LHC searches: what role for QCD?

Gavin Salam

LPTHE, CNRS and UPMC (Univ. Paris 6)

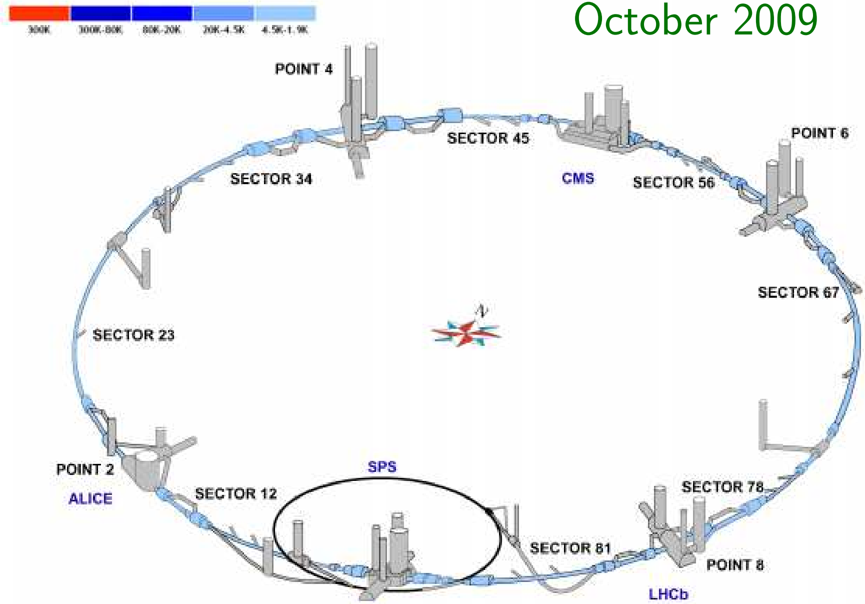
Paul Scherrer Institut, Villigen
1 April 2010

Including examples based on work with Butterworth, Davison & Rubin

Startup (again) for LHC

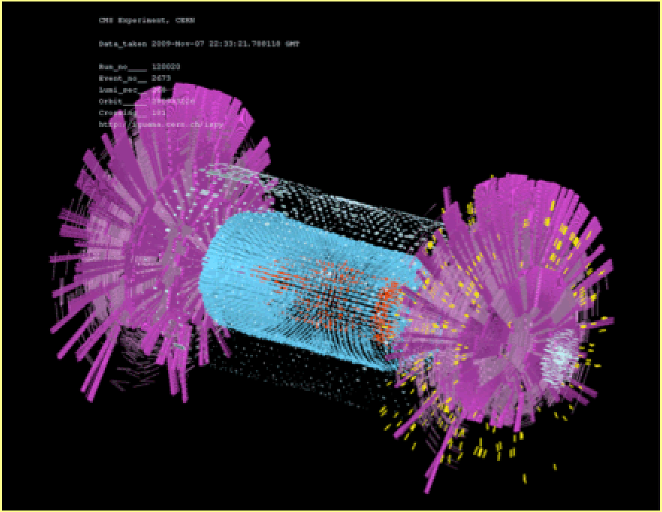
Startup (again) for LHC

October 2009



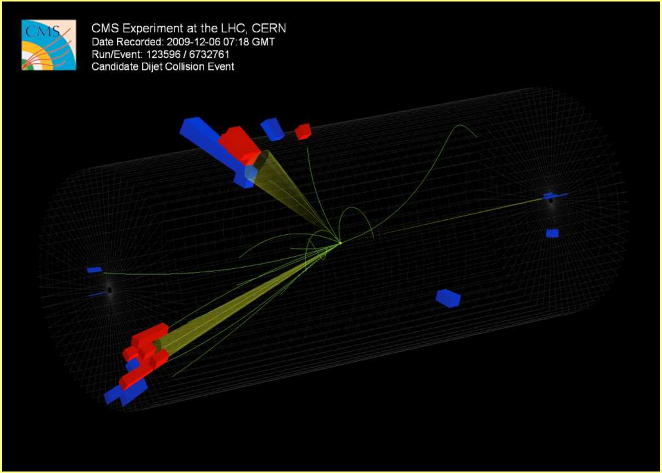
Startup (again) for LHC

7 November: first beam (picture: CMS)



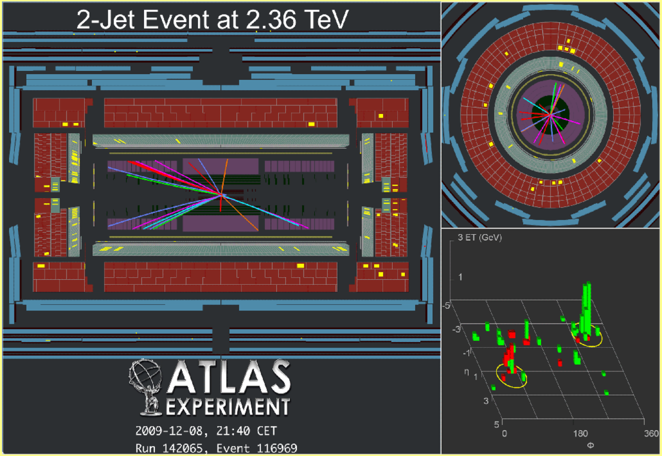
Startup (again) for LHC

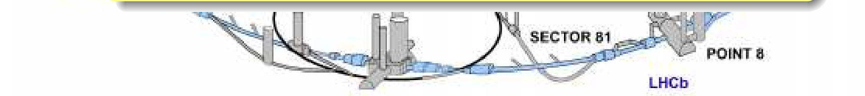
December: 10^6 collisions at $\sqrt{s} = 900$ GeV



Startup (again) for LHC

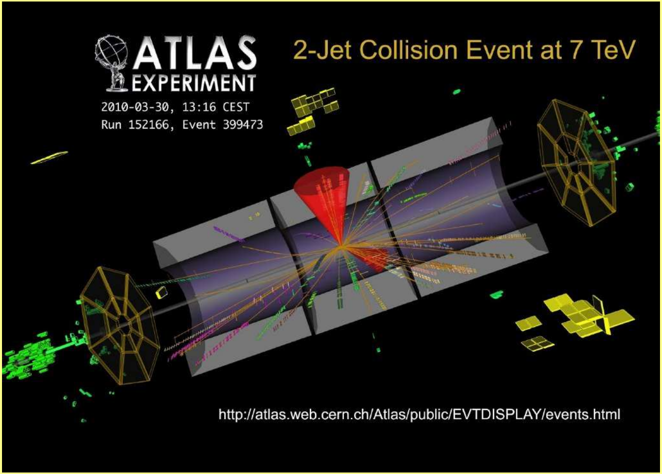
December: collisions at $\sqrt{s} = 2360$ GeV





Startup (again) for LHC

30 March 2010: collisions at $\sqrt{s} = 7000$ GeV



Compared to current biggest collider (Tevatron)

- LHC energy will be **7 times higher**
- Total number of collisions (over 6 years) **50 times higher** $(10^9/s)$

Aims are varied:

- *Higgs discovery* key element in design and funding decisions
- *Searches for new physics*
  - supersymmetry
  - extra dimensions
  - new resonances (e.g. Z')
  - etc. [or something as yet unpostulated]
- *Standard model physics*
  - High statistics top physics
  - etc.

Compared to current biggest collider (Tevatron)

- LHC energy will be **7 times higher**
- Total number of collisions (over 6 years) **50 times higher** ($10^9/s$)

Aims are varied:

- *Higgs discovery* key element in design and funding decisions
- *Searches for new physics*
  - supersymmetry
  - extra dimensions
  - new resonances (e.g. Z')
  - etc. [or something as yet unpostulated]
- *Standard model physics*
  - High statistics top physics
  - etc.

An often-repeated argument

LHC collides quarks and gluons

Quarks and gluons interact strongly → huge QCD backgrounds

Therefore we will need to rely on our understanding of QCD in order to make discoveries at LHC.

True, false, or only half the story?

An often-repeated argument

LHC collides quarks and gluons

Quarks and gluons interact strongly $\longrightarrow$ huge QCD backgrounds

Therefore we will need to rely on our understanding of QCD in order to make discoveries at LHC.

True, false, or only half the story?

Contrasting views (1)

It must be true, otherwise why would there be such a large effort devoted to LHC-QCD calculations?

- Parton shower Monte Carlo Generators — Pythia, Herwig, Sherpa
- LO tree-level calculations — Alpgen, Madgraph, Sherpa, ...
- NLO calculations — $\sim$ 50 people
- NNLO calculations — Higgs, W/Z, next step jets
- All-orders calculations — resummations, SCET
- Parton Distribution Functions (PDFs) — CTEQ, MSTW, NNPDF, ...

Order 100,000,000 $/£/CHF/€ spent over 10 years

The most pervasive role of QCD at LHC

Every paper that comes out from the ATLAS and CMS pp physics programmes will involve the use of one or more QCD-based parton-shower Monte Carlo event generators: Pythia, Herwig or Sherpa.

For simulating physics signals.

For simulating background signals.

For simulating pileup.

As input to simulating detector respone.

Pythia

ISUB	Subprocess name
11	f + f' -> f + f' (QCD)
12	f + fbar -> f' + fbar'
13	f + fbar -> g + g
28	f + g -> f + g
53	g + g -> f + fbar
68	g + g -> g + g
96	Semihard QCD 2 -> 2

e of QCD at LHC

nes out from the ATLAS and CMS pp physics olve the use of one or more QCD-based e Carlo event generators: Pythia, Herwig or Sherpa.

For simulating physics signals.

For simulating background signals.

For simulating pileup.

As input to simulating detector respone.

Pythia

ISUB Subprocess name

ISUB	Subprocess name
11	f +
12	f +
13	f +
28	f +
53	g +
68	g +
96	Sem

Event listing (standard)

I	particle/jet	K(I,1)		P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!		21	0.00000	0.00000	6999.99994	7000.00000	0.93827
2	!p+!		21	0.00000	0.00000	-6999.99994	7000.00000	0.93827
3	!u!		21	-0.20478	-1.99677	4200.93192	4200.93240	0.00000
4	!u!		21	-0.52164	-0.53530	-1227.35705	1227.35728	0.00000
5	!g!		21	69.88093	-38.60332	186.26860	202.65624	0.00000
6	!u!		21	-3.29805	0.22934	-594.30442	594.31361	0.00000
7	!g!		21	342.80888	-101.05545	-85.04352	367.37248	0.00000
8	!u!		21	-276.22601	62.68148	-322.99229	429.59738	0.33000
9	(u)	A	12	2.92305	6.37706	2.55209	7.47216	0.33000
10	(g)	I	12	-0.12086	-0.05387	0.23937	0.27351	0.00000
11	(g)	I	12	2.90849	0.44667	3.06707	4.25039	0.00000
12	(g)	I	12	0.44539	0.19658	1.08590	1.19004	0.00000
13	(g)	I	12	0.72977	2.84935	0.81600	3.05241	0.00000
14	(g)	I	12	0.12403	0.47094	-1.65408	1.72428	0.00000
15	(g)	I	12	0.63915	1.19608	-6.31736	6.46128	0.00000
16	(g)	I	12	1.26081	0.95080	-9.60839	9.73729	0.00000
17	(g)	I	12	1.39862	-0.87388	-14.36959	14.46392	0.00000
18	(g)	I	12	0.94209	-0.92748	-58.84151	58.85636	0.00000
19	(g)	I	12	2.85917	0.96504	-201.26331	201.28593	0.00000
20	(g)	I	12	-0.94209	0.92748	-163.96216	163.96749	0.00000
21	(g)	I	12	-2.90849	-0.44667	-423.55274	423.56296	0.00000
22	(g)	I	12	-0.03667	-0.02590	0.00503	0.04517	0.00000
23	...	....	....	....	....	....	....	....

Pythia

ISUB	Subprocess name
11	f +
12	f +
13	f +
28	f +
53	g +
68	g +
96	Sem

Event listing (standard)

I	particle/jet	K(I,1)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!p+!	21	0.00000	0.00000	6999.99994	7000.00000	0.93827
2	!p+!	21	0.00000	0.00000	-6999.99994	7000.00000	0.93827
3	!u!	21	-0.20478	-1.99677	4200.93192	4200.93240	0.00000
4	!u!	21	-0.52164	-0.53530	-1227.35705	1227.35728	0.00000
5	!g!	21	69.88093	-38.60332	186.26860	202.65624	0.00000
6	!u!	21	-3.29805	0.22934	-594.30442	594.31361	0.00000
7	!g!	21	342.80888	-101.05545	-85.04352	367.37248	0.00000
8	!u!	21	-276.22601	62.68148	-322.99229	429.59738	0.33000
165	(rho0)	11	9.26285	-1.51905	-1.63571	9.55696	0.74292
166	pi-	1	2.97622	-0.72739	-0.31237	3.08286	0.13957
167	pi+	1	2.90207	-0.46804	-0.08318	2.94405	0.13957
168	(omega)	11	6.33127	-0.15752	0.01513	6.38115	0.78042
169	(rho-)	11	1.27652	-1.77925	0.66381	2.39534	0.70836
170	(omega)	11	-0.38942	0.17068	1.21017	1.50136	0.78024
171	pi+	1	-0.09283	0.10773	0.32113	0.37793	0.13957
172	(rho-)	11	-0.24864	-0.18762	1.86992	2.14719	1.00837
173	(K*+)	11	-1.87908	0.80841	1.49858	2.68439	0.88076
174	(K*-)	11	-3.82206	2.20136	2.34838	5.07340	0.87770
175	(rho+)	11	-13.22858	5.42242	4.50921	15.02121	0.95161
176	(rho0)	11	-11.94640	5.71075	4.73622	14.07218	0.51488
177	(eta)	11	-10.84249	4.63993	3.47786	12.30788	0.54745
178	(rho0)	11	-11.59191	4.94873	5.09943	13.62590	0.89360
179	(rho0)	11	-3.47439	1.79711	1.42757	4.24437	0.82201
180	(rho-)	11	-1.09464	0.50862	0.33785	1.41536	0.65739
181	(omega)	11	-3.07966	1.34675	0.70043	3.52173	0.78355
182	(rho+)	11	-3.57280	0.49038	1.66254	4.07286	0.90486

Contrasting views (2)

Words of caution

> *[...] unless each of the background components can be separately tested and validated, it will not be possible to draw conclusions from the mere comparison of data against the theory predictions.*
>
> *I am not saying this because I do not believe in the goodness of our predictions. But because claiming that supersymmetry exists is far too important a conclusion to make it follow from the straight comparison against a Monte Carlo.*

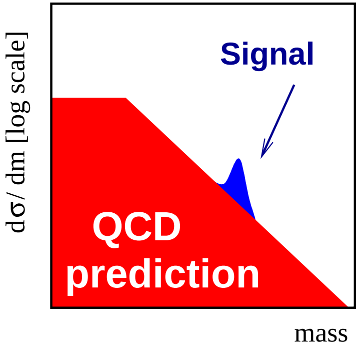
Mangano, 0809.1567

This talk

Try to examine the question of how much QCD matters, how much it can help with searches.

What kinds of searches?

mass peak



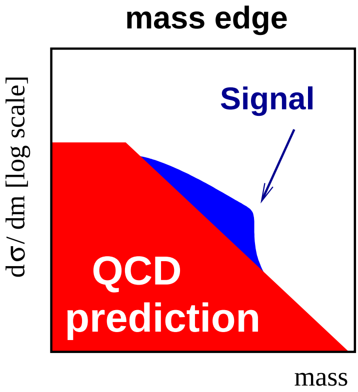
New resonance (e.g. Z') where you see all decay products and reconstruct an invariant mass

QCD may:

- swamp signal
- smear signal

leptonic case easy; hadronic case harder

What kinds of searches?



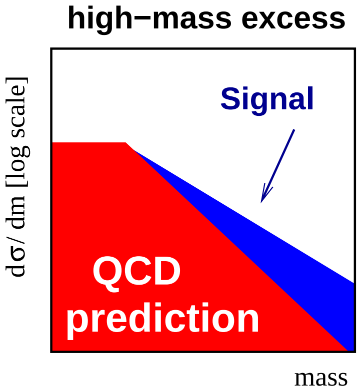
New resonance (e.g. R-parity conserving SUSY), where undetected new stable particle escapes detection.

Reconstruct only *part* of an invariant mass $\rightarrow$ kinematic edge.

QCD may:

- swamp signal
- smear signal

What kinds of searches?

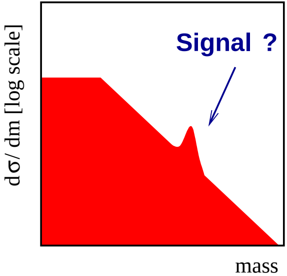


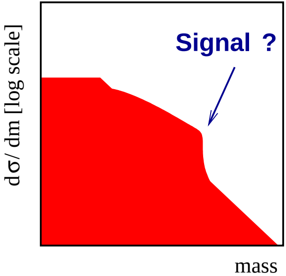
Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).

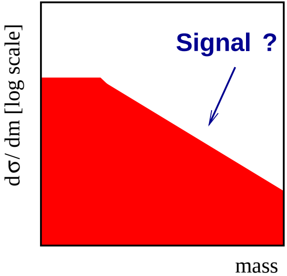
Broad excess at high mass scales.

Knowledge of backgrounds is crucial is declaring discovery.

QCD is *one way* of getting handle on background.

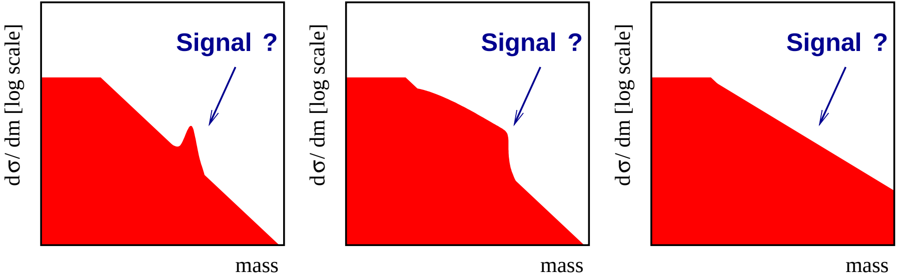






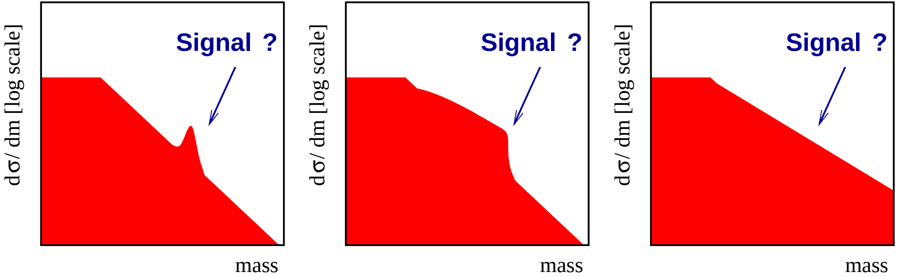
CONTINUE HERE

START HERE



CONTINUE
HERE

**START
HERE**



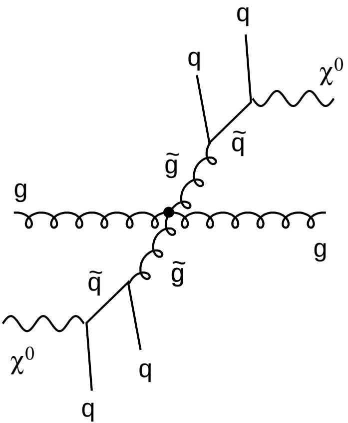
CONTINUE HERE

START HERE

Predicting QCD

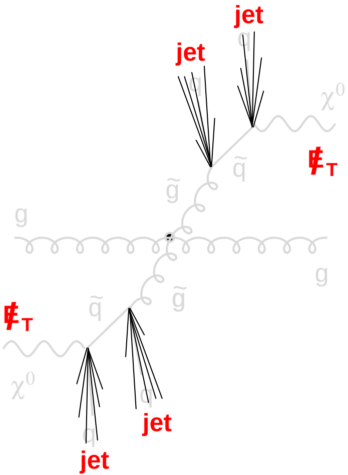
SUSY example: gluino pair production

Signal



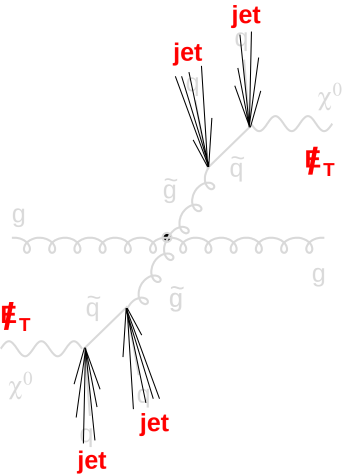
SUSY example: gluino pair production

Signal

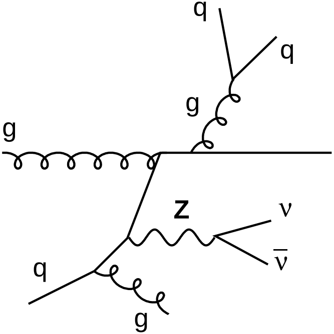


SUSY example: gluino pair production

Signal

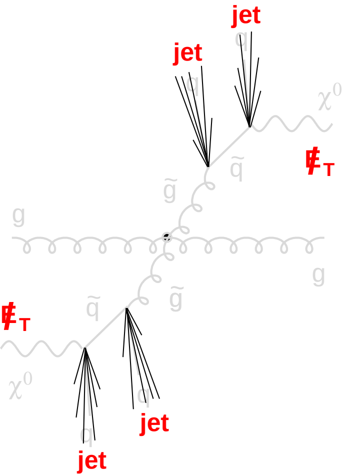


Background

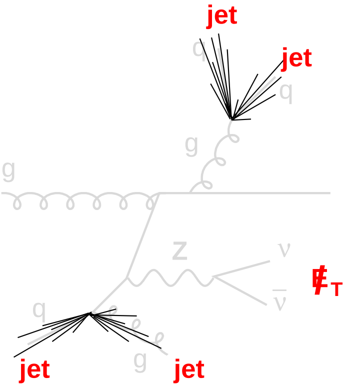


SUSY example: gluino pair production

Signal



Background

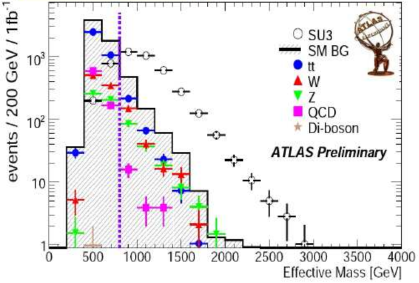


SUSY searches: what excesses?

Atlas selection [all hadronic]

- no lepton
- MET > 100 GeV
- $1^{st}, 2^{nd}$ jet > 100 GeV
- $3^{rd}, 4^{th}$ jet > 50 GeV
- MET / m_{eff} > 20%

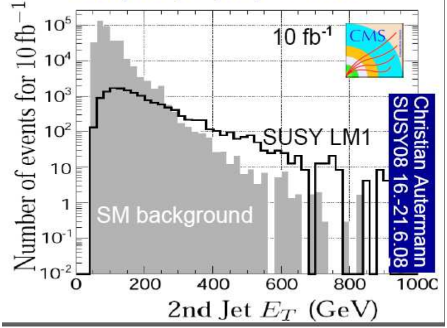
Christian Autermann
SUSY08 16.-21.6.08
4



CMS selection [leptonic incl.]

(optimized for 10fb^{-1}, using genetic algorithm)

- 1 muon pT > 30 GeV
- MET > 130 GeV
- 1^{st}, 2^{nd} jet > 440 GeV
- 3^{rd} jet > 50 GeV
- $-0.95 < \cos(\text{MET}, 1^{st}\text{jet}) < 0.3$
- $\cos(\text{MET}, 2^{nd}\text{jet}) < 0.85$

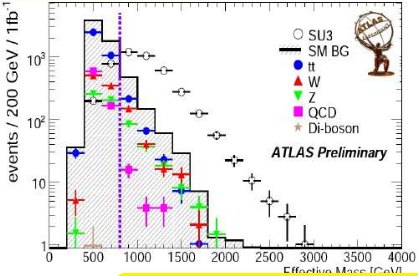


SUSY searches: what excesses?

Atlas selection [all hadronic]

- no lepton
- MET > 100 GeV
- $1^{st}, 2^{nd}$ jet > 100 GeV
- $3^{rd}, 4^{th}$ jet > 50 GeV
- MET / m_{eff} > 20%

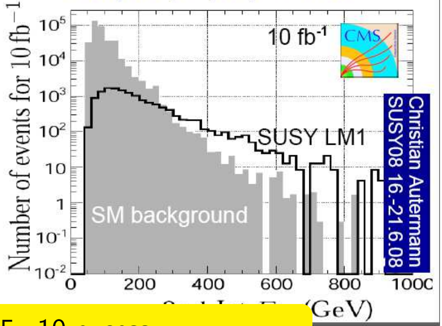
Christian Autermann
SUSY08 16.-21.6.08
4



CMS selection [leptonic incl.]

(optimized for 10fb^{-1}, using genetic algorithm)

- 1 muon pT > 30 GeV
- MET > 130 GeV
- 1^{st}, 2^{nd} jet > 440 GeV
- 3^{rd} jet > 50 GeV
- −0.95 < cos(MET,1^{st}jet)<0.3
- cos(MET,2^{nd}jet) < 0.85



SUSY ≃ factor 5−10 excess

How accurate is perturbative QCD?

$$\sigma = c_0 + c_1\alpha_s + c_2\alpha_s^2 + \ldots$$

$$\alpha_s \simeq 0.1$$

That implies LO QCD (just c_0) should be accurate to within 10%

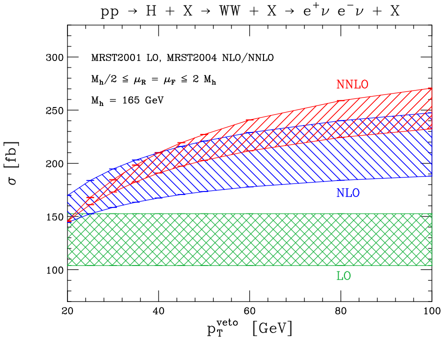
It isn't

Rules of thumb:

LO good to within factor of 2

NLO good to within scale uncertainty

How accurate is perturbative QCD?



Anastasiou, Melnikov & Petriello '04
Anastasiou, Dissertori & Stöckli '07

$$\sigma = c_0 + c_1\alpha_s + c_2\alpha_s^2 + \ldots$$

$$\alpha_s \simeq 0.1$$

That implies LO QCD (just c_0) should be accurate to within 10%

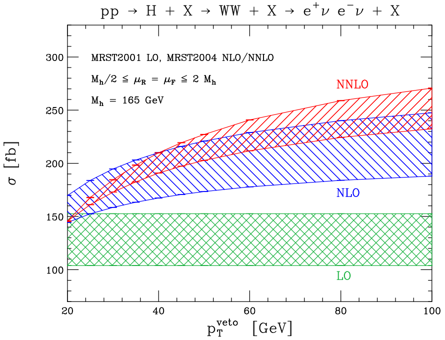
It isn't

Rules of thumb:

LO good to within factor of 2

NLO good to within scale uncertainty

How accurate is perturbative QCD?



Anastasiou, Melnikov & Petriello '04
Anastasiou, Dissertori & Stöckli '07

$$\sigma = c_0 + c_1\alpha_s + c_2\alpha_s^2 + \ldots$$

$$\alpha_s \simeq 0.1$$

That implies LO QCD (just c_0) should be accurate to within 10%

It isn't

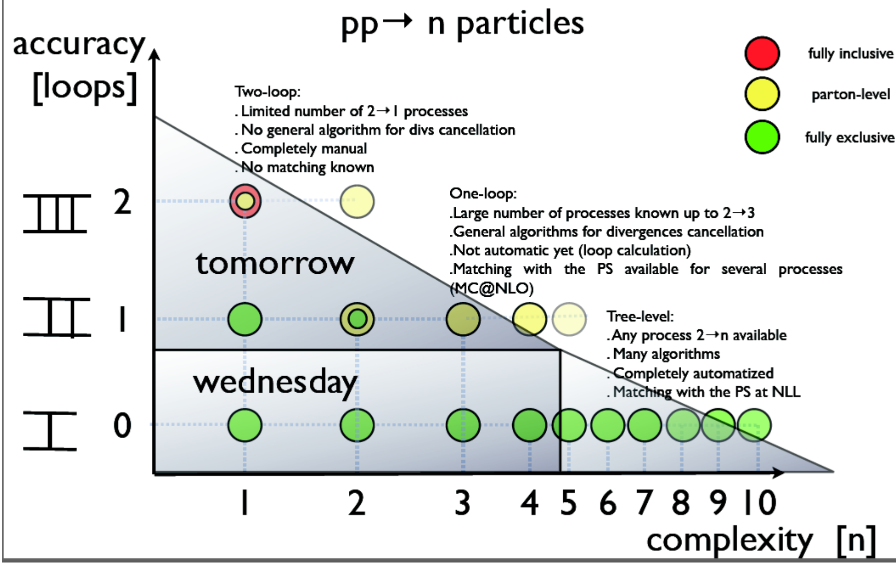
<u>Rules of thumb:</u>

LO good to within factor of 2

NLO good to within scale uncertainty

Theory status

from lectures
by F. Maltoni '07



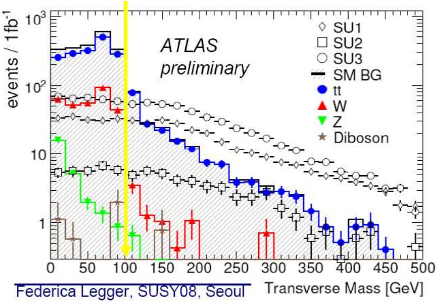
Control samples

We don't have NLO for the background (e.g. 4 jets + Z, a $2 \to 5$ process).

Only LO (matched with parton showers). How does one verify it?

Common procedure (roughly):

- Get control sample at low p_t
- SUSY should be small(er) contamination there
- Once validated, trust LO prediction at high-p_t



Is this safe?

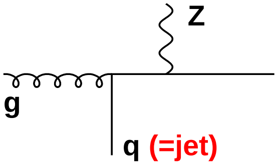
A conservative QCD theory point of view:

It's hard to be sure: since we can't calculate Z+4 jets beyond LO.

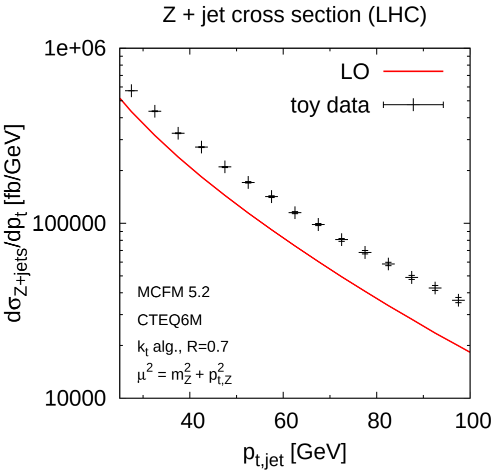
But we would tend to think it is safe, as long as control data are within usual factor of two of LO prediction

Illustrate issues with toy example: Z+jet production

- It's known to NLO — and a candidate for "first" $2 \to 2$ NNLO
  $\sim e^+e^- \to \gamma^*/Z \to 3$ jets, NNLO: Gehrman et al '08, Weinzierl '08
- But let's pretend we only know it to LO, and look at the p_t distribution of the hardest jet (no other cuts — keep it simple)



Toy data, control sample



stage 1: get control sample

Check LO v. data at low p_t

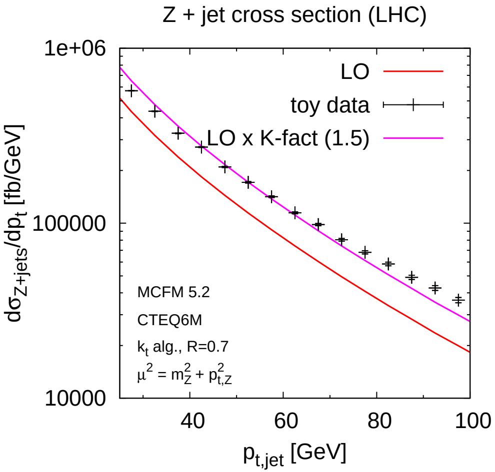
- normalisation off by factor 1.5 (consistent with expectations)

  So renormalise LO by K-fact

- shape OKish

  Don't be too fussy: SUSY could bias higher p_t

Toy data, control sample



stage 1: get control sample

Check LO v. data at low p_t

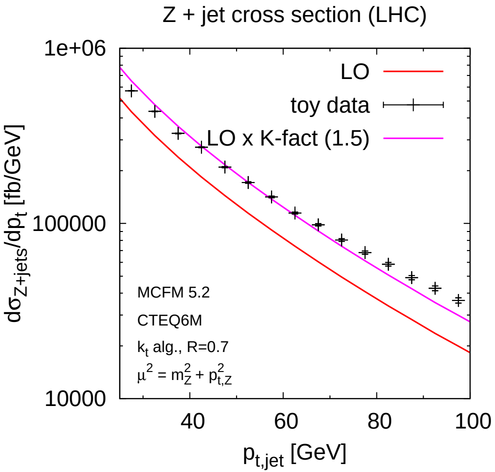
- normalisation off by factor 1.5 (consistent with expectations)

  So renormalise LO by K-fact

- shape OKish

  Don't be too fussy: SUSY could bias higher p_t

Toy data, control sample



stage 1: get control sample

Check LO v. data at low p_t

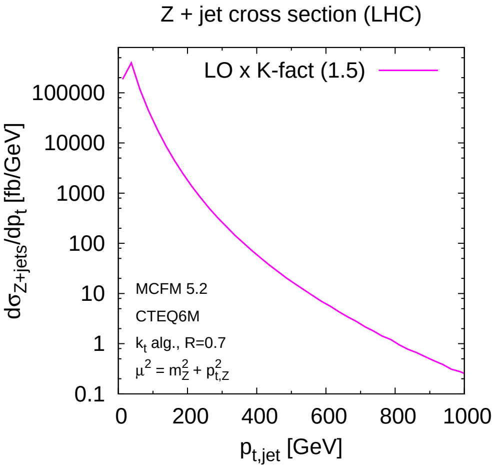
- normalisation off by factor 1.5 (consistent with expectations)

  So renormalise LO by K-fact

- shape OKish

  Don't be too fussy: SUSY could bias higher p_t

Toy data, high p_t



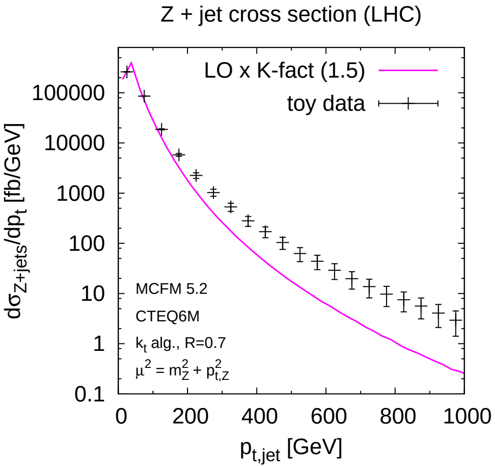
stage 2: look at high p_t

- good agreement at low p_t, by construction
- excess of factor $\sim$ 10 at high p_t
- check scale dependence of LO

  [NB: not always done except e.g. Alwall et al. 0706.2569]

  still big excess

Toy data, high p_t



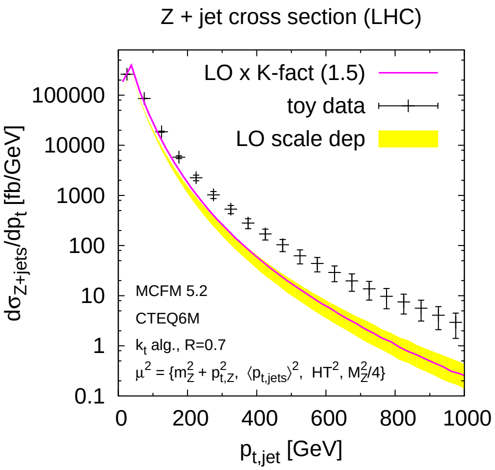
stage 2: look at high p_t

- good agreement at low p_t, by construction
- excess of factor ~ 10 at high p_t
- check scale dependence of LO

[NB: not always done except e.g. Alwall et al. 0706.2569]

still big excess

Toy data, high p_t



stage 2: look at high p_t

- good agreement at low p_t, by construction
- excess of factor ~ 10 at high p_t
- check scale dependence of LO

[NB: not always done except e.g. Alwall et al. 0706.2569]

still big excess

What's in the toy data?

Is it:

- QCD + extra signal?
- just QCD? But then where does a K-factor of 10 come from?

Here it's just a toy illustration. In a year or two it may be for real:

- Do Nature / Science / PRL accept the paper?

  Discovery of New Physics at the TeV scale

  We report a 5.7σ excess in MET + jets production that is consistent with a signal of new physics ...

- Do we proceed immediately with a linear collider?

  It'll take 10–15 years to build; the sooner we start the better

- At what energy? It would be a shame to be locked in to the wrong energy...

What's in the toy data?

Is it:

- QCD + extra signal?
- just QCD? But then where does a K-factor of 10 come from?

Here it's just a toy illustration. In a year or two it may be for real:

- Do Nature / Science / PRL accept the paper?

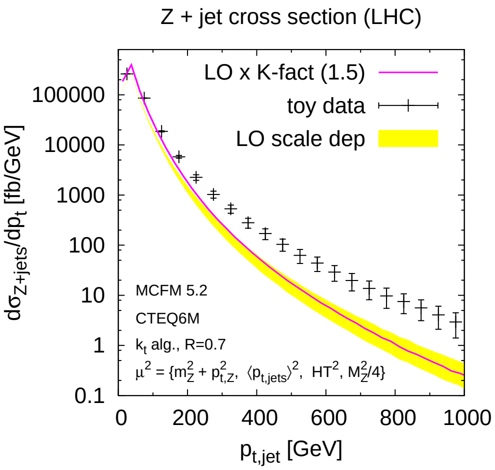
  Discovery of New Physics at the TeV scale
  We report a 5.7σ *excess in MET + jets production that is consistent with a signal of new physics . . .*

- Do we proceed immediately with a linear collider?

  It'll take 10–15 years to build; the sooner we start the better

- At what energy? It would be a shame to be locked in to the wrong energy. . .

Open the box...



Unlike for SUSY multi-jet searches, in the Z+jet case we do have NLO.

Once NLO is included the excess disappears

The "toy data" were just the upper edge of the NLO band

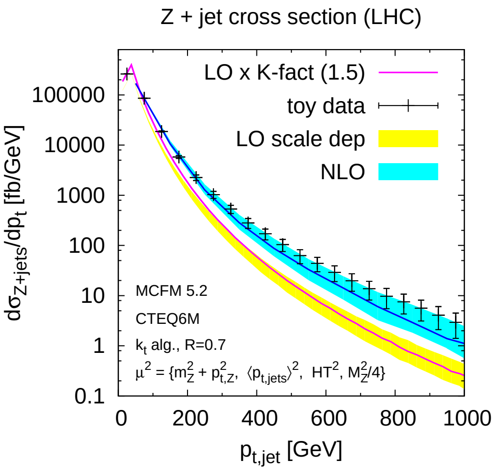
Example based on background work for Butterworth, Davison, Rubin & GPS '08

Related observations also by Bauer & Lange '09; Denner, Dittmaier, Kasprzik & Muck '09

Hold on a second: how does QCD give a K-factor $\mathcal{O}(5-10)$?

NB: DYRAD, MCFM consistent

Open the box. . .



Unlike for SUSY multi-jet searches, in the Z+jet case we do have NLO.

Once NLO is included the excess disappears

The "toy data" were just the upper edge of the NLO band

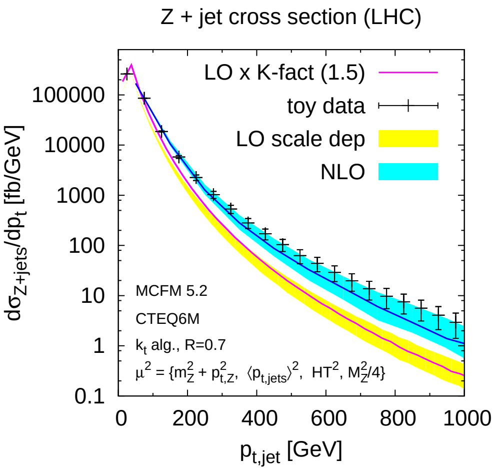
Example based on background work for Butterworth, Davison, Rubin & GPS '08

Related observations also by Bauer & Lange '09; Denner, Dittmaier, Kasprzik & Muck '09

Hold on a second: how does QCD give a K-factor $\mathcal{O}(5-10)$?

NB: DYRAD, MCFM consistent

Open the box. . .



Unlike for SUSY multi-jet searches, in the Z+jet case we do have NLO.

Once NLO is included the excess disappears

The "toy data" were just the upper edge of the NLO band

Example based on background work for Butterworth, Davison, Rubin & GPS '08

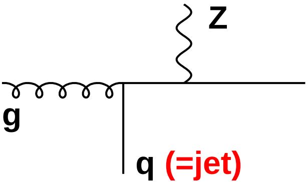
Related observations also by Bauer & Lange '09; Denner, Dittmaier, Kasprzik & Muck '09

Hold on a second: how does QCD give a K-factor $\mathcal{O}(5-10)$?

NB: DYRAD, MCFM consistent

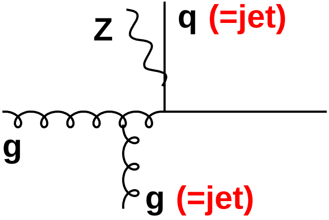
Why the large K-factor?

Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order

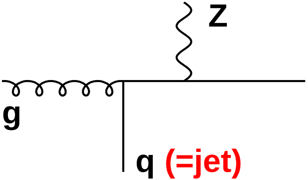


$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

LHC will probe scales well above EW scale, $\sqrt{s} \gg M_Z$.
QCD and EW effects **mix**, EW bosons are **light**.
New logarithms (enhancements) appear.

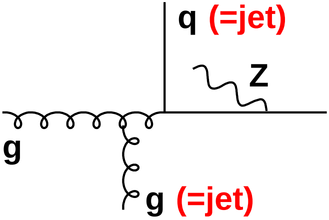
Why the large K-factor?

Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order

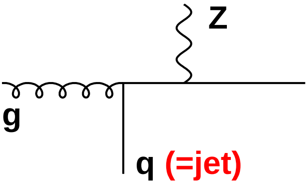


$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

LHC will probe scales well above EW scale, $\sqrt{s} \gg M_Z$.
QCD and EW effects **mix**, EW bosons are **light**.
New logarithms (enhancements) appear.

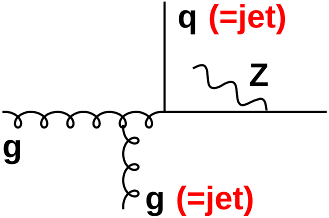
Why the large K-factor?

Leading Order



$\alpha_s \alpha_{EW}$

Next-to-Leading Order



$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$

LHC will probe scales well above EW scale, $\sqrt{s} \gg M_Z$.
QCD and EW effects **mix**, EW bosons are **light**.
New logarithms (enhancements) appear.

Where does this leave us?

Excess ≡ New Physics, **iff** you are really, really sure you understand backgrounds

- Control samples may not be good enough cross-check
- Plain LO QCD can be misleading, understanding the physics is crucial

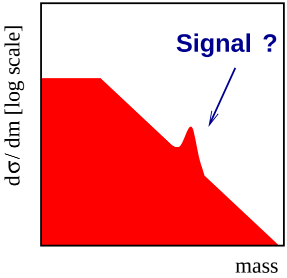
  Can be non-trivial even in simplest of cases
- NLO provides a powerful cross check — and progress is being made in multi-jet case, e.g. $W + 3$jet & $t\bar{t}b\bar{b}$ calculations @ NLO

  BlackHat '08-; Rocket '08-; CutTools '08-; Bredenstein et al '09
- What about MLM, CKKW matching for combining different tree-level contributions? "LO++": gets much of the answer [de Visscher & Maltoni]

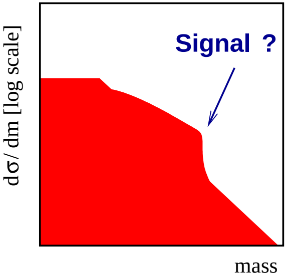
  First systematic comparisons with NLO: Melnikov & Zanderighi '09

Viewing QCD

Consider case of *mass peaks* — but bear in mind that other kinematic structures are fundamentally related.

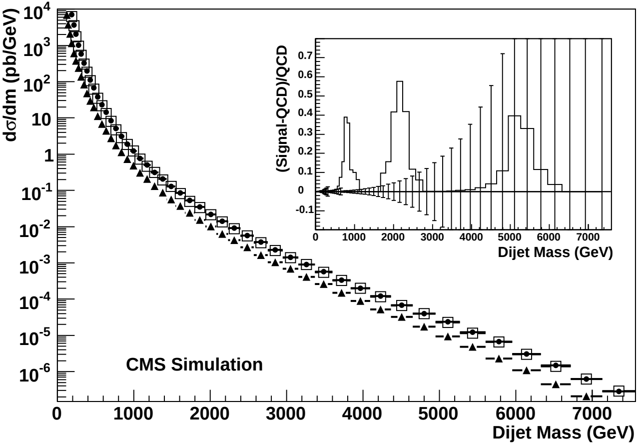


$$\sim \frac{d}{dm}$$



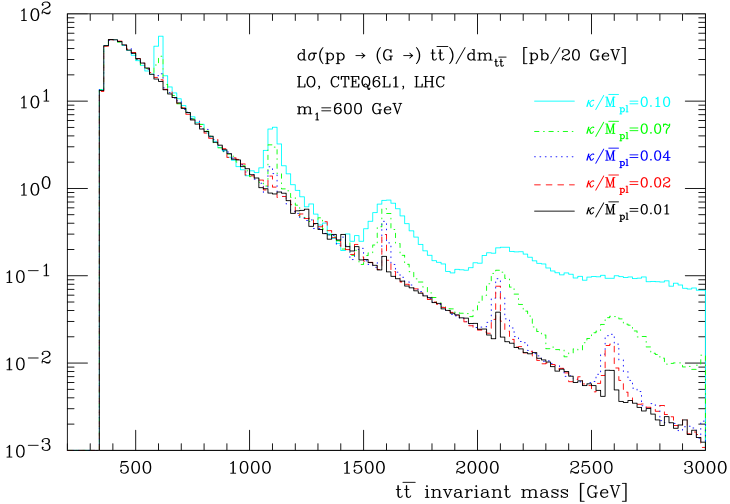
Some peaks are easy — QCD not needed

e.g. resonance $\to \ell^+\ell^-$, or big broad resonance to jets



Bhatti et al (for CMS), study of dijet mass resonances (q^*), 0807.4961

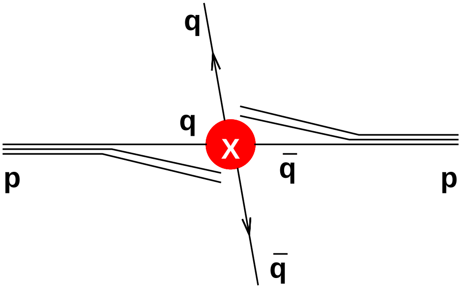
Observability may depend on parameters



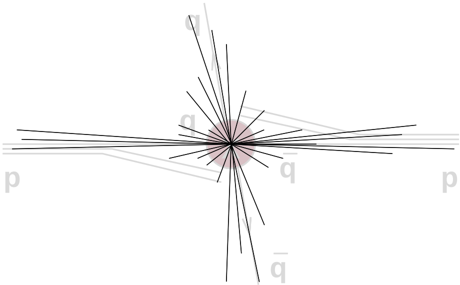
RS KK resonances, from Frederix & Maltoni, 0712.2355

Cases where QCD has the most to contribute are those that are borderline

Basic question:
Can we make kinematic "structures" emerge more clearly?



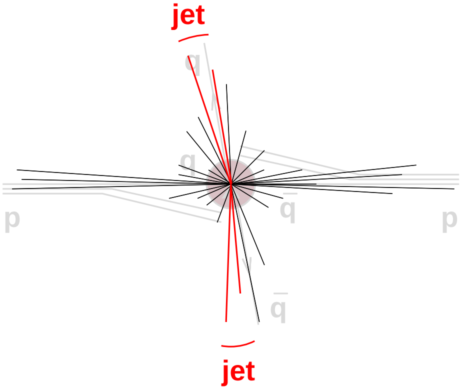
Basic question:
Can we make kinematic "structures" emerge more clearly?



Which particles should one choose in order to best reconstruct the resonance?

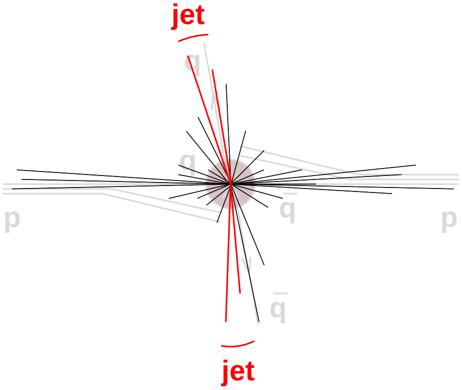
Basic question:

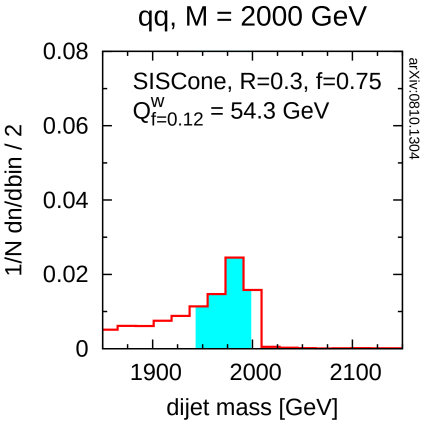
Can we make kinematic "structures" emerge more clearly?



How should one define the "jets"?

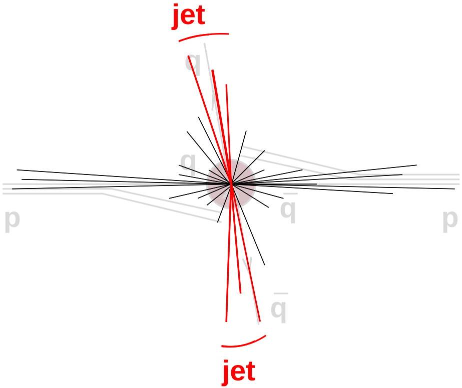
Basic question:
Can we make kinematic "structures" emerge more clearly?

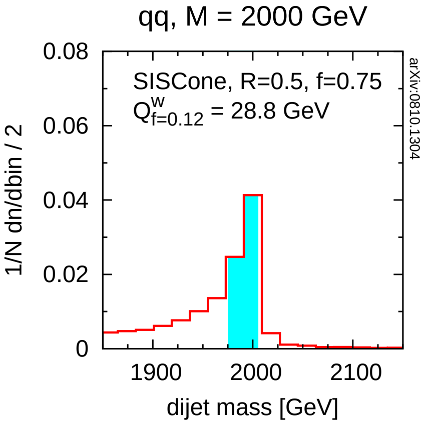




from Cacciari, Rojo, GPS & Soyez '08

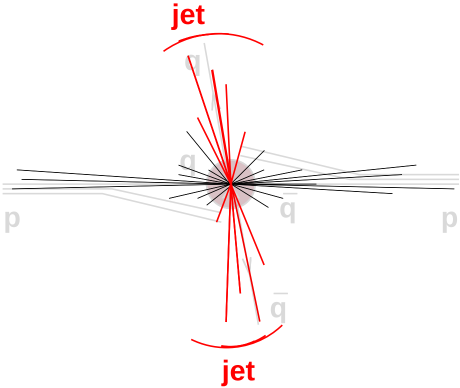
Basic question:
Can we make kinematic “structures” emerge more clearly?

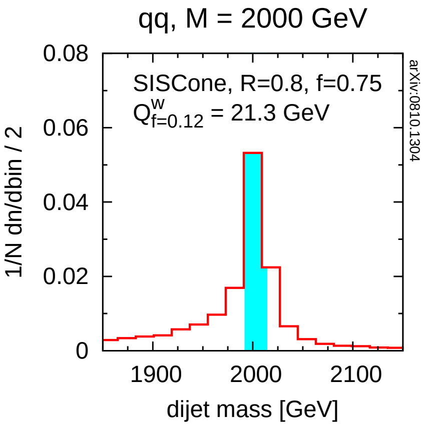




from Cacciari, Rojo, GPS & Soyez ’08

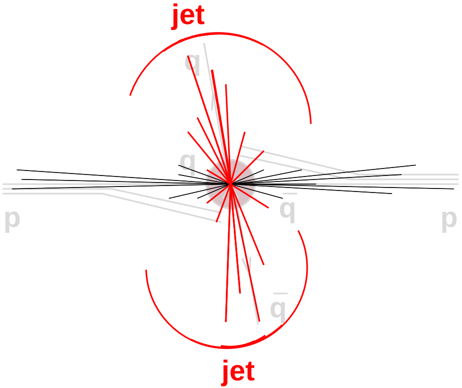
Basic question:
Can we make kinematic "structures" emerge more clearly?

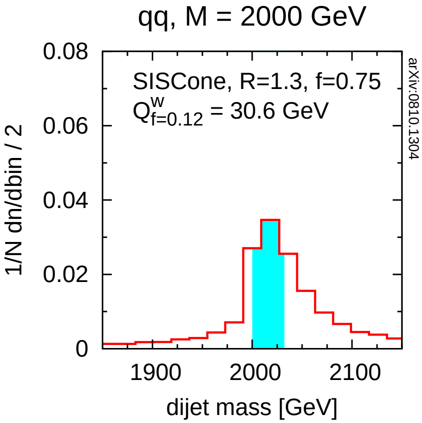




from Cacciari, Rojo, GPS & Soyez '08

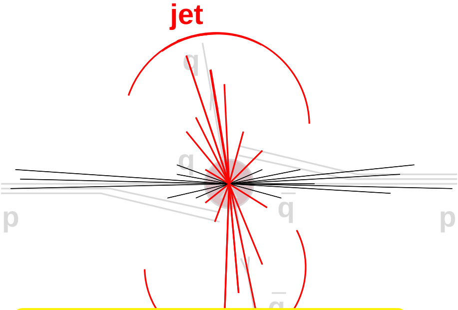
Basic question:
Can we make kinematic "structures" emerge more clearly?



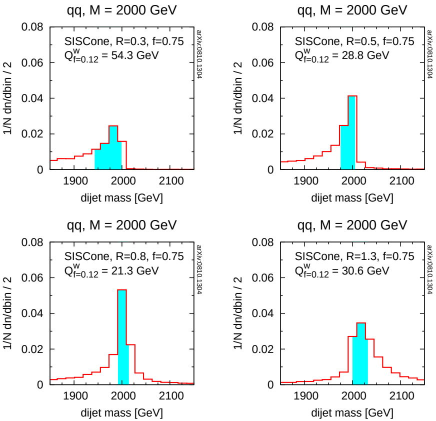


from Cacciari, Rojo, GPS & Soyez '08

Basic question:
Can we make kinematic "structures" emerge more clearly?



Choice of jet-definition has significant impact



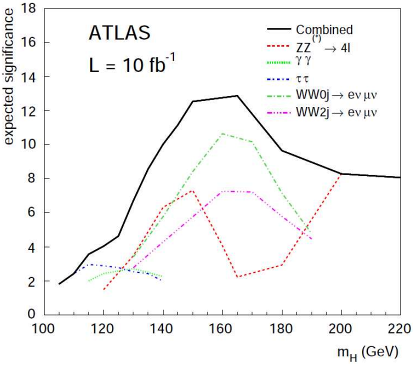
from Cacciari, Rojo, GPS & Soyez '08

As example, a Higgs-boson search illustrates two things:

- Using LHC scale hierarchy $\sqrt{s} \gg M_{EW}$ to our advantage
- Using QCD to help us extract cleaner signals

taken from Butterworth, Davison, Rubin & GPS '08

LHC search propspects



Low-mass Higgs search (**$115 \lesssim m_h \lesssim 130$ GeV**) complex because dominant decay channel, $H \to bb$, often swamped by backgrounds.

Various production & decay processes

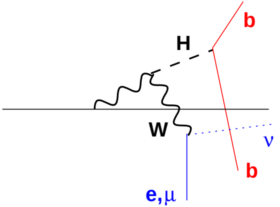
- $gg \to H \to \gamma\gamma$ — feasible
- $WW \to H \to \tau\tau$ — feasible
- $gg \to H \to ZZ^* \to 4\ell$ — feasible
- $gg \to t\bar{t}H, H \to b\bar{b}$ — v. hard
- $q\bar{q} \to WH, ZH, H \to b\bar{b}$ — v. hard

WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$. Studied e.g. in ATLAS TDR
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...

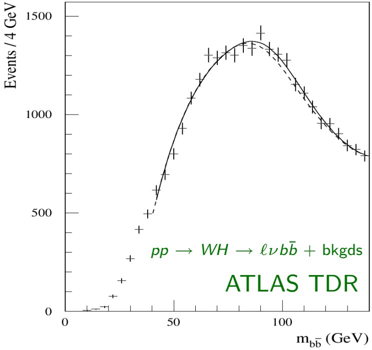
Difficulties, e.g.

- Poor acceptance ($\sim 12\%$)
  Easily lose 1 of 4 decay products
- p_t cuts introduce intrinsic bkgd mass scale;
- $gg \to t\bar{t} \to \ell\nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape



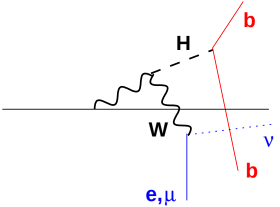
WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$. Studied e.g. in ATLAS TDR
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...



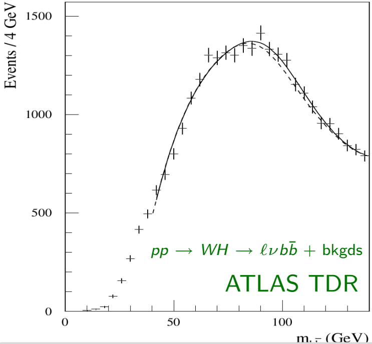
Difficulties, e.g.

- Poor acceptance ($\sim 12\%$)
  Easily lose 1 of 4 decay products
- p_t cuts introduce intrinsic bkgd mass scale;
- $gg \to t\bar{t} \to \ell\nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape



WH/ZH search channel @ LHC

- Signal is $W \to \ell\nu$, $H \to b\bar{b}$. Studied e.g. in ATLAS TDR
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell\nu b\bar{b}jj$, ...

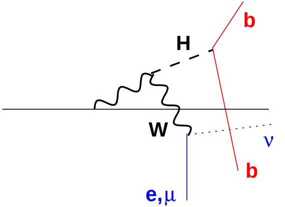


Difficulties, e.g.

- Poor acceptance ($\sim 12\%$)
  Easily lose 1 of 4 decay products
- p_t cuts introduce intrinsic bkgd mass scale;
- $gg \to t\bar{t} \to \ell\nu b\bar{b}[jj]$ has similar scale
- small S/B
- Need exquisite control of bkgd shape

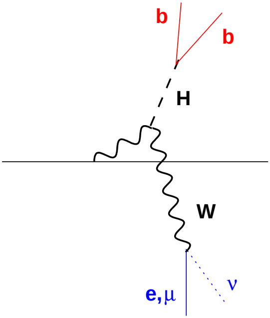
Conclusion (ATLAS TDR):

"The extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions [...]"



Study subset of WH/ZH with high p_t

Take advantage of the fact that $\sqrt{s} \gg M_H, m_t, \ldots$



Go to high p_t:

✓ Higgs and W/Z more likely to be central

✓ high-p_t $Z \to \nu\bar{\nu}$ becomes visible

✓ Fairly collimated decays: high-p_t $\ell^{\pm}, \nu, b$

Good detector acceptance

✓ Backgrounds lose cut-induced scale

✓ $t\bar{t}$ kinematics cannot simulate bkgd

Gain clarity and S/B

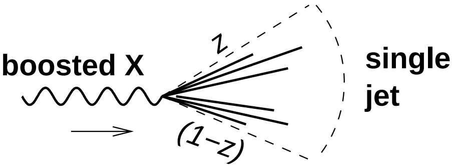
✗ Cross section will drop dramatically

By a factor of 20 for $p_{tH} > 200$ GeV

Will the benefits outweigh this?

Boosted EW bosons

Hadronically decaying Higgs boson at high p_t = single massive jet?



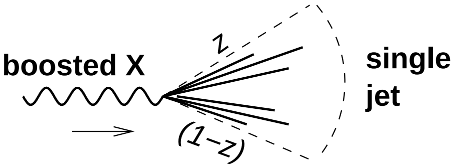
$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

discussion of this & related problems: Seymour '93; Butterworth, Cox & Forshaw '02; Butterworth, Ellis & Raklev '07; Skiba & Tucker-Smith '07; Holdom '07; Baur '07; Agashe et al. '07; Lillie, Randall & Wang '07; Contino & Servant '08; Brooijmans '08; Thaler & Wang '08; Kaplan et al '08; Almeida et al '08; [. . .]

What does QCD tell us about how to deal with this?

Boosted EW bosons

Hadronically decaying Higgs boson at high $\mathbf{p_t}$ = single massive jet?



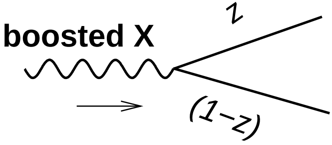
$$R \gtrsim \frac{m}{p_t}\frac{1}{\sqrt{z(1-z)}}$$

discussion of this & related problems: Seymour '93; Butterworth, Cox & Forshaw '02; Butterworth, Ellis & Raklev '07; Skiba & Tucker-Smith '07; Holdom '07; Baur '07; Agashe et al. '07; Lillie, Randall & Wang '07; Contino & Servant '08; Brooijmans '08; Thaler & Wang '08; Kaplan et al '08; Almeida et al '08; [. . .]

What does QCD tell us about how to deal with this?

QCD principle: soft divergence

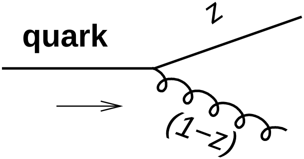
Signal



Splitting probability for Higgs:

$$P(z) \propto 1$$

Background



Splitting probability for quark:

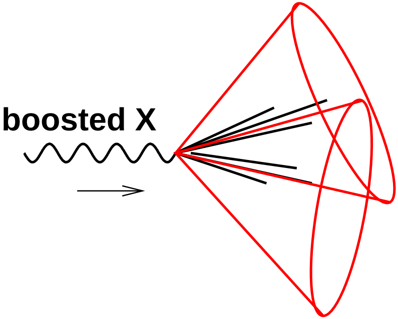
$$P(z) \propto \frac{1 + z^2}{1 - z}$$

$1/(1-z)$ divergence enhances background

Remove divergence in bkdg with cut on z
Can choose cut analytically so as to maximise $S/\sqrt{B}$

Originally: ad-hoc cut on (related) k_t-distance
Seymour '93; Butterworth, Cox & Forshaw '02

QCD principle: angular ordering



Given a color-singlet $q\bar{q}$ pair of opening angle R_{bb}:

Nearly all the radiation from the pair is contained in two cones of opening angle R_{bb}, one centred on each quark.

Standard result also in QED

Use this to capture just the radiation from the $q\bar{q} \Rightarrow$ good mass resol^n

#1: Our tool

The Cambridge/Aachen jet alg.

Dokshitzer et al '97
Wengler & Wobisch '98

Work out $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$ between all pairs of objects i, j;
Recombine the closest pair;
Repeat until all objects separated by $\Delta R_{ij} > R$.

Provides a "hierarchical" view of the event;
work through it backwards to analyse a jet

Implemented in FastJet
Cacciari, GPS & Soyez, '05-08, `http://fastjet.fr/`

All MC done with Herwig 6.510 and Jimmy 4.31

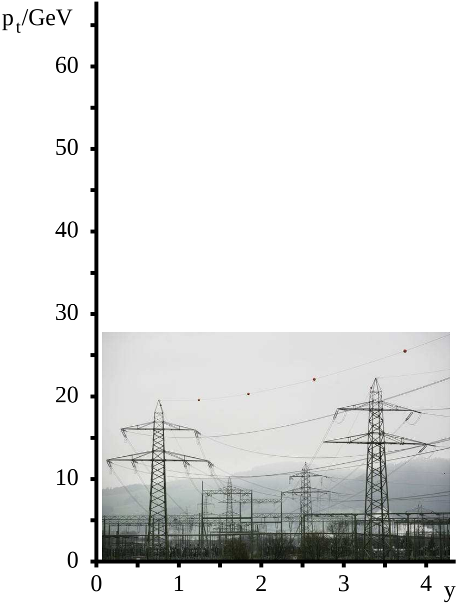
Cambridge/Aachen at work

Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

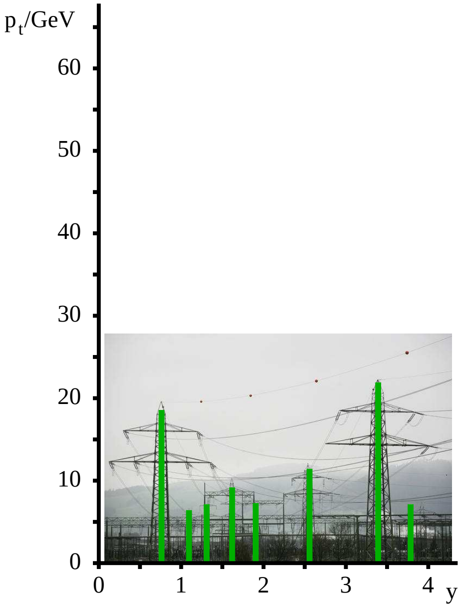


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

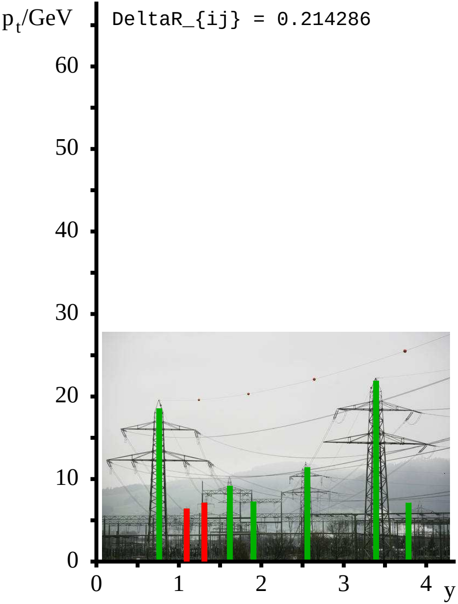


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

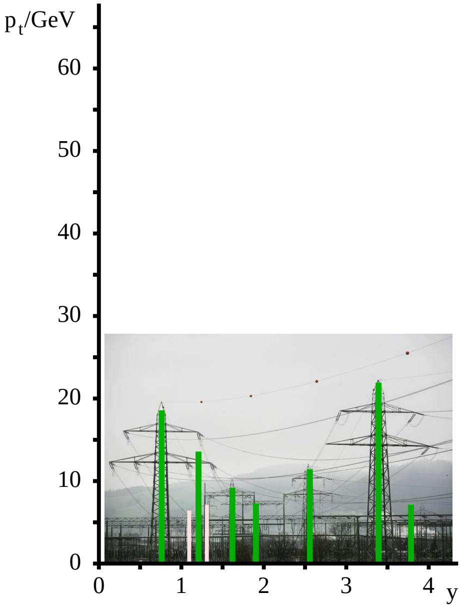


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

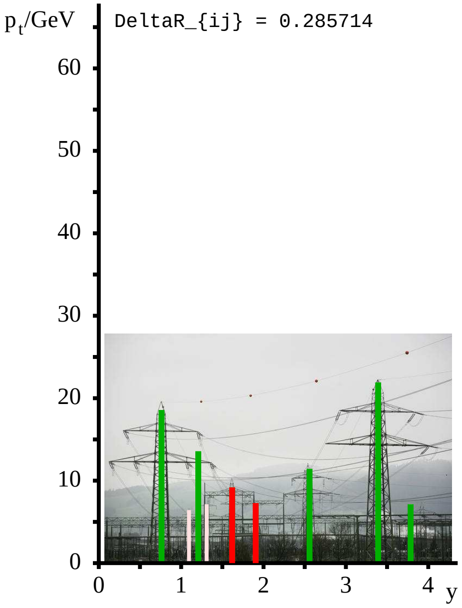


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

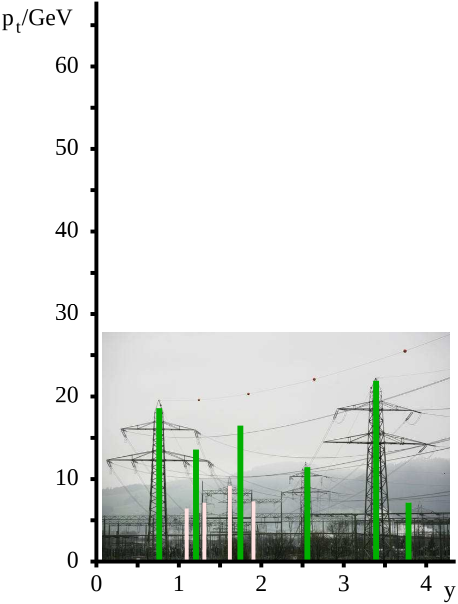


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

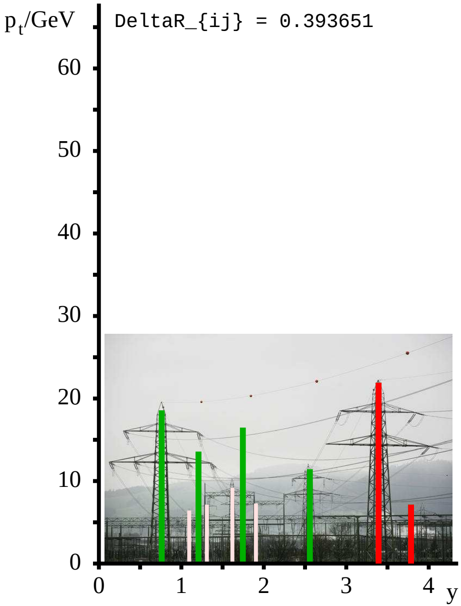


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

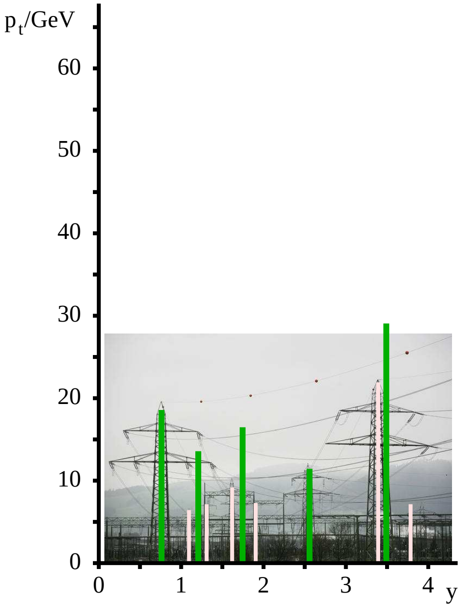


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

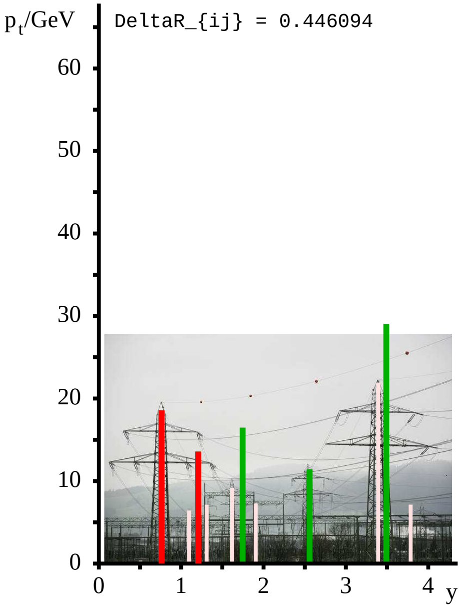


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

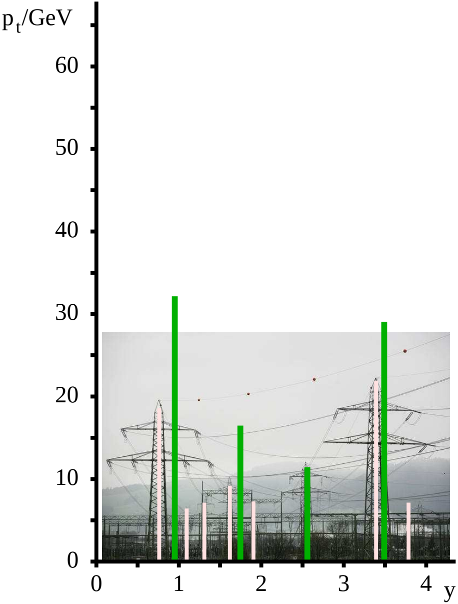


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

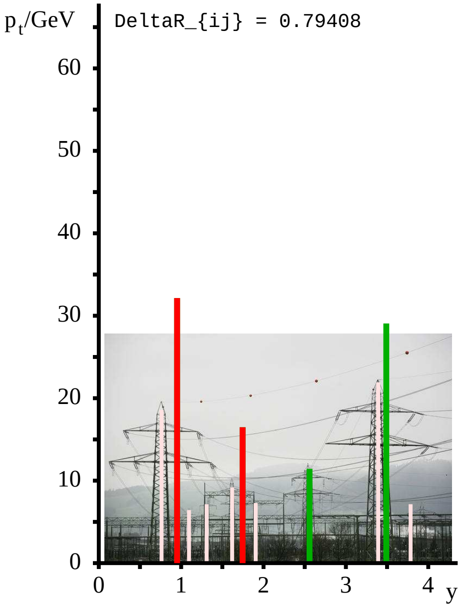


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

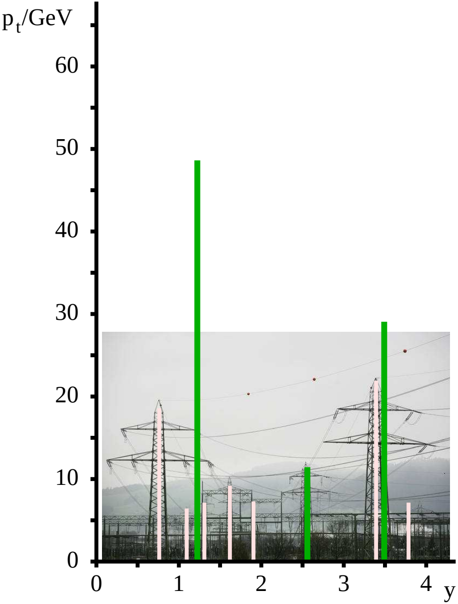


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

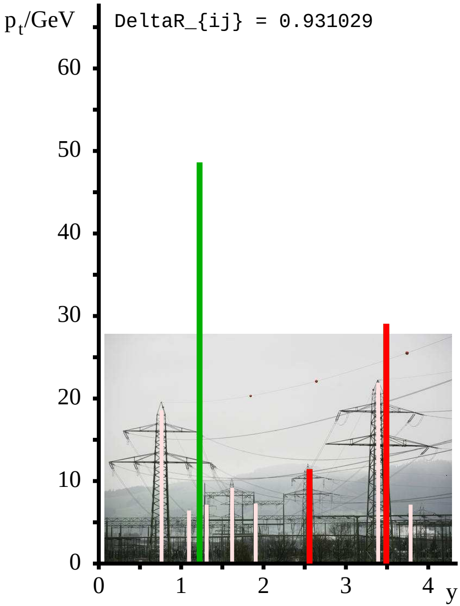


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

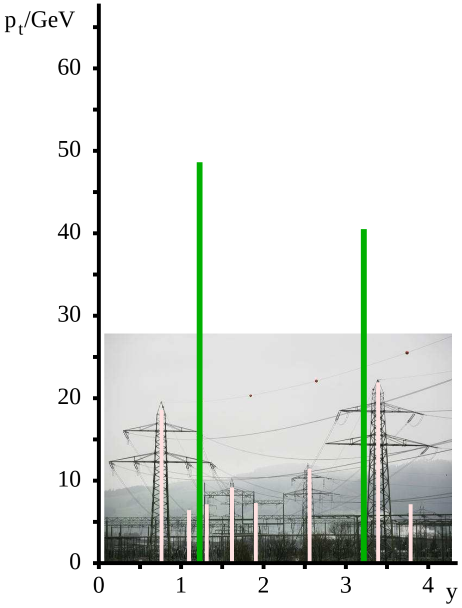


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

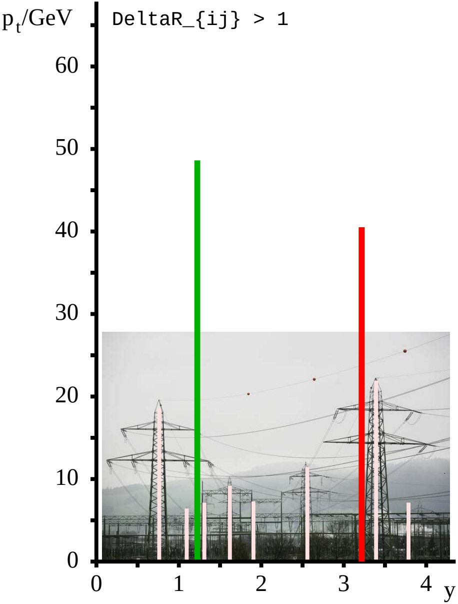


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

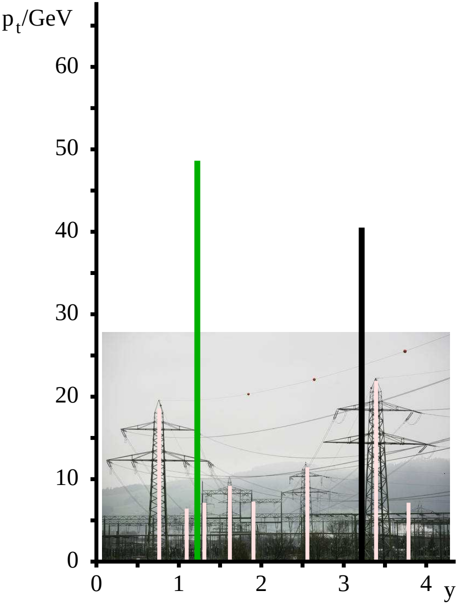


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

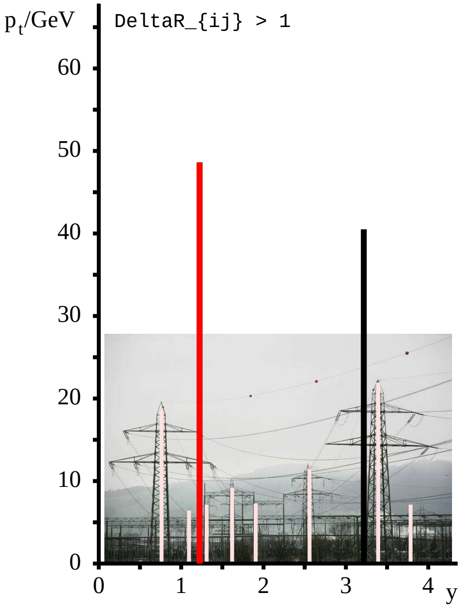


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work

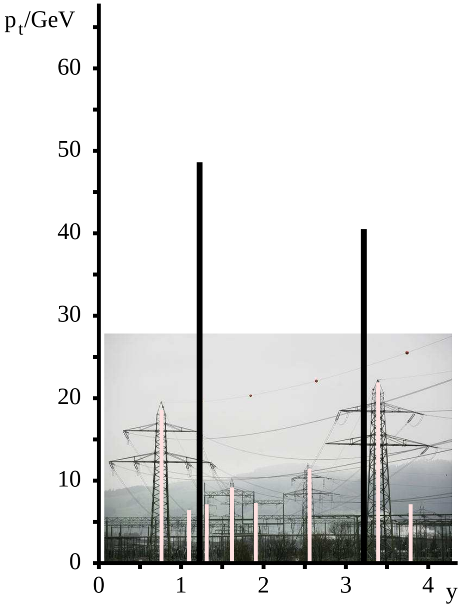


Example clustering with C/A algorithm, $R = 1.0$

Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

Cambridge/Aachen at work



Example clustering with C/A algorithm, $R = 1.0$

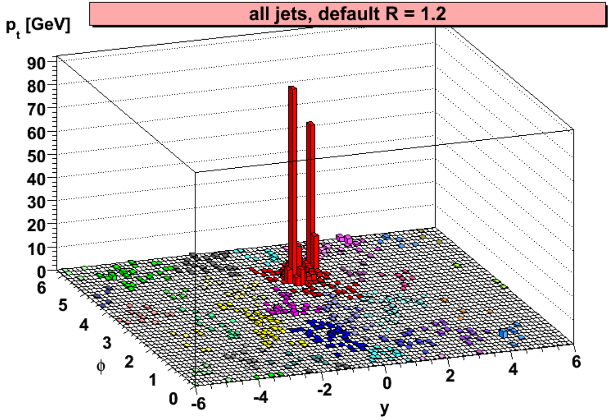
Repeatedly recombine closest pair of objects, until all separated by $\Delta R_{ij} > R$.

ϕ assumed 0 for all towers

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

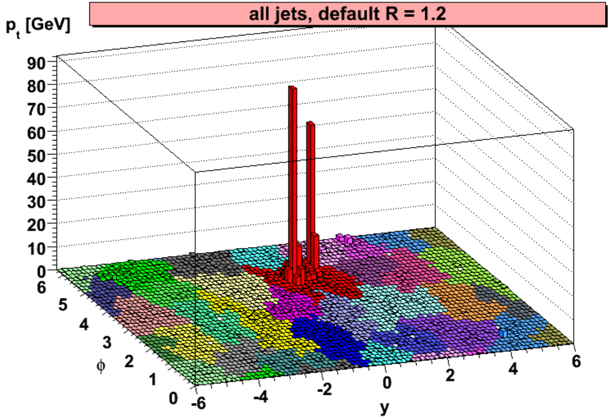
Cluster event, C/A, R=1.2

arbitrary norm.

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

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



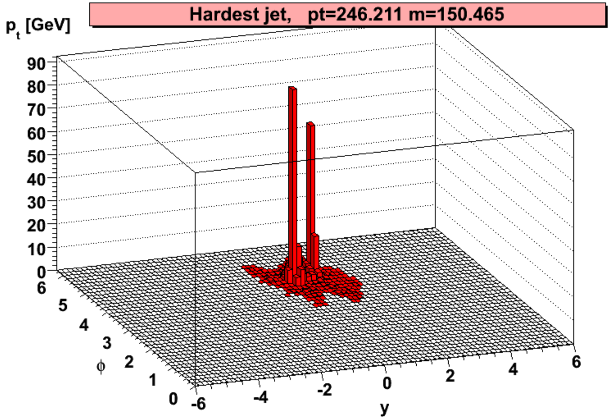
Zbb BACKGROUND

Fill it in, → show jets more clearly

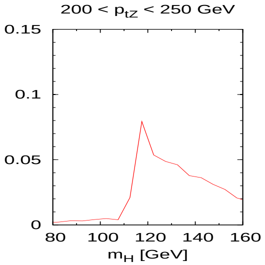
arbitrary norm.

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

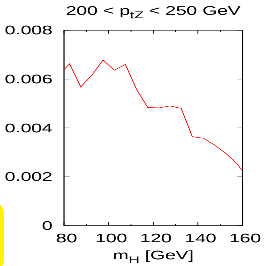
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

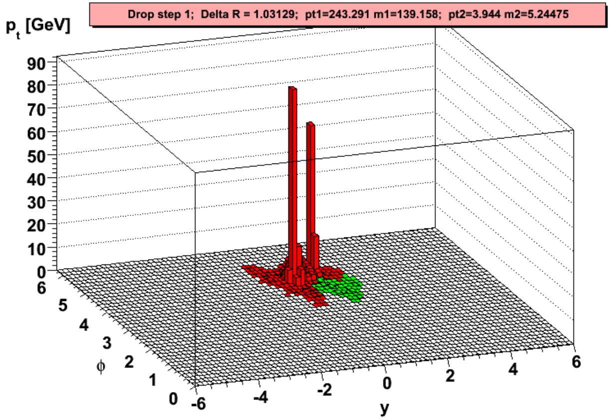


Consider hardest jet, $m = 150$ GeV

arbitrary norm.

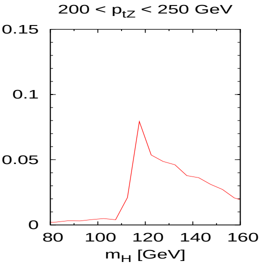
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

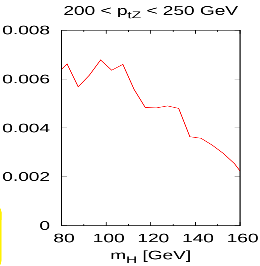


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

SIGNAL



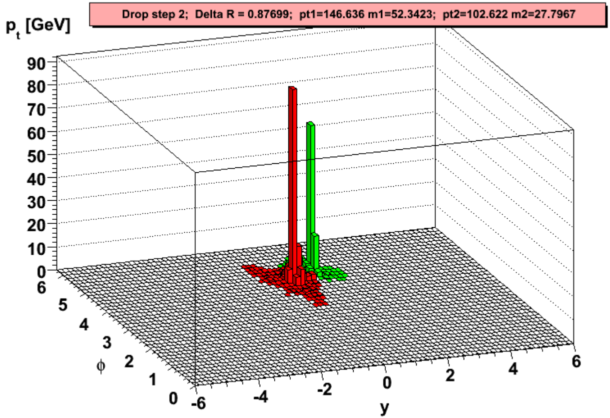
Zbb BACKGROUND



arbitrary norm.

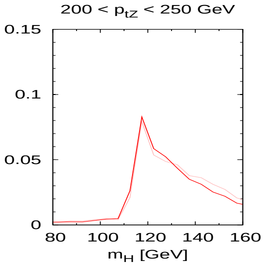
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

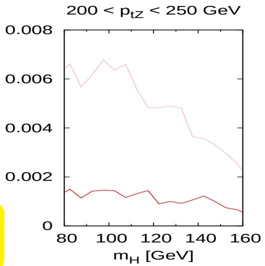


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

SIGNAL



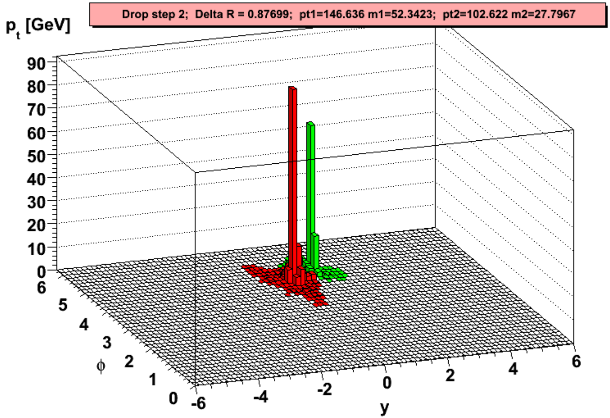
Zbb BACKGROUND



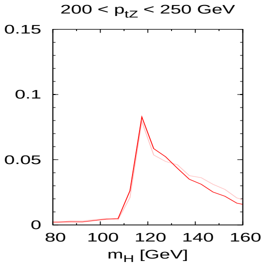
arbitrary norm.

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

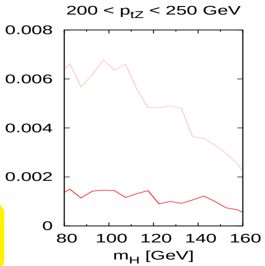
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

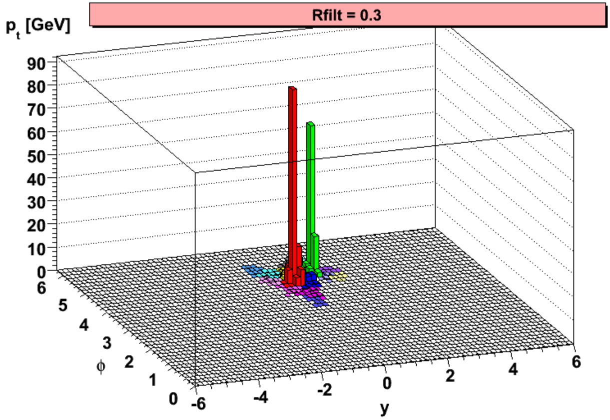


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \rightarrow \text{OK} + 2\ b\text{-tags (anti-QCD)}$

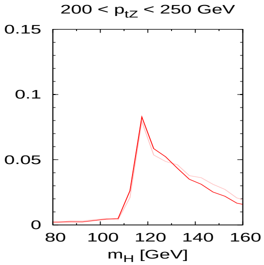
arbitrary norm.

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

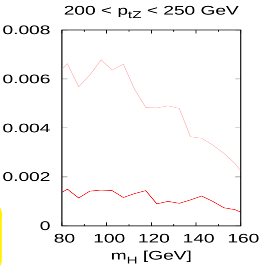
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

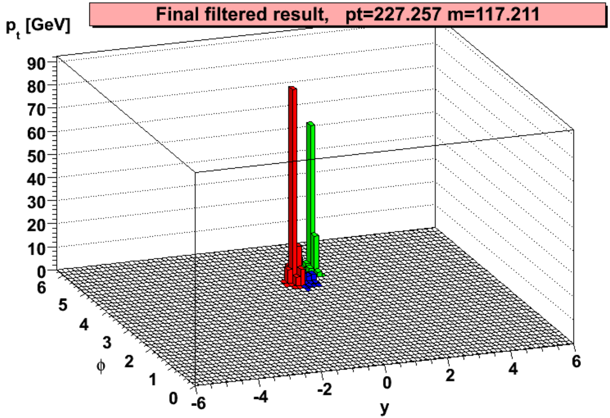


$R_{filt} = 0.3$

arbitrary norm.

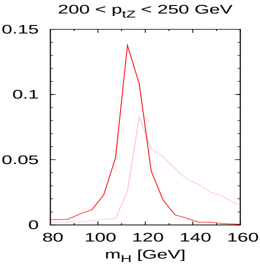
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

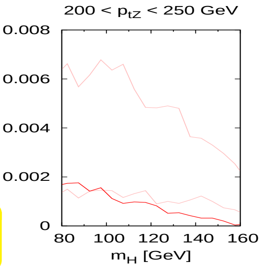


$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

SIGNAL



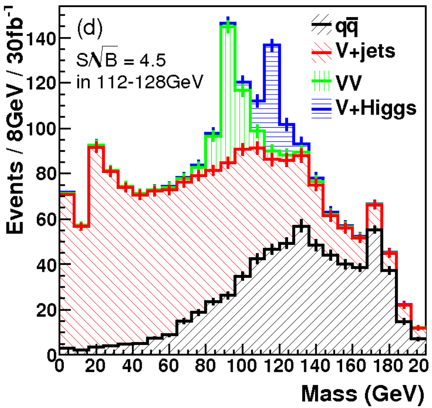
Zbb BACKGROUND



arbitrary norm.

combine HZ and HW, $p_t > 200$ GeV

3 channels combined



Particle-level analysis

Butterworth, Davison, Rubin & GPS '08

Herwig 6.5 + Jimmy 4.3 + FastJet 2.3

3 channels:

- WH, $W \to \ell\nu$ $\qquad \ell \equiv e, \mu$
- ZH, $Z \to \nu\bar{\nu}$
- ZH, $Z \to \ell^+\ell^-$

Basic cuts:

- $p_{tZ,W,H} > 200$ GeV
- Rapidity acceptance: $|y| < 2.5$
- b-tagging: 60% eff, 2% fakes

At 4.5σ for 30 fb^{-1} this looks like a possible new channel for light Higgs discovery/study. **Deserves serious exp. investigation!**

ATLAS detector-level study

Mixture of full and fast simulation for all 3 channels, combined by likelihood-based analysis, predicts signal significance for $m_H = 120$ GeV of

3.7σ for 30 fb^{-1}

ATL-PHYS-PUB-2009-088

To be compared with 4.2σ in hadron-level analysis for $m_H = 120$ GeV

With 5% (20%) background uncertainty, ATLAS result becomes 3.5σ (2.8σ)

Comparison to other channels at ATLAS ($m_H = 120$, 30 fb^{-1}):

$gg \to H \to \gamma\gamma$	$WW \to H \to \tau\tau$	$gg \to H \to ZZ^*$
4.2σ	4.9σ	2.6σ

Only viable channel to see the main decay of a light Higgs, $H \to b\bar{b}$

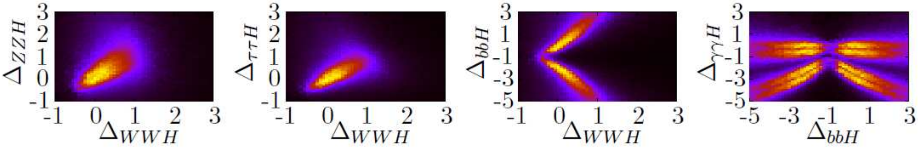
Except perhaps boosted $t\bar{t}H$; Plehn, GPS & Spannowsky '09

Higgs coupling measurements

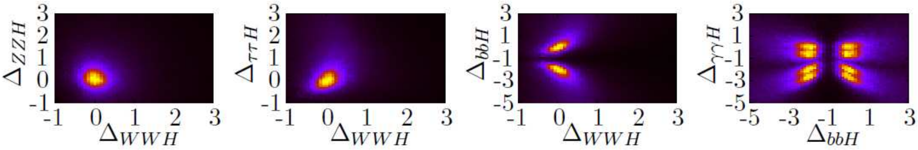
You only know it's the SM Higgs if couplings agree with SM expectations.

Detailed study of all observable LHC Higgs production/decay channels carried out by Lafaye, Plehn, Rauch, Zerwas, Duhrssen '09

Without VH, $H \to b\bar{b}$



With VH, $H \to b\bar{b}$



Without direct $H \to b\bar{b}$ measurement, errors on couplings increase by $\sim 100\%$

Conclusions

Conclusions

We've seen examples where doing the QCD "well" makes a big difference.

From first part: it's clear that relative $\mathcal{O}(\alpha_s)$ ("the details") in QCD predictions (NLO) may be more than just a luxury refinement.

Part of the motivation for the large calculational effort in the field

Crucial in building confidence in our understanding of any LHC "excess"

From second part: QCD at LHC is not *just* about calculating backgrounds. Learning to "view" events properly can have a major impact.

QCD can guide us in making good choices

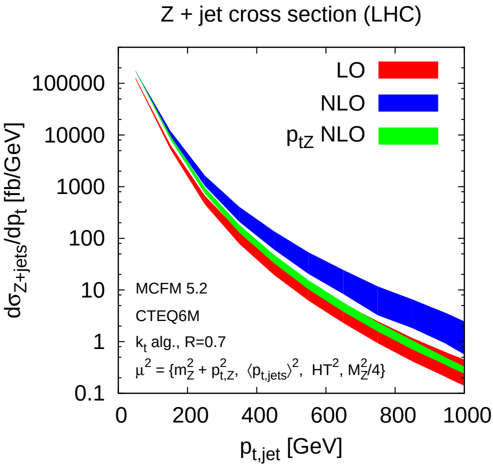
A much smaller field — but several groups making progress

Crucial in order to maximise LHC's sensitivity to new physics

Common theme: LHC will probe a broad range of scales: from below EW scale, to 1.5 orders of magnitude above it. This brings challenges & opportunities.

EXTRAS

Z+jet Cross-check

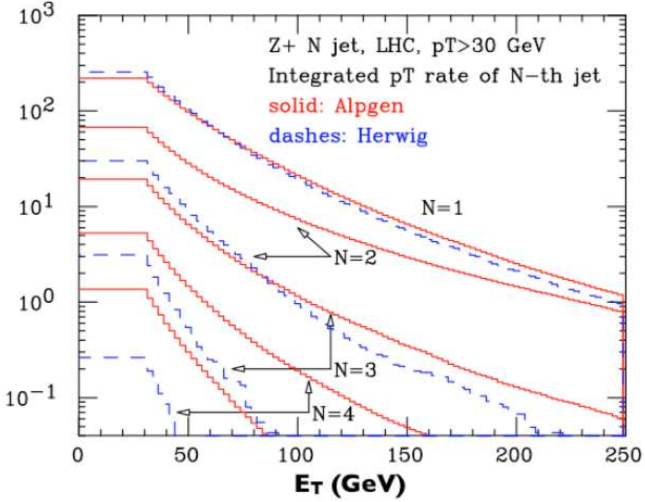


Plot distribution for p_{tZ}.

This selects events in which the Z is the hardest object.

Kills diags with EW double-logs.

NLO is well-behaved.



Mangano, 0809.1567

Not matched

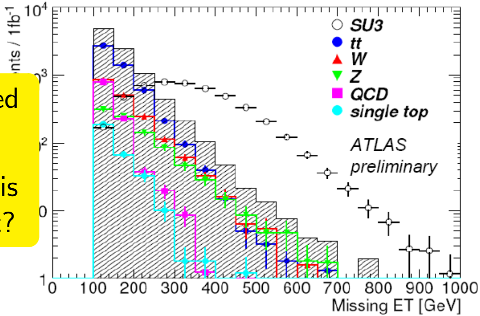
But see 2-jet $\simeq$ 1-jet, which is sign of problems

0-lepton search

Is there a larger excess when plotted v. MET ($\sim p_{tZ}$)?

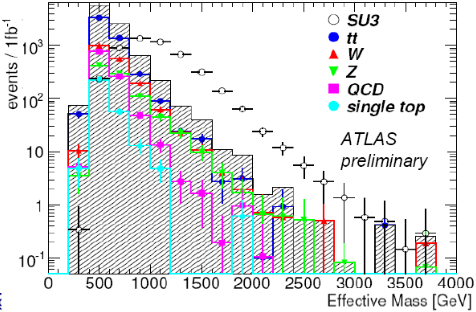
Is this because Eff.Mass ($\sim p_{t,jet}$) is enhanced in bkgd, but MET is not?

- at least 1 jet with PT>100GeV
- 0 lepton (e, μ) with PT > 20 GeV
- MET > 100 GeV
- MET > 0.2 effective mass
- Transverse Sphericity ST > 0.2
- Δφ(ET – jet *i*) > 0.2 (*i* = 1, 2, 3)

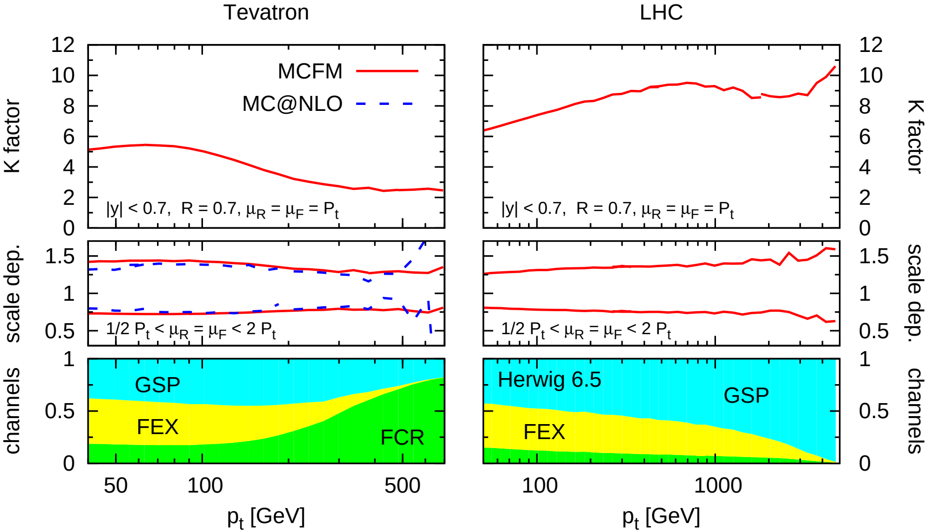


- Main backgrounds:
  - tt
  - W+jets
  - Z+jets
  - QCD

SM	0-l
tt	62%
W	17%
Z	10%
QCD	10%

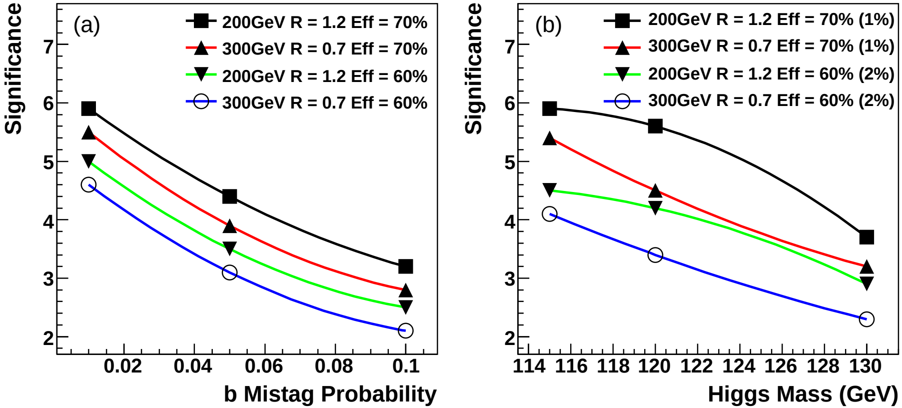


Another example: b-jet production



Banfi, GPS & Zanderighi, '07

Impact of *b*-tagging, Higgs mass

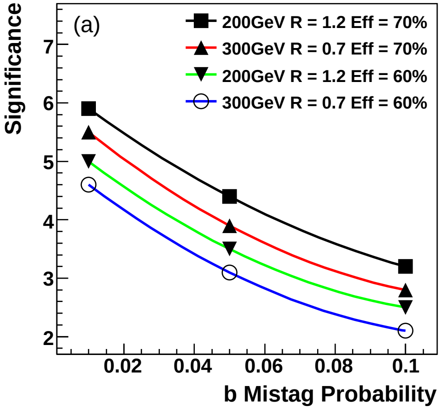


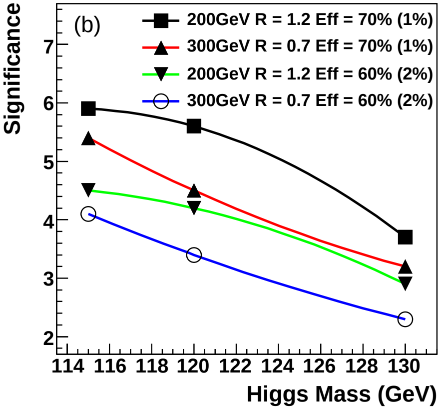
Most scenarios above 3σ

For it to be a significant discovery channel requires decent b-tagging, lowish mass Higgs [and good experimental resolution]

In nearly all cases, suitable for extracting $b\bar{b}$H, WWH, ZZH couplings

Impact of *b*-tagging, Higgs mass





Most scenarios above 3σ

For it to be a significant discovery channel requires decent *b*-tagging, lowish mass Higgs [and good experimental resolution]

In nearly all cases, suitable for extracting $b\bar{b}$H, WWH, ZZH couplings

ATLAS analysis

As of August 2009: ATLAS have preliminary public analysis of this channel

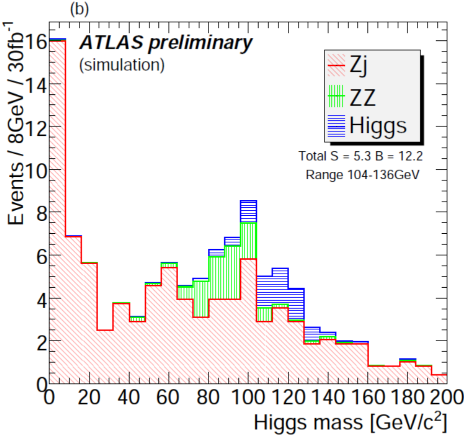
ATL-PHYS-PUB-2009-088

What changes?

- Inclusion of detector simulation — mixture of full and validated ATLFAST-II
- Study of triggers — All OK
- New issue: *importance of fake b tags from charm quarks*
- *New background: Wt production* with $t \to bW$, $W \to cs$, giving bc as a Higgs candidate.
- Larger mass windows, $24 - 32$ GeV rather than 16 GeV for signal, reflecting full detector resolution
- Various changes in details of cuts
- ATLAS numbers shown for $m_H = 120$ GeV (previous plots: $m_H = 115$ GeV)

ATLAS results

Leptonic channel



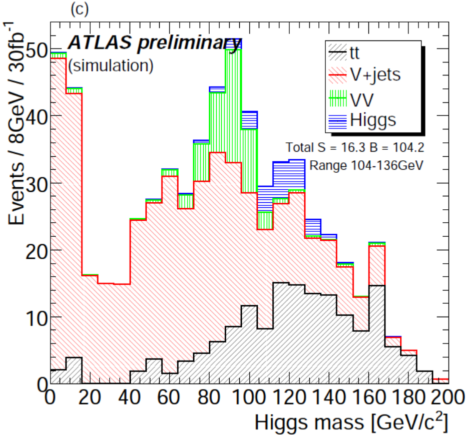
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 2.1σ

Expected given larger mass window

ATLAS results

Missing E_T channel



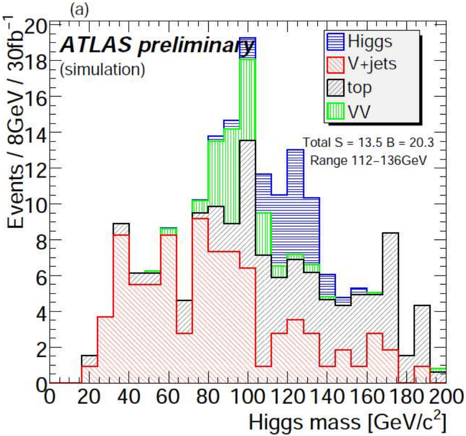
What changes compared to particle-level analysis?

$\sim 1.5\sigma$ as compared to 3σ

Suffers: some events redistributed to semi-leptonic channel

ATLAS results

Semi-leptonic channel



What changes compared to particle-level analysis?

$\sim 3\sigma$ as compared to 3σ

Benefits: some events redistributed from missing E_T channel

ATLAS combined results

Likelihood-based analysis of all three channels together gives signal significance of

3.7σ for 30 fb^{-1}

To be compared with 4.2σ in hadron-level analysis for $m_H = 120$ GeV

With 5% (20%) background uncertainty, ATLAS result becomes 3.5σ (2.8σ)

Comparison to other channels at ATLAS ($m_H = 120$, 30 fb^{-1}):

$gg \to H \to \gamma\gamma$	$WW \to H \to \tau\tau$	$gg \to H \to ZZ^*$
4.2σ	4.9σ	2.6σ

Extracted from 0901.0512

Prospects?

ATLAS: "Future improvements can be expected in this analysis:"

- b-tagging might be calibrated [for this] kinematic region
- jet calibration [...] hopefully improving the mass resolution
- background can be extracted directly from the data
- multivariate techniques

CMS is looking at this channel

- Biggest difference wrt ATLAS could be jet mass resolution

But CMS have plenty of good ideas that might compensate for worse hadronic calorimeter

Combination of different kinematic regions

- E.g. in original analysis, $p_t > 300$ GeV (only 1% of VH, but very clear signal) was almost as good as $p_t > 300$ GeV (5% of VH).
- Treating different p_t ranges independently may have benefits.

Tagging boosted top-quarks

High-p_t top production often envisaged in New Physics processes.
$\sim$ high-p_t EW boson, but: top has 3-body decay and is coloured.

7 papers on top tagging in '08-'09 (at least): jet mass + something extra.

Questions

- What efficiency for tagging top?
- What rate of fake tags for normal jets?

Rough results for top quark with $p_t \sim 1$ TeV

	"Extra"	eff.	fake
[from T&W]	just jet mass	50%	10%
Brooijmans '08	3,4 k_t subjets, d_{cut}	45%	5%
Thaler & Wang '08	2,3 k_t subjets, z_{cut} + various	40%	5%
Kaplan et al. '08	3,4 C/A subjets, $z_{cut} + \theta_h$	40%	1%
Almeida et al. '08	predict mass dist^n, use jet-shape	–	–
Ellis et al. '09	C/A pruning	10%	0.05%
ATLAS '09	3,4 k_t subjets, d_{cut} MC likelihood	90%	15%
Plehn et al. '09	C/A mass drops, θ_h [busy evs, $p_t \sim 250$]	40%	2.5%

$t\bar{t}H$

boosted top and Higgs together?

(NB: inclusive ttH deemed unviable in past years by ATLAS & CMS)

Resurrecting $t\bar{t}H$?

$$pp \to t\bar{t}H$$

$t \to b\ell(\not{E}_T)$

$t \to \text{jet}_{jjj}$ (boosted)

$H \to \text{jet}_{b\bar{b}}$ (boosted)

Ask for just two boosted particles in order to maintain some cross-section

Plehn, GPS & Spannowsky '09

Main ingredients

- one lepton $p_t > 15$ GeV, $|y| < 2.5$
- 2 C/A ($R = 1.5$) jets with $p_T > 200$ GeV, $|y| < 2.5$
- Mass-drop based substructure ID — With filtering to reduce UE

  Allow for extraneous subjets since busy environment
- After eliminating constituents from tagged hadronic top and H, require one extra b-jet (C/A, R=0.6, $p_t > 40$ GeV).
- Cut on mass of top candidate (and hadronic W), plot mass of Higgs candidate

Resurrecting $t\bar{t}H$?

$pp \to t\bar{t}H$

$t \to b\ell(\not{E}_T)$

$t \to \text{jet}_{jjj}$ (boosted)

$H \to \text{jet}_{b\bar{b}}$ (boosted)

Ask for just two boosted particles in order to maintain some cross-section

Plehn, GPS & Spannowsky '09

Main ingredients

- one lepton $p_t > 15$ GeV, $|y| < 2.5$
- 2 C/A ($R = 1.5$) jets with $p_T > 200$ GeV, $|y| < 2.5$
- Mass-drop based substructure ID

  With filtering to reduce UE

  Allow for extraneous subjets since busy environment
- After eliminating constituents from tagged hadronic top and H, require one extra b-jet (C/A, R=0.6, $p_t > 40$ GeV).
- Cut on mass of top candidate (and hadronic W), plot mass of Higgs candidate

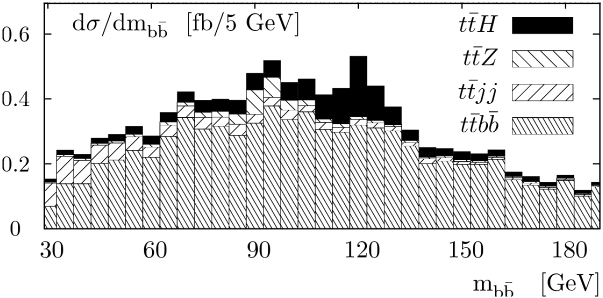
$t\bar{t}H$ results

	S[fb]	B[fb]	S/B	$S/\sqrt{B}$ (100 fb^{-1})
m_H = 115 GeV	0.57	1.39	1/2.4	4.8
120 GeV	0.48	1.36	1/2.8	4.1
130 GeV	0.29	1.21	1/4.2	2.6

Numbers of events in 20 GeV window centred on Higgs mass, including *K*-factors

Using 0.7/0.01 for *b*-tag rate/fake within subjet (cf. ATLAS '09)

and 0.6/0.02 for *b*-tag rate/fake in "normal" jet



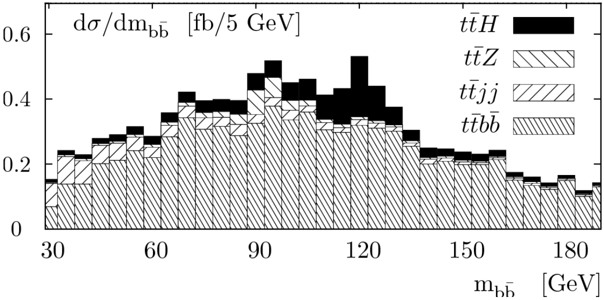
$t\bar{t}H$ results

	S[fb]	B[fb]	S/B	$S/\sqrt{B}$ (100 fb^{-1})
m_H = 115 GeV	0.57	1.39	1/2.4	4.8
120 GeV	0.48	1.36	1/2.8	4.1
130 GeV	0.29	1.21	1/4.2	2.6

Numbers of events in 20 GeV window centred on Higgs mass, including K-factors

Using 0.7/0.01 for b-tag rate/fake within subjet (cf. ATLAS '09)

and 0.6/0.02 for b-tag rate/fake in "normal" jet



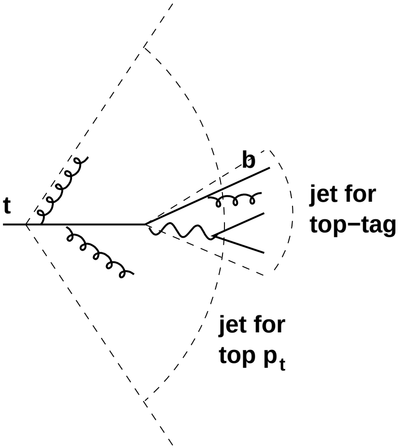
Doesn't recover $t\bar{t}H$ as a discovery channel, but promising for coupling measurements

Next step: see what ATLAS & CMS say

Using (coloured!) boosted top-quarks

If you want to use the tagged top (e.g. for $t\bar{t}$ invariant mass) QCD tells you:

the jet you use to tag a top quark $\neq$ the jet you use to get its p_t



Within inner cone $\sim \frac{2m_t}{p_t}$ (dead cone) you have the top-quark decay products, but no radiation from top

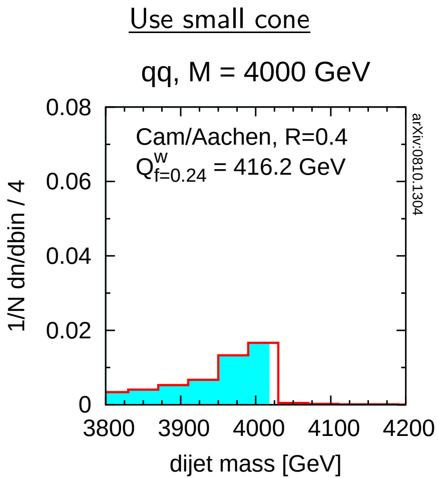
ideal for reconstructing top mass

Outside dead cone, you have radiation from top quark

essential for top p_t

Cacciari, Rojo, GPS & Soyez '09

Impact of using small cone angle



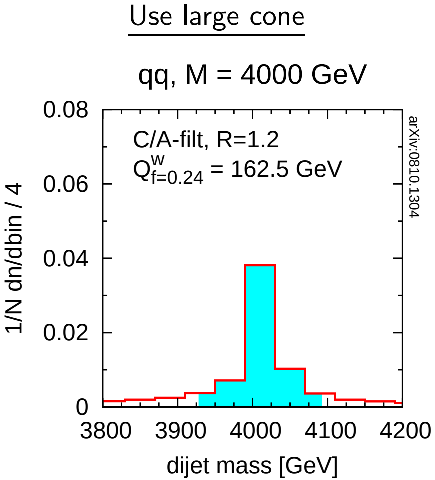


Figure actually from 0810.1304 (Cacciari, Rojo, GPS & Soyez)
for light $q\bar{q}$ resonance — but $t\bar{t}$ will be similar

How you look at your event matters: `http://quality.fastjet.fr/`