On strategies for determination and characterization of the underlying event

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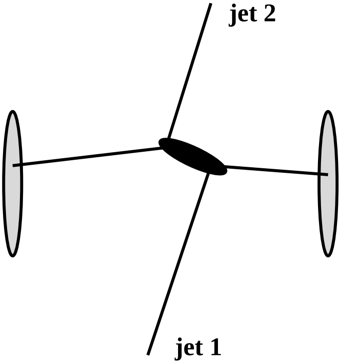
Rencontres de Moriond, QCD and High Energy Interactions, La Thuile, March 13-20, 2010

*M.Cacciari, G.P.Salam and SS, arXiv:0912.4926

What is the underlying event?

$pp \to jj \;=$



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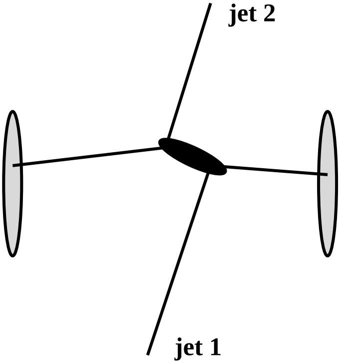

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+ initial state radiation
+ multiple-parton interactions
+ ...

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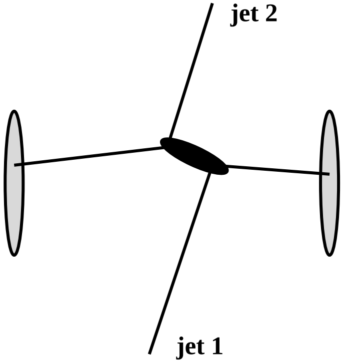

+ beam remnants
+ initial state radiation
+ multiple-parton interactions
+ ...

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 ($\equiv \sigma$)
- fluctuations from event to event
- point-to-point correlations

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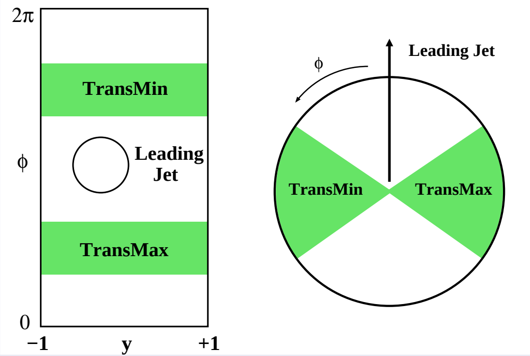
Two existing methods for measuring UE

- traditional approach
- 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 $|y| < 1$
2. cluster with cone jet algorithm with $R = 0.7$ 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

Area/median approach [Cacciari, Salam, Soyez (2008), http://fastjet.fr]

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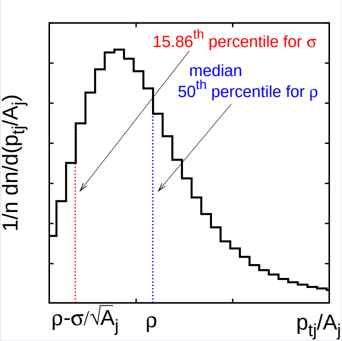

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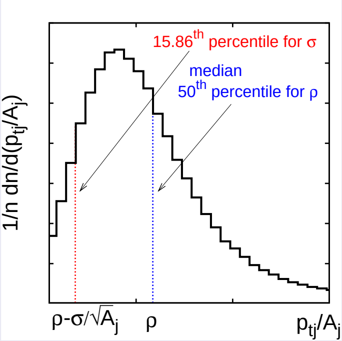
4. from the list of all jets (no cuts required!) determine
$$\rho = \text{median}\left[\left\{\frac{p_{t,j}}{A_j}\right\}\right]$$
and its uncertainty σ
   - median gives a typical value of p_t/A for a given event
   - using median is a way to **dynamically** separate hard and soft parts of the event



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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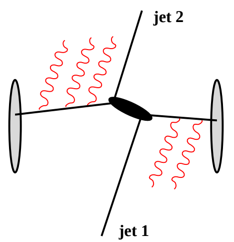
hard component (ISR)



- 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

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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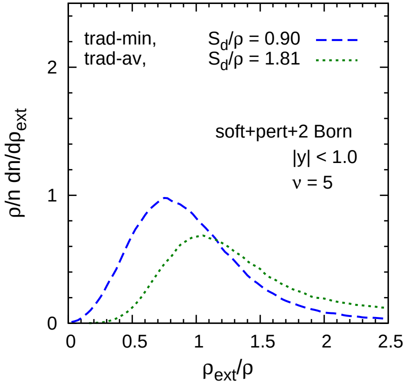

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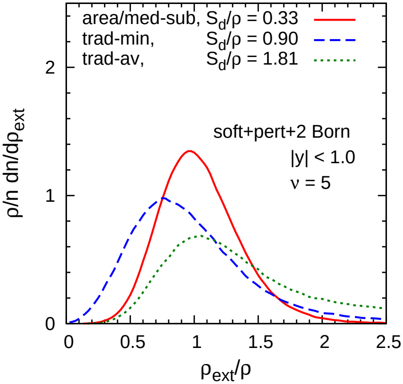
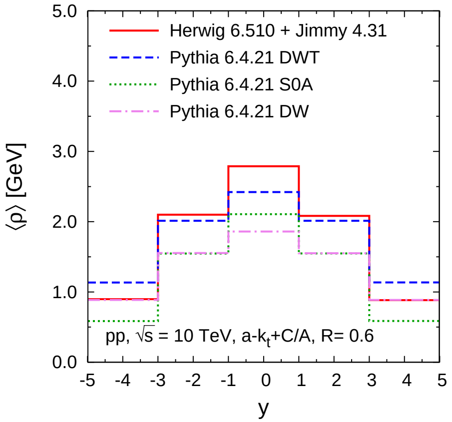


- traditional approach suffers significantly more from the hard contamination $S_d \sim Q$

Approaching real life – Monte Carlo study

Average ρ as a function of y

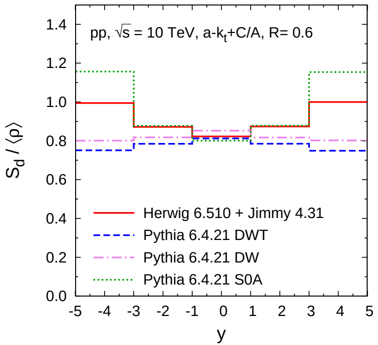
- dijets at the LHC, $\sqrt{s} = 10$ TeV, $p_t > 100$ GeV, $|y| < 4$



- significant y dependence
- strips of $\Delta y{=}2$ sufficient for robust ρ determination

Fluctuations

- from event to event



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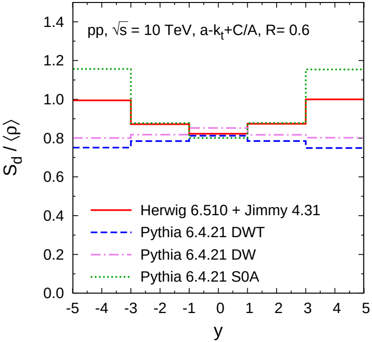
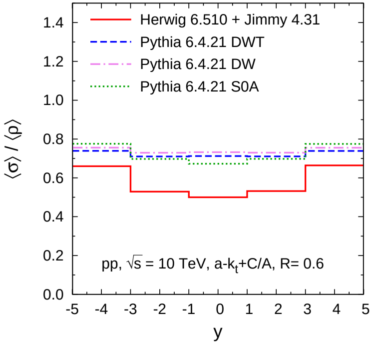
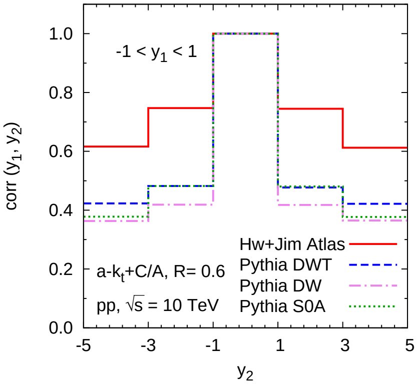


- within an event



- 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 $\Delta y = 2$
- $\langle \dots \rangle$ – average over many events

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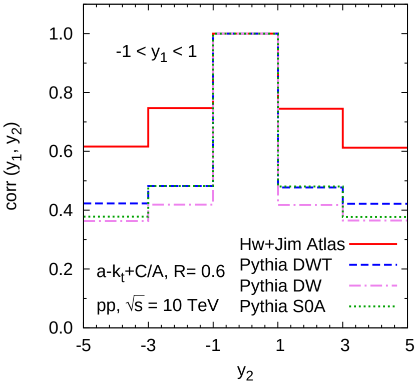

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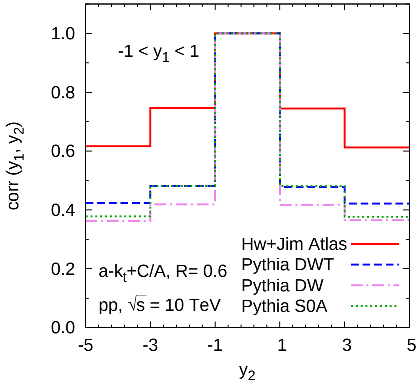

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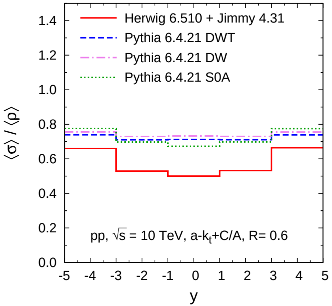
- significant difference between Herwig + Jimmy and Pythia
- qualitatively consistent with $\langle \sigma \rangle / \langle \rho \rangle$: smaller fluctuations within event $\Leftrightarrow$ larger correlations



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
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$\longrightarrow$ for more details see: arXiv:0912.4926

BACKUP SLIDES

Jets have areas

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

- supplement a set of physical particles $\{p_i\}$ with an ensemble of dense, infinitely soft and 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

$$A(J) \equiv \lim_{\nu_g \to \infty} \langle A(J \mid \{g_i\}) \rangle_g$$

Toy model: soft UE (extraction of ρ)

Traditional approach

$$\begin{aligned}\langle\rho_{\rm ext,av}\rangle &= \rho\\ \langle\rho_{\rm ext,min}\rangle &= \rho - \sigma/\sqrt{\pi A_{\rm Trans}}\\ \langle\rho_{\rm ext,max}\rangle &= \rho + \sigma/\sqrt{\pi A_{\rm Trans}}\end{aligned}$$

for $A_{\rm Trans} = 2$ and $\sigma \simeq 0.5 - 0.7\rho$

$$\sigma/\sqrt{\pi A_{\rm Trans}} \simeq 20 - 30\%$$

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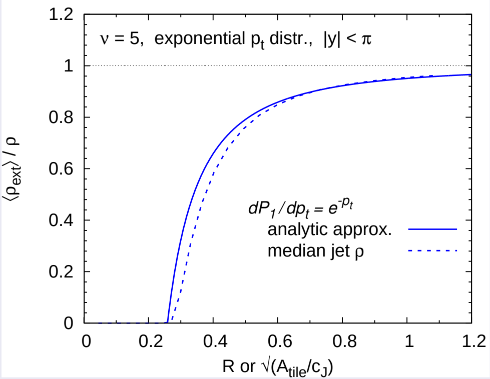
for $A_{\text{Trans}} = 2$ and $\sigma \simeq 0.5 - 0.7\rho$

$$\sigma / \sqrt{\pi A_{\text{Trans}}} \simeq 20 - 30\%$$

Area/median based approach

$$\frac{\langle \rho_{\text{ext}} \rangle}{\rho} \simeq \frac{c_J R^2 \nu - \ln 2}{c_J R^2 \nu - \ln 2 + \frac{1}{2}} \Theta(c_J R^2 \nu - \ln 2)$$

$$c_J \simeq 2 , \quad \nu = \text{particle density}$$



Two component model: biases

Traditional approach

- in the events with at least one perturbative emission the bias of $\rho_{\mathrm{ext,soft}}$ is removed and the bias of $\rho_{\mathrm{ext,hard}}$ dominates

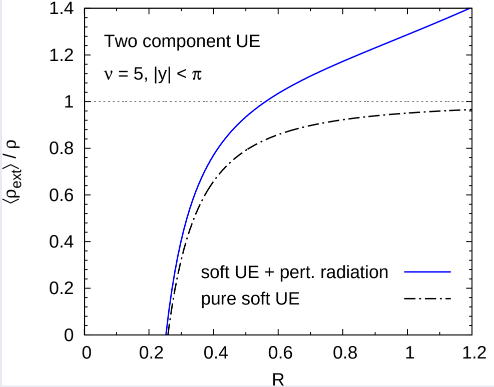
$$\langle \rho_{\mathrm{ext,Av}} \rangle = \rho + \frac{C_i \alpha_s}{\pi^2} Q$$

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

$\mathcal{P}$ – 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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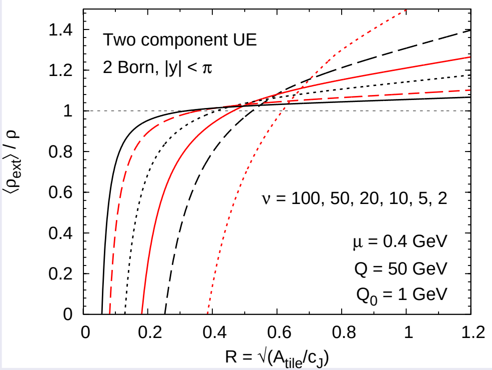


Turn-on point:

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

Point of zero bias:

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

- for $R \simeq 0.5 - 0.6$ (used in most MC analysis of UE) the biases largely cancel

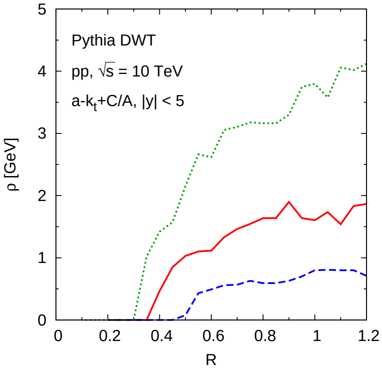
Summary of biases

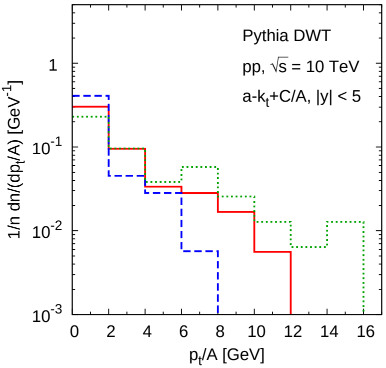
quantity	method	result	numerical value
$\frac{\delta\rho^{(\mathrm{soft})}}{\rho}$	TransAv	0	0
	TransMin	$-\frac{\sigma}{\rho}\frac{\mathcal{P}}{\sqrt{\pi A_{\mathrm{Trans}}}}$	-0.09
	Area/Med*	$-\frac{\sigma^2}{\rho^2}\frac{1}{4c_J R^2}$	-0.14
$\frac{\delta\rho^{(\mathrm{hard})}}{\rho}$	TransAv	$\frac{C_i\alpha_s}{\pi^2}\frac{Q}{\rho}$	0.99
	TransMin	$2\left(\frac{C_i\alpha_s}{\pi^2}\right)^2\frac{A_{\mathrm{Trans}}Q}{\rho}$	0.16
	Area/Med	$\frac{\sigma R}{\rho}\sqrt{\frac{\pi c_J}{2}}\left(\frac{n_b}{A_{\mathrm{tot}}}+\frac{C_i}{\pi^2}\frac{L}{2b_0}\right)$	0.17

Summary of biases (cont.)

quantity	method	result	numerical value
$\frac{S_d^{(\mathrm{soft})}}{\rho}$	TransAv	$\frac{\sigma}{\rho}\sqrt{\frac{1}{2A_{\mathrm{Trans}}}}$	0.31
	TransMin	$\frac{\sigma}{\rho}\sqrt{\frac{\pi-1}{\pi A_{\mathrm{Trans}}}}$	0.36
	Area/Med	$\frac{\sigma}{\rho}\sqrt{\frac{\pi}{2A_{\mathrm{tot}}}}$	0.22
$\frac{S_d^{(\mathrm{hard})}}{\rho}$	TransAv	$\sqrt{\frac{C_i\alpha_s}{4A_{\mathrm{Trans}}\pi^2}}\,\frac{Q}{\rho}$	1.72
	TransMin	$\frac{C_i\alpha_s}{\pi^2\sqrt{2}}\,\frac{Q}{\rho}$	0.70
	Area/Med	$\frac{\sigma R}{\rho}\sqrt{\frac{2\pi c_J}{A_{\mathrm{tot}}}}\left(\frac{n_b}{A_{\mathrm{tot}}}+\frac{C_i}{\pi^2}\frac{L}{2b_0}\right)^{\frac{1}{2}}$	0.19

Comparison of characteristics: toy model vs MC

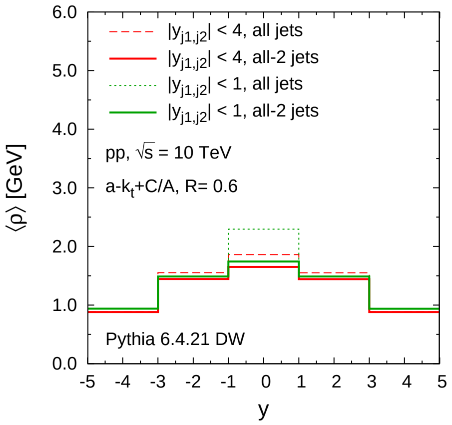




- the pattern for $\rho(R)$ from the toy model present in MC events: (i) turn-on at low R, (ii) linear growth at larger R
- variation in the curves indicative of the inter-event fluctuations
- growth of ρ with R produced by the tails of distributions of p_t/A

Average ρ as a function of y

- dijets at the LHC, $\sqrt{s} = 14$ TeV, $p_{t,\min} = 50$ GeV



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