Precision QCD for the Tevatron and LHC

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β function in perturbation theory

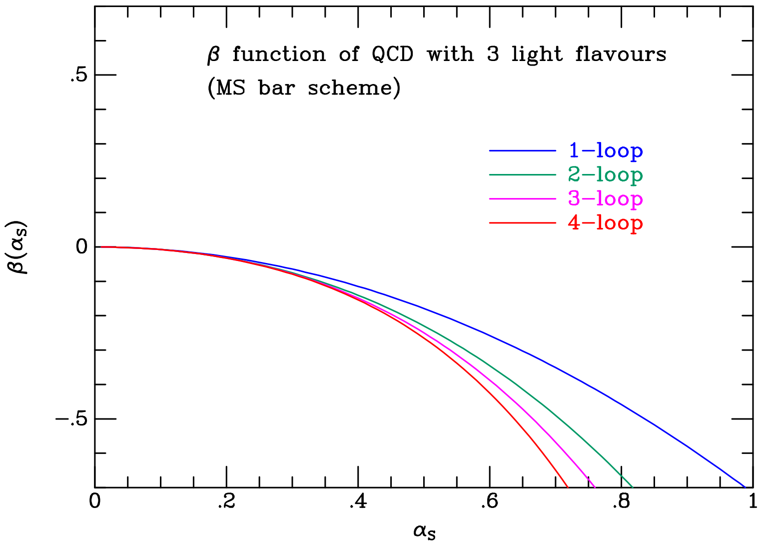
- Running of the QCD coupling α_S is determined by the β function,
- The β-function of QCD is negative.

$$\beta(\alpha_S) = -b\alpha_S^2(1 + b'\alpha_S) + \mathcal{O}(\alpha_S^4)$$

$$b = \frac{(11C_A - 2n_{lf})}{12\pi}, \quad b' = \frac{(17C_A^2 - 5C_A n_{lf} - 3C_F n_{lf})}{2\pi(11C_A - 2n_{lf})},$$

where n_{lf} is number of “active” light flavors. b', (Caswell, Jones)

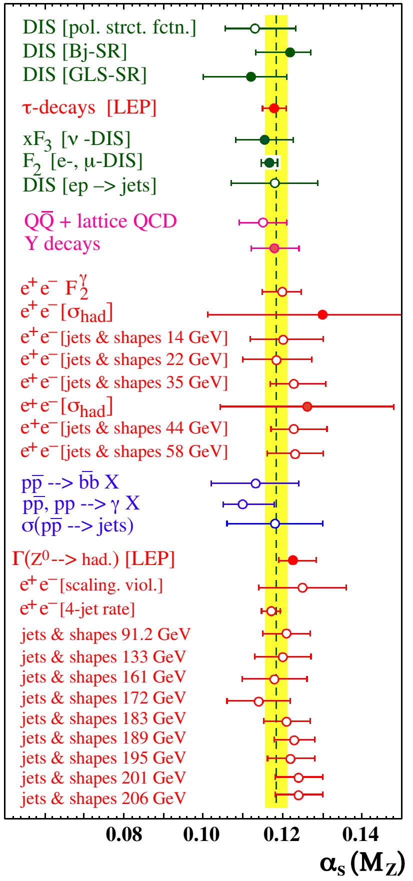
- β-function now known up to four loops!



Current experimental results on α_S

Bethke,hep-ph/0407021

$\alpha_S(M_Z) = 0.1182 \pm 0.0027, \overline{\text{MS}}$, NNLO



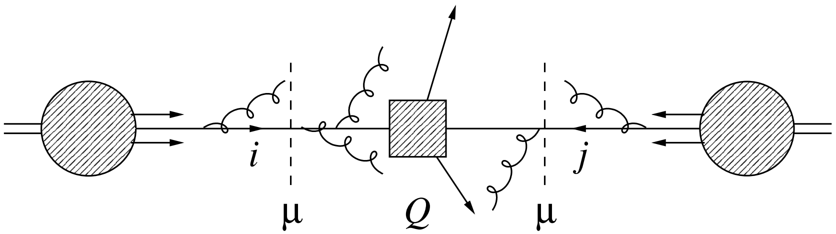
- α_S is large at current scales.
- Measurement α_S is stable, ($\alpha_S(M_Z) = 0.1182 \pm 0.0027$ in 2002).
- The decrease of α_S is quite slow – as the inverse power of a logarithm.
- Higher order corrections are and will continue to be important.

The challenge

- The challenge is to provide the most accurate information possible to experimenters working at the Tevatron and the LHC.
- Proton (anti)proton collisions give rise to a rich event structure.
- Complexity of the events will increase as we pass from the Tevatron to the LHC.
- The goals
  - ⋆ To provide physics software tools which are both flexible and give the most accurate representations of the underlying theories.
  - ⋆ To discover new efficient ways of calculating in perturbative QCD, (e.g. MHV amplitudes).

Hadron-hadron processes

- In hard hadron-hadron scattering, constituent partons from each incoming hadron interact at short distance (large momentum transfer Q^2).



- Form of cross section is

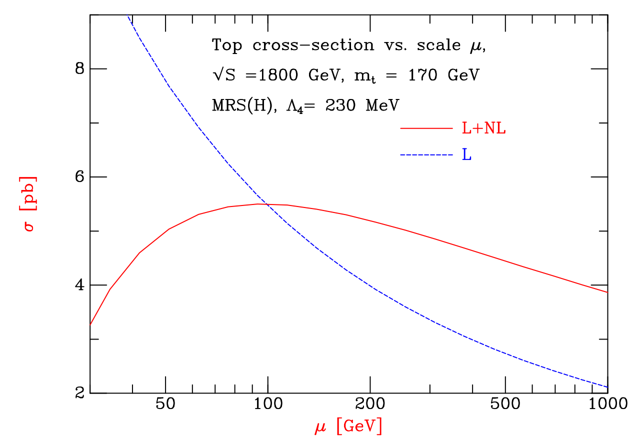
$$\frac{d\sigma}{dX} = \sum_{i,j} \sum_{\tilde{X}} \int dx_1 dx_2 \; f_i(x_1, \mu^2) f_j(x_2, \mu^2)$$
$$\times \quad \hat{\sigma}_{ij}^{\tilde{X}}(\alpha_S(\mu^2), Q^2, \mu^2) \; F(\tilde{X} \to X, \mu^2)$$

where μ^2 is factorization scale and $\hat{\sigma}_{ij}$ is subprocess cross section for parton types i, j and X represents the hadronic final state.

Hadron-hadron processes II

- Short distance cross section $\hat{\sigma}_{ij}$ is calculable as a perturbation series in α_S.
- Notice that factorization scale is in principle arbitrary: affects only what we call part of subprocess or part of initial-state evolution (parton shower), eg. if

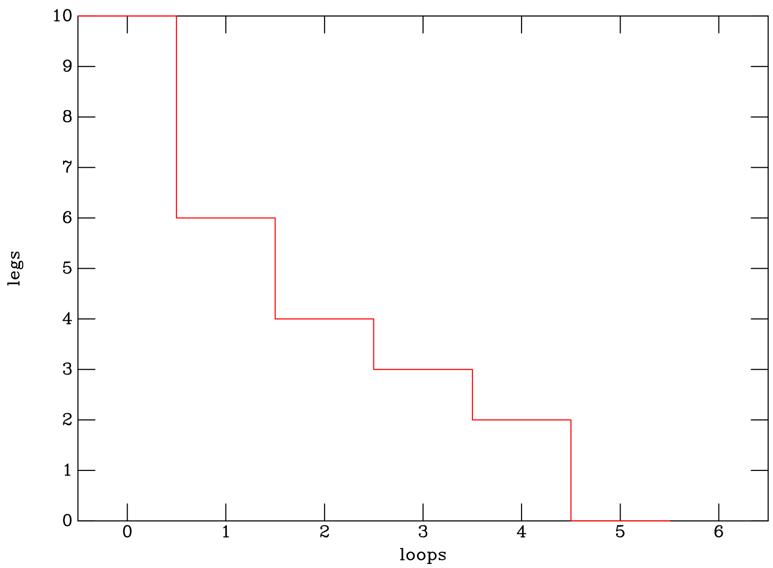
$$\sigma = q(x_1,\mu^2)q(x_2,\mu^2) \otimes \left[\alpha_S^2(\mu^2)f^{(0)} + \alpha_S^3(\mu^2)f^{(1)}\right], \quad \frac{d\sigma}{d\ln\mu^2} = O(\alpha_S^4)$$



- There are also interactions between spectator partons, leading to *soft underlying event* and/or *multiple hard scattering*. This an important issue, but I will not talk further about it.

Many loops or many legs?

- For radiative corrections to hard processes the state of the art can calculate loops or legs, but not both.



- At LHC, trend is toward large numbers of legs.
- Most phenemonologically interesting processes involve vector bosons, leptons, missing energy, heavy flavours.
- Many processes can contribute to the same signature, argues for one (or several) unified approaches.
- NNLO desirable everywhere, but probably only available for a few specialized processes.
- For LHC theoretical effort should be given to multi-leg processes at one loop (NLO).

Why NLO?

The benefits of higher order calculations are:-

- Less sensitivity to unphysical input scales (eg. renormalization and factorization scales)
- First prediction of normalization of observables at NLO
- Hence more accurate estimates of backgrounds for new physics searches.
- Confidence that cross-sections are under control for precision measurements.
- It is a necessary prerequisite for other techniques matching with resummed calculations, (eg. MC@NLO).
- More physics
  - ⋆ Parton merging to give structure in jets.
  - ⋆ Initial state radiation.
  - ⋆ More species of incoming partons enter at NLO.

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}\leq 3j$	$W+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}\leq 3j$	$W+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$Z+b\bar{b}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{b}\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$	$ZZZ+\leq 3j$	$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}\leq 3j$	$\gamma\gamma+b\bar{b}\leq 3j$		single top
$\gamma+c\bar{c}\leq 3j$	$\gamma\gamma+c\bar{c}\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}\leq 3j$		
	$WZ+c\bar{c}\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

A more realistic list

Les Houches workshop 2005

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
⋆ 3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton

What is MCFM?

- A parton-level event integrator for many processes
- Includes processes involving heavy quarks, vector and Higgs bosons, missing energy, with spin correlations in decay.
- Distributions of all variables are available.
- Most processes are included at NLO, with all the attendant benefits.
  - ⋆ reduced dependence on unphysical scales.
  - ⋆ better estimate of rates for physical processes.
  - ⋆ More than one parton in a jet, giving (primitive) structure to the jet.
  - ⋆ Better estimate than parton shower, for well separated jets, as required for the decays of heavy objects.
- Many processes included in a unified framework, allowing easy comparison

MCFM overview

John Campbell and R.K. Ellis

- Parton level cross-sections predicted to NLO in α_S

$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm + \gamma$	$p\bar{p} \to W^\pm/Z + H$
$p\bar{p} \to W^\pm + g^\star\ (\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^\pm/Z +$ 1 jet	$p\bar{p} \to W^\pm/Z +$ 2 jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H +$ 1 jet
$p\bar{p}(VV) \to H +$ 2 jets	$p\bar{p} \to t + X$
$pp \to t + W$	

$\oplus$ less sensitivity to μ_R, μ_F, rates are better normalized, fully differential distributions.

$\ominus$ low particle multiplicity (no showering), no hadronization, hard to model detector effects

References

- Calculation of the Wbb background to a WH signal at the Tevatron. R.K. Ellis, Sinisa Veseli, hep-ph/9810489.
- Vector boson pair production at the Tevatron, including all spin correlations of the boson decay products. J.M. Campbell, R.K. Ellis, hep-ph/9905386.
- Calculation of the Zbb and other backgrounds to a ZH signal at the Tevatron. J.M. Campbell, R.K. Ellis, hep-ph/0006304.
- Next-to-leading order corrections to W+2 jet and Z+2 jet production at hadron colliders. John Campbell, R.K. Ellis, hep-ph/0202176.
- Higgs Boson Production in Association with a Single Bottom Quark. J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, hep-ph/0204093.
- Next-to-Leading Order QCD Predictions for W+2 jet and Z+2 jet Production at the CERN LHC. J. Campbell, R.K. Ellis and D. Rainwater, hep-ph/0308195.
- Associated Production of a Z Boson and a Single Heavy Quark Jet. J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, hep-ph/0312024.
- Single top production and decay at next-to-leading order, J. Campbell, R.K. Ellis and F. Tramontano, hep-ph/0408158.
- Next-to-leading order corrections to WT production and decay, J. Campbell, and F. Tramontano, hep-ph/0506289.
- J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Production of a Z boson and two jets with one heavy-quark tag, hep-ph/0510362.

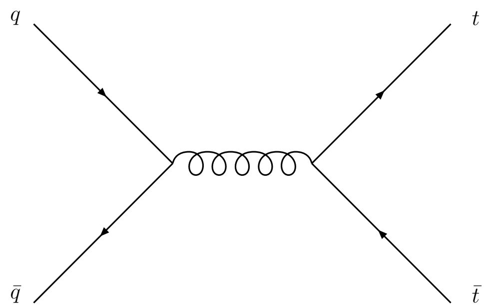
Shortcomings of MCFM

- No attachment of parton shower, (cf MC@NLO) Webber, Frixione . . .), (but, NLO is a necessary prerequisite for MC@NLO)
- No hadronization model, so hard to model detector effects.
- No inclusion of pure QCD processes, such as $gg \to gg, gg \to ggg, gg \to gggg$, (cf NLOJet++) Nagy, Giele, Kilgore
- Weighted events

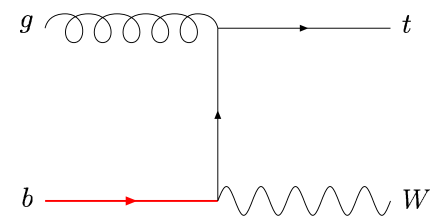
MCFM v. 5.1

- MCFM v.5.1 released June 1st, 2006
- Available for download at http://mcfm.fnal.gov
- Processes added in NLO, ($f \equiv q, \bar{q}, g$, generic parton)
  $f + f \to W^{\pm} + t$
  $f + b \to Z^0 + b + f$
  $f + c \to Z^0 + c + f$
- Processes added in LO
  $f + f \to Z^0(\to e^- + e^+) + c + c$
  $f + f \to t\bar{t} + g$
  $f + f \to H + f + f + f[\text{in heavy top limit}]$
  $f + f \to W^-(\to e^- + \nu\ ) + t + b[\text{massive b}]$

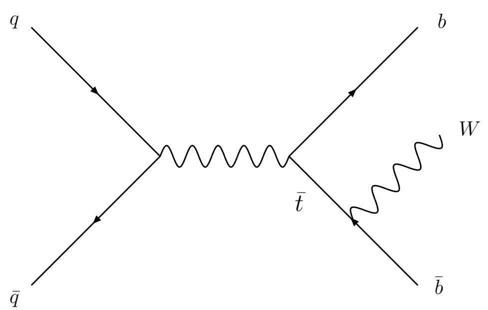
Top production rates



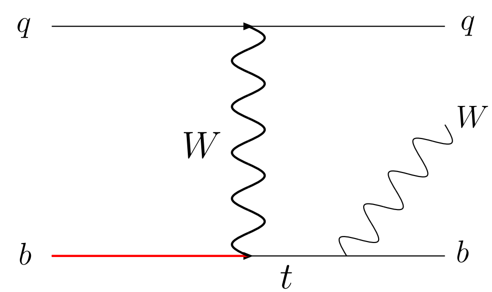
6 pb
720 pb



0.14 pb
66 pb



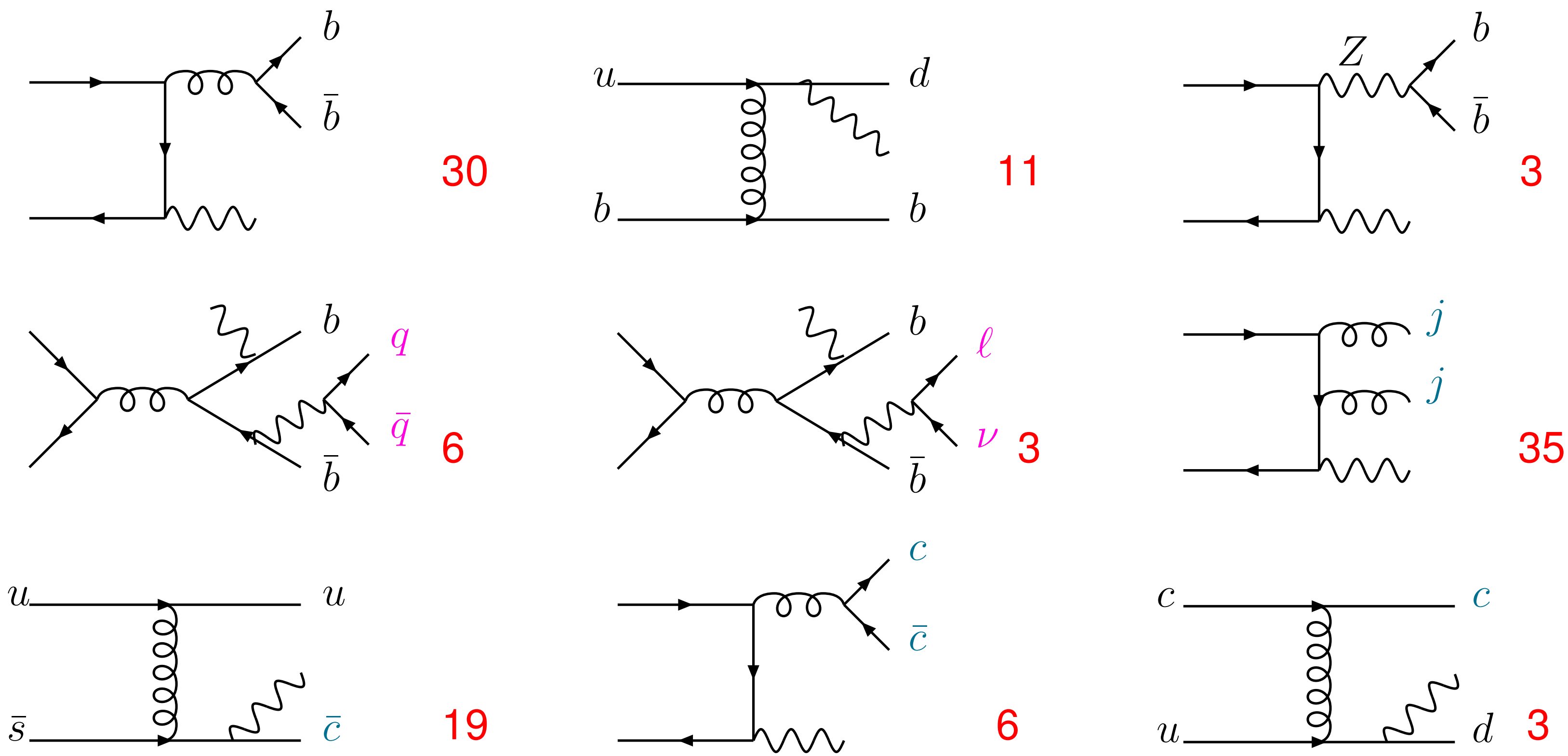
0.8 pb
10 pb



1.8 pb
240 pb

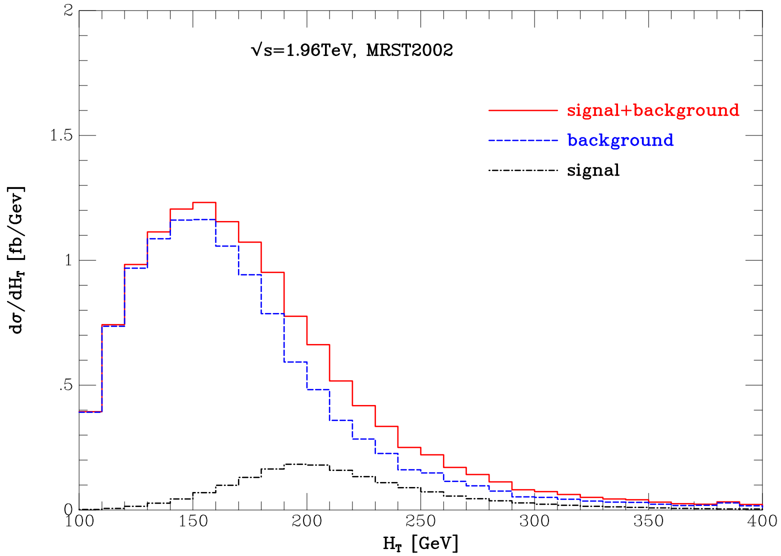
- All cross-sections are known to NLO (Tevatron / LHC)
- The total single top cross-section is smaller than the $t\bar{t}$ rate by about a factor of two, at both machines

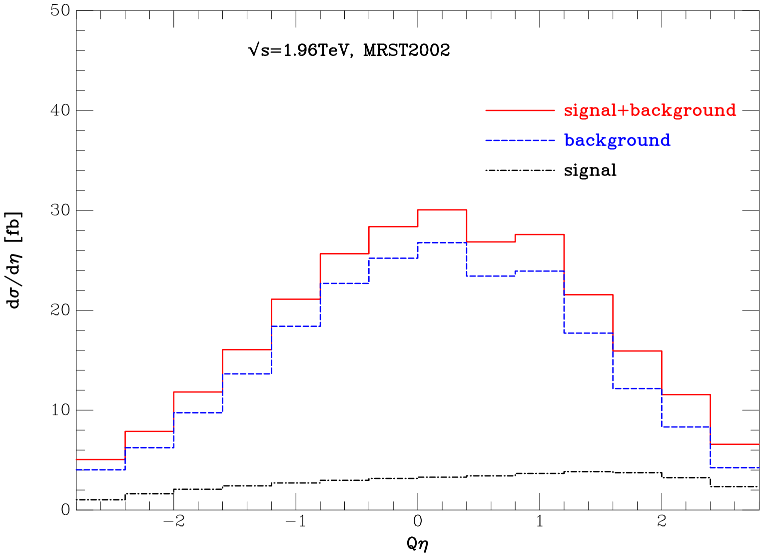
Backgrounds for single top



- Cross-sections in fb include nominal tagging efficiences and mis-tagging/fake rates. Calculated with MCFM, most at NLO at $\sqrt{S} = 2$ TeV.
- Rates are 7 fb and 11 fb for s- and $t-$channel signal

Single top signal vs. backgrounds

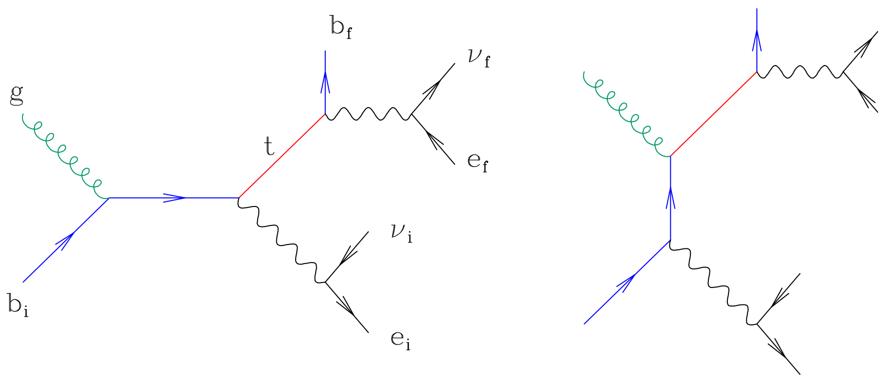




- H_T = scalar sum of jet, lepton and missing E_T
- $Q\eta$ is the product of the lepton charge and the rapidity of the untagged jet, useful for picking out the t-channel process
- Signal:Background (with our nominal efficiencies) is about $1:6$.
- it will take 1.5 fb^{-1} to have evidence (3σ) for single top from a single experiment at the Tevatron (Gresele, Moriond 2006).

Wt production

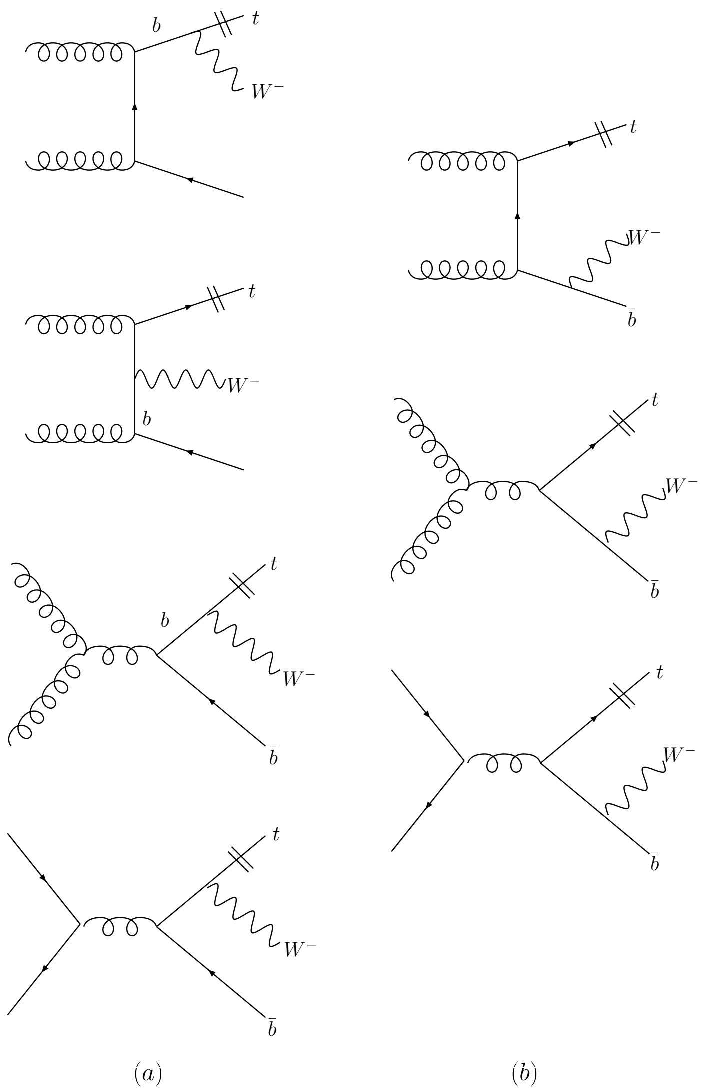
Campbell, Tramontano



- The last of the single top processes.
- Wt process important at LHC, negligible at Tevatron.

- Rate depends on b-quark distribution.
- Top quark, (shown in red) is taken onshell, but all spin correlations are retained.
- Including real radiation we obtain both diagrams with and without a resonant $\bar{t}$ propagator.
- The former are properly considered as contributions to $t\bar{t}$ production, whereas the latter are contributions to single top production.

Separation of Wt and $t\bar{t}$ diagrams



- diagrams (a) are "genuine" single top contributions, whereas diagrams (b) contain doubly resonant propagators.
- Apply a veto on the p_T of the additional $\bar{b}$ quark which appears in NLO.
- Choose factorization scale μ_F of the same order as the maximum p_T which is allowed.
- When the $p_T > \mu_F$ doubly resonant diagrams dominate and a better description is obtained by using the $t\bar{t}$ process.

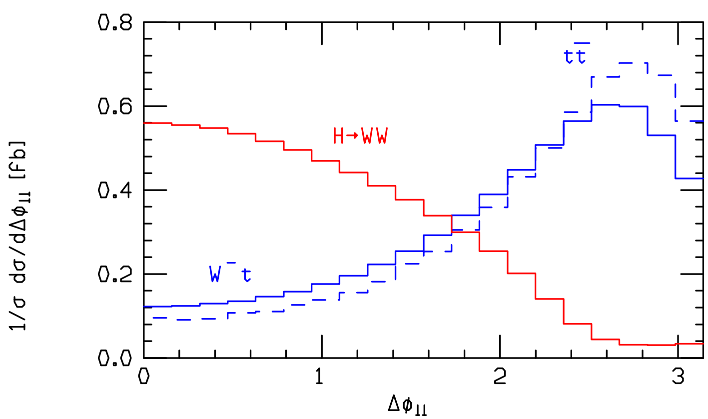
Wt background to $H \to WW^\star$

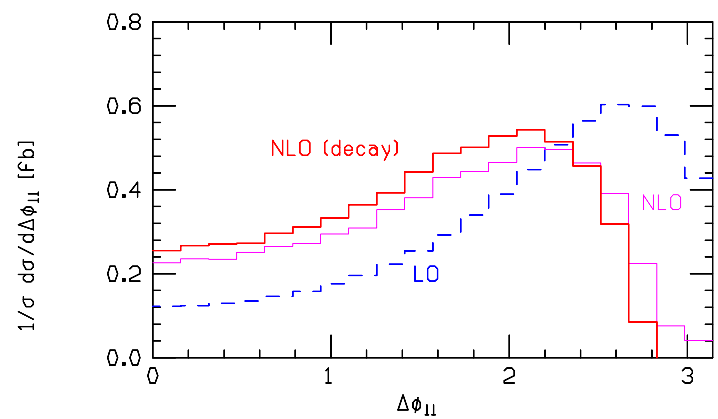
$$g + g \to H \quad \to \quad W^- + W^+$$

$$W^+ \to \nu + e^+$$

$$W^- \to e^- + \bar{\nu}$$

Process	σ [fb]
H–> WW($m_H = 155$ GeV)	58.1
continuum WW	270.5
$t\bar{t}$	43.9
Wt	40.1





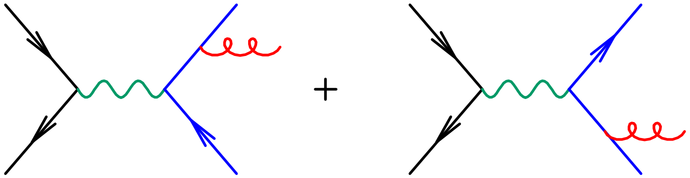
- $t\bar{t}$ and Wt backgrounds are of similar size.
- Shape of contribution of Wt process to Dittmar-Dreiner angle modified at NLO

Automatic NLO corrections

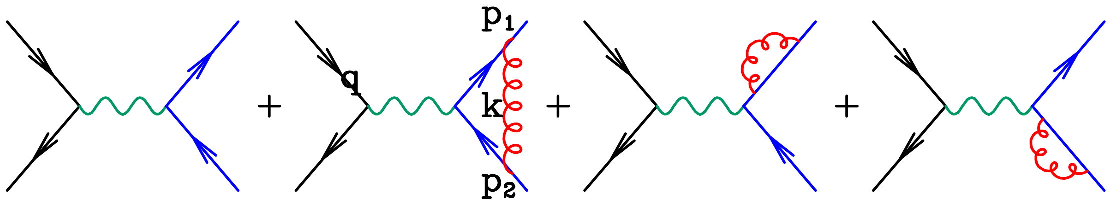
- What is needed is an automatic procedure to calculate NLO corrections (MadLoop?).
- Current stumbling block is the calculation of virtual corrections.
- The virtual corrections contain singularities from the regions of collinear and soft gluon emission, (and in general also UV divergences).
- Divergences are normally controlled by dimensional regularization. A completely numerical procedure using, say, a gluon mass could cause problems with gauge invariance and is hence deprecated.

Example: e^+e^- total rate

- Consider the corrections to total $e^+e^- \to q\bar{q}$ rate.



(a)



(b)

$$\sigma^{q\bar{q}g} = 2\sigma_0 \frac{\alpha_S}{\pi} H(\epsilon) \left[\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} - \pi^2 + \mathcal{O}(\epsilon) \right] .$$

- Soft and collinear singularities in real emisssion amplitudes (a) are regulated, appearing instead as poles at $D = 4$.

Virtual gluon contributions

- Virtual gluon contributions (b): using dimensional regularization again

$$\sigma^{q\bar{q}} \; = \; 3\sigma_0 \left\{ 1 + \frac{2\alpha_S}{3\pi} \, H(\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \pi^2 + \mathcal{O}(\epsilon) \right] \right\} \; .$$

- Adding real and virtual contributions, poles cancel and result is finite as $\epsilon \to 0$. R is an infrared safe quantity.

$$R \; = \; 3 \sum_q Q_q^2 \; \left\{ 1 + \frac{\alpha_S}{\pi} + \mathcal{O}(\alpha_S^2) \right\} .$$

- However the virtual corrections to $W^+ \to u\bar{d}gggg$ are not so easily calculated.

Historical perspective

We want to consider tensor integrals of the form

$$I^{\mu_1\cdots\mu_M} = \int \frac{d^D l}{i\pi^{D/2}} \; \frac{l^{\mu_1}\ldots l^{\mu_M}}{d_1 d_2 \ldots d_N}$$

where $d_i = (l + \sum_{j=1}^{j=i} p_j)^2$ are the standard propagator factors.
Passarino and Veltman (1979) wrote a form factor expansion for one-loop integrals, with $M \le N, N \le 4$. For example,

$$\int \frac{d^D l}{i\pi^{D/2}} \frac{l^\mu}{l^2(l+p_1)^2(l+p_1+p_2)^2} = C_1(p_1,p_2)p_1^\mu + C_2(p_1,p_2)p_2^\mu$$

Contracting with p_1 and p_2 and using the identities

$$l\cdot p_1 = \tfrac{1}{2}[(l+p_1)^2 - l^2 - p_1^2], l\cdot p_2 = \tfrac{1}{2}[(l+p_1+p_2)^2 - (l+p_1)^2 - p_2^2 - 2p_1\cdot p_2]$$

Historical perspective II

We derive a linear equation expressing C_1, C_2 in terms of scalar integrals

$$\left(\begin{array}{cc} 2p_1 \cdot p_1 & 2p_1 \cdot p_2 \\ 2p_2 \cdot p_1 & 2p_2 \cdot p_2 \end{array}\right)\left(\begin{array}{c} C_1 \\ C_2 \end{array}\right) = \left(\begin{array}{c} R_1 \\ R_2 \end{array}\right)$$

where $R_1 = [B_0(p_1+p_2) - B_0(p_2) - p_1^2\, C_0(p_1,p_2)]$

and $R_2 = [B_0(p_1) - B_0(p_1+p_2) - (p_2^2 + 2p_1 \cdot p_2)\, C_0(p_1,p_2)]$

$$C_0(p_1,p_2) = \int [dl] \frac{1}{l^2(l+p_1)^2(l+p_1+p_2)^2}, B_0(p_1) = \int [dl] \frac{1}{l^2(l+p_1)^2}$$

Solution involves the inverse of the Gram matrix, $G_{ij} \equiv 2p_i \cdot p_j$

$$G^{-1} = \left(\begin{array}{cc} +p_2 \cdot p_2 & -p_1 \cdot p_2 \\ -p_1 \cdot p_2 & +p_1 \cdot p_1 \end{array}\right) /[2(p_1 \cdot p_1\, p_2 \cdot p_2 - (p_1 \cdot p_2)^2)]$$

Historical perspective III

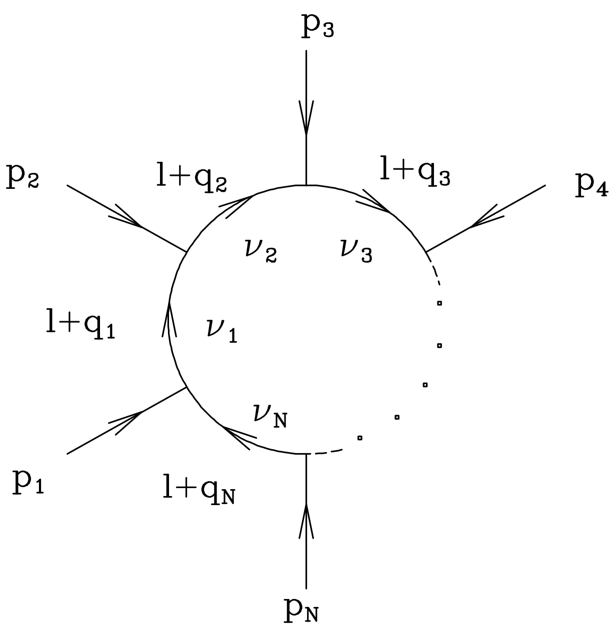
- M. Veltman wrote a CDC program for numerical evaluation of the formfactors in processes with only UV divergences, Utrecht (1979).
- He dealt with exceptional regions, (e.g. regions where the Gram determinant vanishes), by implementing parts of the program in quadruple precision.
- Translation and improvement by Van Oldenborgh (1990) and further work on interface by T. Hahn and M. Perez-Victoria (1998).

However this is not sufficient for our needs.

- We are interested in processes with more than 4 external legs.
- We are often interested in loop processes with collinear and soft singularities due to the presence of massless particles. These are most commonly (and elegantly) controlled by dimensional regularization.

Recursion relations I

Define generalized scalar integrals



$$d_i \equiv (l + q_i)^2$$

$$q_i \equiv \sum_{j=1}^{i} p_j$$

$$q_N \equiv \sum_{j=1}^{N} p_j = 0,$$

$$I(D; \nu_1, \nu_2, \ldots, \nu_N) = I(D; \{\nu_k\}_{k=1}^{N}) \equiv \int \frac{d^D\, l}{i\pi^{D/2}} \; \frac{1}{d_1^{\nu_1} d_2^{\nu_2} \cdots d_N^{\nu_N}} \,,$$

Form-factor expansion

Davydchev

- For form factor expansion in terms of the q's the coefficients are generalized scalar integrals in shifted dimensionalities
- e.g., the rank-1 and rank-2 tensor integrals with N external legs can be decomposed as

$$
\begin{aligned}
I^{\mu_1}(D; q_1, \ldots, q_N) &= \sum_{i_1=1}^{N} I(D+2; \{1+\delta_{i_1 k}\}_{k=1}^{N})\, q_{i_1}^{\mu_1} \\
&= I(D+2; 2,1,1,\ldots,1)\, q_1^{\mu_1} + I(D+2; 1,2,1,\ldots,1)\, q_2^{\mu_1} \\
&+ \cdots + I(D+2; 1,1,1,\ldots,2)\, q_N^{\mu_1}\,. \\
I^{\mu_1\mu_2}(D; q_1, \ldots, q_N) &= -\frac{1}{2} I(D+2; 1,1,1,\ldots,1)\, g^{\mu_1\mu_2} \\
&+2\, I(D+4; 3,1,1,\ldots,1)\, q_1^{\mu_1} q_1^{\mu_2} \\
&+ I(D+4; 2,2,1,\ldots,1)\, \left(q_1^{\mu_1} q_2^{\mu_2} + q_1^{\mu_2} q_2^{\mu_1}\right) + \cdots
\end{aligned}
$$

Recursion relations II

Using integration by parts methods we derive the basic recursion relation

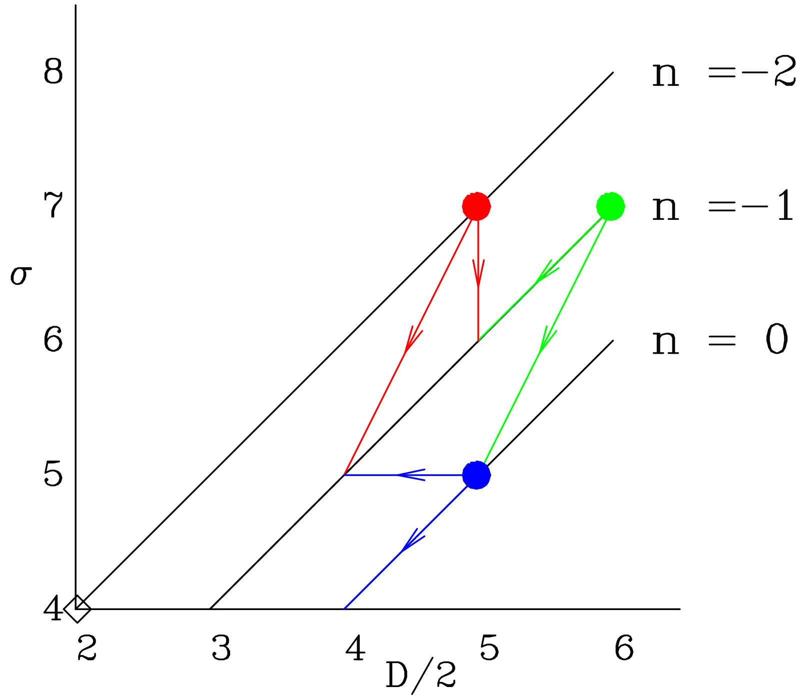
$$
\begin{aligned}
&(\nu_l - 1) I(D; \{\nu_k\}_{k=1}^N) \\
&= \quad -\sum_{i=1}^{N} S_{li}^{-1} I(D-2; \{\nu_k - \delta_{ik} - \delta_{lk}\}_{k=1}^N) \\
&- \quad b_l\,(D-\sigma)\,I(D; \{\nu_k - \delta_{lk}\}_{k=1}^N).
\end{aligned}
$$

$$
\sigma \equiv \sum_{i=1}^{N} \nu_i; \quad b_i \equiv \sum_{j=1}^{N} S_{ij}^{-1}; \quad B \equiv \sum_{i=1}^{N} b_i = \sum_{i,j=1}^{N} S_{ij}^{-1}\,.
$$

The strategy is to reduce more complicated integrals to a set of simpler basis integrals which are known analytically.
Hence the method is seminumerical.

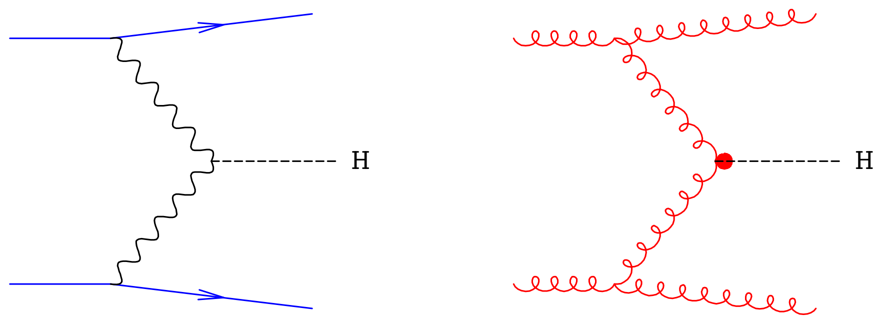
Recursion relations (cont)

- Example: reduction of boxes, $\sigma = \sum_i \nu_i$



- Using the basic identity (red lines) and other subsidiary identities (blue and green lines) one can always arrive at the basis integral, (four-dimensional box), denoted by a diamond, (or integrals with fewer external legs).

H+2 jet calculation

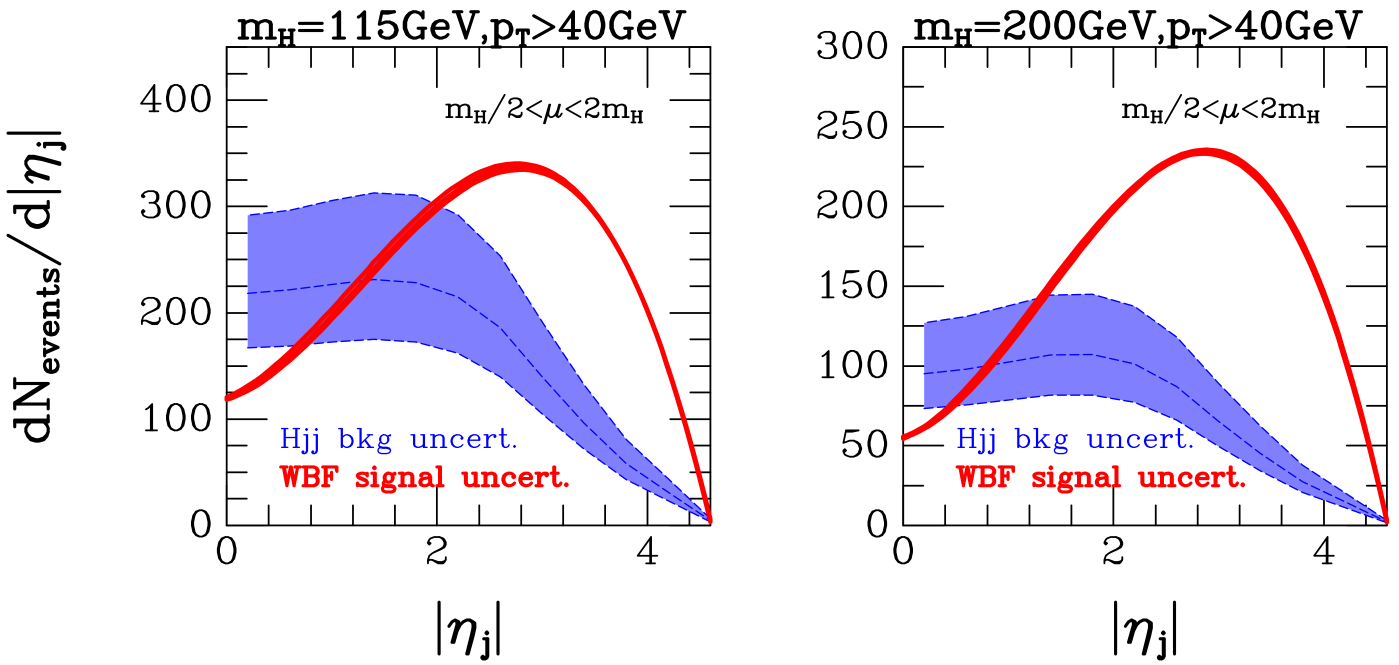


- NLO corrections to W-fusion mechanism already calculated by many authors.
- All the elements are in place for a full NLO Higgs + 2 jets calculation via gluon fusion mechanism
  - ⋆ Born level calculation Higgs + 4 partons
  - ⋆ Real calculation Higgs + 5 partons, Del Duca et al, Dixon et al, Badger et al
  - ⋆ Virtual calculation Ellis, Giele and Zanderighi, presented here
  - ⋆ Subtraction terms Campbell, Ellis and Zanderighi, in preparation

Comparison of signal and "background"

- Large uncertainty in blue curves because NLO correction not included.

Berger,Campbell



Proof of principle

Ellis, Giele, Zanderighi

Use the effective theory ($m_t \to \infty$) for Hgg coupling

$$\mathcal{L}_{\rm eff} = \frac{1}{4} A(1+\Delta) H G^a_{\mu\nu} G^{a\,\mu\nu} \,.$$

$G^a_{\mu\nu}$ is the field strength of the gluon field and H is the Higgs-boson field, $A = \frac{g^2}{12\pi^2 v}$ where g is the bare strong coupling and v is the vacuum expectation value parameter, $v^2 = (G_F\sqrt{2})^{-1} = (246\ \mathrm{GeV})^2$. Δ is a finite correction. Calculate virtual corrections to

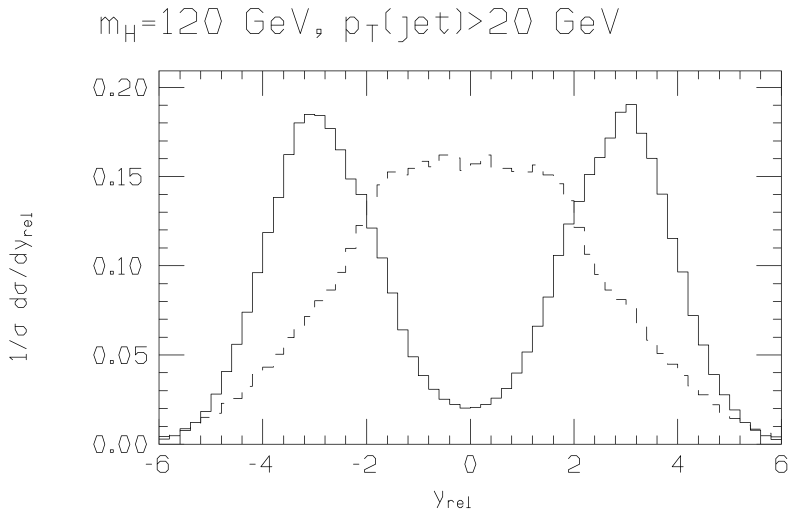
$$\begin{array}{llll} A) & H & \to & q\bar{q}q'\bar{q}', \quad (30 \text{ diagrams}), \\ B) & H & \to & q\bar{q}q\bar{q}, \quad (60 \text{ diagrams}), \\ C) & H & \to & q\bar{q}gg, \quad (191 \text{ diagrams}), \\ D) & H & \to & gggg, \quad (739 \text{ diagrams}). \end{array}$$

Comparison of numerical and analytic results for $H \to$ four partons

	$\frac{1}{\epsilon^2}$	$\frac{1}{\epsilon}$	1
A_B	0	0	12.9162958212387
$A_{V,N}$	-68.8869110466063	-114.642248172519	120.018444115458
$A_{V,A}$	-68.8869110466064	-114.642248172523	120.018444115429
B_B	0	0	858.856417157052
$B_{V,N}$	-4580.56755817094	-436.142317955208	26470.9608978350
$B_{V,A}$	-4580.56755817099	-436.142317955660	26470.9608978346
C_B	0	0	968.590160211857
$C_{V,N}$	-8394.44805516930	-19808.0396331354	-1287.9057494911 2
$C_{V,A}$	-8394.44805516942	-19808.0396331363	not known analytically
D_B	0	0	3576991.27960852
$D_{V,N}$	-4.29238953553022 $\cdot 10^7$	-1.04436372655580 $\cdot 10^8$	-6.79830911471604$\cdot 10^7$
$D_{V,A}$	-4.29238953553022$\cdot 10^7$	-1.04436372655580 $\cdot 10^8$	not known analytically

Higgs+ 3 jets at LO

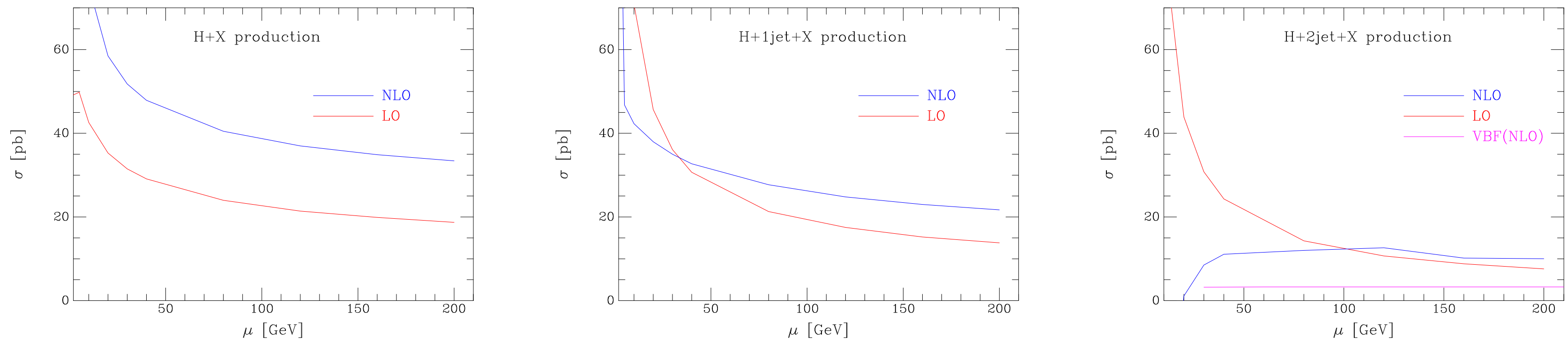
- Implementation of $gg \rightarrow Hggg$ + other diagrams.
- Distribution of the rapidity of the third jet, y_{j_3} measured with respect to the rapidity average of the tagging jets. $y_{rel} = y_{j_3} - (y_{j_1} + y_{j_2})/2$ cf, Del Duca,Frizzo,Maltoni



- $|y_{j_1} - y_{j_2}| > 4.2$,
  $y_{j_1} \cdot y_{j_2} < 0$,
  $m_{jj} > 600$ GeV
- Rapidity of third jet in Vector-boson fusion (solid line) closer to tagging jets than in gluon fusion (dotted line).

H+2 jet results

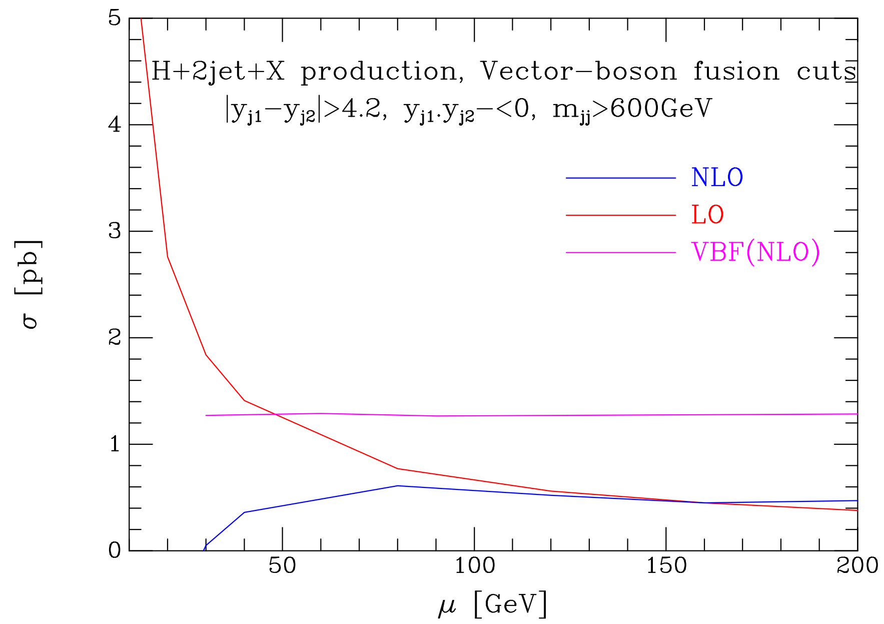
- Define jets with $p_t(jet) > 20$ GeV, $|y_j| < 5, R_{jj} > 0.6$
- We vary renormalization and factorization scale together.



- H + 0jet, H + 1 jet inclusive results from MCFMv5.0
- Our preliminary results indicate the Higgs + 2 jet inclusive rate is the better behaved at NLO than the rate for Higgs+X rate, or Higgs + 1 jet+X.
- Suggests that a relatively high scale $\mu \sim m_H$ is appropriate for the Higgs.
- NNLO known for Higgs + X, Harlander+Kilgore, Anastasiou+Melnikov

H+2 jet results, continued

- When we impose cuts to enhance vector boson fusion, (without central jet veto) we obtain a similar pattern
- Too early to comment on particular parton subprocesses, individual contributions, separated factorization and normalization scale dependence.



Conclusions

- A serious program is underway to calculate NLO corrections to SM processes, relevant for LHC physics. MCFM is a beginning, but it is clearly not enough.
- Release of MCFM version 5.1, new processes, $pp \to Wt, pp \to Zbj$, bug fixes, general housekeeping, (available at mcfm.fnal.gov)
- Benefits of a unified approach are beginning to be seen. Calculation of signal and background in same program, e.g. for single top.
- Preliminary results for Higgs + 2 jets at NLO indicate
  - ⋆ a good prediction and stable result for H+2jets
  - ⋆ viability of seminumerical method