Recent progress in defining and understanding jets

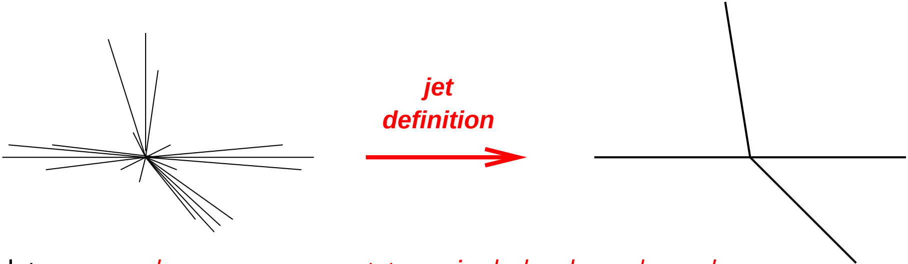
Gavin Salam

LPTHE, Universities of Paris VI and VII and CNRS

A summary of work (in progress) with A. Banfi, M. Cacciari, M. Dasgupta, L. Magnea, G. Soyez, G. Zanderighi

ISMD 2007
Berkeley, 5–9 August 2007

Jets essentially **project away the multiparticle dynamics**, so as to leave a simple picture of what happened in an event:



Jets are *as close as we can get to a single hard quark or gluon:*

- A jet has almost the same momentum as the ‘initiating parton’
- A jet may maintain heavy flavour from the initiating parton

But projection to jets is fundamentally ambiguous, reflecting divergent and quantum-mechanical nature of QCD.

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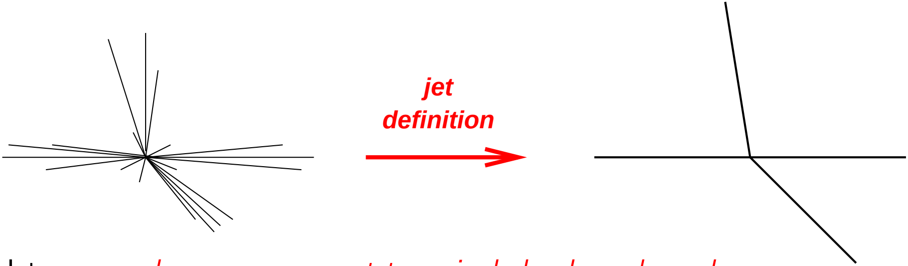

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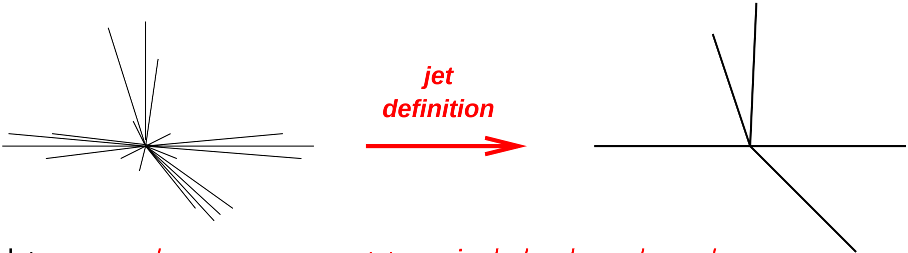

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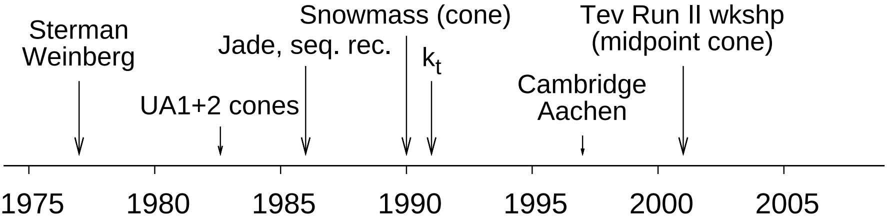
Jet Definition History

- Periodic key developments in jet definitions spurred by ever-increasing experimental sophistication.
- Approach of LHC provides motivation for taking a new, fresh, systematic look at jets.
- This talk: **some of the discoveries along the way**



Definitions shown are those with widest exptl. impact

NB: also ARCLUS, OJF, ...

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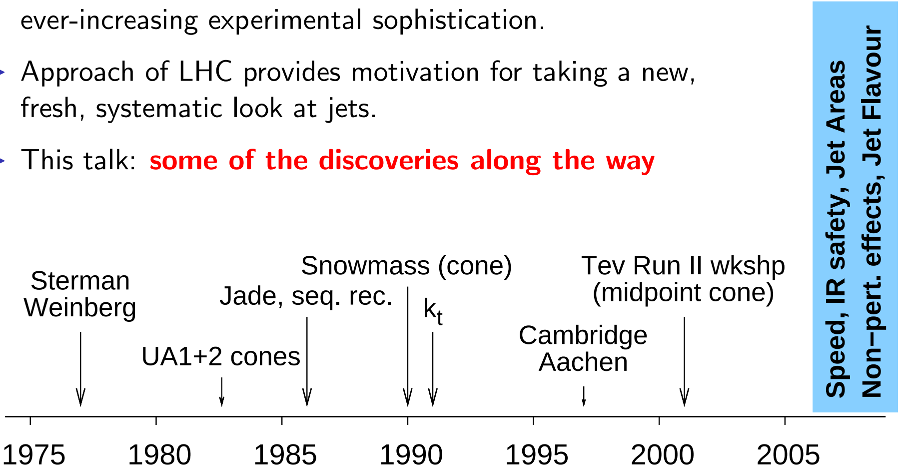

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What's new for jets @ LHC?

Number of particles:

Experiment	N
LEP, HERA	50
Tevatron	100–400
LHC low-lumi	800
LHC high-lumi	4000
LHC PbPb	30000

Range of processes:

- jets, $t\bar{t}$, tj, Wj, Hj, $t\bar{t}j$, WWj, Wjj, ...
- Many NLO calculations being done
- 50 people × 10 years ($30 – 50M)
- Multijet-NLO calculations only make sense for *infrared safe* jet definitions

Physics scales:

Experiment	Physics	Scale
LEP, HERA	Electroweak	100 GeV
	+ Hadronisation	0.5 GeV
Tevatron	+ Underlying event	2.5 – 5 GeV
LHC	+ BSM	1 TeV?
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This talk

Three (short) parts

- Technical advances
  - k_t and Cam/Aachen speed — Cacciari & GPS '05
  - seedless cone ↔ IR safety + speed — GPS & Soyez '07
- Understanding of jet-alg. behaviour
  - Jet areas — Cacciari, GPS & Soyez, prelim.
  - Hadronisation — Cacciari, Dasgupta, Magnea & GPS, prelim.
- Using understanding to make better algorithms
  - Area-based subtraction — Cacciari & GPS '07
  - The flavour-k_t alg, and b-jets — Banfi, GPS & Zanderighi '06–07

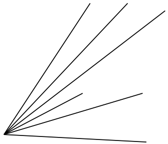
Two classes of jet algorithm

Sequential recombination	**Cone**
k_t, Jade, Cam/Aachen, ...	UA1, JetClu, Midpoint, ...
Bottom-up: Cluster 'closest' particles repeatedly until few left $\rightarrow$ jets.	Top-down: Find coarse regions of energy flow (cones), and call them jets.
Works because of mapping: *closeness* $\Leftrightarrow$ *QCD divergence*	Works because *QCD only modifies energy flow on small scales*
Loved by e^+e^-, *ep* and theorists	Loved by *pp* and few(er) theorists

Sequential recombination algorithms

k_t algorithm

- Find smallest of all $d_{ij}= \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2/R^2$ and $d_{iB} = k_i^2$
- Recombine i, j (if iB: $i \rightarrow$ jet)
- Repeat



'Trivial' computational issue:

- for N particles: N^2 d_{ij} searched through N times $= N^3$
- 4000 particles (or calo cells): 1 minute

NB: often study $10^7 - 10^8$ events

Advance #1: factorise momentum and geometry

Borrow methods & tools from Computational Geometry:

Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

Time reduced to **Nn** or **N ln N**: 25ms for N=4000. Cacciari & GPS '05

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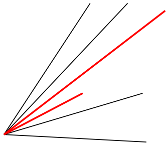

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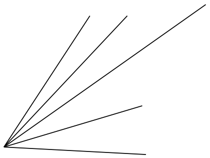

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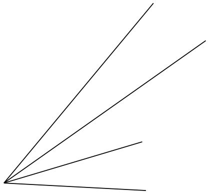

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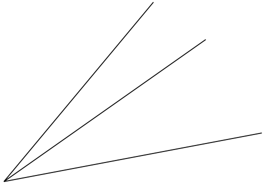

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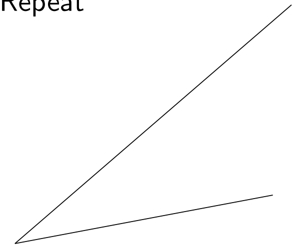

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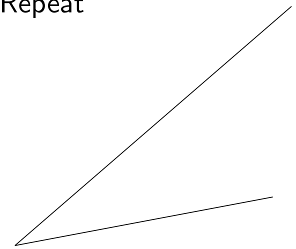

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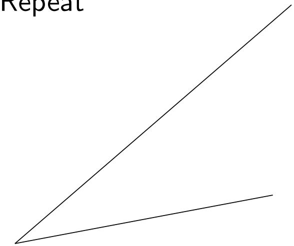

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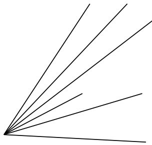
Modern cone algs have two main steps:

- Find some/all stable cones

  ≡ cone pointing in same direction as the momentum of its contents

- Resolve cases of overlapping stable cones

  By running a 'split–merge' procedure



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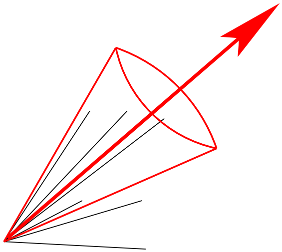

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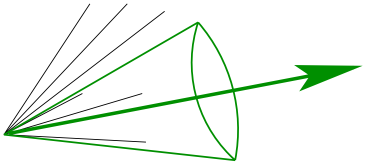

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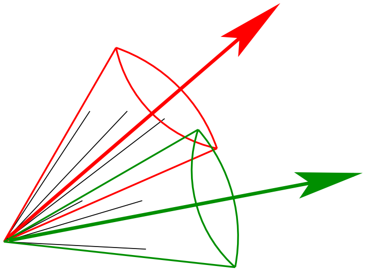

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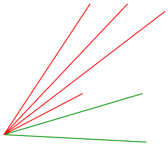

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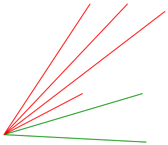

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  100 particles: 10^{17} **years**

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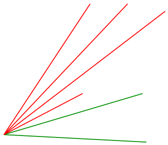

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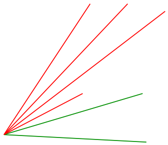

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Cones & IR safety

Among consequences of IR unsafety:

	Last meaningful order	
	It. cone	MidPoint
Inclusive jets	LO	NLO
$W/Z + 1$ jet	LO	NLO
3 jets	**none**	LO
$W/Z + 2$ jets	**none**	LO
$m_{\rm jet}$ in $2j + X$	**none**	**none**

Recall \$$30 - 50$M investment in NLO

Advance #2: IR safe seedless cone separate mom. and geometry (again)

New comp. geometry techniques: 2D all distinct circular enclosures

Then for each check whether → stable cone

Time reduced from $N2^N$ to $\mathbf{N^2 \ln N}$: 6s for N=4000. GPS & Soyez '07

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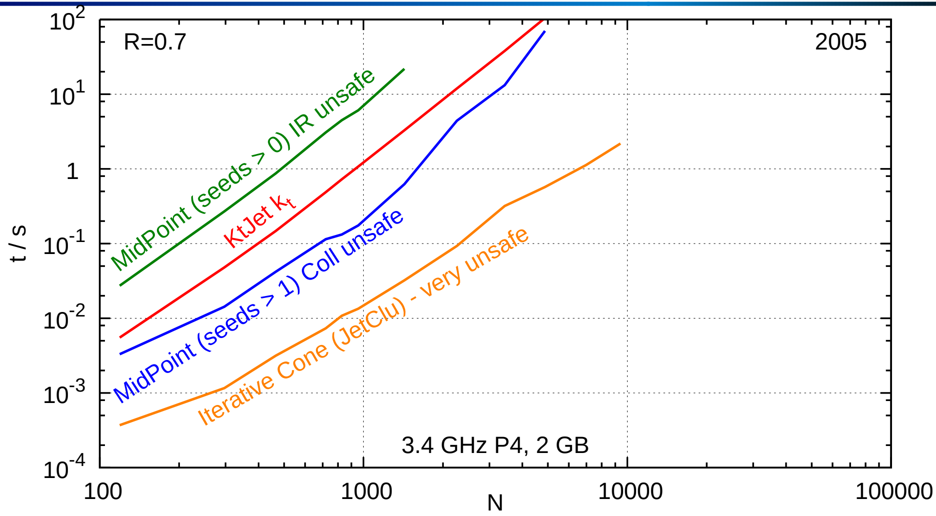
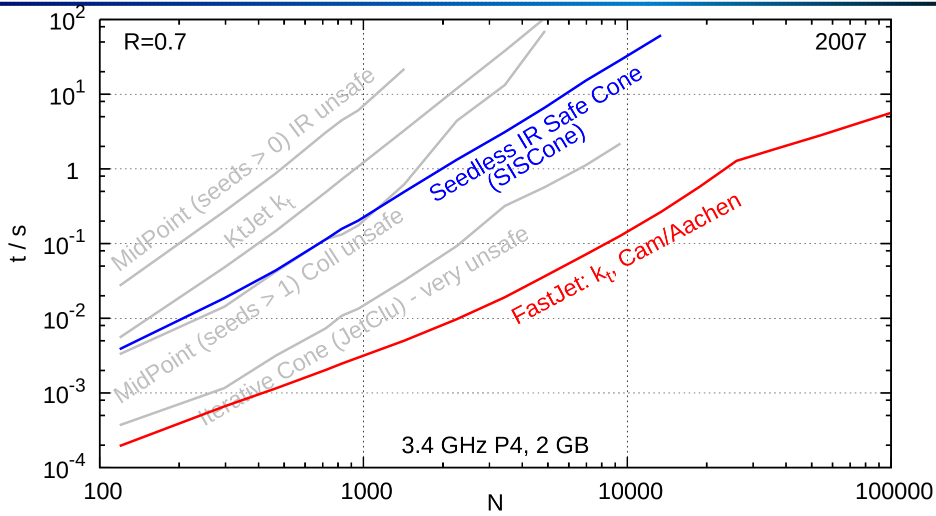


Single package, **FastJet**, to access all developments, natively (k_t, Cam/Aachen) or as plugins (SISCone): Cacciari, GPS & Soyez '05–07

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

Status in 2007



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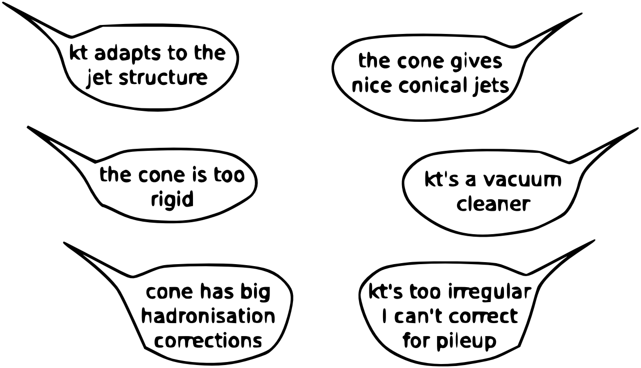
Jet Folklore

Jet discussions: polarised, often driven by unquantified statements



Instead let's quantify things:

- Areas = susceptibility to pileup and underlying event (UE)
- Hadronisation = change in momentum from parton → hadron level (excluding UE)

Jet areas

Can show that jet area goes as:

$$A = A_0 + D\frac{C_{F/A}}{\pi b_0} \ln \frac{\alpha_s(Q_0)}{\alpha_s(Rp_t)} + \mathcal{O}\left(\alpha_s^2 \ln p_t^2\right)$$

Cacciari, GPS & Soyez, prelim

Passive area: suscept. to **point-like** radiation:

	$A_0/\pi R^2$	$D/\pi R^2$
k_t	1	0.56
Cam/Aachen	1	0.08
SISCone	1	-0.06

- Analytical calcs capture main MC features
- k_t has larger area than cone, neither is πR^2
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Active area: suscept. to **diffuse** radiation:

	$A_0/\pi R^2$	$D/\pi R^2$
k_t	$1 \to 0.81$	$0.56 \to 0.52$
Cam/Aachen	$1 \to 0.81$	$0.08 \to 0.08$
SISCone	$1 \to 0.25$	$-0.06 \to 0.12$

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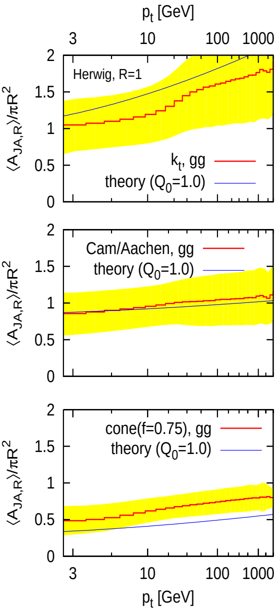

Hadronisation

How does the jet p_t change in parton $\rightarrow$ hadron transition?

Methods from e^+e^- event shapes predict same at LO for all algs:

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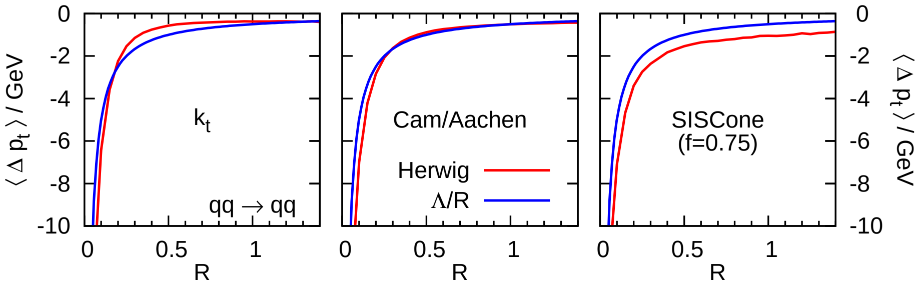

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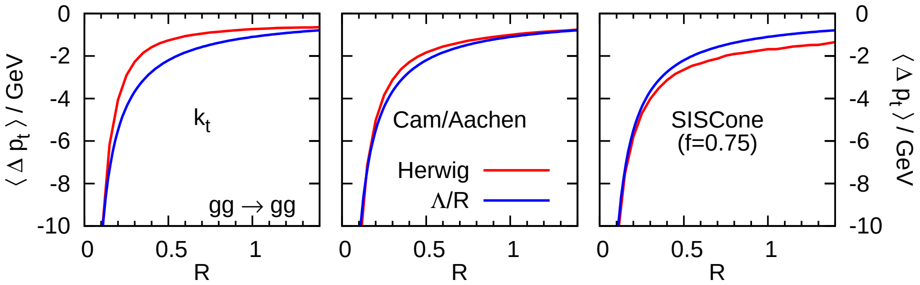


These and other results help produce a **quantitative** picture of jet behaviour:

- Similarities between algorithms are greater than differences
- Once you have tools to quantify behaviours of algorithms you can start to think about designing new, better procedures and algorithms

<u>Illustrations that follow:</u>

- subtraction of pileup based on jet areas
- properly incorporating the *'flavour dimension'* into the k_t algorithm.

Area-based subtraction

Basic Procedure:

- Use p_t/A from majority of jets (pileup jets) to get level, ρ, of pileup and UE in event
- Subtract pileup from hard jets:

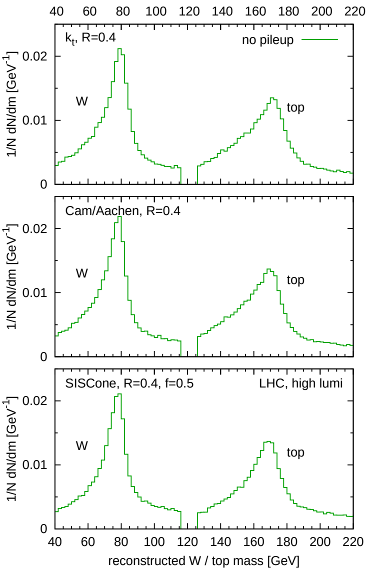
$$p_t \to p_{t,sub} = p_t - A\rho$$

Cacciari & GPS '07

Illustration:

- semi-leptonic $t\bar{t}$ production at LHC
- high-lumi pileup ($\sim$ 20 ev/bunch-X)

Same simple procedure works for a range of algorithms



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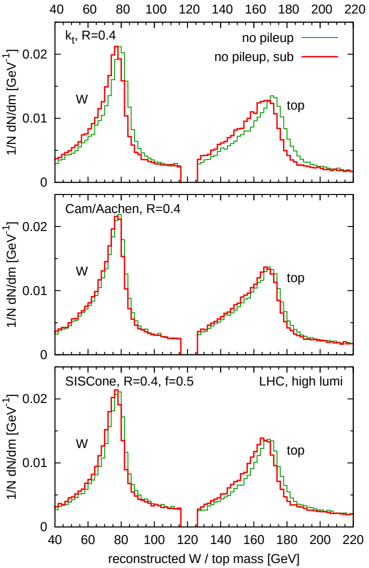

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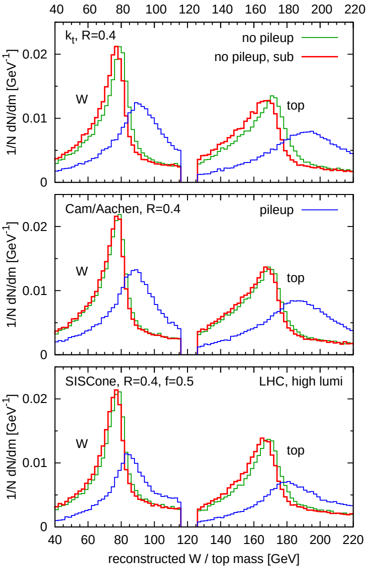

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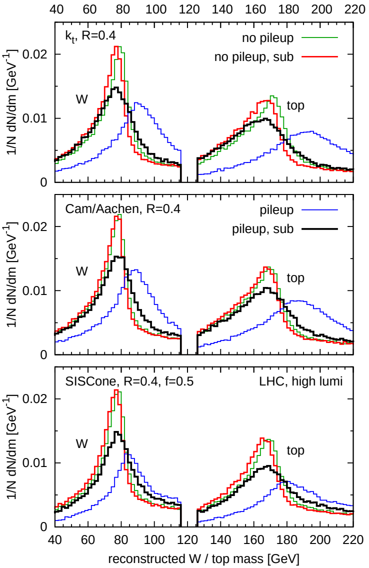
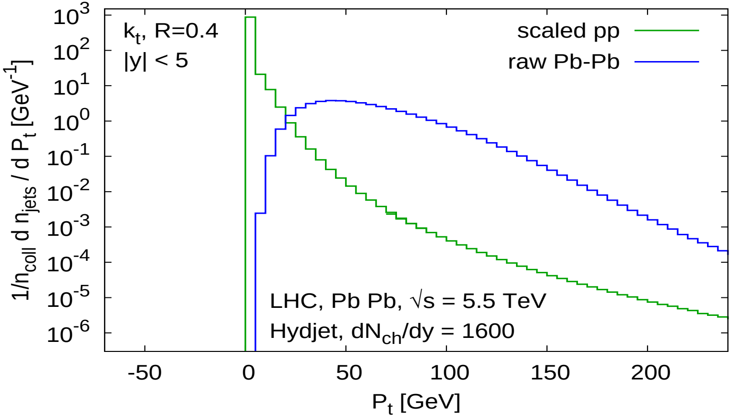


Subtraction for Pb Pb at LHC

Example: inclusive jet spectrum

- Speed makes it easy to run k_t and Cam/Aachen on all 30k particles in HI event
- Subtraction provides a way to get sensible results, without biases from cut on low-p_t particles.



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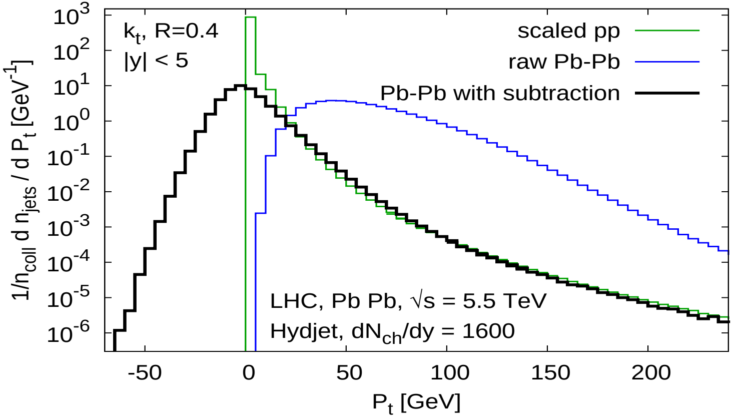
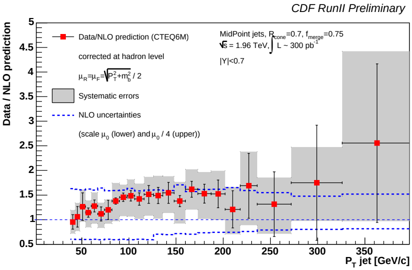


Heavy-flavour jets

One of the least accurate NLO predictions is for b-jets: $\pm \sim 50\%$



Experimental definition

- Run normal jet-algorithm
- a jet containing ≥ 1 b, $\bar{b}$ is a b-jet.

Even though $m_b \ll p_t$, this b-jet definition requires a fully massive calculation, and *higher order terms are enhanced by powers of* $\ln p_t/m_b$.

FCR = LO; FEX+GSP = NLO

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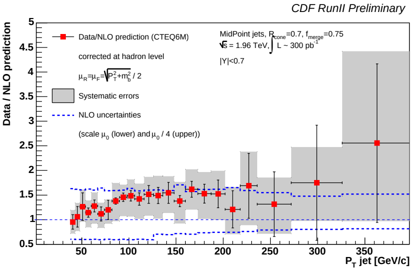

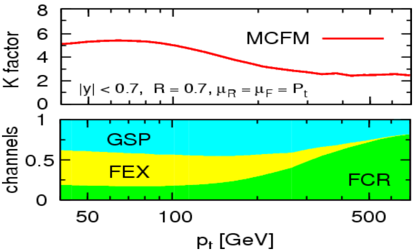

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Jet with b and $\bar{b}$ is *not a b-jet*

Non-trivial experimentally

But removes many logs

'Flavour-k_t' distance measure:

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \times \begin{cases} \min(k_{ti}^2, k_{tj}^2) & \text{harder is } \not{b} \\ \max(k_{ti}^2, k_{tj}^2) & \text{harder is } b \end{cases}$$

Reflects different divergences for q, g

This allows one to

- Resum remaining logs in b-PDF

  Collinear factorisation

- No logs left → take massless limit
- **Bring uncertainty down from 50% to 15%.**

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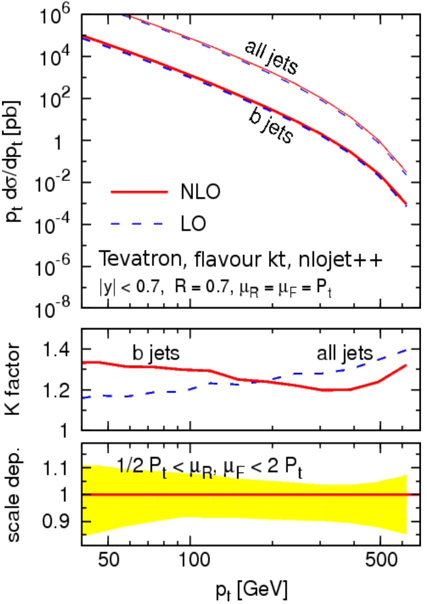

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- proper (seedless) cone algorithm is now a reality, eliminating need for hacks & approximations

Different jet algorithms starting to be compared quantitatively

- Measures of jet areas ($\rightarrow$ surprises: cone area not πR^2)
- Hadronisation has simple fairly universal $1/R$ behaviour
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