

# Thoughts on jet reconstruction in heavy-ion collisions

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Based on work with Paloma Quiroga, Sebastian Sapeta & Gregory Soyez

Jet quenching: the interface between theory and experiment

CERN, 11-14 February 2013

# The questions I'll try to examine

[bearing in mind that I'm not an expert on heavy-ion physics]

Subtraction, its characterisation and systematics

Unfolding: what this even means  
(and how a pp physicist might react to it)

# Subtraction methods and their systematics

# Jet reconstruction

HYDJET simulations		$\rho$ (GeV) ( $y=0, 0-10\%$ )	$\sigma$ (GeV)	$\sigma_\rho$ (GeV)	$\sigma_{\text{jet}}$ (GeV) (anti-kt, $R=0.4$ )
LHC 2.76 TeV	all	250	<b>18</b>	36	<b>16</b>
	charged only	147	<b>12.5</b>	22	<b>11.3</b>
Data LHC 2.76 TeV		$\rho$ (GeV) ( $y=0, 0-10\%$ )	$\sigma$ (GeV)	$\sigma_\rho$ (GeV)	$\sigma_{\text{jet}}$ (GeV) (anti-kt, $R=0.4$ )
ALICE, charged only 1201.2423		138		18.5	<b>11.2</b>
CMS 1205.0206					<b>5.2</b> ( $R=0.3 + \text{NR}$ )
ATLAS 1208.1967					<b>12.5</b>

Only background-induced component, no calorimeter effects

While  $\sigma_{\text{jet}}$  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

	<b>ALICE</b> <small>[FastJet area/median method]</small>	<b>ATLAS</b>	<b>CMS</b> <small>[Iterative Cone Subtraction]</small>
Background estimated in	whole detector <small>[optionally: jet neighbourhood]</small>	$\eta$ strips	$\eta$ strips
Hard jets excluded from bkgd estimate	by median	by $p_t$ cut	by $p_t$ cut
Flow corrections	no <small>[unless use jet neighbourhood]</small>	yes	no
Subtract bkgd from	<b>jets</b> <small>[after jet clustering]</small>	<b>towers</b> <small>[after jet clustering]</small>	<b>towers</b> <small>[before jet clustering]</small>
Noise suppression	no	no	yes <small>[subtract <math>\rho + \sigma</math> from each tower, suppress -ve towers]</small>

[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**

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

[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

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

$O(1 \text{ GeV})$  ———  $\frac{\sigma^2}{\rho}$  ———  $\frac{1}{8R^2}$  ———  $N_{\text{hard-jets}}$  ———  $A_{\text{tot}}$

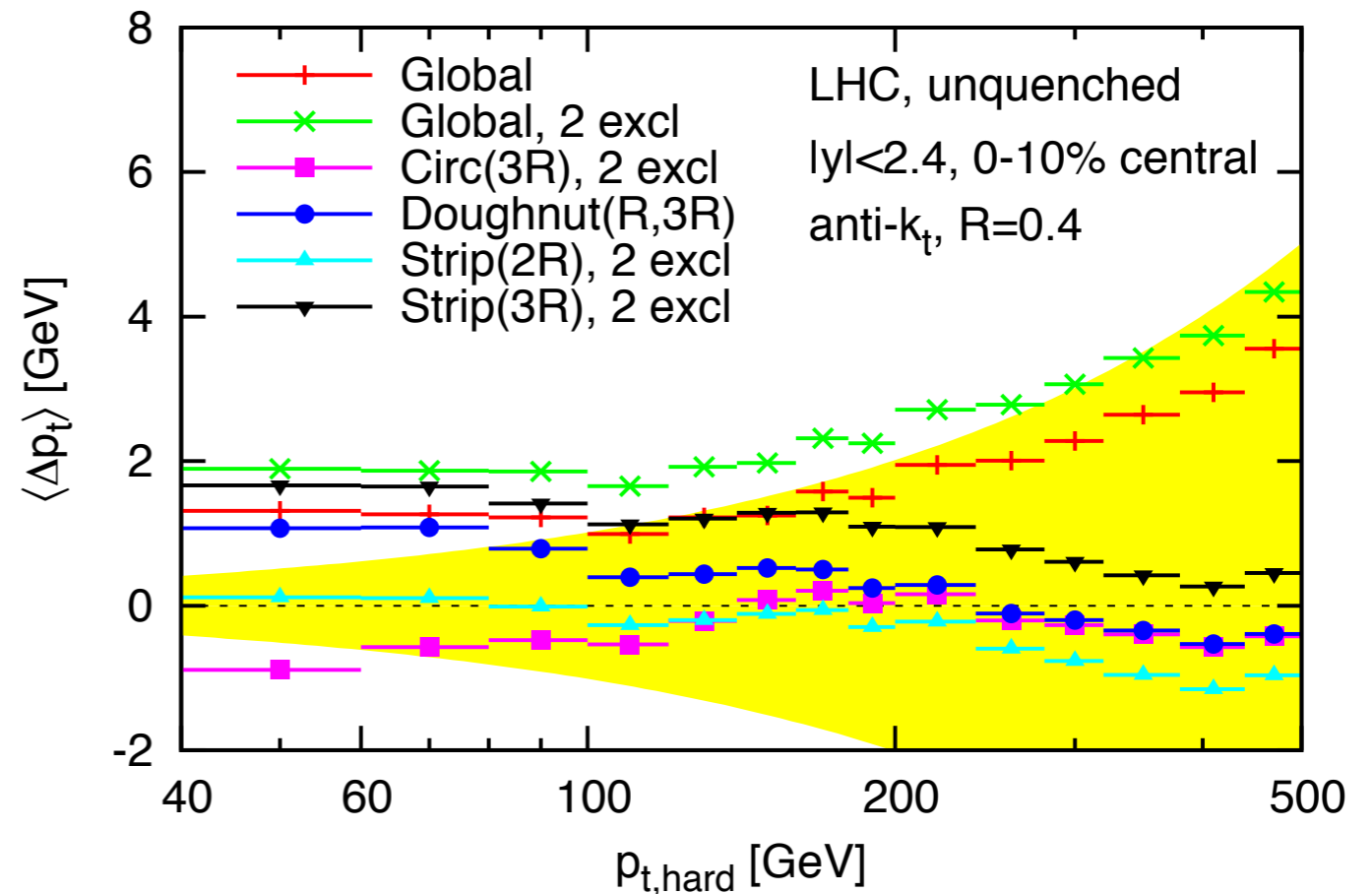
$N$  of jets harder than bkgd fluctuations [ $\sim O(\alpha_s)$  for HIC]

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



# Background subtraction methods

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Subtract bkgd from	jets [after jet clustering]	towers [after jet clustering]	towers [before jet clustering]
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[If there are errors here, let me know!]

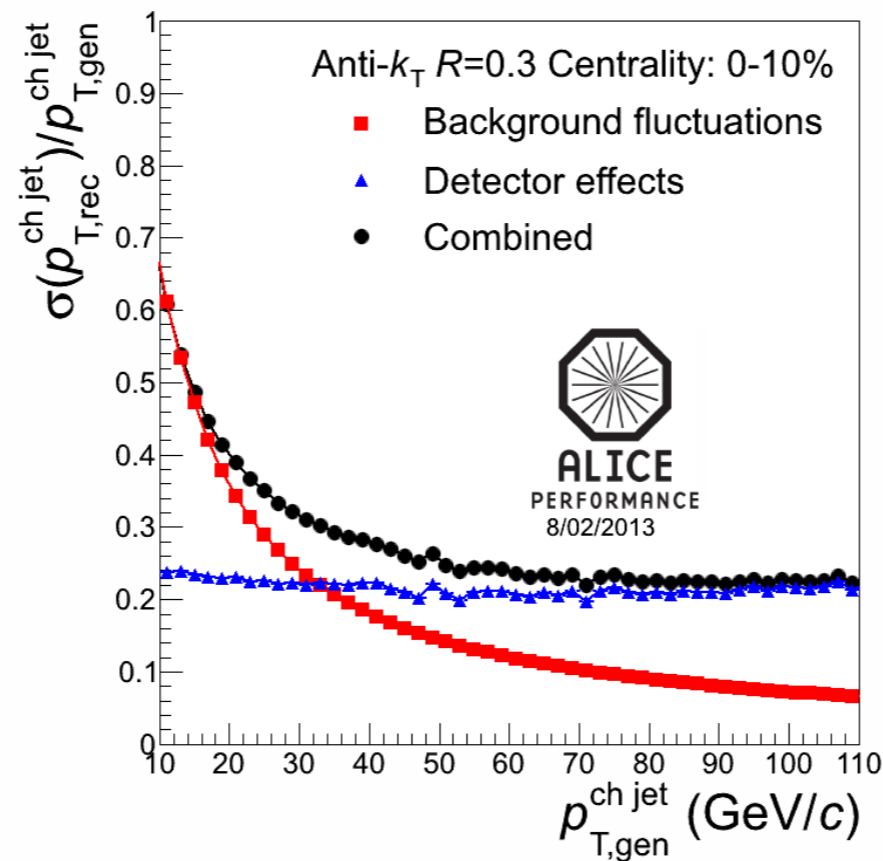
# Why do noise reduction?

## Jet $p_T$ resolution

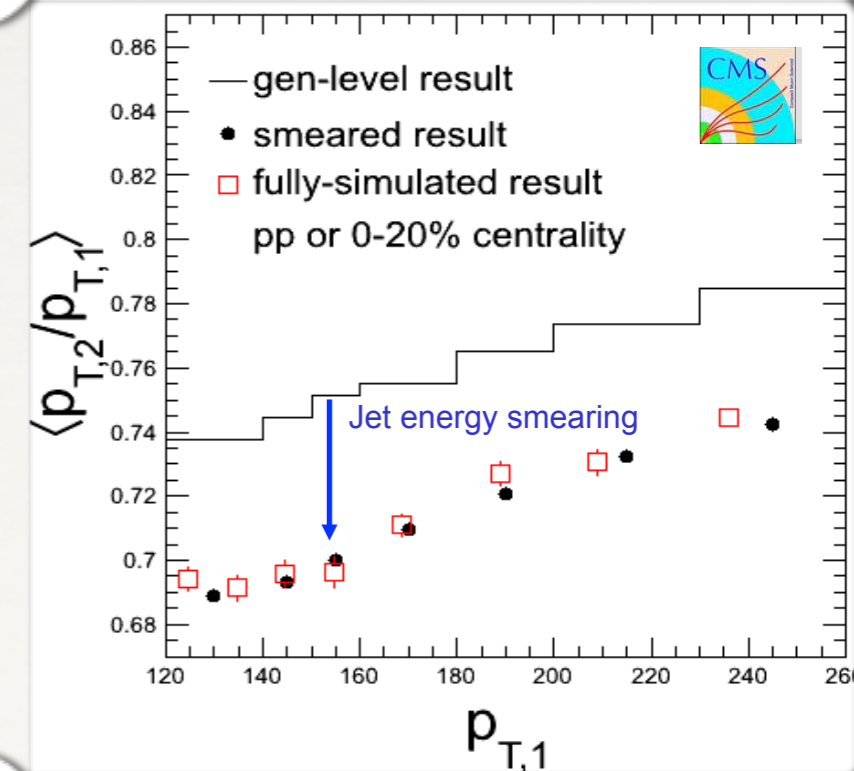


- Detector effects and Background Fluctuations: Partially compensating effects
- At low  $p_T$  background fluctuations dominate
- At high  $p_T$  detector effects dominate
- Correction done all at once via unfolding

Charged Jet Response



Because bkgd fluctuations often induce major distortions of results



# Iterative Cone Subtraction bias

Smaller fluctuations:

MC, Salam, Soyez, I 101.2878

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

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

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

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

**~ 100 GeV !!!**

Only positive background  
fluctuations are kept

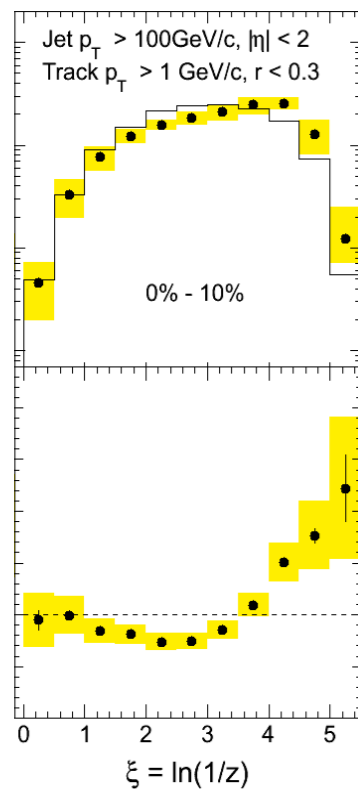
Each active tower oversubtracted  
by 1 sigma

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

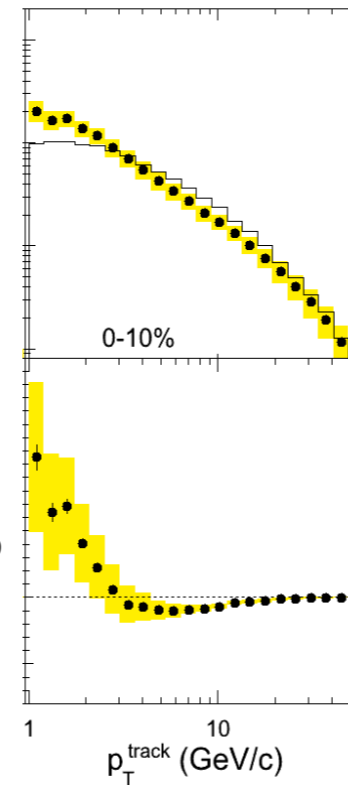
What happens to  $f$  in case of quenching?  
If the occupancy is very different, an offset bias may ensue

# Do noise-reduction biases matter in practice?

## Fragmentation effects on jets



- The hard part of the fragmentation is slightly modified
  - May affect calorimeter-related resolution
- Effects can be estimated by
  - Modified Pythia parton content
  - Various Pyquen tunes
- There appears to be an enhanced soft component
  - May interfere with PU subtraction to affect energy scale
- Effects can be estimated by
  - Embedding tracks into jets
  - Various Pyquen tunes



CMS-PAS-HIN-12-013



Jet Quenching Workshop @ CERN

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There are differences between vacuum and in-medium fragmentation.

But they appear not to be huge.

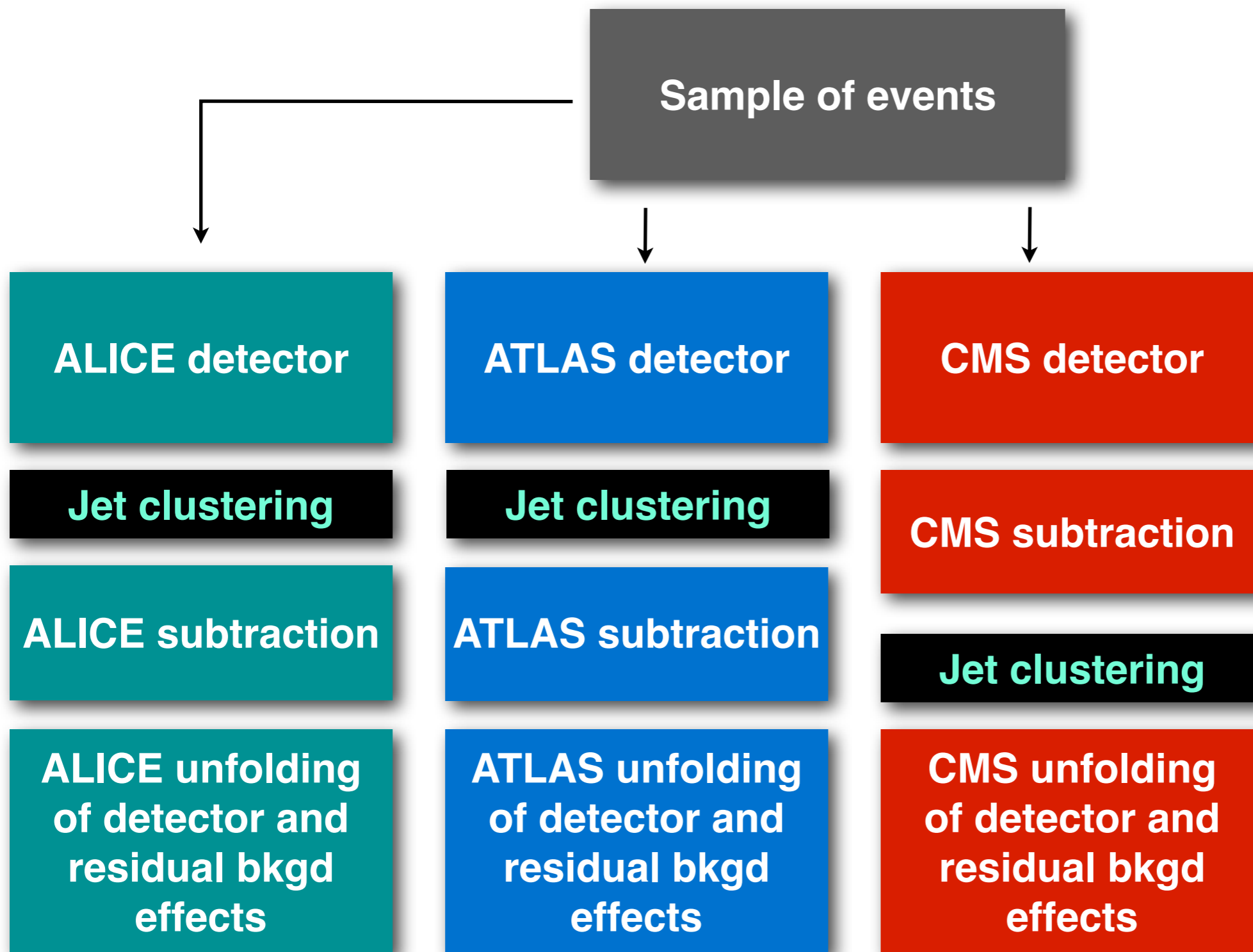
And modelled acceptably by PyQuen



Are under control for now?

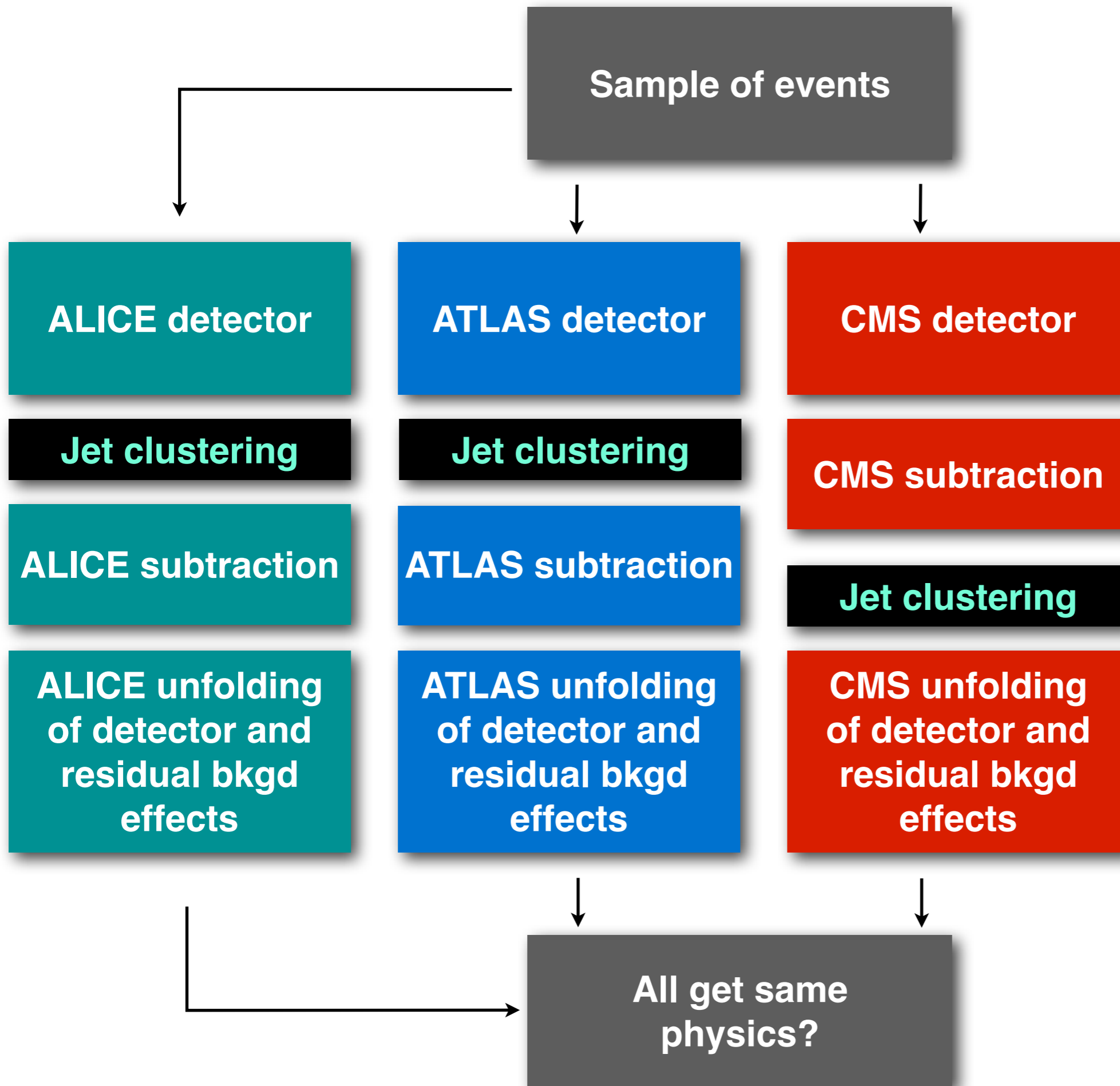
You still need to ask if Pyquen gets the correct spatial distribution of extra soft emissions, but overall difference in fragmentation is moderate,  $\sim 1-2$  tracks per jet

# Bringing in “Unfolding”



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

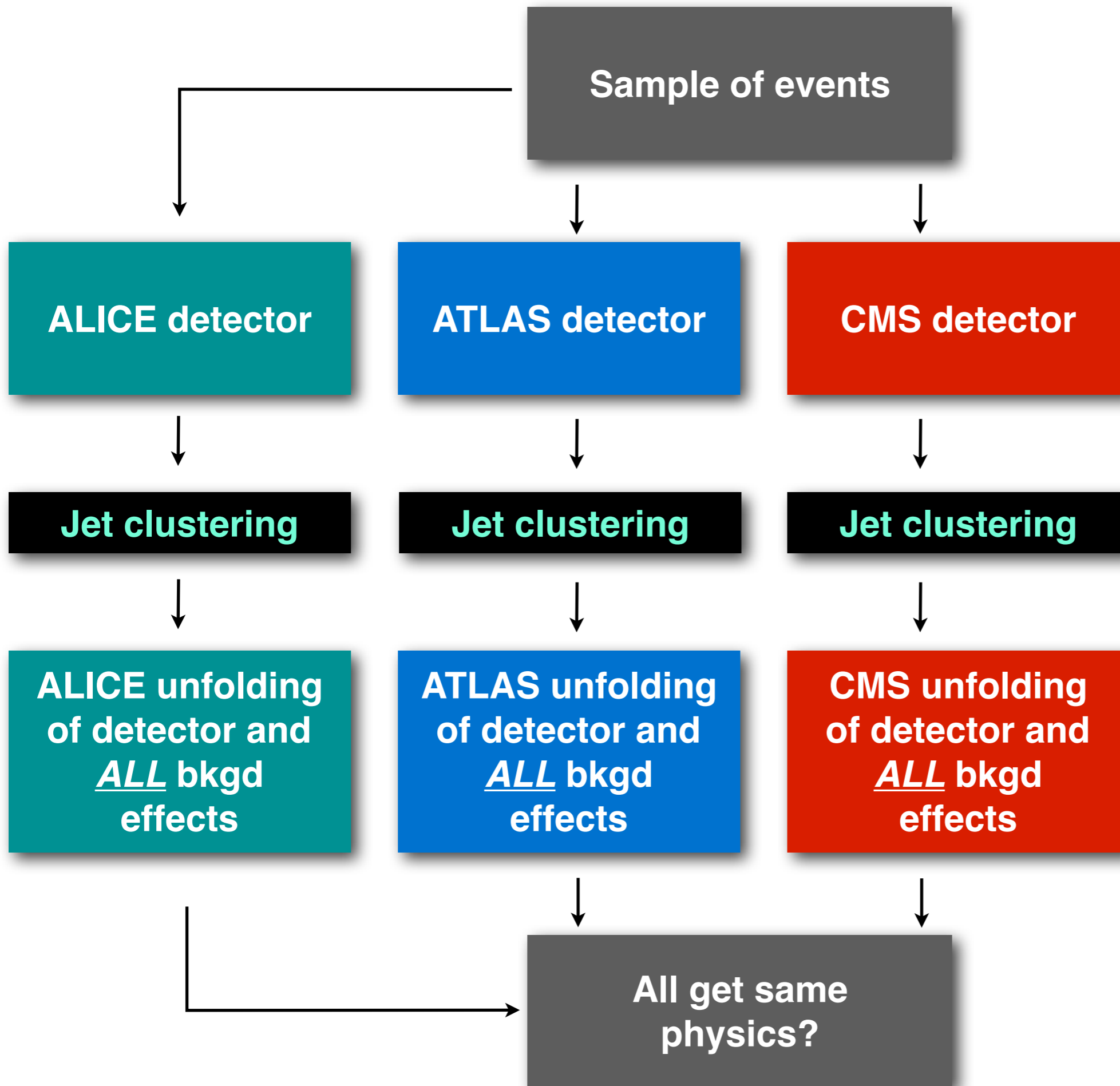
If unfolding is meaningful and done correctly, then it should eliminate all differences between subtractions and detectors.



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

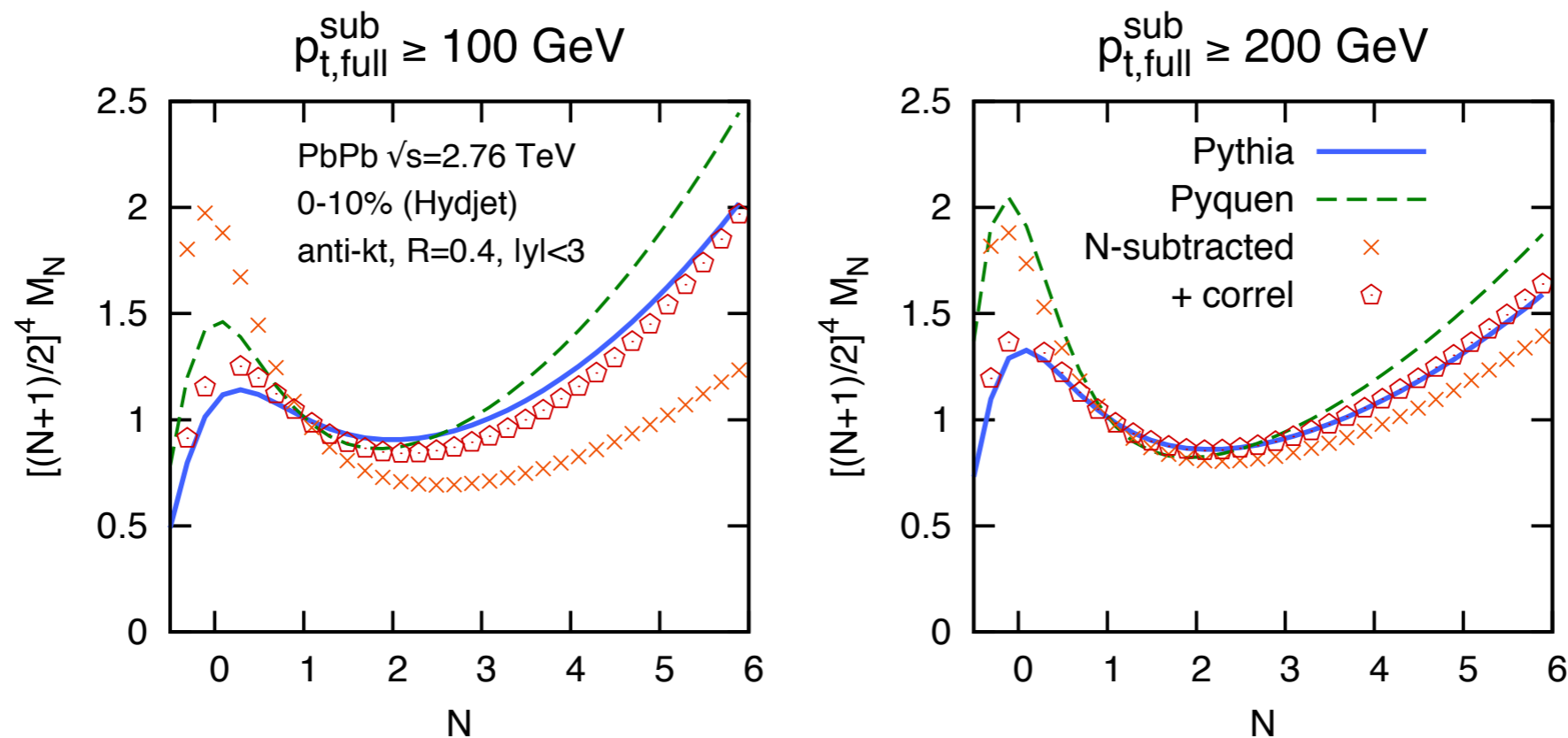
[as a way of further limiting the need for unfolding]

# 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,  $\mu$  can be measured in pp collisions



Improvement: from the **orange crosses** to the **red circles**

using a new measurable quantity  $r_N$  – correlation between  $N^{\text{th}}$  and  $1^{\text{st}}$  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 addition 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 your “pp-unfolded” results come out the same regardless of how you do 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

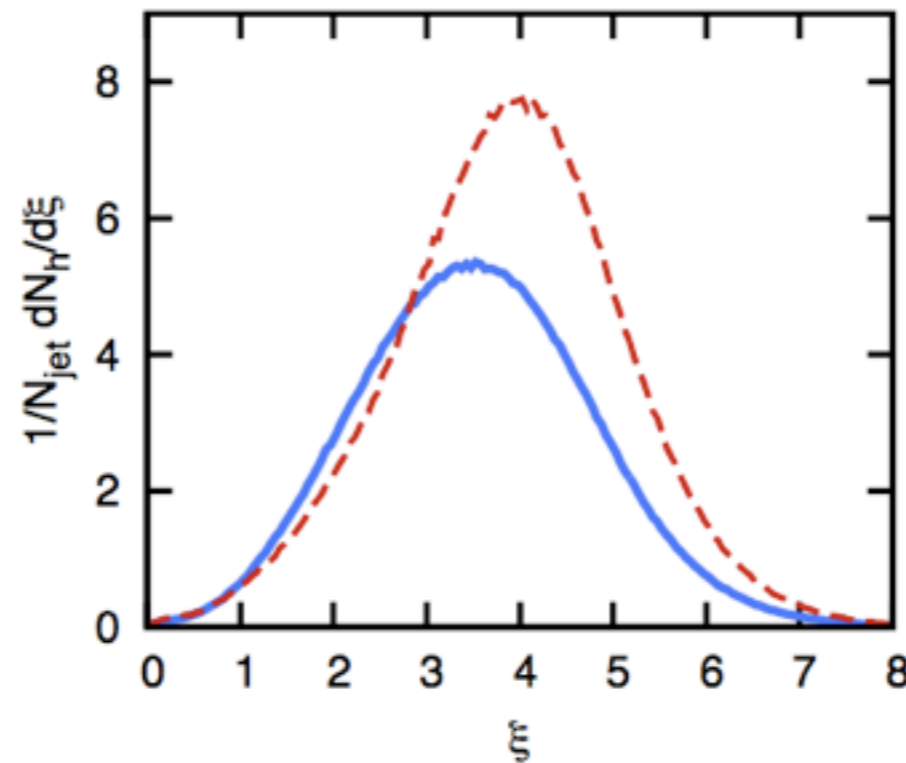
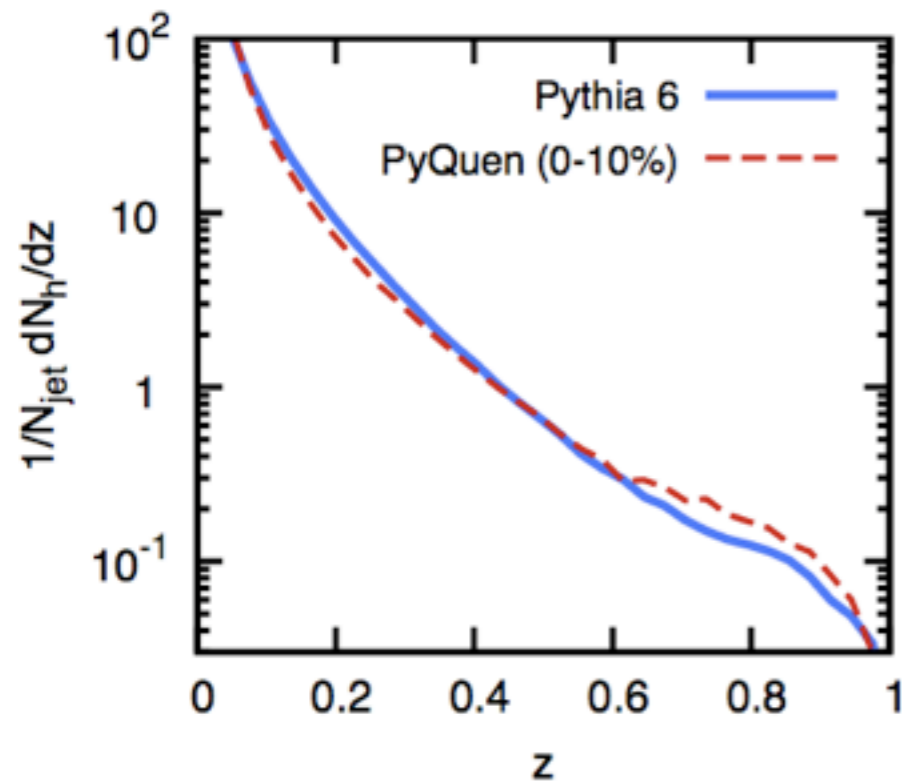
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RHIC		100	8	14	
LHC 5.5 TeV		310	20	45	18
LHC 2.76 TeV	all	250	<b>18</b>	36	<b>16</b>
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[where relevant, for jets  
of  $p_t = 100$  GeV]

- ▶ 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?

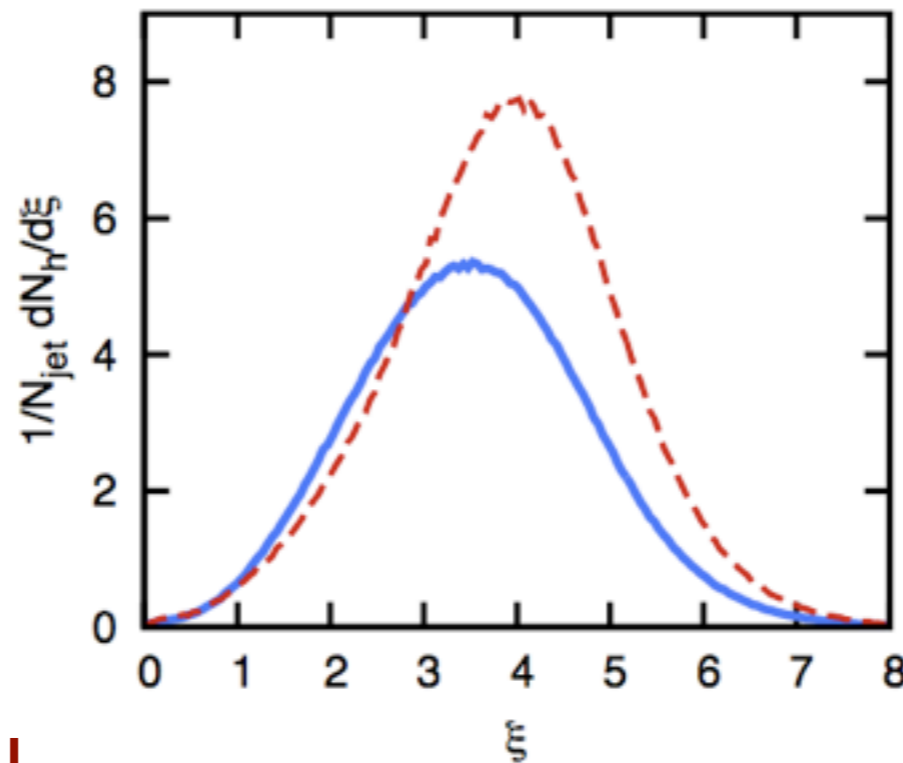
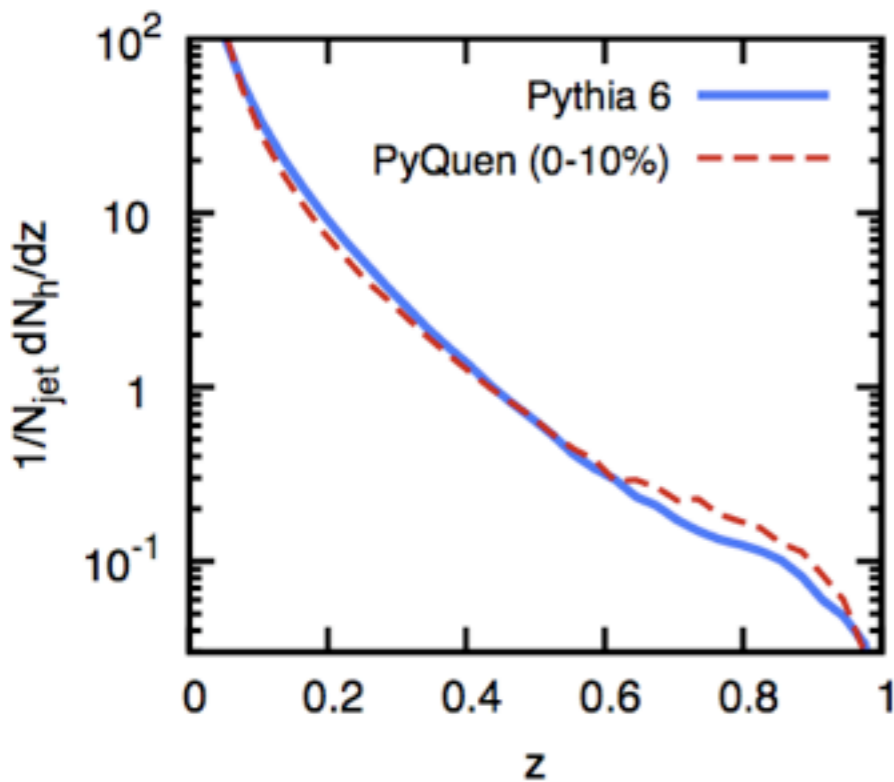
Two (main) issues: background determination, and fluctuations

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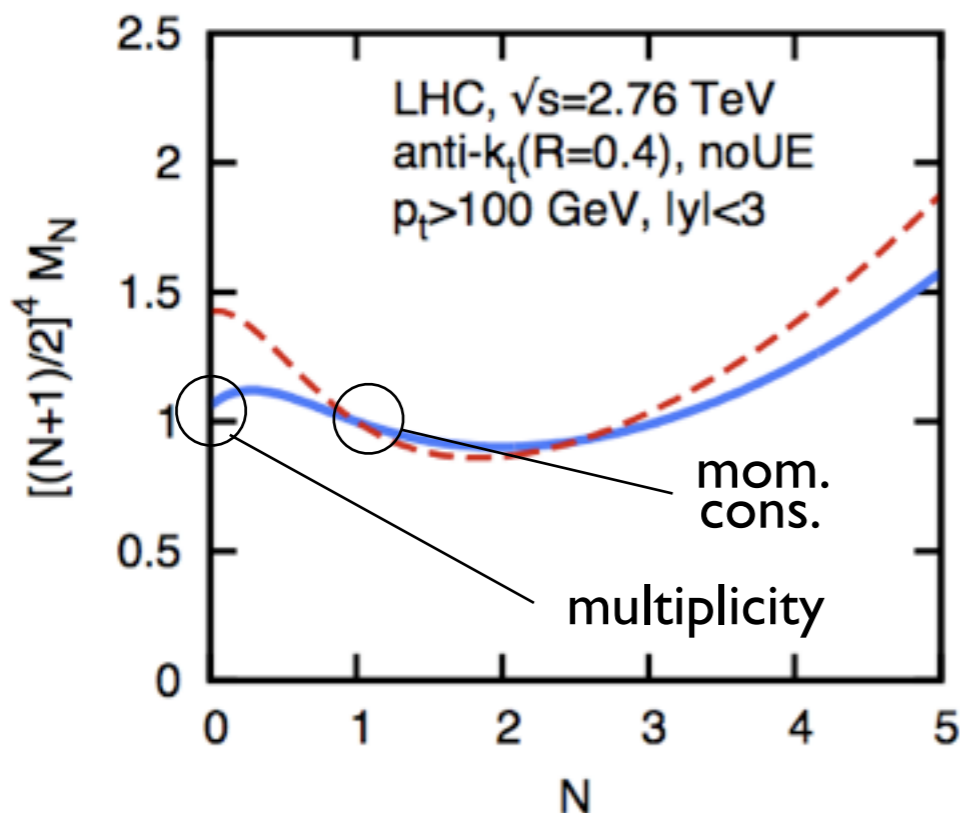
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**Step I:** go from momentum fraction distributions to **moments**



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

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

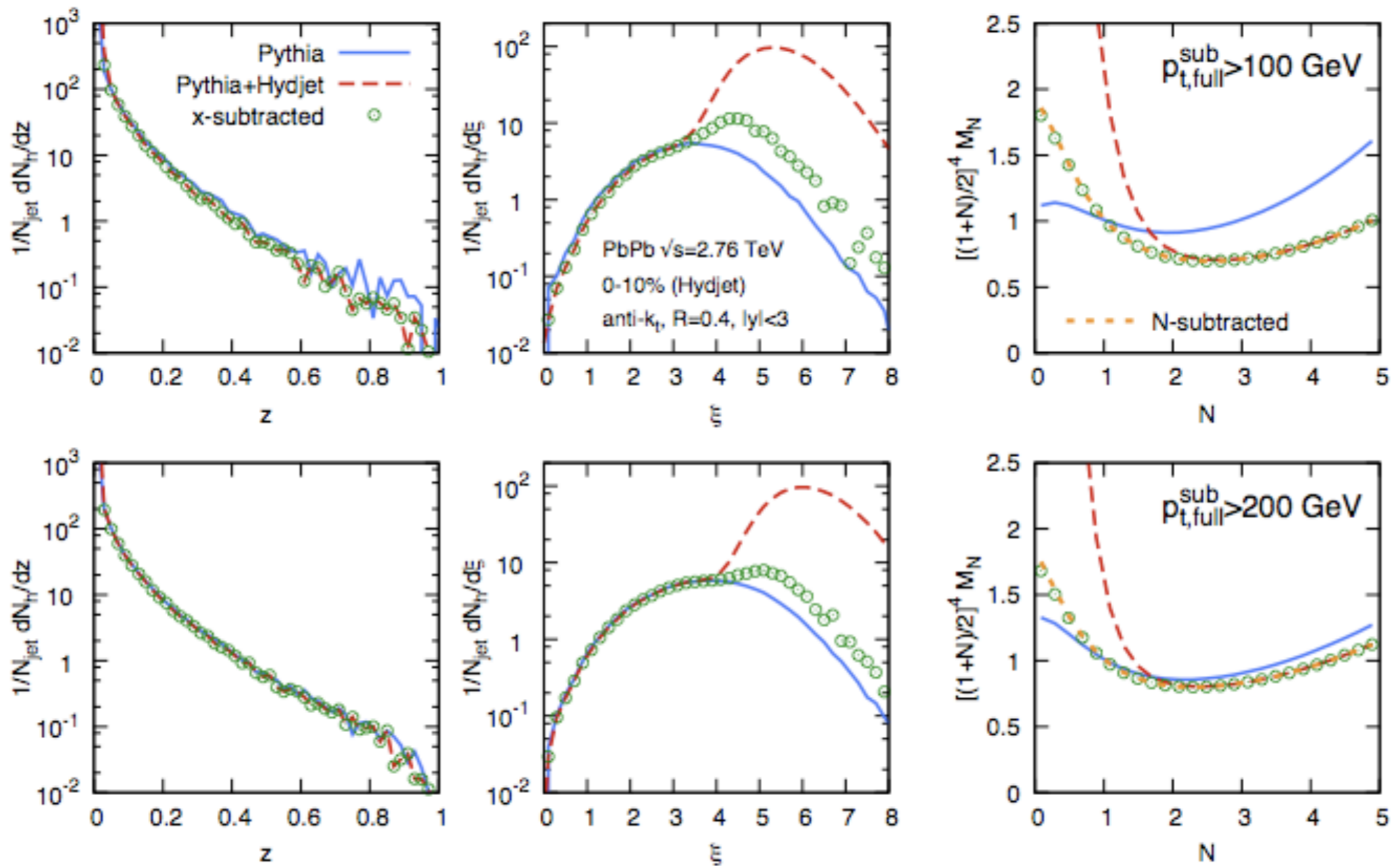
**Step 2:** alongside the usual  $\rho$ , extract from the background the quantities

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

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

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The effect of fluctuations can be written as

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

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:

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

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

correlation coefficient