Jets at LHC: from basics to Higgs hunting

Gavin P. Salam

LPTHE, UPMC Paris 6 & CNRS

CP3, Université Catholique de Louvain
15 May 2008

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

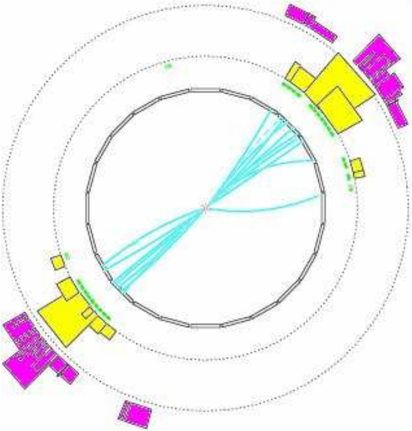
- Quarks and gluons are inevitable in initial state
- and ubiquitous in the final state

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

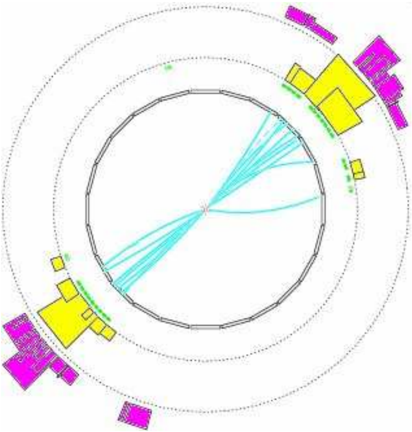


Jets are what we see.
Clearly(?) 2 of them.

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?

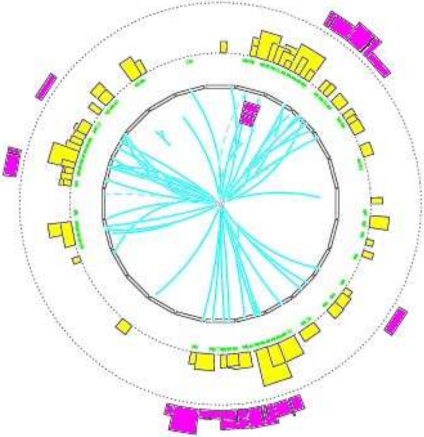
Seeing v. defining jets



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

2 partons?

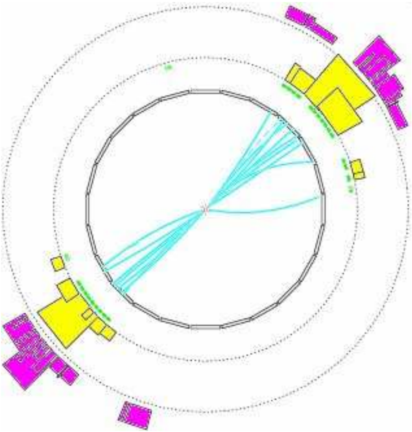
$E_{parton} = M_z/2$?

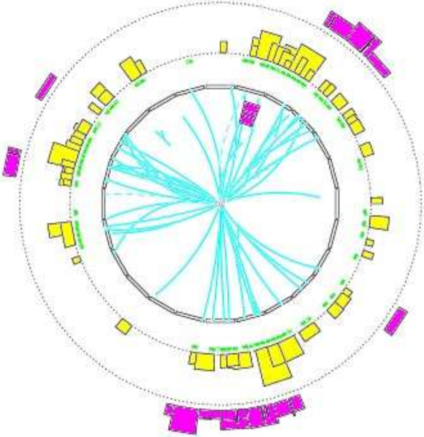


How many jets do you see?

Do you really want to ask yourself this question for 10^8 events?

Seeing v. defining jets





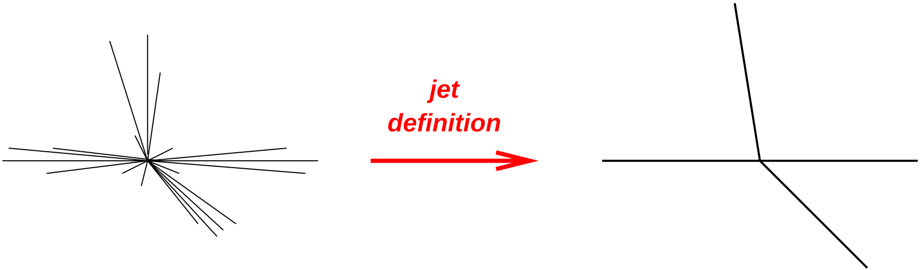
Jets are what we see.
Clearly(?) 2 of them.

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?

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:



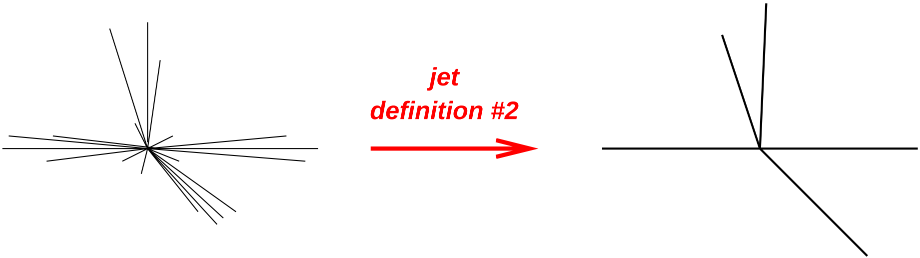
Jets are *as close as we can get to a physical single hard quark or gluon:* with good definitions their properties (multiplicity, energies, [flavour]) are

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

NB: finiteness ⟷ set of jets depends on jet def.

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

NB: finiteness ⟷ set of jets depends on jet def.

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,
but gives flexibility in one's view of events
→ Jets non-trivial!

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,
but gives flexibility in one's view of events
→ Jets non-trivial!

There is no unique jet definition

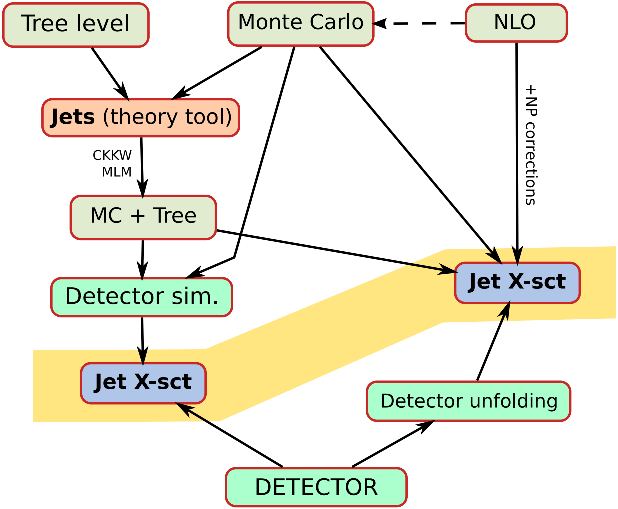
The construction of a jet is unavoidably ambiguous. On at least two fronts:

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,
but gives flexibility in one's view of events
→ Jets non-trivial!

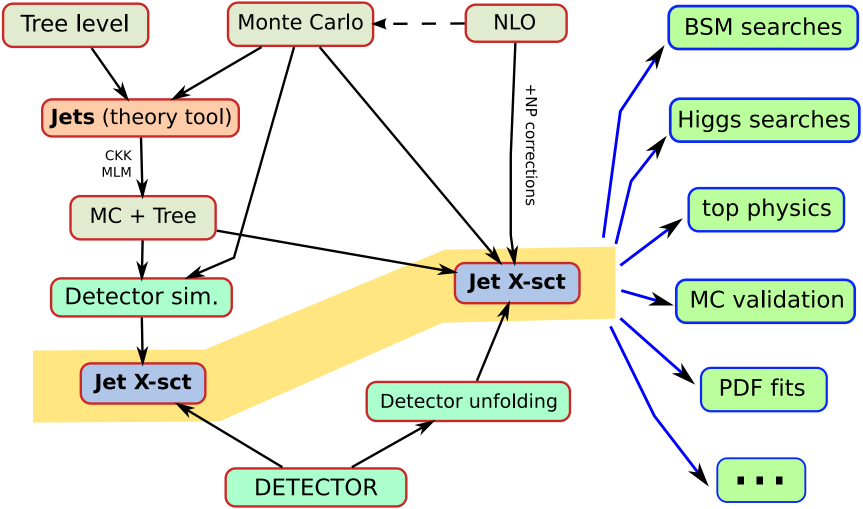
QCD jets flowchart



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

And jets are the input to almost all analyses

QCD jets flowchart



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

And jets are the input to almost all analyses

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 Accord (1990):

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

Toward a Standardization of Jet Definitions *

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

- Criteria date from the early 90's and reiterated over the years
- Let's examine them with a "chain" of CDF analyses related to Higgs searches ($p\bar{p} \to HW \to \ell\nu b\bar{b}$)

Though example taken from one expt., pattern will be general

Snowmass

Snowmass Accord (1990):

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

Toward a Standardization of Jet Definitions *

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

- Criteria date from the early 90's and reiterated over the years
- Let's examine them with a "chain" of CDF analyses related to Higgs searches ($p\bar{p} \to HW \to \ell\nu b\bar{b}$)

Though example taken from one expt., pattern will be general

Snowmass: hadronisation

Snowmass Accord (1990):

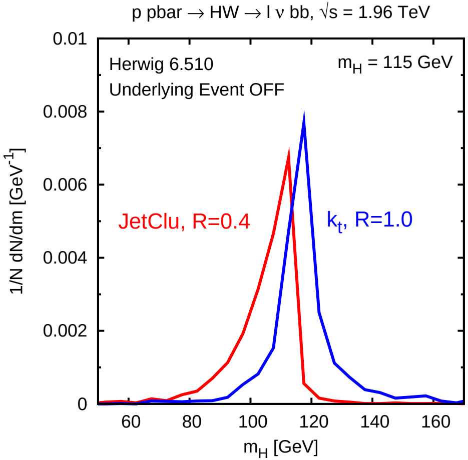
FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Non-pert. effects (Tevatron Higgs)



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:

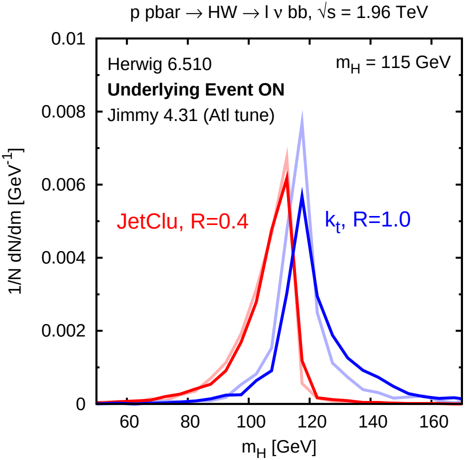
- Higgs peak $\sim$ 15% higher with k_t, $R = 1$ → use 30% less lumi?

With UE:

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

Non-perturbative effects matter!

Non-pert. effects (Tevatron Higgs)



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, $R = 1$ → use 30% less lumi?

With UE:

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

Non-perturbative effects matter!

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 ($V+\text{jet(s)}$) 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 $V+\text{jet(s)}$ 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

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

The jets in each $W \to e\nu$ event are reconstructed using the JETCLU cone algorithm [9] with cone radius $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$.

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?

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

The jets in each $W \to e\nu$ event are reconstructed using the JETCLU cone algorithm [9] with cone radius $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$.

...

In the case of the NLO predictions, the final states are not evolved through a parton shower nor hadronized. Jets are reconstructed with a cone algorithm $R = 0.4$, such that two partons are merged if they are within $1.3 \times R$ of each other and within R of the resulting jet centroid [27].

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?

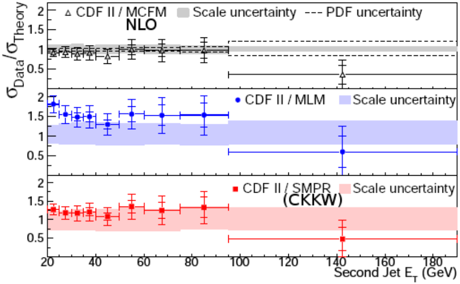
Background to Tevatron Higgs

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

The jets in each $W \to e\nu$ event are reconstructed using the JETCLU cone algorithm [9] with cone radius $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$.

...

In the case of the NLO predictions, the final states are not evolved through a parton shower nor hadronized. Jets are reconstructed with a cone algorithm $R = 0.4$, such that two partons are merged if they are within $1.3 \times R$ of each other and within R of the resulting jet centroid [27].



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?

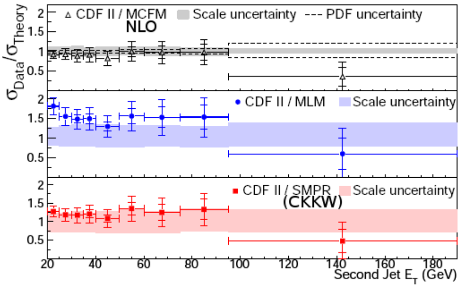
Background to Tevatron Higgs

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

The jets in each $W \to e\nu$ event are reconstructed using the JETCLU cone algorithm [9] with cone radius $R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$.

. . .

In the case of the NLO predictions, the final states are not evolved through a parton shower nor hadronized. Jets are reconstructed with a cone algorithm $R = 0.4$, such that two partons are merged if they are within $1.3 \times R$ of each other and within R of the resulting jet centroid [27].



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(!?)

<u>Data & NLO agree beautifully!</u>

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

So, why the 2 different jet defs?

Snowmass: finiteness (IR safety)

Snowmass Accord (1990):

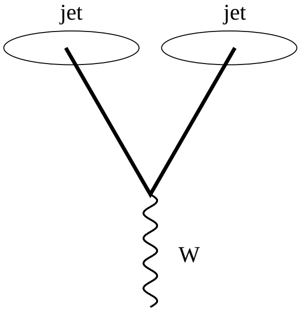
FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

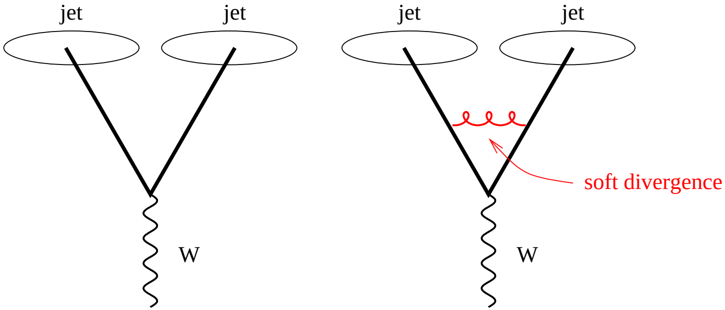
JetClu (& Atlas Cone) in Wjj @ NLO



	$\alpha_s^2\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	**0**

With these (& most) cone algorithms, perturbative infinities fail to cancel at some order $\equiv$ **IR unsafety**

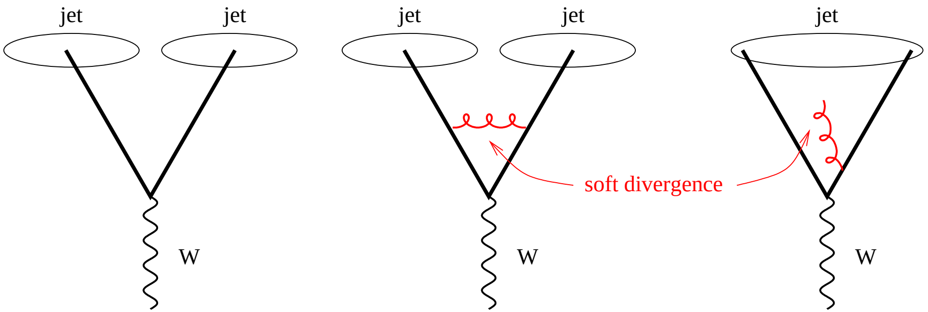
JetClu (& Atlas Cone) in Wjj @ NLO



	$\alpha_s^2\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	**0**

With these (& most) cone algorithms, perturbative infinities fail to cancel at some order ≡ **IR unsafety**

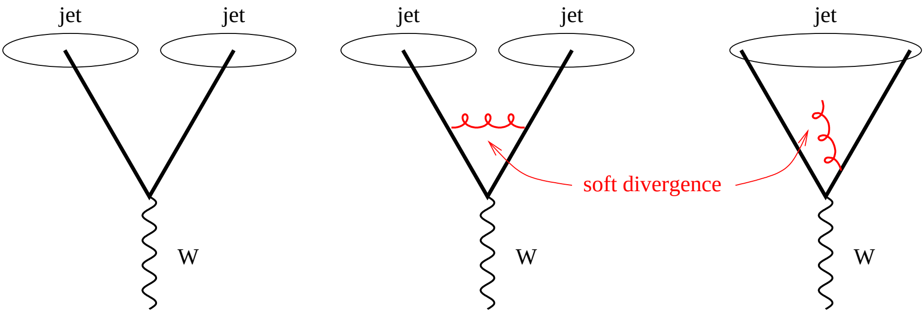
JetClu (& Atlas Cone) in Wjj @ NLO



	$\alpha_s^2 \alpha_{EW}$	$\alpha_s^3 \alpha_{EW}$	$\alpha_s^3 \alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	**0**

With these (& most) cone algorithms, perturbative infinities fail to cancel at some order ≡ **IR unsafety**

JetClu (& Atlas Cone) in Wjj @ NLO



	$\alpha_s^2\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$	$\alpha_s^3\alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	**0**

With these (& most) cone algorithms, perturbative infinities fail to cancel at some order $\equiv$ **IR unsafety**

So what alg. was used for the NLO?

- It's not too clear from the text. A recurrent problem
- 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 $\mathbf{N2^N}$.

10^{17} years for 100 particles [Tev, LHC $\sim 200 - 4000$]

So what alg. was used for the NLO?

- It's not too clear from the text. A recurrent problem
- Chances are it's the "seedless" cone algorithm in MCFM.

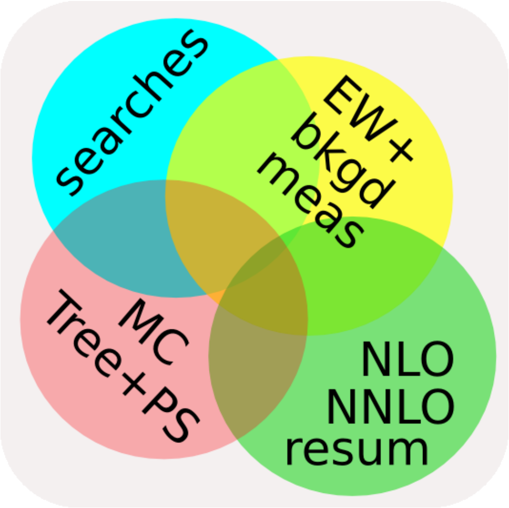
So why not use it for the experimental measurement too?

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

10^{17} years for 100 particles [Tev, LHC $\sim 200-4000$]

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.



For everything to fit together **all of Snowmass criteria needed**.

Given need to compromise, the IR safety usually goes first.

This breaks connection between different parts of QCD.

$\sim$ 80% of Tevatron and LHC work based on IRC unsafe algs — a pervasive problem.

For everything to fit together **all of Snowmass criteria needed**.

Given need to compromise, the IR safety usually goes first.

This breaks connection between different parts of QCD.

$\sim$ 80% of Tevatron and LHC work based on IRC unsafe algs — a pervasive problem.

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			
	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_{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

IRC safety & real-life

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

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

Among consequences of IR unsafety:

	Last meaningful order			Known at
	JetClu, ATLAS cone [IC-SM]	MidPoint [IC$_{mp}$-SM]	CMS it. cone [IC-PR]	
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_{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

IRC safety & real-life

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

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

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_{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

Our logic re Snowmass/IRC safety

- **IRC safety is non-negotiable**
  - It's part of why jets were defined originally — Sterman-Weinberg '77
  - It's essential for theory calculations to make sense
  - This is a consensus view — or at least, has been affirmed by every major "jet-workshop" since 1991. — Snowmass '91, Run II '00, Tev4LHC '06, Les Houches '07

- **But:** some IRC unsafe algorithms might have other "nice" properties
  - particularly low UE sensitivity
  - circularity of jets

So let's find out what's out there, engineer away the IRC unsafety & other problems, but keep any nice properties

- Any solution has to be **practical**
  - not too slow — was issue also for k_t
  - implemented as computer code — reduce barrier to adoption

Our logic re Snowmass/IRC safety

- **IRC safety is non-negotiable**
  - It's part of why jets were defined originally — Sterman-Weinberg '77
  - It's essential for theory calculations to make sense
  - This is a consensus view — or at least, has been affirmed by every major "jet-workshop" since 1991. — Snowmass '91, Run II '00, Tev4LHC '06, Les Houches '07

- **But:** some IRC unsafe algorithms might have other "nice" properties
  - particularly low UE sensitivity
  - circularity of jets

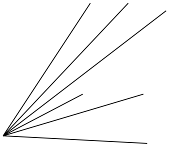
So let's find out what's out there, engineer away the IRC unsafety & other problems, but keep any nice properties

- Any solution has to be **practical**
  - not too slow — was issue also for k_t
  - implemented as computer code — reduce barrier to adoption

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:

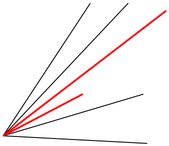
Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

Time reduced to $N\sqrt{n}$ 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)
- 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

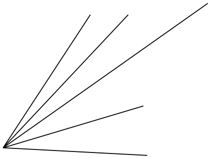
k_t algorithm

- 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)
- 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:

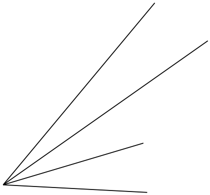
Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

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: $i \rightarrow$ jet)
- Repeat



'Trivial' computational issue:

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

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

Advance #1: factorise momentum and geometry

Borrow methods & tools from Computational Geometry:

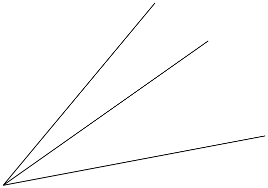
Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

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

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:

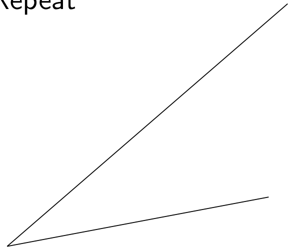
Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

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)
- 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:

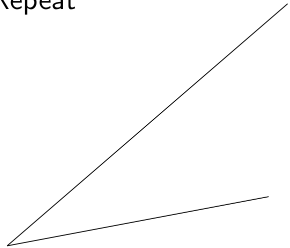
Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

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)
- 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:

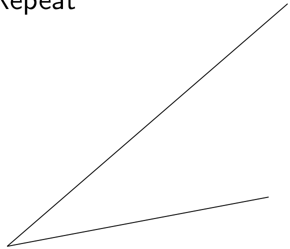
Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

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



'Trivial' computational issue:

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

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

Advance #1: factorise momentum and geometry

Borrow methods & tools from Computational Geometry:

Bucketing, dynamic Voronoi diagrams, CGAL, Chan CP

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

Cones with Split Merge (SM)

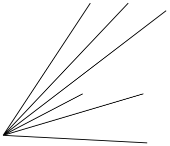
Modern cone algs have two main steps:

- 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



Cones with Split Merge (SM)

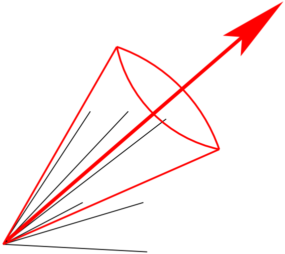
Modern cone algs have two main steps:

- 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



Cones with Split Merge (SM)

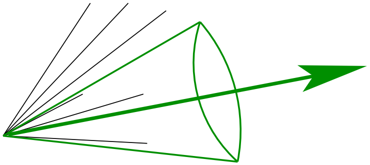
Modern cone algs have two main steps:

- 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



Cones with Split Merge (SM)

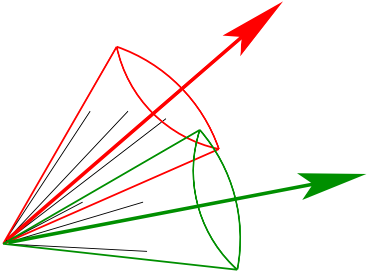
Modern cone algs have two main steps:

- 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



Cones with Split Merge (SM)

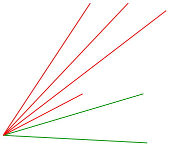
Modern cone algs have two main steps:

- 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



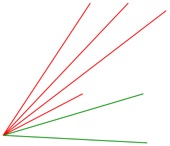
Cones with Split Merge (SM)

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



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**

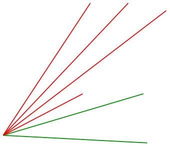
Cones with Split Merge (SM)

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



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**

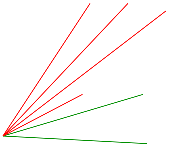
Cones with Split Merge (SM)

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



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**

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

How do you find the stable cones?

- Iterate from 'seed' particles

  Done originally, very IR unsafe, N^2 [JetClu, Atlas]

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 → stable cone

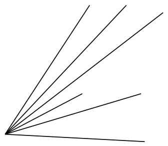
Time reduced from $N2^N$ to $\mathbf{N^2 \ln N}$: 6s for N=4000. GPS & Soyez '07

"SISCone"

Cone basics II: IC-PR

Other cones avoid split-merge:

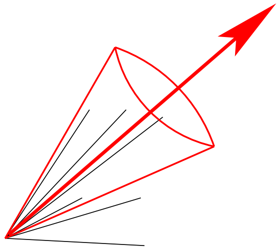
- Find one stable cone — E.g. by iterating from hardest seed particle
- Call it a jet;remove its particles from the event; repeat



Cone basics II: IC-PR

Other cones avoid split-merge:

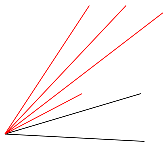
- Find one stable cone E.g. by iterating from hardest seed particle
- Call it a jet;remove its particles from the event; repeat



Cone basics II: IC-PR

Other cones avoid split-merge:

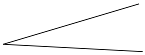
- Find one stable cone — E.g. by iterating from hardest seed particle
- Call it a jet; remove its particles from the event; repeat



Cone basics II: IC-PR

Other cones avoid split-merge:

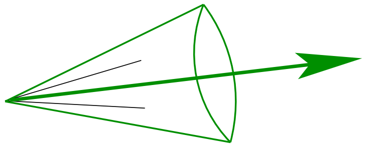
- Find one stable cone E.g. by iterating from hardest seed particle
- Call it a jet;remove its particles from the event; repeat



Cone basics II: IC-PR

Other cones avoid split-merge:

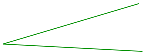
- Find one stable cone — E.g. by iterating from hardest seed particle
- Call it a jet;remove its particles from the event; repeat



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



Cone basics II: IC-PR

Other cones avoid split-merge:

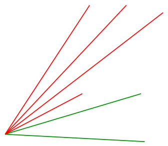
- Find one stable cone — E.g. by iterating from hardest seed particle
- Call it a jet;remove its particles from the event; repeat

- 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]



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

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

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	$SR_{p=1}$	OK	
inclusive k_t	$SR_{p=1}$	OK	widespread in QCD theory
Cambridge/Aachen	$SR_{p=0}$	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	$IC_{se,mp}$-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	$N^3 \to N \ln N$
inclusive k_t	$\mathrm{SR}_{p=1}$	OK	$N^3 \to N \ln N$
Cambridge/Aachen	$\mathrm{SR}_{p=0}$	OK	$N^3 \to N \ln N$
Run II Seedless cone	SC-SM	OK	$\to$ SISCone
CDF JetClu	IC_r-SM	IR_{2+1}	[$\to$ SISCone]
CDF MidPoint cone	IC_{mp}-SM	IR_{3+1}	$\to$ SISCone
CDF MidPoint searchcone	$\mathrm{IC}_{se,mp}$-SM	IR_{2+1}	[$\to$ SISCone]
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;

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

non-COMMERCIAL BREAK

Use FastJet — it's free!

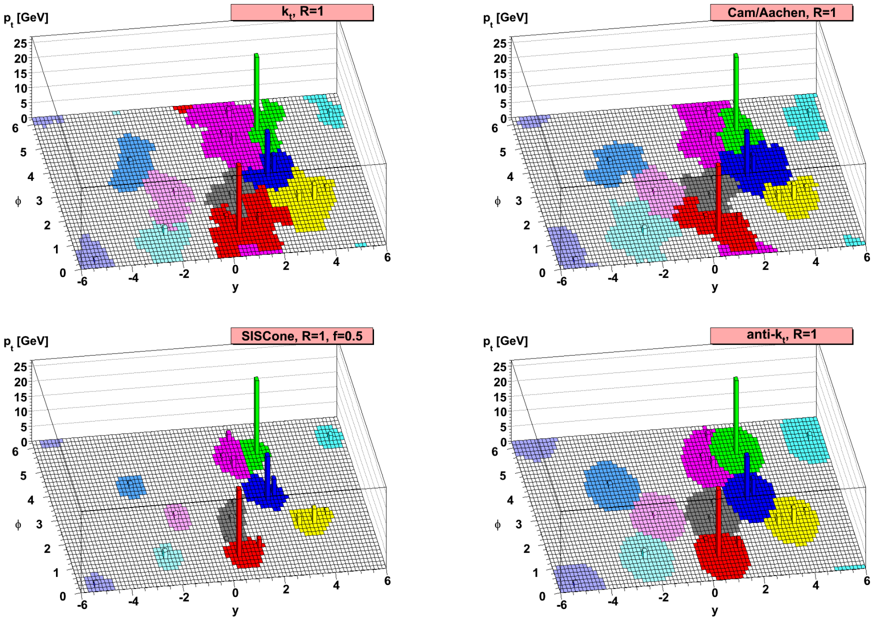
One place to stop for your jet-finding needs:

FastJet

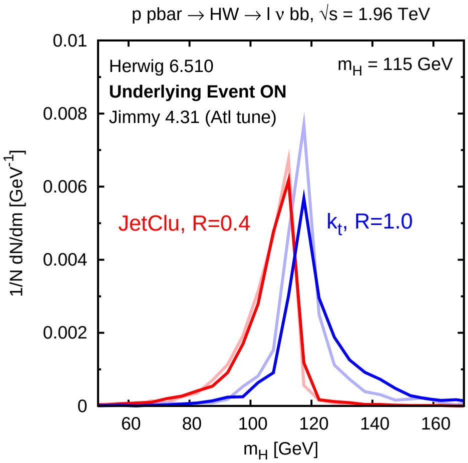
http://www.lpthe.jussieu.fr/~salam/fastjet
Cacciari, GPS & Soyez '05–08

- 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

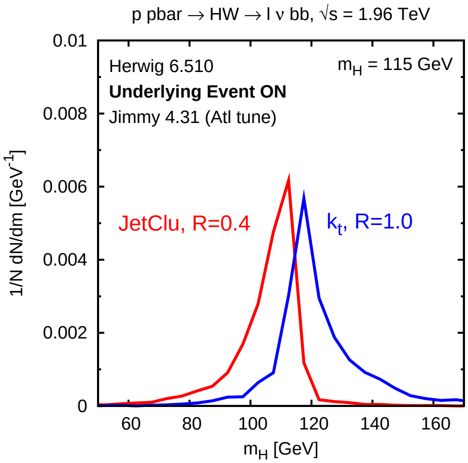
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

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

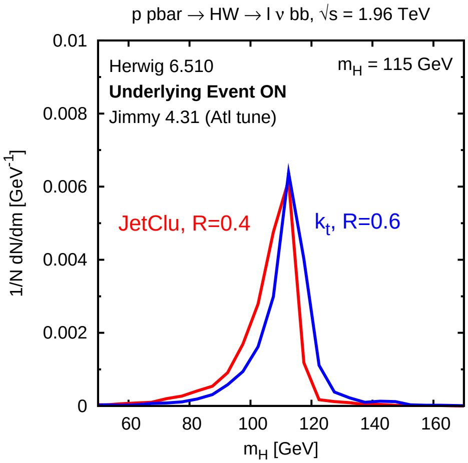
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

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

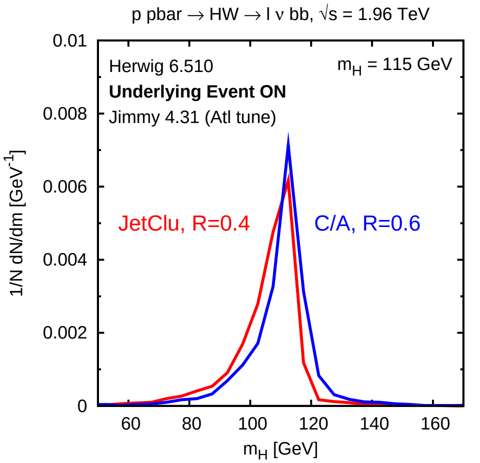
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

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

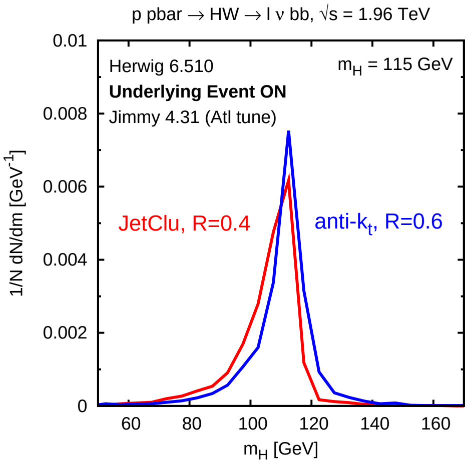
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

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

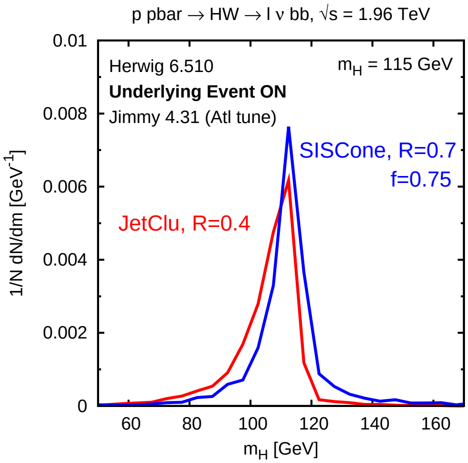
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

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

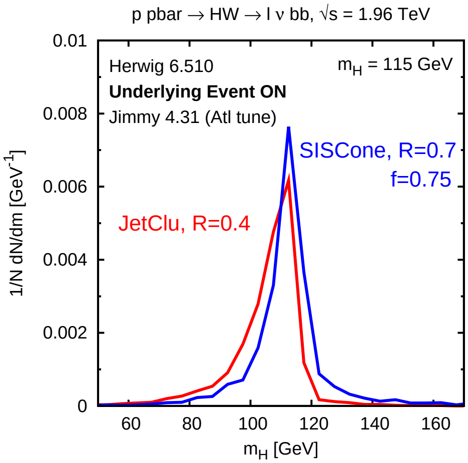
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

Are the algs any good for physics?



Return to Tevatron Higgs example

Try various jet definitions

Jet def. ≡ 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

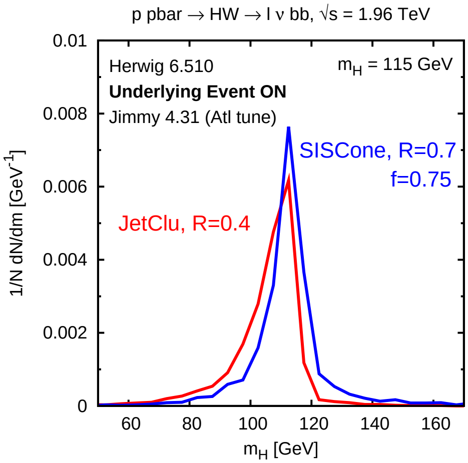
NB: also need detector + bkgds

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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

Are the algs any good for physics?



Return to Tevatron Higgs example

Try various jet definitions

Jet def. ≡ 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

Büge, Heinrich, Klein & Rabbertz '08; Campanelli, Geerlins & Huston '08

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. $\qquad \sim \alpha_s M_{EW}$
- $p_{t,\text{hadr.}} \sim 0.5$ GeV/unit rap.

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

LHC is not LEP or Tevatron

Tevatron

- $M_{BSM} \sim 1$ TeV?
- $M_{EW} \sim 100$ GeV $\sim \alpha_s M_{BSM}$
- $p_{t,\text{pileup}} \sim 25 - 50$ GeV/unit rap. $\sim M_{EW}$
- $p_{t,\text{UE}} \sim 2.5 - 5$ GeV/unit rap. $\sim \alpha_s M_{EW}$
- $p_{t,\text{hadr.}} \sim 0.5 - 1$ GeV/unit rap.

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

LHC is not LEP or Tevatron

LHC

- $M_{BSM} \sim 1$ TeV?
- $M_{EW} \sim 100$ GeV $\sim \alpha_s M_{BSM}$
- $p_{t,\text{pileup}} \sim 25 - 50$ GeV/unit rap. $\sim M_{EW}$
- $p_{t,\text{UE}} \sim 5 - 10$ GeV/unit rap. $\sim \alpha_s M_{EW}$
- $p_{t,\text{hadr.}} \sim 0.5 - 1$ GeV/unit rap.

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^n),** *and* **physics of scale** B

LHC is not LEP or Tevatron

LHC

- $M_{BSM} \sim 1$ TeV?
- $M_{EW} \sim 100$ GeV $\sim \alpha_s M_{BSM}$
- $p_{t,\text{pileup}} \sim 25 - 50$ GeV/unit rap. $\sim M_{EW}$
- $p_{t,\text{UE}} \sim 5 - 10$ GeV/unit rap. $\sim \alpha_s M_{EW}$
- $p_{t,\text{hadr.}} \sim 0.5 - 1$ GeV/unit rap.

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^n),** *and* **physics of scale** B

LHC is not LEP or Tevatron

LHC

- $M_{BSM} \sim 1$ TeV?
- $M_{EW} \sim 100$ GeV — $\sim \alpha_s M_{BSM}$
- $p_{t,\text{pileup}} \sim 25 - 50$ GeV/unit rap. — $\sim M_{EW}$
- $p_{t,\text{UE}} \sim 5 - 10$ GeV/unit rap. — $\sim \alpha_s M_{EW}$
- $p_{t,\text{hadr.}} \sim 0.5 - 1$ GeV/unit rap.

Multitude of scales
Interplays between them change how one does the physics

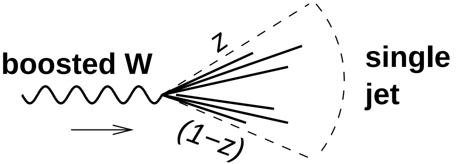
$M_B \sim \alpha_s M_A \rightarrow$ the physics of B is as important as pert. QCD in "clouding" one's view of A

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

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?



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

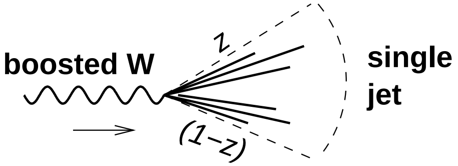
Significant discussion over years: **heavy new things decay to EW states**

- Seymour '94 [Higgs $\to WW \to \nu\ell$jets]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
- Butterworth, Ellis & Raklev '07 [SUSY decay chains $\to W, H$]
- Skiba & Tucker-Smith '07 [vector quarks]
- Contino & Servant '08 [top partners]
- ...

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?



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

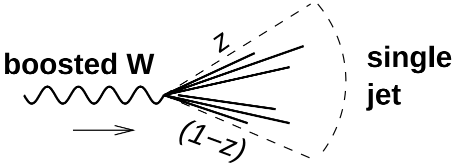
Significant discussion over years: **heavy new things decay to EW states**

- Seymour '94 [Higgs $\to WW \to \nu\ell$jets]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
- Butterworth, Ellis & Raklev '07 [SUSY decay chains $\to W, H$]
- Skiba & Tucker-Smith '07 [vector quarks]
- Contino & Servant '08 [top partners]
- ...

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]
- Butterworth, Cox & Forshaw '02 [$WW \to WW \to \nu\ell$jets]
- Butterworth, Ellis & Raklev '07 [SUSY decay chains $\to W, H$]
- Skiba & Tucker-Smith '07 [vector quarks]
- Contino & Servant '08 [top partners]
- ...

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, Cos & 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]

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 $\mathbf{k_t}$ alg to resolve structure**

Seymour '93; Butterworth, Cos & 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]

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 $\mathbf{k_t}$ alg to resolve structure**

Seymour '93; Butterworth, Cos & 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]

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?
- Maybe kill $t\bar{t}$ & gain clarity?

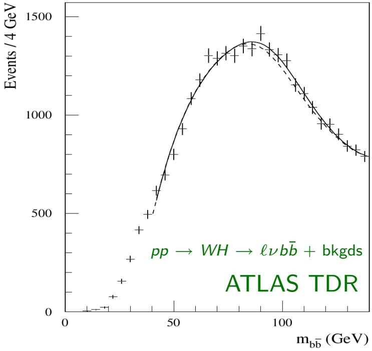
A challenging application

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?
- Maybe kill $t\bar{t}$ & gain clarity?

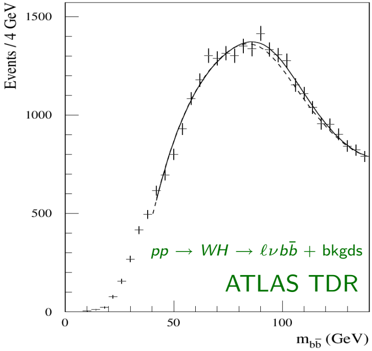
A challenging application

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

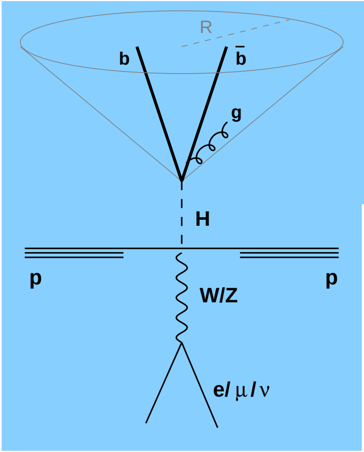
Try a long shot?

- Go to high p_t ($p_{tH}, p_{tV} > 200$ GeV)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?

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

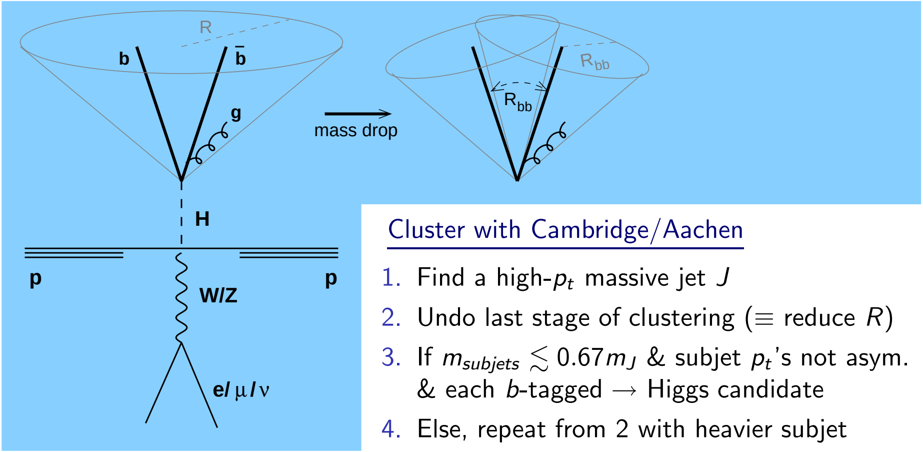
1. Find a high-p_t massive jet J
2. Undo last stage of clustering ($\equiv$ reduce R)
3. If $m_{subjets} \lesssim 0.67 m_J$ & subjet p_t's not asym. & each b-tagged $\rightarrow$ Higgs candidate
4. Else, repeat from 2 with heavier subjet

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.

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

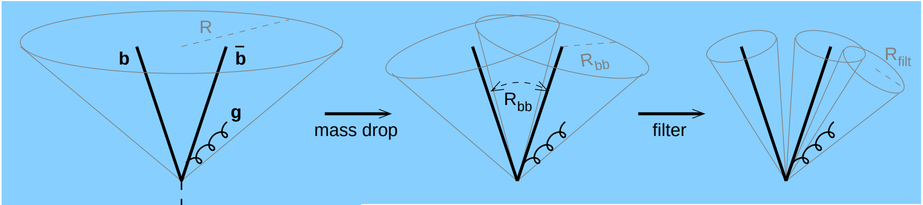
1. Find a high-p_t massive jet J
2. Undo last stage of clustering ($\equiv$ reduce R)
3. If $m_{subjets} \lesssim 0.67 m_J$ & subjet p_t's not asym. & each b-tagged $\rightarrow$ Higgs candidate
4. Else, repeat from 2 with heavier subjet

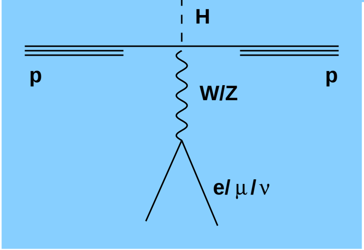
Then on the Higgs-candidate: *filter* away UE/pileup by reducing $R \rightarrow R_{filt}$, take *three hardest subjets* (keep LO gluon rad^n) + require b-tags on two hardest.

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



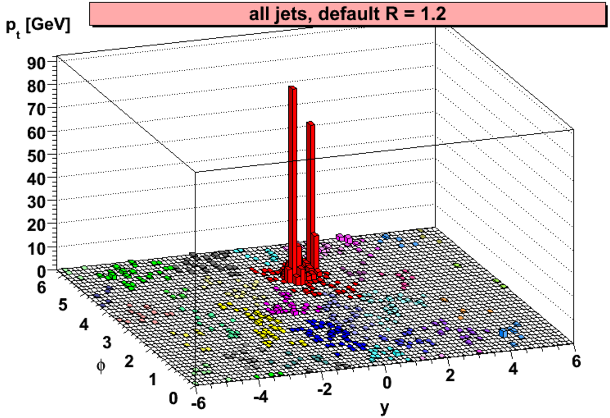


Cluster with Cambridge/Aachen

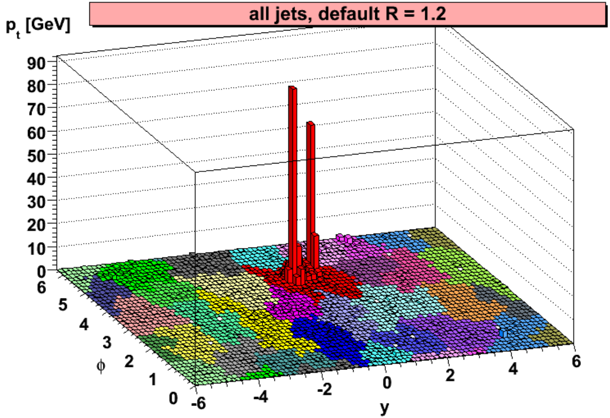
1. Find a high-p_t massive jet J
2. Undo last stage of clustering ($\equiv$ reduce R)
3. If $m_{subjets} \lesssim 0.67 m_J$ & subjet p_t's not asym. & each b-tagged $\rightarrow$ Higgs candidate
4. Else, repeat from 2 with heavier subjet

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.

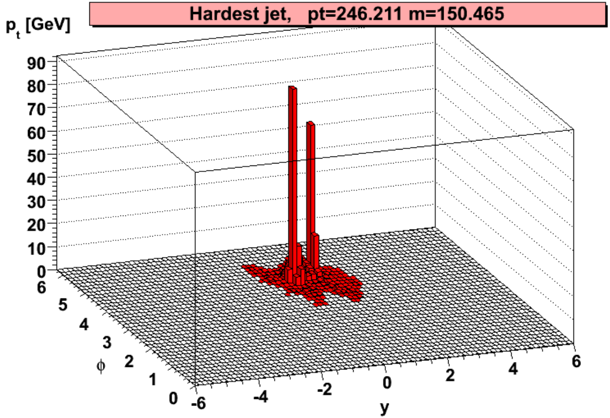
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

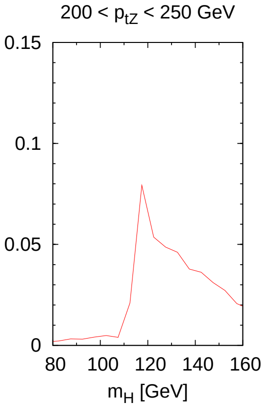


$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

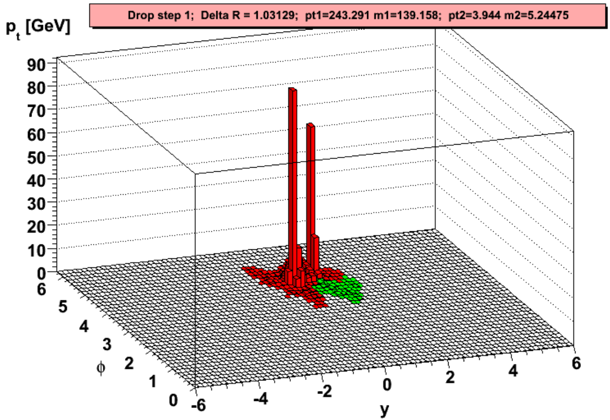


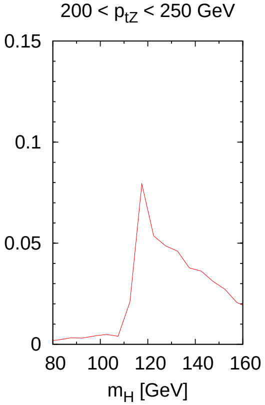
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV



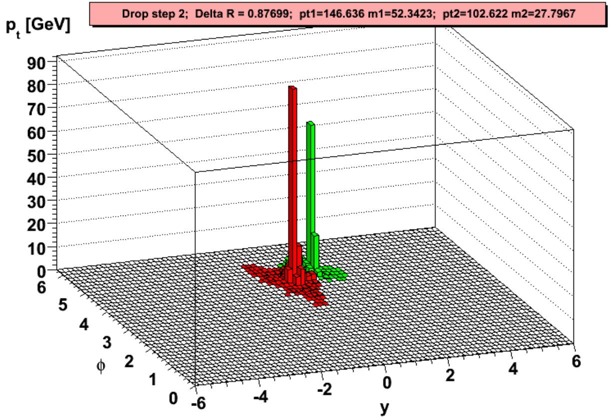


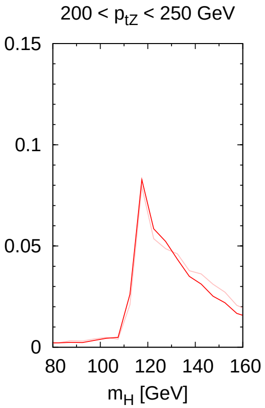
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV



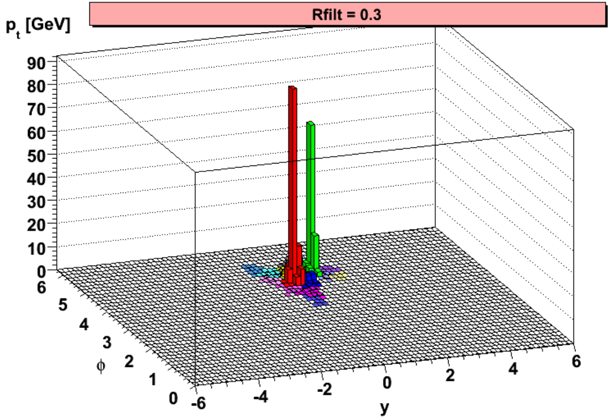


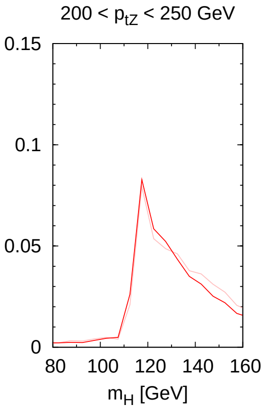
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV



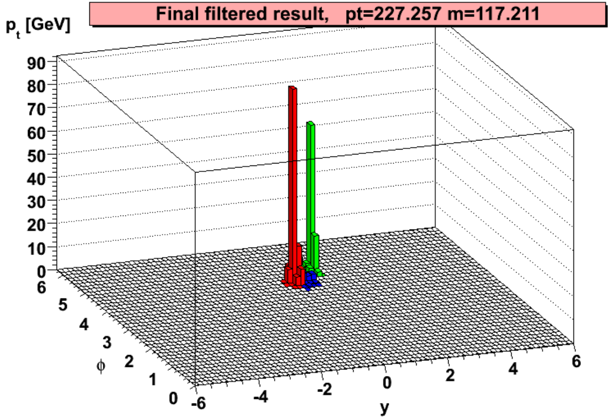


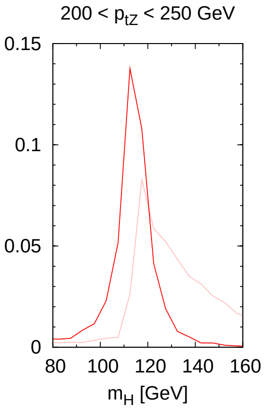
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV





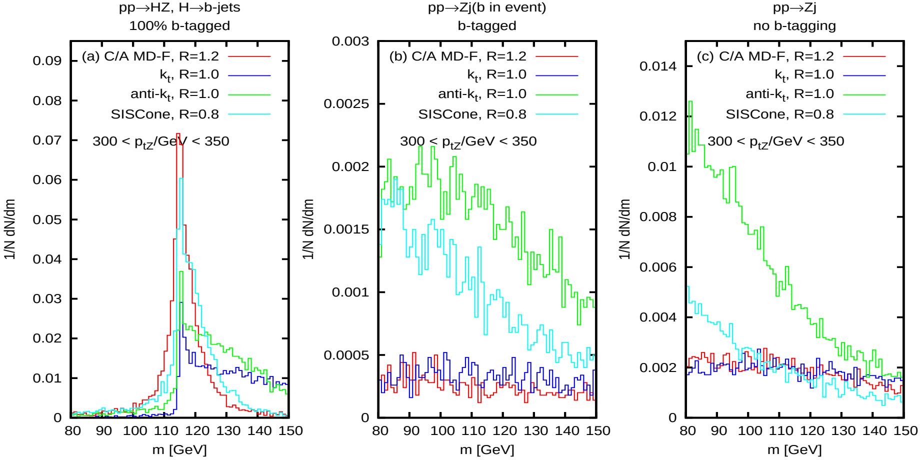
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV





Compare with "standard" algorithms

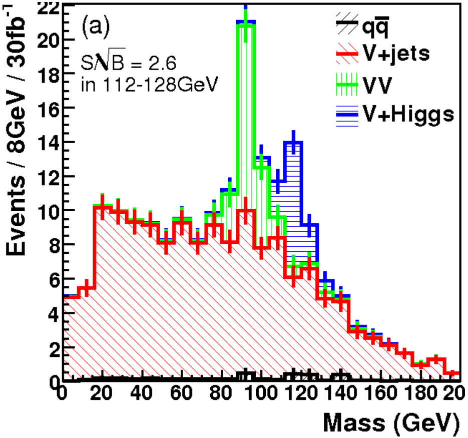
Check mass spectra in HZ channel, $H \to b\bar{b}$, $Z \to \ell^+\ell^-$



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

combine HZ and HW, $p_t > 200$ GeV

Leptonic channel



<u>Common cuts</u>

- $p_{tV}, p_{tH} > 200$ 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

<u>Leptonic channel</u>

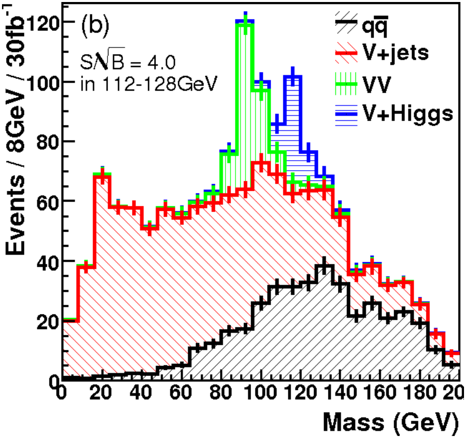
$Z \to \mu^+\mu^-, e^+e^-$

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

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

combine HZ and HW, $p_t > 200$ GeV

Missing E_T 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

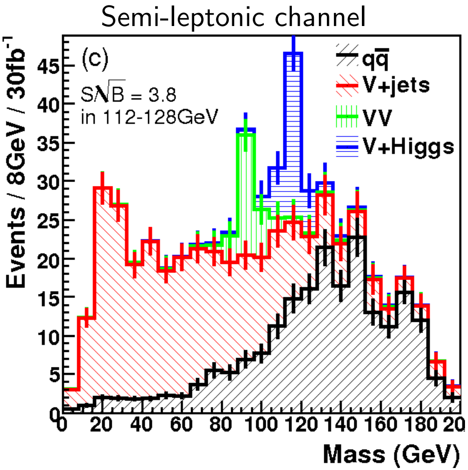
Missing-E_t channel

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

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

At 5.9σ for 30 fb^{-1} 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

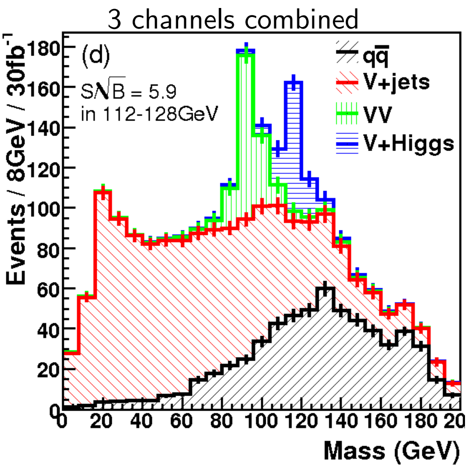
Semi-leptonic channel

$W \to \nu\ell$

- $\not{E}_T > 30$ 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



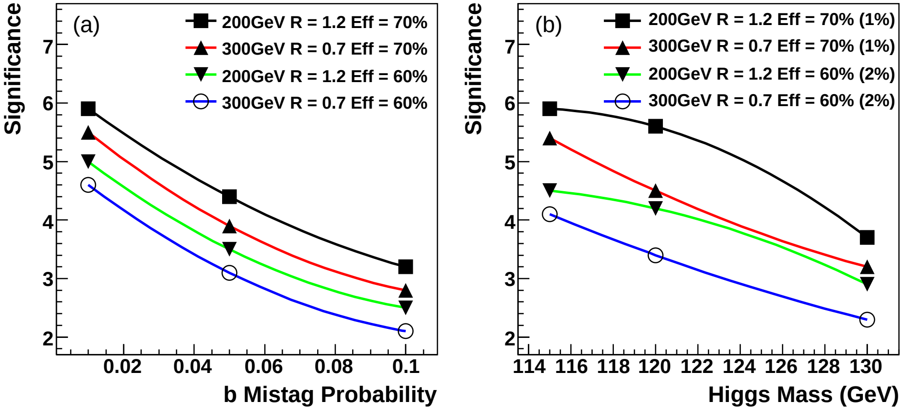
<u>Common cuts</u>

- $p_{tV}, p_{tH} > 200$ 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

<u>3 channels combined</u>

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

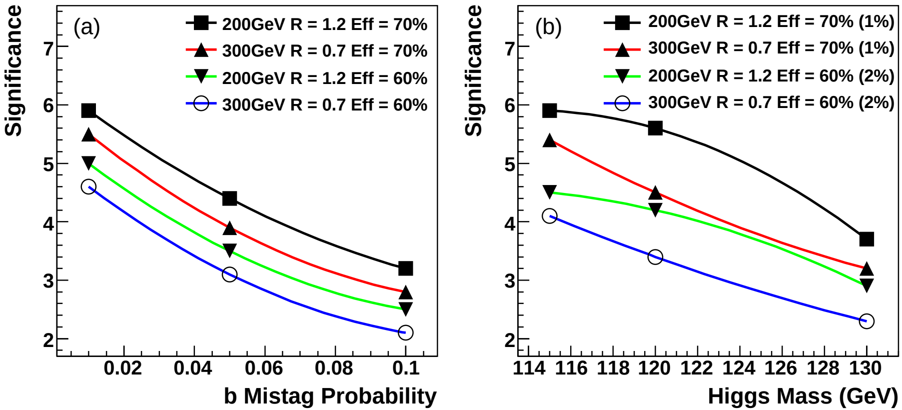
Impact of *b*-tagging, Higgs mass



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



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.

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