Shape variables at hadron colliders

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Work done in collaboration with

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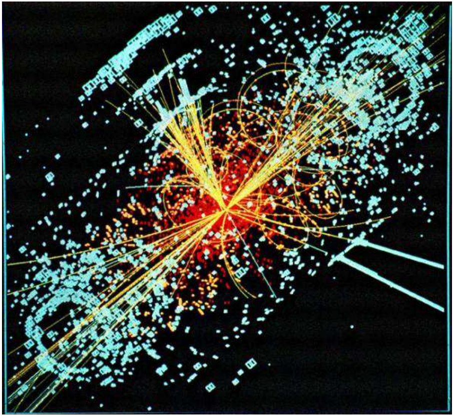
Hadronic final states at the LHC

Final states at the LHC are characterised by large hadron multiplicities



Shape variables are IR and collinear (IRC) safe observables obtained from suitable combinations of hadron momenta (e.g. event shapes)

☺ IRC safety $\Rightarrow$ Hadronic final states can be described with PT QCD!

Outline

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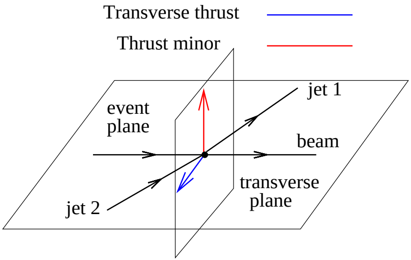
Event shapes explore the geometry of hadronic energy-momentum flow (i.e. if hadronic events are planar, spherical, etc.)

- Two examples: transverse thrust and thrust minor



$$T_t \equiv \max_{\vec{n}_t} \frac{\sum_i |\vec{q}_{ti} \cdot \vec{n}_t|}{\sum_i q_{ti}}$$

$$T_m \equiv \frac{\sum_i |\vec{q}_{ti} \times \vec{n}_t|}{\sum_i q_{ti}}$$

- Event shapes can involve also longitudinal momenta, e.g. total and heavy-jet mass ρ_T, ρ_H, total and wide-jet broadening B_T, B_W, three-jet resolution parameter y_{23}

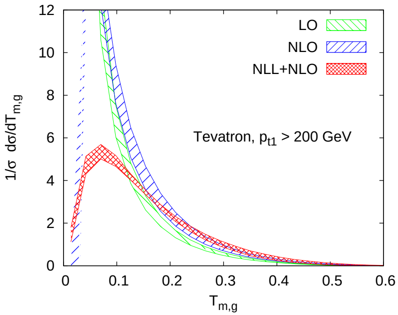
- All event shapes we consider vanish in the two-jet limit

- Fixed order predictions (3 jets at NLO) diverge at small T_m

  [Nagy PRD **68** (2003) 094002]

- Resummation of large logarithms $\exp\{\alpha_s^n \ln^{n+1} T_m + \alpha_s^n \ln^n T_m\}$ (NLL) restores correct physical behaviour for $T_m \to 0$

  [AB Salam Zanderighi JHEP **1006** (2010) 038]



Peak of T_m distribution where $d/dT_m(d\sigma/dT_m) = 0 \Rightarrow \alpha_s \ln T_m \sim 1$

Peak position and height stabilised by NLL resummation

Computer automated resummation: CAESAR

General NLL resummation for any suitable event shape is possible with the Computer Automated Expert Semi-Analytical Resummer

[AB Salam Zanderighi JHEP **0503** (2005) 073, qcd-caesar.org]

Given a computer subroutine that computes $V(k_1, \ldots, k_n)$, CAESAR

1. checks whether V is resummable within NLL accuracy
2. performs the NLL resummation using a general master formula

The core of the automation lies in

- high-precision arithmetic to take soft and collinear limits
- methods of Experimental Mathematics to verify of falsify hypotheses

⚠ CAESAR is not one more parton shower

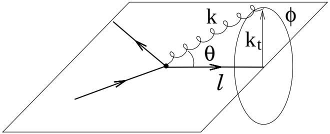
- the produced results have the quality of analytical predictions
- an answer is provided only if NLL accuracy is guaranteed

Conditions for NLL resummation

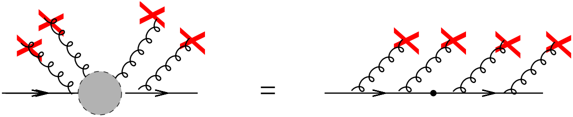
An event shape $V(k_1,\ldots,k_n)$ is resummable at NLL accuracy if

1. $V(k)$ has a specific functional dependence on a single soft and emission k collinear to a leg ℓ

$$V(k) = \left(\frac{k_t}{Q}\right)^{a_\ell} e^{-b_\ell \eta} g_\ell(\phi)$$



2. it is (continuously) global, i.e. it is sensitive to soft/collinear emissions in the whole of the phase space
3. it is recursively IRC safe, i.e. it has good scaling properties with respect to multiple emissions



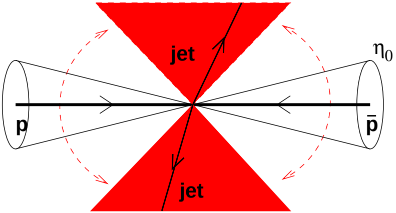
Globalness + rIRC safety + QCD coherence ⇒ angular ordered parton branching accounts for all LL and NLL contributions

Classes of global event shapes

In spite of limited detector acceptance $|\eta| < \eta_0$ (~ 5 at the LHC), it is possible to devise global event shapes even in hadron collisions

[AB Salam Zanderighi JHEP **0408** (2004) 062]

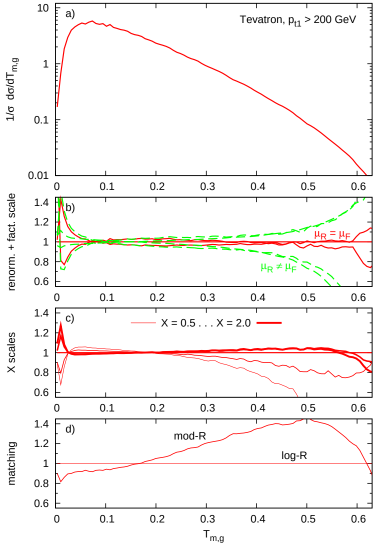
- Directly global: measure all hadrons up to η_0
  ☹ NLL valid up to $v \sim e^{-c_V \eta_0}$, e.g. $T_m \sim e^{-\eta_0}$
- Exponentially suppressed: event shape in central region $\mathcal{C}$ + exponentially suppressed forward term $\mathcal{E}_{\bar{\mathcal{C}}}$
  [Similar to recent proposal by Stewart Tackmann Waalewijn PRD **81** (2010) 094035]
  ☹ potentially affected by coherence violating logarithms?
  [Forshaw Kyrieleis Seymour JHEP **0608** (2006) 059]
- Recoil: event shape in central region $\mathcal{C}$ + recoil term $\mathcal{R}_{t,\mathcal{C}}$
  ☹ NLL predictions diverge at small v



$$\mathcal{E}_{\bar{\mathcal{C}}} \sim \sum_{i \notin \mathcal{C}} q_{ti}\, e^{-|\eta_i - \eta_{\mathcal{C}}|}$$

$$\mathcal{R}_{t,\mathcal{C}} \sim \left|\sum_{i \in \mathcal{C}} \vec{q}_{ti}\right| = \left|\sum_{i \notin \mathcal{C}} \vec{q}_{ti}\right|$$

Theoretical uncertainties are under control and within $\pm 20\%$



- Asymmetric variation of μ_R and μ_F around $p_t = (p_{t1} + p_{t2})/2$

$$p_t/2 \leq \mu_R \leq 2p_t$$

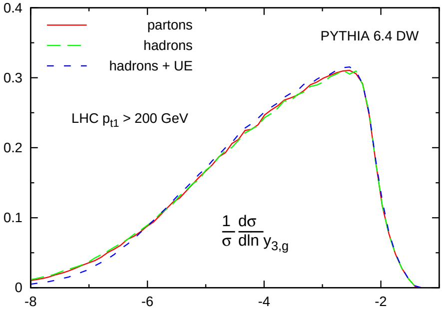
$$\mu_R/2 \leq \mu_F \leq 2\mu_R$$

- Rescaling of the argument of the logs to be resummed

$$\ln T_m \to \ln(XT_m) \qquad 1/2 \leq X \leq 2$$

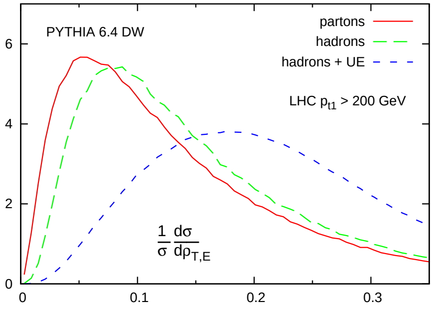
- Change the procedure to match NLL with NLO

Three-jet fractions are hardly affected by hadronisation and UE



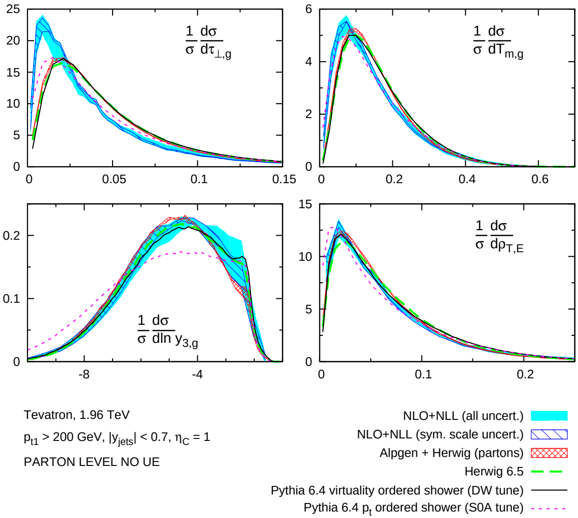
- PT predictions directly compared to data $\Rightarrow$ PT consistency checks
- Suitable for tunings of parton shower parameters

Event-shape distributions get large corrections from UE



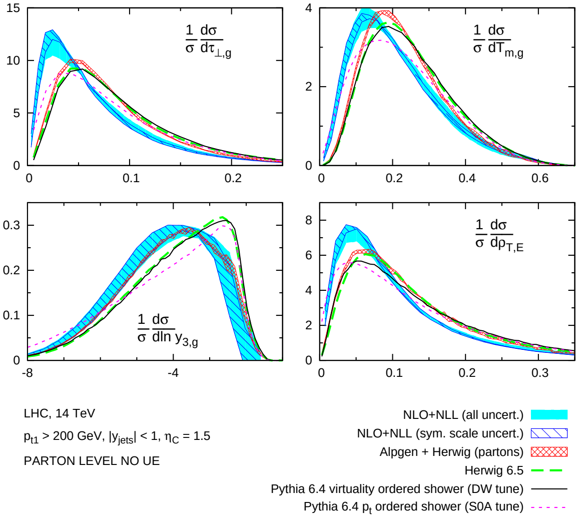
- Comparison to parton level MC for tests of parton shower
- Suitable for tests and tunings of UE models

NLL vs parton showers: Tevatron high-p_t (quark dominated)



Agreement between NLL and parton level MC is good for quark-dominated samples

NLL vs parton showers: LHC low-p_t (gluon dominated)



Sizable differences in gluon dominated samples $\Rightarrow$ new tests of initial state gluon branching?

Future developments for global observables

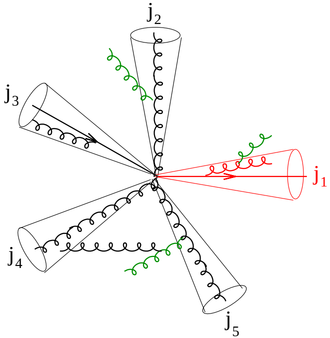
1. Straightforward extension to event shapes in processes with massive particles (Drell-Yan, Higgs, top, SUSY,etc.)
   - Characterisation of boson+jets with hadronic final states (out-of-plane radiation, jet mass, etc.)
   - Suitable event-shape distributions as central-jet vetoes [Stewart Tackmann Waalewijn PRL **105** (2010) 092002]
2. Resummation of transverse momentum distributions
   - Globalness and rIRC safety $\Rightarrow$ angular ordered branching at NLL
   - LL do not exponentiate in variable space $\Rightarrow$ CAESAR's automated predictions diverge for small transverse momentum
   - Check resummability conditions and perform analytic resummation in impact parameter space (see e.g. Z-boson a_T distribution) [AB Dasgupta Duran-Delgado JHEP **0912** (2009) 022]
3. Automated NNLL resummation $\Rightarrow$ new physical picture needed due to interplay between logarithms $\alpha_s^n L^m$ and constants α_s^m [Becher Schwartz JHEP **0807** (2008) 034]
   - Precision determination of $\alpha_s(M_Z)$ using e^+e^- event shapes [Abbate Fickinger, Hoang, Mateu Stewart, arXiv:1006.3080 [hep-ph]]

Outline

1. Event shapes at hadron colliders
2. Jet shapes and non-global logarithms
3. Shape variables for New Physics

Jet shapes are defined using hadrons in a single jet

- Less sensitive to initial-state radiation and underlying event
- Their distributions depend strongly (at the LL level) on the underlying jet flavour (quark or gluon jet)



Example: angularities of the observed jet, with jet minimum transverse energy E_0

[Ellis Hornig Lee Vermilion Walsh PLB **689** (2010) 82]

Example of angularity: distribution in jet invariant mass $M^2_{j_1}$

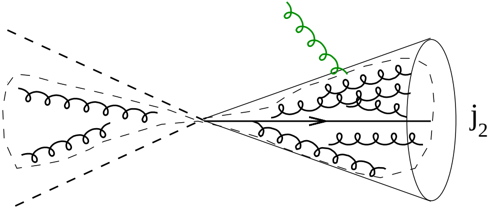
$$\Sigma(\rho, E_0) = \text{Prob}\left[\frac{M^2_{j_1}}{Q^2} < \rho, \sum_{i \notin \text{jets}} k_{ti} < E_0\right]$$

New sources of NLL contributions

Jet-shape distributions like $\Sigma(\rho, E_0)$ are non-global, because no hadrons are measured inside the unobserved jets $j_2, j_3, \ldots, j_N$

Non-global observables receive extra NLL contributions from soft large-angle gluons

- Non-global logarithms: gluons inside a jet coherently emitting a softer gluon in the interjet region (or viceversa)



These non-abelian contributions are resummed only in the large-N_c limit by solving a non-linear evolution equation

[Dasgupta Salam PLB **512** (2001) 323; AB Marchesini Smye JHEP **0208** (2002) 006]

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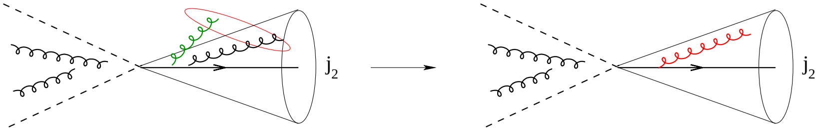
- Jet-clustering logarithms: gluons independently emitted in two different angular regions get recombined in the same jet



Resummed numerically with a generalisation of CAESAR branching algorithm from soft large-angle gluons

[AB Dasgupta PLB **628** (2005) 49]

In the anti-k_t algorithm (i.e. jets $=$ circular cones of radius R), jet-clustering logarithms are absent

NLL resummation for jet shapes

General NLL resummation of jet shapes for well-separated jets with the scale hierarchy $p_{t,\mathrm{jets}} \sim Q \gg E_0 \gg \rho Q/R^2$

[AB Dasgupta Khelifa-Kerfa Marzani JHEP **1008** (2010) 064]

$$\Sigma(\rho, E_0) = \Sigma^{\mathrm{sc}}\left(\frac{R^2}{\rho}, \frac{Q}{E_0}\right) S^{\mathrm{ng}}\left(\frac{R^2}{\rho}, \frac{Q}{E_0}\right) \Sigma^{\mathrm{cluster}}(\rho)$$

- Σ^{sc} is the jet-shape distribution obtained with only soft and collinear real emissions (the CAESAR's way)
- S^{ng} is the contribution from non-global logarithms

$$S^{\mathrm{ng}}\left(\frac{R^2}{\rho}, \frac{Q}{E_0}\right) = S_{j_1}\left(\frac{E_0}{\rho Q/R^2}\right) \prod_{i=2}^{N} S_{j_i}\left(\frac{Q}{E_0}\right)$$

  S^{ng} is the product of individual contributions of each jet

- $\Sigma^{\mathrm{cluster}}(\rho)$ is the contribution of jet-clustering logs

Both non-global and jet-clustering logarithms are finite for $R \to 0$

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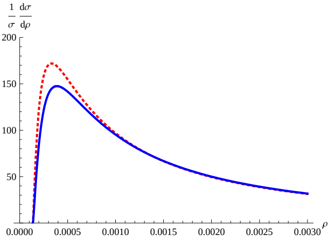
Impact of non-global logarithms

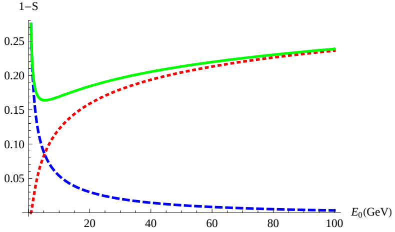
Toy example: two jets in e^+e^- annihilation with the anti-k_t algorithm

$$\Sigma^{\mathrm{ng}}\left(\frac{R^2}{\rho},\frac{Q}{E_0}\right)=S_{\mathrm{meas}}\left(\frac{E_0}{\rho Q/R^2}\right)\,S_{\mathrm{unmeas}}\left(\frac{Q}{E_0}\right)$$

Non-global logarithms arise when emissions in two different angular regions have widely separated characteristic scales

- Non-global logs modify the the peak height in distributions
- It is not possible to play with scales so as to get rid simultaneously of all non-global logarithms

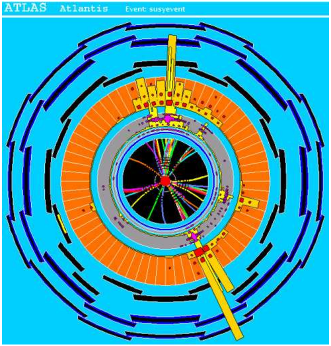




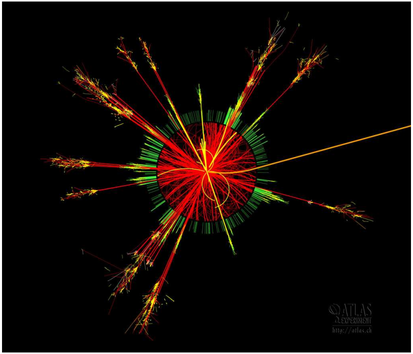
Outline

Which shapes for new physics?

New Physics events are generally broader than dijet events



SUSY multi-jet event

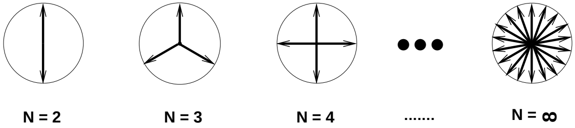


Black hole production

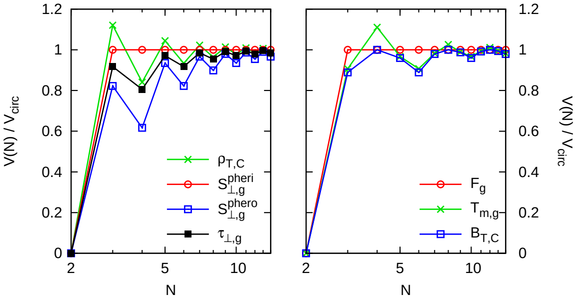
Use event shapes to discriminate among different topologies?

Discrimination between two- and multi-jet events

Consider a maximally symmetric event in the transverse plane

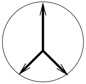


- Event shapes can discriminate between two- and multi-jet events
- Current event shapes are not monotonic with number of jets ⇒ no distinction among different multi-jet samples



Sensitivity to spherical topologies

Consider two selected 3-jet events at $\eta = 0$ with Herwig parton shower



Event 1 (generic)		Event 2 (Mercedes)	
$p_{t1} = 828$ GeV,	$\phi_1 = 0$	$p_{t1} = 666$ GeV,	$\phi_1 = 0$
$p_{t2} = 588$ GeV,	$\phi_2 = 3\pi/4$	$p_{t2} = 666$ GeV,	$\phi_2 = 2\pi/3$
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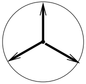
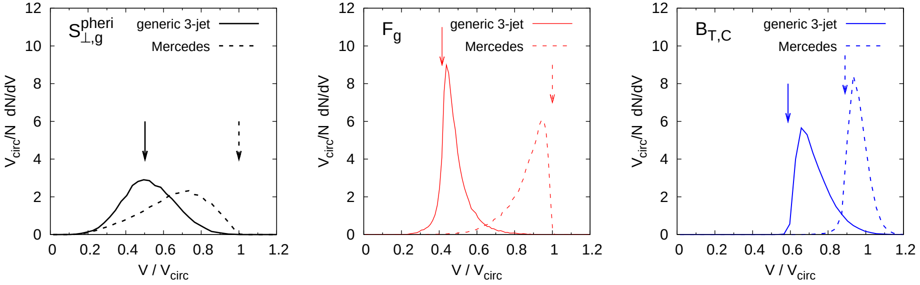


- IRC safe shape variables give better resolution in discriminating among different topologies in a given n-jet sample
- Variables like $B_{T,\mathcal{C}}$ or $\rho_{T,\mathcal{C}}$, equally sensitive to transverse and longitudinal degrees of freedom, better suited for identification of massive particle decays



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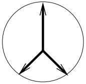

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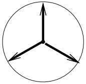

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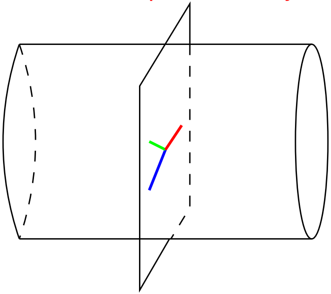

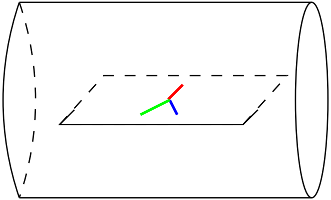

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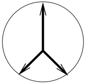
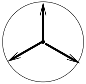
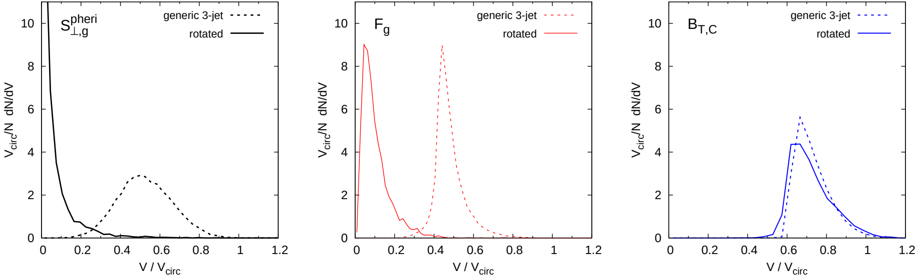


Event 1 (generic)	Event 2 (Mercedes)
$p_{t1} = 828$ GeV, $\phi_1 = 0$ $p_{t2} = 588$ GeV, $\phi_2 = 3\pi/4$ $p_{t3} = 588$ GeV, $\phi_3 = -3\pi/4$	$p_{t1} = 666$ GeV, $\phi_1 = 0$ $p_{t2} = 666$ GeV, $\phi_2 = 2\pi/3$ $p_{t3} = 666$ GeV, $\phi_3 = -2\pi/3$



- IRC safe shape variables give better resolution in discriminating among different topologies in a given n-jet sample
- Variables like $B_{T,\mathcal{C}}$ or $\rho_{T,\mathcal{C}}$, equally sensitive to transverse and longitudinal degrees of freedom, better suited for identification of massive particle decays



Summary

Phenomenology of global event shapes at hadron colliders is very rich and challenging

- First ever NLL+NLO predictions with full theoretical uncertainties
- Event shapes extremely useful for tuning of MC shower and UE

Event-shape measurements have been performed at the Tevatron and are being performed at the LHC

Resummation of non-global observables remains extremely tricky

- Non-global logarithms are well understood in the large-N_c limit
- Jet-clustering logarithms can be computed at all orders but very little general features are known (e.g. behaviour with jet radius)
- Coherence violating logarithms might have large impact

Important research directions

- Better event shapes for New Physics searches
- Transverse momentum resummations (e.g. $t\bar{t}$, dijets)
- Automated NNLL for global observables