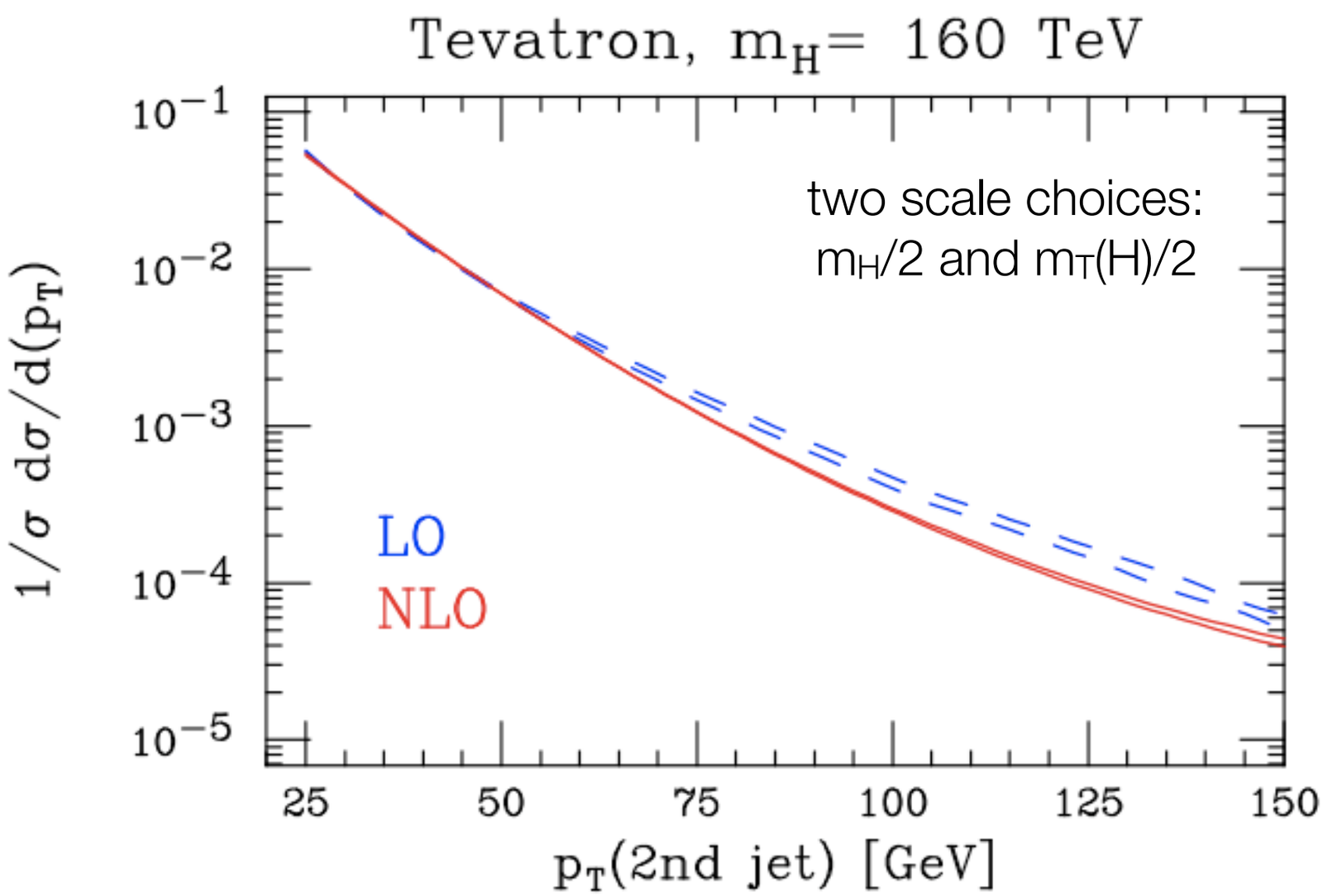
expected jet composition after preselection

- The 2-jet bin is only a small fraction of the total, but the large uncertainty results in a sizeable contribution to the overall uncertainty → update to NLO:

$$\frac{\Delta N_{\rm signal}(\text{scale})}{N_{\rm signal}} = 60\% \cdot \left(^{+5\%}_{-9\%}\right) + 29\% \cdot \left(^{+24\%}_{-23\%}\right) + 11\% \cdot \boxed{\left(^{+35\%}_{-31\%}\right)} = \boxed{\left(^{+13.8\%}_{-15.5\%}\right)}$$

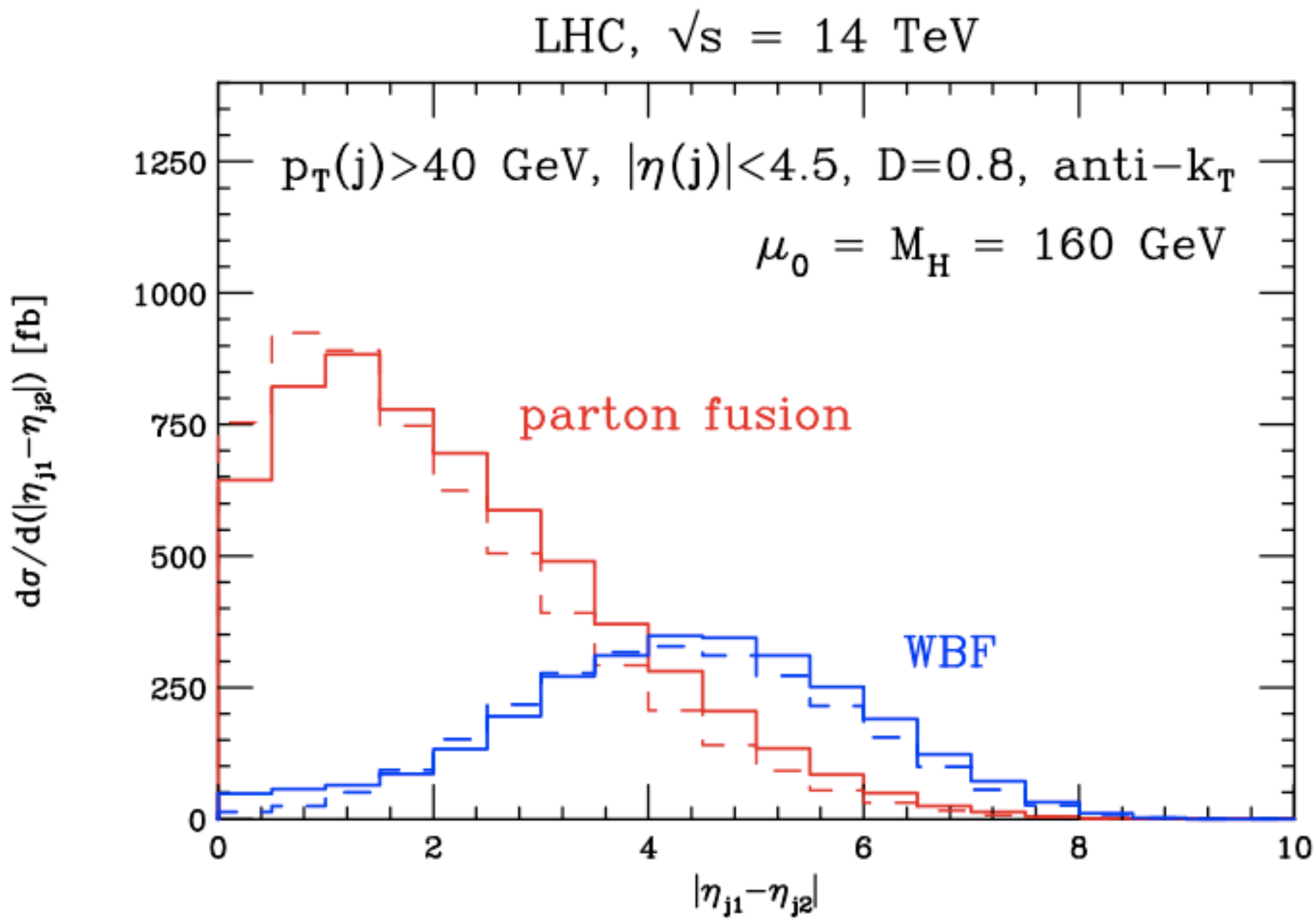
Beyond cross sections

- Existing analyses match Pythia to NNLL to correct for hard radiation.
- Ongoing discussion about how best to utilize NLO information in the 2-jet bin.



Comparison with WBF @ 14 TeV LHC

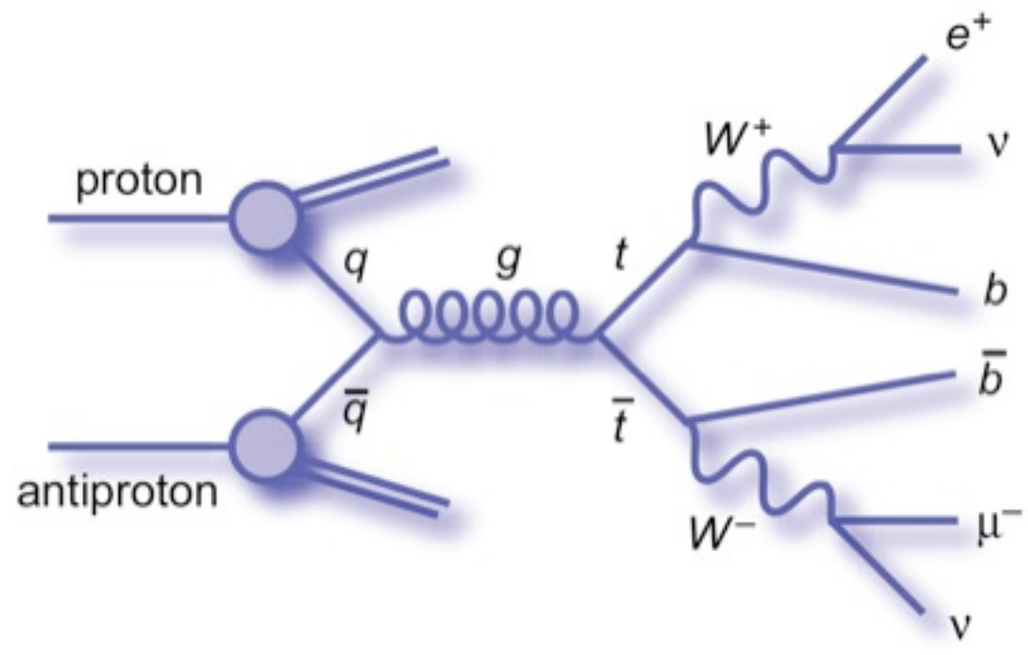
- WBF sample can be isolated by imposing a large rapidity separation between two of the jets, but some “contamination” from parton fusion remains.



largest absolute rapidity difference between two jets

Another recent addition

- Top production including decay
  - spin correlations included
  - top quark must be kept strictly on-shell, no radiation in decay
  - implementation of a previous matrix element calculation
    Korner and Merebashvili, hep-ph/0207054



- This is not a new result - a number of calculations already in the literature.

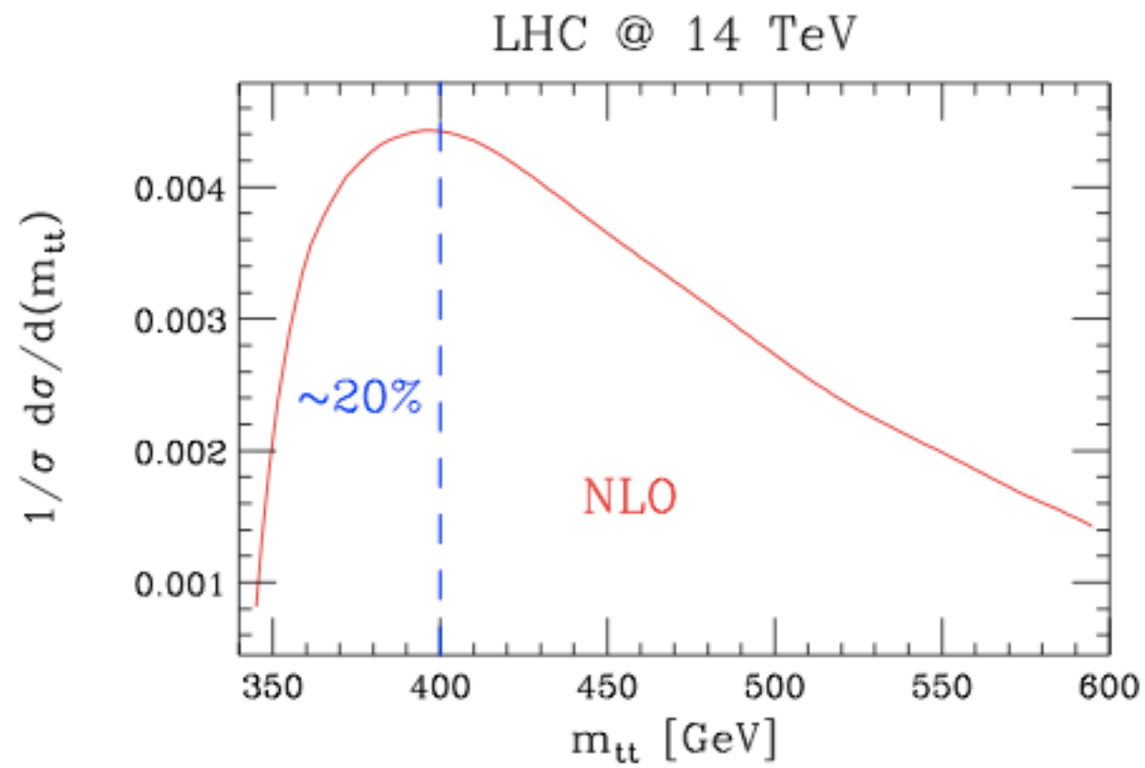
  Bernreuther, Brandenburg, Si and Uwer, hep-ph/0107086

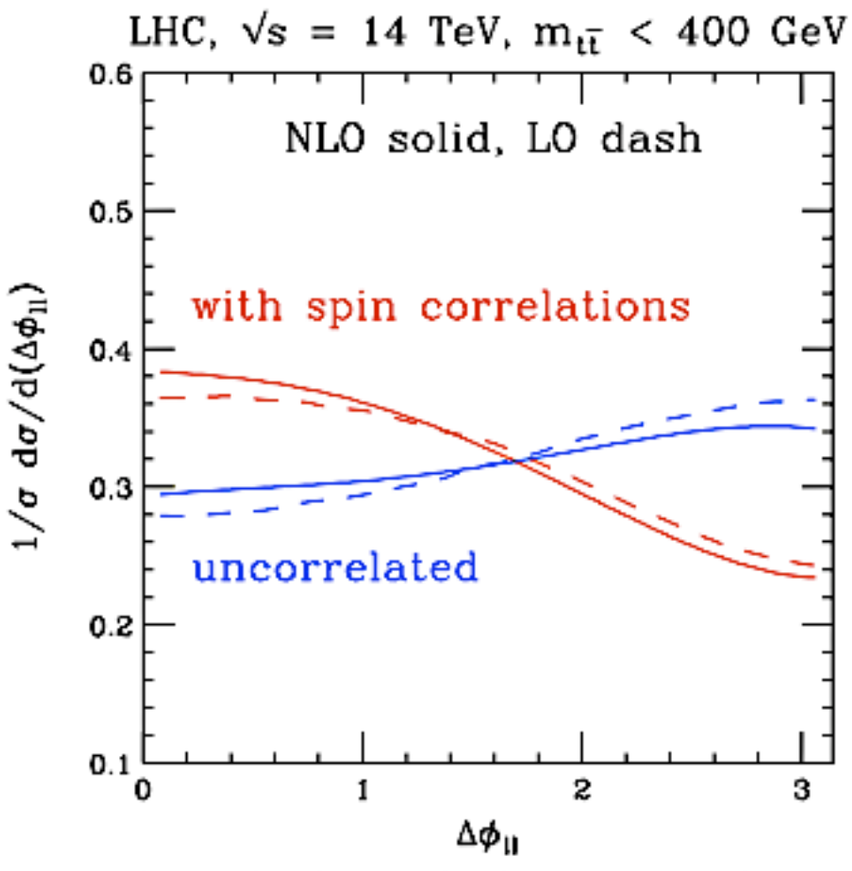
  Melnikov and Schulze, arXiv:0907.3090

- The importance of this process at the LHC - particularly as a background - still merits its inclusion in MCFM.
  - v5.8 onwards.

Measuring spin correlations at the LHC

- Spin correlations in top pair production are more easily observed at the LHC once an invariant mass cut is applied.
  Mahlon and Parke, arXiv:1001.3422
- A cut at 400 GeV still retains about 20% of all top pair events.





azimuthal angle between leptons

- No .of dilepton events/fb^{-1} ~ 1000 (acceptance+efficiency ~ 10%)
  - plenty for distributions
  - factor of 5 less at 7 TeV, not as convincing (similar to Tevatron)
- Study of the correlation expected at NLO shows slight change from LO.

Summary

- Calculations beyond leading order are not only theoretically better behaved, but they also make a phenomenological difference.
  - a variety of signal and background processes included at NLO in MCFM;
  - new recently: Higgs+2 jets, top pairs with decay, t-channel single top (4F);
  - all of these speak to ongoing analyses at the Tevatron.
- Analytic calculations of amplitudes are still tough, even with a full bag of tricks
  - ... although there's probably a lot of structure in the amplitudes that is still not fully understood;
  - numerical approaches are clearly the most efficient way forward.
- The MCFM code contains expressions for many virtual matrix elements and could provide a starting point for future implementations in a parton shower.