

The cookbook for jets in heavy-ion collisions?

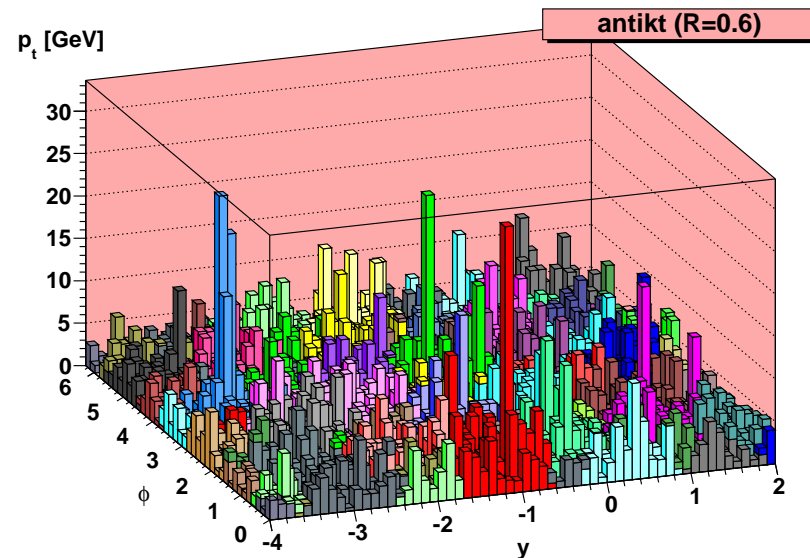
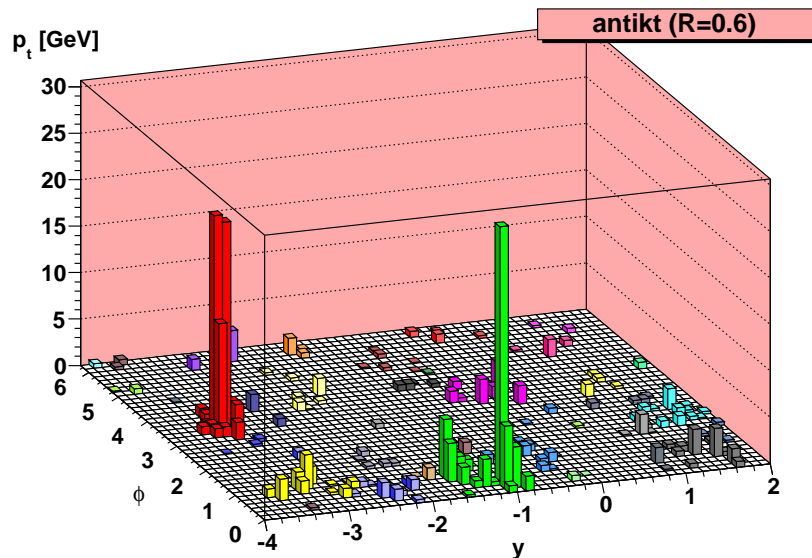
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IPhT, CEA Saclay

In collaboration with Gavin Salam, Matteo Cacciari and Juan Rojo

Hard Probes 2010 — Eilat, Israel — Oct 11-15 2010

How to “see” jets in a soft background



Valid for many backgrounds

- UE in pp (~ 1 GeV)
- pileup in pp (~ 10 GeV)
- UE in AA (~ 100 GeV)

(Hopefully) for everyone

- Standard method
- **New hints**
- comments for experts

Central formula

One basic formula for **background subtraction for a single event**

$$p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{bkg}} A_{\text{jet}}$$

assumes that the background is uniform

3 things needed:

- Define a **jet**
- Define the **area** of a jet
- Obtain ρ_{bkg} , the **background p_t density** per unit area

[Cacciari, Salam, 07]

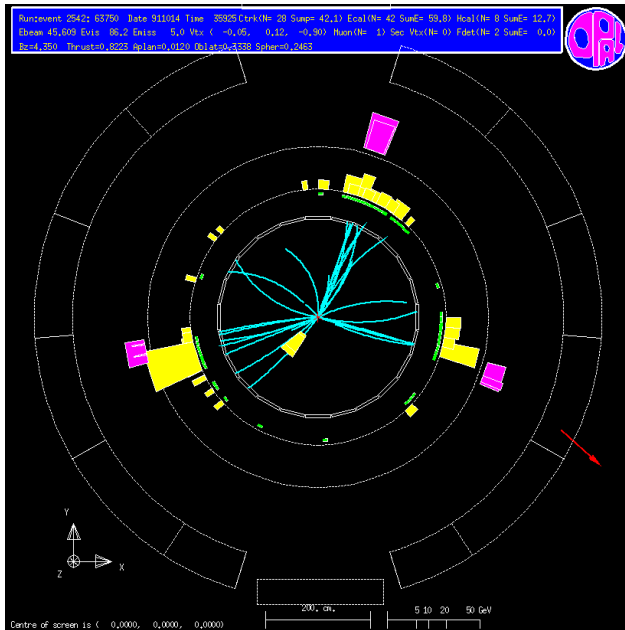
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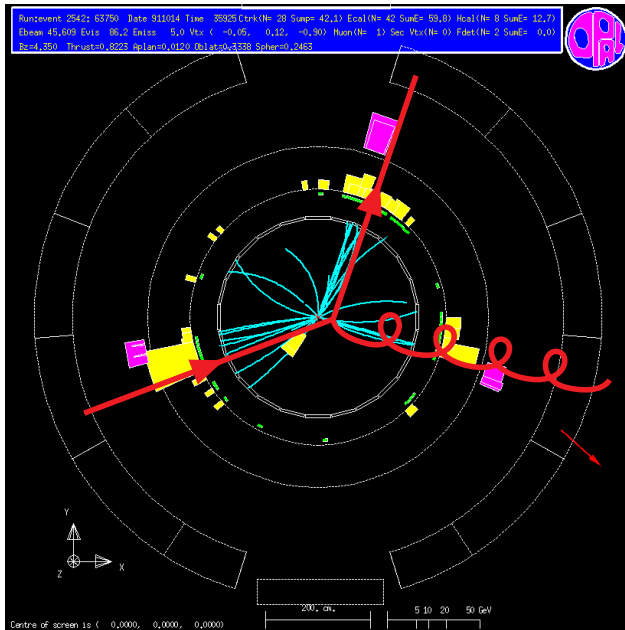
Jet definitions

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



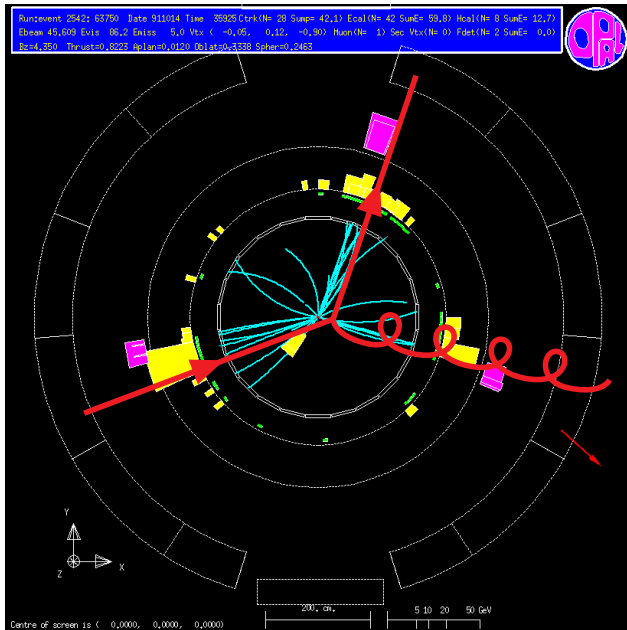
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In practice: use a jet definition

particles $\{p_i\}$ $\xrightarrow[\text{definition}]{\text{jet}}$ jets $\{j_k\}$

algorithm: the recipe (insufficient!)
definition: algorithm + params

Jet=hadron is too simplistic: NLO? What opening for “collimated”?

Examples of jet definitions

- **Recombination**: successively recombine the closest pair

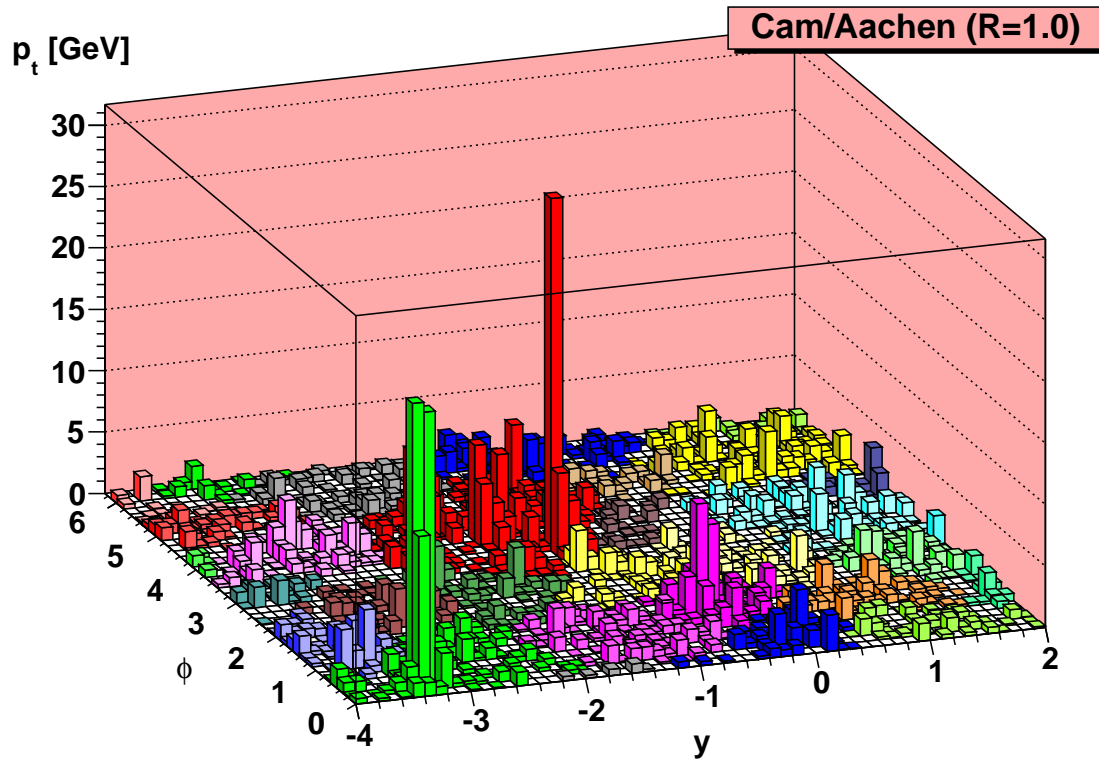
$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2)$$

Stop at distance R

- $p = 1$: k_t algorithm (very close to QCD)
[Catani, Dokshitzer, Seymour, Webber, 93]
- $p = 0$: **Cambridge/Aachen (C/A)** algorithm (substructure studies)
[Dokshitzer, Leder, Moretti, Webber, 93]
- $p = -1$: **anti- k_t** algorithm (the default at the LHC)
[Cacciari, Salam, GS, 08]
- **Cone**: \approx flow of energy in a cone (of fixed R) centred on the cone centre: **SISCone**
[Salam, GS, 07]

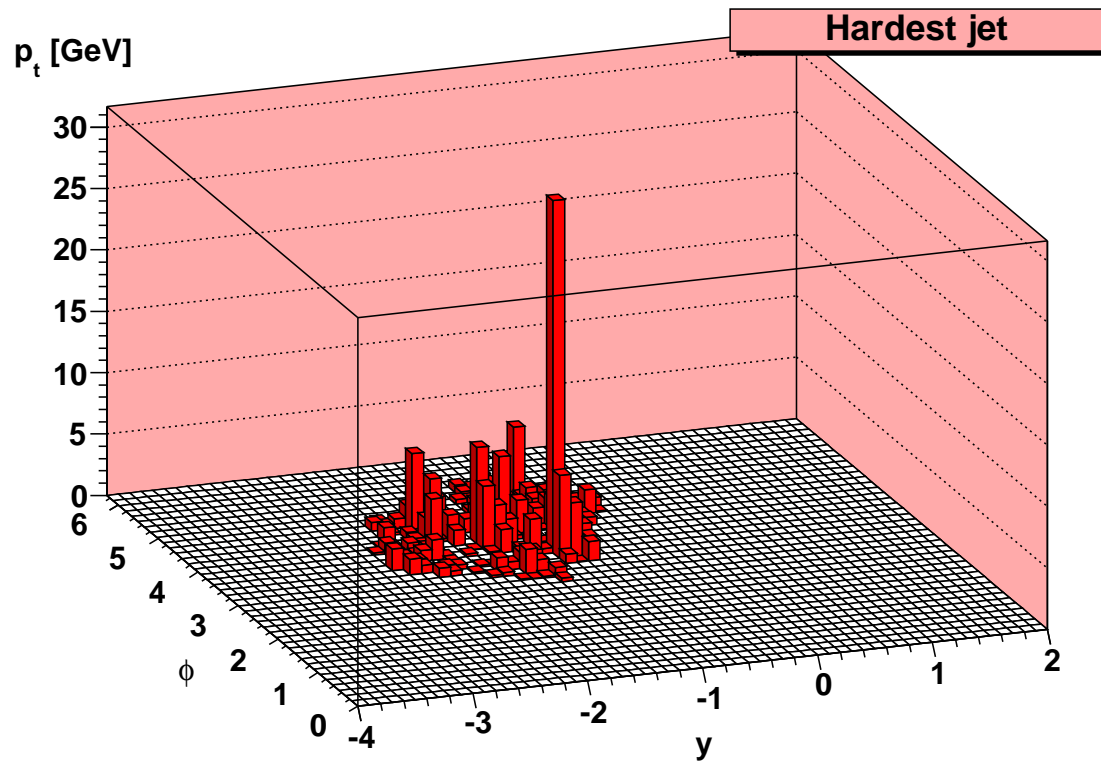
Finite perturbative cross-section: only consider **infrared-and-collinear-safe** algorithms

New suggestion #1: Filtering



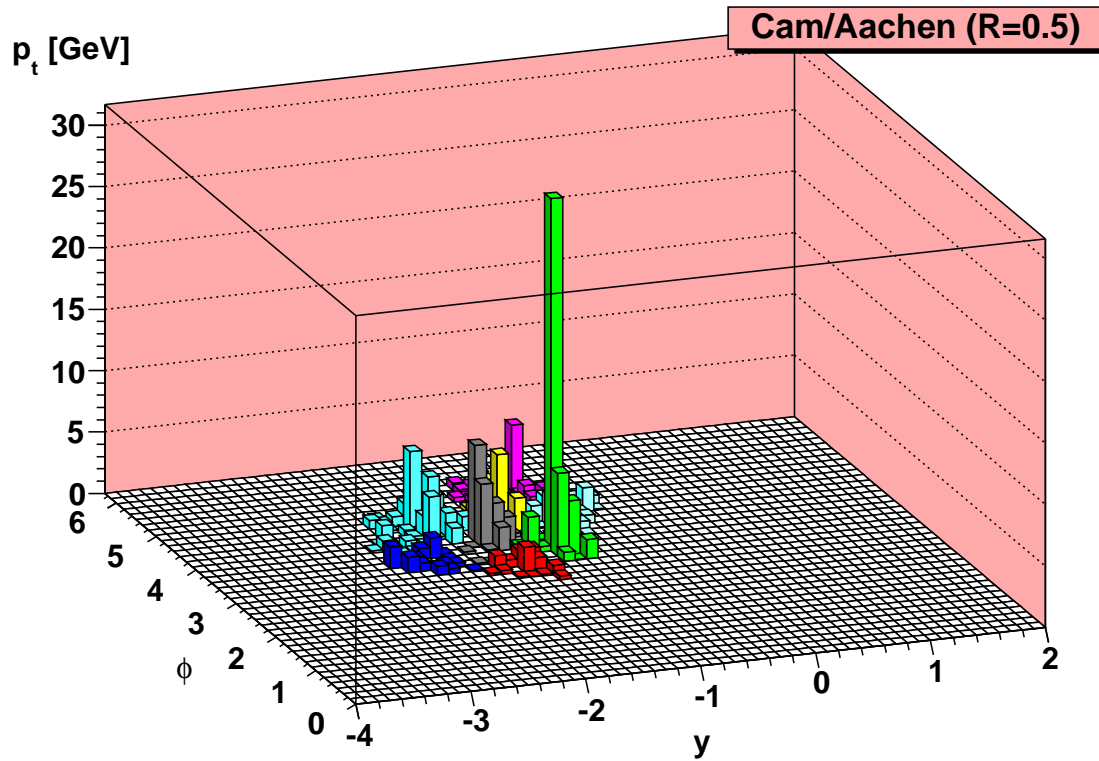
- cluster with Cambridge/Aachen(R)

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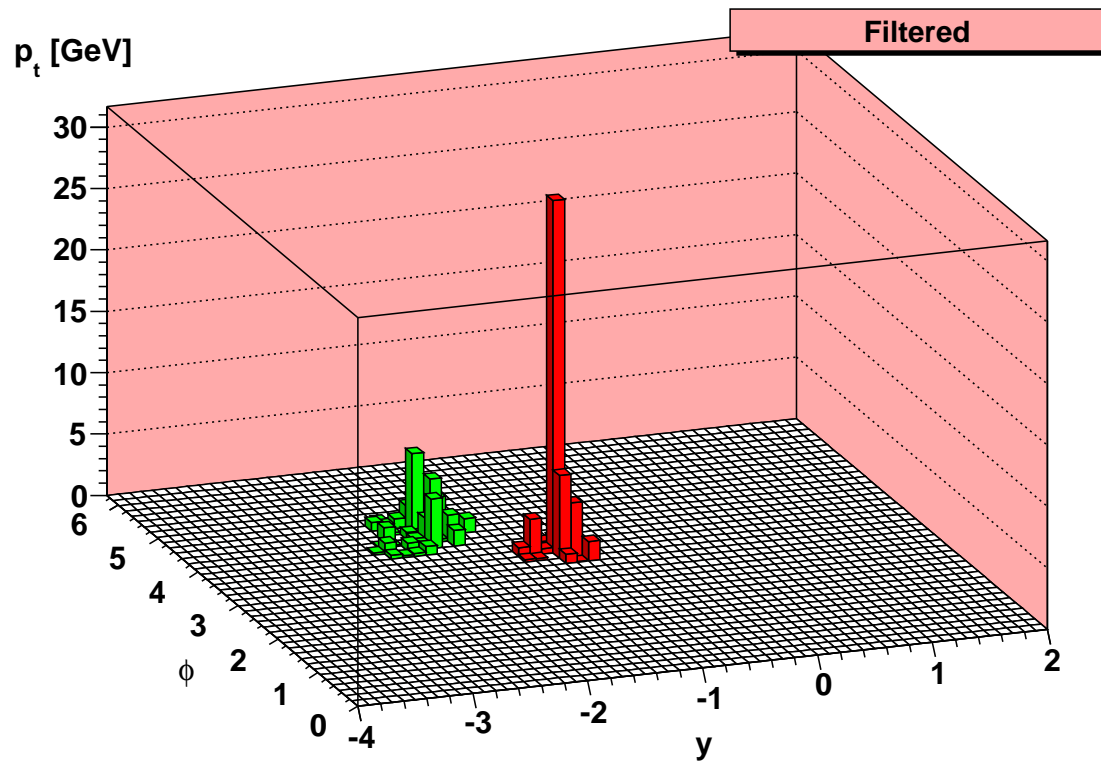
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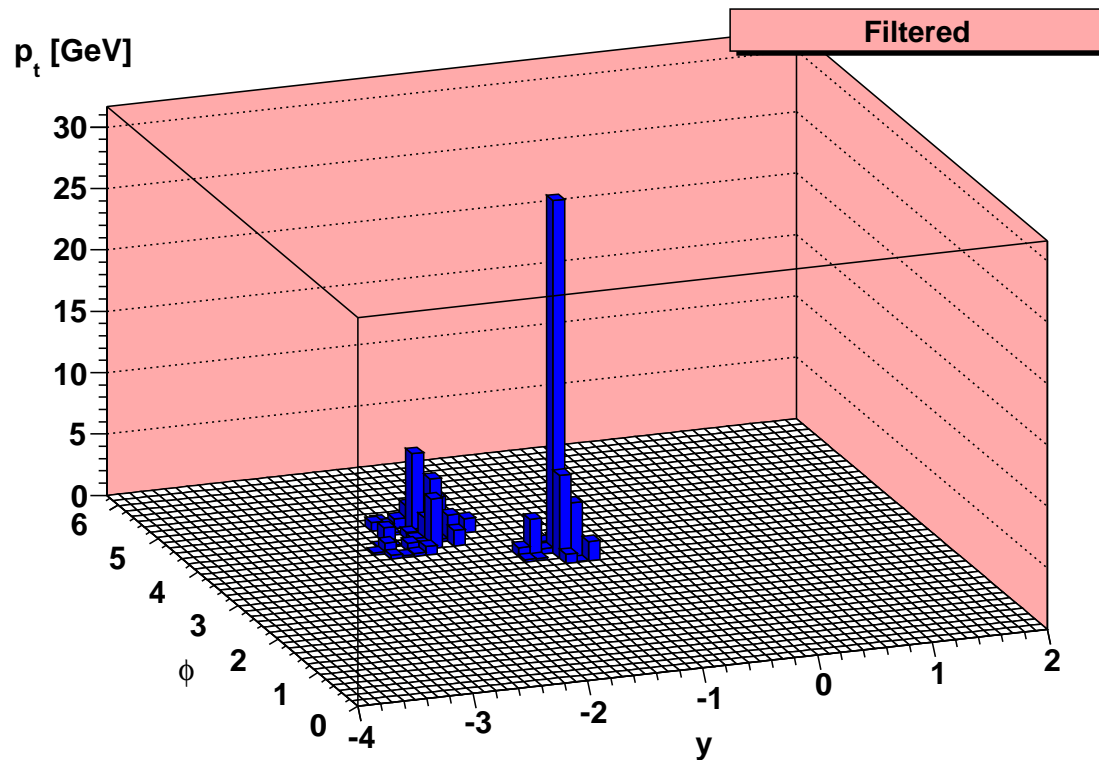
- cluster with Cambridge/Aachen(R)
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 - recluster with Cambridge/Aachen(R/2)

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 - keep the 2 hardest subjets

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Idea:

- ✓ keep perturb. radiation
- ✓ remove UE

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

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

- Proven useful for kinematic reconstructions

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

$$p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{bkg}} A_{\text{jet}}$$

3 things needed:

- Define a jet
- Define the **area** of a jet
- Obtain ρ_{bkg} , the background p_t density per unit area

Area definitions

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

Area \equiv region where the jet catches soft particles

- Recipe: add a dense coverage of infinitely soft particles (**ghosts**)
(active) area = region where a jet catches the ghosts
- Idea: ghost \approx background particle
 \Rightarrow area where catching ghost \equiv area where catching background
- Advantages:
 - generic/universal definition (e.g. independent of a calorimeter)
 - allow for analytic computations
- Notes for experts:
 - put ghosts up to at least $y_{\text{jet,max}} + R$
 - preferably use a “4-vector” definition of the area (sum ghost 4-momenta)
 - require an IRC-safe algorithm!
 - alternative: passive area (equivalent for large multiplicities)
 - Better handling with `active_area_explicit_ghosts`

$$p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{bkg}} A_{\text{jet}}$$

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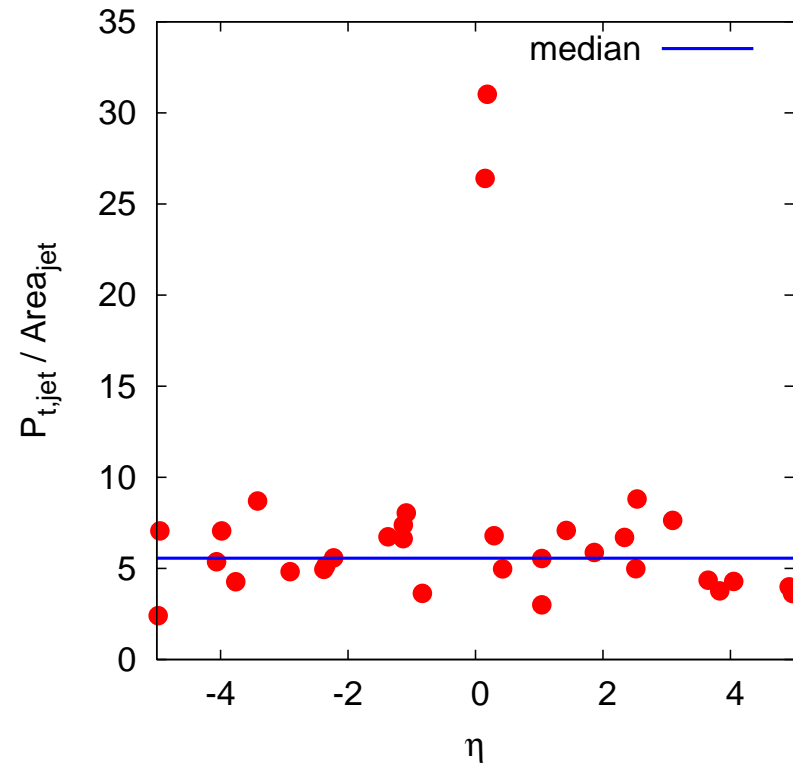
- Define a jet
- Define the area of a jet
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Example: ρ_{bkg} from jets

Recipe for estimating ρ_{bkg} :

- Cluster with k_t of C/A with “radius” R_ρ
- Estimate ρ_{bkg} using

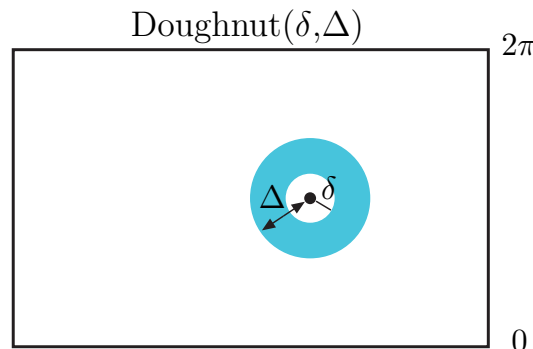
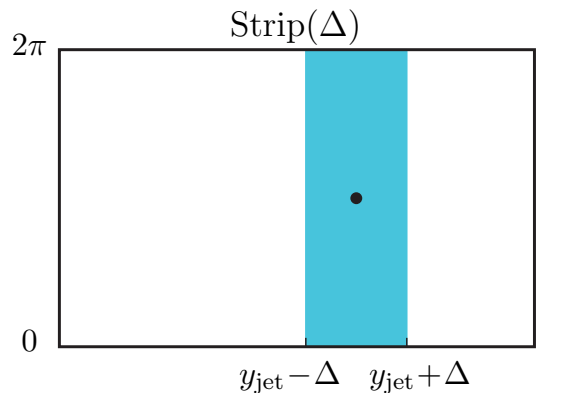
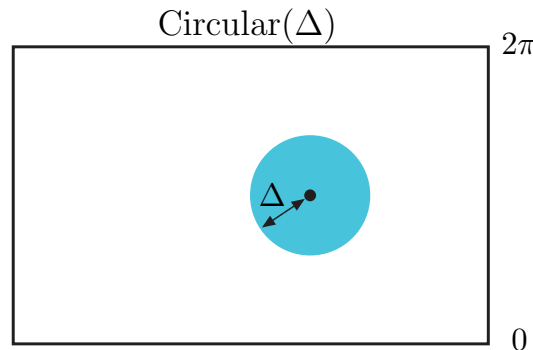
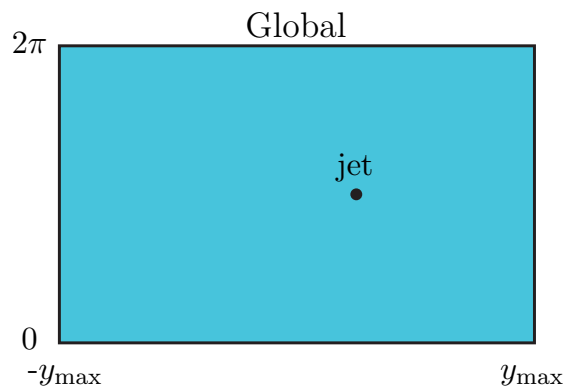
$$\rho_{\text{bkg}} = \text{median}_{j \in \text{jets}} \left\{ \frac{p_{t,j}}{A_j} \right\}$$



- Notes for experts
 - Other algorithms produce unwanted jets with small area
 - Typically, R_ρ between 0.3 and 0.6 is OK (I'll take 0.5)

New suggestion #2: Use a local range

Fluctuating background (e.g. rapidity dependence) → **local range**



$$\rho_{\text{bkg}}(j) =$$
$$= \text{median}_{j' \in \mathcal{R}(j)} \left\{ \frac{p_{t,j'}}{A_{j'}} \right\}$$

Also:
exclude the n (typically 2)
hardest jets in the event

Notes for experts:

- Limited acceptance \equiv local range
- Put ghosts at least up to $|y_{\text{jet},\text{max}}| + \Delta + R...$
- ... but for limited acceptance: put ghosts over the acceptance and keep all jets (tbc)

Subtraction uncertainties

- Background fluctuations: (inside an event!)

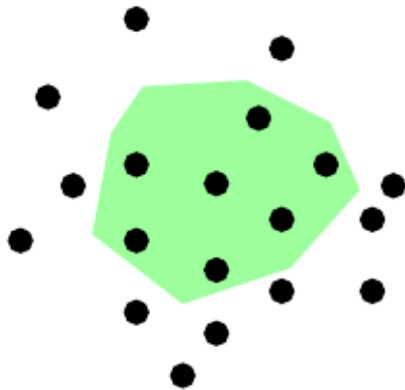
$$p_{t,\text{jet}} = p_{t,\text{jet}}^{\text{hard}} + \rho_{\text{bkg}} A_{\text{jet}} \pm \sigma_{\text{bkg}} \sqrt{A_{\text{jet}}}$$

Subtraction uncertainties

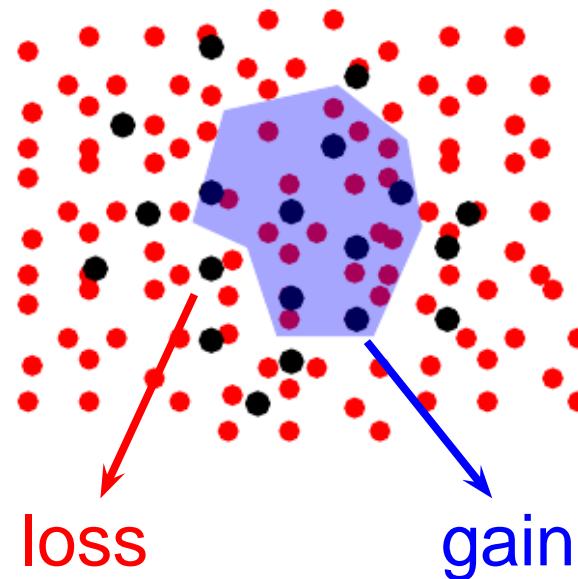
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$$p_{t,\text{jet}} = p_{t,\text{jet}}^{\text{hard}} + \rho_{\text{bkg}} A_{\text{jet}} \pm \sigma_{\text{bkg}} \sqrt{A_{\text{jet}}}$$

- Back-reaction:
No background



With background

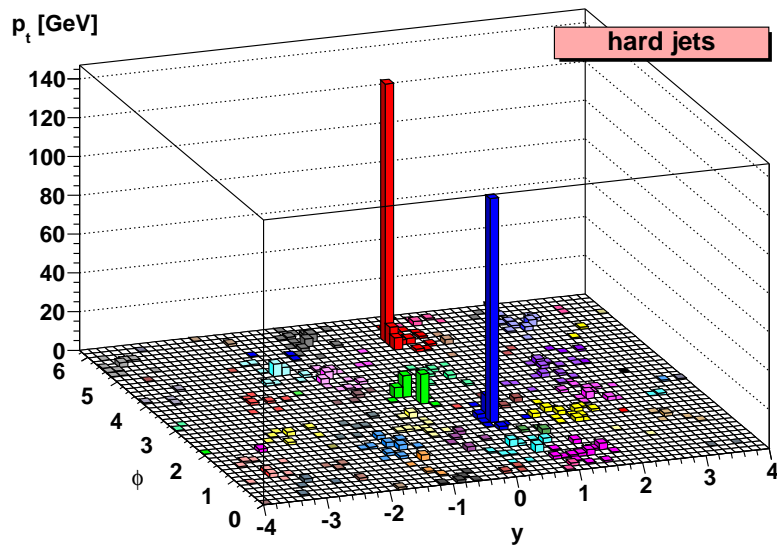


***Subtraction efficiency:
what precision may we hope for?***

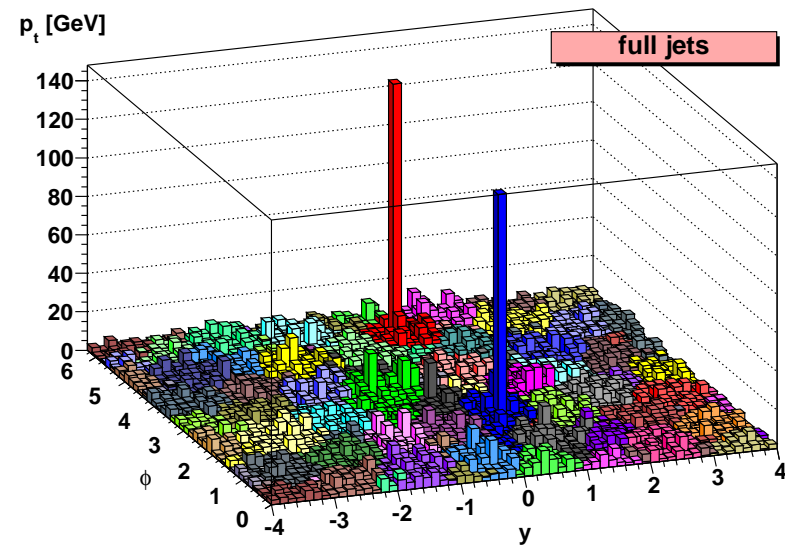
[Cacciari, Rojo, Salam, GS, 1010.1759]

Framework for study

Hard (Pythia) event



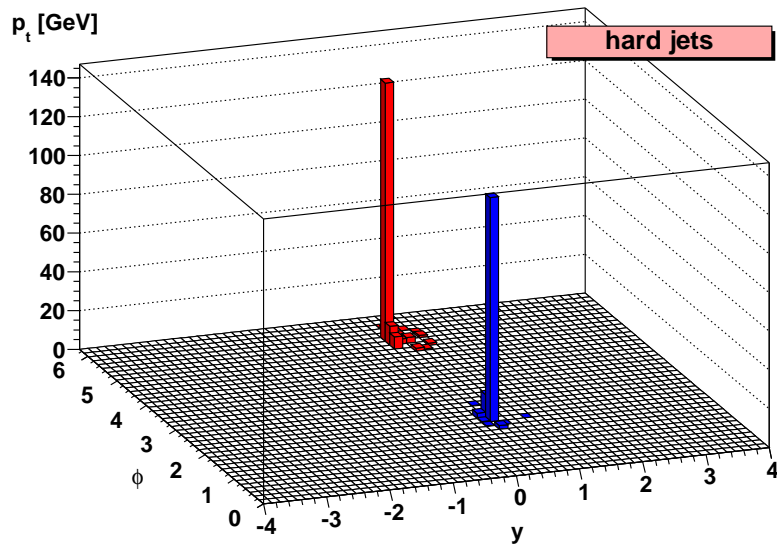
... embedded in AA (Hydjet) event



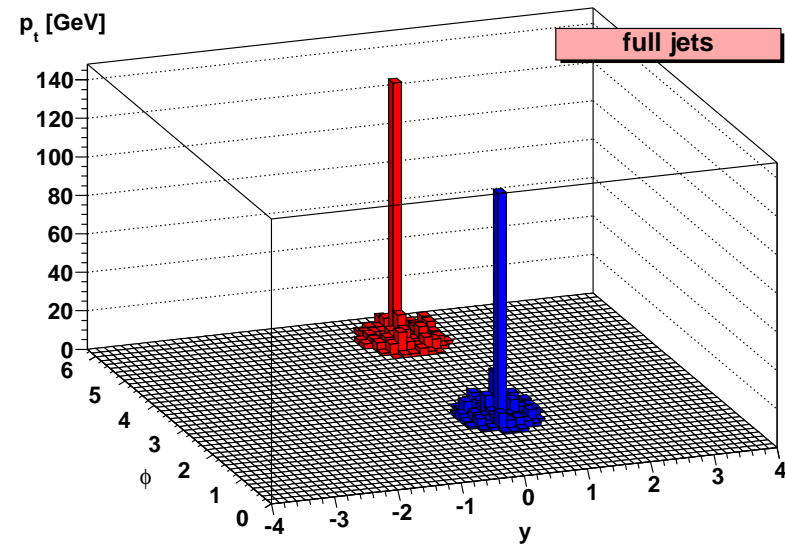
- Get the jets and apply subtraction in both cases ($R = 0.4$)
test different algs. and ρ -estimation ranges

Framework for study

Hard (Pythia) event



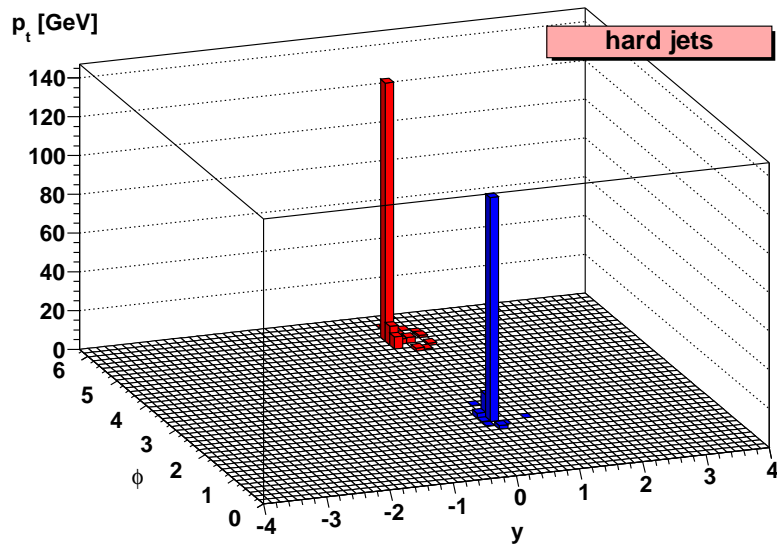
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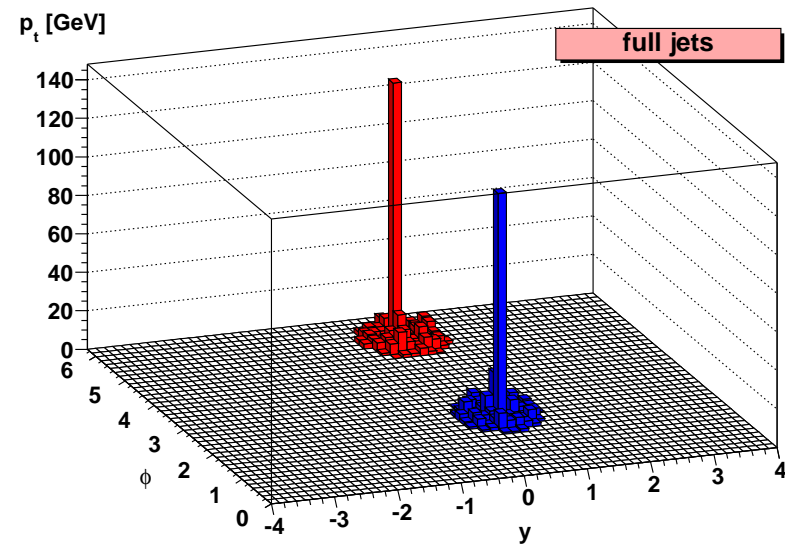
- Get the jets and apply subtraction in both cases ($R = 0.4$)
 - Match the 2 hardest jets
at least 50% of the hard contents recovered after embedding
- Efficiencies $\geq 95\%$

Framework for study

Hard (Pythia) event



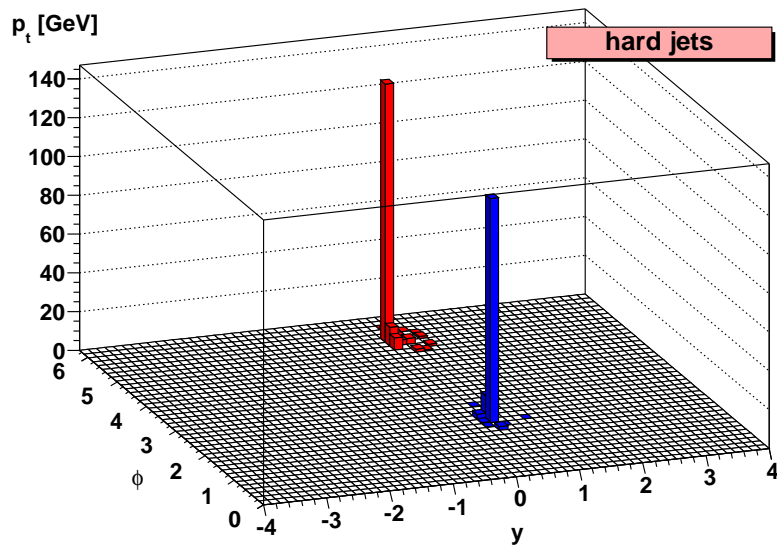
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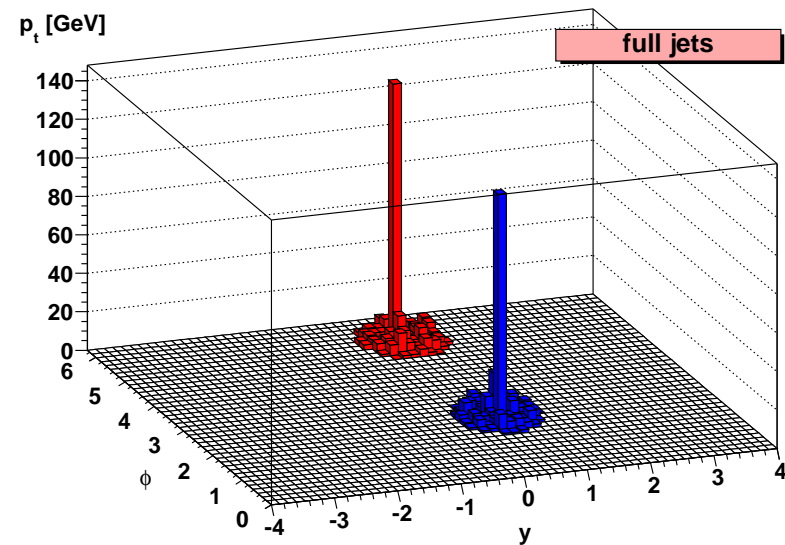
- Get the jets and apply subtraction in both cases ($R = 0.4$)
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- Subtraction quality: $\Delta p_t = p_t^{AA,sub} - p_t^{pp,sub}$
- Study $\langle \Delta p_t \rangle$ and $\sigma_{\Delta p_t}$

Framework for study

Hard (Pythia) event



... embedded in AA (Hydjet) event



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- Match the 2 hardest jets
- Subtraction quality: $\Delta p_t = p_t^{AA,sub} - p_t^{pp,sub}$
- Study $\langle \Delta p_t \rangle$ and $\sigma_{\Delta p_t}$
- Used: Pythia(v6.4), Hydjet(v1.6) + PyQuen(v1.5) + FastJet(v2.4.2)

Cross-check: Q-Pythia, Hydjet++

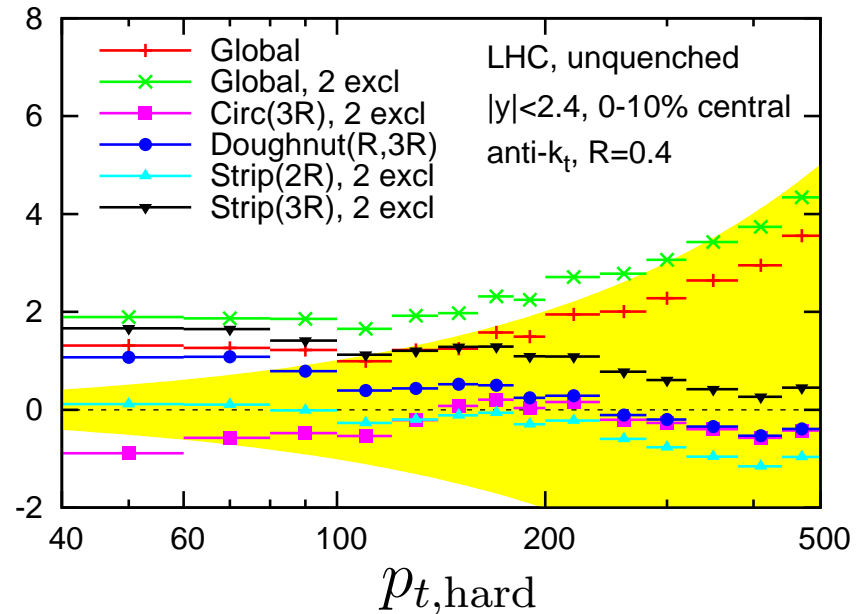
Effect of choosing a local range

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

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

$\langle \Delta p_t \rangle$



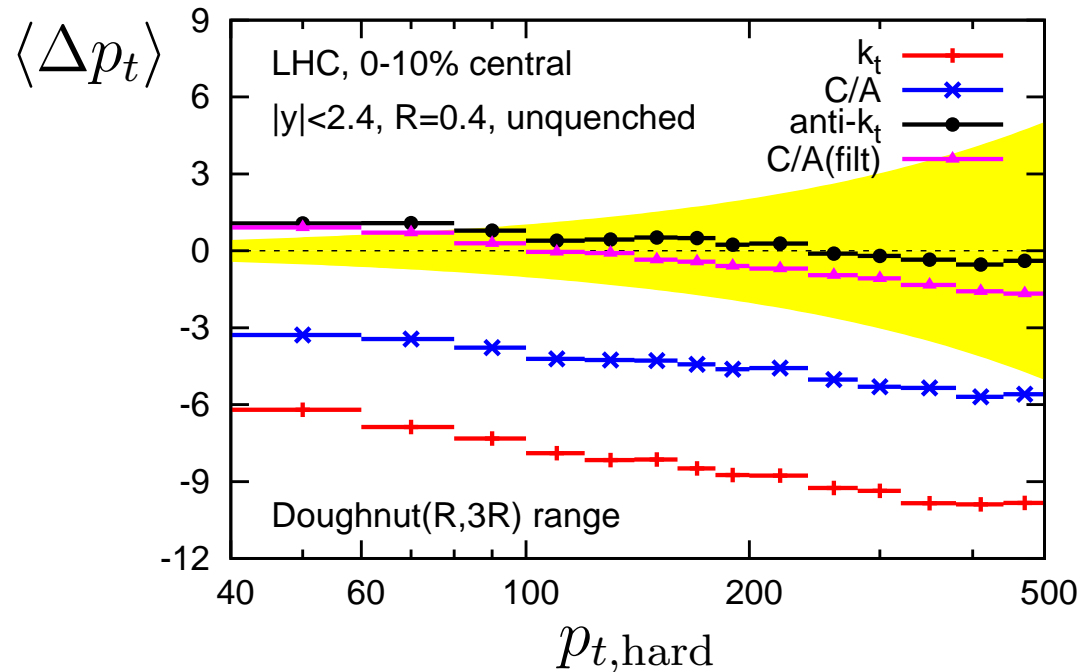
- rule of thumb: **at least 8 jets needed to estimate ρ**
- global range: OK with limited accept., worsen for larger
- different ranges \longrightarrow **estimate of the uncertainty**

Note for experts: Analytic estimate show that at least 8 jets

\Rightarrow less than 10% of $\sigma_{\Delta p_t}$ due to ρ misestimation

Differences between algorithms

- Average shift: preference for anti- k_t and C/A+filt^(*)



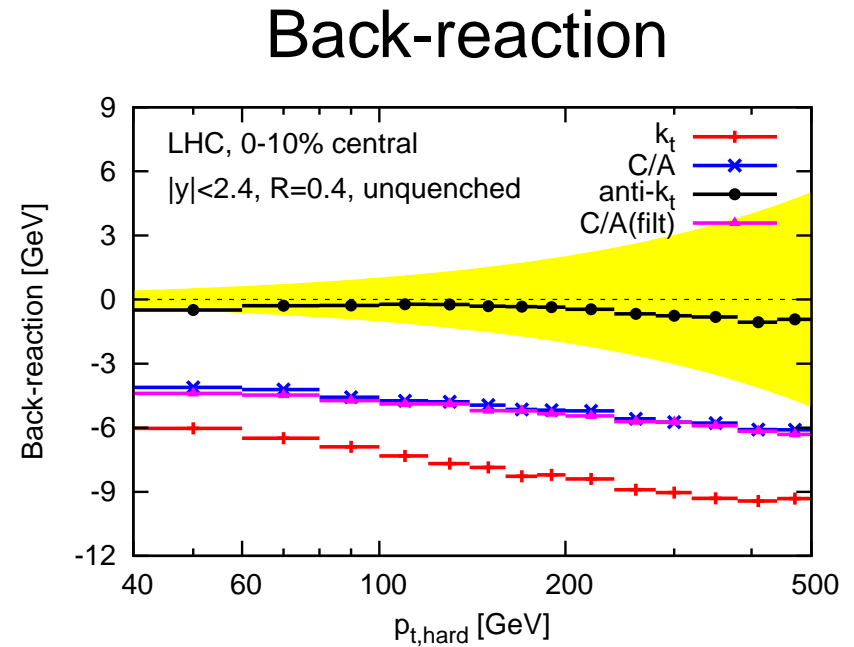
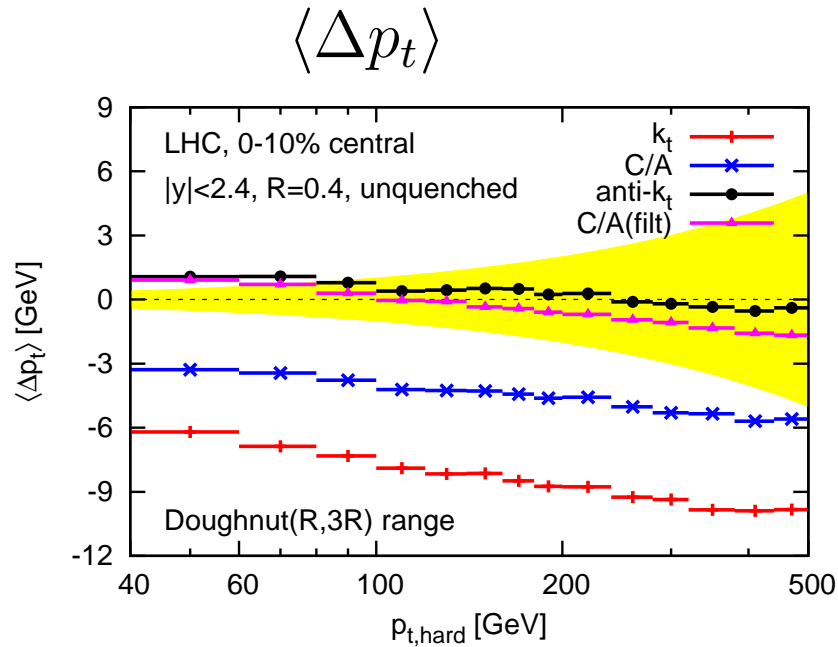
1-2 GeV precision for a contamination of ~ 150 GeV!

Notes for experts:

- C/A & k_t : offset due to *back-reaction*
- (*) C/A+filt: watch out: cancellation between back-reaction and filtering bias

Differences between algorithms

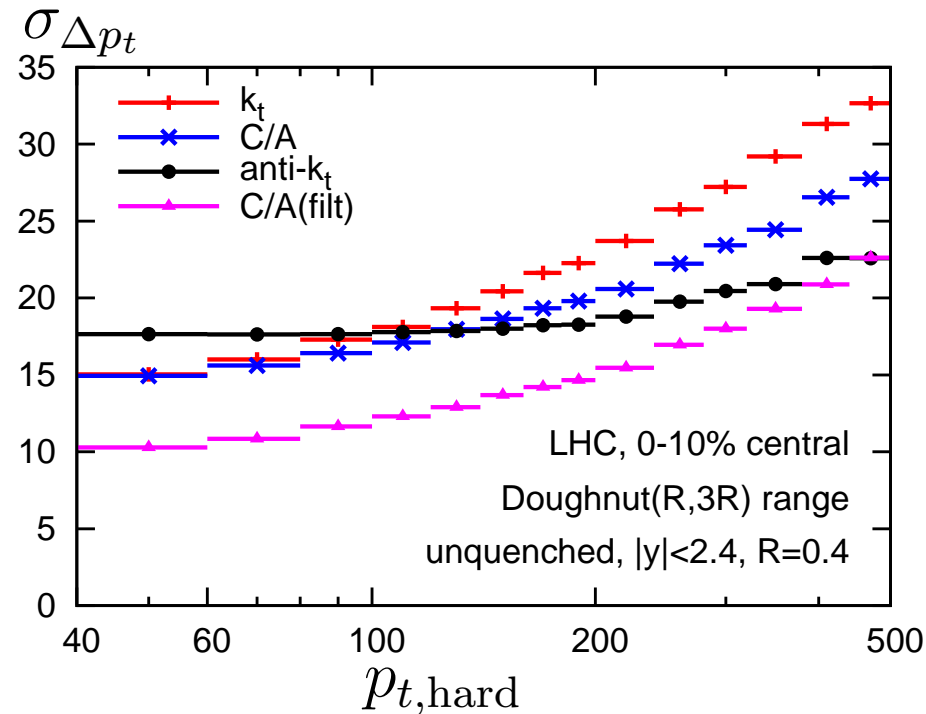
- Average shift: preference for anti- k_t and C/A+filt



- diff. between k_t , C/A and anti- k_t from back-reaction
- (fortuitous) cancellation with a filtering bias for C/A(filt)

Differences between algorithms

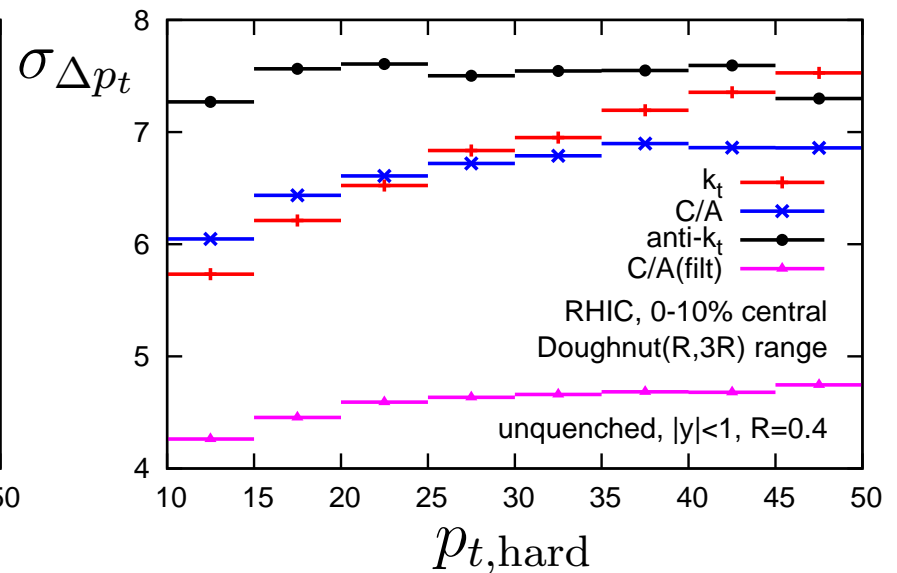
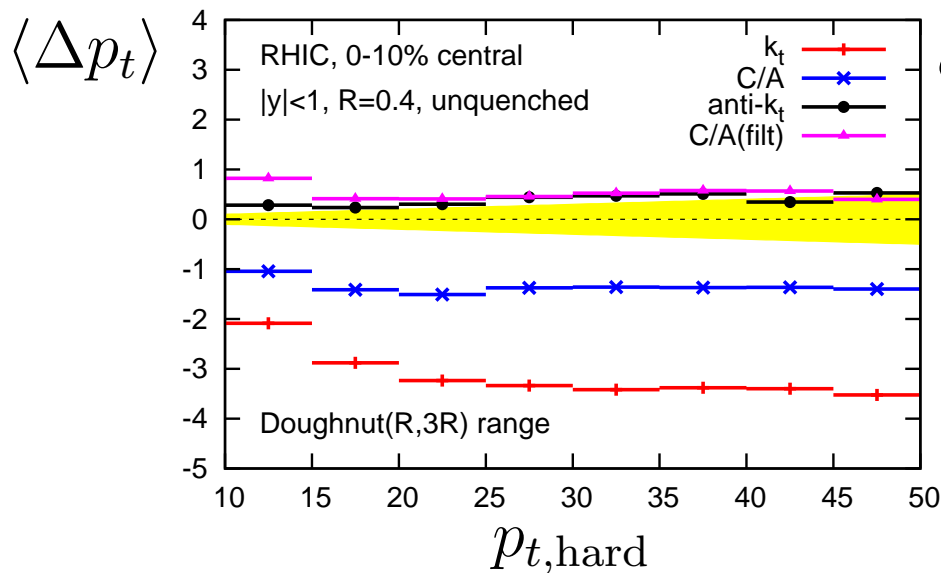
- Average shift: preference for anti- k_t and C/A+filt
- Dispersion: preference for C/A+filtering



$$A_{C/A+filt} \approx \frac{1}{2} A_{C/A} \quad \Rightarrow \quad \sigma_{\Delta p_t}^{(C/A+filt)} \approx \frac{1}{\sqrt{2}} \sigma_{\Delta p_t}^{(C/A)}$$

Differences between algorithms

- Average shift: preference for anti- k_t and C/A+filt
- Dispersion: preference for C/A+filtering
- Same conclusions for the RHIC



- No subtraction bias due to quenching (at most a 2% effect at the LHC)
- Valid for non-central collisions (smaller background but v_2)
(with a residual ϕ dependence!)

Example: inclusive jet cross-section

Original hard spectrum:

$$\frac{d\sigma^{pp}}{dp_t} = \lambda\sigma_0 e^{-\lambda p_t}$$

In the background, after subtraction

$$\begin{aligned} \frac{d\sigma^{AA,\text{sub}}}{dp_t} &= \frac{d\sigma^{pp}}{dp_t} \otimes \text{Gaussian}(\langle\Delta p_t\rangle, \sigma_{\Delta p_t}) \\ &= \frac{d\sigma^{pp}}{dp_t} \exp\left(\lambda\langle\Delta p_t\rangle + \frac{\lambda^2\sigma_{\Delta p_t}^2}{2}\right) \end{aligned}$$

In practice, we have $\lambda \approx 0.3 \text{ GeV}^{-1}$ for RHIC, 0.05 for the LHC

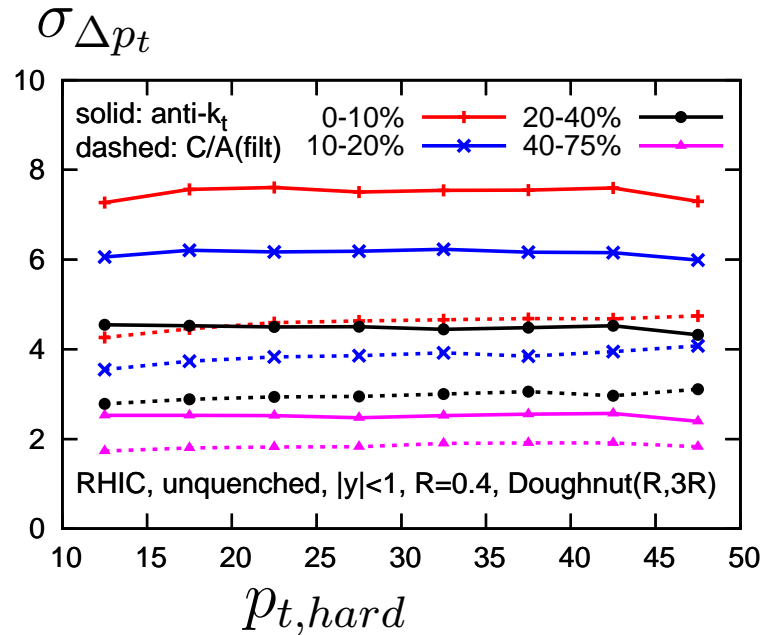
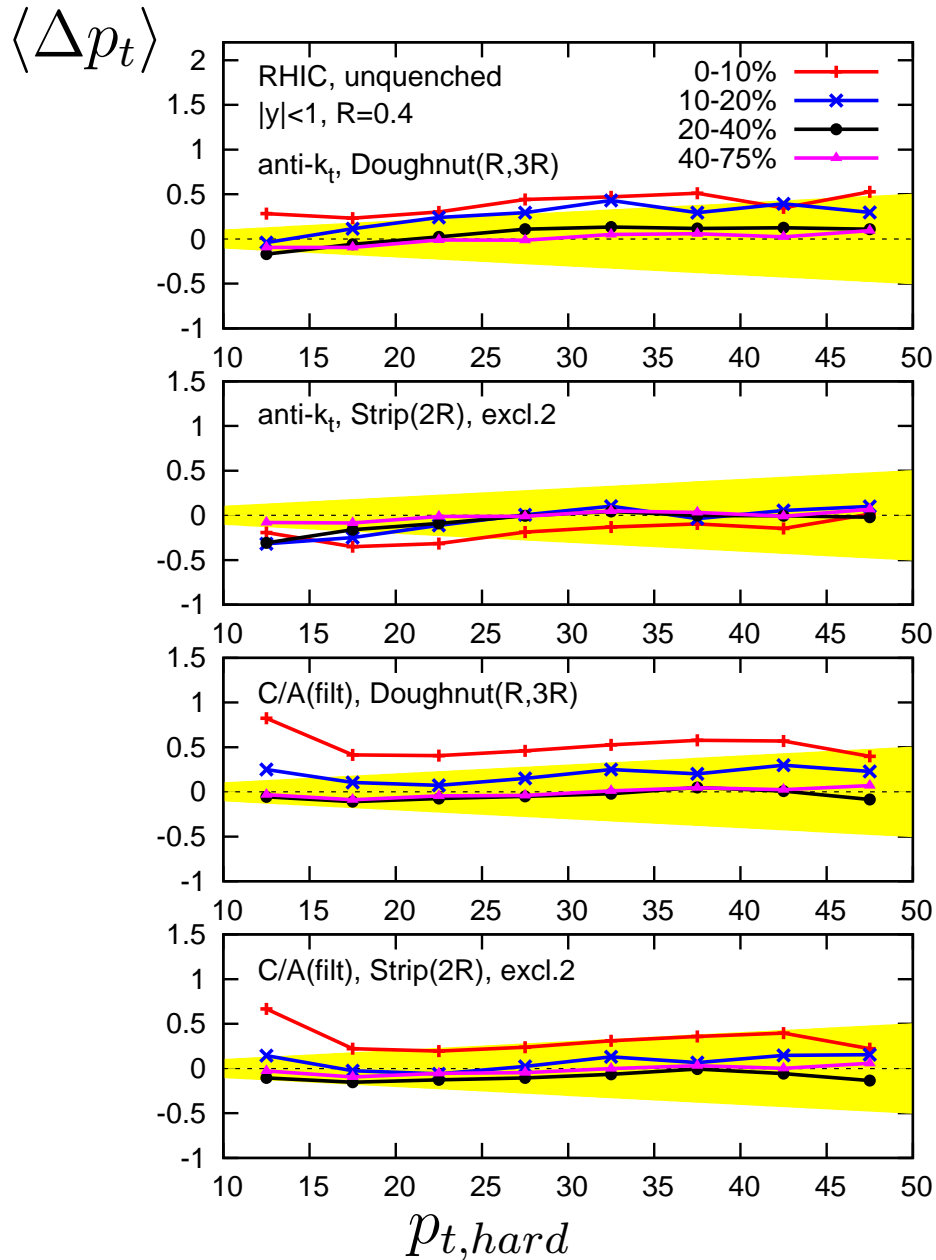
	RHIC			LHC		
	$\langle\Delta p_t\rangle$	$\sigma_{\Delta p_t}$	$\frac{d\sigma^{AA,\text{sub}}/dp_t}{d\sigma^{pp}/dp_t}$	$\langle\Delta p_t\rangle$	$\sigma_{\Delta p_t}$	$\frac{d\sigma^{AA,\text{sub}}/dp_t}{d\sigma^{pp}/dp_t}$
$R = 0.4$						
anti- k_t	0	7.5	12	0	18	1.5
C/A+filt	0	4.8	3	0	13	1.2

Summary

- **The recipe:** $p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{bkg}} A_{\text{jet}}$
 - Define a **jet**: use an IRC-safe one
 - Define the **area** of a jet: ghost-based active area
 - Obtain ρ_{bkg} , the **background p_t density** per unit area: median of $\{p_{t,j}/A_j\}$
- **New hints:**
 1. Use **filtering**: reduce sensitivity to background (smaller $\sigma_{\Delta p_t}$)
 2. Use **local ranges**:
handle non-uniform backgrounds (+ estimate subtraction error)
- **Efficiency:**
 - At least ≈ 8 jets in a local range
 - anti- k_t and C/A+filt give $\langle \Delta p_t \rangle \approx 0$ ($\langle \Delta p_t \rangle / p_t \lesssim 1\%$)
 - C/A+filt has reduced $\sigma_{\Delta p_t}$ (helps unfolding especially at RHIC)

Further investigation

Centrality dependence

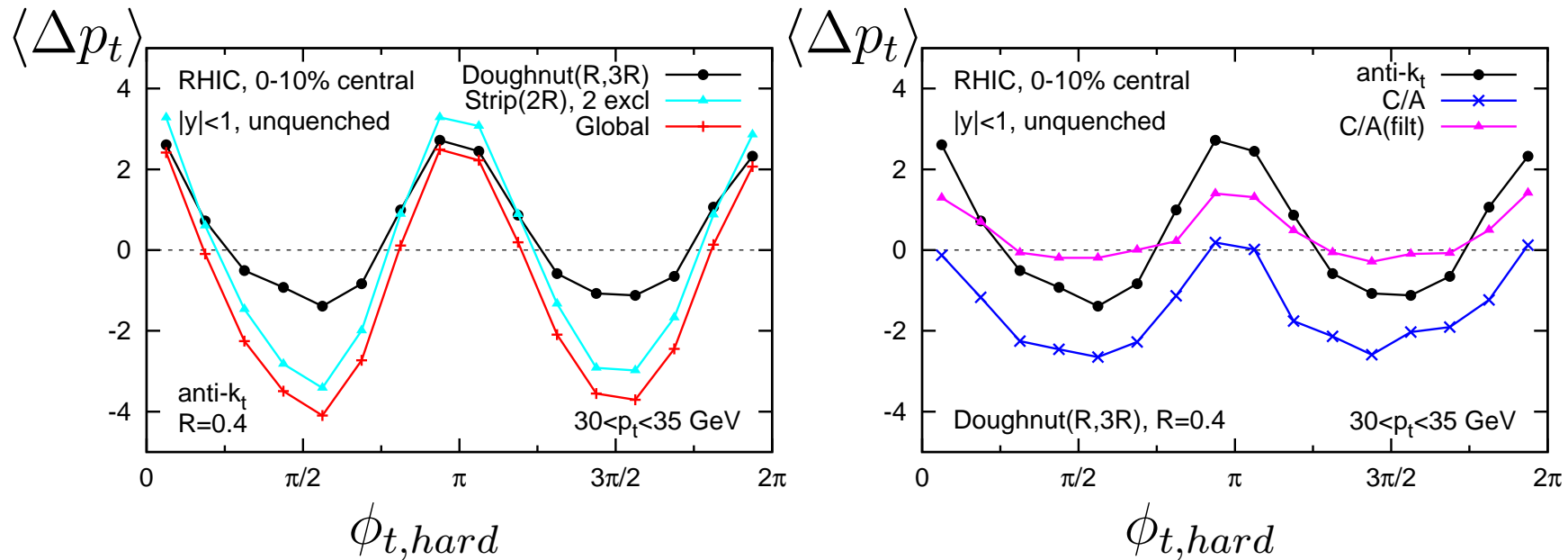


● $\langle \Delta p_t \rangle \approx 0$

● $\sigma \Delta p_t$ decreases with centrality

Centrality dependence (2)

Look at $\langle \Delta p_t \rangle$ as a function of ϕ (wrt. reaction plane)



- the Doughnut range has less variations (less ϕ averaging!)
- C/A+filt has less variations (reduced area/dispersion)

Issue: background fluctuations may “mimic” a hard jet without a “real hard origin”

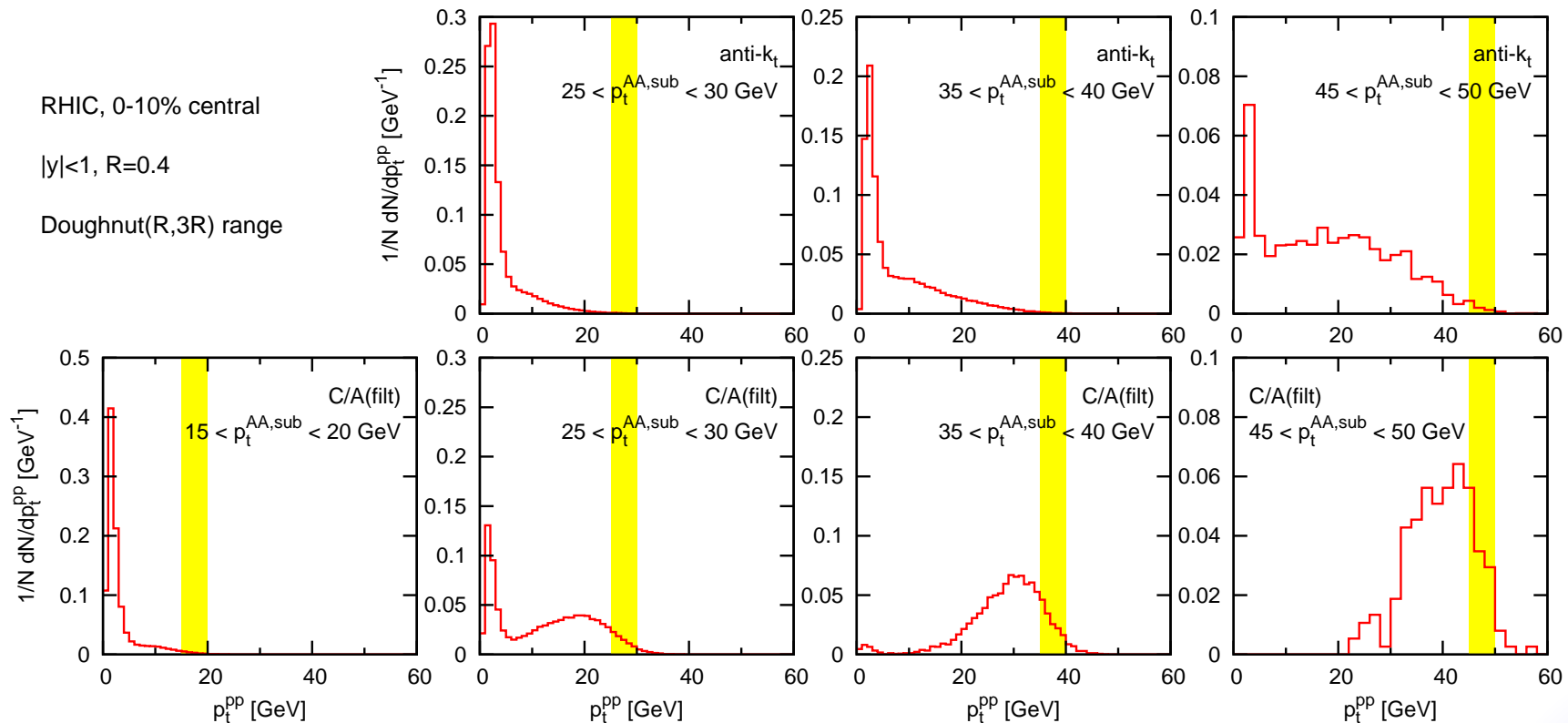
- separation hard/soft is unclear/model-dependent
- there is a large number of semi-hard jets

⇒ the question is more: “if we observe a jet with a given reconstructed p_t , is the original semi-hard jet softish or close to p_t ?”

- Inclusive spectrum: fakes → unfolding
- Exclusive (e.g. Dijets): hard-soft separation clearer

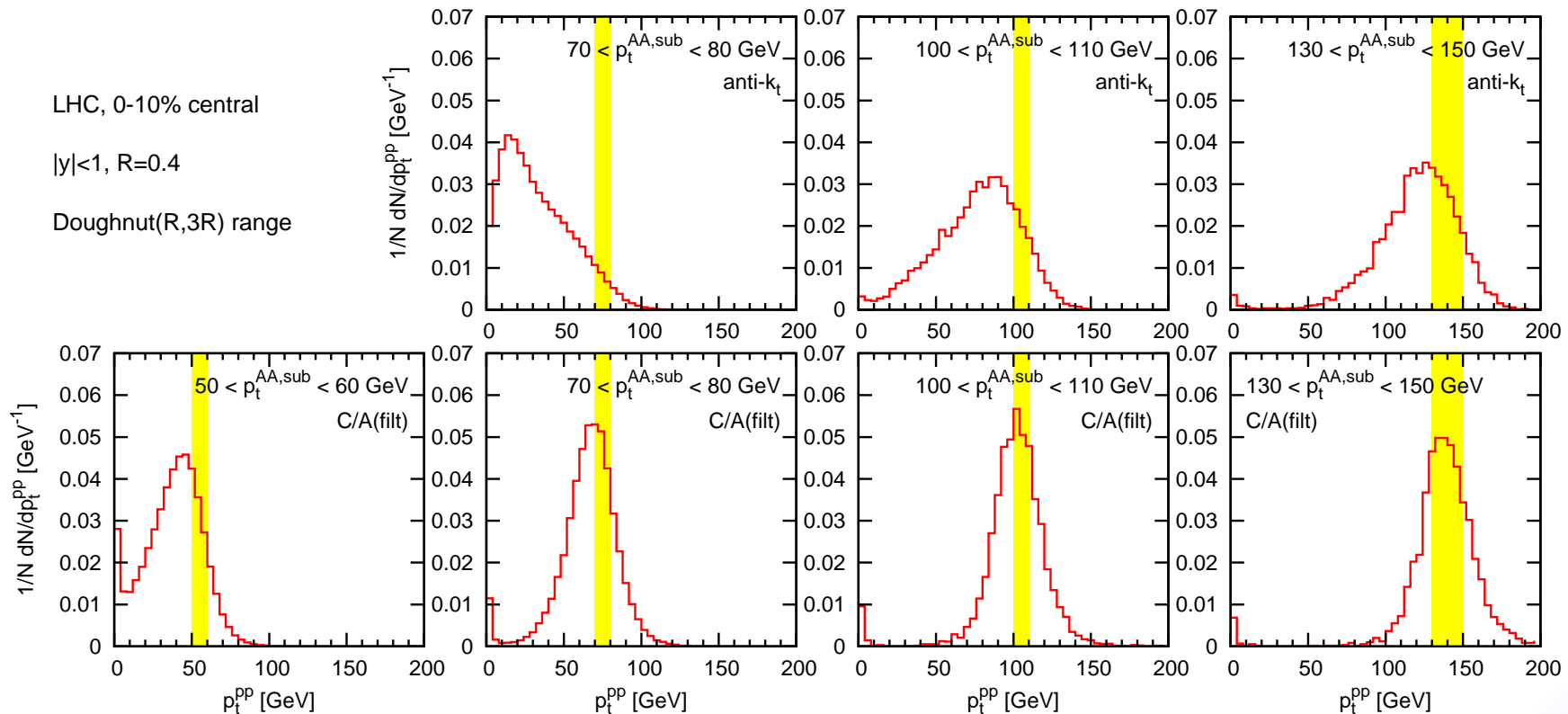
Fakes – origin (RHIC)

- HYDJET: HYDRO + many semi-hard pp event
- take each of the of the full (subtracted) jets
- find the corresponding semi-hard pp jet



Fakes – origin (LHC)

- HYDJET: HYDRO + many semi-hard pp event
- take each of the of the full (subtracted) jets
- find the corresponding semi-hard pp jet

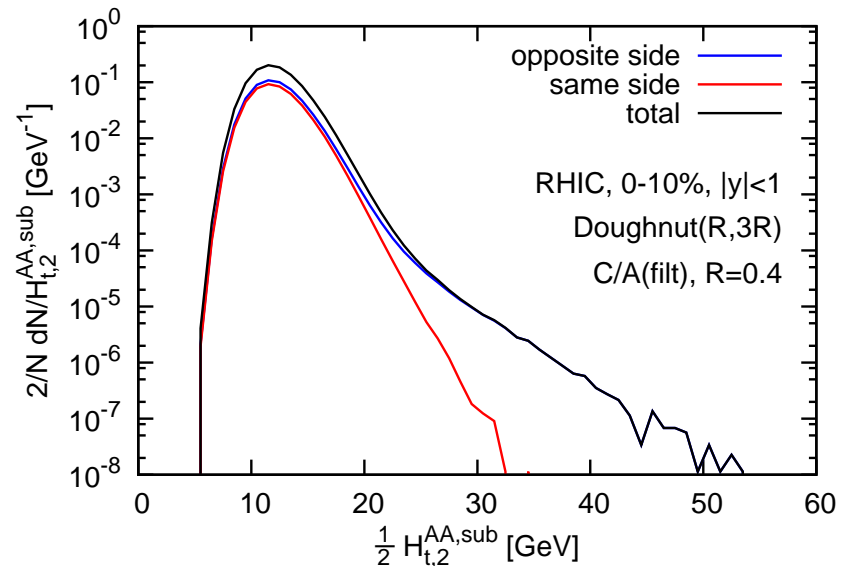
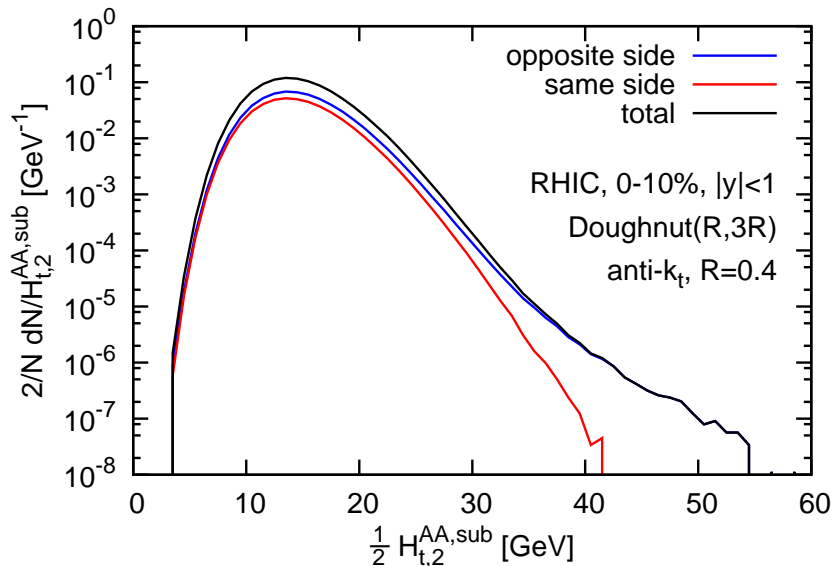


Fakes – dijet case (RHIC)

- Take the 2 hardest jets in a HYDJET event

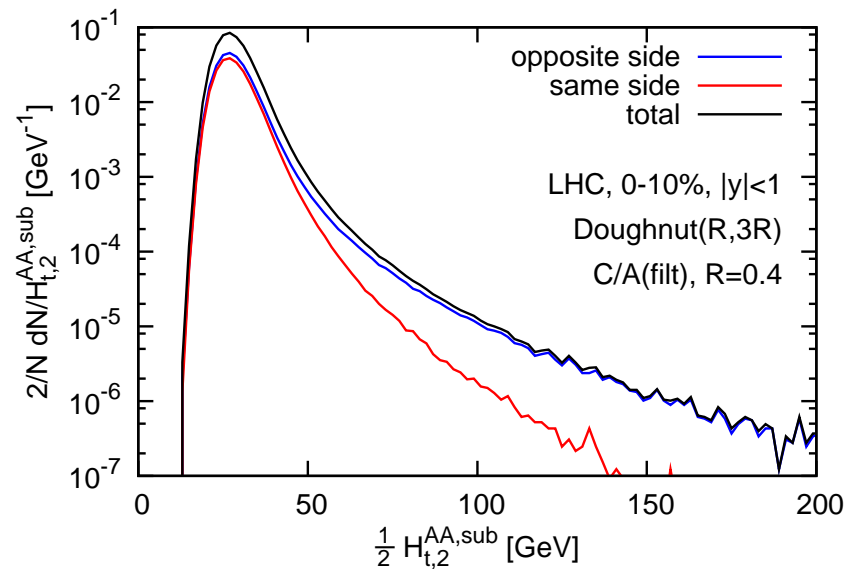
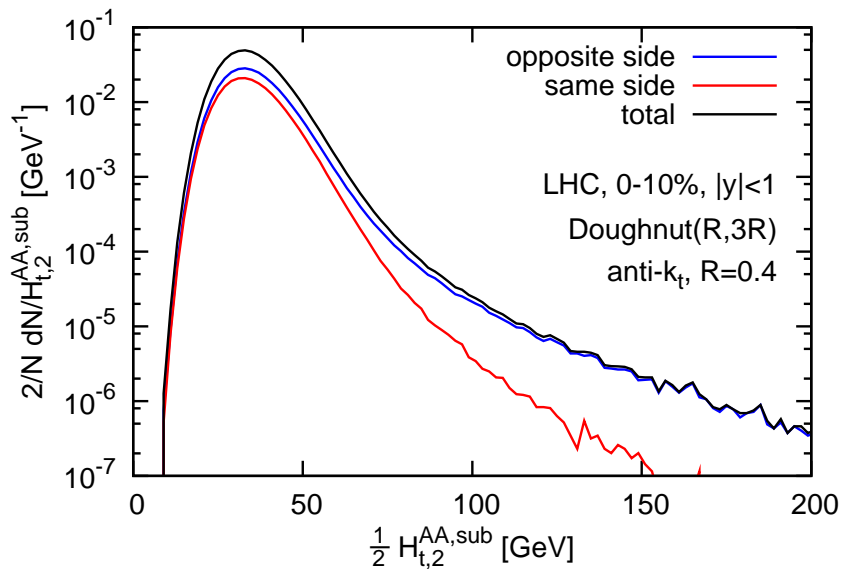
$$H_{T,2} = p_{t,1}^{AA,sub} + p_{t,2}^{AA,sub}$$

- split into same-side and opposite-side
- data-driven estimate of “fakes”



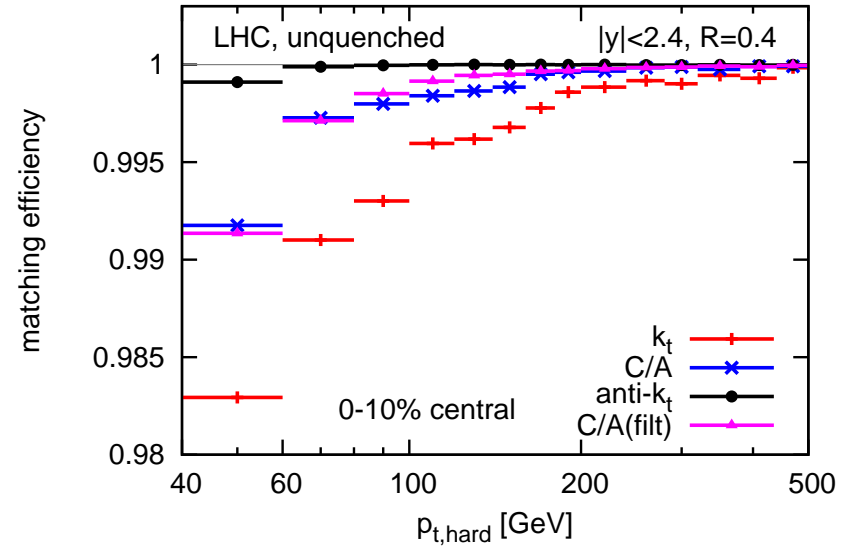
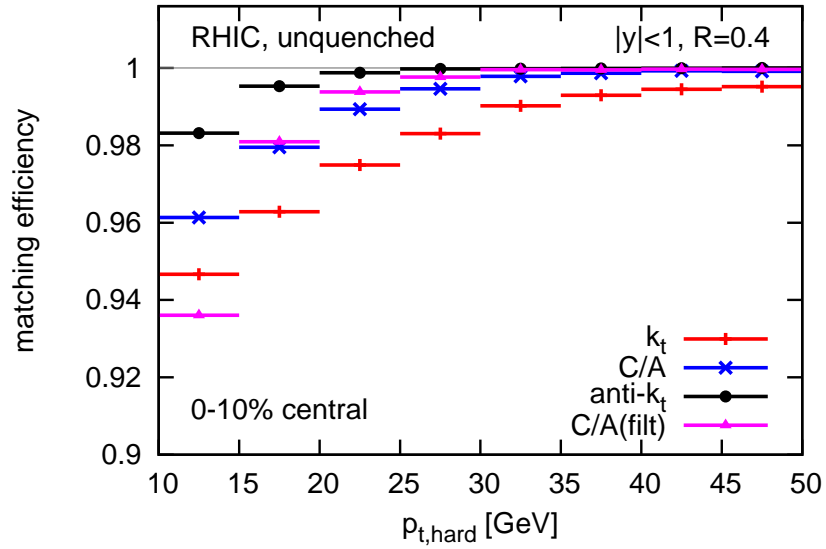
Fakes – dijet case (LHC)

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- data-driven estimate of “fakes”

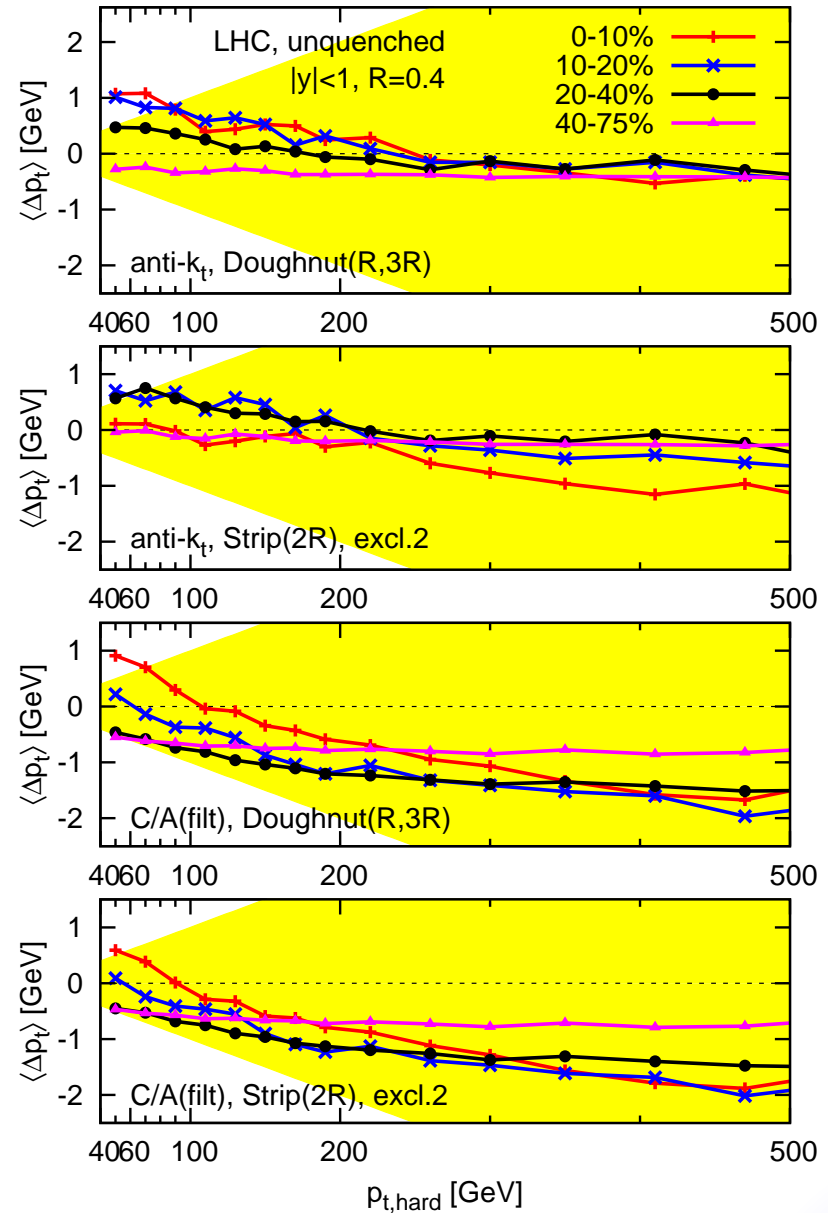
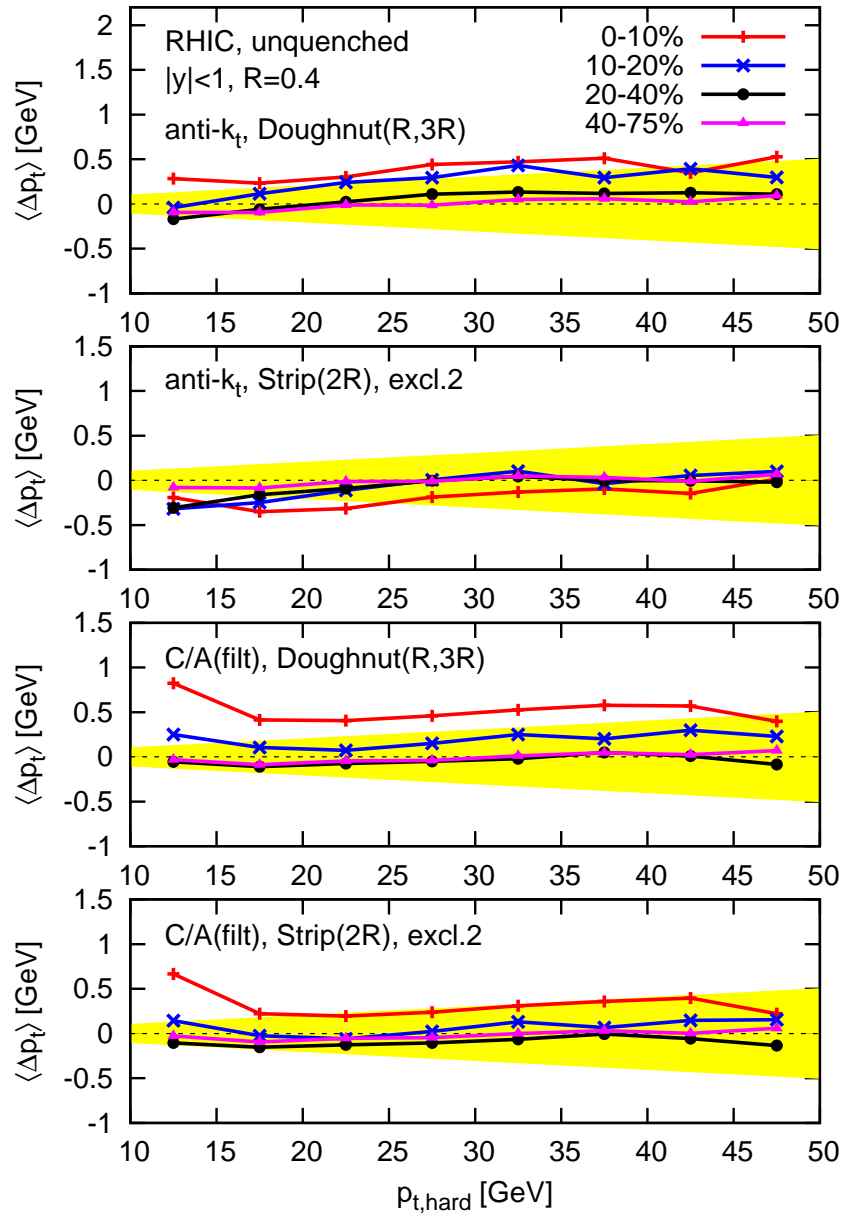


Backup slides

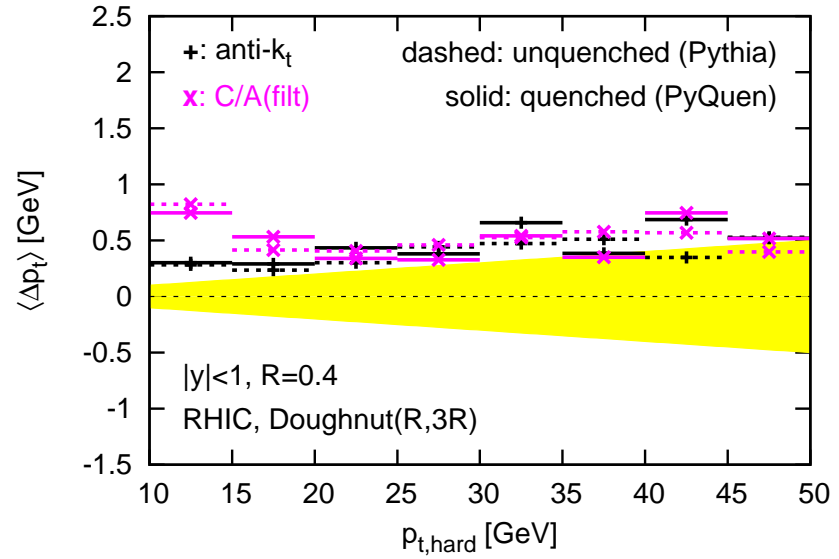
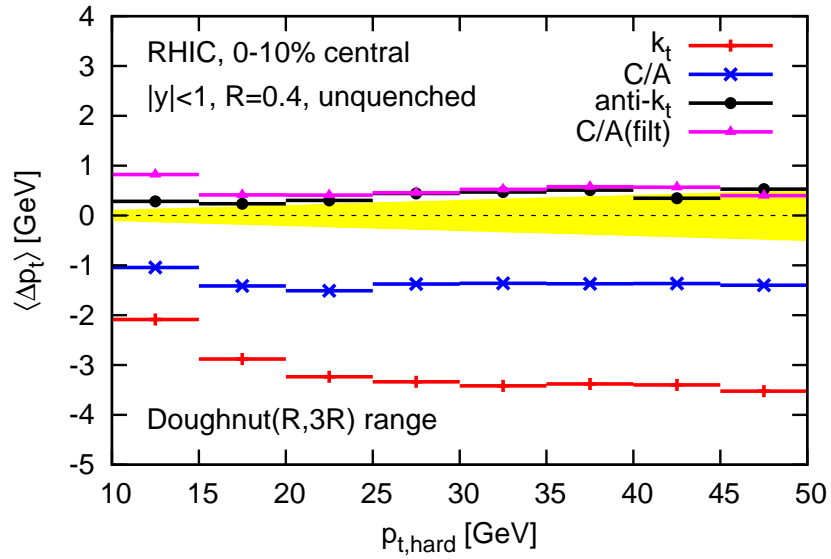
Efficiency



Centrality dependence: LHC



Quenching effects - RHIC



Quenching effects - LHC

