Jet reconstruction with FastJet

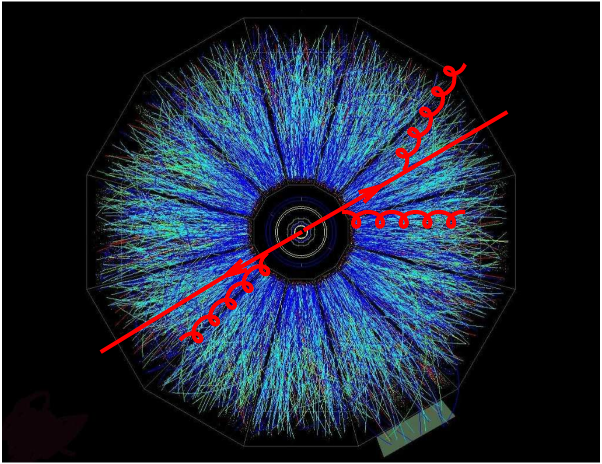
Gavin P. Salam

LPTHE, UPMC Paris 6 & CNRS

Jets in Proton-Proton and Heavy-Ion Collisions
Prague, 12 August 2010

Based on work (some preliminary) with
Matteo Cacciari, Juan Rojo, Sebastian Sapeta, Gregory Soyez

Jets in Heavy-Ion Collisions



Radiation from high-momentum quarks & gluons traversing hot medium can tell us about the medium

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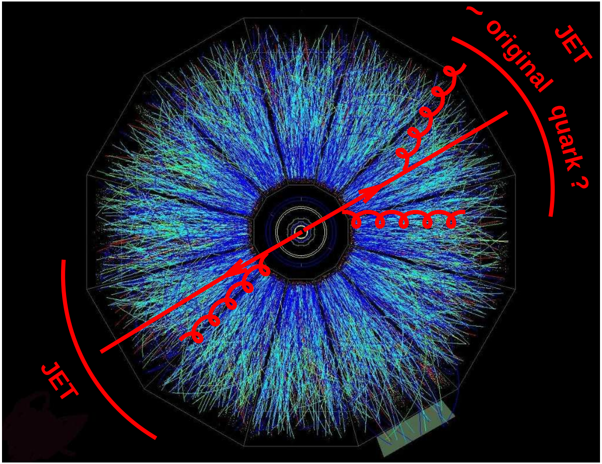

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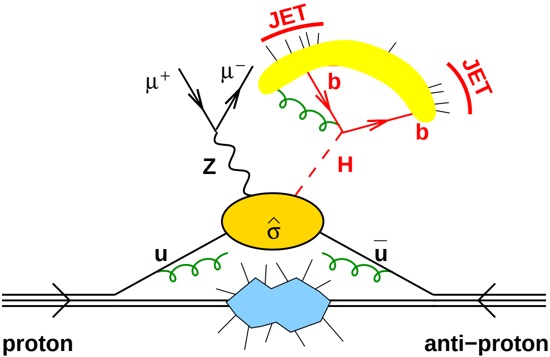

Use jets to reconstruct quarks from decay of some new heavy object

e.g. a Higgs boson

At high luminosity, many simultaneous *pp* collisions – not unlike AuAu/PbPb collision

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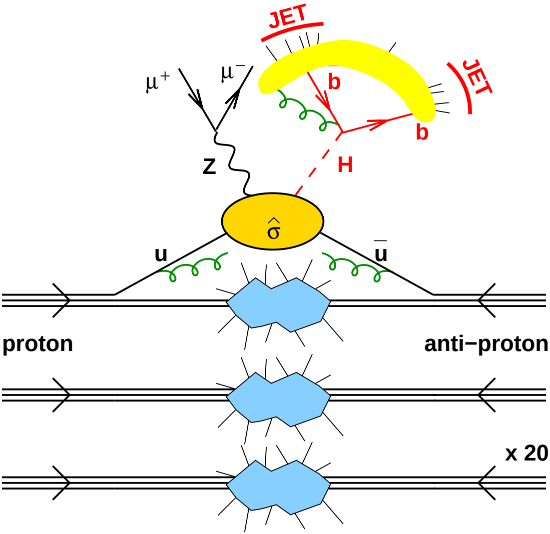

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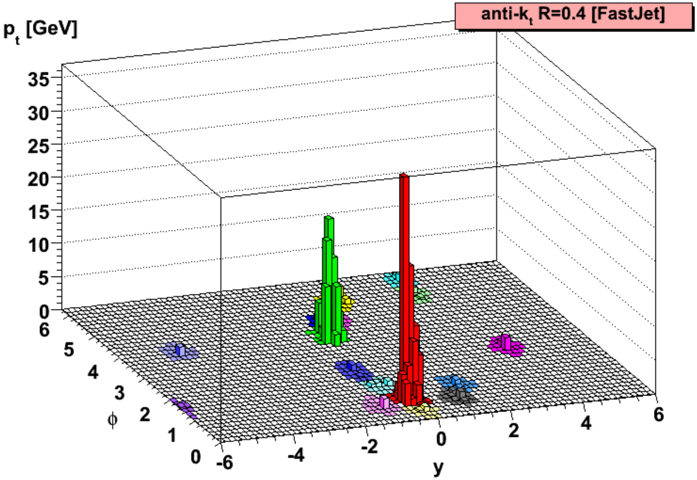

A pp event (LHC 5.5 TeV, Pythia)

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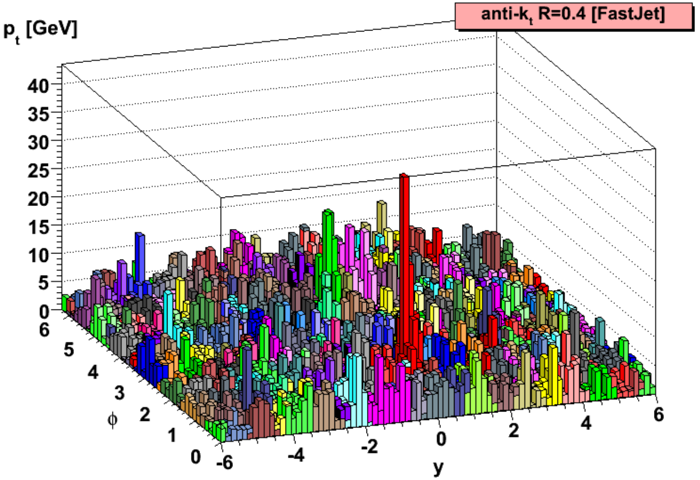

Contamination in jet

RHIC AuAu: $\mathcal{O}(40\text{ GeV})$

LHC PbPb: $\mathcal{O}(100\text{ GeV})$

LHC pp (hi-lumi) $\mathcal{O}(5-40\text{ GeV})$

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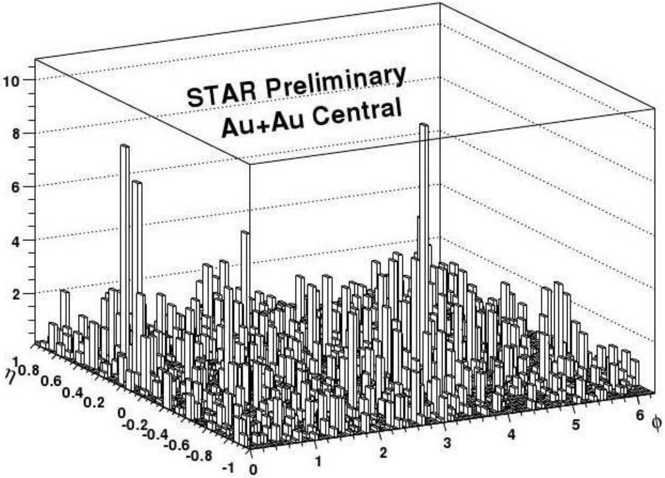

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A pp event (LHC 5.5 TeV, Pythia), embedded in a HI collision background (Hydjet 1.5) and an actual STAR event

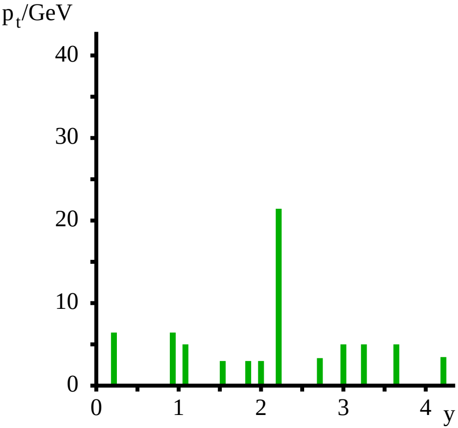
What are ingredients of jet finding in noisy environments?

1. Jets
2. Jet areas
3. Noise estimation
4. Noise subtraction

[5. Noise suppression]

1. Jet algorithms

Jets?



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Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2 > R^2$.

R parameter sets angular resolution

ϕ assumed 0 for all towers

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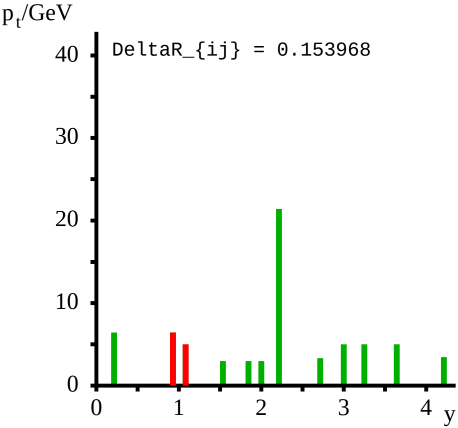

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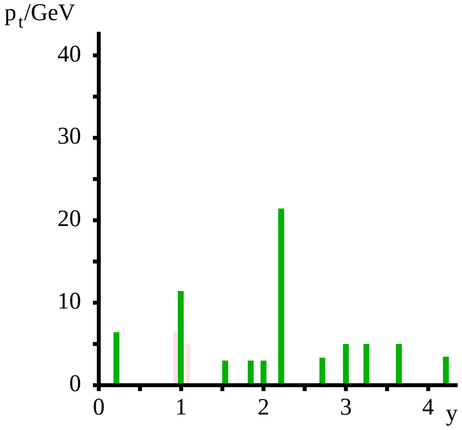

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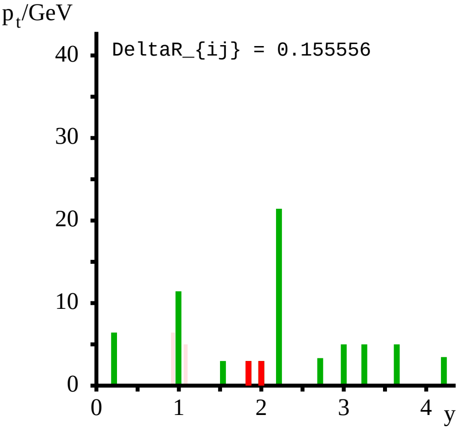

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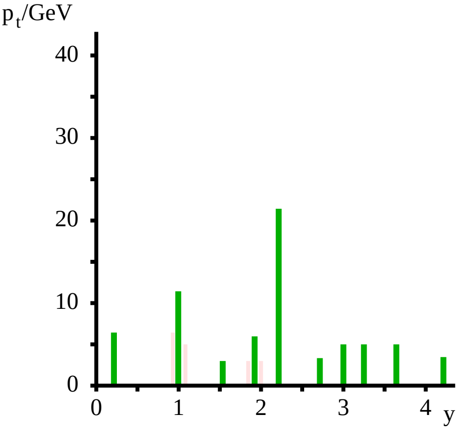

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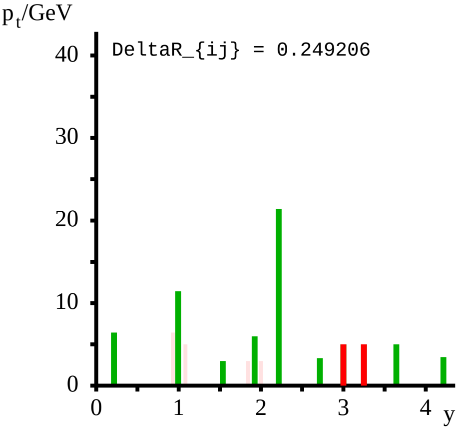

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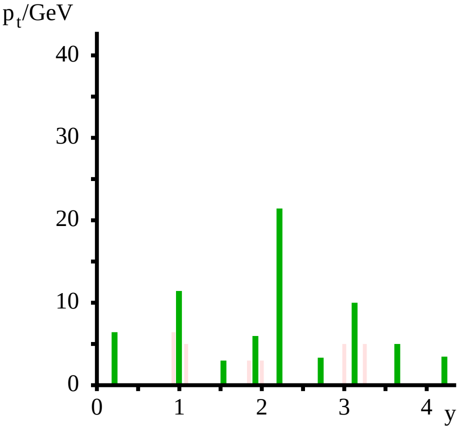

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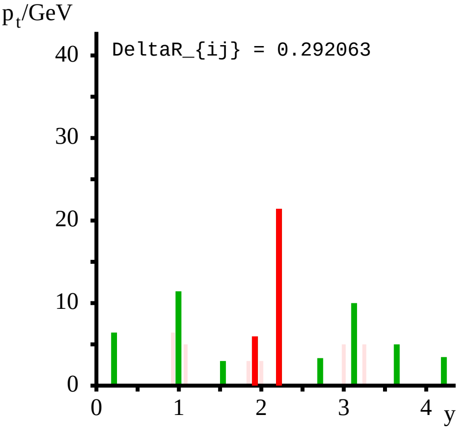

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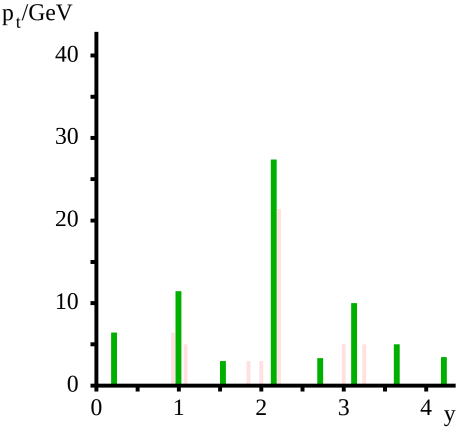

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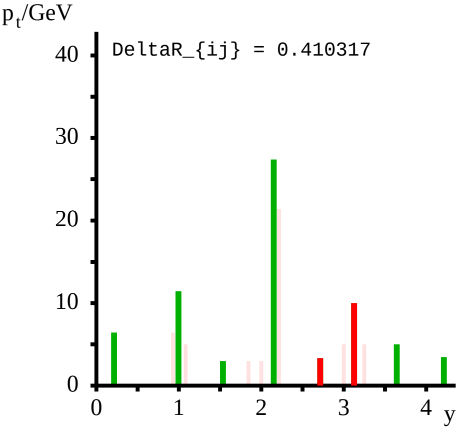

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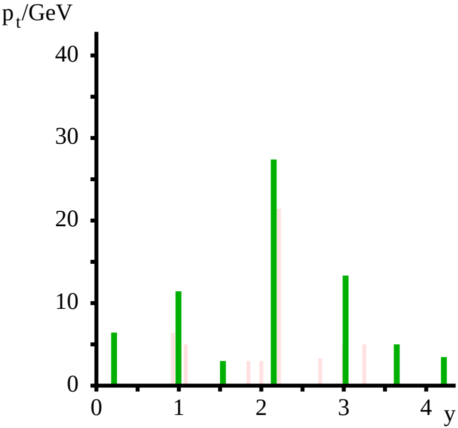

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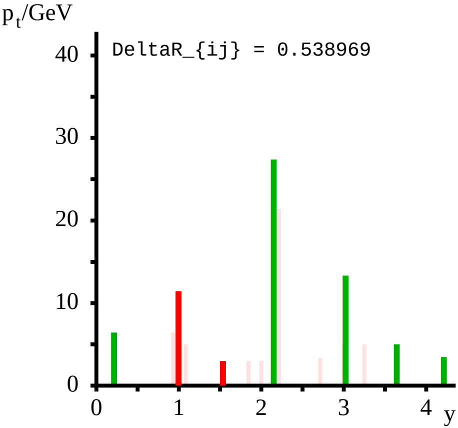

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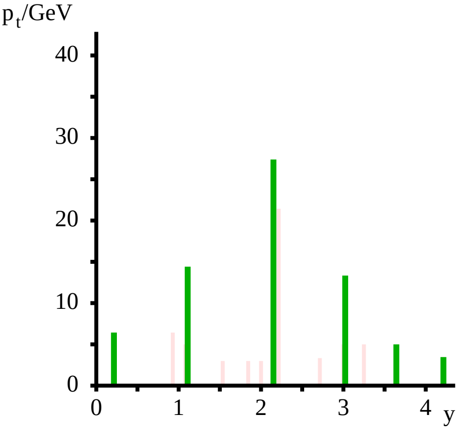

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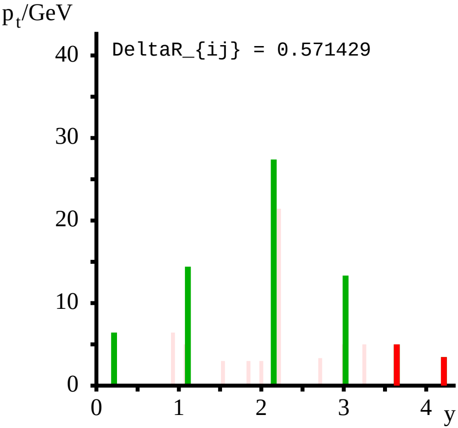

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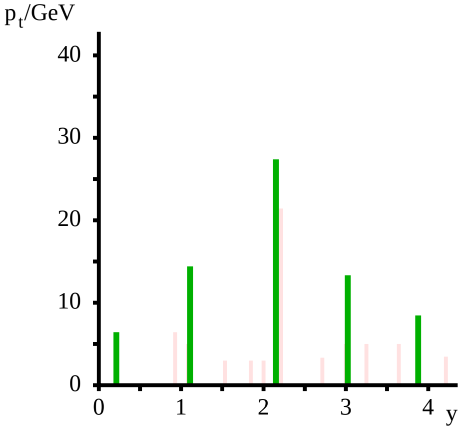

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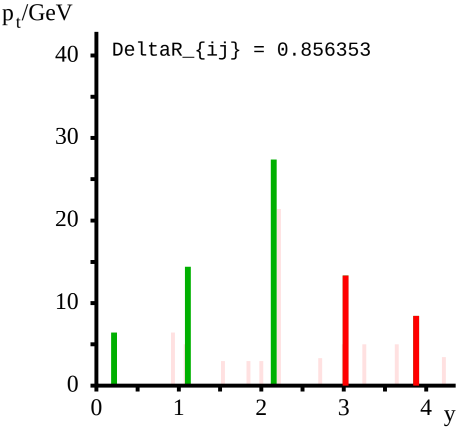

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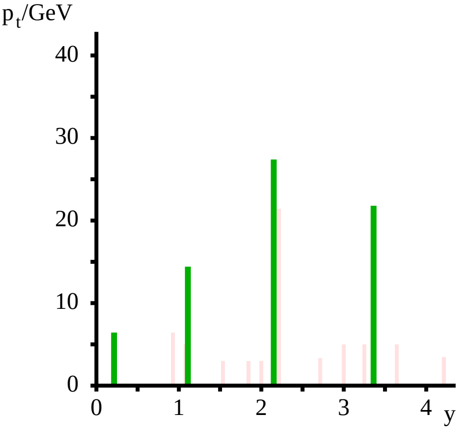

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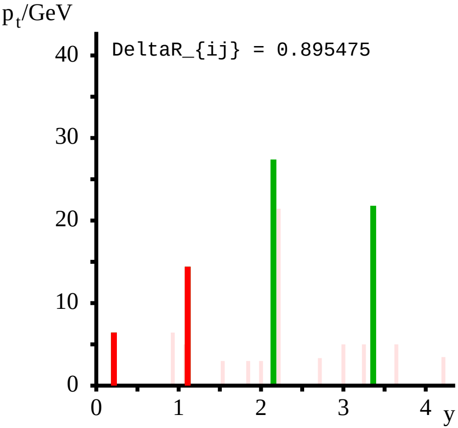

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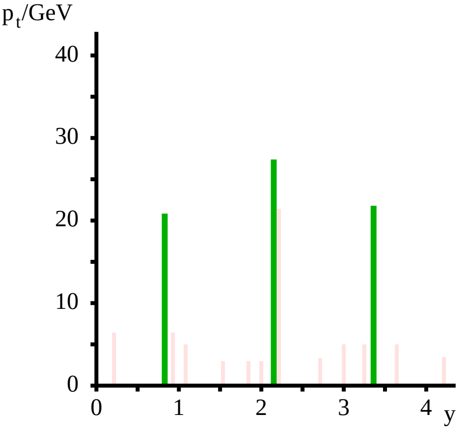

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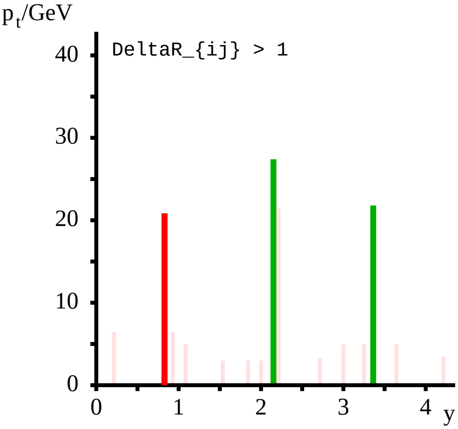

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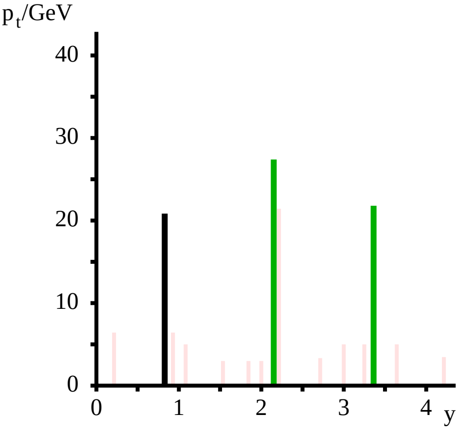

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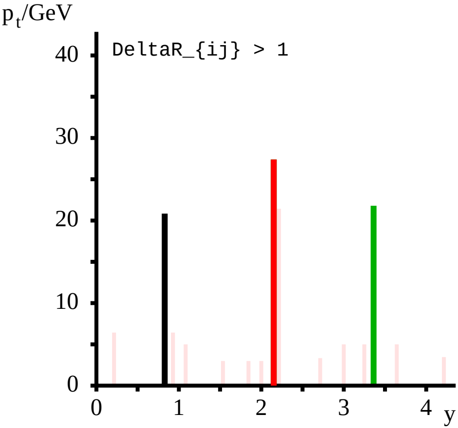

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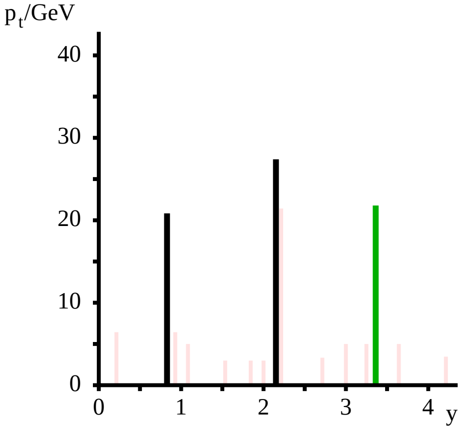

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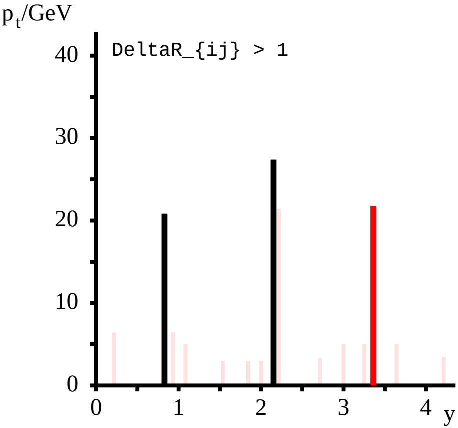

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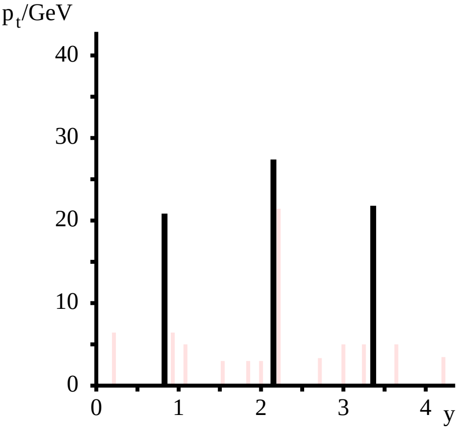

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A full set of IRC-safe jet algorithms

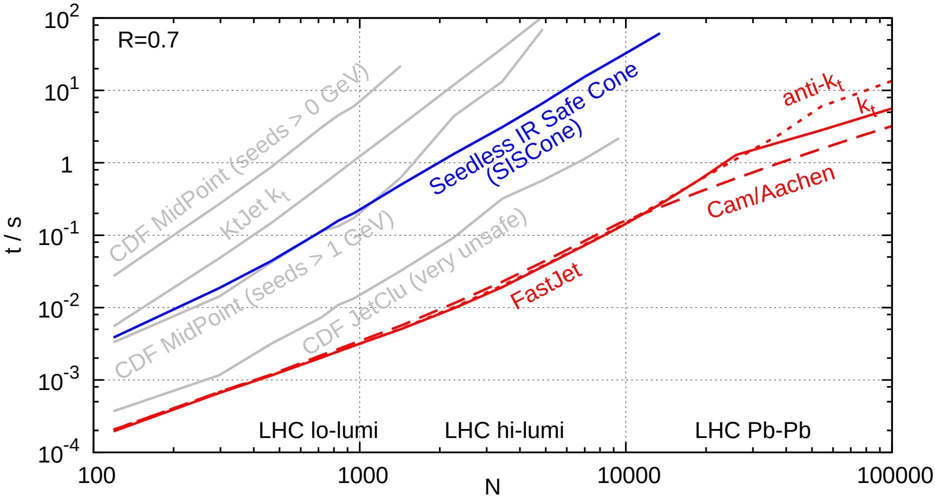
Generalise inclusive-type sequential recombination with

$$d_{ij} = \min(k_{ti}^{2\mathbf{p}}, k_{tj}^{2\mathbf{p}})\Delta R_{ij}^2/R^2 \qquad d_{iB} = k_{ti}^{2\mathbf{p}}$$

	Alg. name	Comment	time
$p = 1$	k_t CDOSTW '91-93; ES '93	Hierarchical in rel. k_t	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Hierarchical in angle Scan multiple R at once $\leftrightarrow$ QCD angular ordering	$N \ln N$
$p = -1$	anti-k_t Cacciari, GPS, Soyez '08 $\sim$ reverse-k_t Delsart	Hierarchy meaningless, jets like CMS cone (IC-PR)	$N^{3/2}$
SC-SM	SISCone GPS Soyez '07 + Tevatron run II '00	Replaces JetClu, ATLAS MidPoint (xC-SM) cones	$N^2 \ln N$ exp.

All these algorithms [& much more] coded in (efficient) `C++` **at**
`http://fastjet.fr/` (Cacciari, GPS & Soyez '05-'10)

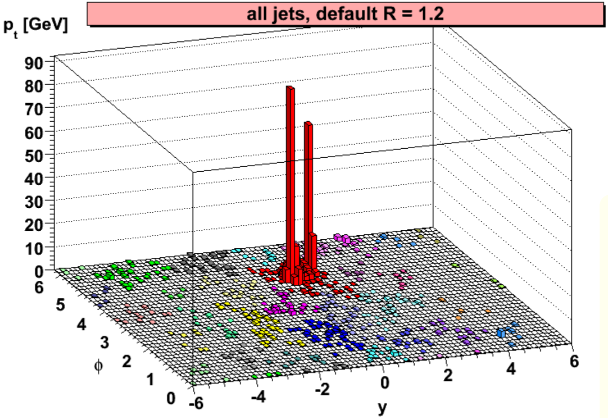
FastJet: time to cluster *N* particles



2. Jet areas

Measure jets' susceptibility to contamination by noise

Jet areas



Jets are made of finite number of pointlike particles.

Area not unambiguous concept

Jet areas must be defined

Add many soft particles to event

10^{-100} GeV each

$A \propto \#$ inside jet

Cacciari, GPS & Soyez '08

measure of jet's susceptibility to contamination from soft radiation

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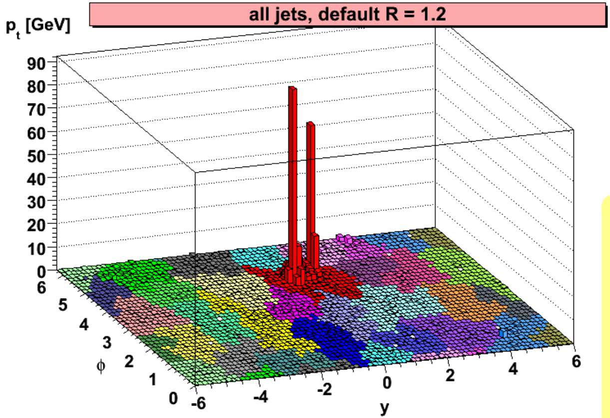

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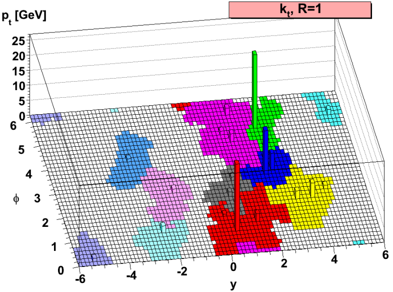
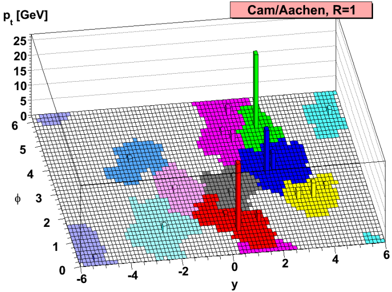
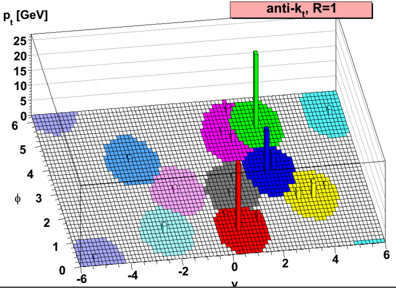
measure of jet's susceptibility to contamination from soft radiation

Areas for 3 jet algorithms







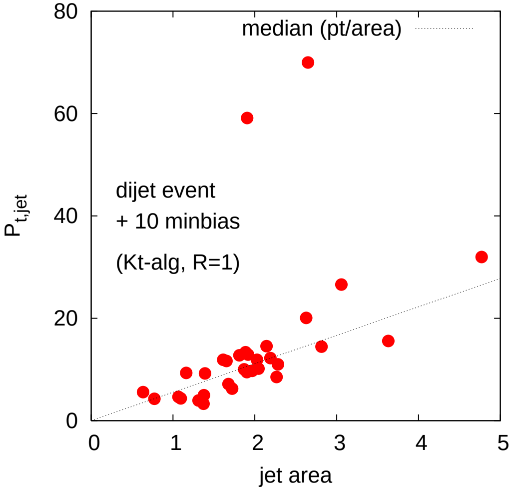
A family of algorithms, all cluster pair with smallest d_{ij}:

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$p = \begin{cases} 1 & k_t \\ 0 & \text{C/A} \\ -1 & \text{anti-}k_t \end{cases}$$

3. Noise estimation

Estimating $\rho \equiv$ background noise level



Most jets in event are "background"

Their p_t is correlated with their area.

Estimate ρ:

$$\rho \simeq \underset{\{jets\}}{\text{median}} \left[\frac{p_{t,jet}}{A_{jet}} \right]$$

Median limits bias
from hard jets
Cacciari & GPS '07

4. Noise subtration

Subtracting noise from jets

$$p_{t,jet}^{\mathrm{subtracted}} = p_{t,jet} - \rho \times A_{jet}$$

$$A_{jet} = \text{jet area}$$

$$\rho = p_t \text{ per unit area from underlying event}$$

(or “background”)

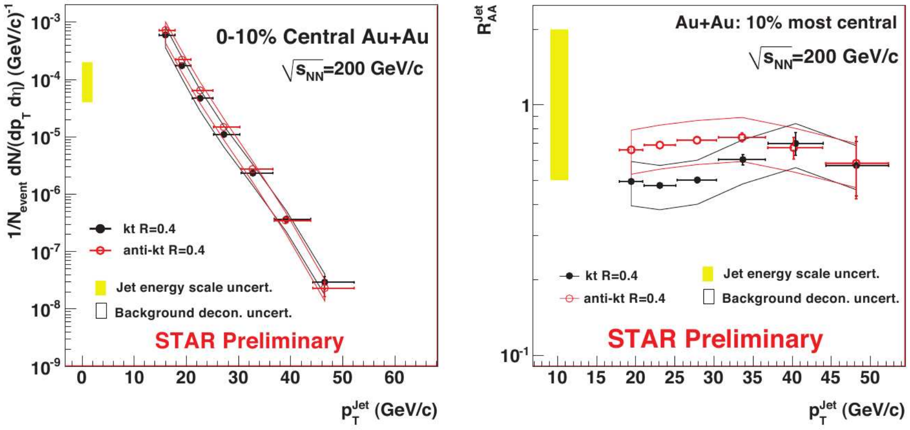
This procedure is intended to be common to pp, pp with pileup (multiple simultaneous minbias) and HIC

NB in AuAu at RHIC: $p_{t,jet}^{\text{subtracted}} = 20 - 50$ GeV, $\rho \simeq 80$ GeV and $A_{jet} \simeq 0.5$

Use at RHIC?

Let's examine some of the issues

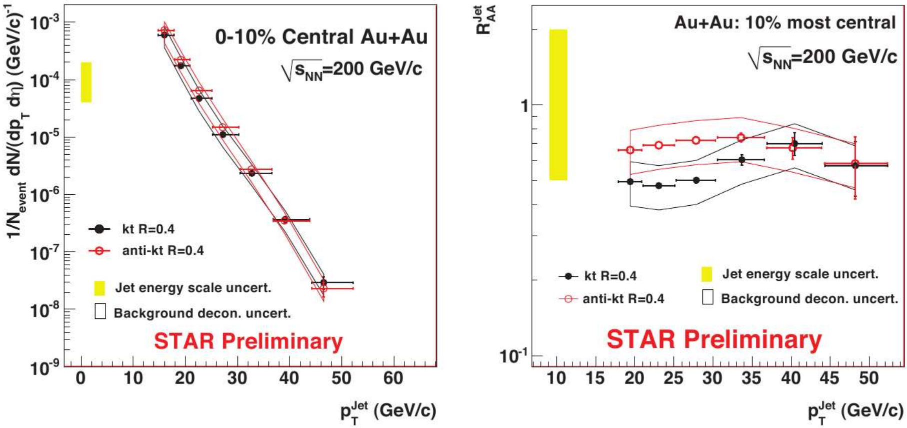
Area/median method → STAR jet results



Method designed to minimise biases, but some still persist.

Question: can we calculate size of biases? Can we further reduce them?

Area/median method → STAR jet results



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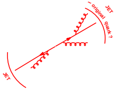
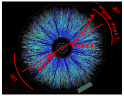
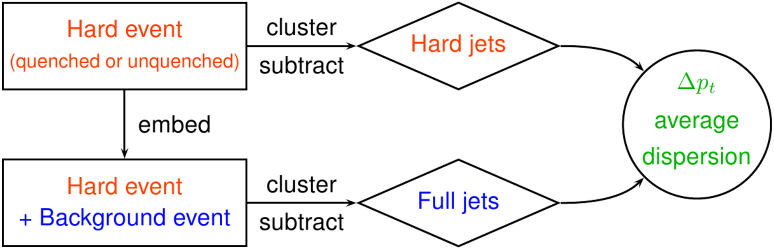
Question: can we calculate size of biases? Can we further reduce them?

Framework for a theorists' study







Hard event
(quenched or unquenched)

cluster
subtract

Hard jets

embed

Hard event
+ Background event

cluster
subtract

Full jets

Δp_t
average
dispersion

Define:

$$\Delta p_t = p_t^{\text{full(subtracted)}} - p_t^{\text{hard}}$$

Study:

average of Δp_t, $\langle \Delta p_t \rangle$

dispersion of Δp_t, $\sigma_{\Delta p_t}$

This study

We don't have real background (or hard!) events, so use

- Hard event: Pythia 6.4, and optionally PyQyen 1.5 / QPythia
- Background: Hydjet 1.6 (Hydjet++ 2.1 for cross-checks)
- Analysis: FastJet 2.4 (& 2.5-devel), $R = 0.4$ for all main jet finders (k_t with $R = 0.5$ for bkgd estimation).

Cacciari, Rojo, GPS & Soyez, to appear soon…

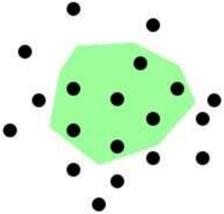
Example #1: non-zero $\langle \Delta p_t \rangle$

(background does not *just* linearly add noise to jet)

BACK REACTION

"How (much) a jet changes when immersed in a background"

Without background



Slide from M. Cacciari

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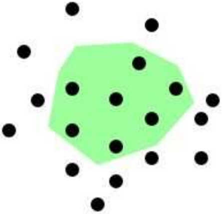

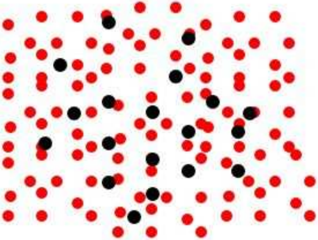

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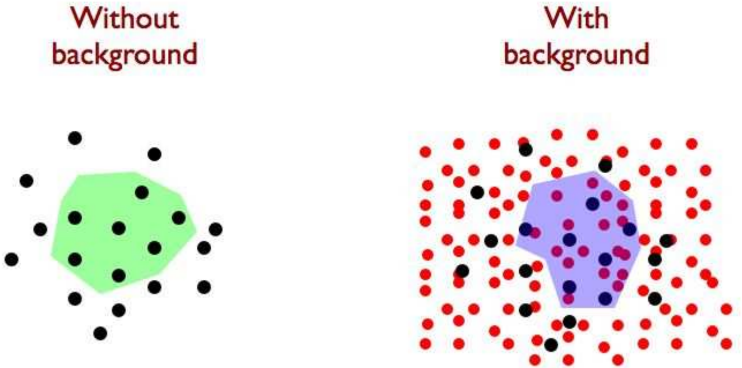

Without background

With background

Slide from M. Cacciari

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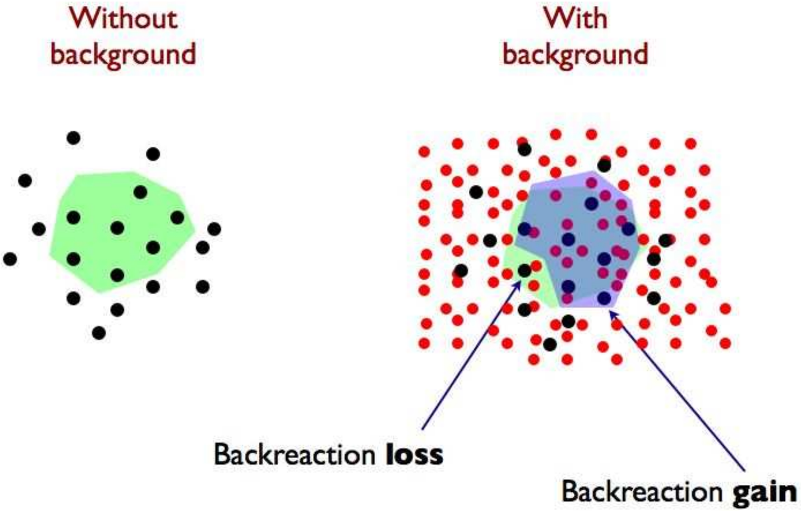

Slide from M. Cacciari

Backreaction can be calculated (sort of...)

Soft & collinear approximation:

$$\delta p_t^{BR} = \mathcal{B}_{alg} \cdot \rho R^2 \frac{2C_i}{\pi} \alpha_s \ln \frac{p_t}{\rho R^2}$$

Cacciari, GPS & Soyez '08
+ large corrections

jet alg	$\mathcal{B}_{alg}$
k_t	-0.3
C/A	-0.3
anti-k_t	0

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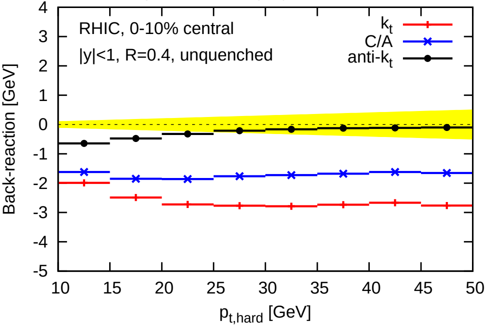
Pythia + Hydjet + FastJet



Cacciari, Rojo, GPS & Soyez, prelim.

anti-k_t bias = 0, as expected

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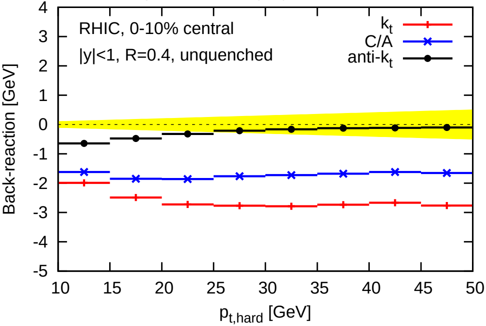


Cacciari, Rojo, GPS & Soyez, prelim.

anti-k_t bias = 0, as expected

Different jet algorithms have different systematics
Use of more than one provides important cross-checks

Example #2: fluctuations

Fluctuations

Fluctuations of amount of background / underlying-event in a square of unit area can be characterised in terms of σ_{UE}, which is $\mathcal{O}(10 \text{ GeV})$ at RHIC.

Dispersion in jet subtraction, σ_{jet} is given by

$$\sigma_{\Delta p_t} = \sigma_{UE} \times \sqrt{A_{jet}}$$

jet alg	$\langle A_{jet} \rangle$
k_t	$0.81\pi R^2$
C/A	$0.81\pi R^2$
anti-k_t	πR^2

+ p_t-dependent scaling violations for k_t and C/A

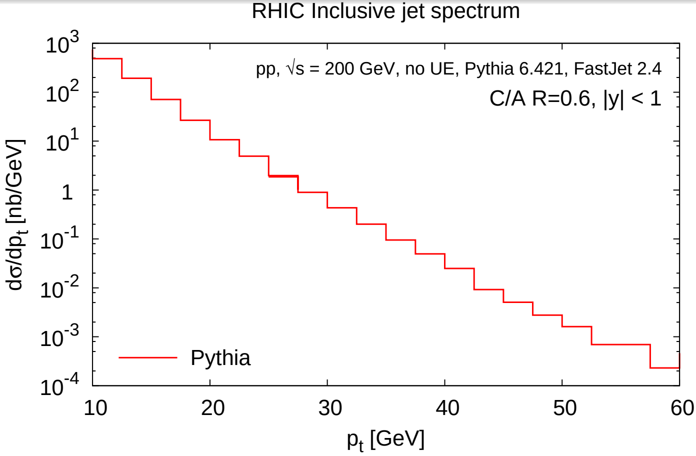
Put in numbers:

$$\sigma_{UE} \simeq 8 - 10 \text{ GeV}$$

$$\rightarrow \quad \boldsymbol{\sigma_{\Delta p_t} \sim 6 - 7 \textbf{ GeV}}$$

What impact does this have?

Context: a steeply falling X-section



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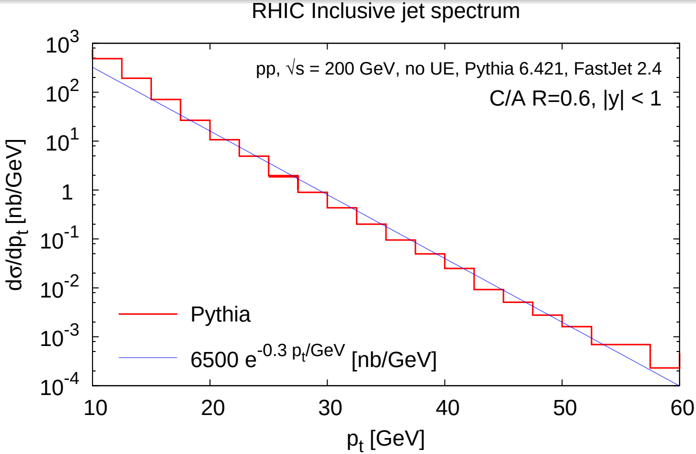


To help think about impact of falling cross section at RHIC, approximate it as: $\frac{d\sigma}{dp_t} \sim \exp(-0.3 p_t / \text{ GeV})$

Interplay of PDFs & $1/p_t^4$ matrix element

Exponential spectrum ⊗ Gaussian fluctuations

$$\exp(-ap_t) \otimes \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{\Delta p_t^2}{2\sigma^2}\right)$$

Real fluctuations not quite Gaussian

Real spectrum not quite exponential (especially at low & high p_t!)

But simple approximations give instructive analytical answers

Convolution rescales spectrum by factor:

$$\exp\left(\frac{1}{2}a^2\sigma^2\right) \sim 10 \text{ for } \sigma \sim 7 \text{ GeV}$$

Convolution migrates $\mathbf{p_t}$'s by

$$a\sigma^2 \sim 15 \text{ GeV for } \sigma \sim 7 \text{ GeV}$$

Reducing fluctuations, while limiting bias:

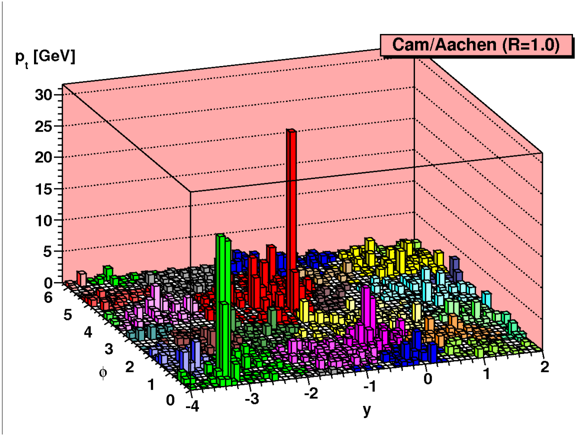
filtering

Filtering

Idea to improve resolution for an LHC Higgs search in $H \to b\bar{b}$ decay mode!

Keep hardest $\mathcal{O}(\alpha_s)$ gluon emission in jet, while throwing out soft "junk"

Butterworth, Davison, Rubin & GPS '08



1. Consider a jet
2. View it on smaller angular resolution scale R_{filt}
3. Take (e.g.) 2 hardest "subjets"
   leading quark + 1 gluon
4. The result is a "filtered" jet

Related ideas by Ellis, Vermillion & Walsh '09 and Krohn, Thaler & Wang '09

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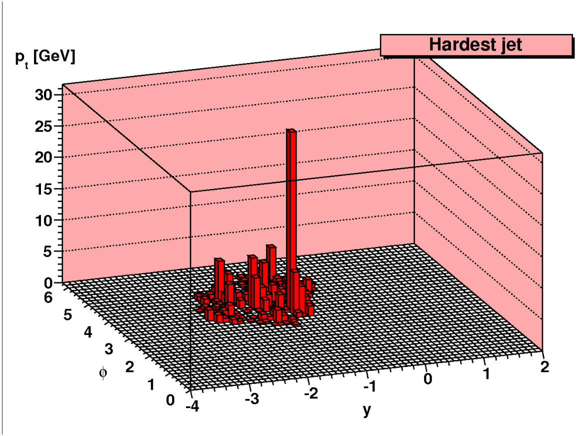

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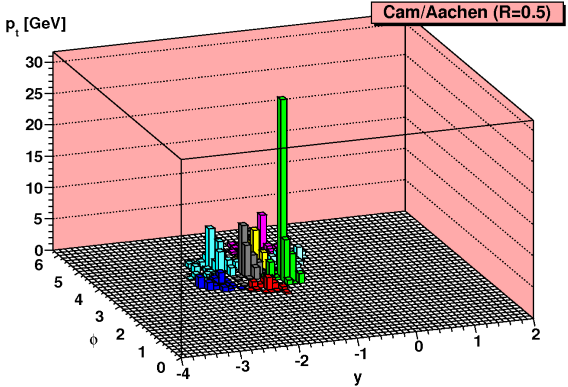

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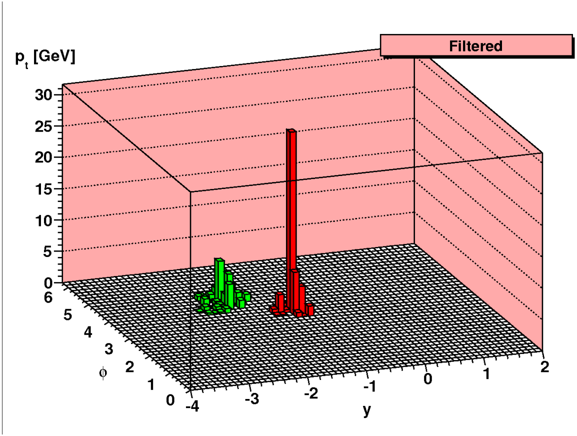

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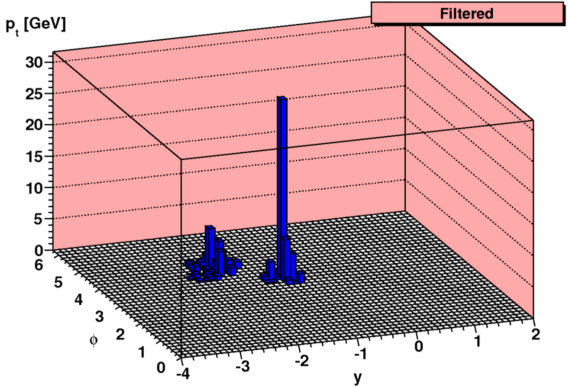

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LHC Higgs-boson search & filtering

Reconstructed mass for jets from decay of high-p_t Higgs-boson

[without pileup]

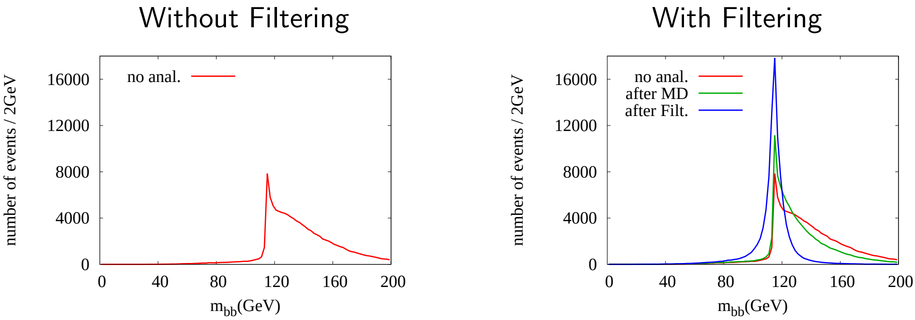
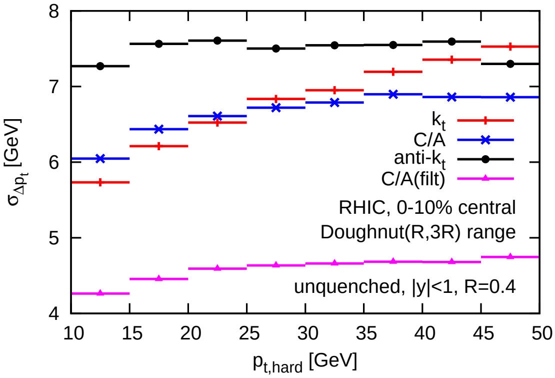


Figure from Rubin

Among the techniques adopted in search for $H \to b\bar{b}$ at LHC

Impact of filtering on dispersion in HIC



Filtering reduces jet area by $\sim \frac{1}{2}$

Fluctuations $\propto \sqrt{A}$ should go down by $\sim \sqrt{\frac{1}{2}}$

And they do

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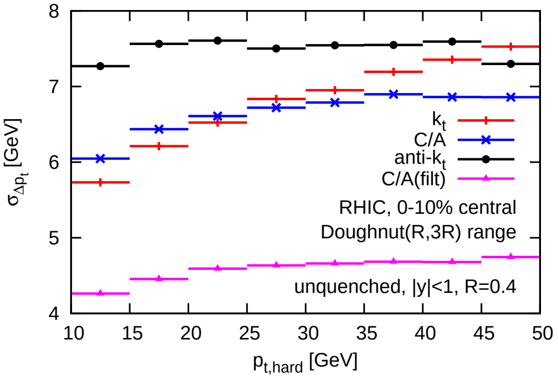


Filtering reduces jet area by $\sim \frac{1}{2}$

Fluctuations $\propto \sqrt{A}$ should go down by $\sim \sqrt{\frac{1}{2}}$

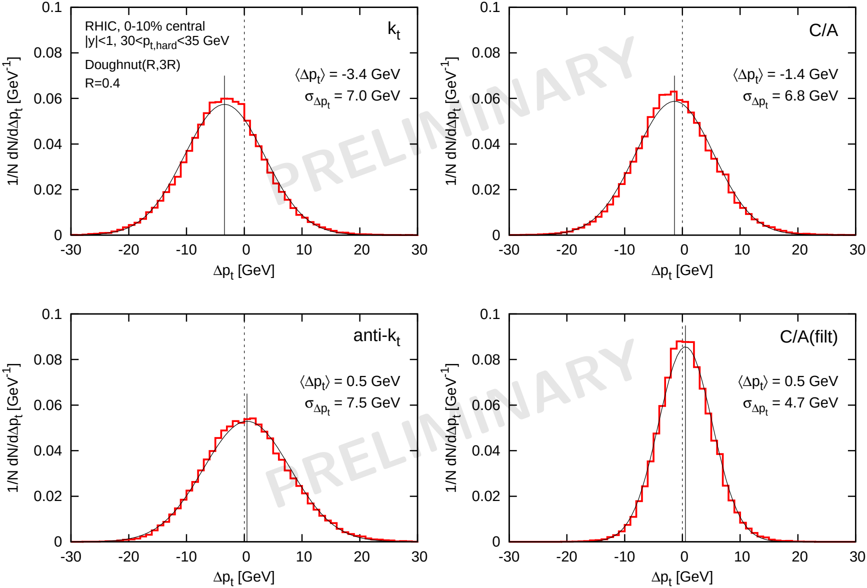
And they do

Filtering's reduction of dispersion from 7 GeV to 5 GeV means experimental "unfolding" might be factor 3 instead of factor 10

Numbers are rough – intended to give an idea of impact

NB: Gaussian filtering (Cole & Lai '08) not the same thing

Full Δp_t distributions



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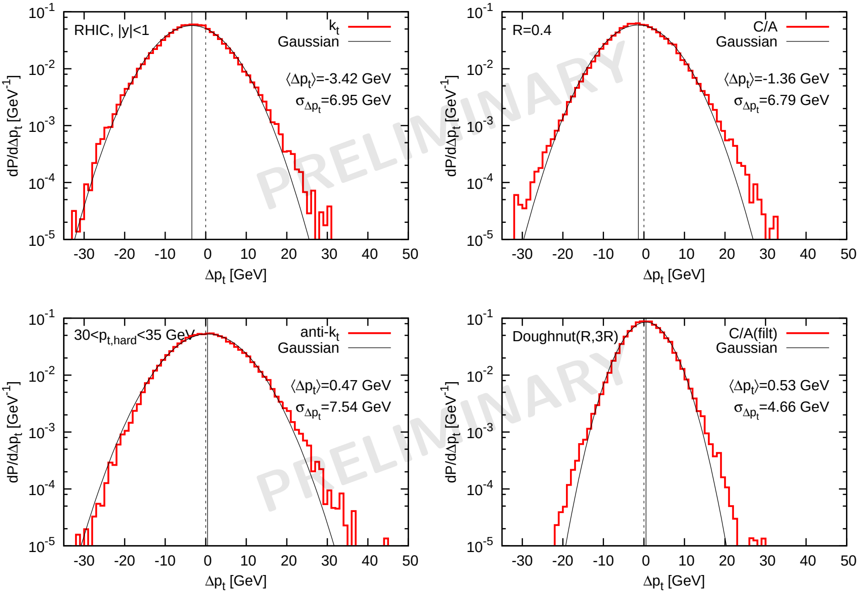


Does filtering introduce new biases in jets in quenched case?

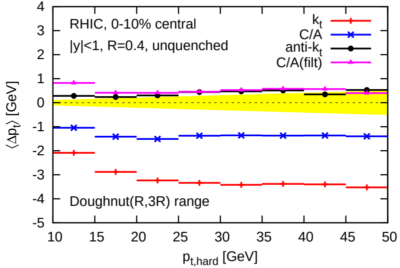
Vacuum QCD: we know how much gluon radiation we lose

QCD in medium: extra medium-induced radiation lost?

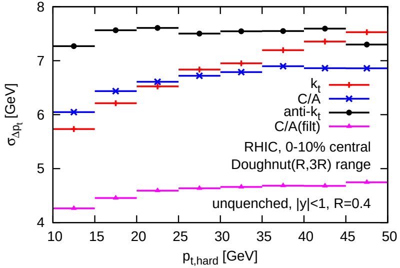
Summary RHIC (Pythia/Hydjet)

UNQUENCHED

PT SHIFT



DISPERSION



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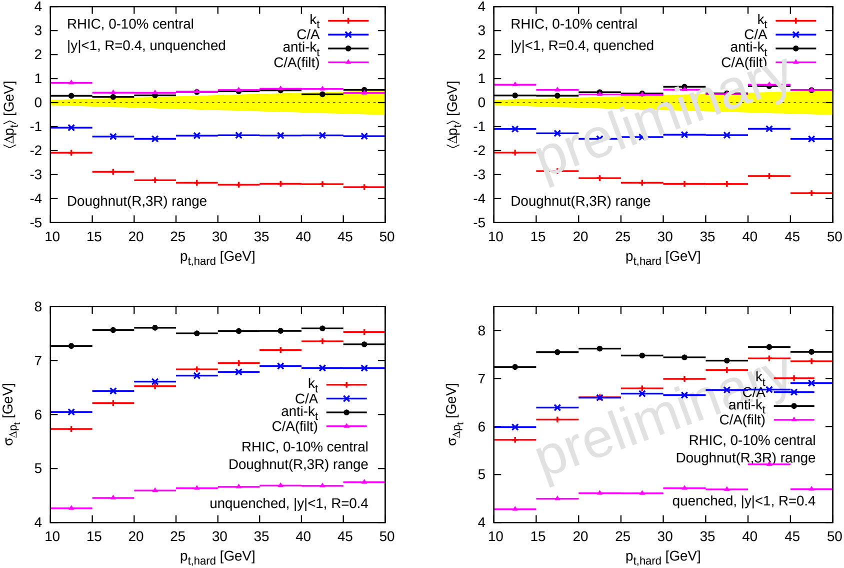

Summary LHC (Pythia/Hydjet)

UNQUENCHED

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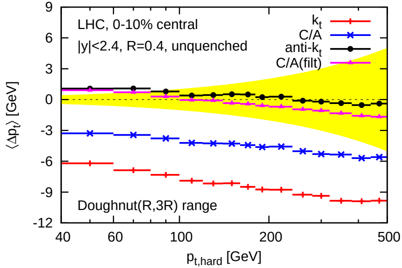

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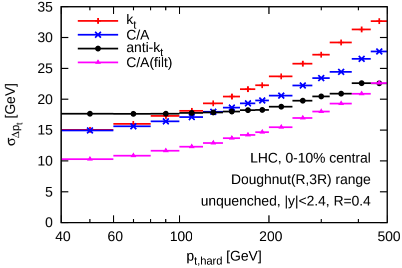
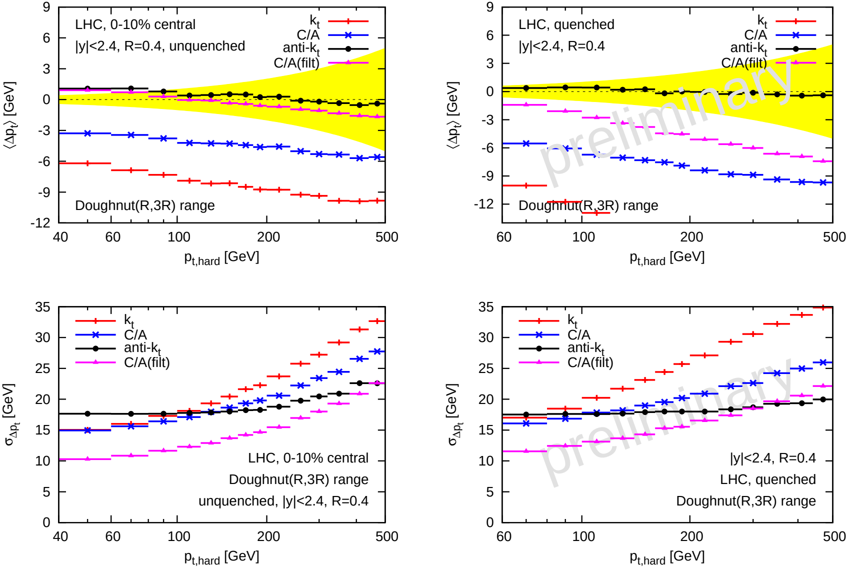


Summary LHC (Pythia/Hydjet)

UNQUENCHED QUENCHED

PT SHIFT

DISPERSION



Conclusions

It's still early days for jet-finding in HIC (& high-luminosity LHC)

It's a tough job to accurately remove 40 GeV *of noise from a* 40 GeV *hard jet in the context of a steeply falling cross-section.*

Theory calculations can guide the choices one makes

- Give us an idea of size of corrections semi-independently of Monte Carlo

  Some of them are rather large

- Tell us which approaches are complementary in their systematics

  Adding to robustness of experimental measurements, e.g. k_t v. anti-k_t

  NB: it's still hard to estimate how quenching affects systematics

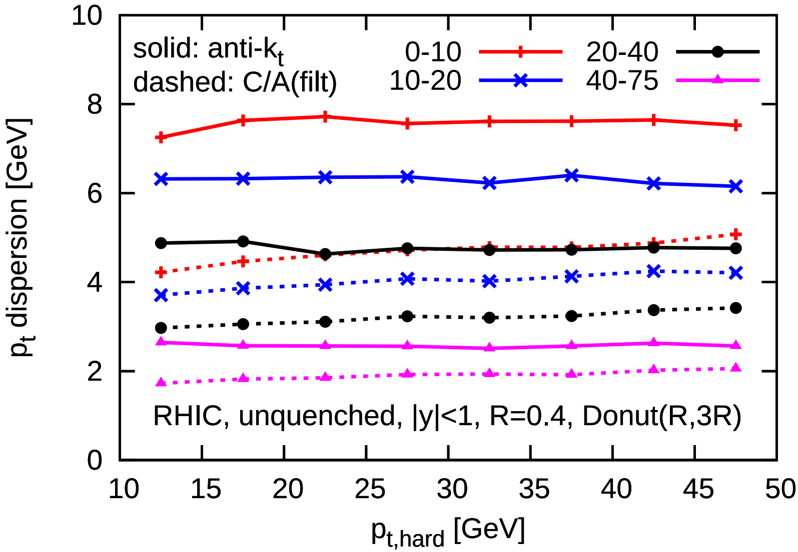
- Guide design of new tools that have smaller systematics

  Like filtering, yet to be tried out at RHIC

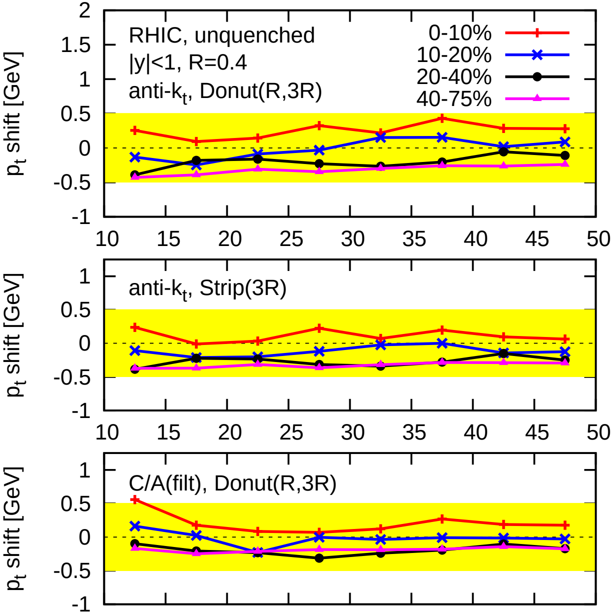
Important potential for cross-fertilization between ideas in HIC and LHC pp programs.

EXTRAS

Disperson for non central AuAu



P_t shift for non central AuAu



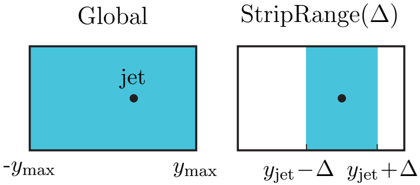
Example #2: another bias

is ρ measured correctly?

Bias in median estimate for ρ?

What could go wrong?

- Rapidity and azimuth dependence of ρ distribution means ρ near jet $\neq \rho$ measured over large region. So try various regions:



- Median estimate $\neq$ mean contamination. Can be studied in toy models:

$$\rho^{median} \simeq \rho^{true}\left(1-\frac{1}{3\nu R^2}\right)$$

ν = number of particles / unit area

With $\nu = 100$, $R = 0.4$, $\mathcal{O}(2\%) \rightarrow \mathcal{O}(1\text{ GeV})$ on jet p_t

Cacciari, GPS & Sapeta '09, for measuring $\rho \sim 2$ GeV in pp collisions!

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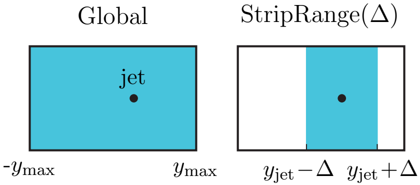

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