Phenomenology of event shapes at hadron colliders

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Work done in collaboration with
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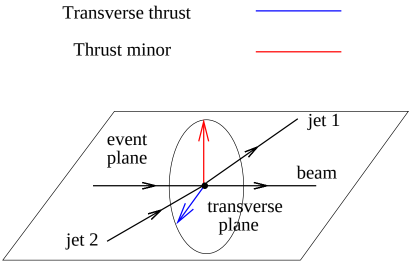
Event shapes in hadron-hadron collisions

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



$$T_{t,g} \equiv \max_{\vec{n}_t} \frac{\sum_i |\vec{q}_{ti} \cdot \vec{n}_t|}{\sum_i q_{ti}}$$

$$T_{m,g} \equiv \frac{\sum_i |\vec{q}_{ti} \times \vec{n}_t|}{\sum_i q_{ti}}$$

Event shapes can be measured with very first LHC data

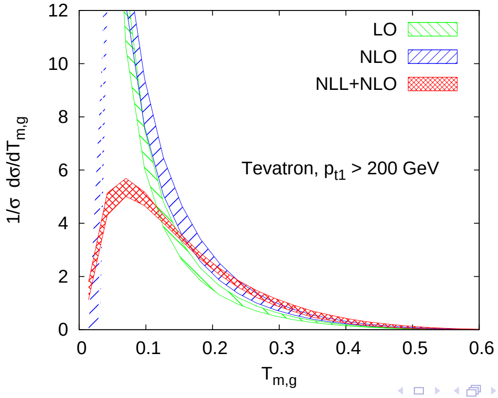
- Normalisation of T_t and T_m gives a reduced sensitivity to detector calibration effects
- Measure event-shape fractions (e.g. $1/\sigma d\sigma/dT_m$) $\Rightarrow$ no need to measure luminosity

Event shapes sensitive to longitudinal momenta: $\rho_T, \rho_H, B_T, B_W, y_{23}$

Comparison of resummation and fixed order

General feature of event shape differential distributions in PT QCD

- Fixed order predictions ($\alpha_s + \alpha_s^2$) diverge at small T_m
  [Nagy PRD **68** (2003) 094002]
- Resummation of large logarithms $\exp\{\alpha_s^n \ln^{n+1} T_m + \alpha_s^n \ln^n T_m\}$ restores correct physical behaviour for $T_m \to 0$
  [AB Salam Zanderighi arXiv:1001.4082]



Computer automated resummation: CAESAR

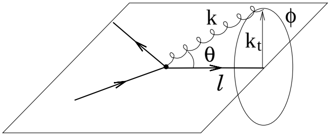
General NLL resummation for any event shape is possible with the Computer Automated Expert Semi-Analytical Resummer

[AB Salam Zanderighi hep-ph/0407286, qcd-caesar.org]

An event shape $V(k_1, \ldots, k_n)$ is resummable with CAESAR if

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

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

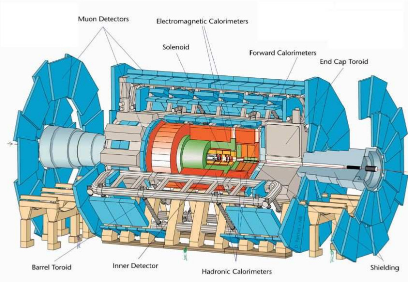


2. it is (continuously) global, i.e. it is sensitive to soft/collinear emissions in the whole of the phase space
3. it is recursively IRC safe, i.e. it has good scaling properties with respect to multiple emissions

Experimental setup and globalness

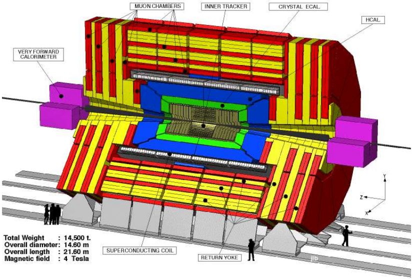
Experimental analyses cannot cover the whole of the phase space

- Observed hadrons are usually charged particles in the central tracker region, at the LHC central region is $|\eta| < 2.5$
- Outside the central region no measurements possible in the beam pipe, at the LHC $|\eta| \gtrsim 5$



The ATLAS detector

The CMS detector

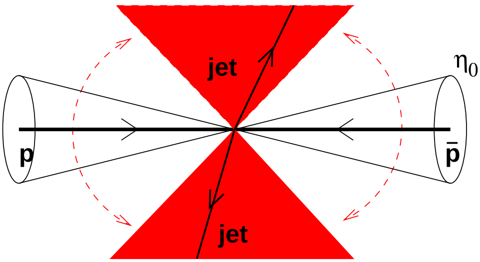


Experimental setup can lead to non-global observables

Three classes of global event shapes

- Directly global: measure all hadrons up to the maximum available rapidity η_0

  ☹ NLL resummations valid down to $v_{\min} \simeq e^{-c_V \eta_0}$ with observable dependent constant c_V (e.g. $[T_{m,g}]_{\min} \simeq e^{-\eta_0}$)



V	g	$\mathcal{E}$	$\mathcal{R}$
$\tau_\perp$	✓		
T_m	✓		
y_3	✓		
ρ_T	–		
ρ_H	–		
B_T	–		
B_W	–		
F	✓		
S	✓		

Definition of global event shapes

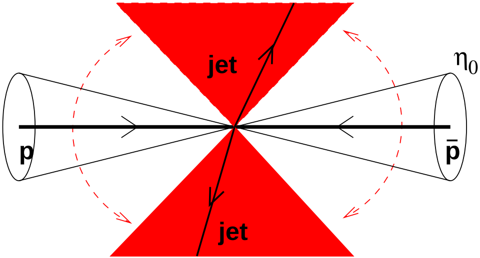
Three classes of global event shapes

- Exponentially suppressed: define event shape in central region $\mathcal{C}$ and add exponentially suppressed forward term $\mathcal{E}_{\bar{\mathcal{C}}}$

$$\mathcal{E}_{\bar{\mathcal{C}}} = \frac{1}{Q_{t,\mathcal{C}}} \sum_{i \notin \mathcal{C}} q_{ti}\, e^{-|\eta_i - \eta_{\mathcal{C}}|} \qquad Q_{t,\mathcal{C}} = \sum_{i \in \mathcal{C}} q_{ti}$$

☹ Affected by coherence violating logarithms?

[Forshaw Kyrieleis Seymour JHEP **0608** (2006) 059]



V	g	$\mathcal{E}$	$\mathcal{R}$
$\tau_\perp$	✓	✓	
T_m	✓	✓	
y_3	✓	✓	
ρ_T	–	✓	
ρ_H	–	✓	
B_T	–	✓	
B_W	–	✓	
F	✓	✓	
S	✓	✓	

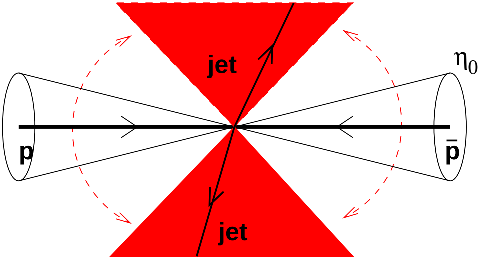
Definition of global event shapes

Three classes of global event shapes

- Recoil: define event shape in central region and add recoil term

$$\mathcal{R}_{t,\mathcal{C}} \equiv \frac{1}{Q_{t,\mathcal{C}}}\left|\sum_{i\in\mathcal{C}} \vec{q}_{ti}\right| = \frac{1}{Q_{t,\mathcal{C}}}\left|\sum_{i\notin\mathcal{C}} \vec{q}_{ti}\right| \qquad Q_{t,\mathcal{C}} = \sum_{i\in\mathcal{C}} q_{ti}$$

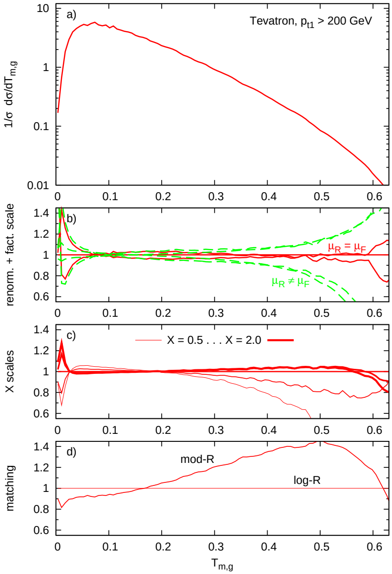
☹ Divergence of NLL resummation at observable dependent v_c



V	g	$\mathcal{E}$	$\mathcal{R}$
$\tau_\perp$	✓	✓	✓
T_m	✓	✓	✓
y_3	✓	✓	✓
ρ_T	–	✓	✓
ρ_H	–	✓	✓
B_T	–	✓	✓
B_W	–	✓	✓
F	✓	✓	✓
S	✓	✓	✓

Estimate of theoretical uncertainties

Event selection: at least two central jets with a cut on highest-p_t jet



- 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 estimate NNLL corrections

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

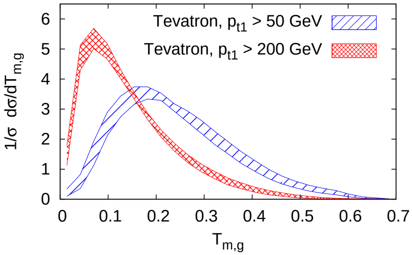
- Change the procedure to match NLL resummation with NLO, so as to estimate NNLO contributions

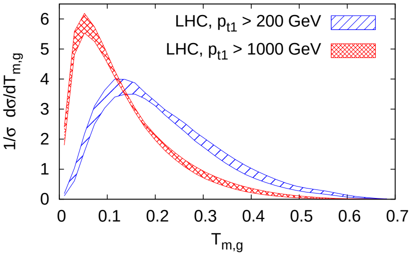
Effect of hard kinematical cuts

High-statistics low- and high-p_t samples at Tevatron and at the LHC

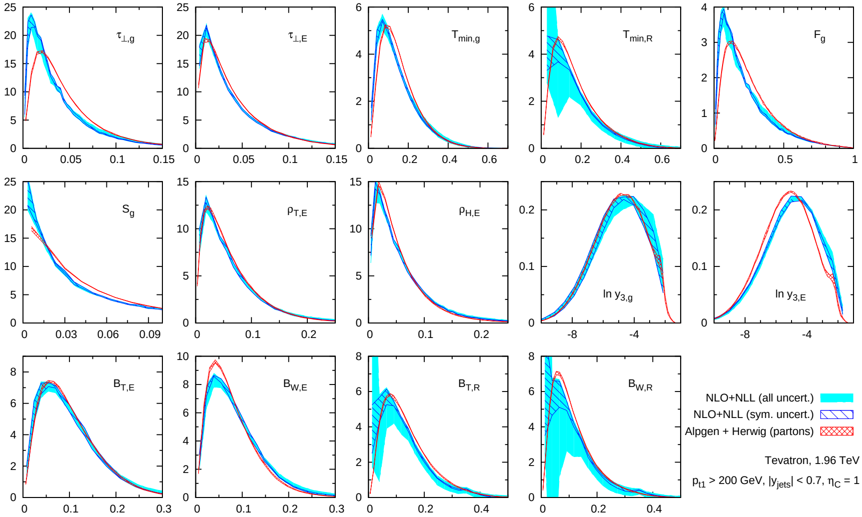
	LO	NLO	$qq \to qq$	$qg \to qg$	$gg \to gg$
Tevatron, $p_{t1} > 50\mathrm{GeV}$	$60\mathrm{nb}$	$116\mathrm{nb}$	10%	43%	45%
Tevatron, $p_{t1} > 200\mathrm{GeV}$	$59\mathrm{pb}$	$101\mathrm{pb}$	41%	43%	12%
$14\mathrm{TeV}$ LHC, $p_{t1} > 200\mathrm{GeV}$	$13.3\mathrm{nb}$	$23.8\mathrm{nb}$	7%	40%	50%
$14\mathrm{TeV}$ LHC, $p_{t1} > 1\mathrm{TeV}$	$6.4\mathrm{pb}$	$10.5\mathrm{pb}$	31%	51%	17%

Variation of the p_t cut changes flavour composition and hence double logarithmic contributions responsible for the position of the peak

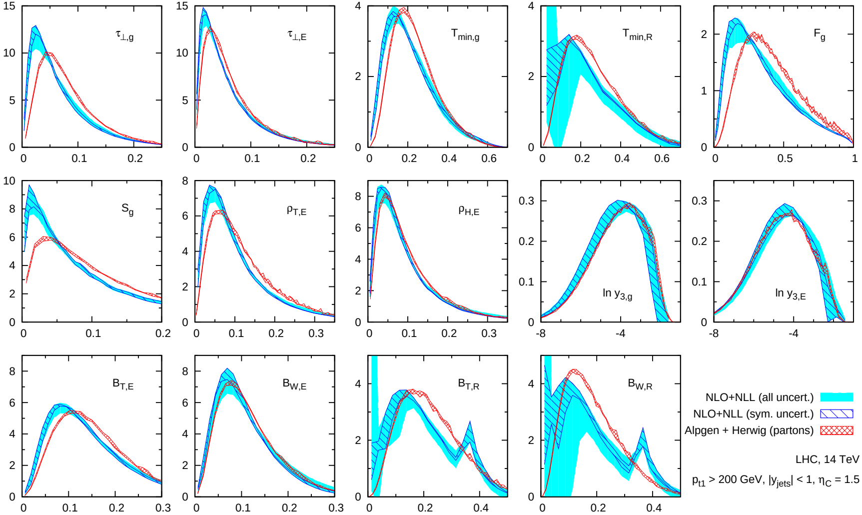




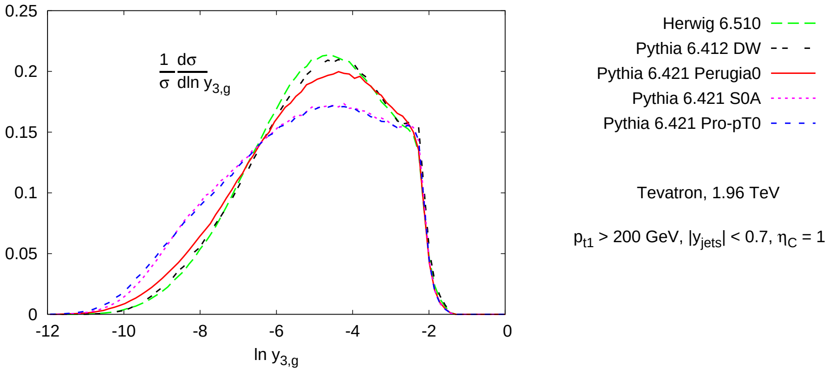
Comparison with parton shower: Tevatron high-p_t sample



Comparison with parton shower: LHC low-p_t sample



Sensitivity to parton shower tunings



- Historical Herwig (angular-ordered) and Pythia DW (mass-ordered) showers agree with Alpgen+Herwig
- Predictions with new p_t-ordered Pythia show large sensitivity to shower parameters

Event shapes are ideal for testing new parton shower algorithms

Messages from perturbative studies

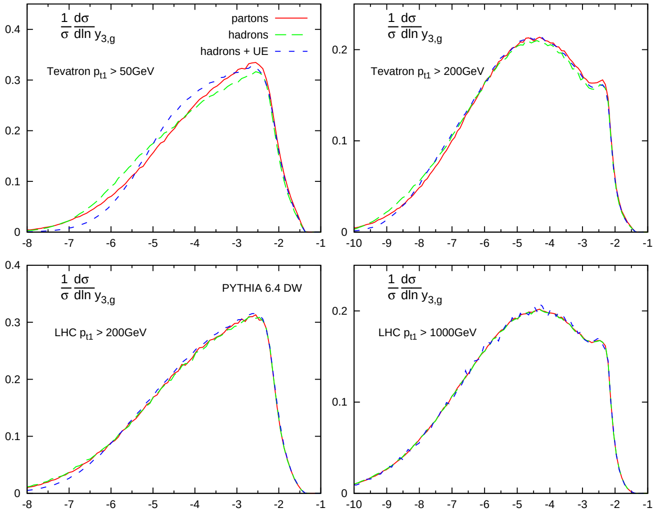
Pure perturbative studies

- Full theoretical uncertainties around 20%, underestimated by symmetric scale variations $\mu_R = \mu_F$
- Divergence of recoil observables increase uncertainty of resummations close to the peak region
- Hard emissions at the boundary of central region give bumps in fixed order for recoil observables, e.g. $B_{T,\mathcal{R}}, B_{W,\mathcal{R}} \sim 0.4$

Comparison with parton showers

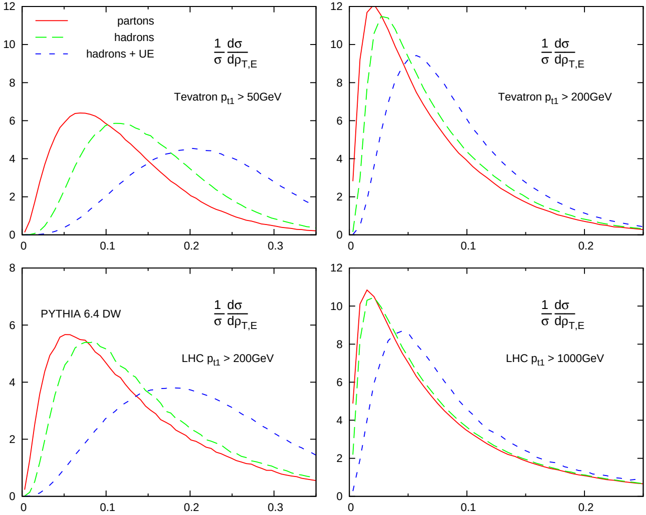
- Overall good agreement, although MC predictions tend to be harder, especially for gluon dominated samples.
- Agreement is good for historical showers, poorer for Pythia p_t-ordered in some tunes $\Rightarrow$ event-shapes should be used for testing and tuning new showers

Hadronisation and underlying event: low sensitivity



Jet resolution variables suitable for tuning parton shower parameters

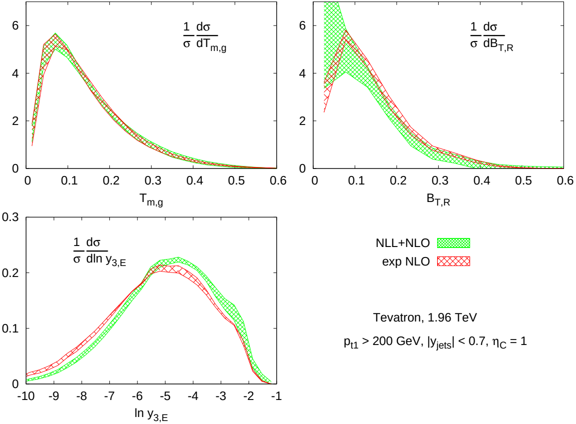
Hadronisation and underlying event: high sensitivity



Event shape variables good for tests of UE and hadronisation models

Recipe to exploit fixed order to estimate resummation effects

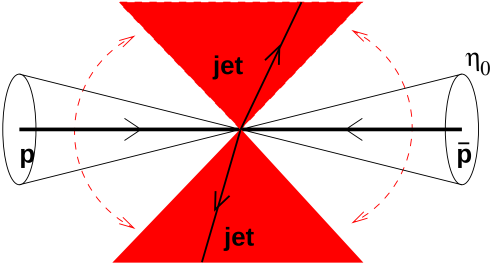
$$\frac{d\sigma}{dv} = \frac{d}{dv}\left[\exp\left\{\Sigma_1(v) + \Sigma_2(v) - \frac{1}{2}[\Sigma_1(v)]^2\right\}\right] \qquad \Sigma_i(v) = \sigma_i + \int_{v_{\max}}^{v} dv' \frac{d\sigma_i}{dv'}$$



Particles vs. jets as inputs

Event shapes preferably measured with jets rather than hadrons $\Rightarrow$ problems with globalness

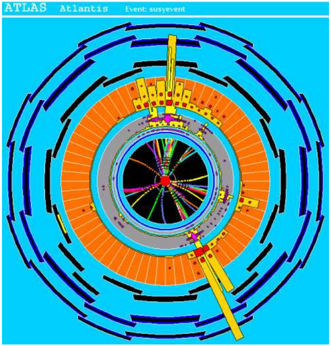
- Cutoff p_{t0} to eliminate contamination from UE
  $\Rightarrow$ NLL resummation sensible for $v \gg (p_{t0}/Q)^a$
- No sensitivity to emissions clustered in the same outgoing jet
  $\Rightarrow$ use topoclusters/energy flows inside central jets and jets elsewhere



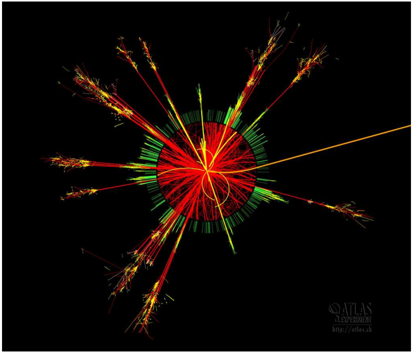
Jets as inputs can be used for event shapes in new-physics searches

Event shapes for new physics?

New physics events are generally broader than dijet events



SUSY multi-jet event

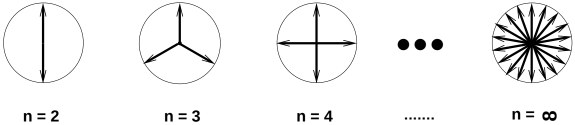


Black hole production

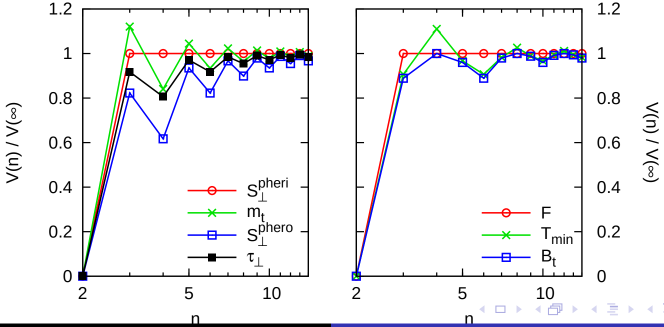
Use event shapes to discriminate among different topologies?

Discrimination between two- and multi-jet events

Consider a maximally symmetric event in the transverse plane

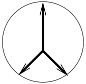


- Event shapes can discriminate between two- and multi-jet events
- Current event shapes are not monotonic with number of jets $\Rightarrow$ no distinction among different multi-jet samples

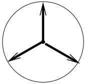


Sensitivity to the symmetric topologies

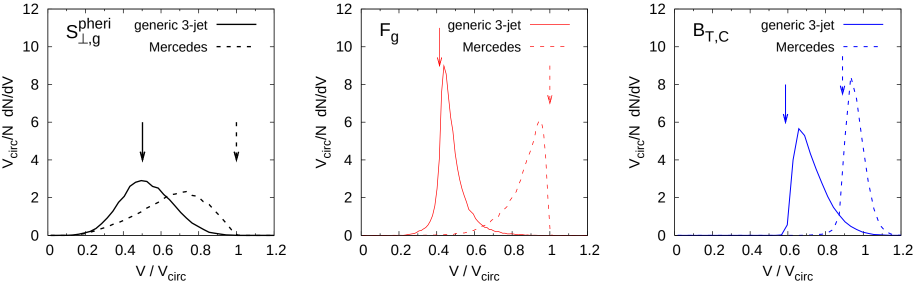
Consider two selected 3-jet events at $\eta = 0$ with Herwig parton shower



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,	$\phi_2 = 2\pi/3$
$p_{t3} = 588$ GeV,	$\phi_3 = -3\pi/4$	$p_{t3} = 666$ GeV,	$\phi_3 = -2\pi/3$



- IRC event shapes give better resolution in discriminating among different topologies in a given n-jet sample
- Rotationally invariant event-shapes, like central broadening $B_{T,\mathcal{C}}$, can be used for identification of massive particle decays



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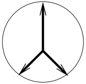

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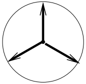

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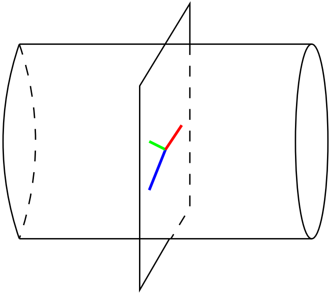

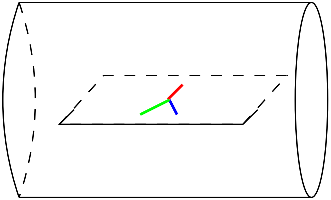

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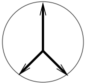

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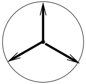

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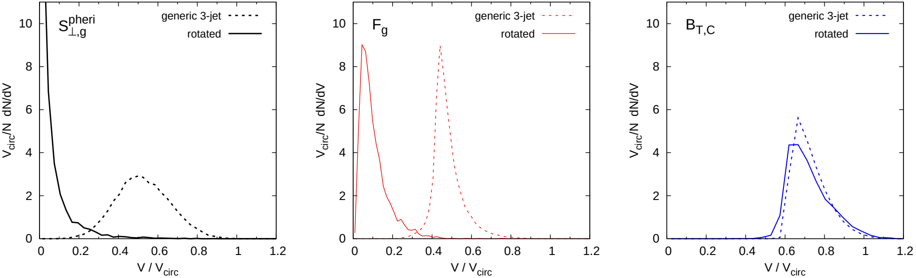

Conclusions

Phenomenology of event shapes at hadron colliders is extremely rich

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

There are many intriguing issues, including

- using jets rather than particles as inputs
- a trick to extend range of validity of NLO predictions without computing the resummation
- new variable supersphero with increased sensitivity to the spherical limit

Important research direction

- Better event shapes for New Physics searches

Preliminary measurements have been performed at the Tevatron and will be performed at the LHC

We are ready for many years of Physics. . .