Jet physics at colliders

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HERA-LHC Workshop
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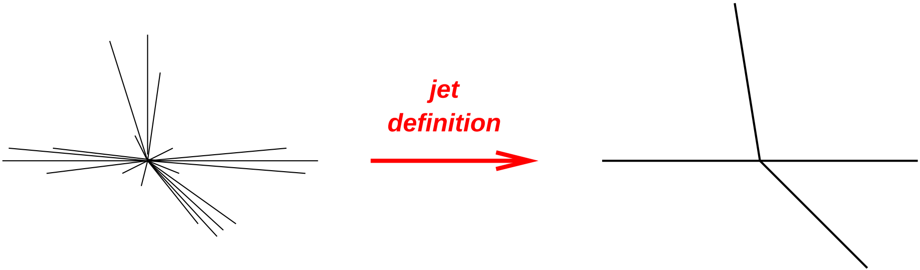
Jet definition / algorithm

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 $\rightarrow$ hadron transition

NB: finiteness $\longleftrightarrow$ set of jets depends on jet def.

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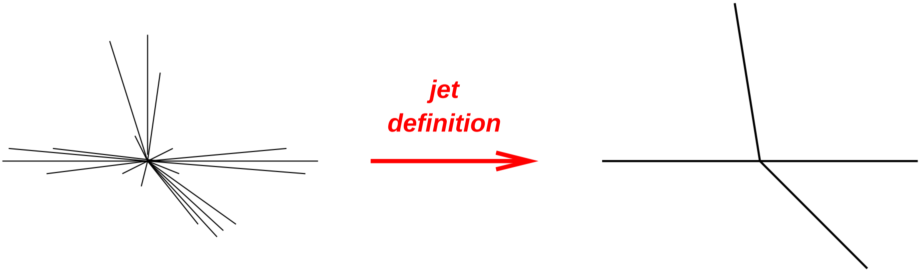

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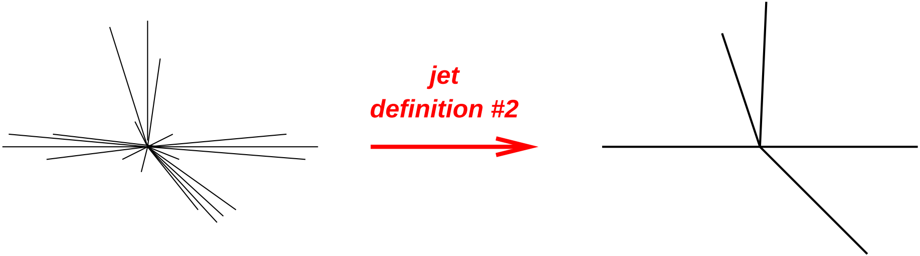

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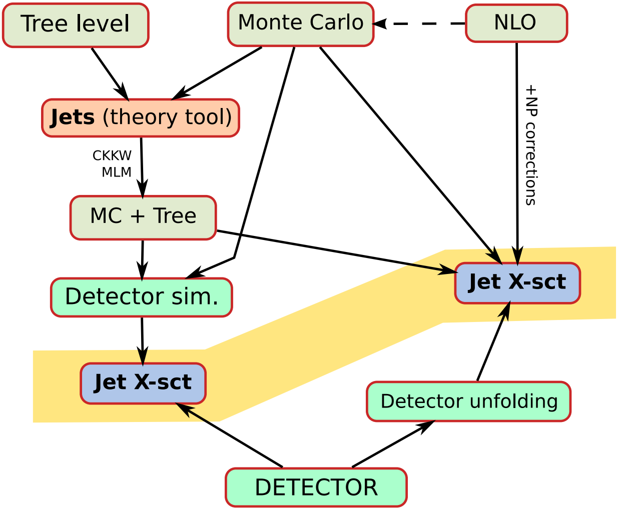
QCD jets flowchart



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

And jets are an input to almost all analyses

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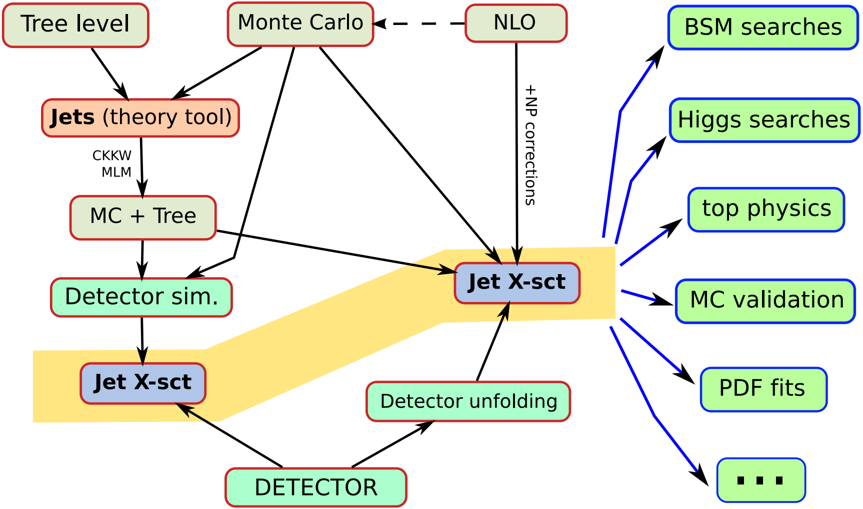

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1. Infrared and Collinear unsafe jet algorithms have been with us for a long time

It's time to relegate them to where they belong

20th century history

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Jet-finding has been painless at HERA, but not at Tevatron. **WHY?**

I don't know the true answer, but here are some guesses

HERA	**Tevatron**
Inherited JADE-type algorithms	Inherited *pp* cone algs Problematic/complex from the start
Much QCD, some searches Jet-finding had to be decent	Many searches, some QCD Jet-finding relevance is more subtle
Complexity $\sim$ that of LEP Moderate multiplicites UE small, $dp_t/d\eta \sim 0.5 - 1$ GeV e^+e^--inspired solutions work	Complexity $\gg$ that of LEP Multiplicites higher UE large, $dp_t/d\eta \sim 2.5 - 5$ GeV e^+e^--inspired solutions have issues

NB: LHC more like Tevatron than HERA

What's out there?

Algorithm	Type	IRC status	Notes
exclusive k_t	$SR_{p=1}$	OK	
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Cambridge/Aachen	$SR_{p=0}$	OK	
Run II Seedless cone	SC-SM	OK	slow: $N2^N$!!
CDF JetClu	IC_r-SM	IR_{2+1}	for top physics, searches
CDF MidPoint cone	IC_{mp}-SM	IR_{3+1}	$\simeq$ Tev Run II recommend^n
CDF MidPoint searchcone	$IC_{se,mp}$-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

IR_{n+1}: for n nearby hard partons, 1 soft emitted gluon can change hard jets
$Coll_{n+1}$: for n nearby hard partons, 1 collinear splitting can change hard jets

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Does lack of IRC safety matter?

I do searches, not QCD. Why should I care about IRC safety?

- If you're looking for an invariant mass peak, it's not 100% crucial

IRC unsafety $\simeq$ R is ill-defined

A huge mass peak will stick out regardless

Well, actually my signal's a little more complex than that. . .

- If you're looking for an excess over background you need confidence in backgrounds E.g. some SUSY signals
  - Check W+1 jet, W+2-jets data against NLO in control region
  - Check W+n jets data against LO in control region
  - Extrapolate into measured region
- IRC unsafety means NLO senseless for simple topologies, *LO senseless for complex topologies*

Breaks consistency of whole

Wastes ∼ 50,000,000$/£/CHF/€

But I like my cone algorithm, it's fast, has good resolution, etc.

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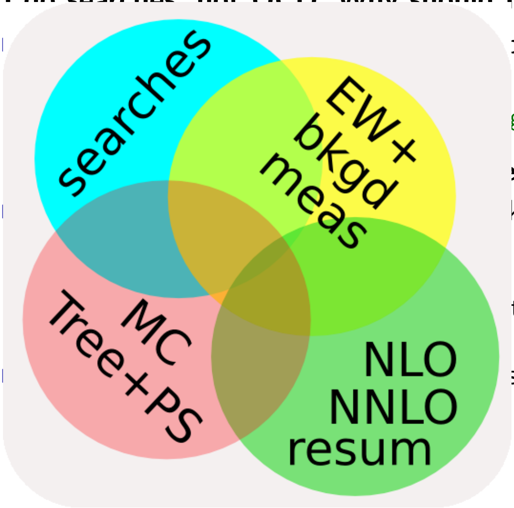

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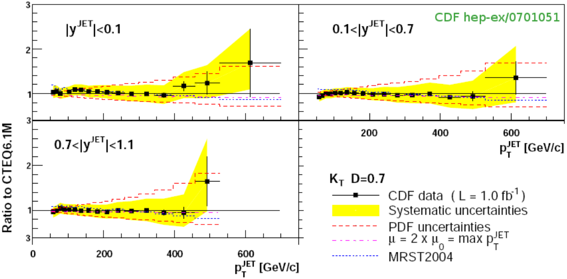
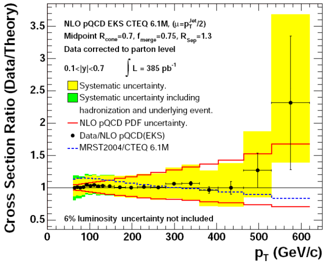
#1b: Demonstration non-Cone algs work in *pp*

CDF hep-ex/0512062 & hep-ex/0701051 inclusive-jet measurements show that basic behaviour of k_t algorithm is as good as that of cone.





Crucial difference relative to HERA is use of $R < 1$ (NB $R \equiv D$)

Why? Because of different scale of UE

Lesson adopted by LHC experiments in past couple of years

#2: fixing available algs

Algorithm	Type	IRC status	Evolution
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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

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

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A full set of IRC-safe jet algorithms

Generalise inclusive-type sequential recombination with

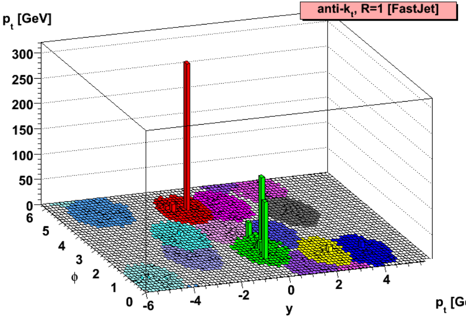
$$d_{ij} = \min(k_{ti}^{2\mathbf{p}}, k_{tj}^{2\mathbf{p}})\Delta R_{ij}^2/R^2 \qquad d_{iB} = k_{ti}^{2\mathbf{p}}$$

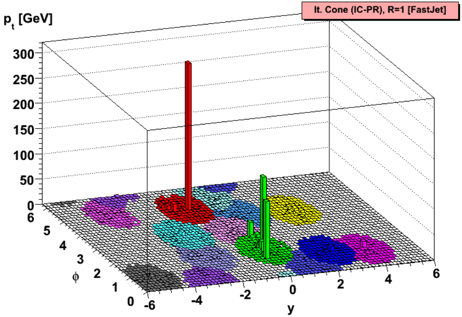
	Alg. name	Comment	time
$p = 1$	k_t CDOSTW '91-93; ES '93	Hierarchical in rel. k_t	$N \ln N$ exp.
$p = 0$	Cambridge/Aachen Dok, Leder, Moretti, Webber '97 Wengler, Wobisch '98	Hierarchical in angle Scan multiple R at once $\leftrightarrow$ QCD angular ordering	$N \ln N$
$p = -1$	anti-k_t Cacciari, GPS, Soyez '08 $\sim$ reverse-k_t Delsart, Loch et al.	Hierarchy meaningless. Behaves like IC-PR	$N^{3/2}$
SC-SM	SISCone GPS Soyez '07 + Tevatron run II '00	Replacement for IC-SM notably "MidPoint" cones	$N^2 \ln N$ exp.

Compromise between having a limited set of algs.
and a good range of complementary properties

See talk by G. Soyez about the newer algs., SISCone & anti-k_t

anti-k_t v. Cone (ICPR) jets





2.
Let's ask *useful* questions about jets

- When a jet is 1 parton
- When a jet is 2, 3 partons
- When a jet is 0 partons

Traditional use of jets: **as a stand-in for a single parton**

Basic questions:

- Which jet algorithms work best?
- What value of jet angular radius R is best?
- How does answer depend on the momentum scale?

LHC ranges from 25 GeV to 5 TeV

- How does answer depend on pileup?
- *What logic behind all of this?*

How to establish jet-def^n quality?

Partons are not physical objects — divergent, meaningless @ NLO, etc.

Parton-jet matching is *not* the way to go

Instead: use physical decays (imaginary narrow Z', H) to investigate question rigorously. Cacciari et al.; Büge et al., LH'07

How do you measure quality?

- Look at invariant mass peak
- Do not fit a Gaussian!
- **Instead** measure minimal width containing 40% (say) of invariant mass peak

See talk by J. Rojo in final-states session

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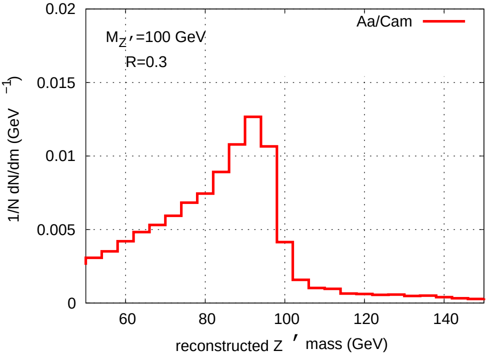

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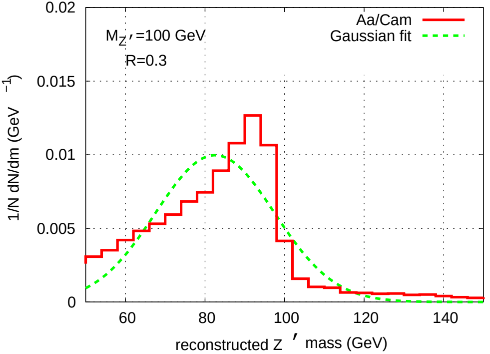

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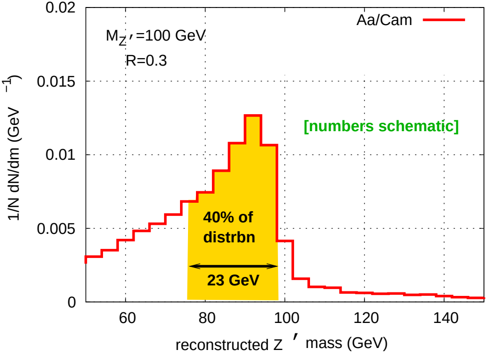

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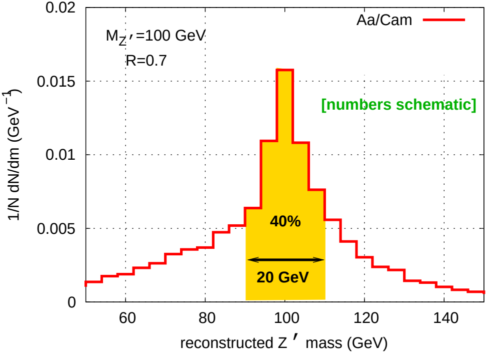

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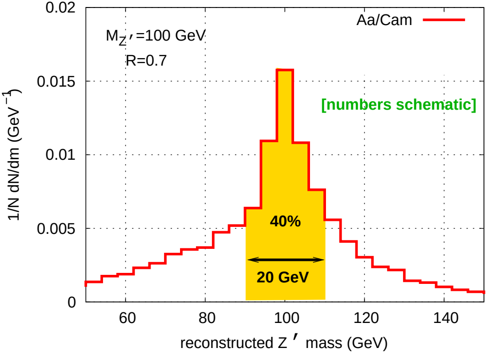

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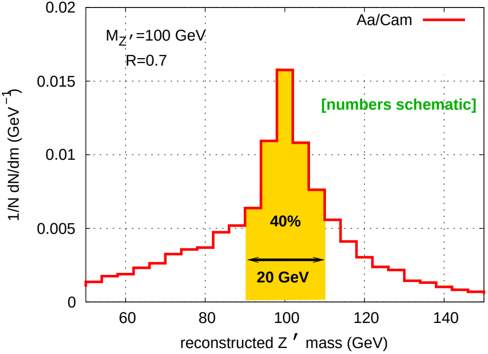

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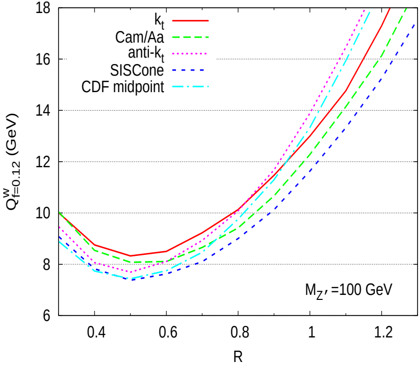
What's the "best" jet-def?

Jet definition ≡ jet-alg + choice of parameters

Try all options



Pythia 6.4 + DWT tune + FastJet
Cacciari, Rojo, GPS & Soyez '08

- R dependence is crucial
- Non-trivial interplay with hard scale high-p_t → large R
- Qualitative understanding based on analytical arguments

Knowledge of R-dep of PT, Hadr, UE effects is key to good choice of jet def.

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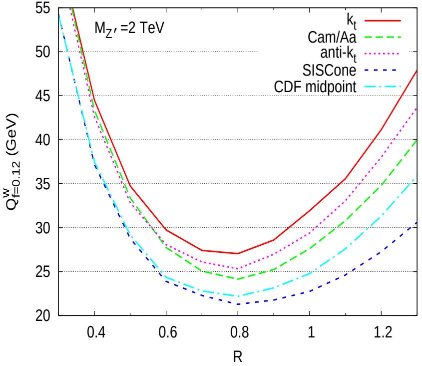

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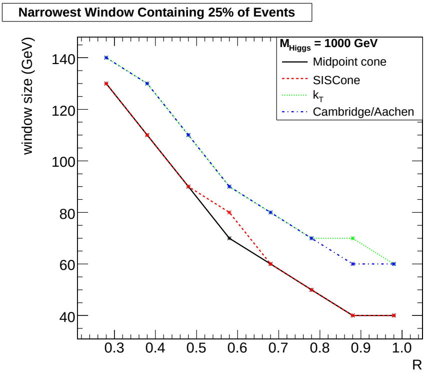

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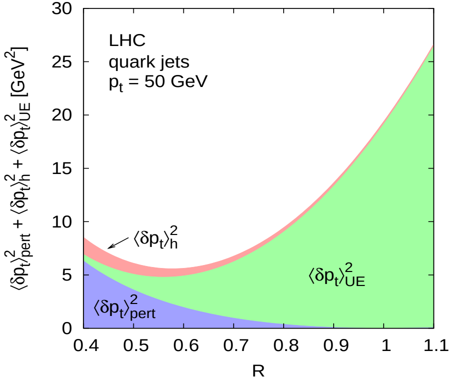

Crude analytical estimates
Dasgupta, Magnea & GPS '07

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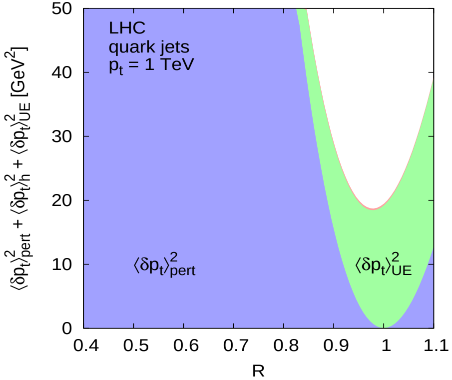

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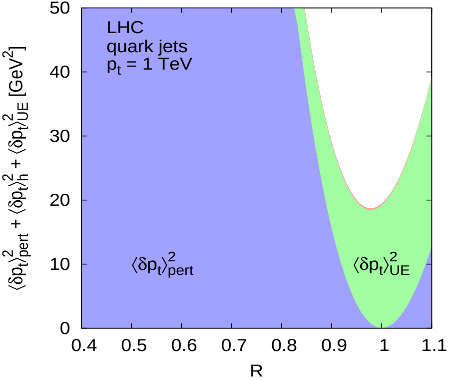

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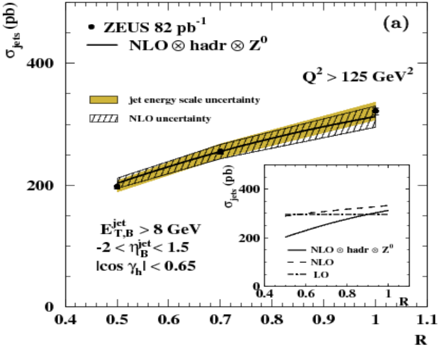
Understanding R-dep: exp. input

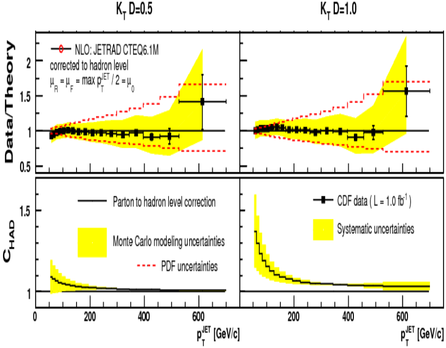
R is a free parameter — a bit like “focus” in a camera.

Measuring several R-values helps inform our understanding of non-perturbative effects & contributes to a habit of **flexible jet finding**.

ZEUS



CDF



Powerful cross check on theoretical ideas & MCs;
Please: more like this, also with larger range of R!

Pushing jets to their limit:

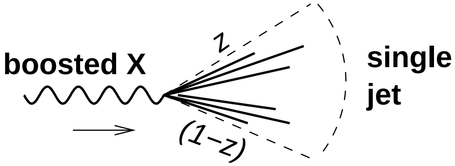
when a W, Z, H or a top $\rightarrow$ a single jet

Not unusual at LHC: $m_W, m_t \ll 14$ TeV

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 $\to WW \to \nu\ell$jets]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
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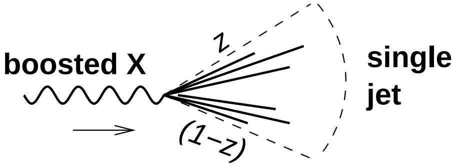
EW bosons at @ high p_t

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?



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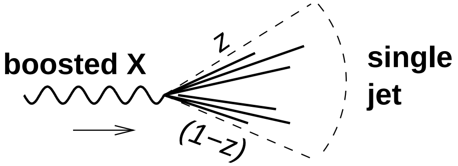

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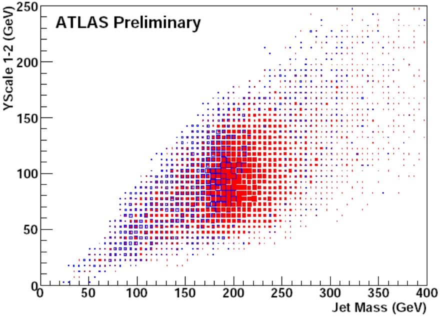
High-p_t top $\longrightarrow$ $bq\bar{q}'$

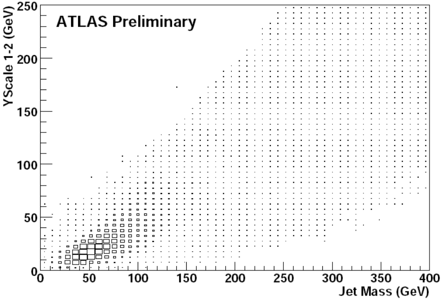
Brooijmans '08 ATL-PHYS-CONF-2008-008, based on k_t algorithm

Use subjet relative transverse-momentum scale ("y-scale") & correlation with jet mass to pick out top quarks from background

top quarks $p_t \sim 1$ TeV



normal jets



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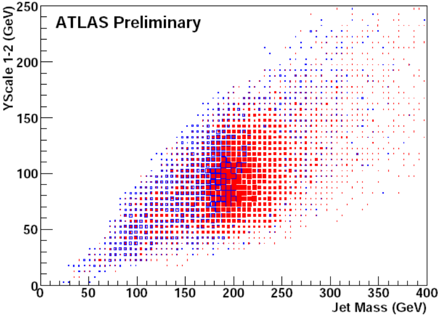
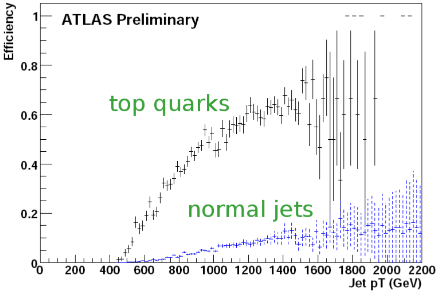
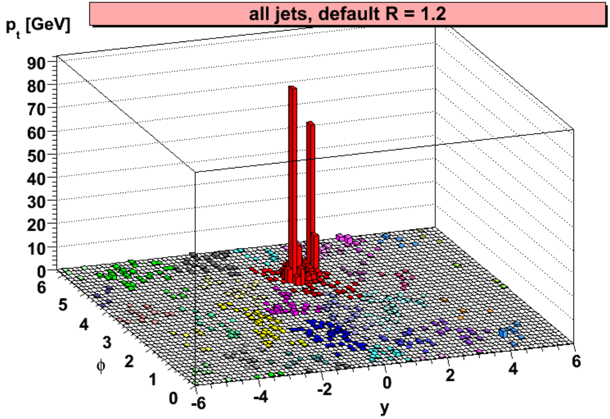


efficiencies



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



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Butterworth, Davison, Rubin & GPS ’08

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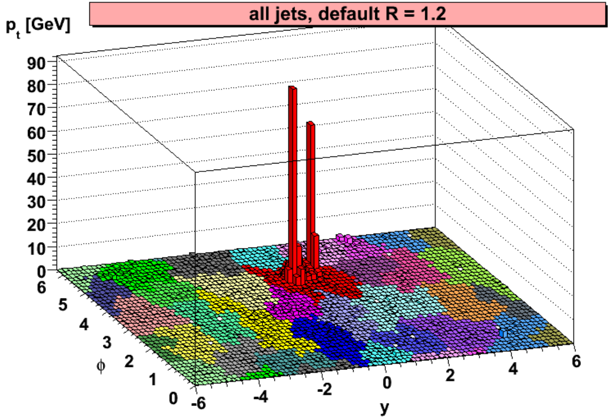

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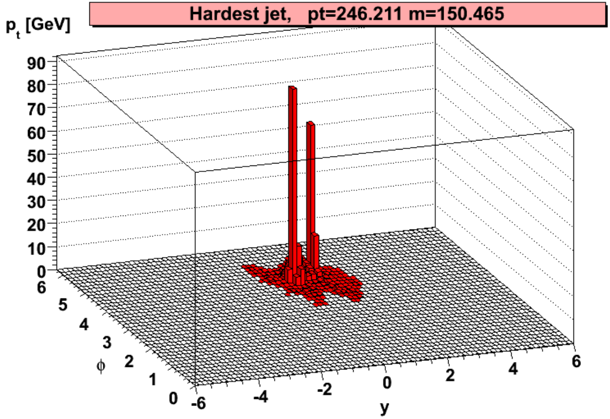

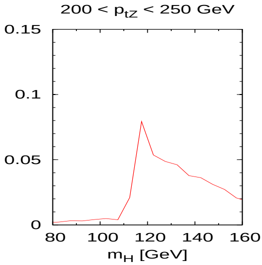

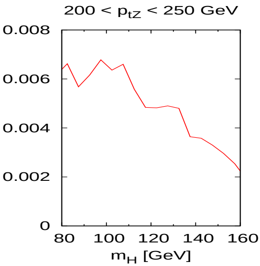

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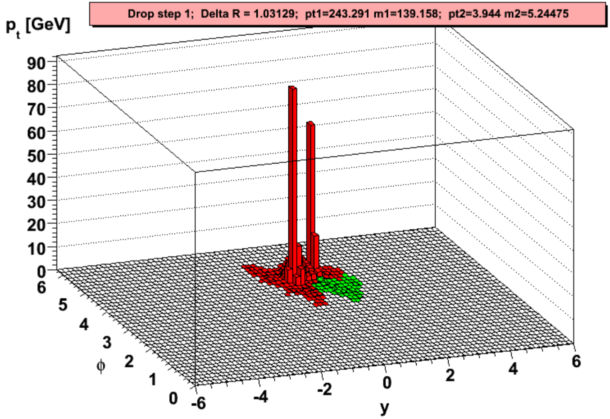

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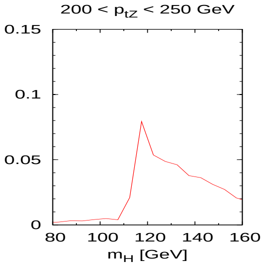

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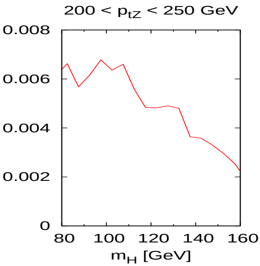

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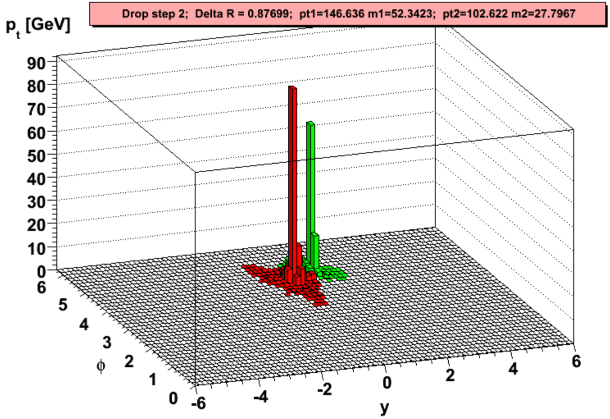

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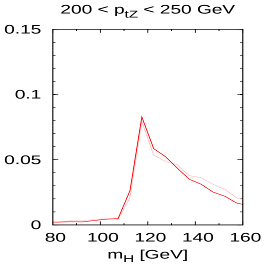

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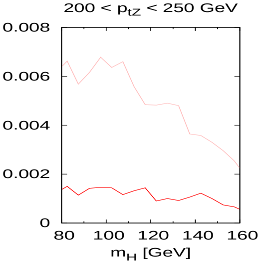

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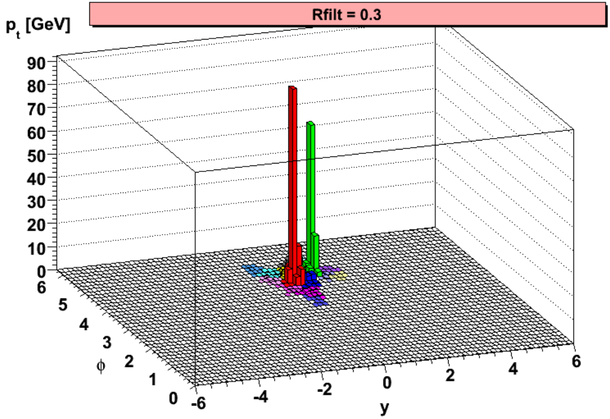

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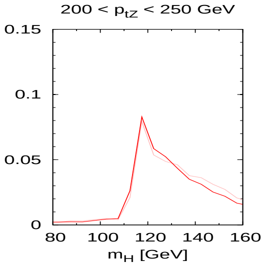

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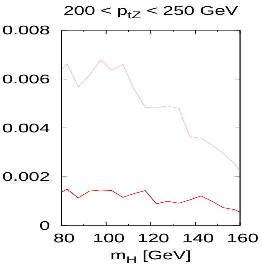

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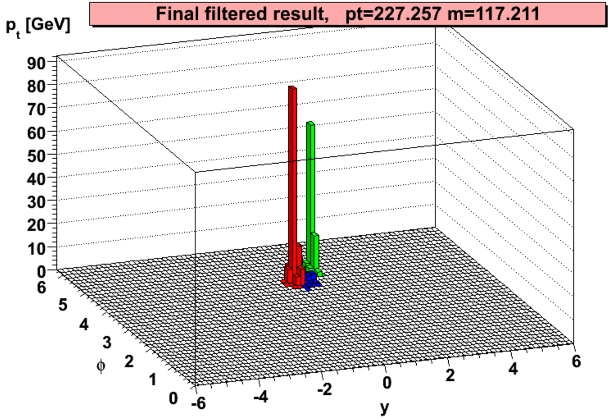

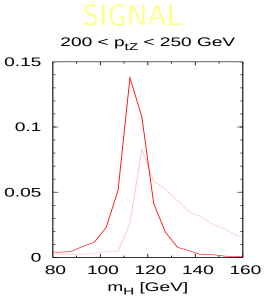

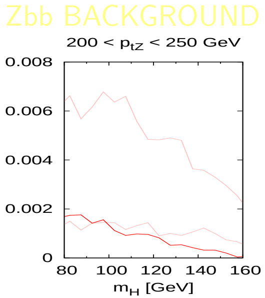

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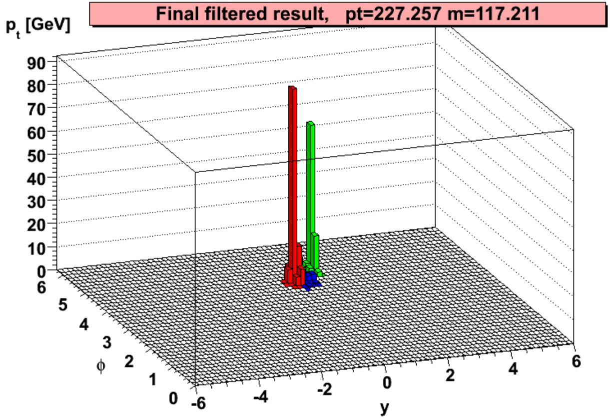

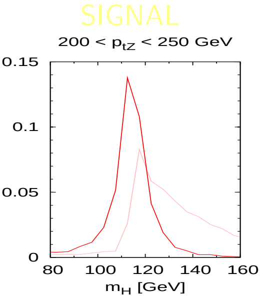

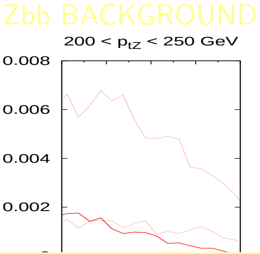

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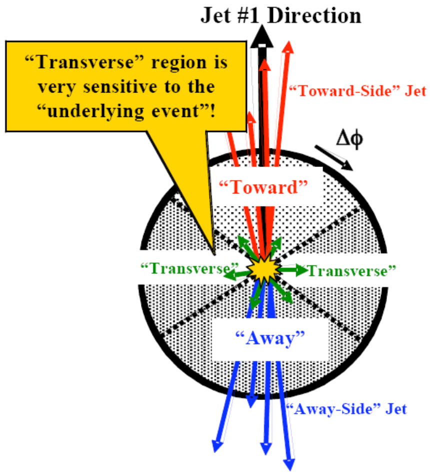
Much to be learnt still about extracting boosted W/H/Z/top from bkgd; NB HERA has extensive experience with subjets.

Jets without hard partons:

Most jet algorithms give you $\sim 50 - 100$ "jets," mostly not hard.

provide window on UE and min-bias

Usual approach to UE



Marchesini-Webber idea:
look at transverse region to measure underlying event

Topological selection

The jets are classified as belonging to the noise on the ground of their **position**

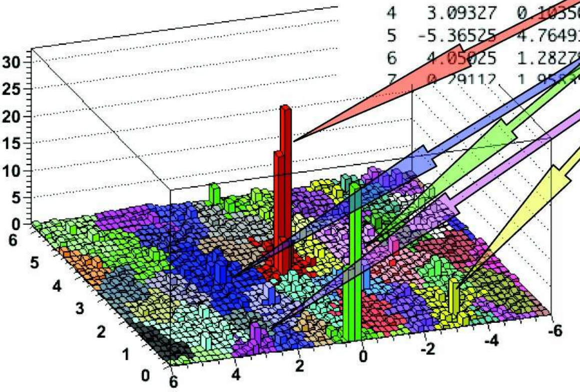
So far mostly *average* quantities

But full tuning of UE models needs point-to-point fluctuations & correlations, as well as event-to-event fluctuations

And difficult to use in complex events, e.g. top

Making use of *all* jets

```
iev 0 (irepeat 24): number of particles = 1428
strategy used =  NlnN
number of particles = 9051
Total area: 76.0265
Expected area: 76.0265
 ijet     eta        phi         Pt         area  +-    err
    0   0.15050   3.24498     69.970      2.625 +-   0.020
    1   0.18579   0.13150     59.133      1.896 +-   0.020
    2   2.33840   3.23960     31.976      4.749 +-   0.028
    3  -3.41796   0.52394     26.595      3.084 +-   0.021
    4   3.09327   0.10350     20.072      2.688 +-   0.023
    5  -5.36525   4.76491     19.593      2.780 +-   0.012
    6   4.05025   1.28279     15.861      3.592 +-   0.028
    7   0.29112   1.95835     14.566      2.114 +-   0.018
```

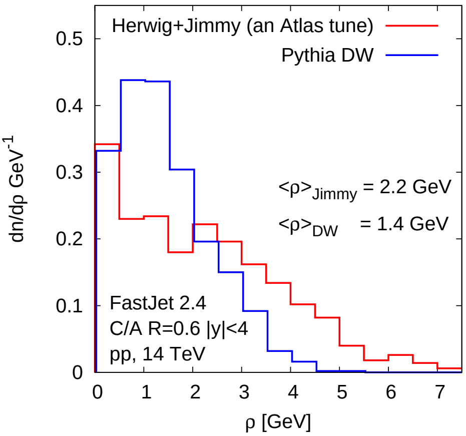


Approximate linear relation between Pt and area for minimum bias jets.

Can be used on an event-by-event basis to correct the hard jets

Probability dist. of ρ, the UE p_t density

E.g. take dijet events with $p_t > 50$ GeV, extract ρ from the soft jets. Look at **distribution** of ρ across events:



Result for ρ consistent in topological and jet-based methods;

But also get event-by-event dist.

Jet-based method works in complex events too (e.g. $t\bar{t}$)

E.g. select quiet events for clean studies

See talk by M. Cacciari for explanations and bacground

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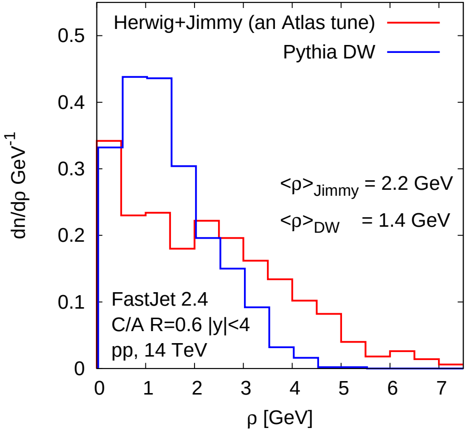

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Conclusions

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Unlocking the power of jets at LHC means going beyond stale discussions of whether we really need IRC safe algorithms.

For each IRC unsafe alg., there's a good safe alternative

HERA offers a good example in its approach to jets

The questions we face on jets cover LHC's whole dynamic range:

From ~ 1 GeV to multi-TeV

The scales mix: UE with pileup with EW with TeV

Understanding of low scales, substructure $\leftrightarrow$ HERA

The key to focusing with clarity on LHC events will be **flexbility**

Powerful ideas that rely on flexibility are here; more will come

LHC experiments' ongoing efforts to build in flexibility are essential

Much more material & discussion in parallel session!

EXTRAS

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			
	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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Cone basics I: IC-SM

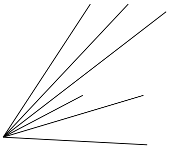
Many cone algs have two main steps:

- 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 [Blazey et al. '00 (Run II jet physics)]



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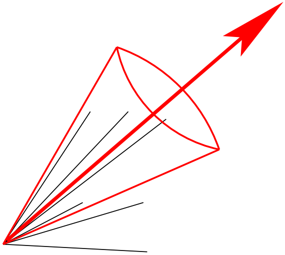

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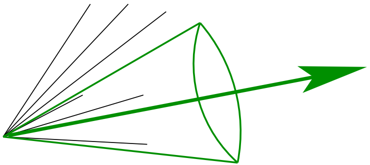

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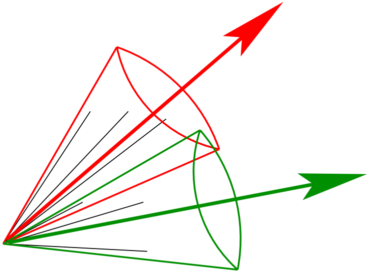

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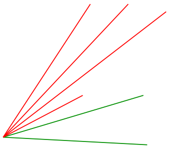

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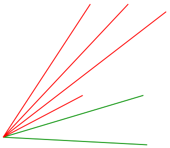


Qu: How do you find the stable cones?

Until recently used iterative methods:

- use each particle as a starting direction for cone; use sum of contents as new starting direction; repeat.

Iterative Cone with Split Merge (IC-SM)

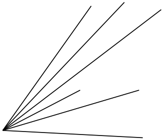
e.g. Tevatron cones (JetClu, midpoint)

ATLAS cone

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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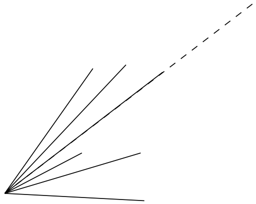

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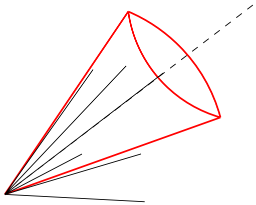

Iterative Cone [with progressive removal]

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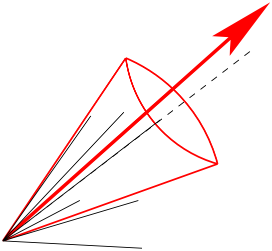

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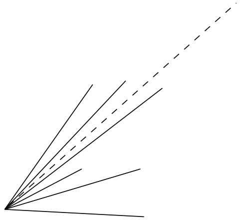

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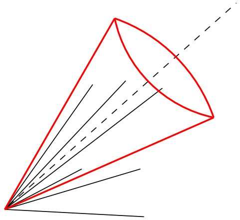

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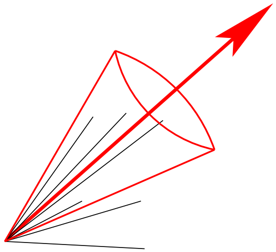

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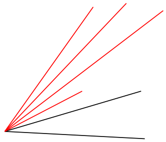

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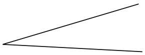

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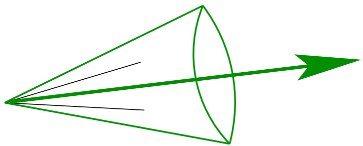

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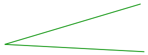

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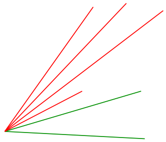

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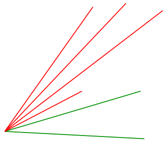
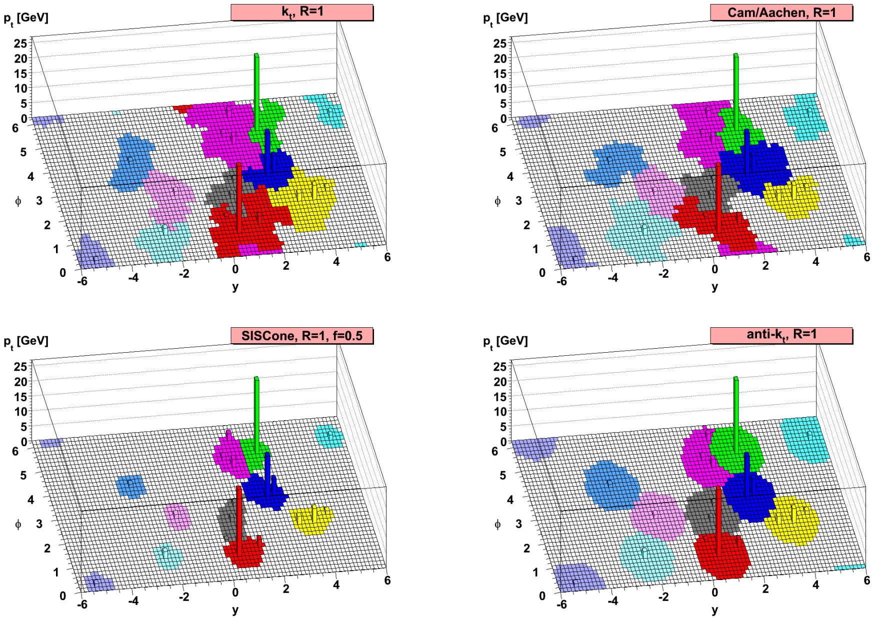


Iterative Cone with Progressive Removal (IC-PR)

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

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

Jet contours – visualised



IRC safety & triggering

One last reason sometimes quoted for using IRC unsafe algs:

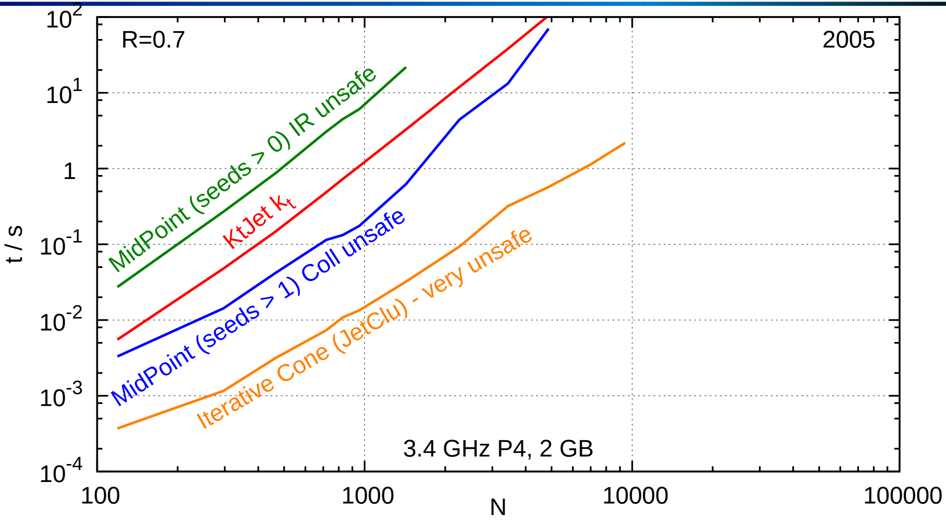
"Our trigger uses the XYZ cone, and we want to have the same algorithm in the trigger and the physics analyses"

And our trigger people are **very** *conservative*
and will **never** *change algorithm*

A possible response:

- Low-level and high level triggers often use different algs anyway
- Algs like anti-k_t are definitely fast enough (1ms [20ms] at low [high] lumi) to fit comfortably within the time per event, $\mathcal{O}(1\,\mathrm{s})$, in the HLT
- anti-k_t and plain (trigger) cones should give similar jets: you can trigger if jets from *either* pass the cuts — increase in bandwidth should be negligible and if you really want your old trigger cone, you've still got it.

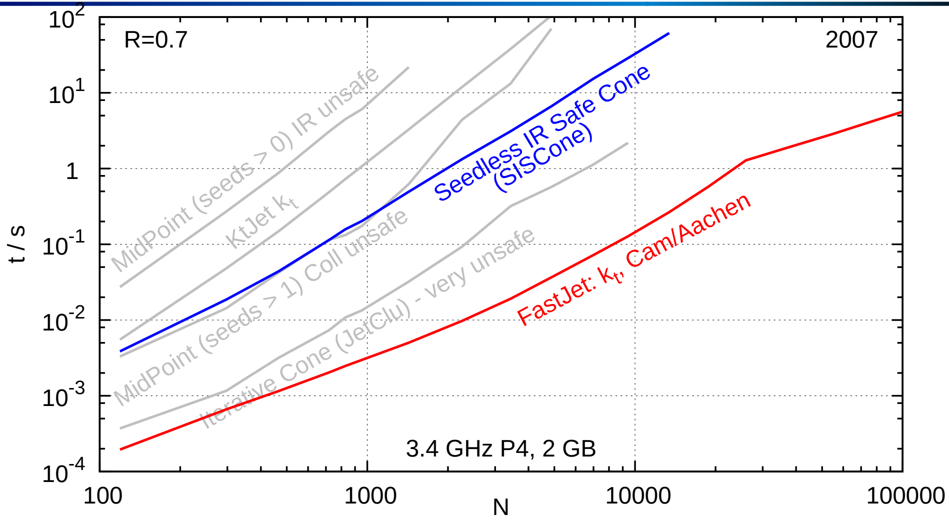
Status in 2005



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

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

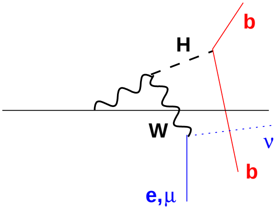
Studied e.g. in ATLAS TDR

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)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?



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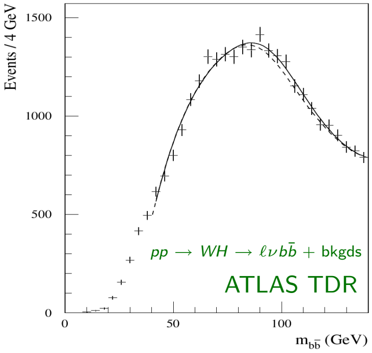

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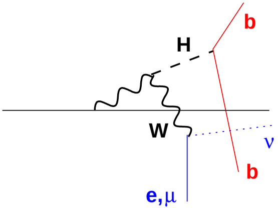

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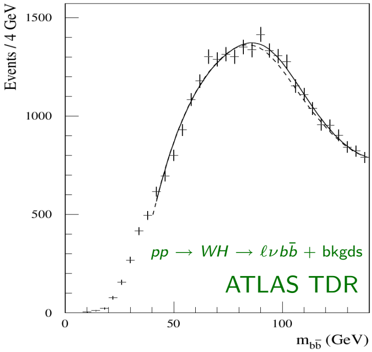

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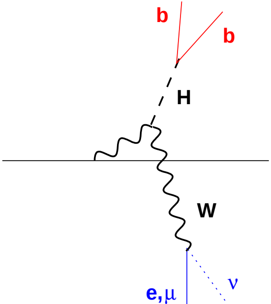

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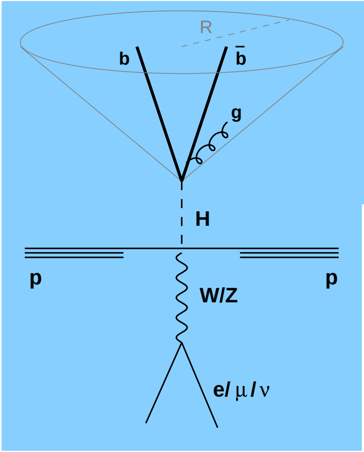
Searching for high-p_t HW/HZ?

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 $\rightarrow$ 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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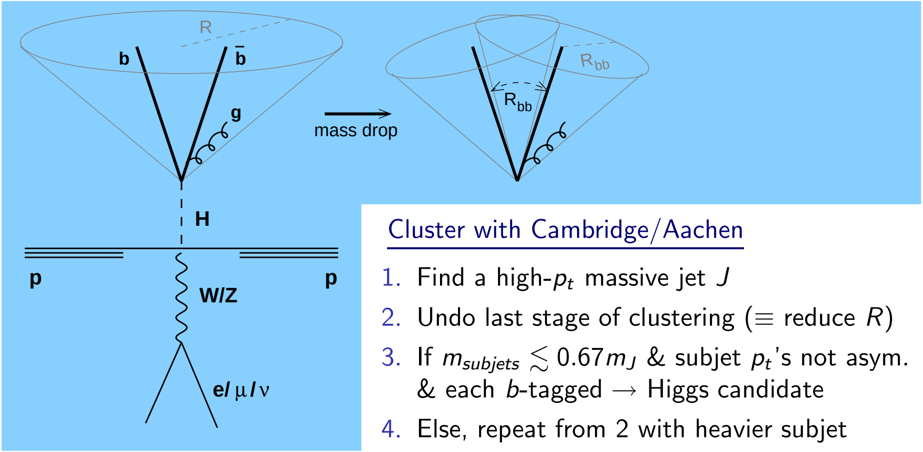

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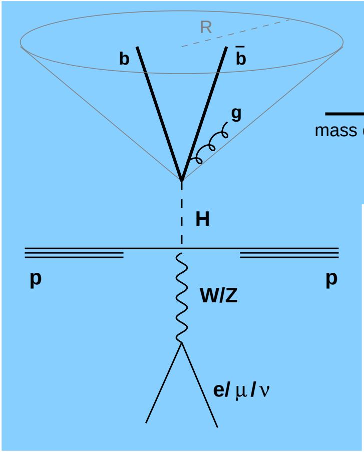

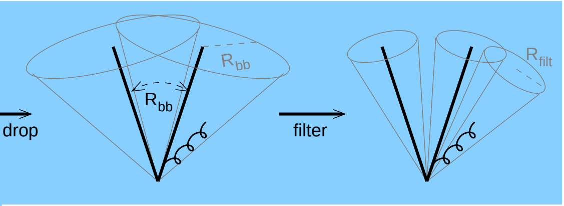

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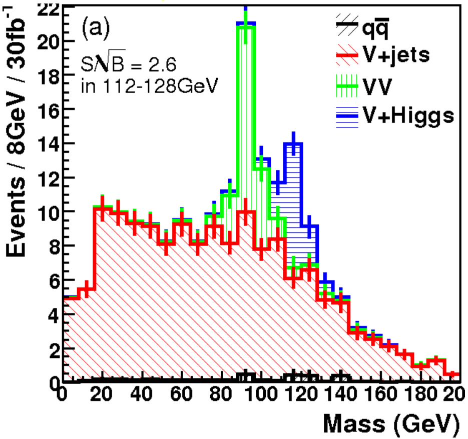
combine HZ and HW, $p_t > 200$ GeV

Leptonic channel



Common cuts

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

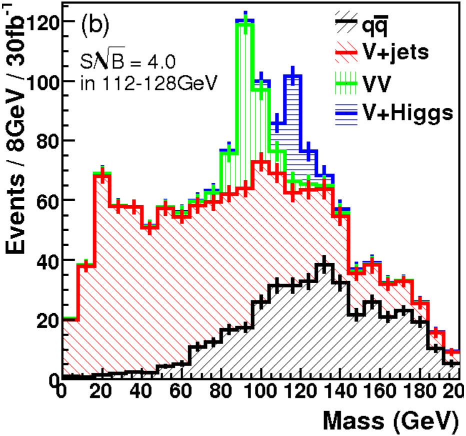
$Z \to \mu^+\mu^-, e^+e^-$

- $80 < m_{\ell^+\ell^-} < 100$ 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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Missing-E_t channel

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

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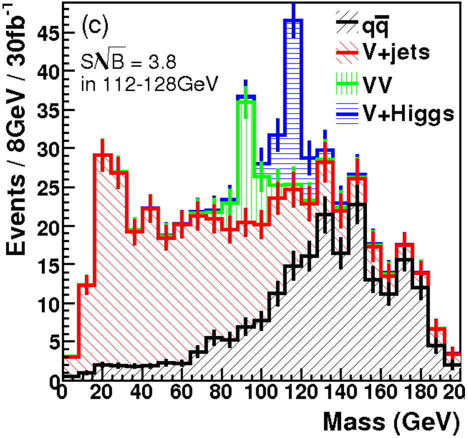
Semi-leptonic channel



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Semi-leptonic channel

$W \to \nu\ell$

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

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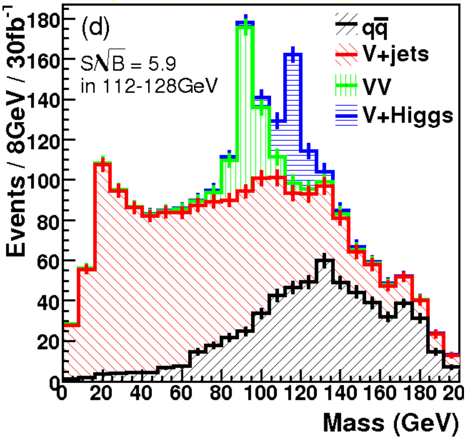
combine HZ and HW, $p_t > 200$ GeV

3 channels combined



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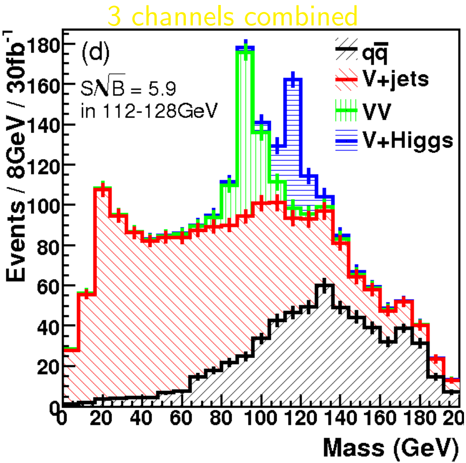

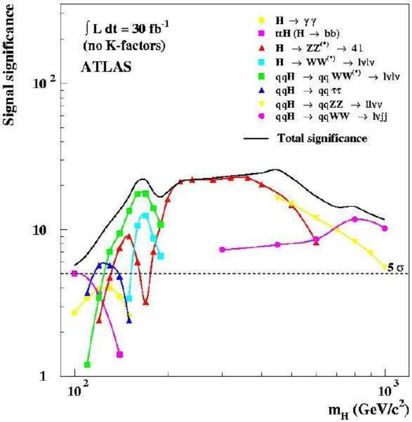

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