Jets, underlying event and HIC

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From Particles and Partons to Nuclei and Fields:
An international workshop and symposium in honor of Al Mueller's 70th birthday

23-25 October 2009, Columbia University, NY, USA

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

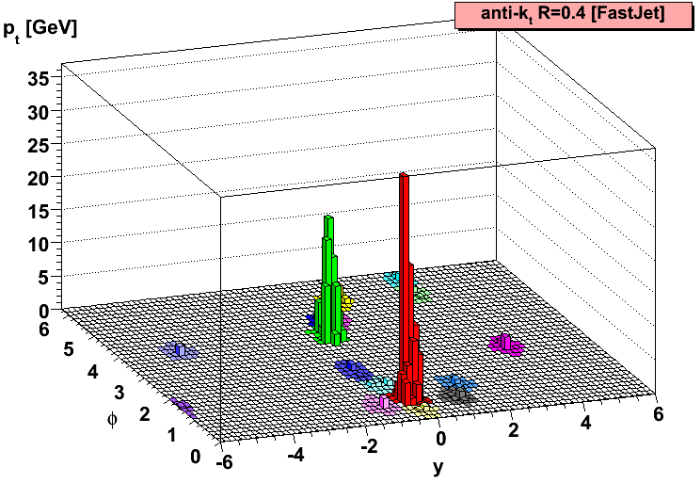
STAR and PHENIX are making extensive studies of fully reconstructed jets in AuAu collisions.

What are the challenges of measuring jets in HIC?

Relevant when using jets for studies of quenching, including BDMPS

How do these challenges relate to questions in pp collider physics?

Challenge: large contamination



A pp event (LHC 5.5 TeV, Pythia)

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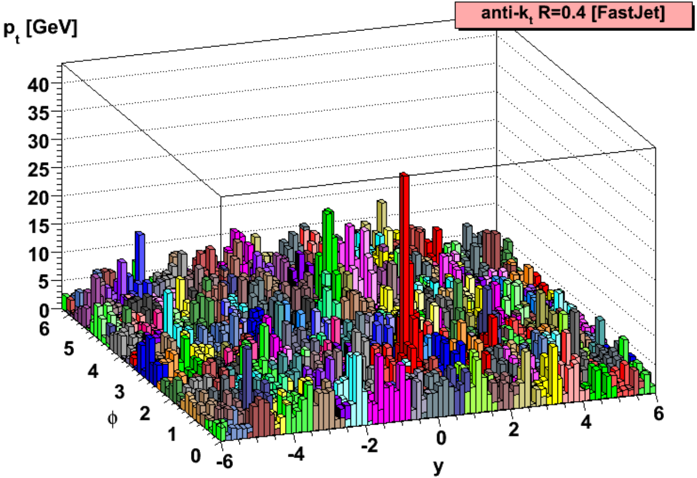

Contamination in jet

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

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

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

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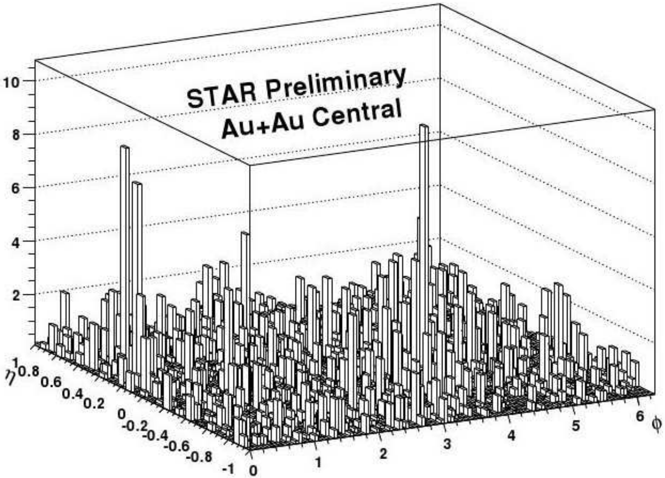


Contamination in jet

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

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

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 heavy-ion jet finding?

Jets?

A jet algorithms provides a mapping:

$$\text{particles} \xrightarrow[\text{jet.def.}]{} \text{jets}$$

Simplest pp jet algorithm is "Cambridge/Aachen"

Dokshitzer et al '97

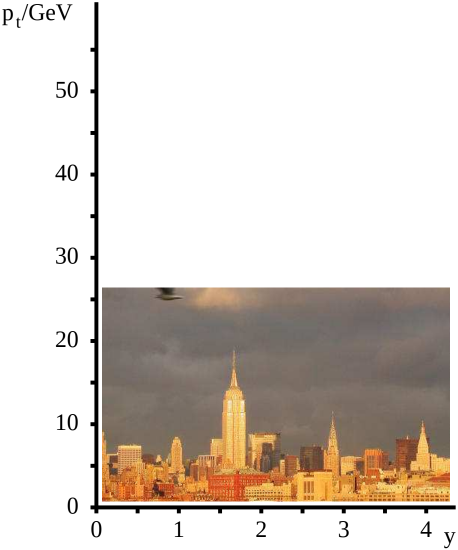
Wengler & Wobisch '98

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

Jets?



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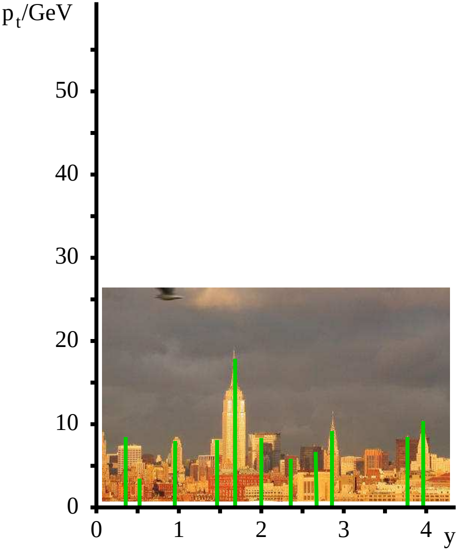

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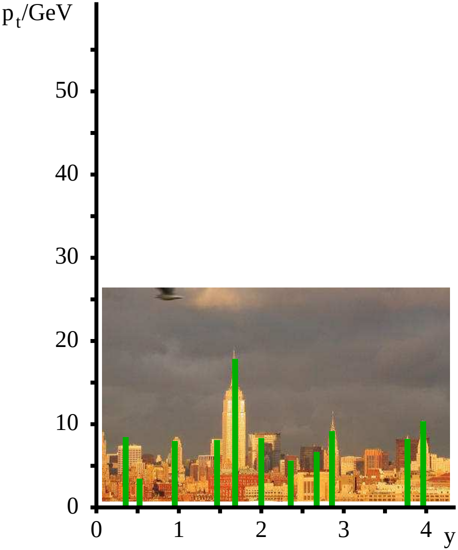

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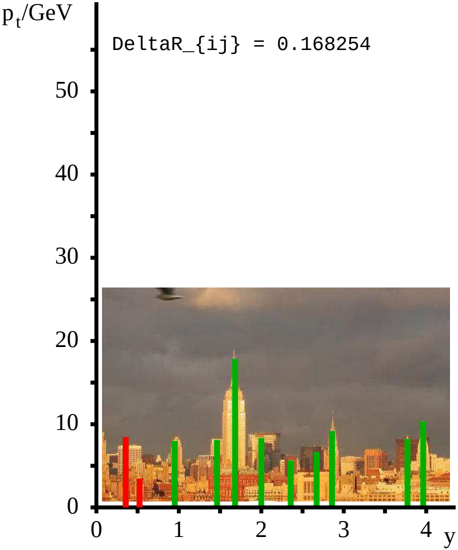

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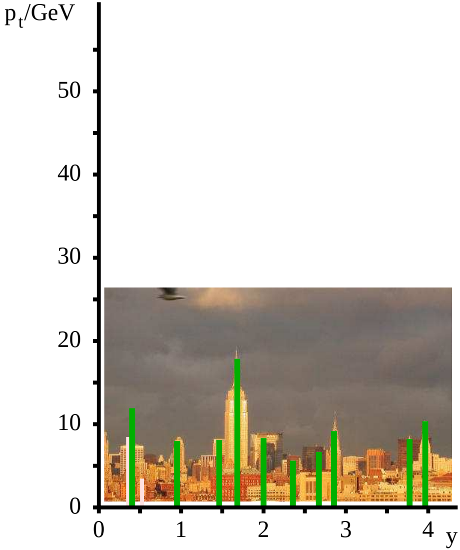

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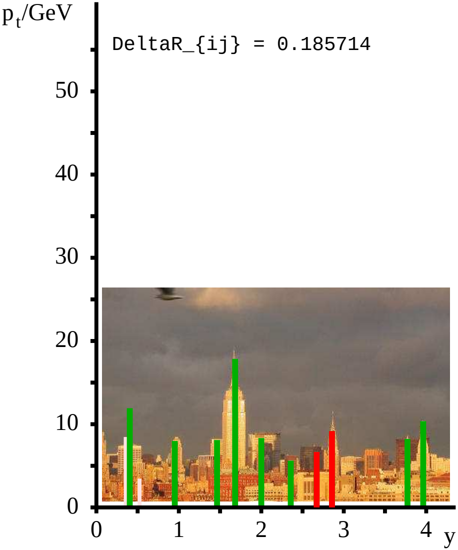

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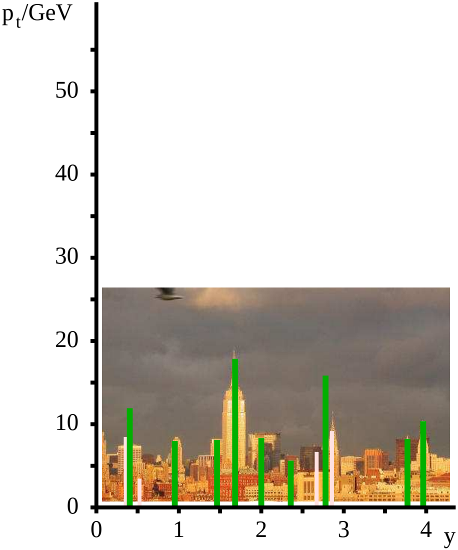

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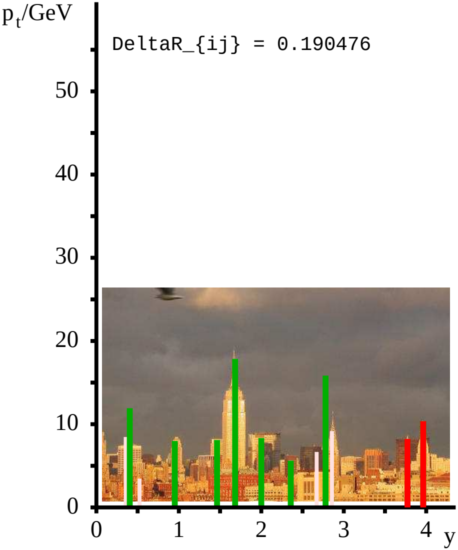

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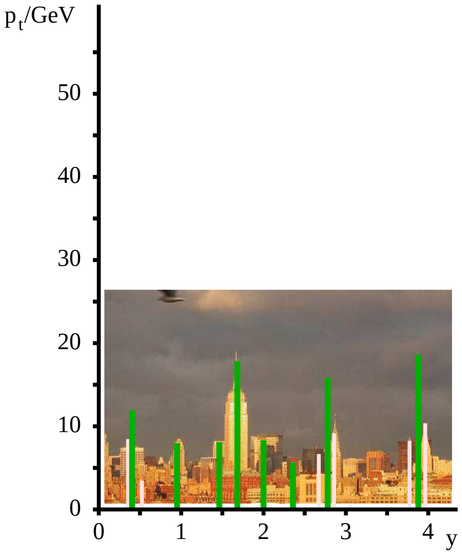

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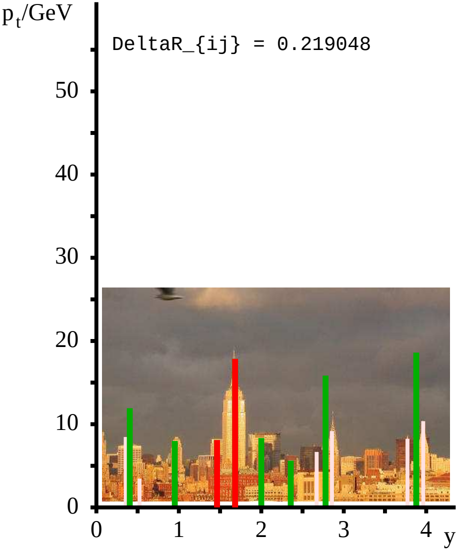

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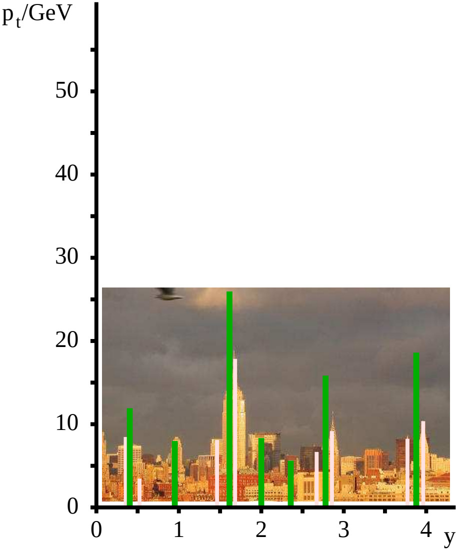

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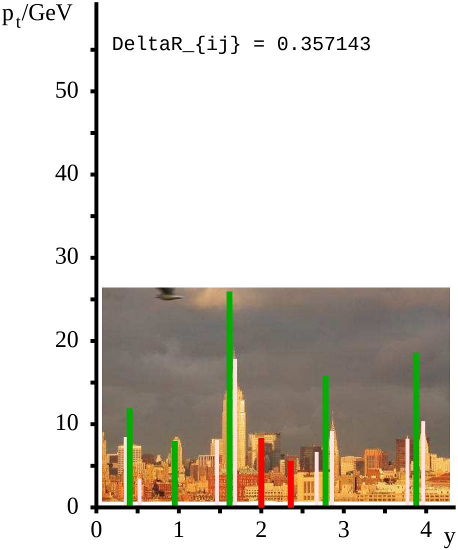

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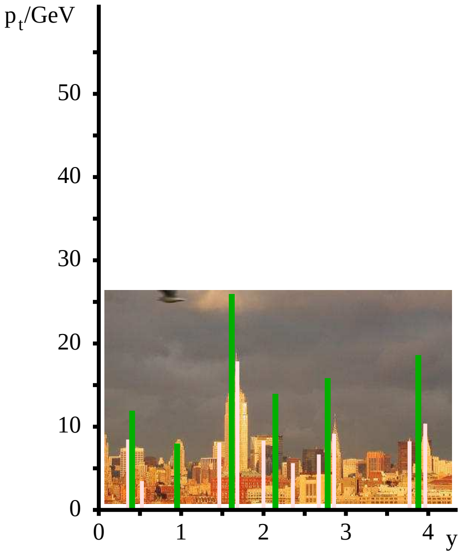

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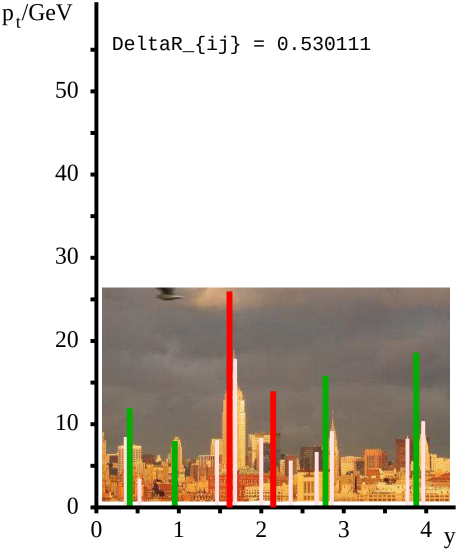

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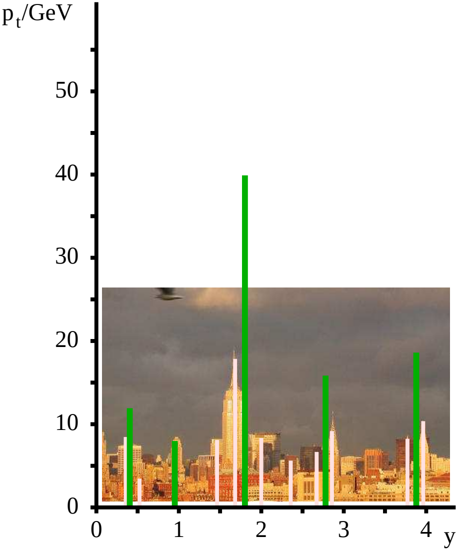

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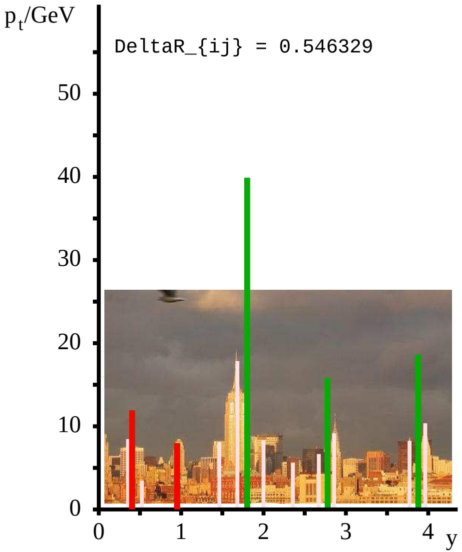

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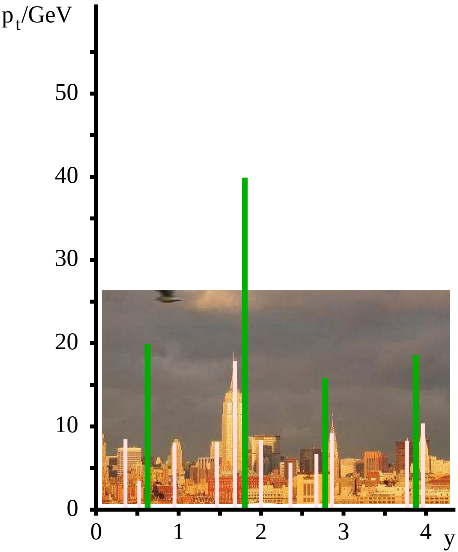

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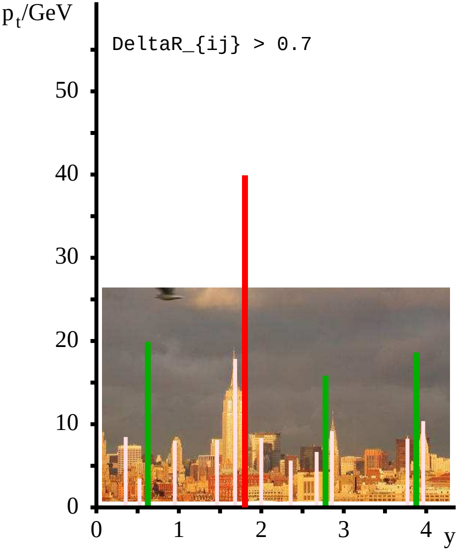

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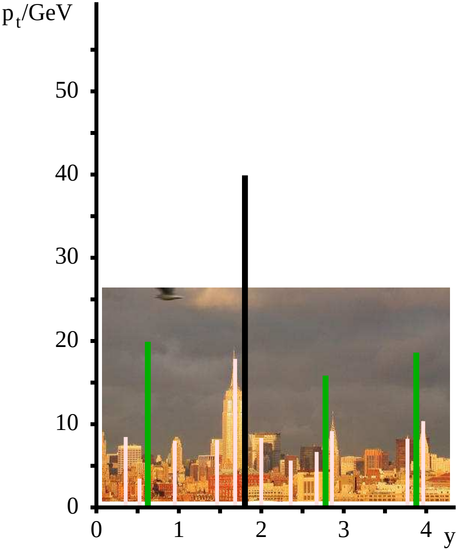

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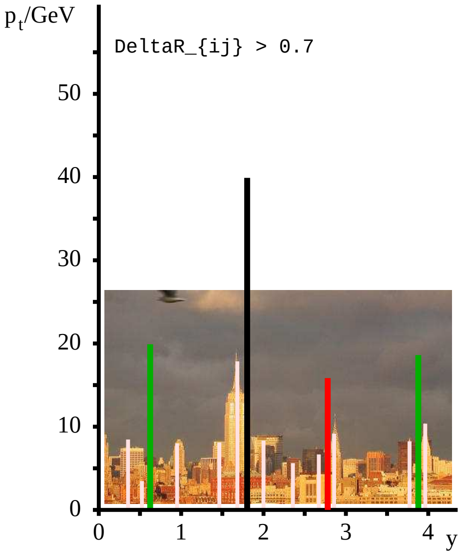

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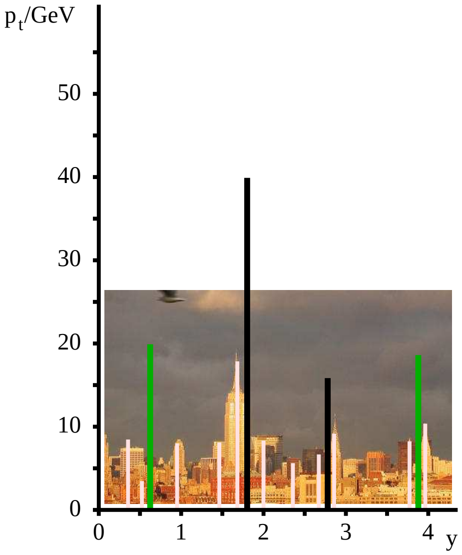

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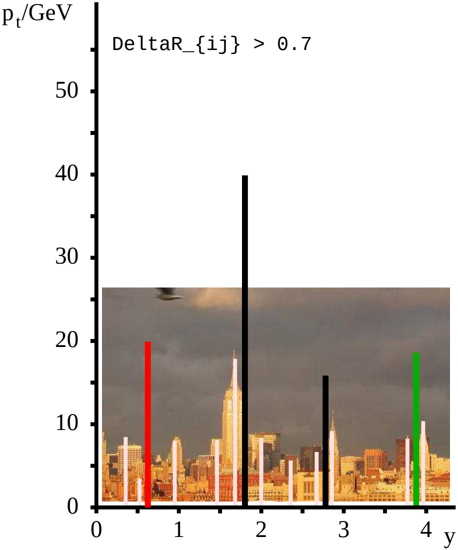

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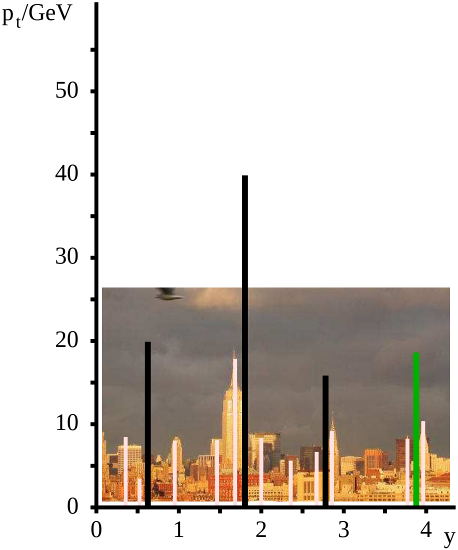

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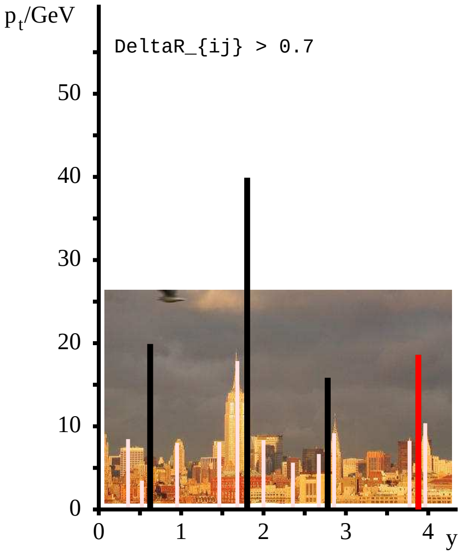

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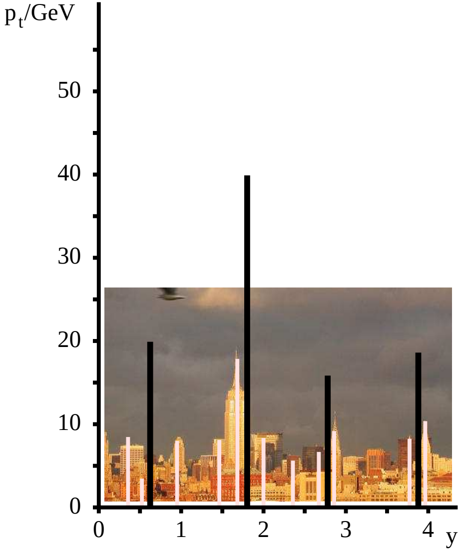

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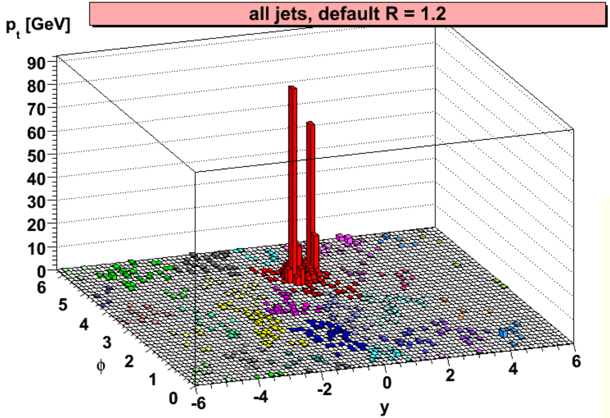
Jet areas



Jets are made of finite number of pointlike particles.

Area not unambiguous concept

Jet areas must be defined

Add many soft particles to event

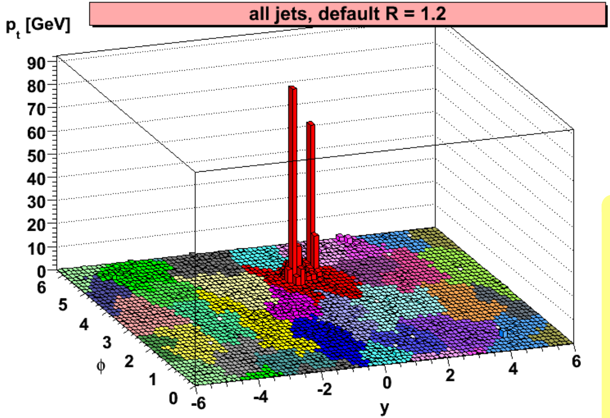
10^{-100} GeV each

$A \propto \#$ inside jet

Cacciari, GPS & Soyez '08

measure of jet's susceptibility to contamination from soft radiation

Jet areas



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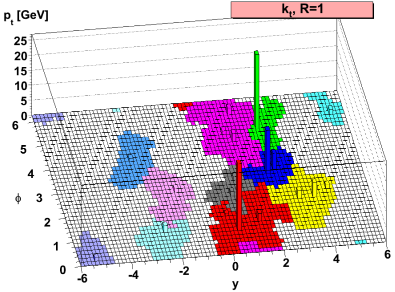
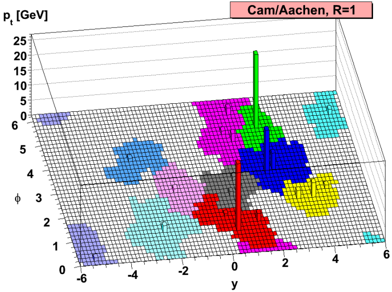
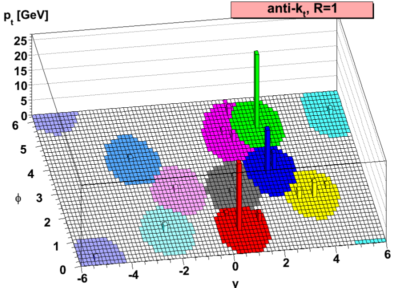
Areas for 3 jet algorithms





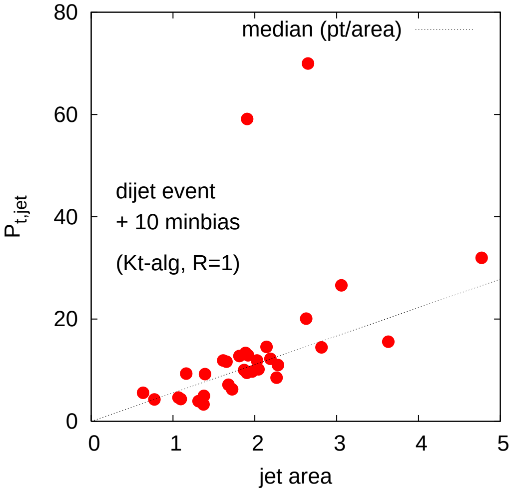


A family of algorithms, all cluster pair with smallest d_{ij}:

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

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

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

Subtracting noise from jets

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

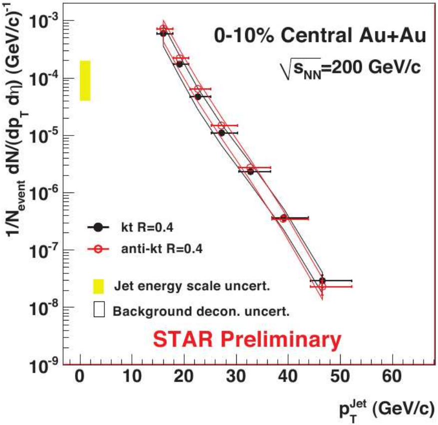
$$A_{jet} = \text{jet area}$$

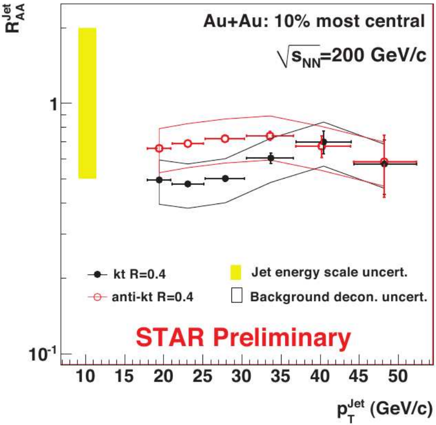
$\rho = p_t$ per unit area from underlying event (or "background")

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

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

This method is basis of STAR jet results

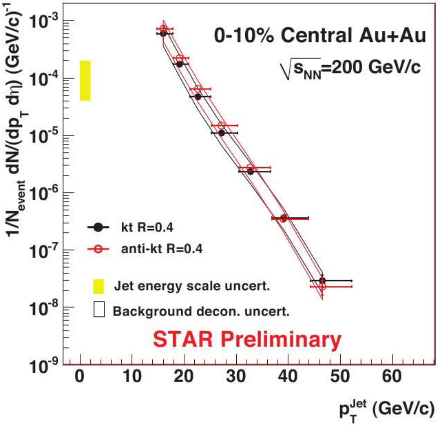


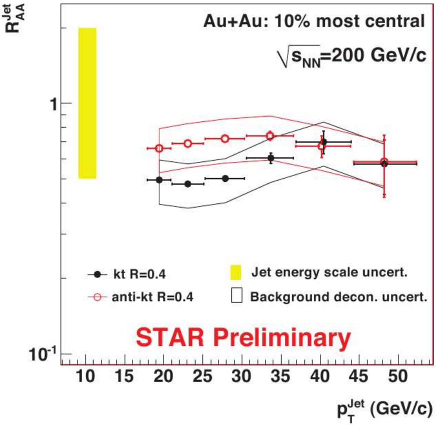


Method designed to minimise biases, but some still persist.
STAR corrects remaining biases based (partly) on Monte Carlo modelling.

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

This method is basis of STAR jet results

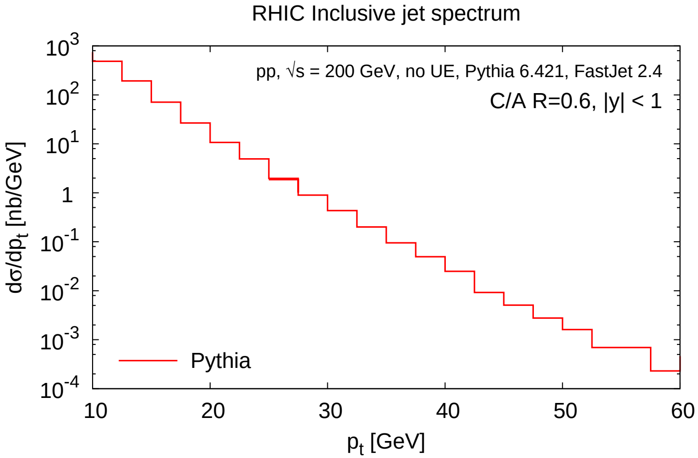




Method designed to minimise biases, but some still persist.
STAR corrects remaining biases based (partly) on Monte Carlo modelling.

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

Context: a steeply falling X-section



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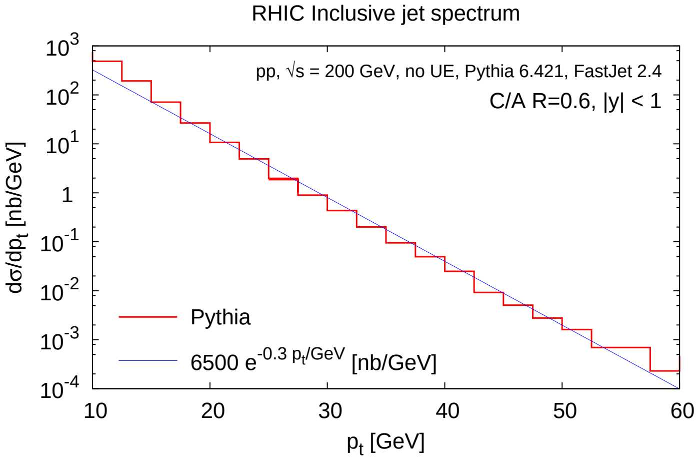


To help think about impact of falling cross section at RHIC, approximate it as:

$$\frac{d\sigma}{dp_t} \sim \exp(-0.3 p_t/\text{ GeV})$$

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

The numbers (for RHIC)

The problem is basically about **subtracting the correct** amount of "underlying event" from each jet, in order to reconstruct correct jet energy.

Take the model for the jet spectrum, $\exp(-a p_t)$ $a = 0.3\ \text{GeV}^{-1}$

Suppose you make a "mistake":

- Systematic offset in p_t by $\delta p_{t,jet}$
  $\longrightarrow$ mistake in spectrum by **factor** $\exp(a\,\delta p_{t,jet})$
  If $\delta p_{t,jet} = 3$ GeV, factor $= 2.5$
- Gaussian error of std.dev. σ_{jet} in subtraction
  $\longrightarrow$ mistake in spectrum by **factor** $\exp(a^2 \sigma_{jet}^2/2)$
  If $\sigma_{jet} = 5$ GeV, factor $= 3.1$

You want to know R_{AA} to within a few tens of percent.
Residual systematic offsets must be understood to within 1 GeV.
Fluctuations must be as small as possible, and accurately known.

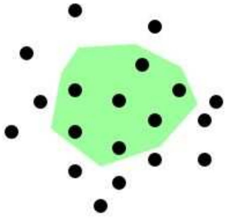
Example #1: a bias

(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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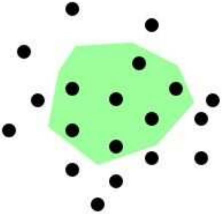

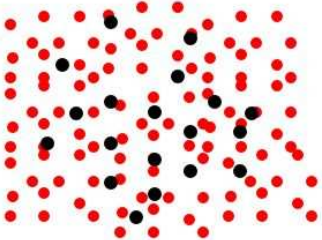

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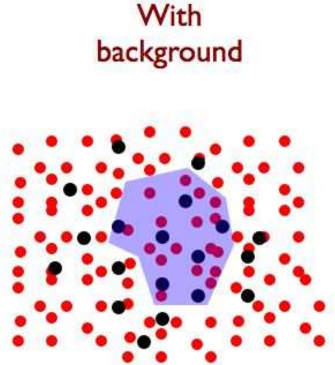

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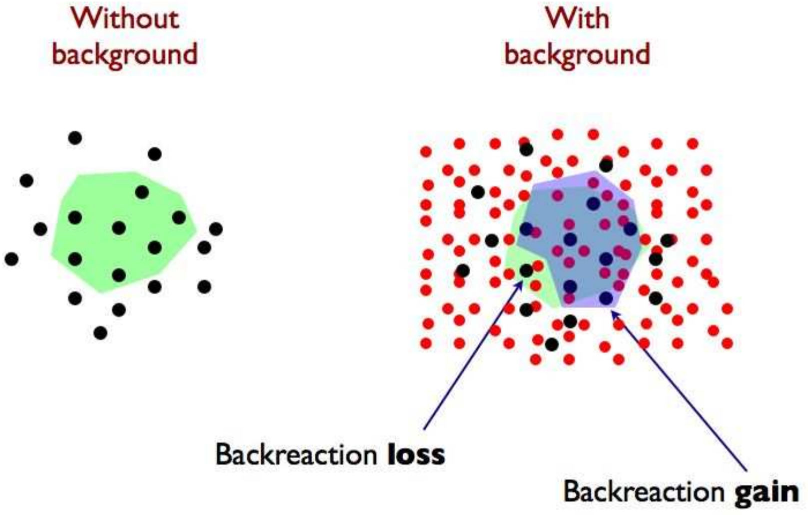

Slide from M. Cacciari

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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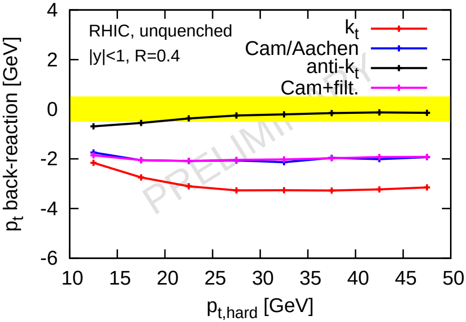
Pythia + Hydjet + FastJet



Cacciari, Rojo, GPS & Soyez, prelim.

anti-k_t bias = 0, as expected

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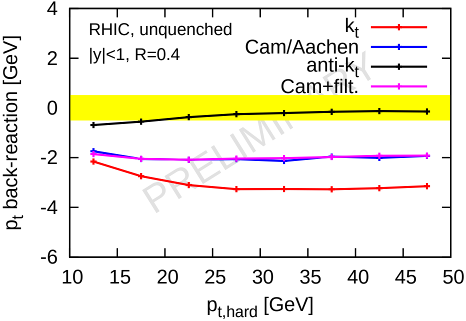


Cacciari, Rojo, GPS & Soyez, prelim.

anti-k_t bias = 0, as expected

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

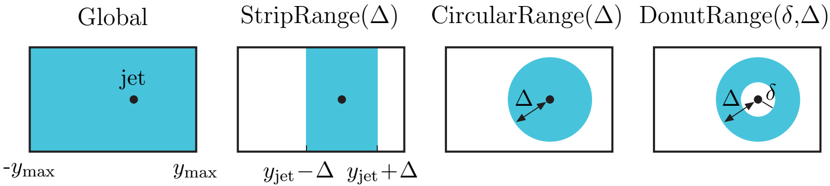
Example #2: another bias

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

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

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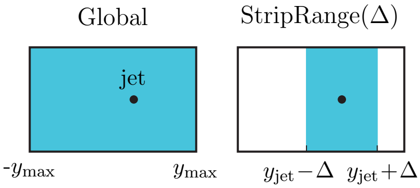

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Example #3: fluctuations

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

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

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 and find $\sigma_{jet} \sim 7$ GeV.

This is dangerous

Steeply falling spectrum rescaled by $\times 10$?

Obvious solution: reduce R

But then lose gluon radiation

Can be very severe with quenching

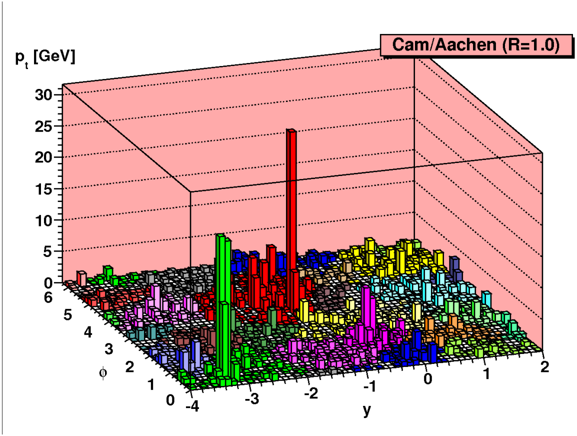
cf. STAR tried $R = 0.2$ instead of 0.4

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

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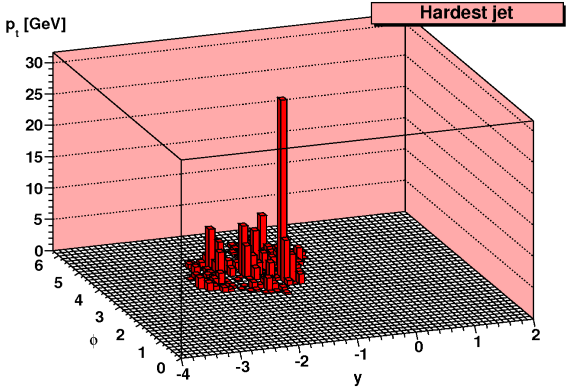

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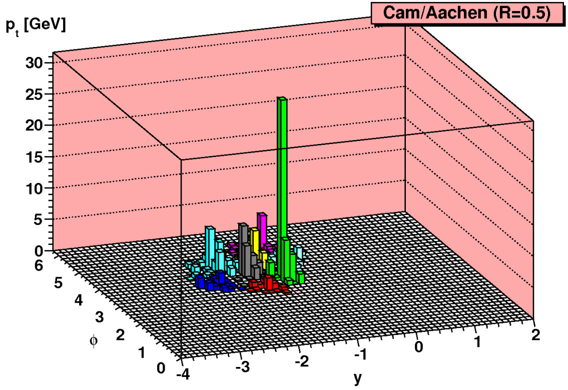

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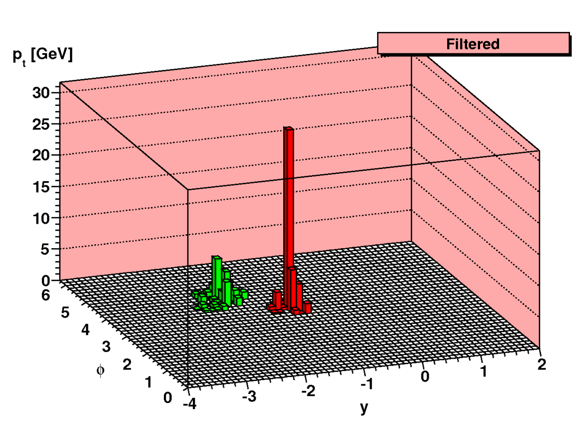

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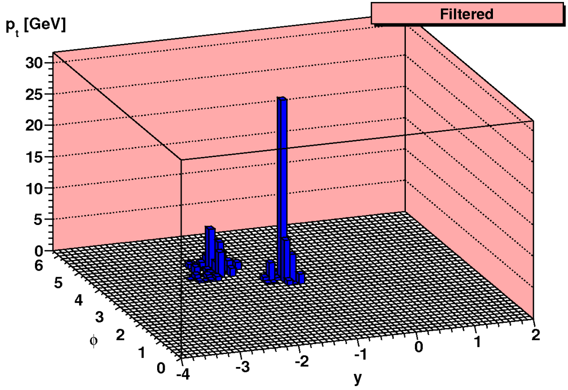

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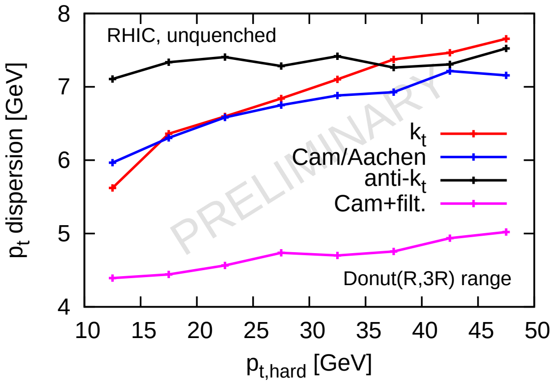
Impact of filtering on dispersion

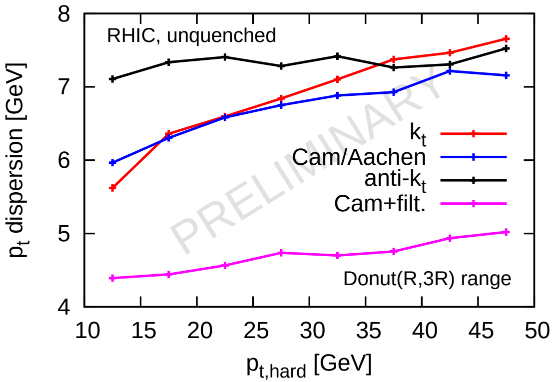


Filtering reduces jet area by $\sim \frac{1}{2}$

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

And they do

Impact of filtering on dispersion



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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

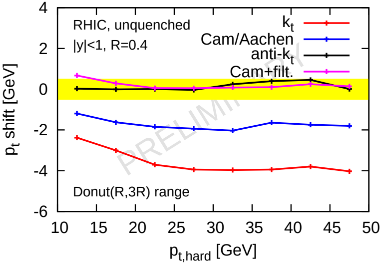
Numbers are rough – intended to give an idea of impact

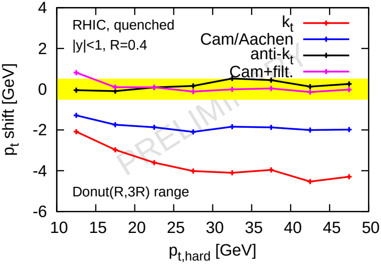
Alternative ideas: see Cole & Lai '08

Summary RHIC (Pythia/Hydjet)

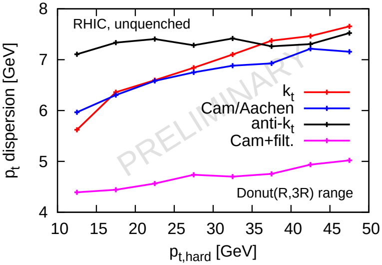
UNQUENCHED | QUENCHED

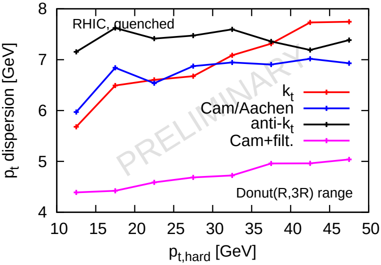
PT SHIFT





DISPERSION





Summary LHC (Pythia/Hydjet)

PT SHIFT

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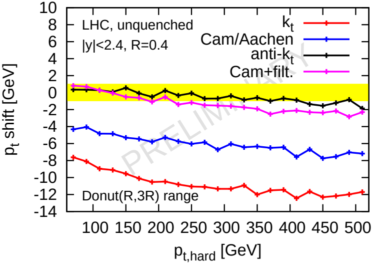

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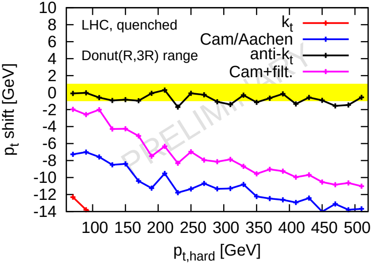

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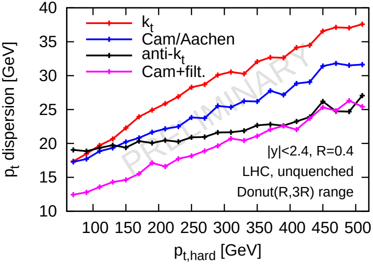

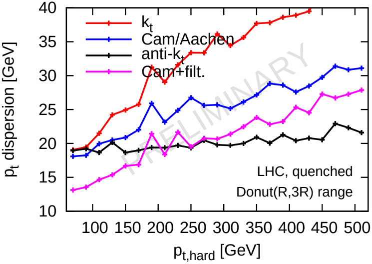

Conclusions

It's still early days for jet-finding in HIC

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 do three things:

- 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 hard to estimate how quenching affects systematics

- Guide design of new tools that have smaller systematics

  Like filtering, yet to be tried out by the experiments

All the analytical theory study so far has been without quenching: so what happens if we include it...?

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EXTRAS