Jet substructure and SUSY

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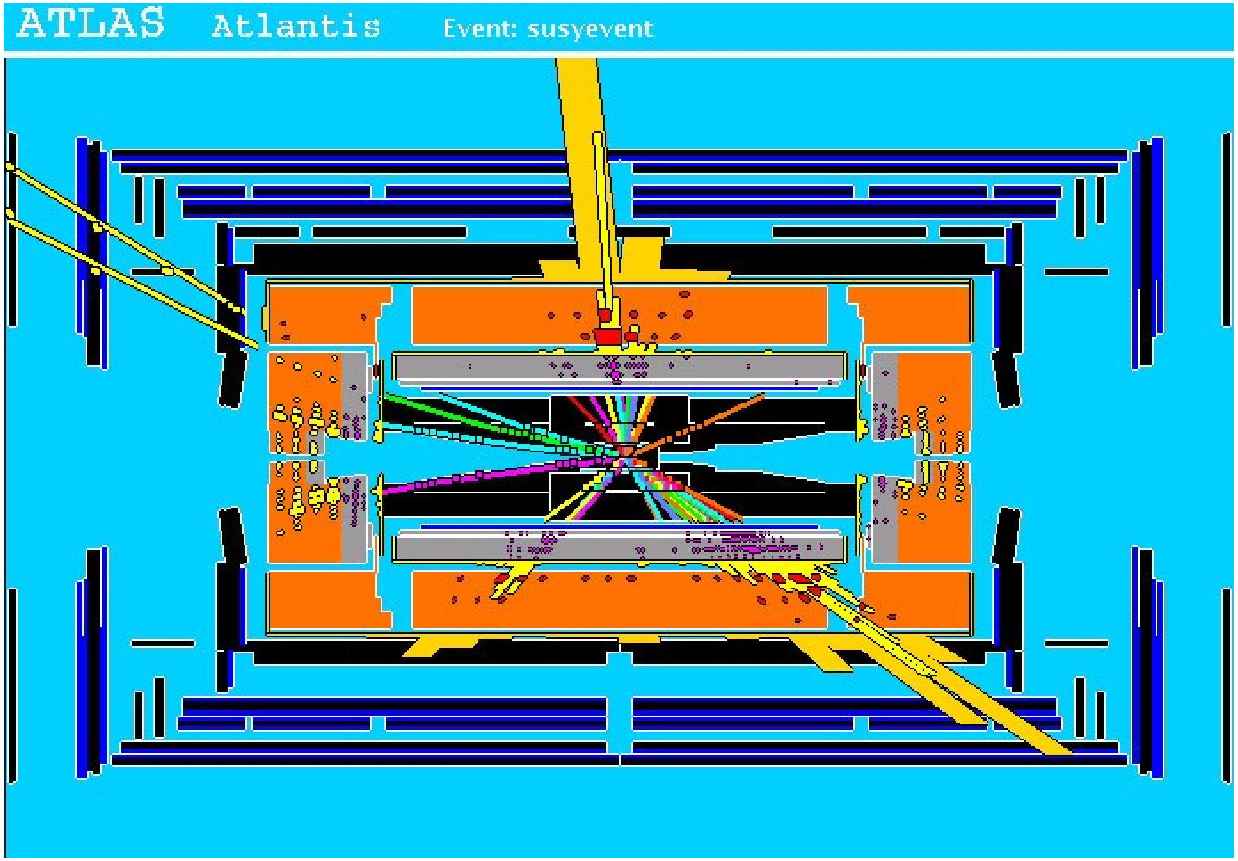
Content

- Introduction to jets @ hadron colliders.
- Using «fat-jets» in SUSY.
- Three applications of jet substructure in SUSY:
  - Massive bosons in SUSY cascade decays.
    [Butterworth, Ellis, ARR, hep-ph/0702150]
  - Neutralino decay to three quarks @ the LHC.
    [Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]
  - Gluino decay to three quarks @ the Tevatron.
    [ARR, Salam, Wacker, arXiv:1005.1229]
- Conclusions.

Stating the obvious...

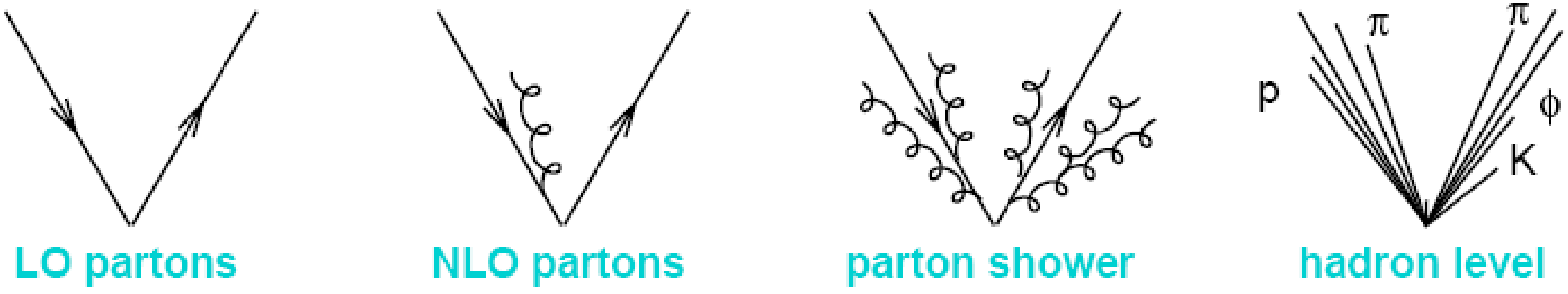
- The LHC is a proton-proton collider.
- If light enough, dominant NP cross section comes from the production of color charged NP particles.
- It seems probable that the lightest NP particle is a (super?)WIMP.
- Decays should rid themselves of color charge **multiple (high pT?) jets** and **missing energy** as a minimum **NP expectation @ the LHC**.

What's in a jet?



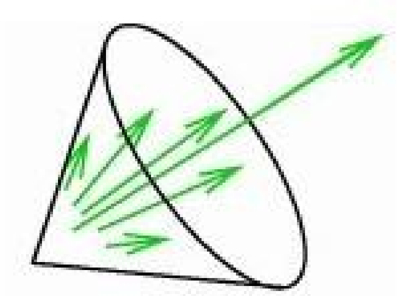
What's in a jet?

- Which partons/particles/calorimetry towers (hereafter called objects) are joined into a jet?
  - Jet algorithm.
  - Parameters of algorithm (*e.g.* cone radius R).
- How are their four-momenta joined?
  - Four-vector sum / Snowmass (E_T scheme).



Jet algorithms

- «Cone»
  - Try to find geometric regions that maximise the energy (not always a cone!).
  - Sort of mimics the event-display + eye method.



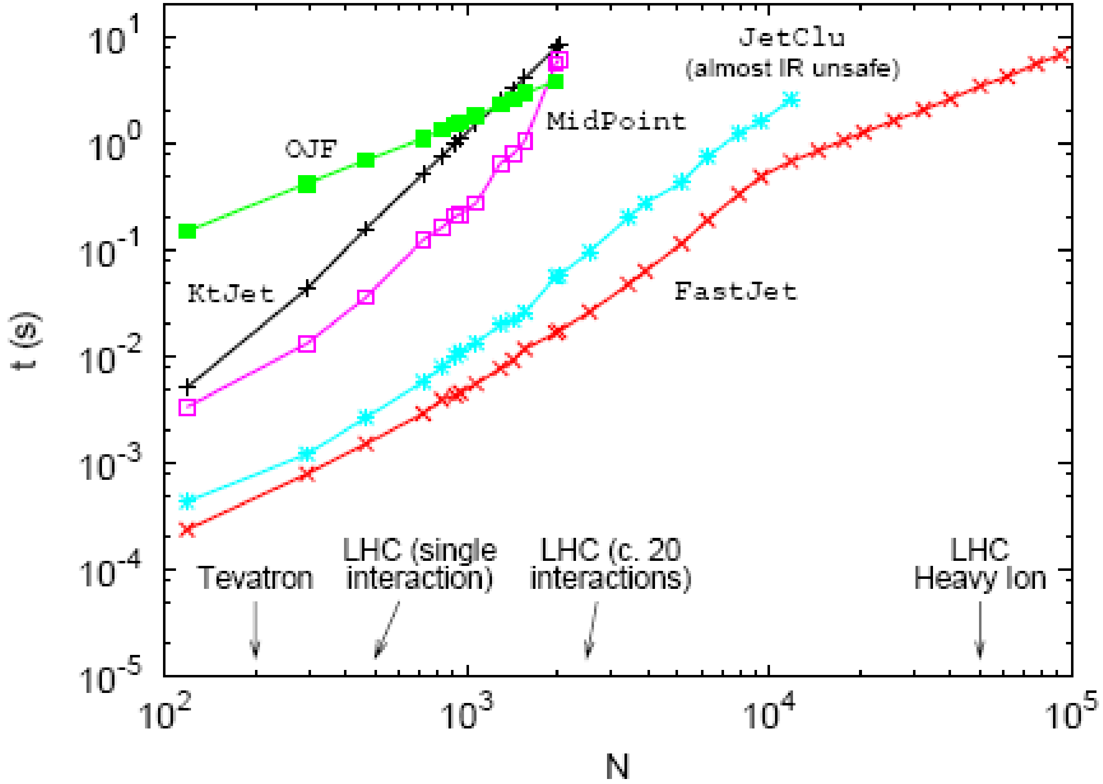
- «Cluster»
  - Start from the elementary objects available, and perform an iterative pair-wise clustering to build larger objects (using either geometrical or kinematical properties for clustering rules).
  - Sort of inverts the QCD parton shower idea.

Jet algorithms - issues

- Cone
  - (historically) **infrared and/or collinear unsafe**.
  - Solved in **SiSCone** [Salam, Soyez, arXiv:0704.0292]
- Cluster
  - Was thought to be too slow for high mulitplicities (N^3).
  - Solved in **fastJet** implementation (N ln N).

  [Cacciari, Salam, hep-ph/0512210]
- The pragmatic approach: different algorithms have different advantages, *e.g* wrt to ISR/FSR.

Jet algorithms - issues



Cluster example: kT-algorithm

- For every pair of objects (k,l) calculate the distance *d*

$$d_{kl} = \min(p_{Tk}^2, p_{Tl}^2)\ \Delta R_{kl}^2 / R^2$$

$$d_{kB} = p_{kT}^2, \quad d_{lB} = p_{lT}^2$$

- If a d_{kB} is smaller, object is labeled as jet and removed.
- If d_{kl} is smaller, k and l are merged (adding 4-vectors).
- Process repeated until all objects are gone.

Cluster example: kT-algorithm(s)

- For every pair of objects (k,l) calculate the distance *d*

$$d_{kl} = \min\left(p_{Tk}^{2n}, p_{Tl}^{2n}\right) \Delta R_{kl}^{2} / R^{2}$$

$$d_{kB} = p_{kT}^{2n}, \quad d_{lB} = p_{lT}^{2n}$$

- If a d_{kB} is smaller, object is labeled as jet and removed.
- If d_{kl} is smaller, k and l are merged (adding 4-vectors).
- Process repeated until all objects are gone.
- n=1: kT, n=0: Cambridge/Aachen, n=-1 anti-kT.

Subjet separation scale

Idea taken from WW scattering study. Undo the last clustering (1), and look at **subjet separation scale** for a **W candidate**:

$$y_1 \equiv \frac{d_{kl}^{(1)}}{p_T^2}$$

kT algorithm distance

where pT is the total jet momentum.

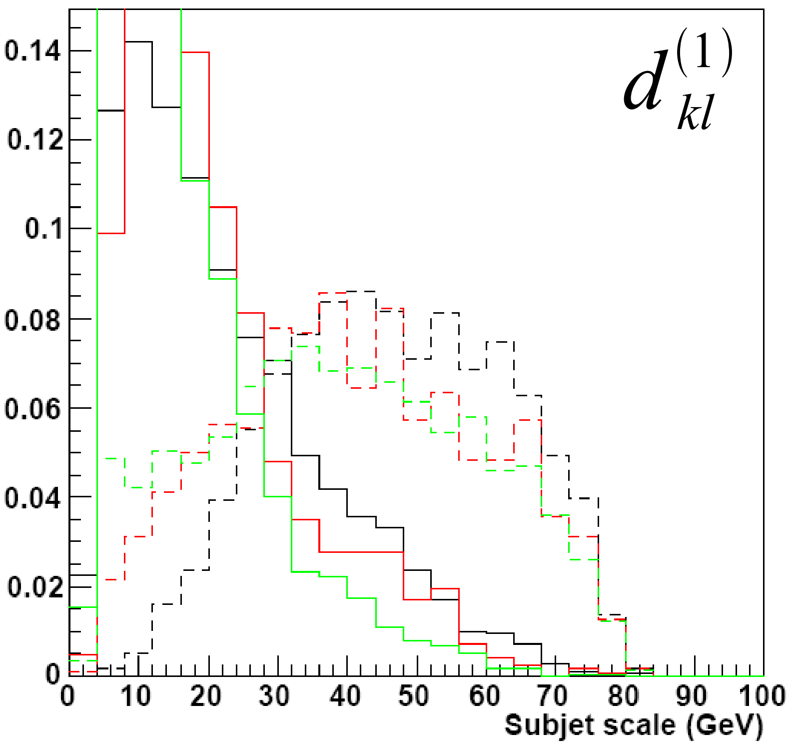
For collimated jets from the decay of a boosted particle the expectation is that

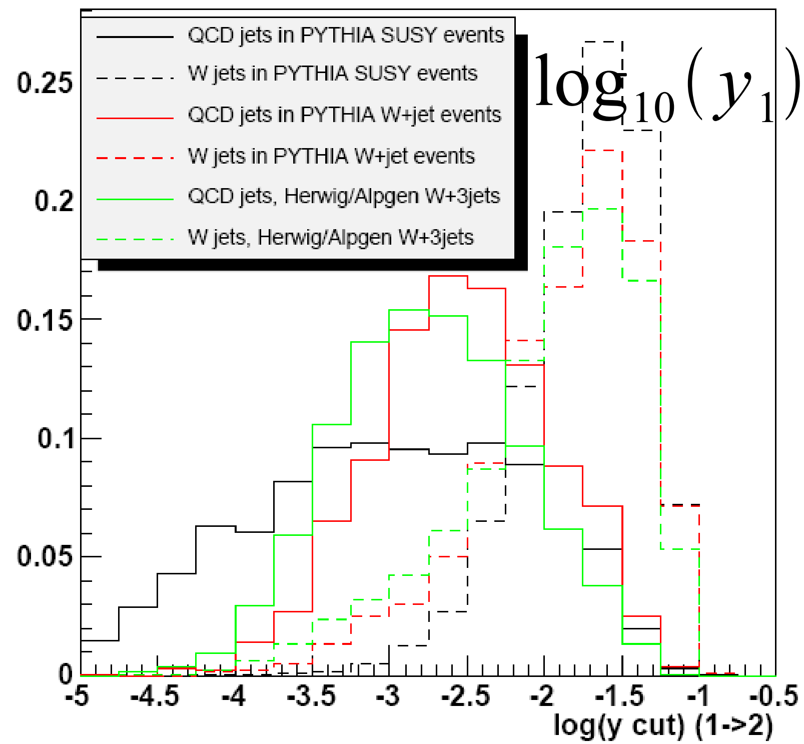
$$y_1 p_T^2 = O(M^2)$$

while for QCD jets y_1 « 1.

[Butterworth *et al.*, hep-ph/0201098]

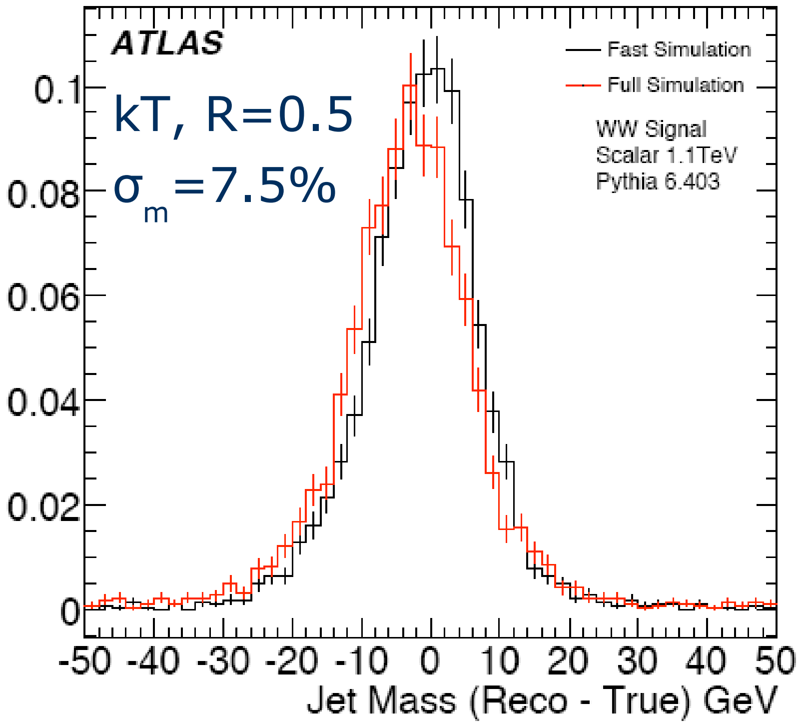
Subjet separation scale

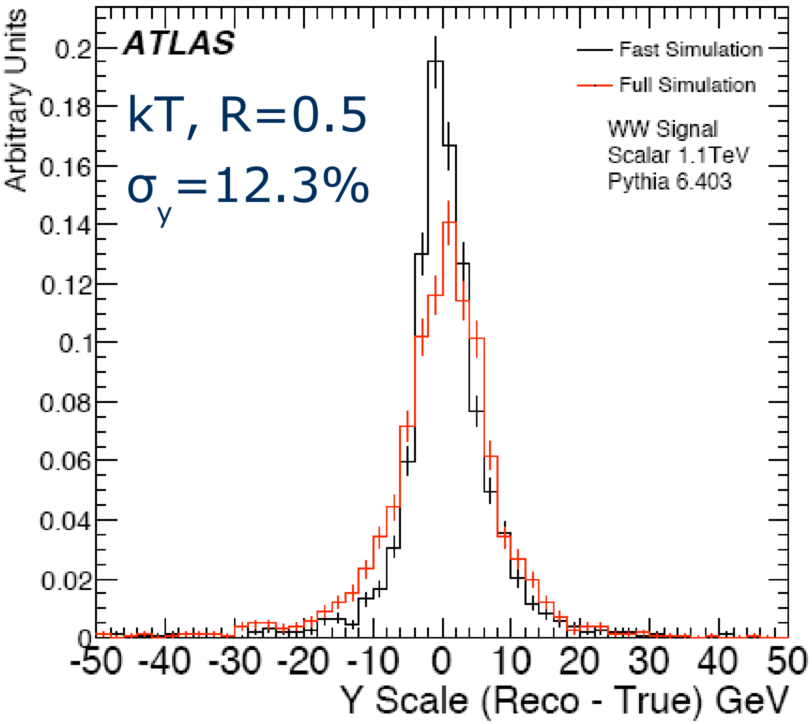




[Butterworth, Ellis, ARR, hep-ph/0702150]

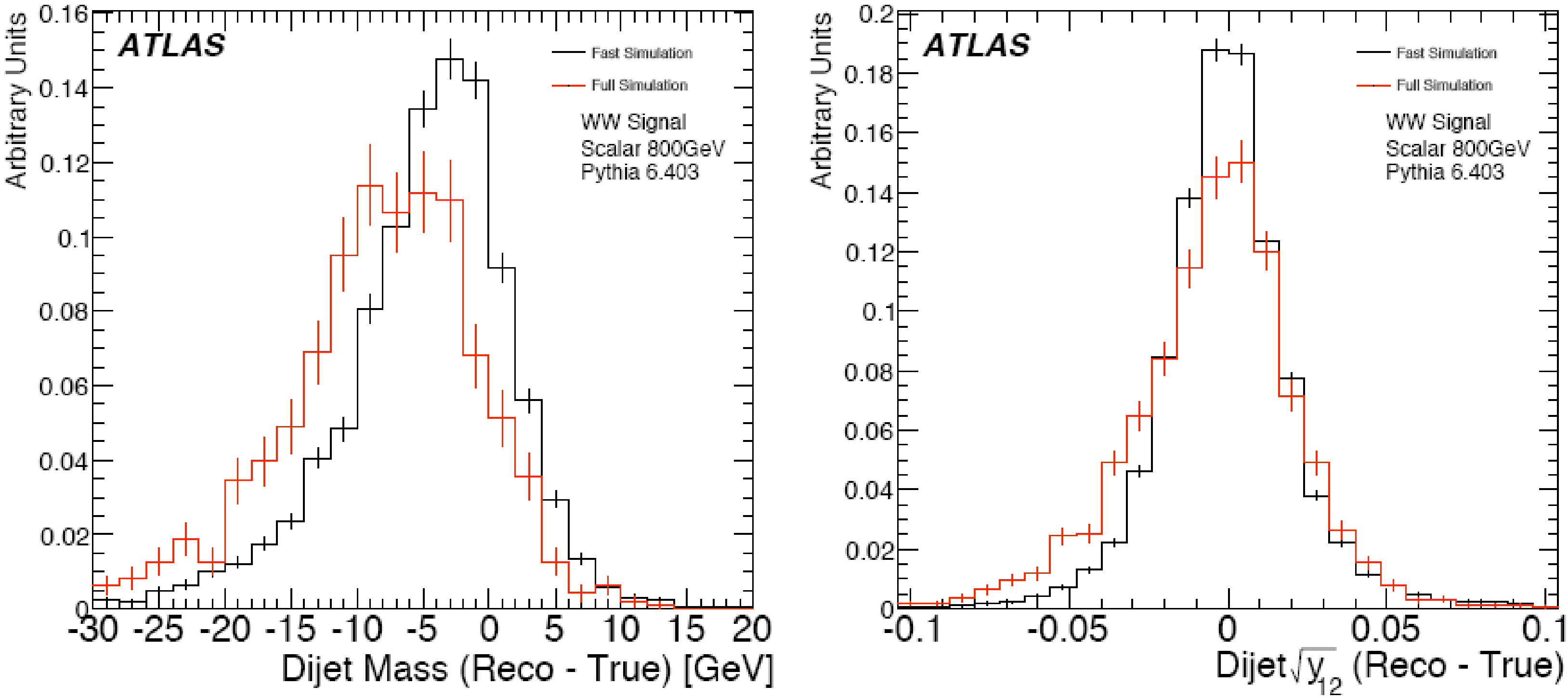
Detector resolution





[ATLAS, arXiv:0901.0512]

Using di-jets



[ATLAS, arXiv:0901.0512]

Sophisticated uses of jet substructure

- Identifying the hadronic decays of boosted massive SM particles:
  - WW scattering.
  - Discovery of Higgs in h b + bbar.
  - “Top tagging” (e.g. from heavy graviton resonances).
  - Cascade decay chains in NP.
- New Physics resonances with hadronic decays.
- Important aside: note that even our standard quark and gluon jets have “mass“! Beware of Snowmass!

Today

Case I: all-hadronic cascade decays

- We know how to do long cascade decays with «clean» leptons at the LHC, *e.g.*

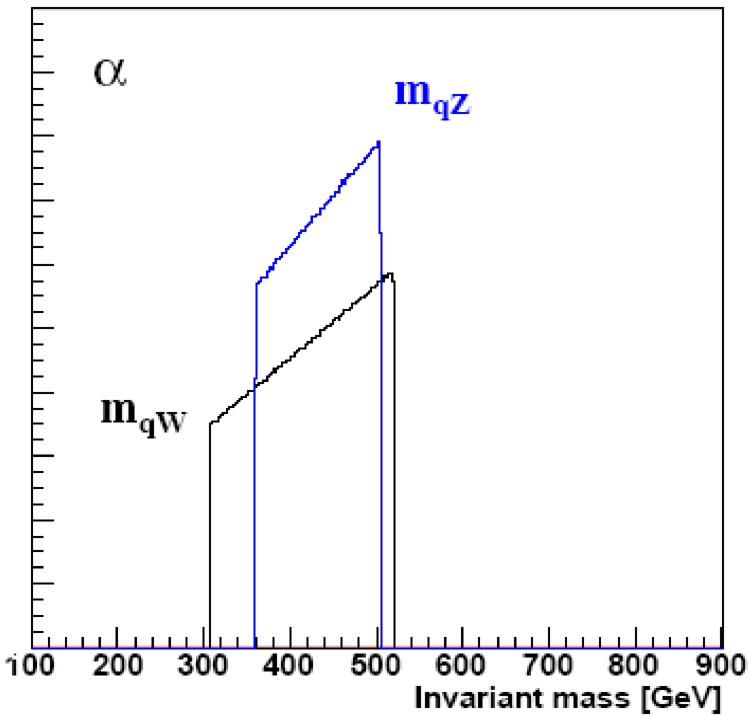
$$\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow q l^{\pm} \tilde{l}^{\mp} \rightarrow q l^{\pm} l^{\mp} \tilde{\chi}_1^0$$

- What about gaugino decays to SM bosons in SUSY?

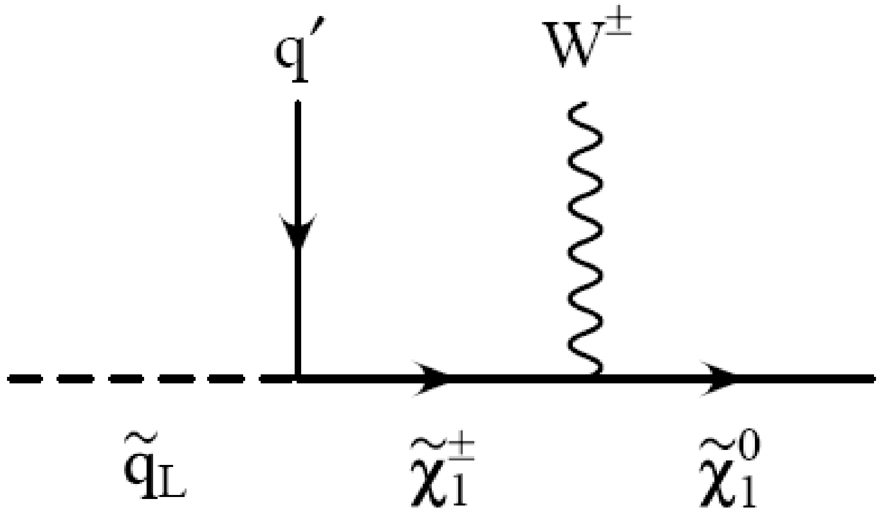
$$\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} \tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0, \quad \tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$$

The only decay that works well with leptons is $Z \rightarrow l^+ l^-$
What about $W \rightarrow q q'$ or $h \rightarrow b\bar{b}$?

Case I: all-hadronic cascade decays



Edge measurements can be used as in «standard» decay chains, taking care to include SM masses:



Case I: but why do we care?

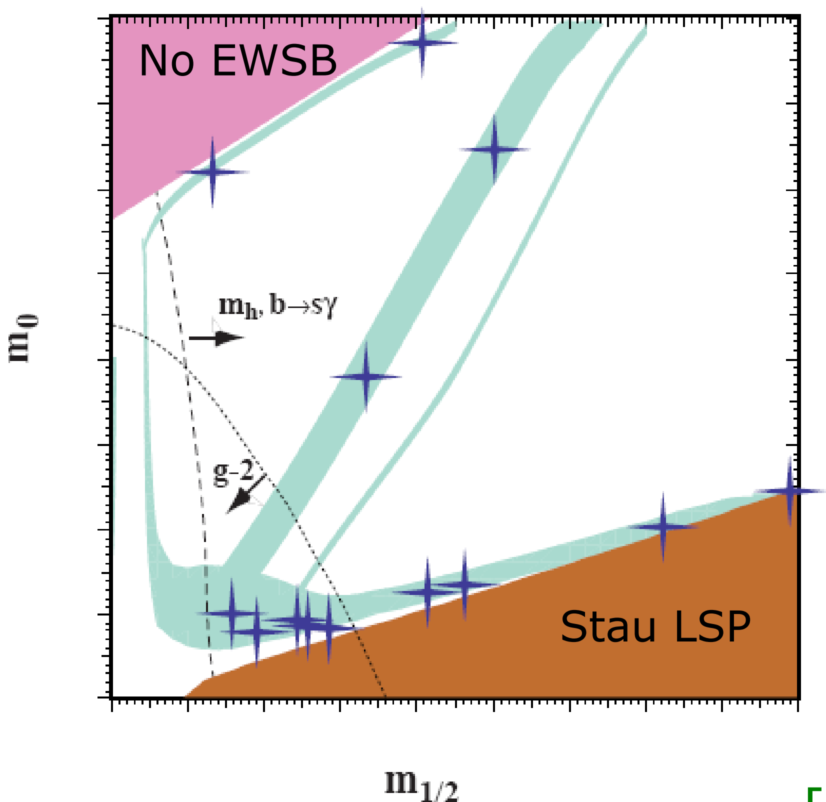


Illustration of CMSSM/mSUGRA for generic values of

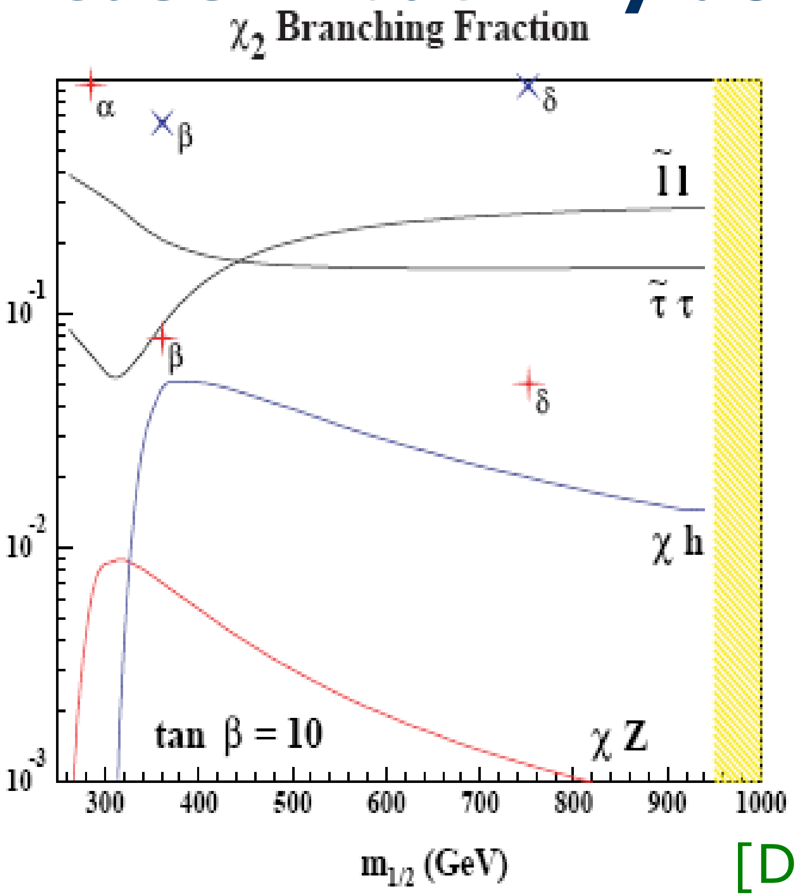
$$A_0,\ \tan\beta,\ \mathrm{sgn}\,\mu$$

Very limited production of massive SM bosons (W,Z,h) in DM allowed regions.

Small relaxation of unification assumptions can give larger BRs.

[Battaglia *et al.*, hep-ph/0106204]

Case I: but why do we care?

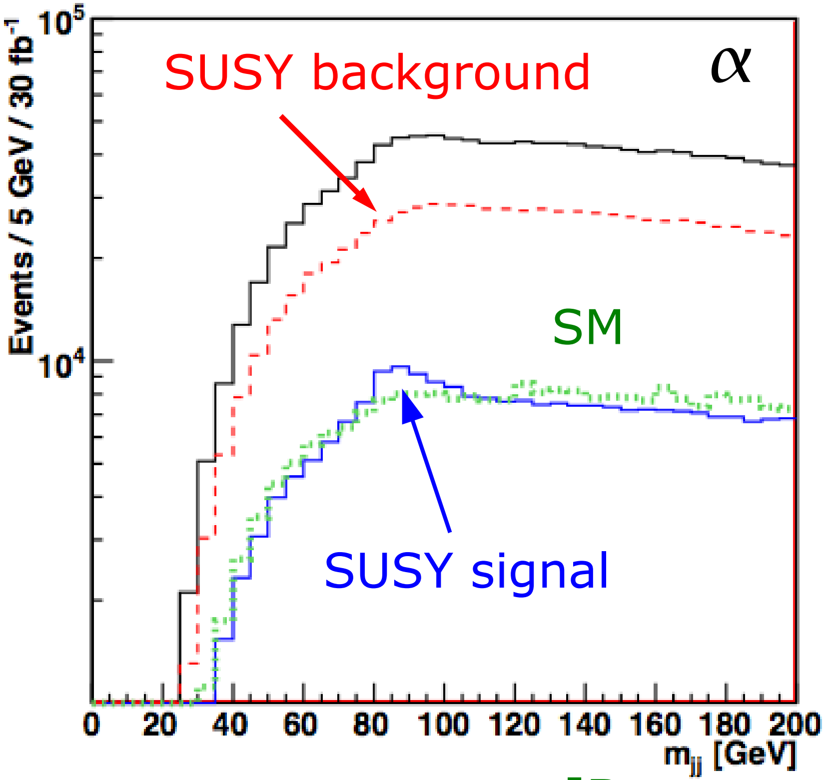


Non-Universal Higgs Mass (NUHM) and Gravitino Dark Matter (GDM) scenarios change DM allowed regions.

Point/BR	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$	$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm$
α	98.6	0.0	99.6
β	7.5	64.5	79.0
γ	0.0	0.0	99.9
δ	5.4	92.0	97.5

[De Roeck *et al.*, hep-ph/0508198]

Case I: a whole lotta hadrons



MC study using ALPGEN/Herwig6.510/JIMMY for multiple jet backgrounds.

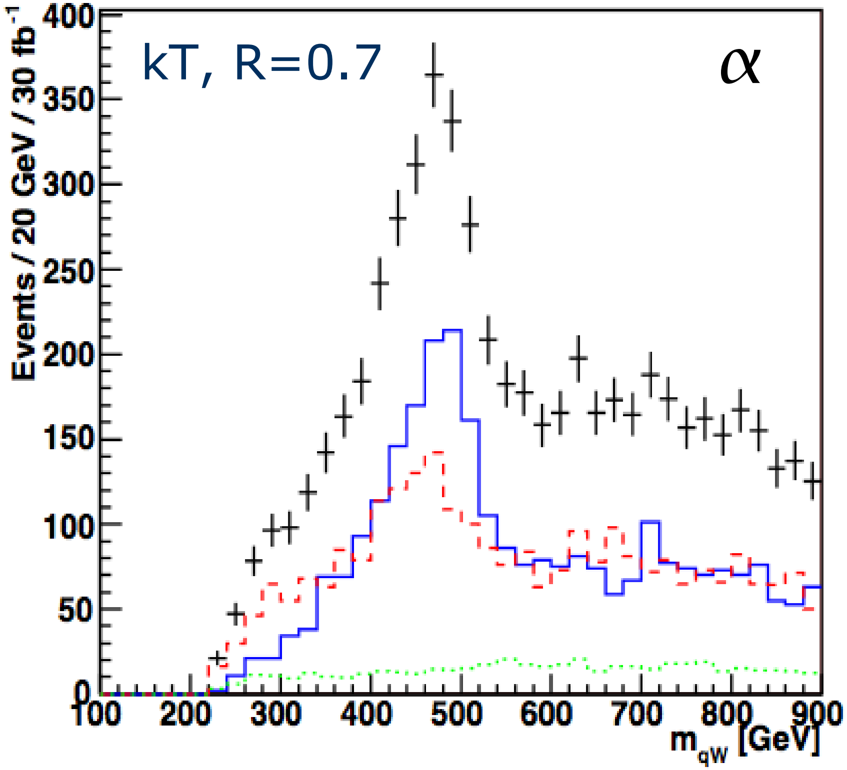
Looking for Ws in

$$\tilde{q}_L \to q' \tilde{\chi}_1^{\pm} \to q' W^{\pm} \tilde{\chi}_1^0$$

with di-jet invariant mass after 300 GeV cut on ETmiss.

[Butterworth, Ellis, ARR, hep-ph/0702150]

Case I: with di-jet substructure cuts



SM rejection cuts:

$$p_T^{\text{jet}} \geqslant 200,\ 200,\ 150\ \text{GeV}$$

$$E_T^{\text{miss}} \geqslant 300\ \text{GeV}$$

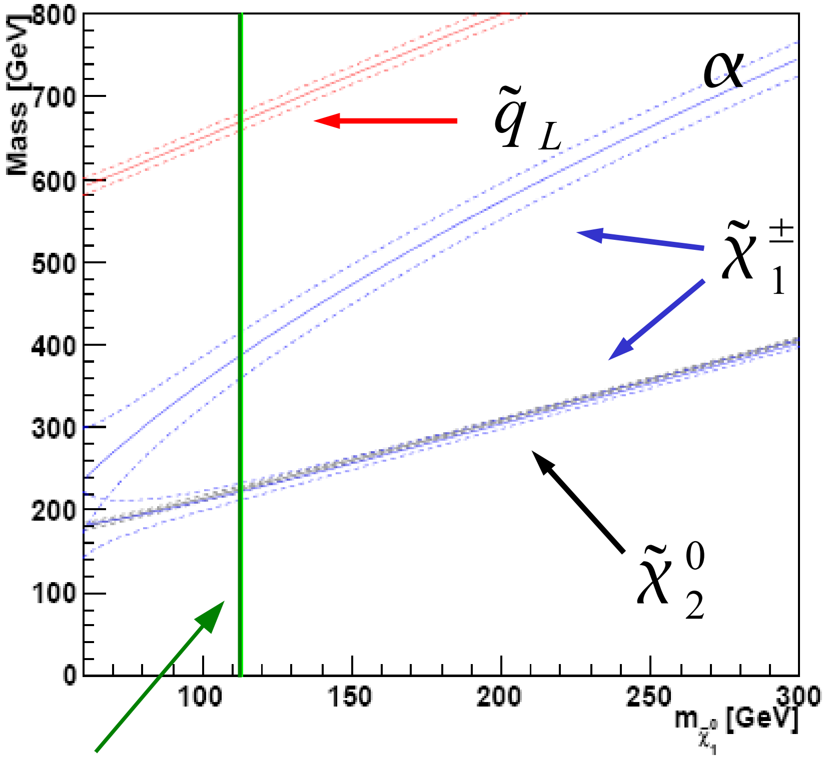
W candidate jet cuts:

$$75\ \text{GeV} < m_j < 105\ \text{GeV}$$

$$1.5 < \log_{10}\left(p_T^{\text{jet}}\sqrt{y_1}\right) < 1.9$$

[Butterworth, Ellis, ARR, hep-ph/0702150]

Case I: results



Nominal LSP mass

Using both decay chains

$$\tilde{q}_L \to q' \tilde{\chi}_1^{\pm} \to q' W^{\pm} \tilde{\chi}_1^0$$

$$\tilde{q}_L \to q \tilde{\chi}_2^0 \to q Z \tilde{\chi}_1^0$$

we get strong correlations between masses from measuring edges.

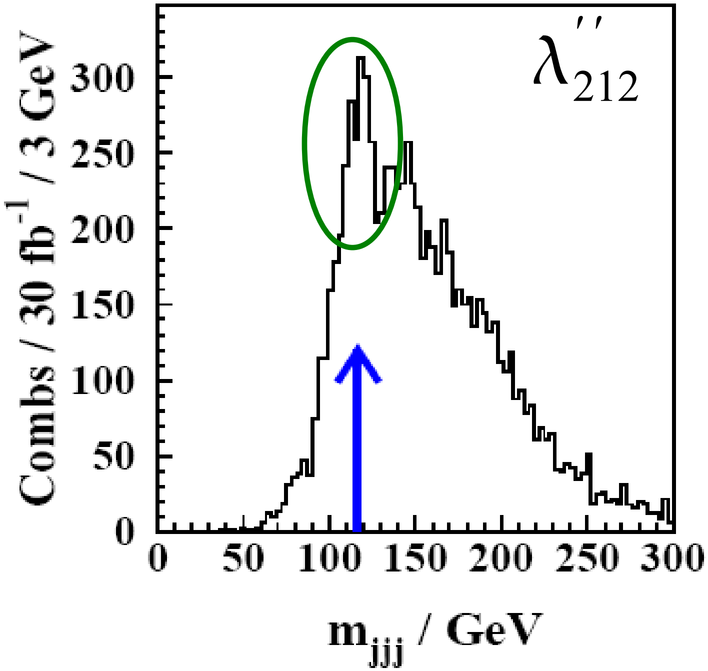
Error bands from 1σ statistical errors on edge determination.

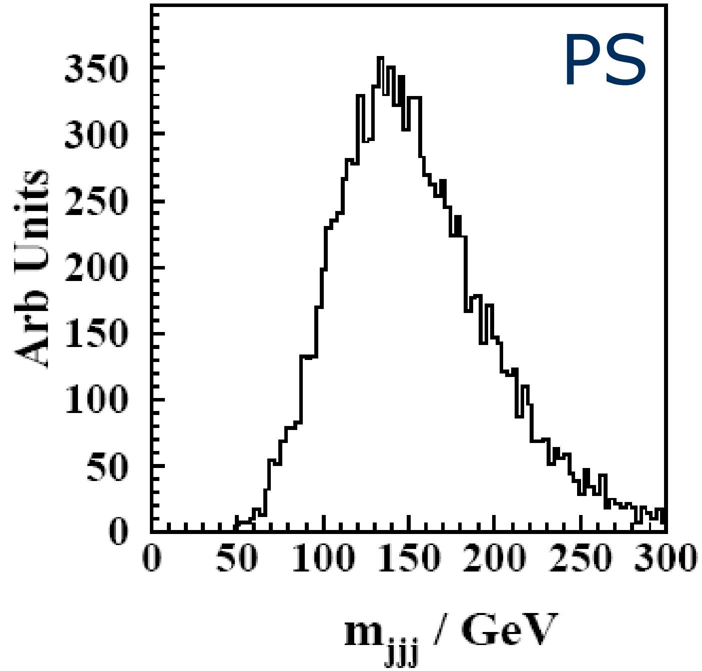
[Butterworth, Ellis, ARR, hep-ph/0702150]

Case II: hadronic RPV LSP decays

- Can we also use the hadronic W identification techniques for new particle searches?
- With R-parity violation a neutralino (N)LSP can decay promptly into three quarks ($10^{-6} < \lambda < 10^{-2}$).
- The decay $\tilde{\chi}_1^0 \rightarrow qqq$ is notoriously difficult to reconstruct unless there are heavy flavours present.
- Marginally doable if additonal leptons are present in the decay chain, but this is model dependent!

Case II: the classic literature

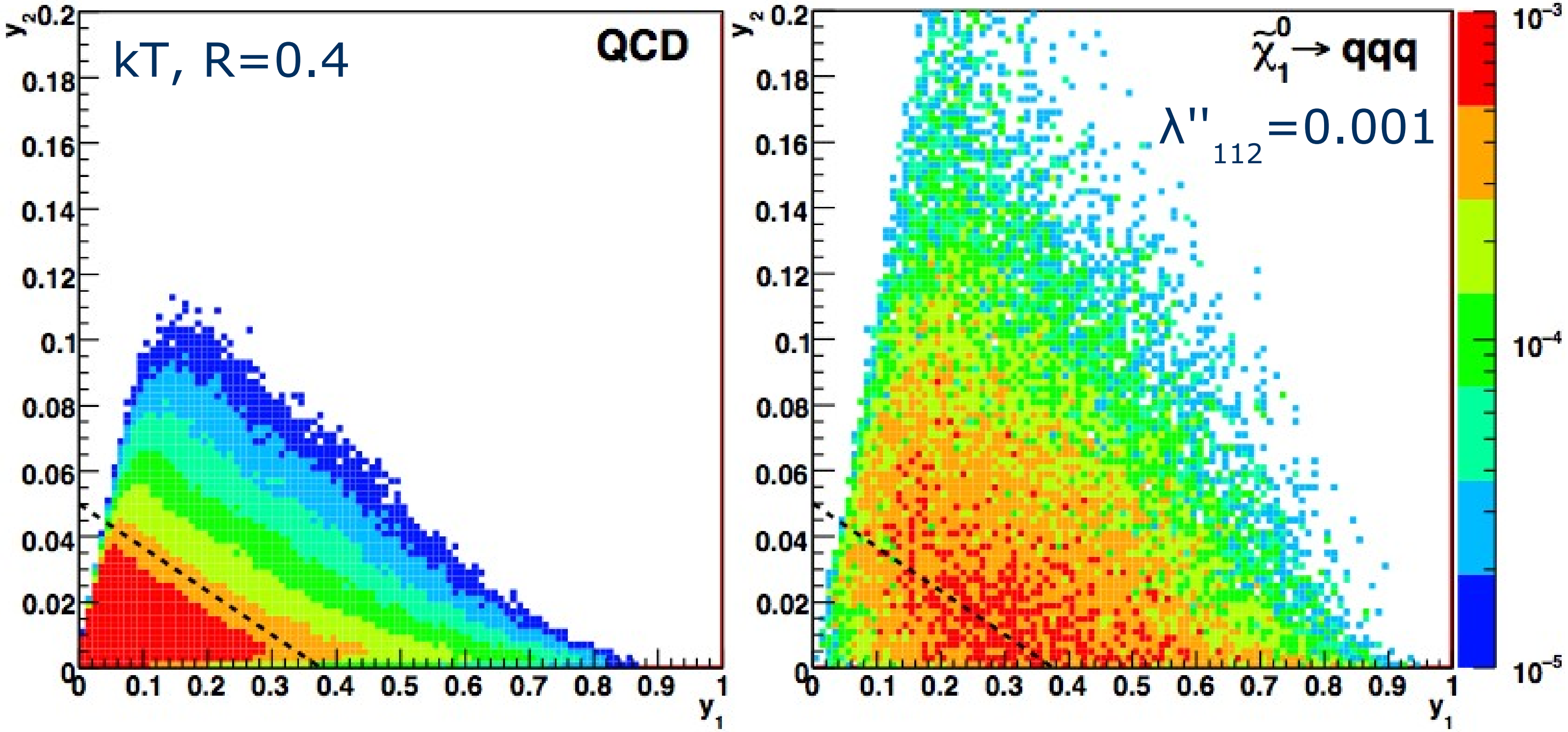




Require two leptons with p_T > 15 GeV.

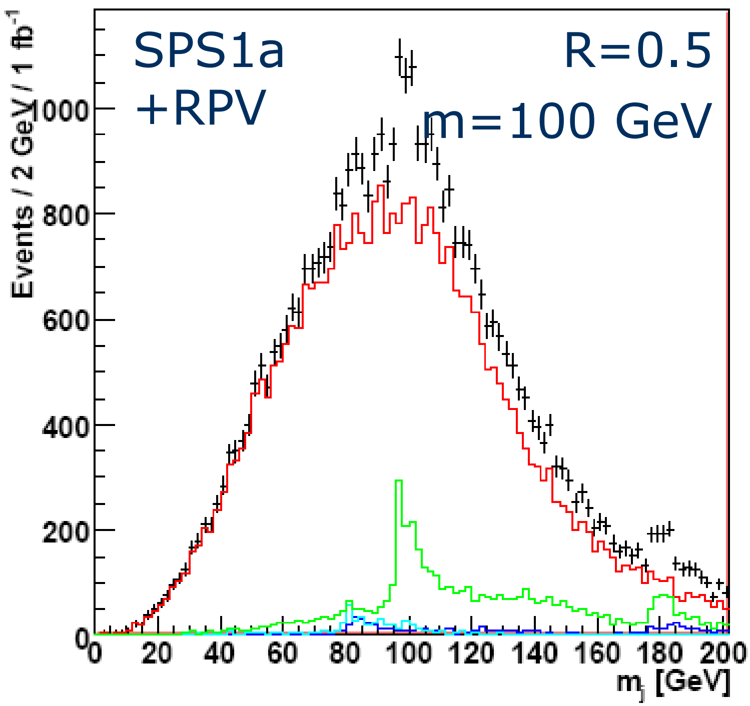
[Allanach et al., hep-ph/0102173]

Case II: an attempt with the k_T algorithm



[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Case II: an attempt with the k_T algorithm



Problem: y_1-cut suppresses background, but shapes it to look like signal.

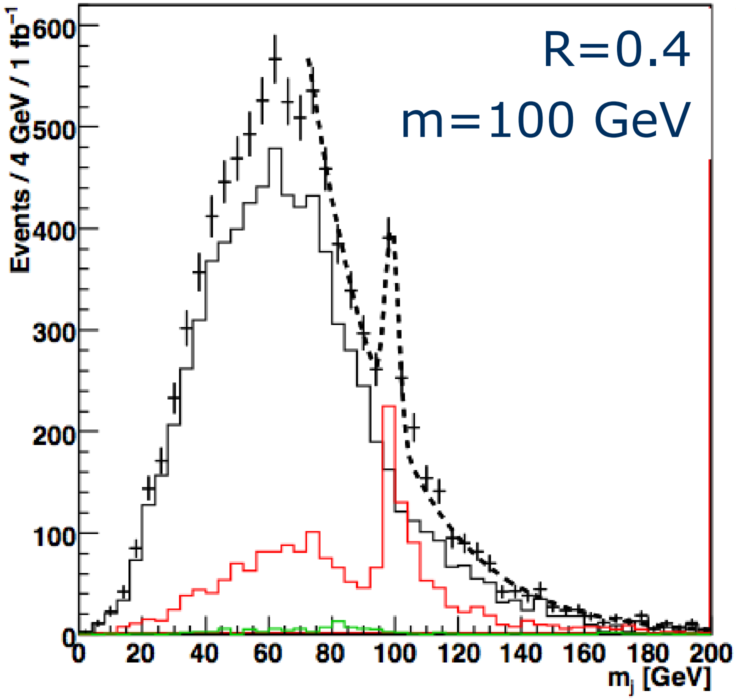
$$y_1 = \min(p_{Tk}^2, p_{Tl}^2)/p_T^2 \times \Delta R_{kl}^2/R^2$$

Redefine y-cut to something not so mass-scale dependent:

$$y_1' = \min(p_{Tk}^2, p_{Tl}^2)/m_j^2 \times \Delta R_{kl}^2$$

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Case II: an attempt with the k_T algorithm



Some help also in lowering R. However, you start to loose signal when

$$R < \frac{2m_j}{p_T}$$

Exclusive analysis requiring two **neutralino candidate** jets gives clear mass peak on exponentially falling background.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Case II: now with the C/A algorithm

With Cambridge/Aachen there is no p_T ordering of clusters. We pick significant clusterings by requiring:

$$z_{kl} = \frac{\min(p_{Tk}, p_{Tl})}{p_{Tk} + p_{Tl}} > z_{cut}$$

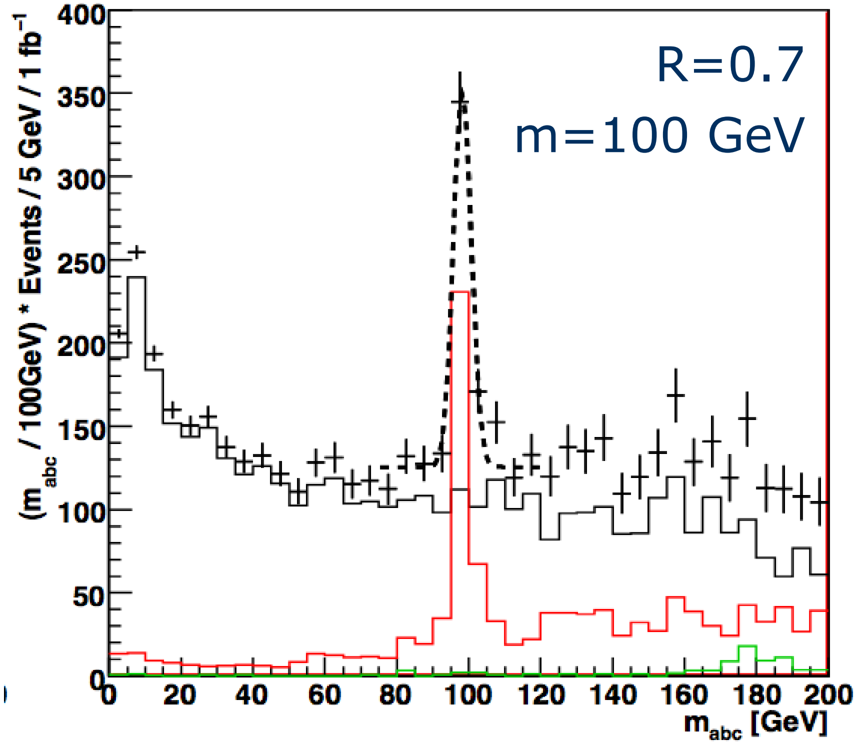
One can then show that for QCD jets

$$m_j \frac{dn}{dm_j} \propto \frac{2C_F}{\pi}\left(\ln\frac{1}{z_{cut}} - \frac{3}{4}\right)$$

when $\varepsilon < m_j < R p_T z_{cut}^{1/2}$.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Case II: now with the C/A algorithm



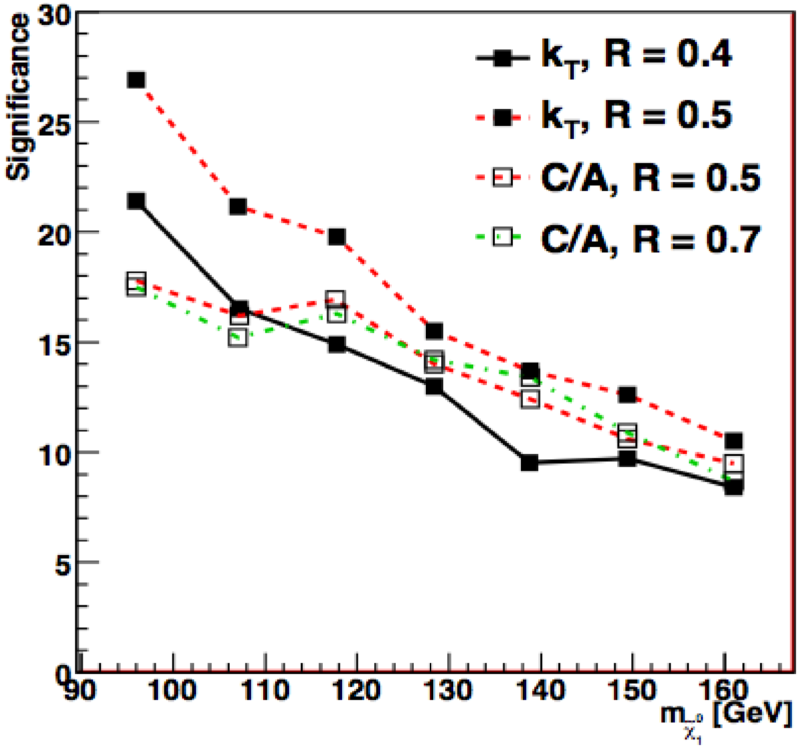
Inclusive analysis picking one very hard jet with two mergers that have $z_{cut} > 0.15$ and the largest JADE distance:

$$d_{kl} = p_{Tk}\, p_{Tl}\, \Delta R_{kl}^2$$

Require one merger to be a subset of the other and to have a significant mass ratio.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Case II: overall performance



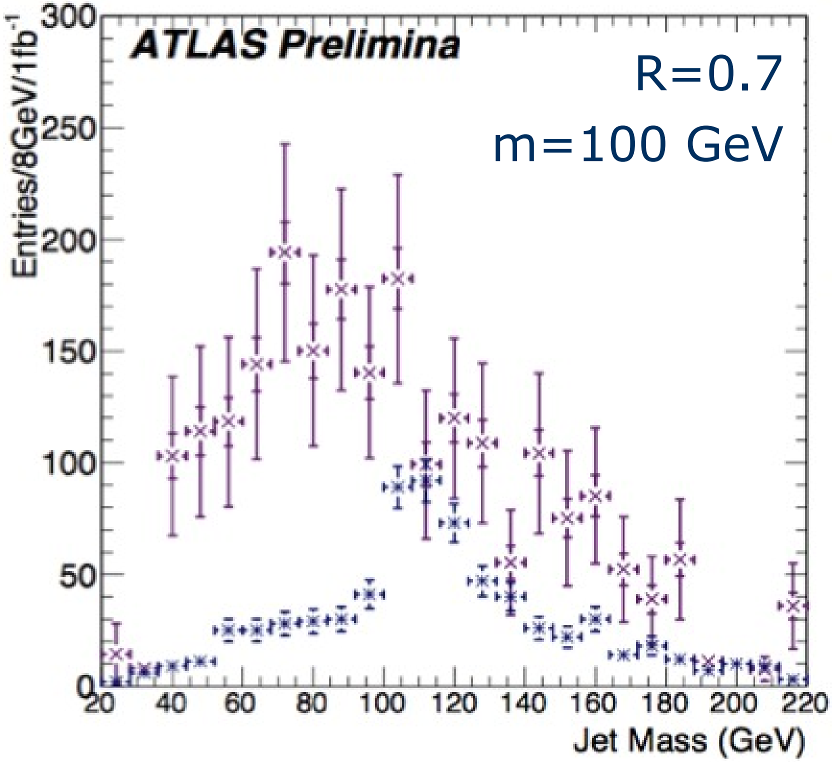
LHC potential with 1 fb^{-1}.

Mass determination seems limited by ATLAS/CMS jet mass resolution (~8 GeV).

Combining neutralino candidate with extra hard jet gives squark mass estimate.

[Butterworth, Ellis, ARR, Salam, arXiv:0906.0728]

Case II: full simulation in ATLAS

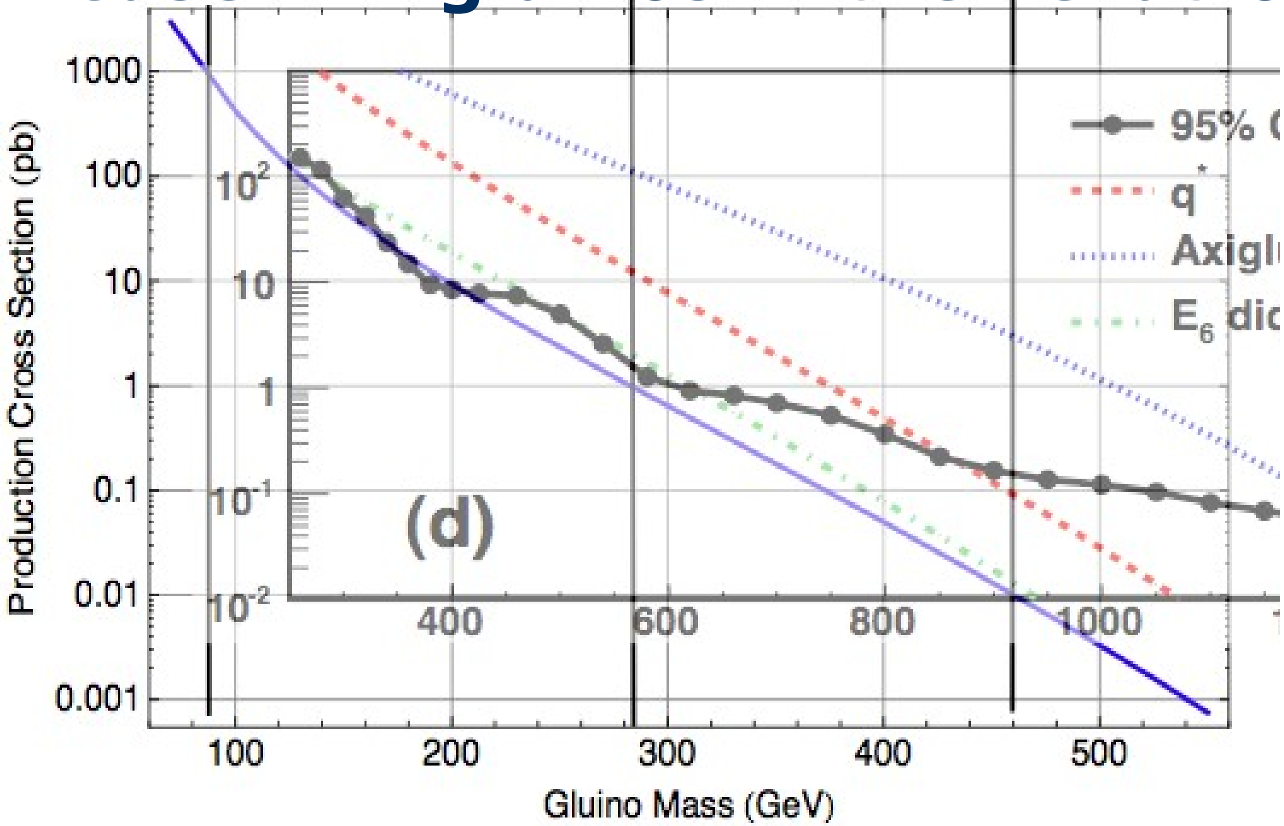


Full detector simulation on identical benchmark points with k_T algorithm encouraging.

Large error bars on QCD background, but this will not be a problem with data (see small error bars for indication).

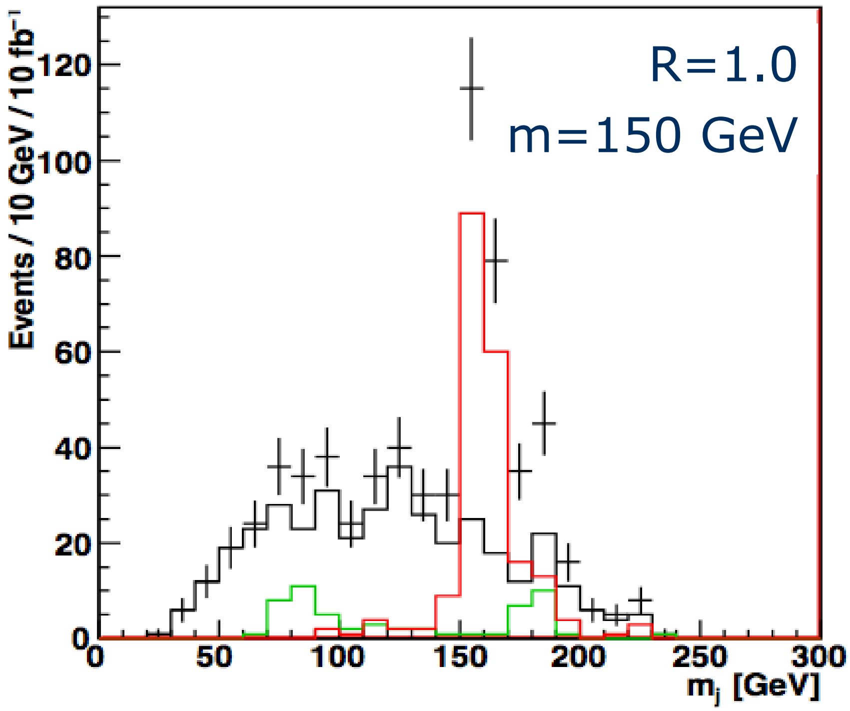
[French *et al.*, ATL-COM-PHYS-2009-272]

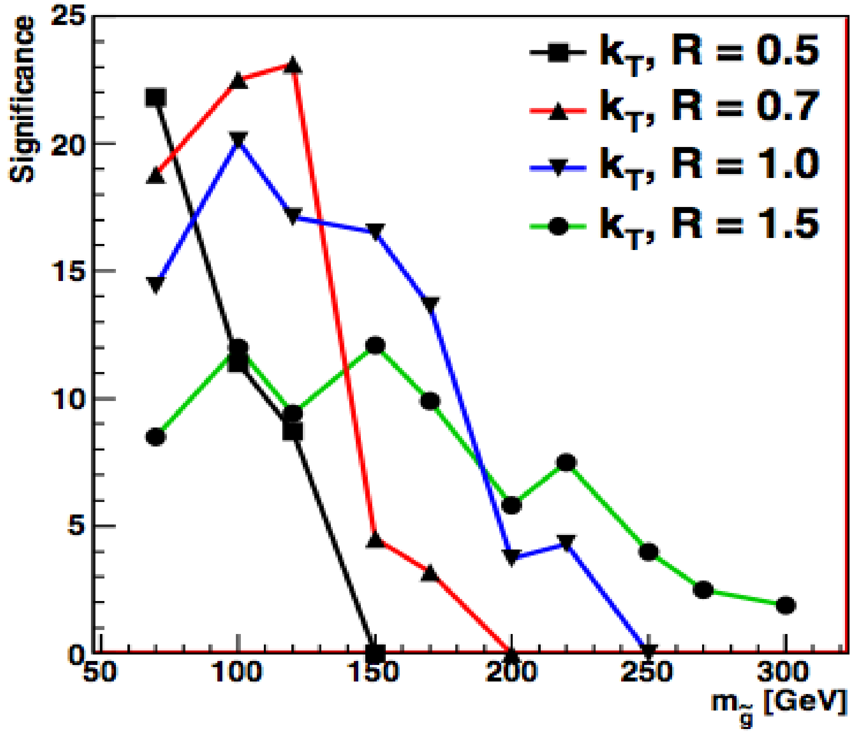
Case III: gluinos in the Tevatron heystack



[CDF Collaboration, arXiv:0812.4036]

Case III: finding gluinos with k_T algorithm





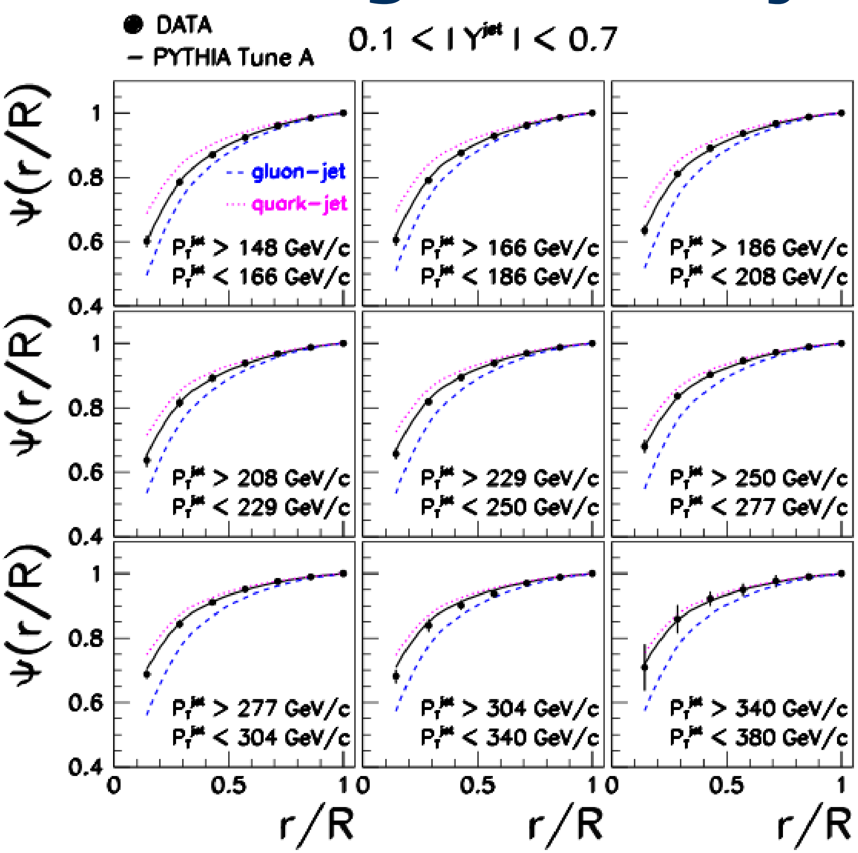
[ARR, Salam, Wacker, arXiv:1005.1229]

Conclusions

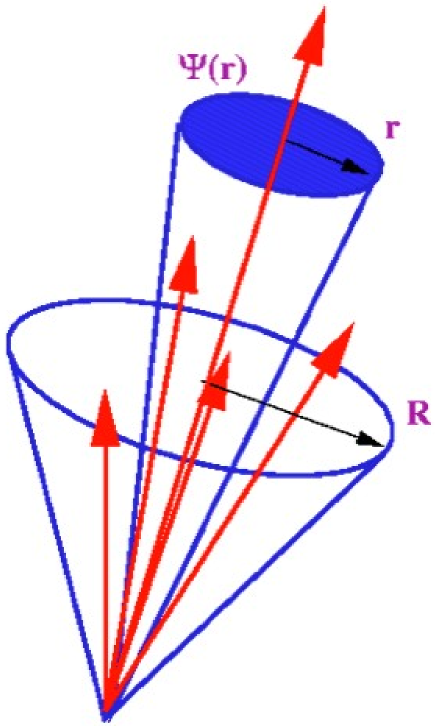
- Jets – ubiquitous for NP searches @ hadron colliders.
- Wide choice of algorithms, suitable for different purposes.
- Jet structure is effective in isolating collimated jets from the decays of boosted massive particles.
- Large potential for discovering New Physics, however:
  - Watch out for inducing signal shapes in backgrounds.
  - Clever use of algorithms & cuts gives predictable background behaviour.

Back-ups

Are MC generator jets realistic?

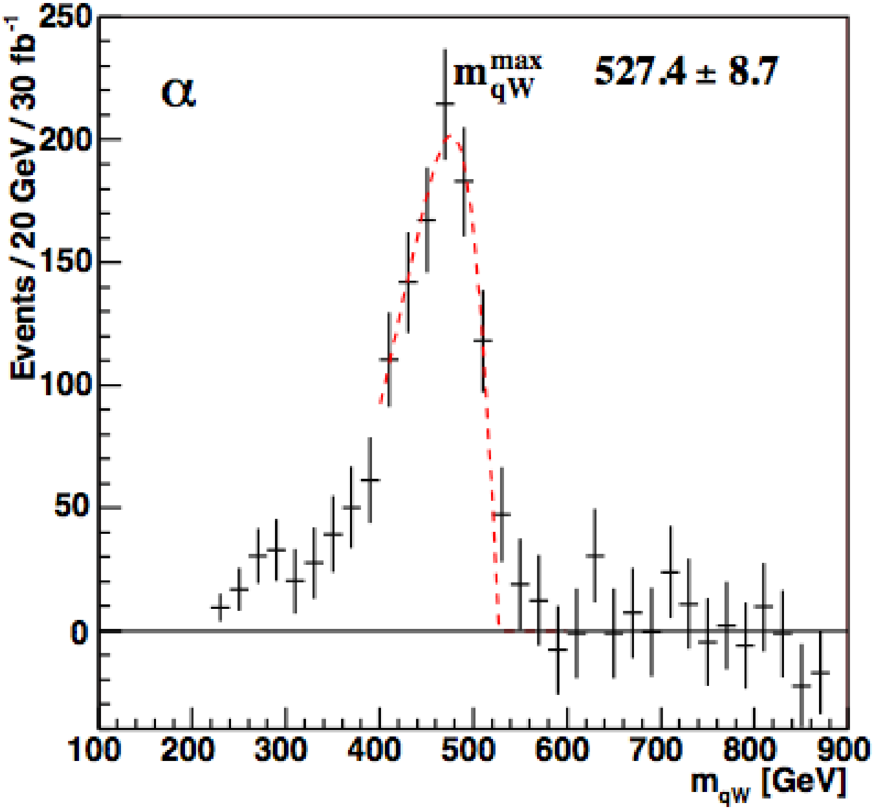


Jet shape:



[CDF, hep-ex/0505013]

Case I: finding edges



Subtract backgrounds using sidebands. Fit to Gaussian smeared edge.

Case I: SM backgrounds

Sample	$N_{generated}$	$\mathcal{L}$ [fb^{-1}]	$N_{pass}(\alpha-\gamma)$	$N_{pass}(\delta)$
$t\bar{t}$			256.7	1287.0
50-150	26,500,000	93.0		
150-250	10,000,000	95.6		
250-400	3,500,000	120.0		
400-600	500,000	129.6		
600-	500,000	902.4		
Wj			5.2	34.5
50-150	1,100,000	0.1		
150-250	1,100,000	2.9		
250-400	1,100,000	20.2		
400-600	1,100,000	154.3		
600-	600,000	507.2		
Zj			3.2	3.0
50-150	100,000	0.0		
150-250	100,000	0.6		
250-400	100,000	4.3		
400-600	100,000	32.7		
600-	100,000	199.7		
Wjj	157,800	114.5	49.2	450.5
Zjj	112,000	99.9	43.9	417.7
$Wjjj$	50,300	227.9	127.8	1109.4
$Zjjj$	27,300	156.6	194.4	1782.9
$WW/WZ/ZZ$			9.6	95.3
50-150	100,000	1.8		
150-250	100,000	29.2		
250-400	100,000	158.2		
400-600	100,000	945.2		
600-	10,000	437.0		
WWj	201,200	100.7	9.8	98.3
WZj	162,400	90.2	0.0	0.0
ZZj	69,500	426.5	2.3	17.6
$WWjj$	107,300	98.7	23.4	215.8
$WZjj$	179,000	248.4	55.2	455.5
$ZZjj$	18,900	167.0	5.9	59.3