Jet Modification in the RHIC and LHC Era
Wayne State University
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Jet Reconstruction Algorithms in HI Environment

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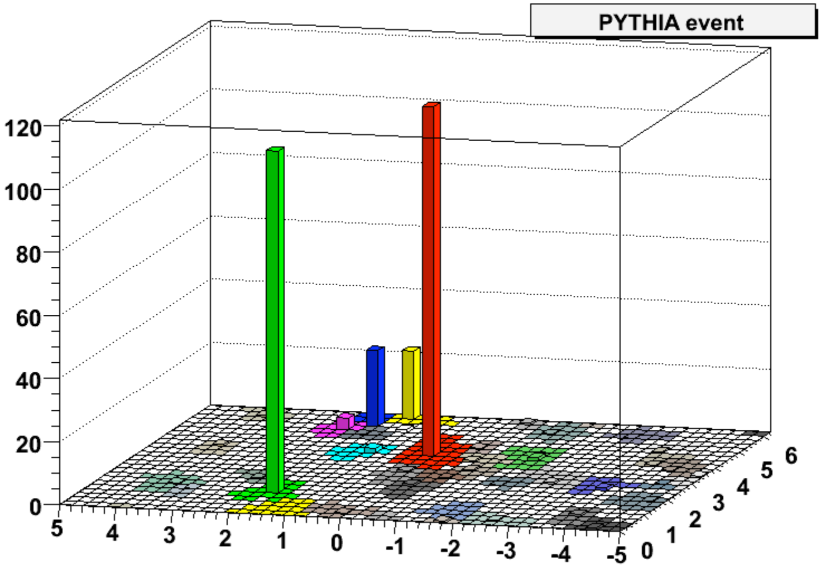
In collaboration with G. Salam and G. Soyez,
with contributions from P. Quiroga and J. Rojo

Outline

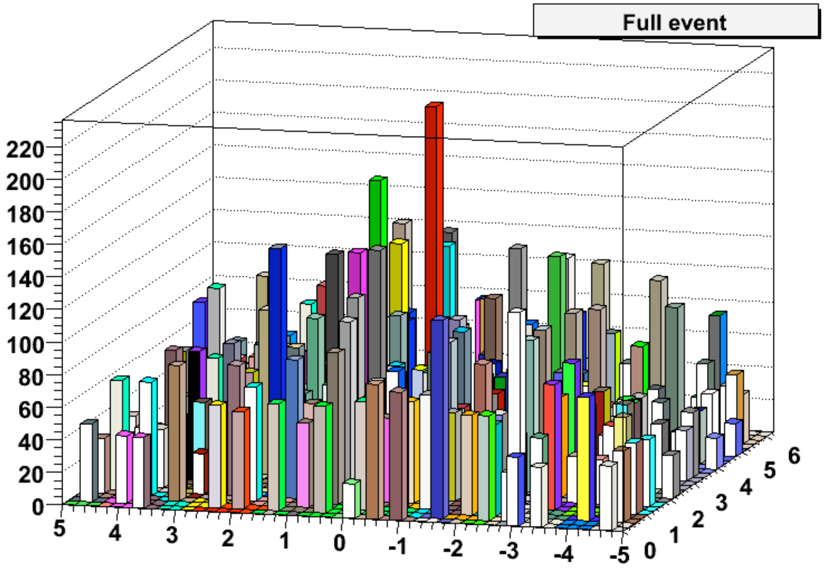
- Background and jet reconstruction
- A new approach to jet fragmentation functions?

Hard jets and background



Hard jets

(pp collisions)



Hard jets + background

(AA collisions)

- In pp collisions, the background is a small correction. In heavy ions, it is overwhelming.
- It makes sense to consider background subtraction together with jet clustering: both are needed to ***reconstruct*** the jets
- As such, the same desiderata can apply: standard algorithms, well defined, with known behaviour, and well tested

Experimental progress

- Impressive experimental progress in the past couple of years, as we have gone from "observation" of jets in heavy ions to a long list of detailed analyses and measurements, both at the level of jet observables and of the background
- Can't even begin reviewing the complex details of all analyses. This talk is rather a 'naive' list of aspects that are possibly common to various techniques
- As precision of measurements improves, it may become desirable to have a set of predetermined 'reconstruction procedures', in the same way we have a set of clustering algorithms, so as to properly evaluate them and also communicate and compare results more easily

Effect of background

background characteristics

(momentum density, fluctuations, flow, ...)

This step usually very experiment-specific. While detector characteristics certainly play a fundamental role here, it may be worth standardizing some components related to the background

effect on jet reconstruction

(energy scale, resolution)

I'll say something on jet fragmentation functions, and we have work in progress on jet shapes. But this should really be another talk

effect on specific observable

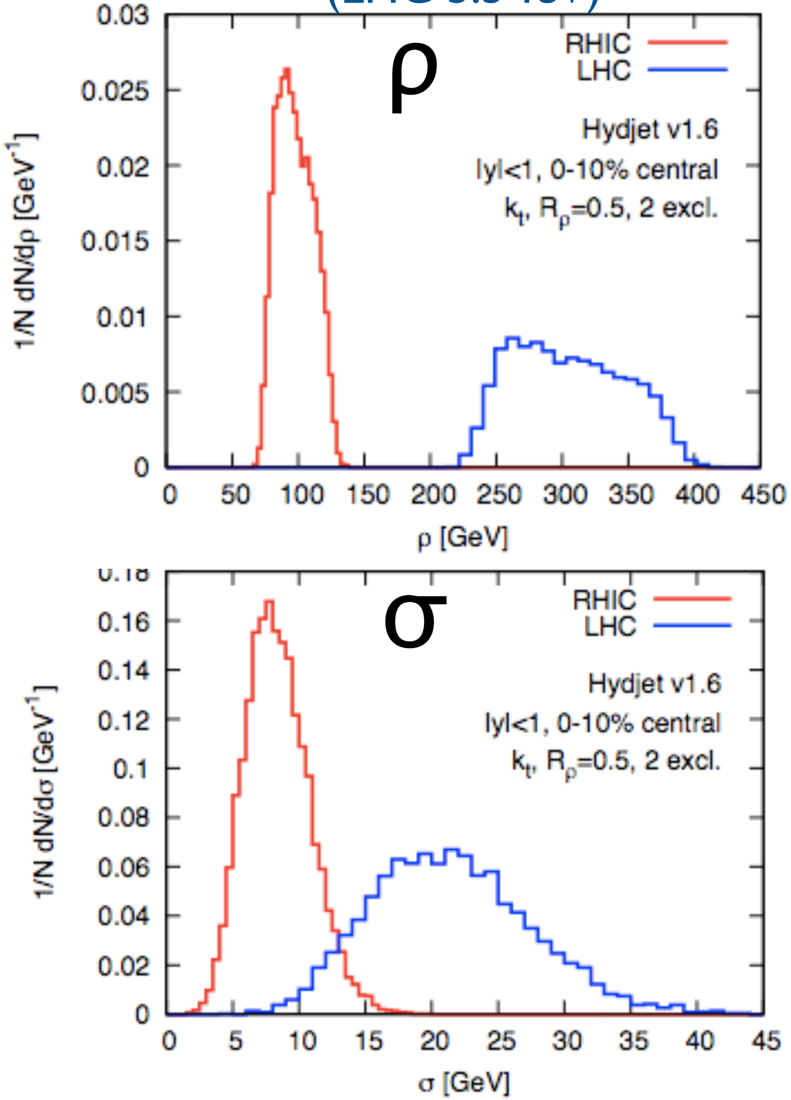
(jet fragmentation functions, jet shape, ...)

The background

Usefully characterized by its transverse momentum per unit area (ρ) and its fluctuations in a single event (σ)

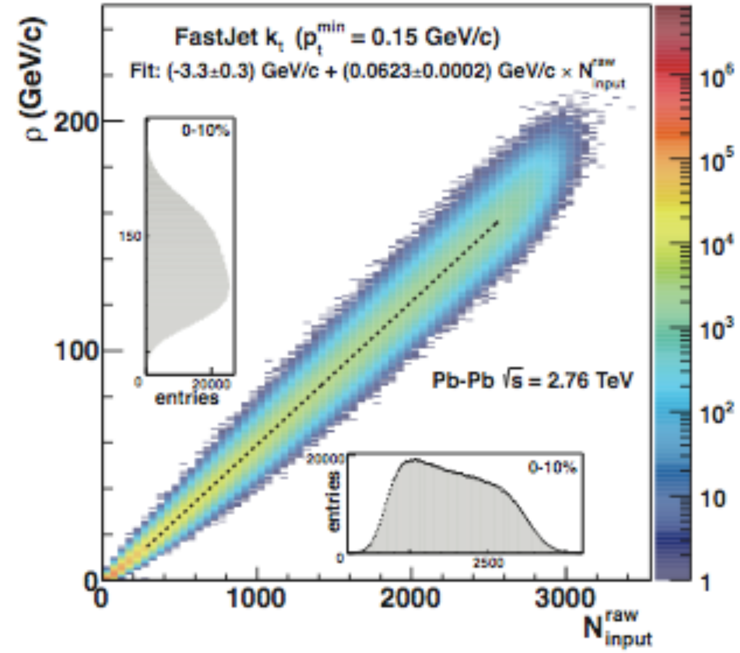
HYDJET simulations

(LHC 5.5 TeV)



ρ from ALICE data

(LHC 2.76 TeV, charged only)



Hard jets and background

How is a pp jet's p_t modified by the HI background?

$$p_t^{AA} - p_t^{pp} =$$

$$= \boxed{\rho A \pm (\sigma\sqrt{A} + \xcancel{\sigma_\rho A} + \xcancel{\rho\sqrt{\langle A^2\rangle - \langle A\rangle^2}})}$$

Background momentum density (per unit area)

jet area

background fluctuations

'susceptibility'

(background contamination, gain of **UE** particles)

$$+ \boxed{\Delta p_t^{BR} \pm \sigma^{BR}}$$

'resiliency'

(backreaction, gain or loss of **hard** particles)

event-by-event and jet-by-jet background determination and subtraction will eliminate these two contributions to dispersion

Jet reconstruction techniques

- ALICE
- ATLAS
- CMS
- review of generic reconstruction results

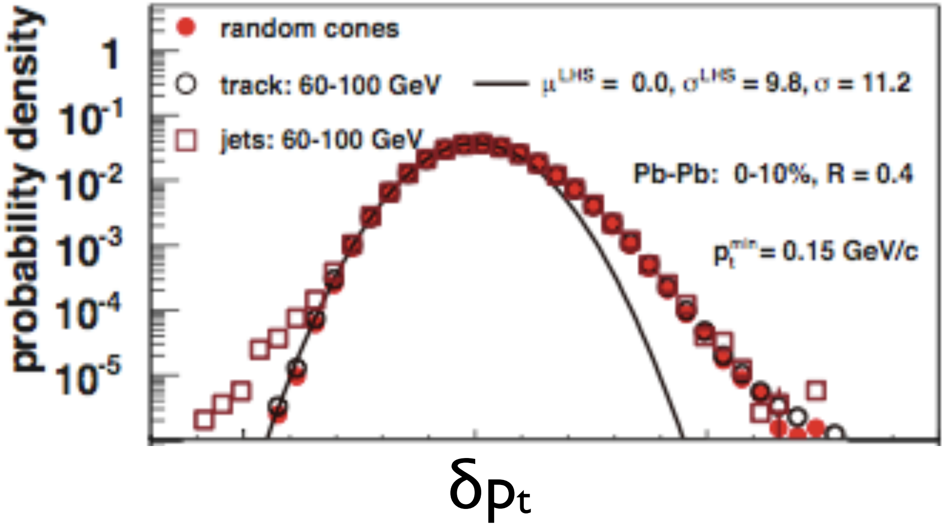
ALICE subtraction

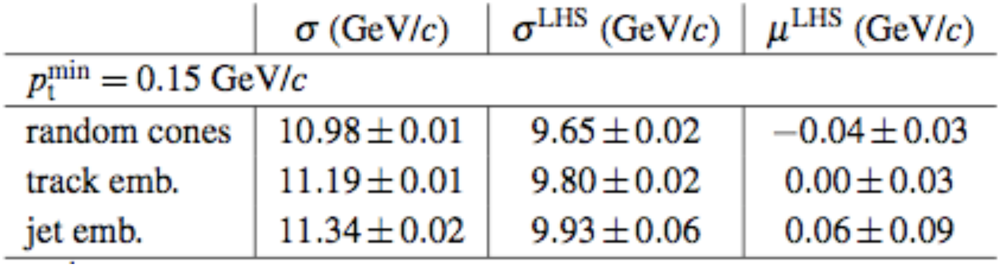
arXiv:1201.2423

1. Consider tracks in $|\eta| < 0.9$ and $p_t > 0.15$ GeV. Construct both anti-k_t and k_t jets out of them.

2. Determine background density ρ using $\rho \equiv \underset{k_t\ jets\ \in\ |\eta| < 0.5}{\mathrm{median}} \left[\left\{ \frac{p_t^{jet}}{\mathrm{Area}_{jet}} \right\} \right]$

3. Subtract background from anti-k_t jets according to $p_t^{jet} = p_t^{jet,rec} - \rho A^{jet,rec}$





	σ (GeV/c)	σ^{LHS} (GeV/c)	μ^{LHS} (GeV/c)
$p_t^{min} = 0.15$ GeV/c			
random cones	10.98 ± 0.01	9.65 ± 0.02	-0.04 ± 0.03
track emb.	11.19 ± 0.01	9.80 ± 0.02	0.00 ± 0.03
jet emb.	11.34 ± 0.02	9.93 ± 0.06	0.06 ± 0.09

ATLAS subtraction

arXiv:1208.1967 and ATLAS-CONF-2012-045

1. First step: estimate UE density in 0.1-wide pseudorapidity strips, excluding towers belonging to 'seed jets' (seed jet = anti-kt R=0.2 jets containing at least a tower with $E_T > 3$ GeV and having a ratio $E_T^{max}/\langle E_T \rangle > 4$)

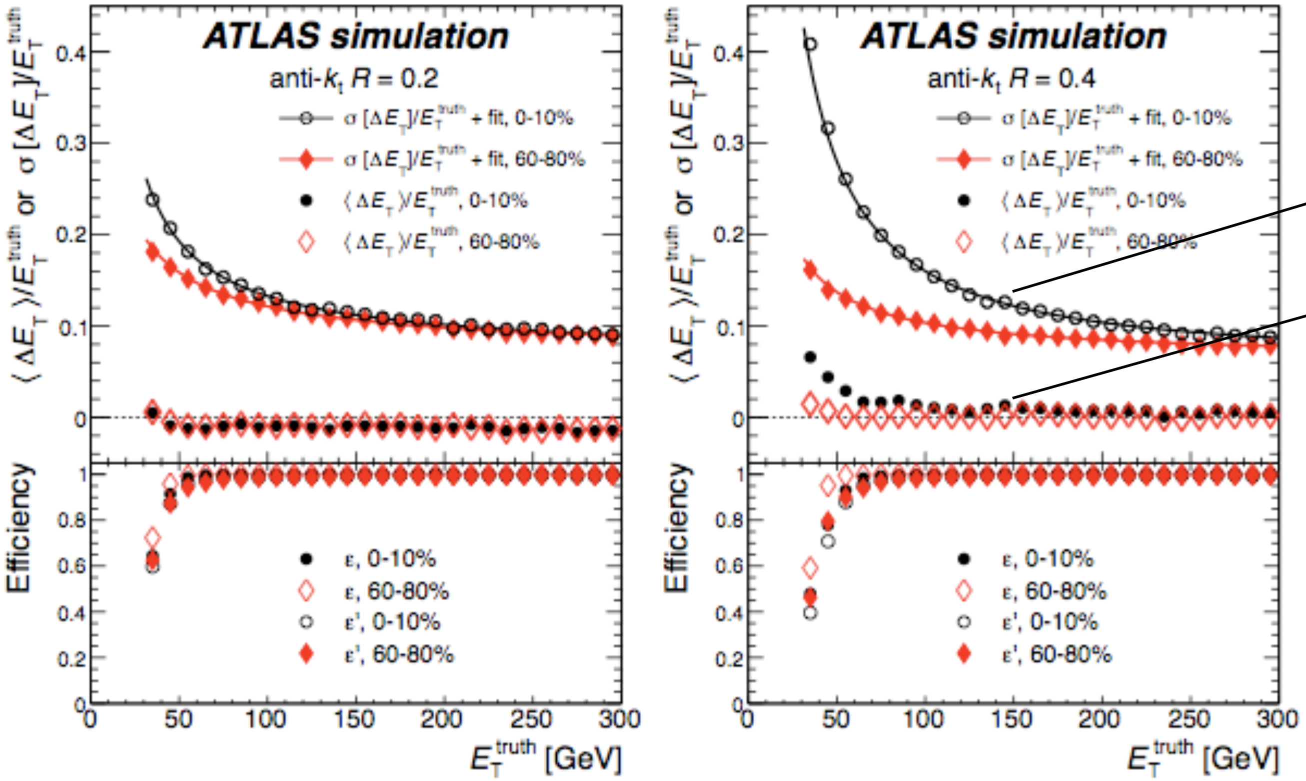
2. Subtract cells according to $E_{\mathrm{T}\,j}^{\mathrm{sub}} = E_{\mathrm{T}\,j} - A_j\;\rho_i(\eta_j)\left(1 + 2v_{2i}\cos\left[2\left(\phi_j - \Psi_2\right)\right]\right)$ (this accounts for modulation due to flow). Obtain R=0.2 jets with subtracted values

3. Second step: define a new set of seed jets, combination of previous ones with $E_T > 25$ GeV and track jets (constructed from tracks with $p_T^{track} > 4$ GeV) with $p_T > 10$ GeV. Recalculate UE (ρ and v_2) excluding cells within $\Delta R < 0.4$ of the new seed jets

4. Subtract the original cell energies, using the new determination of the UE

5. Recalculate the jets

ATLAS subtraction



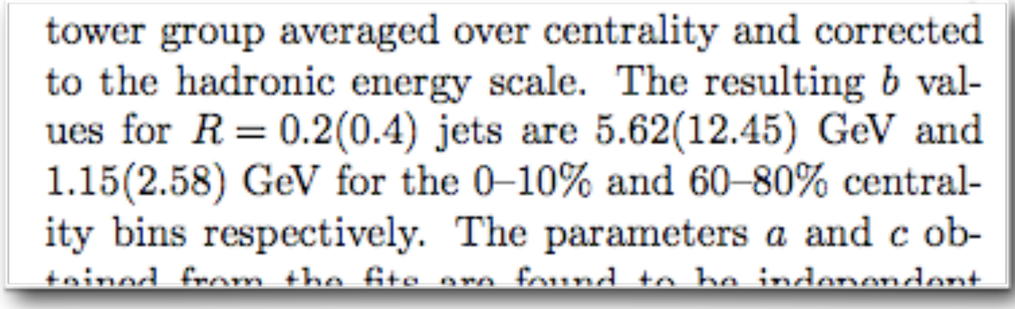
resolution

ΔE_T bias

$$\frac{\sigma[\Delta E_T]}{E_T^{truth}} = \frac{a}{\sqrt{E_T^{truth}}} \oplus \frac{b}{E_T^{truth}} \oplus c$$

calorimeter

background fluctuations

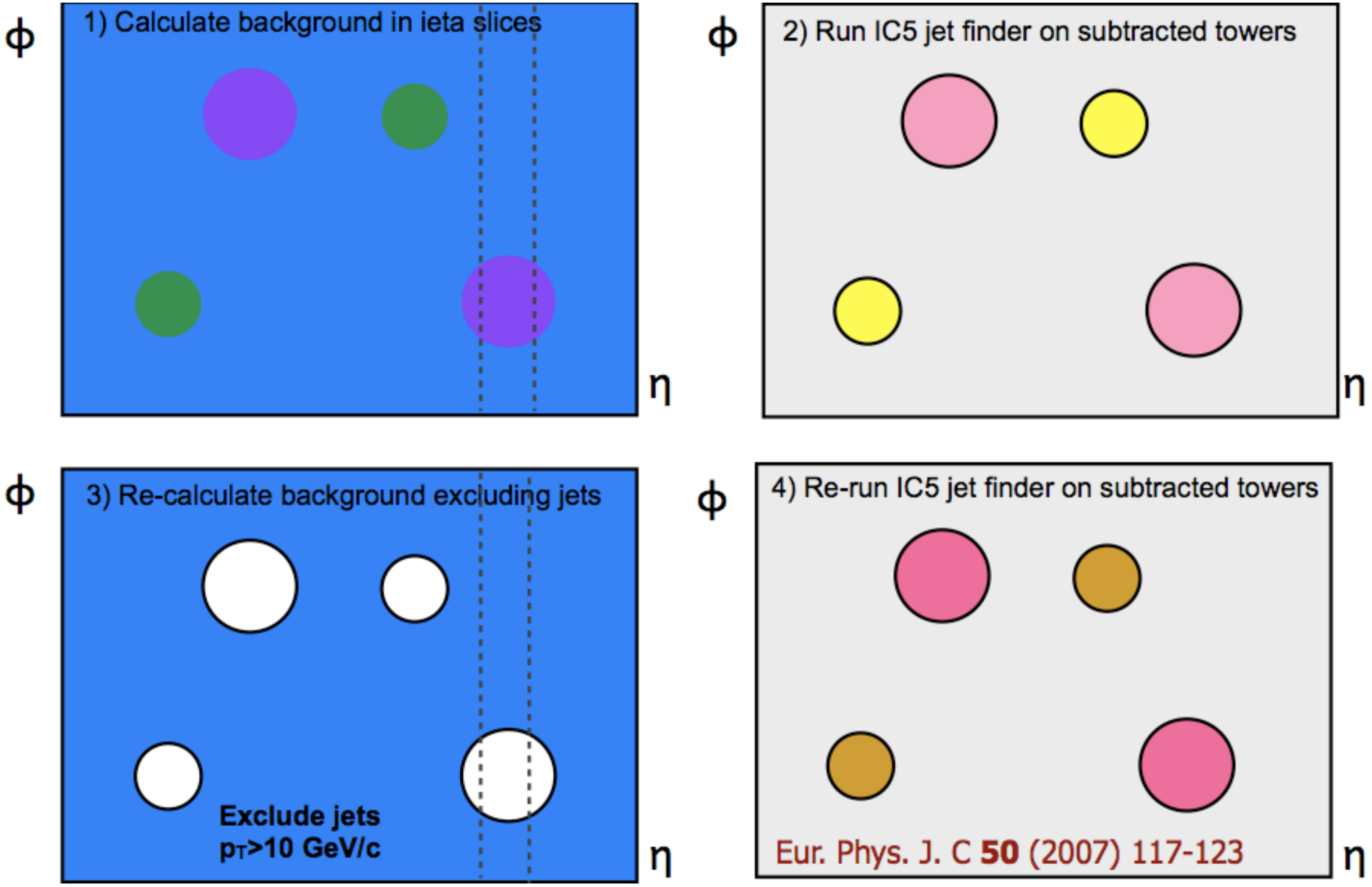

tower group averaged over centrality and corrected to the hadronic energy scale. The resulting b values for $R = 0.2(0.4)$ jets are 5.62(12.45) GeV and 1.15(2.58) GeV for the 0–10% and 60–80% centrality bins respectively. The parameters a and c obtained from the fits are found to be independent

CMS subtraction

Iterative Cone Subtraction

O. Kodolova et al. EPJC 50 (2007) 117

Has also been adapted to be used with anti-k_t



Eur. Phys. J. C **50** (2007) 117-123

This algorithm contains **noise reduction**: only towers with a positive p_t after subtracting average background + σ are retained

Iterative Cone Subtraction bias

Smaller fluctuations:

MC, Salam, Soyez, 1101.2878

$$\sigma_{\rm jet}^{\rm noise-suppressed} \simeq 0.262\,\sigma_{\rm tower}\sqrt{N_{\rm tower}}$$

at the price of a potential bias on the jet p_t:

$$\langle \delta p_{t,\rm jet}^{\rm overall}\rangle = \langle \delta p_{t,\rm jet}^{\rm noise}\rangle + \langle \delta p_{t,\rm jet}^{\rm hard}\rangle \simeq (0.0833 - f) N_{\rm tower}\sigma_{\rm tower}$$

Only positive background fluctuations are kept

Each active tower oversubtracted by 1 sigma

$f \approx 0.1$ is the tower occupancy fraction of a hard perturbative jet with R=0.5
⇒ **large cancellation**

What happens to *f* in case of quenching?

If the occupancy is very different, an offset bias may ensue

Jet reconstruction

HYDJET **simulations**		ρ (GeV) (y=0, 0-10%)	σ (GeV)	σ_ρ (GeV)	σ_{jet} (GeV) (anti-k_t, R=0.4)
RHIC		100	8	14	
LHC 5.5 TeV		310	20	45	18
LHC 2.76 TeV	all	250	**18**	36	**16**
	charged only	147	**12.5**	22	**11.3**

[where relevant, for jets of p_t = 100 GeV]

- No calorimeter simulation in these numbers
- HYDJET predictions in the right ballpark (see next slide) but it would be nice to have an ‘official’ tune based on the latest LHC measurement (Does it exist?)

Jet reconstruction

HYDJET **simulations**		ρ (GeV) (y=0, 0-10%)	σ (GeV)	σ_ρ (GeV)	σ_{jet} (GeV) (anti-kt, R=0.4)
LHC 2.76 TeV	all	250	**18**	36	**16**
	charged only	147	**12.5**	22	**11.3**

Data LHC 2.76 TeV	ρ (GeV) (y=0, 0-10%)	σ (GeV)	σ_ρ (GeV)	σ_{jet} (GeV) (anti-kt, R=0.4)
ALICE, charged only 1201.2423	138		18.5	**11.2**
CMS 1205.0206				**5.2** (R=0.3 + NR)
ATLAS 1208.1967				**12.5**

Only background-induced component, no calorimeter effects

While σ_{jet} is of course ultimately the only relevant number, it would be nice to have all the others too from the experiments, for comparison and cross-checks

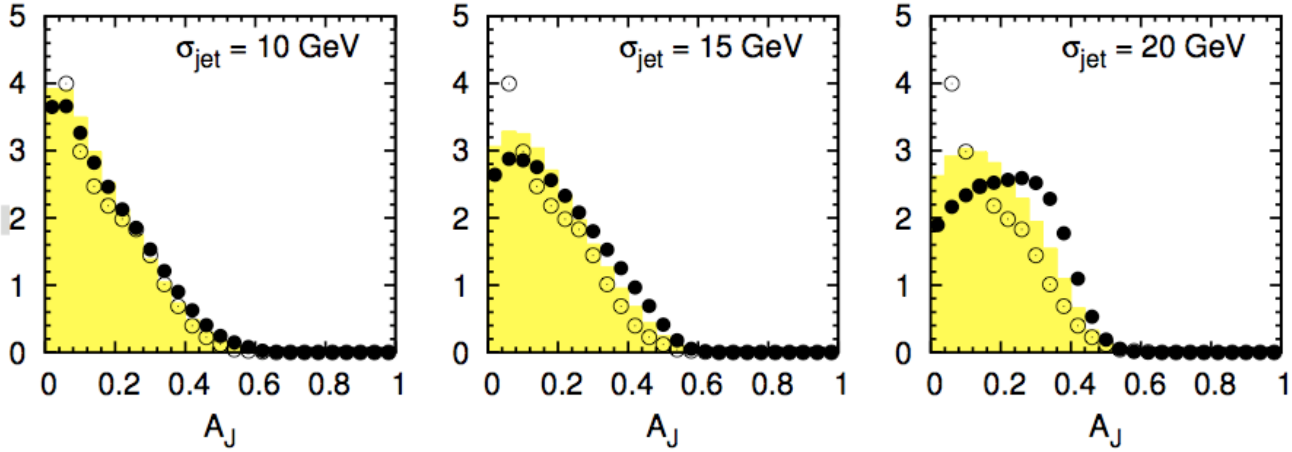
I'd be most happy if I could fill in the blanks at this workshop

Open issue

While the numbers appear to be largely consistent, **one discrepancy** sticks out: fluctuations predicted by HYDJET are in **perfect agreement** with ALICE charged tracks jets (11.3 v. 11.2 GeV), but **disagree** with ATLAS measurement of fluctuations for full jets (16 v. 12.5 GeV)

This number is quite critical because it sits precisely at the threshold where fluctuations start contributing significantly to the dijet asymmetry

MC, Salam, Soyez, 1101.2878



What did I miss of ATLAS analysis? How can the two numbers be reconciled?

Jet reconstruction

How do the different clustering algorithms fare?

Subtract with
$$p^{sub}_{\mu,jet} \equiv p_{\mu,jet} - \rho A_{\mu,jet}$$

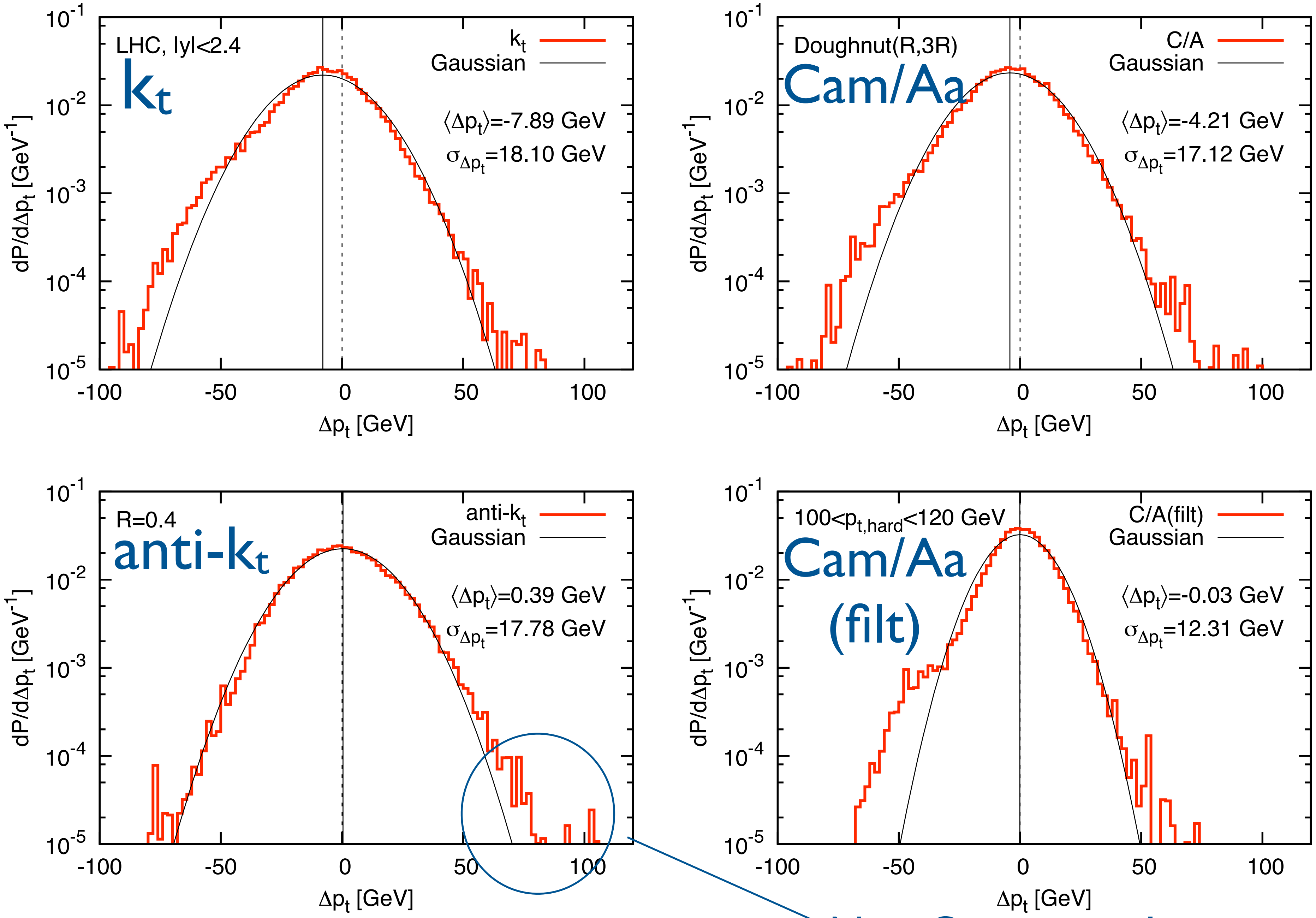
Measure quality of reconstruction looking at

Offset
$$\langle \Delta p_t \rangle \equiv \langle p_t^{AA,sub} - p_t^{pp,sub} \rangle$$

Dispersion
$$\sigma_{jet} \equiv \sigma_{\Delta p_t} \equiv \sqrt{\langle \Delta p_t^2 \rangle - \langle \Delta p_t \rangle^2}$$

[In the following I will use our own study (MC, Rojo, Salam, Soyez, 1010.1759)
as a source of plots, but the results should be quite generic.
NB. 'LHC' will be 5.5 TeV, but the results will be qualitatively similar at 2.76 TeV]

Δp_t distributions in PbPb at LHC



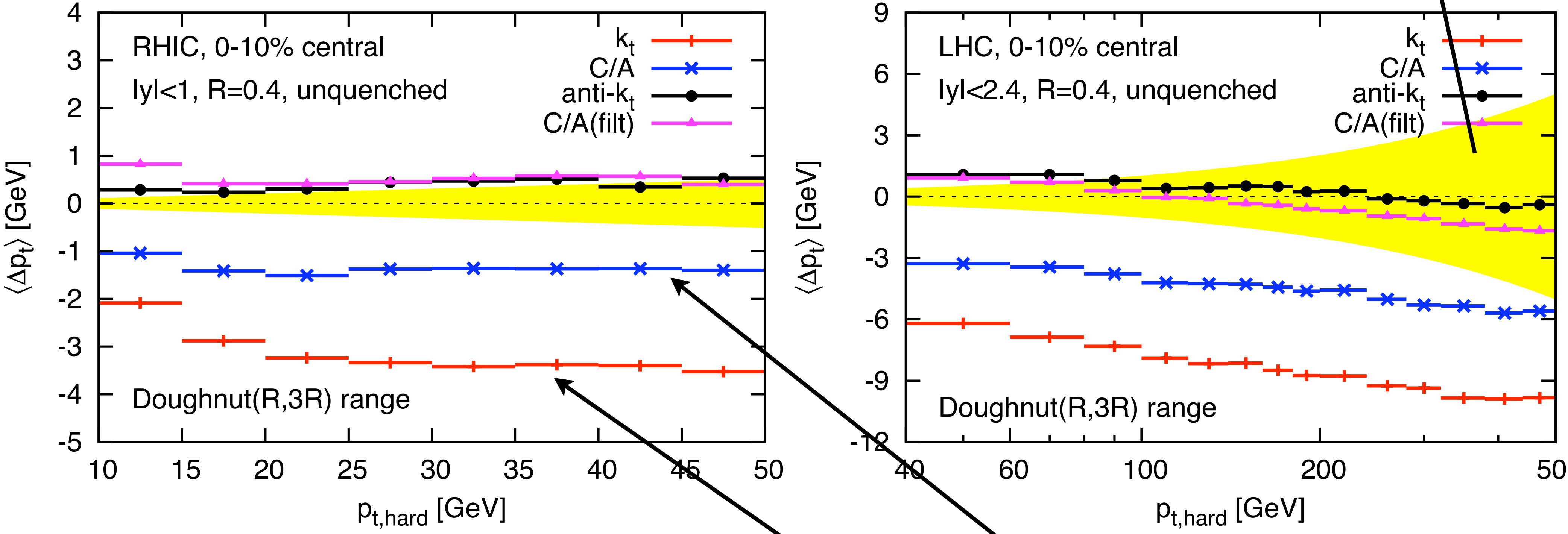
Non-Gaussian tails

$<\Delta p_t>$

anti-k_t and C/A(filt) fare best

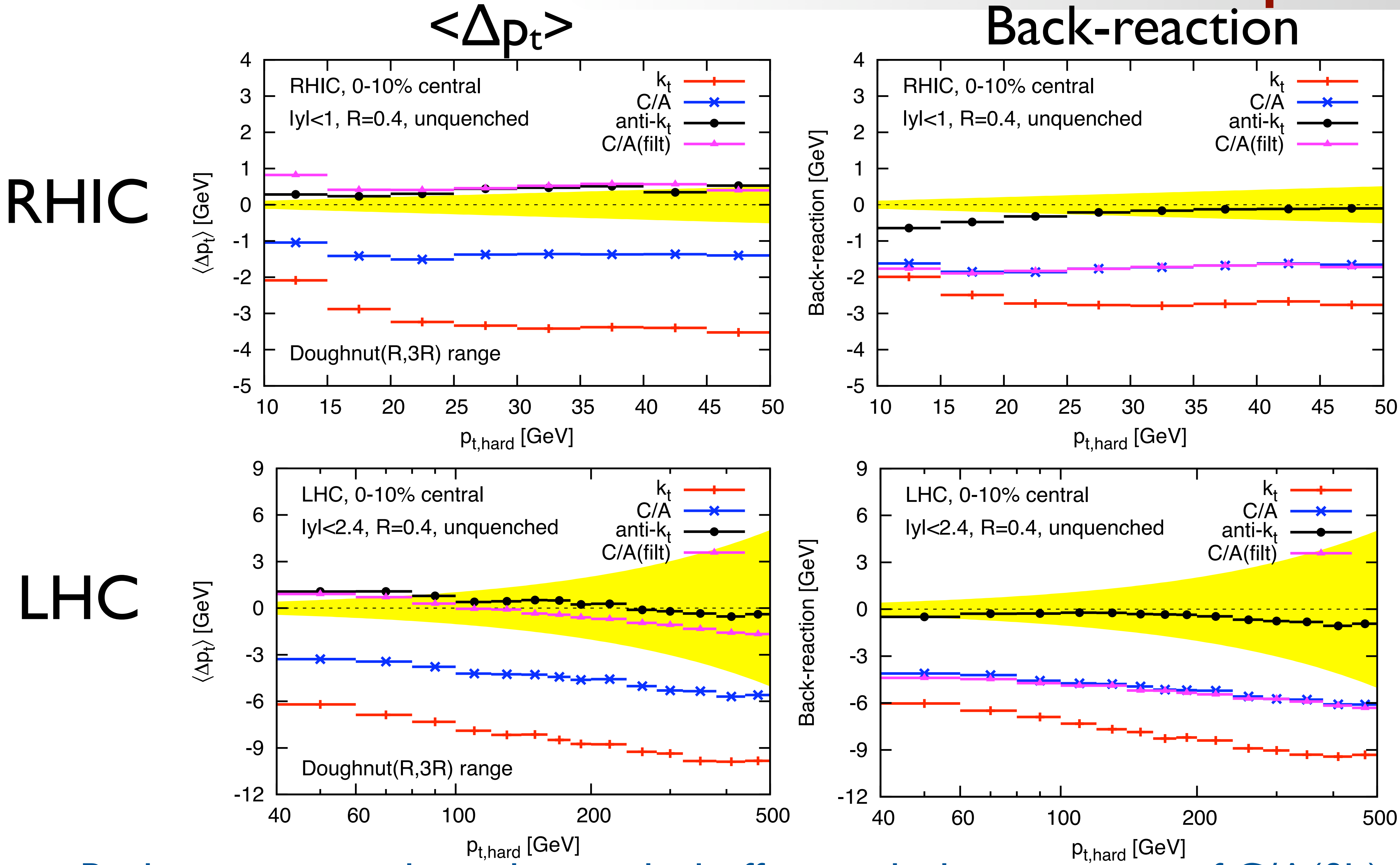
(Results are fairly independent of p_t)

Yellow band:
1% accuracy



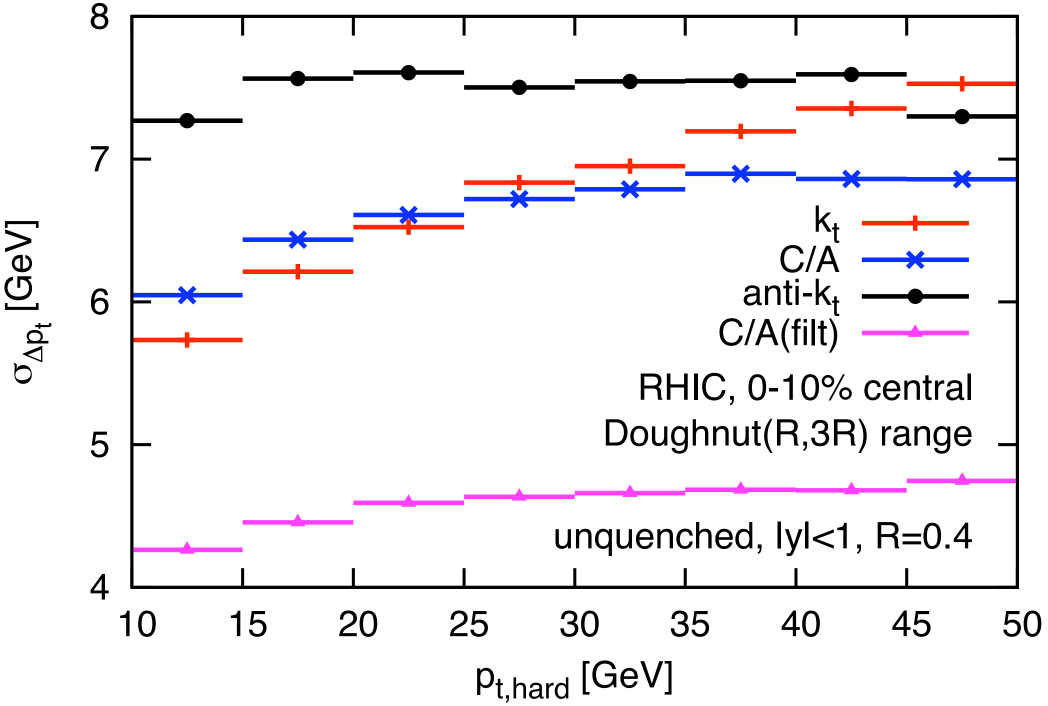
The residual offset of k_t and C/A can be interpreted as an effect of the **back-reaction**

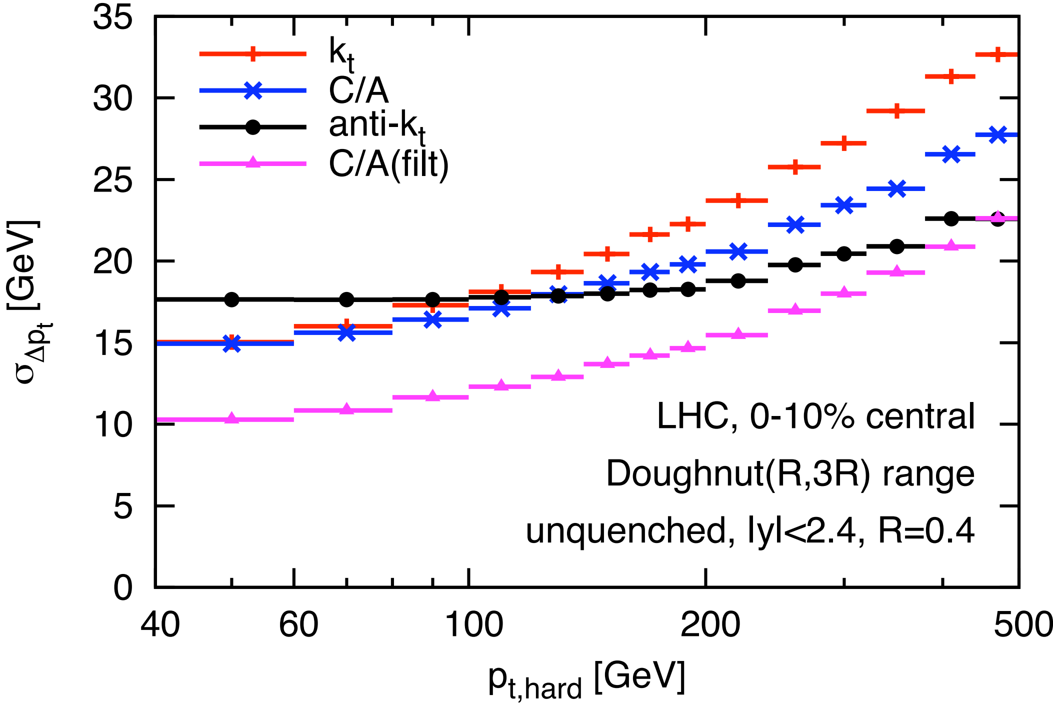
Back-reaction contribution to <Δp_t>



Back-reaction explains the residual offset, with the exception of C/A(filt)
(accidental compensation of back-reaction and positive offset)

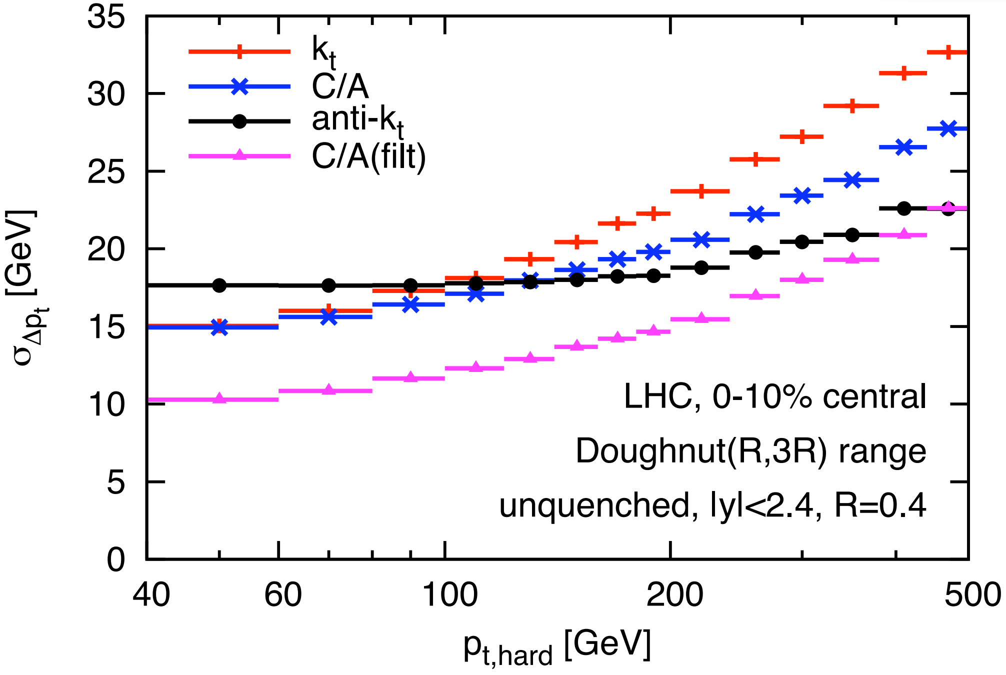
Dispersion of $\Delta p_t = \sigma_{\Delta p_t}$



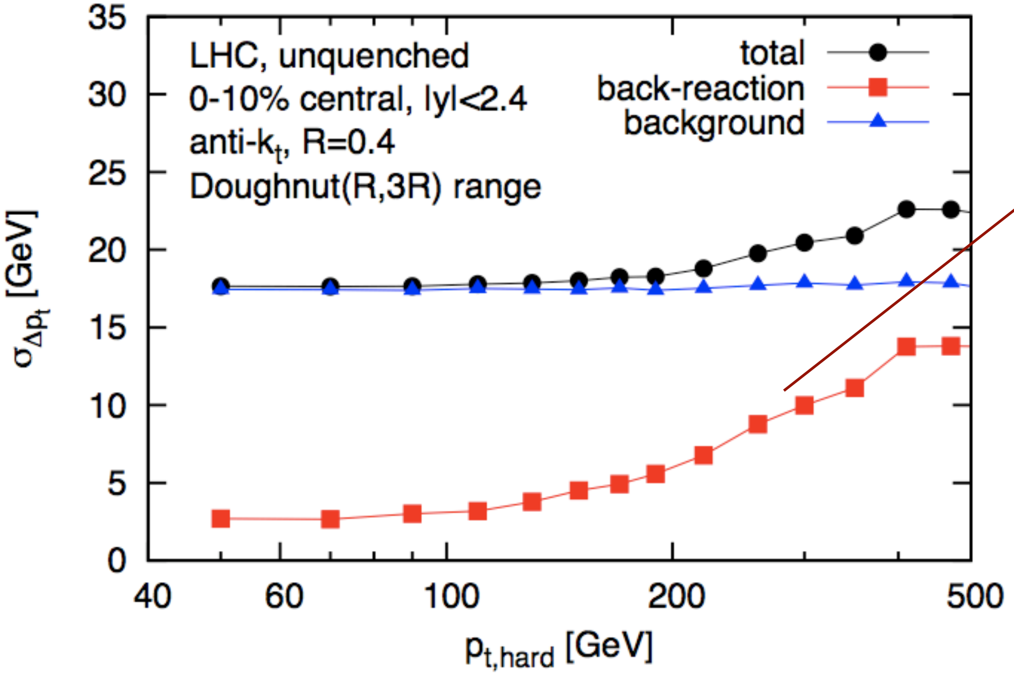


- C/A(filt) markedly better, as a consequence of its smaller effective area
- Dispersions increase at large p_t, probably as a consequence of a larger dispersion of back-reaction
- anti-k_t remains fairly constant ('resiliency'), and eventually becomes better at large p_t

Dispersion from backreaction



While the dispersion component due to fluctuations is constant in p_t, the one due to backreaction grows



Contribution of backreaction to dispersion of subtraction with anti-k_t

Note that the reason for the increase in dispersion with k_t or Cambridge is (at least in part) different: the jet areas increase with increasing p_t

Beyond jet p_t reconstruction

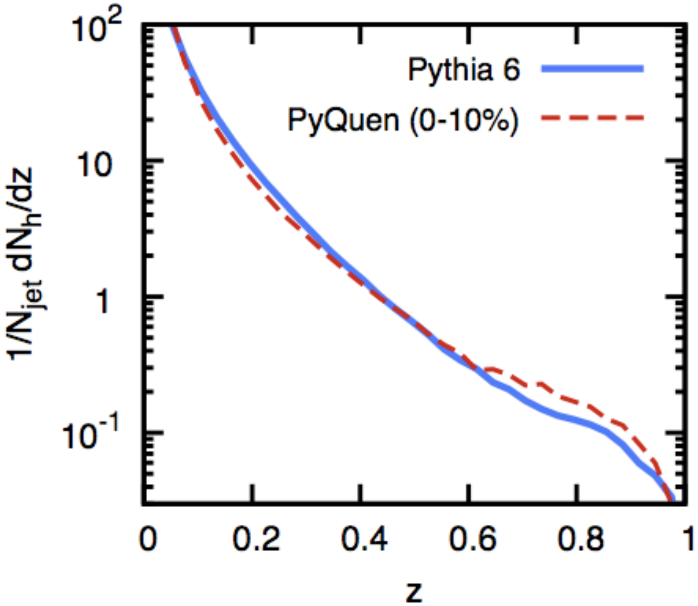
- It would be helpful if a consistently similar background subtraction procedure could be applied not only to a jet's p_t, but also to derived quantities like jet shapes, or more differential observables like a jet fragmentation function

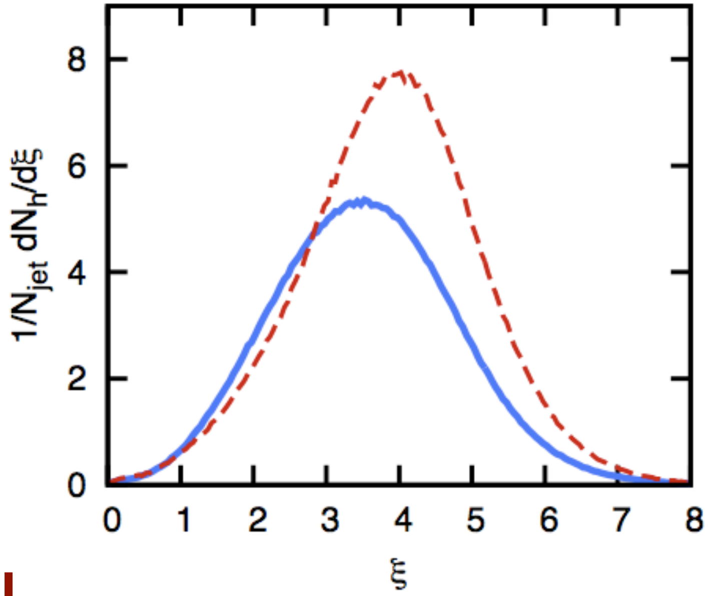
- We (MC, Kim, Salam, Soyez) are working on jet shapes subtraction (though the huge HI background may actually be too much for our procedure, actually aimed at pileup in pp collisions)

- In the meantime, we (MC, Quiroga, Salam, Soyez) have tried applying the **'p_t - ρA' technique** to **jet fragmentation functions**. We propose a technique alternative to the 'standard' subtraction of associated track distributions in displaced/reflected cones. In the following, I will give some preliminary results (the paper should be out in a few days)

Jet fragmentation functions in HI

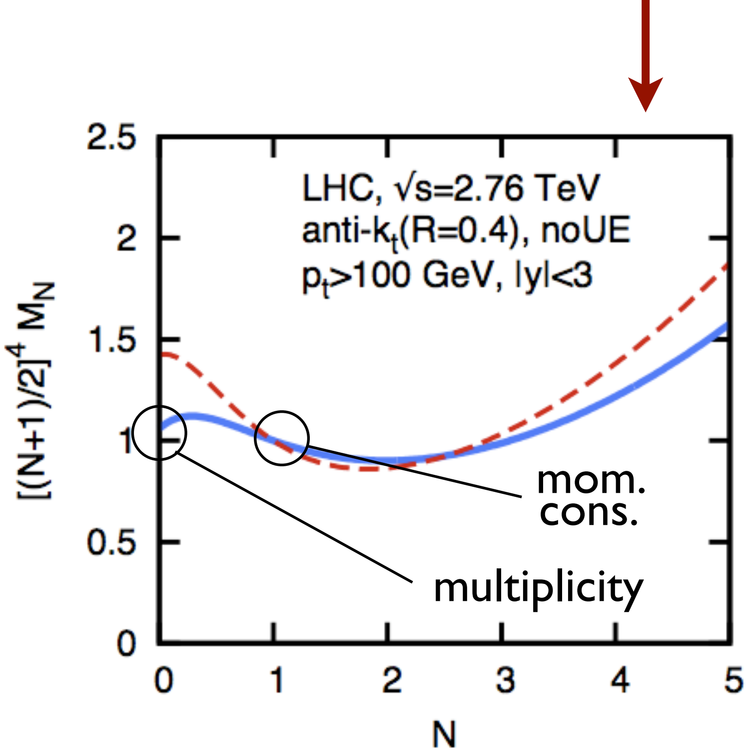
MC, Quiroga, Salam, Soyez, in preparation





How to remove HI background and measure these distributions?

Two (main) issues: background determination, and fluctuations



Step 1: go from momentum fraction distributions to **moments**

$$M_N = \frac{1}{N_{jet}} \int_0^1 z^N \frac{dN_h}{dz}\, dz = \frac{1}{N_{jet}} \int_0^\infty e^{-N\xi} \frac{dN_h}{d\xi}\, d\xi$$

In practice, $M_N^{jet} = \frac{\sum_{i\in jet} p_{t,i}^N}{p_t^N}$ and averaging over many jets

Same information as momentum fraction distributions, in different form

Jet fragmentation functions in HI

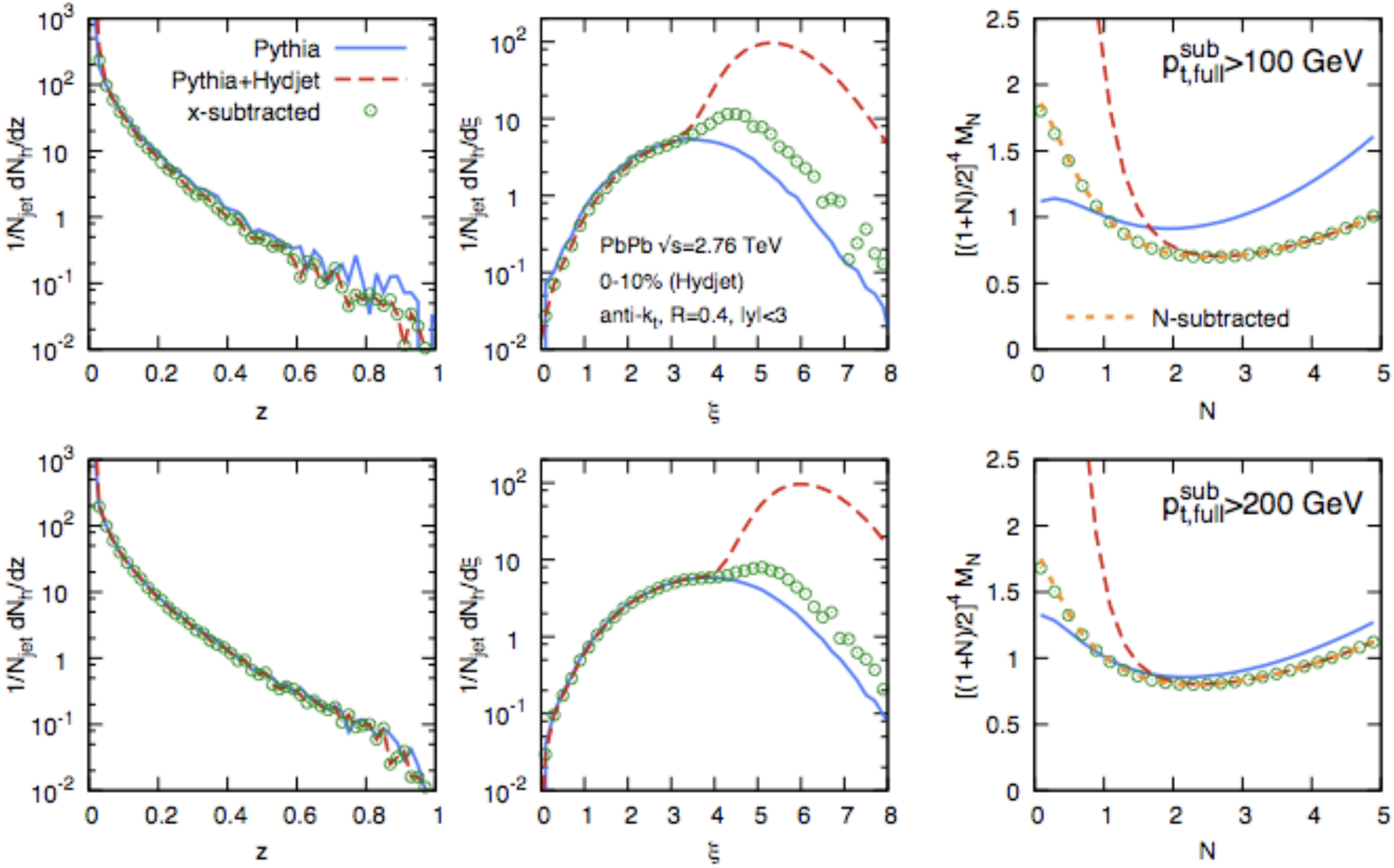
Step 2: alongside the usual ρ, extract from the background the quantities

$$\rho_N = \operatorname*{median}_{\text{patches}} \left\{ \frac{\sum_{i\in\text{patch}} p_{t,i}^N}{A_{\text{patch}}} \right\}$$

and subtract the moments according to

$$M_N^{sub} = \frac{\sum_i p_{t,i}^N - \rho_N A}{(p_t - \rho A)^N} \equiv \frac{S_N}{S_1^N}$$

Jet fragmentation functions in HI



- Subtraction of moments (dashed orange) is no worse but no better than the 'standard' z-space subtraction (green circles)
- Quality of reconstruction of pp-equivalent result ('Pythia', blue line) not great at p_t = 100 GeV, starts getting better at p_t = 200 GeV

Jet fragmentation functions in HI

Step 3: correct for effect of (sufficiently small) fluctuations

Model fluctuations as $B(q_t) \equiv \frac{dP}{dq_t} = \frac{1}{\sqrt{2\pi A\sigma}} \exp\left(-\frac{q_t^2}{2\sigma^2 A}\right)$

and the hard jets p_t spectrum as $H(p_t) \equiv \frac{d\sigma}{dp_t} = \frac{\sigma_0}{\mu} \exp(-p_t/\mu)$

The effect of fluctuations can be written as

$$M_N^{sub} = \frac{1}{\int dq_t\, B(q_t) H(S_1^{\rm hard} - q_t)} \int dq_t\, B(q_t) H(S_1^{\rm hard} - q_t) \frac{S_N^{\rm hard} + \langle Q_N \rangle (q_t)}{(S_1^{\rm hard} + q_t)^N}$$

where 'hard' denotes the hard component of the subtracted moments S_N

The $Q_N = \sum k_{t,i}^N - \rho_N A$ are the moments of the fluctuations

They are **correlated** to the momentum q_t of the fluctuations:

$$\langle Q_N \rangle (q_t) = \frac{\mathrm{Cov}(q_t, Q_N)}{\mathrm{Var}(q_t)} q_t = r_N \frac{\sigma_N}{\sigma} q_t$$

$$r_N = \frac{\mathrm{Cov}(q_t, Q_N)}{\sqrt{\mathrm{Var}(q_t)\mathrm{Var}(Q_N)}}$$

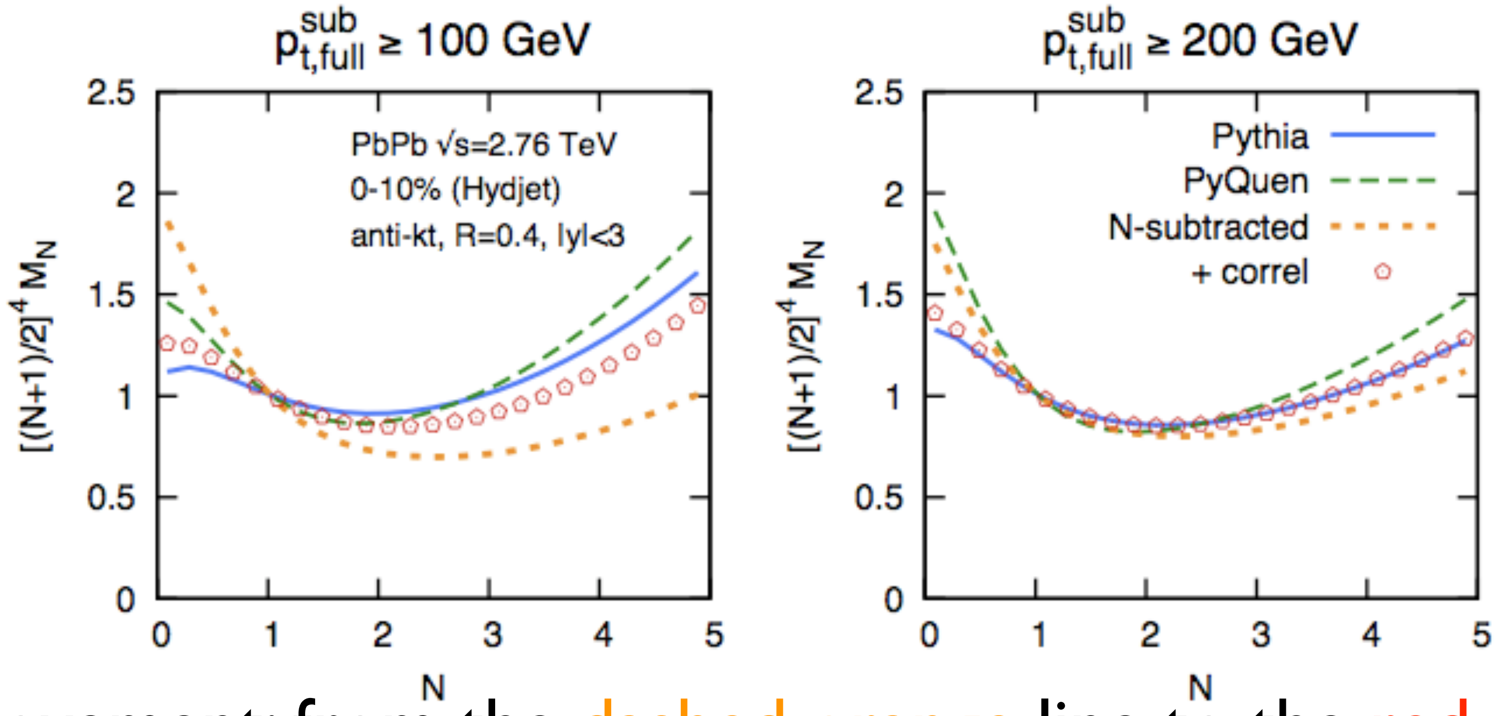
correlation coefficient

Jet fragmentation functions in HI

Expanding to first order, the effect of fluctuations can be corrected for using

$$M_N^{\mathrm{sub,imp}} = M_N^{\mathrm{sub}}\left[1-\left(r_N\frac{\sigma_N}{S_N}-N\frac{\sigma}{S_1}\right)\frac{\sigma A}{\mu}\right]$$

All the ingredients are experimentally measurable, μ can be measured in pp collisions



Improvement: from the dashed orange line to the red circles

Precision now better than potential quenching effects

Tools to do this will be available soon at http://fastjet.hepforge.org/contrib

Final remarks

- Great experimental progess in measuring jets and jet observables in heavy ion collisions
- Background (and fluctuations) subtraction techniques have become highly refined, but are also difficult to compare and evaluate. Would it be possible to move towards an at least partial standardisation?
- As an example, we propose a new moments-based approach to jet fragmentation functions that makes use of the same background subtraction technique one can use for inclusive jets, plus an observable-specific correction for fluctuations

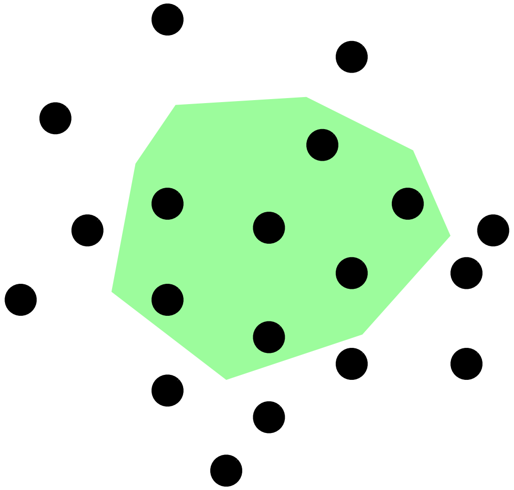
Extra material

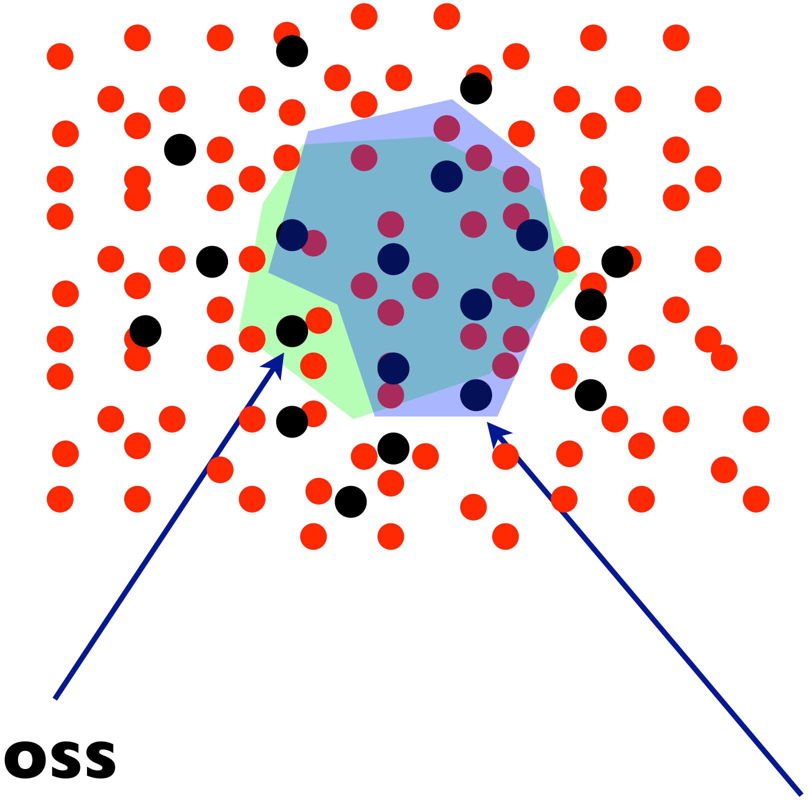
Back-reaction

“How (much) a jet changes when immersed in a background”

Without background

With background



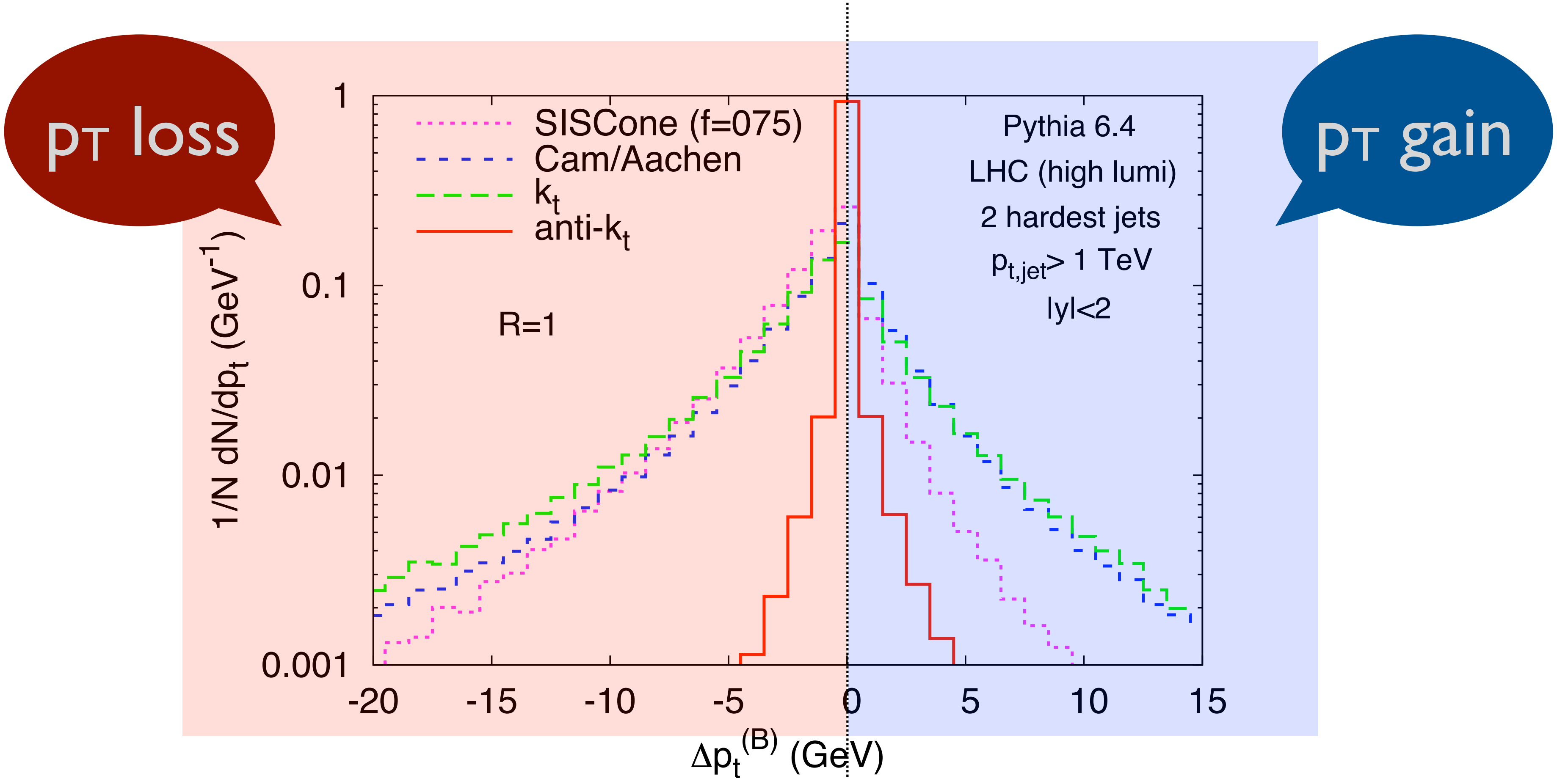


Back-reaction **loss**

Back-reaction **gain**

Back-reaction

MC, Salam, Soyez, arXiv:0802.1188



Anti-k$_t$ jets are much more resilient to changes from background immersion

CMS subtraction

Smaller fluctuations:

MC, Salam, Soyez, 1101.2878

$$\begin{aligned}(\sigma_{\text{jet}}^{\text{noise-suppressed}})^2 &= N_{\text{tower}}\left[\langle(\delta p_{t,\text{tower}}^{\text{noise}})^2\rangle - \langle\delta p_{t,\text{tower}}^{\text{noise}}\rangle^2\right]\\ &= N_{\text{tower}}\left[\int_{\sigma_{\text{tower}}}^{\infty} dx\,\frac{(x-\sigma_{\text{tower}})^2}{\sqrt{2\pi}\sigma_{\text{tower}}}e^{-\frac{x^2}{2\sigma_{\text{tower}}^2}} - \langle\delta p_{t,\text{tower}}^{\text{noise}}\rangle^2\right]\\ &\simeq (0.262\,\sigma_{\text{tower}})^2\,N_{\text{tower}}\,,\end{aligned}$$

p_t bias:

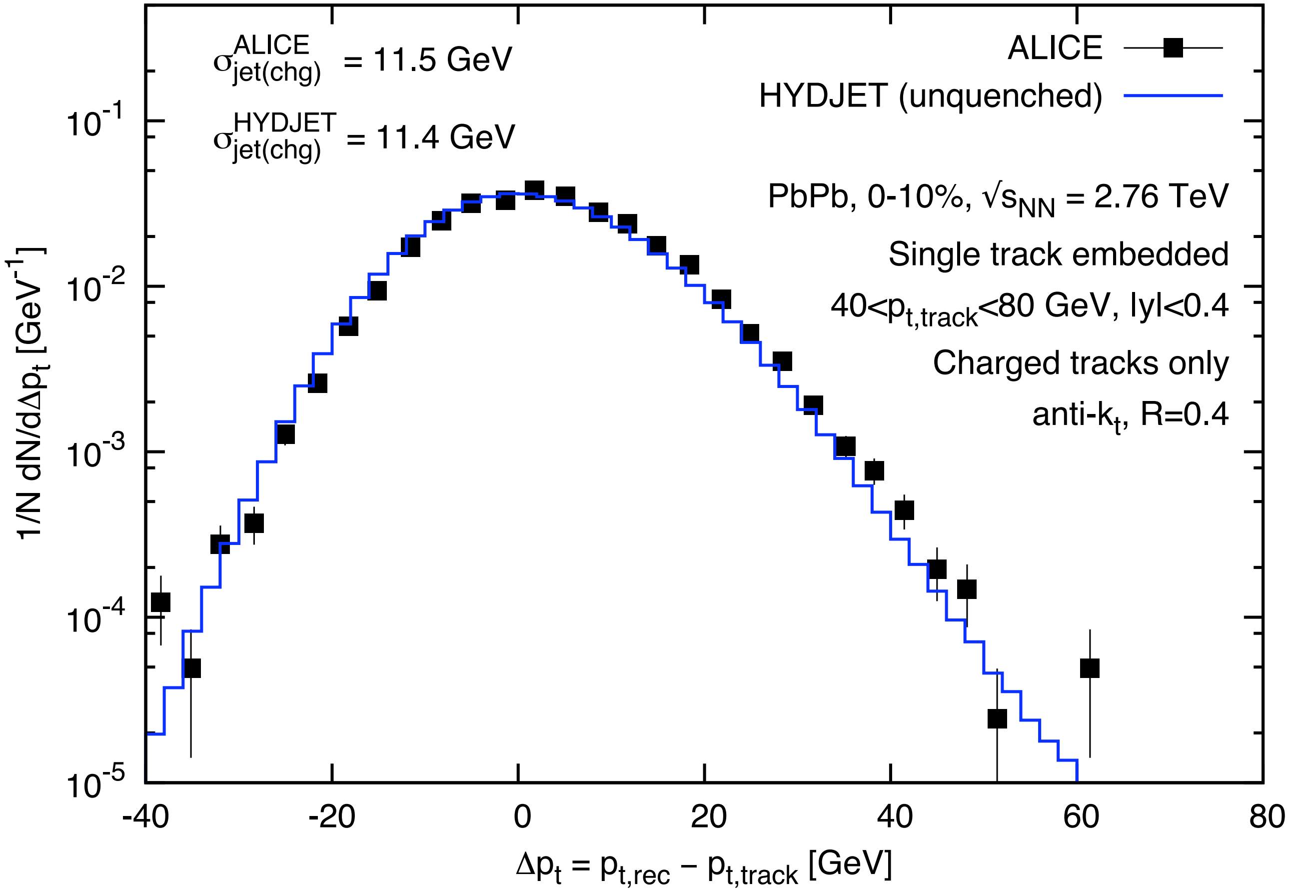
$$\langle\delta p_{t,\text{jet}}^{\text{overall}}\rangle = \langle\delta p_{t,\text{jet}}^{\text{noise}}\rangle + \langle\delta p_{t,\text{jet}}^{\text{hard}}\rangle \simeq (0.0833 - f)N_{\text{tower}}\sigma_{\text{tower}}$$

$$\langle\delta p_{t,\text{jet}}^{\text{hard}}\rangle \simeq -f\,N_{\text{tower}}\sigma_{\text{tower}}$$

$$\langle\delta p_{t,\text{jet}}^{\text{noise}}\rangle = N_{\text{tower}}\langle\delta p_{t,\text{tower}}^{\text{noise}}\rangle = N_{\text{tower}}\int_{\sigma_{\text{tower}}}^{\infty} dx\,\frac{(x-\sigma_{\text{tower}})}{\sqrt{2\pi}\sigma_{\text{tower}}}e^{-\frac{x^2}{2\sigma_{\text{tower}}^2}} \simeq 0.0833\,\sigma_{\text{tower}}\,N_{\text{tower}}$$

HYDJET v. ALICE charged tracks jets

MC, Salam, Soyez, 1101.2878



Striking agreement, and $\sigma_{jet(chg)} \approx 11.5$ GeV

Translates to a full $\sigma_{jet} \approx 17$ GeV

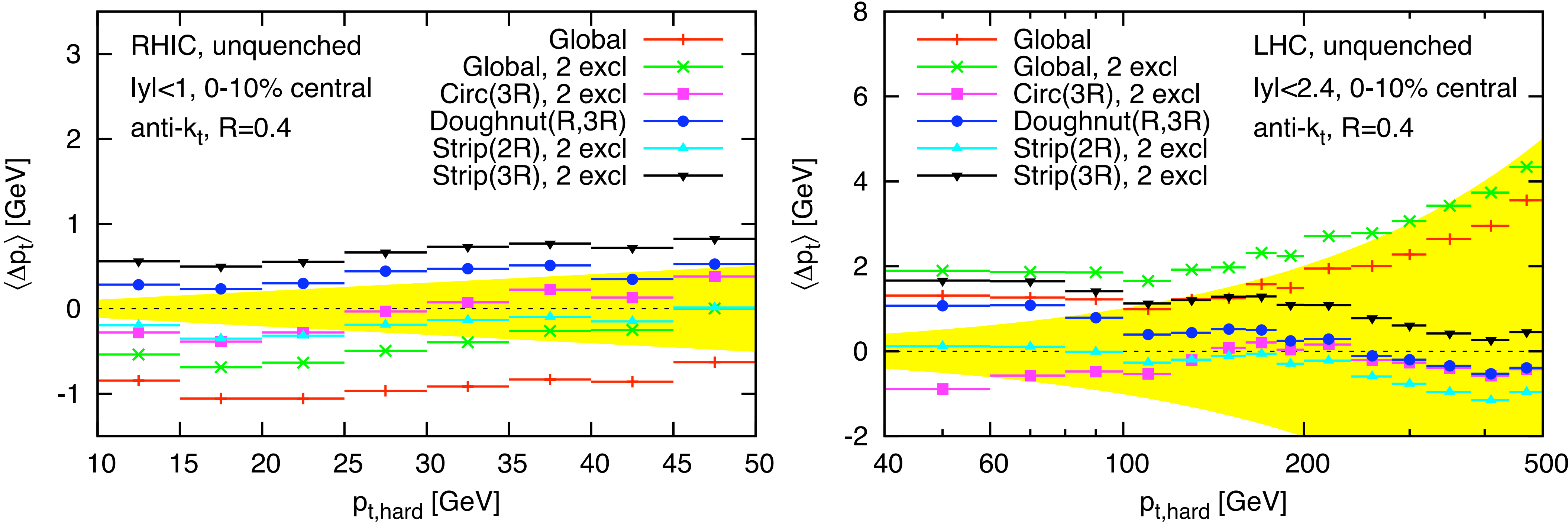
These are **real data**.

It seems that HYDJET does a good job in describing the PbPb background characteristics

(as a side note, HYDJET was not even tuned to LHC data)

Ranges

$<\Delta p_t>$



Intrinsic ambiguity mostly of order 1-2 GeV on Δp_t

The local ranges perform similarly, the exclusion of hardest jets helps a little, the global range also performs fairly well here thanks to the limited rapidity coverage

Cambridge/Aachen with filtering

Butterworth, Davison, Rubin, Salam, arXiv:0802.2470

An example of a **third-generation** jet algorithm

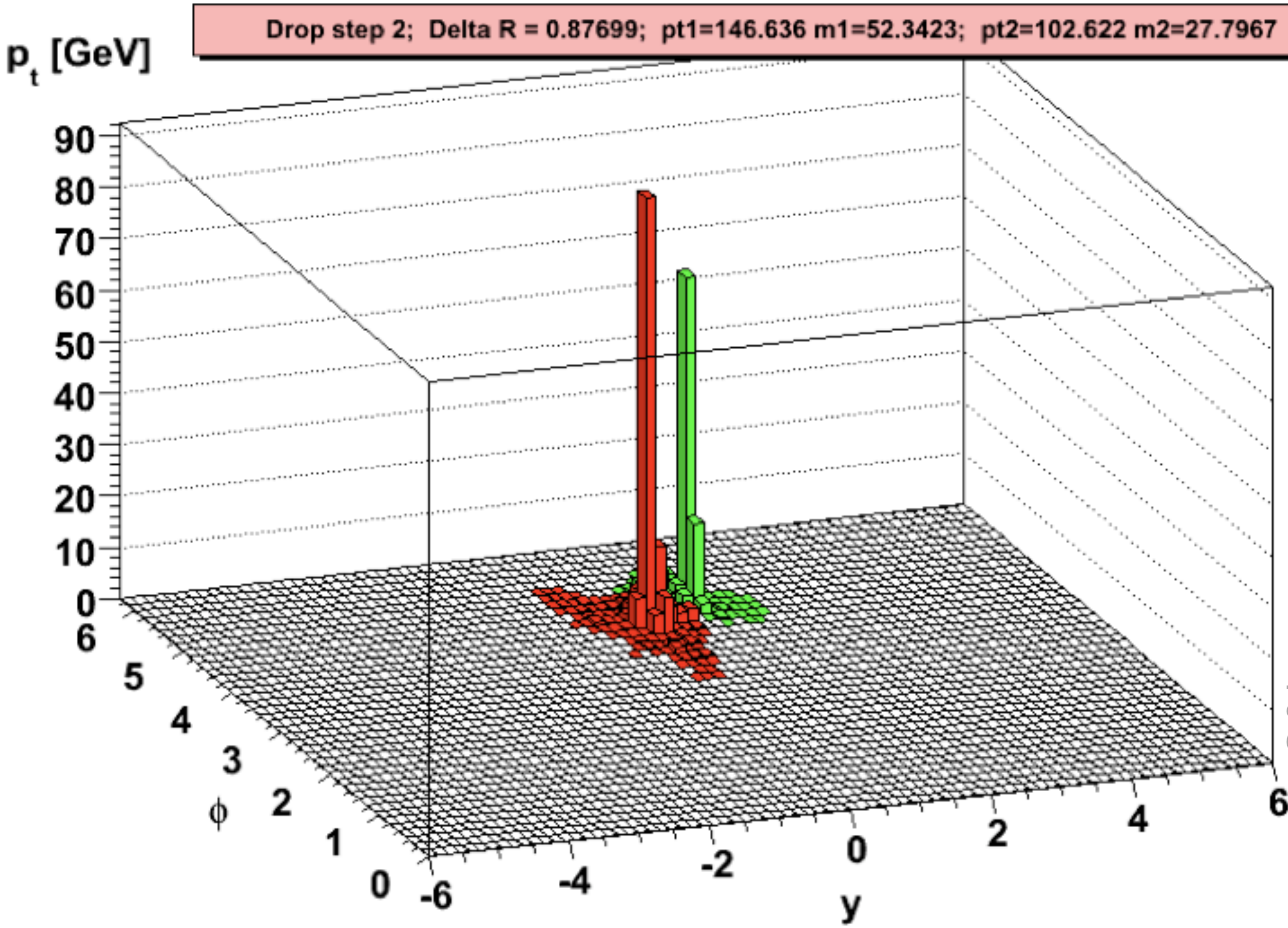
- Cluster with C/A and a given R
- Undo the clustering of each jet down to subjets with radius **$x_{filt}R$**
- Retain only the **n_{filt}** hardest subjets

Idea: filter out soft background, retain hard core

(for this work we'll be using $x_{filt} = 0.5$, $n_{filt} = 2$)

Filtering in action

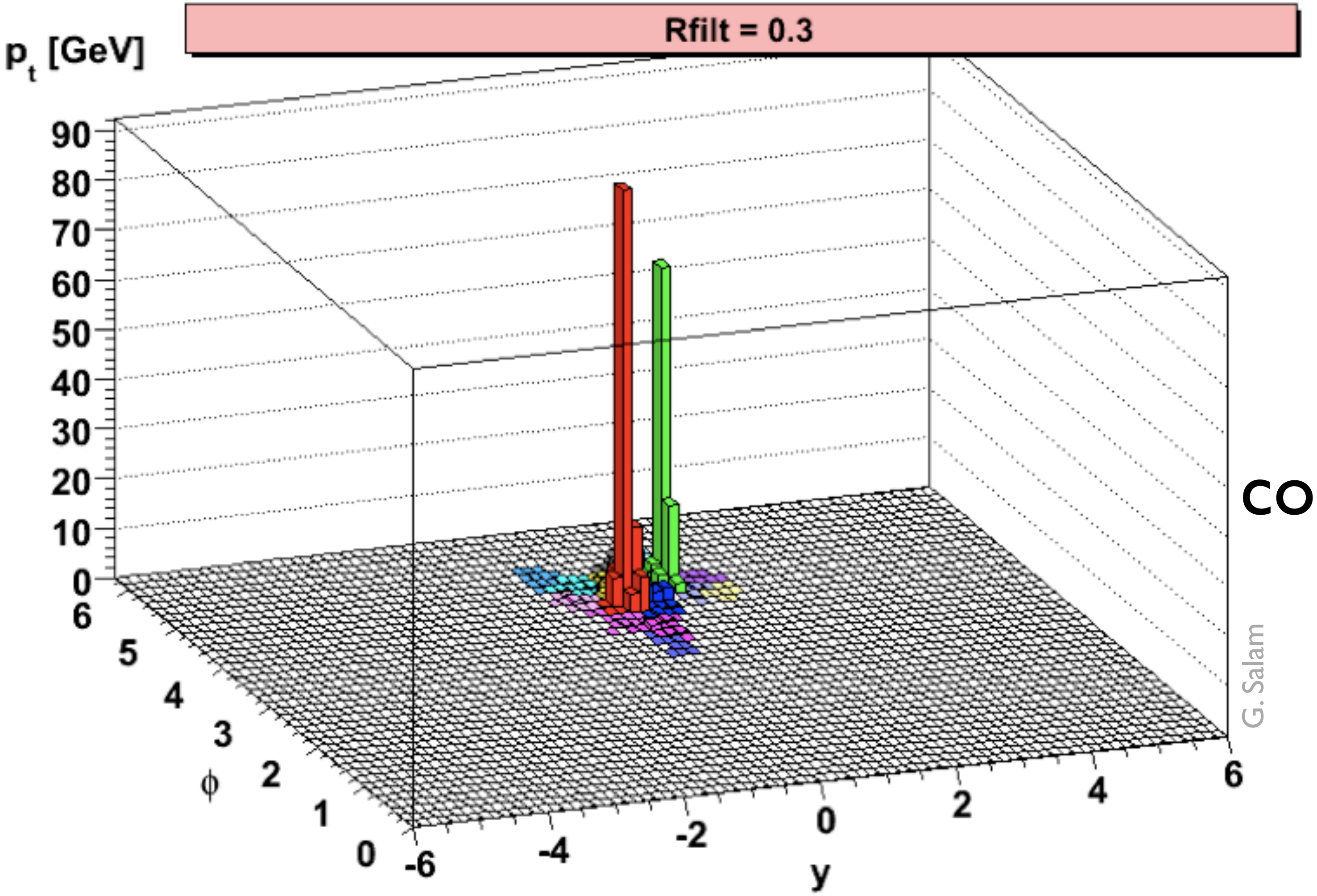
Butterworth, Davison, Rubin, Salam, arXiv:0802.2470



G. Salam

Start with a jet
(the sum of these two)

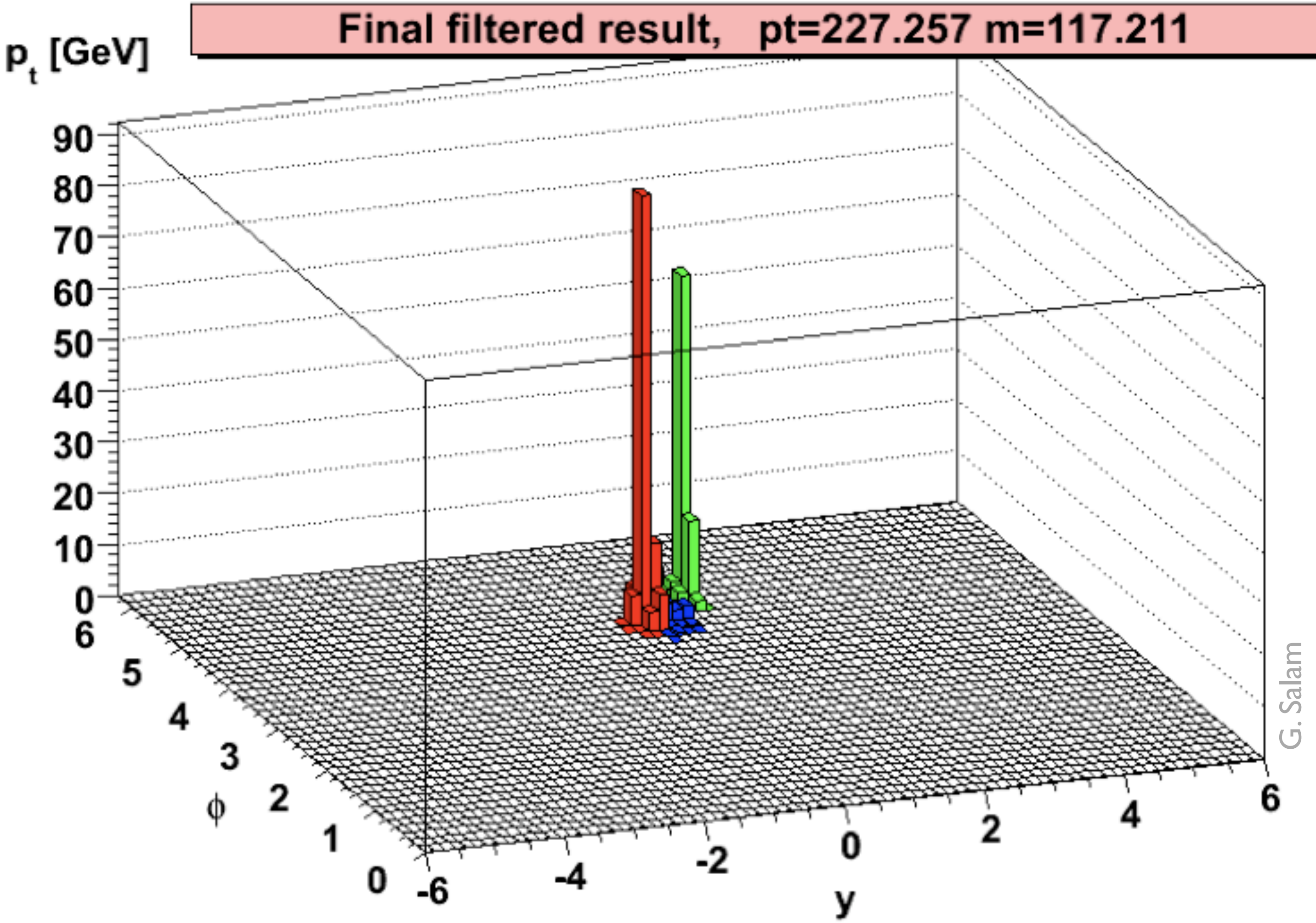
Filtering in action



G. Salam

Recluster the contituents with R_{filt}

Filtering in action



G. Salam

Only keep the n_{filt} hardest jets

The low-momentum stuff surrounding the hard particles has disappeared