Jet Reconstruction in Heavy Ion Collisions

Juan Rojo

Dipartimento di Fisica, Università di Milano

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JETS AND HEAVY ION COLLISIONS

Jets in heavy ion collisions

Jets are of paramount importance to fully exploit the potential of the HIC program at the LHC

- Jets will be most abundant hard probes in HIC at the LHC
  From CMS HIC TDR (J. Phys. G: Nucl. Part. Phys. 34 2307)

Table 1.1. The expected yield of several hard probes in 10^6 s PbPb and pPb LHC runs

	PbPb $\sqrt{s_{NN}} = 5.5$ TeV $\mathcal{L} = 5 \times 10^{26}$ cm^{-2} s^{-1}		pPb $\sqrt{s_{NN}} = 8.8$ TeV $\mathcal{L} = 1.4 \times 10^{30}$ cm^{-2} s^{-1}	
Process	Yield/10^6 s	Ref.	Yield/10^6 s	Ref.
	$\lvert\eta\rvert \leqslant 2.4$			
jet ($p_T > 50$ GeV/c)	2.2×10^7	[47]	1.5×10^{10}	[48]
jet ($p_T > 250$ GeV/c)	2.2×10^3	[47]	5.2×10^6	[48]
Z^0	3.2×10^5	[49]	6.8×10^6	[48]

Jets in heavy ion collisions

Jets are of paramount importance to fully exploit the potential of the HIC program at the LHC

- Jets will be most abundant hard probes in HIC at the LHC
- Jets free of inclusive particle measurements biases
- Subleading jet fragments sensitive medium modeling details
- A solid pQCD baseline is required to detect and quantify medium effects

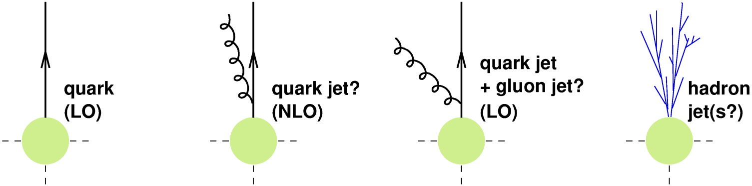
Open questions:

- To which extend can reconstructed QCD jets be disentangled from background?
- Which is the minimum size of medium effects which could then be disentangled?
- Can all the successful jet technology from *pp* be transferred to a HIC environment?

JET CLUSTERING TECHNOLOGY

Jets

Naively: a jet is a **bunch of collimated hadrons** ubiquitous in high energy collisions. Electrons and muons are fundamental, weakly coupled particles — it makes sense physically and experimentally to think of them as concrete objects. *Partons* (quarks, gluons) are not so simple...



- Partons split into further partons
- Jets are a a way of thinking of the 'original parton'
- A 'jet' is a **fundamentally ambiguous concept** (e.g. requires a resolution)

Jets (and partons!) are only meaningful once you've defined a jet algorithm.

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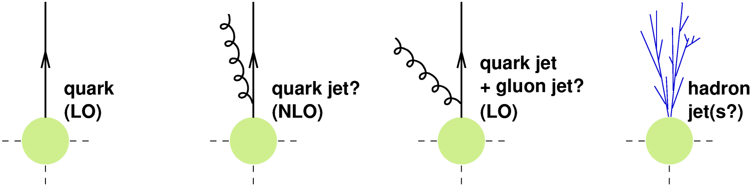

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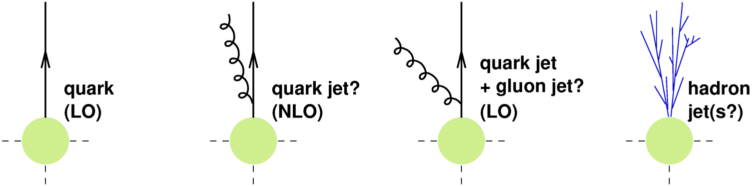

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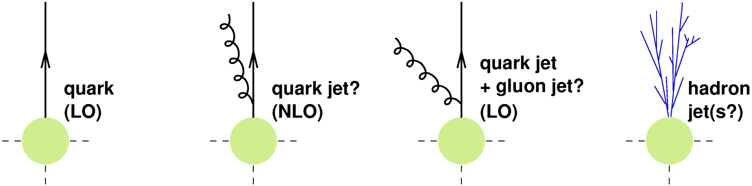

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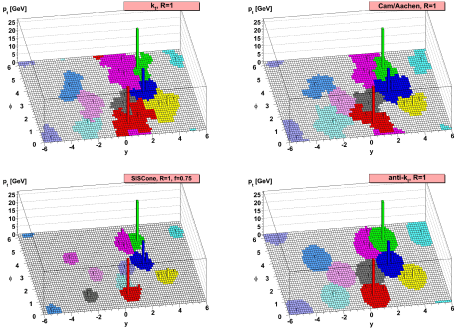
Recent developments

Sizable progress in jet algorithms in recent years (G. Salam, arXiv:0906.1833)

- Fast implementation of sequential recombination clustering algorithms (k_T, Cam/Aa)
- Jet areas ($A_{\rm jet} \neq \pi R^2$ in general)



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- Fast implementation of sequential recombination clustering algorithms (k_T, Cam/Aa)
- Jet areas and area–based subtraction techniques
- New IRC safe jet algorithms: SISCone, anti-k_T, C/A(filt) $\rightarrow$ Replacement for IRC unsafe cone algorithms (IR-SM like MidPoint and IC-PR like ATLAS cone)
- Subjet techniques for BSM searches

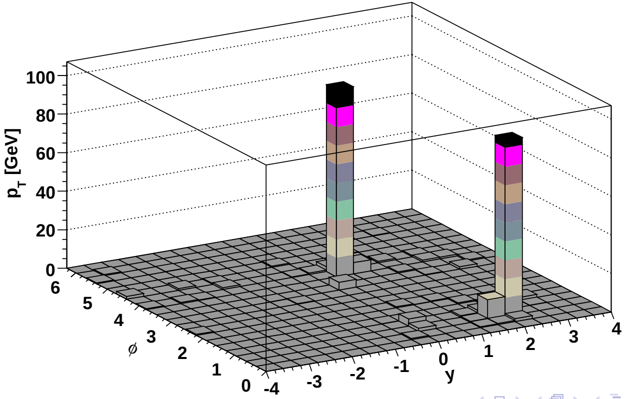
All these tools available from the `FastJet` package
(Cacciari, Salam and Soyez, 05-11)

`http://www.lpthe.jussieu.fr/salam/fastjet/`

together with background subtraction methods
(Anti-kt default in ATLAS and CMS *pp*, also used in HIC analysis)

Jets in HIC $\rightarrow$ A messy environment!

Distribution of jets in $pp \rightarrow gg$ events with $p_T^{\mathrm{jet}} \sim 100$ GeV and $R = 0.4$
No PbPb



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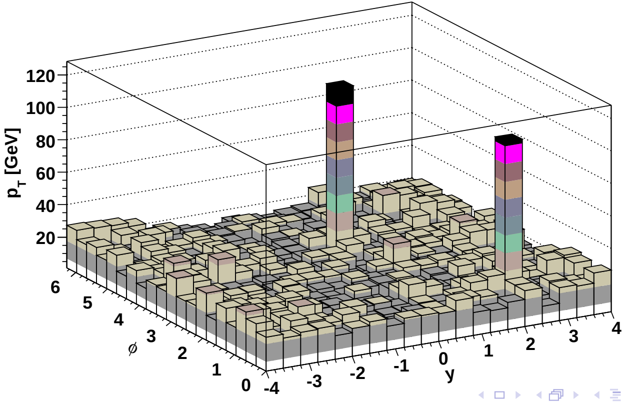
Distribution of jets in $pp \rightarrow gg$ events with $p_T^{\rm jet} \sim 100$ GeV and $R = 0.4$ embedded in PbPb low multiplicity



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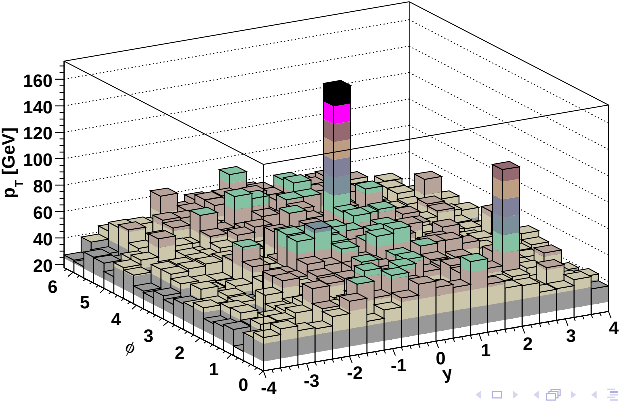
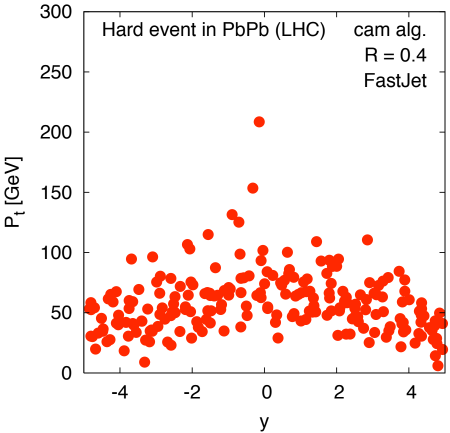


Jet areas for Background subtraction

Data-driven method to estimate the background density per unit area $\rho(\mathbf{y}, \phi)$ (from the Underlying Event) on an event-by-event basis



1.- Measure the p_T of all jets in event

Conceptuallly simple but powerful technique

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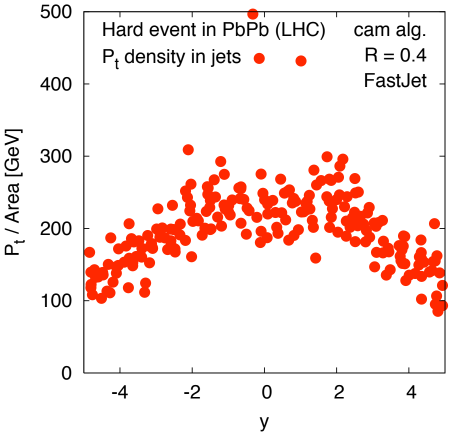

1.- Measure the p_T of all jets in event
2.- Normalize by the jet area A_j
Key observation $\rightarrow$ For UE jets, $p_T^{\rm jet} \sim \rho(y,\phi) A_{\rm jet}$

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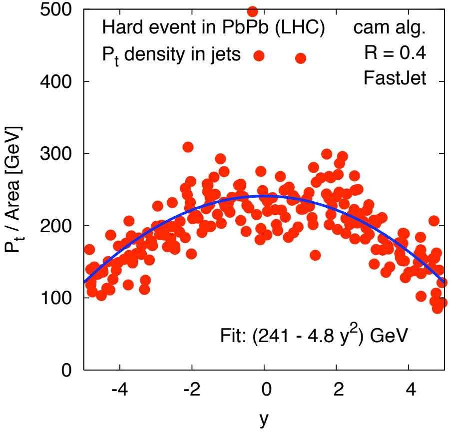

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Key observation → For UE jets, $p_T^{\rm jet} \sim \rho(y, \phi) A_{\rm jet}$
3.- Determine $\rho(y, \phi)$
(No unique strategy, HIC background very complex structure)

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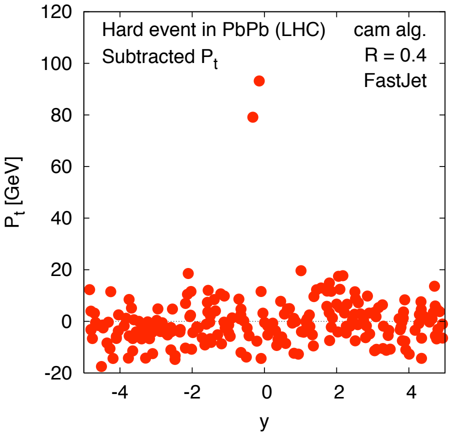

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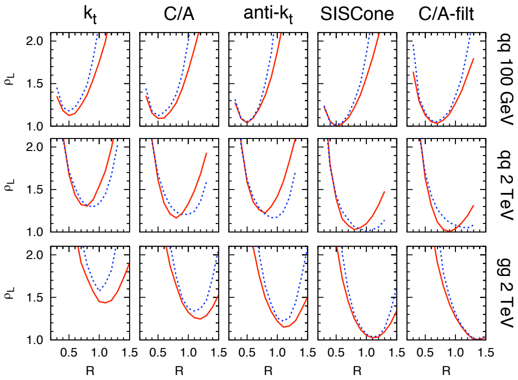
Key observation → For UE jets, $p_T^{\rm jet} \sim \rho(y,\phi) A_{\rm jet}$
3.- Determine $\rho(y,\phi)$
(No unique strategy, HIC background very complex structure)
4.- Subtract $\rho(y,\phi)$ from the all jets using its area A_j

$$p_{\mu j}^{\rm (sub)} = p_{\mu j} - A_{\mu j}\,\rho(y,\phi) \qquad (1)$$

Conceptuallly simple but powerful technique

Jet algorithms performance in pp at LHC



Not all jet definitions equally good:

1. Too small-R $\rightarrow$ Hadronization effects
2. Too large-R $\rightarrow$ Underlying Event and Pile-Up

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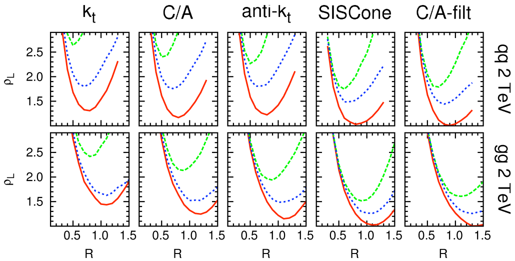


Not all jet definitions equally good:

1. Too small-R $\rightarrow$ Hadronization effects
2. Too large-R $\rightarrow$ Underlying Event and Pile-Up
   Same for High Luminosity LHC Pile-Up

`JetQuality`: Interactive tool compare jet definitions (Cacciari, J.R., Salam, Soyez, JHEP 0812:032,2008)

http://www.lpthe.jussieu.fr/ salam/jet-quality/

JET RECONSTRUCTION IN HEAVY ION COLLISIONS

Cacciari, J.R., Salam and Soyez
Eur.Phys.J.C71:1539,2011, arXiv:1010.1759

General Strategy

Systematic comparison of jet algs performance in HIC

Embed *pp* events (with and wo quenching) into minbias PbPb events

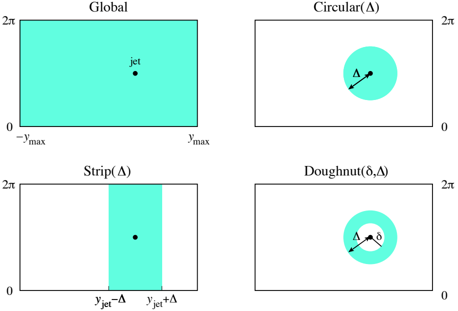
- p_t **offset**: $\Delta p_t \equiv p_t^{AA,\mathrm{sub}} - p_t^{pp,\mathrm{sub}}$
- p_t **dispersion**: $\sigma_{\Delta p_t} \equiv \sqrt{\langle \Delta p_t^2 \rangle - \langle \Delta p_t \rangle^2}$

Jet algorithms

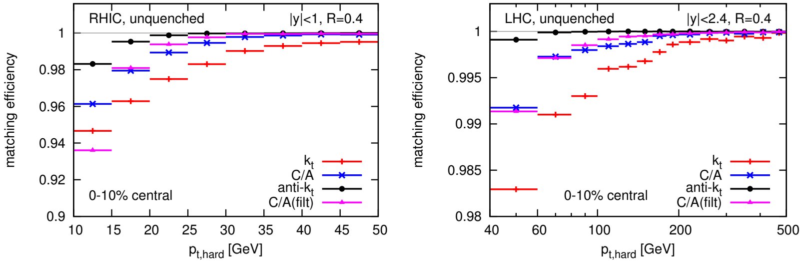
- kt
- Cambridge/Aachen
- Anti-kt
- Cam/Aa with filtering

with $\mathbf{R} = \mathbf{0.4}$, $\mathbf{R}_\rho = \mathbf{0.3} - \mathbf{0.5}$

Range where $\rho(y,\phi)$ estimated

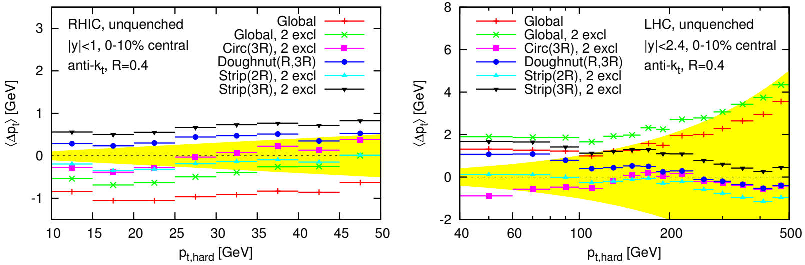


Jet matching efficiency



- Jets in the medium matched to a “bare” hard jet when their common particle content accounts for at least 50% of the original p_t
- For anti-kt, efficiency at permille level at LHC

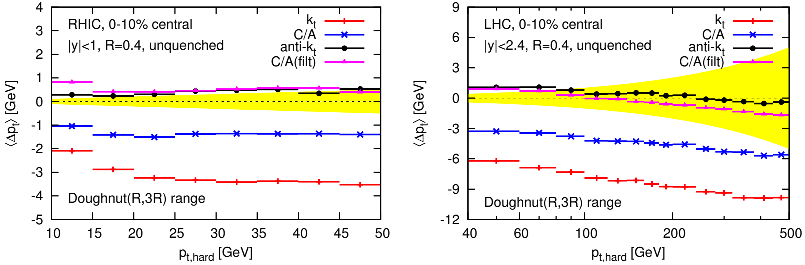
Dependence with range for ρ determination



- $\rho(y,\phi) \rightarrow$ Large both inter-event and intra-event fluctuations
- Local ranges better in determining background density ρ at LHC
- RHIC restricted acceptance $|y| \leq 1 \rightarrow$ All ranges similar

Yellow band $\rightarrow$ 1% p_t jet

Choice of jet algorithm



- Anti-kt and C/A(filt) → Small p_t offset
  $\langle \Delta p_t \rangle / p_t \lesssim 1\%$ at LHC
- kt and C/A algorithms → Large p_t offsets

Yellow band → 1% p_t jet

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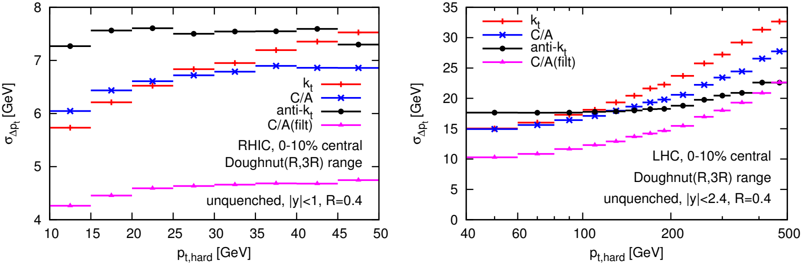
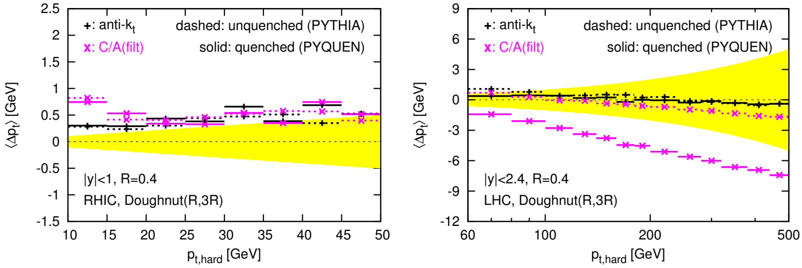


- C/A(filt) → smallest p_t dispersion
- C/A(filt) efficently filters part of the Undelying Event already before background subtraction

Robustness against quenching effects



- Jet quenching affects jet reconstruction
  e.g. more low p_t particles, radiation at wider angles ...
- Anti-kt is robust in the presence of quenching effects
- C/A(filt) ok at RHIC, but bias in presence of quenching at LHC

Summary

- Modern jet clustering algorithms and background subtraction related techniques are very promising tools to probe the new state of matter created in Heavy Ion Collisions
- Anti-kt and C/A(filt) $\rightarrow$ best performance in HIC at RHIC and LHC
- Local ranges preferred over global ranges $\rightarrow$ Better sensitivity to UE fluctuations
- The flexibility in jet algorithms allows the estimation of systematic uncertainties associated to background subtraction
- Jet algorithm technology ready for quantitative characterization of the Quark-Gluon Plasma in HIC

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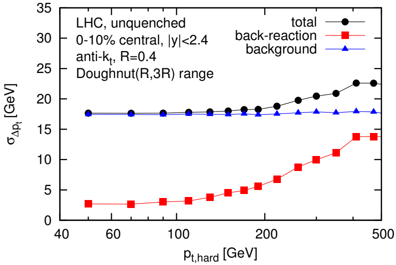
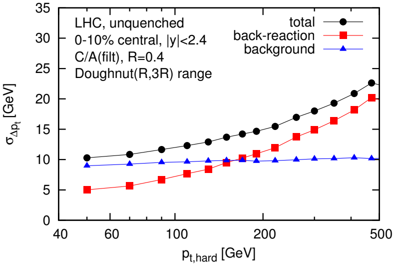
EXTRA MATERIAL

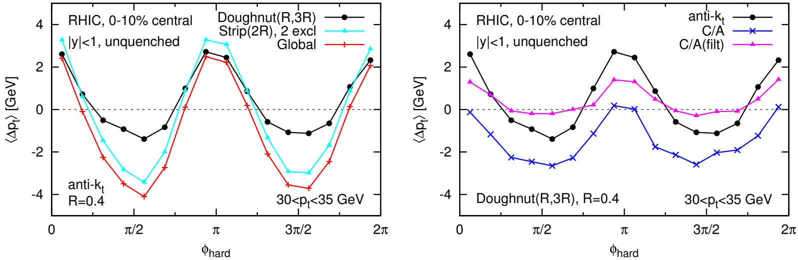
Back reaction vs Background fluctuations





- Contribution from backreaction increases with pt
- For anti-kt backreaction negligible up to the largest pt

Azimuthal dependence



- Azimuthal dependence → Challenging subtraction
- Azimuthal effects decrease with C/A(filt) and local ranges

The p_t offset and backreaction