SLAC-PUB 15911, IPPP/14/18, DCPT/14/36, ZU-TH 06/14, LPN14-051, HT-14-005, MCNET-14-05

Next-to-leading order QCD predictions for top-quark pair production with up to two jets merged with a parton shower

Stefan Höche,[1] Frank Krauss,[2] Philipp Maierhöfer,[3] Stefano Pozzorini,[3] Marek Schönherr,[2] and Frank Siegert[4]

[1]*SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*
[2]*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*
[3]*Physik–Institut, Universität Zürich, CH–8057 Zürich, Switzerland*
[4]*Institut für Kern- und Teilchenphysik, TU Dresden, D–01062 Dresden, Germany*

We present differential cross sections for the production of top-quark pairs in conjunction with up to two jets, computed at next-to leading order in perturbative QCD and consistently merged with a parton shower in the Sherpa+OpenLoops framework. Top quark decays including spin correlation effects are taken into account at leading order accuracy. The calculation yields a unified description of top-pair plus multi-jet production, and detailed results are presented for various key observables at the Large Hadron Collider. A large improvement is found for the total transverse energy spectrum, which plays a prominent role in searches for physics beyond the Standard Model.

arXiv:1402.6293v1 [hep-ph] 25 Feb 2014

The top quark as the heaviest particle in the Standard Model is believed to play a fundamental role in many new physics scenarios. In a large variety of measurements at the Large Hadron Collider (LHC), top-quark events form either part of the signal or contribute a significant background in Higgs boson studies and new physics searches. Top quarks are produced in abundance at the LHC, either in pairs or singly, and frequently in conjunction with several hard QCD jets. Some first measurements of both inclusive production cross sections and of important kinematic distributions have already been reported by the ATLAS and CMS experiments [1]. Top-quark pair production at hadron colliders suffers from large theoretical uncertainties at the leading order (LO) in perturbative QCD. These uncertainties grow rapidly with the number of additional jets and represent a serious limitation for searches based on multi-jet signatures. A number of precision calculations were completed recently, aimed at reducing these uncertainties: The inclusive production cross section has been determined at next–to–next–to leading order (NNLO) in the perturbative expansion [2]. Parton-level predictions of top-quark pair production in association with up to two jets have been computed at the next–to leading order (NLO) in the coupling [3], and NLO calculations for top-quark pair production in association with one jet [4] and with a bottom-quark pair [5] were matched to parton showers.

The need for increasingly accurate and realistic simulations of $t\bar{t}$+jets production calls for a combination of parton showering with NLO calculations up to the highest possible jet multiplicity. Addressing this need in this letter NLO matrix elements for the production of top-quark pairs in association with up to two jets are matched to the parton shower. Additionally, we also merge, for the first time, NLO matrix elements with lower jet multiplicities, *i.e.* we combine $t\bar{t}$, $t\bar{t}j$ and $t\bar{t}jj$, thereby extending previous results for $t\bar{t}+0,1$ jets [6]. This provides a fully inclusive simulation, which simultaneously describes $t\bar{t}+0$, 1, 2 jet configurations at NLO accuracy supplemented by the resummation of large logarithmic corrections provided by the parton shower.

Parton shower simulations in conjunction with LO QCD calculations of the hard scattering process have been the de-facto standard for computing observables at hadron colliders for decades. Parton showers dress hard-scattering events with multiple emissions of QCD partons, thereby resumming large logarithmic corrections to all orders in perturbation theory. Being based on the collinear approximation, they lack however a proper description of jet production at high transverse momenta or at wide angular separation. The first techniques to remedy this deficiency were LO merging algorithms [7, 8], which consistently combine a description of multiple hard-jet emissions through higher-order tree-level matrix elements with the resummation of large soft and collinear logarithms through the parton-shower. Another method to improve parton-shower simulations consists of matching them to a full NLO calculation for a given final state [9], which yields NLO accurate predictions for observables that are inclusive with respect to extra jet radiation. This method is however limited to improvements to first order in the strong coupling and therefore does not lead to an improved description of multiple jet production.

Recent theoretical developments have lead to new methods that combine the complementary advantages of matching and merging, resulting in an NLO accurate description of final states with varying jet multiplicity [10, 11]. One of these new NLO merging techniques, the MePs@NLO method [10] is used in this publication. In this approach, NLO-matched simulations with increasing jet multiplicity are merged by vetoing emissions above a predefined hardness threshold, Q_{cut}, denoted as merging scale. In analogy to LO merging, an optimal renormalization scale choice in presence of multiple jet emissions is defined, and the calculations with n hard, well separated jets are made exclusive by means of appropriate Sudakov form factors. The $\mathcal{O}(\alpha_s)$ corrections gen-

Work supported by US Department of Energy under contract DE-AC02-76SF00515 and HEP.

erated by this procedure are consistently subtracted in order to preserve both the fixed-order accuracy of the NLO calculations and the logarithmic accuracy of the parton shower [10–12]. The parton-shower matching used in MePs@NLO presents a modified version of the original Mc@Nlo algorithm [9], called S–Mc@Nlo. It is based on including the fully coherent soft radiation pattern for the first emission [13] by exponentiating dipole subtraction terms originally constructed for NLO calculations [14]. This is achieved through a reweighting technique, which allows the generation of non-probabilistic expressions as part of a Markov chain.

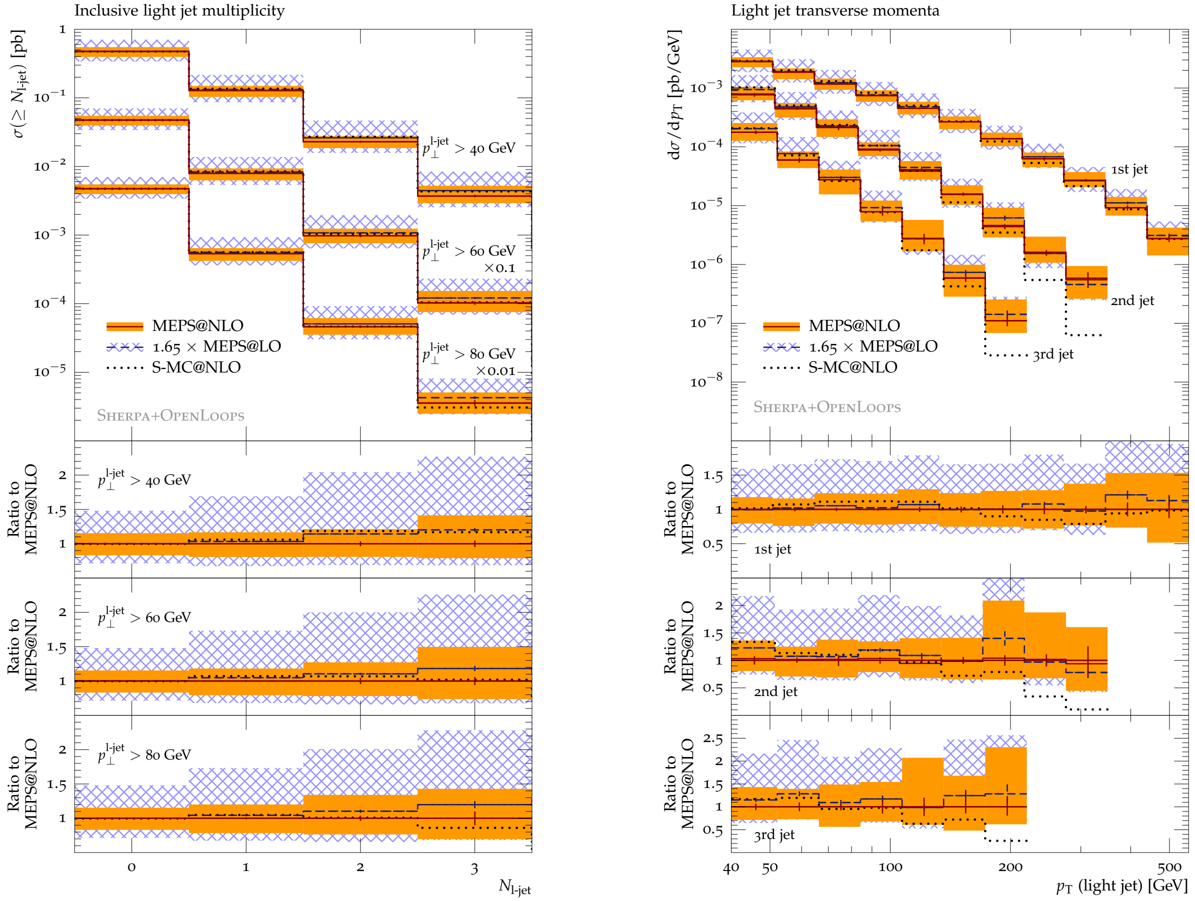
The MePs@NLO simulation of $t\bar{t} + 0, 1, 2$ jets presented in this letter merges multi-jet matrix elements at an unprecedented level of complexity. This is achieved by combining the event generator Sherpa [15] with OpenLoops [16], a fully automated one-loop generator based on a numerical recursion that allows the fast evaluation of scattering amplitudes with many external particles. For the numerically stable determination of both scalar and tensor integrals the Collier library [17] is employed, which implements the methods of [18]. The parton shower in Sherpa is based on Catani-Seymour subtraction [19]. The infrared subtraction is performed by the dipole method [14] automated in both the Amegic++ and Comix modules of Sherpa [20], which also compute the tree-level amplitudes and evaluate the phase-space integrals. Top-quark decays are treated at LO including spin correlations based on $t\bar{t}$+jets Born matrix elements.

We simulate $t\bar{t}$+jets production at the 7 TeV LHC to be applicable to ongoing analyses. We use the MSTW 2008 NLO PDF set [21] and the corresponding strong coupling. Matrix elements are computed with massless b-quarks, but b-quark mass effects are consistently included in the parton shower. According to the CKKW prescription [8], the renormalization scale for $t\bar{t} + n$ jet contributions is defined to be the solution of $\alpha_s(\mu_\mathrm{R})^{2+n} = \alpha_s(\mu_\mathrm{core})^2 \prod \alpha_s(t_i)$, where the α_s terms associated with jet emissions are evaluated at the corresponding clustering scales t_i, while the scale associated with the $pp \to t\bar{t}$ core process is defined by $1/\mu^2_\mathrm{core} = 1/s + 1/(m_t^2 - t) + 1/(m_t^2 - u)$. μ_core is also used as factorization scale (μ_F) and as the parton-shower starting scale, μ_Q. The merging scale is set to $Q_\mathrm{cut} = 30$ GeV. To assess theoretical uncertainties we rescale μ_R and μ_F by factors of two, while μ_Q is varied by $\sqrt{2}$ and Q_cut is varied between 20 and 40 GeV. Additionally, intrinsic parton shower uncertainties are assessed by variation between the two recoil schemes detailed in [19, 22]. The combined renormalization- and factorization-scale uncertainty is added in quadrature with all other variations to form the total theoretical uncertainty. Our results do not include the simulation of multiple parton scattering or hadronization. The publicly available version 2.1.0 of the Sherpa event generator is used, and analyses are made with Rivet [23].

We identify the top quarks through their full decay final state and select events containing a positron and a muon with $p_\mathrm{T} > 25$ GeV and $|\eta| < 2.5$, $E_\mathrm{T}^\mathrm{miss} > 30$ GeV is directly reconstructed from the neutrinos. Jets are defined using the anti-k_t algorithm [24] with $R = 0.4$. Ideal b-jet tagging is modeled based on the flavor of the jet constituent partons. Defining the sign of each b-jet according to its b-quark contents, exactly one b- and one anti-b-jet with $p_\mathrm{T} > 25$ GeV and $|\eta| < 2.5$ are required.

Figures 1-2 feature various observables that characterize multiple light-jet emissions in this $t\bar{t}$+jets event selection. Our best predictions, based on MePs@NLO next-to-leading order merging, are compared to leading-order merged results (MePs@LO), evaluated in an identical setting but rescaled by the inclusive K-factor of 1.65, and to an inclusive S–Mc@Nlo simulation for $pp \to t\bar{t}$. The latter two simulations represent the typical level of theoretical accuracy that is currently employed for the analysis of LHC data. The multiplicity distribution of light-flavor jets is displayed for thresholds of $p_\mathrm{T} > 40$, 60 and 80 GeV in Fig. 1(a). As compared to MePs@LO, the uncertainty of the inclusive MePs@NLO cross section within acceptance cuts is steeply reduced from 48% to 17%, while that for events with at least one light-flavor jet of $p_\mathrm{T} > 40/60/80$ GeV is reduced from 64/65/66% to 19/21/22%. Particularly striking is the reduction in the uncertainty of the cross section of producing the $t\bar{t}$-pair in association with at least two jets: 79/81/83% to 21/27/34%. Thanks to the high quality of the employed merging technique, the Q_cut dependence of MePs@NLO predictions is typically well below ten percent, while the combined theoretical uncertainty is dominated by renormalization scale variations. For observables dominated by one- and two-jet final states S–Mc@Nlo uncertainties (not shown here) are similarly large as MePs@LO ones. This confirms that our MePs@NLO calculation is the most precise prediction to date of differential distributions in top-quark pair production with up to two jets.

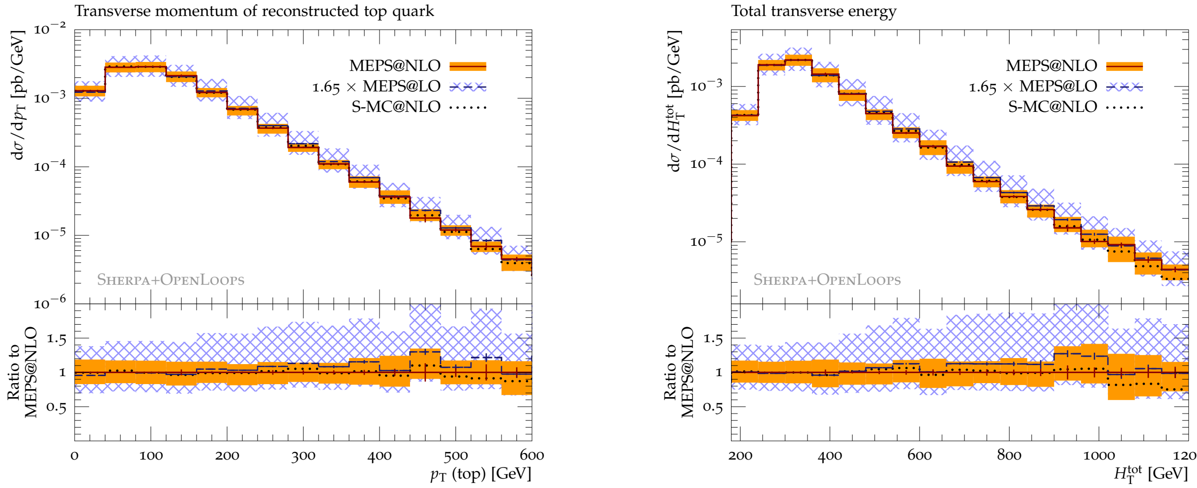
The jet transverse momentum distributions are shown in Fig. 1(b). For the first jet, especially at moderate transverse momenta, we find a strong reduction of the scale uncertainty, while for the third jet NLO uncertainties tend to be as large as LO ones, as expected. Also for the second jet we find rather large MePs@NLO uncertainties at high p_T. This can be attributed to the fact that the high-p_T region is dominated by three-jet topologies, which are described at leading order accuracy in our calculation. The prediction could be further improved by also merging next-to-leading order prediction with even more jets. Figure 2(a) shows the transverse momentum of the reconstructed top quark. Again we observe a strong reduction of uncertainties, particularly at larger transverse momenta. This will significantly increase the precision in measurements of Standard Model $t\bar{t}$ production. Finally, we analyze the total transverse



(a)

(b)

FIG. 1. Light-flavor jet multiplicity distribution (including c- but not b-jets) for transverse momentum thresholds of 40, 60 and 80 GeV (a) and transverse momentum spectra of the three leading light-flavor jets (b). Solid (red) lines indicate MEPS@NLO predictions, and the full (orange) band shows the corresponding total theoretical uncertainty. Dashed lines indicate MEPS@LO predictions, with the corresponding uncertainties shown as hatched (blue) bands. S–MC@NLO predictions are shown as dotted histograms. Statistical uncertainties for each calculation are indicated by error bars.



(a)

(b)

FIG. 2. Transverse momentum of the reconstructed top quark (a) and total transverse energy (b), see Fig. 1 for details.

energy, $H_{\mathrm{T}}^{\mathrm{tot}} = \sum p_{\mathrm{T,b\text{-}jet}} + \sum p_{\mathrm{T,l\text{-}jet}} + \sum p_{\mathrm{T,lep}} + E_{\mathrm{T}}^{\mathrm{miss}}$, of the full final state. This observable plays a key role in searches for new physics, and its high sensitivity to QCD radiation requires accurate modeling of multi-jet emissions. Fig. 2(b) shows a strong reduction of perturbative uncertainties, especially in the high-$H_{\mathrm{T}}^{\mathrm{tot}}$ region. We believe that this makes MEPS@NLO the prime tool for computing $t\bar{t}$+jets backgrounds to new-physics searches. It is worth mentioning that for various observables in Figs. 1–2 the MEPS@NLO, MEPS@LO and S–MC@NLO predictions agree remarkably well. However, especially the tails of S–MC@NLO p_{T}-distributions are systematically lower in the case of the 2nd and 3rd jet.

In summary we have presented the first unified simulation of top-quark pair production in association with up to two jets including top-quark decays and merging with the parton shower at the next-to-leading order in perturbative QCD. Residual theoretical uncertainties are reduced to the level of 20-30%. A wide range of experimental analyses based on multi-jet final states can strongly benefit from this improvement. In particular we observe a drastic reduction of uncertainties for large values of the total transverse energy, $H_{\mathrm{T}}^{\mathrm{tot}}$, which is highly relevant for new physics searches at the Large Hadron Collider.

We are grateful to A. Denner, S. Dittmaier and L. Hofer for providing us with the COLLIER library. This work was supported by the SNSF, by the US Department of Energy under contract DE–AC02–76SF00515, and by the European Commission through the networks PITN–GA–2010–264564, PITN–GA–2012–315877, and PITN–GA–2012–316704. We used resources of the Open Science Grid, supported by the National Science Foundation and the U.S. Department of Energy's Office of Science [25].

[1] G. Aad *et al.* (ATLAS Collaboration), Eur.Phys.J. **C73**, 2261 (2013), arXiv:1207.5644 [hep-ex]; S. Chatrchyan *et al.* (CMS Collaboration), JHEP **1402**, 024 (2014), arXiv:1312.7582 [hep-ex].

[2] M. Czakon, P. Fiedler, and A. Mitov, Phys.Rev.Lett. **110**, 252004 (2013), arXiv:1303.6254 [hep-ph].

[3] S. Dittmaier, P. Uwer, and S. Weinzierl, Phys.Rev.Lett. **98**, 262002 (2007), hep-ph/0703120 [hep-ph]; A. Bredenstein, A. Denner, S. Dittmaier, and S. Pozzorini, Phys. Rev. Lett. **103**, 012002 (2009), arXiv:0905.0110 [hep-ph]; JHEP **1003**, 021 (2010), arXiv:1001.4006 [hep-ph]; G. Bevilacqua, M. Czakon, C. Papadopoulos, R. Pittau, and M. Worek, JHEP **0909**, 109 (2009), arXiv:0907.4723 [hep-ph]; G. Bevilacqua, M. Czakon, C. Papadopoulos, and M. Worek, Phys. Rev. Lett. **104**, 162002 (2010), arXiv:1002.4009 [hep-ph]; Phys.Rev. **D84**, 114017 (2011), arXiv:1108.2851 [hep-ph].

[4] A. Kardos, C. Papadopoulos, and Z. Trocsanyi, Phys.Lett. **B705**, 76 (2011), arXiv:1101.2672 [hep-ph]; S. Alioli, S.-O. Moch, and P. Uwer, JHEP **1201**, 137 (2012), arXiv:1110.5251 [hep-ph].

[5] A. Kardos and Z. Trocsanyi, (2013), arXiv:1303.6291 [hep-ph]; F. Cascioli, P. Maierhöfer, N. Moretti, S. Pozzorini, and F. Siegert, (2013), arXiv:1309.5912 [hep-ph].

[6] S. Höche, J. Huang, G. Luisoni, M. Schönherr, and J. Winter, Phys.Rev. **D88**, 014040 (2013), arXiv:1306.2703 [hep-ph].

[7] S. Catani, F. Krauss, R. Kuhn, and B. R. Webber, JHEP **11**, 063 (2001), hep-ph/0109231; L. Lönnblad, **05**, 046 (2002), hep-ph/0112284; F. Krauss, **0208**, 015 (2002), hep-ph/0205283; M. L. Mangano, M. Moretti, and R. Pittau, Nucl. Phys. **B632**, 343 (2002), hep-ph/0108069; J. Alwall *et al.*, Eur. Phys. J. **C53**, 473 (2008), arXiv:0706.2569 [hep-ph]; K. Hamilton, P. Richardson, and J. Tully, JHEP **11**, 038 (2009), arXiv:0905.3072 [hep-ph].

[8] S. Höche, F. Krauss, S. Schumann, and F. Siegert, JHEP **05**, 053 (2009), arXiv:0903.1219 [hep-ph].

[9] S. Frixione and B. R. Webber, JHEP **06**, 029 (2002), hep-ph/0204244; S. Frixione, P. Nason, and B. R. Webber, **08**, 007 (2003), hep-ph/0305252.

[10] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, JHEP **1304**, 027 (2013), arXiv:1207.5030 [hep-ph]; T. Gehrmann, S. Höche, F. Krauss, M. Schönherr, and F. Siegert, JHEP **1301**, 144 (2013), arXiv:1207.5031 [hep-ph].

[11] L. Lönnblad and S. Prestel, JHEP **1303**, 166 (2013), arXiv:1211.7278 [hep-ph]; R. Frederix and S. Frixione, JHEP **1212**, 061 (2012), arXiv:1209.6215 [hep-ph].

[12] N. Lavesson and L. Lönnblad, JHEP **12**, 070 (2008), arXiv:0811.2912 [hep-ph].

[13] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, JHEP **09**, 049 (2012), arXiv:1111.1220 [hep-ph]; Phys.Rev.Lett. **110**, 052001 (2013), arXiv:1201.5882 [hep-ph]; S. Höche and M. Schönherr, Phys.Rev. **D86**, 094042 (2012), arXiv:1208.2815 [hep-ph].

[14] S. Catani and M. H. Seymour, Nucl. Phys. **B485**, 291 (1997), hep-ph/9605323; S. Catani, S. Dittmaier, M. H. Seymour, and Z. Trocsanyi, **B627**, 189 (2002), hep-ph/0201036.

[15] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert, and J. Winter, JHEP **02**, 007 (2009), arXiv:0811.4622 [hep-ph].

[16] F. Cascioli, P. Maierhöfer, and S. Pozzorini, Eur.Phys.J. **C72**, 1889 (2012), arXiv:1111.5206 [hep-ph].

[17] A. Denner, D. Dittmaier, and L. Hofer, In preparation.

[18] A. Denner and S. Dittmaier, Nucl. Phys. **B658**, 175 (2003), hep-ph/0212259; Nucl. Phys. **B734**, 62 (2006), hep-ph/0509141 [hep-ph]; Nucl. Phys. **B844**, 199 (2011).

[19] S. Schumann and F. Krauss, JHEP **03**, 038 (2008), arXiv:0709.1027 [hep-ph].

[20] T. Gleisberg and F. Krauss, Eur. Phys. J. **C53**, 501 (2008), arXiv:0709.2881 [hep-ph]; T. Gleisberg and S. Höche, JHEP **12**, 039 (2008), arXiv:0808.3674 [hep-ph].

[21] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. **C63**, 189 (2009), arXiv:0901.0002 [hep-ph].

[22] S. Höche, S. Schumann, and F. Siegert, Phys. Rev. **D81**, 034026 (2010), arXiv:0912.3501 [hep-ph].

[23] A. Buckley, J. Butterworth, L. Lönnblad, D. Grellscheid, H. Hoeth, *et al.*, Comput.Phys.Commun. **184**, 2803 (2013), arXiv:1003.0694 [hep-ph].

[24] M. Cacciari, G. P. Salam, and G. Soyez, JHEP **0804**, 063 (2008), arXiv:0802.1189 [hep-ph].

[25] L. Bauerdick *et al.* (Open Science Grid), J.Phys.Conf.Ser. **396**, 042048 (2012).