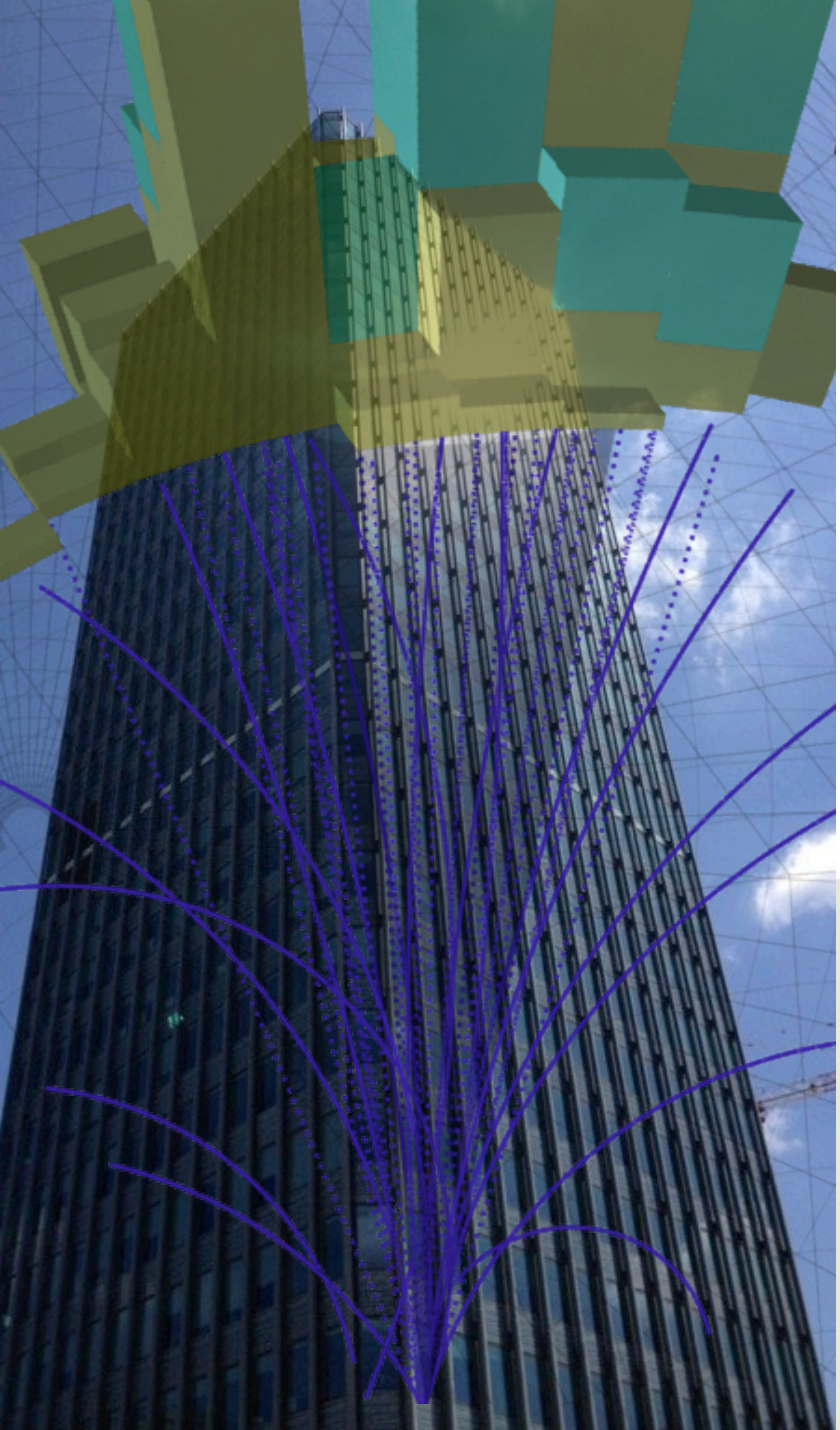


Jet finding in high-energy (HI) collisions

Gavin Salam (CERN & LPTHE/CNRS)
Based on work with Matteo Cacciari, Gregory Soyez, Paloma Quiroga and Sebastian Sapeta

Jet Workshop 2013
LPTHE/UPMC & MIT, Paris, July 2013

As an energetic parton travels through the medium it radiates and exchanges momentum with the medium in ways that may enable us to learn about the medium's properties.

"Jets" are a physically well-defined way of giving meaning to the concept of parton.

They also facilitate the study of associated radiation

The core ingredients

A jet definition

Background characterisation

Background removal

Unfolding

The core ingredients

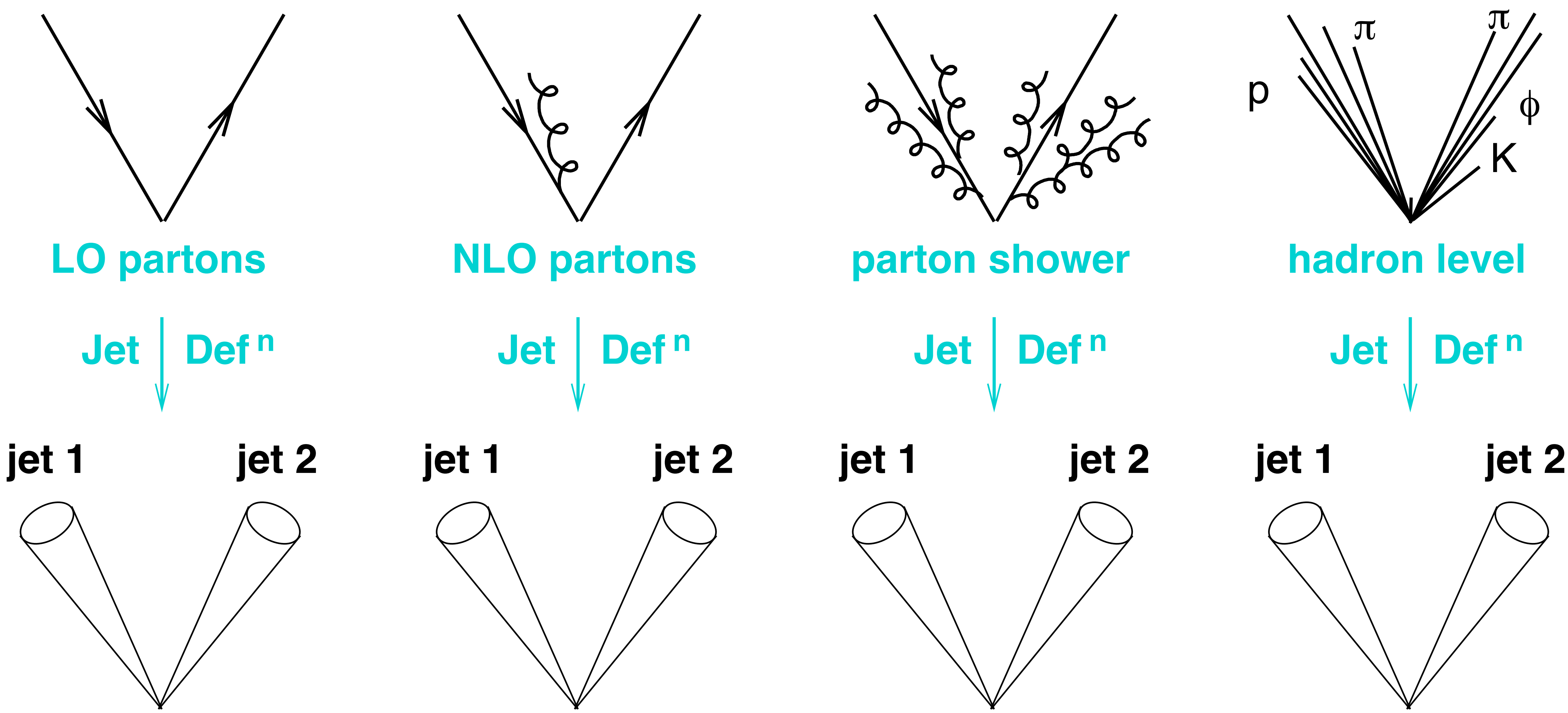
A jet definition

Background characterisation

Background removal

Unfolding

Jet finding as a form of projection

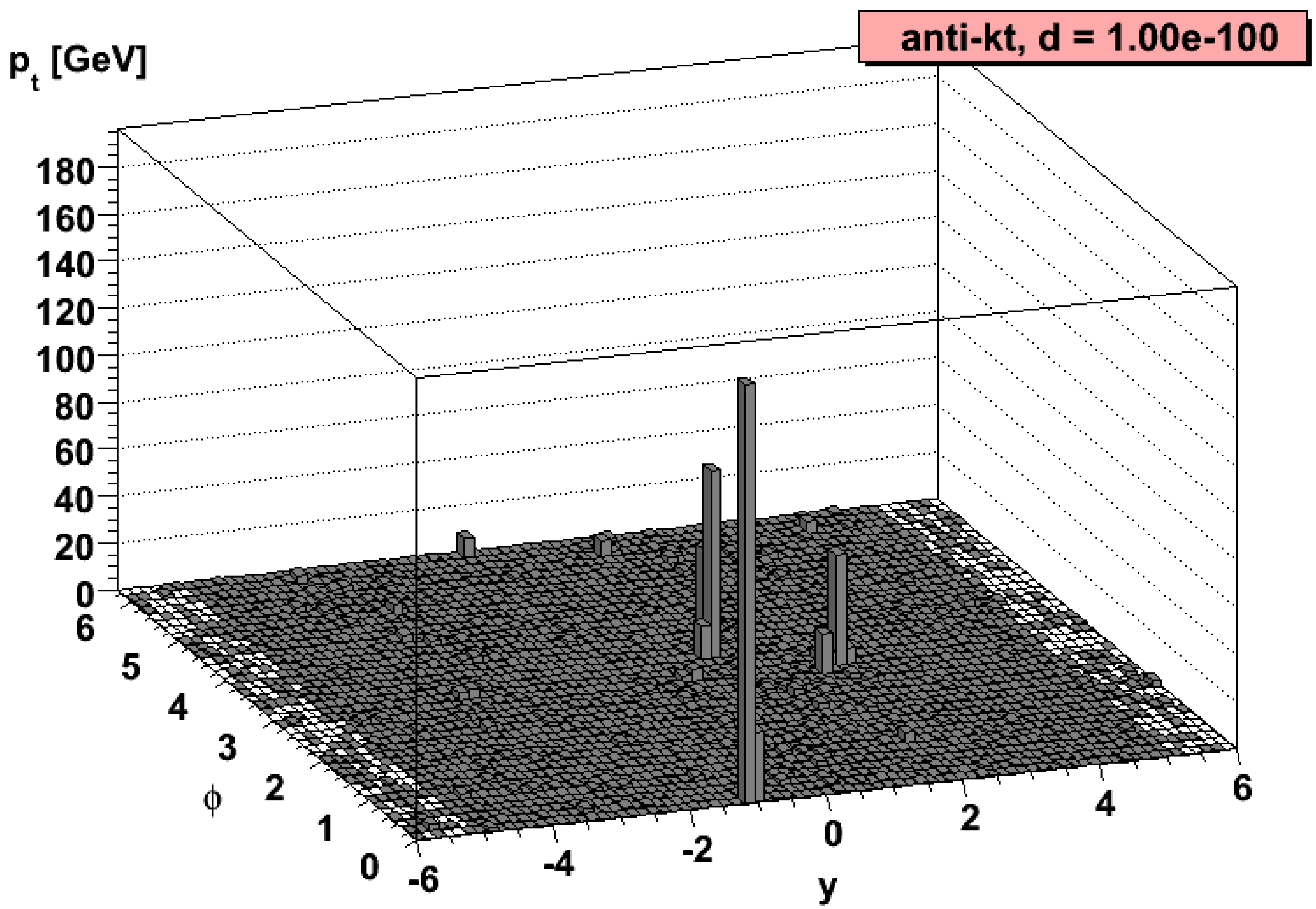


Projection to jets should be resilient to QCD effects

The anti-k_t jet algorithm

Clustering grows around hard cores

$$d_{ij} = \frac{1}{\max(p_{ti}^2, p_{tj}^2)} \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = \frac{1}{p_{ti}^2}$$



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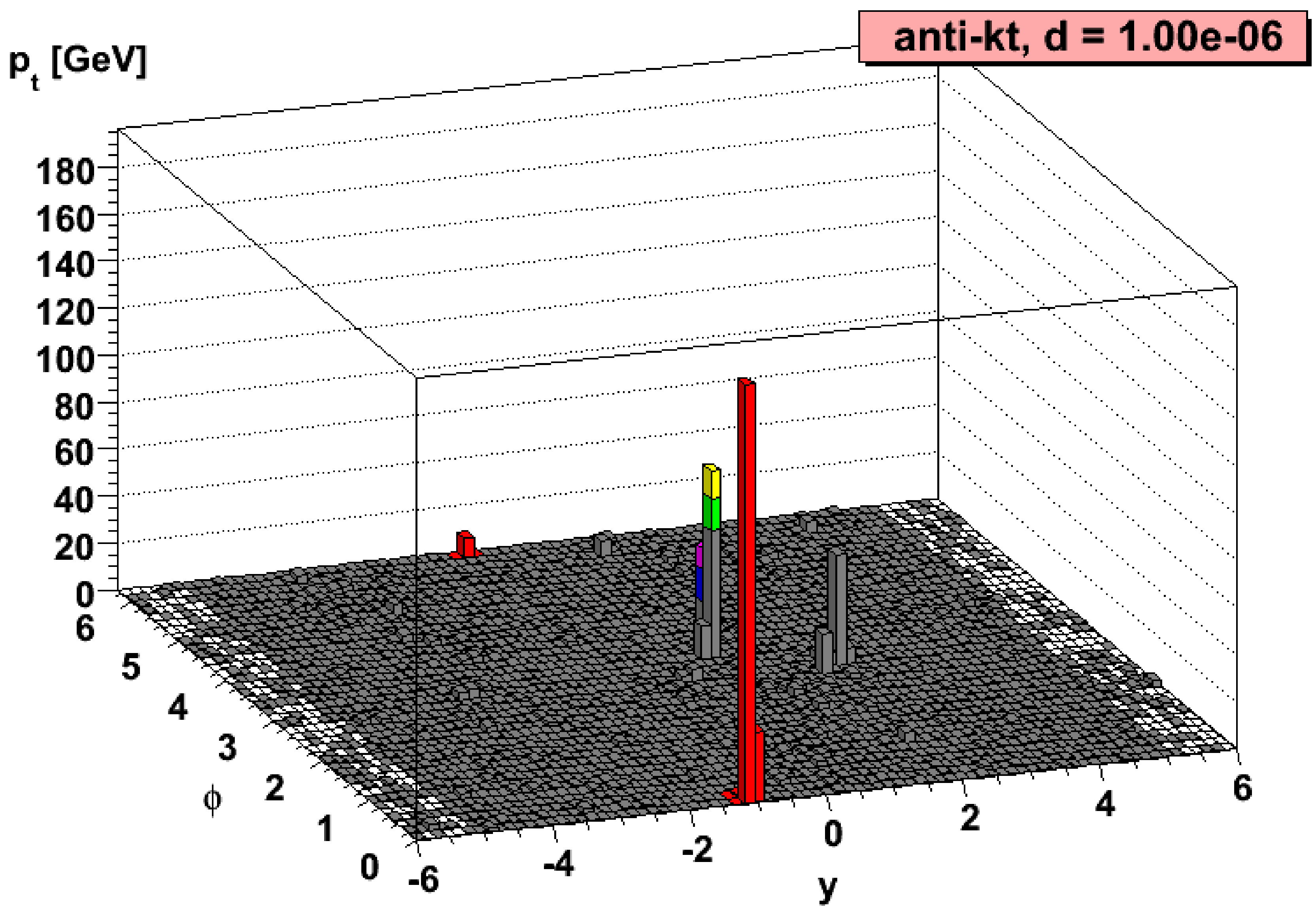

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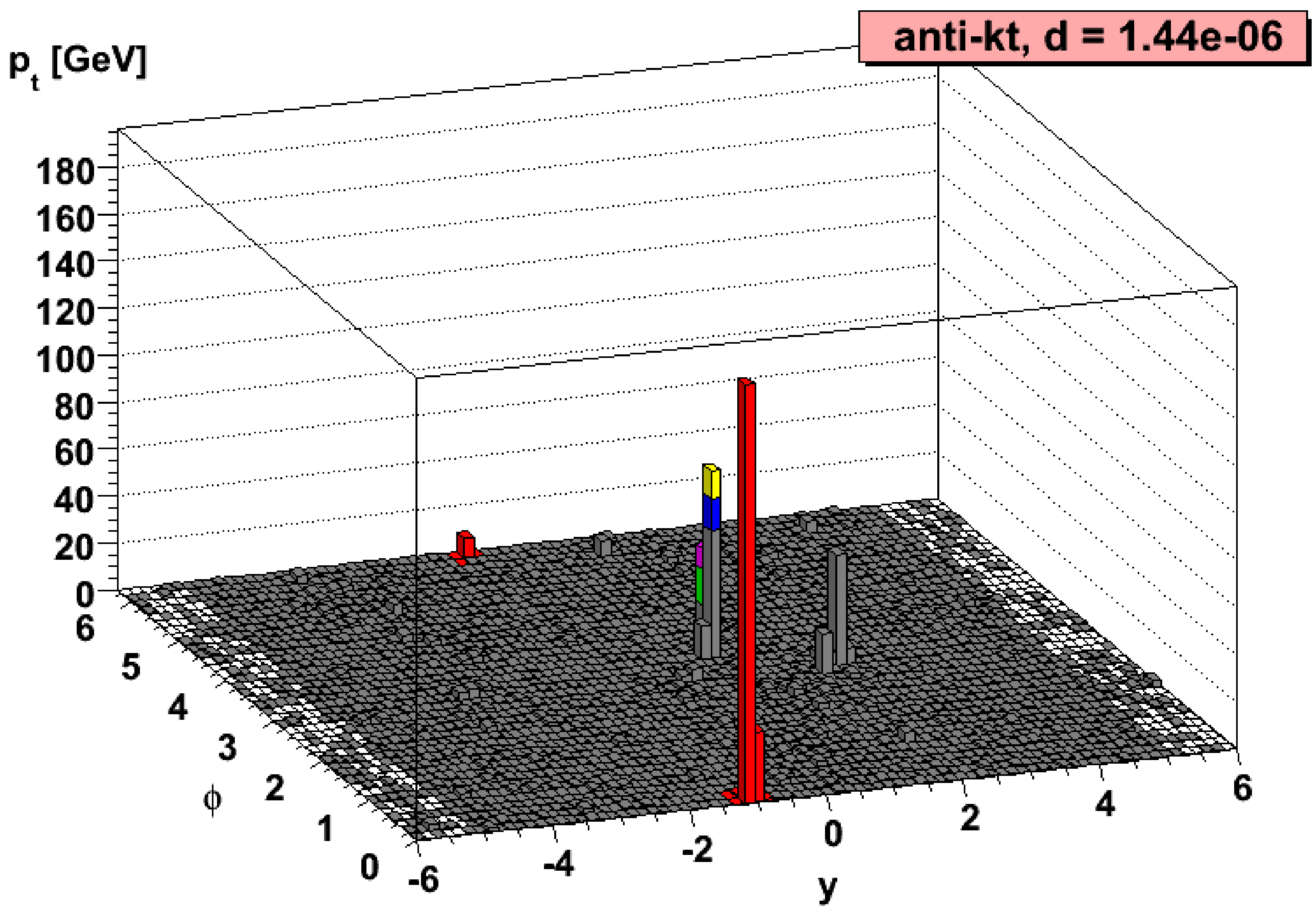

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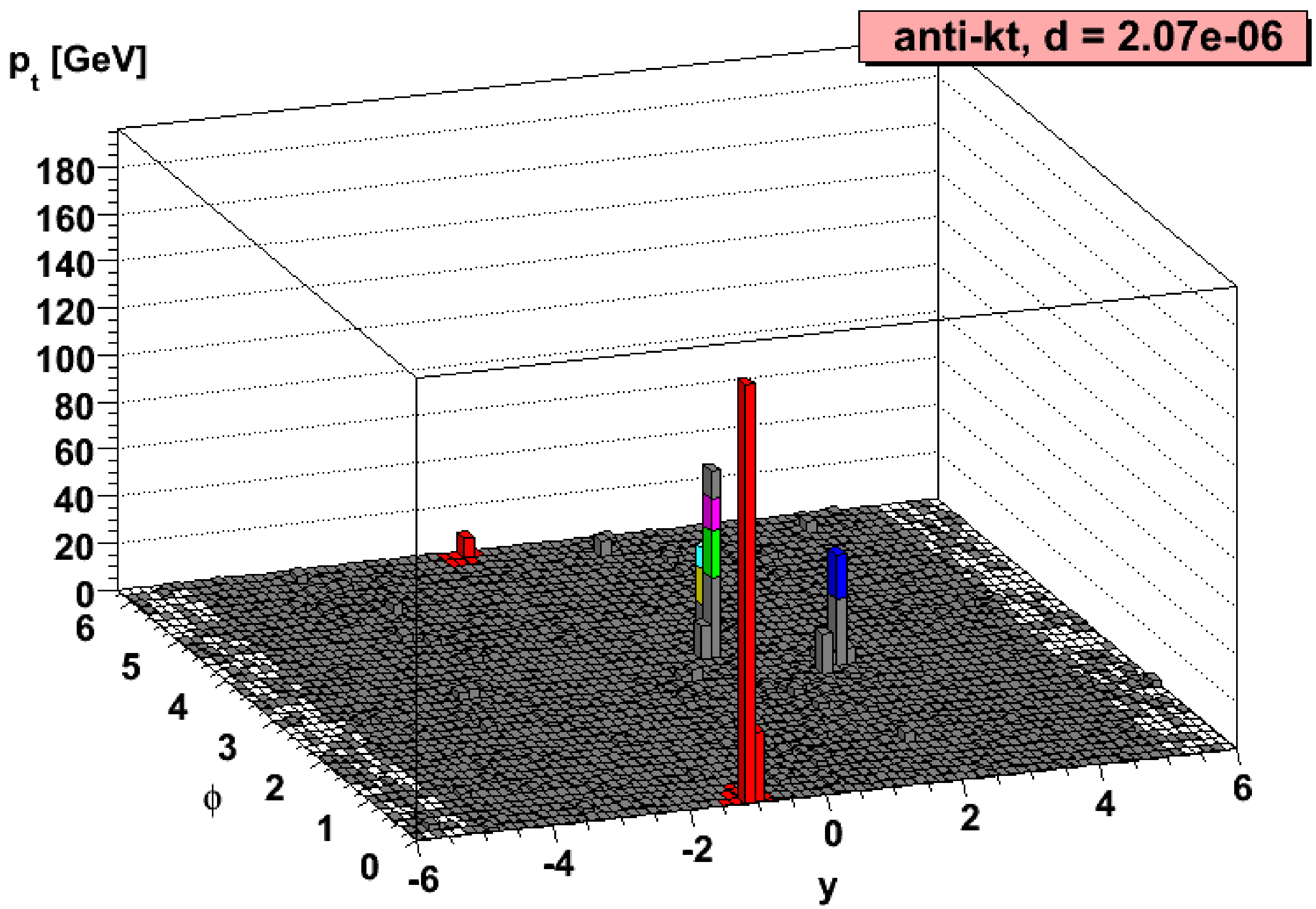

The anti-k$_t$ jet algorithm

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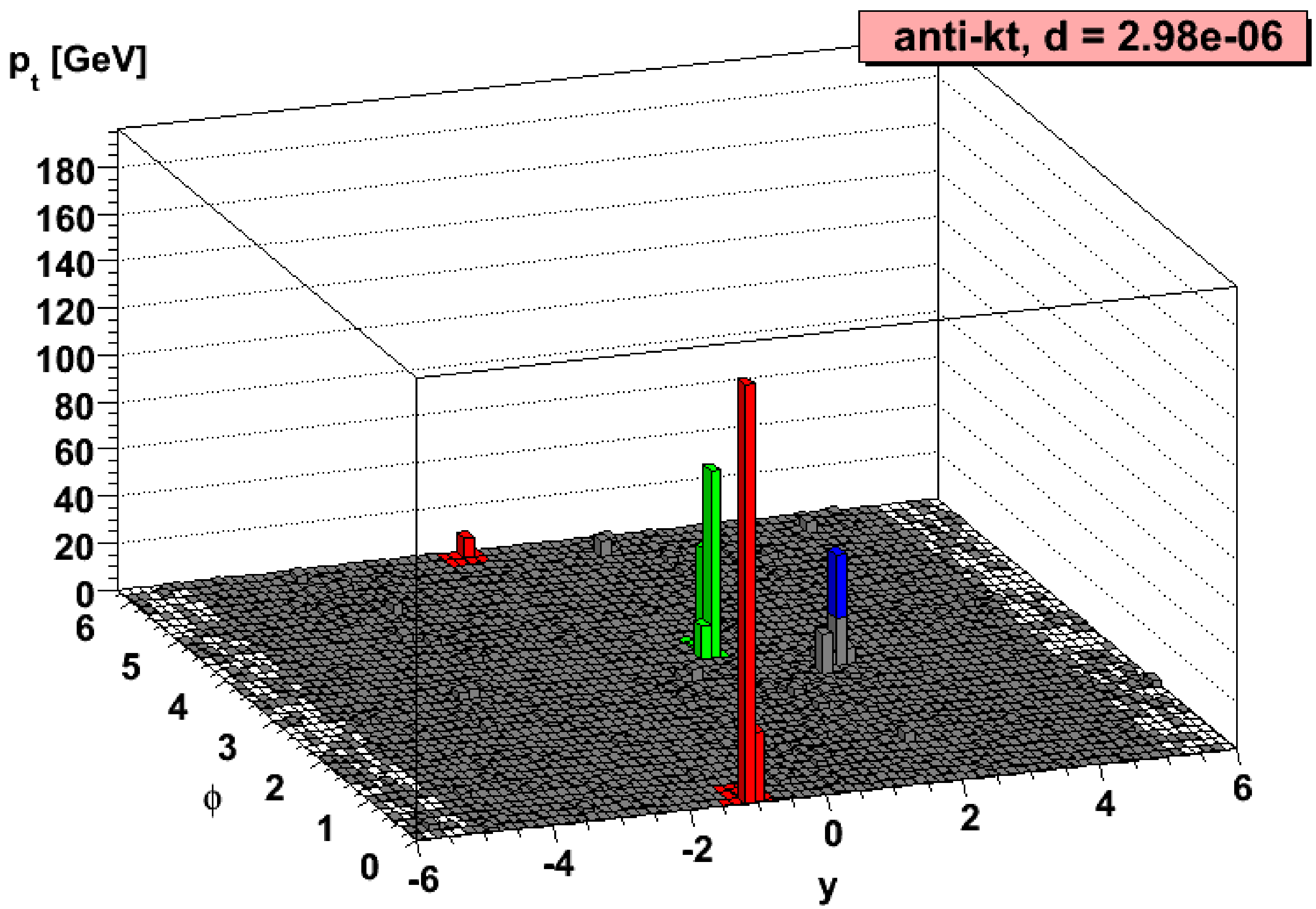

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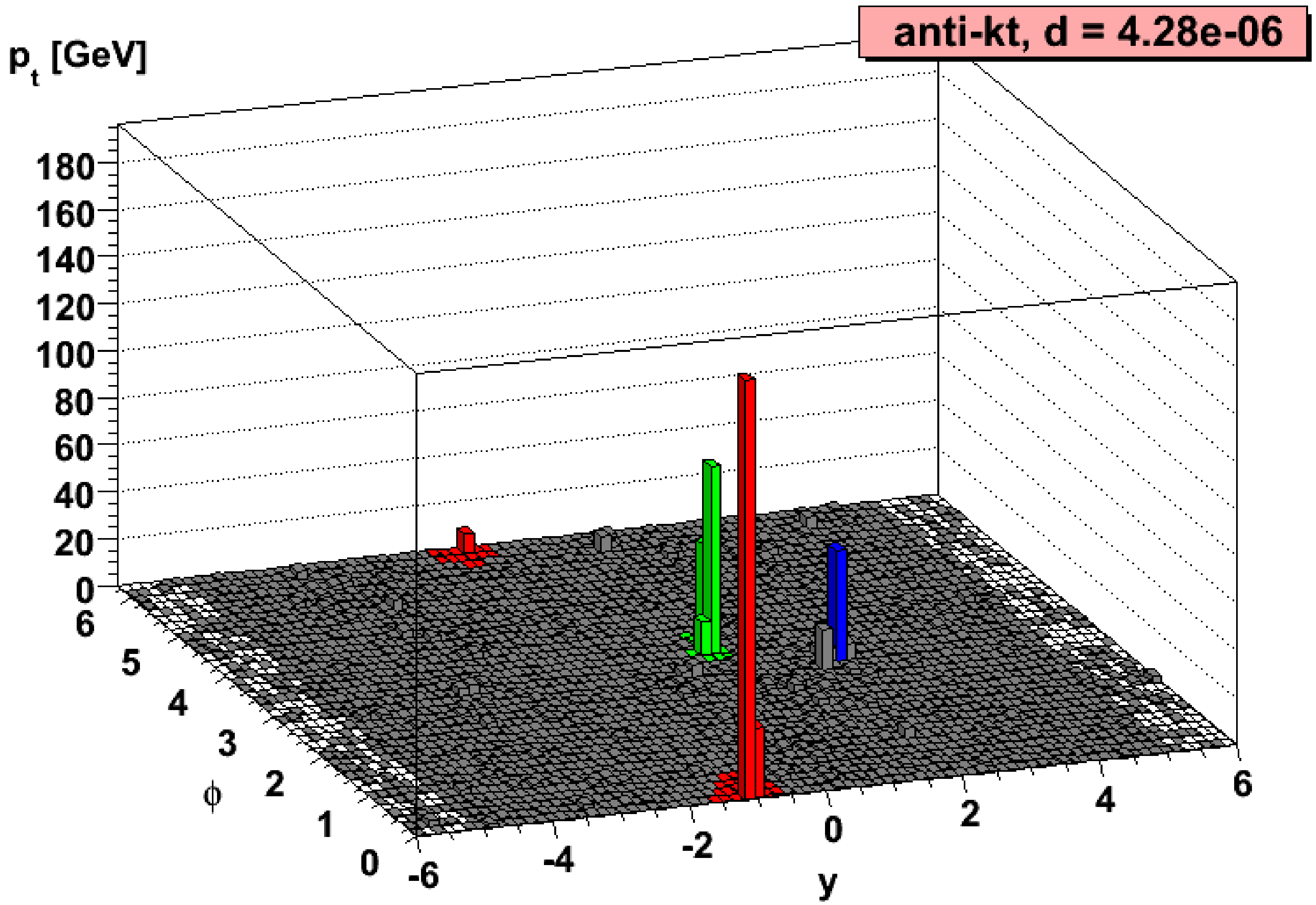

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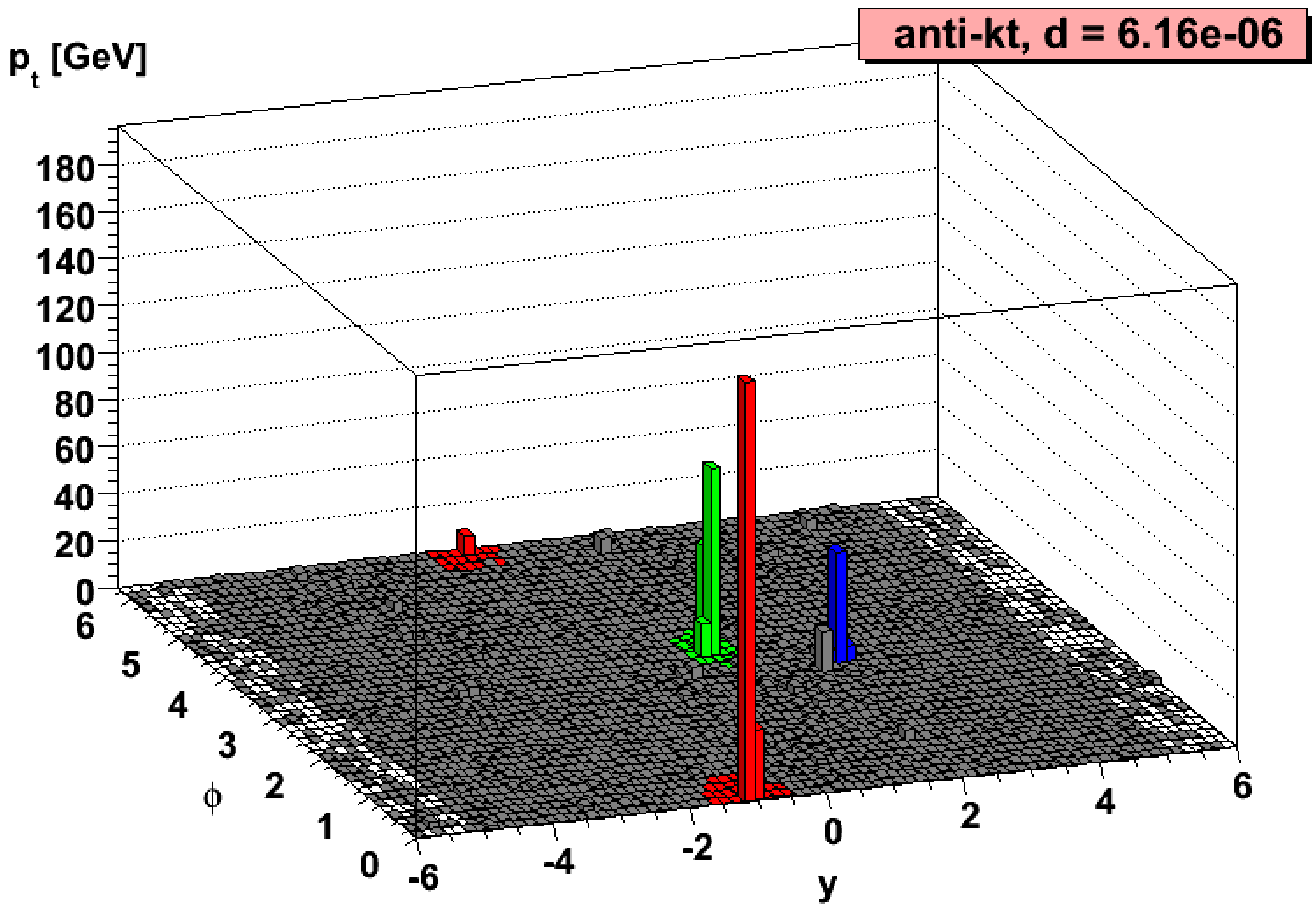

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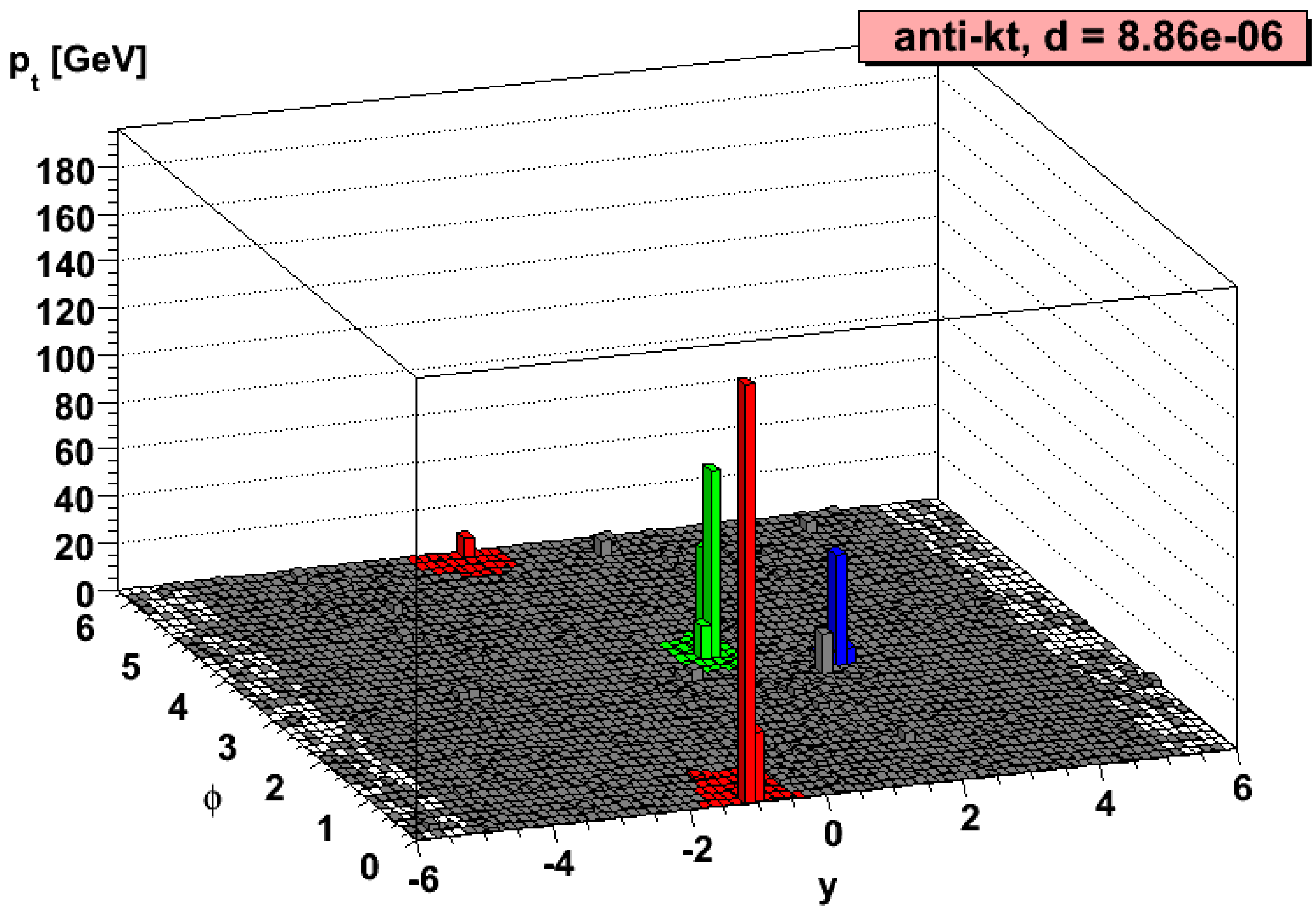

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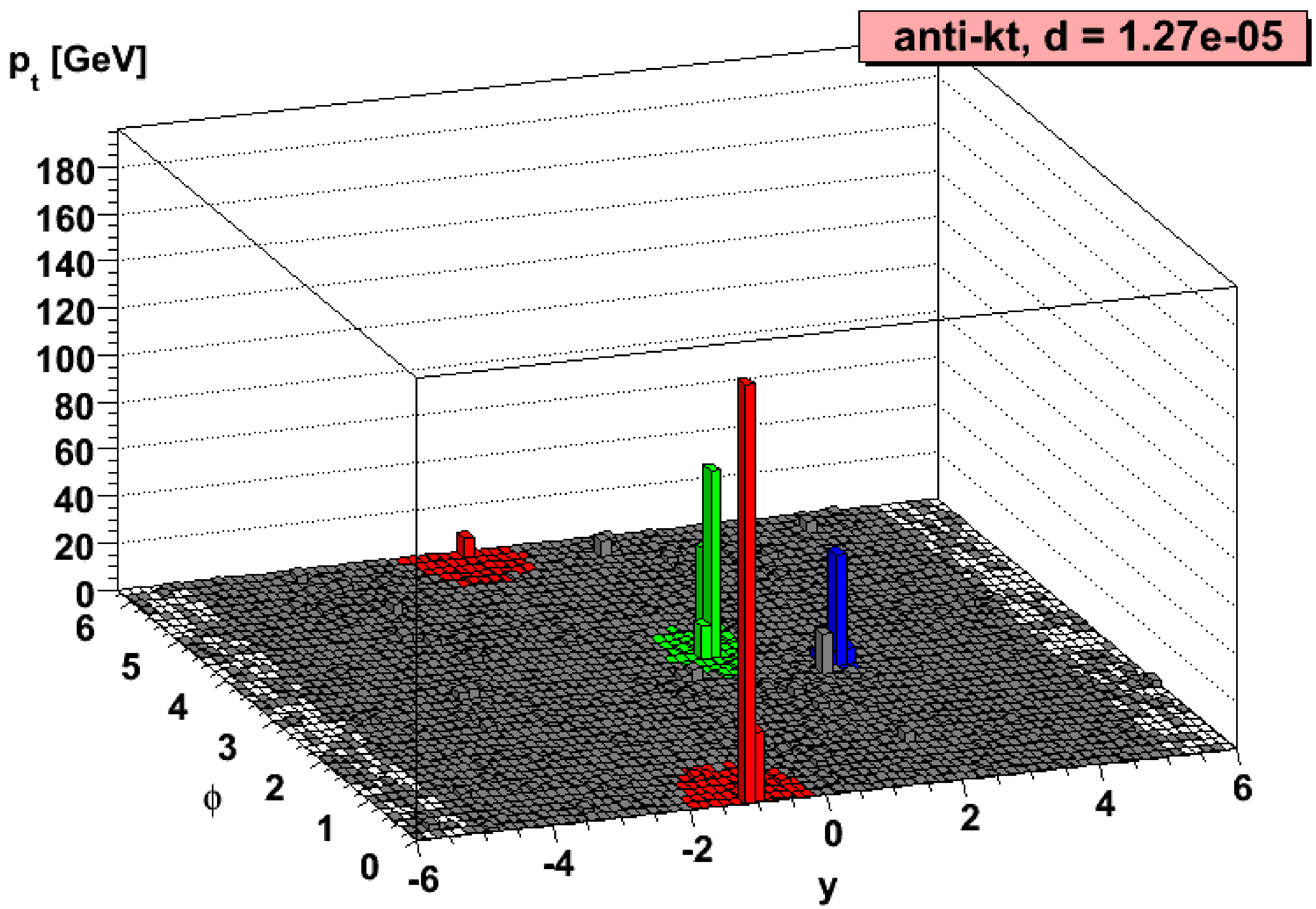

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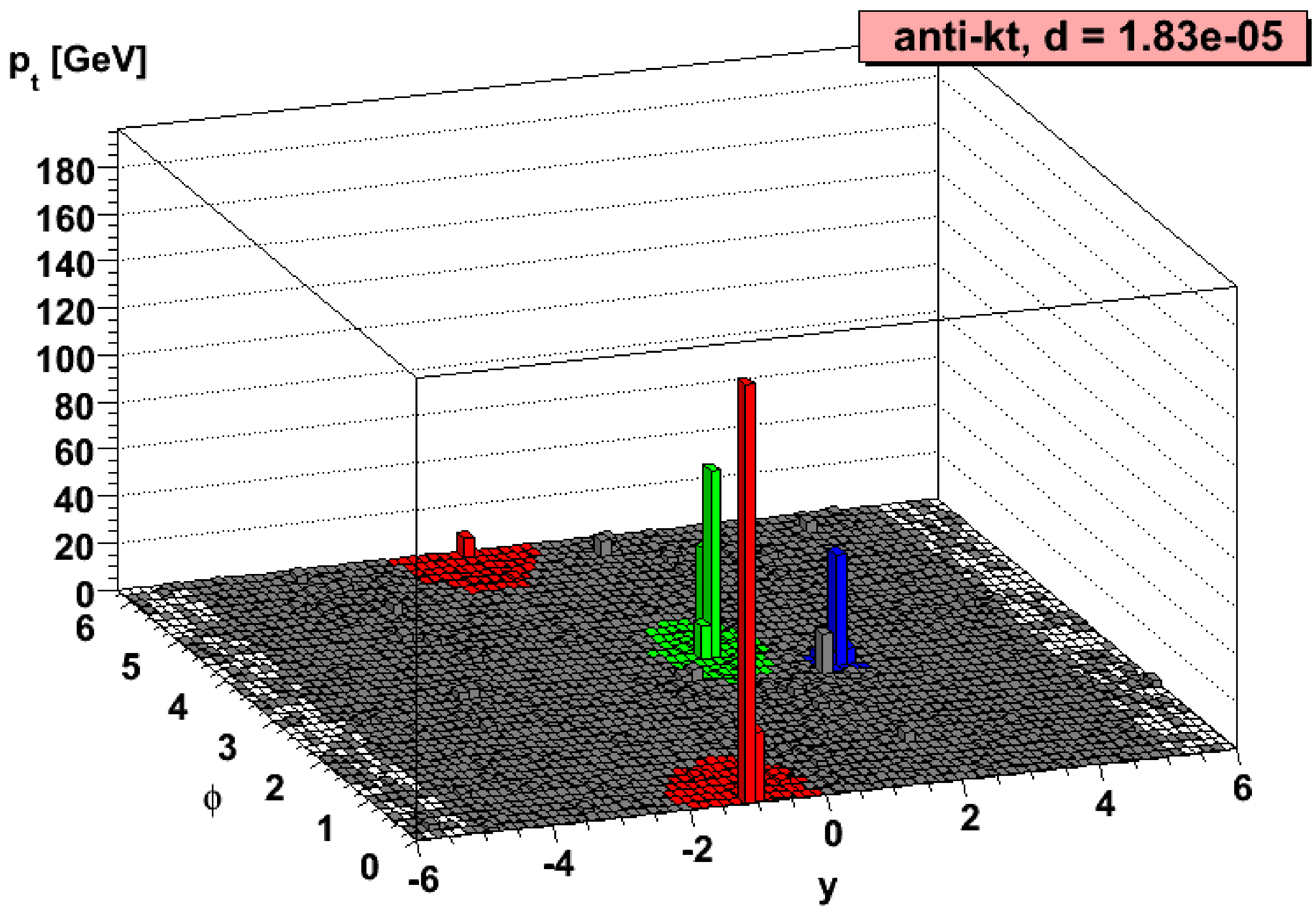

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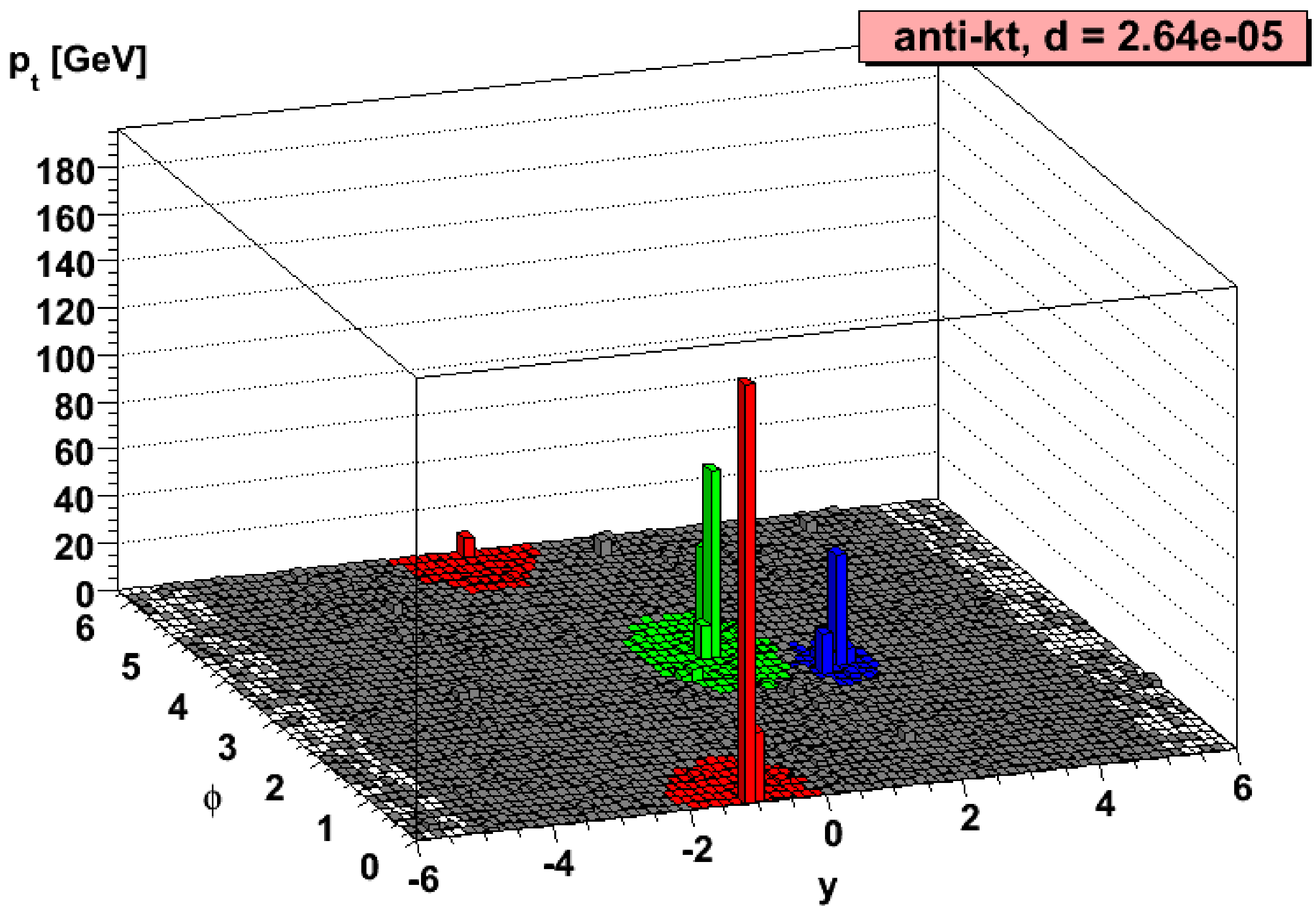

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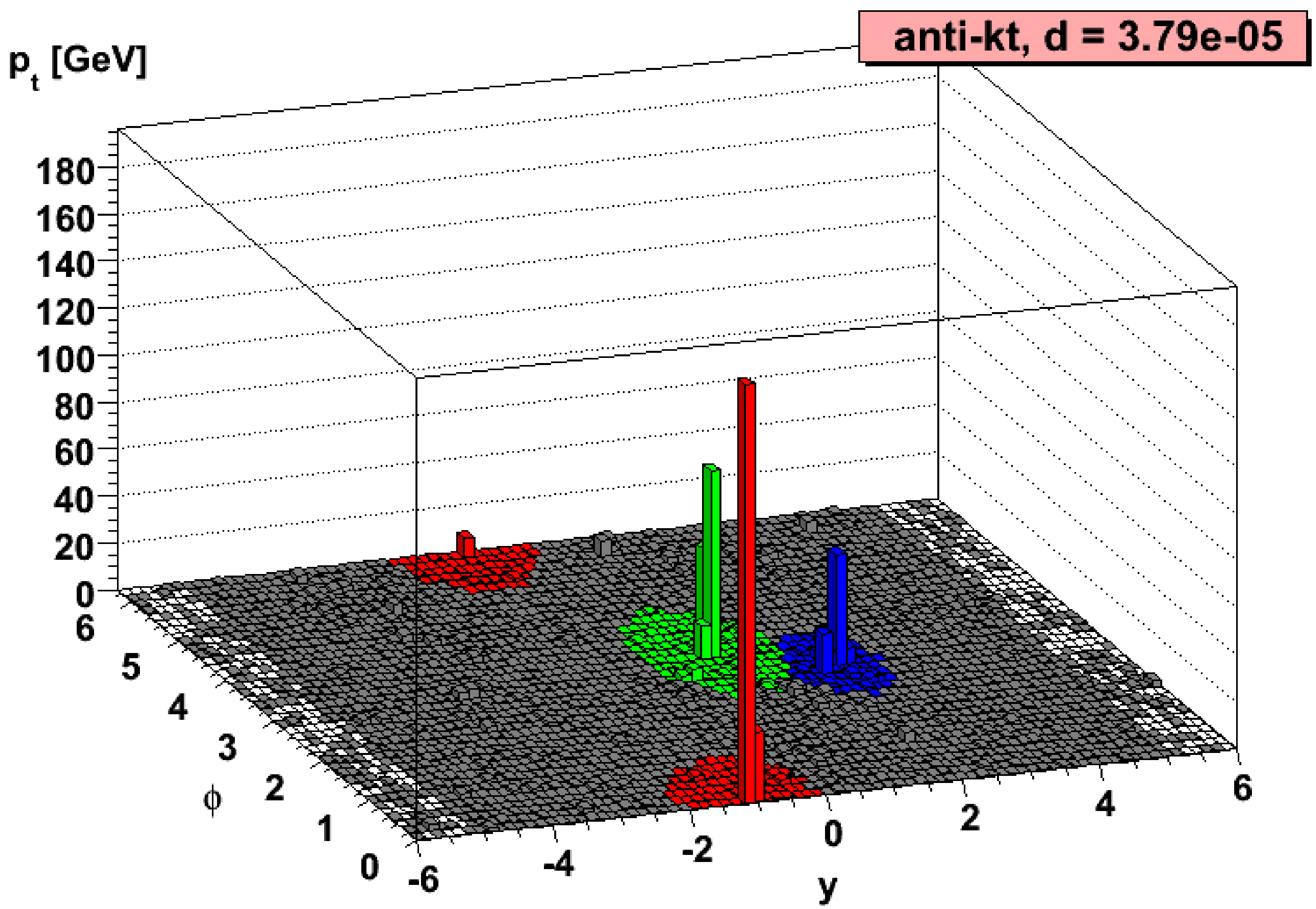

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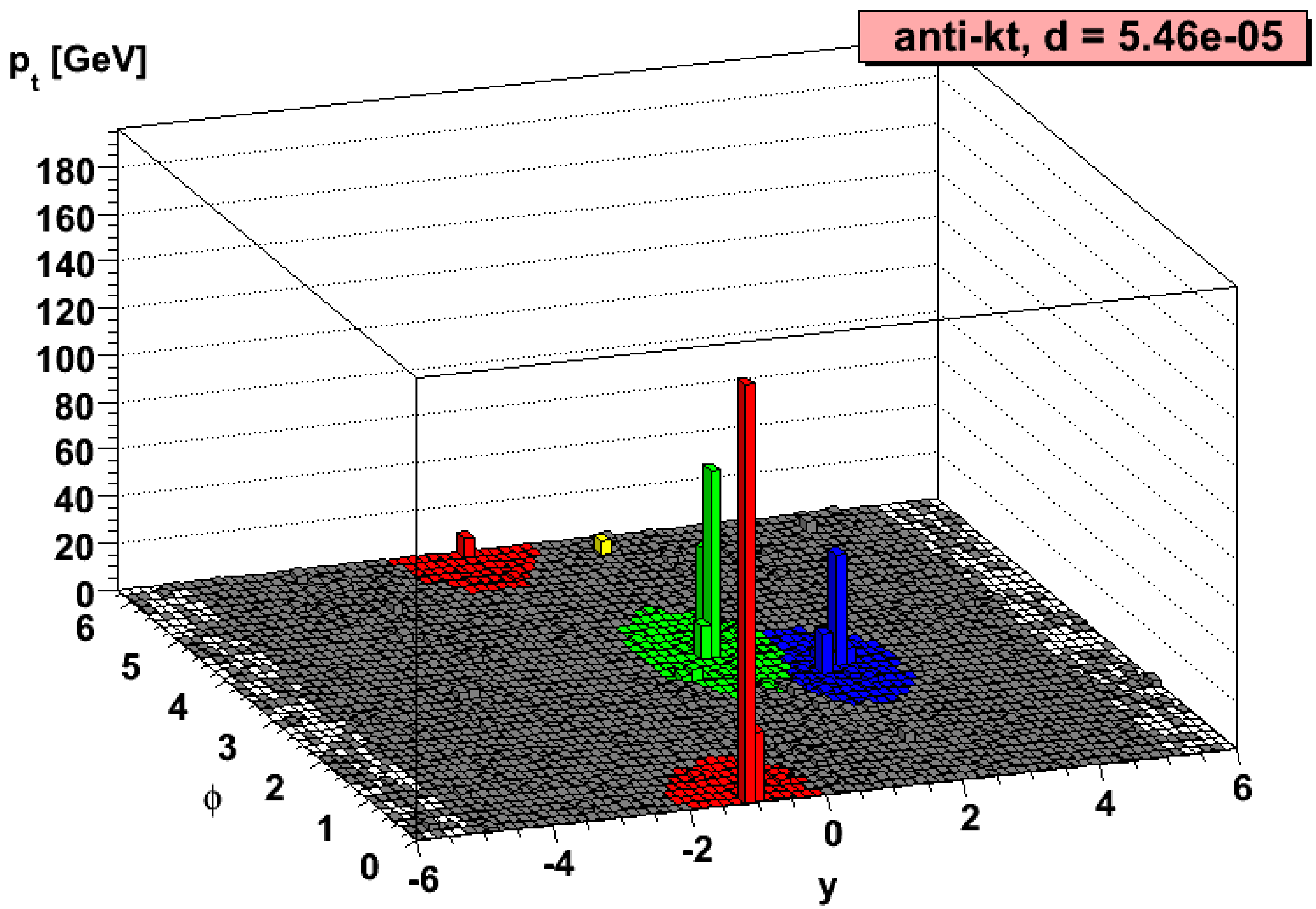

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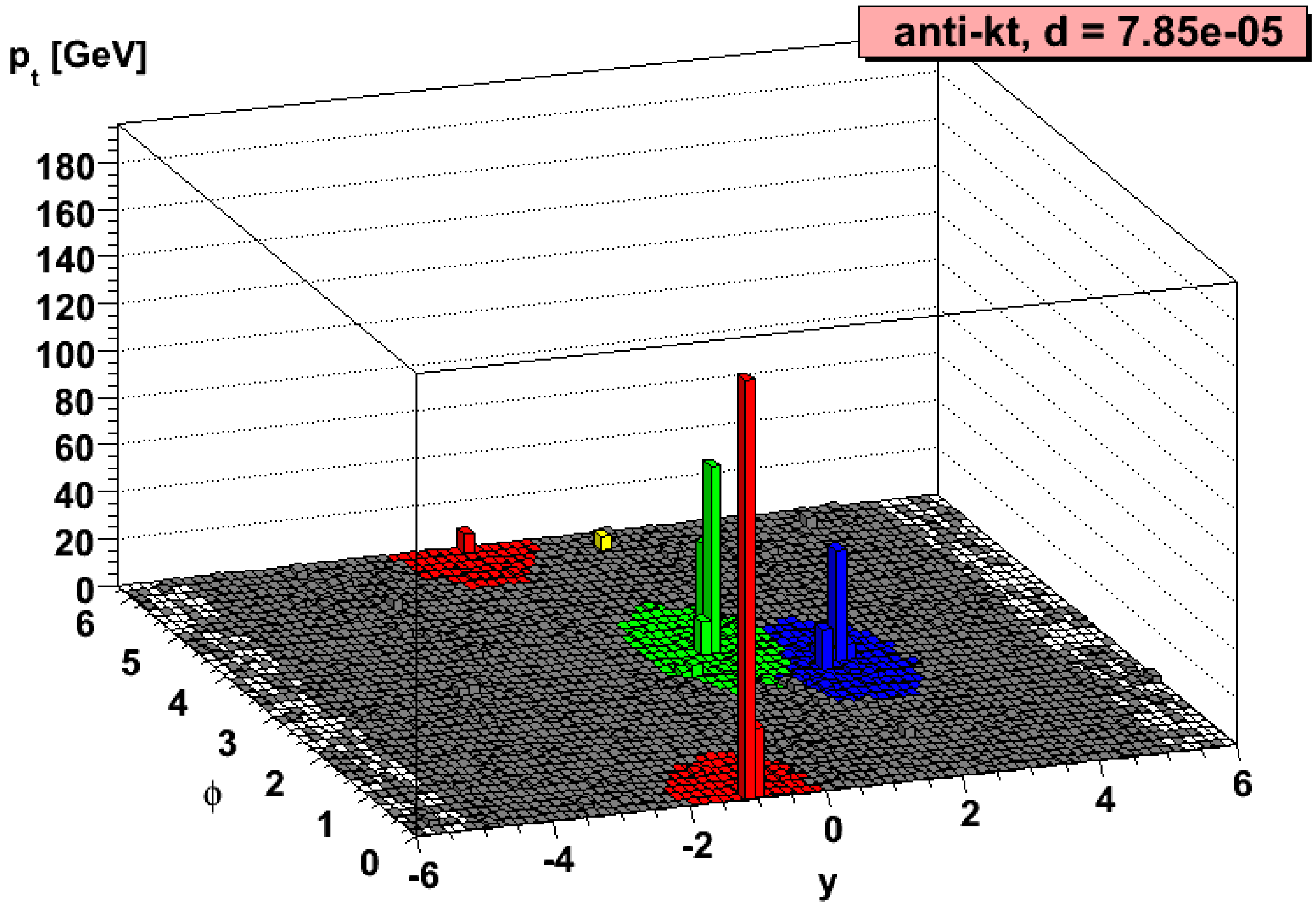

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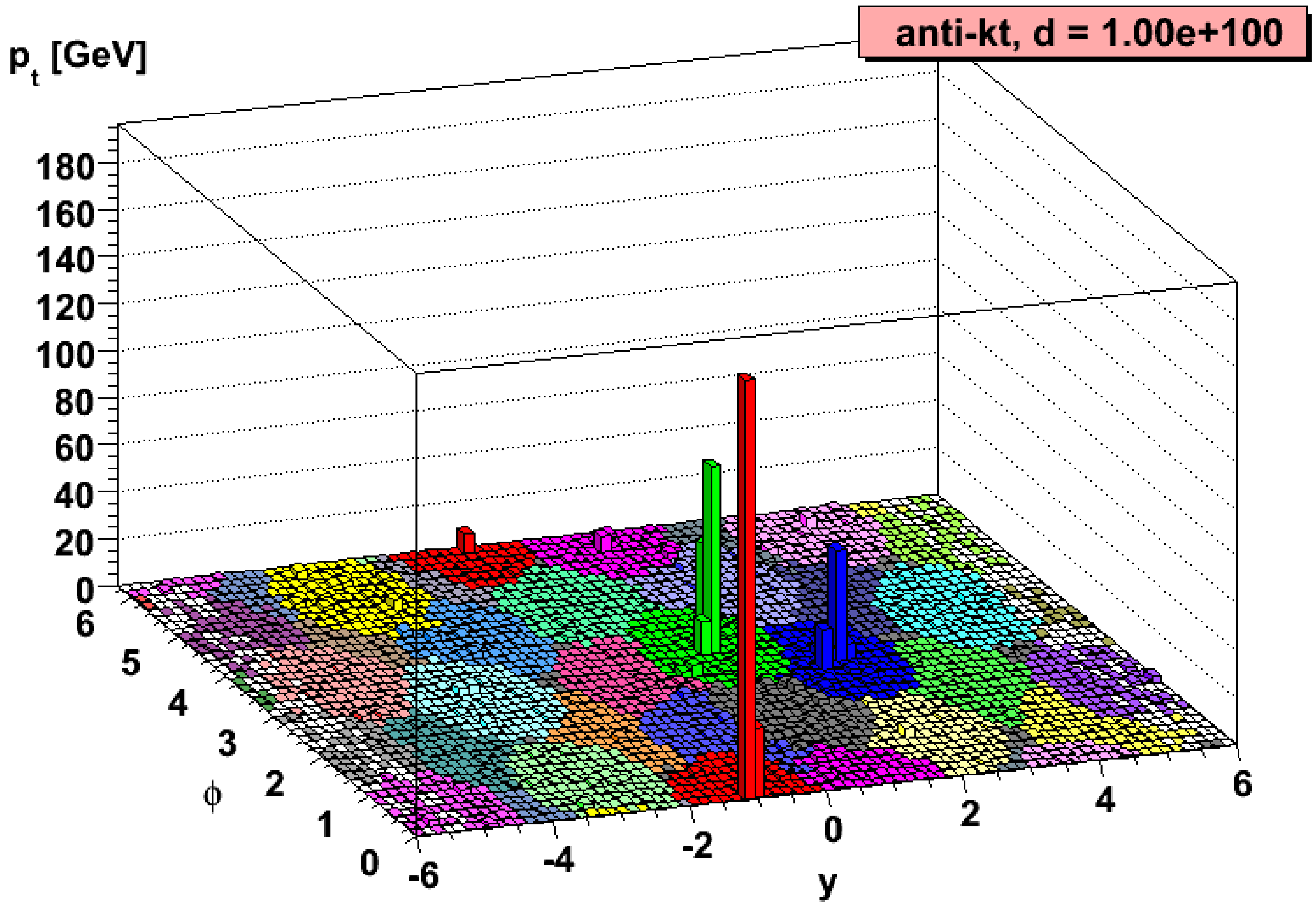
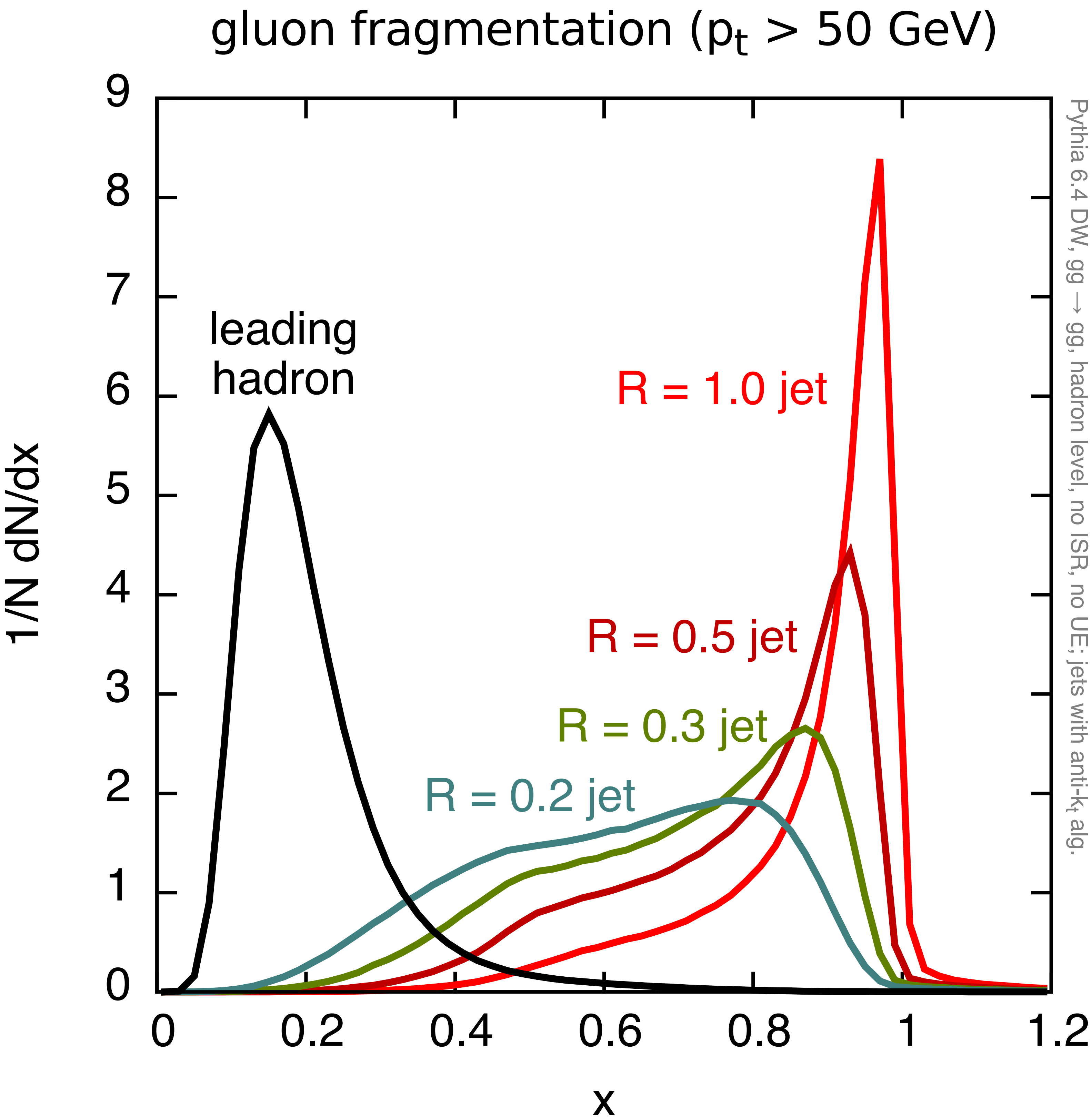
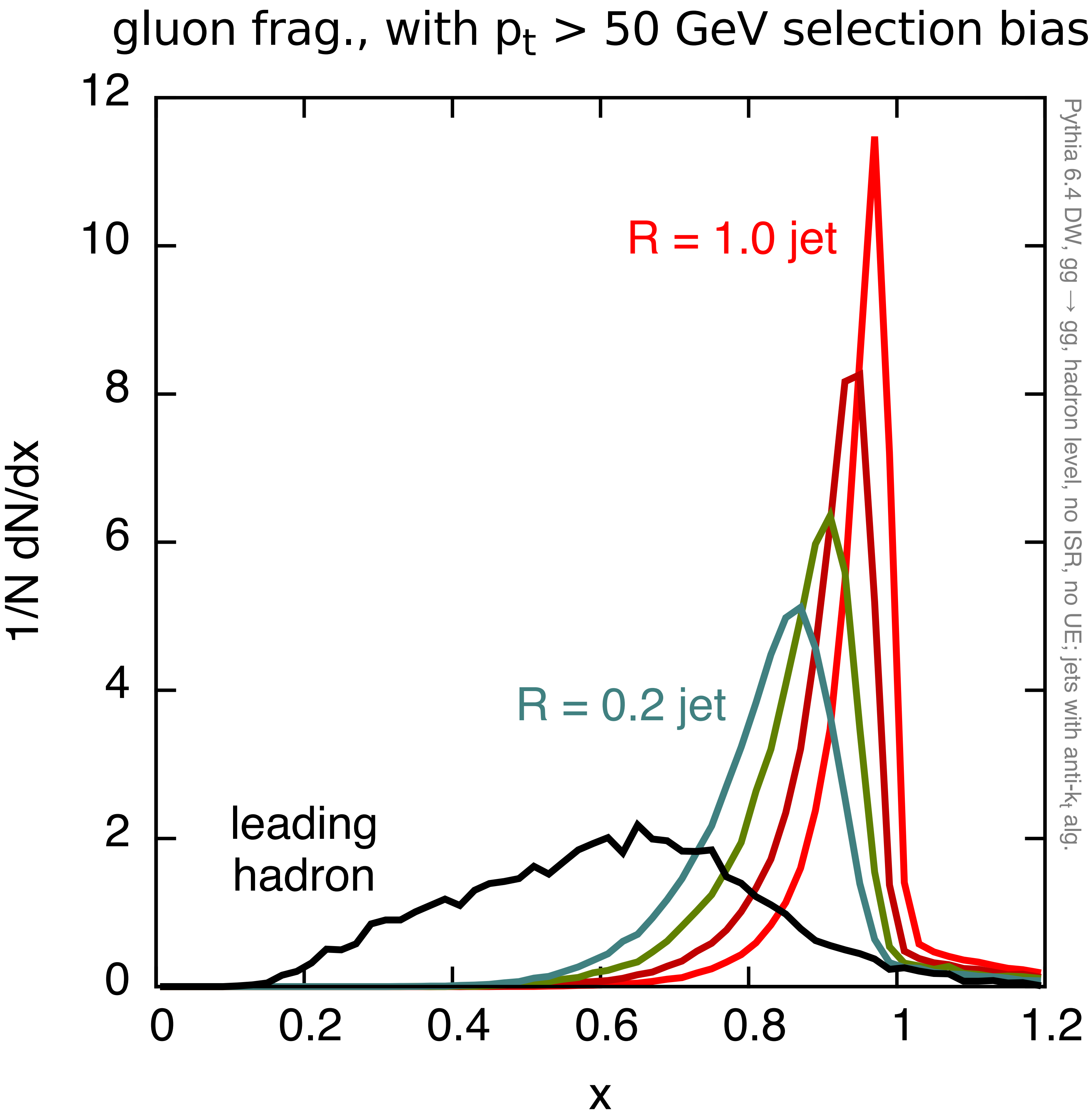


Anti-k_t gives cone-like jets (without using stable cones)



Fraction of a (Pythia) gluon's energy that finds its way into a jet, or into the jet's leading hadron

[p_t selection applied to original parton]



Fraction of a (Pythia) gluon's energy that finds its way into a jet, or into the jet's leading hadron

[p_t selection applied to **reconstructed jet/ hadron**]

The core ingredients

A jet definition

Background characterisation

Background removal

Unfolding

Background properties

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

Background subtraction methods

	ALICE [FastJet area/median method]	**ATLAS**	**CMS** [Iterative Cone Subtraction]
Background estimated in	whole detector [optionally: jet neighbourghood]	η strips	η strips
Hard jets excluded from bkgd estimate	by median	by p_t cut	by p_t cut
Flow corrections	no [unless use jet neighbourhood]	yes	no
Subtract bkgd from	jets [after jet clustering]	towers [after jet clustering]	towers [before jet clustering]
Noise suppression	no	no	yes [subtract ρ+σ from each tower, suppress -ve towers]

[If there are errors here, let me know!]

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[If there are errors here, let me know!]

Background subtraction

- If this is your definition of a jet
  - ➡ Energy clustered in a jet reconstruction algorithm above the uncorrelated underlying event
- Then all jets appearing the final measurement should be excluded from the background and anything not in a jet should be included in the background
  - This is hard to get exactly right
  - ➡ Goal should be to minimize the bias in the background determination
- Two scenarios
  - I. A jet is mistakenly included in the background
  - II. Something that is not a jet is excluded from the background

ATLAS EXPERIMENT

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Tuesday, February 12, 13

6

I'm not sure there can be unambiguous separation between jets and background.

You can tune the p_t cut to "work" for one centrality class.

But it will probably introduce biases for others **(E.g. imagine using a 20 GeV separation cut in pp collisions)**

[we played a lot with p_t cuts while developing the median/area method and could never get something that satisfied us]

All background estimation methods have biases

Analytical quantification of those biases brings insight:

That means you know order-of-magnitude of effects to expect and how they scale with method's parameters

E.g. for median/area method in Cacciari, GPS & Sapeta '09

O(1 GeV)

$$\langle \rho_{\text{ext}} \rangle \simeq \rho - \boxed{\frac{\sigma^2}{\rho}} \frac{1}{8R^2} + 1.8\sigma R \frac{N_{\text{hard-jets}}}{A_{\text{tot}}}$$

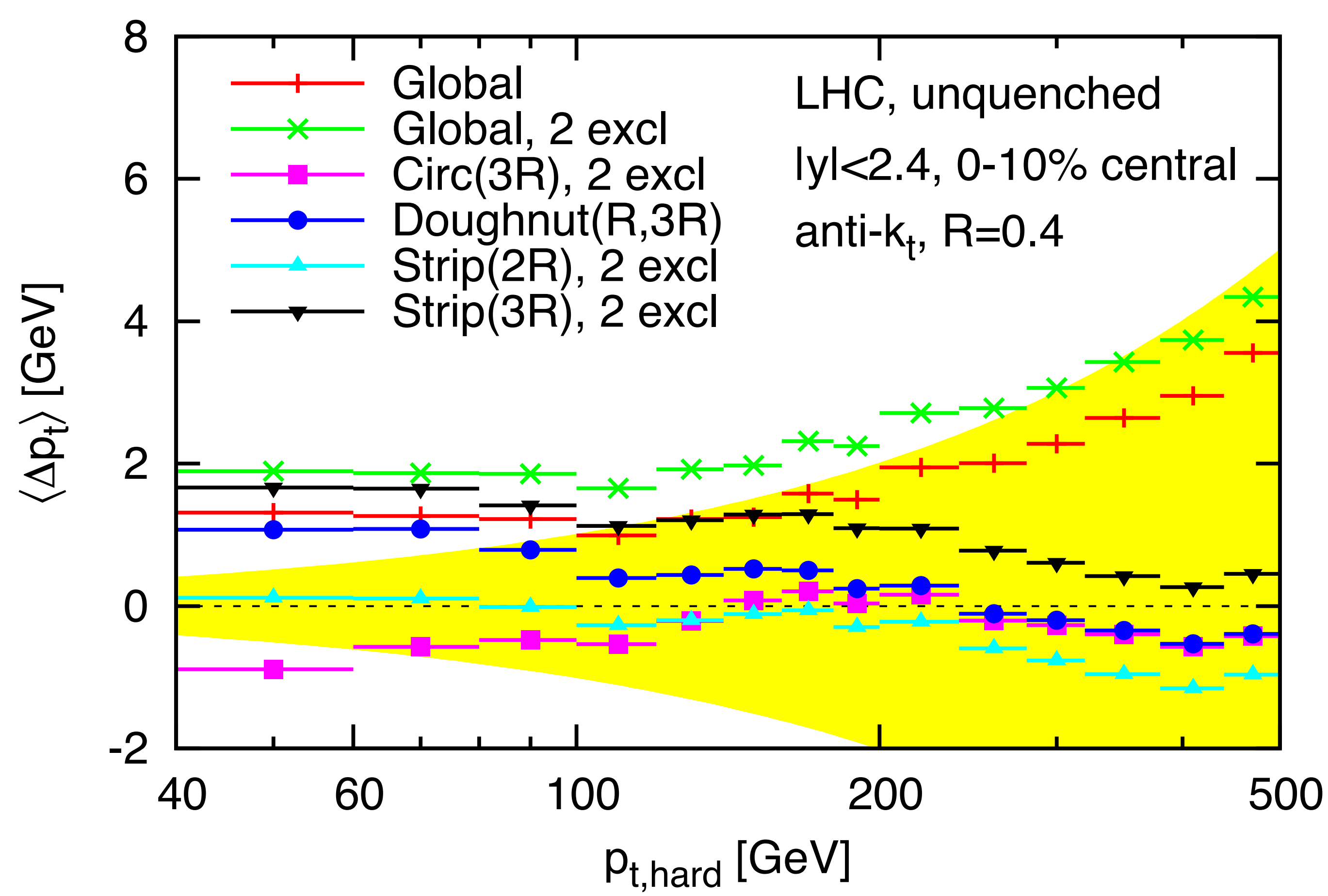
N of jets harder than bkgd fluctuations [~O(α_s) for HIC]

Total area of bkgd estimation region

Those biases are (mostly) independent of jet p_t

They decrease in absolute terms as background vanishes

In practice, numerically modest



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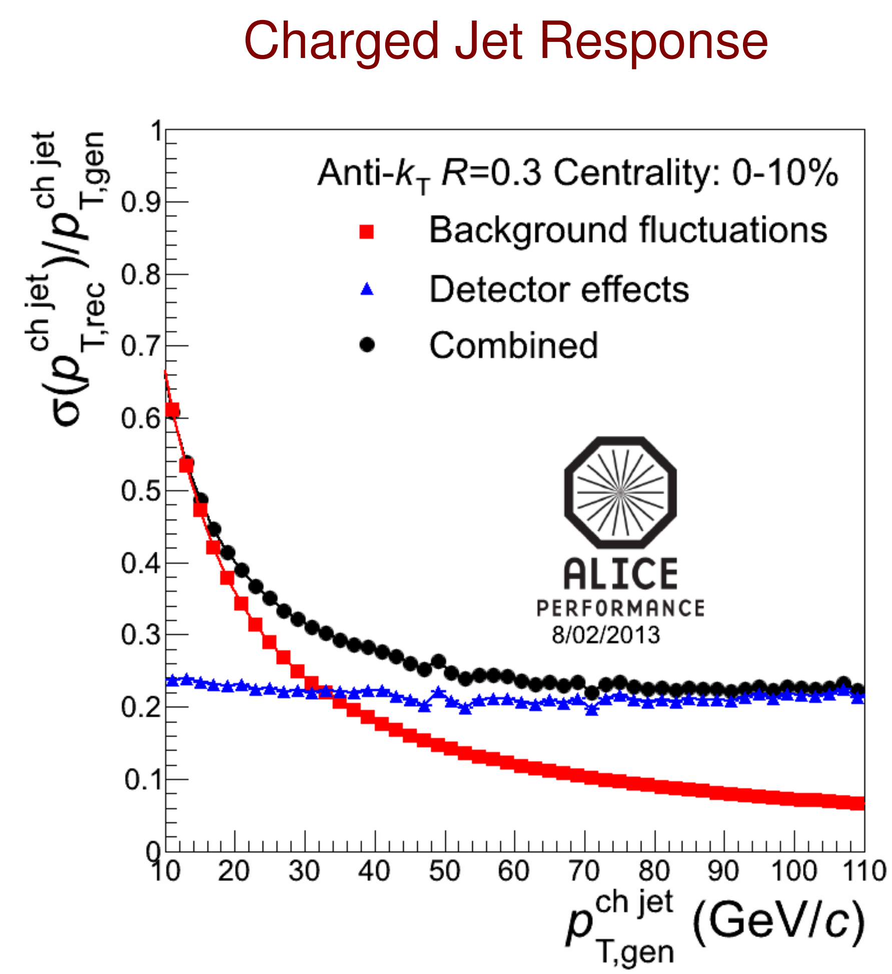
[If there are errors here, let me know!]

Why do noise reduction?

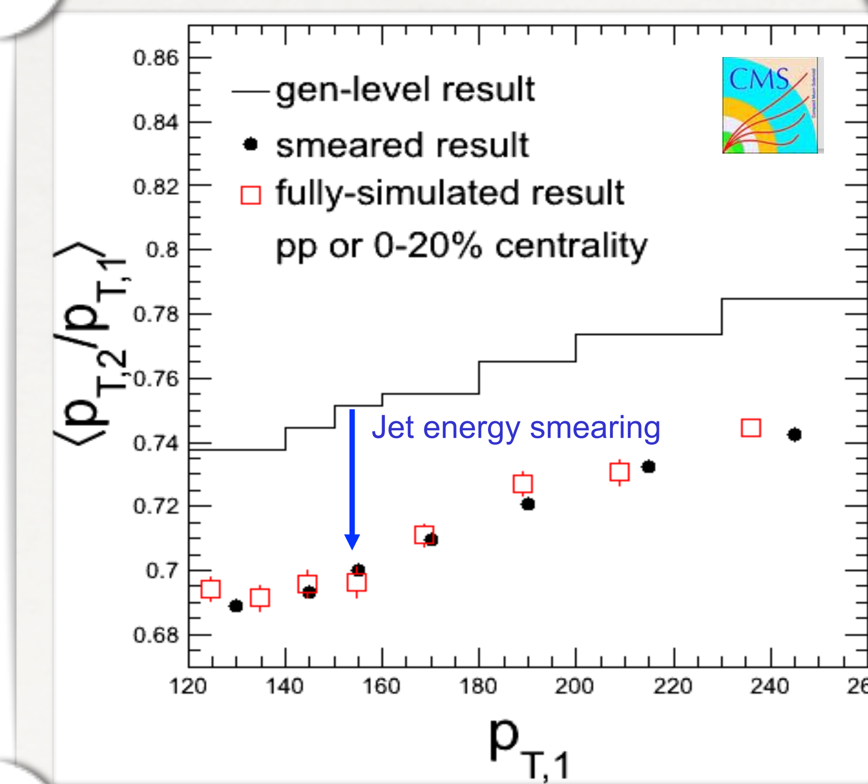
Jet p_T resolution

- Detector effects and Background Fluctuations: Partially compensating effects
  - At low p_T background fluctuations dominate
  - At high p_T detector effects dominate
- Correction done all at once via unfolding



Marta Verweij Jet Quenching Workshop CERN 14

Because bkgd fluctuations often induce major distortions of results



Iterative Cone Subtraction bias

Smaller fluctuations:

MC, Salam, Soyez, 1101.2878

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

[About 1/4 of usual fluctuations (real-life not quite so good!)]

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

~ 100 GeV !!!

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

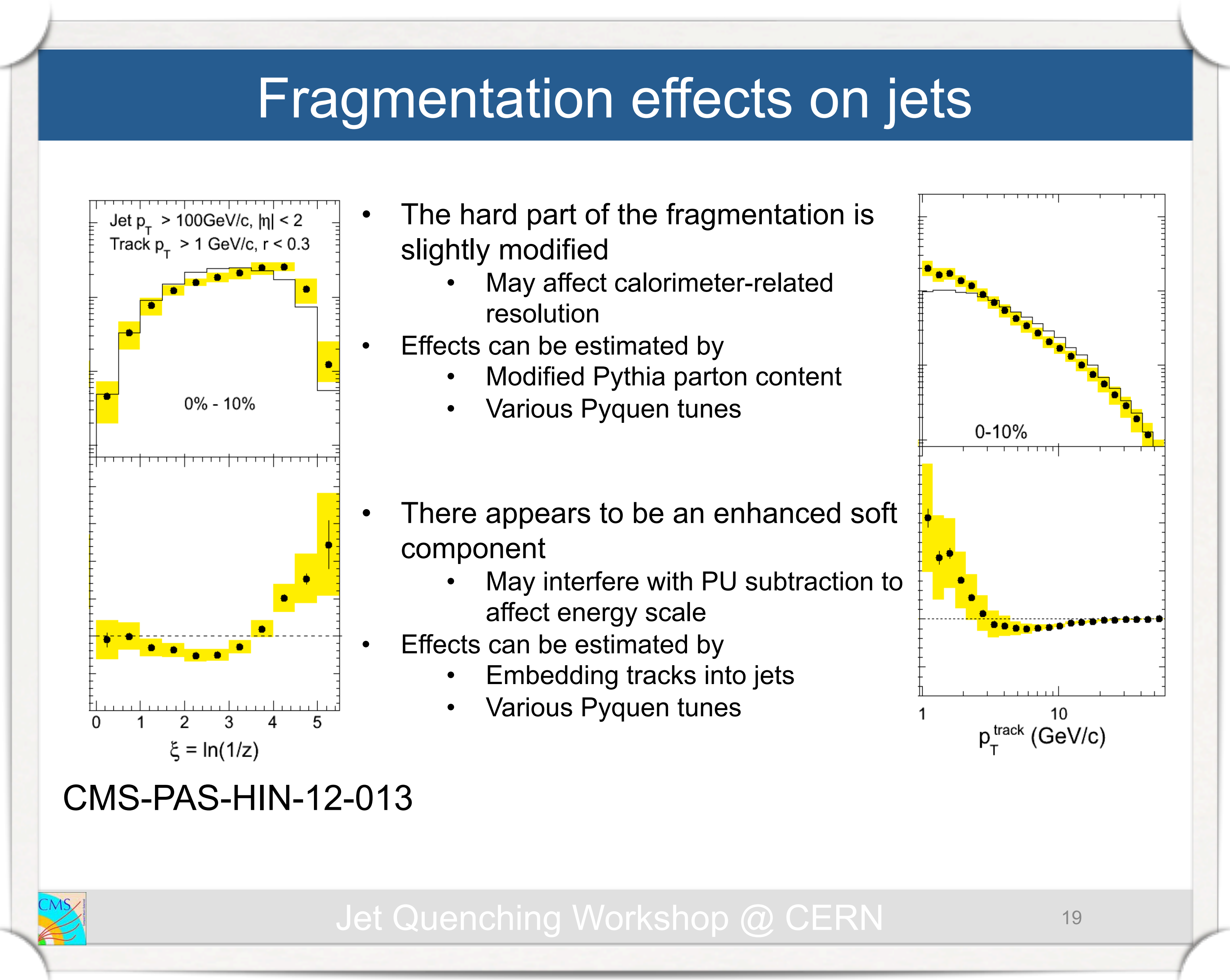
Only positive background fluctuations are kept

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

Do noise-reduction biases matter in practice?



There are differences between vacuum and in-medium fragmentation.

But they appear not to be huge.

And modelled acceptably by PyQuen

Are under control for now?

You still need to ask if Pyquen gets the correct spatial distribution of extra soft emissions, but overall difference in fragmentation is moderate, ~1-2 tracks per jet

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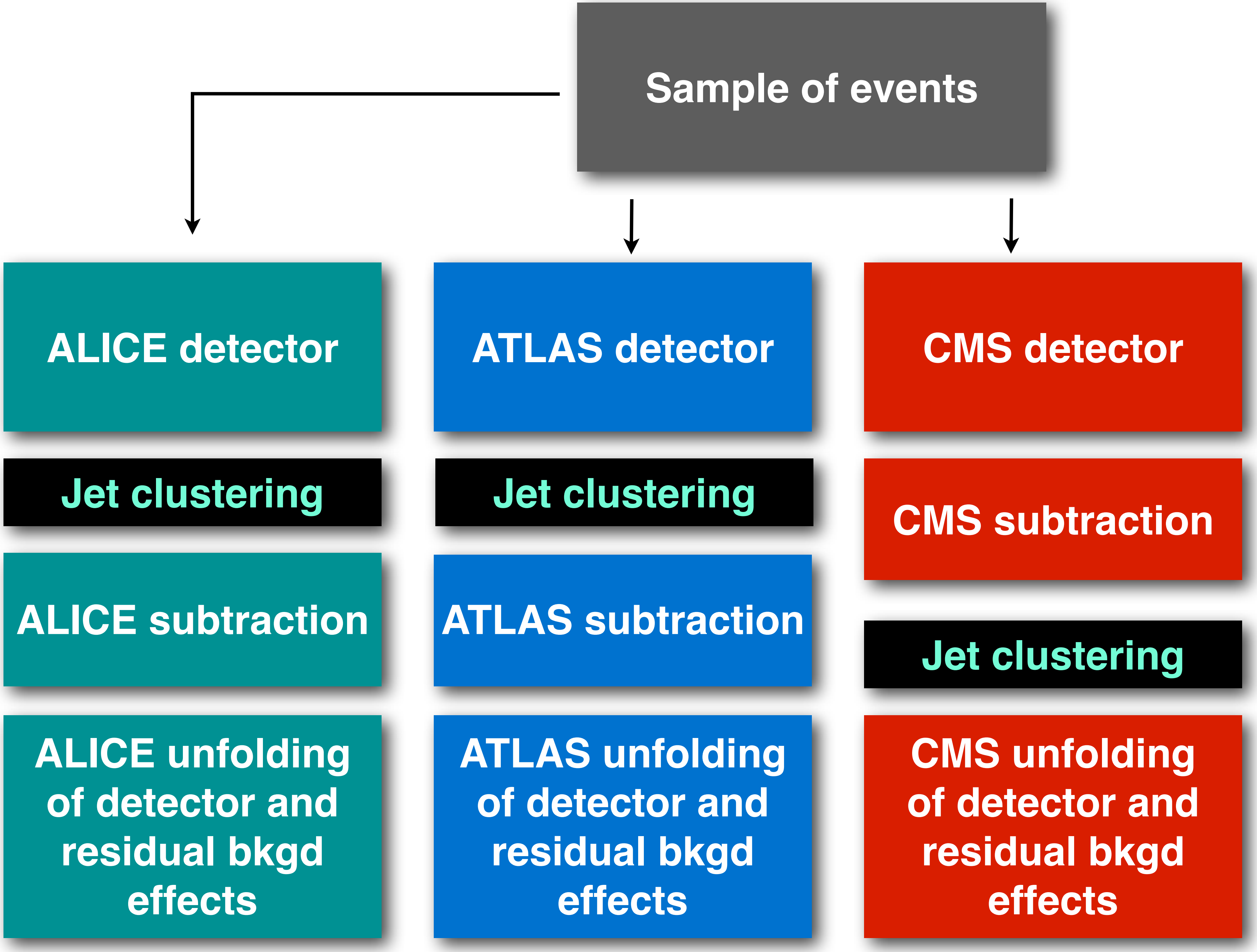
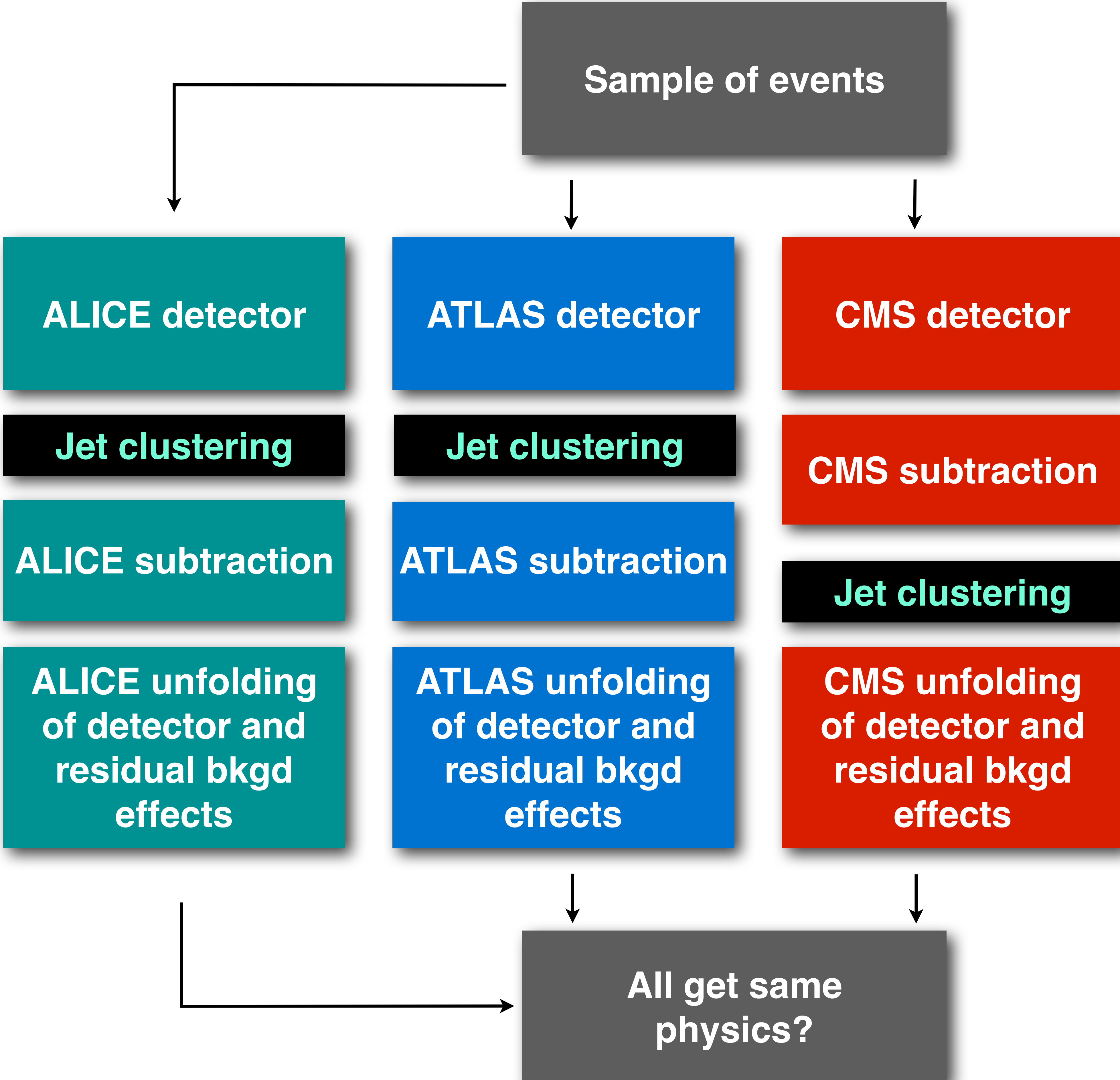


Does it matter that each experiment uses different subtraction, with different systematics?

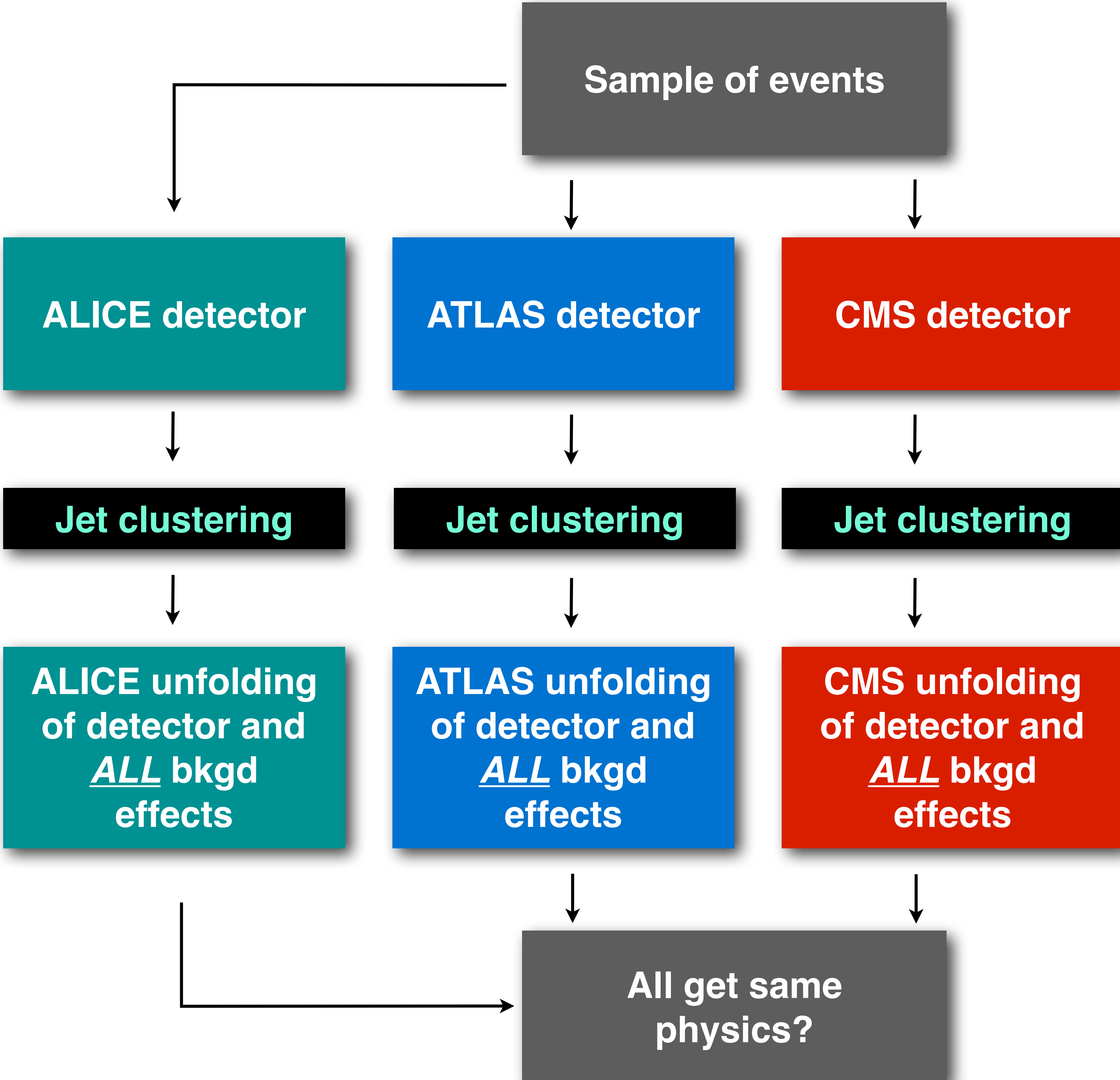
If unfolding is meaningful and done correctly, then it should eliminate all differences between subtractions and detectors.



Does it matter that each experiment uses different subtraction, with different systematics?

If unfolding is meaningful and done correctly, then it should eliminate all differences between subtractions and detectors.

This is what should be checked systematically
[for a common jet R choice]



You could even do away with subtraction altogether!

Unfolding would still be possible, but harder and with larger dependence on the "unknowns" of the background.

Subtraction makes the unfolding easier, because it incorporates data-deduced info about the background

Using more info in subtraction

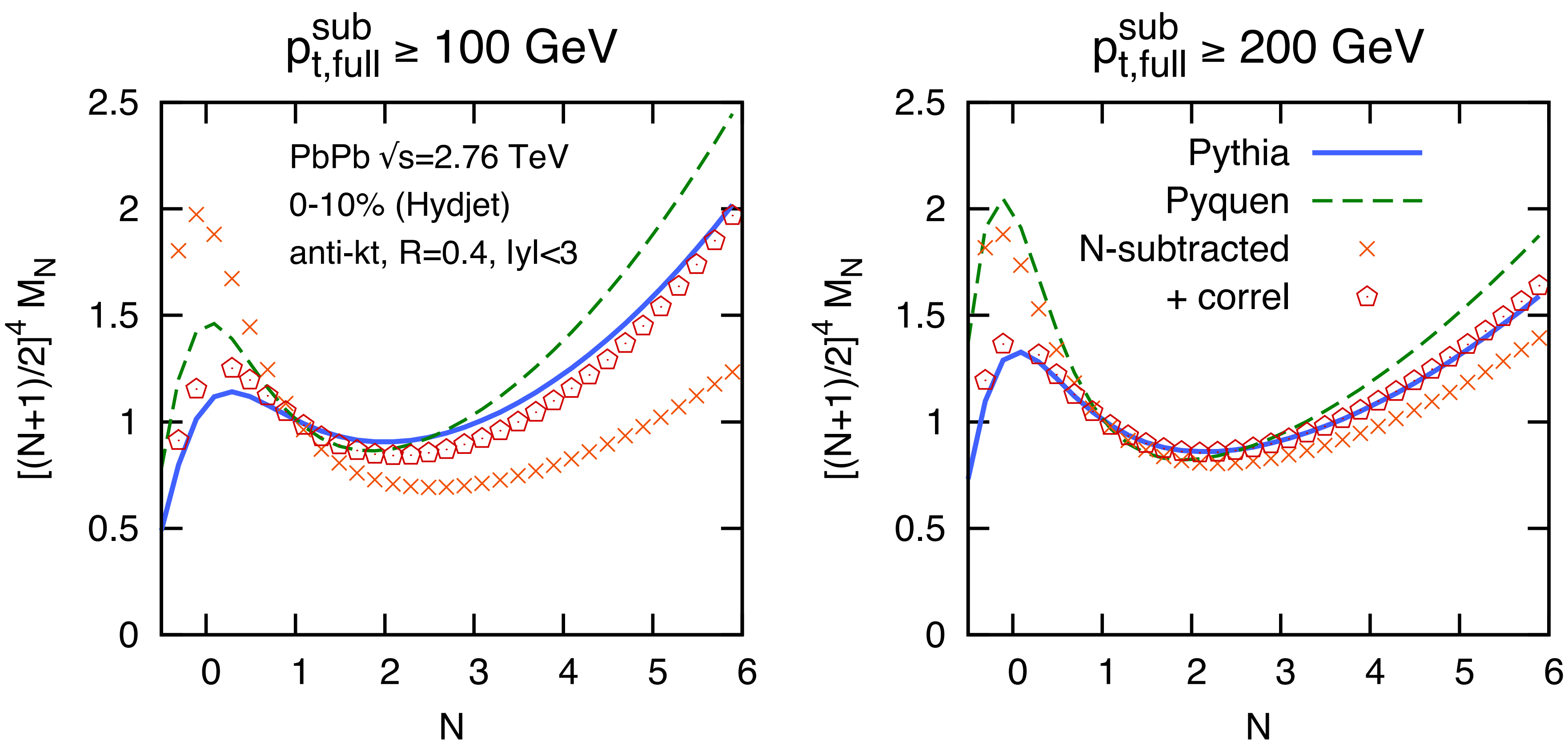
[as a way of further limiting the need for unfolding]

Jet fragmentation-function moments in HI

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

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

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



Improvement: from the orange crosses to the red circles

using a new measurable quantity r_N – correlation between N^{th} and 1^{st} moments of background fluctuations

Cacciari, Quiroga, GPS & Soyez '12, http://fastjet.hepforge.org/contrib

Subtraction as a *definition* of the jet–background distinction

[or: should we be unfolding background effects at all?]

What do people do in pp?

It used to be standard practice to quote jet results with hadronisation and underlying event “removed”.

This was done by switching them on and off in Pythia or Herwig.

When people tried to use the data in later years, it quickly became clear that

- Old versions/tunes of MCs weren’t a perfect model of the UE.
- It often wasn’t clear which precise tunes had been used in Pythia and Herwig – so there was no way of “uncorrecting” back to hadron level.
- As a result the value of the data was “lost”

Nowadays, experiments always quote **“particle-level”** as their main result, i.e. what would be measured with a perfect detector.

Unfolded results in HI are *not* particle-level results

They inevitably involve a model where one

- takes a model for the "jetty" event
- takes a model for the background (or actual experimental events)
- embeds one in the other

But the separation of jet and UE is **not physical**.
(Think elastic scattering of jet parton off medium parton)

Even with a perfect detector (or theory) there is no way of comparing to the experimental result without putting in additional unphysical assumptions.

As a result, the 2.76 TeV data may, even on a short timescale, lose all but "qualitative" value.

A possibly unrealistic proposal?

Carry out a fully reproducible analysis

- formulated exclusively in terms of event particles
- may use a subtraction procedure as a **definition** of the separation between “hard” part of jet and “background contamination”.
- unfolding should only serve to eliminate detector imperfections

[probably more easily done for track-based measurements]

This completely eliminates issues of as-yet poorly understood “jet-background correlations” in the measurement, and leaves data in form that is good for the long-term.

[and nothing stops experiments from also unfolding for residual background effects in some well-described approx.]

Summary

Practical considerations

- Part of the discussion is about confidence building
- Are possible systematics in subtraction and unfolding well understood?
- Does the "pp-unfolded" results come out the same regardless of how one does the background subtraction? [Within one experiment?]
- If different experiments take the same jet definition do they get the same answer (R_{AA}, etc.)?

Formal considerations [→ future years' practical considerations]

- Subtraction provides a **prescription** for what you mean by the background versus the jet
- The usual "unfolding" eliminates the prescription and takes you back to an ill-defined starting point

EXTRAS

Jet reconstruction

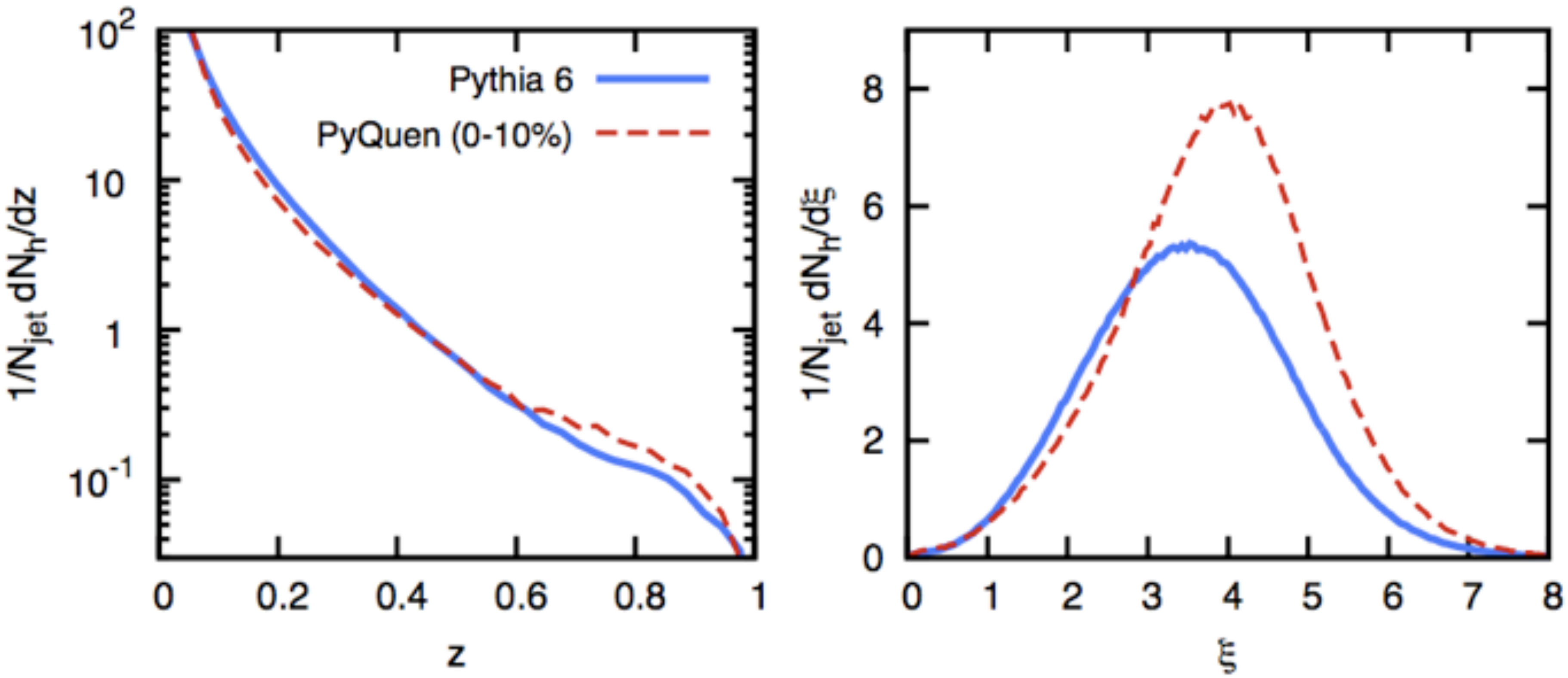
HYDJET **simulations**		ρ (GeV) (y=0, 0-10%)	σ (GeV)	σ_ρ (GeV)	σ_{jet} (GeV) (anti-k_t, R=0.4)
RHIC		100	8	14	
LHC 5.5 TeV		310	20	45	18
LHC 2.76 TeV	all	250	**18**	36	**16**
	charged only	147	**12.5**	22	**11.3**

[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 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

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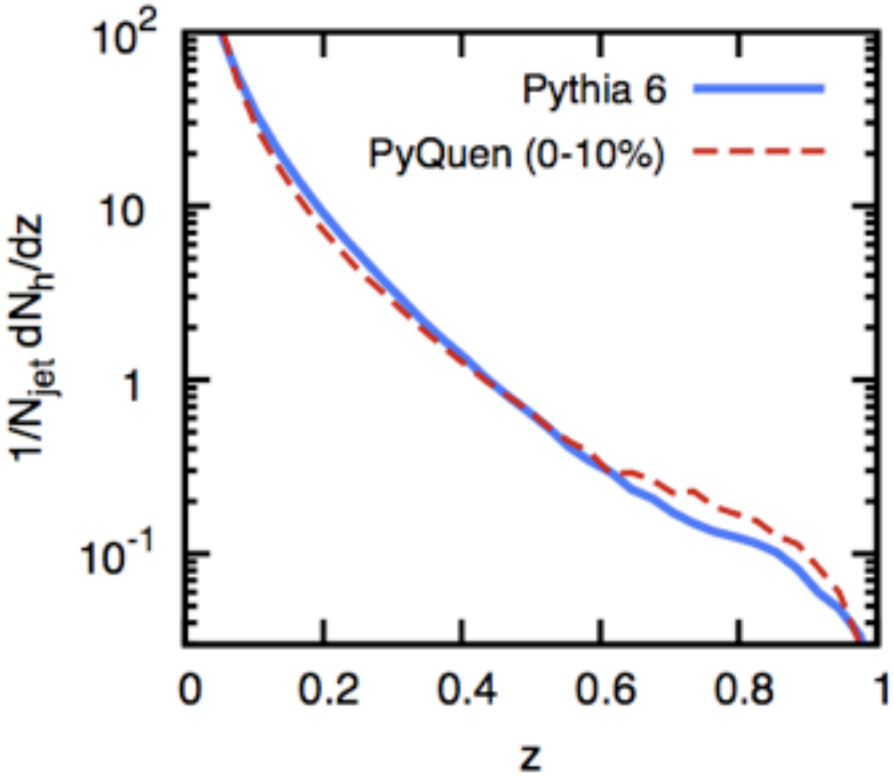

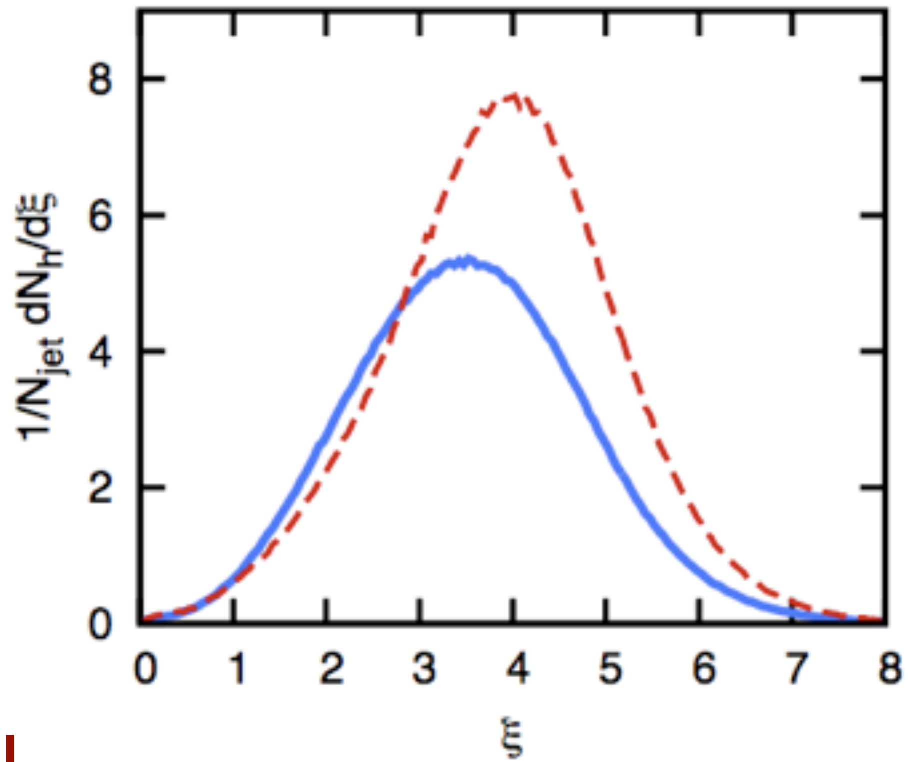

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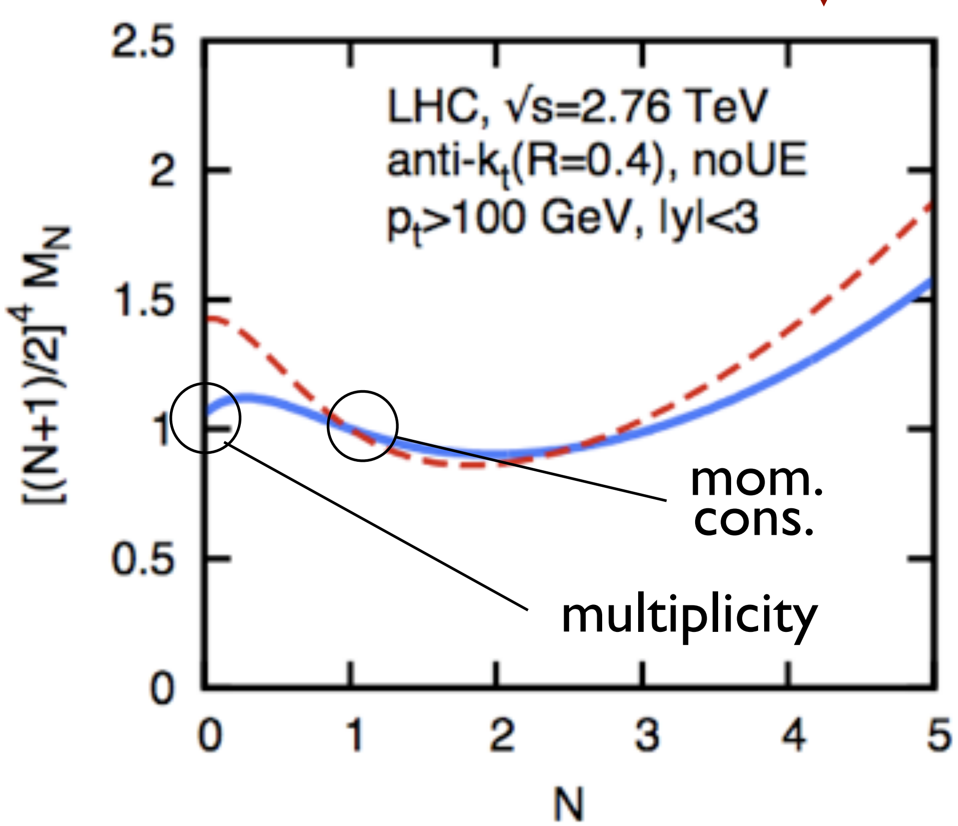


Step 1: go from momentum fraction distributions to **moments**

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

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

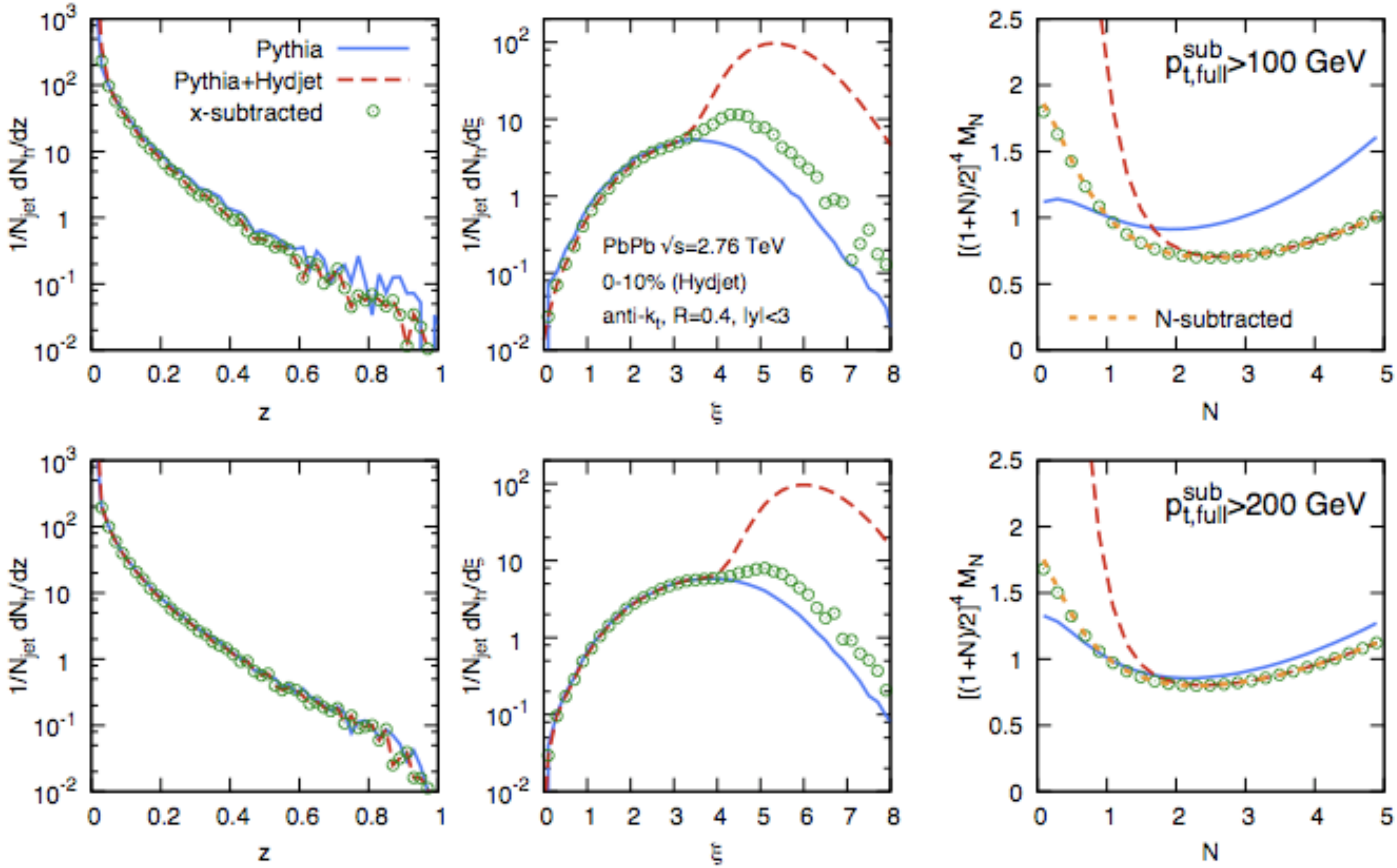
Step 2: alongside the usual ρ, extract from the background the quantities

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

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

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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 $$H(p_t) \equiv \frac{d\sigma}{dp_t} = \frac{\sigma_0}{\mu} \exp(-p_t/\mu)$$

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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

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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