Characterizing the underlying event in hadron-hadron collisions

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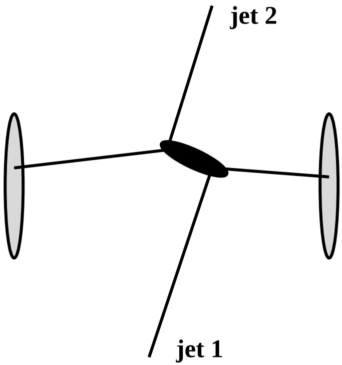
ECT - Trento, Nov 29th - Dec 3rd, 2010*

[§]M.Cacciari, G.P.Salam and SS, JHEP 1004 (2010) 065

What is the underlying event?

$pp \rightarrow jj \;=$ 

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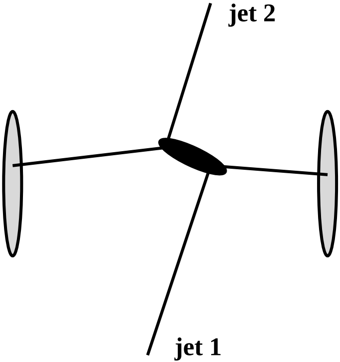
$pp \to jj \;=$ 

+ beam remnants
+ initial state radiation
+ multiple-parton interactions
+ ...

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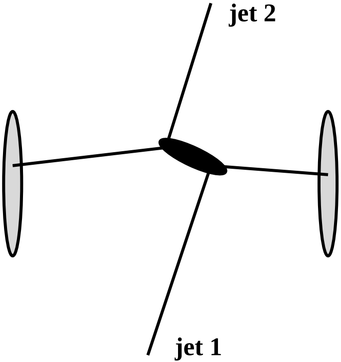

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+ initial state radiation
+ multiple-parton interactions
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hard interaction | **underlying activity**

- these are ingredients of present Monte Carlo models

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This leads us to the following two questions:

1. what do we really measure with existing methods of UE determination?
   $\longrightarrow$ test the methods with toy model
2. which observables are interesting to measure?
   $\longrightarrow$ study UE from Monte Carlo models

What can we measure about UE?

Relevant characteristics of energy flow of UE

- ρ – level of transverse momentum per unit area
- rapidity dependence of ρ
- point-to-point fluctuations within a single event ($\equiv \sigma$)
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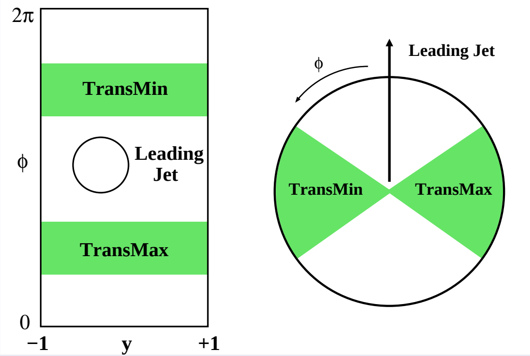
Two existing methods for measuring UE

- traditional approach
- jet area/median based approach

Traditional approach [Marchesini & Webber (1988), UA1 (1988), Field et al.]

For each event

1. take charged particles with $p_t > 0.5$ GeV and $|y| < y_{\max}$
2. cluster with cone jet algorithm with $R = 0.5 - 0.7$ to find the leading jet
3. define typical p_t of UE as $\langle p_t \rangle$ in TransMin, TransMax or TransAv regions



TransAv: $\mathcal{O}(\alpha_s)$

TransMax: $\mathcal{O}(\alpha_s)$

TransMin: $\mathcal{O}(\alpha_s^2)$

- **topological** separation: UE defined as particles entering certain region of (y, ϕ) space

Parenthesis: Sequential recombination jet algorithms

Distance measure between pair of particles d_{ij} and between particle and beam d_{iB}

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}\,, \qquad\qquad d_{iB} = k_{ti}^{2p}\,,$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ is a geometrical distance in the (y, ϕ) plane

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- identify the smallest of d_{ij} and d_{iB}
- recombine particles i and j (if d_{iB} is the smallest call i a jet and remove it)
- recalculate distances and repeat the procedure until no entries are left

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$p = 1$: k_t algorithm
[Catani, Dokshitzer, Seymour, Webber (1993); Ellis, Soper (1993)]

$p = 0$: Cambridge/Aachen algorithm
[Dokshitzer, Leder, Moretti, Webber (1997); Wobisch, Wengler (1999)]

$p = -1$: anti-k_t algorithm
[Cacciari, Salam, Soyez (2008)]

Parenthesis: Jets have areas [Cacciari, Salam, Soyez (2008)]

To determine the **active area** of a jet

- supplement a set of physical particles $\{p_i\}$ with an ensemble of dense, infinitely soft, randomly distributed *ghost particles* $\{g_i\}$
- cluster the set $\{p_i, g_i\}$
- compute the active area of a jet J for this specific ensemble of ghosts $\{g_i\}$

$$A(J \mid \{g_i\}) = \frac{\mathcal{N}(J)}{\nu_g},$$

  where $\mathcal{N}(J)$ is the number of ghosts contained in the jet J and ν_g is the number of ghosts per unit area

- average over many ghost ensembles

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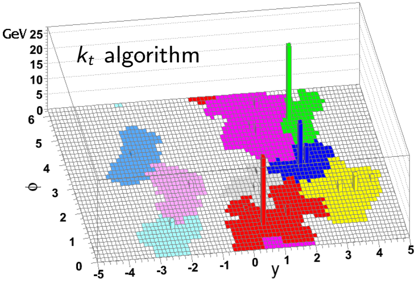
http://fastjet.fr



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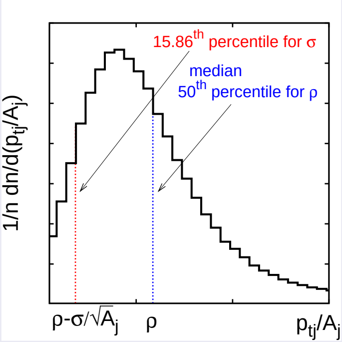
2. from the list of all jets (no cuts required!) determine

$$\rho = \text{median}\left[\left\{\frac{p_{t,j}}{A_j}\right\}\right]$$

   and its uncertainty σ

   - median gives a typical value of p_t/A for a given event
   - using median is a way to **dynamically** separate hard and soft parts of the event



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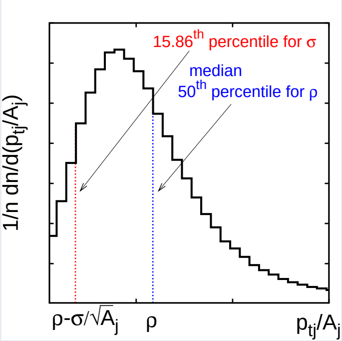

- ρ may be used e.g. to correct hard jet transverse momentum

$$p_{t,j}^{(\text{sub})} = p_{t,j} - \rho\, A_j \pm \sigma\sqrt{A_j}$$

since jet area measures the jet susceptibility to the soft radiation

Understanding the methods – a toy model study

Two component model: soft UE + hard contamination

soft component (UE)

- take the region of area A in (y, ϕ) space $\longrightarrow$ transverse region (traditional approach) or jet area (area/median approach)
- number of particles in this region, n, given by Poisson distribution with the average $\langle n \rangle$
- single-particle p_t distribution given by

$$\frac{dpt_1}{dp_t} = \frac{1}{\mu} e^{-p_t/\mu}$$

- parameters:
  μ – average p_t of particle,
  $\nu = \frac{\langle n \rangle}{A}$ – density of particles
- in this model $\rho = \mu\nu$ is the true value of p_t/A of UE

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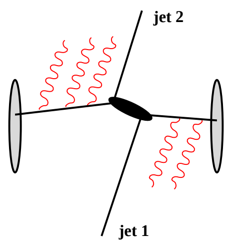
hard component (ISR)

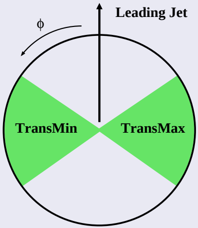


- soft and collinear partons from primary emissions:
  $$\frac{dn}{dp_t dy d\phi} \simeq \frac{C_i}{\pi^2} \frac{\alpha_s(p_t)}{p_t}$$
- hard scale cut $Q = \frac{1}{2} p_t = 50$ GeV
- partons distributed uniformly in angle and rapidity

Two component model: biases

Traditional approach

- TransAv and TransMin variants



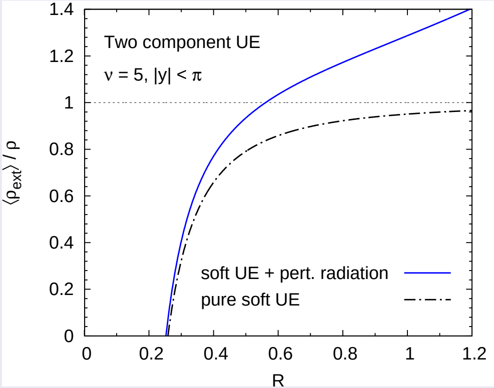
$$\langle \rho_{\text{ext,Av}} \rangle = \rho + \frac{C_i \alpha_s}{\pi^2} Q$$

$$\langle \rho_{\text{ext,Min}} \rangle \simeq \rho - \frac{\sigma \mathcal{P}}{\sqrt{\pi A_{\text{Trans}}}} + 2 \left(\frac{C_i \alpha_s}{\pi^2} \right)^2 A_{\text{Trans}}\, Q$$

$\mathcal{P}$ – fraction of events with perturbative radiation smaller then soft fluctuations

Two component model: biases

Area/median approach



$$\langle \rho_{\rm ext} \rangle \simeq \langle \rho_{\rm ext}^{\rm (soft)} \rangle + \sqrt{\frac{\pi c_J}{2}} \sigma R \frac{\langle n_h \rangle}{A_{\rm tot}}$$

$\langle n_h \rangle$ – number of perturbative part.

σ – measure of fluctuations

ρ – true value of p_t/A

$$\frac{\langle n_h \rangle}{A_{\rm tot}} \simeq \frac{n_b}{A_{\rm tot}} + \frac{C_i}{\pi^2} \frac{1}{2b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Q)}$$

- the two terms bias $\langle \rho_{\rm ext} \rangle$ in opposite directions
- for $R \simeq 0.5 - 0.6$ (used in most MC analysis of UE) the biases largely cancel
- similar picture and conclusions for σ

Two component model: biases

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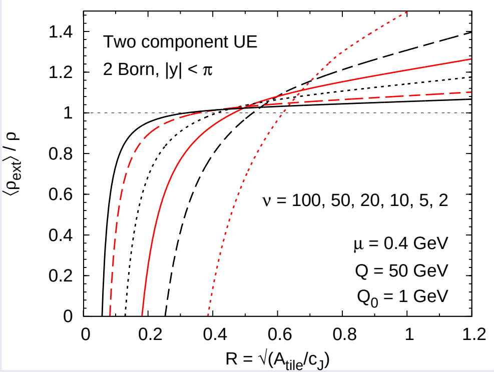

Turn-on point:

$$R_{\text{crit}} \simeq 0.41 \cdot \frac{\sigma}{\rho} = 0.41 \cdot \sqrt{\frac{2}{\nu}}$$

Point of zero bias:

$$R_{\text{zero-bias}} \simeq 0.87\, R_{\text{crit}}^{\frac{1}{3}} \left(\frac{C_A}{C_i}\right)^{\frac{1}{3}}$$

- for $R \simeq 0.5 - 0.6$ the uncertainty always stays below 20% for a broad range of particle densities ν

Fluctuations in estimation of ρ

In the toy model: the same ρ distribution used to generate all events

- however, there are event-to-event fluctuations of ρ due to restricted area
- this sets the lower limit for the uncertainty of ρ determination

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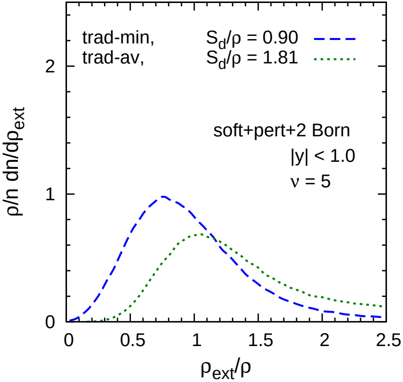

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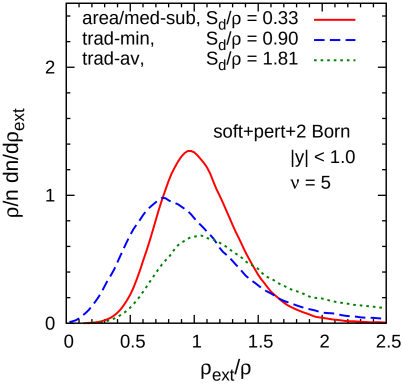
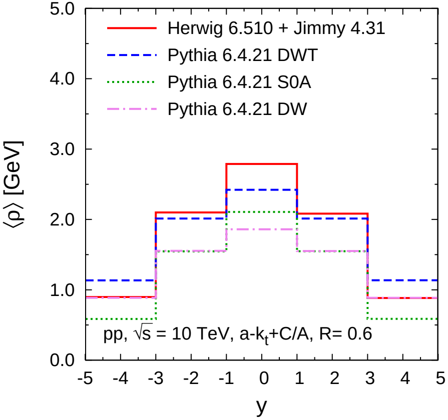


- traditional approach suffers significantly more from the hard contamination $S_d \sim Q$

Approaching real life – Monte Carlo study

Average ρ as a function of y

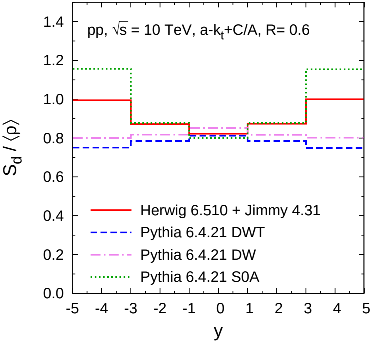
- dijets at the LHC, $\sqrt{s} = 10$ TeV, $p_t > 100$ GeV, $|y| < 4$



- significant y dependence
- strips of Δy=2 sufficient for robust ρ determination

Fluctuations

- from event to event



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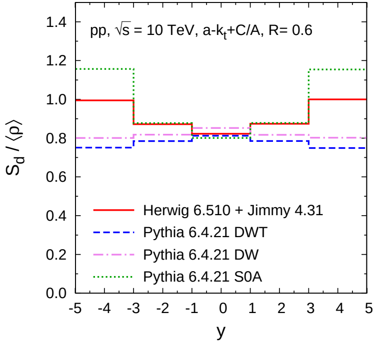
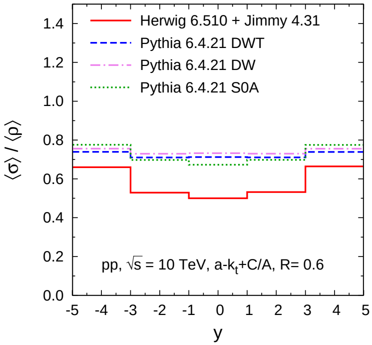
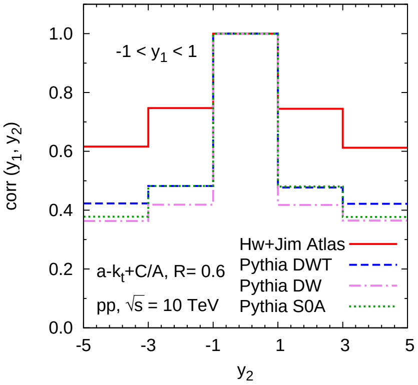


- within an event



- large inter-event and intra-event
- two patterns of rapidity dependence
- sizable difference between Herwig+Jimmy and Pythia

Correlations



$$\mathrm{corr}(y_1, y_2) = \frac{\langle \rho(y_1)\rho(y_2) \rangle - \langle \rho(y_1) \rangle \langle \rho(y_2) \rangle}{S_d(y_1) S_d(y_2)}$$

- y_1, y_2 – rapidity bins of width $\Delta y = 2$
- $\langle \ldots \rangle$ – average over many events

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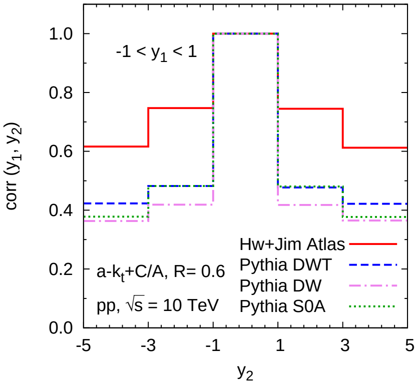

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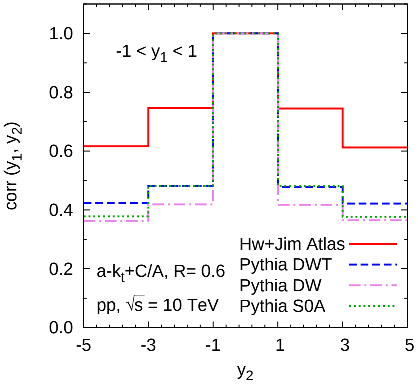

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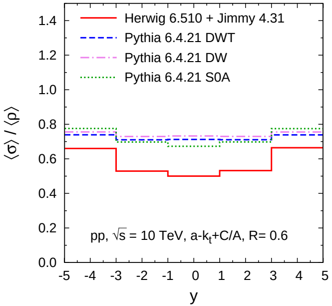
- significant difference between Herwig + Jimmy and Pythia
- qualitatively consistent with $\langle \sigma \rangle / \langle \rho \rangle$: smaller fluctuations within event ⇔ larger correlations



CMS analysis at $\sqrt{s} = 0.9$ TeV

Experimental conditions

- only charged tracks
- $p_t > 0.3$ GeV
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Modification of $\rho \longrightarrow \rho'$

$$\rho' = \underset{j \in \text{physical jets}}{\text{median}} \left[\left\{ \frac{p_{t,j}}{A_j} \right\} \right] \cdot \mathcal{C}$$

$$\mathcal{C} = \frac{\sum_{j \in \text{physical jets}} A_j}{A_{\text{tot}}}$$

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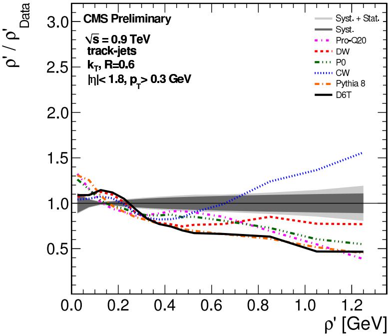

- can discriminate between UE tunes even at extreme conditions
- none of the tunes describes data
- looking forward to the 7 TeV results (also for other observables)

Summary

Measurement of UE is difficult both in principle and in practice

- we have considered a simple toy model to better understand the methods
- both traditional and area/based approach perform comparably well in measuring average quantities
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The study of UE from MC with the area/median method suggests the set of observables deserving dedicated measurements

- dependence of ρ on rapidity
- fluctuations from event to event (large for all generators/tunes)
- fluctuations within an event, σ, (significant differences between Herwig+Jimmy and Pythia)
- correlations (large differences between Herwig+Jimmy and Pythia)