Jets, UE and early LHC data

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LHC@BNL
Joint Theory/Experiment Workshop on Early Physics at the LHC

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Based on work with
Jon Butterworth, Andrea Banfi, Matteo Cacciari, John Ellis,
Are Raklev, Sebastian Sapeta, Gregory Soyez, Giulia Zanderighi

LHC is a parton collider

- Quarks and gluons are inevitable in initial state
- and ubiquitous in the final state

Partons — quarks and gluons — are key concepts of QCD.

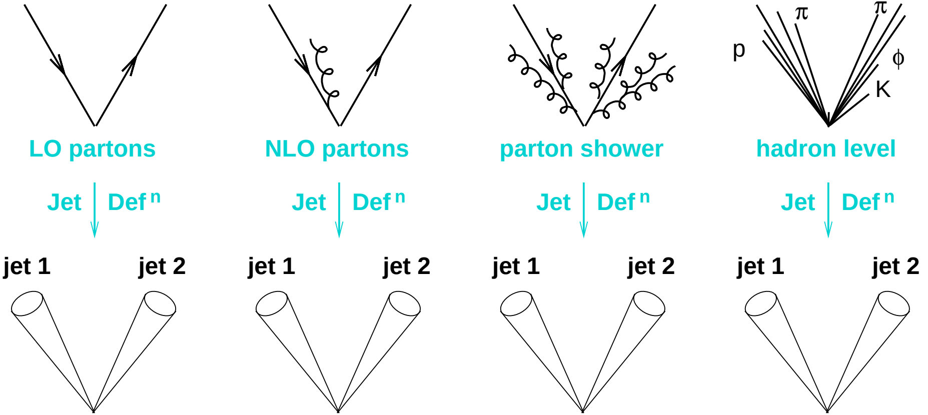
- Lagrangian is in terms of quark and gluon fields
- Perturbative QCD *only* deals with partons

Though we often talk of quarks and gluons, we never see them

- Not an asymptotic state of the theory — because of confinement
- But also even in perturbation theory

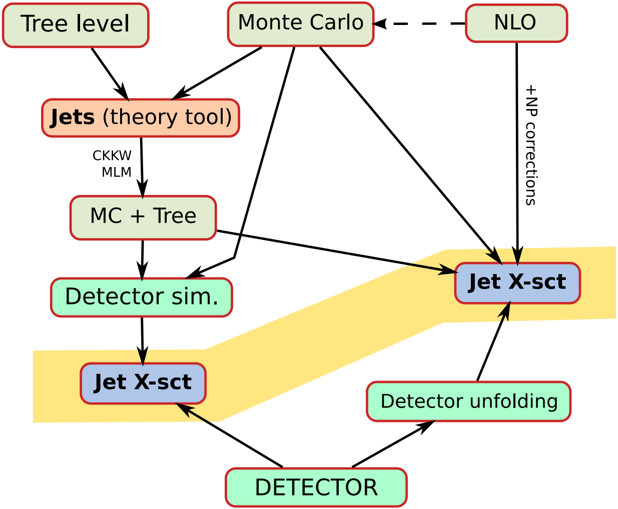
  because of collinear divergences (in massless approx.)
- The closest we can get to handling final-state partons is **jets**

Jets as projections



Projection to jets provides "universal" view of event

QCD jets flowchart



Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

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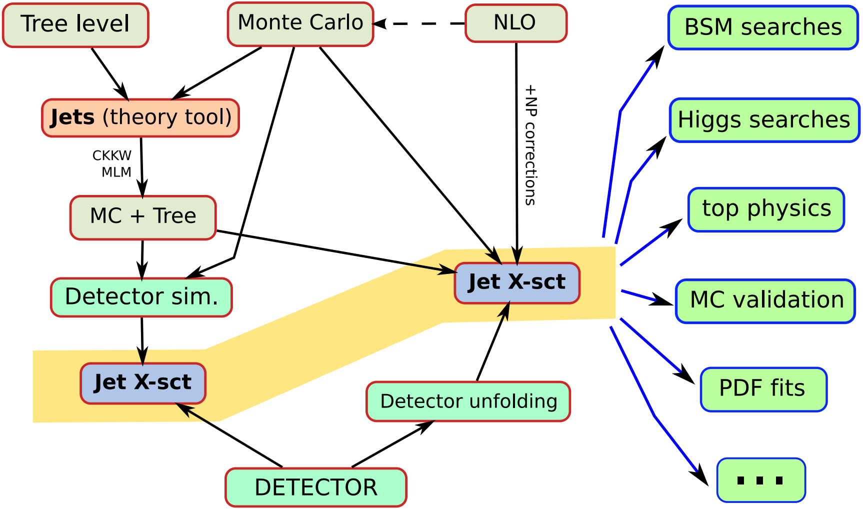

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Sequential recombination algorithms

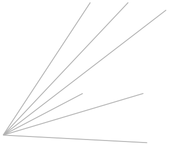
k_t algorithm — Catani, Dokshizter, Olsson, Seymour, Turnock, Webber '91–'93; Ellis, Soper '93

- Find smallest of all $d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ and $d_{iB} = k_i^2$
- Recombine
- Repeat

Bottom-up jets:

Sequential recombination

(attempt to invert QCD branching)



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- rapidity $y_i = \frac{1}{2} \ln \frac{E_i + p_{zi}}{E_i - p_{zi}}$
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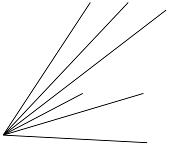

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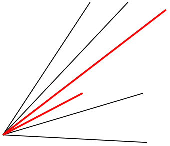

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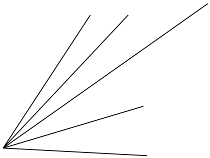

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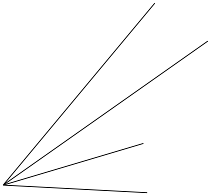

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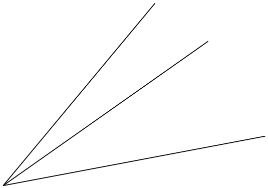

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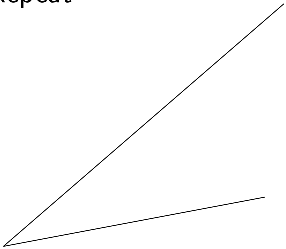

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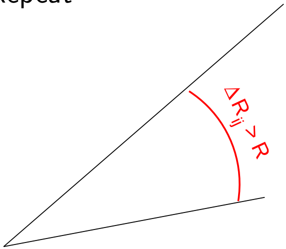

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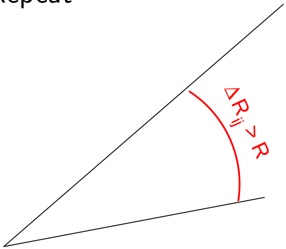

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NB: d_{ij} distance $\leftrightarrow$ QCD branching probability $\sim \alpha_s \frac{dk_{tj}^2 dR_{ij}^2}{d_{ij}}$

Adapting seq. rec. to give circular jets

Soft stuff clusters with nearest neighbour

$$k_t\text{: } d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2 \longrightarrow \textbf{anti-}\mathbf{k_t}\text{: } d_{ij} = \frac{\Delta R_{ij}^2}{\max(k_{ti}^2, k_{tj}^2)}$$

Hard stuff clusters with nearest neighbour

Privilege collinear divergence over soft divergence

Cacciari, GPS & Soyez '08

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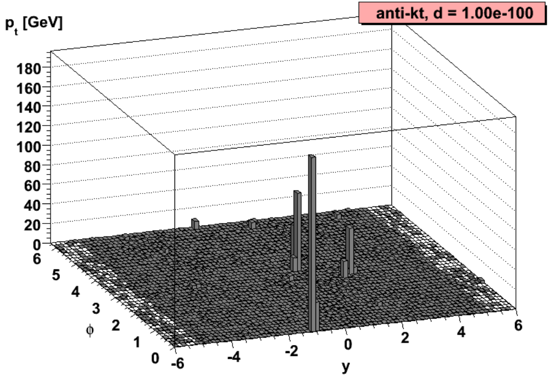

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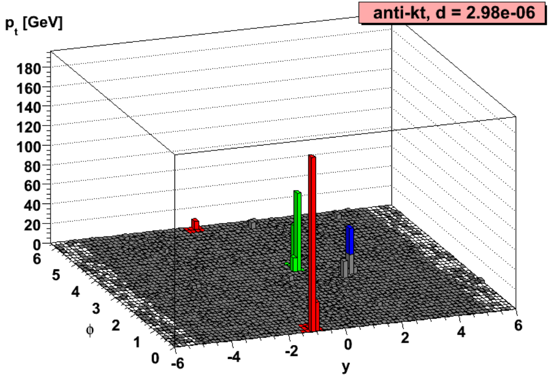

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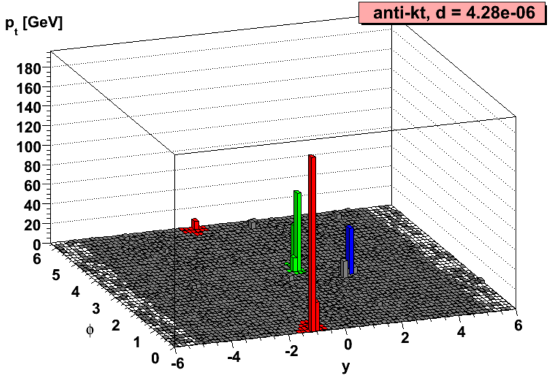

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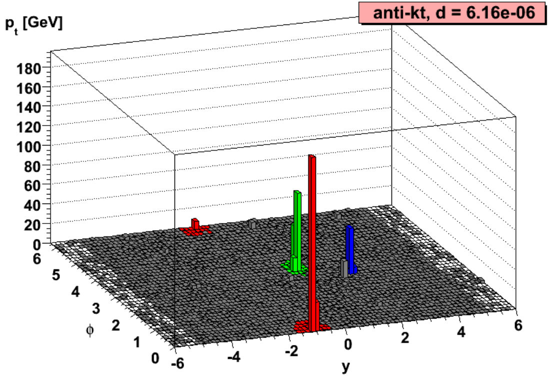

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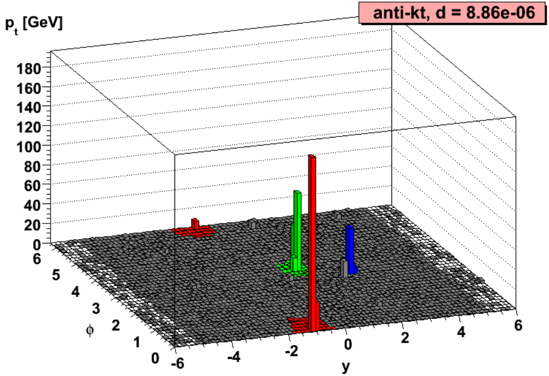

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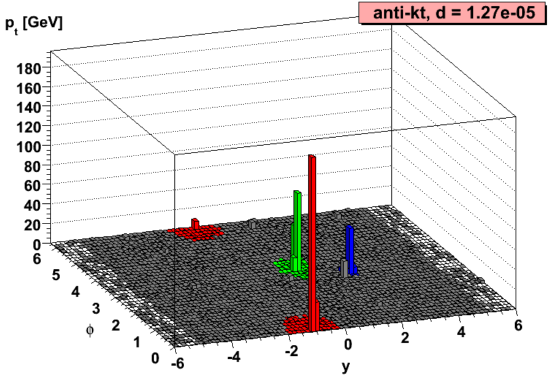

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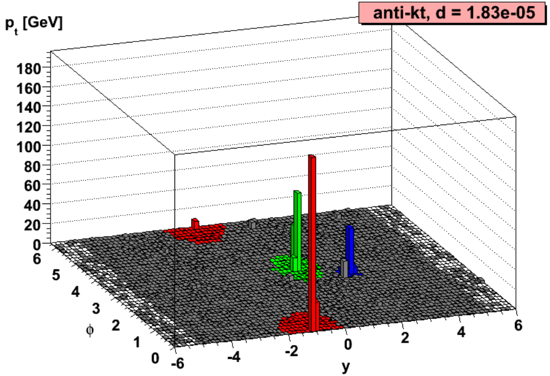

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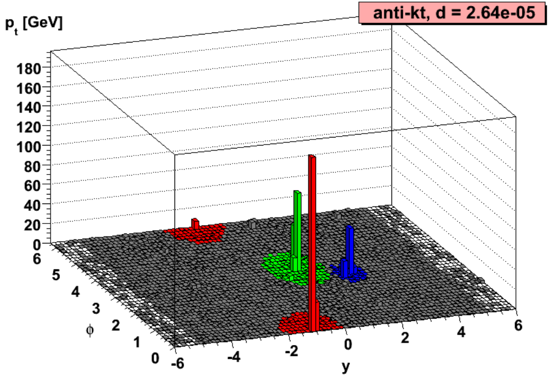

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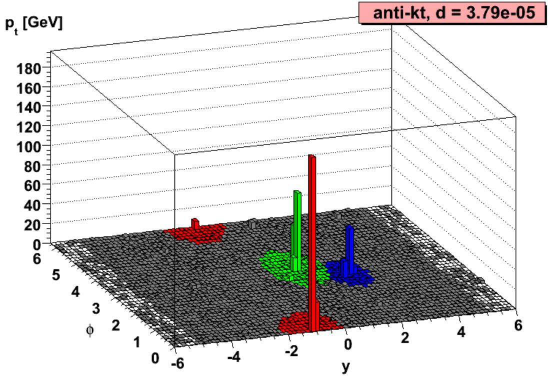

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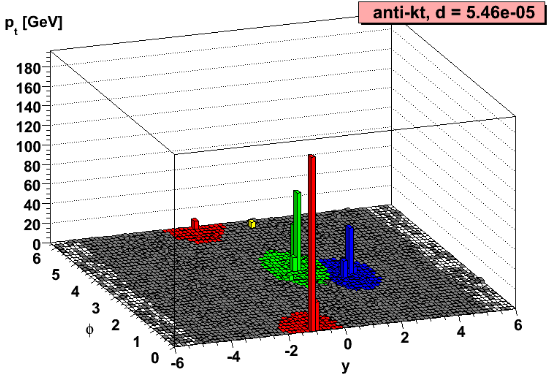

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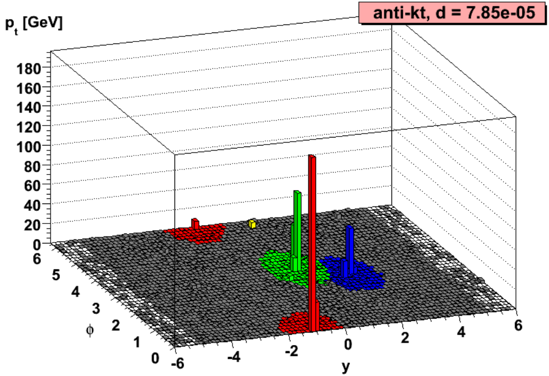

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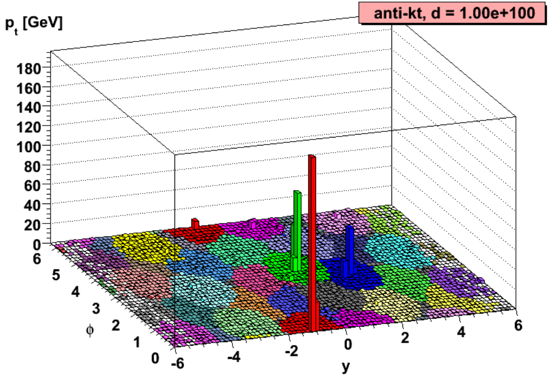
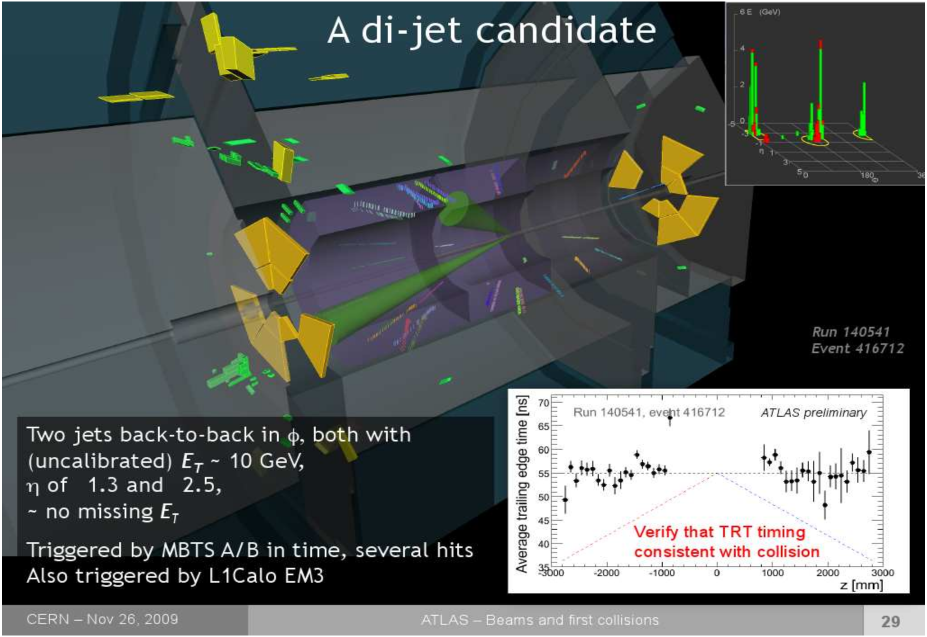
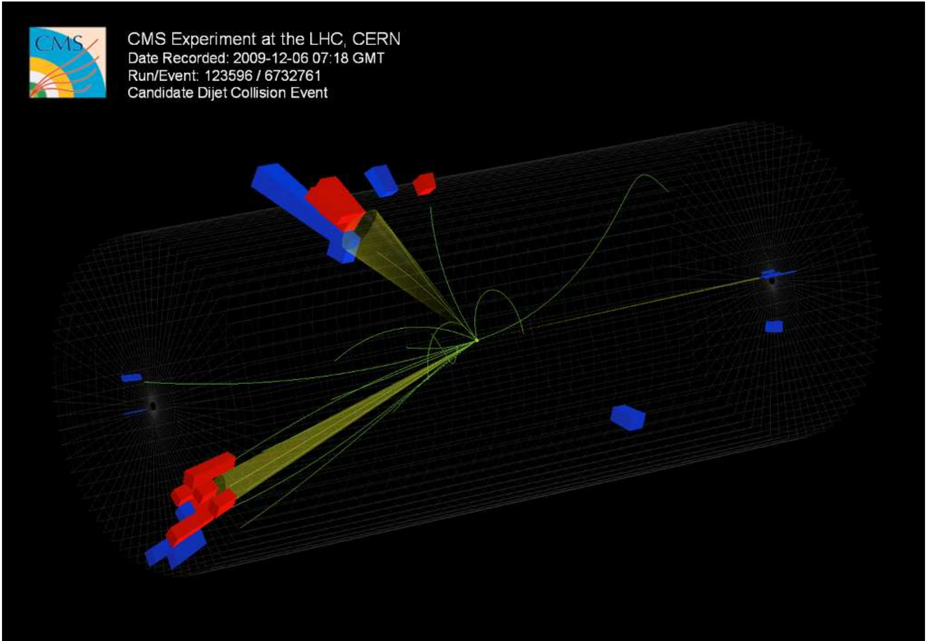


anti-k$_t$ gives cone-like jets without using stable cones

ATLAS: first dijet event, with anti-k_t



CMS: first dijet event, with anti-k_t



With ATLAS and CMS having adopted anti-k_t as their default jet algorithm, LHC is the first hadron collider experiment to start running with a clear prospect for infrared and collinear jet-finding.

Crucial for future comparisons to QCD.

Early data?

Limited luminosity

Jet energy scale poorly constrained ($\pm 10\%$?)

Steeply falling jet cross sections not well measured

Strategy?

Use purely hadronic events (large X-sct)

Measure ratios of jet p_t's, ratios of cross sections

y_{23}, a simple event shape

1) Select events with two central jets, hardest with $p_{t1} > 100$ GeV

$\sigma = \mathcal{O}(100 \text{ nb})$ @ 7 TeV

2) Define d_{23} = maximum of

- 3rd hardest jet, p_{t3}^2
- k_t splitting scale of either of two central jets — cf. substructure studies

3) Normalise to $Q^2 = (p_{t1} + p_{t2})^2$, $y_{23} = d_{23}/Q^2$

cancel (most of) Jet Energy Scale uncertainty

4) Plot differential distribution within selected events

uncertainty on selected X-section cancels

You can compare to Monte Carlo parton showers

Pythia, Herwig, Sherpa

Parton showers matched to tree-level matrix elements

Alpgen (MLM), Madgraph (MLM), Sherpa (CKKW)

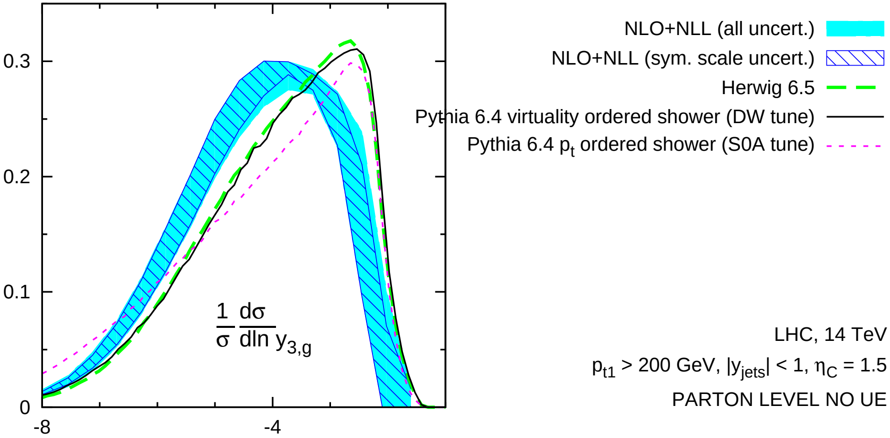
Non-MC predictions: NLL resummation + NLO

CAESAR + NLOJET: controlled approximations

Banfi, GPS & Zanderighi '10

NLL+NLO v. showers

Low p_t, gluon dominated



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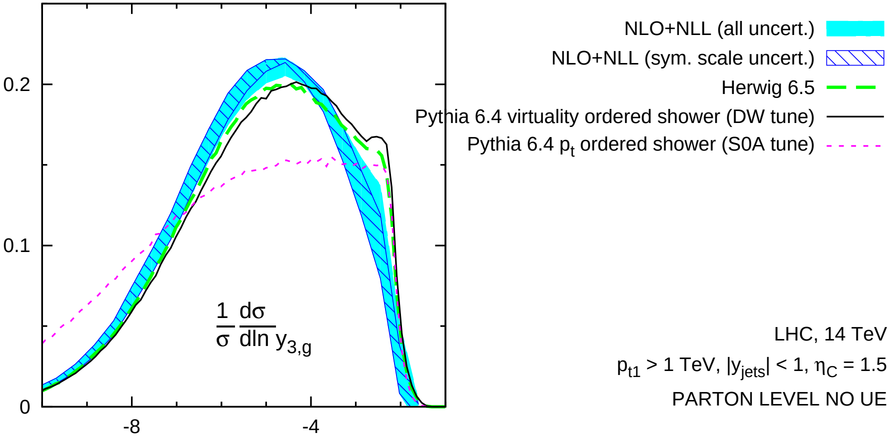

Several showers

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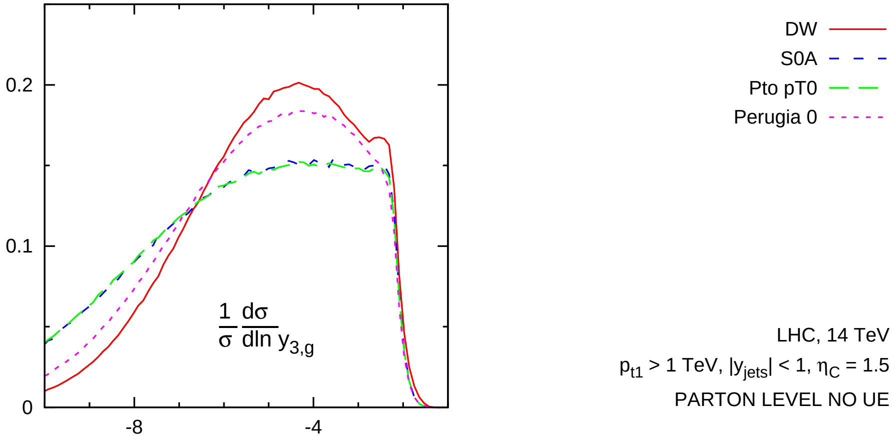

NLL+NLO v. Alpgen+Herwig

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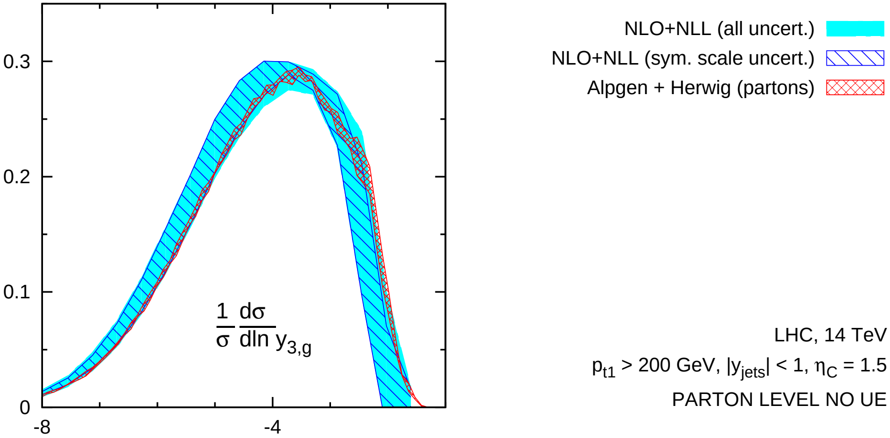
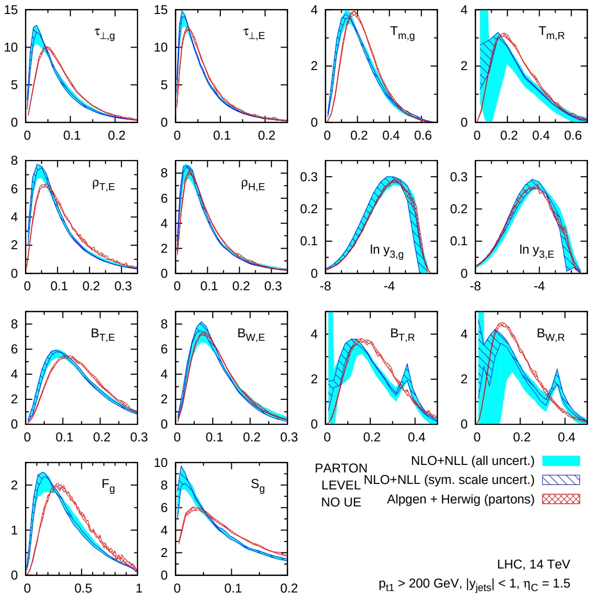


Other event shapes [http://tr.im/Nj9z]



There are many other ways of combining event particle momenta to get "event shapes"

e.g. transverse thrust

Each with different sensitivity to QCD branching.

Hadronic observables not just for constraining Monte Carlos

R-parity violating SUSY

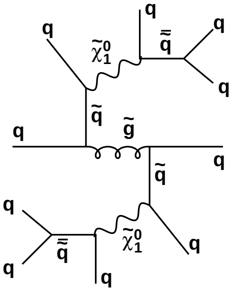
As an example, a search for neutralinos in R-parity violating supersymmetry.

Normal SPS1A type SUSY scenario, *except* that neutralino is not LSP, but instead decays, $\tilde{\chi}_1^0 \to qqq$.

Jet combinatorics makes this a tough channel for discovery

- Produce pairs of squarks, $m_{\tilde{q}} \sim 500$ GeV.
- Each squark decays to quark + neutralino, $m_{\tilde{\chi}_1^0} \sim 100$ GeV
- Neutralino is somewhat boosted → jet with substructure

Butterworth, Ellis, Raklev & GPS '09



R-parity violating SUSY

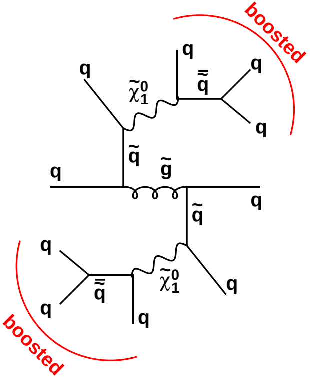
As an example, a search for neutralinos in R-parity violating supersymmetry.

Normal SPS1A type SUSY scenario, *except* that neutralino is not LSP, but instead decays, $\tilde{\chi}_1^0 \to qqq$.

Jet combinatorics makes this a tough channel for discovery

- Produce pairs of squarks, $m_{\tilde{q}} \sim 500$ GeV.
- Each squark decays to quark + neutralino, $m_{\tilde{\chi}_1^0} \sim 100$ GeV
- Neutralino is somewhat boosted → jet with substructure

Butterworth, Ellis, Raklev & GPS '09



Analytics (back-of-the-enveolope)

Subjet decomposition procedures are not *just* trial and error.

Mass distribution for undecomposed jet:

$$\frac{1}{N}\frac{dN}{dm} \sim \frac{2C\alpha_s \ln Rp_t/m}{m} e^{-C\alpha_s \ln^2 Rp_t/m + \cdots}$$

Strongly shaped, with Sudakov peak, etc.

Mass distribution for hardest (largest Jade distance) substructure within C/A jet that satisfies a symmetry cut ($z > z_{min}$):

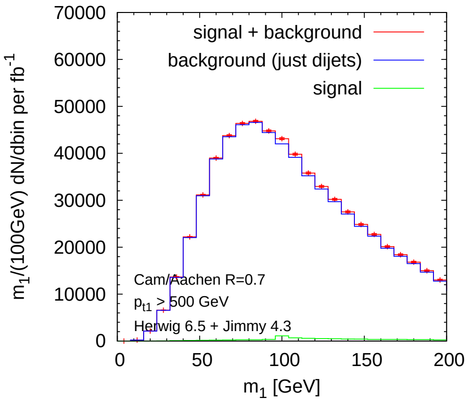
$$\frac{1}{N}\frac{dN}{dm} \sim \frac{C'\alpha_s(m)}{m} e^{-C'\alpha_s \ln Rp_t/m + \cdots}$$

$$\sim \frac{C'\alpha_s(Rp_t)}{m}\left[1 + \underbrace{(2b_0 - C')}_{\text{partial cancellation}} \alpha_s \ln Rp_t/m + \mathcal{O}\left(\alpha_s^2 \ln^2\right)\right]$$

Procedure gives nearly flat distribution in $m dN/dm$

Neutralino procedure involves 2 hard substructures, but ideas are similar

RPV SUSY, SPS1a, 1 fb^{-1} [14 TeV]



Keep it simple:

Look at mass of leading jet

- Plot $\frac{m}{100\text{ GeV}}\frac{dN}{dm}$ for hardest jet ($p_t > 500$ GeV)
- Require 3-pronged substructure
- And third jet
- And fourth central jet

99% background rejection
scale-invariant procedure
so remaining bkgd is flat

Once you've found neutralino:

- Look at m_{14} using events with m_1 in neutralino peak and in sidebands

Out comes the squark!

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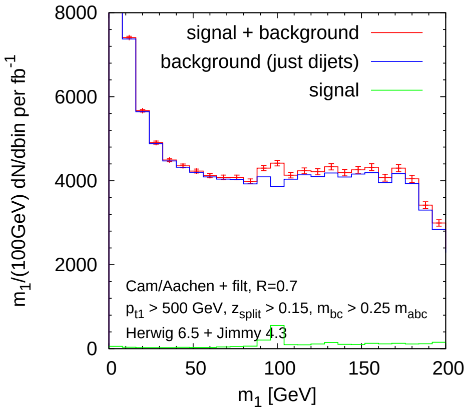

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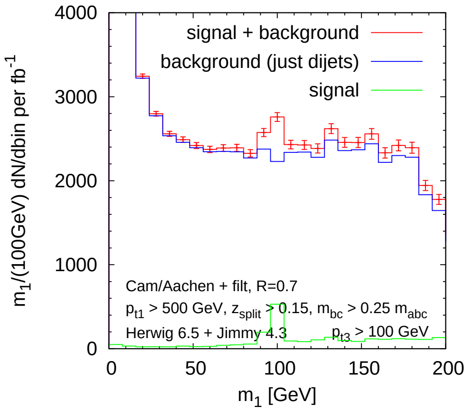

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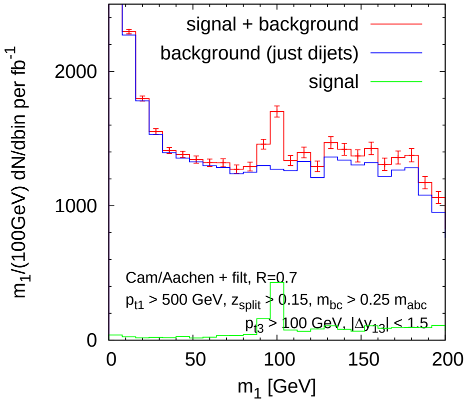

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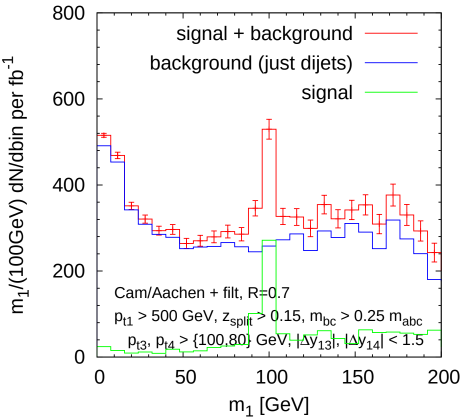

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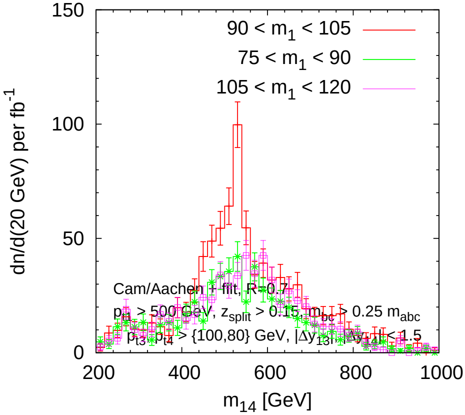

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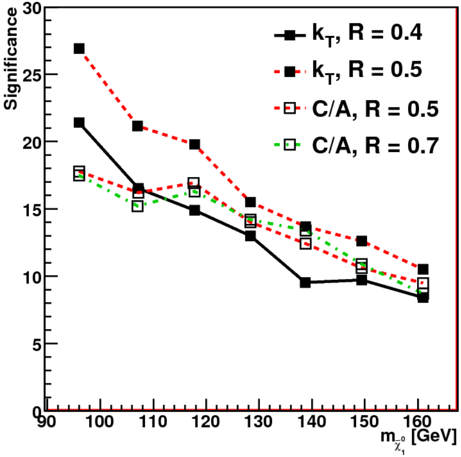
RPV SUSY: significance v. mass scale



- All points use 1 fb^{-1}, 14 TeV
- Divide significance by ~ 3 for 7 TeV
- as m_χ increases, $m_{\tilde{q}}$ goes from 530 GeV to 815 GeV
- Same cuts as for main SPS1A analysis

no particular optimisation

Constraining low-p_t part of Monte Carlos

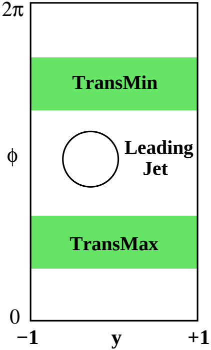
Underlying Event

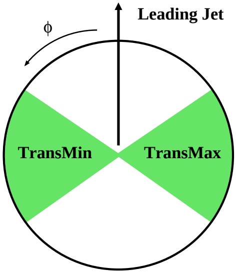
Traditional approach

For each event

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

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

For each event

[Cacciari, Salam, Soyez ('08), `http://fastjet.fr`]

1. cluster particles with an infrared safe jet finding algorithm (all particles are clustered so we have set of jets ranging from hard to soft) only k_t or C/A algs
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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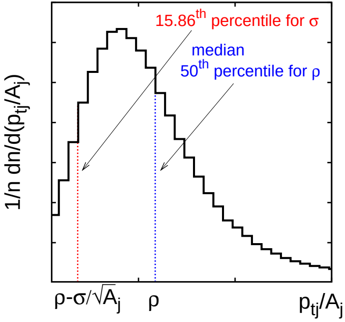


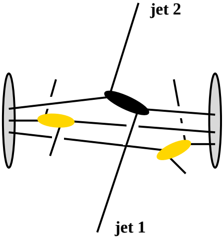
How do you decide when one method works better than another?

Cacciari, GPS & Sapeta '10

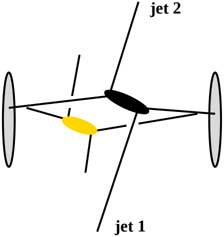
What is the underlying event?

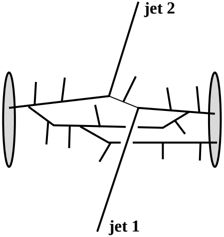
Questions

- should initial and final state radiation be called part of the underlying event?
- are multiple parton interactions responsible for most of the underlying activity?



- what about correlations? BFKL chains?





A toy model for the UE

Do the methods measure "UE" or perturbative radiation?

If you can't define what UE is, you can't answer the question

So try a simplistic, but well-defined **toy model**

Soft component (UE)

Independent emission with spectrum

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

$\langle$Number$\rangle$ of emissions and $\langle p_t \rangle = \mu$ set its characteristics

Hard component (PT)

Independent emission with spectrum

$$\frac{dn}{dp_t dy d\phi} = \frac{C_i}{\pi^2}\frac{\alpha_s(p_t)}{p_t}$$

up to scale $Q \sim p_{t,hard}/2$
(C_i is $C_A = 3$ or $C_F = \frac{4}{3}$)

Fluctuations in estimation of ρ

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

- nevertheless: 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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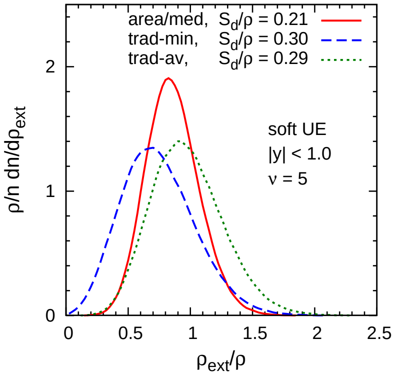

- lower fluctuations for area/median approach due to larger available area
- traditional approach suffers more from the hard contamination $S_d \sim Q$

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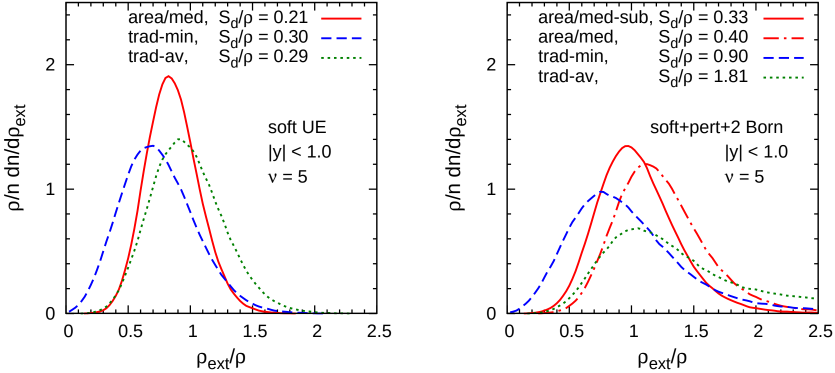

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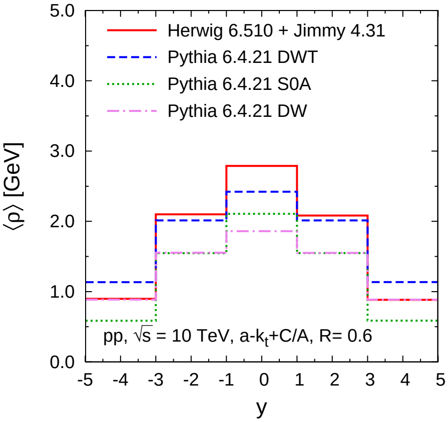
UE in Monte Carlo with median method?

Average ρ as a function of y

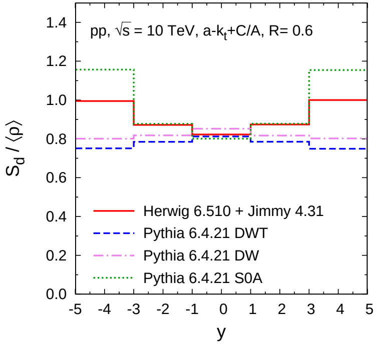
- dijets at the LHC, $\sqrt{s} = 10$ TeV, $p_t > 100$ GeV, $|y| < 4$

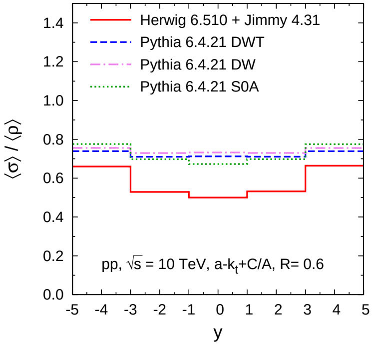


- significant y dependence
- strips of Δy=2 sufficient for robust ρ determination

Fluctuations within an event

- from event to event
- within an event





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

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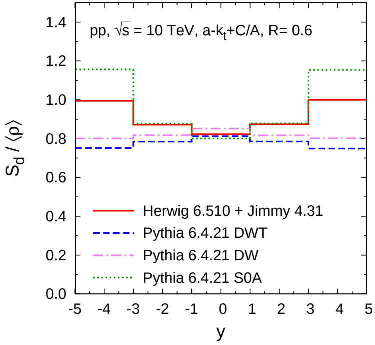
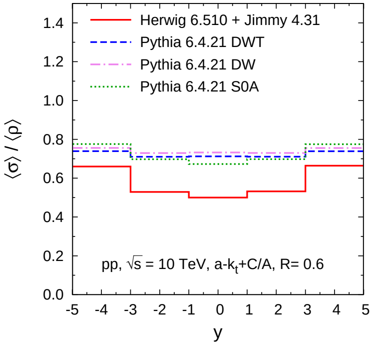


- within an event



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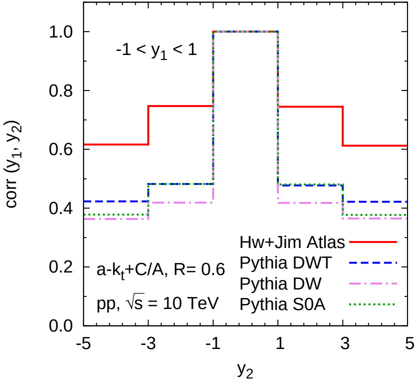
Correlations



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

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

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

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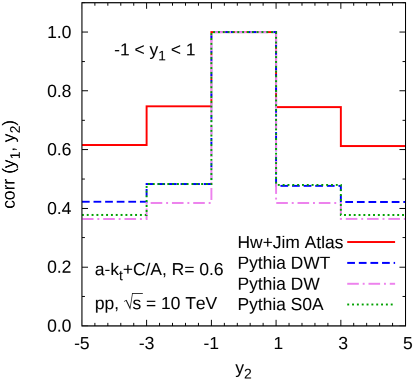

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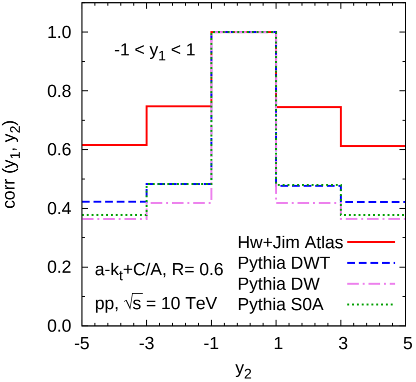

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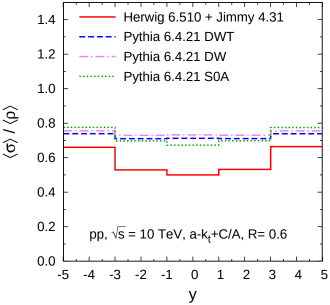

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Conclusions

- In early data, look at ratios of observables.

  Much scope for constraining our QCD predictions

- There's more information in the Underlying Event than we're extracting currently

  Jets offer a way of extracting it

- Searches, e.g. multi-jet + jet-substructure, have interesting potential in 2010-2011 data

EXTRAS

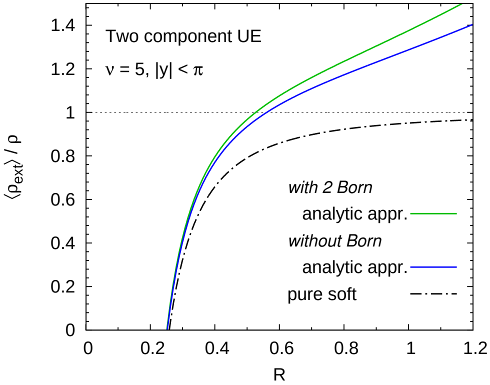
Some high-p_t cross sections

7 TeV LHC (leading order, from Herwig 6.5):

dijets, $p_t > 100$ GeV	2.7×10^5 pb	65% glue
dijets, $p_t > 300$ GeV	1000 pb	
dijets, $p_t > 500$ GeV	53 pb	30% glue
$W_{\to e/\mu+\nu}+j$, $p_{tW} > 50$ GeV	620pb	
$W_{\to e/\mu+\nu}+j$, $p_{tW} > 100$ GeV	90pb	
$Z_{\to\mu^+\mu^-/e^+e^-}+j$, $p_{tZ} > 50$ GeV	66pb	
$t\bar{t}$	70pb	
$t\bar{t}$, $p_{t,t} > 300$ GeV	1.5 pb	

Two component model: soft UE + hard PT

Area/median approach



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

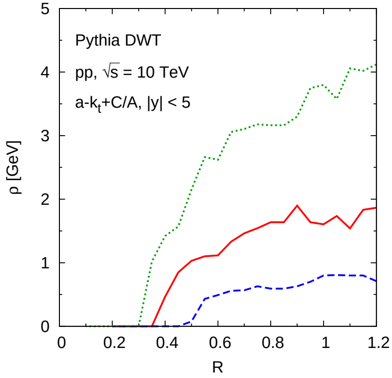
$\langle n_h \rangle$ – number of perturbative part.
σ – measure of fluctuations
ρ – true value of p_t/A

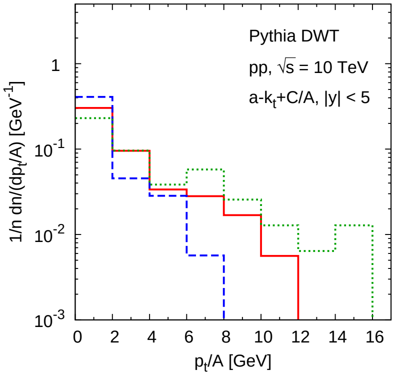
$$\langle \rho_{\rm ext}^{\rm (soft)} \rangle \simeq \rho \frac{c_J R^2 \nu - \ln 2}{c_J R^2 \nu - \ln 2 + \frac{1}{2}} \Theta(R_{\rm cr})$$

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

- 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

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