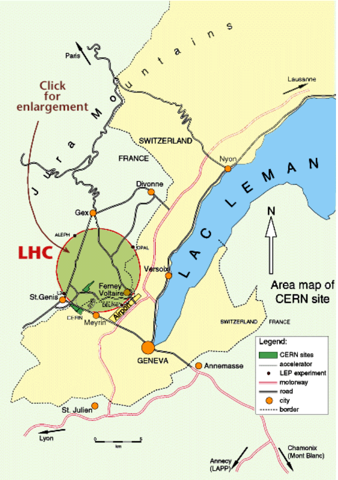
Jets, our window on partons at the LHC

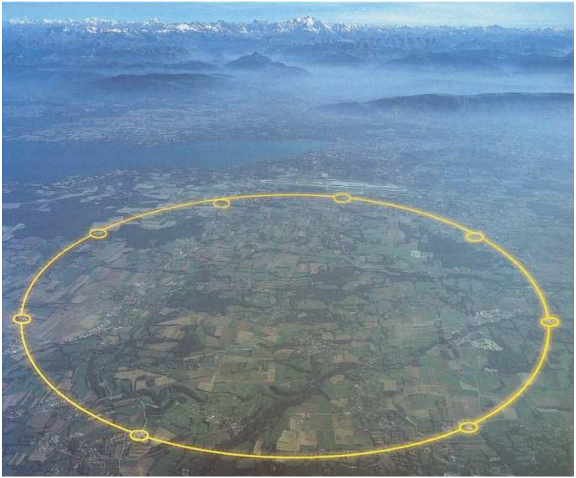
Gavin P. Salam
LPTHE, UPMC Paris 6 & CNRS

Torino, 23 May 2008

Basics: Cacciari (LPTHE) & Soyez (BNL)
Higgs: Butterworth, Davison (ATLAS UCL) & Rubin (LPTHE)
Other related work: Dasgupta (Manchester), Magnea (Turin), Rojo (LPTHE)

Startup approaches for LHC





1,000,000,000 times per second

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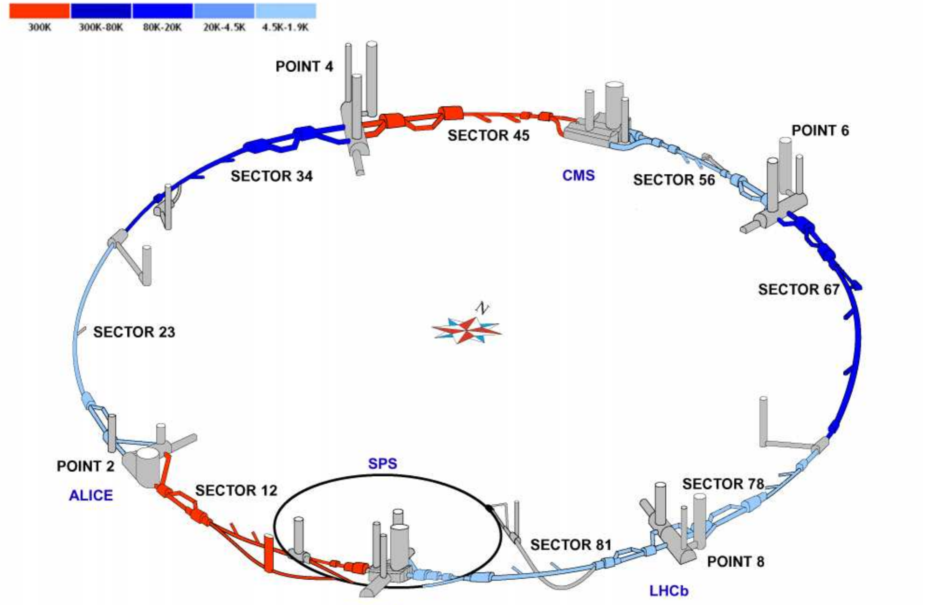
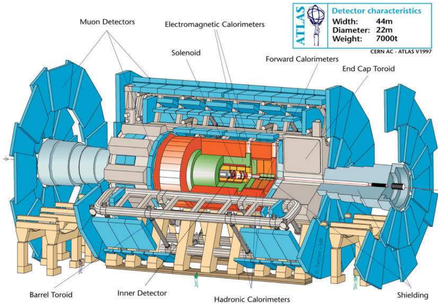
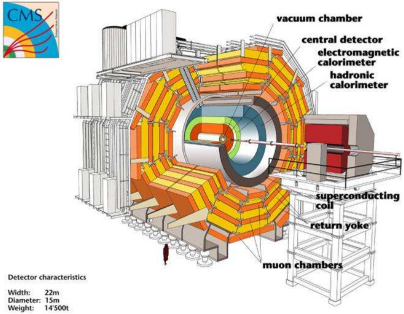


2 general purpose detectors





Compared to current biggest collider (Tevatron)

- LHC energy will be **7 times higher**
- Total number of collisions (over 6 years) **50 times higher**

Aims are varied; Higgs discovery top priority

Last undiscovered component of standard model

ϕ has vacuum expectation value v,

$\phi = v + H \leftrightarrow$ particle masses

$$\mathcal{L} = \cdots + (v+H)^2 \bar{q} q + (v+H)^2 W^+ W^- + \cdots$$

Excitations H around v are the Higgs $\equiv$ sign of what's going on.

Plus searches for anything NEW in this energy domain

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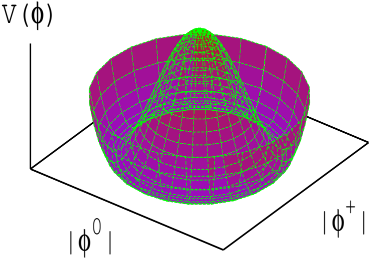

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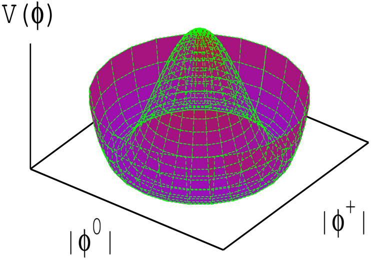

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LHC is a parton collider

- Quarks and gluons are inevitable in initial state
- and ubiquitous in the final state

Partons — quarks and gluons — are key concepts of QCD.

- Lagrangian is in terms of quark and gluon fields
- Perturbative QCD *only* deals with partons

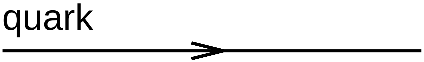
Though we often talk of quarks and gluons, we never see them

- Not an asymptotic state of the theory — because of confinement
- But also even in perturbation theory

  because of collinear divergences (in massless approx.)
- The closest we can get to handling final-state partons is **jets**

1. Jets Introduction

Parton fragmentation



Gluon emission:

$$\int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \gg 1$$

At low scales:

$$\alpha_s \to 1$$

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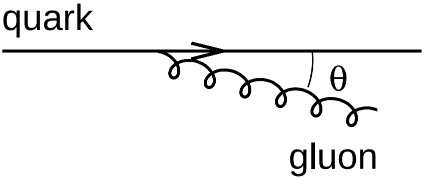

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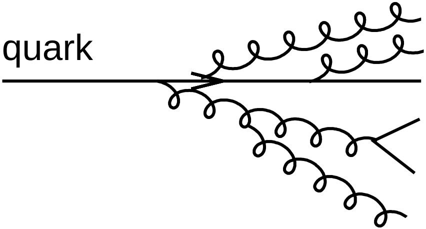

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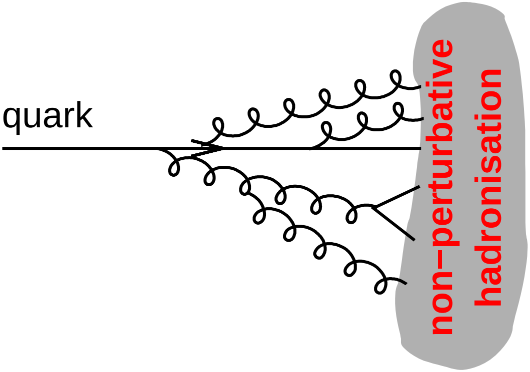

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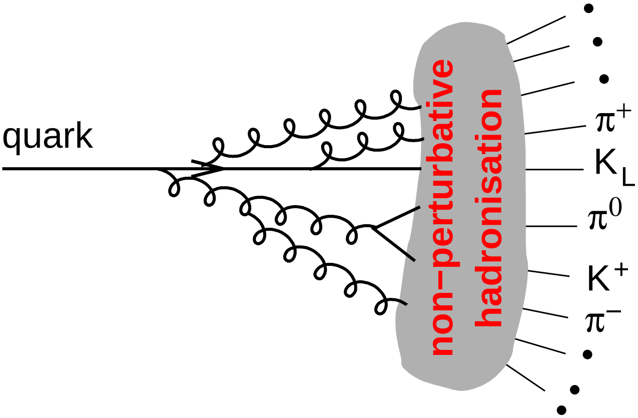

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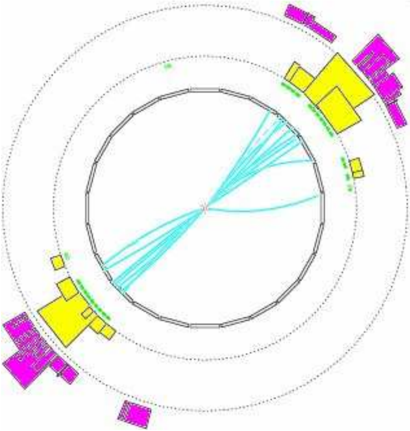
Seeing v. defining jets



Jets are what we see.
Clearly(?) 2 of them.

2 partons?
$E_{parton} = M_z/2$?

How many jets do you see?
Do you really want to ask yourself this question for 10^8 events?

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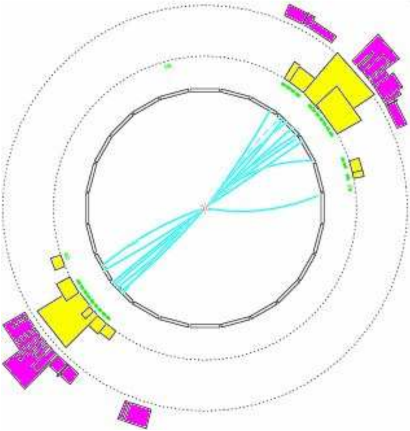

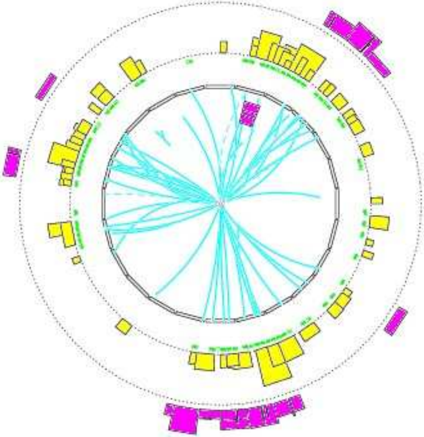

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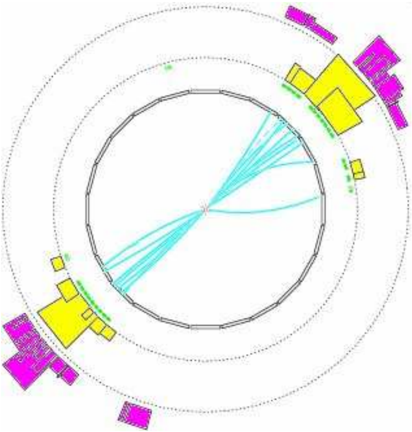

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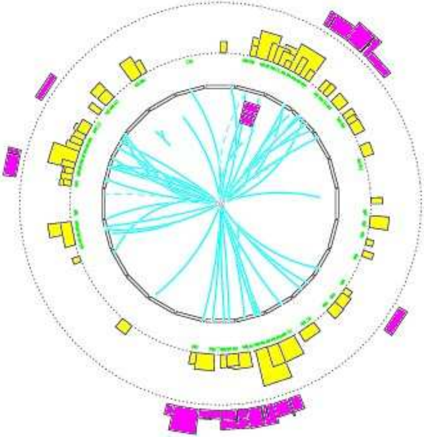

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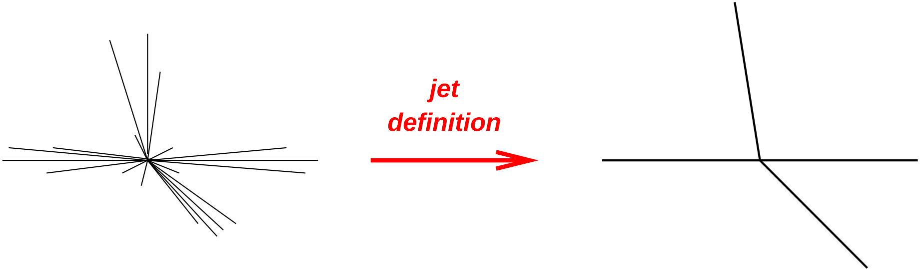
Jet definition / algorithm

A jet definition is a systematic procedure that **projects 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 physical single hard quark or gluon:* with good definitions their properties (multiplicity, energies, [flavour]) are

- finite at any order of perturbation theory
- insensitive to the parton → hadron transition

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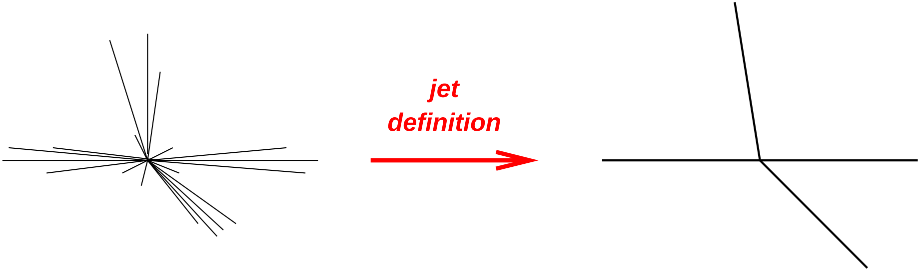

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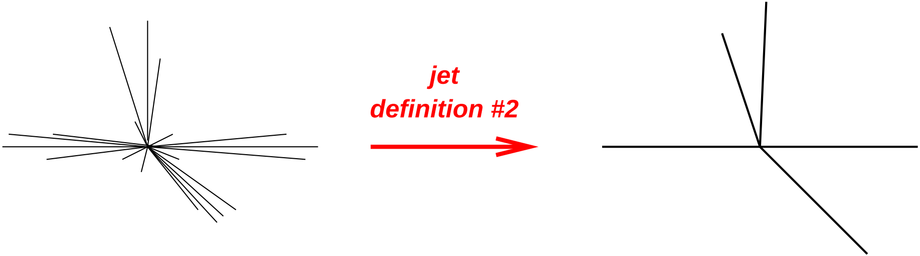

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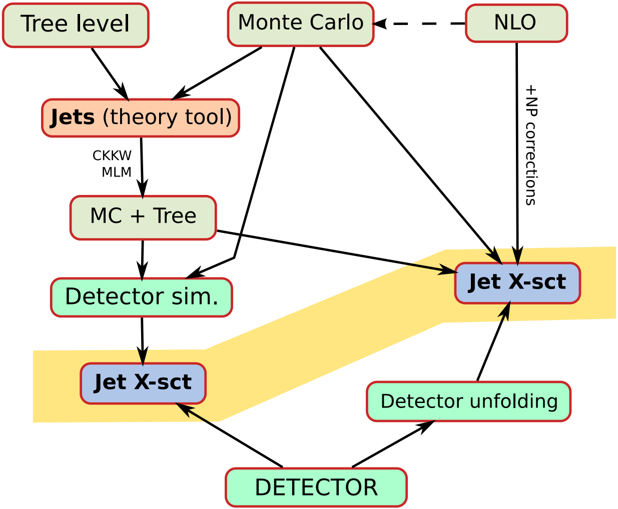
QCD jets flowchart



Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

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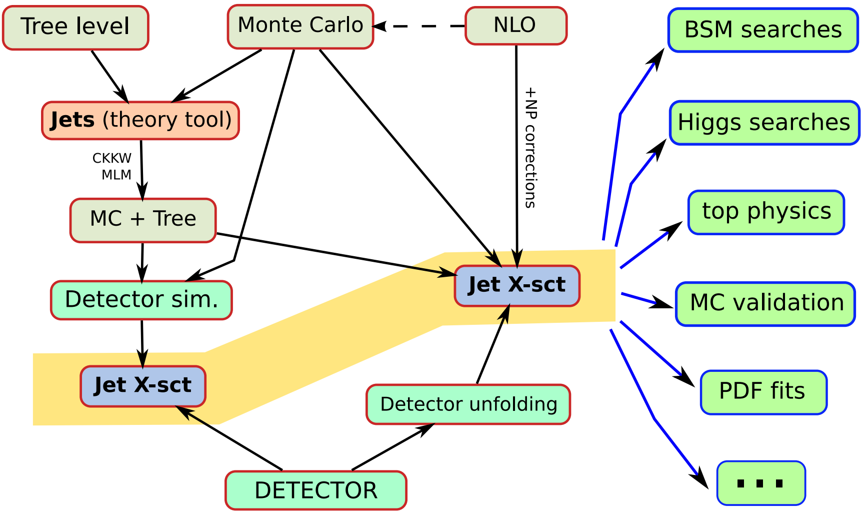

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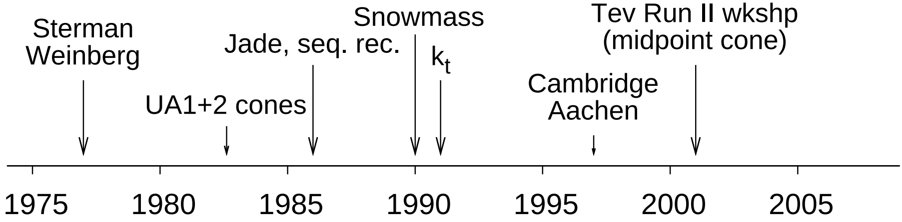
Jet Definition History

- Periodic key developments in jet definitions spurred by ever-increasing experimental/theoretical 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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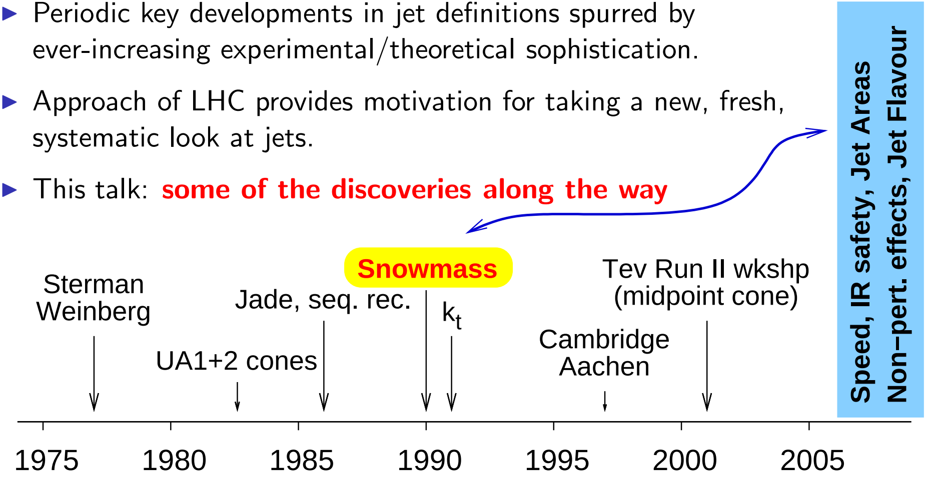

Sterman Weinberg

UA1+2 cones

Jade, seq. rec.

Snowmass

k_t

Cambridge Aachen

Tev Run II wkshp (midpoint cone)

Speed, IR safety, Jet Areas
Non–pert. effects, Jet Flavour

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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 & complexity of signatures (jets, $t\bar{t}$, tj, Wj, Hj, $t\bar{t}j$, WWj, Wjj, SUSY, etc.)
- e.g. ~ 5 million $t\bar{t} \to 6$ jet events/year
- Theory investment

~ 100 people $\times$ 10 years

$60 - 100$ million $

Physics scales:

Experiment	Physics	Scale
LEP, HERA	Electroweak	100 GeV
	+ Hadronisation	0.5 GeV
Tevatron → LHC	+ Underlying event	4 → 15 GeV?
LHC	+ BSM	1 TeV?
	+ Pileup	30 – 120 GeV

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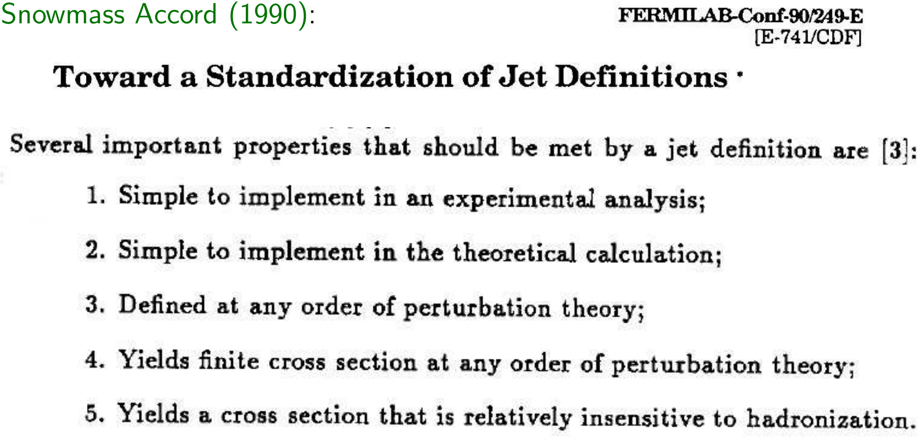

FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

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Without these, either the experiment won’t use the jet-definition, or the theoretical calculations will be compromised

Long satisfied in e^+e^- and DIS

Satisfied in $\lesssim 10\%$ of jet work at Tevatron

Hardly discussed in LHC TDRs

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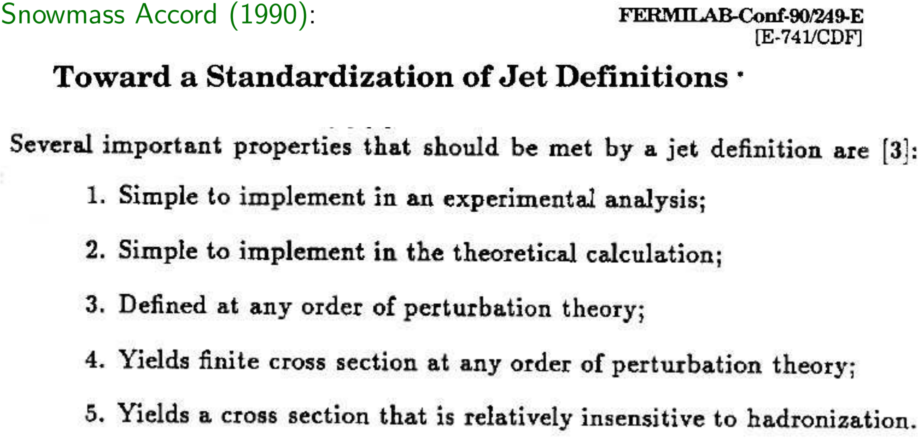

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2. Safe, practical jet-finding

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 → jets.	Top-down: Find coarse regions of energy flow (cones), and call them jets.
Works because of mapping: *closeness ⇔ 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

Both had serious issues that got in way of practical use and/or physical validity

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Sequential recombination algorithms

k_t algorithm

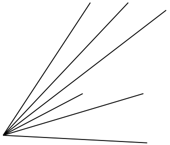
Catani, Dokshizter, Olsson, Seymour, Turnock, Webber '91–'93
Ellis, Soper '93

- 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: $i \to$ jet)
- Repeat

NB: hadron collider variables

- $\Delta R_{ij}^2 = (\phi_i - \phi_j)^2 + (y_i - y_j)^2$
- rapidity $y_i = \frac{1}{2} \ln \frac{E_i + p_{zi}}{E_i - p_{zi}}$
- ΔR_{ij} is boost invariant angle

R sets jet opening angle



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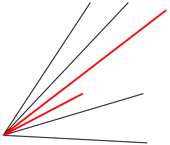

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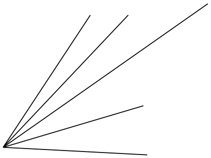

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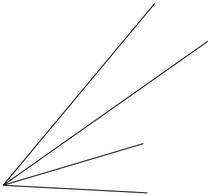

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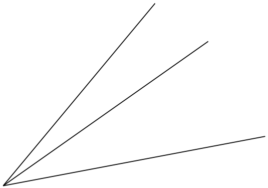

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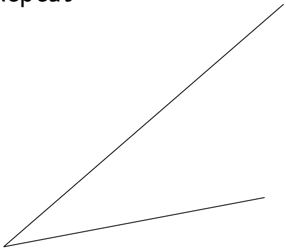

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- rapidity $y_i = \frac{1}{2} \ln \frac{E_i + p_{zi}}{E_i - p_{zi}}$
- ΔR_{ij} is boost invariant angle

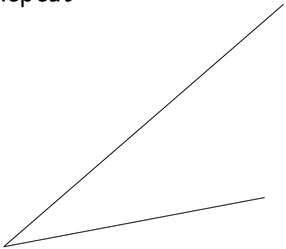
R sets jet opening angle

Sequential recombination algorithms

k_t algorithm

Catani, Dokshizter, Olsson, Seymour, Turnock, Webber '91–'93
Ellis, Soper '93

- 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



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Why k_t?

k_t distance measures

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\Delta R_{ij}^2, \qquad d_{iB} = k_{ti}^2$$

are closely related to structure of divergences for QCD emissions

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \sim \frac{\alpha_s C_A}{2\pi}\frac{dk_{tj}}{\min(k_{ti},k_{tj})}\frac{d\Delta R_{ij}}{\Delta R_{ij}}\,, \qquad (k_{tj} \ll k_{ti}\,,\ \ \Delta R_{ij} \ll 1)$$

and

$$[dk_i]|M^2_{Beam\to Beam+g_i}(k_i)| \sim \frac{\alpha_s C_A}{\pi}\frac{dk_{ti}}{k_{ti}}\,d\eta_i\,, \qquad (k_{ti}^2 \ll \{\hat{s},\hat{t},\hat{u}\})$$

k_t algorithm attempts approximate inversion of branching process

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k_t algorithm attempts approximate inversion of branching process

Computing...

‘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 (20-200 CPU years)
- Heavy Ions: 30000 particles: 10 hours/event

As far as possible physics choices should not be limited by computing.

Even if we’re clever about repeating the full search each time, we still have $\mathcal{O}\left(N^2\right)$ d_{ij}’s to establish

k_t is a form of Hierarchical Clustering

arXiv:cs.DS/9912014 v1 22 Dec 1999

Fast Hierarchical Clustering and Other Applications of Dynamic Closest Pairs

David Eppstein
UC Irvine

We develop data structures for dynamic closest pair problems with arbitrary distance functions, that do not necessarily come from any geometric structure on the objects. Based on a technique previously used by the author for Euclidean closest pairs, we show how to insert and delete objects from an n-object set, maintaining the closest pair, in $O(n \log^2 n)$ time per update and $O(n)$ space. With quadratic space, we can instead use a quadtree-like structure to achieve an optimal time bound, $O(n)$ per update. We apply these data structures to hierarchical clustering, greedy matching, and TSP heuristics, and discuss other potential applications in machine learning, Gröbner bases, and local improvement algorithms for partition and placement problems. Experiments show our new methods to be faster in practice than previously used heuristics.

Categories and Subject Descriptors: F.2.2 [**Analysis of Algorithms**]: Nonnumeric Algorithms

General Terms: Closest Pair, Agglomerative Clustering

Additional Key Words and Phrases: TSP, matching, conga line data structure, quadtree, nearest neighbor heuristic

1. INTRODUCTION

Hierarchical clustering has long been a mainstay of statistical analysis, and clustering based methods have attracted attention in other fields: computational biology (reconstruction of evolutionary trees; tree-based multiple sequence alignment), scientific simulation (n-body problems), theoretical computer science (network design and nearest neighbor searching) and of course the web (hierarchical indices such as Yahoo). Many clustering methods have been devised and used in these applications, but less effort has gone into algorithmic speedups of these methods.

In this paper we identify and demonstrate speedups for a key subroutine used in several clustering algorithms, that of maintaining closest pairs in a dynamic set of objects. We also describe several other applications or potential applications of the

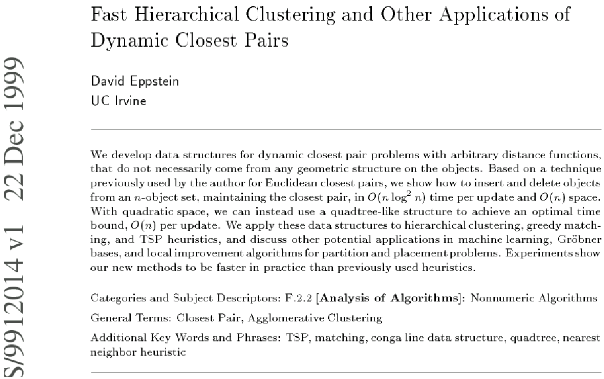
k_t alg. is so good it's used throughout science!

NB HEP is not only field to use brute-force...

For general distance measures problem reduces to $\sim N^2$ (factor $\sim$ 20 for $N = 1000$).

Eppstein '99
+ Cardinal '03

k_t is a form of Hierarchical Clustering



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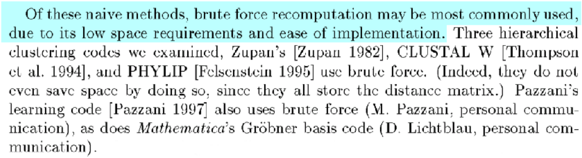

Of these naive methods, brute force recomputation may be most commonly used, due to its low space requirements and ease of implementation. Three hierarchical clustering codes we examined, Zupan's [Zupan 1982], CLUSTAL W [Thompson et al. 1994], and PHYLIP [Felsenstein 1995] use brute force. (Indeed, they do not even save space by doing so, since they all store the distance matrix.) Pazzani's learning code [Pazzani 1997] also uses brute force (M. Pazzani, personal communication), as does *Mathematica*'s Gröbner basis code (D. Lichtblau, personal communication).

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Can we do better than N^2?

There are $N(N-1)/2$ distances d_{ij} — surely we have to calculate them all in order to find smallest?

k_t distance measure is partly *geometrical:*

$$\begin{aligned}\min_{i,j} d_{ij} &\equiv \min_{i,j}(\min\{k_{ti}^2, k_{tj}^2\}\Delta_{ij}^2) \\ &= \min_{i,j}(k_{ti}^2\Delta_{ij}^2) \\ &= \min_{i}(k_{ti}^2 \min_{j} \Delta_{ij}^2)\end{aligned}$$

In words: if i, j form smallest d_{ij} then j is geometrical nearest neighbour (GNN) of i.

k_t distance need only be calculated between GNNs

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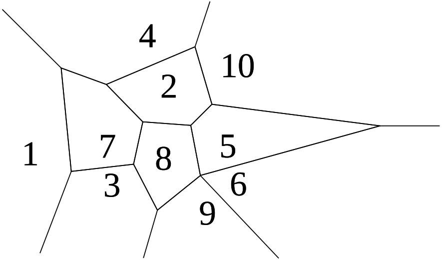
Finding Geom Nearest Neighbours



Given a set of vertices on plane (1...10) a *Voronoi diagram* partitions plane into cells containing all points closest to each vertex

Dirichlet '1850, Voronoi '1908

A vertex's nearest other vertex is always in an adjacent cell.

E.g. GNN of point 7 will be found among 1,4,2,8,3 (it turns out to be 3)

Construction of Voronoi diagram for N points: $N \ln N$ time Fortune '88

Update of 1 point in Voronoi diagram: $\ln N$ time

Devillers '99 [+ related work by other authors]

Convenient C++ package available: **CGAL** `http://www.cgal.org`

Assemble with other comp. science methods: **FastJet**

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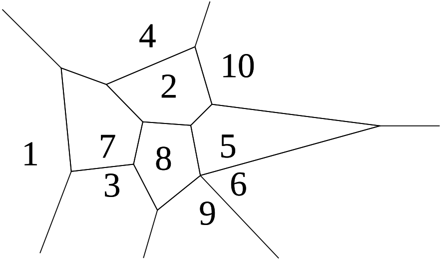

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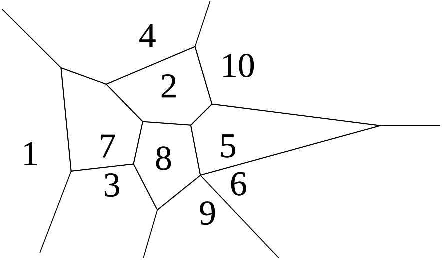

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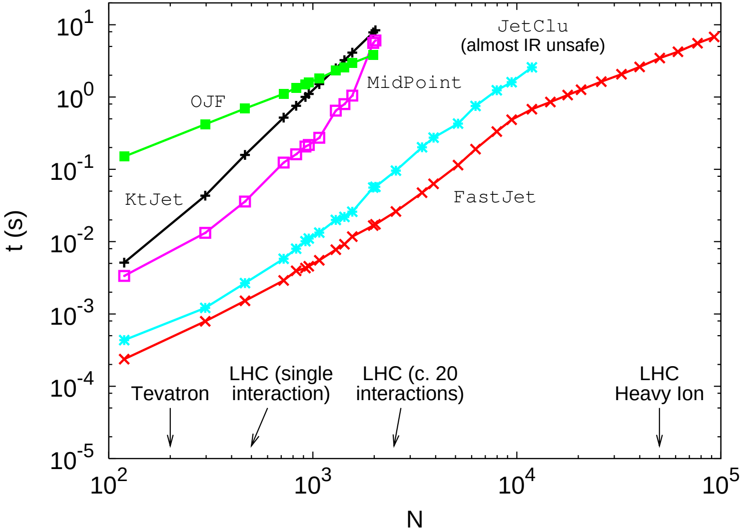
`FastJet` performance

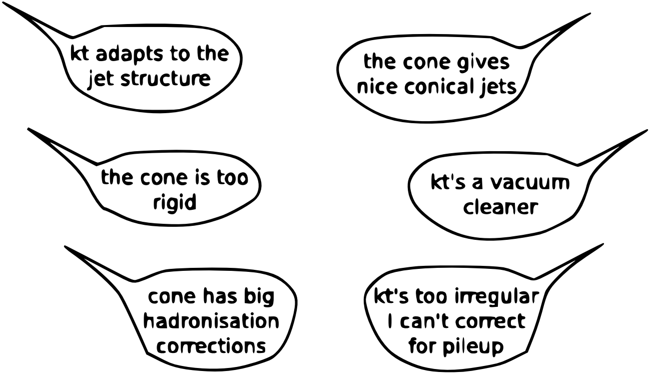


NB: for $N < 10^4$, `FastJet` switches to a related geometrical N^2 alg.

Conclusion: speed issues for k_t resolved

Jet Folklore

Jet discussions: often polarised, driven by unquantified statements

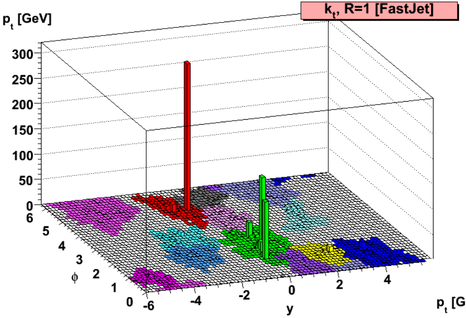


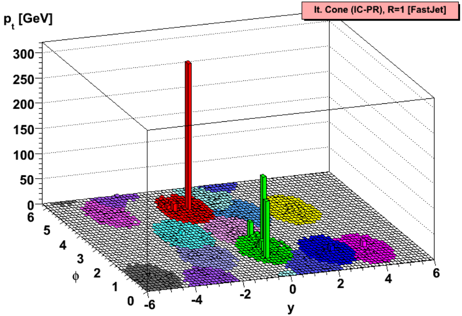
- Rigorous approach is to quantify similarities & differences

  Dasgupta, Magnea & GPS '07; Cacciari, GPS & Soyez '08
- Bottom line: grains of truth in the qualitative statements

  So want good cone algorithms too [NB: two varieties, IC-SM & IC-PR]

k_t v. Cone (ICPR) jets

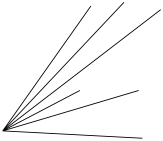




Iterative Cone [with progressive removal]

Procedure:

- Find one stable cone By iterating from hardest seed particle
- Call it a jet; remove its particles from the event; repeat



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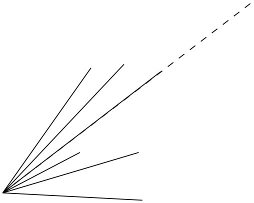

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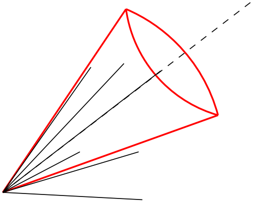

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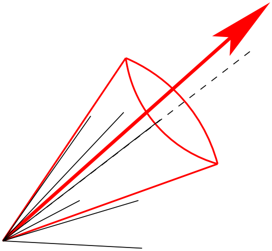

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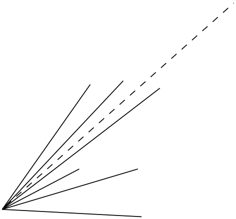

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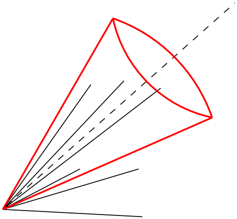

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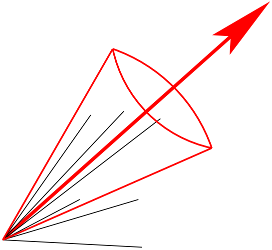

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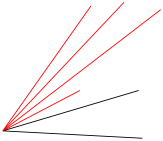

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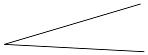

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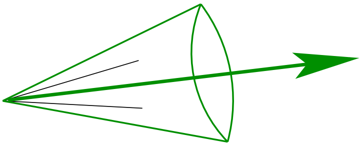

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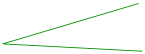

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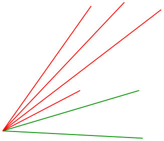

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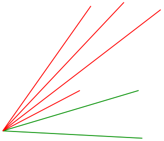
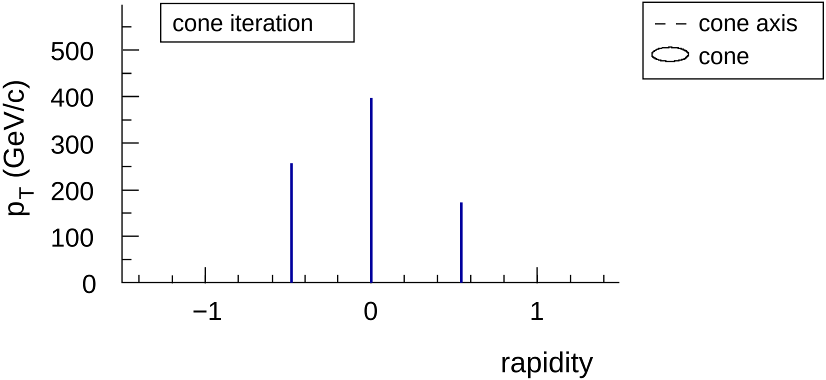


Iterative Cone with Progressive Removal (IC-PR)

e.g. CMS it. cone, [Pythia Cone, GetJet], ...

- NB: not same type of algorithm as Atlas Cone, MidPoint, SISCone

ICPR iteration issue



Collinear splitting can modify the hard jets: ICPR algorithms are collinear unsafe $\Longrightarrow$ perturbative calculations give ∞

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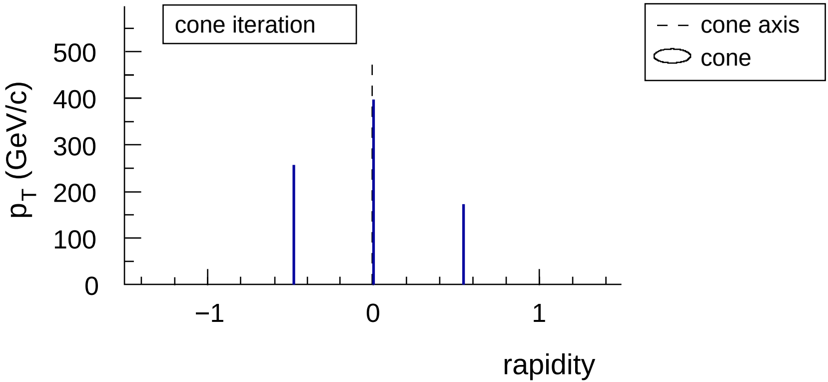

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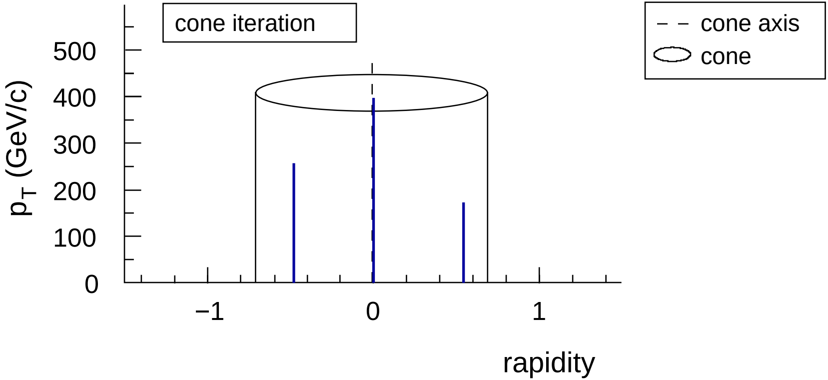

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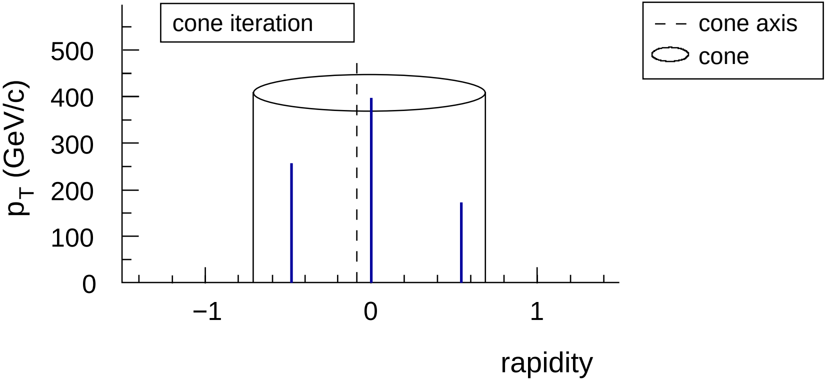

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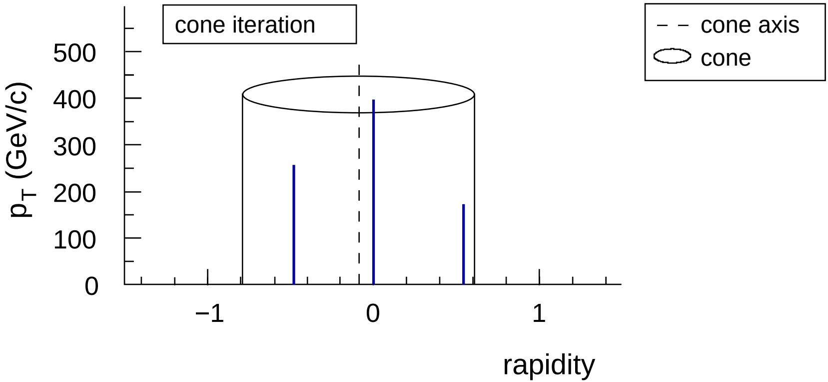

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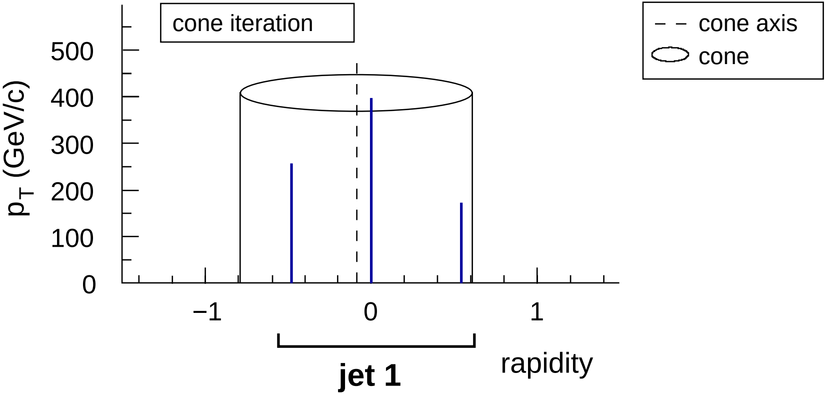

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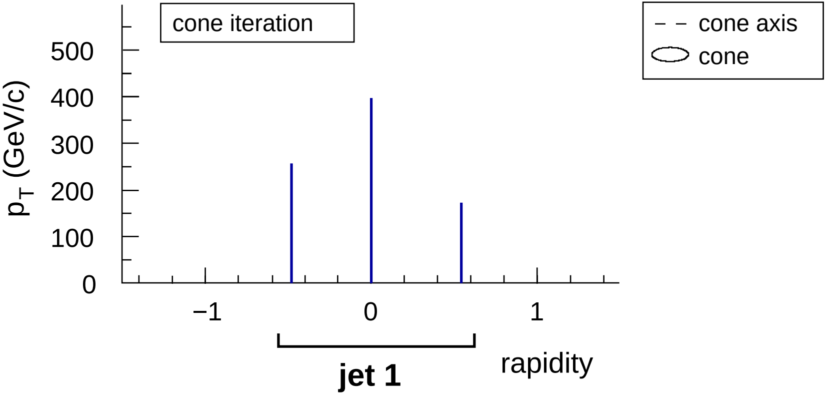

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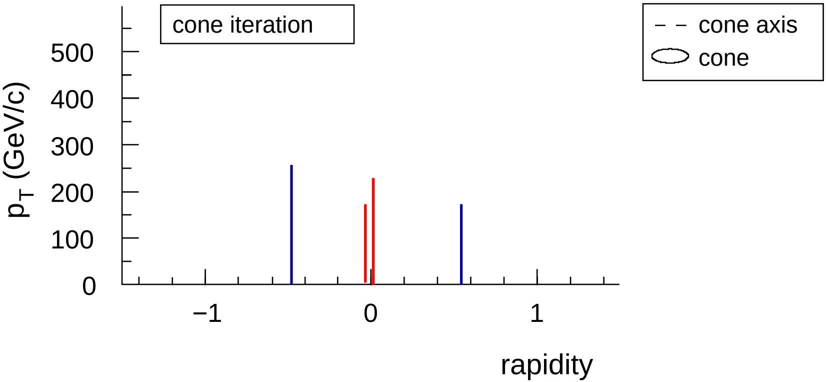

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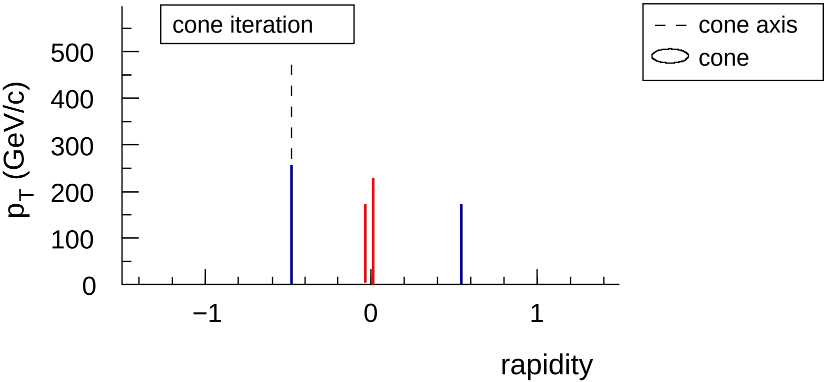

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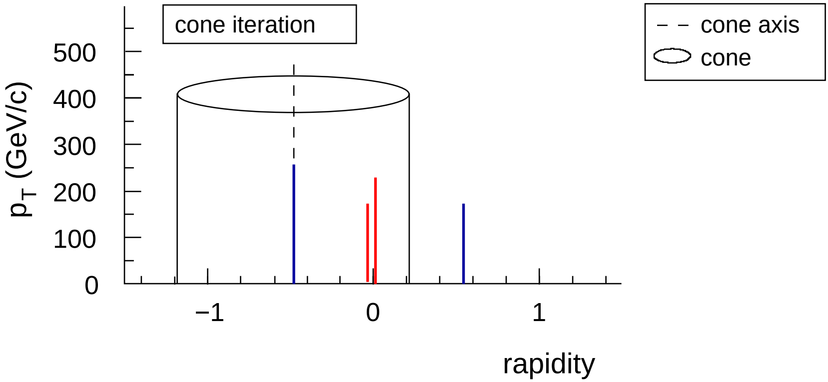

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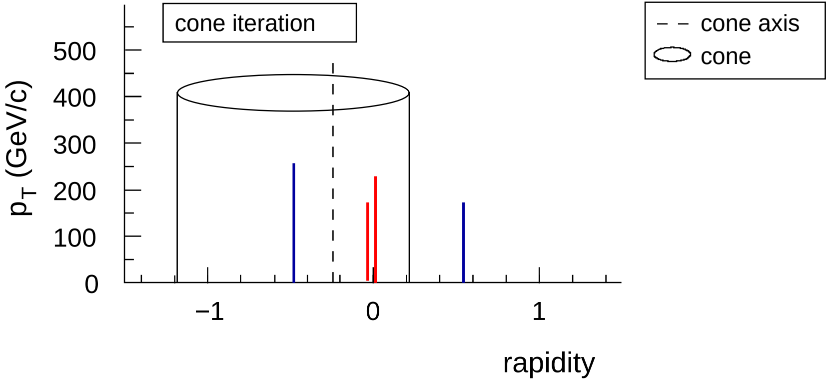

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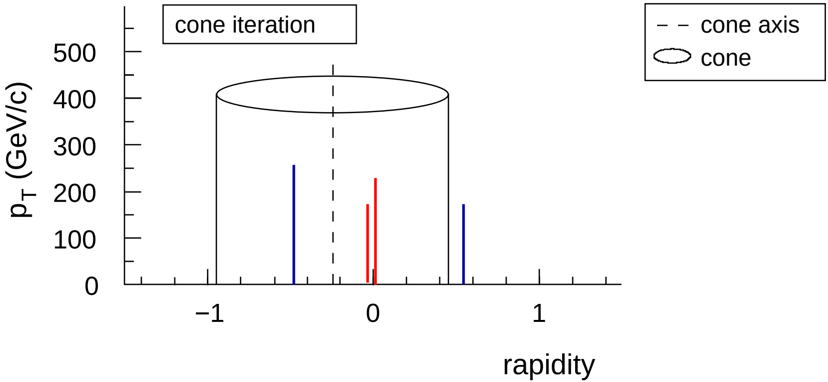

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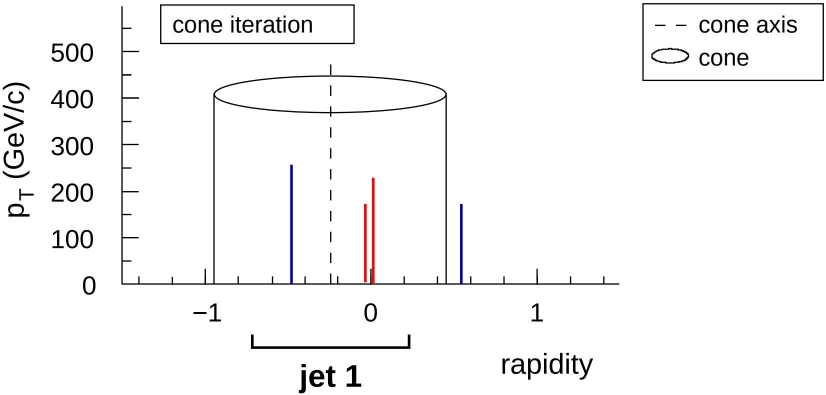

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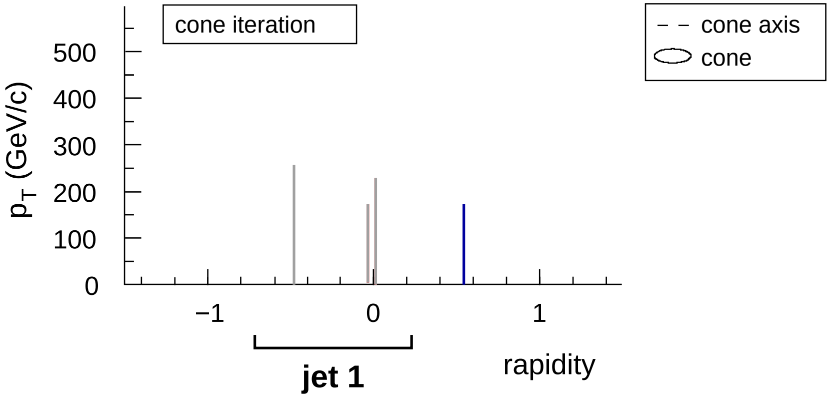

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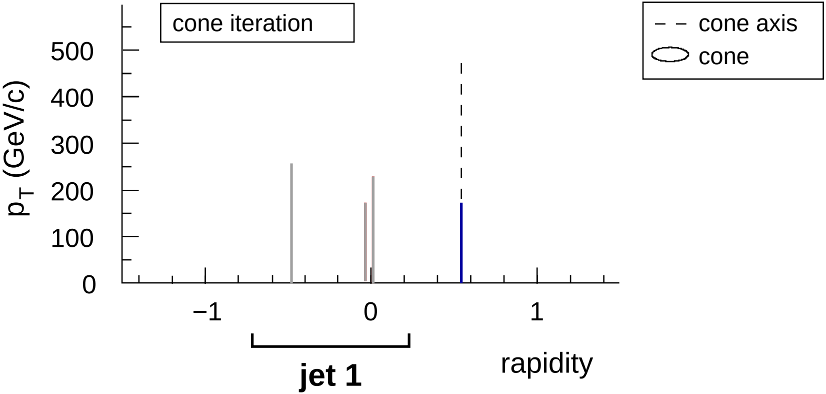

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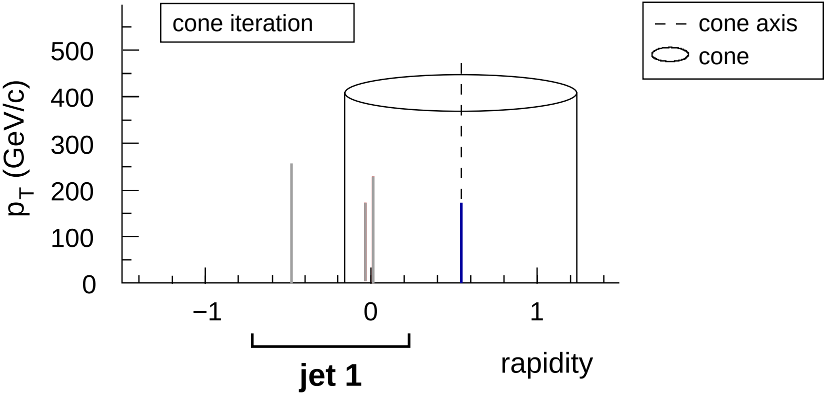

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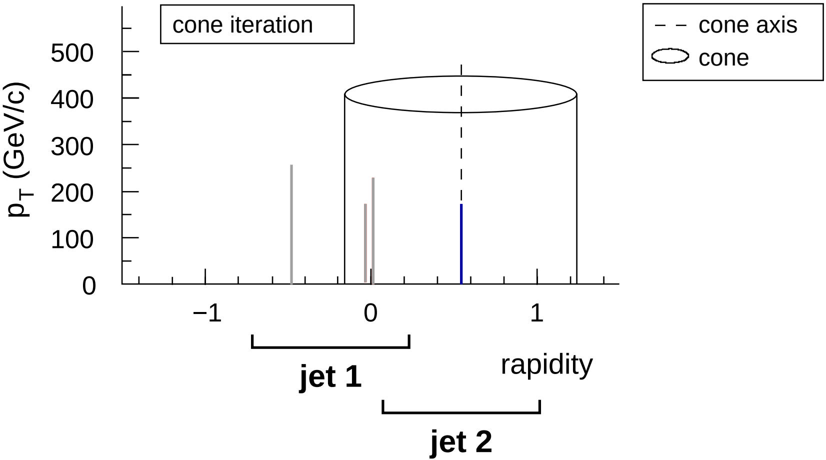

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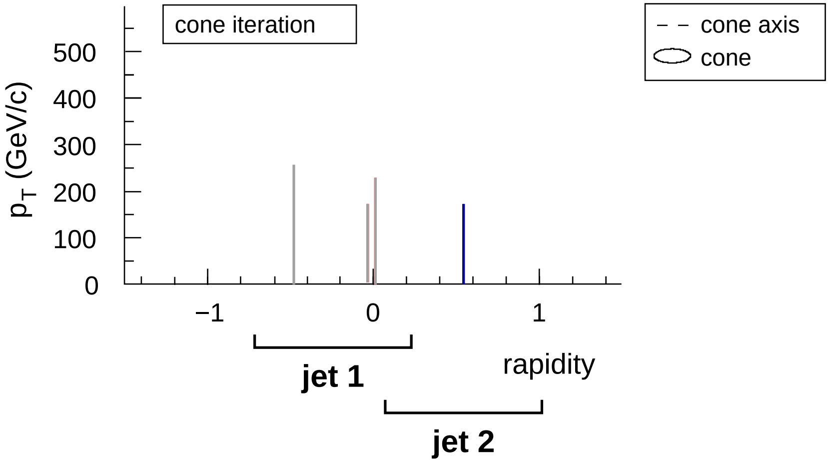

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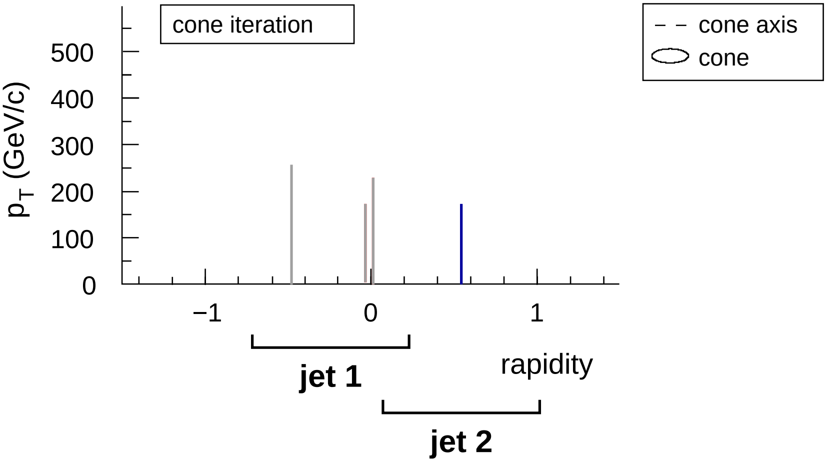

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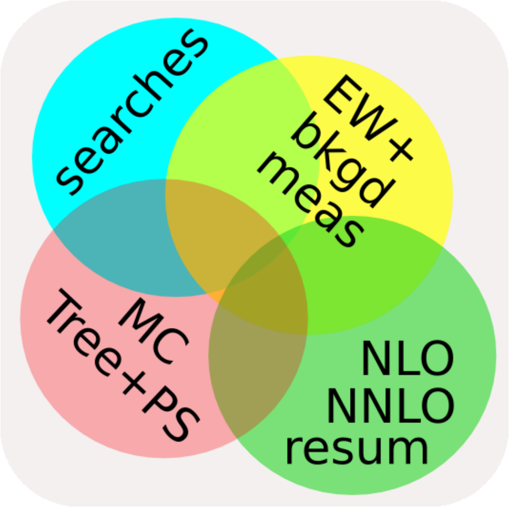

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anti-k_t

What we want: something that behaves like a cone algorithm (circular jets), but that is IRC safe.

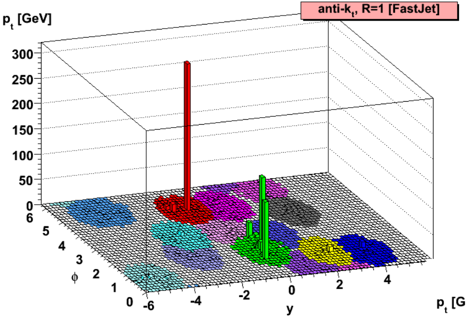
Approach: drop the “cone” in definition, but design an algorithm that still acts like a cone: **anti-**k_t

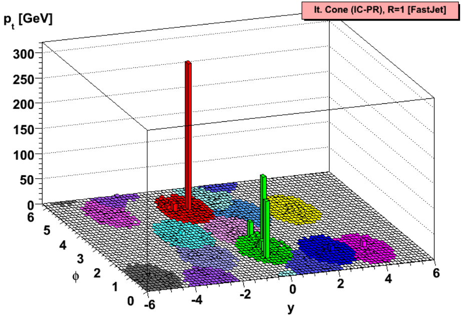
1. Find smallest of d_{ij}, d_{iB}: $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\Delta R_{ij}^2/R^2\,, \qquad d_{iB} = k_{ti}^{-2}$
2. if ij, recombine them; if iB, call i a jet, and remove from list of particles
3. repeat from step 1 until no particles left.

Cacciari, GPS & Soyez ’08

Looks like k_t but momentum in *denominator* causes d_{ij} to involve largest k_t → jets grows outward from hard “seeds”.

anti-k_t v. Cone (ICPR) jets





A full set of algs

Complementary set of IR/Collinear safe jet algs ⟶ flexbility in studying complex events.

Consider families of jet algs: e.g. sequential recombination with

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \Delta R_{ij}^2 / R^2$$

	Alg. name	Comp. Geometry problem	time
$p = 1$	k_t CDOSTW '91-93; ES '93	Dynamic Nearest Neighbour CGAL (Devillers et al)	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Dynamic Closest Pair T. Chan '02	$N \ln N$
$p = -1$	anti-k_t (cone-like) Cacciari, GPS, Soyez, in prep.	Dynamic Nearest Neighbour CGAL (worst case)	$N^{3/2}$
cone	SISCone GPS Soyez '07 + Tevatron run II '00	All circular enclosures previously unconsidered	$N^2 \ln N$ exp.

All accessible in FastJet

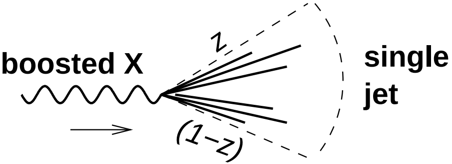
FastJet in software of all (4) LHC collaborations

3. An example: boosted Higgs search

EW bosons at @ high p_t

Illustrate LHC challenges with a recently widely discussed class of problems:

Can you identify hadronically decaying EW bosons when they're produced at high $\mathbf{p_t}$?



$$R \gtrsim \frac{m}{p_t}\frac{1}{\sqrt{z(1-z)}}$$

Significant discussion over years: **heavy new things decay to EW states**

- Seymour '94 [Higgs → $WW \to \nu\ell$jets]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
- Butterworth, Ellis & Raklev '07 [SUSY decay chains → W, H]
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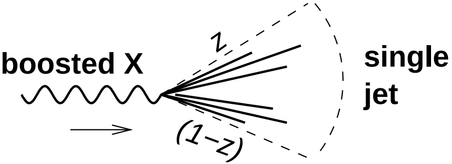

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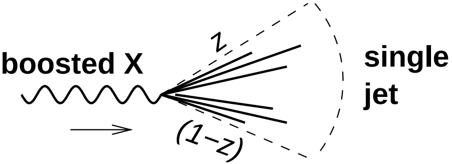

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Boosted bosons: how to?

Most obvious method: look at the **jet mass**, but

- QCD jets can be massive too → large backgrounds
- Non-pert mass resol^n $\sim \delta M \sim R^4 \Lambda_{UE} \frac{p_t}{M}$ Dasgupta, Magnea & GPS '07

Natural idea: **use hierarchical structure of $\mathbf{k_t}$ alg to resolve structure**

Seymour '93; Butterworth, Cox & Forshaw '02 [Ysplitter]

- You can cut on d_{ij} (rel. ⊥ mom.^{2}), correl. with mass helps reject bkgds
- But not ideal: k_t intrinsic mass resolution often poor

What you really want:

- Stay with hierarchical-type alg: study two subjets
- Dynamically choose R based on p_t & M → best mass resolution

→ **Cambridge/Aachen** algorithm

Repeatedly cluster pair of objects closest in angle until all separated by $\geq R$

[Can then undo clustering & look at jet on a range of angular scales]

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E.g.: WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$.
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...

Studied e.g. in ATLAS TDR

Difficulties, e.g.

- $gg \to t\bar{t}$ has $\ell\nu b\bar{b}$ with **same intrinsic mass scale**, but much higher partonic luminosity
- Need exquisite control of bkgd shape

Try a long shot?

- Go to high p_t ($p_{tH}, p_{tV} > 200$ GeV)
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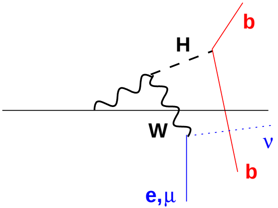

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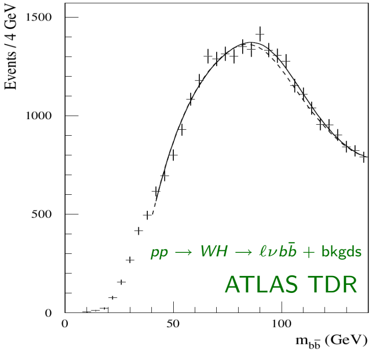

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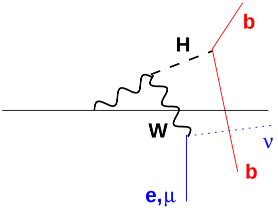

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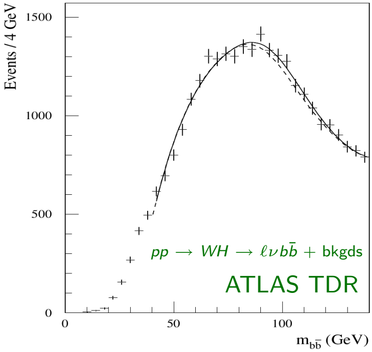

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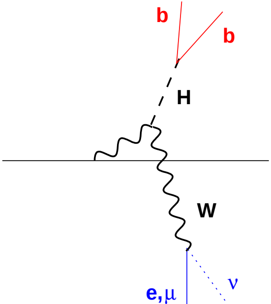

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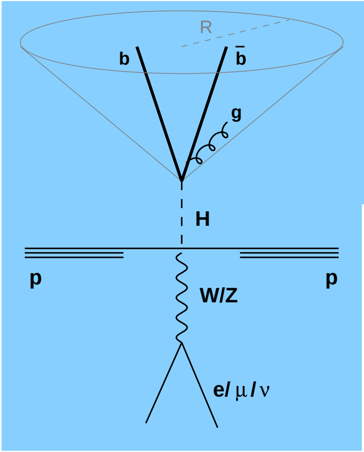
High-p_t light Higgs decays to $b\bar{b}$ inside a single jet. Can this be seen?

Butterworth, Davison, Rubin & GPS '08



Cluster with Cambridge/Aachen

1. Find a high-p_t massive jet J
2. Undo last stage of clustering ($\equiv$ reduce R)
3. If $m_{subjets} \lesssim 0.67 m_J$ & subjet p_t's not asym. & each b-tagged → Higgs candidate
4. Else, repeat from 2 with heavier subjet

Then on the Higgs-candidate: *filter* away UE/pileup by reducing $R \to R_{filt}$, take *three hardest subjets* (keep LO gluon rad^n) + require b-tags on two hardest.

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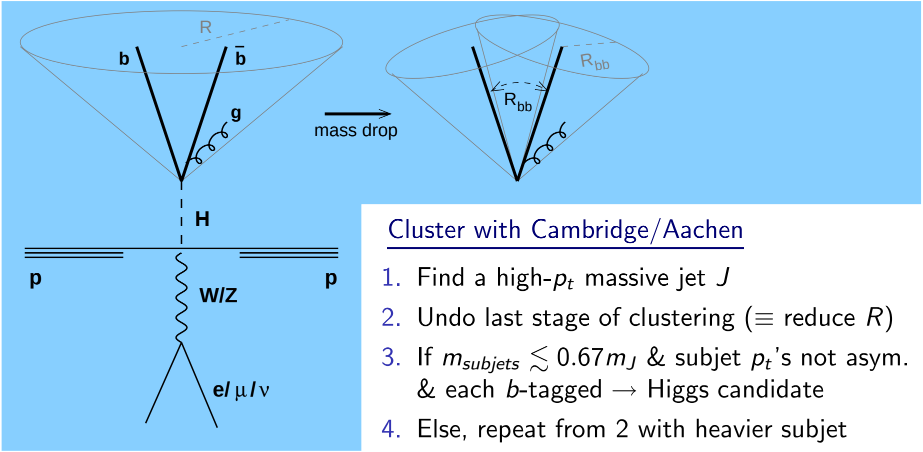

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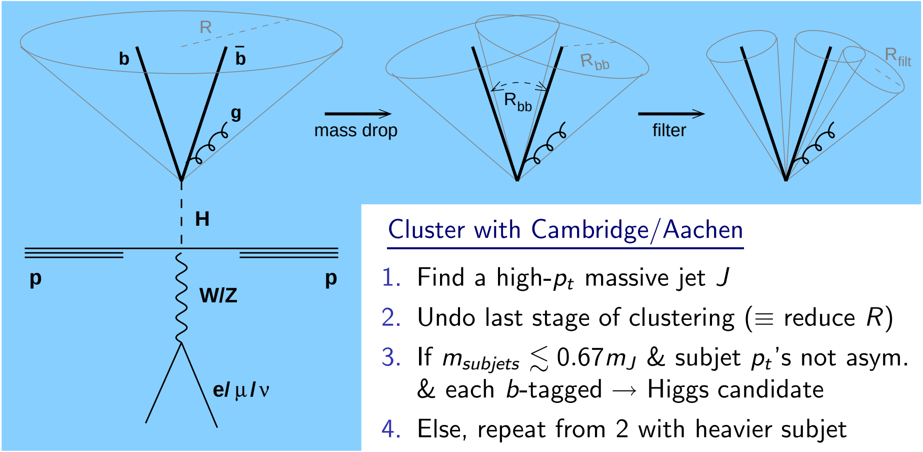

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$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

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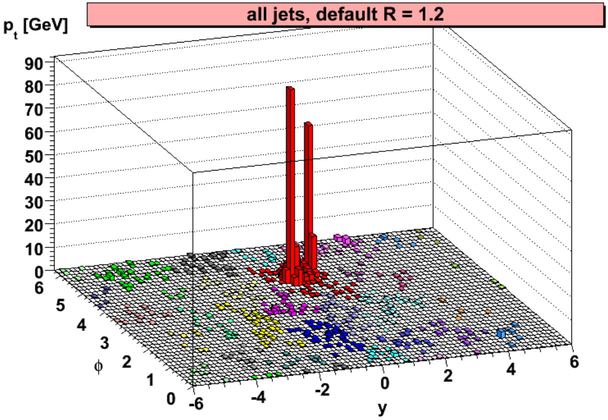

Zbb BACKGROUND

arbitrary norm.

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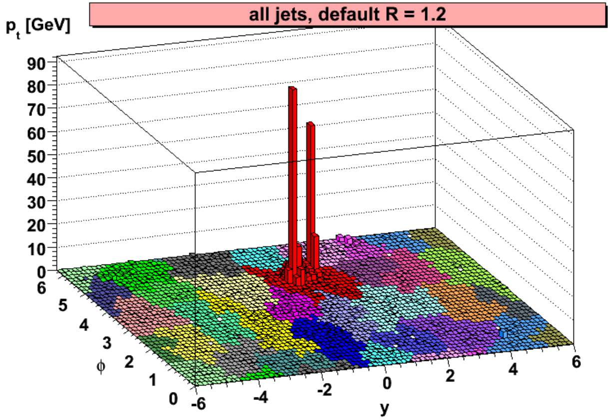

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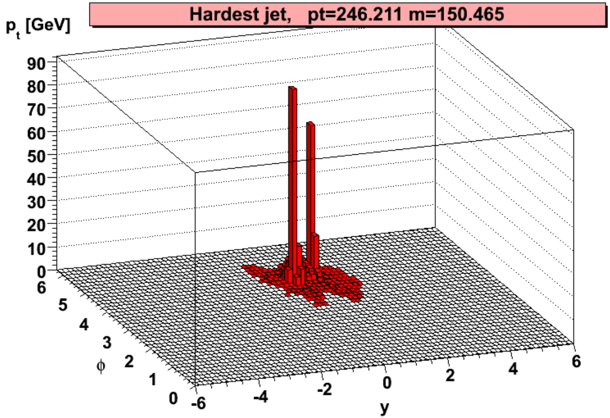

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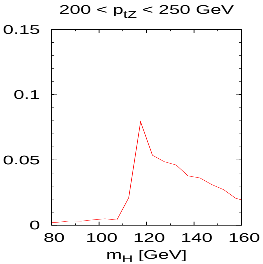

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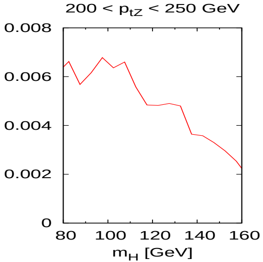

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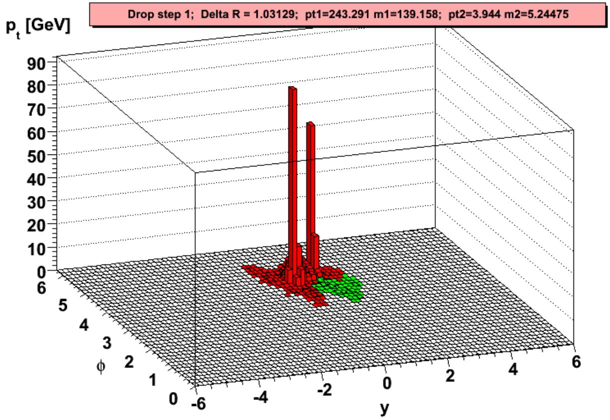

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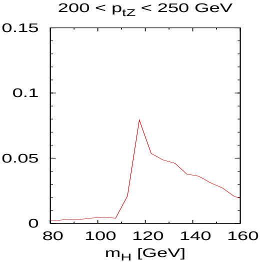

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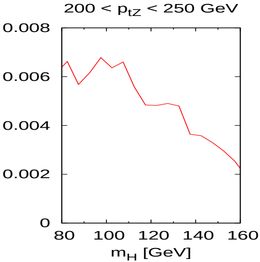

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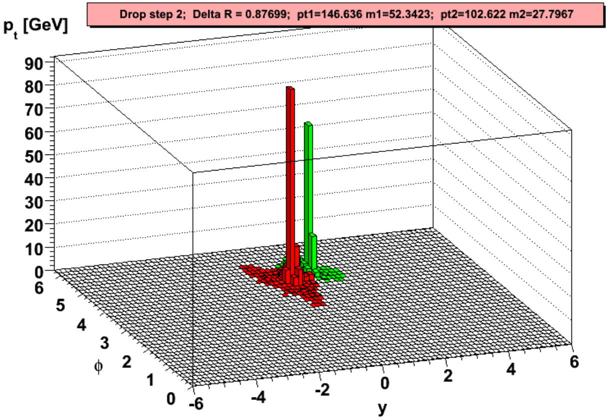
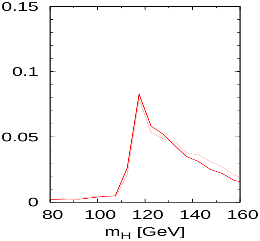
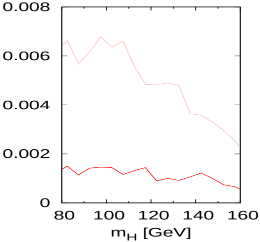



SIGNAL

200 < p_{tZ} < 250 GeV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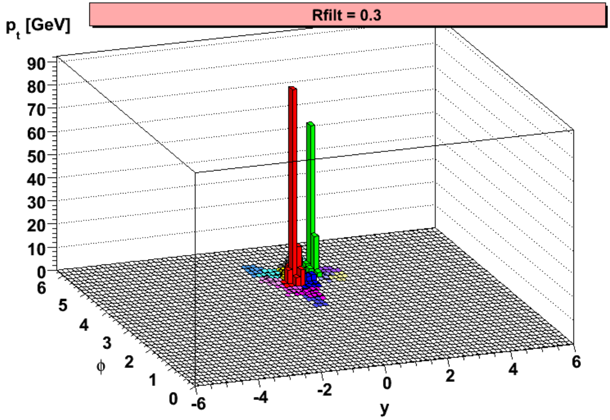
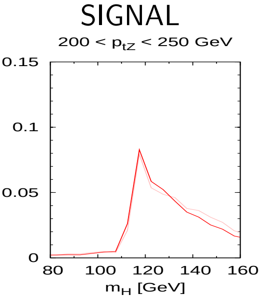
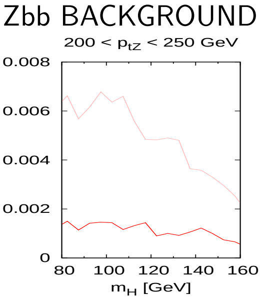
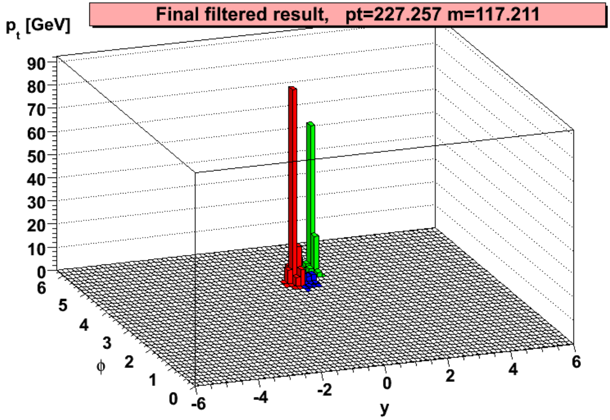




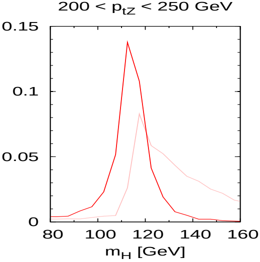


arbitrary norm.

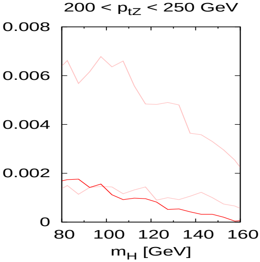
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV



SIGNAL



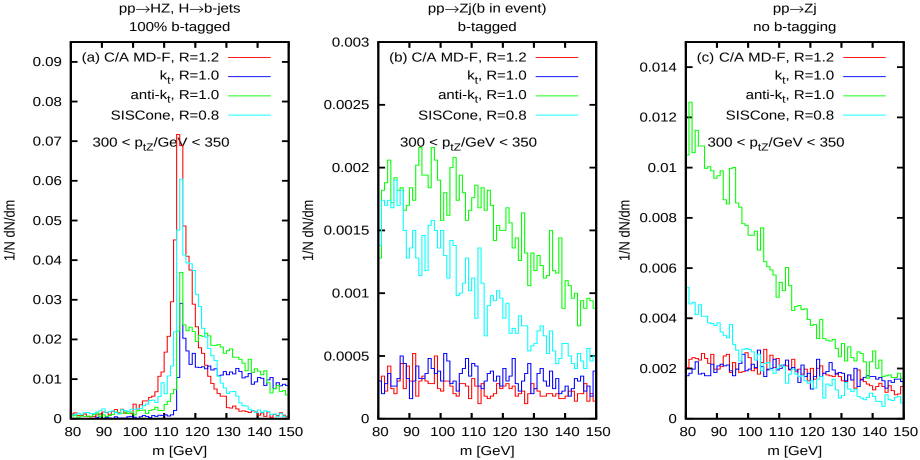
Zbb BACKGROUND



arbitrary norm.

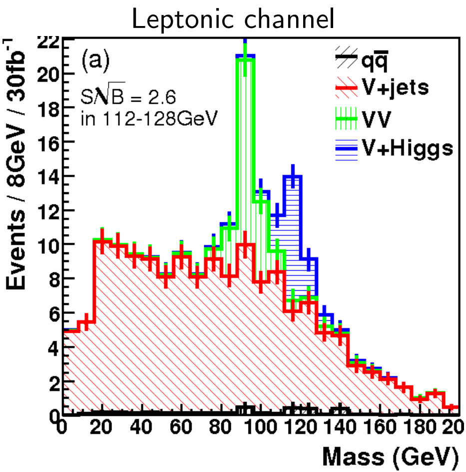
Compare with "standard" algorithms

Check mass spectra in HZ channel, $H \to b\bar{b}$, $Z \to \ell^+\ell^-$



Cambridge/Aachen (C/A) with mass-drop and filtering (MD/F) works best

combine HZ and HW, $p_t > 200$ GeV



Leptonic channel

Common cuts

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30 \text{ GeV}, |\eta_\ell| < 2.5]$
- No extra ℓ, b's with $|\eta| < 2.5$
- Real/fake b-tag rates: 0.7/0.01
- $S/\sqrt{B}$ from 18 GeV window

Leptonic channel

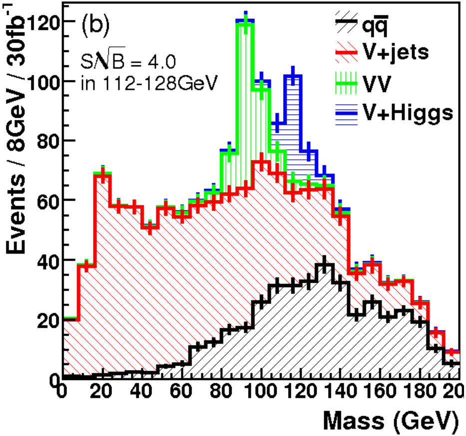
$Z \to \mu^+\mu^-, e^+e^-$

- $80 < m_{\ell^+\ell^-} < 100$ GeV

At 5.9σ for 30 fb^{-1} for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. Deserves serious exp. study!

combine HZ and HW, $p_t > 200$ GeV

Missing E_T channel



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- Real/fake b-tag rates: 0.7/0.01
- $S/\sqrt{B}$ from 18 GeV window

Missing-E_t channel

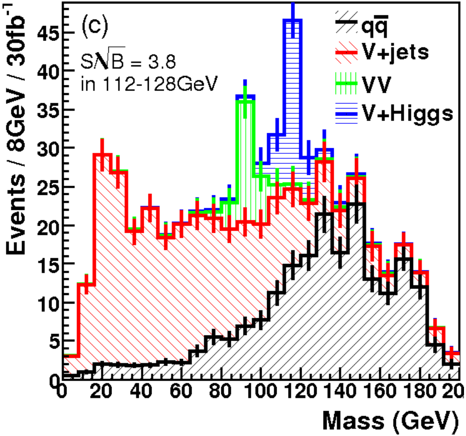
$Z \to \nu\bar{\nu}$, $W \to \nu[\ell]$

- $\not{E}_T > 200$ GeV

At 5.9σ for 30 fb^{-1} for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

combine HZ and HW, $p_t > 200$ GeV

Semi-leptonic channel



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- Real/fake b-tag rates: 0.7/0.01
- $S/\sqrt{B}$ from 18 GeV window

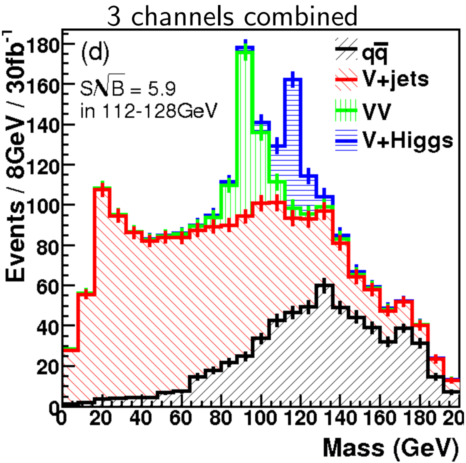
Semi-leptonic channel

$W \to \nu\ell$

- $\not{E}_T > 30$ GeV (& consistent W.)
- no extra jets $|\eta| < 3, p_t > 30$

At 5.9σ for 30 fb^{-1} for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

combine HZ and HW, $p_t > 200$ GeV



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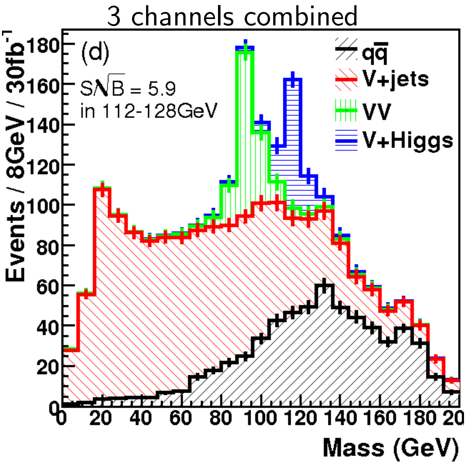
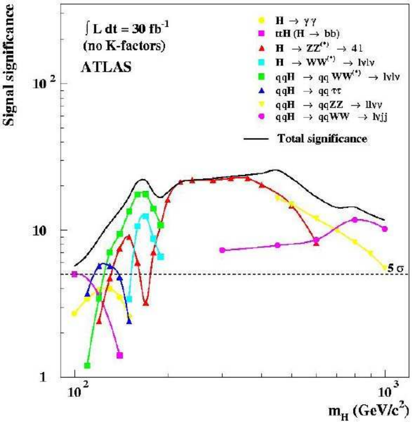
3 channels combined

At 5.9σ for 30 fb^{-1} for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

combine HZ and HW, $p_t > 200$ GeV





At 5.9σ for 30 fb^{-1} for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**

Closing

Conclusions / Outlook

- Jets are the closest we can get to seeing and giving meaning to partons
- Play a pivotal role in experimental analyses, comparisons to QCD calculations
- Significant progress in past 2 years towards making them *consistent* (IR/Collinear safe) and *practical*

  Link with computational geometry

  All tools are made public:

  `http://www.lpthe.jussieu.fr/~salam/fastjet/`
- The physics of how jets behave in a hadron-collider environment is a rich subject — much to be understood, and potential for significant impact in how jets are used at LHC

  E.g. Boosted higgs search

EXTRA SLIDES

IRC safety & real-life

Real life does not have infinities, but pert. infinity leaves a real-life trace

$$\alpha_s^2+\alpha_s^3+\alpha_s^4\times\infty \to \alpha_s^2+\alpha_s^3+\alpha_s^4\times \ln p_t/\Lambda \to \alpha_s^2+\underbrace{\alpha_s^3+\alpha_s^3}_{\textbf{BOTH WASTED}}$$

Among consequences of IR unsafety:

	Last meaningful order			
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC$_{mp}$-SM]	CMS it. cone [IC-PR]	Known at
Inclusive jets	LO	NLO	NLO	NLO (→ NNLO)
W/Z + 1 jet	LO	NLO	NLO	NLO
3 jets	**none**	LO	LO	NLO [`nlojet++`]
W/Z + 2 jets	**none**	LO	LO	NLO [`MCFM`]
$m_{\rm jet}$ in $2j+X$	**none**	**none**	**none**	LO

NB: \$30 – 50M investment in NLO

Multi-jet contexts much more sensitive: **ubiquitous at LHC**

And LHC will rely on QCD for background double-checks
extraction of cross sections, extraction of parameters

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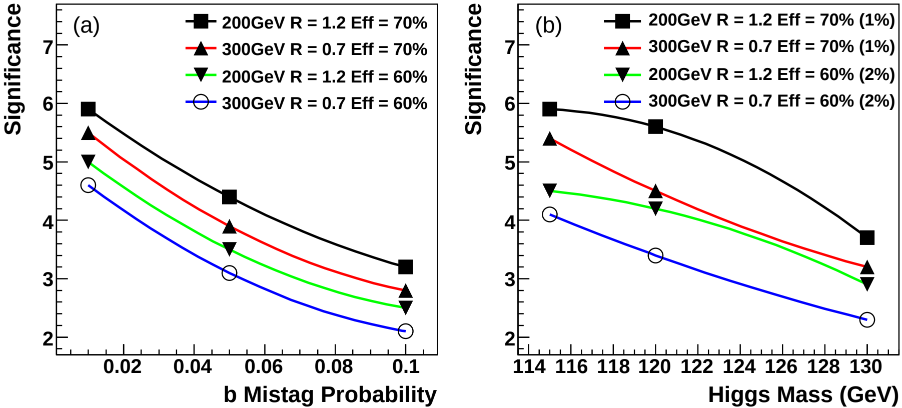
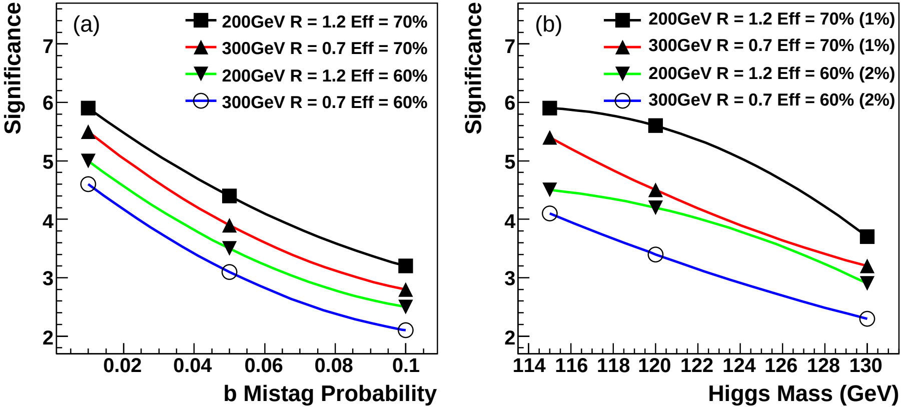
Impact of *b*-tagging, Higgs mass



Most scenarios above 3σ; still much work to be done, notably on verification of experimental resolution.

Regardless of final outcome, illustrates value of choosing appropriate "jet-methods," and of potential for progress with new ideas.

Impact of *b*-tagging, Higgs mass



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