BERGISCHE UNIVERSITÄT WUPPERTAL

NLO calculations finally fully automatic (?)

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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Meeting of the GDR Terascale in Heidelberg, 14^{th} - 16^{th} October 2009

Outline of the Talk

- Introduction
- NLO cross section
- Real emission: **HELAC-DIPOLES**
- Virtual contributions: **OPP, CUTTOOLS, HELAC-1LOOP**
- First results: pp $\rightarrow$ ttbb
- Conclusions & Outlook

Fully Automatic LO

- Possible to go to quite high orders 8-10 partons in the final state
- Well separated to avoid phase space regions where divergences become troublesome
- Parton level tools which are completely self contained and automated
- Provide amplitudes and integrators on their own
- Standard Model and beyond tools @ tree level (just few examples)

ALPGEN, AMEGIC++/SHERPA, COMIX/SHERPA, HELAC/PHEGAS, MADGRAPH/MADEVENT, O'MEGA/WHIZARD, ...

- General purpose Monte Carlo programs (parton shower, hadronisation, multiple interactions, hadrons decays, etc.)

HERWIG, HERWIG++, PYTHIA 6.4, PYTHIA 8.1, SHERPA, ...

- To improve accuracy of prediction higher order calculations are needed

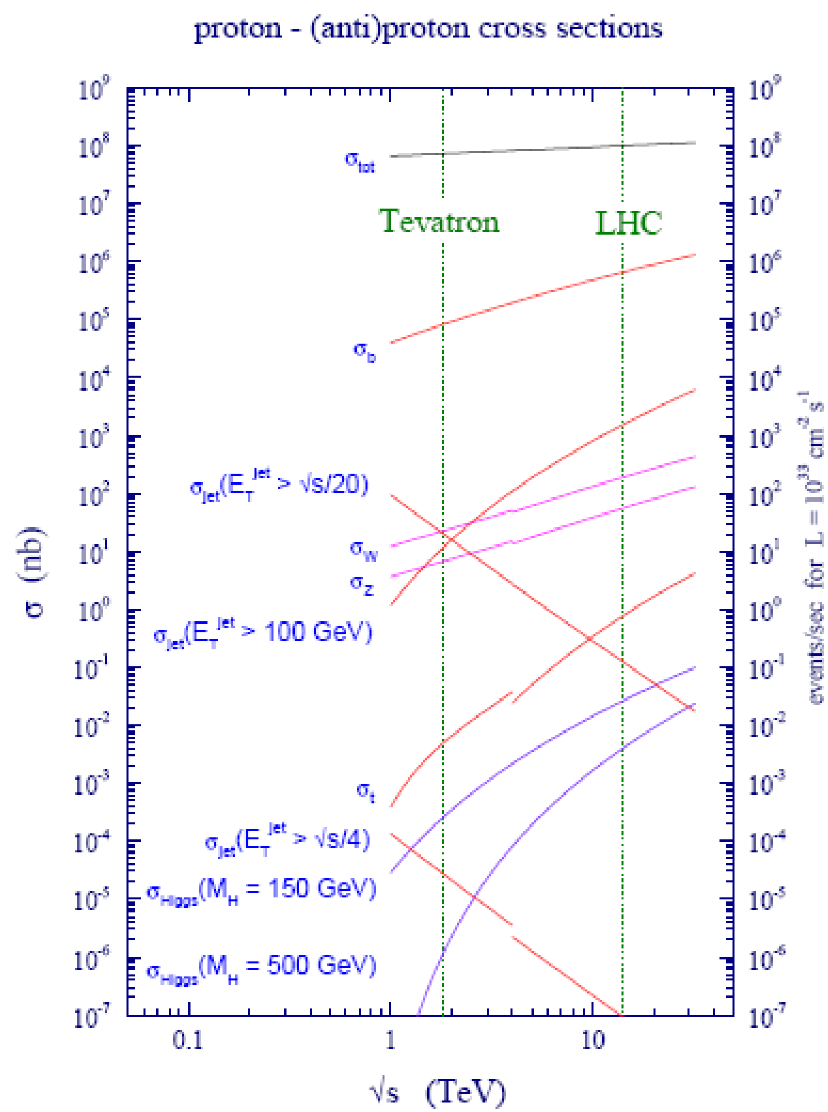
Why NLO

Multi-leg processes at the LHC

- Huge W, Z and top-quark production rates plus multiple jet emission
- Multi-particle signatures with leptons, jets and missing energy
- Backgrounds to Higgs boson(s) and new physics

Benefits of higher order calculations

- Less sensitivity to unphysical input scales
  - ⇒ LO up to a factor of 2, NLO 10%-20%
- First predictive normalisation of observables
- Improved shape of distributions
- Improve description of jets



NLO Cross Sections

- NLO schematically

$$\langle O \rangle^{NLO} = \int_{n+1} O_{n+1}\, d\sigma^{R} + \int_{n} O_{n}\, d\sigma^{V} + \int_{n} O_{n}\, d\sigma^{C}$$

Real emission contribution ⇨
emission of additional parton - matrix element given by square of Born amplitude with n+1 partons

Virtual contribution ⇨
one loop corrections - matrix element given by interference term of 1-loop amplitude with n partons with Born amplitude for n partons

Collinear subtraction term ⇨
orginates from factorisation of initial state collinear singularities

- Taken separately the individual contributions are IR divergent
- Only their sum is finite ⇨ KLN & factorization theorem
- How to get individual contributions finite ⇨ phase-space integration via MC methods

Subtraction Procedure

- Define subtraction term which regularizes divergences which comes from soft and collinear regions
- Proper aproximation of $d\sigma^R$ - same singular behavior in $d=4-2\epsilon$ dimensions as $d\sigma^R$
- Integrated over unresolved 1-parton phase-space

Massless: S. Catani, M.H. Seymour, 1997
Massive: S. Catani, S. Dittmaier, M.H. Seymour, Z. Trocsanyi, 2002
Polarized: M. Czakon, C. G. Papadopoulos, MW, 2009

$$\langle O\rangle^{NLO} = \int_{n+1} (O_{n+1}\, d\sigma^R - O_n\, d\sigma^A) + \int_n (O_n\, d\sigma^V + O_n\, d\sigma^C + O_n \int_1 d\sigma^A)$$

- Matrix element corresponding to $d\sigma^A$ given as sum over dipoles

$$d\sigma^A \propto \sum_{pairs\ i,j} \sum_{k\neq i,j} D_{ij,k}$$

- $d\sigma^A$ acts as local counter term for $d\sigma^R$, limit $\epsilon\to 0$ can be safely performed
- Finite contributions

$$\langle O\rangle^{NLO}_{\{n+1\}} \int_{n+1} (O_{n+1}\, d\sigma^R|_{\epsilon=0} - O_n\, d\sigma^A|_{\epsilon=0})$$

Subtraction Procedure

- Universality of soft and collinear limits of QCD matrix elements is the basis for the construction of the dipole subtraction terms
- Integrated subtraction term, spin correlations average out, color correlations still remain

$$d\sigma^C + \int_1 d\sigma^A = \boldsymbol{I} \circ d\sigma^B + \boldsymbol{K} \circ d\sigma^B + \boldsymbol{P} \circ d\sigma^B$$

Contains all poles which come from $d\sigma^A$ and $d\sigma^C$ that are necessary to cancel poles in $d\sigma^V$

Finite remainder left after factorization of initial state collinear singularities into PDF, involve an integration over momentum fraction x, finite for $\epsilon \to 0$

$$\langle O \rangle_{\{n\}}^{NLO} = \int_n O_n \left(d\sigma^V + \boldsymbol{I} \circ d\sigma^B + \boldsymbol{K} \circ d\sigma^B + \boldsymbol{P} \circ d\sigma^B \right)_{\epsilon=0}$$

- These functions are universal
- Independent of scattering process and of jet observables

Real Radiation

HELAC-DIPOLES

http://helac-phegas.web.cern.ch/helac-phegas/

- Complete and publicly available automatic implementation of Catani-Seymour dipole subtraction
  - ⇨ phase space integration of subtracted real radiation and integrated dipoles in both massless and massive cases

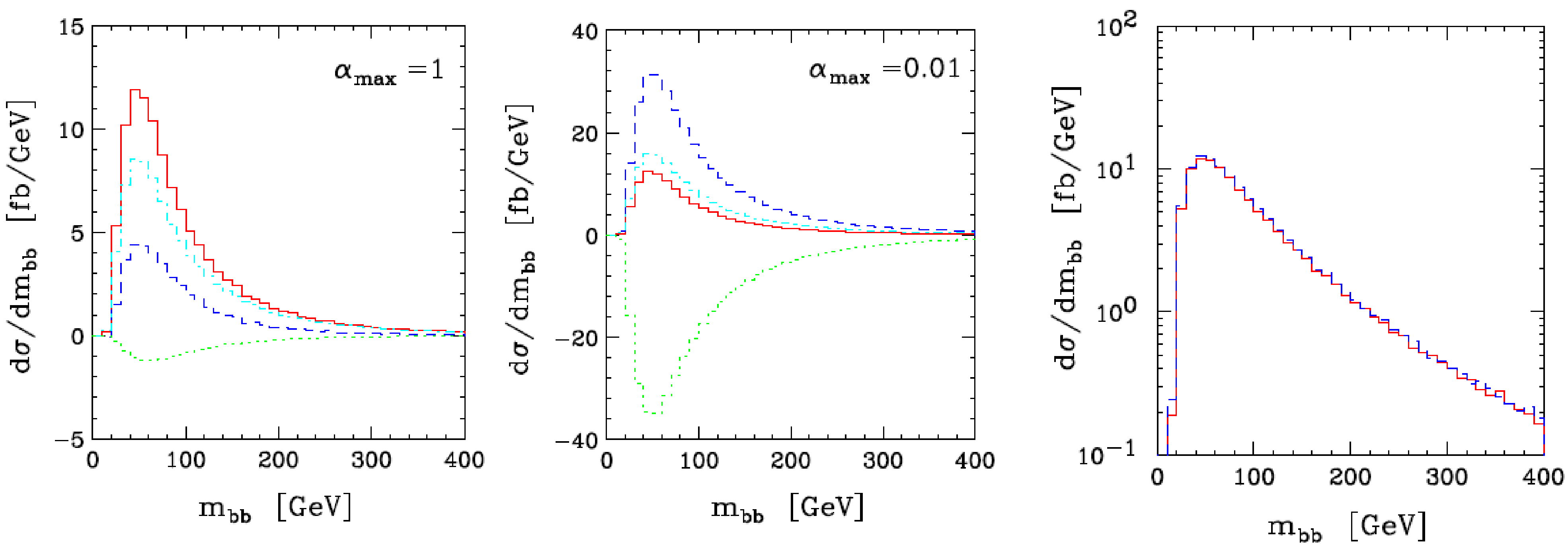
- Extended for arbitrary polarizations M. Czakon, C. G. Papadopoulos, MW, 2009
  - ⇨ Monte Carlo over polarization states of external particles implemented

- Phase space restriction on the dipole phase space implemented, $\alpha_{max} \in (0,1)$
  - ⇨ Cuts off dipole function for phase space regions away from singularity
  - ⇨ Less dipole subtraction terms needed per event
  - ⇨ Increase numerical stability by decreasing size of dipole phase space
  - ⇨ Reduce missed binning problem
  - ⇨ Large cancellations between dipole subtracted real radiation and integrated dipoles

Real Radiation

- Different parts of real radiation contribution with different choices of α_{max}
- Check of calculations, full correction is independent of this parameter

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, MW, 2009



- Red solid line ⇨ All contributions
- Blue dashed line ⇨ Dipole subtracted real emission
- Cyan dot-dashed line ⇨ Sum of K and P insertion operators
- Green dotted ⇨ I insertion operator

- Sum of all contributions for two different choices of α_{max} = 1 and 0.01

Virtual Corrections

- One-loop n particle amplitude

$$A = \sum_{I \in \{1,2,\dots,n\}} \int \frac{\mu^{4-d} d^d \bar{q}}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i \in I} \bar{D}_i(\bar{q})} \qquad \bar{D}_i(\bar{q}) = (\bar{q} + p_i)^2 - m_i^2, \quad i = 1,2,\dots,n$$

$$A = \sum_i d_i \, Box_i + \sum_i c_i \, Triangle_i + \sum_i b_i \, Bubble_i + \sum_i a_i \, Tadpole_i + R$$

- Amplitude can be expressed in basis of known integrals such 4-, 3-, 2-, 1-point scalar integrals

- In order to calculate one loop amplitude three main building blocks are needed:

  - ⇨ Evaluation of numerator function N(q) - **HELAC-1LOOP**
  - ⇨ Determination of coefficients via reduction method - **OPP, CUTTOOLS**
  - ⇨ Evaluation of scalar functions - **ONELOOP**

Virtual Corrections

- Reduction at integrand level – OPP method imptemented in **CUTTOOLS**

$$N(q) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i$$
$$+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i$$
$$+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i$$
$$+ \tilde{P}(q) \prod_{i}^{m-1} D_i \,.$$

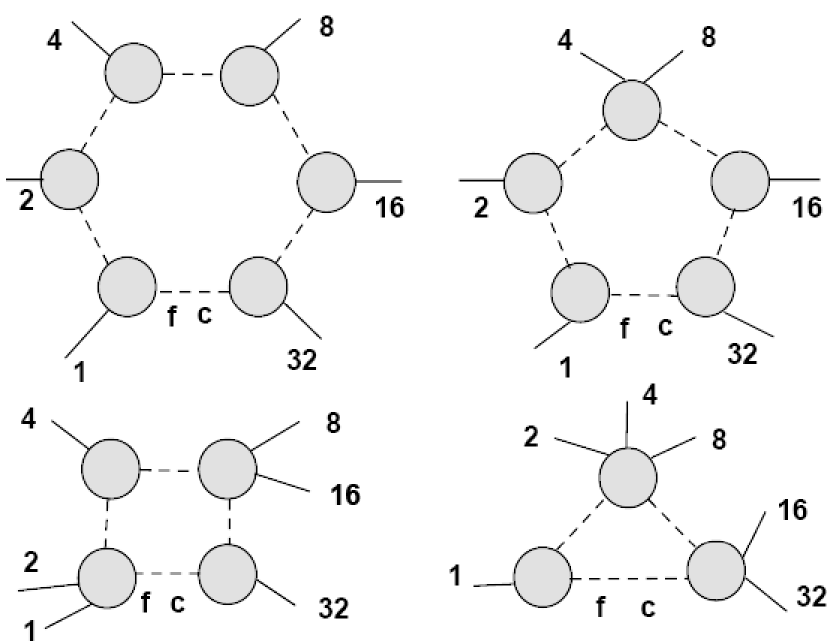
G. Ossola, C.G. Papadopoulos, R. Pittau, 2007
G. Ossola, C.G. Papadopoulos, R. Pittau, 2008

- Solved using a method closely resembling generalized unitarity - computing numerator functions for specific values of loop momenta that are solutions of equations:
- It is customary to refer to these equations as quadruple (M = 4), triple (M = 3), double (M = 2) and single (M = 1) cuts

$$D_i(q) = 0, \qquad \text{for} \quad i = 0, \ldots, M-1$$

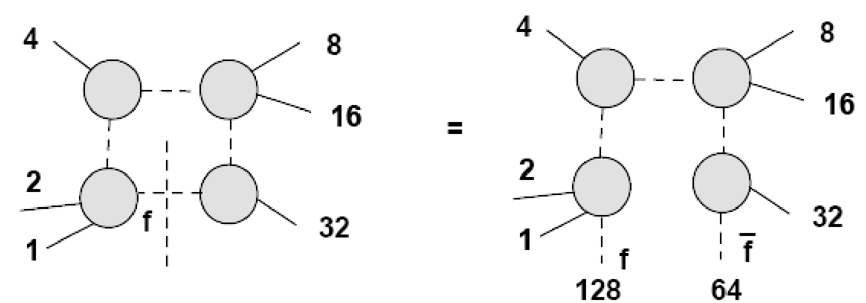
Virtual Corrections

- Calculating numerator function for specific values of loop momenta - possibility to use tree level amplitudes as building blocks
- Collecting all contributions with given loop propagator via **HELAC-1LOOP**
- Calculated as part of tree level amplitude with n+2 particles (in 4 dimensions) via **HELAC-1LOOP**



Typical collections of possible contributions

A. van Hameren, C.G. Papadopoulos, R. Pittau, 2009



Constrain: attached blobs contain no propagator depending on loop momenta, no denominator used for internal loop propagators

Virtual corrections

Procedure to calculate one-loop amplitude fully automatically

- Construction of all numerator functions using **HELAC-1LOOP**, all flavours within SM can be included either as external or internal (loop) momenta, all particles can have arbitrary masses
- Each numerator function is reduced using **CUTTOOLS**
- N(q) is calculated for particular q given by **CUTTOOLS** via **HELAC-1LOOP**
- Construction of rational terms
- Construction of all UV counter term contributions needed to renormalize amplitude

Motivation

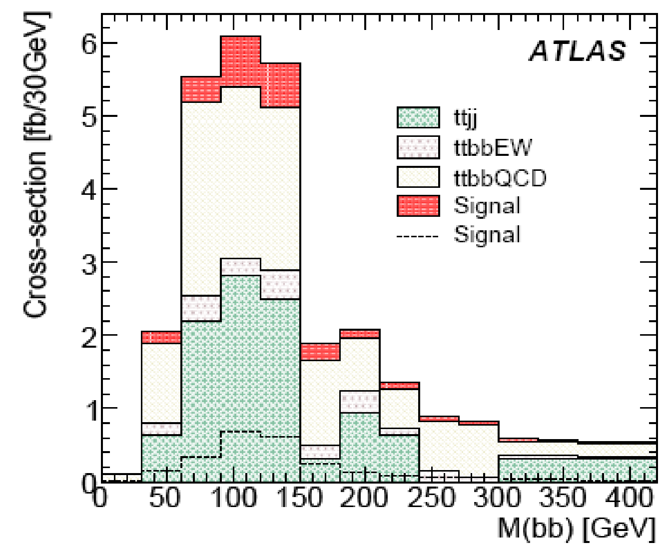
On the experimental side

- Very important background to **ttH** production where the Higgs boson decays into a bb pair

$$m_H \leqslant 135\ GeV$$

- Early studies of ttH production at ATLAS and CMS suggested discovery potential
- Analyses with more realistic backgrounds show that the signal significanceis jeopardized if the background from **ttbb** and **tt + jets** final states is not controlled very well
- **ttjj** ⇨ 'reducibe' background, b-tagging
- **ttbb** ⇨ 'irreducibe' background
- **Problem:** misassociation of b-tagged jets to the orginal partons

ATLAS TDR, CERN-OPEN-2008-020



- Reconstructed mass distribution
- All samples, contributions stacked
- Signal contribution also shown separately at the bottom.

Motivation

On the theoretical side

- Calculation of NLO corrections to 2 → 4 particle processes represents the current technical frontier
- The complexity of such calculations triggered the creation of prioritized experimenters' wishlists
- ttbb production ranges among the most wanted candidates

- NLO QCD corrections to ttH

  W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira, P.M. Zerwas, 2001
  L. Reina, S. Dawson, 2001
  S. Dawson, L.H. Orr, L. Reina, D. Wackeroth, 2003

- NLO QCD corrections to ttbb

  A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini, 2008
  A. Bredenstein, A. Denner , S. Dittmaier , S. Pozzorini, 2009

- Confirm published results
- Demonstrate the power of system based on **HELAC-PHEGAS**, **HELAC-1LOOP**, **CUTTOOLS** and **HELAC-DIPOLES** in realistic computation with 6 external legs and massive partons

First Results

- Cross sections for pp → ttbb + X at the LHC @ LO & NLO
- Scale choice $\mu_F = \mu_R = m_t$

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, MW, 2009
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, 2008
A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini, 2009

Process	$\sigma^{\rm LO}_{[23,\,24]}$ [fb]	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}_{[23,\,24]}$ [fb]	$\sigma^{\rm NLO}_{\alpha_{\max}=1}$ [fb]	$\sigma^{\rm NLO}_{\alpha_{\max}=0.01}$ [fb]
$q\bar{q} \to t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)	87.581(134)
$pp \to t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)	2636(3)

- **K = 1.77**, reduced to **K = 1.2** by introducing veto on extra jet
- For qq initial state **K = 1.03** only

Scale Dependence

- Scale dependence of the total cross sectionsat the LHC for LO and NLO and for distinct values of ξ

$\xi \cdot m_t$	$1/8 \cdot m_t$	$1/2 \cdot m_t$	$1 \cdot m_t$	$2 \cdot m_t$	$8 \cdot m_t$
$\sigma^{\rm LO}$ [fb]	8885(36)	2526(10)	1489.2(0.9)	923.4(3.8)	388.8(1.4)
$\sigma^{\rm NLO}$ [fb]	4213(65)	3498(11)	2636(3)	1933.0(3.8)	1044.7(1.7)

$$\sigma^{\rm LO}_{t\bar{t}b\bar{b}}({\rm LHC}, m_t = 176.2 \ {\rm GeV}, {\rm CTEQ6L1}) = 1489.2 \ {}^{+1036.8 \ (70\%)}_{- \ \ 565.8 \ (38\%)} \ {\rm fb}$$

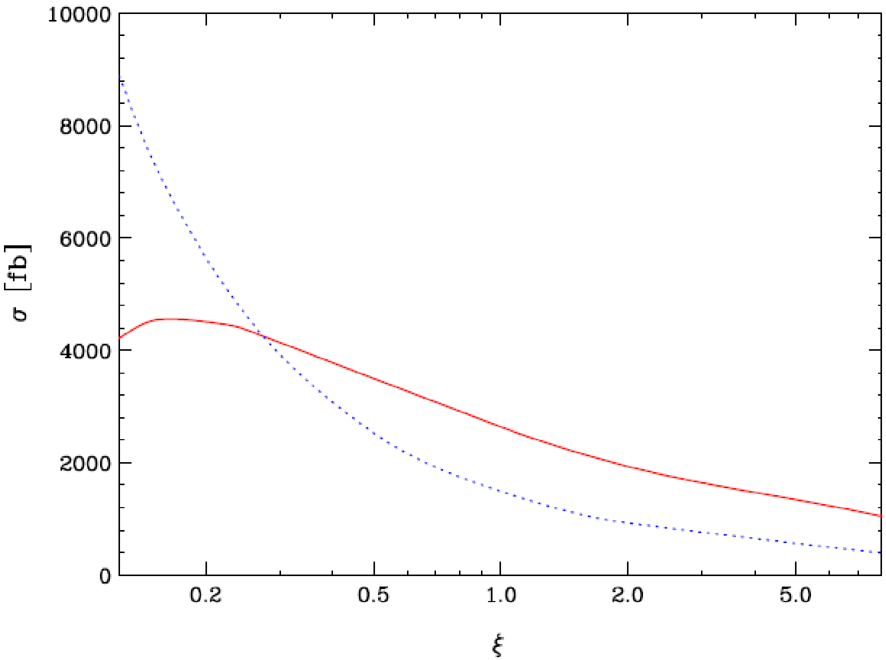
$$\sigma^{\rm NLO}_{t\bar{t}b\bar{b}}({\rm LHC}, m_t = 176.2 \ {\rm GeV}, {\rm CTEQ6M}) = 2636 \ {}^{+862 \ (33\%)}_{-703 \ (27\%)} \ {\rm fb} \ .$$

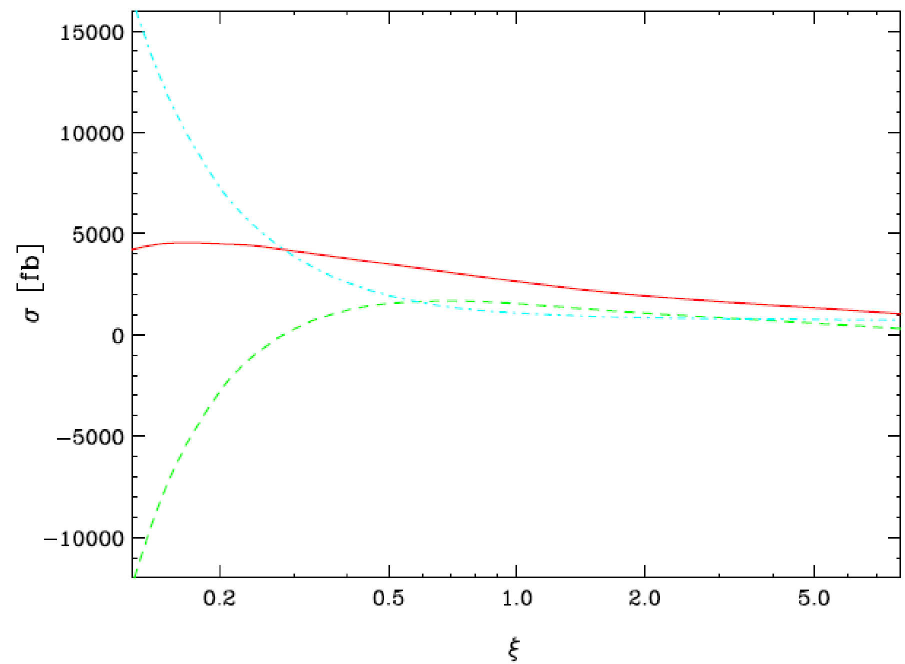
G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, MW, 2009

Scale Dependence

- Scale dependence at the LHC for $\mu_R = \mu_F = \xi \cdot m_t$ at LO & NLO

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, MW, 2009



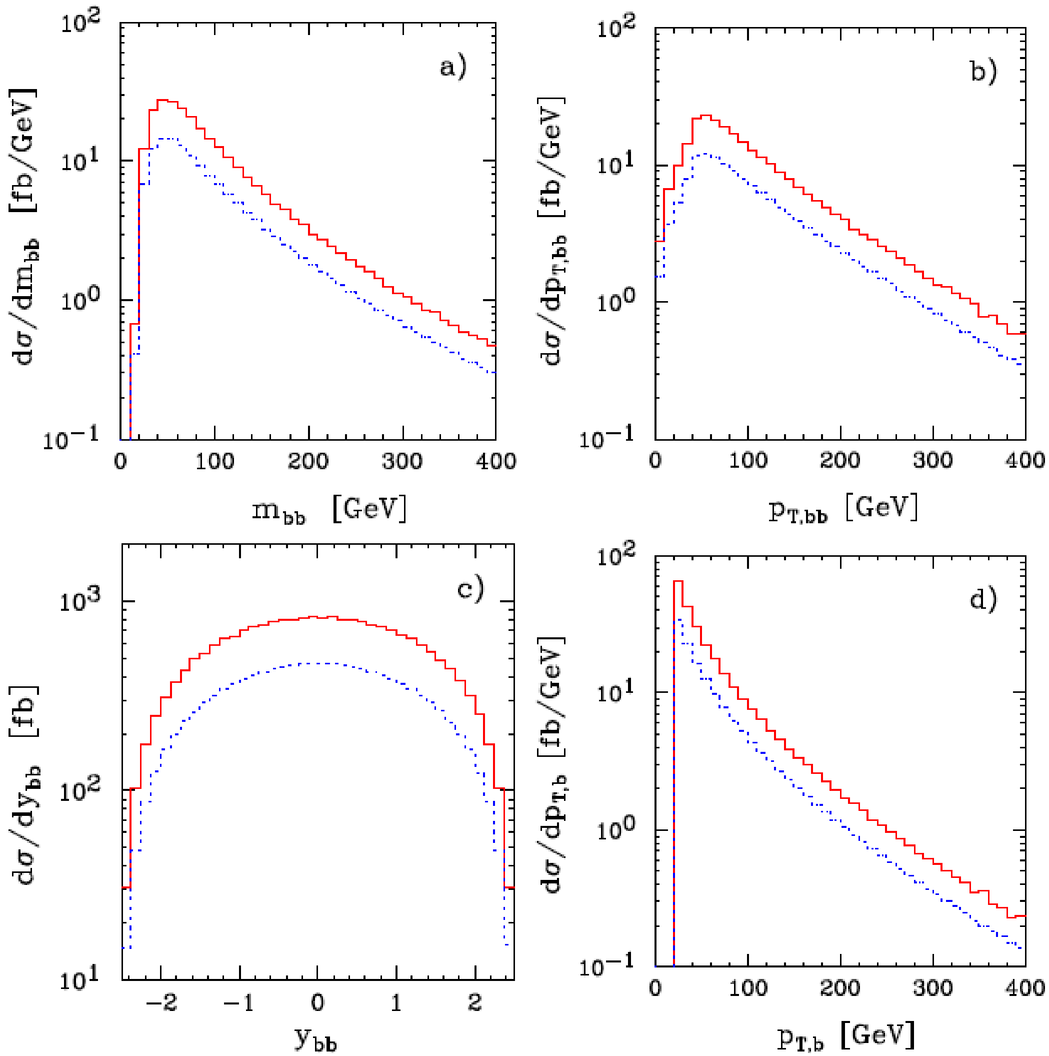


- Varying scale up or down by a factor 2 changes cross section by **70%** in LO and by **33%** in NLO

- Scale dependence at NLO decomposed into contribution of virtual corrections
  - green dased line, and real radiation
  - cyan dash-dotted line

Distributions

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, MW, 2009



- Differential cross sections at the LHC for pp → ttbb + X

- Invariant mass distribution of bb pair
- Transverse momentum of bb pair
- Rapidity distribution of bb pair
- Transverse momentum of b quark

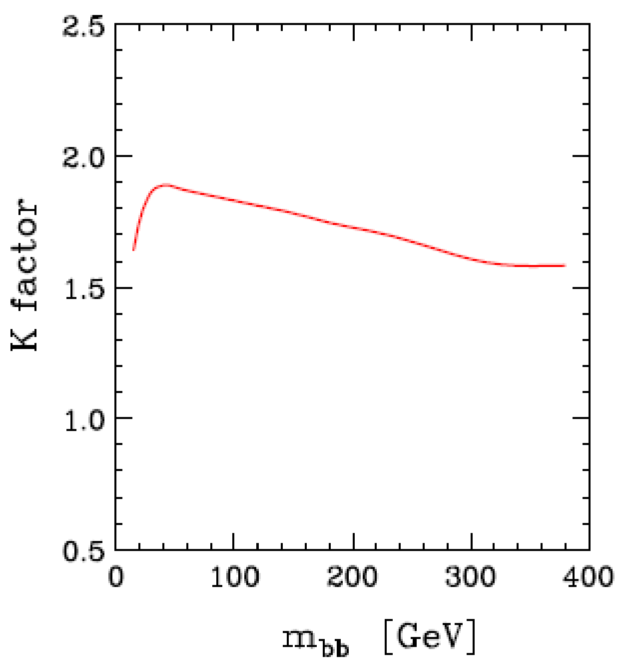
- LO → blue dashed line
- NLO → red solid line

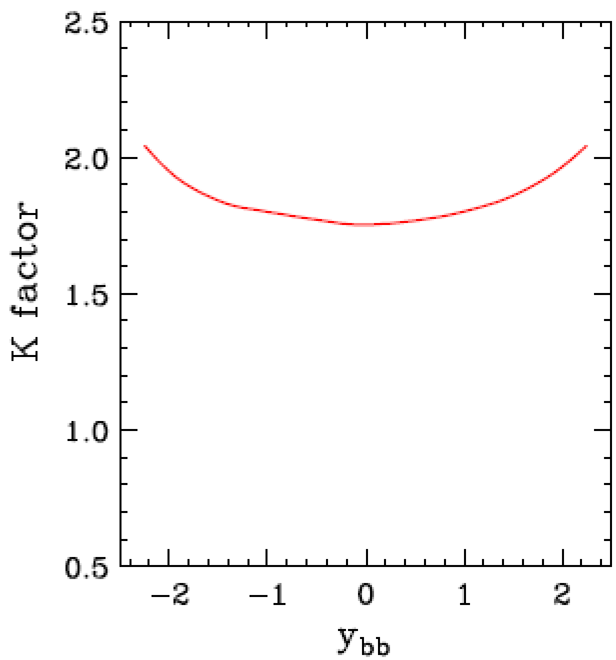
- All distributions for $\alpha_{max} = 0.01$
- Large corrections, relatively constant, contrary to case of quark initial states

Dynamical K-factor

- Ratio of NLO and LO distributions at the LHC for pp → ttbb + X
- Relatively small variation when compared with their size

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, MW, 2009





$$K(m_{b\bar{b}}) = \frac{d\sigma^{NLO}/dm_{b\bar{b}}}{d\sigma^{LO}/dm_{b\bar{b}}}$$

$$K(y_{b\bar{b}}) = \frac{d\sigma^{NLO}/dy_{b\bar{b}}}{d\sigma^{LO}/dy_{b\bar{b}}}$$

Summary & Outlook

- NLO cross sections and distributions display reduction in renormalization- and factorization-scale dependence compared to quantities calculated at LO

- Automated approach build around **HELAC**

  HELAC-PHEGAS, HELAC-1LOOP, CUTTOOLS, HELAC-DIPOLES, ONELOOP

- Four different parts have to been run separately right now: V, R-D, I & KP

- First results have already been presented

- More 2 $\to$ 4 processes in preparation

- Next big step – matching to parton shower