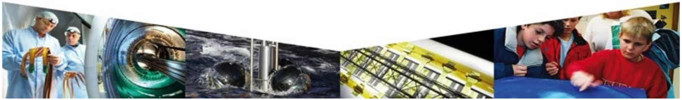


With Automation towards the Four b-Jet Rate at NLO in QCD

5th Vienna Central European Seminar on Particle Physics and QFT, 28–30/11/2008

Overview

Motivation

The `GOLEM` Approach

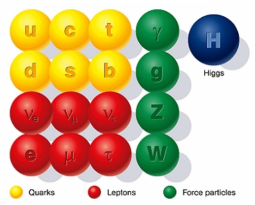
Summary

Results for $q\bar{q} \rightarrow b\bar{b}b\bar{b} + X$

Conclusion

The Missing Link in the Standard Model (SM)

- SM requires symmetry breaking for mass generation ⇒ Higgs boson
- SM Higgs will be found at LHC
- SM does not explain everything
  - Dark matter
  - Unification of forces
  - Hierarchy of masses and mixing angles
  - Gravity
  - ...
- Need to look at extensions
- Promising candidate: Supersymmetry
  - Testable at LHC (if $\approx 1\,\text{TeV}$)
  - Solves some (most?) problems



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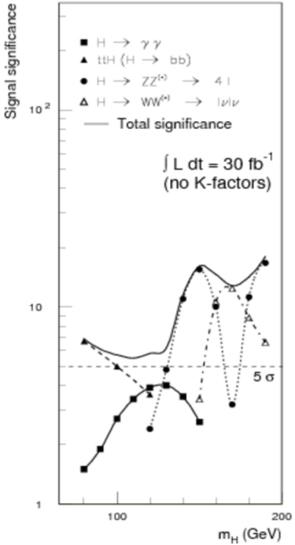

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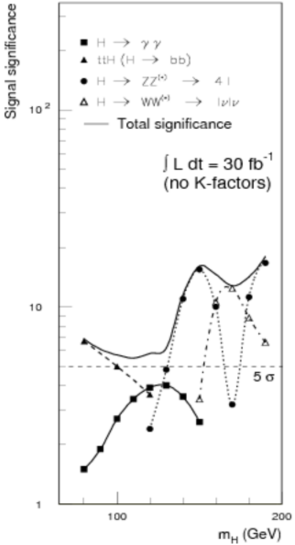

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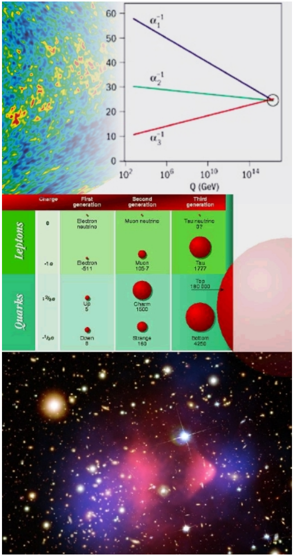

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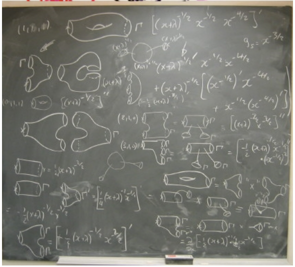

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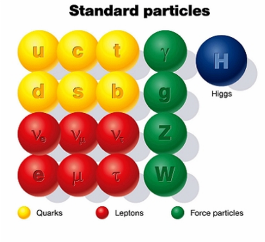

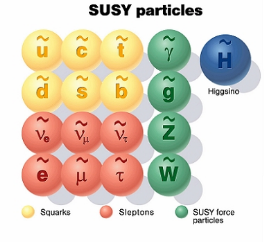

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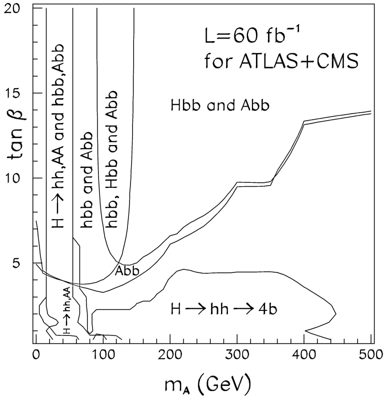
If the MSSM is realized in nature: Higgs sector $(h^0, H^0, H^\pm, A)$



[Dai, Gunion, Vega]

- no a priori knowledge of MSSM parameters $(m_A, \tan\beta)$
- still want to find a Higgs boson
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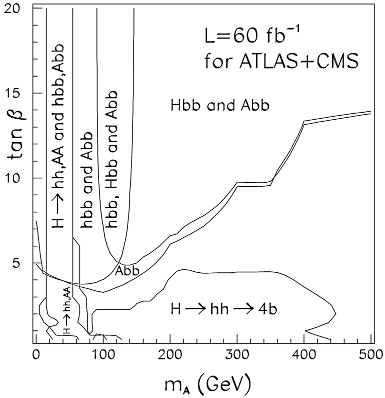

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- "Traditional" approach:
  - use LO + parton shower for the shape and
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- not always enough:
  - In QCD: large renomalisation scale dependency at LO
  - LO and NLO may differ in shape $\Rightarrow$ no global K-factor
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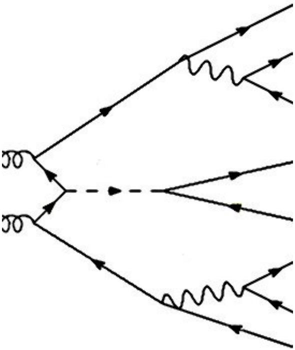

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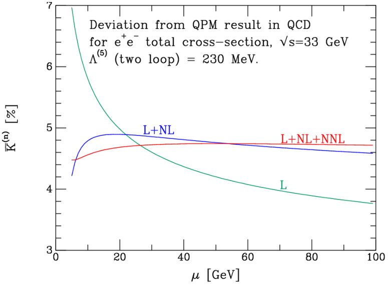

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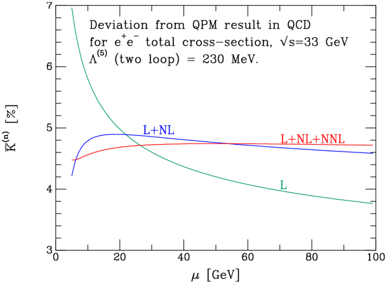
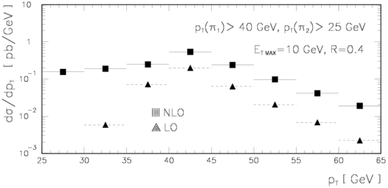


[Binoth, Guillet, Pilon, Werlen]



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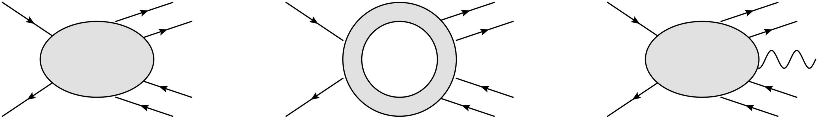
After after first LHC data: more to come

GOLEM:

General One Loop Evaluator for Matrix Elements



	LO	NLO
Method	standard tool	hand crafted code
Time scale	hours – days	months – years

The (main) problems with NLO calculations:

- bottle neck: loop diagrams
- complexity: #diagrams × #terms per diagram
- tensor integrals, cancellations ↔ numerical (in-)stability
- computational challenge: memory and run time

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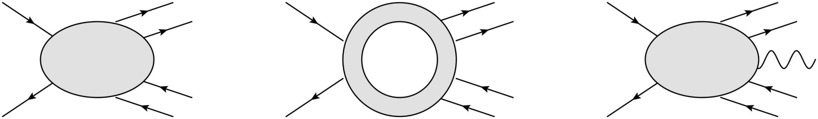

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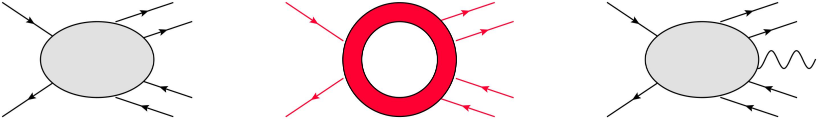

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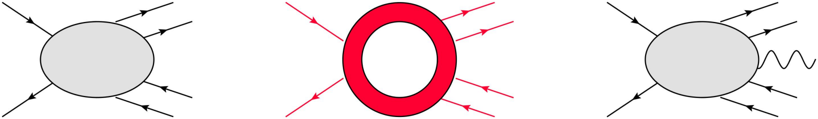

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The GOLEM and the Tensor Integrals

Problem: solve $\int \frac{\mathrm{d}^n k}{i\pi^{n/2}} \frac{q_{a_1}^{\mu_1} \cdots q_{a_r}^{\mu_r}}{\prod_{j=1}^{N}(q_j^2 - m_j^2 + i\delta)}, \quad q_a^\mu = k^\mu + r_a^\mu$

- tensor reduction separates tensor structure from integrals
- usually: expression in terms of scalar integrals $I_N^n()$
  $\Rightarrow$ (Gram determinants)$^{-1}$
- in GOLEM: allow for certain numerators $I_N^n(l_1, \ldots, l_p)$
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Implementation: golem95 — publicly available [arXiv:0810.0992]

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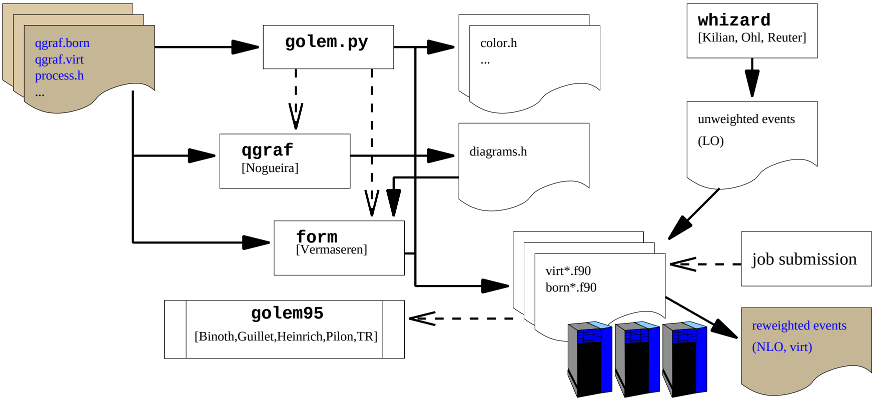

Phase Space Integration of One-Loop Amplitudes

- at LO: adaptive MC integration over phase space
- at NLO: adaption can become unstable in presence of integrable singularities.
- alternative: adapt to LO matrix element but integrate one-loop amplitude
- in practice: reweighting of unweighted LO events:

$$\langle O\rangle_{\text{one-loop}} = \frac{\sigma_{\text{LO}}}{|U|}\sum_{e\in U} O(e)\frac{\mathrm{d}\sigma_{\text{one-loop}}(e)}{\mathrm{d}\sigma_{\text{LO}}(e)}$$

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- GOLEM is
  - an algorithm for the reduction of tensor integrals plus its implementation (golem95)
  - an algorithm for the automatic algebraic simplification and numerical evaluation of one-loop matrix elements plus its implementation (under development)
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  - building a reliable, general tool (based on existing frameworks)
  - extending golem95 to massive propagators
  - doing phenomenology, e.g. $pp \longrightarrow b\bar{b}b\bar{b}$

    [Binoth, Guffanti, TR, Reuter]
- GOLEM in the past:
  - $pp \longrightarrow VV +$ jet [Karg, Sanguinetti] also [Dittmaier et al.; Campbell et al.]
  - $\gamma\gamma\gamma\gamma\gamma\gamma \longrightarrow 0$ [Binoth, Heinrich, Gehrmann, Mastrolia]; [Bernicot, Guillet]
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$q\bar{q} \to b\bar{b}b\bar{b} + X$: Setup

- software setup as described before
- check through second, independent implementation (FeynArts, Form, Maple — no code in common)
- improved IR Dipole subtraction [Catani, Seymour, Nagy]
- here: only $\mathrm{d}\sigma_{\text{virtual}} + \mathrm{d}\sigma_{\text{LO}} + \langle I(\varepsilon, \alpha) \rangle$ (full result soon)
- cuts and parameters
  - $m_b = 0$
  - $p_T > 25$ GeV, $|\eta| < 2.5$, $\Delta R > 0.4$
  - $\mu_R = \mu_F = \sum_{i=1}^{4} p_T^{(i)}/4$
  - pdfs CTEQ6.5
  - Nagy's $\alpha = 0.1$ (for the shown results)
- performance on ECDF cluster
  - one phase-space point per node (Xeon5450 quad-core 3 GHz)
  - 8.9 s in double precision
  - 17.6 s in quadruple precision

$q\bar{q} \to b\bar{b}b\bar{b} + X$: Setup

- software setup as described before
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- here: only $\mathrm{d}\sigma_{\text{virtual}} + \mathrm{d}\sigma_{\text{LO}} + \langle I(\varepsilon, \alpha)\rangle$ (full result soon)
- cuts and parameters
  - $m_b = 0$
  - $p_T > 25$ GeV, $|\eta| < 2.5$, $\Delta R > 0.4$
  - $\mu_R = \mu_F = \sum_{i=1}^{4} p_T^{(i)}/4$
  - pdfs CTEQ6.5
  - Nagy's $\alpha = 0.1$ (for the shown results)
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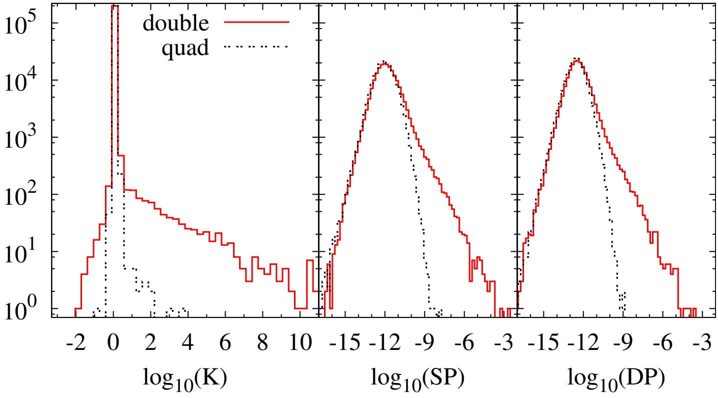
$q\bar{q} \to b\bar{b}b\bar{b} + X$: Quality Management (QM)

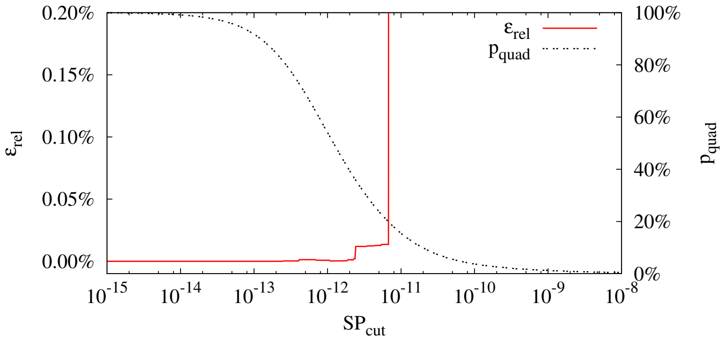
200,000 random phase space points



- Need to look at integrated results

$q\bar{q} \to b\bar{b}b\bar{b} + X$: Finding Good QM Criteria

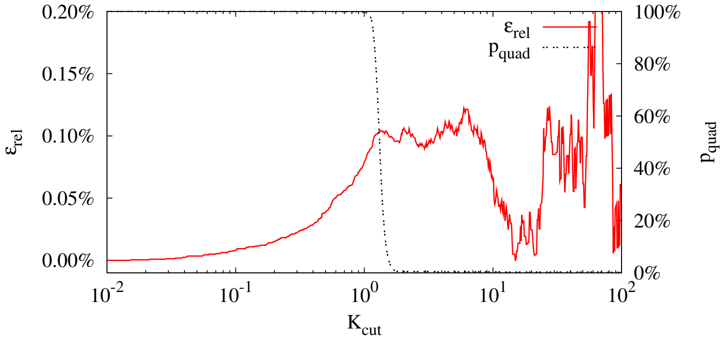
Switch to quadruple precision if single pole $> \mathrm{SP_{cut}}$:
$\varepsilon_{\mathrm{rel}} = |\sigma(\mathrm{SP_{cut}}) - \sigma(0)|/\sigma(0)$.



- precision goal $\varepsilon_{\mathrm{rel}} \leq 0.1\%$
  $\Rightarrow$ requires 20% of evaluations in quadruple precision
- nearly identical plot for double pole

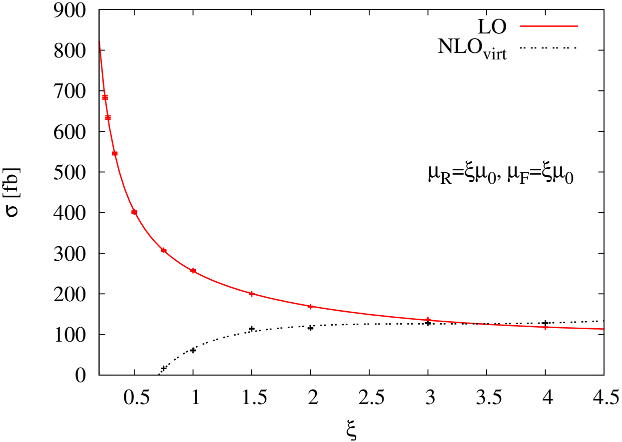
$q\bar{q} \to b\bar{b}b\bar{b} + X$: Finding Good QM Criteria

Switch to quadruple precision if $\mathrm{d}\sigma_{\text{1-loop}}/\mathrm{d}\sigma_{\text{LO}} > \mathrm{K}_{\text{cut}}$:



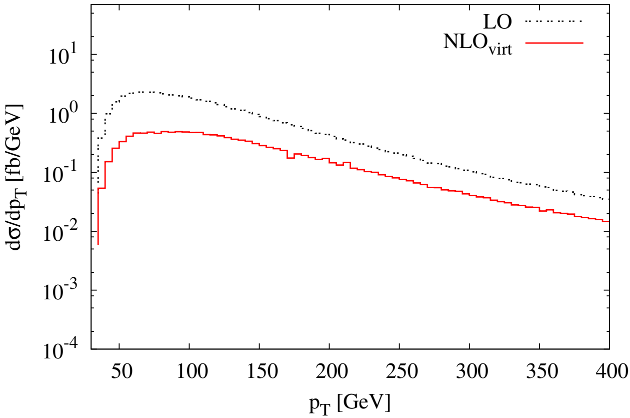
- precision goal $\varepsilon_{\text{rel}} \leq 0.1\%$
  $\Rightarrow$ requires 0.5% of evaluations in quadruple precision
- better efficiency than by looking at the pole part

$q\bar{q} \to b\bar{b}b\bar{b} + X$: Scale Variation (virtual part)



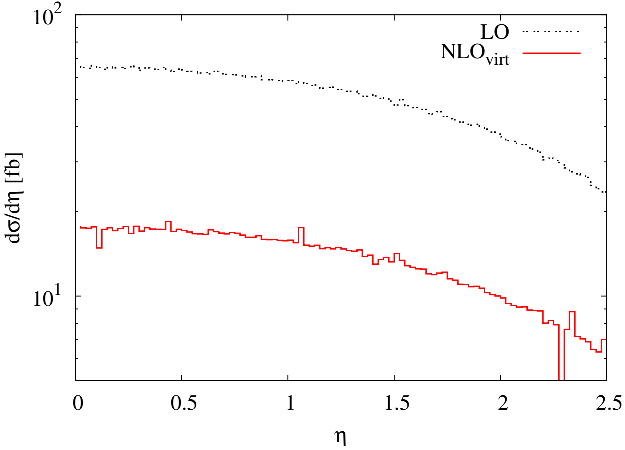
- simultaneous parallel variation of μ_R and μ_F
- $\text{NLO}_{\text{virt}} = \sigma_{\text{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$

$q\bar{q} \to b\bar{b}b\bar{b} + X$: p_T Distributions (virtual part)



- p_T of the hardest jet
- $\text{NLO}_{\text{virt}} = \sigma_{\text{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$

$q\bar{q} \to b\bar{b}b\bar{b} + X$: Rapidity Distributions (virtual part)



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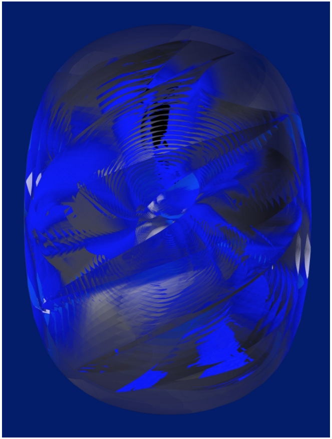
- $\text{NLO}_{\text{virt}} = \sigma_{\text{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$

Summary II

- Reliable precision (≥NLO) predictions needed to interpret LHC results, for SM and beyond
- Only feasable if NLO calculations can be done at shorter time scales
- GOLEM project important step towards fully automated NLO tool
- $pp \to b\bar{b}b\bar{b}$ important irreducible background for BSM signatures
- one of many examples that GOLEM approach works



[Jan-Henrik Andersen]

http://lappweb.in2p3.fr/lapth/Golem/golem95.html

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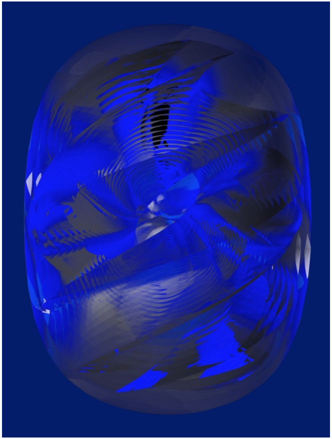

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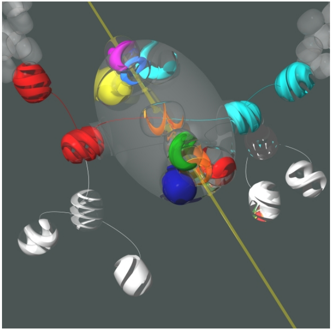
Outlook



[Jan-Henrik Andersen]

Some work remains to be done:

- extend GOLEM for massive integrals
- better user interface
  preferrably linked into existing
  frameworks
- finish $pp \longrightarrow b\bar{b}b\bar{b}$ program
  - real corrections + dipoles
  - gluon induced subprocess
- apply GOLEM technology to other interesting $2 \longrightarrow 4$ processes
- explore how far we can get beyond 4 final state particles

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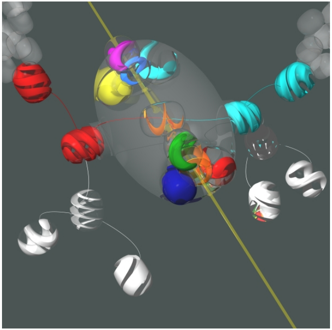

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Backup Slides

Amplitude Organisation

Integral Reduction

More Results

Amplitude Organisation

$$\sigma = \int_n \mathrm{d}\sigma^{\mathrm{LO}}$$

The full NLO amplitude calculation consits of

- LO (tree level) diagrams
- virtual corrections (loop diagrams)
- real corrections ($(n+1)$-particle tree diagrams)
- subtraction terms (for explicit cancellation of IR poles)

Amplitude Organisation

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Amplitude Organisation

$$\mathcal{M}_{c_1\ldots c_n}(p_1,\ldots,p_n) = \sum_{\lambda} \mathcal{A}_{c_1\ldots c_n}(p_1^{\lambda_1},\ldots,p_n^{\lambda_n})$$

- gauge invariant helicity subamplitudes: independent, no cancellations expected
- color subamplitudes: minimal basis by choosing irreducible representation
- subamplitudes are sums of diagrams

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$$\mathcal{M}_{c_1\ldots c_n}(p_1,\ldots,p_n)=\sum_{\lambda}\sum_{c}C^{c}_{c_1\ldots c_n}\mathcal{A}^{c}(p_1^{\lambda_1},\ldots,p_n^{\lambda_n})$$

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- color subamplitudes: minimal basis by choosing irreducible representation
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Integral Reduction

- One-loop diagrams lead to integrals like

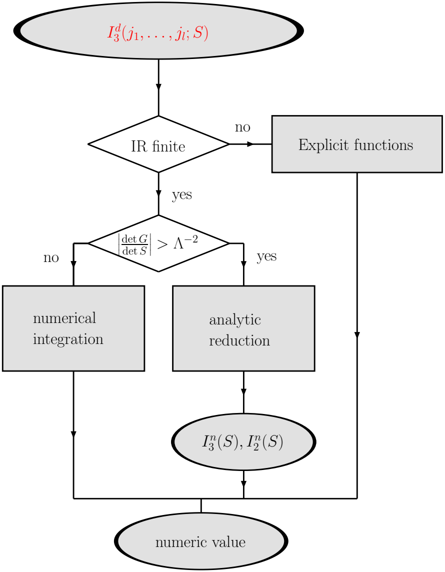
$$I_N^{d;\mu_1\ldots\mu_r}(a_1,\ldots a_r;S) \equiv \int \frac{\mathrm{d}^d k}{i\pi^{d/2}} \frac{q_{a_1}^{\mu_1}\cdots q_{a_r}^{\mu_r}}{\prod_{j=1}^{N}(q_j^2 - m_j^2 + i\delta)},$$

$q_i = k + p_i - p_{i-1}$.

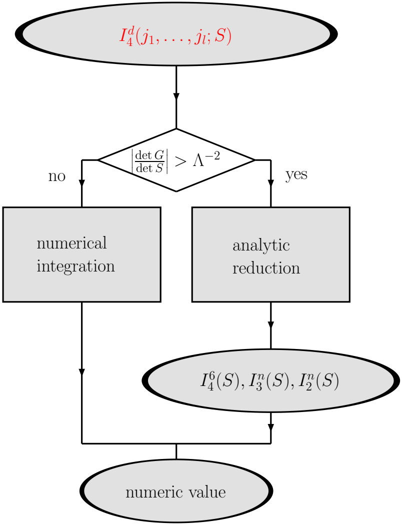
- tensor integrals have to undergo tensor reduction.
- form factors can be written in terms of Feynman-parameter integrals.
- relations between Feynman-parameter integrals lead to redution formalism for integrals.
- Tensor Reduction by Subtraction

[Binoth, Guillet, Heinrich, Pilon, Schubert: JHEP 0510:015,2005]

Integral Reduction: Three-Point Functions

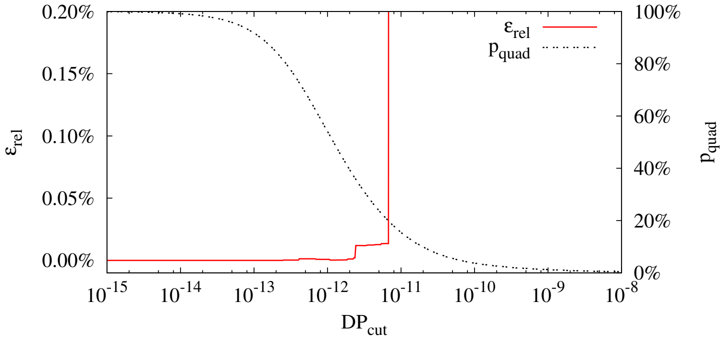


Integral Reduction: Four-Point Functions



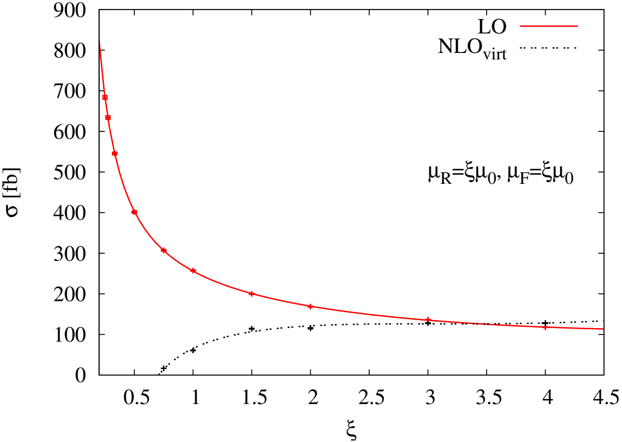
$q\bar{q} \to b\bar{b}b\bar{b} + X$: Finding Good QM Criteria

Switch to quadruple precision if single pole > DP_{cut}:



- each point evaluated at either double or quad precision
- error defined over the integral of 200,000 phase space points

$q\bar{q} \to b\bar{b}b\bar{b} + X$: Scale Variation (virtual part)



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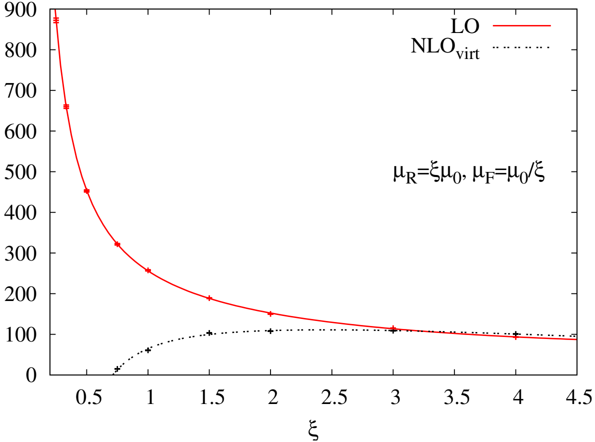

- simultaneous anti-parallel variation of μ_R and μ_F
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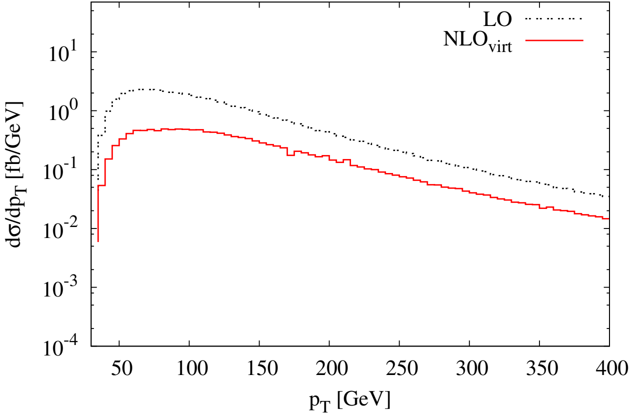
$q\bar{q} \to b\bar{b}b\bar{b} + X$: p_T Distributions (virtual part)



- p_T of the hardest jet
- $\mathrm{NLO}_{\mathrm{virt}} = \sigma_{\mathrm{LO}} + \sigma_{\mathrm{one\text{-}loop}} + I(\varepsilon, \alpha)$

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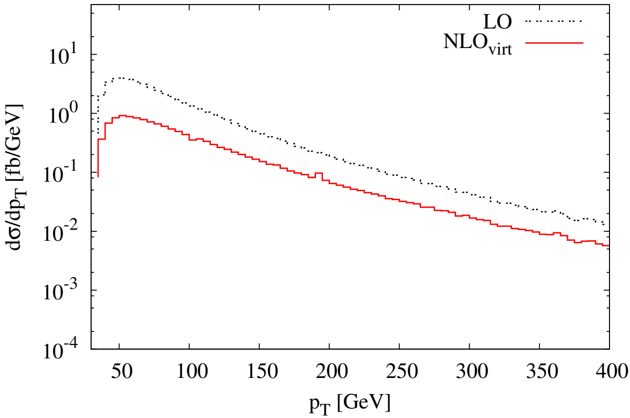

- p_T of the second hardest jet
- $\text{NLO}_{\text{virt}} = \sigma_{\text{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$

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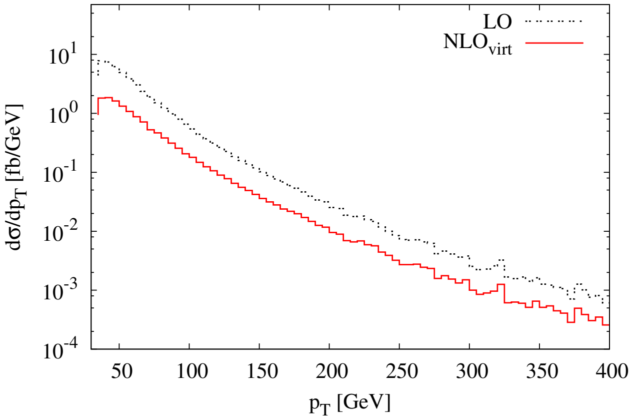

- p_T of the third hardest jet
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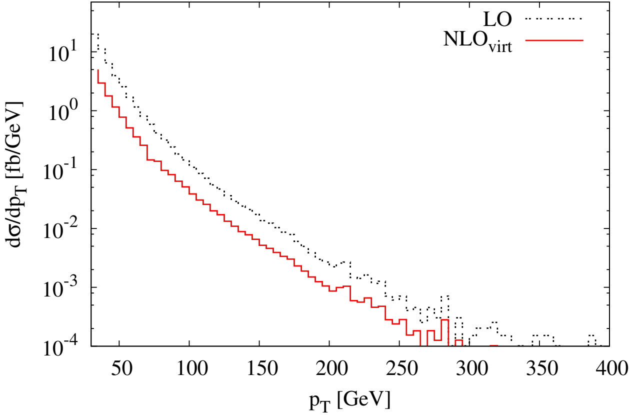
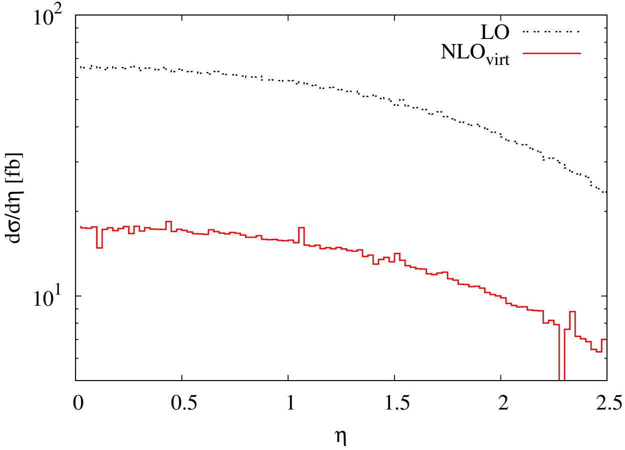


- p_T of the softest jet
- $\text{NLO}_{\text{virt}} = \sigma_{\text{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$

$q\bar{q} \to b\bar{b}b\bar{b} + X$: Rapidity Distributions (virtual part)



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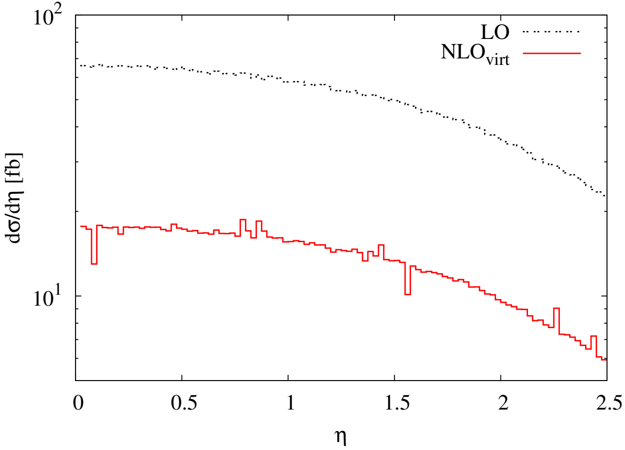

- rapidity of the second hardest jet
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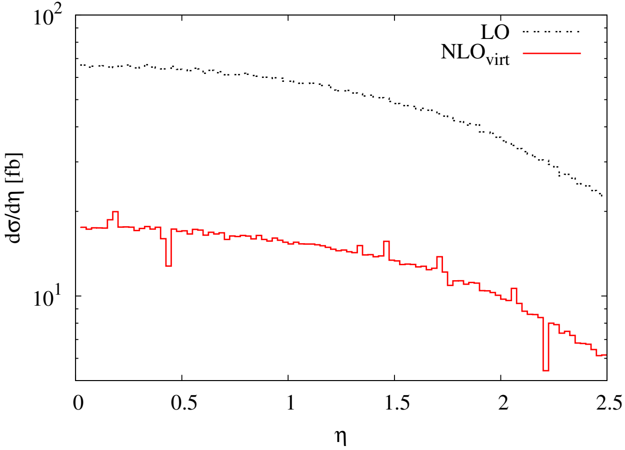

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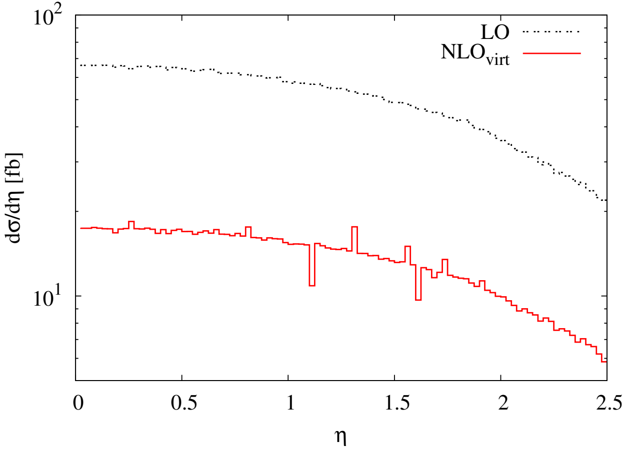
$q\bar{q} \to b\bar{b}b\bar{b} + X$: Rapidity Distributions (virtual part)



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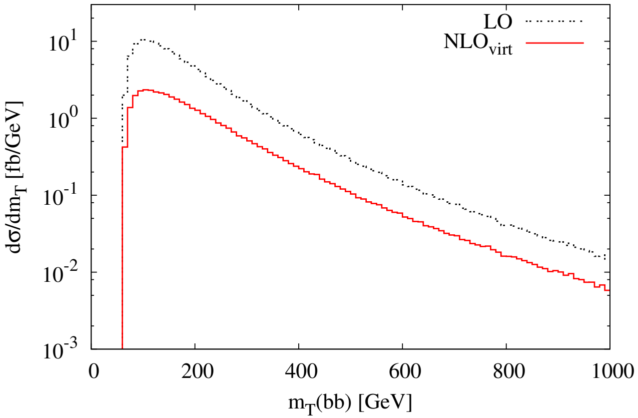
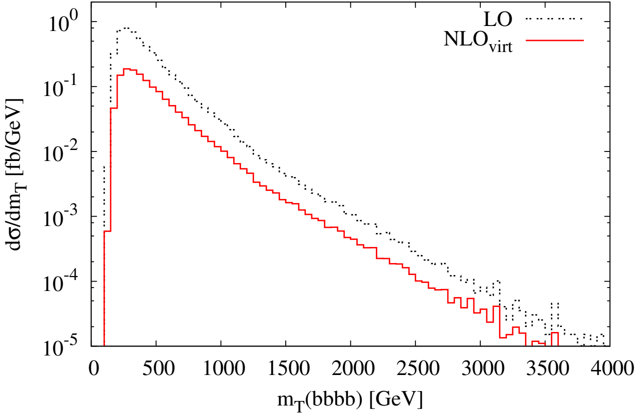
$q\bar{q} \to b\bar{b}b\bar{b} + X$: Transverse Mass (virtual part)



- Sum of m_T of all b-quark pairings
- $\mathrm{NLO_{virt}} = \sigma_{\mathrm{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$

$q\bar{q} \rightarrow b\bar{b}b\bar{b} + X$: Transverse Mass (virtual part)



- Sum of m_T of the four-b system
- $\text{NLO}_{\text{virt}} = \sigma_{\text{LO}} + \sigma_{\text{one-loop}} + I(\varepsilon, \alpha)$