Automated NLO calculations for top quark observables at hadron colliders

Johannes Schlenk

Max Planck Institute for Physics

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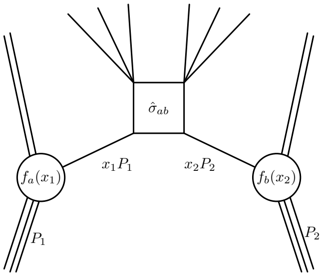
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Overview

1. QCD processes at hadron colliders
2. Calculation of virtual corrections
3. GoSam and Sherpa
4. The process $pp \to W^+W^-b\bar{b}$ at NLO
5. The observable m_{lb}
6. Top quark asymmetries

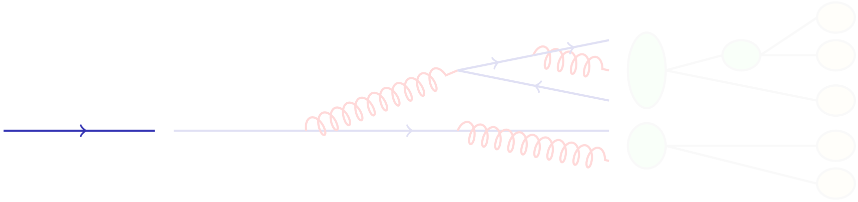
QCD processes at hadron colliders



- Scattering of hadrons which are bound states of quarks and gluons
- Factorization of short and long distance physics
- Parton distribution functions $f_a(x)$ (universal) have to be measured
- Partonic cross section $\hat{\sigma}_{ab}$ can be calculated perturbatively

$$d\sigma(P_1, P_2) = \sum_{a,b} \int dx_1\, dx_2\, f_a(x_1)\, f_b(x_2)\, d\hat{\sigma}_{ab}(x_1 P_1, x_2 P_2)$$

Parton shower and hadronization (final state evolution)



Parton level
Final state contains only particles generated by the hard scattering

Shower level
Additional gluons and quark pairs due to soft and collinear emissions

Hadron level
Coloured particles in the final state are clustered into hadrons which subsequently decay to stable particles

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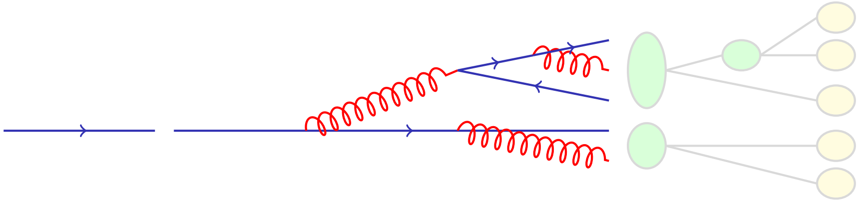

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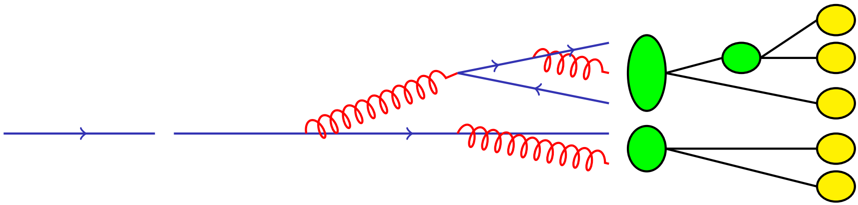

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The partonic cross section

Perturbative expansion in α_S

$$d\hat{\sigma}_{ab} = \alpha_S^k(\mu) \sum_{m=0}^{\infty} d\hat{\sigma}_{ab}^{(m)}(\mu)\, \alpha_S^m(\mu)$$

NLO cross section

$$\sigma^{NLO} = \int_N d\sigma^B + \int_N d\sigma^V + \int_{N+1} d\sigma^R$$

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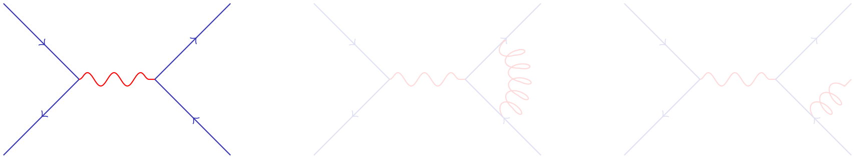

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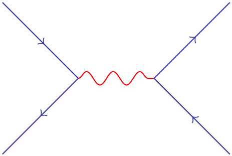

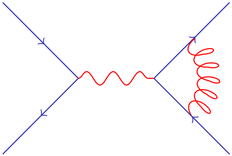

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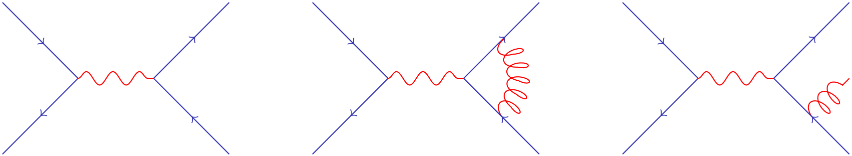


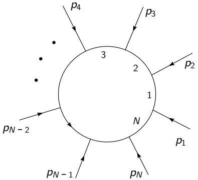
Infrared subtraction

- Virtual and real part diverge separately in the infrared limit
- The sum of both is finite
- Introduce subtraction terms which locally cancel the divergences:

$$\sigma^{NLO} = \int_N d\sigma^B + \int_N \underbrace{\left[d\sigma^V + \int_1 d\sigma^A \right]}_{\text{poles cancel after 1D integration}} + \int_{N+1} \underbrace{\left[d\sigma^R - d\sigma^A \right]}_{\text{finite}}$$

- Different possibilities for choosing the subtraction terms: Catani-Seymour subtraction Catani, Seymour (1997), Antenna subtraction Kosower (1998) Gehrmann-De Ridder, Gehrmann, Glover (2005), FKS subtraction Frixione, Kunszt, Signer (1996)

Calculation of virtual corrections



$$\mathcal{M}_N = \int d^D q \frac{N(q)}{D_1(q)...D_N(q)}$$

with

$$N(q) = C_0 + C_1^{\mu_1} q_{\mu_1} + C_2^{\mu_1 \mu_2} q_{\mu_1} q_{\mu_2} + ...$$

$$D_i(q) = (q + \sum_{k=1}^{i} p_k)^2 - m_i^2$$

$\mathcal{M}_N$ can be expanded in a basis of scalar master integrals:

Master integrals are known.

Different approaches to amplitude reduction: Passarino-Veltman reduction Passarino, Veltman (1979), OPP method Ossola, Papadopoulos, Pittau (2007), ...

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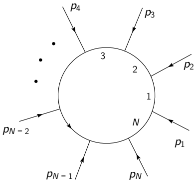

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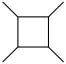
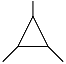
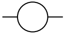
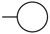
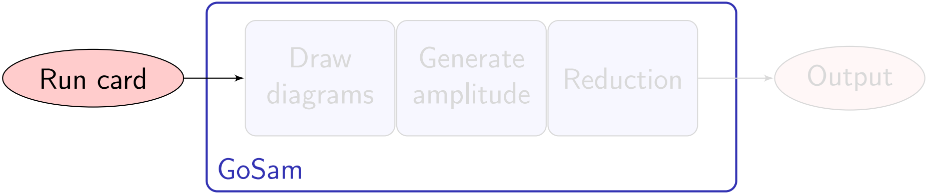
$\mathcal{M}_N = d$  $+ c$  $+ b$  $+ a$  $+ \mathcal{R}$

Master integrals are known.

Different approaches to amplitude reduction: Passarino-Veltman reduction Passarino, Veltman (1979), OPP method Ossola, Papadopoulos, Pittau (2007), ...

GoSam

Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano (2011)



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- Integrand is generated with FORM Vermaseren (1984 -) and Fortran code is produced
- Integrand reduction can be chosen at runtime: Samurai (D-dimensional OPP) Mastrolia, Ossola, Reiter, Tramontano (2010), Golem95c (Tensor-reduction) Binoth, Cullen, Guillet, Heinrich, Kleinschmidt, Pilon, Reiter, Rodgers, von Soden-Fraunhofen (2005 -)
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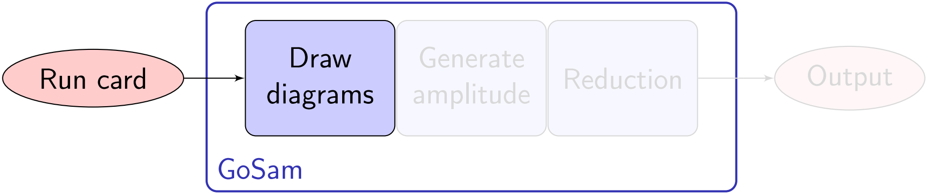

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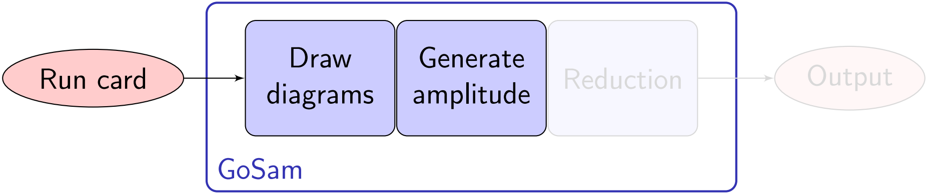

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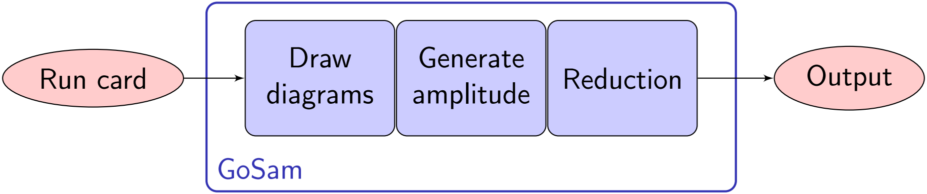

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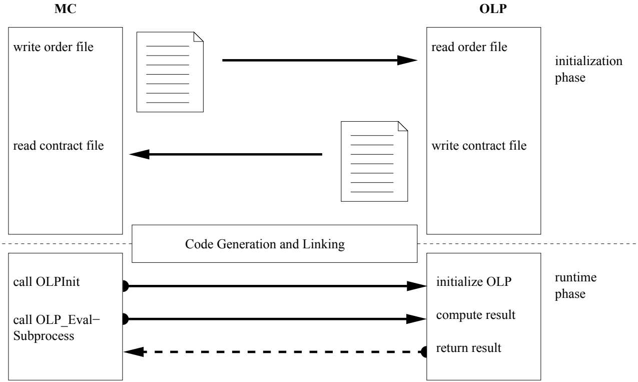
Sherpa

- General purpose Monte Carlo event generator
- Provides
  - Multi-leg tree level matrix elements (Born and real part)
  - Implementation of Catani-Seymour dipole subtraction
  - Phase space integration
  - Parton shower
  - Hadronization
  - Hadron decays
- Event generation is possible at parton, shower and hadron level

Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter, Zapp

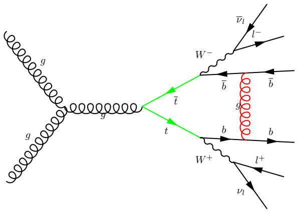
The Binoth Les Houches Accord

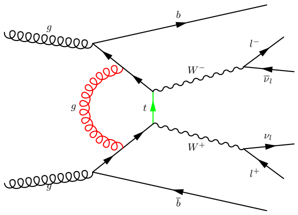


- Interface between Monte-Carlo program (MC) and one-loop amplitude provider (OLP)
- Divided in initialization and runtime phase
- The interface is implemented in GoSam and Sherpa

Binoth et al. (2010)

The process $pp \to W^+W^-b\bar{b}$





- Top quark pair production and decay including nonresonant contributions
- Both W bosons decay leptonically (dilepton channel)
- The approximation $m_b = 0$ is made
- Previous top quark calculations were done under the assumption that production and decay factorize (Neglects contributions which are suppressed by powers of $\frac{\Gamma_t}{m_t} \sim 0.02$)
  Biswas, Melnikov, Schulze (2010)
- First calculated at NLO by Denner, Dittmaier, Kallweit, Pozzorini (2011) and Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek (2011)

The process $pp \to W^+W^-b\bar{b}$

- Four subprocesses:

	Diagrams	Hel.	$t/PS[ms]$
$u\bar{u}$	$14 + 334$	4	53
$d\bar{d}$	$14 + 334$	4	52
$b\bar{b}$	$28 + 668$	4	141
gg	$31 + 1068$	8	859

- Complex mass scheme for top quarks: $m_t^2 \to m_t^2 - im_t\Gamma_t$

NLO comparison with arxiv:1207.5018

Comparison for one phase space point taken from arxiv:1207.5018 Denner, Dittmaier, Kallweit, Pozzorini (2012)

$$|\mathcal{M}|^2_{tree} = a_0$$

$$|\mathcal{M}|^2_{1-loop} \propto c_0 + \frac{c_{-1}}{\epsilon} + \frac{c_{-2}}{\epsilon^2} + \mathcal{O}(\epsilon)$$

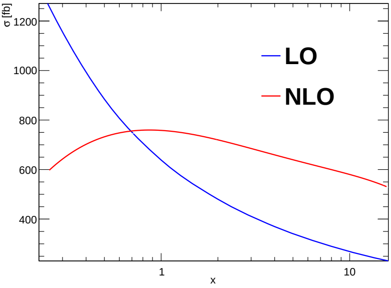
$u\bar{u}$	GoSam	[1207.5018]
$a_0 \cdot 10^{-5}$	1.568863069202787	1.568863069202805
c_0	0.3465309799416799	0.346530980271734
c_{-1}	−0.1030794160242820	−0.103079416107610
c_{-2}	−0.09296228519248788	−0.0929622851927013
gg		
$a_0 \cdot 10^{-5}$	4.554053154627902	4.554053154627972
c_0	0.5717396603625836	0.571739679133372
c_{-1}	−0.03212591118591111	−0.032125892699063
c_{-2}	−0.1510637134379715	−0.1510637134378864

Cross section

Renormalization scale:

$$\mu = \frac{H_T}{2} = \frac{1}{2}\sum_i p_{T,i}$$

Scalar sum over transverse momenta of all final state particles



$$x = \frac{\mu}{H_T/2}$$

Total cross section (LHC 7 TeV):

$$\sigma_{\rm LO}[\text{fb}] = 638.5^{+38.5\%}_{-24.8\%}(\text{scale}) \pm 0.014\%(\text{stat.})$$

$$\sigma_{\rm NLO}[\text{fb}] = 757.3^{-3.0\%}_{-5.4\%}(\text{scale}) \pm 0.3\%(\text{stat.})$$

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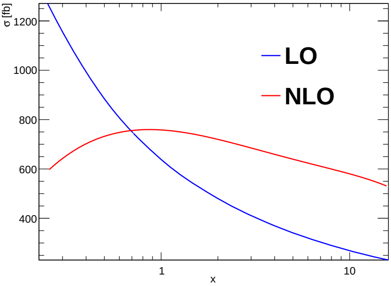

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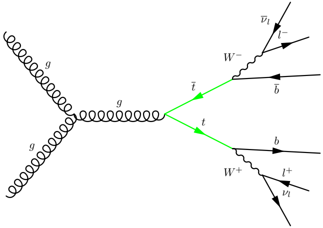
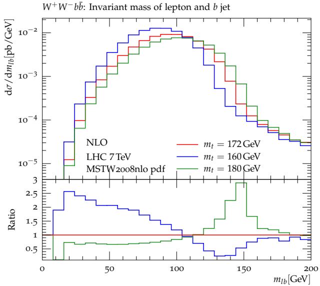
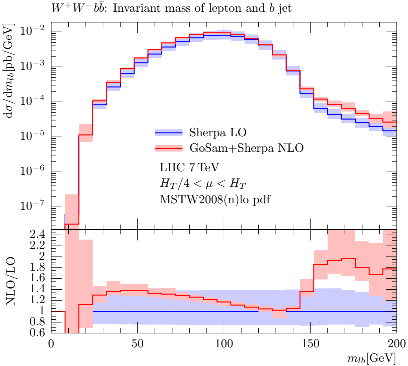
Invariant mass of b-jet and lepton m_{lb}





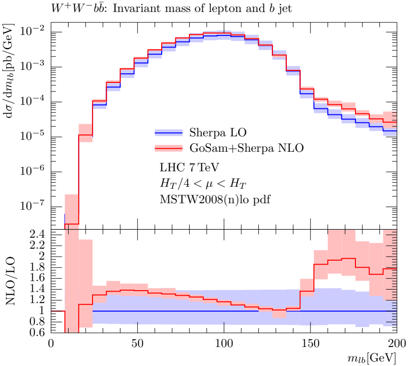
- Definition: $m_{lb} = (p_{\text{b-jet}} + p_l)^2$
- Parton level calculation at next to leading order
- Distribution is sensitive to the value of the top quark mass
- Useful handle for precision measurement of the top quark mass
- Collaboration with the ATLAS group at MPI

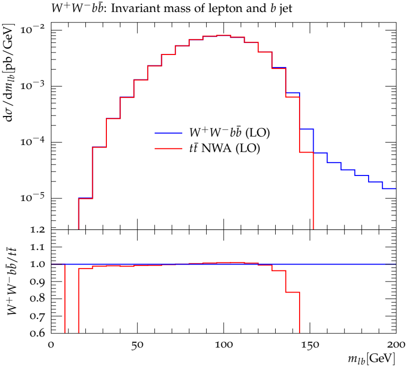
m_{lb} at NLO



- Large NLO corrections to the shape of m_{lb}

m_{lb} at NLO





- Large NLO corrections to the shape of m_{lb}
- m_{lb} has sharp cut-off at $\sqrt{m_t^2 - m_W^2}$ in narrow width approximation

Top quark asymmetries

Top quark forward-backward asymmetry at Tevatron

$$A_{t\bar{t}}^{FB} = \frac{\sigma\left(\Delta y > 0\right) - \sigma\left(\Delta y < 0\right)}{\sigma\left(\Delta y > 0\right) + \sigma\left(\Delta y < 0\right)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

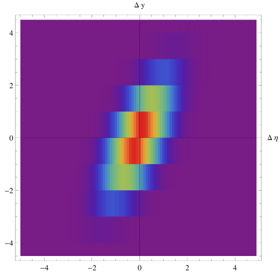
Leptonic asymmetry

$$\Delta y \to \Delta\eta = \eta_{l^+} - \eta_{l^-}$$

Partly inherits Δy effect, no dependence on reconstruction

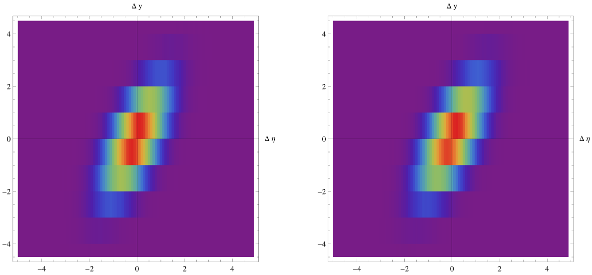
- Discrepancy between Tevatron data and SM predictions ($\sim 2.5\sigma$)
- Asymmetries are zero for LO top quark production

Correlation between Δy and $\Delta\eta$



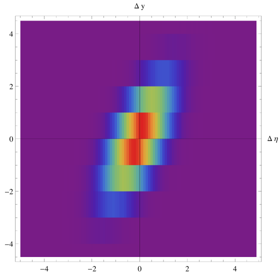
$$\frac{1}{\sigma_{\mathrm{LO}}}\frac{\mathrm{d}\sigma_{\mathrm{LO}}}{\mathrm{d}\eta\mathrm{d}y}$$

Correlation between Δy and $\Delta\eta$

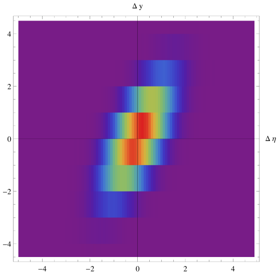


$$\frac{1}{\sigma_{\mathrm{LO}}}\frac{\mathrm{d}\sigma_{\mathrm{LO}}}{\mathrm{d}\eta\mathrm{d}y} \qquad \frac{1}{\sigma_{\mathrm{NLO}}}\frac{\mathrm{d}\sigma_{\mathrm{NLO}}}{\mathrm{d}\eta\mathrm{d}y}$$

Correlation between Δy and $\Delta\eta$



$$\frac{1}{\sigma_{\mathrm{LO}}}\frac{d\sigma_{\mathrm{LO}}}{d\eta dy}$$



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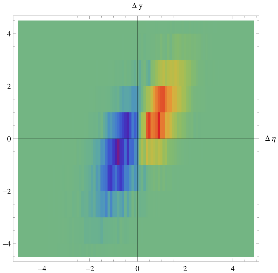
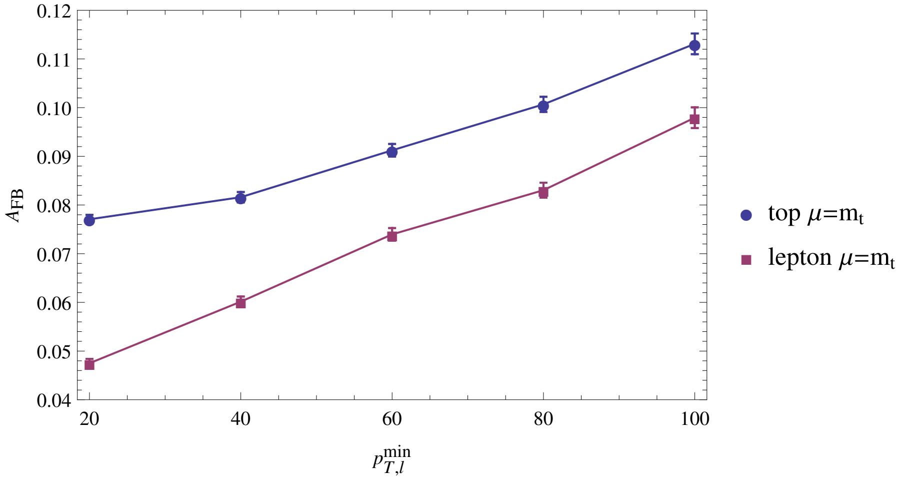


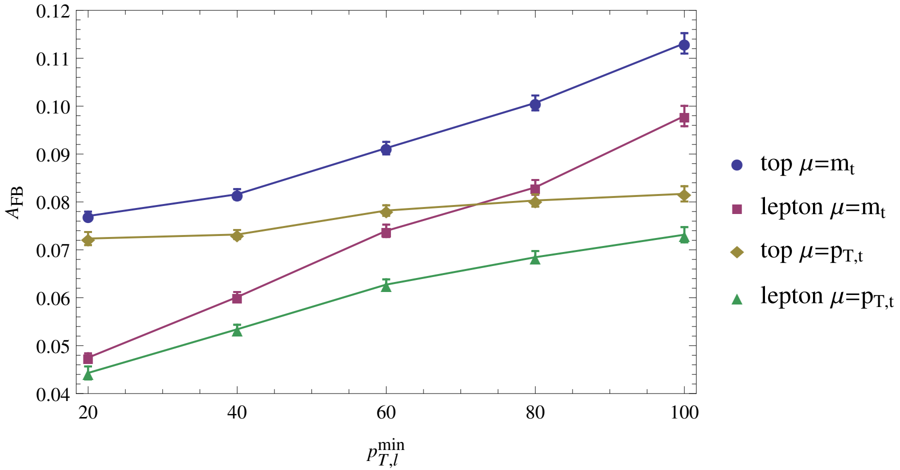
$$\frac{1}{\sigma_{\mathrm{NLO}}}\frac{d\sigma_{\mathrm{NLO}}}{d\eta dy} - \frac{1}{\sigma_{\mathrm{LO}}}\frac{d\sigma_{\mathrm{LO}}}{d\eta dy}$$

Dependence on $p_{T,l}$ cut



$$\mu = m_t$$

Dependence on $p_{T,l}$ cut



$$\mu = p_{T,t} = \sqrt{m_t^2 + p_{T,\text{leading jet}}^2}$$

Conclusions

Summary

- NLO QCD calculations at hadron colliders
- Overview over physics of GoSam (one loop amplitude provider) and Sherpa (MC generator)
- The process $pp \to W^+W^-b\bar{b}$
  - The observable m_{lb}: Precision top quark mass determination
  - Top quark asymmetries: Lepton-based asymmetries as clean handle to improve understanding of SM contribution to asymmetry

Thank you for your attention

Conclusions

Summary

- NLO QCD calculations at hadron colliders
- Overview over physics of GoSam (one loop amplitude provider) and Sherpa (MC generator)
- The process $pp \to W^+W^-b\bar{b}$
  - The observable m_{lb}: Precision top quark mass determination
  - Top quark asymmetries: Lepton-based asymmetries as clean handle to improve understanding of SM contribution to asymmetry

Thank you for your attention

Backup

NLO distributions