On the Feasibility and Utility of ISR Tagging

David Krohn and Lisa Randall

Department of Physics, Harvard University, Cambridge MA, 02138

Lian-Tao Wang

Department of Physics, Princeton University, Princeton NJ, 08544

(Dated: January 6, 2011)

The production of new particles at a hadron collider like the LHC is always accompanied by QCD radiation attributable to the initial state (i.e. ISR). This tends to complicate analyses, so ISR is normally regarded as a nuisance. Nevertheless, we show that ISR can also be valuable, yielding information that can help in the discovery and interpretation of physics beyond the Standard Model. To access this information we will introduce new techniques designed to identify ISR jets on an event-by-event basis, a process we term ISR tagging. As a demonstration of their utility, we will apply these techniques to SUSY di-squark (di-gluino) production to show that they can be used to identify ISR jets in roughly 40% (15%) of the events, with a mistag rate of around 10% (15%). We then show that, through the application of a new method which we will introduce, knowledge of an ISR jet allows us to infer the squark (gluino) mass to within roughly 20% of its true value.

I. INTRODUCTION

Quarks and gluons are always splitting apart and recombining [1]. When they are scattered at high energies this process is interrupted, and the result is that additional quarks and gluons which could not be recombined end up in the final state. This radiation, attributable to the splitting of the incoming states, is termed initial state radiation (ISR).

ISR often complicates analyses. For example, it can overlap with, and thus contaminate, jets formed from the decay of new particles (we will call these FSR jets). Furthermore, when ISR emissions yield additional independent jets (i.e. ISR jets), sorting out the combinatorics of an event can be even more difficult. These are not irresolvable difficulties, and indeed recently progress has been made toward removing sources of jet contamination [2], mitigating combinatorial difficulties [3], defining new observables less sensitive to contamination [4], and more accurately accounting for the physics of ISR in Monte Carlo simulations [5].

However, ISR – rather than always proving to be an obstacle – can actually be helpful in the study of physics beyond the SM. The mass scale of the event and the states it couples to – independently of any intermediate or final decay products. So while the kinematic quantities measured of FSR jets in BSM processes depend upon some combination of all the masses involved in the process, the kinematics of ISR depend upon only the masses of the particles involved in the production process (i.e. not upon those produced subsequently in a cascade/decay) and their couplings to initial state particles.

Here we will make use of this information carried by ISR, with the main new feature of our approach being that rather than treating ISR in an inclusive way, as in Ref. [7], we will seek to identify a particular jet as attributable to ISR. We will see that such jets can be identified on an event-by-event basis with a small mistagging probability. We will then show that this sort of technique for tagging ISR jets provides a powerful tool for understanding BSM physics that can be applied to many interesting processes. We focus in particular on a new kinematic method that can be used to evaluate squark and gluino masses.

The outline of this paper is as follows. Sec. II will discuss the sort of techniques one can use to tag ISR jets, Sec. III will discuss one example of what we can learn about BSM physics through the study of ISR jets based solely on kinematics, and Sec. IV will apply these ideas to di-squark and di-gluino production as a demonstration of their feasibility and utility. Finally, Sec. V contains our conclusions.

II. TAGGING AN ISR JET

Tagging an ISR jet requires identifying characteristics that distinguish it from the other jets in an event. Although ISR possesses some general traits that hold true regardless of the process at hand [5], tagging ISR jets solely based on these properties would be challenging, if not impossible. We instead focus on tagging ISR in a
particular class of interesting processes – the pair production of BSM particles, each of which decays into jets and an invisible particle (i.e. $pp \rightarrow N_f J + 2\tilde{\chi}_1^0 + \text{ISR}$ where $N_f = 2/4$ for di-squark/di-gluino production). Although we will restrict ourself to these topologies, we expect that ISR jets are also identifiable in other cases and that similar techniques could be developed for more complicated processes. Nonetheless, this will serve as a proof of concept, that we employ later in Sec. IV, in what is already an important application of these ideas to BSM physics.

It turns out that the modest assumption of pair production gives one a significant handle for identifying ISR jets. Suppose one expects to see $N_f$ FSR jets in a BSM event. As long as there’s no reason for these to be particularly soft, one can assume that of the $N_f + 1$ hardest jets in the event, $N_f$ are attributable to FSR and one to ISR. As the production process is symmetric, all of the properties governing the production of one FSR jet should hold for the others. Thus, of the $N_f + 1$ hardest jets in the event, we can identify the ISR jet as the one which is in some way distinguished from the others.

The method we prescribe for accomplishing this is to consider the $N_f + 1$ hardest jets in an event and identify a candidate ISR jet (here labeled $i$) for which at least one of the following conditions is met [9]:

1. The jet’s $p_T$ is distinct (i.e. it is harder or softer than the others):
\[
\frac{\max(p_{T_i}, p_{T_j})}{\min(p_{T_i}, p_{T_j})} > 2 \forall j \neq i \tag{1}
\]

2. The jet is separated from the others in rapidity:
\[
|y_i - y_j| > 1.5 \forall j \neq i \tag{2}
\]

3. The jet is distinguished by its $m_i/p_{T_i} \equiv \Delta_i$ ratio [10]:
\[
\frac{\max(\Delta_i, \Delta_j)}{\min(\Delta_i, \Delta_j)} > 1.5 \forall j \neq i \tag{3}
\]

If a jet (again labeled $i$) is selected by any of the above criteria it should then satisfy all of the following:

- The selected jet must not be central: $|y_i| > 1$.

- It must not be too close to the other jets, which are all implicitly FSR jets:
\[
|y_i - y_j| > 0.5 \forall j \neq i \tag{4}
\]

- These other jets must be reasonably close to each other in $p_T$:
\[
\frac{p_{T_i}}{p_{T_k}} < \rho + \frac{1/2}{1 - \alpha} \tag{5}
\]

for $p_{T_{i(k)}} = \max(\min\{p_{T_l} \forall l \neq i\}$, with $\rho = 2(3)$ for $N_f = 2(4)$, and where we have introduced the variable
\[
\alpha = \frac{\min(p_{T_i}, E_T)}{\max(p_{T_i}, E_T)} \tag{6}
\]

to relax this condition when the ISR is very hard.

- Finally, the implicit FSR jets must be somewhat central: $|y_j| < 2 \forall j \neq i$

If any of the above conditions is not satisfied, the jet being considered is not tagged and other jets are checked to see if they pass any of the distinguishing criteria (Eqs. 1-3).

We note that it is surely possible to improve upon the technique presented above, and that the numerical values we presented have not been thoroughly optimized. Even so, we will see these criteria already work quite well, triggering on $40\%$ ($15\%$) of the events, for $N_f = 2(4)$ topologies, with a small $10\%$ ($15\%$) mistag rate.

### III. USES OF AN ISR JET

Once an ISR jet has been identified in an event it can be used in multiple ways to shed light upon the underlying physics that produced it. As the production of ISR is determined by the mass scale probed by the process, the identity of the partons in the initial state, and the relevant parton distribution functions (PDFs), the resulting ISR kinematical distributions will reflect all of these influences [11]. Here though, rather than focus on general properties of the aforementioned distributions, whose calculation would depend upon a careful treatment of QCD, we will instead present a simple new kinematical technique useful in measuring $m_{BSM}$, the center of mass energy for the two heaviest BSM particles produced in the symmetric processes we are considering. Because hadron colliders tend to produce heavy states close to threshold, a measurement of $m_{BSM}$ is nearly equivalent to a measurement of the new-physics particle’s mass: $m_{BSM} = \sqrt{p_{\tilde{q}/\tilde{g}}^2 + p_{\tilde{q}/\tilde{g}}^2} \approx 2m_{\tilde{q}/\tilde{g}}$.

Other kinematic variables are also sensitive in some way to $m_{BSM}$. Examples include $M_{\text{eff}}$ [12], $M_{T_2}$ [13], and their more advanced extensions [14]. Some recent works [15] have also made use of ISR to give their $M_{T_2}$ distributions additional structure. However, these techniques are in general sensitive to all of the masses in the decay chain, or only work for very specific processes (e.g. gluino transverse mass [14]).

Remarkably, by looking to ISR we can construct a new kinematic measure sensitive only to $m_{BSM}$, independent of any other assumptions on the spectrum. The basic idea behind this method stems from the observation that any BSM particles produced must be recoiling against ISR in the transverse plane. Boosting the FSR system back along the transverse plane to compensate for the
ISR jet’s $p_T$ requires an assumption for the system’s center of mass energy, and only when we have assumed the correct value will the boost function properly. Before proceeding, we note that while any BSM particles are, in fact, recoiling against all of the ISR particles (rather than only the leading jet), in practice the ISR jets assume a strong $p_T$ hierarchy and, using only the leading jet to apply a boost will serve as a reasonable approximation.

In detail, the method we prescribe to measure $m_{\text{BSM}}$ using the ISR jet’s kinematics is to:

1. Identify all of the visible FSR jets and boost them along the $z$ direction so that the visible FSR is at rest in the $z$ frame (i.e. the net $p_z$ for FSR jets is zero). That is, each FSR four-vector (here labeled $i$) is shifted

$$E_i \rightarrow \gamma (E_i + \beta p_{iz}) , \ p_{iz} \rightarrow \gamma (\beta E_i + p_{iz}) \quad (7)$$

where $\beta = -p_z/E$ and $\gamma = 1/\sqrt{1 - \beta^2}$, for $p_z$ and $E$ the sum longitudinal momentum and energy taken over all observable particles in the system. This boost is performed because, while ideally the system will be at rest in the $z$ direction before boosting in the transverse plane (step two), this is a configuration we cannot achieve because of uncertainties introduced by missing energy. However, by applying the boost in Eq. (7) we approximate this condition.

2. Boost the system along the direction transverse to the beam, parallel to the transverse momentum of the ISR jet, assuming some system mass $M$. This means that the projection of each FSR $p_T$ vector along the ISR direction transforms as

$$p_{Ti} \rightarrow \frac{p_{Ti}^{\text{ISR}}}{M} E_i + \sqrt{1 + \left(\frac{p_{Ti}^{\text{ISR}}}{M}\right)^2 p_{Ti}} \quad (8)$$

where $p_{Ti}^{\text{ISR}} = \hat{p}_i \cdot \hat{p}_i^{\text{ISR}}$ is the projection of each $p_T$ along the ISR $p_T$ direction.

3. Measure the sum projection of the resulting boosted FSR along the ISR transverse direction, assigning the result a $\pm 1$ depending upon the sign:

$$\sigma = \begin{cases} +1 & \text{if } \sum_i p_{Ti} > 0 \\ -1 & \text{if } \sum_i p_{Ti} < 0 \end{cases} \quad (9)$$

4. Finally, the average projection across many events is measured: $\langle \sigma \rangle = \sum_{i=1}^N \sigma_i/N$

When $\langle \sigma \rangle$ is positive there is a net projection along the ISR axis, indicating the assumed mass is too small, while when it is negative, the assumed mass is too large. Examples of the resulting distributions are shown in Fig. 1 for the case of di-squark and di-gluino production.

Before proceeding, we call attention to two choices we made in the analysis that might be improved in a more careful treatment. The first is in step one, where we boosted the FSR along the $z$ direction to approximate the longitudinal rest frame. While this technique seems to operate reasonably well, it may be possible to better infer the $z$-boost using beam thrust techniques as suggested in Ref. [10]. We further note that Eq. (9) assigns each event an equal weight when computing $\langle \sigma \rangle$, regardless of the measured imbalance. This choice was made because weighting events by their $p_T$ imbalance ($\sum_i p_{Ti}$) tends to make $\langle \sigma \rangle$ sensitive to only a few outlier events. Perhaps a better measure exists, but we do not pursue it here.

### IV. Example: Di-squark & Di-gluino Production

We now apply the aforementioned techniques to the pair production of squarks and gluinos, letting $\tilde{q} \rightarrow q + \chi_1^0$ and $\tilde{g} \rightarrow q\bar{q} + \chi_1^0$ (via an off-shell squark). To perform this analysis we use Madgraph v4.4.51 [17] to generate $10^5$-event samples at matrix-element level, assuming a 14 TeV LHC, which are then showered in Pythia v6.422 [18] and matched using the MLM procedure [19]. Fully showered and hadronized events are then grouped into $0.1 \times 0.1$ cells ($\eta, \phi$) cells between $-5 < \eta < 5$, which are clustered in Fastjet v2.4.2 [20] using the anti-$k_T$ algorithm [21]. Our di-squark samples were clustered using $R = 0.7$, while $R = 0.4$ was used for the busier di-gluino events. Note that, to simplify matters, we have not accounted for the effects of multiple interactions or pileup.

Table I shows the efficiencies found using the tagging procedure of Sec. II. Remarkably, we see that the tagging efficiency (i.e. the percent of events in which an ISR jet is tagged) and the mistag rate (the percent of events in which a jet that has been tagged as ISR was tagged incorrectly) are stable, even when comparing a standard SUSY spectrum with $m_{\text{LSP}} = 100$ GeV to one in which the LSP is nearly degenerate with the supersymmetric particle that decayed into it.

| Spectrum | Efficiencies [%] | Type of tag applied [%] |
|----------|-----------------|-------------------------|
| $m_{\tilde{g}}/m_{\tilde{q}}$ | Trigger | Mistag | Eq. (1) | Eq. (2) | Eq. (3) |
| 500 GeV 100 GeV | 42 | 15 | 69 | 22 | 9 |
| 1 TeV 100 GeV | 41 | 11 | 79 | 14 | 7 |
| 1 TeV 950 GeV | 41 | 9 | 52 | 39 | 9 |
| 500 GeV 100 GeV | 13 | 22 | 48 | 42 | 10 |
| 1 TeV 100 GeV | 12 | 25 | 59 | 30 | 11 |
| 1 TeV 900 GeV | 16 | 8 | 37 | 57 | 6 |

When $\langle \sigma \rangle$ is positive there is a net projection along the ISR axis, indicating the assumed mass is too small, while when it is negative, the assumed mass is too large. Examples of the resulting distributions are shown in Fig. 1 for the case of di-squark and di-gluino production.
for $m_{\tilde{q}}/m_{\tilde{g}} = 500$ GeV and $\langle m_{\text{BSM}} \rangle = 2.5$ TeV for $m_{\tilde{q}}/m_{\tilde{g}} = 1$ TeV, values which are quite close to those measured by the point at which the FSR momentum have been boosted to have no preferred direction ($\langle \sigma \rangle = 0$).

V. CONCLUSION

While ISR is normally regarded as a nuisance, here we have seen that it can instead be useful, allowing for qualitatively new measurements of BSM physics that would be difficult or impossible to otherwise access. In this paper, we have introduced a set of techniques for tagging the ISR created in the pair production of BSM states, each of which decays into jets and an invisible particle. Although the methods we introduced are specific to this sort of process, they can be readily extended to scenarios where BSM physics realizes a more complicated final state topology.

We have applied these techniques to SUSY di-squark (di-gluino) production, where we saw they tagged ISR in roughly 40% (15%) of the events, with a mistag rate for-gluino production, where we saw they tagged ISR to 50 million, and by an LHC-TI travel grant. LR is supported by NSF grant PHY-0556111. L.-T.W. is supported by the NSF under grant PHY-0756966, and by a DOE OJI award under grant DE-FG02-90ER40542

We would like to thank D. Feldman, E. Kuflic, I. Kim, M. Lisanti, G. Salam, M. Schwartz, I. Stewart, and J. Thaler for helpful discussions. DK is supported by a Simon’s postdoctoral fellowship and by an LHC-TI travel grant. We would like to thank D. Feldman, E. Kuflic, I. Kim, M. Lisanti, G. Salam, M. Schwartz, I. Stewart, and J. Thaler for helpful discussions. DK is supported by a Simon’s postdoctoral fellowship and by an LHC-TI travel grant. LR is supported by NSF grant PHY-0556111. L.-T.W. is supported by the NSF under grant PHY-0756966, and by a DOE OJI award under grant DE-FG02-90ER40542

Acknowledgments

[1] G. Altarelli and G. Parisi, Nucl. Phys., B126, 298 (1977).
[2] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, Phys.Rev.Lett., 100, 242001 (2008).
[3] J. Alwall, K. Hiramatsu, M. M. Nojiri, and Y. Shimizu, Phys.Rev.Lett., 103, 151802 (2009).
[4] J. Alwall, S. Hoeche, F. Krauss, N. Lavesson, L. Lonnblad, et al., Eur.Phys.J., C53, 473 (2008).
[5] J. Alwall, A. Freitas, and O. Mattelaer, (2010), arXiv:1010.2263 [hep-ph].
[6] J. Alwall, S. Hoeche, F. Krauss, N. Lavesson, L. Lonnblad, et al., Eur.Phys.J., C53, 473 (2008).
[7] J. Alwall, A. Freitas, and O. Mattelaer, (2010), arXiv:1010.2263 [hep-ph].
[8] T. Plehn, D. Rainwater, and F. Z. Skands, Phys.Lett., B645, 217 (2007).
[9] J. Alwall, S. de Visscher, and P. Maltoni, JHEP, 0902, 017 (2009).
[10] J. Alwall, M. P. Le, M. Lisanti, and J. G. Wacker, Phys.Lett., B666, 34 (2008).
[11] J. Alwall, M. P. Le, M. Lisanti, and J. G. Wacker, Phys.Lett., B666, 34 (2008).
[12] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[13] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[14] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[15] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[16] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[17] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[18] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[19] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[20] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[21] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
[22] A. Papageorgiou and B. Webber, JHEP, 0906, 069 (2009).
FIG. 1. The average sign of the FSR projection along the transverse ISR direction for, proceeding left to right, di-squark production using $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{q}} = 1$ TeV, and then di-gluino production with $m_{\tilde{g}} = 500$ GeV, $m_{\tilde{g}} = 1$ TeV, with the LSP mass indicated in the legends. The position at which the points intersect $\langle \sigma \rangle = 0$ is what we would identify as $m_{\text{BSM}}$, i.e. it where the FSR momenta are balanced because the boost is ‘correct’. We see that it is in general close to $2m_{\tilde{q}/\tilde{g}}$. Note that the errors indicated are just the statistical errors associated with our Monte Carlo sample sizes.

[18] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP, 0605, 026 (2006), arXiv:hep-ph/0603175 [hep-ph].
[19] S. Hoeche, F. Krauss, N. Lavesson, L. Lonnblad, M. Mangano, et al., (2006), arXiv:hep-ph/0602031 [hep-ph].
[20] M. Cacciari, G. Salam, and G. Soyez, “FastJet,” Http://fastjet.fr/; M. Cacciari and G. P. Salam, Phys. Lett., B641, 57 (2006), arXiv:hep-ph/0512210.
[21] M. Cacciari, G. P. Salam, and G. Soyez, JHEP, 04, 063 (2008), arXiv:0802.1189 [hep-ph].
[22] A. Abdesselam, E. Kuutmann, U. Bitenc, G. Brooijmans, J. Butterworth, et al., (2010), arXiv:1012.5412 [hep-ph]. G. P. Salam, Eur.Phys.J., C67, 637 (2010), arXiv:0906.1833 [hep-ph].