NLO QCD corrections to pp $\longrightarrow$ 4b

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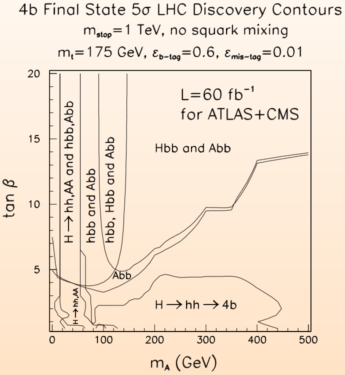
Outline

- **Motivation**
- **Details of Calculation**
- **Preliminary results**
- **Conclusions**

Motivation

- NLO QCD corrections can lead to sizeable deviations from LO result.
  $\longrightarrow$ LO result often just rough estimate.
- NLO result reduces theoretical uncertainties. (scale dependence)
- Precision measurements require precise theoretical predictions for SM contribution.
- BSM models (SUSY) naturally have multiparticle final states.
- NLO (NNLO) result desirable for important processes.

Motivation



[Dai,Gunion,Vega]

- For certain MSSM scenarios: $H \to b\bar{b}b\bar{b}$ enhanced.
- maybe the only discovery channel
- also important for other BSM scenarios
- important to know SM background
- added to Les Houches wish list

Calculation

$$\underline{pp \to 4b \ + X}$$

$$LO: \quad \left.\begin{array}{l} q\,\bar{q} \to 4b \\ g\,g \to 4b \end{array}\right\} \text{Virtual corrections.}$$

$$NLO: \quad \left.\begin{array}{l} q\,\bar{q} \to 4b \ + g \\ g\,g \to 4b \ + g \\ q\,g \to 4b \ + q \end{array}\right\} \text{Real emission.}$$

Simplifications:

- b-quark massless
- neglect b-quark in initial state ($q \neq b$)
  Motivated by LHC kinematics and applied cuts.

$$pp \longrightarrow 4b + X$$

$$\sigma_{NLO} = \int_{n+1} \left(d\sigma^R - d\sigma^A \right) + \int_n \left(d\sigma^B + d\sigma^V + \int_1 d\sigma^A \right)$$

2 independent calculations, both free of divergencies.

Virtual corr.: **GOLEM/SAMURAI** [Binoth et. al,Mastrolia,Ossola,Reiter,Tramontano]
Real emission + Born: **MadGraph** [Long,Stelzer], **Whizard** [Kilian,Ohl,Reuter]$(q\bar{q})$
Subtraction terms: **MadDipole** [Frederix,Gehrmann,NG], **Whizard** $(q\bar{q})$
Integration: **MadEvent** [Maltoni,Stelzer]

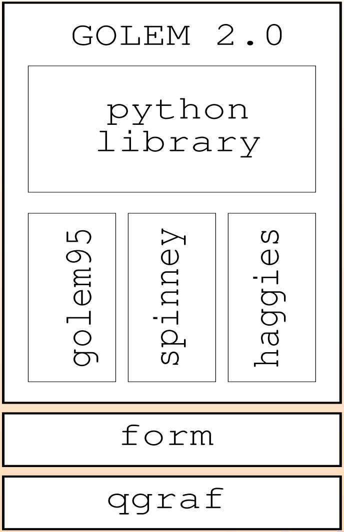
- All ingredients framework independent and stand alone applications.

Virtual corrections

General One Loop Evaluator for Matrix Elements

- Based on Qgraf and Form
- Library for one-loop integrals (golem95)
- Matrix element generator for one-loop amplitudes
- Output: Fortran file for virtual amplitude

→ Giovanni Ossola's talk for details



Scattering AMplitudes from Unitary-based Reduction Algorithm at the Integrand-level

[Mastrolia,Ossola,Reiter,Tramontano]

Idea: Merging GOLEM and SAMURAI to a new package to calculate virtuals for $q\bar{q},\ gg \to b\bar{b}b\bar{b}$.

Principle: Performing reduction on integrand level using OPP-method [Ossola,Papadopoulos,Pittau] in automated way.

Results:

- Increase of speed per point
- Reduction of size of code by factor ~ 10

compared to GOLEM only.

Subtraction terms

MadDipole : Package that automatically generates subtraction terms ($d\sigma^A$) and integrated subtraction terms ($\int_1 d\sigma^A$) in form of Catani-Seymour dipoles. (Color and helicity summed)

User: specify the NLO process
MadDipole: returns Fortran code for all necessary terms.

- unintegrated subtr. terms
- integrated terms: finite terms + coeff. of pole terms
- provides consistent calls of pdfs and cuts.
- includes initial state collinear singularities.

MadDipole now also for QED:

- similar structure to QCD + new features.

Checks

Born:

- Double checked with MadGraph, Golem and Whizard ($q\bar{q}$).

Subtraction terms:

- $q\bar{q}$: Second implementation in Whizard.
- Package checked against MCFM [Campbell,Ellis], unintegrated terms against HELAC [Bevilacqua,Czakon,Garzelli,v.Hameren,Malamos,Papadopoulos,Pittau,Worek]
- Varying the cut-parameter α of subtraction terms provides powerful checks on many levels.
- Subtraction terms are only needed near singularity $\longrightarrow$ Cut away parts of phase space where there is no sing.

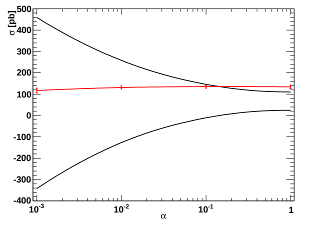
Checks

- Introduce parameter α: $\mathcal{D}_{ij} \to \mathcal{D}_{ij}\theta(\alpha > s_{ij})$ [Nagy,Trocsanyi]

Integrated subtraction terms also depend on α, total result however independent:

$$\int_{n+1} \left(d\sigma^R - d\sigma^A\right) + \int_n \text{(finite parts of int. dip.)} = \text{const}$$

$pp \longrightarrow 4b$



Checks

Virtuals:

- $q\bar{q}$: Independent code based on FeynArts.
- gg: Inclusion of top-loop contribution allowed to compare a single point with existing results [v.Hameren,Papadopoulos,Pittau] (also for $q\bar{q}$).

  $\Rightarrow$Found full agreement!
- Top-loops neglected in the following.

Phase space integration:

- Sanity checks of correct interplay virtual $\leftrightarrow$ reals by comparing Born and coefficients of $1/\epsilon$- and $1/\epsilon^2$-terms.
- Checks on integration level against HELAC. (Born, int. subtr. terms, reals)

Phase space integration

Real emission:

- Cut parameter set to $\alpha = 10^{-2}$.
  $\rightarrow$ Leads to increase of speed and stability of integration.
- CPU-time: $\mathcal{O}(20ms)$ per point.
- 10^9 points used for distributions.

Virtual corrections:

- CPU-time: $\sim$ 18s per point $\Rightarrow$ too slow for normal PS integration $\rightarrow$ Use reweighting method.

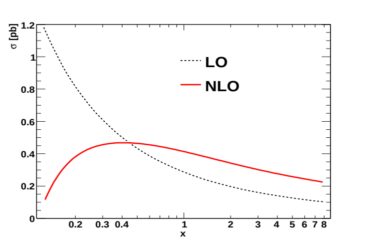
Reweighting:

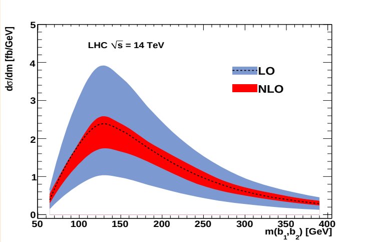
1. Create sample of N unweighted events for tree-level with weight $\frac{\sigma_0}{N}$.
2. Reweight with virtual contribution.
3. Equivalent to importance sampling (k-factor of order unity).

Imposed cuts:

- K_T-algorithm with $R = 0.8$.
- $P_T \geq 30$ GeV, $|\eta| \leq 2.5$ $\Delta R > 0.8$.

$$\mathbf{q\bar{q}} : \begin{cases} \text{Renormalization scale:} \quad \mu_R = x \cdot \mu_0, \quad \mu_0 = \sqrt{\sum_i P_{T,i}^2} \\ \text{Factorization scale:} \quad \mu_F = 100 GeV. \end{cases}$$





$\mu_0/4 \leq \mu_R \leq 2\mu_0$

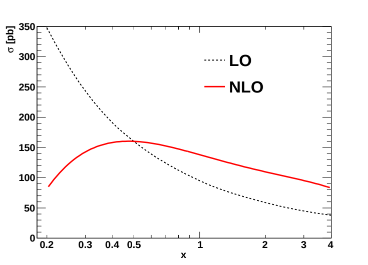
Preliminary results

- Scale choice for $pp \to 4b$:

$$\mu_0 = \frac{1}{4}\sqrt{\sum_i P_{T,i}^2} \approx \frac{1}{4}\sum_i P_{T,i} = \text{ average jet-}P_T$$

Scale choice motivated by results obtained from calculations of jet production at NLO. [Nagy],[Ellis,Saxton]

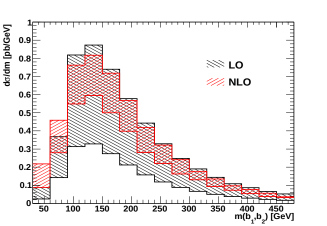
$$\mu_r = \mu_f = X \cdot \mu_0$$



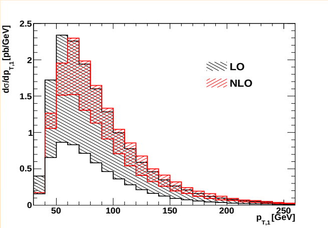
Preliminary results

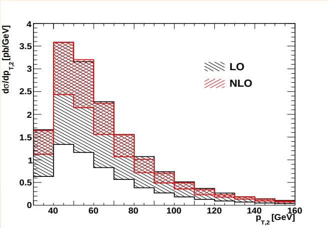
Invariant mass distribution:

$$\mu_0/2 \leq \mu_r = \mu_F \leq 2 \cdot \mu_0$$



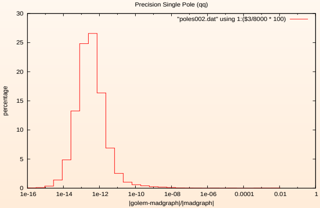
P_T-distribution

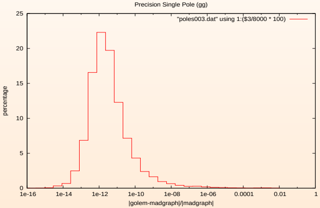




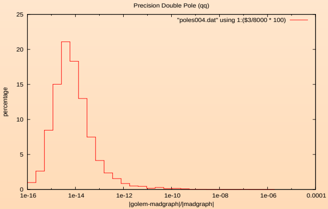
Numerical cancellation of singularities

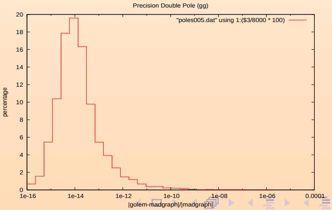
Single Poles:



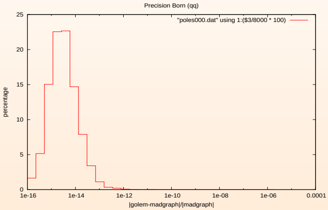


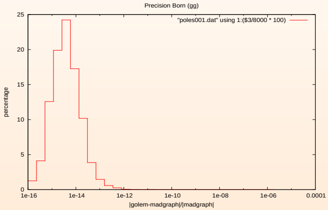
Double Poles:



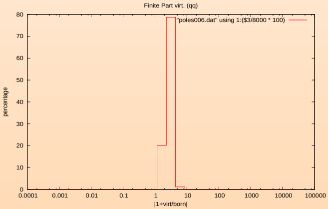


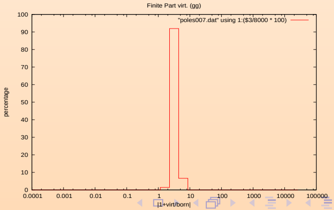
Comparison MadGraph vs Golem/Samurai





'k-factor'





Summary and Outlook

- NLO QCD correction necessary for multi-leg final states at LHC
- Production of 4 b quarks important signal for MSSM/Higgs
- Various checks to ensure correctness
- Ready to exploit phenomenology:
  - various distributions
  - differential k-factors
  - results for 7 TeV
  - inclusion of top-loop contributions
  - inclusion of pdf error
  - ....