Characterising non-perturbative effects in jets

Gavin Salam

LPTHE, Universities of Paris VI and VII and CNRS

work in progress with M. Cacciari
+ close links with with M. Dasgupta & L. Magnea

Ringberg workshop on non-perturbative QCD of jets
8–10 January 2007

History

Much work done on non-perturbative effects in e^+e^- and DIS event shapes. But little understood about jets.

Webber hep-ph/9510283: 3-jet resolution, y_3, gets Λ^2/Q^2 corrections

'Higher' orders give $\sqrt{y_3}\Lambda/Q$ or $\sqrt{y_3}\ln y_3\Lambda/Q$

Seymour, NPB513(1998)269: differential jet shape at angular distance r from jet axis gets correction $\frac{\Lambda}{r^2 p_T}$

Mangano, hep-ph/9911256: hadron-collider inclusive jet-spectrum gets a roughly p_T-independent shift of order Λ.

Can we gain a global understanding of NP effects in hadron-collider jets so as to guide discussion, choices and strategies for LHC jet-finding?

History

Much work done on non-perturbative effects in e^+e^- and DIS event shapes. But little understood about jets.

Webber hep-ph/9510283: 3-jet resolution, y_3, gets Λ^2/Q^2 corrections

'Higher' orders give $\sqrt{y_3}\Lambda/Q$ or $\sqrt{y_3}\ln y_3\Lambda/Q$

Seymour, NPB513(1998)269: differential jet shape at angular distance r from jet axis gets correction $\frac{\Lambda}{r^2 p_T}$

Mangano, hep-ph/9911256: hadron-collider inclusive jet-spectrum gets a roughly p_T-independent shift of order Λ.

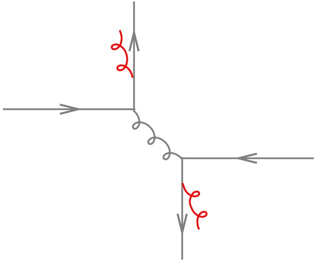
Can we gain a global understanding of NP effects in hadron-collider jets so as to guide discussion, choices and strategies for LHC jet-finding?

Many NP contributions at pp colliders

- **'Universal' hadronization**:
  the part associated with the high-p_t scattering and which should be the same as in e^+e^- and DIS (current hemisphere).

- **Underlying event**:
  emissions from proton remnants, (multiple) interaction between two proton remnants.

- **Pileup**:
  at high luminosity, contribution from simultaneous *pp* collisions in the same bunch crossing.

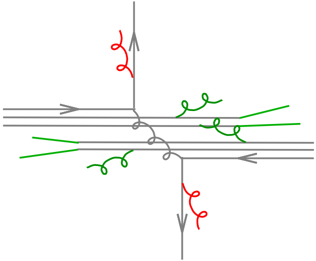


Many NP contributions at pp colliders

- **'Universal' hadronization**:
  the part associated with the high-p_t scattering and which should be the same as in e^+e^- and DIS (current hemisphere).

- **Underlying event**:
  emissions from proton remnants, (multiple) interaction between two proton remnants.

- **Pileup**:
  at high luminosity, contribution from simultaneous *pp* collisions in the same bunch crossing.

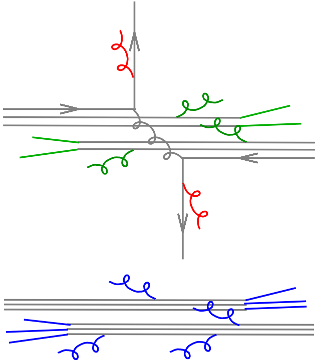


Many NP contributions at pp colliders

- **'Universal' hadronization**:
  the part associated with the high-p_t scattering and which should be the same as in e^+e^- and DIS (current hemisphere).

- **Underlying event**:
  emissions from proton remnants, (multiple) interaction between two proton remnants.

- **Pileup**:
  at high luminosity, contribution from simultaneous *pp* collisions in the same bunch crossing.



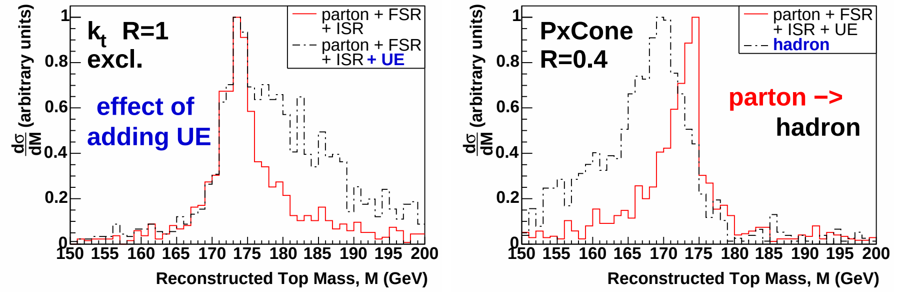
Various Jet Algorithms

- **k_t**:
  Combine pair of particles closest in k_t-distance; repeat until all particles separated by angular ($\Delta R^2 = \Delta y^2 + \Delta\phi^2$) distance $> R$ [inclusive] or k_t distance $> d_{cut}$ [exclusive].
  Catani et al '93; Ellis & Soper '93

- **Cambridge/Aachen**:
  Combine pair of particles closest in angular-distance; repeat until all particles separated by ang. dist. $> R$ [inclusive], or make a particle into jet if about to cluster with harder particle and k_t dist. $> d_{cut}$ [exclusive].
  Dokshitzer et al '97; Wobisch & Wengler '99

- **Cone**:
  Find 'stable cones' of half-angle R; run a split-merge procedure on stable cones that overlap so as to get final jets.
  Sterman & Weinberg '77
  Many variants since then...
  Seedless IR Safe cone (SISCone): GPS & Soyez '07

NP effects in top mass



adapted from Seymour & Tevlin '06

Common statements:

- k_t has larger UE & pileup corrections
- cone has larger hadronization corrections

But k_t and cone often used with different parameters ($R = 1$ v. $R = 0.4$).

Can we get analytic understanding of parameter & algorithm dependence for hadronisation and UE/pileup effects?

One soft gluon approximation

We will try to calculate N.P. corrections to **jet transverse momentum**.

Easily related, e.g., to mass reconstructions

Starting point, as for many NP-calculations, is 1 hard parton (jet) + 1 soft gluon:

- This is a valid approximation only if the observable is **linear** in effects of multiple soft momenta. cf. Milan factor, Dokshitzer et al. '97–'98
  crucial input in Lee & Sterman '06
- Many e^+e^- & DIS event shapes had some form of linearity.
- Jet algorithms **are not linear**.
  But 1-gluon approx. may still be useful for getting first picture
- k_t, Cam/Aachen & cone are **identical** @ 1 soft-gluon level

UE & Pileup (P.U.), 1 soft gluon approx.

Assume soft gluon produced uniformly in y (rapidity) and ϕ with transv. mom. density (averaged over many events):

$$\left\langle \frac{dp_{t,NP}}{dy\, d\phi} \right\rangle = \rho_{U.E.} \sim \Lambda\,, \quad \text{or} \quad \rho_{P.U.} \sim n_{P.U.}\Lambda\,,$$

independently of hard event (marginal for U.E.? Fine for P.U.).

The soft gluon (g) will be clustered into jet (j) if $\Delta R_{gj} < R$. This defines a *jet area* A in y, ϕ space, $A = \pi R^2$, and the jet p_t is increased proportionally to its area:

$$\Delta p_{t,jet,UE} = \pi R^2 \rho_{UE} \qquad \text{(P-scheme)}$$

$$\Delta p_{t,jet,UE} = 2\pi R\, J_1(R)\, \rho_{UE} = \left(\pi R^2 - \frac{\pi}{8} R^4 + \dots\right) \rho_{UE} \qquad \text{(E-scheme)}$$

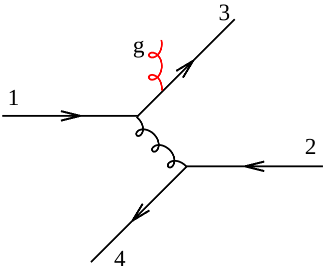
Note: $\mathcal{O}\left(R^4\right)$ depends on recombination scheme

Hadronisation, 1 soft gluon approx.

Universality & Milan factor: calculate hadronisation by calculating effect of a *trigger gluon* (gluer) k on the observable. [keeping it simple!]

$$\delta V = C \sum_{dipoles} \int d\eta_{k,dip} d\phi_{k,dip} dk_{t,dip} \delta(k_{t,dip} - \Lambda) \left(V(\{\tilde{p}_i\}, k) - V(\{p_i\}) \right)$$

with C known from many event shapes in e^+e^-: $C\Lambda \simeq 0.5$ GeV.



NB: recoiled hard momenta $\{\tilde{p}_i\}$ v. orig. $\{p_i\}$.

Event shapes: $V(\{p_i\}) = 0$, recoil irrelevant;

For jets: $V(\{p_i\}) = p_{t,3} \neq 0$
$V(\{\tilde{p}_i\}, k) = \tilde{p}_{t,3}[+k_t]$

$\exists$ **ambiguity** in decision about how to assign k's recoil between $\tilde{p}_3$ and $\tilde{p}_4$

Dealing with recoil

Recoil ambiguity foils any 'traditional' calculation of hadronization corrections to jet p_t's.

Similar issue e.g. for thrust in 3-jet region

Two approximate solutions:

- Go to threshold limit (recoil uniquely defined) ➥talk by Magnea
- Consider only small R: hadronisation dominated by gluer emission close to hard parton; *assume* recoil dominantly taken by that hard parton.

gluon in jet: $p_{t,jet} = k_t + \tilde{p}_{t,3} = p_{t,3}$

gluon out of jet: $p_{t,jet} = \tilde{p}_{t,3} = p_{t,3} - k_t$

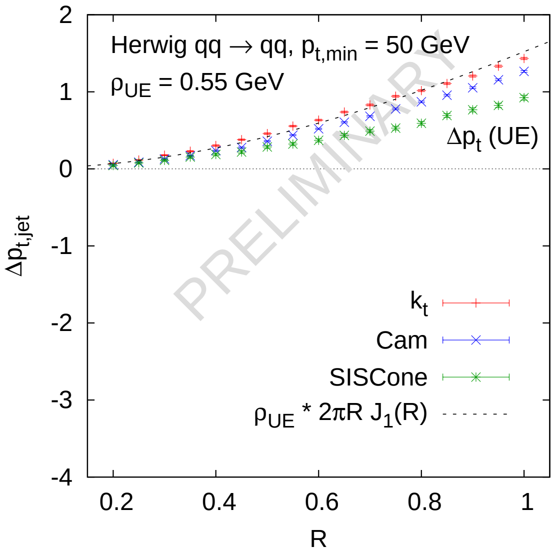
$$\delta p_{t,jet} = C \int^{-\ln \tan R/2} d\eta_{dip} \left(-\Lambda \sinh \eta_{dip}\right) = C\Lambda \left(-\frac{1}{R} + \mathcal{O}(1)\right)$$

Gluonic jet has extra factor C_A/C_F

$1/R$ structure coincides with threshold result by Dasgupta & Magnea

Less accurate than D&M, but holds regardless of event structure

Compare with MC



Analytical results have strong R dependence, but *do not depend on jet algorithm.*

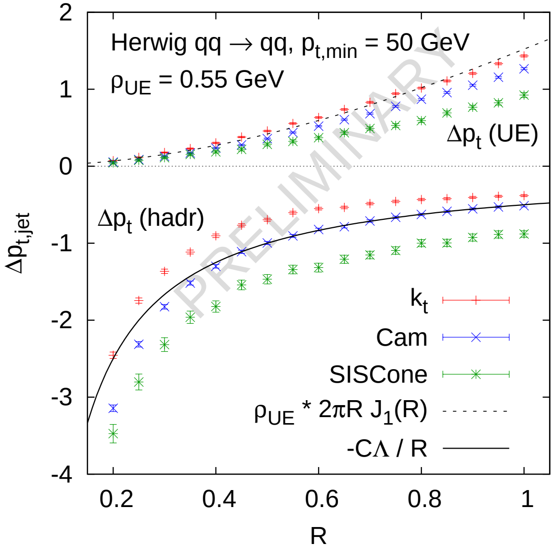
Compare to MC:

- **Broad features agree** with MC
- R-dependence deviates a little
- moderate jet. alg. dependence is present:

$$k_t > \text{Cam} > \text{Cone}$$

NB: normalisations depend on how one selects jets

Compare with MC



Analytical results have strong R dependence, but *do not depend on jet algorithm.*

Compare to MC:

- **Broad features agree** with MC
- R-dependence deviates a little
- moderate jet. alg. dependence is present:

$$k_t > \text{Cam} > \text{Cone}$$

NB: normalisations depend on how one selects jets

Beyond 1 gluon

Jet algorithms are identical at level of 1 soft gluon. Can we understood nature of differences beyond 1 gluon?

Study just UE and pileup:

- They are easier, since no recoil to worry about
- UE larger than appears from previous page, often dominant

  default Herwig underestimates it
- Pileup will be huge at LHC, and will dominate over other effects.

  20 *pp* interactions per bunch crossing

BUT: don't study U.E., pileup effect directly. Instead assume PT content of jet is independent of U.E. & pileup, so that effect of U.E. & pileup is proportional to **jet area, A**:

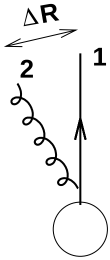
$$\Delta p_{t,jet} = \rho A$$

Including jet substructure

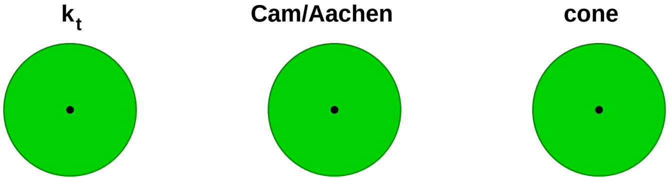
Consider jet composed of two p_t-ordered perturbative partons,

$$p_{t1} \gg p_{t2} \gg \Lambda$$

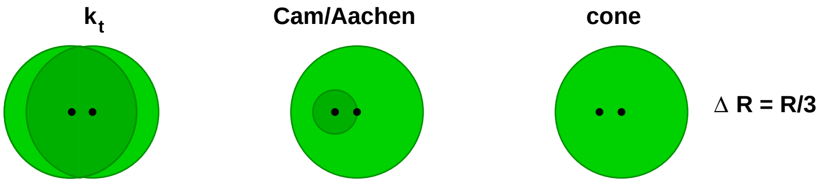
separated by ΔR. Scan a NP gluon, *'ghost'*, over the y-ϕ plane, and see when it goes into the jet containing p_1. From this deduce the jet area.



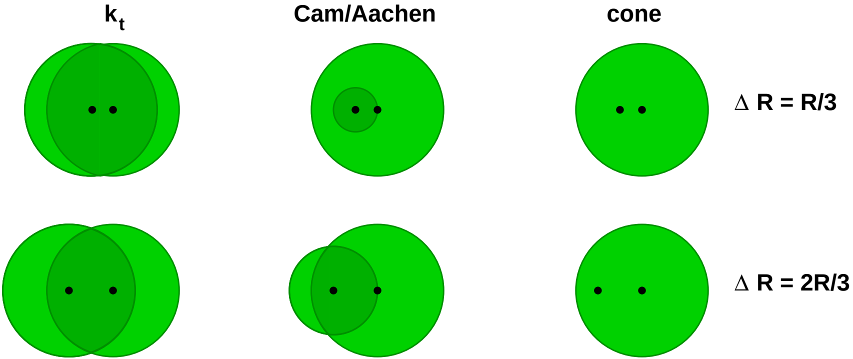
Areas with $\Lambda \ll p_{t2} \ll p_{t1}$



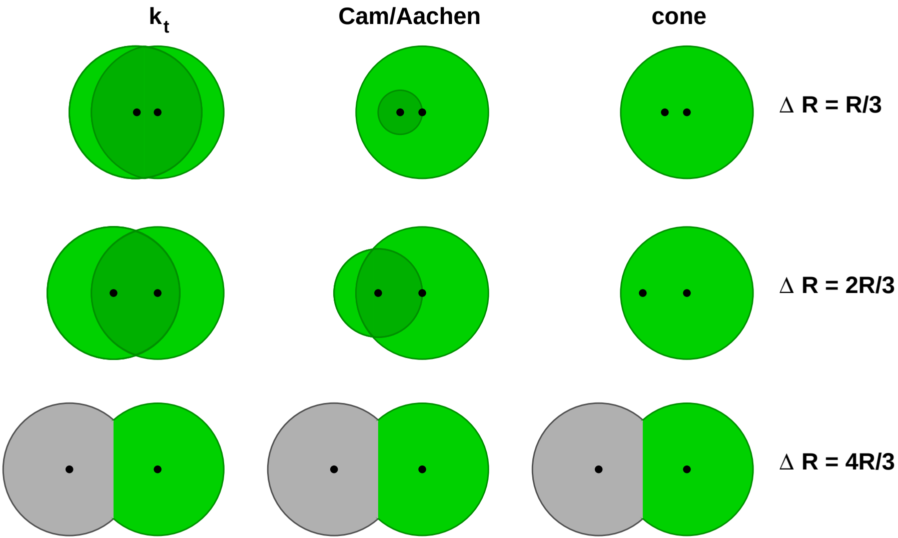
Areas with $\Lambda \ll p_{t2} \ll p_{t1}$



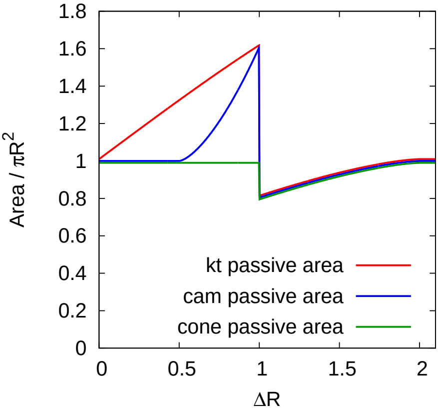
Areas with $\Lambda \ll p_{t2} \ll p_{t1}$

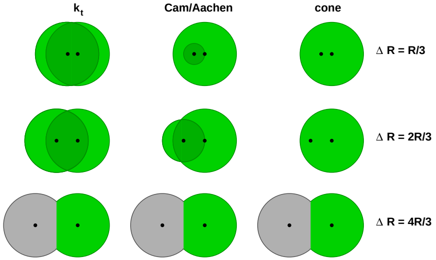


Areas with $\Lambda \ll p_{t2} \ll p_{t1}$



Jet area v. ΔR_{12}





NB: difference in areas is independent of softness of p_{t2}.

$$\langle \Delta A \rangle = \frac{2\alpha_s C_F}{\pi} \int_{\Lambda}^{p_{t1}} \frac{dp_{t2}}{p_{t2}} \int_0^{2R} \frac{d\Delta R}{\Delta R} \Delta A(\Delta R)$$

Perturbative corrections to mean areas

Suppose incoming partons (colour charge C_i) and outgoing jets (col. charge $= C_o$) are not colour connected.

Mean outgoing jet area $\langle A \rangle$ depends on jet P_t as follows:

$$\langle A \rangle = R^2 \left(\pi + (a_0 C_o + a_2 C_i R^2) \frac{\alpha_s}{\pi} \ln \frac{p_{t1}^2}{\Lambda^2} + \mathcal{O}\left(\alpha_s, \alpha_s^2 L^2\right) \right)$$

Have neglected $\mathcal{O}\left(C_o R^2\right)$ term

$\alpha_s^n \ln^n p_t / \Lambda$ terms build up anomalous dimension

	a_0	a_2	comment
k_t	$+1.771$	$+0.325$	significant, positive
Cam / Aachen	$+0.249$	0	small, positive
Cone	-0.200	-0.325	small, negative

For $\Lambda \sim 10$ GeV (pileup), $P_t \sim 100 - 1000$ GeV, $\frac{\alpha_s}{\pi} \ln P_t^2 / Q_0^2 \sim 0.2 - 0.4$

NB: ordering of algorithms is that seen in MC

Active v. Passive areas

Passive area

- Having just 1 NP gluon in event is convenient analytically
- But not very realistic
- In presence of many NP gluons, approx. is equivalent to pretending NP gluons don't cluster between each other: **passive area**

Active area

- Throw in $\mathcal{O}\left(10^4\right)$ NP *'ghost'* gluons (10^{-100} GeV)
- Run clustering on event including ghosts
- Count how many ghosts end up in each jet — this is a more realistic measure/definition of area: **active area**

To run on 10^4 particles requires fast clustering
k_t & Cam: FastJet [Cacciari & GPS '05] $\sim N \ln N$
cone more difficult: SISCone $\sim N^2 \ln N$

Active v. Passive areas

Passive area

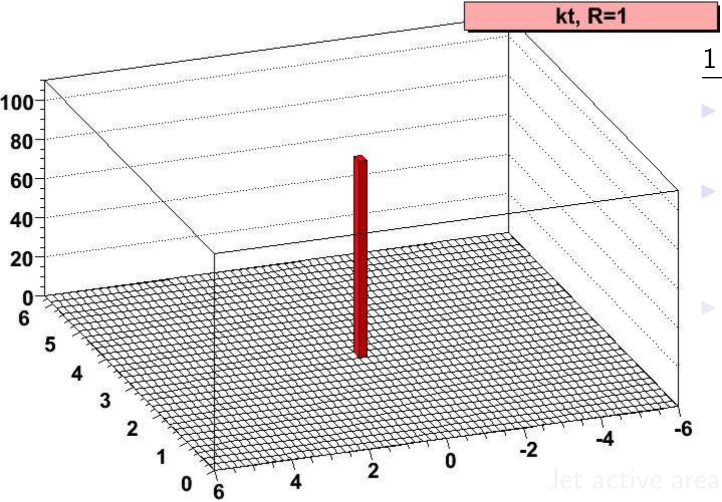
- Having just 1 NP gluon in event is convenient analytically
- But not very realistic
- In presence of many NP gluons, approx. is equivalent to pretending NP gluons don't cluster between each other: **passive area**

Active area

- Throw in $\mathcal{O}\left(10^4\right)$ NP *'ghost'* gluons (10^{-100} GeV)
- Run clustering on event including ghosts
- Count how many ghosts end up in each jet — this is a more realistic measure/definition of area: **active area**

To run on 10^4 particles requires fast clustering
k_t & Cam: FastJet [Cacciari & GPS '05] $\sim N \ln N$
cone more difficult: SISCone $\sim N^2 \ln N$

Active area examples



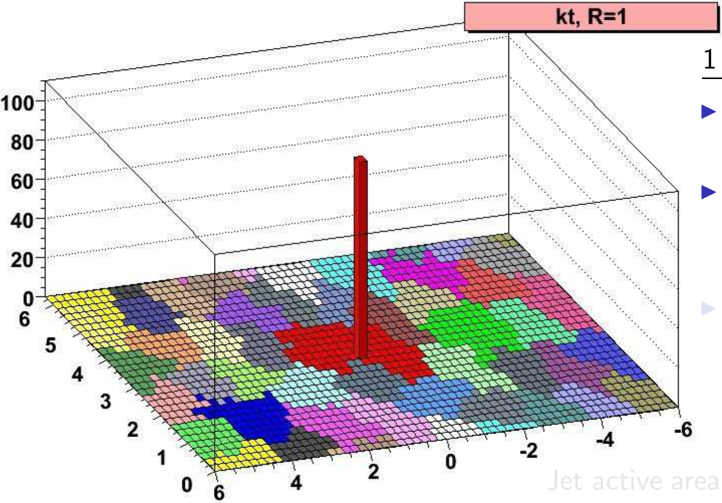
1 hard + 10^4 ghosts

- pure ghost jets model pileup jets
- hard jet has irregular boundary
- perturb ghosts → change jet boundaries

Jet active area only defined after *average* over ghost ensembles.

Fluctuations in soft/hard jet active areas provide a model for fluctuations in pure pileup jets and of pileup in narrow hard jets.

Active area examples



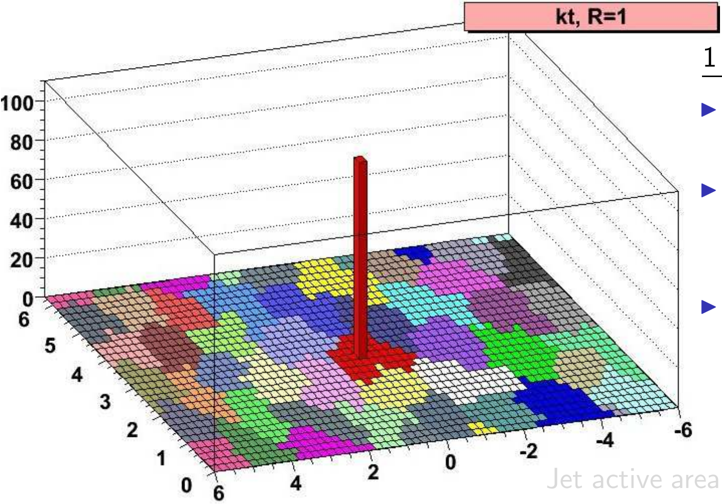
1 hard + 10^4 ghosts

- pure ghost jets
  model pileup jets
- hard jet has irregular boundary
- perturb ghosts → change jet boundaries

Jet active area only defined after *average* over ghost ensembles.

Fluctuations in soft/hard jet active areas provide a model for fluctuations in pure pileup jets and of pileup in narrow hard jets.

Active area examples



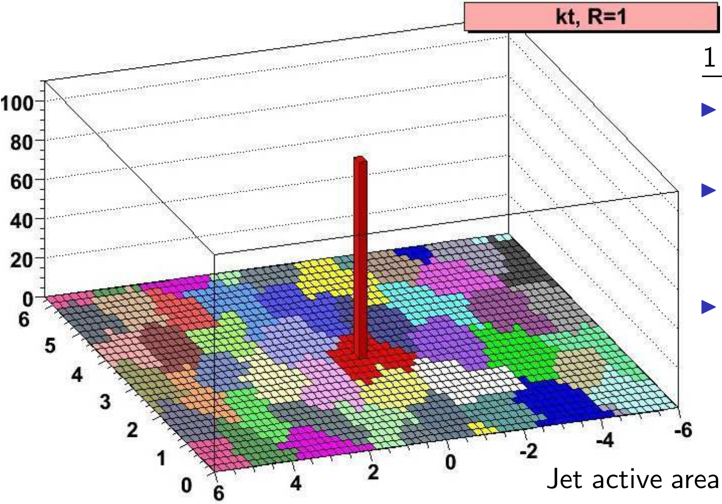
1 hard + 10^4 ghosts

- pure ghost jets
  model pileup jets
- hard jet has irregular boundary
- perturb ghosts
  → change jet boundaries

Jet active area only defined after *average* over ghost ensembles.

Fluctuations in soft/hard jet active areas provide a model for fluctuations in pure pileup jets and of pileup in narrow hard jets.

Active area examples



1 hard + 10^4 ghosts

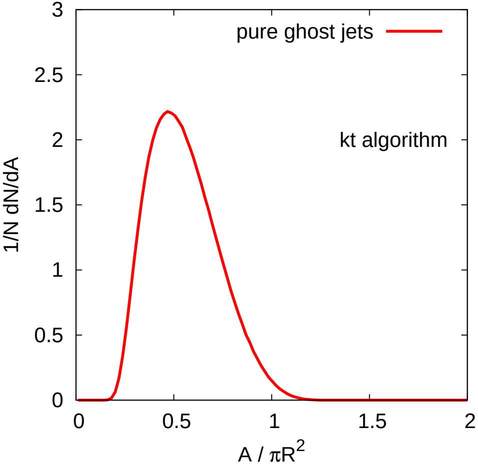
- pure ghost jets
  model pileup jets
- hard jet has irregular boundary
- perturb ghosts $\rightarrow$ change jet boundaries

Jet active area only defined after *average* over ghost ensembles.

Fluctuations in soft/hard jet active areas provide a model for fluctuations in pure pileup jets and of pileup in narrow hard jets.

Distribution of ‘Active’ jet areas

Distribution of jet areas



Ghost v. hard jets:

- $\langle A \rangle_{\mathrm{ghost-jet}} \simeq 0.55\pi R^2$
- $\langle A \rangle_{\mathrm{parton}} \simeq 0.8\pi R^2$

k_t and Cam are similar
Cone still being studied

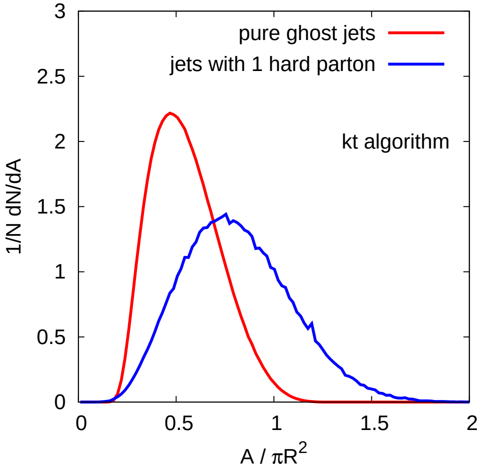
Conclusions:

- Active area < Passive area
- Jet area expands when it is anchored by a hard parton.

- Can one obtain analytical insight into this? To some extent in 1D
- ‘Hierarchical clustering’ is used in many fields (bio, computing, ...) — are similar features of relevance there?

Distribution of 'Active' jet areas

Distribution of jet areas



Ghost v. hard jets:

- $\langle A \rangle_{\mathrm{ghost-jet}} \simeq 0.55\pi R^2$
- $\langle A \rangle_{\mathrm{parton}} \simeq 0.8\pi R^2$

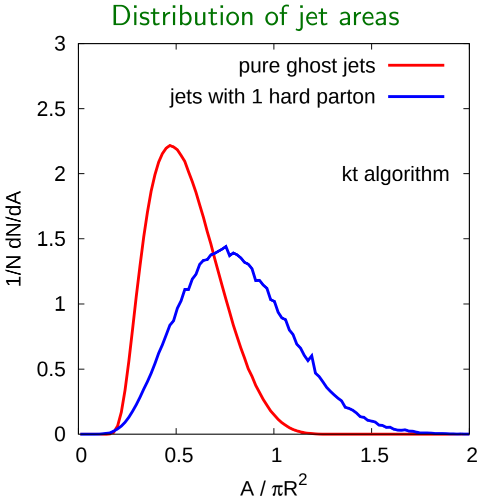
k_t and Cam are similar
Cone still being studied

Conclusions:

- Active area < Passive area
- Jet area expands when it is anchored by a hard parton.

- Can one obtain analytical insight into this? To some extent in 1D
- 'Hierarchical clustering' is used in many fields (bio, computing, ...) — are similar features of relevance there?

Distribution of 'Active' jet areas



Ghost v. hard jets:

- $\langle A \rangle_{\text{ghost-jet}} \simeq 0.55\pi R^2$
- $\langle A \rangle_{\text{parton}} \simeq 0.8\pi R^2$

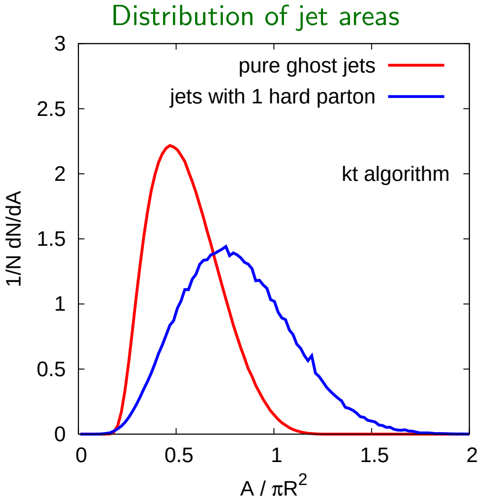
k_t and Cam are similar
Cone still being studied

Conclusions:

- Active area $<$ Passive area
- Jet area expands when it is anchored by a hard parton.

- Can one obtain analytical insight into this? To some extent in 1D
- 'Hierarchical clustering' is used in many fields (bio, computing, ...) — are similar features of relevance there?

Distribution of 'Active' jet areas



Ghost v. hard jets:

- $\langle A \rangle_{\mathrm{ghost-jet}} \simeq 0.55\pi R^2$
- $\langle A \rangle_{\mathrm{parton}} \simeq 0.8\pi R^2$

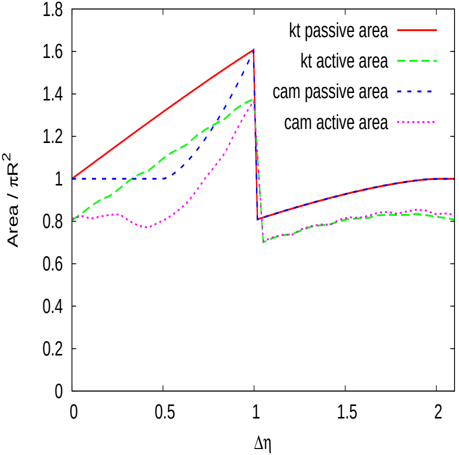
k_t and Cam are similar
Cone still being studied

Conclusions:

- Active area < Passive area
- Jet area expands when it is anchored by a hard parton.

- Can one obtain analytical insight into this? To some extent in 1D
- 'Hierarchical clustering' is used in many fields (bio, computing, ...) — are similar features of relevance there?

Active area + PT substructure



Put 1 hard PT gluon, 1 soft PT gluon (separated by ΔR), as before.

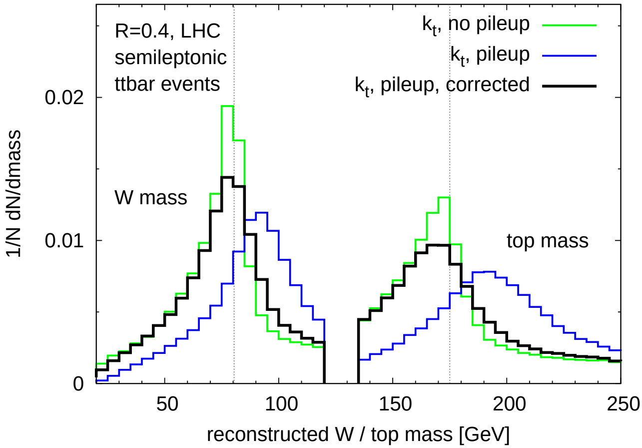
Calculate passive and active areas.

Picture is same for both, but $\sim$ rescaled...

2-parton anomalous dimension should hold also for active area

Will cone also just be rescaled?

Areas: also a tool for correcting jets



Areas not just theoretical tool.

Can be **measured jet-by-jet** in real events and used for pileup corrections.

Each jet corrected by area × median (P_t/area)

E.g.: semileptonic $t\bar{t}$ @ LHC with $\langle n_{P.U.} \rangle \simeq 20$.

Naive analysis: no cuts; assume both b's tagged
Take two hardest non-b jets — call them a W
Take correct sign b, combine with $W \to$ top

Conclusions

- In a first approx. all jet algorithms have *identical* NP effects.
  - hadronisation: $-\Lambda/R$
  - UE & pileup: $+\Lambda R^2$
- Differences that are often noted are mainly due to different R's.
- *Jet areas* are a useful playground for understanding effects beyond 1-NP-gluon level.
  - Perturbative sub-structure → algorithm-specific anomalous dimensions
  - Accounting for self-clustering → rescaling of jet area
  - Full understanding of two together needs further work
- Jet areas are also a useful concept in jet-by-jet *corrections* of pileup contamination.

Les Houches '07 will have jets subgroup — input welcome!

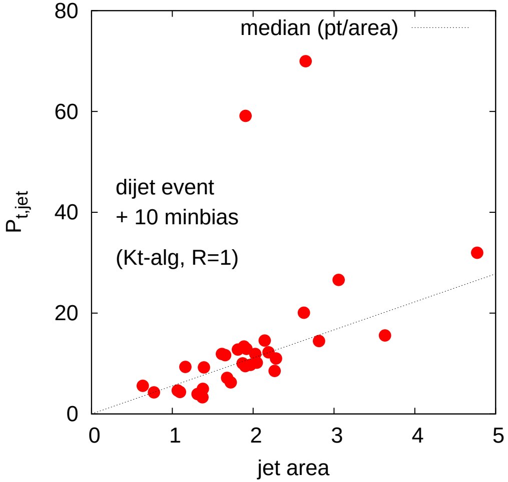
Conclusions

- In a first approx. all jet algorithms have *identical* NP effects.
  - hadronisation: $-\Lambda/R$
  - UE & pileup: $+\Lambda R^2$
- Differences that are often noted are mainly due to different R's.
- *Jet areas* are a useful playground for understanding effects beyond 1-NP-gluon level.
  - Perturbative sub-structure → algorithm-specific anomalous dimensions
  - Accounting for self-clustering → rescaling of jet area
  - Full understanding of two together needs further work
- Jet areas are also a useful concept in jet-by-jet *corrections* of pileup contamination.

Les Houches '07 will have jets subgroup — input welcome!

EXTRA MATERIAL

Jet areas



Jet areas in k_t algorithm are quite varied

Because k_t-alg adapts to the jet structure

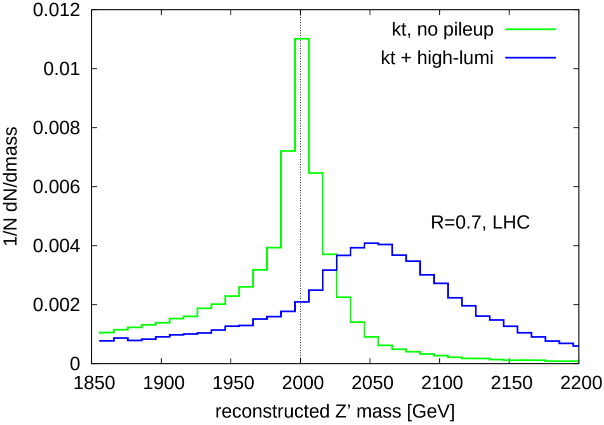
- Contamination from min-bias $\sim$ area

Complicates corrections: min-bias subtraction is different for each jet.

Cone supposedly simpler Area $= \pi R^2$? (Not quite...)

But: area can be measured for each jet, as can typical median p_t/area.

Reconstruct Z' mass [2 TeV]

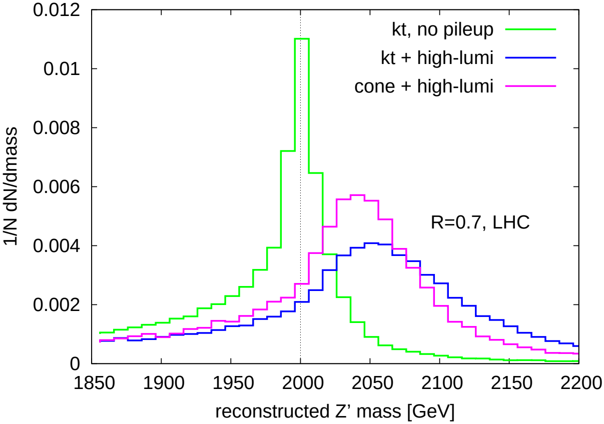


Uncorrected cone better than k_t.

Cam is intermediate ($\langle A_{cam} \rangle \simeq \langle A_{cone} \rangle$, but fluctuations larger)

Corrected Cam (and k_t) is best.

Reconstruct Z' mass [2 TeV]

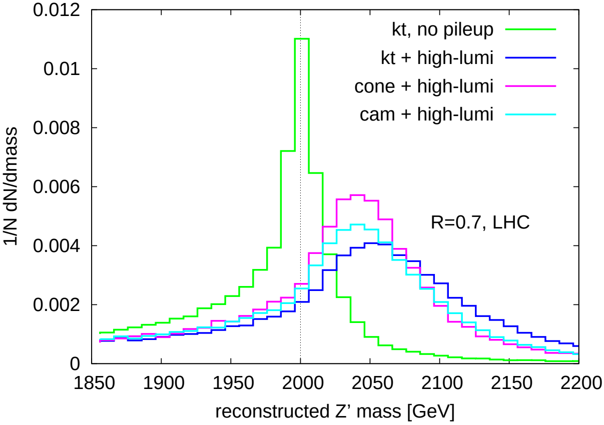


Uncorrected cone better than k_t.

Cam is intermediate ($\langle A_{cam} \rangle \simeq \langle A_{cone} \rangle$, but fluctuations larger)

Corrected Cam (and k_t) is best.

Reconstruct Z' mass [2 TeV]

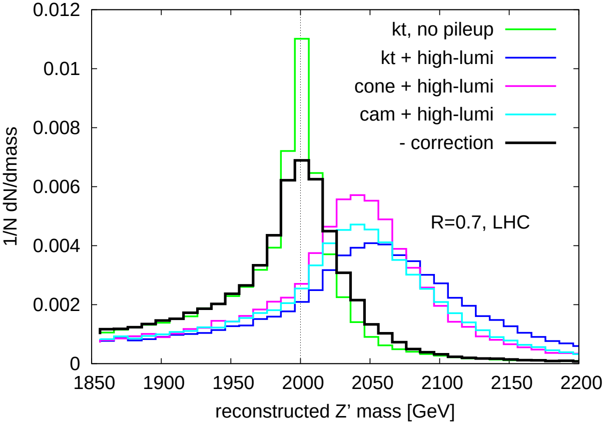


Uncorrected cone better than k_t.

Cam is intermediate ($\langle A_{cam} \rangle \simeq \langle A_{cone} \rangle$, but fluctuations larger)

Corrected Cam (and k_t) is best.

Reconstruct Z' mass [2 TeV]

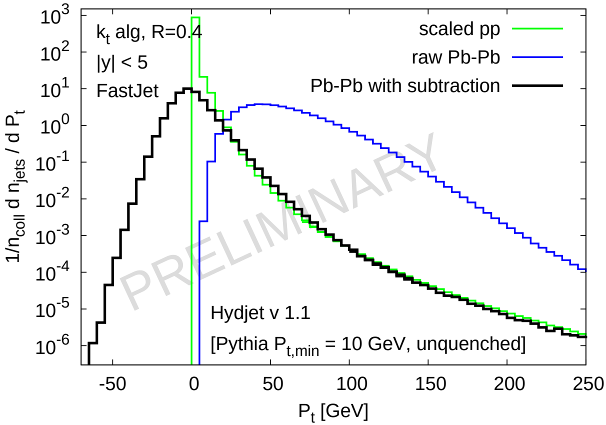


Uncorrected cone better than k_t.

Cam is intermediate ($\langle A_{cam} \rangle \simeq \langle A_{cone} \rangle$, but fluctuations larger)

Corrected Cam (and k_t) is best.

Inclusive jets in Pb-Pb @ LHC



Most HI studies use just particles with $p_t >$ a few GeV IR unsafe

affected by quenching

We use *all* particles and area-based subtraction.

Good results despite the huge subtraction being performed.