# NLO merging in $t\bar{t}$+jets

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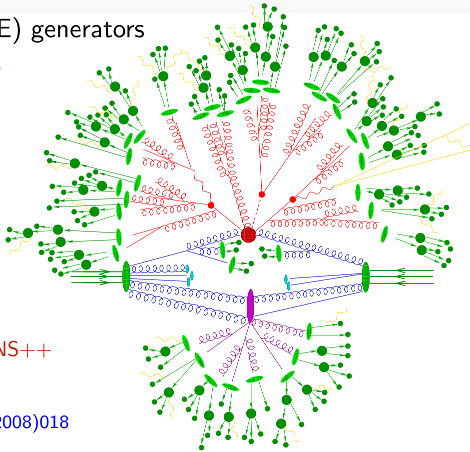
Phys.Rev.D88(2013)014040*

*in collaboration with S. Höche, J. Huang, G. Luisoni, J. Winter

# Contents

# The SHERPA event generator framework



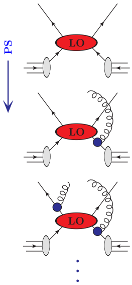
- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044, EPJC53(2008)501
  COMIX JHEP12(2008)039, PRL109(2012)042001
- A Parton Shower (PS) generator
  CSSHOWER++ JHEP03(2008)038
- A multiple interaction simulation
  à la Pythia AMISIC++ hep-ph/0601012
- A cluster fragmentation module
  AHADIC++ EPJC36(2004)381
- A hadron and $\tau$ decay package HADRONS++
- A higher order QED generator using
  YFS-resummation PHOTONS++ JHEP12(2008)018
- A minimum bias simulation SHRiMPS to appear

**Sherpa's traditional strength is the perturbative part of the event**

MEPS (CKKW), S-MC@NLO, MENLOPS, MEPS@NLO

$\rightarrow$ full analytic control mandatory for consistency/accuracy

# Method




**Parton showers**

resummation of (soft-)collinear limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS
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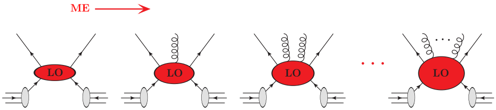


**Matrix elements**

fixed-order in $\alpha_s$
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

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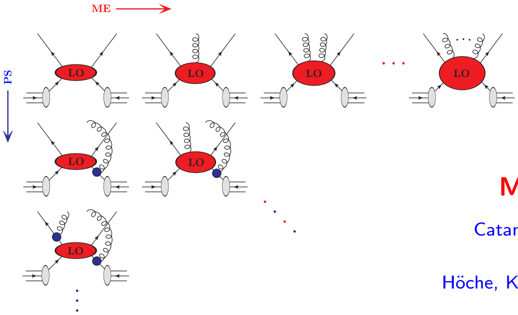


**MEPS** (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053
Lönnblad, Prestel JHEP02(2013)094

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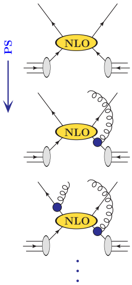


**NLOPS** (MC@NLO,POWHEG,S-MC@NLO)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

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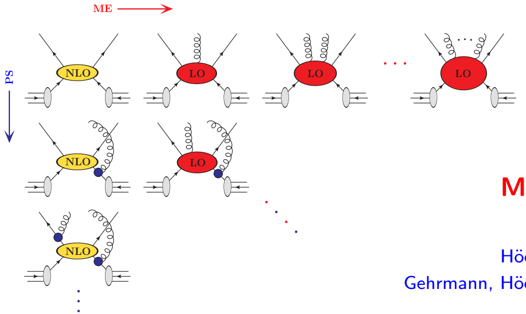


**MENLOPS**

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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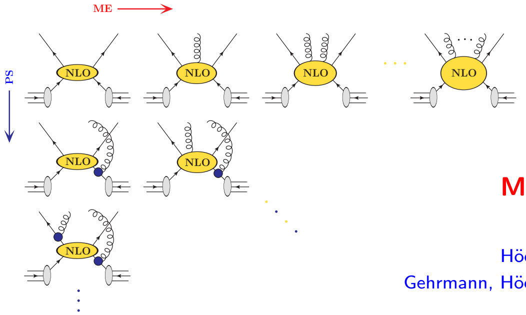


## MEPS@NLO

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
Lönnblad, Prestel JHEP03(2013)166

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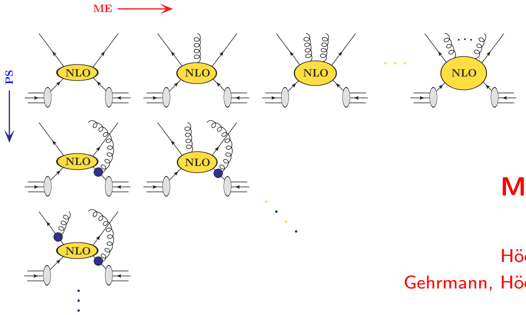


## MEPS@NLO

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- **MEPS@NLO combines multiple NLOPS – keeping either accuracy**

# Contents

# Recent results

Fixed-mulitplicity NLOPS (S-MC@NLO)

- $pp \to W + 0, 1, 2, 3$jets – SHERPA+BLACKHAT
  Höche, Krauss, MS, Siegert Phys.Rev.Lett.110(2013)052001
- $pp \to$ jets – SHERPA+BLACKHAT Höche, MS Phys.Rev.D86(2012)094042
- $pp \to t\bar{t}b\bar{b}$ – SHERPA+OPENLOOPS
  Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.0500

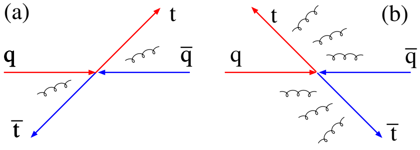
Multijet merging at NLO accuracy (MEPS@NLO)

- $pp \to W +$ jets – SHERPA+BLACKHAT Höche, Krauss, MS, Siegert JHEP04(2013)027
- $e^+e^- \to$ jets – SHERPA+BLACKHAT
  Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
- $pp \to h +$ jets – SHERPA+GOSAM Höche, Krauss, MS, Siegert, in YR3 arXiv:1307.1347
- $p\bar{p} \to t\bar{t} +$ jets – SHERPA+GOSAM
  Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)014040
- $pp \to 4\ell +$ jets – SHERPA+OPENLOOPS
  Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, Siegert arXiv:1309.5912

# Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}} +$ jets – $\mathrm{A_{FB}}$

Skands, Webber, Winter JHEP07(2012)151

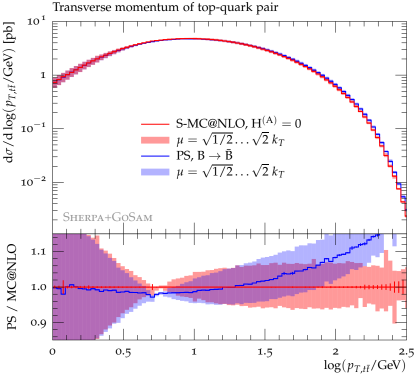
Parton showers and the $t\bar{t}$-asymmetry at the Tevatron




- if colour coherence is respected, PS creates an asymmetry because of asymmetric colour flow
- HERWIG respects colour correlations through angular ordering
- CSSHOWER++ (CS dipoles, 1→2 splittings, recoil to large-$N_c$ partner) → respects colour correlations by choice of radiating dipoles/recoil partners

⇒ **it is important to respect colour-correlations**

# Results – $p\bar{p} \to t\bar{t} + \text{jets}$ – $A_{FB}$




Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

Importance of
$N_c = 3$ colour coherence
(SHERPA's S-MC@NLO)
vs.
$N_c \to \infty$ colour coherence
(SHERPA's CSSHOWER++)

- small effect on standard (rapidity blind) observables, e.g. $p_{\perp,t\bar{t}}$ $\to$ some destructive interference at large $p_{\perp,t\bar{t}}$
- large effect on $A_{FB}(p_{\perp,t\bar{t}})$ $\to$ subleading colour terms increase asym. radiation pattern

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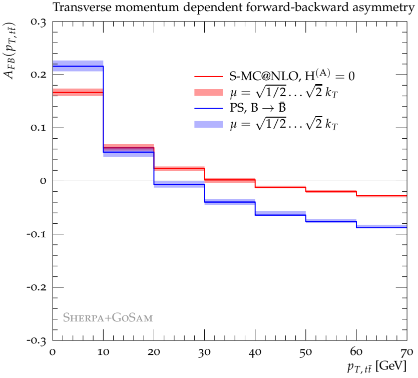


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# Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}}+$jets – $\mathrm{A}_{\mathsf{FB}}$

- Definition of forward-backward asymmetry of an observable $\mathcal{O}$

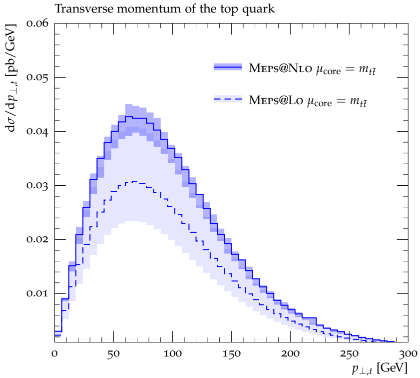
$$A_{\mathsf{FB}}(O) \;=\; \frac{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} - \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} + \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}$$

- $A_{\mathsf{FB}}$ is ratio of expectation values
  $\rightarrow$ conventional scale variations by factor 2 will largely cancel for uncertainty on $A_{\mathsf{FB}}$

$\Rightarrow$ use different functional forms of the scale defintion that behave differently in $\Delta y > 0$ and $\Delta y < 0$ for a realistic estimate of uncertainty

# Results – $p\bar{p} \to t\bar{t}$ + jets – $A_{FB}$

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703



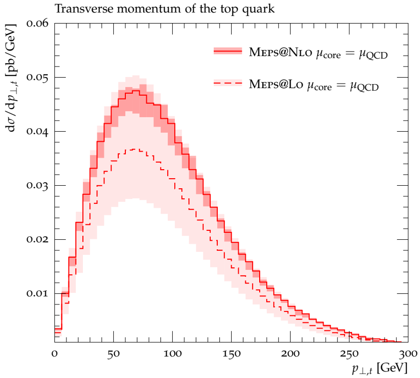

Setup: $p\bar{p} \to t\bar{t}+$ jets

- purely perturbative calculation (no hadronisation, MPI, etc.)
- 0,1 jets @ NLO
  $Q_{\text{cut}} = 7$ GeV
- virtual MEs from GOSAM
- perturbative scale variations
  $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  $\mu_Q \in [\frac{1}{\sqrt{2}}, \sqrt{2}]\, \mu_{\text{core}}$
- variation of merging parameter
  $Q_{\text{cut}} \in \{5, 7, 10\}$ GeV
- scale choices: $\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu_{\text{core}})\, \alpha_s(t_1) \cdots \alpha_s(t_n)$
  **1)** $\mu_{\text{core}} = m_{t\bar{t}}$
  **2)** $\mu_{\text{core}} = \mu_{\text{QCD}} = 2\,|p_i p_j|$
  $i, j \ldots N_c \to \infty$ colour partners, chooses between $s, t, u$

$\Rightarrow$ **different behaviour for forward/backward configurations**

# Results – $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}} +$ jets – $\mathrm{A}_{\mathsf{FB}}$

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

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# Results – $p\bar{p} \to t\bar{t} + \text{jets}$ – $A_{FB}$

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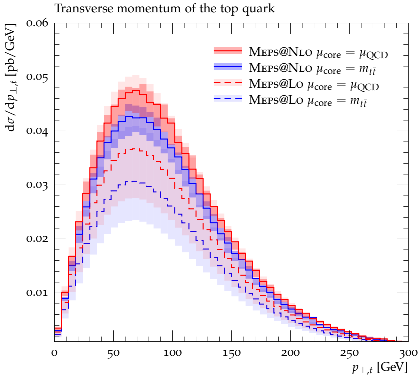
Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

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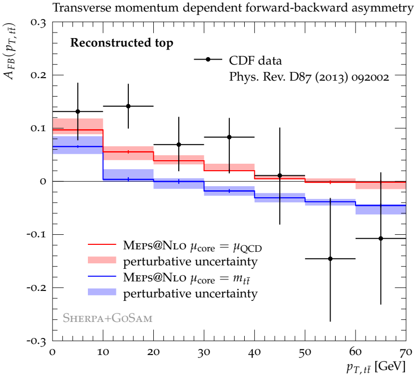
$\Rightarrow$ **different behaviour for forward/backward configurations**

# Results – $p\bar{p} \to t\bar{t}+$jets – $A_{FB}$

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

CDF data Phys.Rev.D87(2013)092002



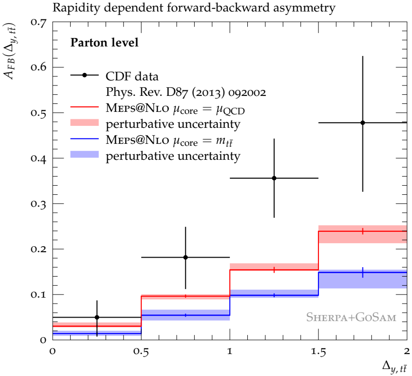

$p\bar{p} \to t\bar{t}$+jets (0,1 @ NLO)

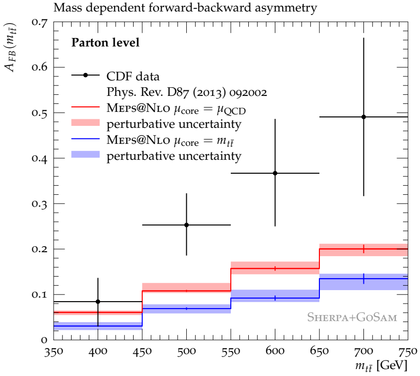
- $A_{FB}(p_{\perp,t\bar{t}})$ NLO accurate in all but the first bin
- tops reconstructed from decay products (jets, lepton, MET)
- no EW corrections

# Results – $p\bar{p} \to t\bar{t} + \text{jets}$ – $A_{FB}$

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703

CDF data Phys.Rev.D87(2013)092002




- parton level (exact top quarks)
- no EW corrections ($\approx 20\%$) effected
- right qualitative bahviour, but consistently below data

# Conclusions

- MEPS merging methods have evolved to NLO: MEPS@NLO
- taking colour correlations properly into account already produces an asymmetry in parton showers
- asymmetry increases when parton shower includes subleading colour terms
- decreasing uncertainties LOPS/MEPS/NLOPS $\rightarrow$MEPS@NLO
- uncertainties on asymmetry observables should be evaluated by choosing different functional forms with different properties towards the asymmetry
- can be improved by adding higher order calculations
  - (N)NLL resummation
  - NNLO corrections

Bärnreuther, Czakon, Mitov Phys.Rev.Lett.109(2012)132001
Czakon, Mitov JHEP01(2013)080
Czakon, Fiedler, Mitov Phys.Rev.Lett.110(2013)252004

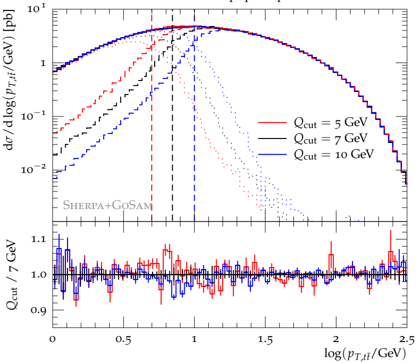
current release SHERPA-2.0.$\beta_2$, when fully tuned SHERPA-2.0.0

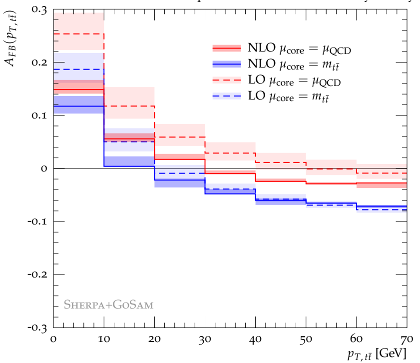
http://sherpa.hepforge.org

Thank you for your attention!

# Results – $p\bar{p} \to t\bar{t} + \text{jets}$

Höche, Huang, Luisoni, MS, Winter arXiv:1306.2703




- very small $Q_{cut}$ dependence
- scale variation shrinks going LO to NLO (both factor and functional form)