Jets at LHC: from basics to Higgs hunting

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Basics: Cacciari (LPTHE) & Soyez (BNL)
Higgs: Butterworth, Davison (ATLAS UCL) & Rubin (LPTHE)
Thanks also to: Dasgupta (Manchester), Magnea (Turin), Rojo (LPTHE)

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

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

LHC is a parton collider

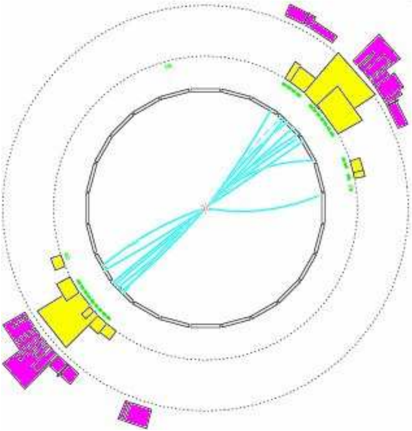
- Quarks and gluons are inevitable in initial state
- and ubiquitous in the final state

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**

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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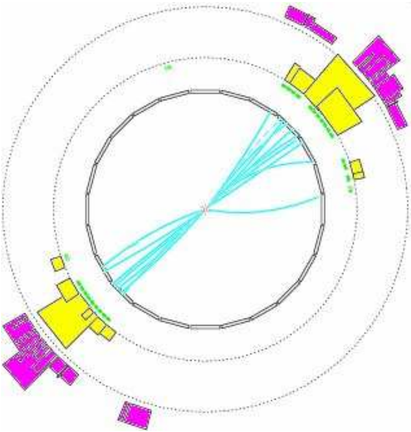

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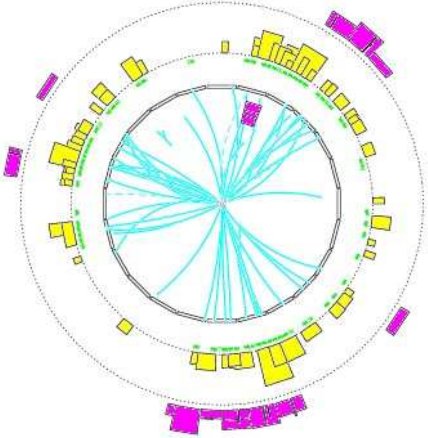

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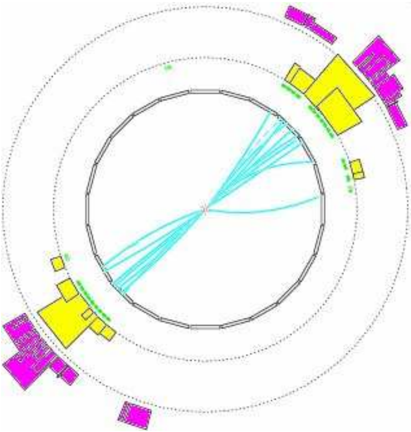

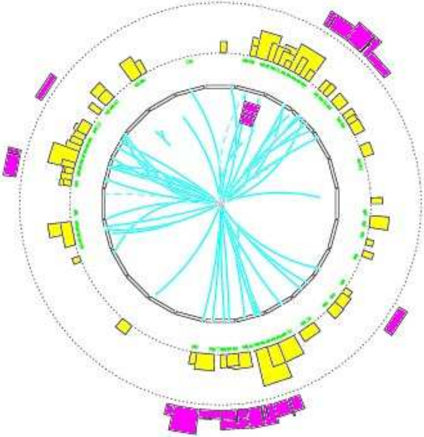

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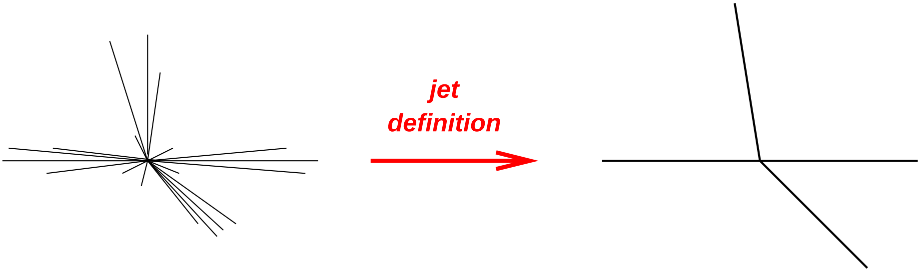
Jet definition / algorithm

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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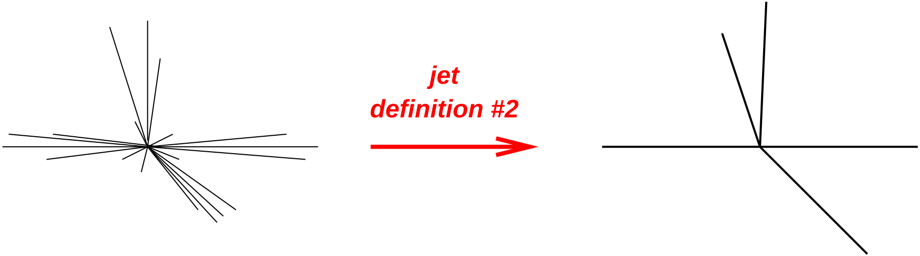

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There is no unique jet definition

The construction of a jet is unavoidably ambiguous. On at least two fronts:

1. which particles get put together into a common jet? Jet algorithm
   + parameters, e.g. jet angular radius R
2. how do you combine their momenta? Recombination scheme
   Most commonly used: direct 4-vector sums (E-scheme)

Taken together, these different elements specify a choice of jet definition

cf. Les Houches '07 nomenclature accord

Ambiguity complicates life,
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→ Jets non-trivial!

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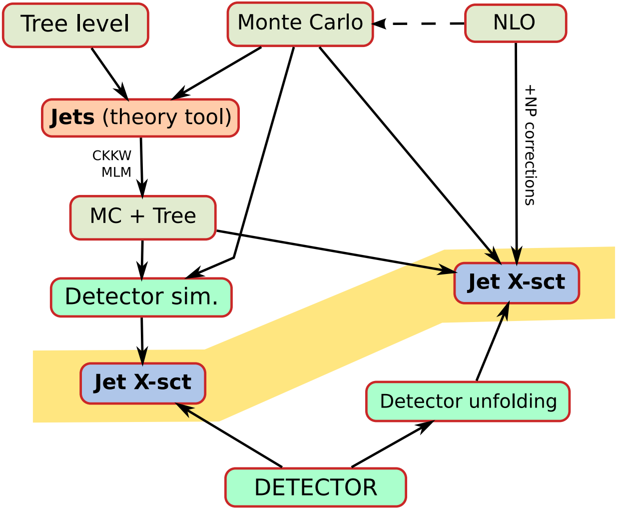
QCD jets flowchart



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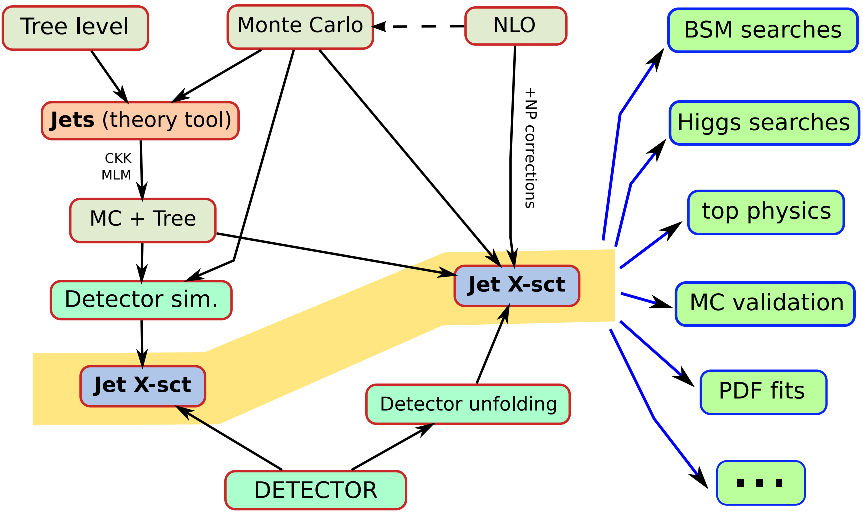

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This talk

Both Tevatron & LHC have been working/simulating with jets for a long time. **So why the need for anything new?**

1. What's wrong with jets@Tevatron

- The principles — Snowmass criteria
- The practice: e.g. $pp \to WH \to \ell\nu b\bar{b}$ signal and the W+jets bkgd

2. Our approach to fixing it

- The "philosophy"
- Some main developments

3. What will be new for jets at LHC

- Scales at play
- An example: searching for a boosted Higgs?

1. Jets @ Tevatron

Snowmass

Snowmass Accord (1990):

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

Toward a Standardization of Jet Definitions *

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- Let's examine them with a "chain" of CDF analyses related to Higgs searches ($p\bar{p} \to HW \to \ell\nu b\bar{b}$)

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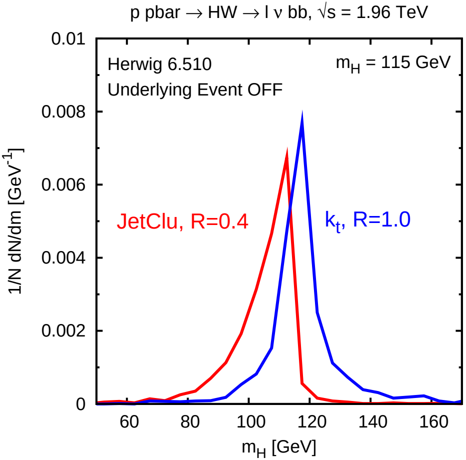

Example: $p\bar{p} \to WH \to \ell\nu b\bar{b}$

Find H mass peak from 2 b-jets

JetClu, $R = 0.4$: common CDF alg.
k_t, $= 1.0$: common "theorist's" alg.

Without UE:

- Higgs peak $\sim$ 15% higher with k_t, $R = 1$ $\to$ use 30% less lumi?

With UE:

- Inversion of hierarchy
  $\to$ CDF uses JetClu with $R = 0.4$, $\sim$ 80% of time

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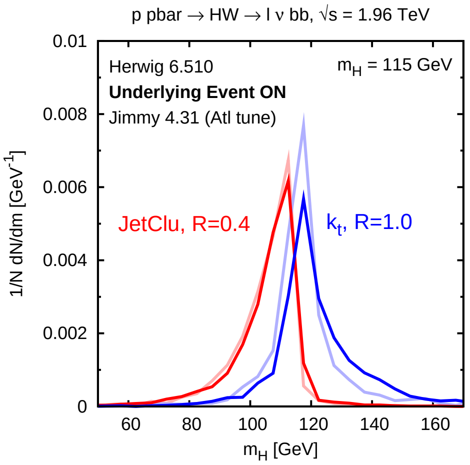

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Background to Tevatron Higgs

Measurement of the cross section for W-boson production in association with jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV (CDF Collaboration*) arXiv:0711.4044

Final states containing a vector boson V ($V = W, Z$) and multiple jets (V + jet(s)) are a key signal channel for important standard model (SM) processes such as $t\bar{t}$ or single top production, as well as a search channel for the Higgs boson and for physics beyond the SM. The production of V+jet(s) via quantum chromodynamics (QCD) presents a very large background to these processes. The ability to describe it accurately is therefore crucial, as well as being a stringent test of the power of perturbative QCD predictions. Consequently, a precise measurement of the cross section for QCD V + jet(s) production is an important component of the hadron collider experimental program. In this paper, we report a measurement [1]

To believe limits / signficance of any signal, you need good control of background.

The ubiquitous background is W+jets

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JetClu is used for signal. So when studying backgrounds, use the same.

At NLO, CDF use a **different** cone algorithm, with a different radius R(!?)

Data & NLO agree beautifully!

- But measuring and calculating 2 different things
- The fact that they agree has **questionable** significance.

So, why the 2 different jet defs?

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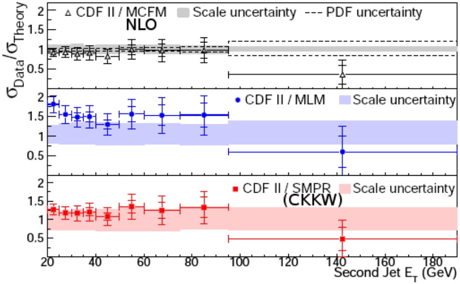

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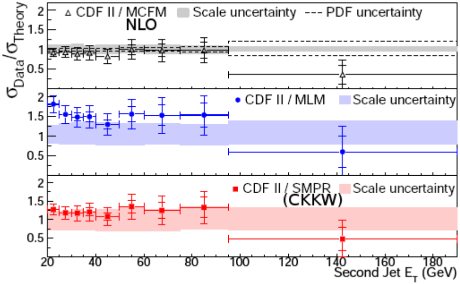

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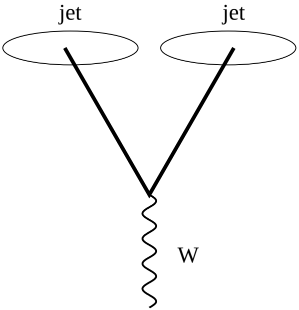

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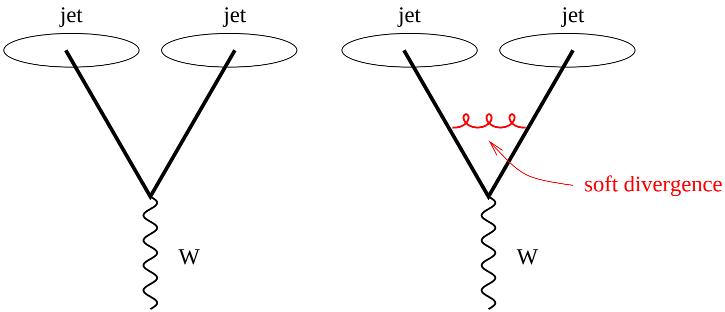

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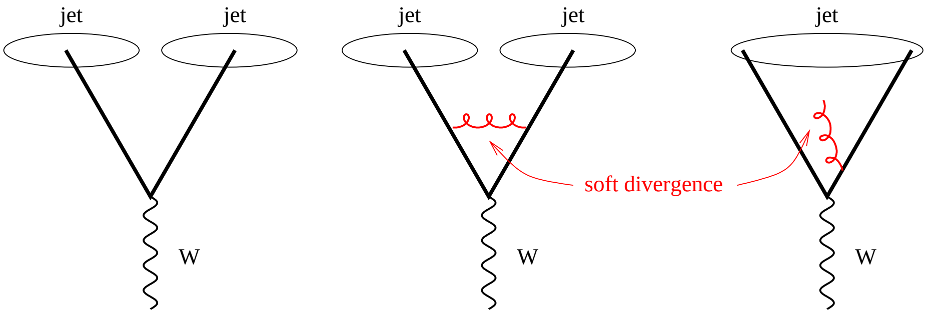

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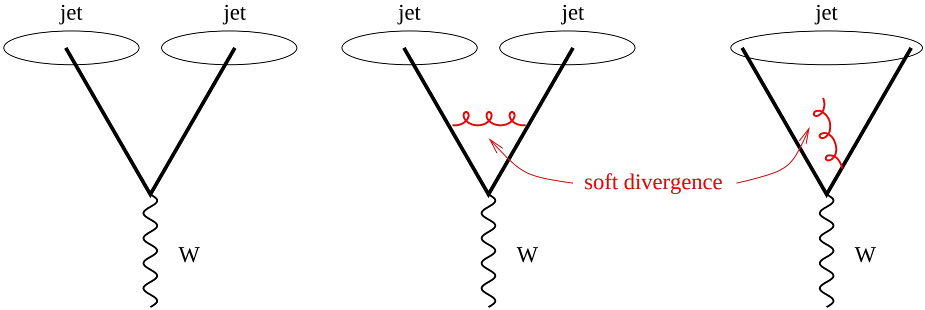

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- Chances are it's the "seedless" cone algorithm in MCFM.

So why not use it for the experimental measurement too?

- Clustering N particles takes time $\mathbf{N2^N}$.

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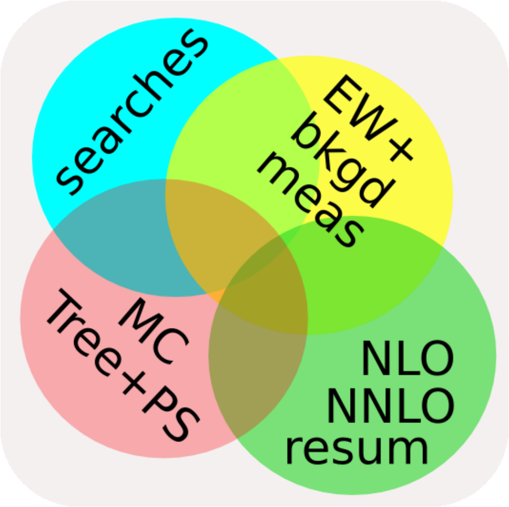

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This breaks connection between different parts of QCD.

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2. Getting the basics right

IRC safety & real-life

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

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

Among consequences of IR unsafety:

	Last meaningful order			
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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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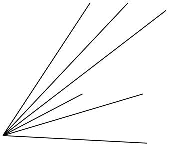
Sequential recombination algorithms

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: $i \to$ 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

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: $i \to$ jet)
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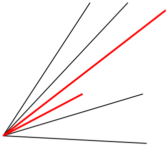

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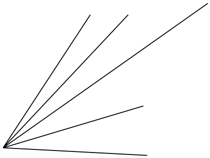

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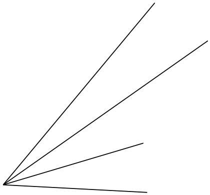

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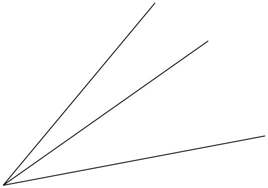

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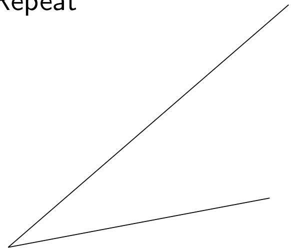

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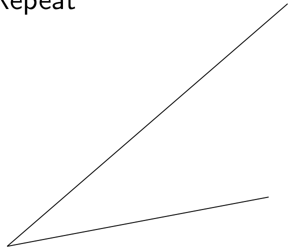

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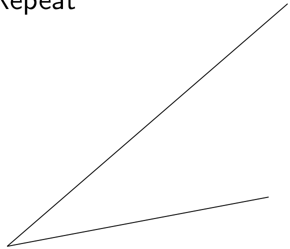

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Cones with Split Merge (SM)

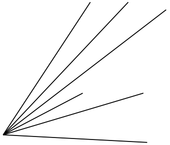
Modern cone algs have two main steps:

- 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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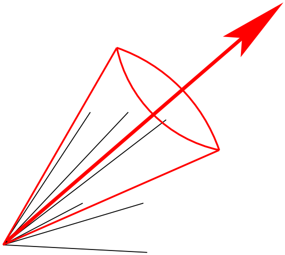

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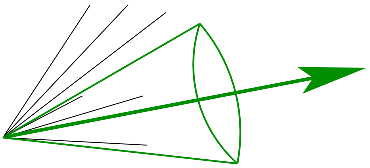

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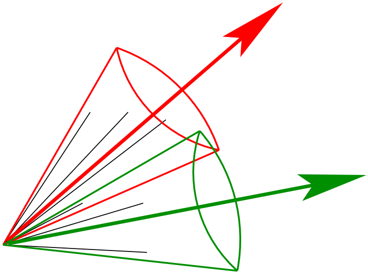

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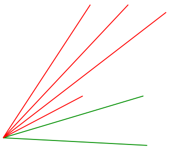

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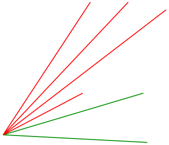

How do you find the stable cones?

- Iterate from 'seed' particles

  Done originally, very IR unsafe, N^2 [JetClu, Atlas]
- Iterate from 'midpoints' between cones from seeds

  Midpoint cone, less IR unsafe, N^3
- Seedless: try all subsets of particles IR safe, $N2^N$

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

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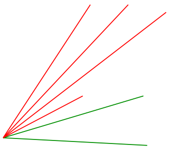

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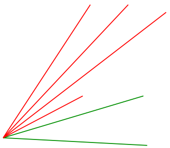

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Advance #2: IR safe seedless cone (SM) separate mom. and geometry

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

Then for each check whether $\longrightarrow$ stable cone

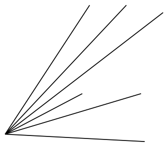
Time reduced from $N2^N$ to $\mathbf{N^2 \ln N}$: 6s for N=4000. GPS & Soyez '07

"SISCone"

Cone basics II: IC-PR

Other cones avoid split-merge:

- Find one stable cone — E.g. by iterating from hardest seed particle
- Call it a jet; remove its particles from the event; repeat



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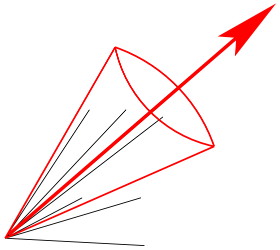

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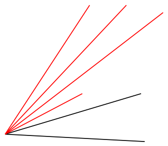

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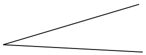

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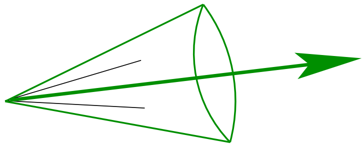

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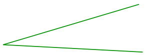

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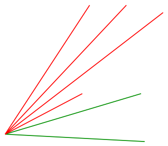

- This is not the same algorithm
- Many physics aspects differ

Iterative Cone with Progressive Removal (IC-PR)

Collinear unsafe [$\leftarrow$ hardest seed]

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

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Iterative Cone with Progressive Removal (IC-PR)

Collinear unsafe [← hardest seed]

Advance #3: anti-k_t algorithm — GPS, Cacciari & Soyez '08

Seq. Rec.: find smallest of d_{ij}, d_{iB}: $d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2})\Delta R_{ij}^2/R^2\,, d_{iB} = p_{ti}^{-2}$

- Grows outwards from hard "seeds," but in collinear safe way
- Has **circular jet "area,"** just like IC-PR & same @ NLO (incl.jets)
- Fast: Nn or $Nn^{1/2}$, 25ms for 4000 particles

What's out there, up to 2005

Algorithm	Type	IRC status	Notes
exclusive k_t	$\mathrm{SR}_{p=1}$	OK	
inclusive k_t	$\mathrm{SR}_{p=1}$	OK	widespread in QCD theory
Cambridge/Aachen	$\mathrm{SR}_{p=0}$	OK	
Run II Seedless cone	SC-SM	OK	slow: $N2^N$!!
CDF JetClu	IC_r-SM	IR_{2+1}	
CDF MidPoint cone	IC_{mp}-SM	IR_{3+1}	$\simeq$ Tev Run II recommend^n
CDF MidPoint searchcone	$\mathrm{IC}_{se,mp}$-SM	IR_{2+1}	
D0 Run II cone	IC_{mp}-SM	IR_{3+1}	Tev Run II + cut on cone p_t
ATLAS Cone	IC-SM	IR_{2+1}	
PxCone	IC_{mp}-SD	IR_{3+1}	has cut on cone p_t,
CMS Iterative Cone	IC-PR	Coll_{3+1}	
PyCell/CellJet (from Pythia)	FC-PR	Coll_{3+1}	widespread in BSM theory
GetJet (from ISAJET)	FC-PR	Coll_{3+1}	likewise

SR = seq.rec.; IC = it.cone; FC = fixed cone;

SM = split–merge; SD = split–drop; PR = progressive removal

Evolution since 2005

Algorithm	Type	IRC status	Evolution
exclusive k_t	$\mathrm{SR}_{p=1}$	OK	$N^3 \to N \ln N$
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D0 Run II cone	IC_{mp}-SM	IR_{3+1}	$\to$ SISCone [with p_t cut?]
ATLAS Cone	IC-SM	IR_{2+1}	$\to$ SISCone
PxCone	IC_{mp}-SD	IR_{3+1}	[little used]
CMS Iterative Cone	IC-PR	Coll_{3+1}	$\to$ anti-k_t
PyCell/CellJet (from Pythia)	FC-PR	Coll_{3+1}	$\to$ anti-k_t
GetJet (from ISAJET)	FC-PR	Coll_{3+1}	$\to$ anti-k_t

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non-COMMERCIAL BREAK

Use FastJet — it's free!

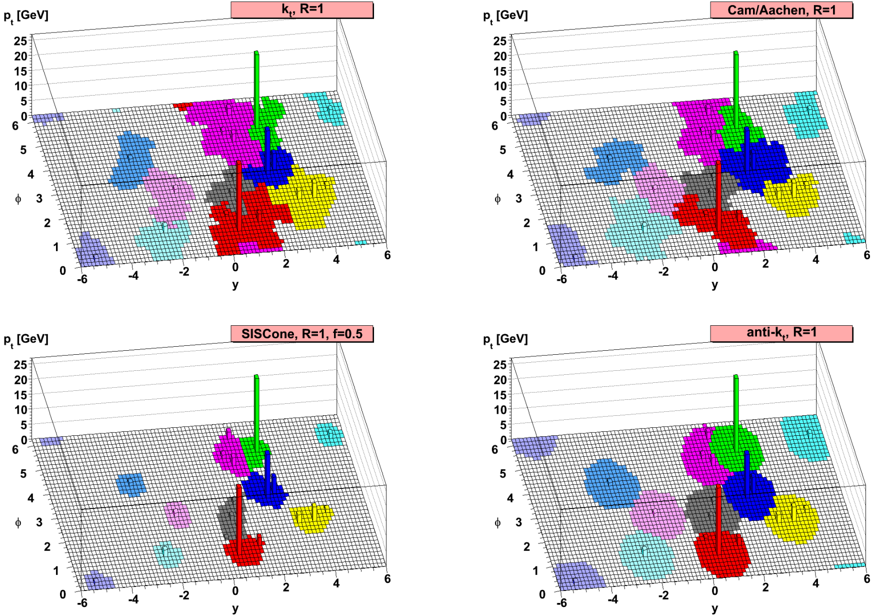
One place to stop for your jet-finding needs:

FastJet

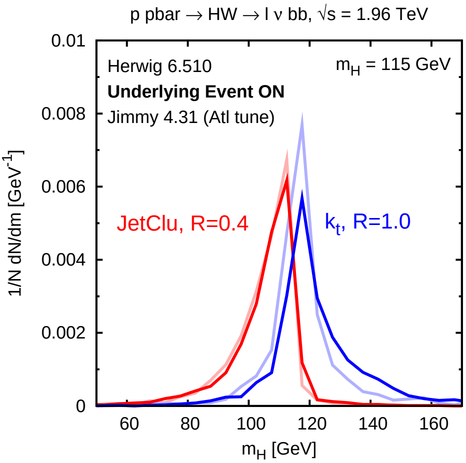
http://www.lpthe.jussieu.fr/~salam/fastjet
Cacciari, GPS & Soyez '05–08

- Fast, native, computational-geometry methods for k_t, Cam/Aachen, anti-k_t
- Plugins for SISCone (plus some other, deprecated, legacy cones)
- Documented user interface for adding extra algorithms of your own
- Tools for jet areas, pileup characterisation & subtraction
- Available in the ATLAS and CMS software.

Jet contours – visualised



Are the algs any good for physics?



Return to Tevatron Higgs example

Try various jet definitions

Jet def. $\equiv$ alg + R

As long as one scans the range of possible R values, **each algorithm is competitive.**

Is Tevatron missing something?

Rumours mention larger R

NB: also need detector + bkgds

NB: Lessons apply also to LHC — best R [and alg] depends strongly on type of problem (few jets, multijet, quark v. gluon jets) & on momentum scale.

Dasgupta, Magnea & GPS '07; Cacciari, Rojo, GPS & Soyez '08

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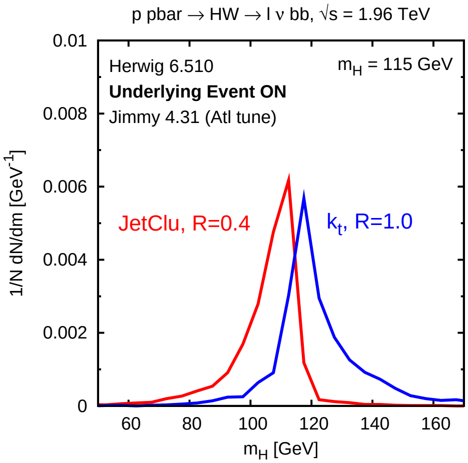

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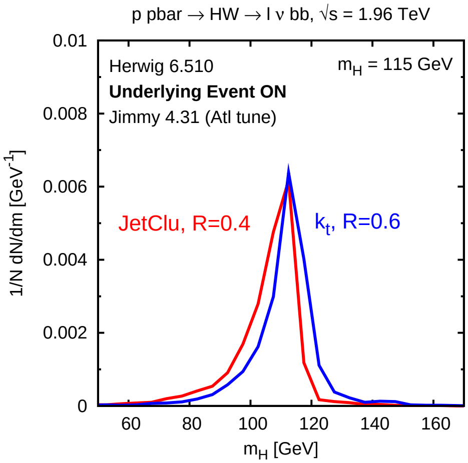

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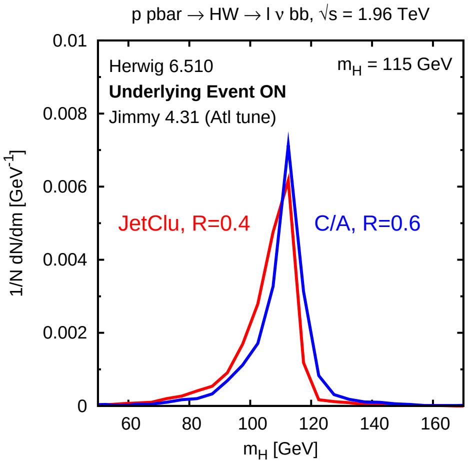

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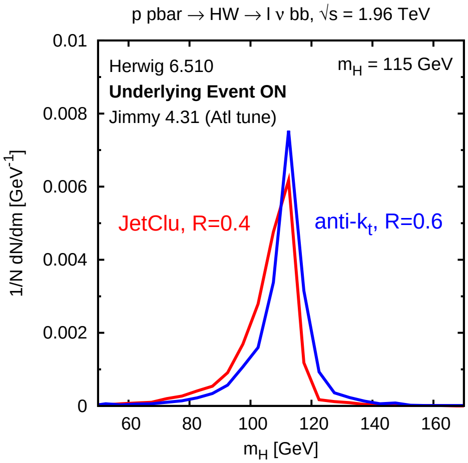

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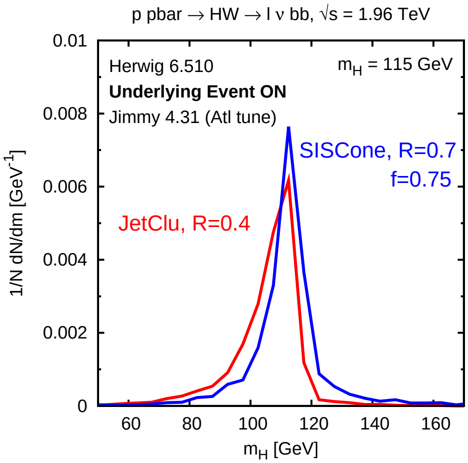

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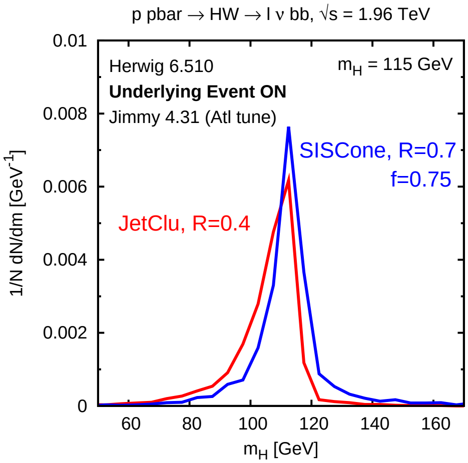

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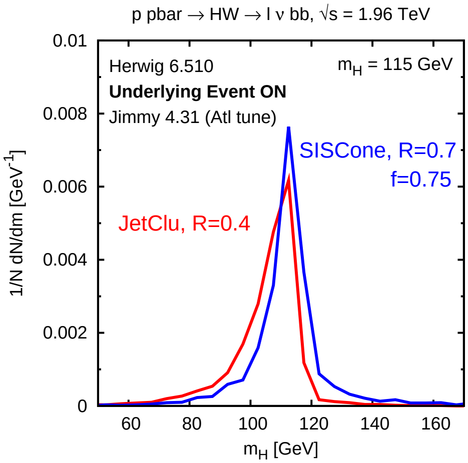

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What changes with jets @ LHC?

LHC is not LEP or Tevatron

LEP & HERA

- $M_{BSM} \sim 1$ TeV?
- $M_{EW} \sim 100$ GeV $\qquad \sim \alpha_s M_{BSM}$
- $p_{t,\text{pileup}} \sim 25-50$ GeV/unit rap.
- $p_{t,\text{UE}} \sim 2.5-5$ GeV/unit rap. $\qquad \sim \alpha_s M_{EW}$
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Multitude of scales
Interplays between them change how one does the physics

$M_B \sim \alpha_s M_A \rightarrow$ the physics of B is as important as pert. QCD in "clouding" one's view of A

$\Rightarrow$ **jets must untangle QCD effects (gluon rad"),** *and* **physics of scale B**

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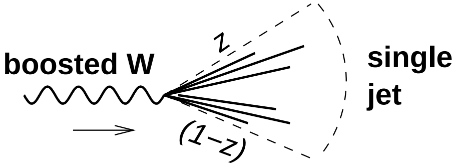
EW bosons at @ high p_t

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

Can you identify hadronically decaying EW bosons when they're produced at high 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 $\to WW \to \nu\ell$jets]
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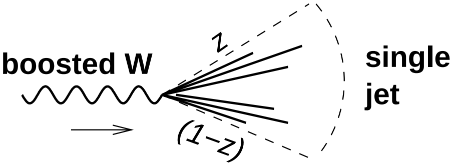

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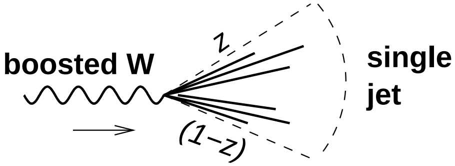

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Boosted bosons: how to?

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

- QCD jets can be massive too → large backgrounds
- As you probe range of p_t with fixed R, mass resolution $\sim \delta M \sim R^4 \Lambda_{UE} \frac{p_t}{M}$

Natural idea: **use hierarchical structure of k_t alg to resolve structure**

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

- You can cut on d_{ij} (rel. $\perp$ 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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A challenging application

Low-mass Higgs search @ LHC: complex because dominant decay channel, $H \to bb$, often swamped by backgrounds.

Three main production processes

- $gg \to H$ $(\to \gamma\gamma)$
- $WW \to H$
- $q\bar{q} \to WH, ZH$ — smallest; but cleanest access to WH and ZH couplings

currently considered impossible

Difficulties, e.g.

- $gg \to t\bar{t}$ has $\ell\nu b\bar{b}$ with same mass range, 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)
- Lose 95% of signal, but more efficient?
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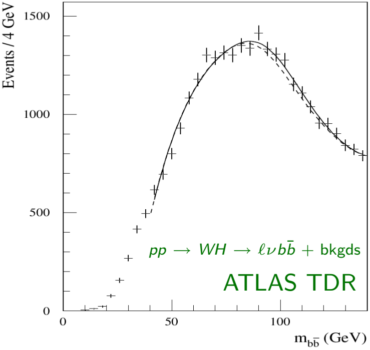

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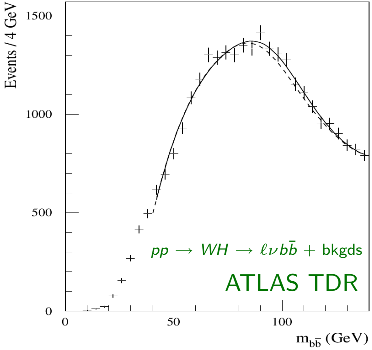

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High-p_t light Higgs decays to $b\bar{b}$ inside a single jet. Can this be seen?

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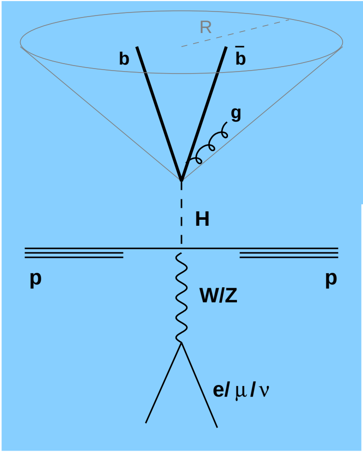

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1. Find a high-p_t massive jet J
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3. If $m_{subjets} \lesssim 0.67 m_J$ & subjet p_t's not asym. & each b-tagged $\rightarrow$ Higgs candidate
4. Else, repeat from 2 with heavier subjet

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

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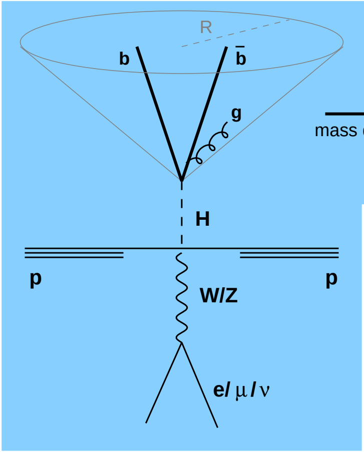

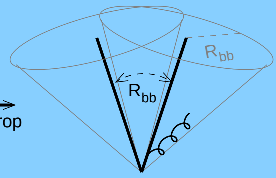

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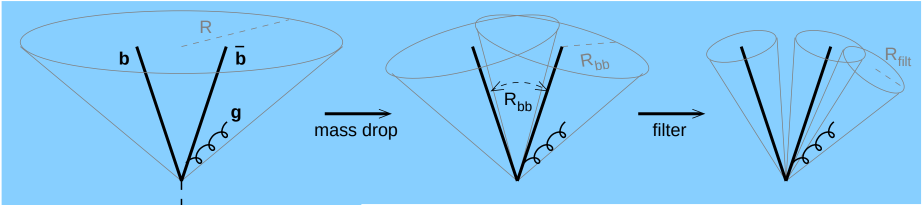

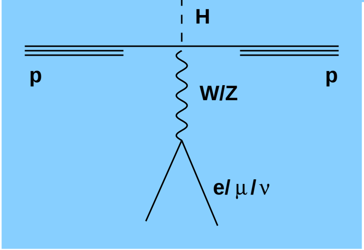

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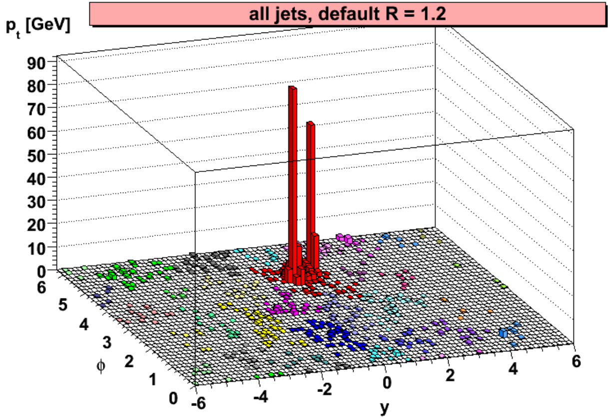

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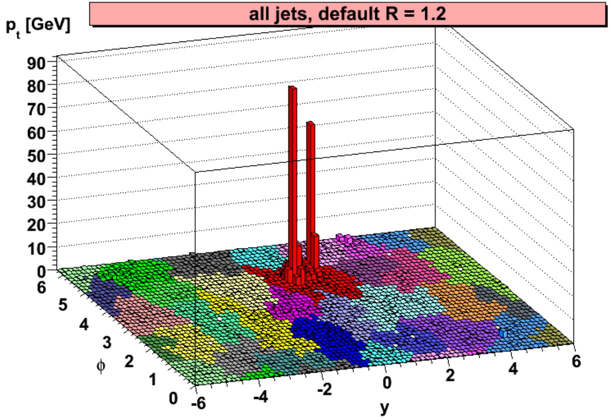

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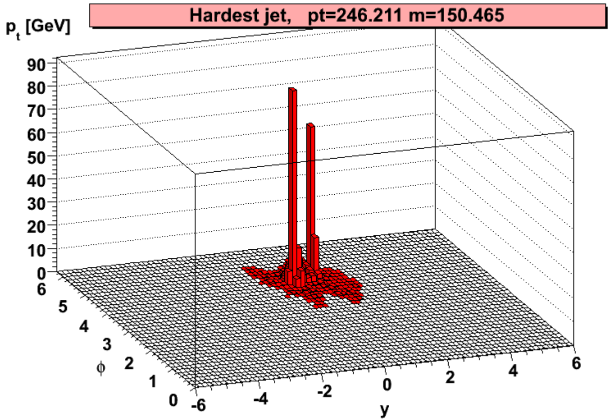

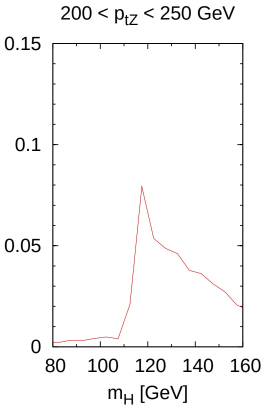

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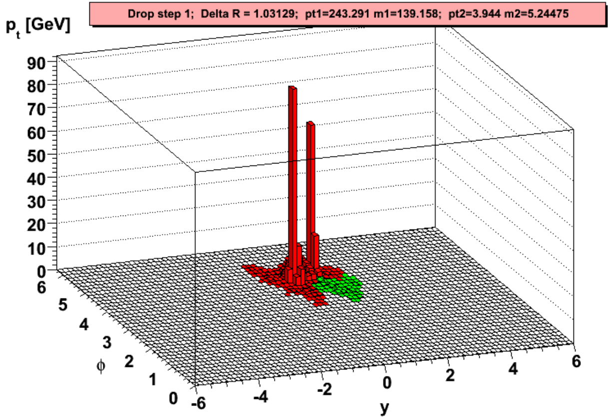

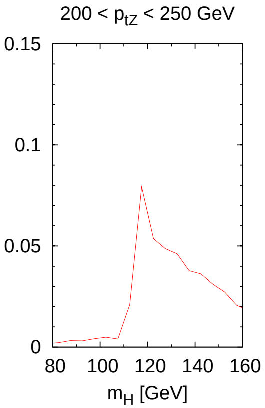

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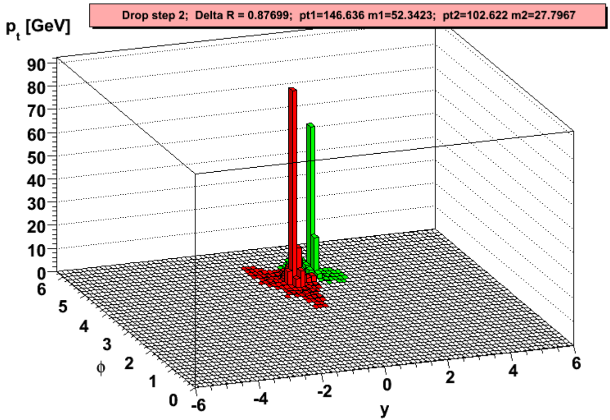

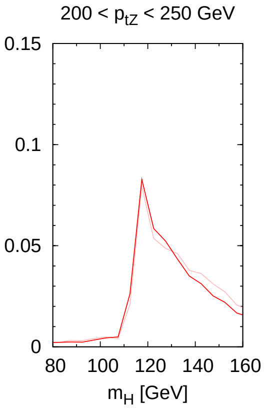

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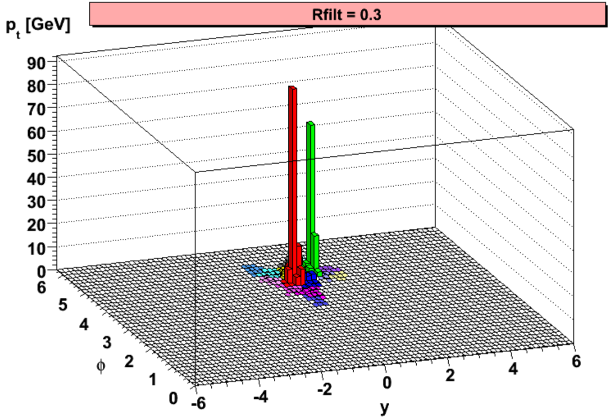

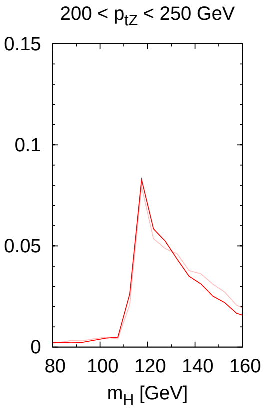

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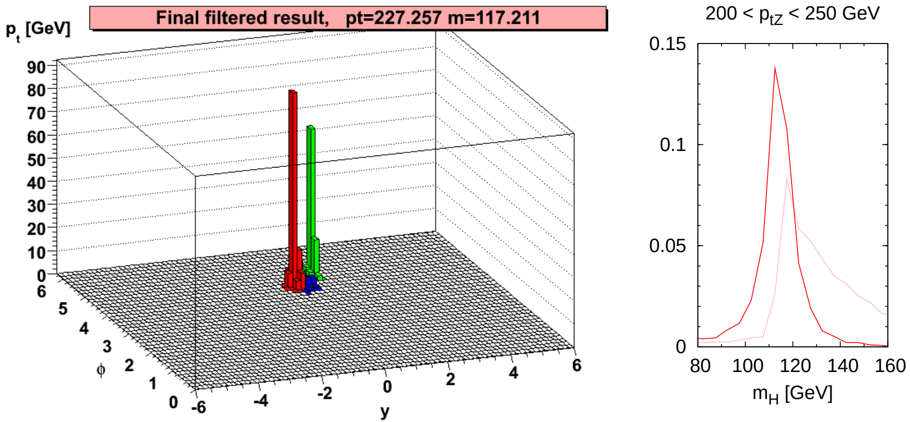
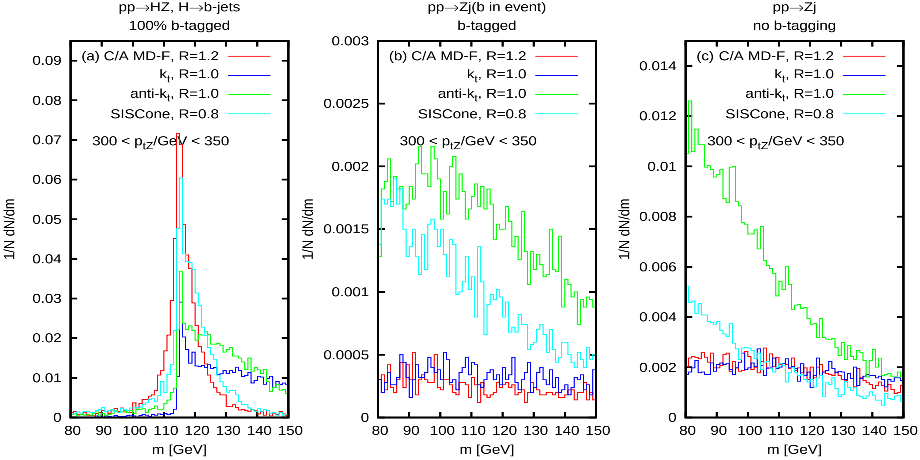


Compare with "standard" algorithms

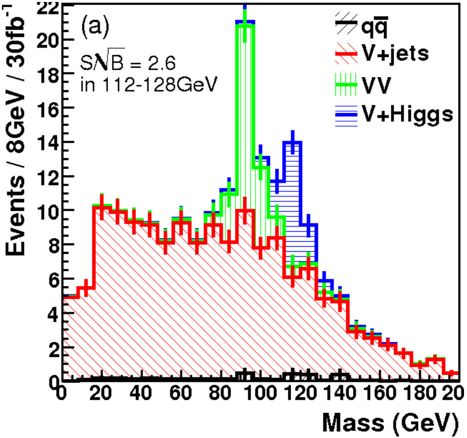
Check mass spectra in HZ channel, $H \to b\bar{b}$, $Z \to \ell^+\ell^-$



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

combine HZ and HW, $p_t > 200$ GeV

Leptonic channel



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- $[p_{t,\ell} > 30$ 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} this looks like a possible channel for light Higgs discovery. **Deserves serious exp. study!**

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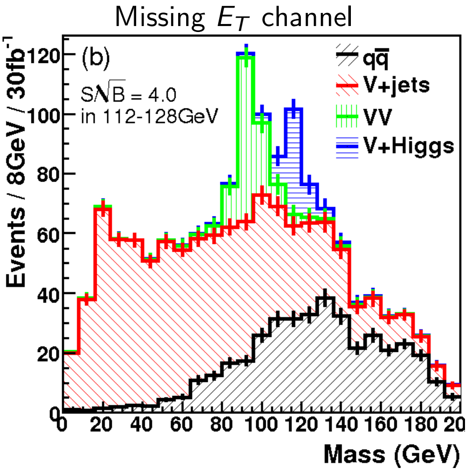

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Missing-E_t channel

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

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

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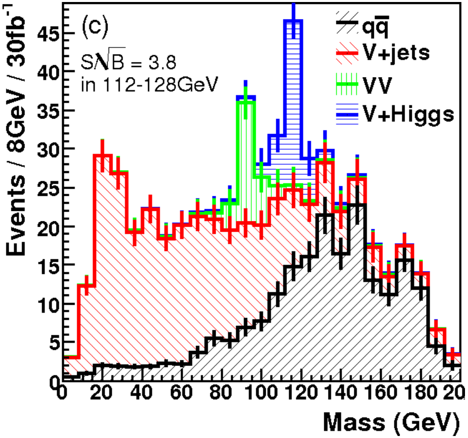
combine HZ and HW, $p_t > 200$ GeV

Semi-leptonic channel



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- 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

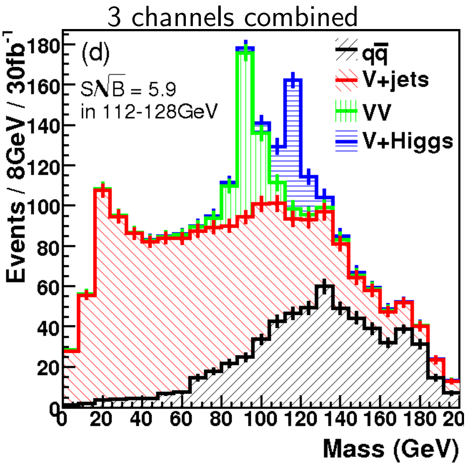
Semi-leptonic channel

$W \to \nu\ell$

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

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

combine HZ and HW, $p_t > 200$ GeV



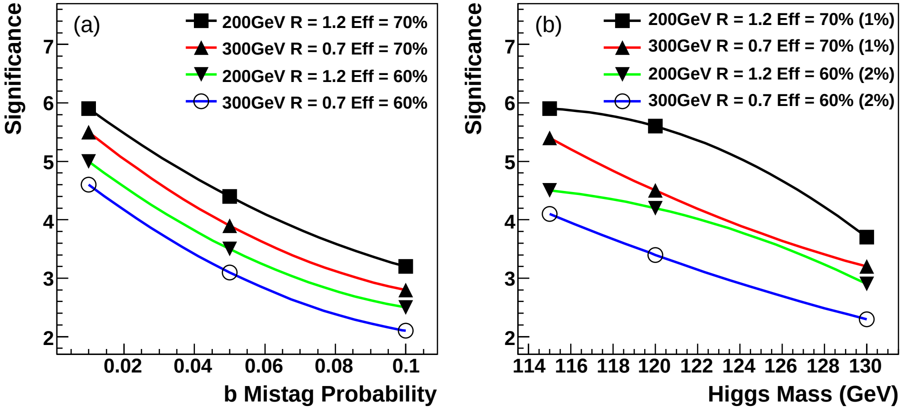
Common cuts

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ 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

3 channels combined

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

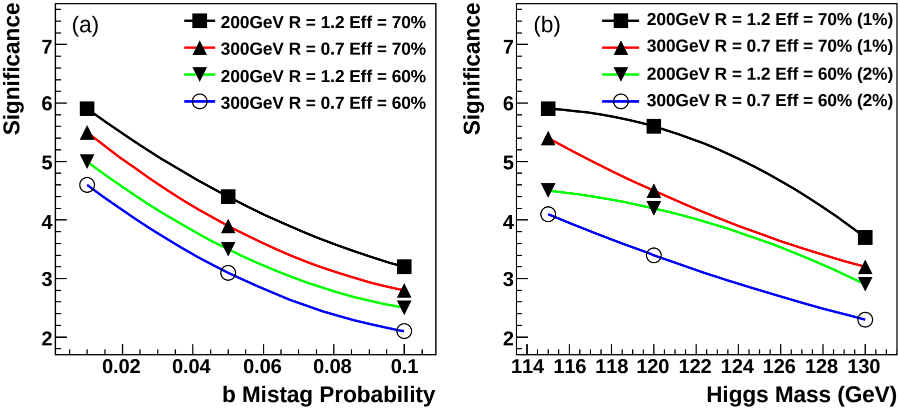
Impact of *b*-tagging, Higgs mass



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

4. Conclusions

Conclusions

IR and Collinear unsafe algs are widespread in current work on jets

Huge investment in them, years of work on tuning, studying etc.

IRC unsafety → **crack** in interface with pQCD

One doesn't always need the pQCD

But once the crack is there, it's hard to paper over

Equivalent or better jet tools now exist without IRC issues

Available in the LHC software frameworks

Hopefully they'll make it into analyses (but old algs have inertia)

Unprecedented multi-scale complexity of LHC's final state calls for **flexibility** (from experiments) and **more thought** (from theorists)

One example of potential payoff: boosted Higgs search

Same subjet-structure tools applicable in many BSM cases too