Jet reconstruction in heavy-ion collisions

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Plan

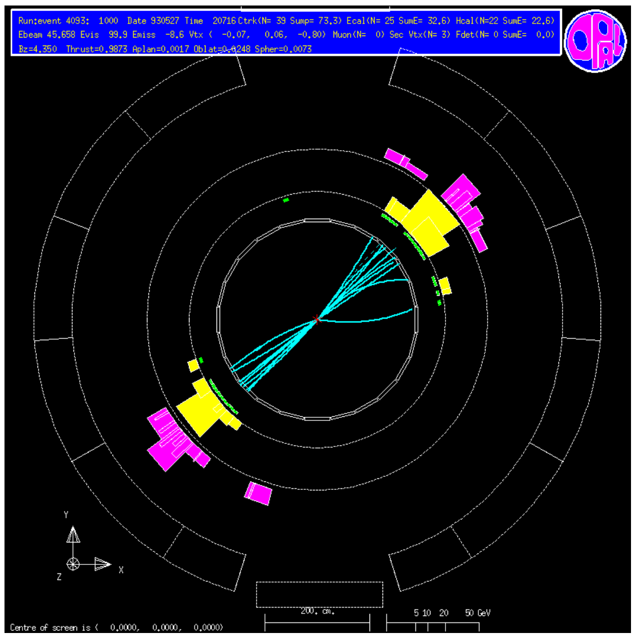
- Motivations
  - Why jets in heavy-ion collisions
  - Why “jets in heavy-ion collisions” is a non-trivial problem
- Howto
  - recap on jets in general
  - background subtraction as the main tool (already in use)
  - refinements: filtering, local ranges
- Practical application: what kind of precision do we expect?

Motivations

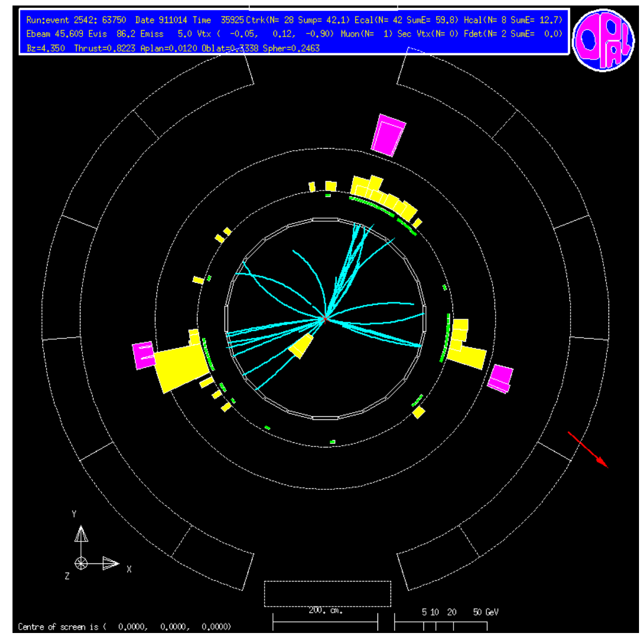
Motivation: why jets in HI

- “Jets” $\equiv$ bunch of collimated particles $\cong$ hard partons

  Example: LEP (OPAL) events



2 jets

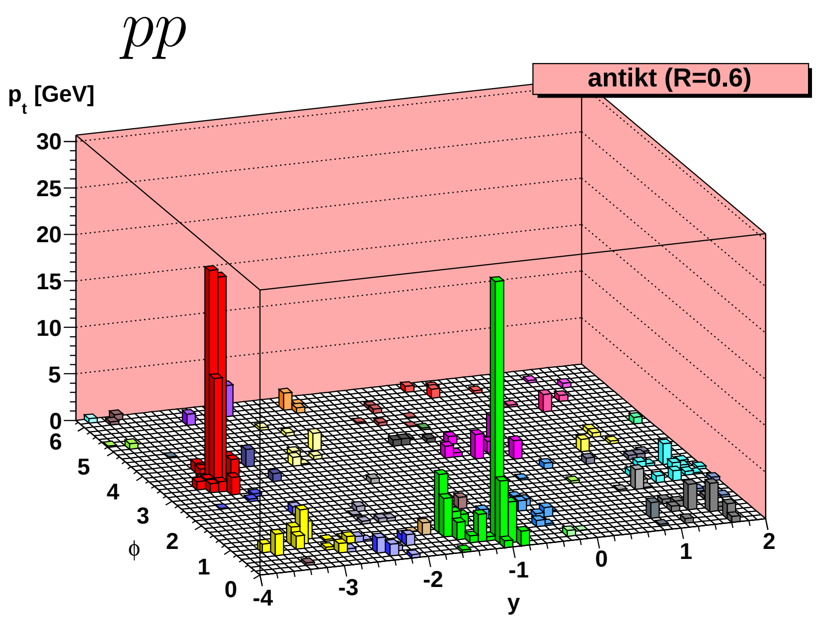


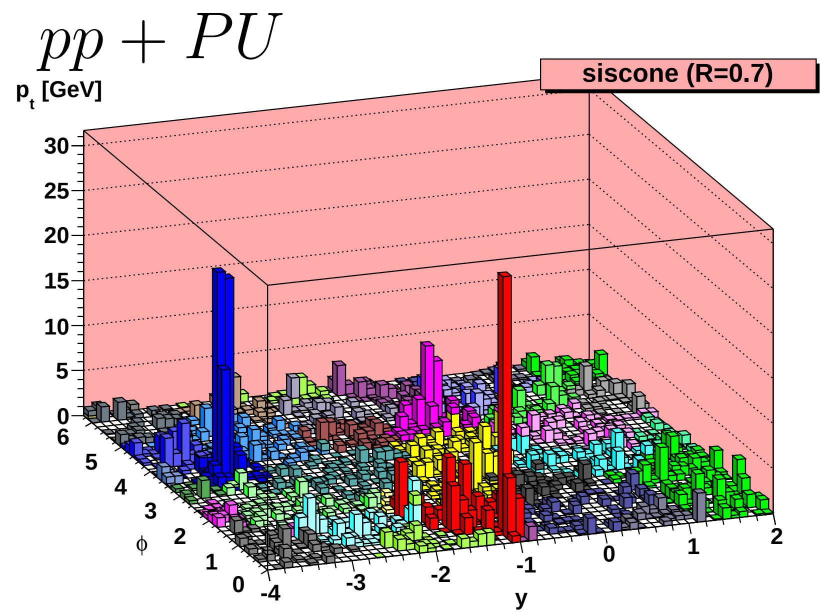
3 jets

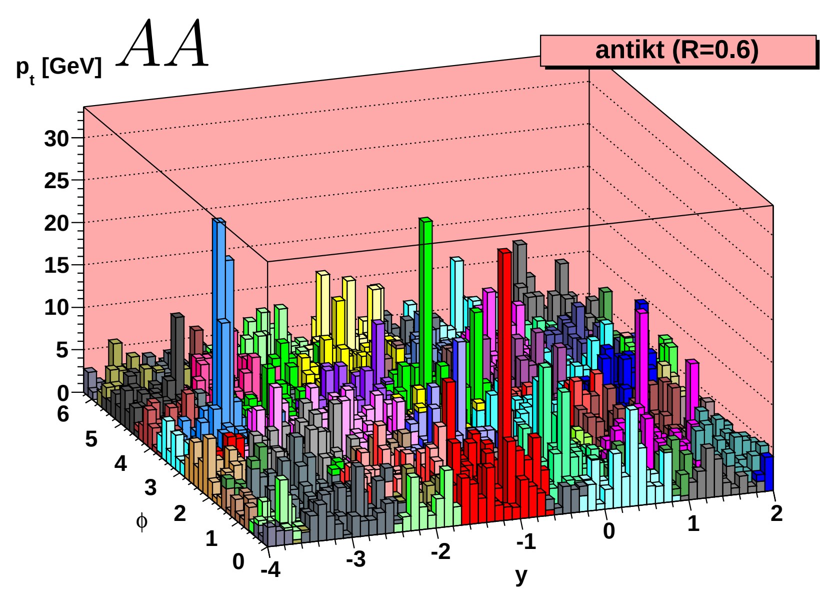
  In other words a jet is a “better” pQCD object than, say, a pion.

- Access to a series of measurements like the jet broadening i.e. information on the HI medium

Motivation: why is it tough





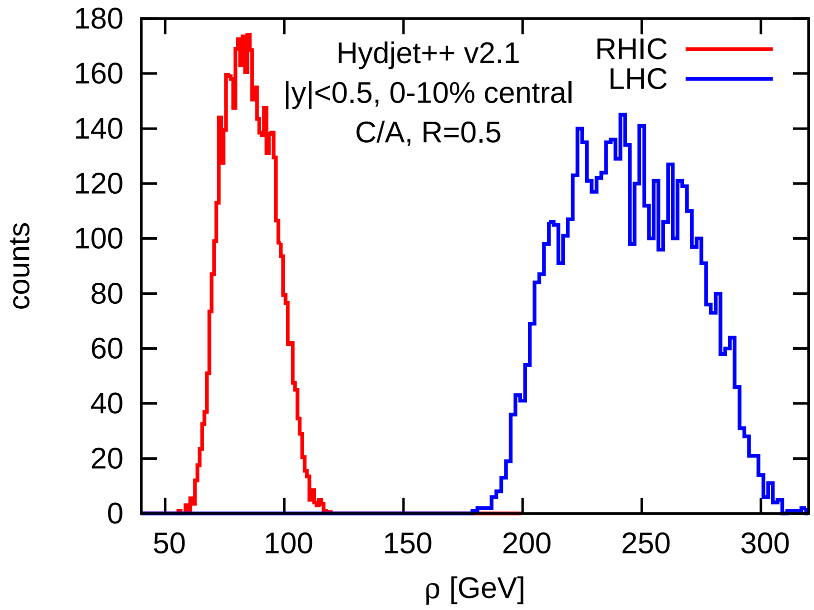


Huge underlying event background

$\Rightarrow$ hard to see the jets

Motivation: why is it tough

background per unit area



$\rho \approx 90$ GeV $\rho \approx 250$ GeV

Motivation: why is it tough

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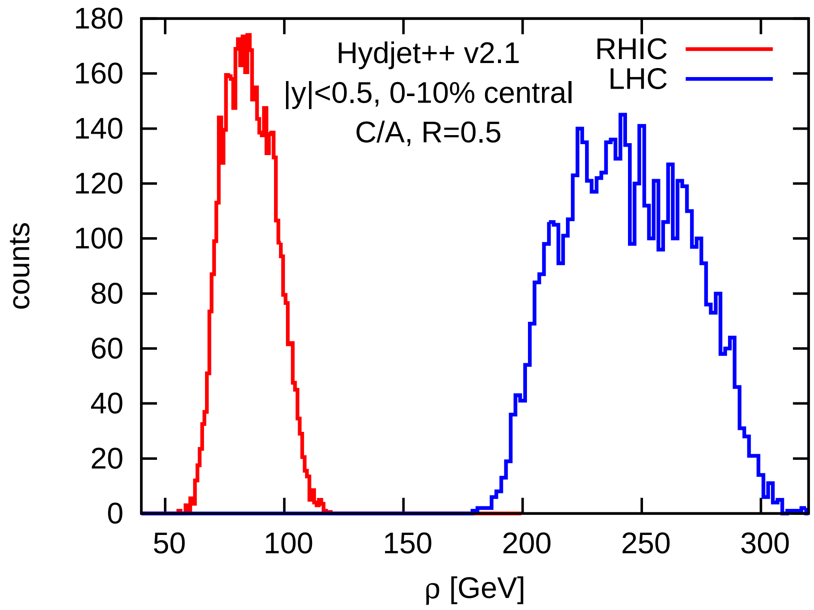
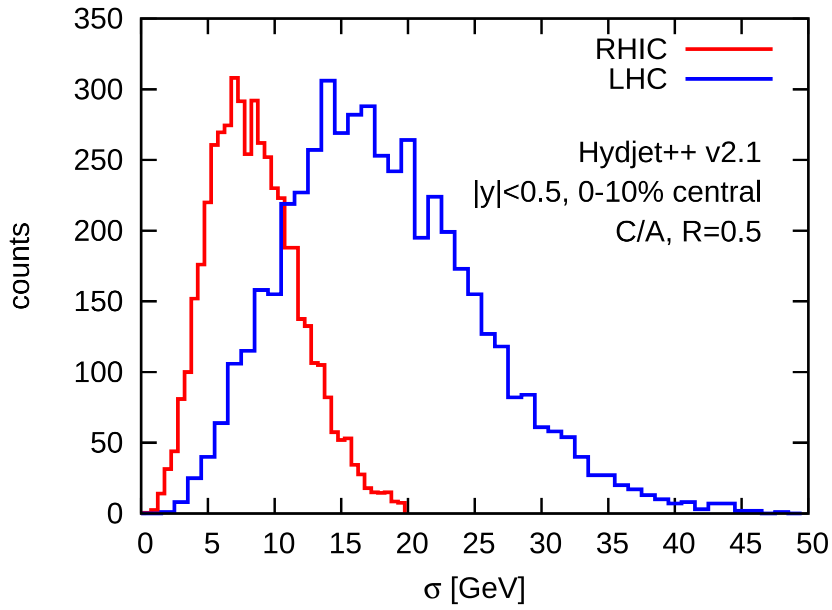


background fluctuations



$\rho \approx 90$ GeV $\quad$ $\rho \approx 250$ GeV $\quad$ $\sigma \approx 10$ GeV $\quad$ $\sigma \approx 19$ GeV

Motivation: why is it tough

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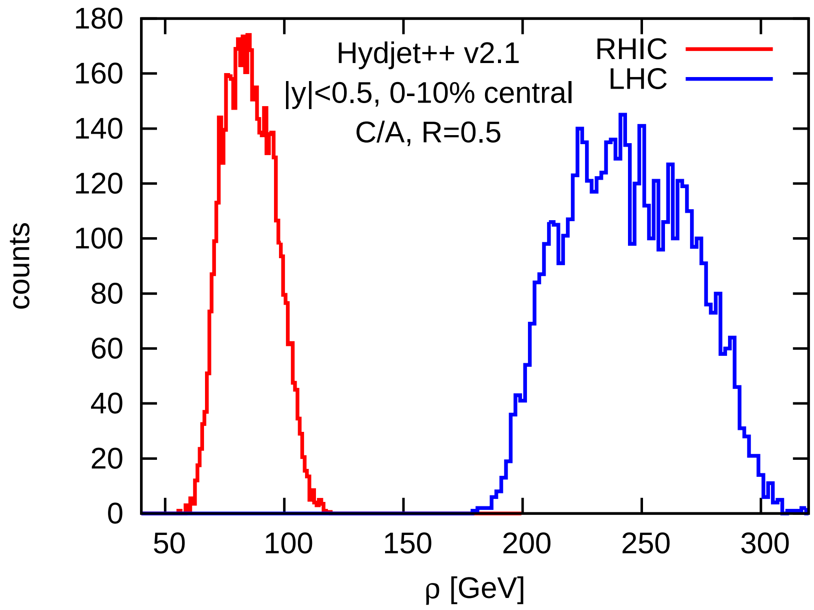

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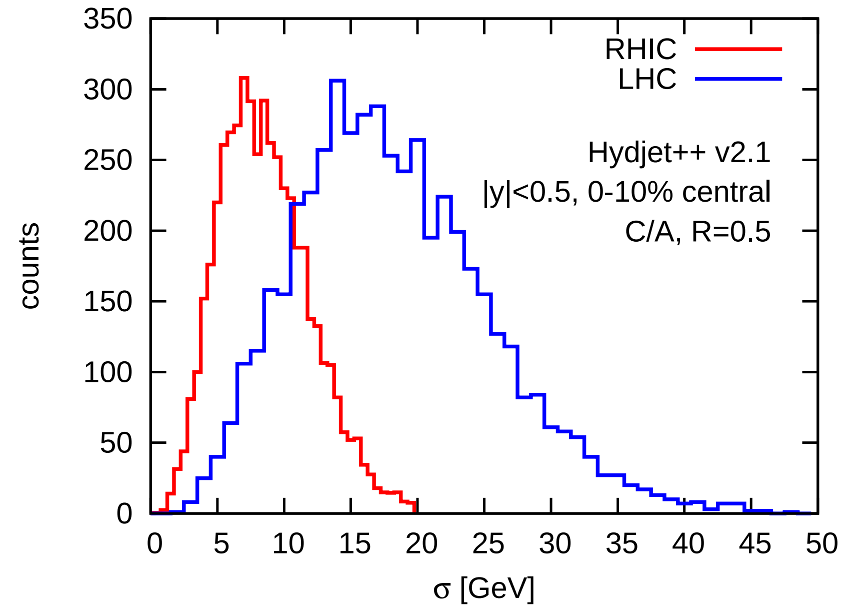


$\rho \approx 90$ GeV $\rho \approx 250$ GeV $\sigma \approx 10$ GeV $\sigma \approx 19$ GeV

For a typical jet with $R = 0.4$ (and area = πR^2)

$(\delta p_t)_{\rm RHIC} \approx 45 \pm 5$ GeV range $10 \lesssim p_t \lesssim 50$ GeV

$(\delta p_t)_{\rm LHC} \approx 125 \pm 10$ GeV range $50 \lesssim p_t \lesssim 500$ GeV

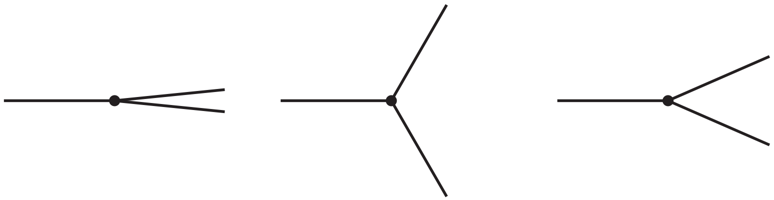
$(\delta p_t)_{\rm PU,LHC} \approx 20$ GeV

Quick summary on jets in general

Jet definitions

"Jets $\equiv$ bunch of collimated particles" is not sufficient in practice

"collinear" has some arbitraryness



2 jets 3 jets ? jets

Jet definitions

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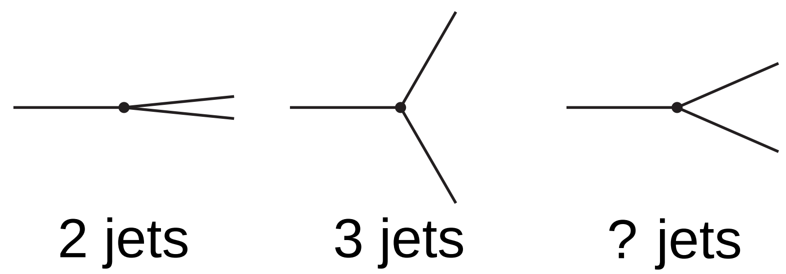

In practice: use of a <u>jet definition</u>

particles $\{p_i\}$ —— jet definition ——→ jets $\{j_k\}$

Jet algorithm: the recipe (insufficient!)

Jet definition: algorithm + the parameters

Useful jet algorithms

Only a handful of theoretically well-behaved/infrared-safe algorithm (For hadron collisions):

- k_t algorithm

  [Catani,Dokshitzer,Seumour,Webber;Ellis,Soper, 93]

- Cambridge/Aachen algorithm

  [Dokshitzer,Leder,Moretti,Webber, 97;Wobish, 99]

- anti-k_t algorithm

  [M.Cacciari,G.Salam,GS, 08]

- SISCone algorithm

  [G.Salam,GS, 07]

Each have their pros and cons!

Useful jet algorithms

Only a handful of theoretically well-behaved/infrared-safe algorithm (For hadron collisions):

- k_t algorithm $p = 1$
  recombine according to QCD soft and collinear divergences
- Cambridge/Aachen algorithm $p = 0$
  matches collinear div; simple geometric algorithm
- anti-k_t algorithm $p = -1$
  produces circular hard jets; default for CMS and ATLAS
- SISCone algorithm
  "safe version of the Tevatron's algs";low background sensitivity

Succesive recombination of the closest pair with

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})(\Delta y_{ij}^2 + \Delta \phi_{ij}^2)$$

NB: all have a parameter R controlling the size

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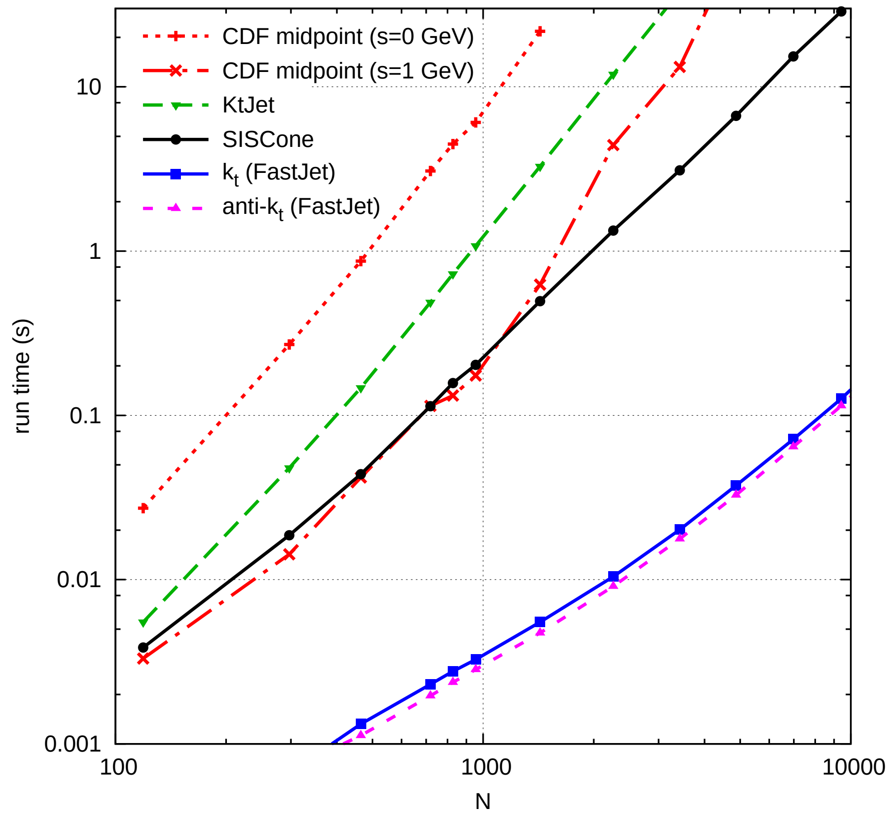
All (and others) implemented in FastJet

[M.Cacciari,G.Salam,GS]

Algorithm timings



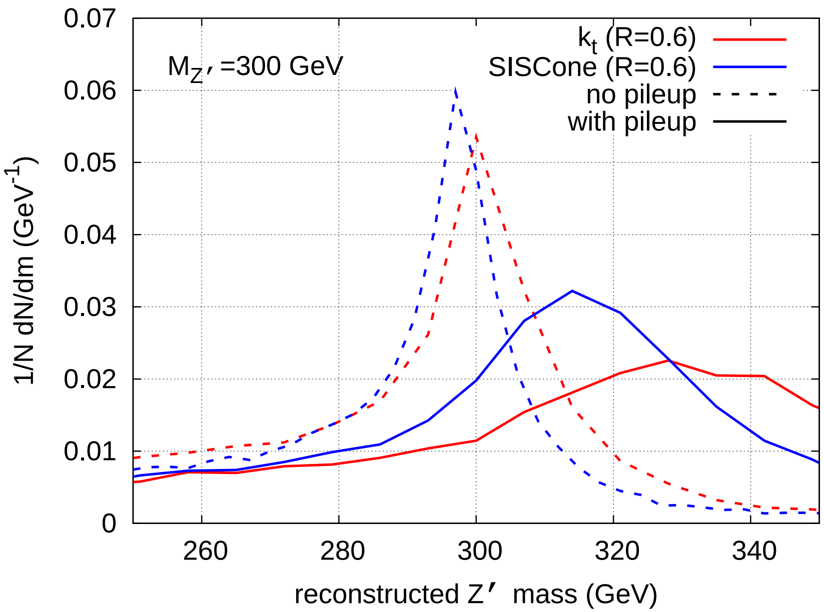
Recombination algorithms very fast

[M. Cacciari, G. Salam, 06]

- Heavy-ion collisions: 2000-40000 particles
- area computations (see later): +O(10000) particles

Background effects: 1. pollution

Background particles end up in the jets



width = 29.5 GeV

width = 21.0 GeV

Example:

$Z' \to q\bar{q} \to$ 2 jets

M=300 GeV

Reconstruct the dijet invariant mass

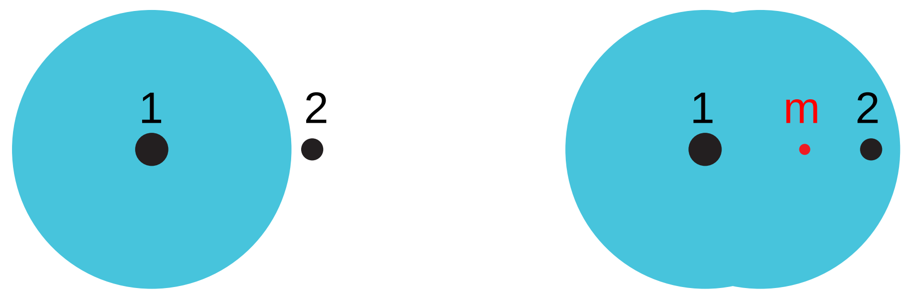
✗ position shifted, amount $\propto \pi R^2 \rho$

✗ peak smeared because ρ fluctuates between the events

Background effects: 2. back-reaction

Background particles affect the “hard particles” clustering

- gain:



no medium: $p_t = p_{t1}$ medium: $p_t = p_{t1} + p_{t2} + p_{tm}$

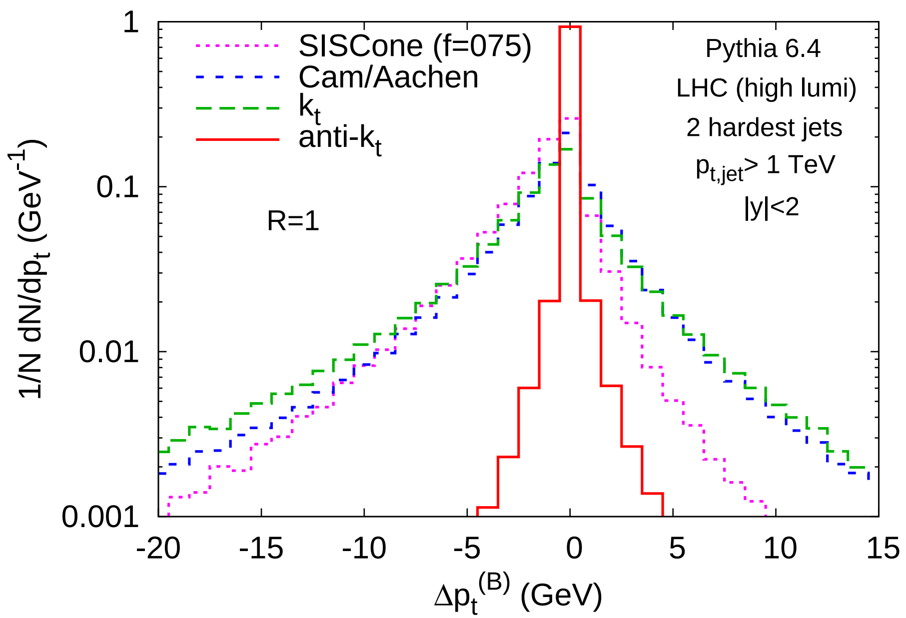
- loss:

no medium: $p_t = p_{t1} + p_{t2}$ medium: $p_t = p_{t1} + p_{tm}$

Background effects: 2. back-reaction

Background particles affect the “hard particles” clustering

- tractable analytically
- $k_t \gtrsim$ Cambridge > SISCone $\gg$ anti-k_t



Reconstruction recipe so far:
background subtraction using jet areas

Jet areas

[M.Cacciari, G.Salam, GS, 08]

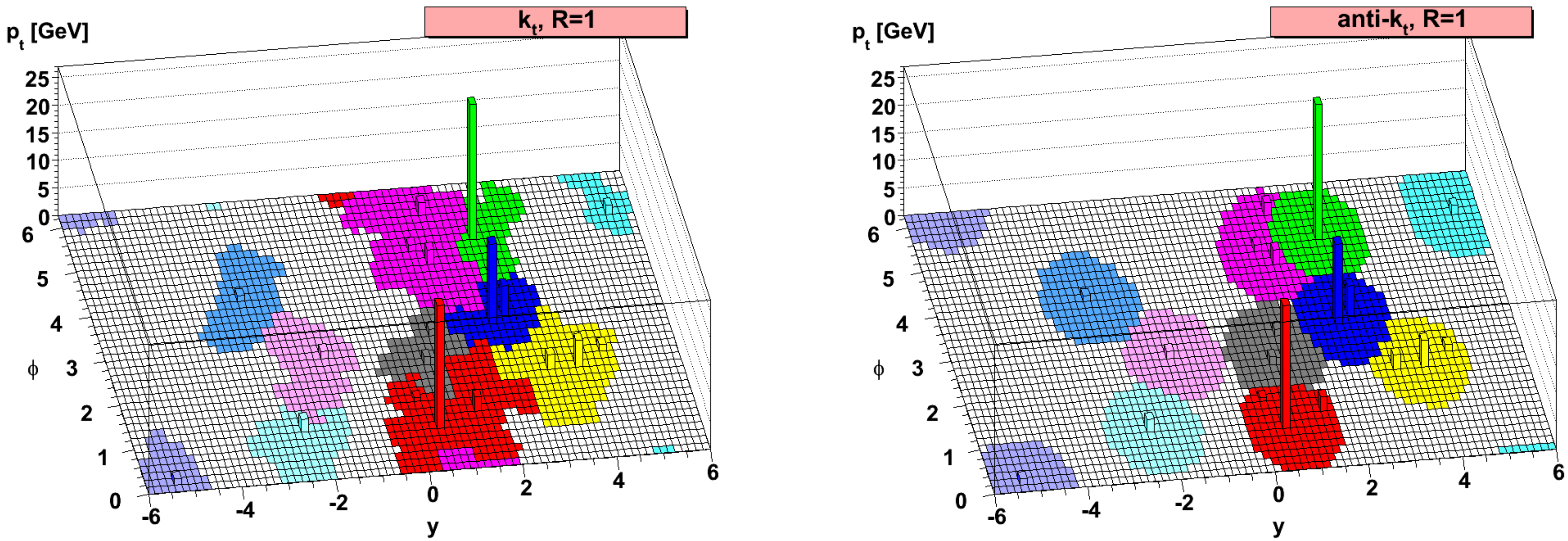
Area $\equiv$ region where the jet catches soft particles

- Recipe: add infinitely soft particles (aka *ghosts*)
  and see in which jet they are clustered
- 2 methods:
  - Passive area: add one ghost at a time and repeat many times
  - Active area: add a set of ghosts and cluster once
- Idea: ghost $\approx$ background particle
  $\Rightarrow$ active area $\approx$ uniform background
  passive area $\approx$ pointlike background
- Notes:
  - passive = active for large multiplicities
  - require an IR-safe algorithm!
  - generic/universal definition (*e.g.* independent of a calorimeter)

Jet area: examples

Example: active area for a simple event

k_t anti-k_t



Note: analytic control

Example: perturbative expansion of areas (at order α_s)

$$\langle \mathcal{A}(p_t, R) \rangle = \mathcal{A}_0 + \frac{C_{F,A}}{b_0 \pi} \pi R^2 \, d \, \log\left(\frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)}\right)$$

- area $\neq \pi R^2$, area $\neq$ const.
- coefficients computable

	$\mathcal{A}_0/(\pi R^2)$		d	
	passive	active	passive	active
k_t	1	0.81	0.56	0.52
Cam/Aachen	1	0.81	0.08	0.08
anti-k_t	1	1	0	0
SISCone	1	1/4	-0.06	0.12

- $Q_0 \equiv$ IR regulator $\propto$ background density

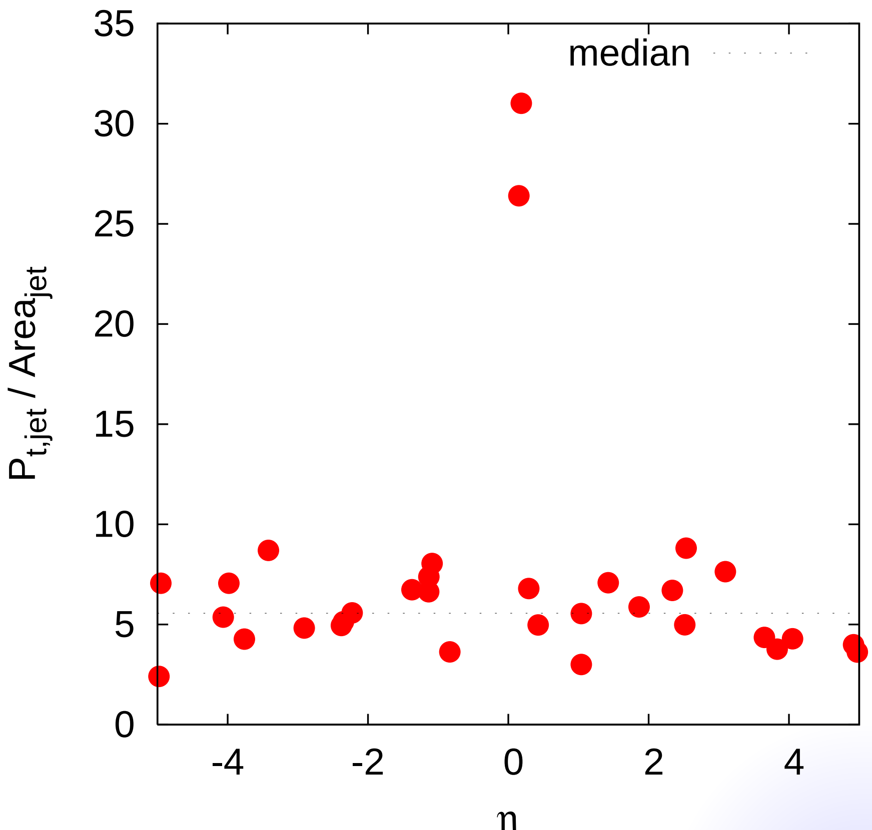
Pileup subtraction *(for uniform backgrounds)*

Basic idea: [M.Cacciari, G.Salam, 08]

$$p_{t,\text{subtracted}} = p_{t,\text{jet}} - \rho_{\text{pileup}} \times \text{Area}_{\text{jet}}$$

- Jet area: [M.Cacciari, G.Salam, G.S., 08]
  - region where the jet catches infinitely soft particles (active/passive)
  - analytic control and understanding in pQCD
- Pileup density per unit area: ρ_{pileup}

  e.g. estimated from the median of $p_{t,\text{jet}}/\text{Area}_{\text{jet}}$



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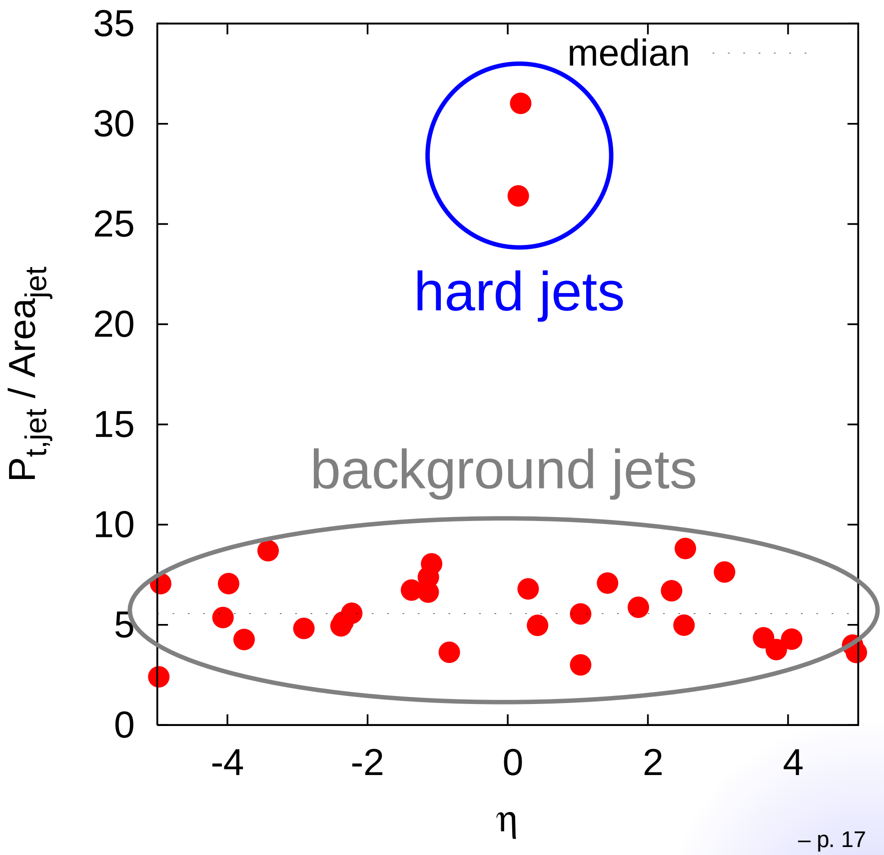

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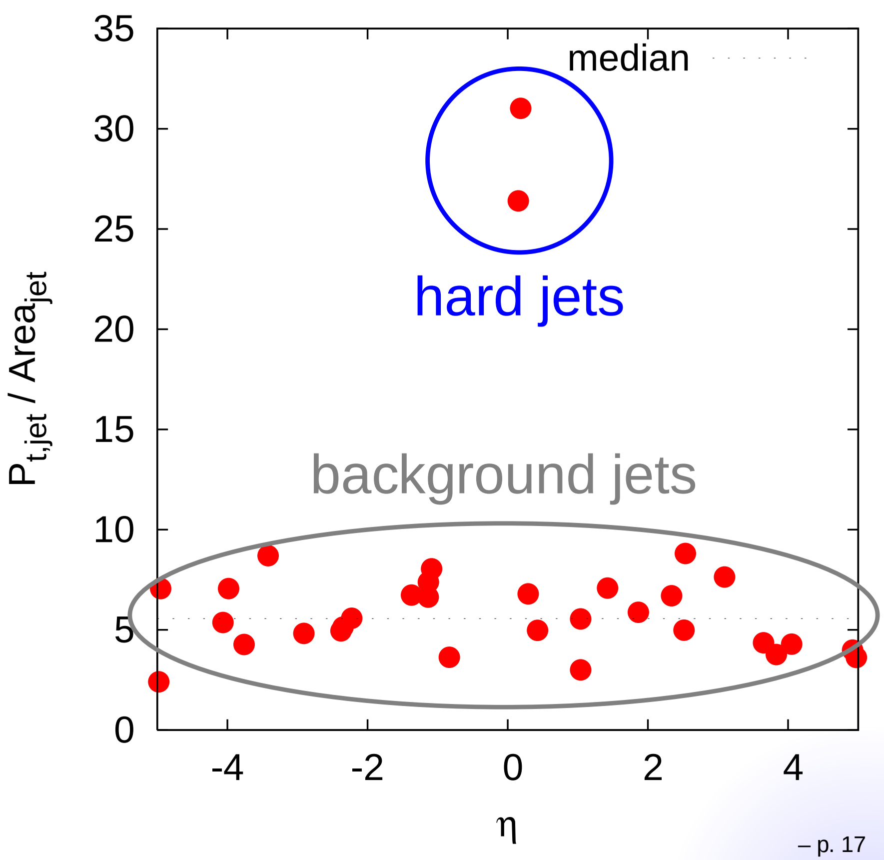
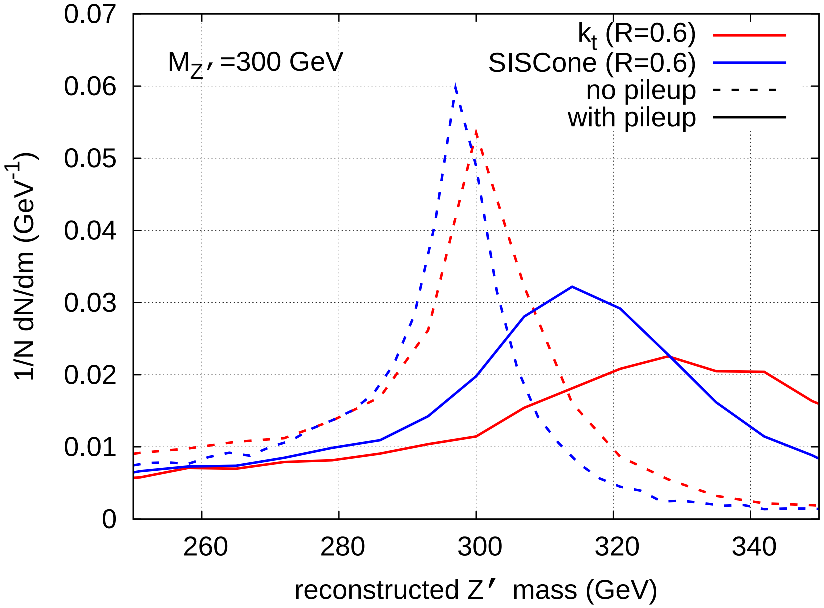
implemented in FastJet
on an event-by-event basis



Effect on dijet reconstruction

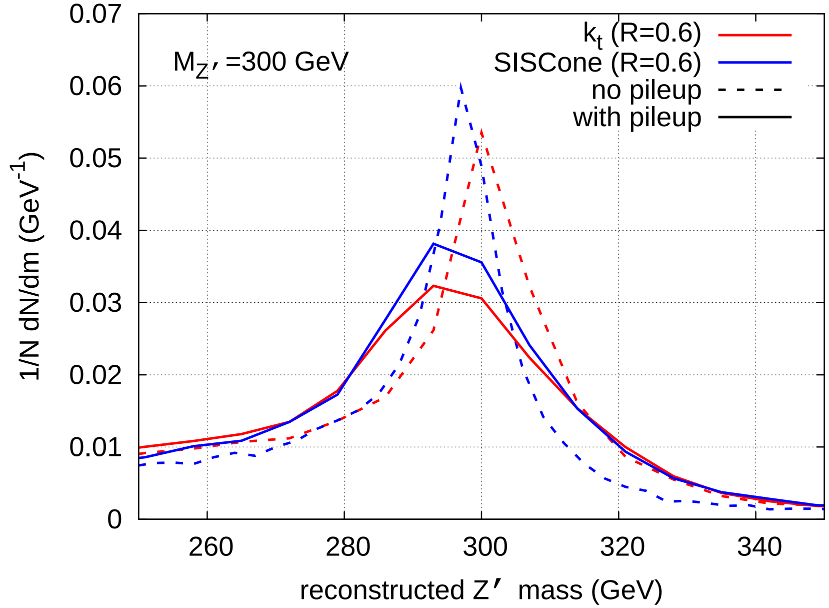
Pileup unsubtracted



width = 29.5 GeV

width = 21.0 GeV

pileup subtracted



width = 21.0 GeV

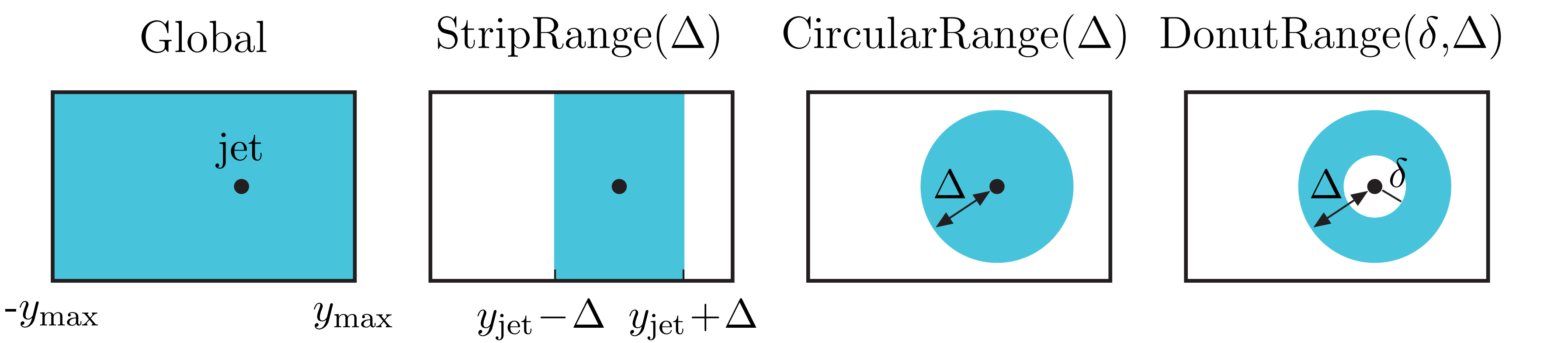
width = 17.7 GeV

- ✓ position reasonnable
- ✓ dispersion reduced (thanks to the event-by-event approach)
- ✓ used by STAR for the first jet analysis in heavy-ions

Improvements:
#1 local ranges

Idea #1: use a local range to compute $\rho_{\rm bkg}$

- Fluctuating background
  $\longrightarrow$ determine the background density $\rho_{\rm bkg}$
  from jets in the vicinity of the jet we want to subtract



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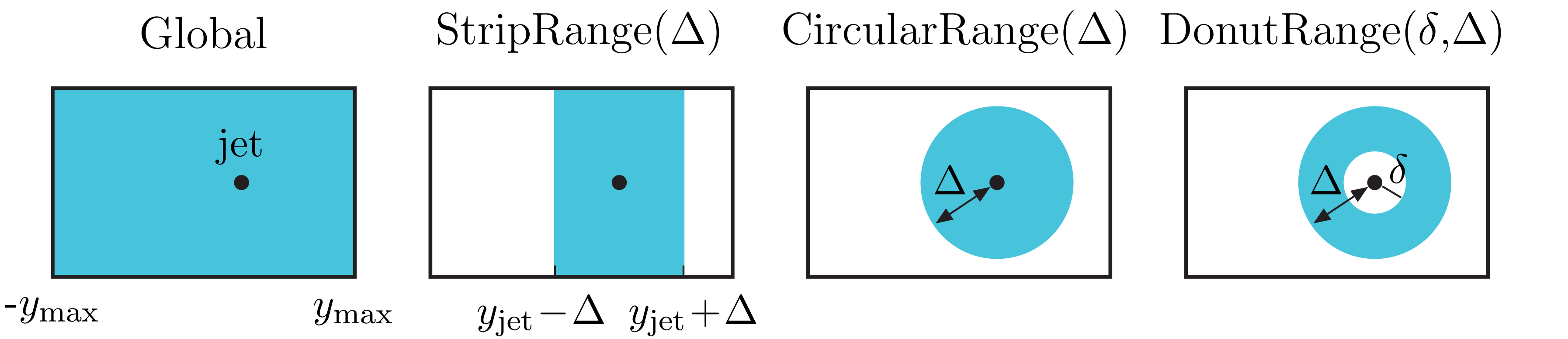


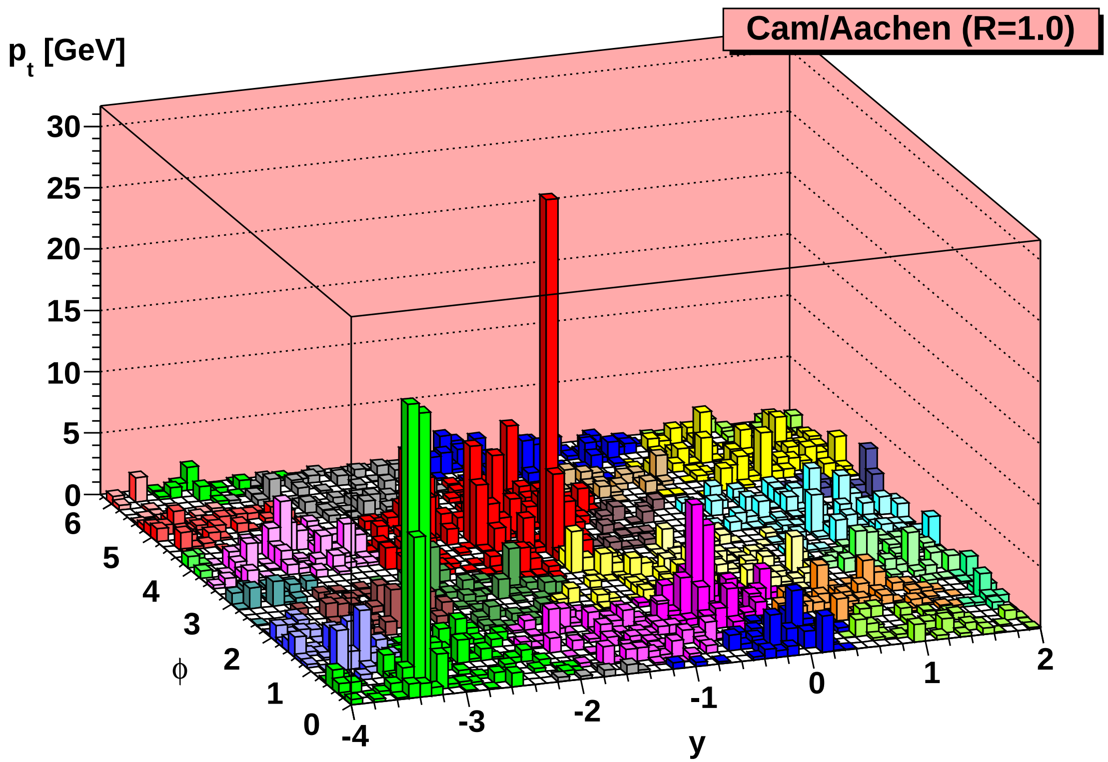
- Exclude the hardest jets from the determination of $\rho_{\rm bkg}$
  $\Rightarrow$ reduce the bias in the computation median

$$\frac{\Delta\rho}{\rho} = \frac{0.55\,\pi R^2}{\mathcal{A}_{\mathcal{R}}}\,\frac{\sigma}{\rho}\,n_{\rm hard}$$

RHIC: $\sigma \approx 10$, $|y| < 1$, $R = 0.4 \longrightarrow \Delta\rho \approx 0.22$ GeV
LHC: $\sigma \approx 20$, $|y| < 2.4$, $R = 0.4 \longrightarrow \Delta\rho \approx 0.18$ GeV

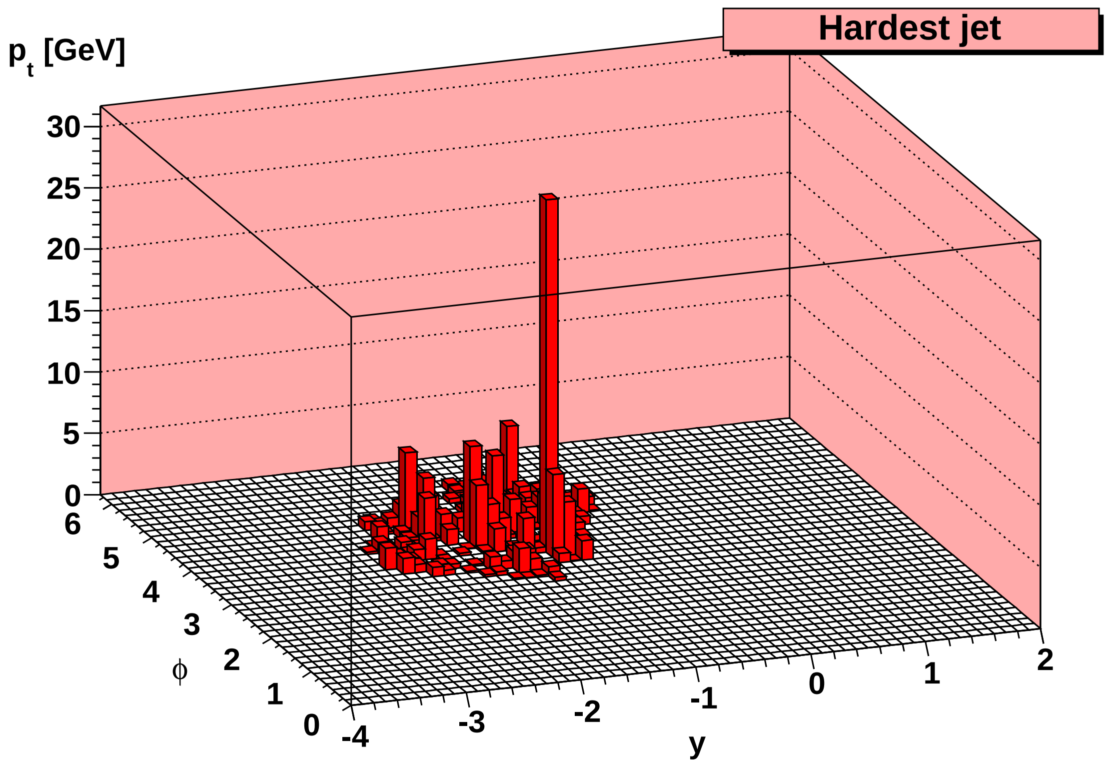
Improvements:
#2 filtering

Filtering



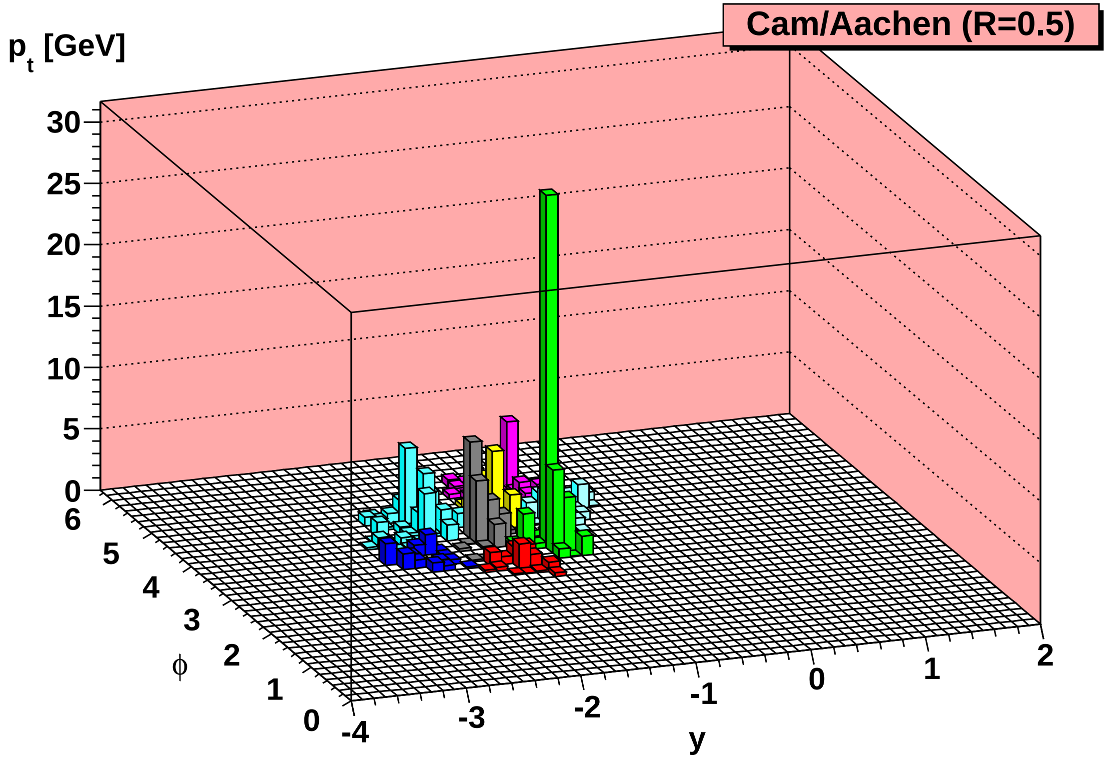
- cluster with Cambridge/Aachen(R)

Filtering



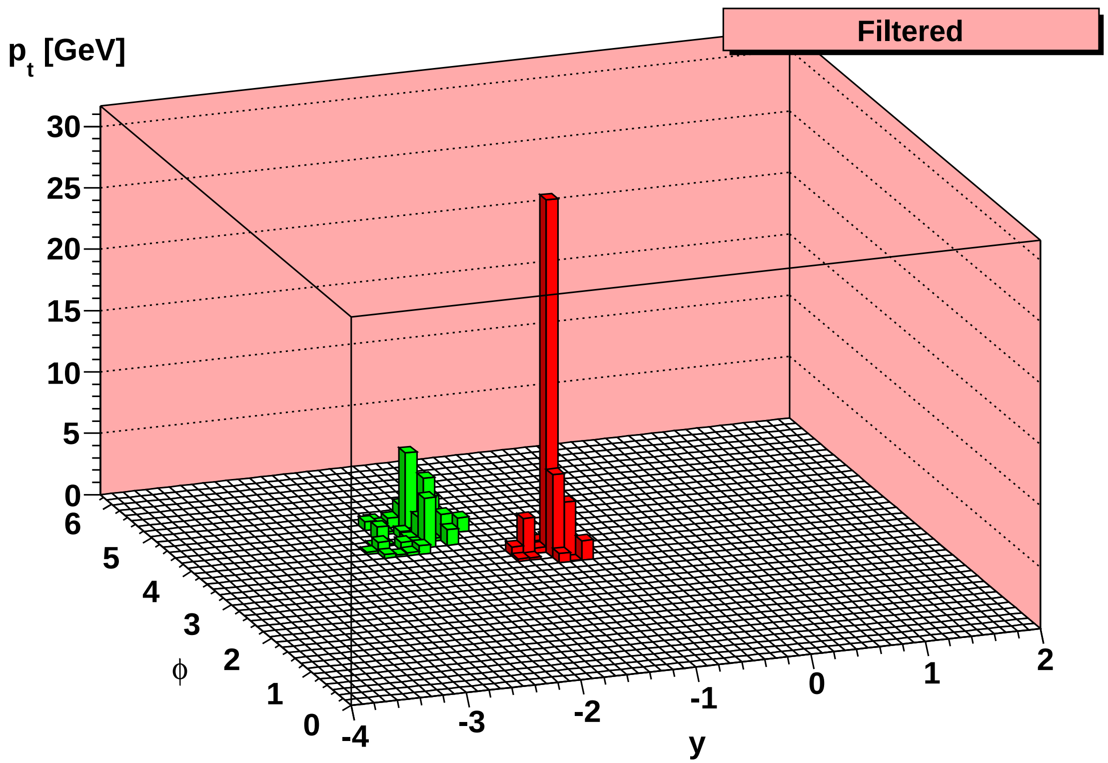
- cluster with Cambridge/Aachen(R)
- for each jet

Filtering



- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)

Filtering



- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)
  - keep the 2 hardest subjets

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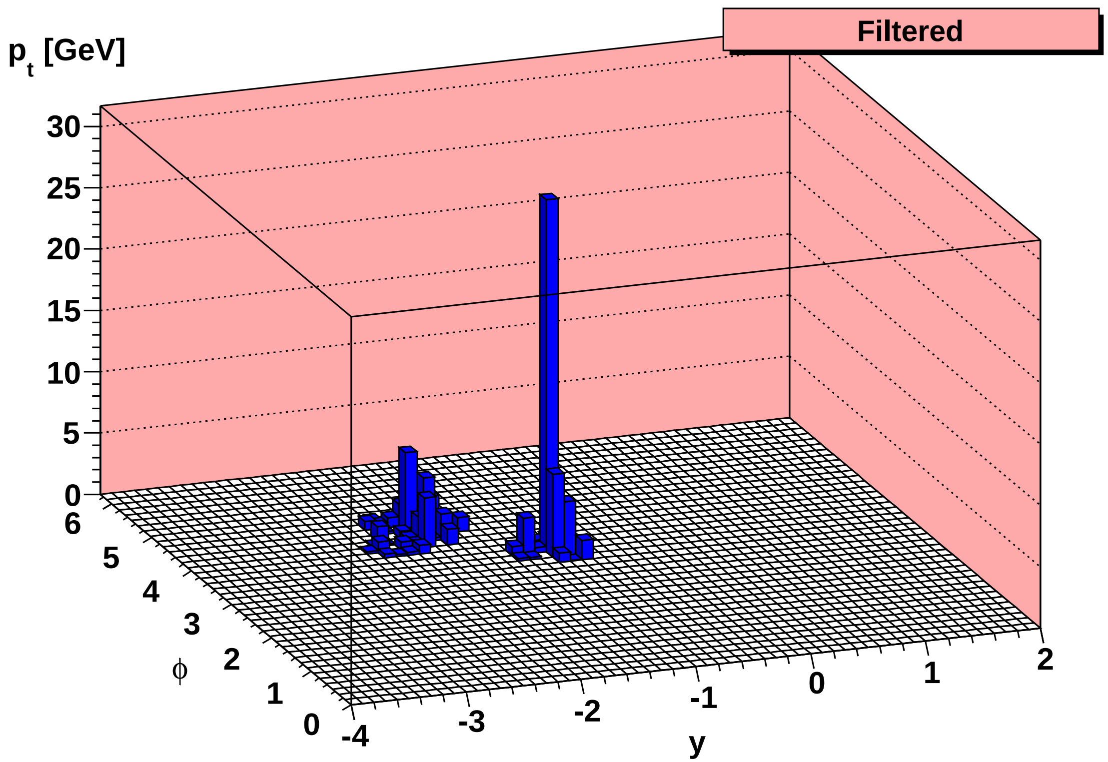


- cluster with Cambridge/Aachen(R)
- for each jet
  - recluster with Cambridge/Aachen(R/2)
  - keep the 2 hardest subjets

Idea:

✓ keep perturb. radiation

✓ remove UE

- Proven useful for boosted jet $H \to b\bar{b}$ tagging

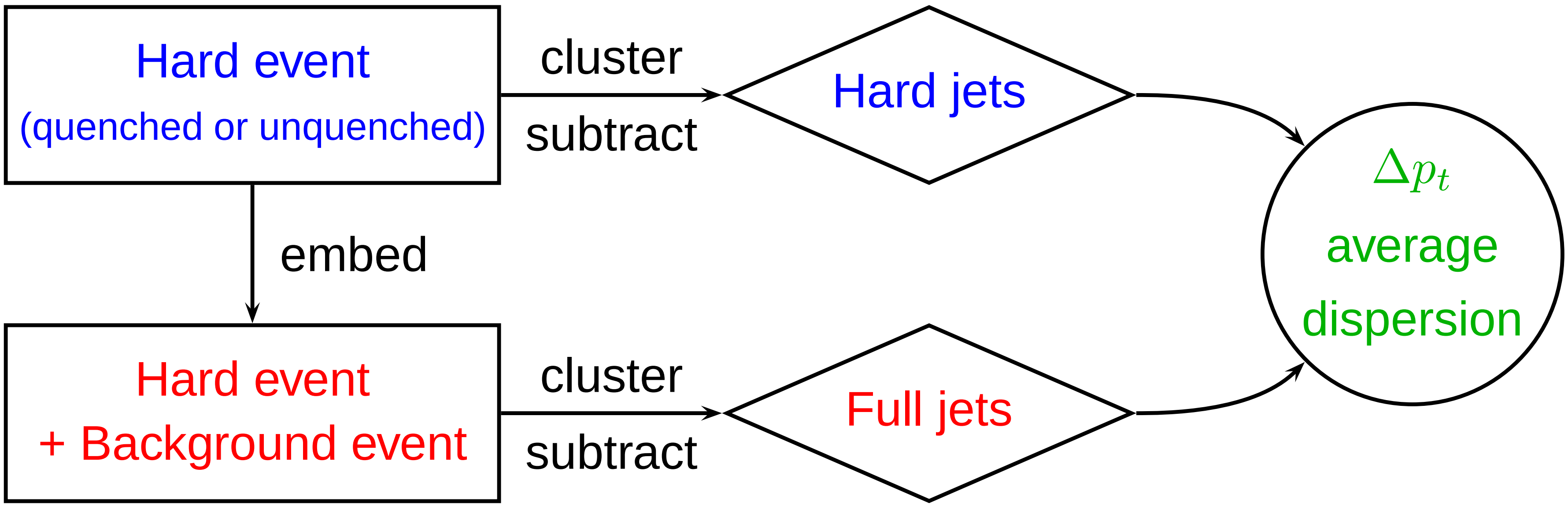
  [J.Butterworth, A.Davison, M.Rubin, G.Salam, 08]

- Proven useful for kinematic reconstructions

  [M.Cacciari, J.Rojo, G.Salam, GS, 08]

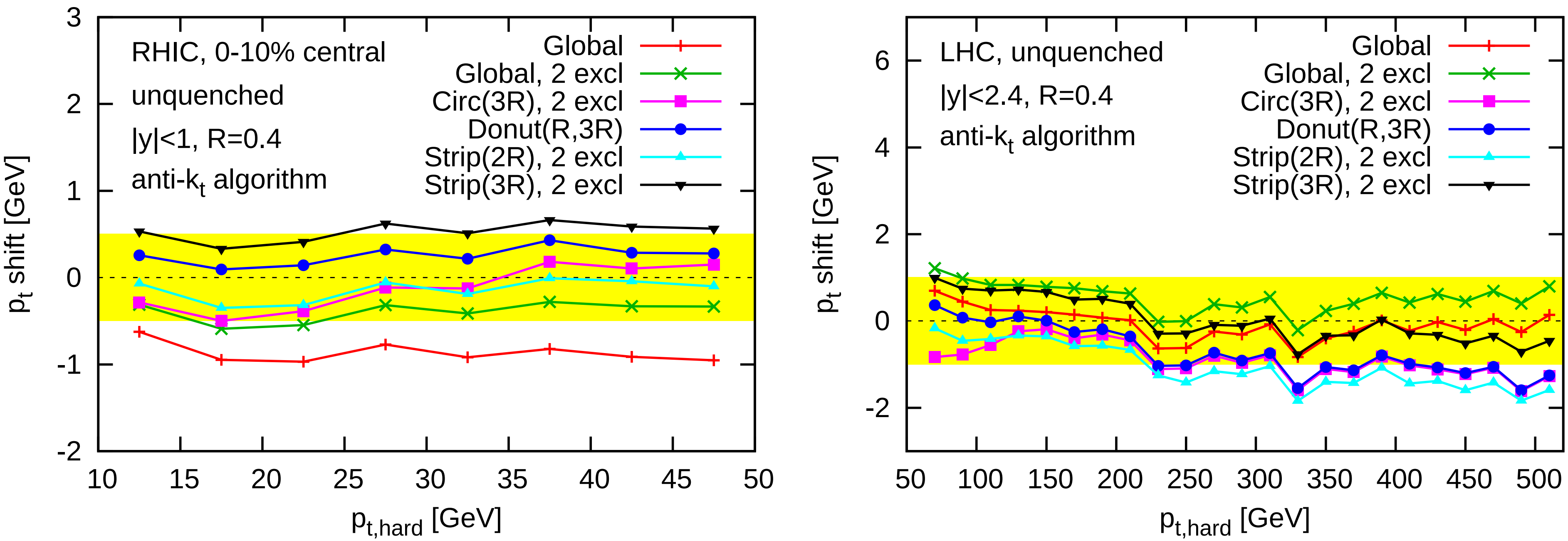
Expected practical effects

Framework for study



- Hard event: Pythia(v6.4) or Pythia(v6.4)+PyQuen(v1.5)
- Background: Hydjet++(v2.1) (cross-checked with others)
- Analysis: FastJet(v2.4)
  Ideally: smallest Δp_t shift, smallest Δp_t dispersion
- Note: in what follows, R fixed to 0.4

Effect of choosing a local range



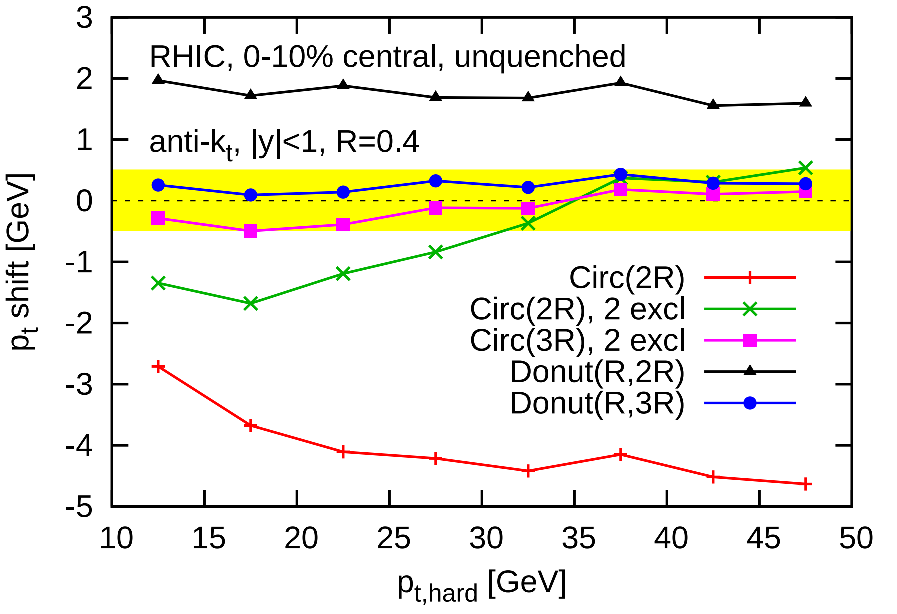
- effect $\sim$ 0.5-1 GeV
- differences between local ranges $\longrightarrow$ subtraction uncertainty
- for limited acceptance, global range $\approx$ local range
- hard rejection agrees with analytic estimates

Effect of choosing a local range

Number of jets in a range

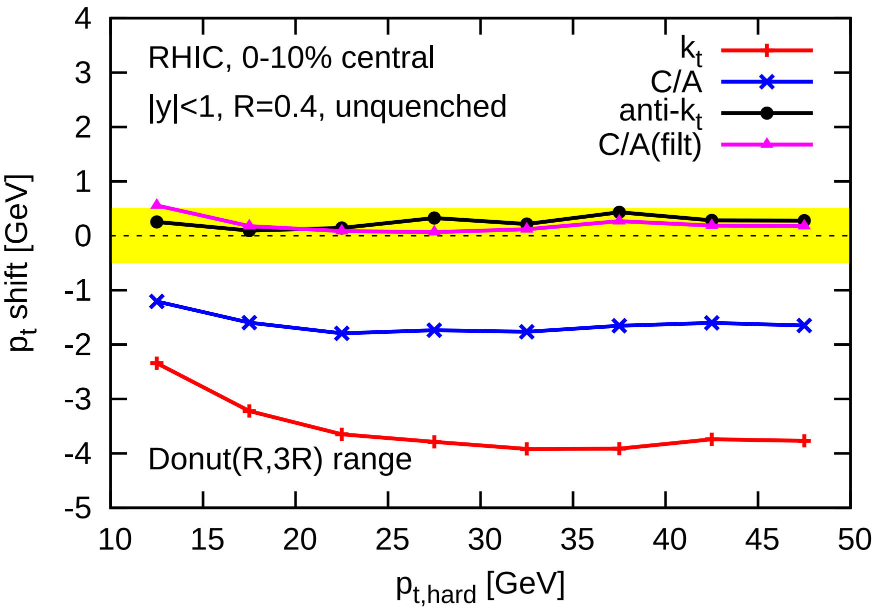
range	area	n_{jets}
Circ(2R)	$4\pi R^2$	4.5
Circ(3R)	$9\pi R^2$	10
Donut(R,2R)	$3\pi R^2$	3.5
Donut(R,3R)	$8\pi R^2$	9
Strip(2R)	$4\pi R$	11

$(R = 0.4, R_\rho = 0.5)$



rule of thumb: at least 7-8 jets needed to estimate ρ

Results: RHIC kinematics



- average p_t shift:
  anti-k_t and C/A+filt. Ok

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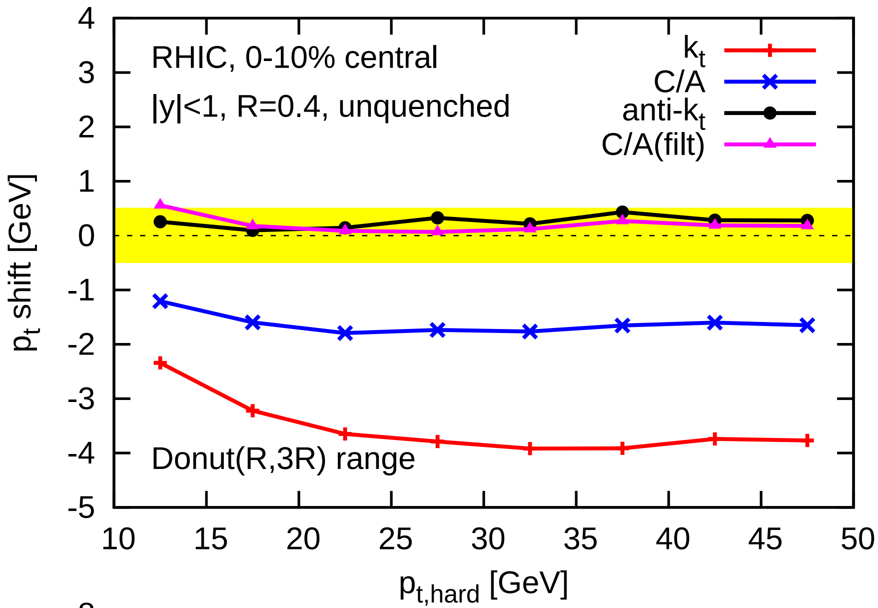

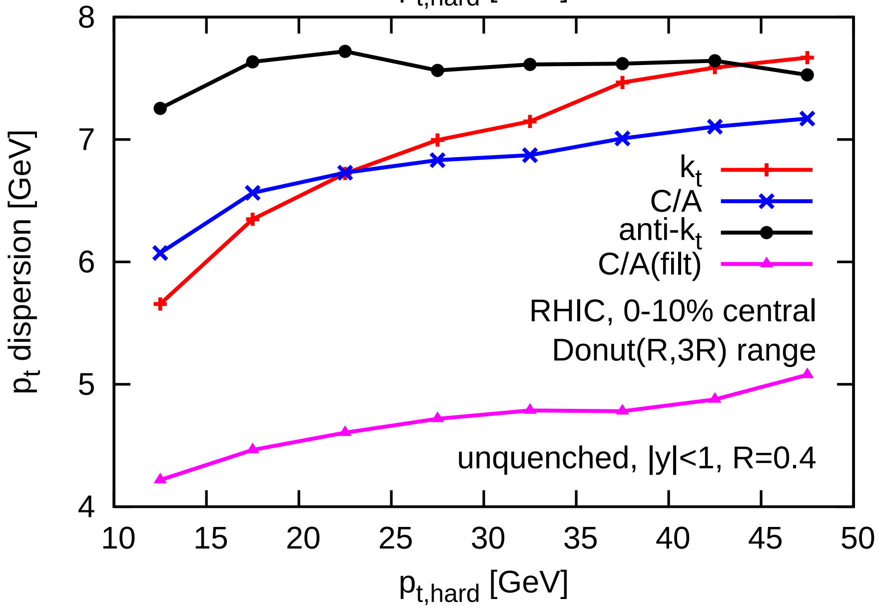

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- p_t shift dispersion:
  C/A+filt. better

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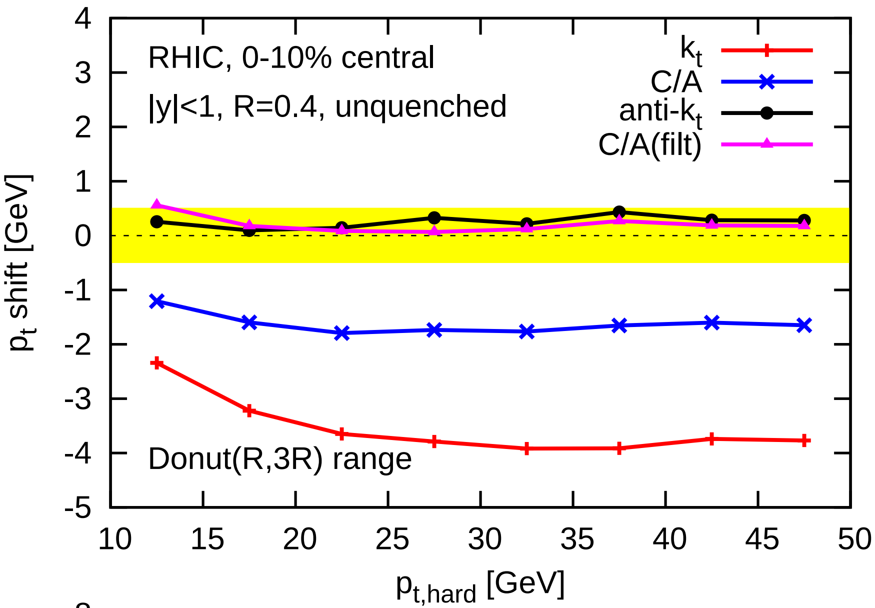
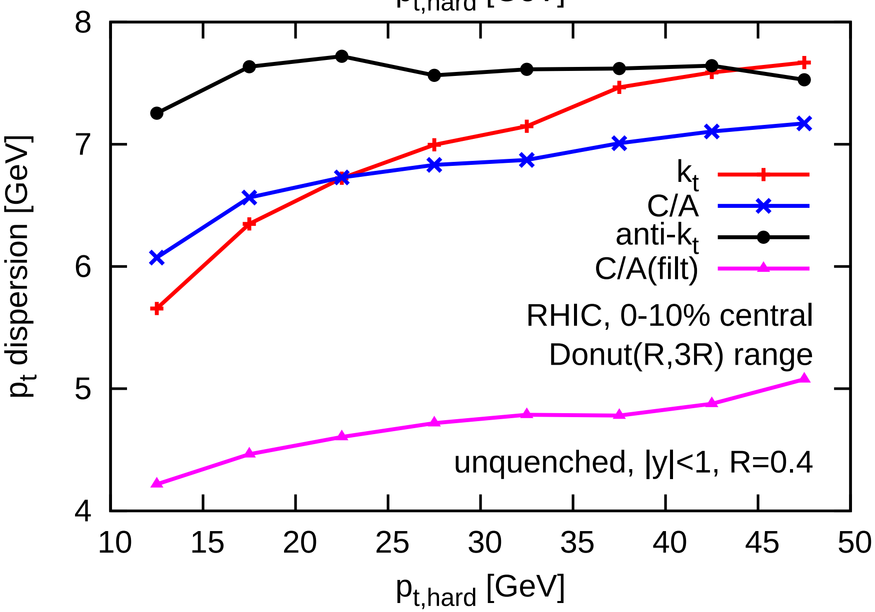
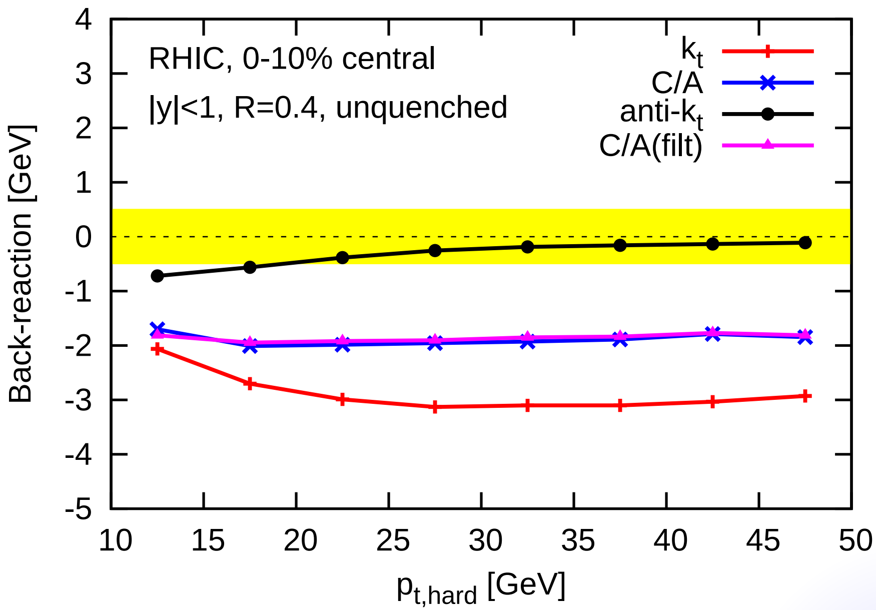
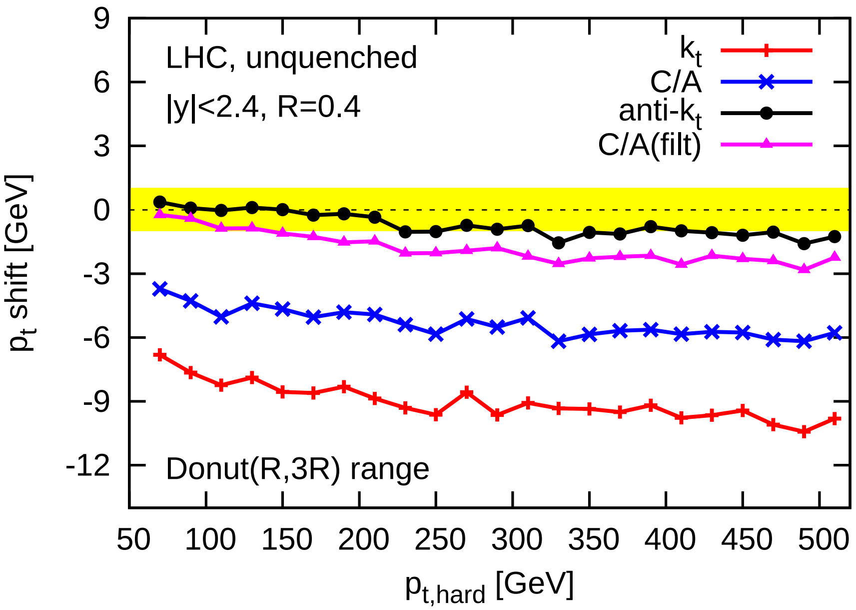


- average p_t shift:
  anti-k_t and C/A+filt. Ok
- p_t shift dispersion:
  C/A+filt. better
- watch out C/A+filt. average:
  back-reaction compensated





Results: LHC kinematics



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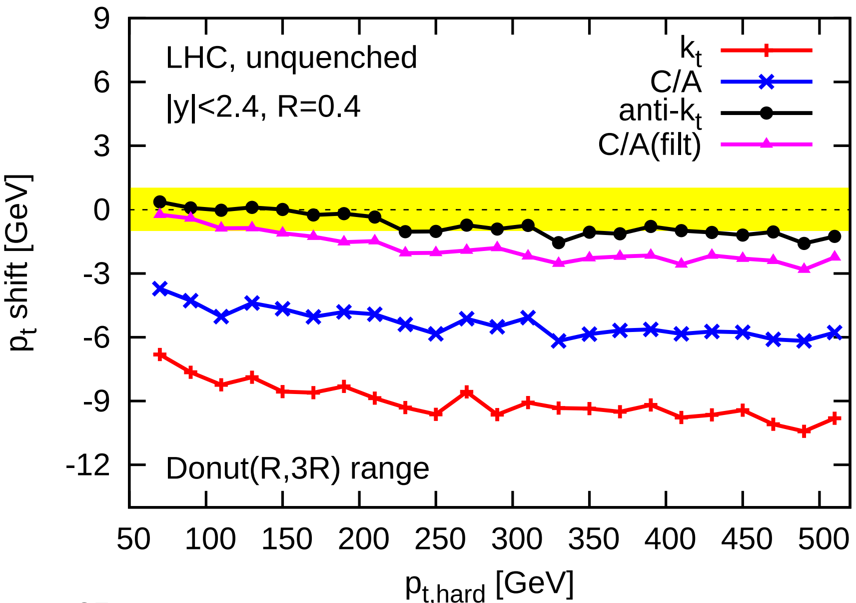
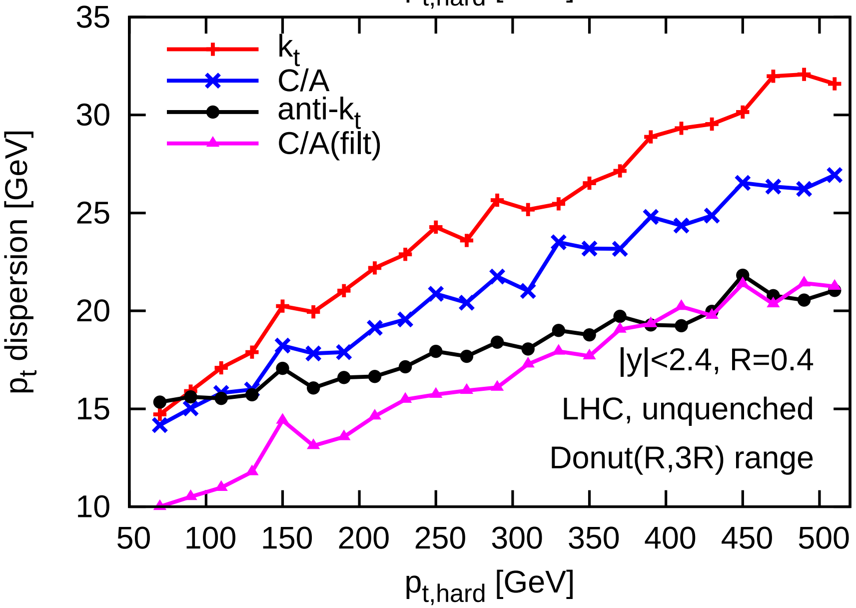
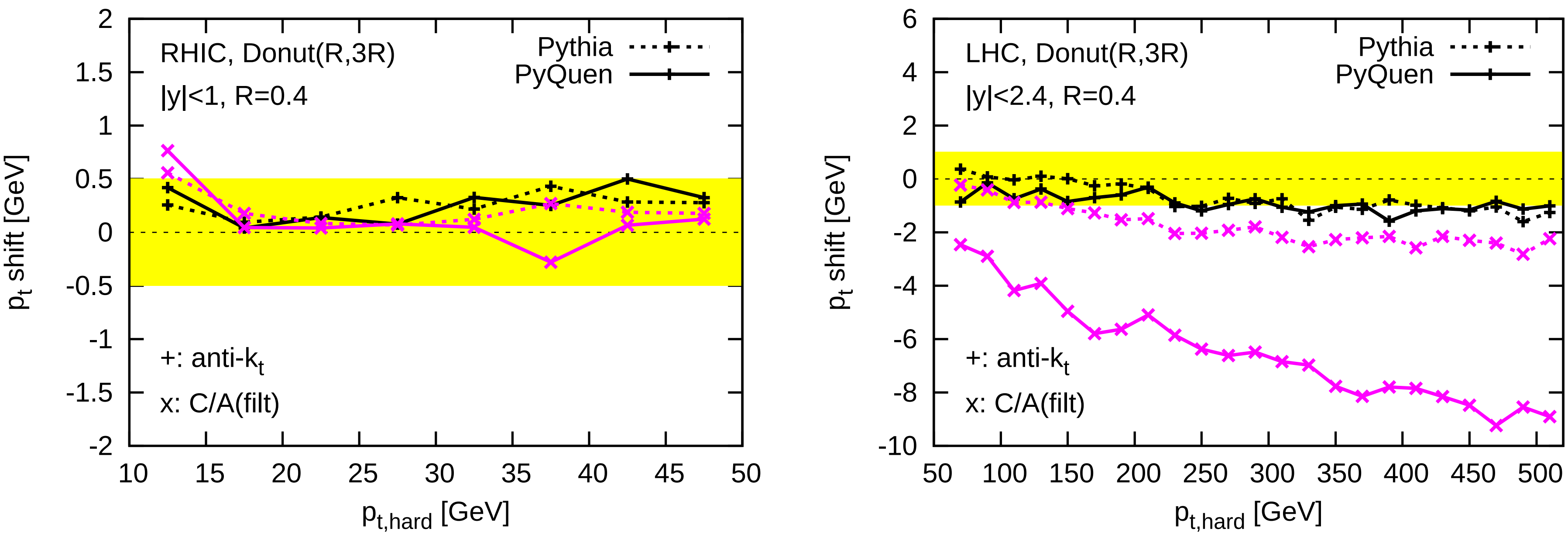




- average p_t shift:
  anti-k_t and C/A+filt. Ok

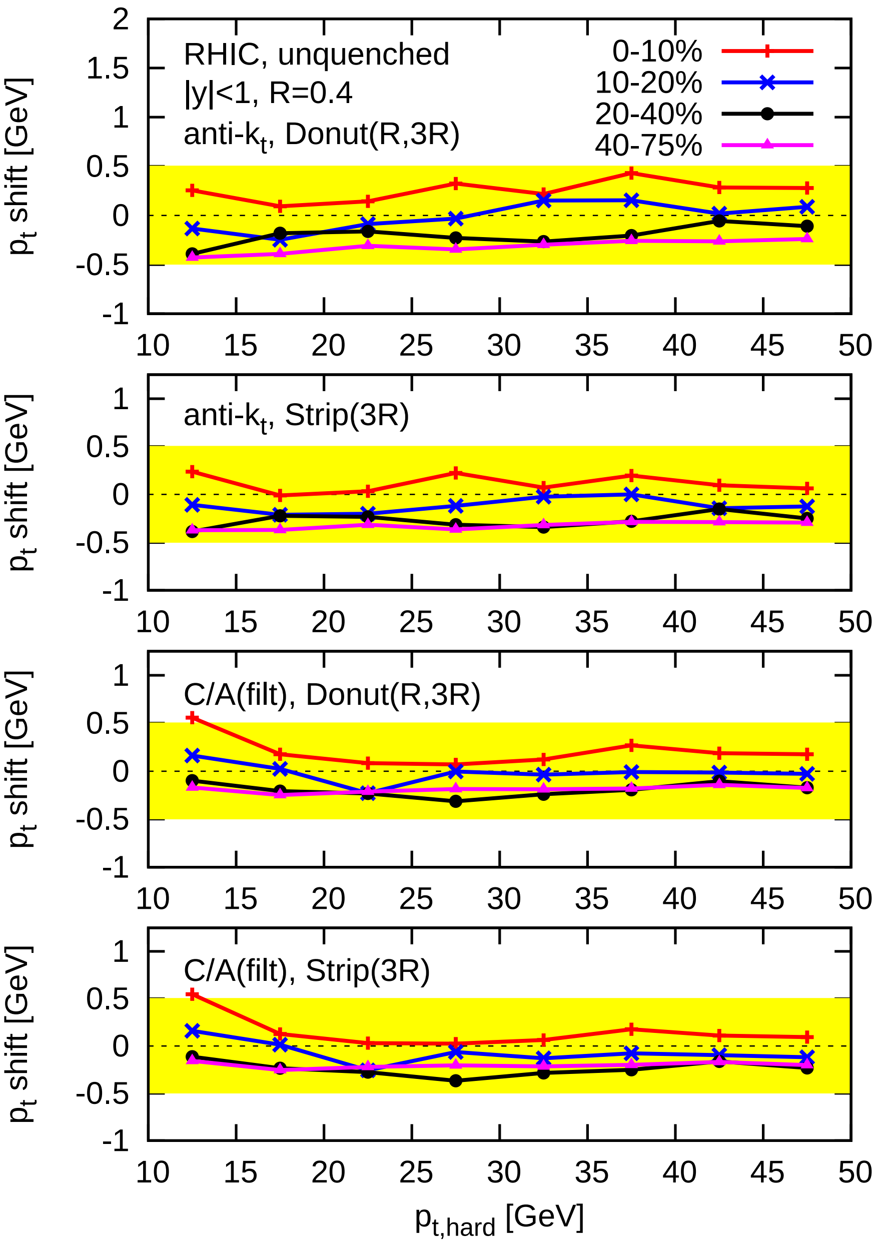
- p_t shift dispersion:
  C/A+filt. better
  anti-k_t Ok

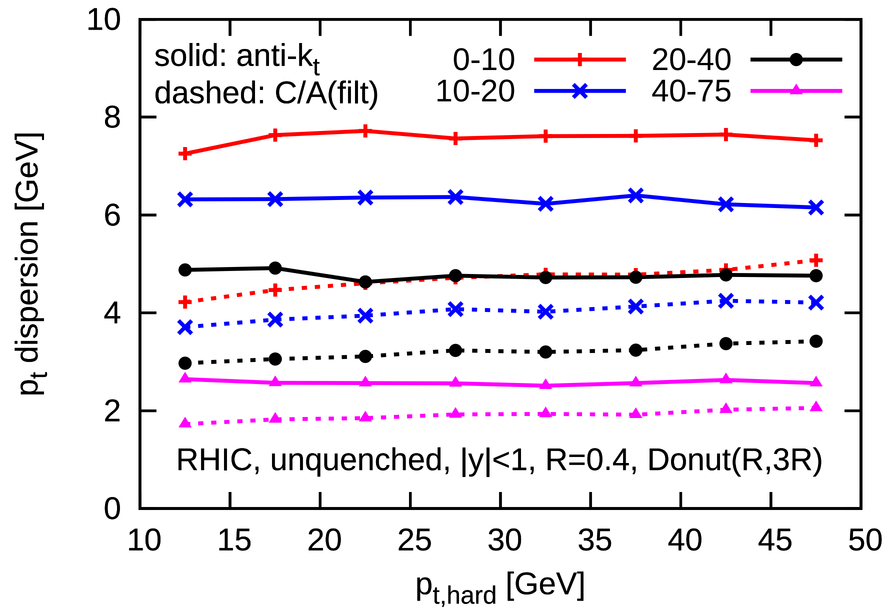
Results: quenching



- Performances not much affected by quenching
- 10 GeV for $p_t = 500$ GeV at the LHC is only a 2% effect
- anti-k_t's rigidity in action
- just illustrative: more quenching models needed

Results: centrality dependence





- good subtraction

  for every centrality bin

- dispersion decreases

  with centrality

Results: comments

- anti-k_t's soft-resilience is the reason for $\langle \Delta p_t \rangle \approx 0$

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Results: comments

- anti-k_t's soft-resilience is the reason for $\langle \Delta p_t \rangle \approx 0$
- C/A+filt's smaller area is the reason for smaller dispersion in agreement with the estimate: dispersion $\sim \sqrt{A_{jet}}\sigma_{\rm bkg}$
- C/A+filt's small $\langle \Delta p_t \rangle$ result from BR and subtraction bias
  - Most of QCD radiation in the hardest subjet
  - Bias: filtering picking the $2^{\rm nd}$ hardest jet as the hardest background fluctuation
  - Estimate for Gaussian fluctuations:

$$\langle (\Delta p_t)_{\rm filt.} \rangle \approx \frac{3\sqrt{0.55\,\pi(R_{\rm filt}R)^2}}{2\sqrt{\pi}}\sigma \approx 0.56\,R\,\sigma$$

2 GeV at RHIC, 5.8 GeV at the LHC *i.e.* nice agreement

Effects of shift and dispersion

RHIC pp jet cross-section is well approximated by

$$\left.\frac{d\sigma}{dp_t}\right|_{\text{bare}} = \mu\sigma_0\, e^{-\mu p_t}$$

Shift $\langle \Delta p_t \rangle$ and dispersion σ (with Gaussian approx.) gives

$$\left.\frac{d\sigma}{dp_t}\right|_{\text{obs.}} = \left.\frac{d\sigma}{dp_t}\right|_{\text{bare}} e^{\mu\langle \Delta p_t \rangle}\, e^{\mu^2\sigma^2/2}.$$

- $\mu = 0.3$, $\langle \Delta p_t \rangle = 0$, $\sigma = 7$ gives factor $\sim$ 9
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- Unfolding the dispersion is an important source of uncertainty
- C/A+filt would help

Fake jets

Fake jet = “hard” fluctuation of the soft background

Estimate:

- Fakes:
  - Gaussian spectrum with σ from studies above
  - scaled by the number of binary collisions
  - scaled by the number of jets in the acceptance
- Hard cross-section:
  - Pythia simulation
  - (approximately) convoluted with Gaussian fluctuations

Fake jets

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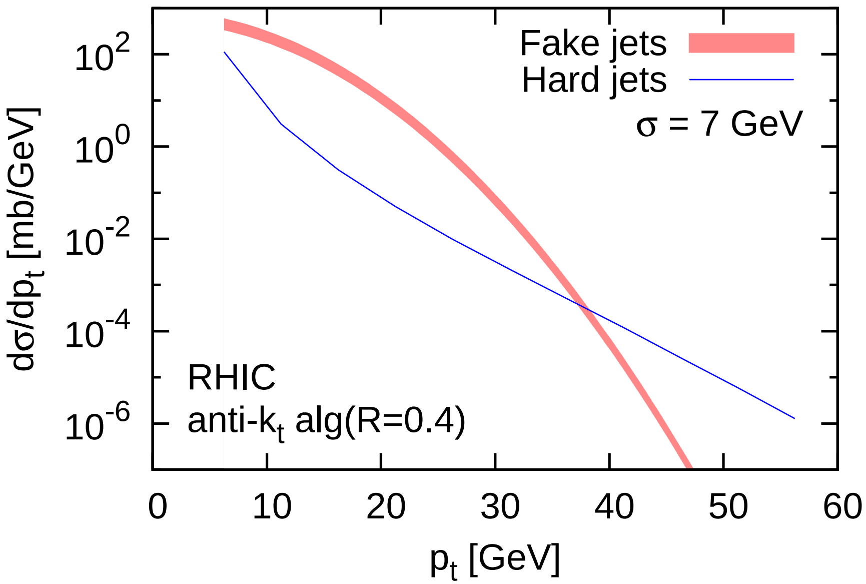

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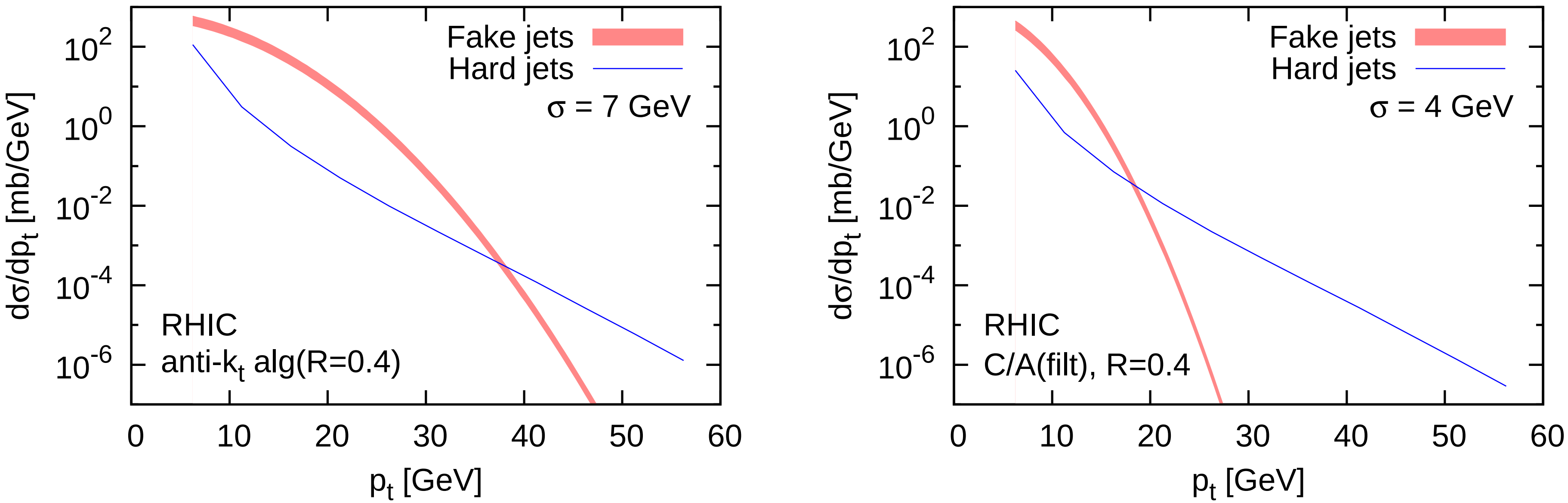


- Need for a good fake-jet rejection mechanism
- Significant improvement
- Not much of a problem at the LHC

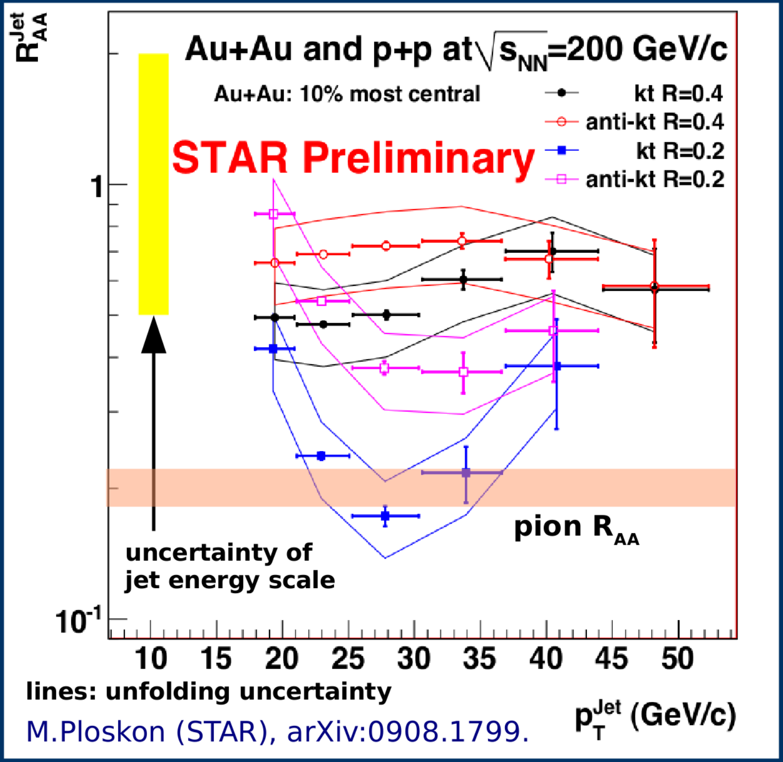
A word on the RHIC results

Generic method

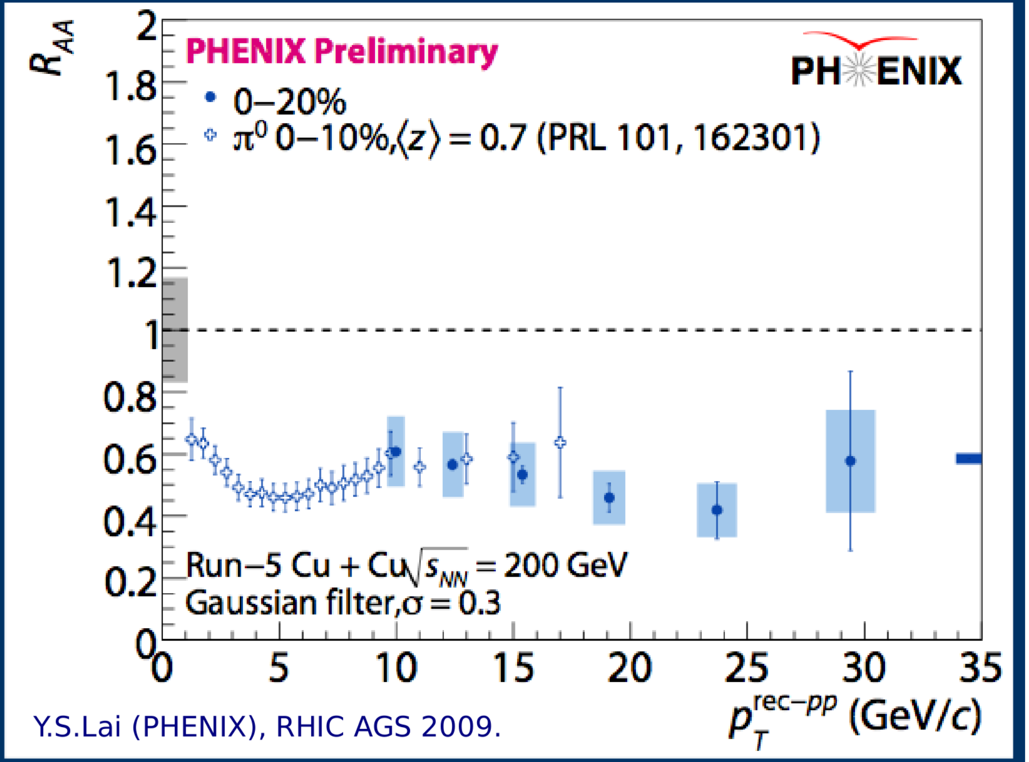
First jet measurements in heavy-ion collisions

- STAR
  - k_t and anti-k_t algorithms
  - “FastJet’s” background subtraction method
  - statistical fake jets rejections
  - dispersion unfolding from MC in AuAu
- PHENIX
  - Gaussian filter ([Y.S.Lai,B.A.Cole,08])
  - Gaussian filter for fake jets rejections
  - dispersion unfolding from pp in CuCu

Medium modification of jet p_T spectra



M.Ploskon (STAR), arXiv:0908.1799.

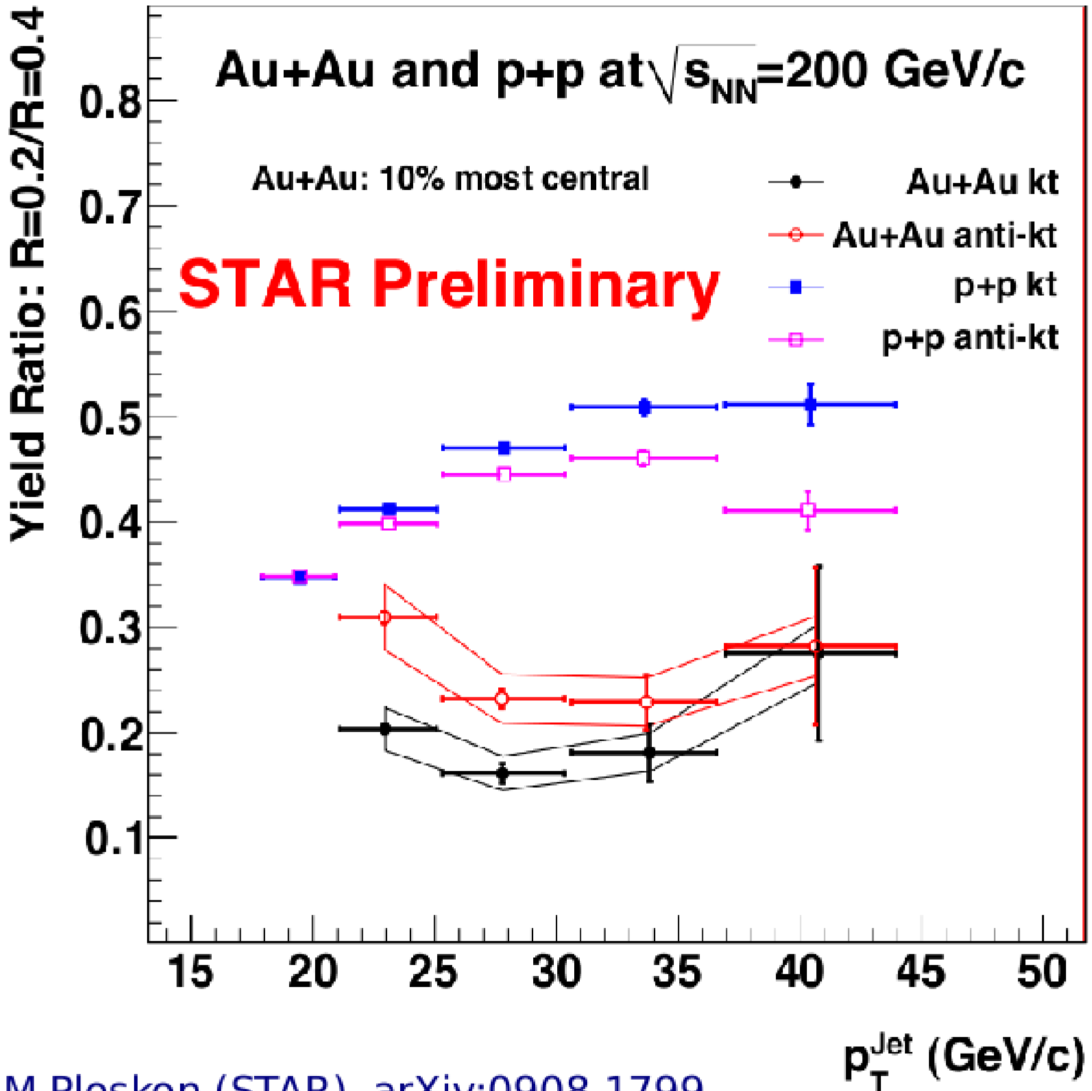


Y.S.Lai (PHENIX), RHIC AGS 2009.

- different sensitivity of algorithms
- R=0.4: indication of energy recovery (cf. pion R_{AA})
- R=0.2 jets suppressed
- → is R=0.4 enough to achieve jet R_{AA} = 1?

- significant jet suppression
- → ?jet broadening -> energy shift
- → ?feature of fake jet rejection algorithm

results (cont'd)



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Compute x-section ratio:

$$\frac{\sigma(R=0.2)}{\sigma(R=0.4)}$$

- pp: less than 1

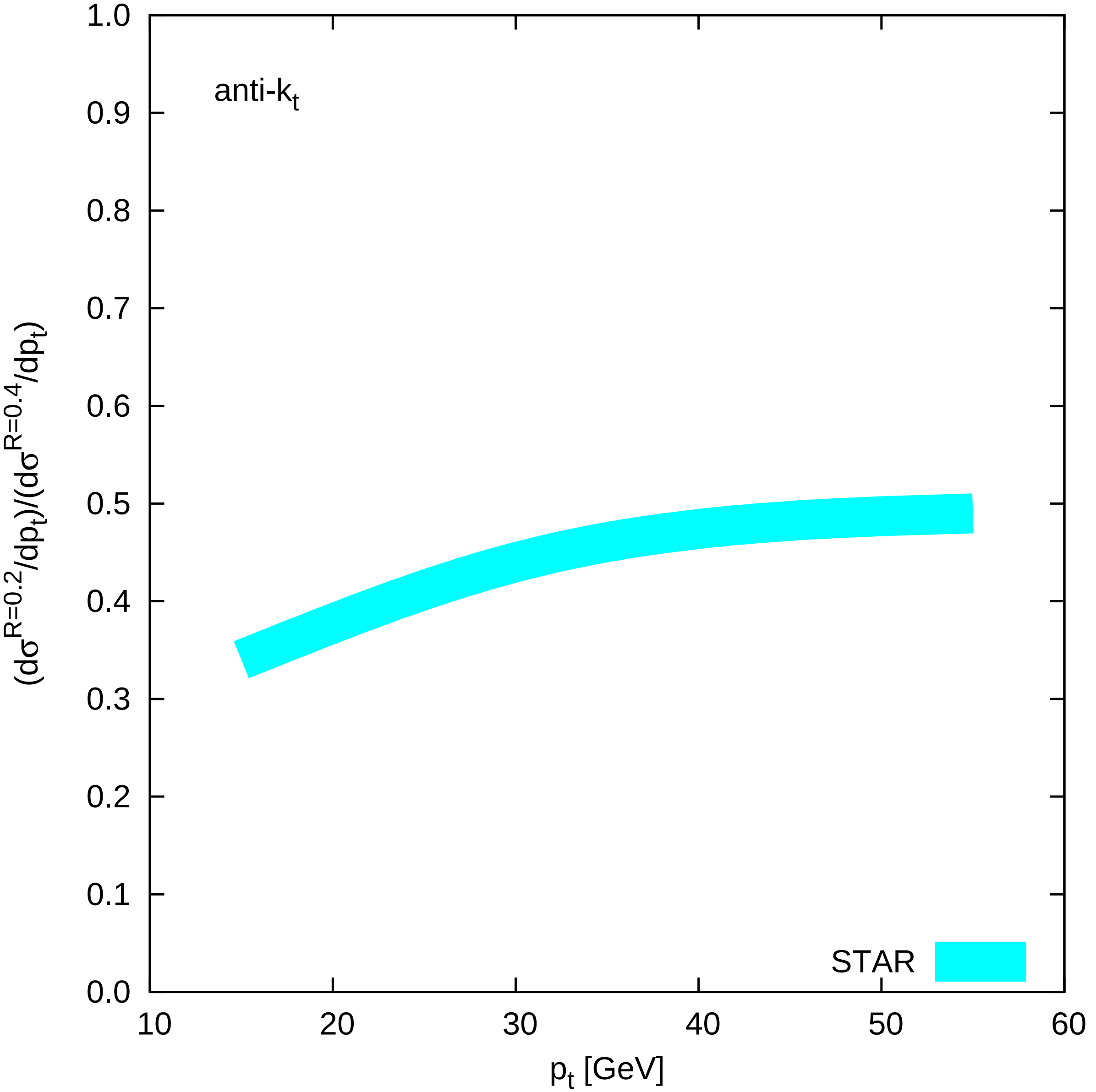
  out of jet radiation

- AA: less than pp

  broadening

A word of caution

Take a closer look at the ratio in pp



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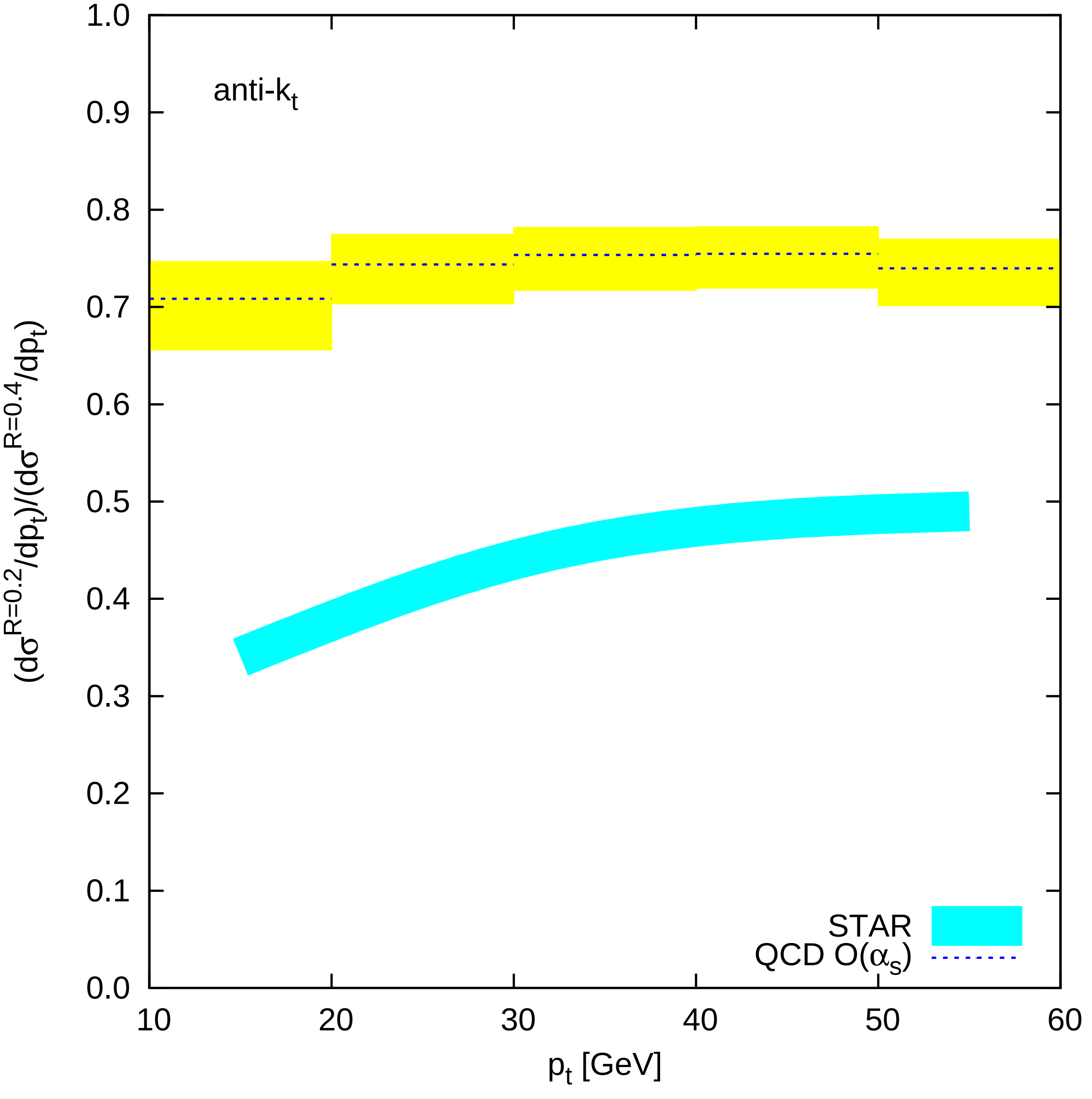

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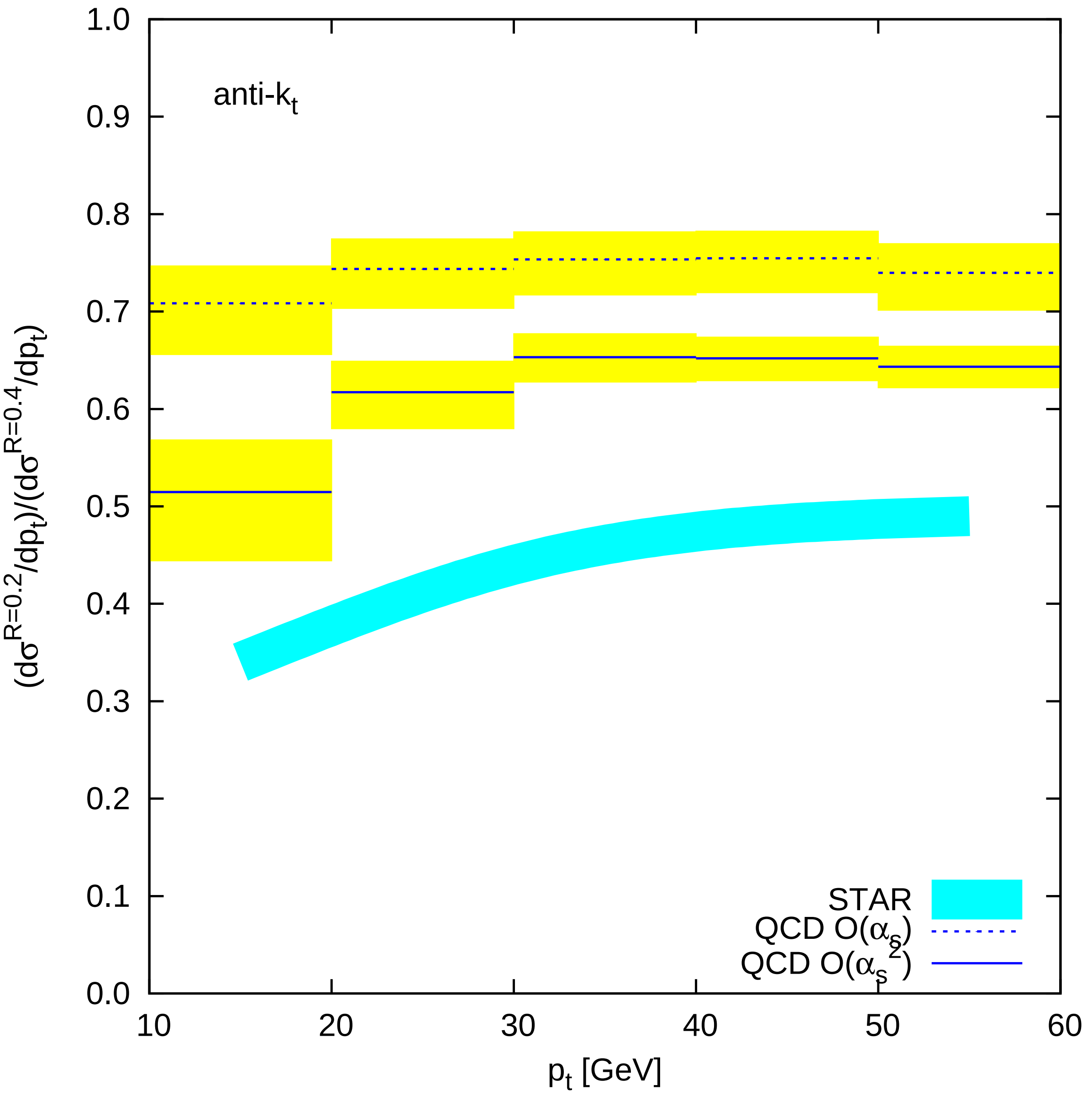

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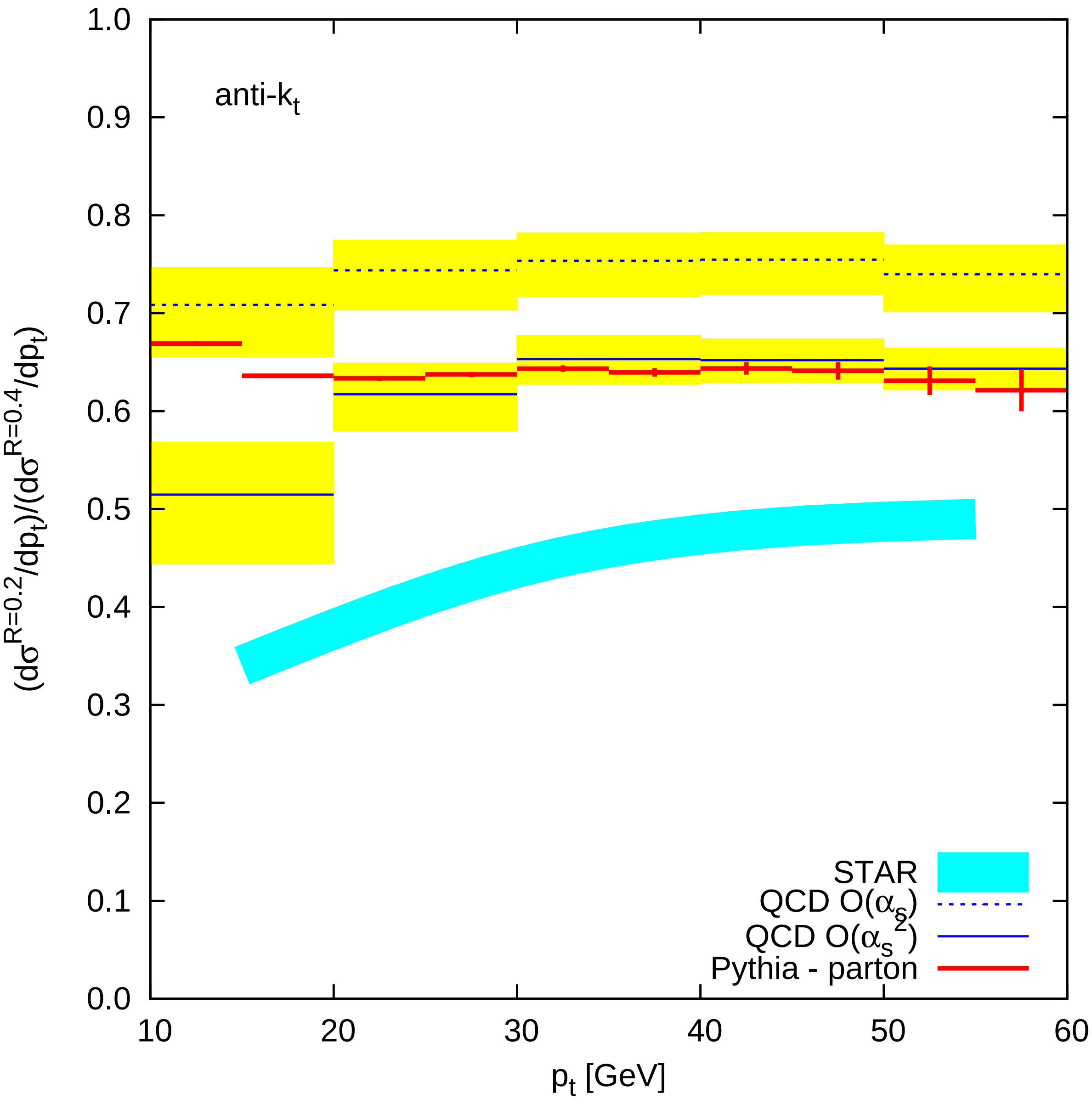

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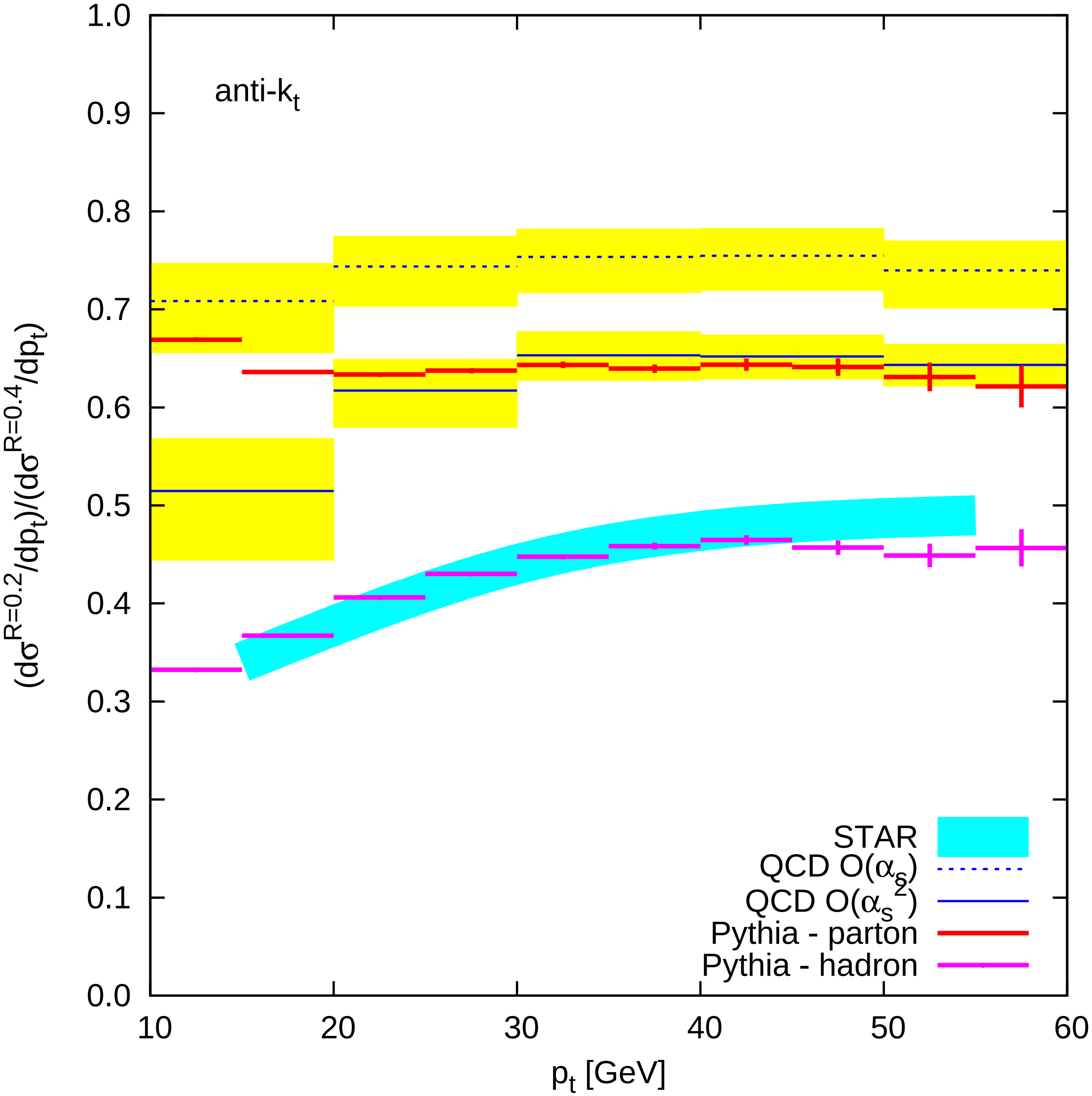

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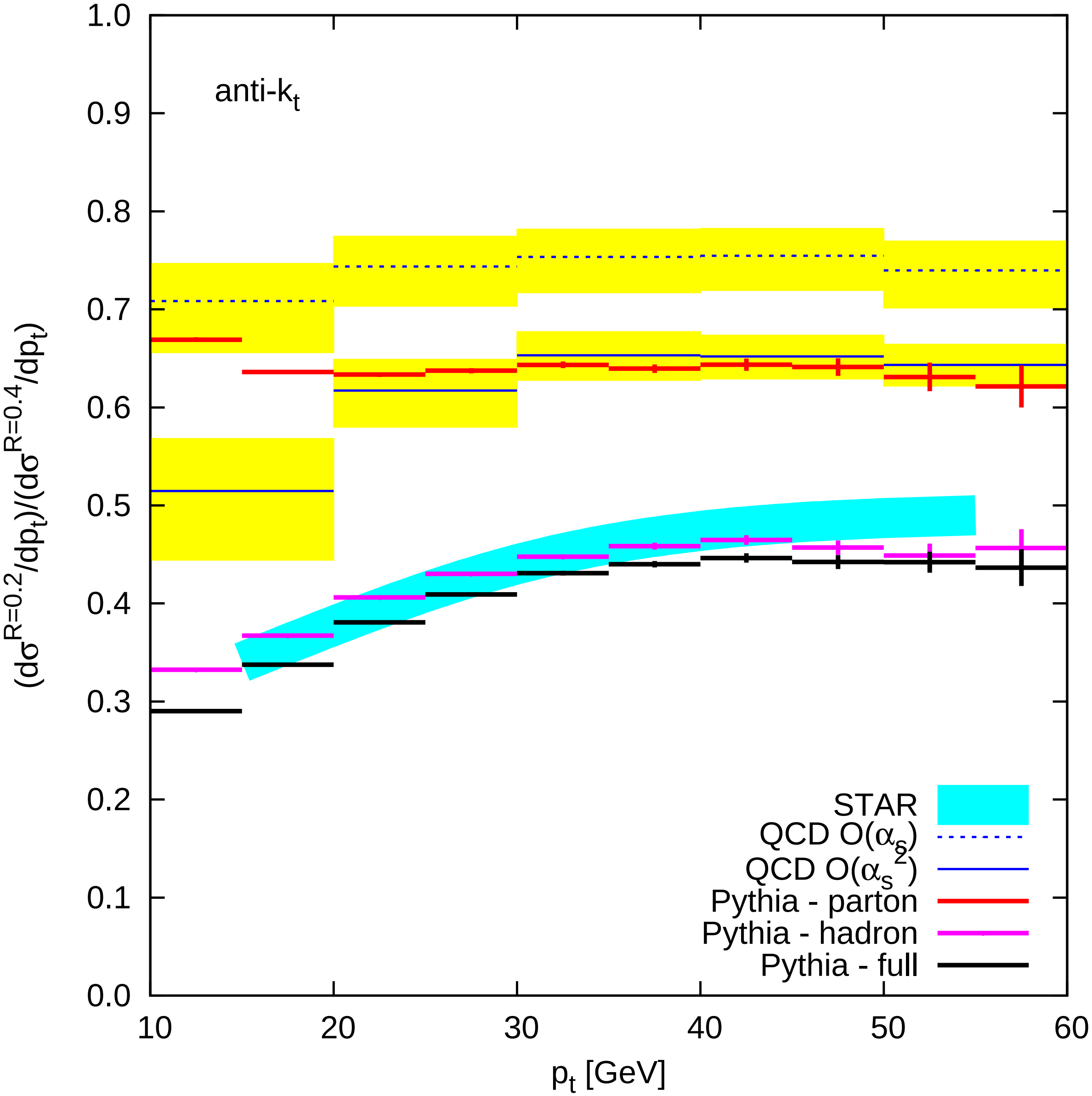
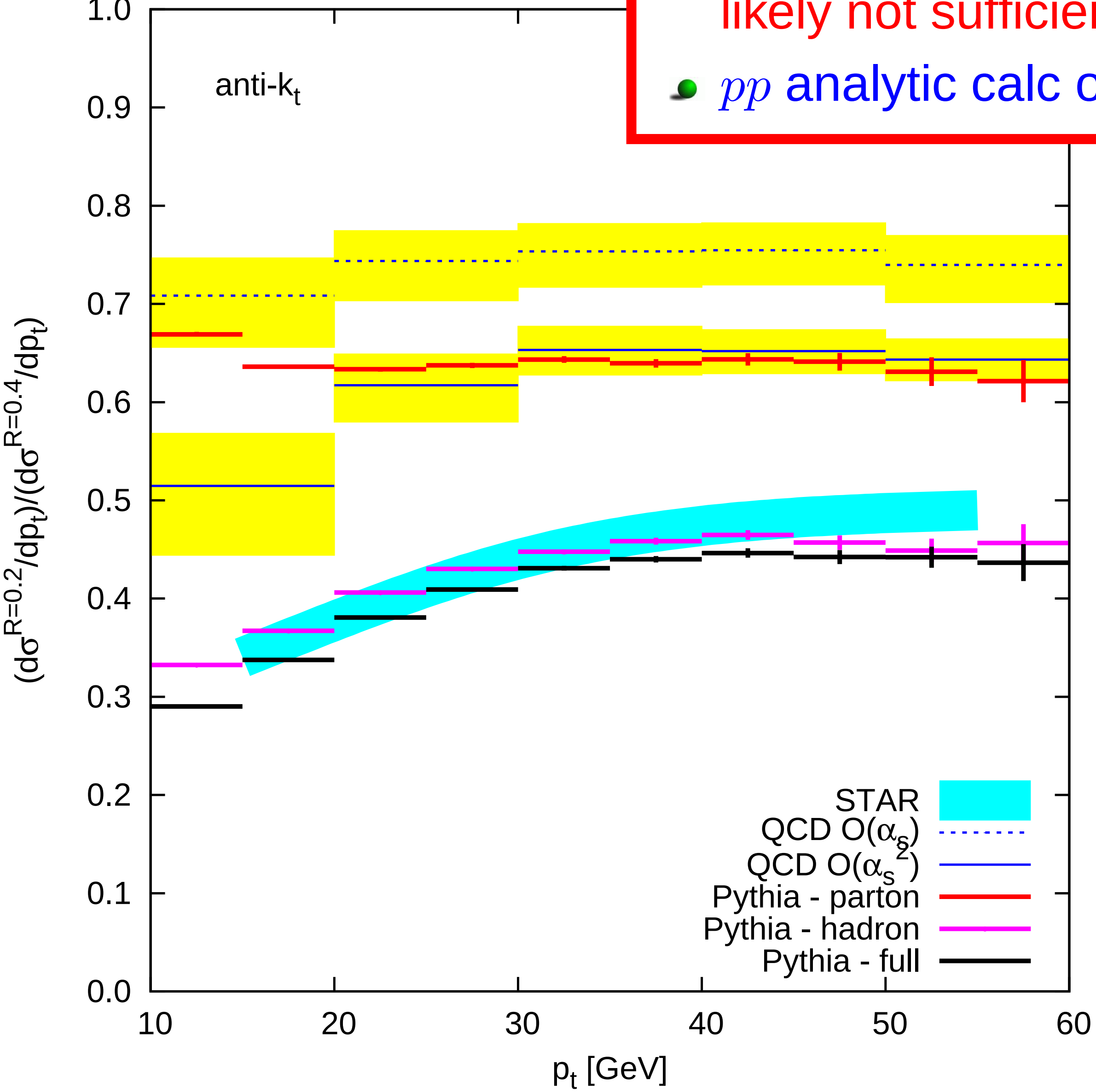


A word of caution

Take a closer look at the ratio in pp

- a single gluon in the medium likely not sufficient
- pp analytic calc on its way



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- measurements
  A one-gluon-emission approach not sufficient