

LHC searches: what role for QCD?

Gavin Salam

LPTHE, CNRS and UPMC (Univ. Paris 6)

Aspen Center for Physics

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Including examples based on work with Butterworth, Cacciari, Davison, Plehn, Rojo, Rubin, Sapeta, Soyez, Spannowsky.

LHC collides quarks and gluons

Quarks and gluons interact strongly \rightarrow 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?

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True, false, or only half the story?

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 ~ 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 response.

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
    
```

Choice of QCD at LHC

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11	f + f' -> f + f' (QCD)						
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13	f + fbar -> g + g	1)					
28	f + g -> f + g						
53	g + g -> f + fbar	21	0.00000	0.00000	6999.99994	7000.00000	0.93827
68	g + g -> g + g	21	0.00000	0.00000	-6999.99994	7000.00000	0.93827
96	Semihard QCD 2 -> 2						
	4 !u!	21	-0.20478	-1.99677	4200.93192	4200.93240	0.00000
	5 !g!	21	-0.52164	-0.53530	-1227.35705	1227.35728	0.00000
	6 !u!	21	69.88093	-38.60332	186.26860	202.65624	0.00000
	7 !g!	21	-3.29805	0.22934	-594.30442	594.31361	0.00000
	8 !u!	21	342.80888	-101.05545	-85.04352	367.37248	0.00000
	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

Sherj

For s

For s

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As in

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	23
	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

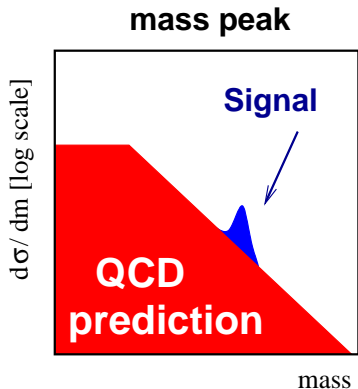
Words of caution

[...] 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

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

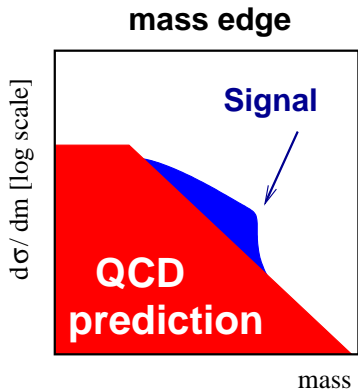


New resonance (e.g. Z') where you see all decay products and reconstruct an invariant mass

QCD may:

- ▶ swamp signal
- ▶ smear signal

leptonic case easy; hadronic case harder

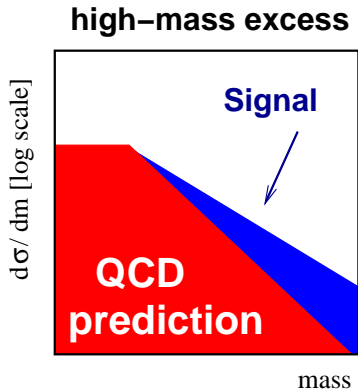


New resonance (e.g. R-parity conserving SUSY), where undetected new stable particle escapes detection.

Reconstruct only *part* of an invariant mass
→ kinematic edge.

QCD may:

- ▶ swamp signal
- ▶ smear signal

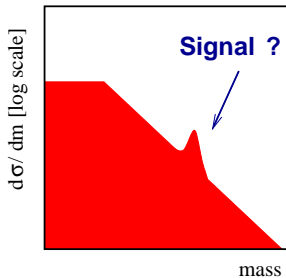


Unreconstructed SUSY cascade. Study *effective* mass (sum of all transverse momenta).

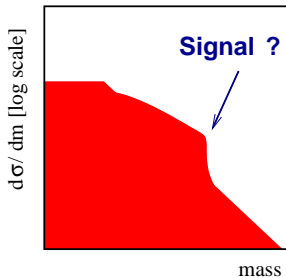
Broad excess at high mass scales.

Knowledge of backgrounds is crucial in declaring discovery.

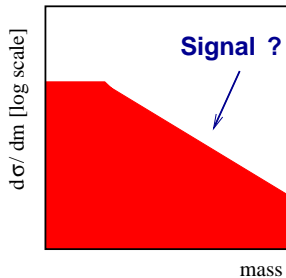
QCD is *one way* of getting handle on background.

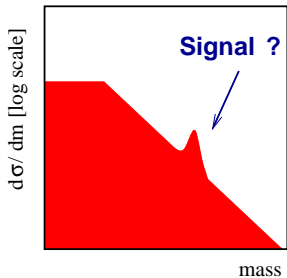


CONTINUE
HERE

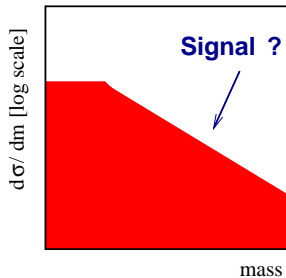
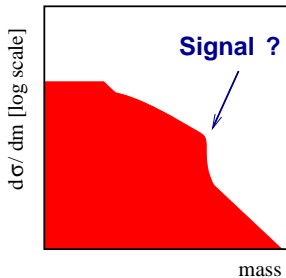


START
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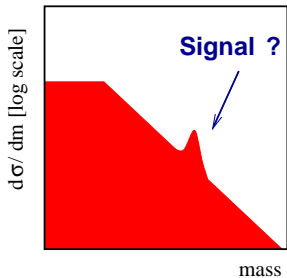




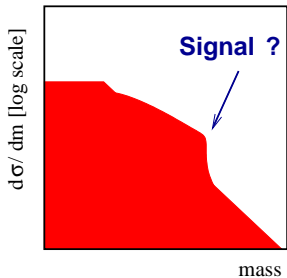
CONTINUE
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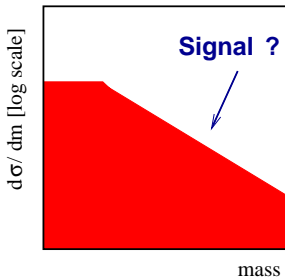
START
HERE



**CONTINUE
HERE**

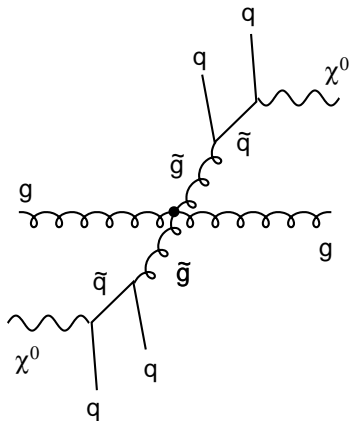


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HERE**

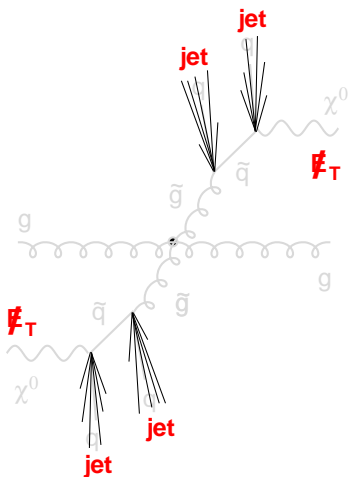


Predicting QCD

Signal

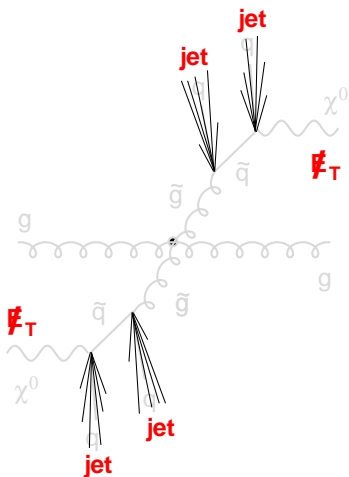


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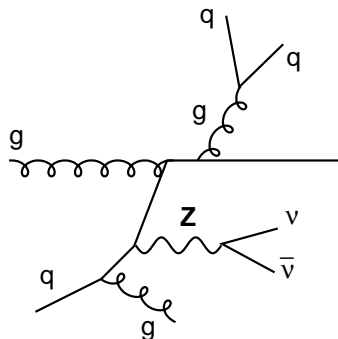


SUSY example: gluino pair production

Signal

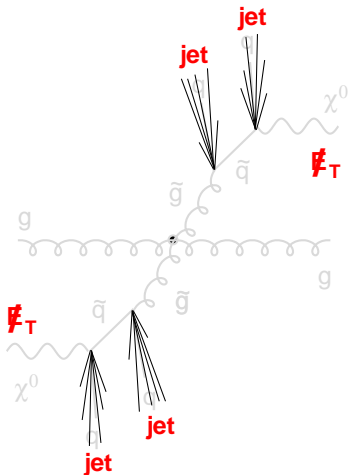


Background

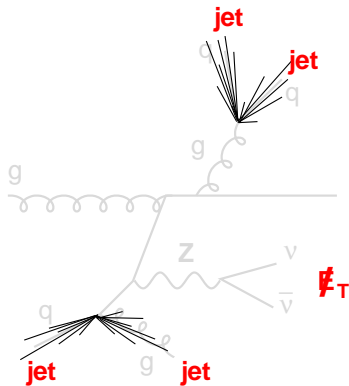


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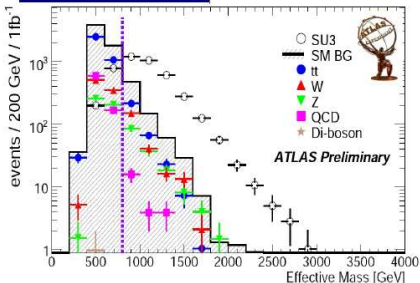
Background



Atlas selection [all hadronic]

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

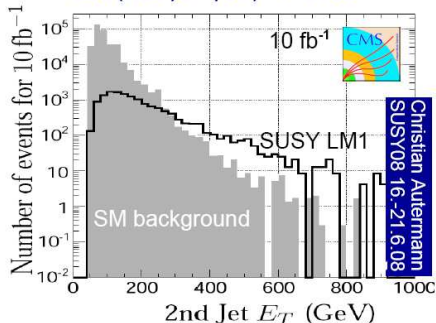
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 SUSY08 16.-21.6.08
 4



CMS selection [leptonic incl.]

(optimized for 10fb⁻¹, using genetic algorithm)

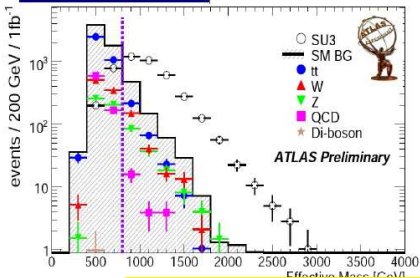
- 1 muon p_T > 30 GeV
- MET > 130 GeV
- 1st, 2nd jet > 440 GeV
- 3rd jet > 50 GeV
- -0.95 < cos(MET, 1st jet) < 0.3
- cos(MET, 2nd jet) < 0.85



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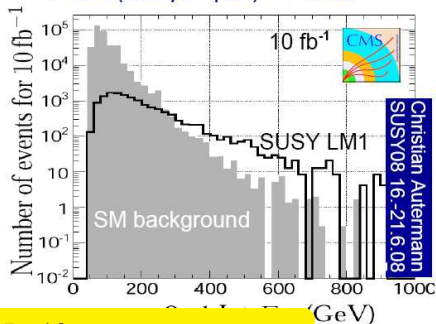
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SUSY \simeq factor 5–10 excess

How accurate is perturbative QCD?

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

$$\alpha_s \simeq 0.1$$

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

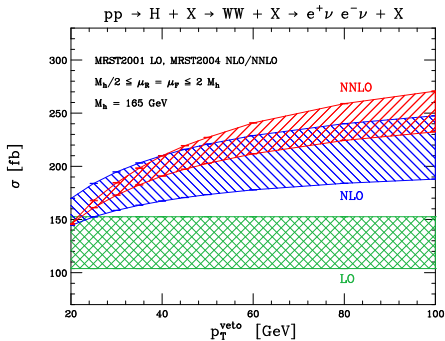
It isn't

Rules of thumb:

LO good to within factor of 2

NLO good to within scale
uncertainty

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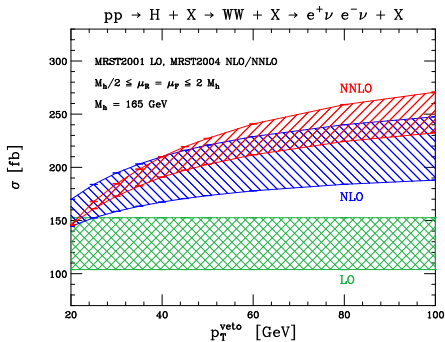
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Anastasiou, Melnikov & Petriello '04
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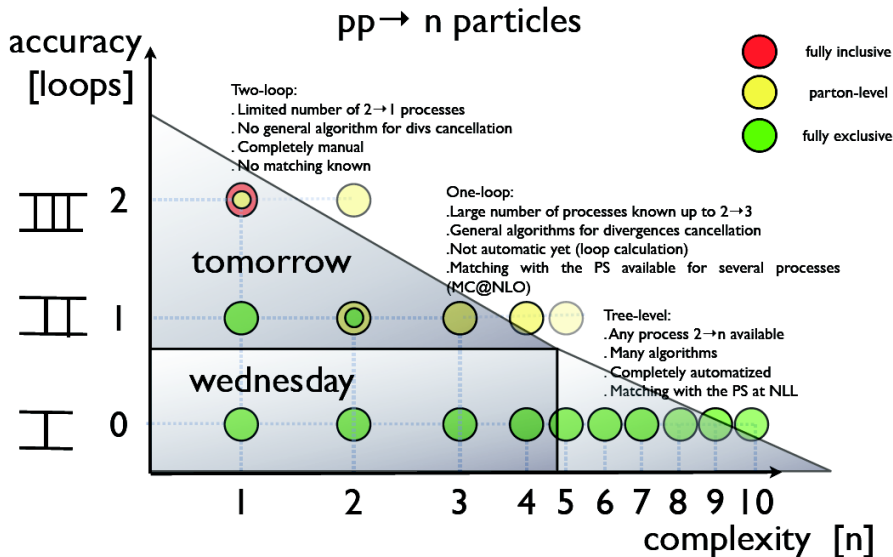
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Theory status

from lectures
by F. Maltoni '07

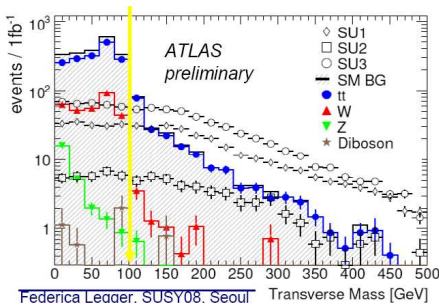


We don't have NLO for the background (e.g. 4 jets + Z, a $2 \rightarrow 5$ process).

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



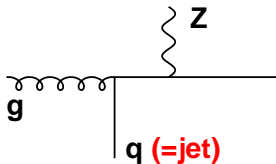
A conservative QCD theory point of view:

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

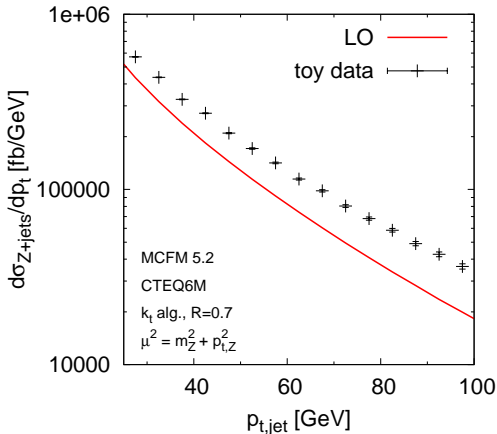
But we would tend to think it is safe, as long as control data are within usual factor of two of LO prediction

Illustrate issues with toy example: Z +jet production

- ▶ It's known to NLO and a candidate for "first" $2 \rightarrow 2$ NNLO
 $\sim e^+e^- \rightarrow \gamma^*/Z \rightarrow 3$ 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)



Z + jet cross section (LHC)



stage 1: get control sample

Check LO v. data at low p_t

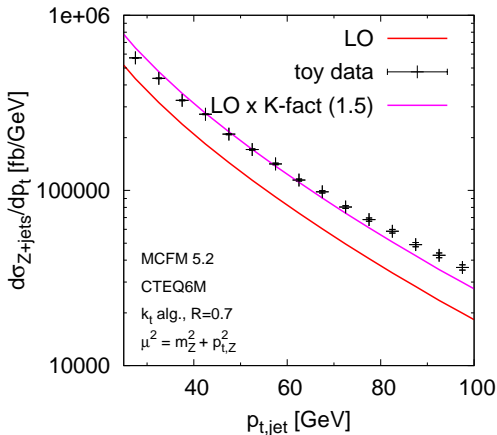
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(consistent with expectations)

So renormalise LO by K-factor

- ▶ shape OKish

Don't be too fussy: SUSY
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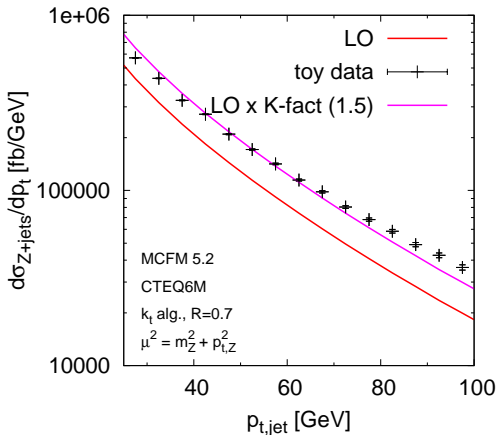
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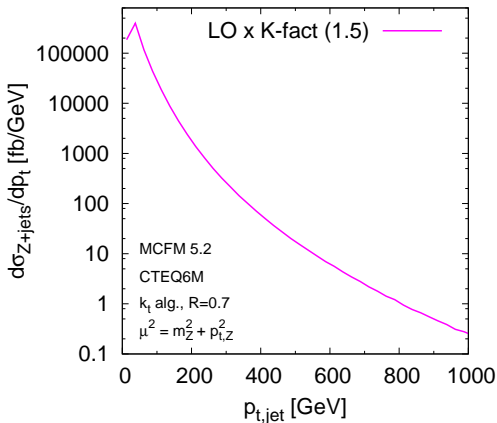
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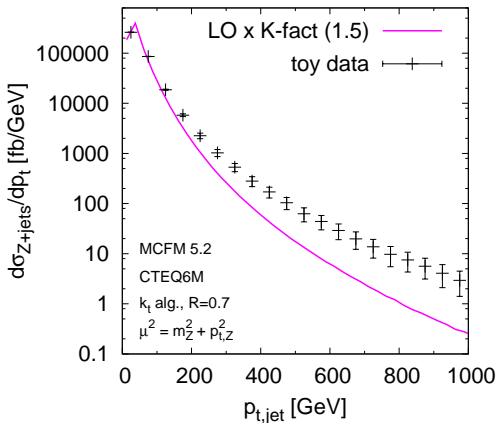
Z + jet cross section (LHC)



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

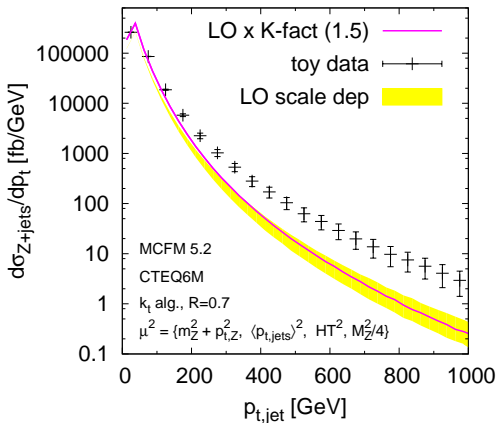
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Is it:

- ▶ 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. . .

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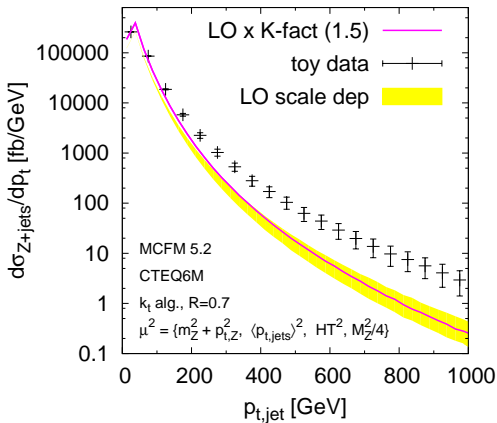
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Z + jet cross section (LHC)



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

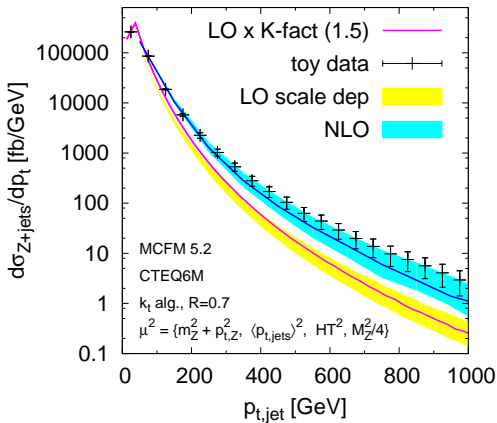
Example based on background work for Butterworth, Davison, Rubin & GPS '08

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

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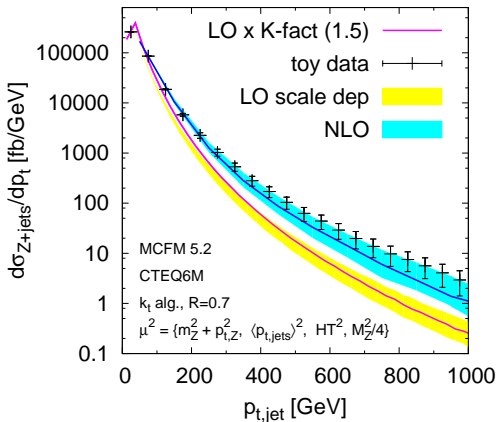
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Z + jet cross section (LHC)



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

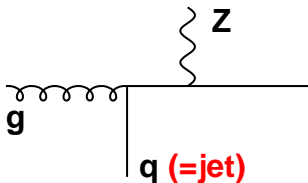
Example based on background work for Butterworth, Davison, Rubin & GPS '08

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

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

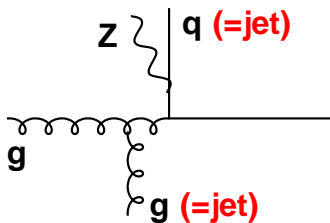
NB: DYRAD, MCFM consistent

Leading Order



$$\alpha_s \alpha_{EW}$$

Next-to-Leading Order



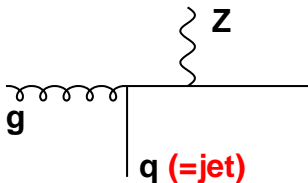
$$\alpha_s^2 \alpha_{EW} \ln^2 \frac{p_t}{M_Z}$$

LHC will probe scales well above EW scale, $\sqrt{s} \gg M_Z$.

QCD and EW effects **mix**, EW bosons are **light**.

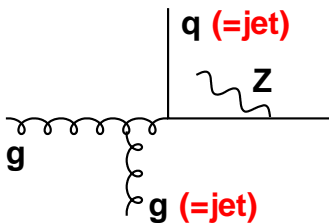
New logarithms (enhancements) appear.

Leading Order



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Next-to-Leading Order



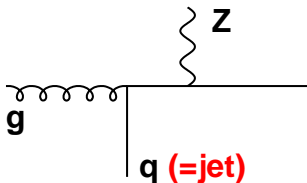
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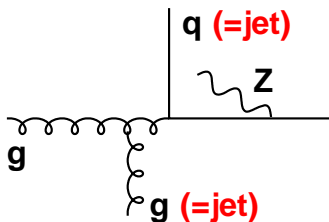
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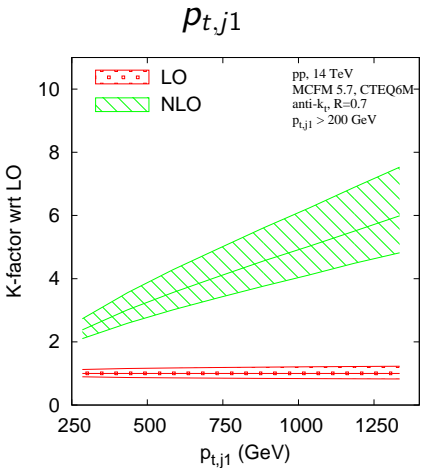
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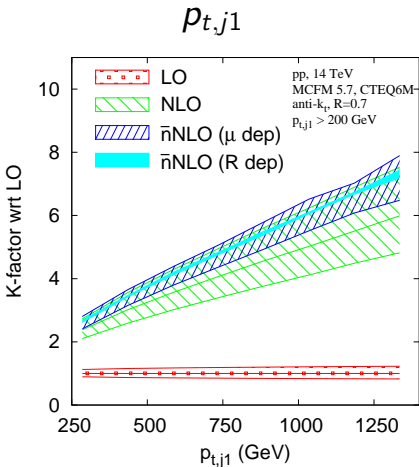
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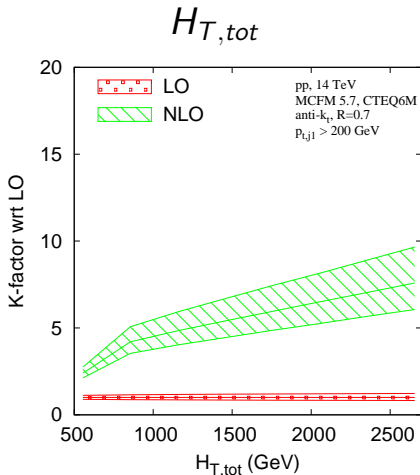
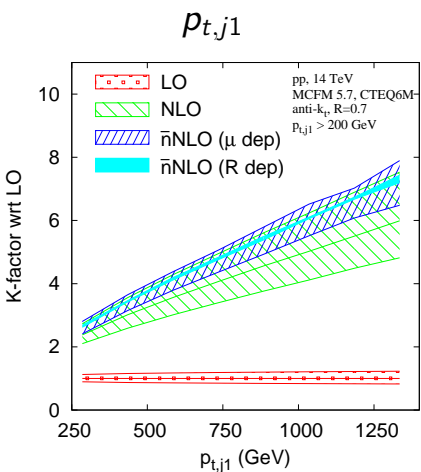
Excess \equiv New Physics, **iff** you are really, really sure you understand backgrounds

- ▶ 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. $W/Z + 3\text{jet}$, $t\bar{t}b\bar{b}$, $t\bar{t}jj$ 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

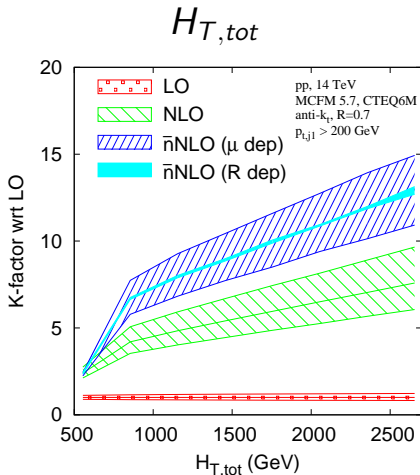
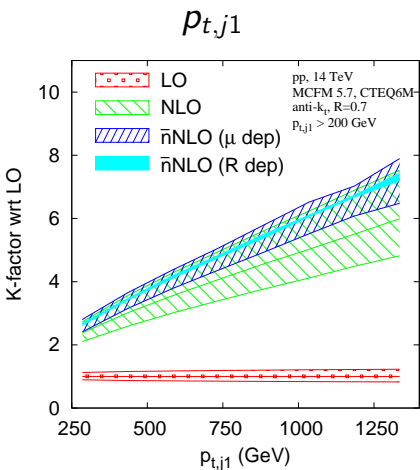




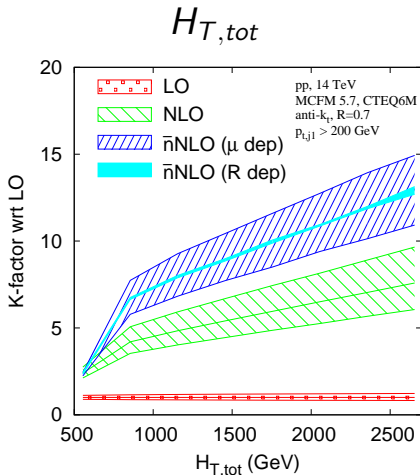
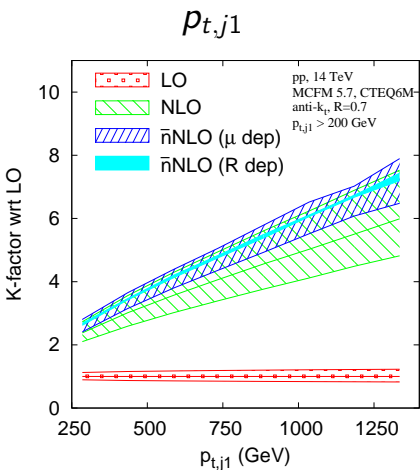
Rubin, GPS & Sapeta, preliminary
 (central $\mu^2 = p_{t,j1}^2 + M_Z^2$)



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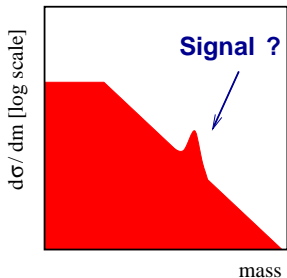


More next week...

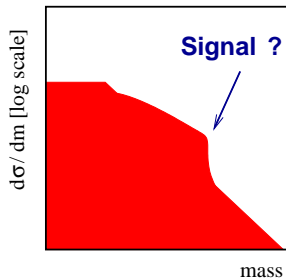
Rubin, GPS & Sapeta, preliminary
 (central $\mu^2 = p_{t,j1}^2 + M_Z^2$)

Viewing QCD

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

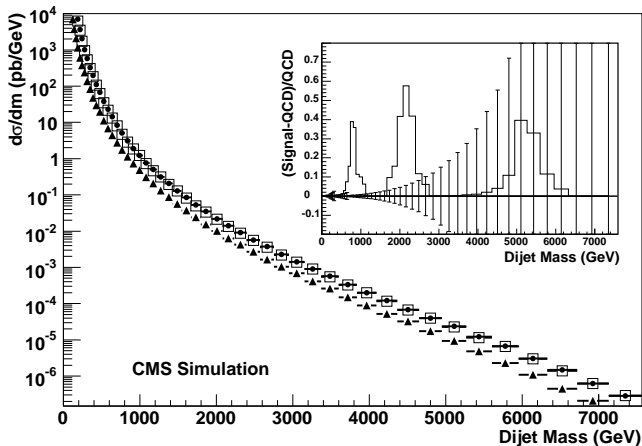


$$\sim \frac{d}{dm}$$



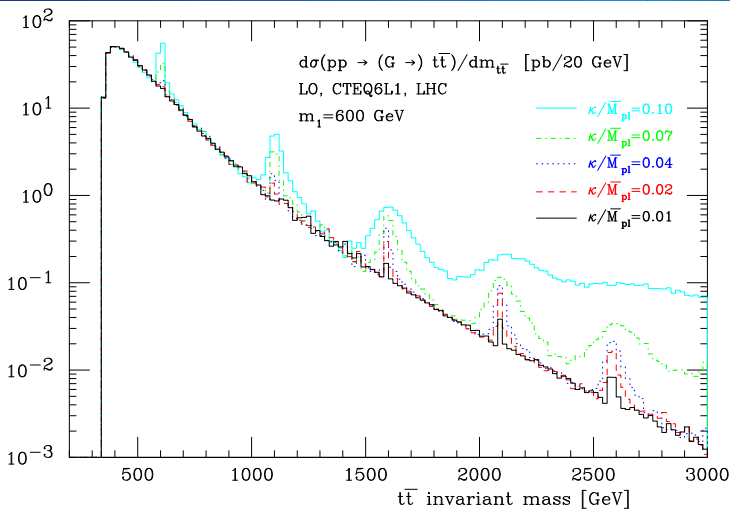
Some peaks are easy — QCD not needed

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



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

Observability may depend on parameters

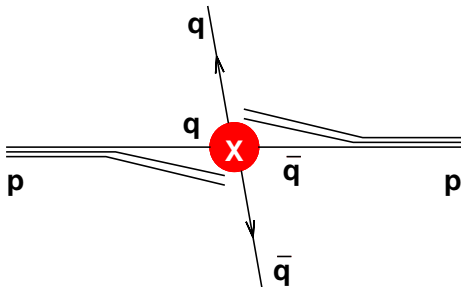


RS KK resonances, from Frederix & Maltoni, 0712.2355

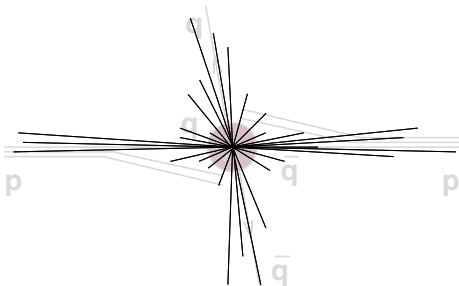
Cases where QCD has the most to contribute are those that are borderline

Basic question:

Can we make kinematic “structures” emerge more clearly?



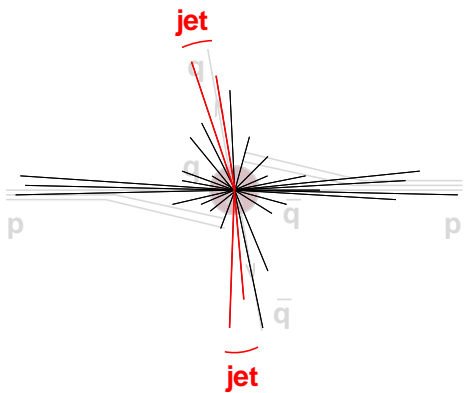
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Which particles should one
choose in order to best
reconstruct the resonance?

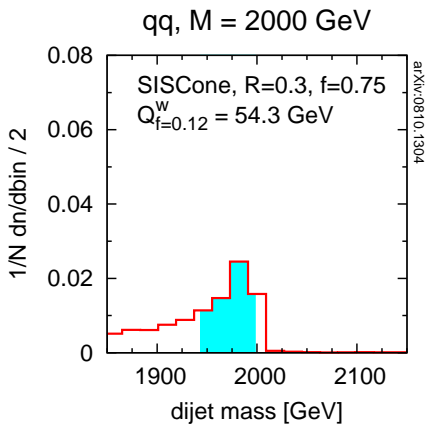
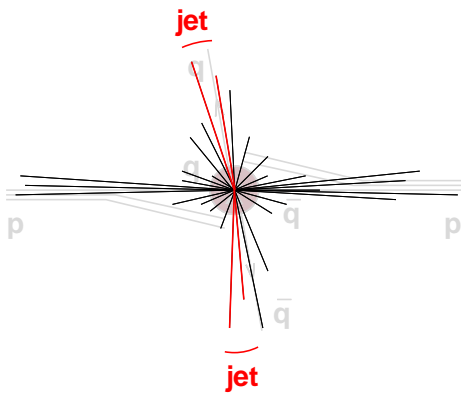
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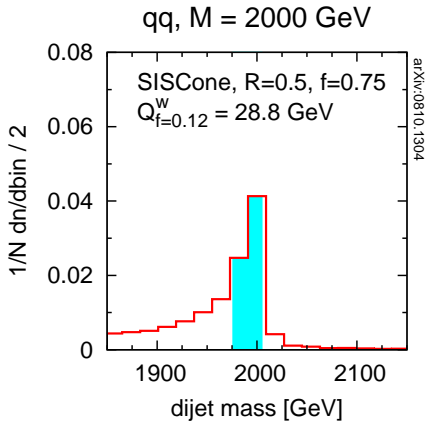
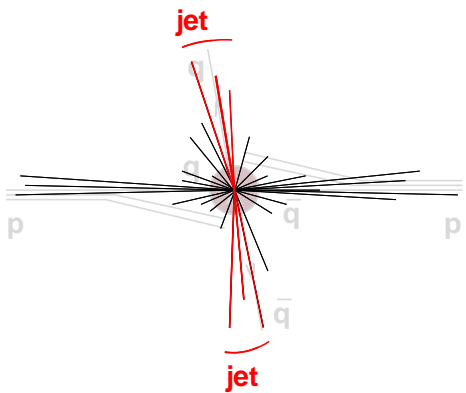
How should one define the “jets”?

Basic question:
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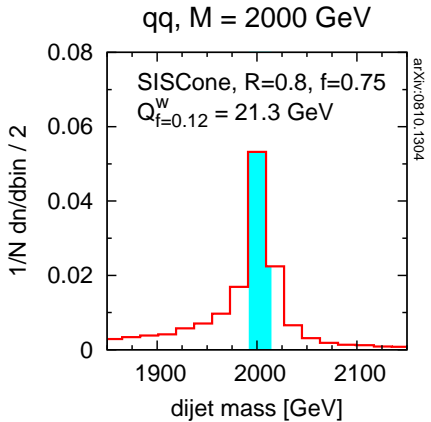
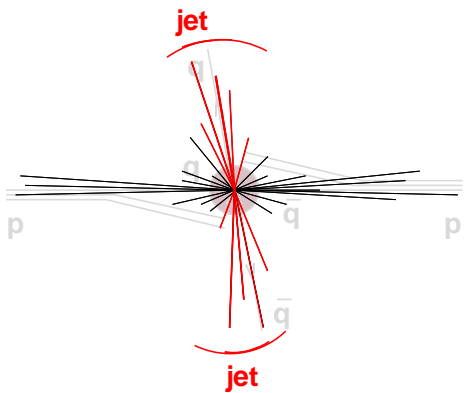


Basic question:

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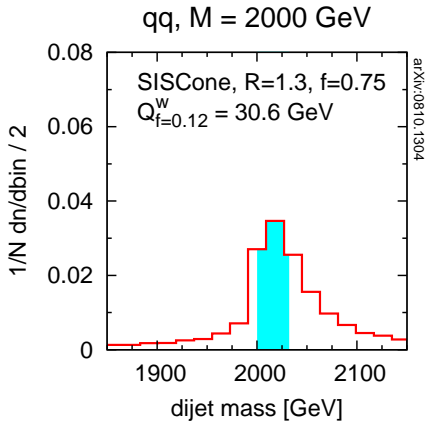
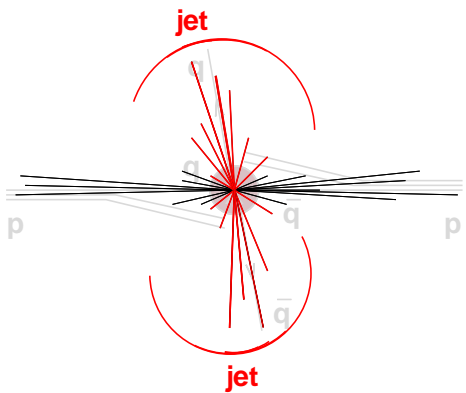


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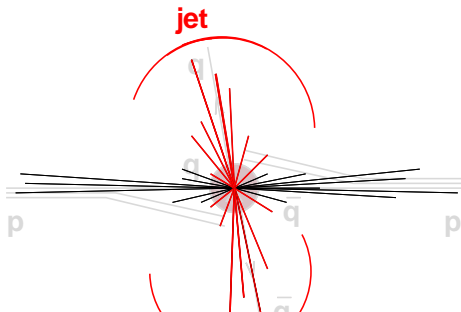
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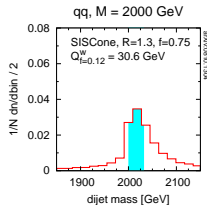
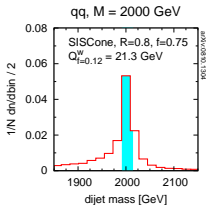
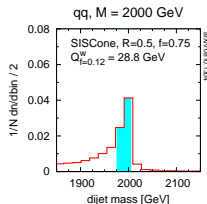
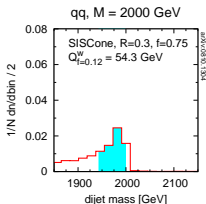


Basic question:

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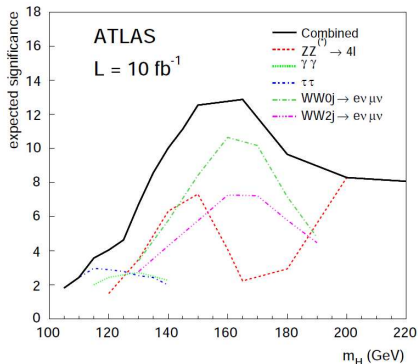
Choice of jet-definition
has significant impact



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



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

Various production & decay processes

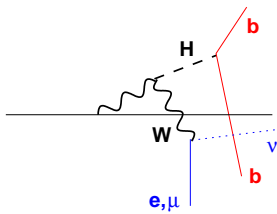
- ▶ $gg \rightarrow H \rightarrow \gamma\gamma$ feasible
- ▶ $WW \rightarrow H \rightarrow \tau\tau$ feasible
- ▶ $gg \rightarrow H \rightarrow ZZ^* \rightarrow 4\ell$ feasible
- ▶ $gg \rightarrow t\bar{t}H, H \rightarrow b\bar{b}$ v. hard
- ▶ $q\bar{q} \rightarrow WH, ZH, H \rightarrow b\bar{b}$ v.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

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

Studied e.g. in ATLAS TDR

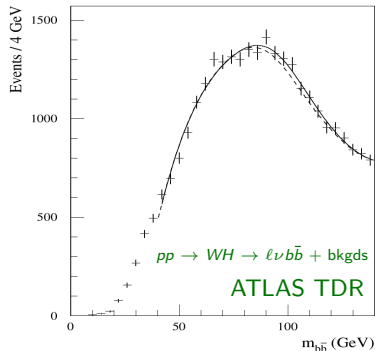
Difficulties, e.g.

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



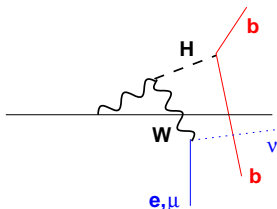
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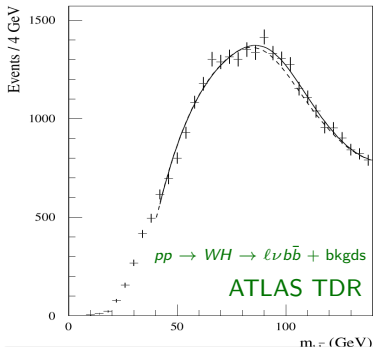
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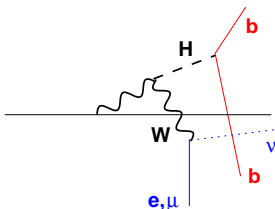


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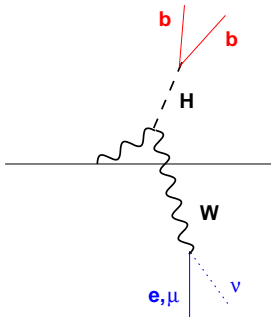
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Conclusion (ATLAS TDR):

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



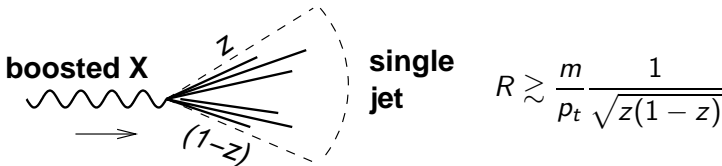
Take advantage of the fact that $\sqrt{s} \gg M_H, m_t, \dots$



Go to high p_t :

- ✓ Higgs and W/Z more likely to be central
- ✓ high- p_t $Z \rightarrow \nu\bar{\nu}$ becomes visible
- ✓ Fairly collimated decays: high- p_t ℓ^\pm, ν, 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?

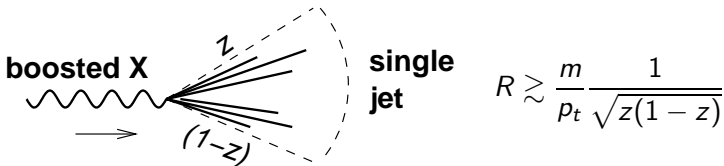
Hadronically decaying Higgs boson at high $p_t =$ single massive jet?



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?

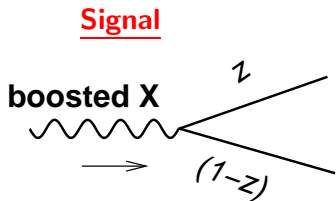
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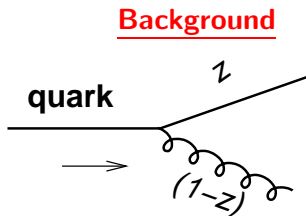
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QCD principle: soft divergence



Splitting probability for Higgs:

$$P(z) \propto 1$$



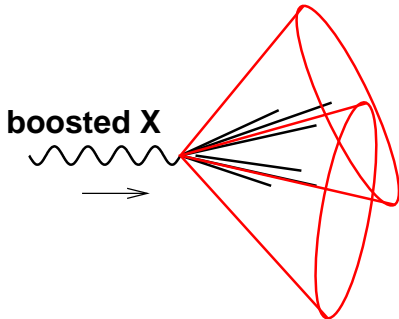
Splitting probability for quark:

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

$1/(1-z)$ 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



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 resolⁿ

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, '05-10, <http://fastjet.fr/>

All MC done with Herwig 6.510 and Jimmy 4.31

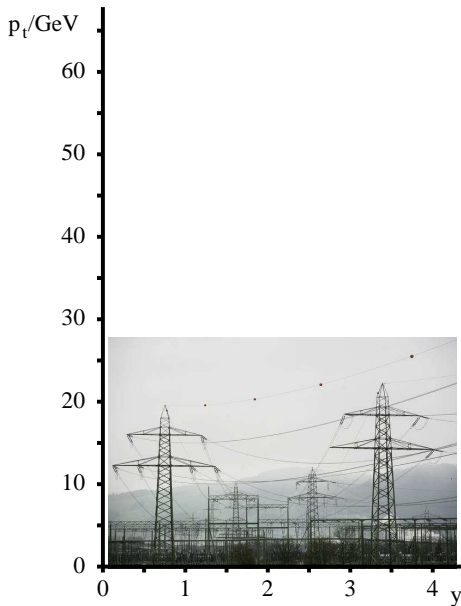
Cambridge/Aachen at work

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

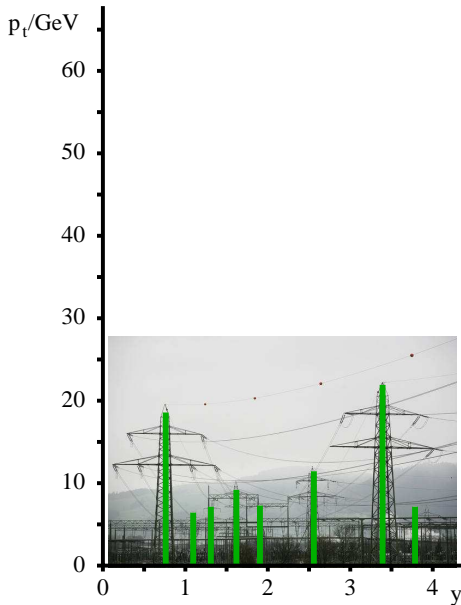




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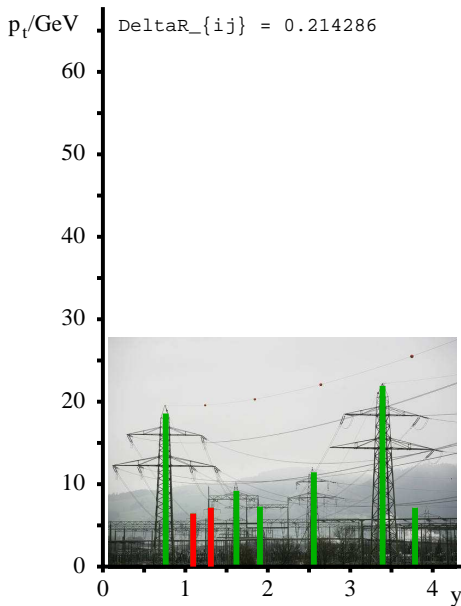
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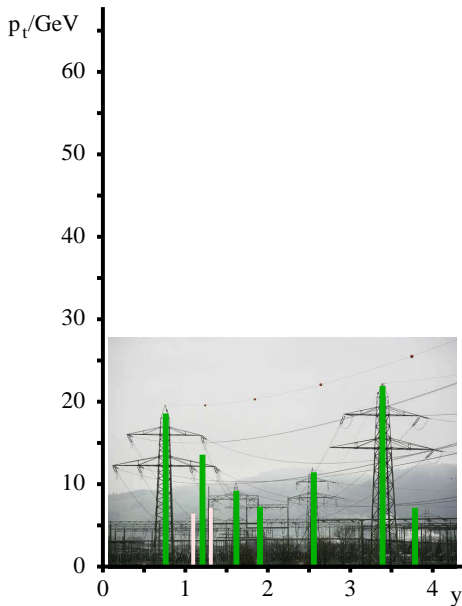
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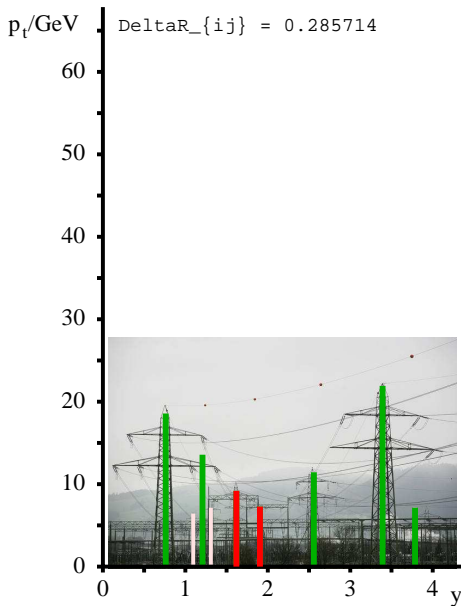
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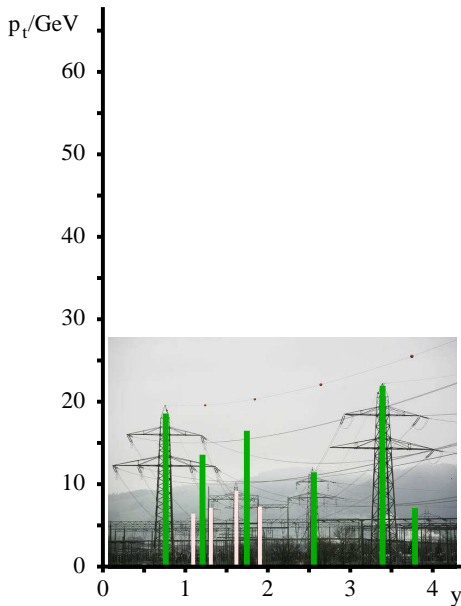
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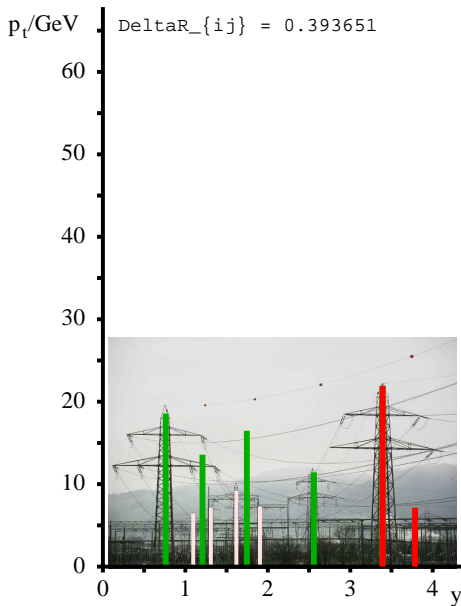
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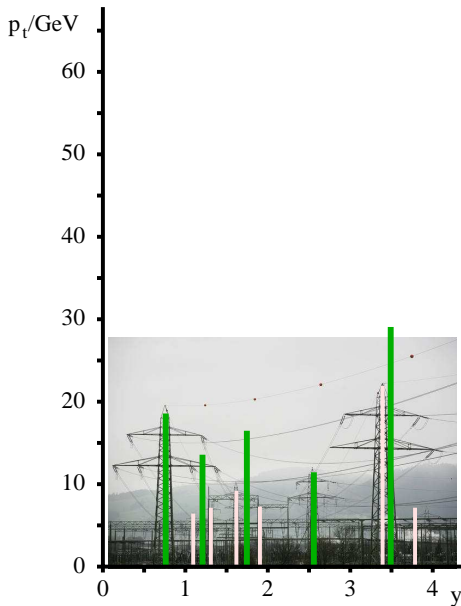
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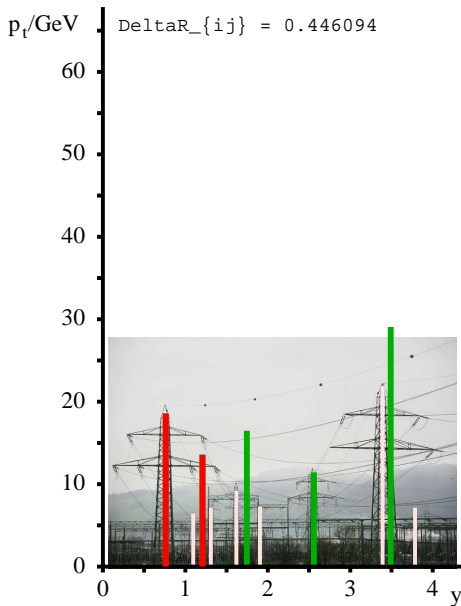
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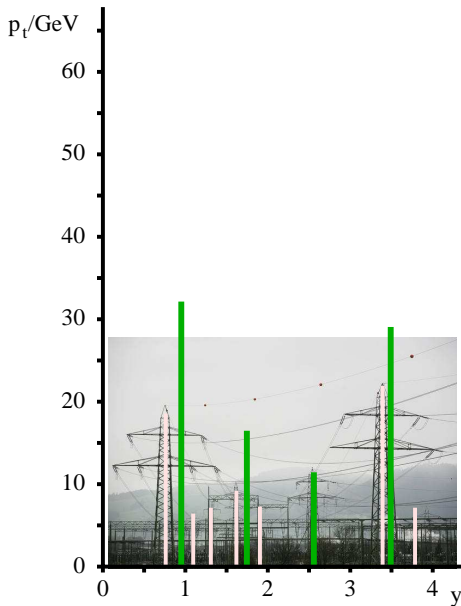
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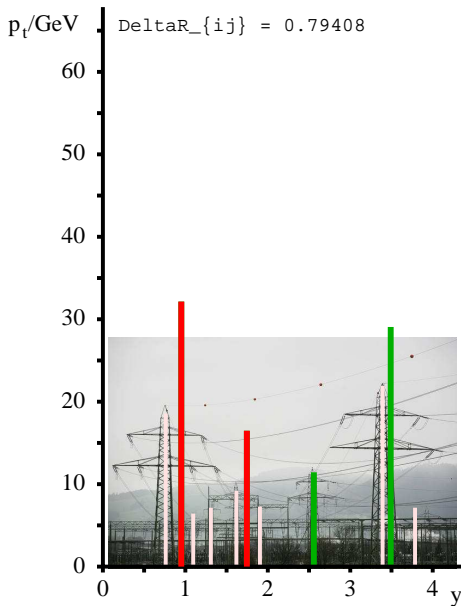
ϕ assumed 0 for all towers



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

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

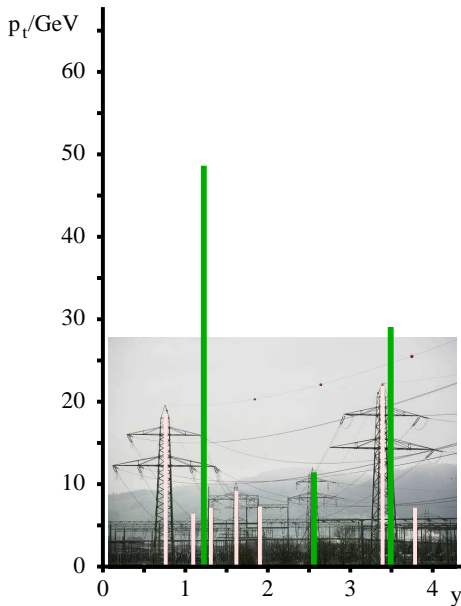
ϕ assumed 0 for all towers



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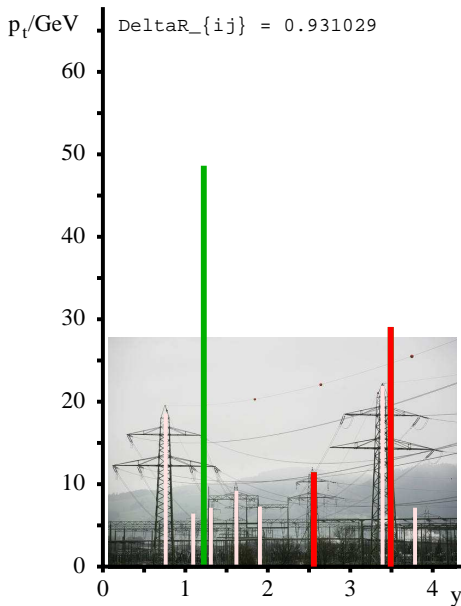
ϕ assumed 0 for all towers



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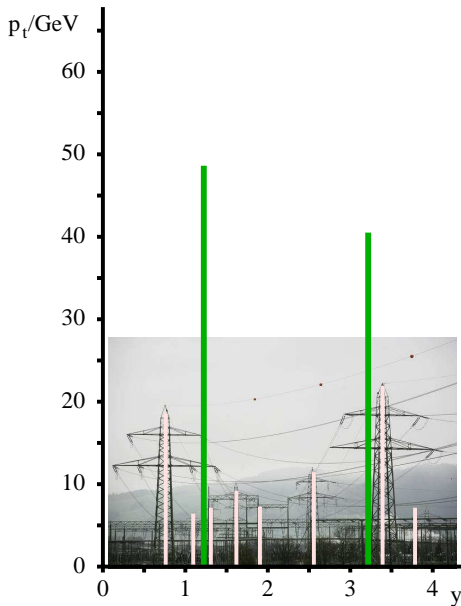
ϕ assumed 0 for all towers



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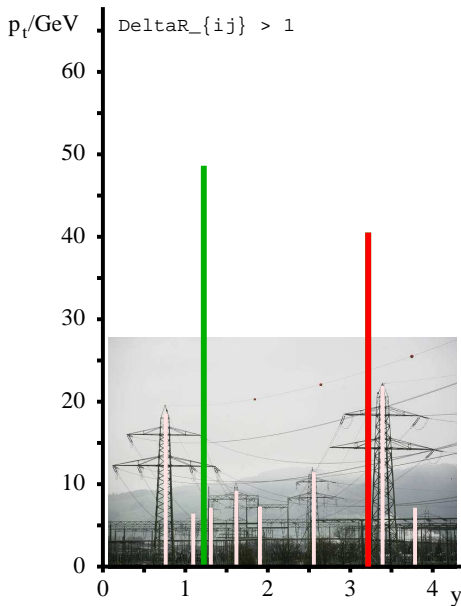
ϕ assumed 0 for all towers



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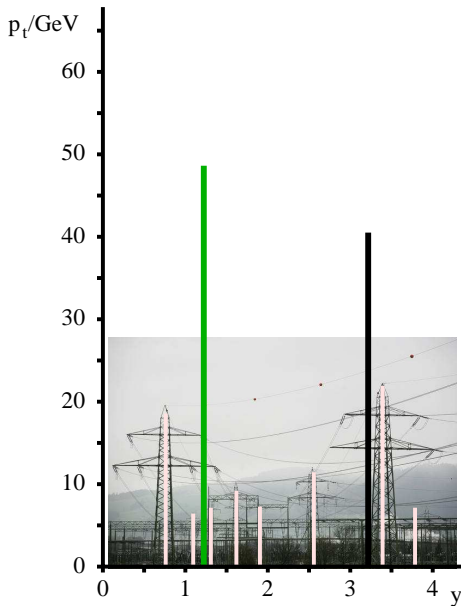
ϕ assumed 0 for all towers



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

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

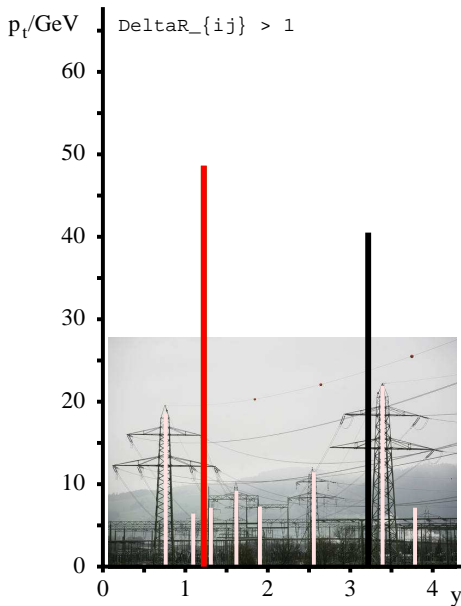
ϕ assumed 0 for all towers



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

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

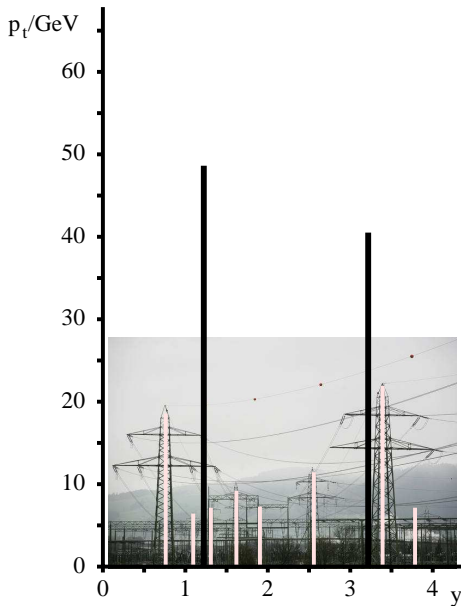
ϕ assumed 0 for all towers



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



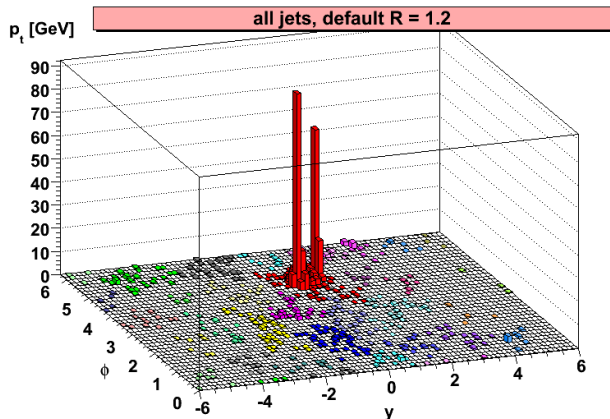
Example clustering with C/A algorithm, $R = 1.0$

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SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



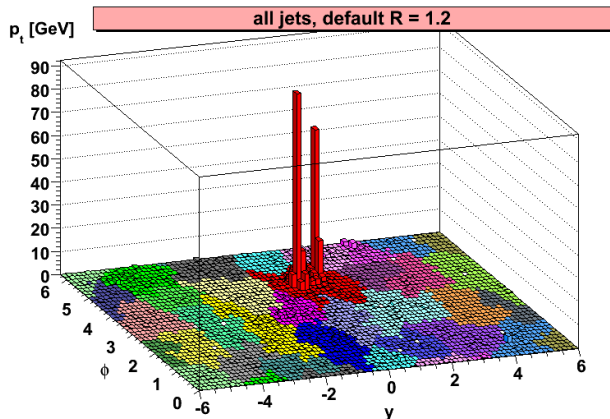
Zbb BACKGROUND

Cluster event, C/A, R=1.2

arbitrary norm.

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

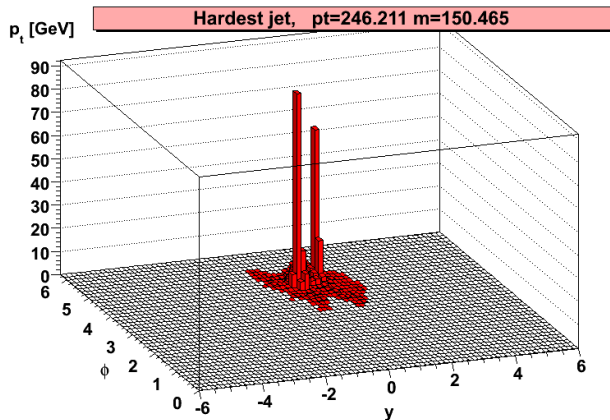


Zbb BACKGROUND

Fill it in, \rightarrow show jets more clearly

arbitrary norm.

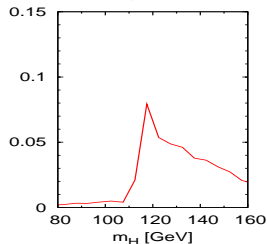
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Consider hardest jet, $m = 150$ GeV

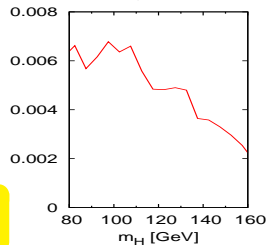
SIGNAL

$200 < p_{tZ} < 250$ GeV



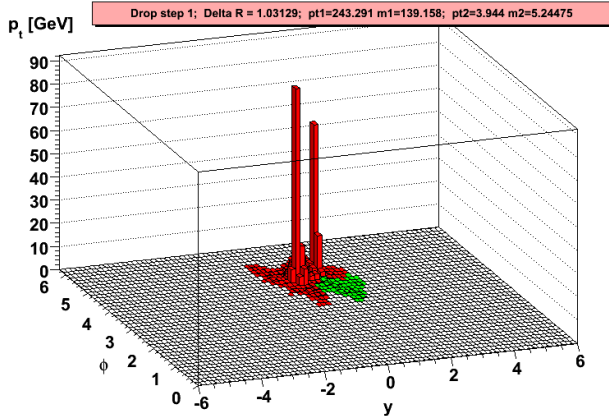
Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



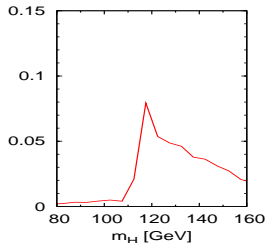
arbitrary norm.

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



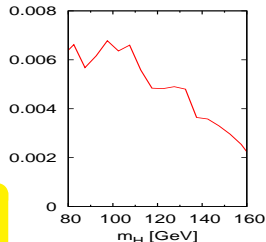
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

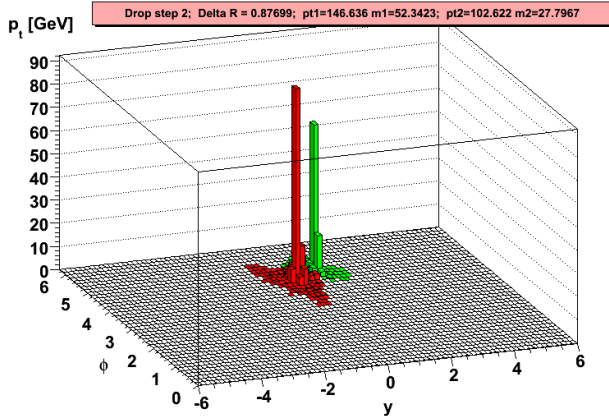
$200 < p_{tZ} < 250$ GeV



split: $m = 150$ GeV, $\frac{\max(m_1, m_2)}{m} = 0.92 \rightarrow$ repeat

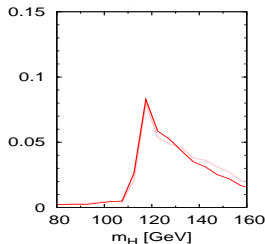
arbitrary norm.

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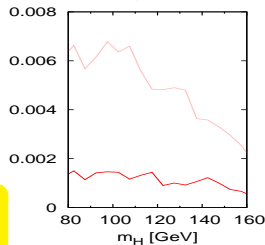
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

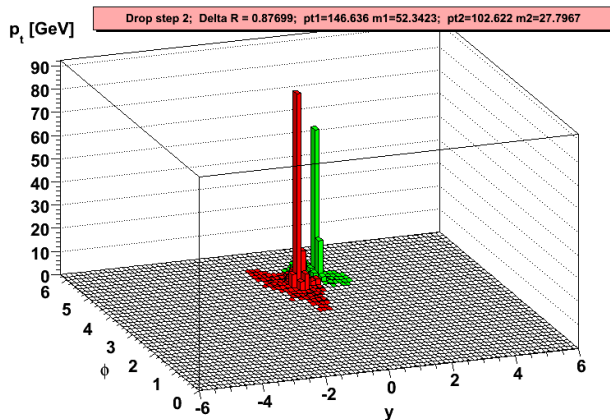
$200 < p_{tZ} < 250$ GeV



split: $m = 139$ GeV, $\frac{\max(m_1, m_2)}{m} = 0.37 \rightarrow$ mass drop

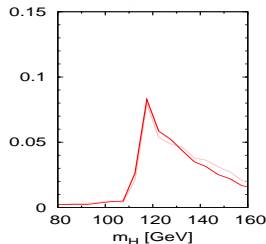
arbitrary norm.

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



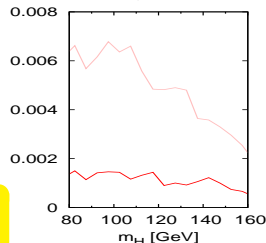
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

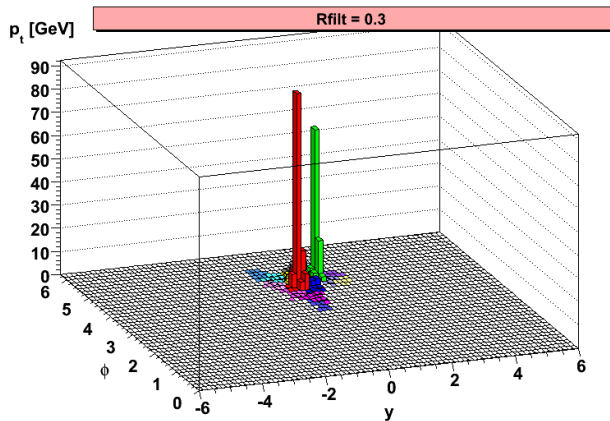
$200 < p_{tZ} < 250$ GeV



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

arbitrary norm.

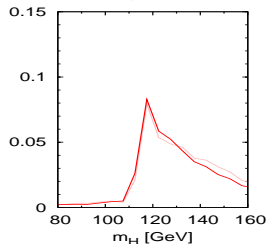
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



$R_{filt} = 0.3$

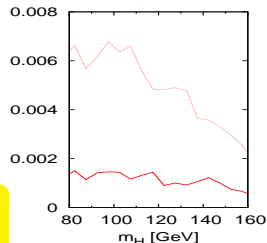
SIGNAL

$200 < p_{tZ} < 250$ GeV



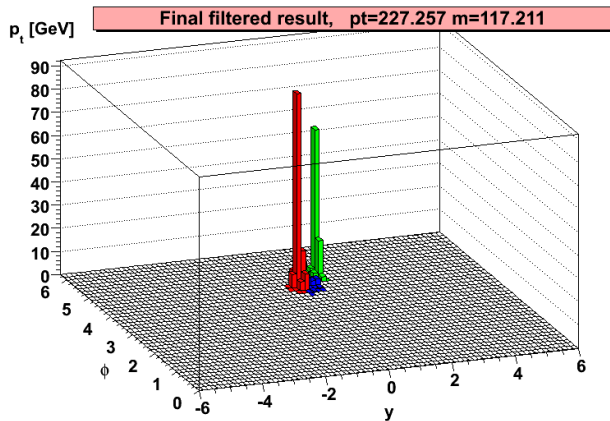
Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



arbitrary norm.

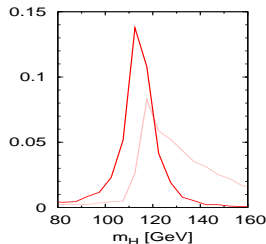
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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

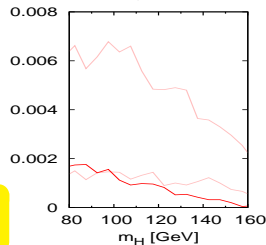
SIGNAL

$200 < p_{tZ} < 250$ GeV



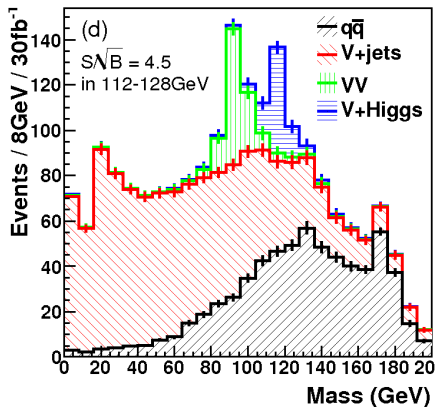
Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



arbitrary norm.

3 channels combined



Particle-level analysis

Butterworth, Davison, Rubin & GPS '08

Herwig 6.5 + Jimmy 4.3 + FastJet 2.3

3 channels:

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

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!**

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

3.7 σ for 30 fb⁻¹

ATL-PHYS-PUB-2009-088

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

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

Comparison to other channels at ATLAS ($m_H = 120$, 30 fb⁻¹):

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

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

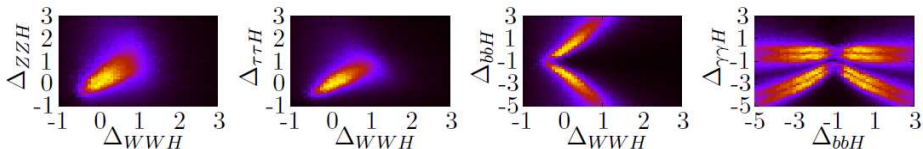
Except perhaps boosted $t\bar{t}H$; Plehn, GPS & Spannowsky '09

NB: further improvements may be possible, e.g. Soper & Spannowsky '10

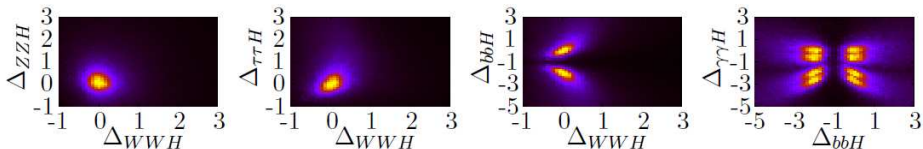
Higgs coupling measurements

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 $VH, H \rightarrow b\bar{b}$



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



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

Boosted taggers have seen a lot of other work in the past two years, especially for high- p_t top quarks.

For more info, see EXTRAS.

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"

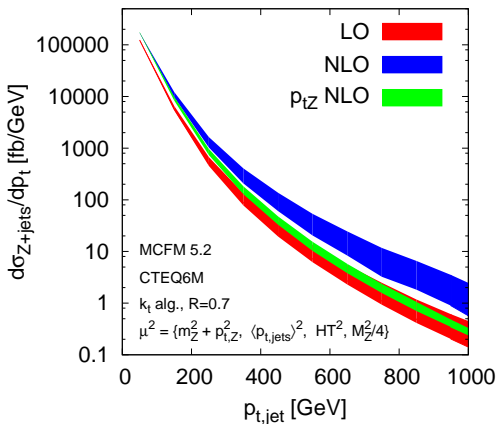
From second part: QCD at LHC is not *just* about calculating backgrounds. Learning to "view" events properly can have a major impact.

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 section (LHC)

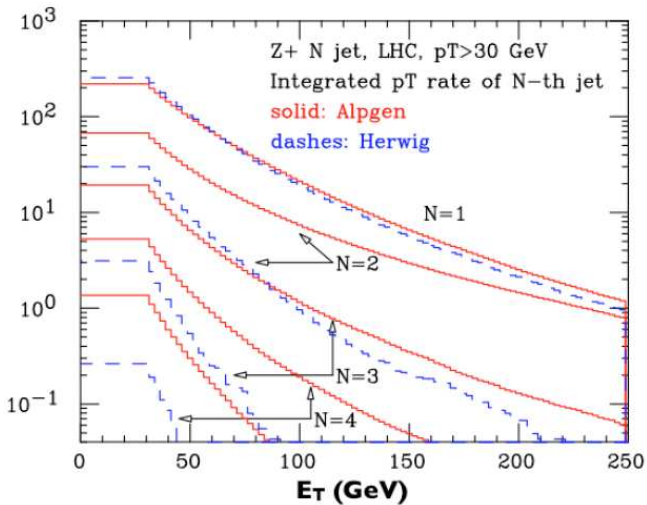


Plot distribution for p_{tZ} .

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 ($\sim p_{tZ}$)?

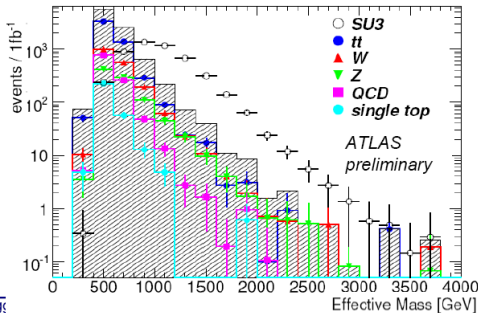
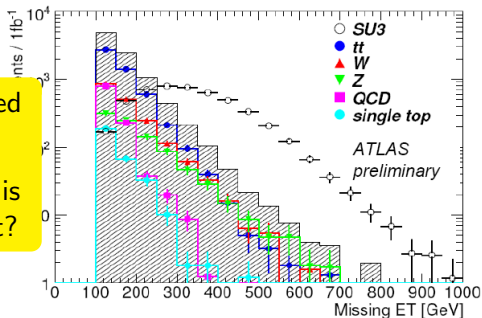
Is this because Eff.Mass ($\sim p_{t,jet}$) is
enhanced in bkgd, but MET is not?

- at least 1 jet with $PT > 100 \text{ GeV}$
- 0 lepton (e, μ) with $PT > 20 \text{ GeV}$
- MET > 100 GeV
- MET > 0.2 effective mass
- Transverse Sphericity $ST > 0.2$
- $\Delta\phi(ET - jet i) > 0.2$ ($i = 1, 2, 3$)

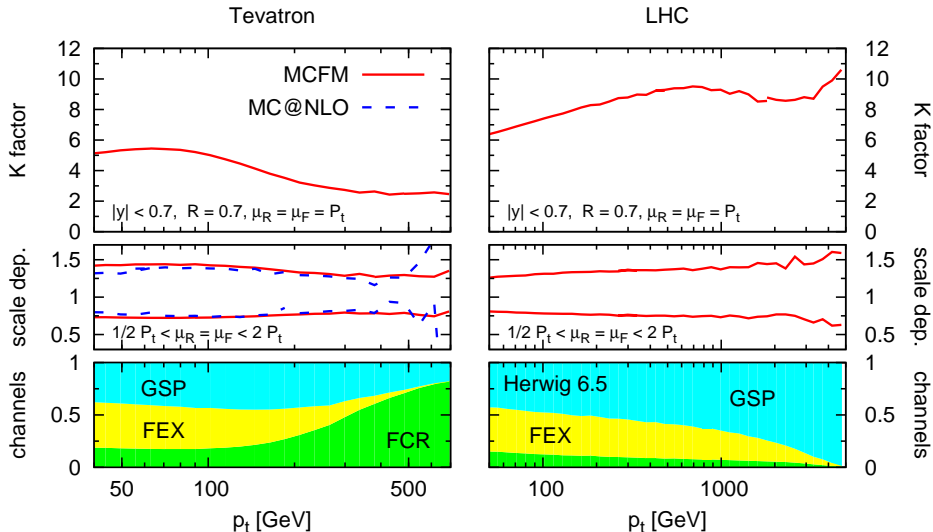
■ Main backgrounds:

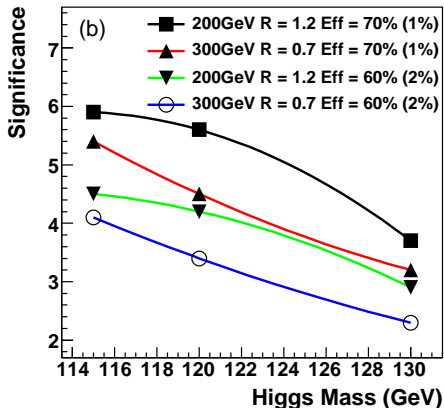
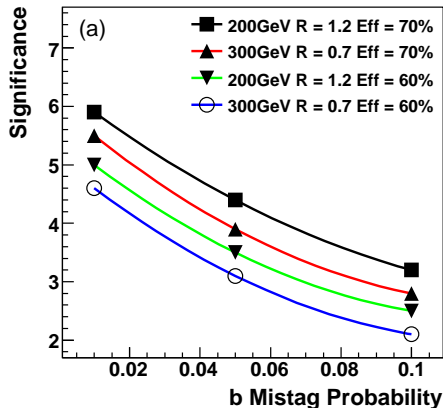
- tt
- W+jets
- Z+jets
- QCD

SM	0-1
tt	62%
W	17%
Z	10%
QCD	10%



Another example: b -jet production

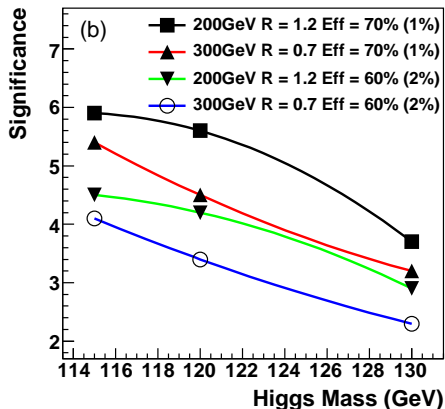
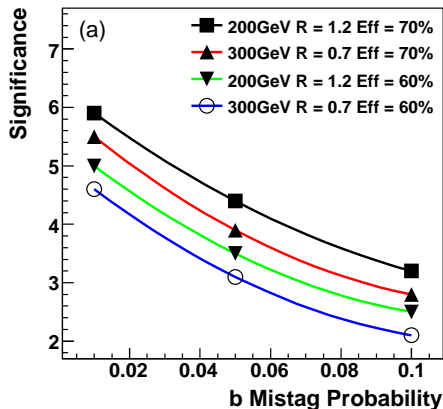


Impact of b -tagging, Higgs mass

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

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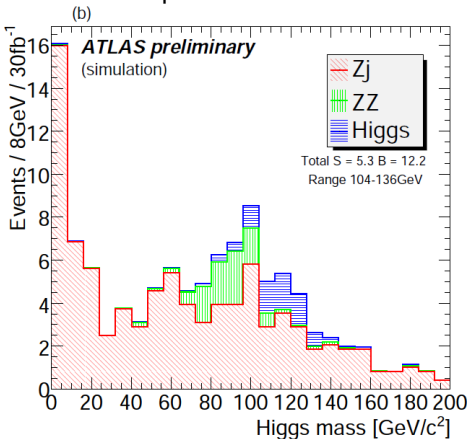
In nearly all cases, suitable for extracting $b\bar{b}H$, WWH , ZZH couplings

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 $t \rightarrow bW$, $W \rightarrow cs$, 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)

Leptonic channel

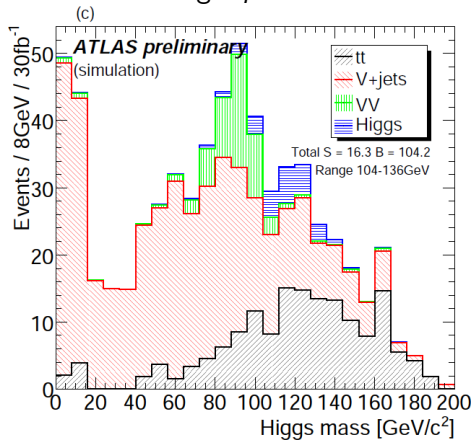


What changes compared to particle-level analysis?

~ 1.5 σ as compared to 2.1 σ

Expected given larger mass window

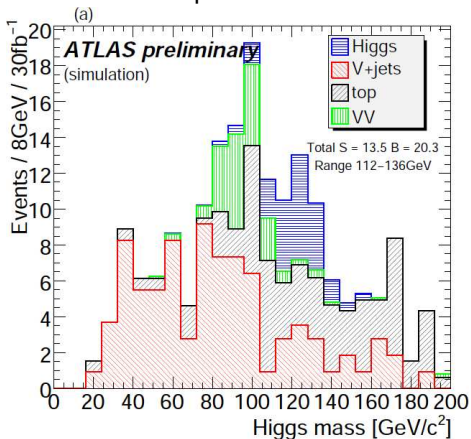
Missing E_T channel



What changes compared to particle-level analysis?

~ 1.5 σ as compared to 3 σ
 Suffers: some events redistributed to semi-leptonic channel

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

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 $m_H = 120 \text{ GeV}$

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

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

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

Extracted from 0901.0512

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.

High- p_t top production often envisaged in New Physics processes.

~ 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} + θ_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)

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

$$t \rightarrow bl(\cancel{E}_T)$$

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

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

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 subjects 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

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

$$t \rightarrow b\ell(\cancel{E}_T)$$

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

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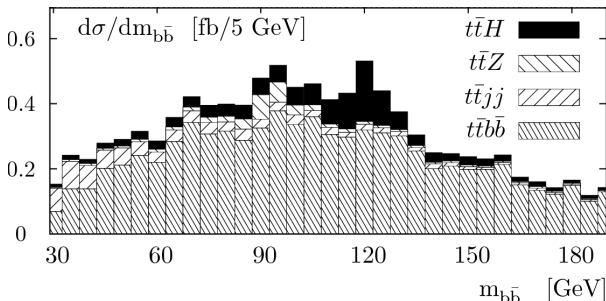
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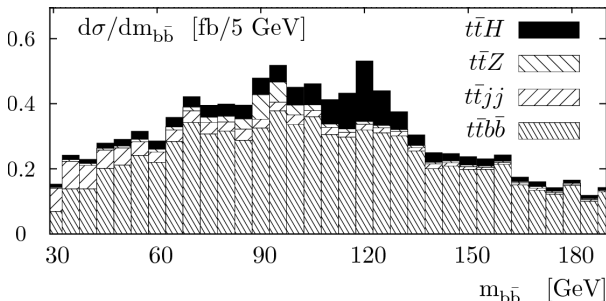
	S [fb]	B [fb]	S/B	S/\sqrt{B} (100 fb $^{-1}$)
$m_H = 115$ GeV	0.57	1.39	1/2.4	4.8
120 GeV	0.48	1.36	1/2.8	4.1
130 GeV	0.29	1.21	1/4.2	2.6

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



	S [fb]	B [fb]	S/B	S/\sqrt{B} (100 fb^{-1})
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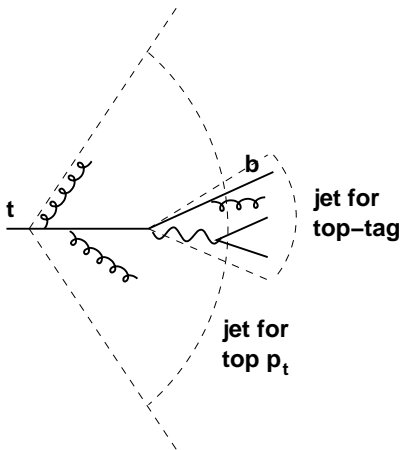
Doesn't recover $t\bar{t}H$
 as a discovery
 channel, but promising
 for coupling
 measurements

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

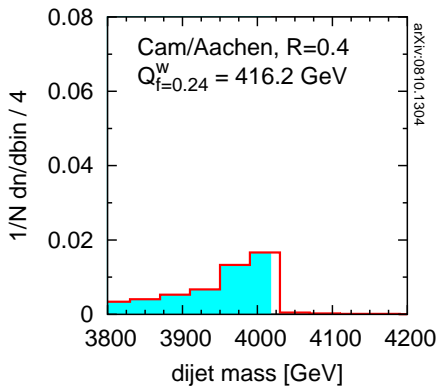
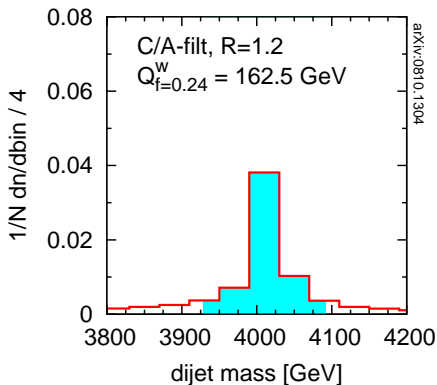
Use small coneqq, $M = 4000$ GeVUse large coneqq, $M = 4000$ GeV

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/>