Jet Substructure and Searches at the LHC

Jon Butterworth

Scales in the experiment

1. Proton mass ~ becomes possible to accurately calculate using perturbative QCD

   around 1 - 5 GeV.

2. W, Z mass / electroweak symmetry-breaking scale / Higgs mass if it exists

   around 50-300 GeV

3. Phase space

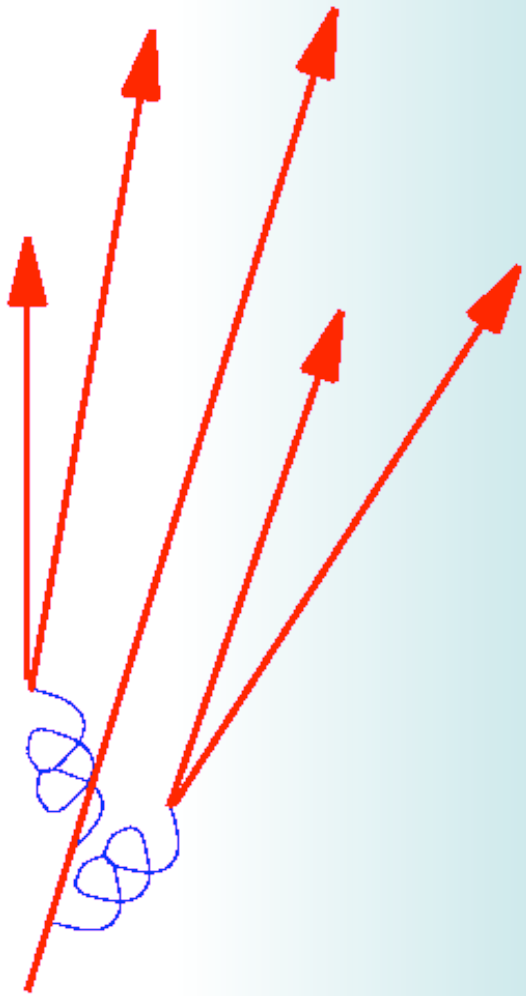
   A few TeV

Scales in the experiment

- For the lifetime of the experiment, there will be interesting physics objects around the electroweak scale.
- Production of multiple EW-scale particles (W,Z,H,t…) and jets either directly or in cascade decays
  - Means we need the new calculations, especially Monte Carlos which match many-leg matrix elements to partons showers/ resummations. (very active field but not the subject of this workshop)
- Copious production of EW-scale particles well above threshold
  - Means highly collimated decay products, and therefore interesting sub-jet structure for hadronic decays.
  - The LHC will be the first place we have ever seen this.

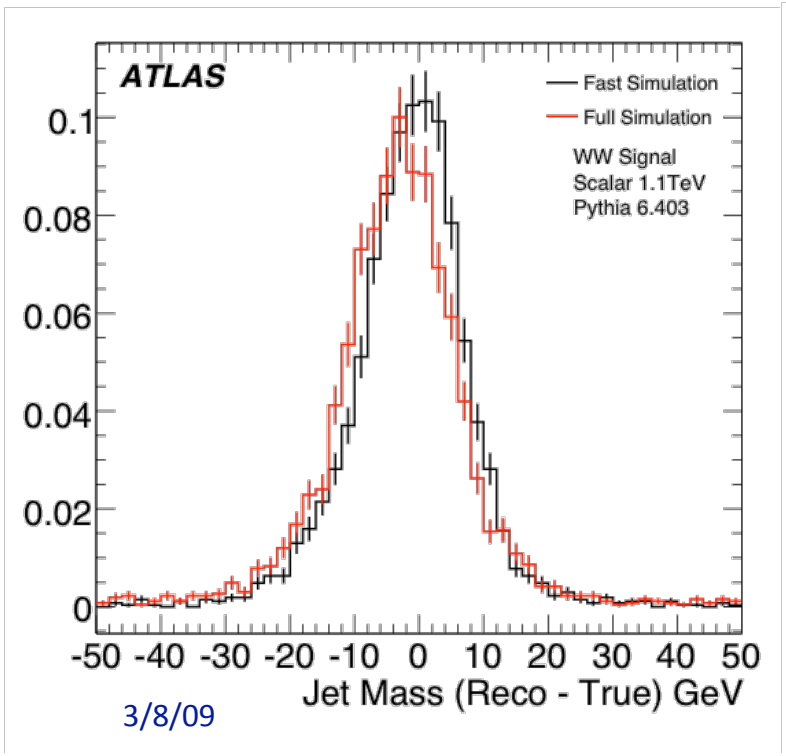
Jet structure

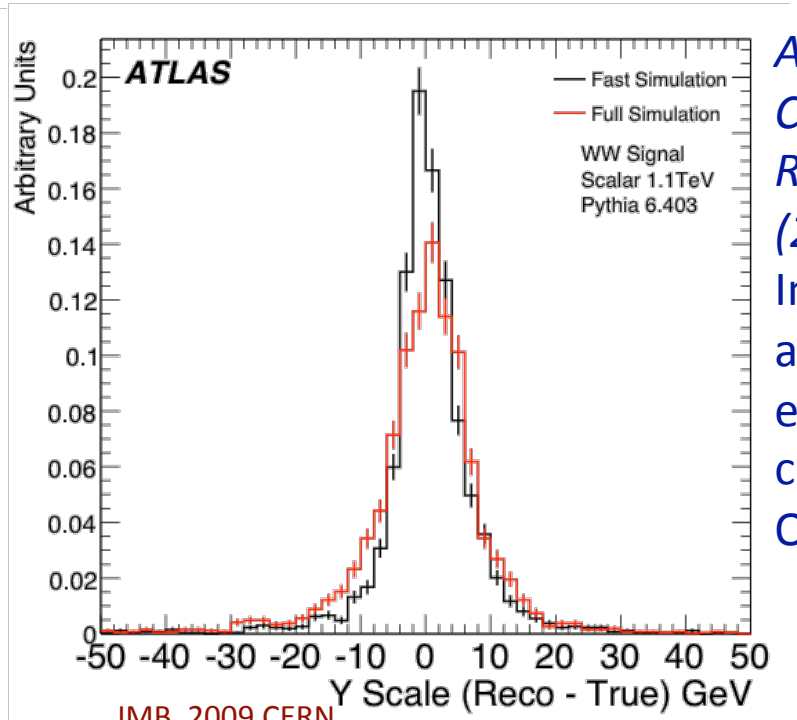
- Evolution from a hard parton to a jet of partons takes place in a regime where:
  - Energy scale is high enough to use perturbation theory
  - x is not very small
  - Collinear logarithms are large
- Leading logarithmic parton showers, as implemented in MC models or resummation programs, should do a good job
- Hadronisation (non-perturbative) stage has a small effect (sub-GeV level) and is well modelled by tuned Monte Carlo simulation (e.g. Lund string)



Jet Substructure in the detectors

- Example (first LHC use case): y scale of the last merge(s) in k_T jets in high mass vector boson scattering.
- Also now looked at for top and neutralino decays.
  - ATL-PHYS-PUB-2009-076, ATL-PHYS-PUB-2009-081





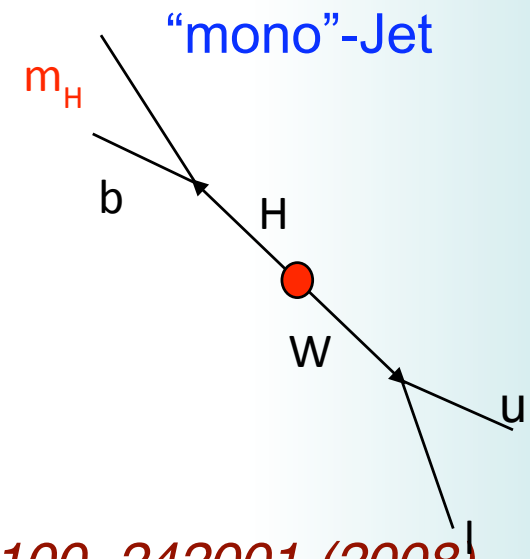
Analysis of JMB, Cox, Forshaw, Phys. Rev. D65; 096014 (2002).
In jet performance and exotics (high energy VBS) chapters of CERN-OPEN-2008-020.

Two goals in Jet Substructure

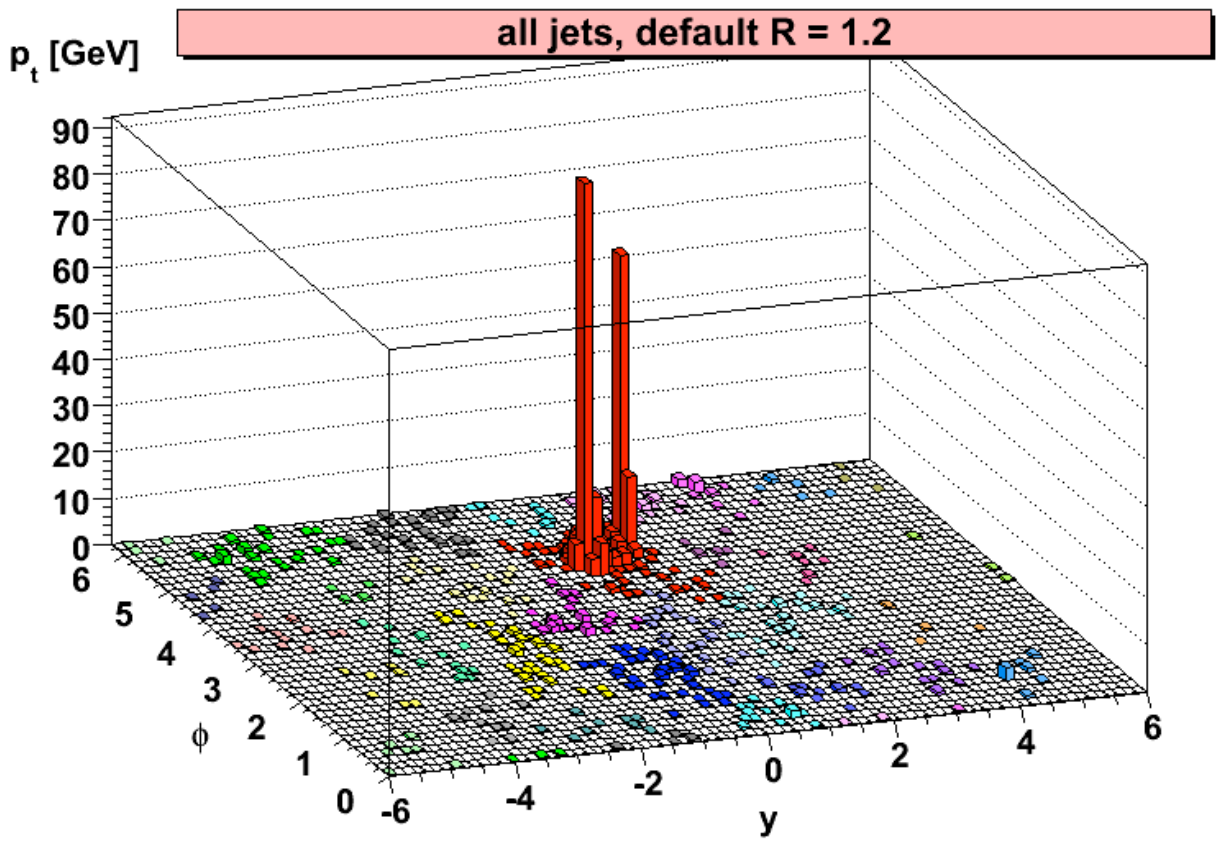
- Improve the single jet mass resolution
  - First unclustering stages in C/A, throw away softer or more distant partner
    - *Kaplan, Rehermann, Schwartz, Tweedie, PRL101:142001,2008.*
    - *JMB, Davison, Rubin, Salam, PRL 100, 242001 (2008)*
  - "Filtering": Rerun algorithm with tighter distance resolutions
    - *JMB, Davison, Rubin, Salam*
  - Variable R parameter
    - *Krohn Thaler, wang, JHEP 0906:059,2009.*
  - "Pruning": Remove soft splittings in clustering
    - *S. Ellis, Vermilion, Walsh, arXiv:0903.5081 [hep-ph]*
- Distinguish between QCD-generated high mass jets and those due to heavy object decays
  - None-strongly order k_T scale
    - *JMB, Cox, Forshaw, PRD 65; 096014 (2002).*
  - Symmetric splitting
    - *Kaplan et al, JMB et al*
  - Anomalously large mass drop
    - *JMB et al*
  - Analytic jet shapes (planar flow etc)
    - *Almieda et al PRD 79:074017,(2009).*

High p_T Higgs and Vector Boson

- By requiring that the Higgs and Vector Boson have a high transverse momentum, we lose a factor of ~20 in cross section
  - However, much of this would have failed other analysis cuts anyway
  - Background cross sections fall by a bigger factor (typically t-channel not s-channel)
- W/Z and H are all central
  - Better b-tagging, better jet resolution
- W/Z and H decay products collimated
  - Simpler topology, fewer combinatorials
  - Difficult for tops to fake this
- Z ➔ neutrinos becomes visible
  - High missing E_T
- *JMB, Davison, Rubin, Salam, Phys. Rev. Lett. 100, 242001 (2008)*

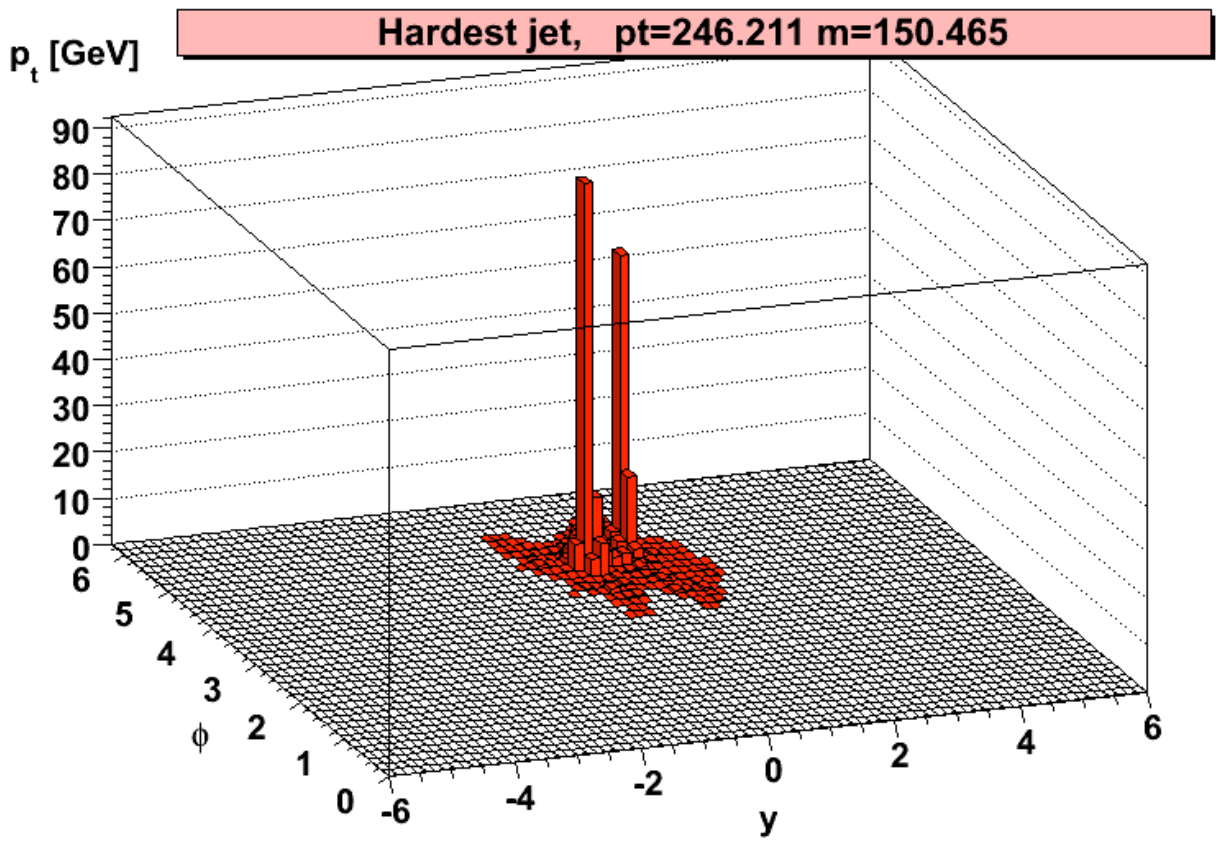


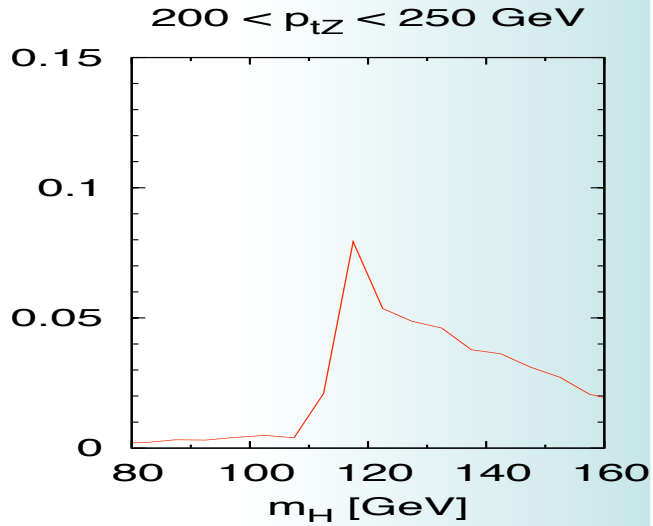
Improved subjet analysis

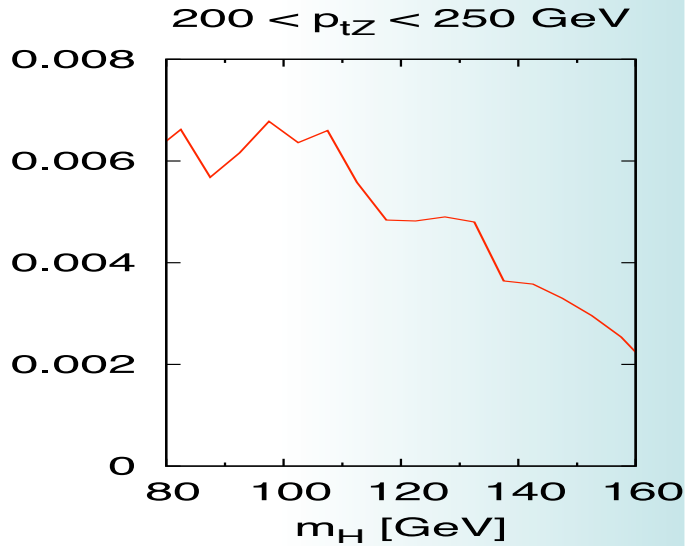


Technique from JMB, Davison, Rubin, Salam.
These slides – thanks Gavin!

Improved subjet analysis







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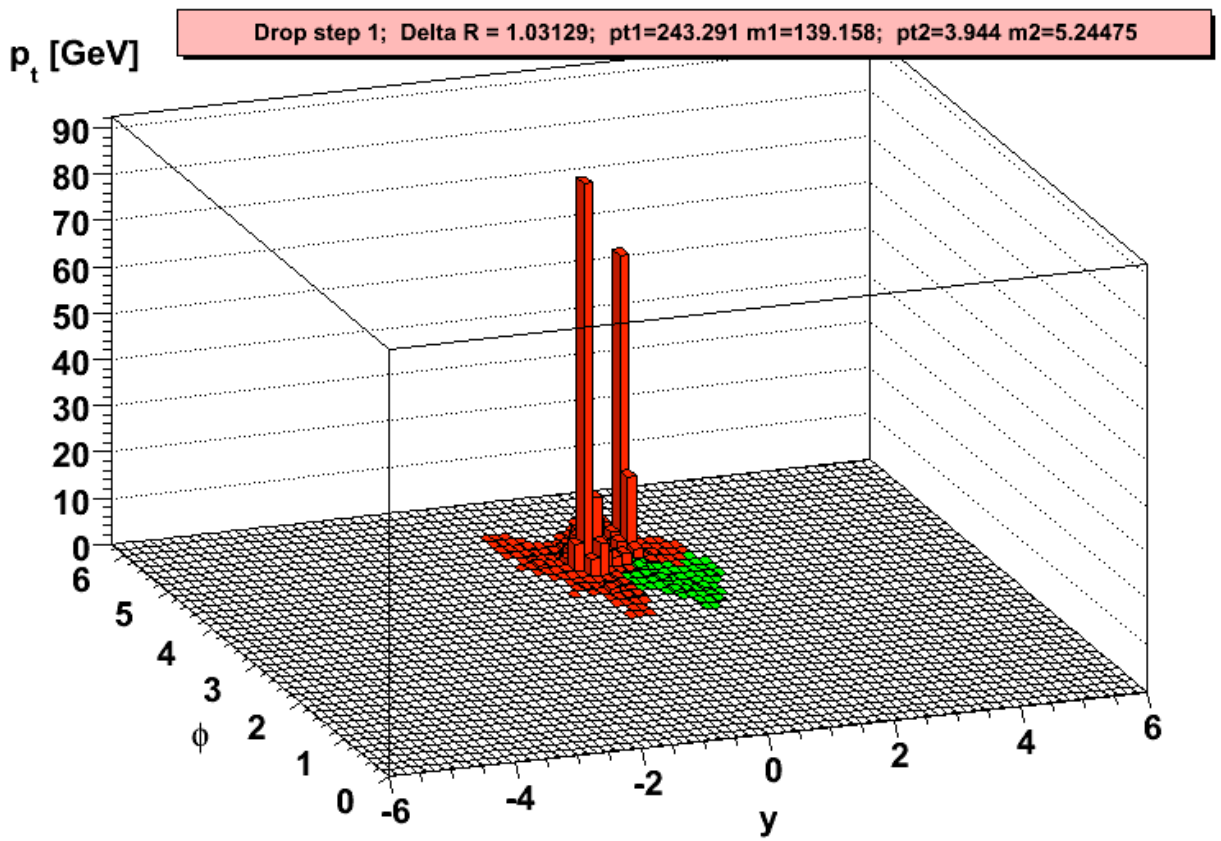

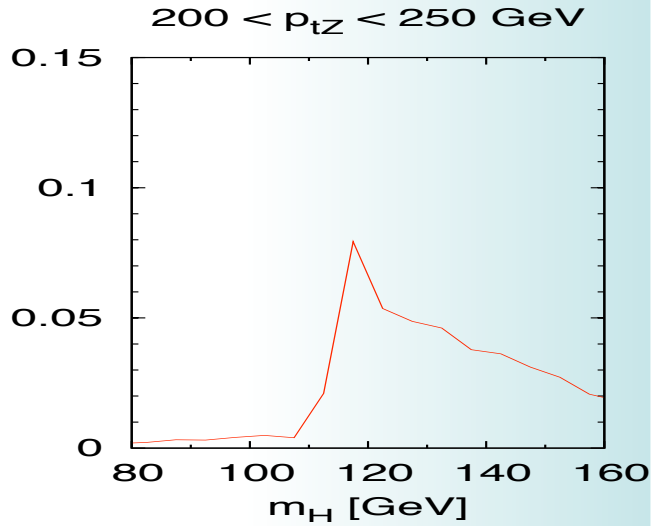

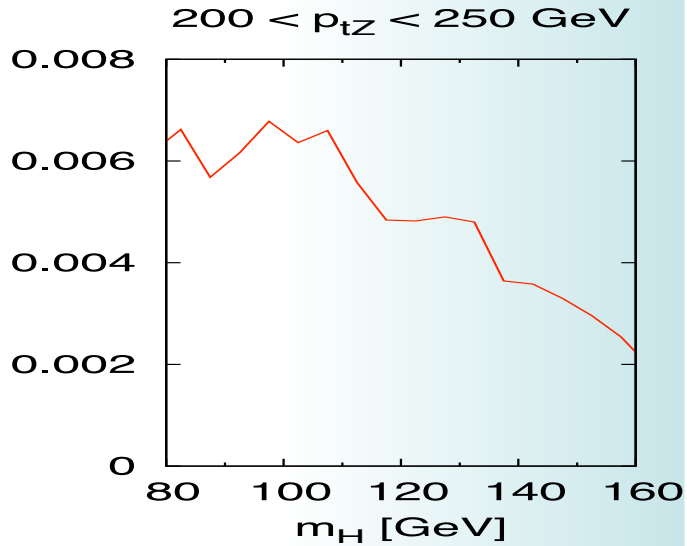

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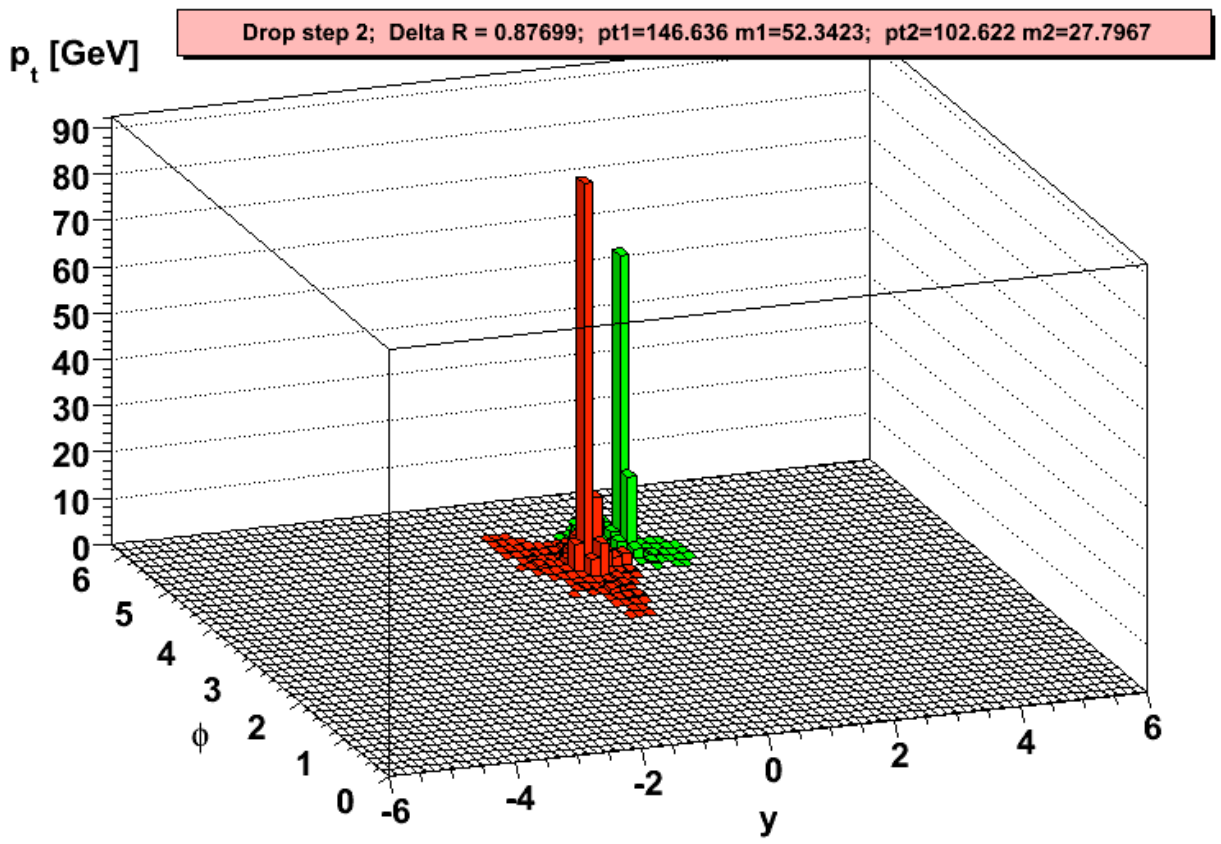

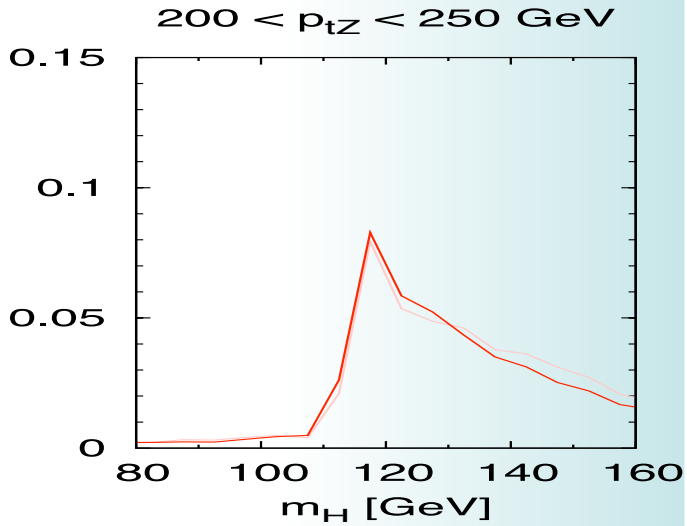

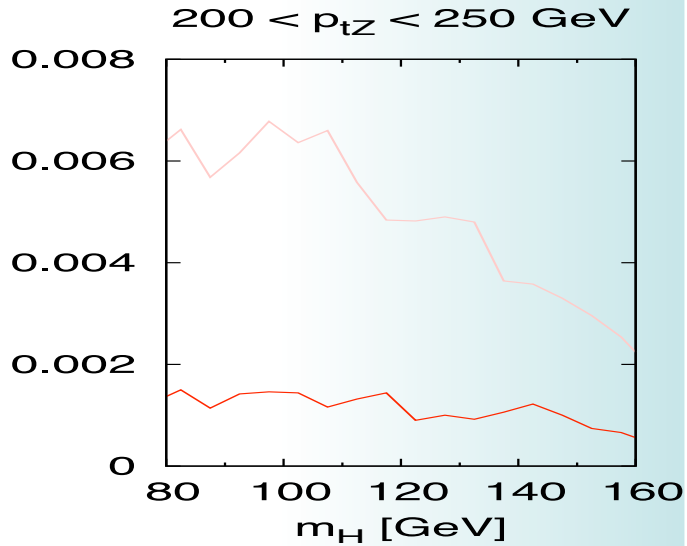

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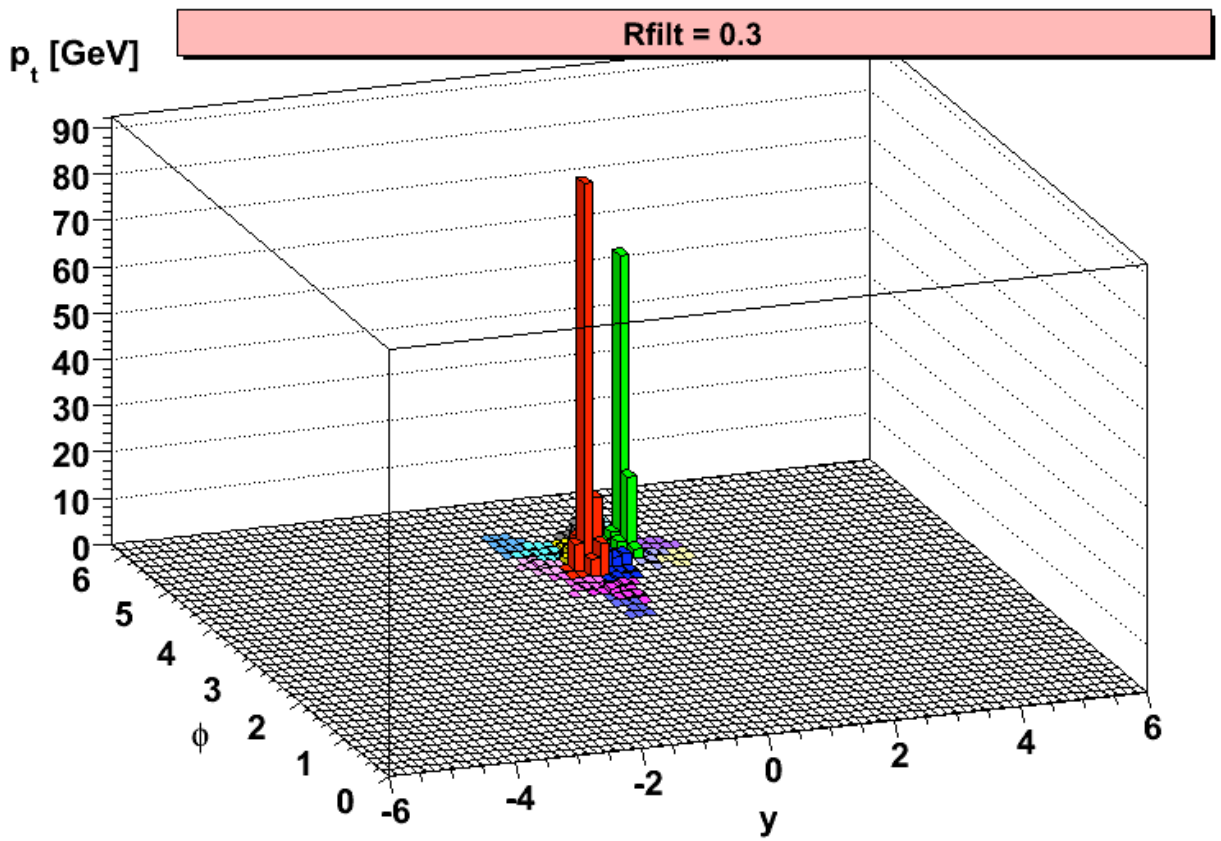

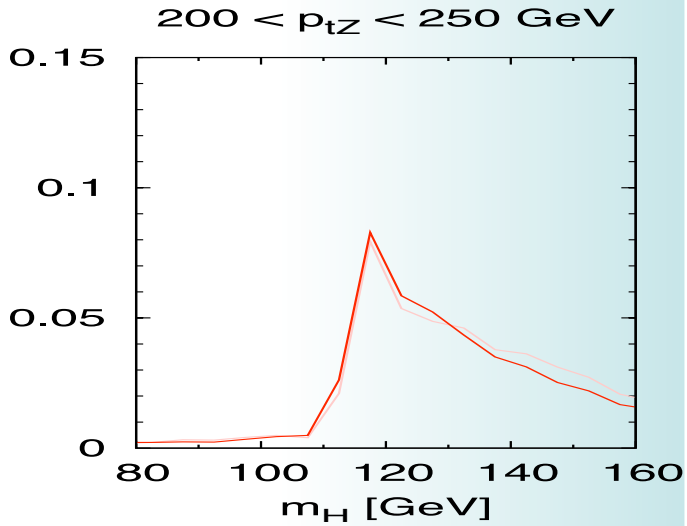

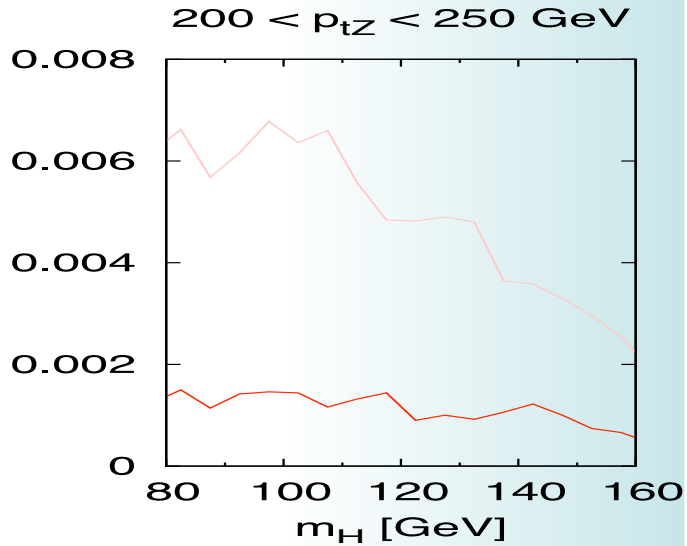

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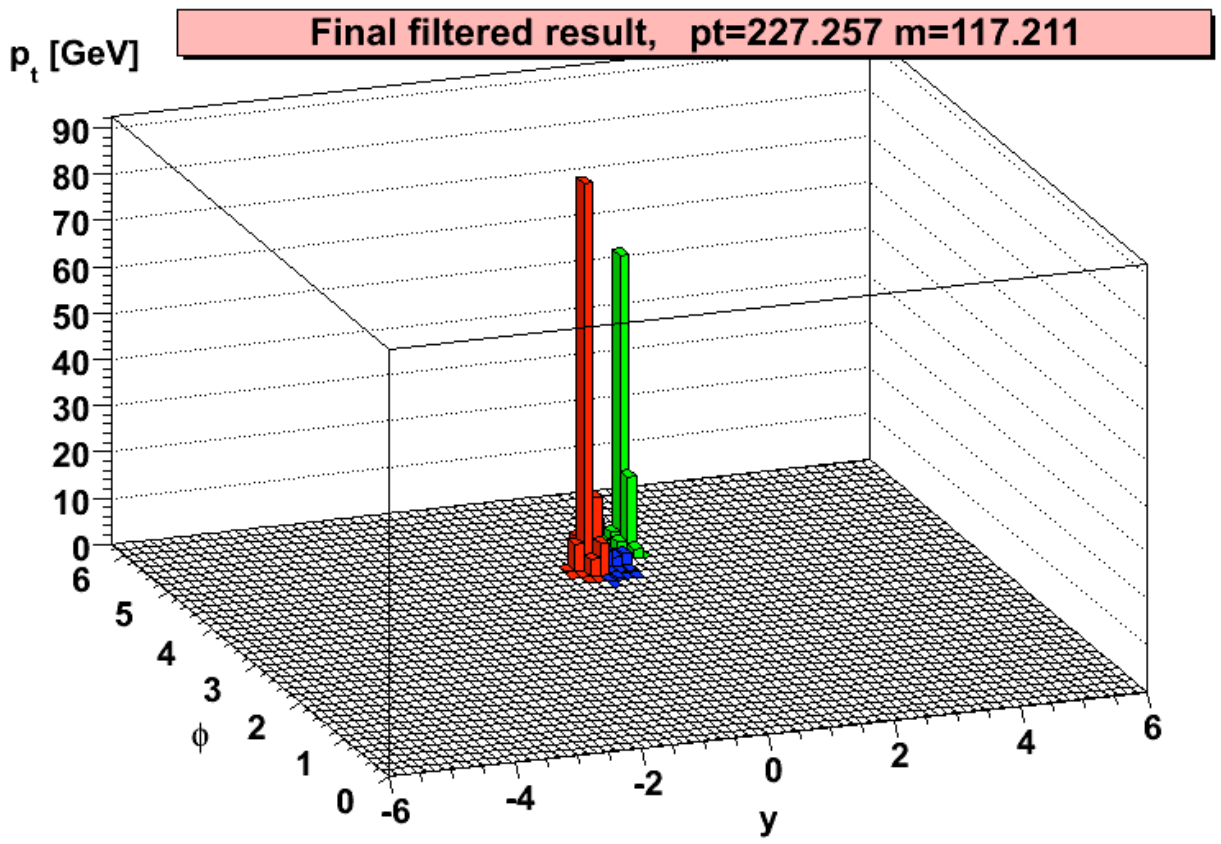

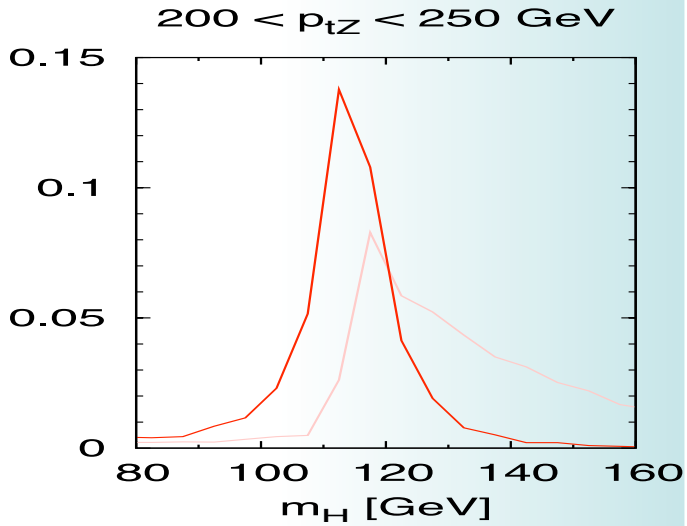

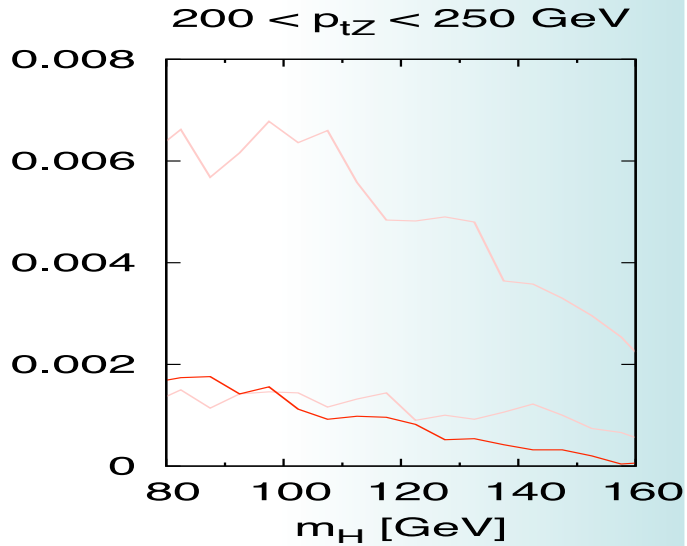

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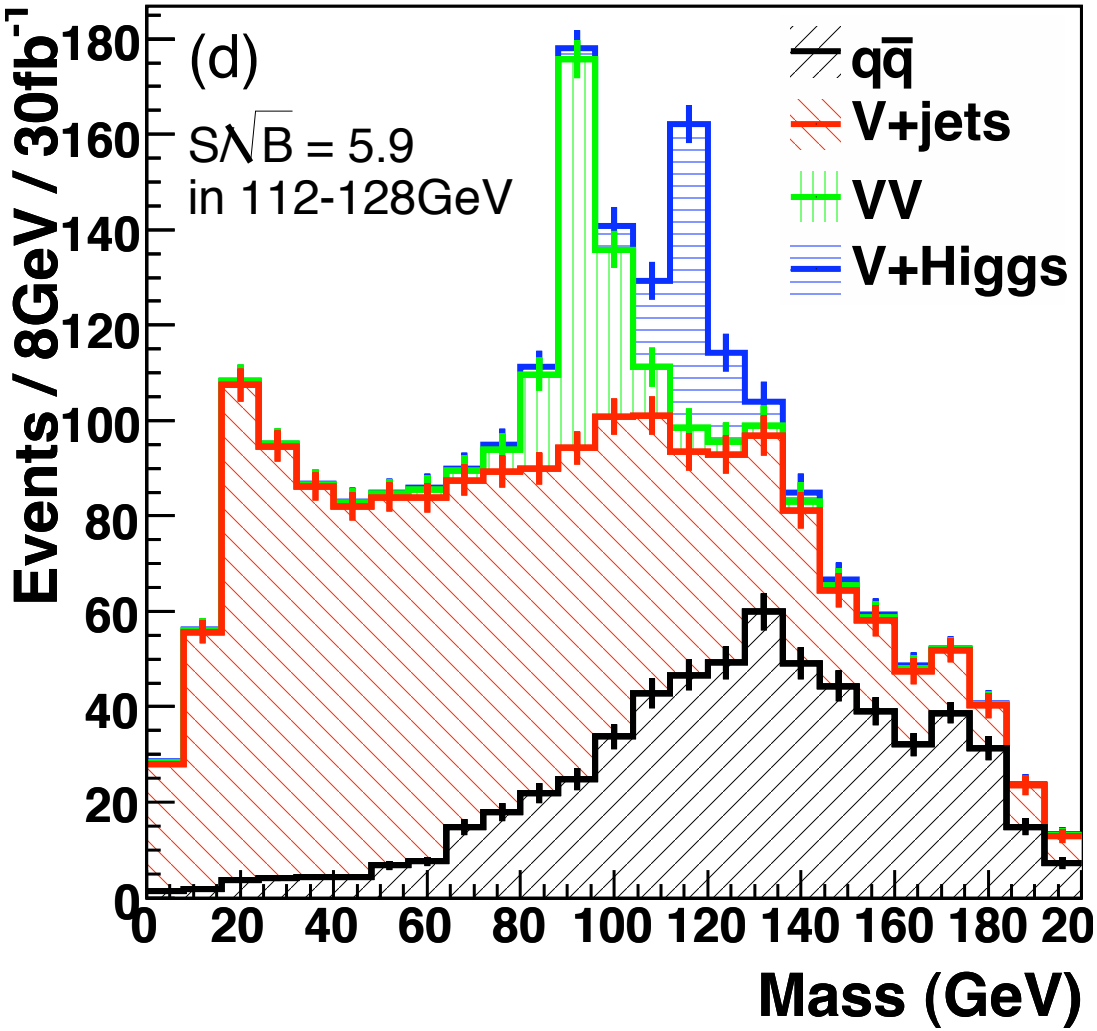
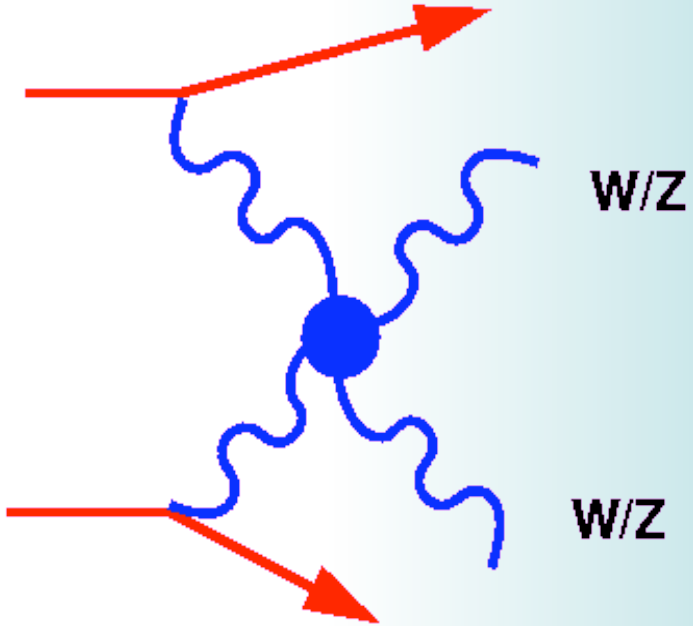
Combined particle-level result



- Note excellent Z peak for calibration
- 5.9 σ; potentially very competitive
- bb branching information critical for extracting Higgs properties
  - *"Measuring the Higgs sector" Lafaye, Plehn, Rauch, D.Zerwas, Duhrssen, arXiv:0904.3866 [hep-ph]*
- Studies within ATLAS are promising and nearly public.

Another Example:WW Scattering

- "No lose" channel for electroweak symmetry breaking.
- Most interesting at high WW mass
- Want to measure WW mass, so at least one W must decay hadronically, or we have too many neutrinos.
- Therefore the most interesting events have a highly-boosted, hadronically-decaying W or Z



K_T y scale ("ysplitter")

- If the jet developed from a QCD cascade (initiated by a hard quark or gluon), dominant emissions are "strongly ordered"
  - First q -> qg splitting is at a scale much lower than the starting scale
  - Characterised by a dimensionless parameter y, such that

$$E_T^2 << E_T^2, \text{ i.e. } y << 1$$

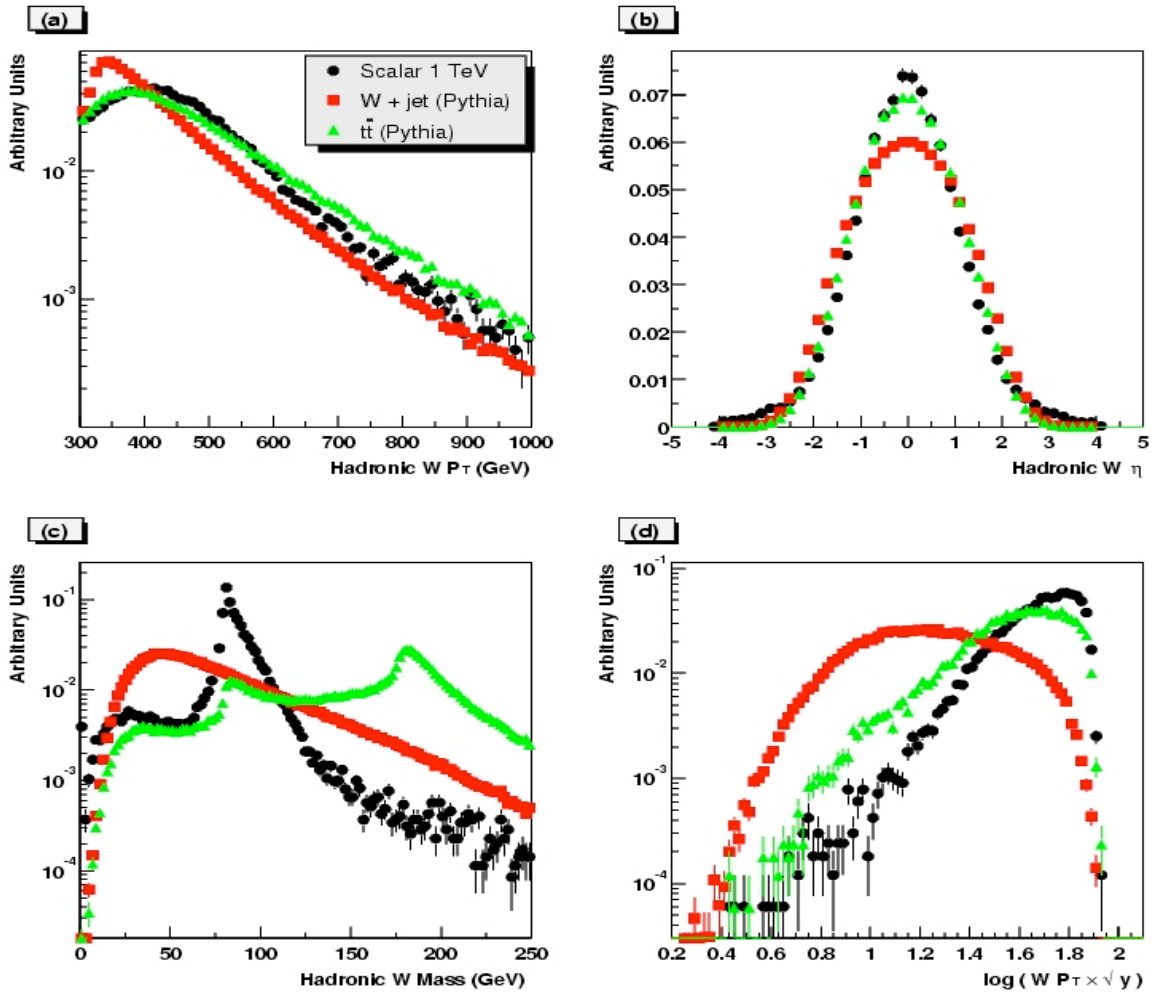
- If the jet developed from a massive particle decay, the first splitting is not necessarily strongly ordered.
  - Actually related to mass of particle, nothing to do with QCD

$$y\, E_T^2 \sim M_X^2 \text{ , i.e. } y \sim M_X^{2/}E_T^2$$

- To get y, treat the contents of the jet ~like a single e^+e^- event

(JMB, B.Cox, J.Forshaw, Phys.Rev.D65:096014,2002.)

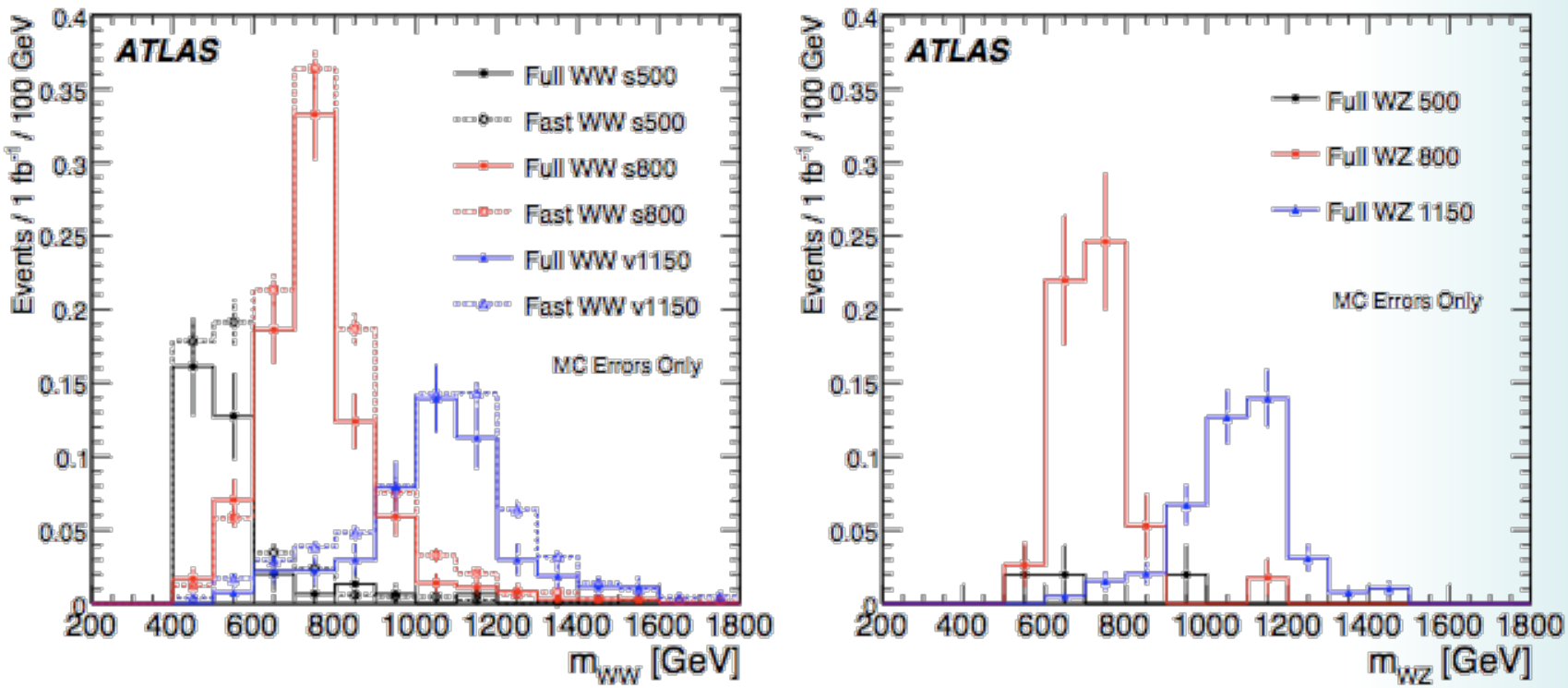
WW final state



- Four-vector level simulation
- W+jet
- WW scattering
- ttbar

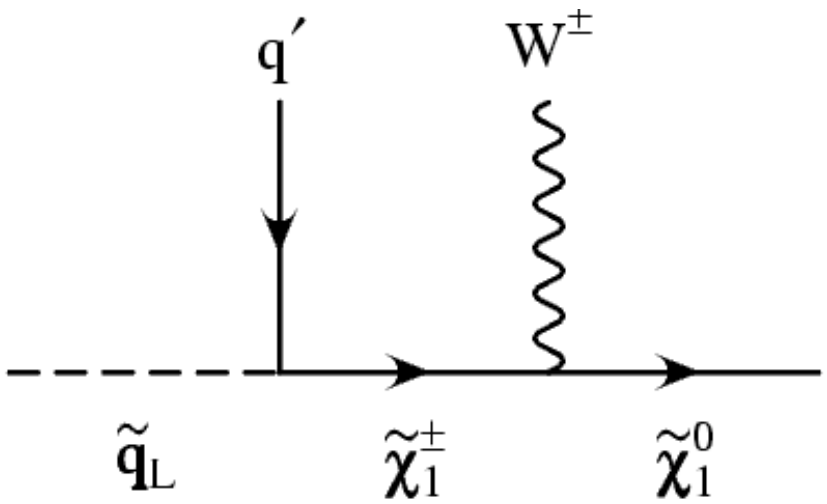
(JMB, B.Cox, J.Forshaw, Phys.Rev.D65:096014,2002.)

WW Final State



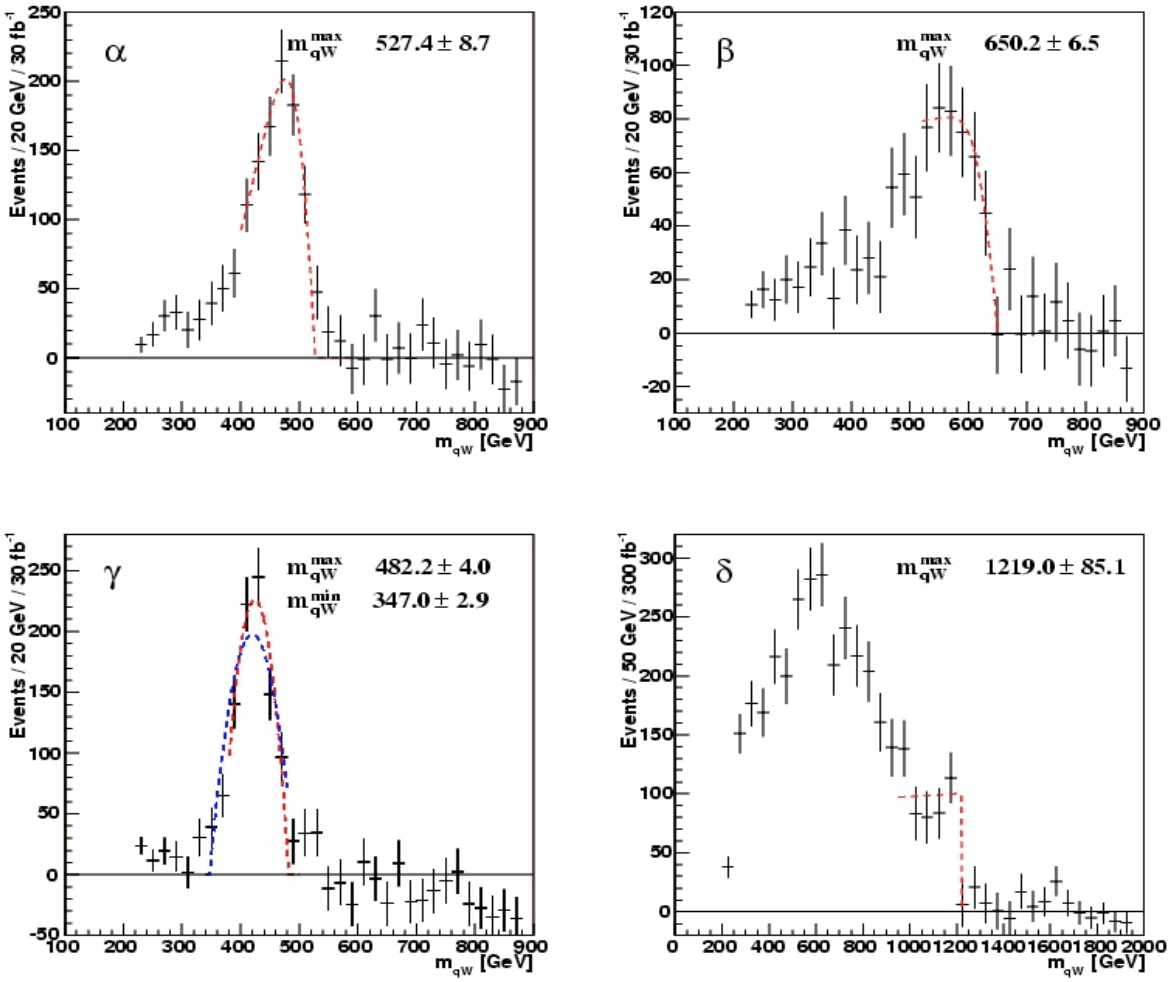
Full (and fast) simulation result
ATLAS CERN-OPEN-3008-020 (arXiv:0901.0512).

Another Example: SUSY decay chains



- e.g. SUSY Benchmarks from *DeRoeck et al, Eur.Phys.J.C49:1041-1066,2007*
  - Massive squark means boosted W.
  - Also get Z, Higgs, top in various decay chains.

SUSY final states



- After background subtraction

JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

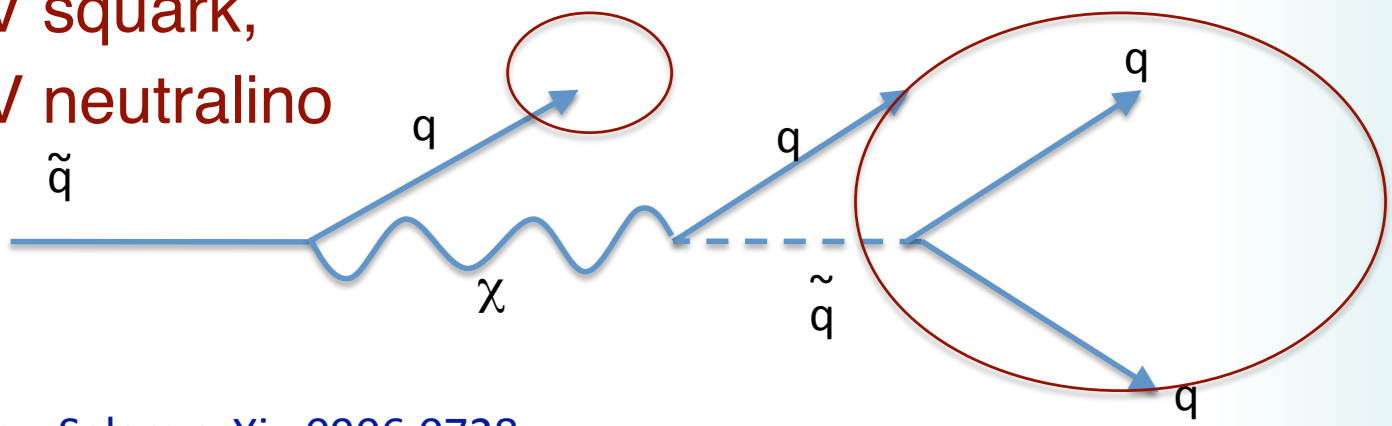
Another Example: Baryon-number violating decays

- In R-parity violating SUSY, extra allowed terms in the langrangian which lead to neutralino decay to 3 quarks.

$$W = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^{i} L_i H_u + \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

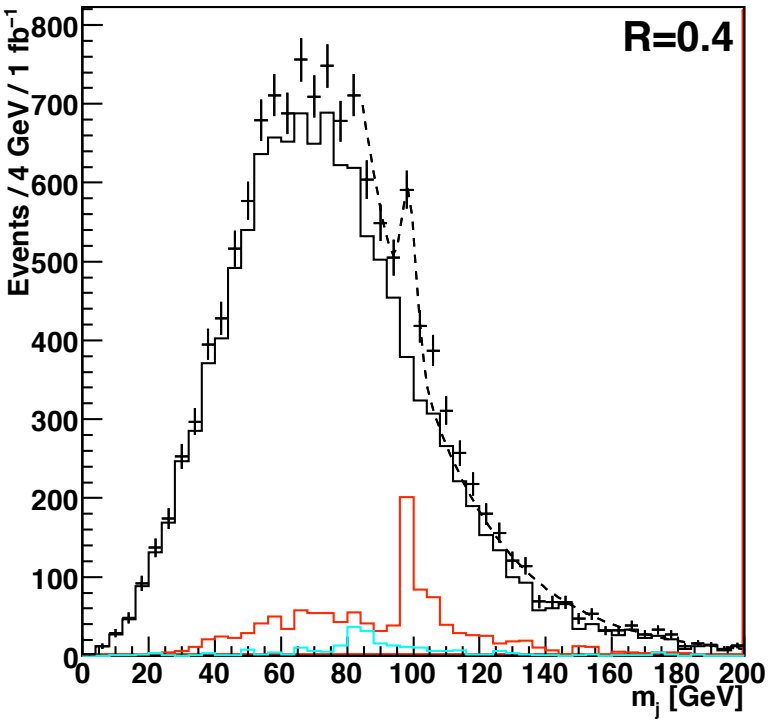
500 GeV squark,

100 GeV neutralino

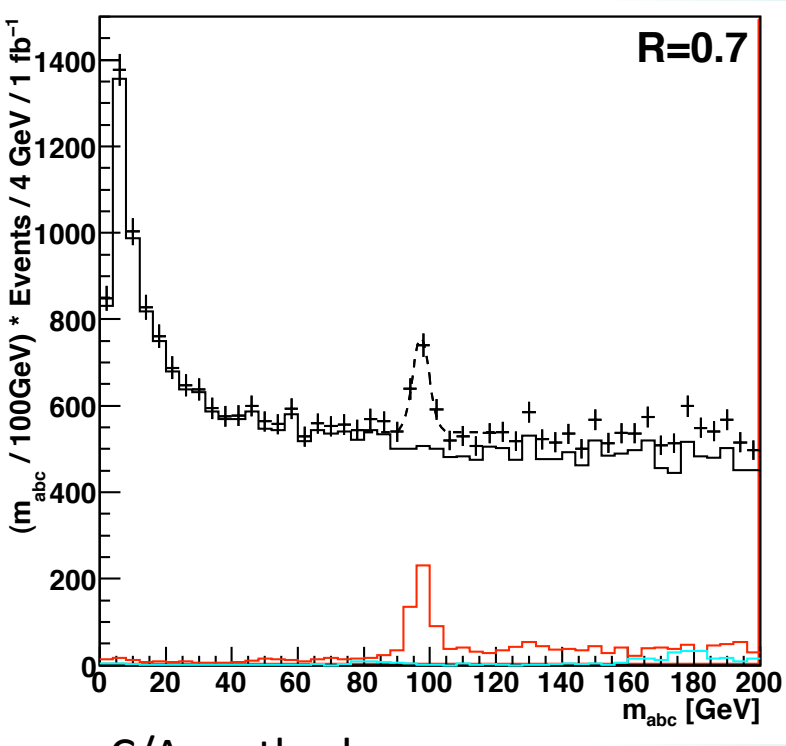


JMB, J.Ellis, Raklev, Salam arXiv:0906.0728

Another Example: Baryon-number violating decays

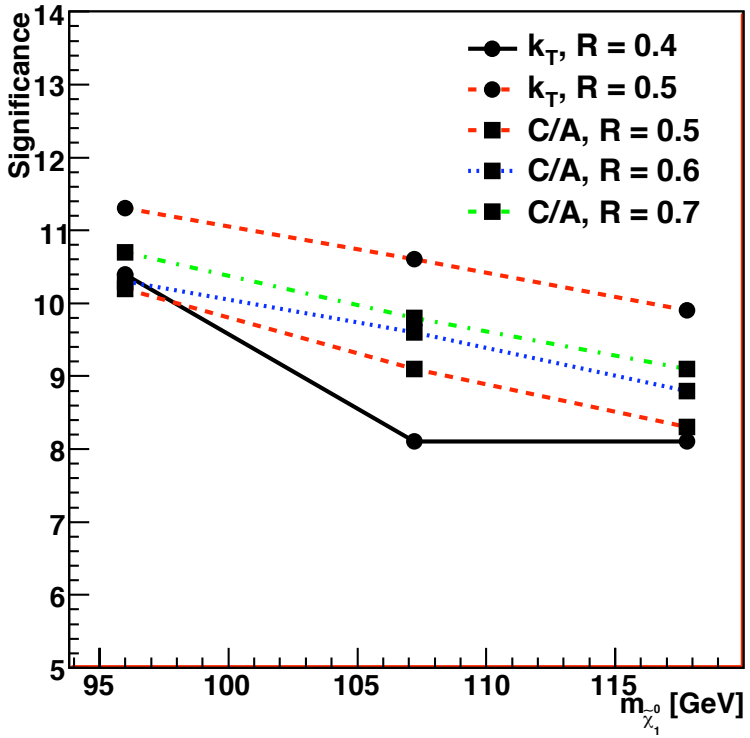


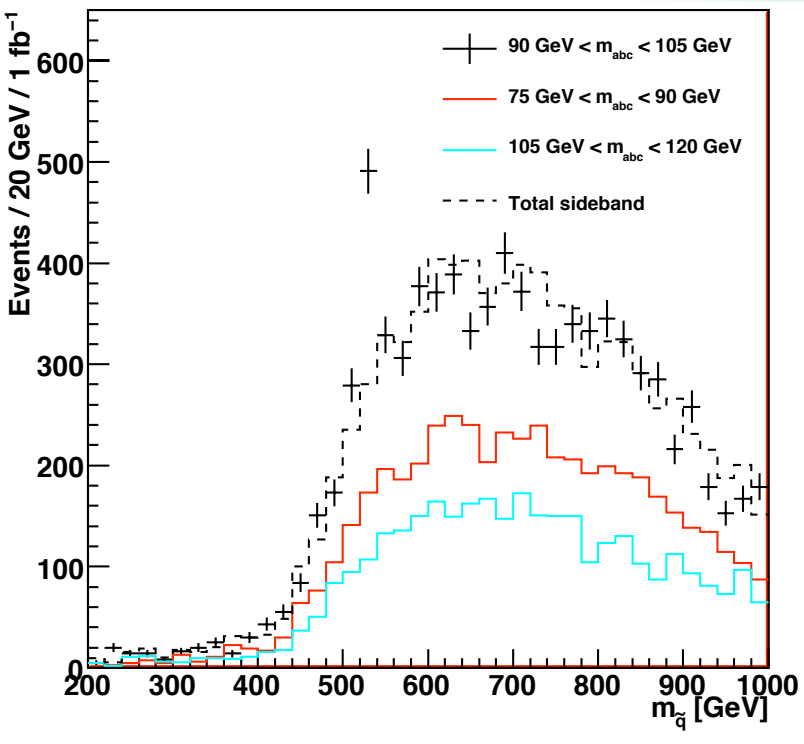
KT method



C/A method

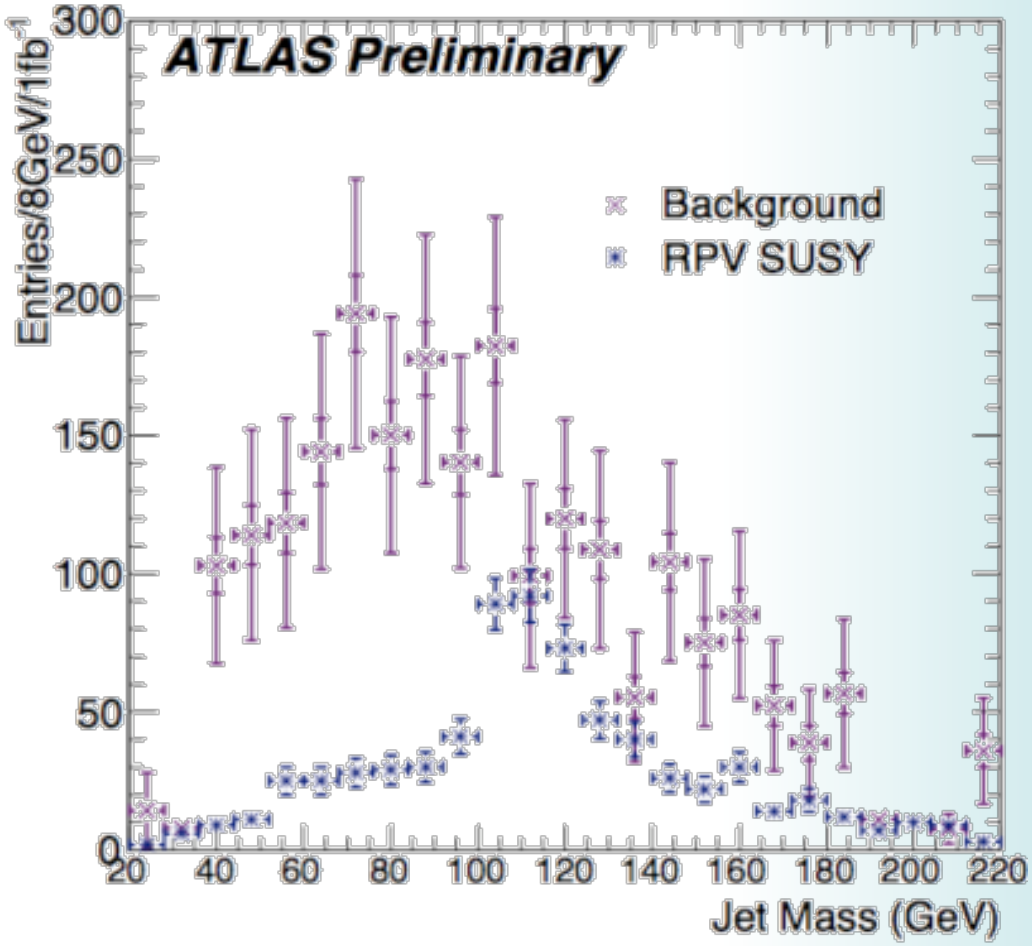
Another Example: Baryon-number violating decays





Another Example: Baryon-number violating decays

- k_T method confirmed by ATLAS fast simulation results.
  - ATL-PHYS-PUB-2009-081
  - S.French (SUSY 09)



Summary

- Jet finding, jet mass, sub-jet technology, and the associated understanding of QCD, have come a long way since (and because of) the previous round of colliders.

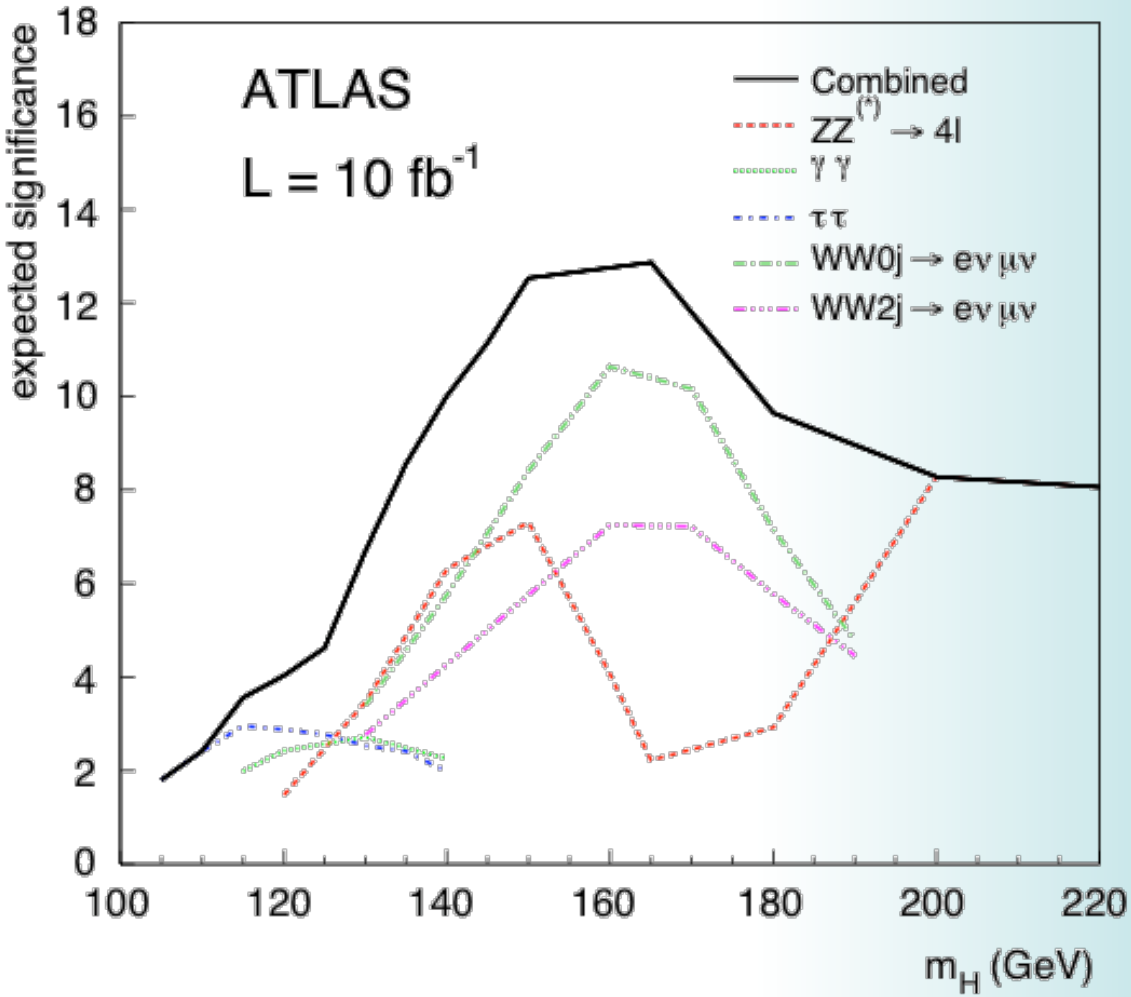
- Subjet analysis has dramatic benefits in several different channels; looks very promising and practical, even after full detector simulation.

- At the LHC we have interesting physics at $\mathcal{O}$(100 GeV), and phase space open at $\mathcal{O}$(1 TeV). This means that a single jet often contains interesting physics. We probably haven't yet appreciated all the consequences of this qualitatively new feature of physics beyond the EWSB scale

EXTRAS

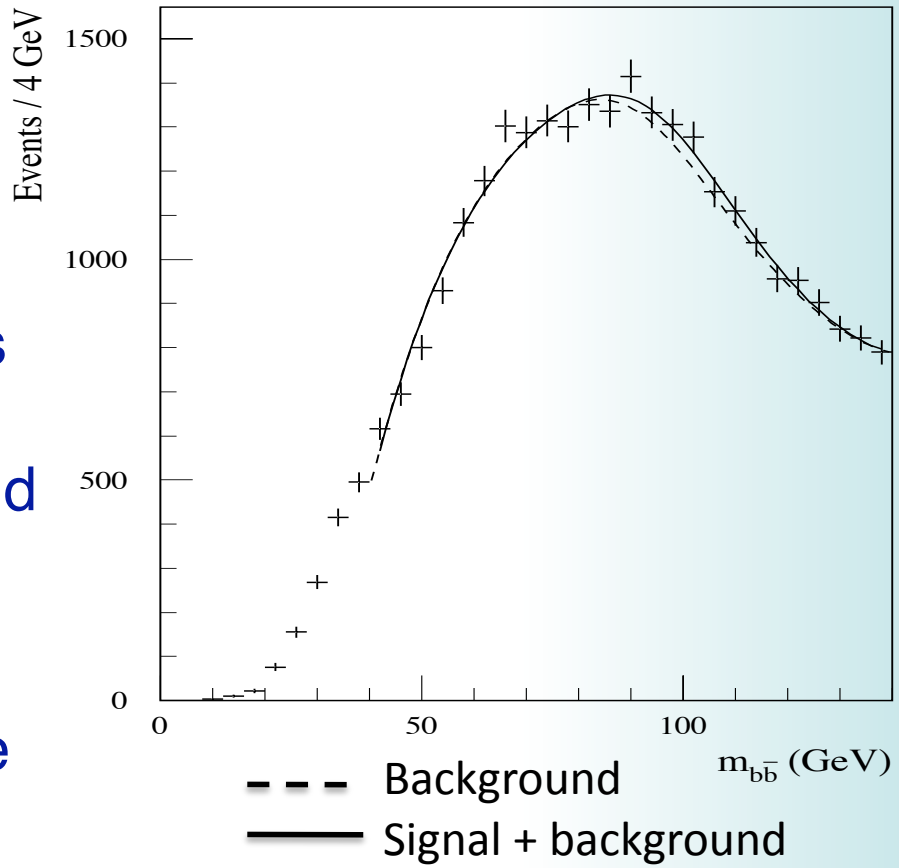
Use cases:Low Mass Higgs

- Around 115 GeV no single channel is (was) above 3σ with 10fb^{-1}
- Need a combination of channels
- WH, ZH with H ➔bb
  - Principal search channel at Tevatron
  - Not competitive at LHC…



Higgs + (W or Z)

- Example: ATLAS Physics TDR (1999)
  - Poor acceptance
  - Cuts introduce artificial mass scale into the background
  - Top anti-top has a similar mass scale
  - Large combinatorial background
- Signal swamped by backgrounds
  - "very difficult … even under the most optimistic assumptions"



Sub-jet analysis

- Cambridge/Aachen algorithm
  - Dokshitzer et al '97, Wengler and Wobisch '98
- Like "k_T without the k_T"
  - Work out $\Delta R_{ij} = \sqrt{(\Delta\phi^2 + \Delta y^2)}$ between all pairs of objects
  - Recombine the closest pair
  - Repeat until all objects are separated by $\Delta R_{ij} > R$
- We tried several values for R;
  - Main value chosen: R = 1.2
  - best value depends on p_T cut
  - Sensitivity not strongly dependent on the p_T / R combination
- Having clustered an event this way, can then work through backwards to analyse a particular jet.

Sub-jet analysis

1. Start with Higgs candidate jet (highest p_T jet in acceptance) with mass m)
2. Undo last stage of clustering (reduce radius to R_{12})

   $J \rightarrow J_1, J_2$
3. If $\max(m_1,m_2) < 2m/3$

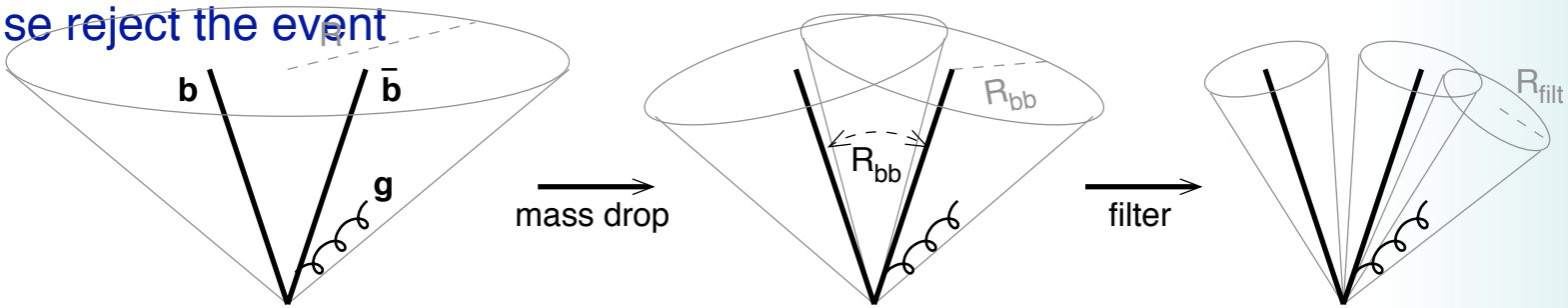
   Call this a "mass drop". This fixes the optimal radius for reconstructing the Higgs decay. Keep the jet J and call it the Higgs candidate.

   Else, go back to 2
4. Require $Y_{12} > 0.09$

   Dimensionless rejection of asymmetric QCD splitting

   Else reject the event
5. Require J_1, J_2 to each contain a b-tag

   Else reject the event



Sub-jet analysis

6. Define $R_{filt} = \min(0.3, R_{bb}/2)$

   Make use event-by-event of the known Higgs decay radius

   Angular ordering means this is the characteristic radius of QCD radiation from Higgs products

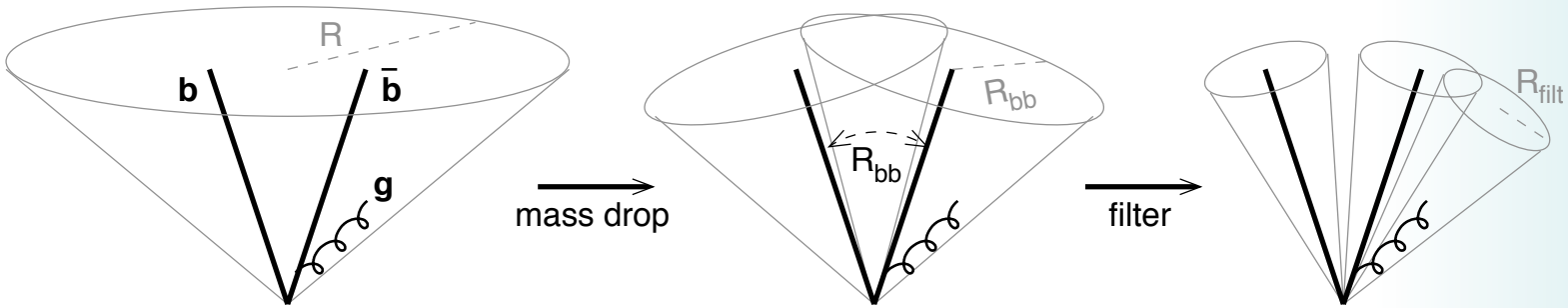
   Stuff outside of this is likely to be underlying event and pileup.

7. Recluster, with Cambridge/Aachen, $R = R_{filt}$

8. Take the 3 hardest subjets and combine to be the Higgs

   b, anti-b and leading order final state gluon radiation

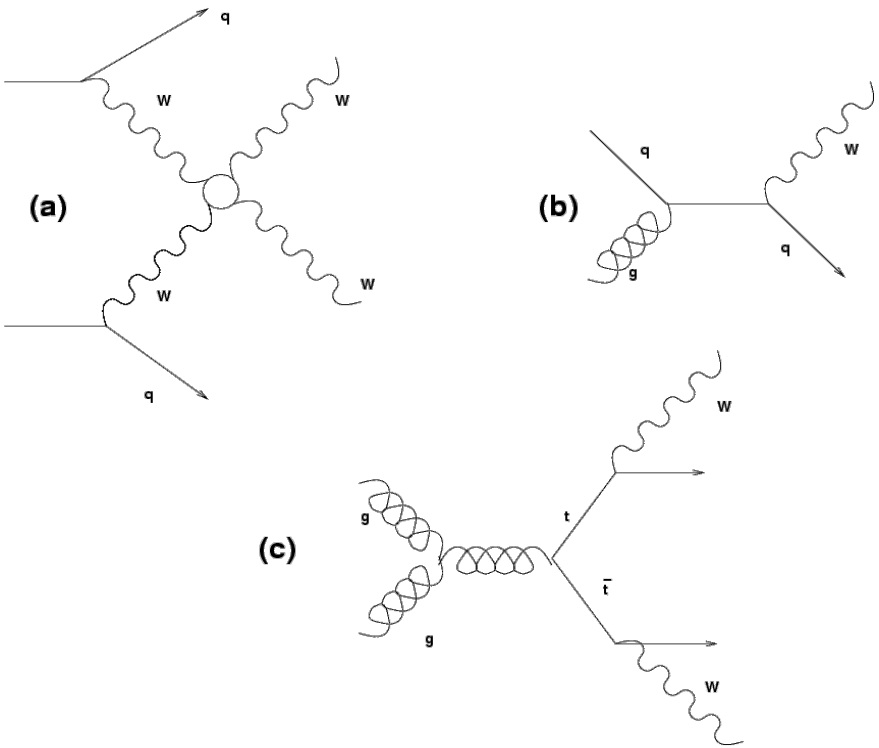
9. Plot the mass



Analysis Overview

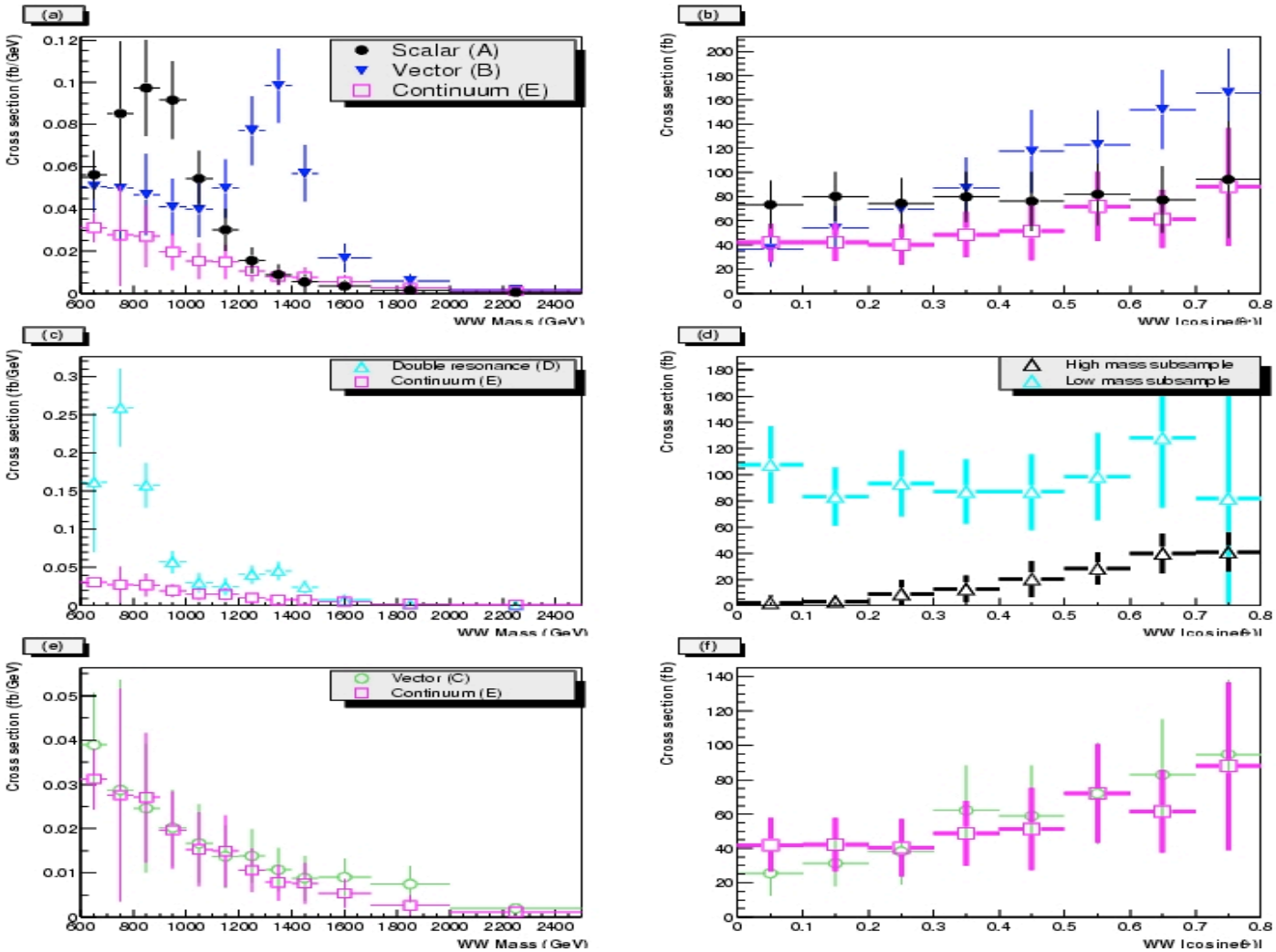
- Consider three cases
  - HZ, Z ➔ ee, $\mu\mu$
  - HZ, Z ➔ $\nu\nu$
  - HW, W➔ e/μ + ν
- Three non-overlapping selections
  - l + missing E_T + jet **("Leptonic W case")**
  - $l^+ l^-$ + jet **("Leptonic Z case")**
  - Missing E_T + jet **("Z ➔ neutrinos case")**
- Common cuts
  - p_T Higgs candidate > 200 GeV, p_T VB candidate > 200 GeV
  - $|\eta| < 2.5$ (Higgs candidate and leptons)
  - $p_T > 30$ GeV, $|\eta| < 2.5$ (leptons)
  - No extra b jet (p_T >30 GeV, $|\eta| < 2.5$) or lepton passing these cuts.

WW final state



- Search for resonances or deviations in the cross section at high masses
  - Leptonically decaying W + hadronically decaying W
- Major backgrounds
  - W + jets: QCD jet fakes a W
  - ttbar: Real W's from tops.
- Internal structure of the W candidate helps with rejection of W+jet background.

WW final state



Particle Level result

JMB, B.Cox, J.Forshaw, Phys.Rev.D65:096014, 2002.)

SUSY final states

- Pair production of heavy sparticles in generic SUSY models
  - Higgs or EW gauge bosons via decays of heavy gauginos
  - Large branching ratios for hadronic decays
    - more information (no neutrinos)
    - more backgrounds (QCD)

e.g. For decay chain

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

the invariant mass of the quark-W system has a minimum and maximum given by:

$$(m_{qW}^{\max/\min})^2 = m_W^2 + \frac{m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^0}}(E_W \pm |\vec{p}_W|)$$

QCD Toolkit: SUSY final states

where

$$|\vec{p}_W|^2 = \frac{(m^2_{\tilde{\chi}_1^\pm} - m^2_{\tilde{\chi}_1^0} - m^2_W)^2 - 4m^2_{\tilde{\chi}_1^0} m^2_W}{4m^2_{\tilde{\chi}_1^\pm}}$$

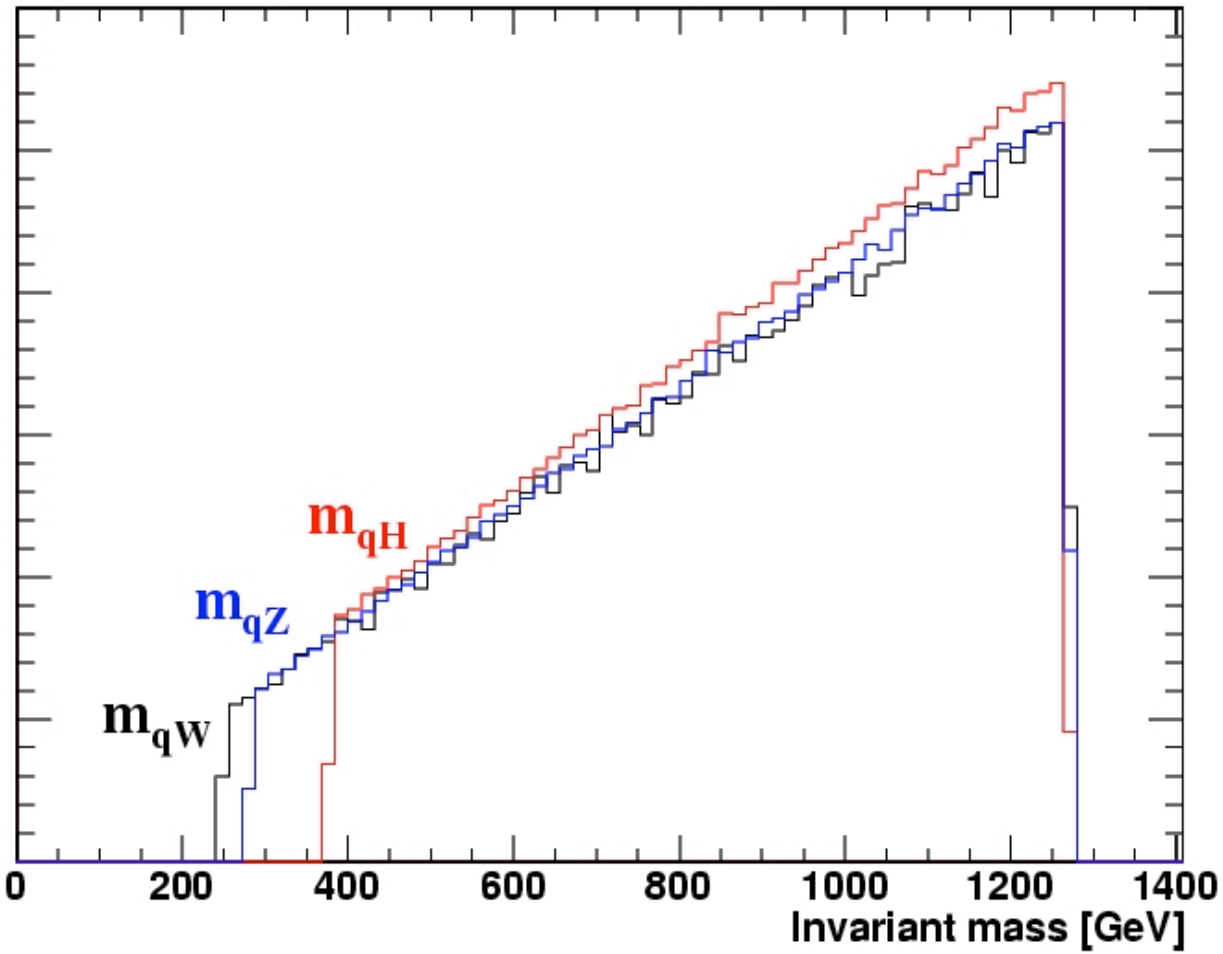
pendent

information on the SUSY mass spectrum.

- Similar decay chains exist involving the Higgs or Z.

SUSY final states

Truth level



JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

QCD Toolkit: SUSY final states

where

$$|\vec{p}_W|^2 = \frac{(m^2_{\tilde{\chi}_1^\pm} - m^2_{\tilde{\chi}_1^0} - m^2_W)^2 - 4m^2_{\tilde{\chi}_1^0} m^2_W}{4m^2_{\tilde{\chi}_1^\pm}}$$

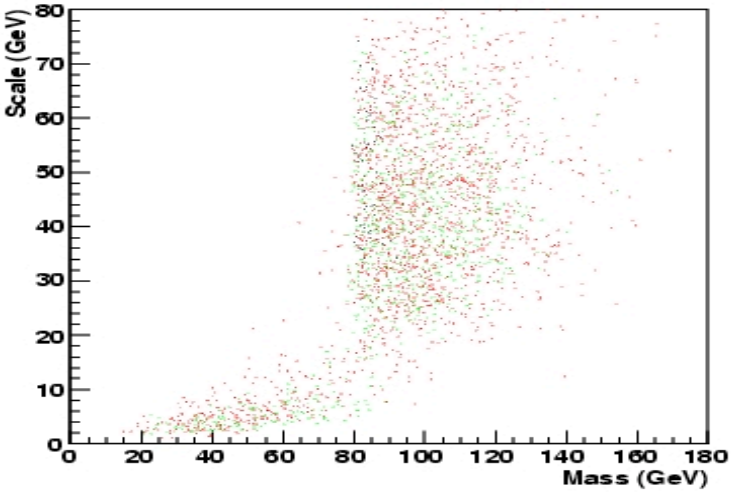
pendent

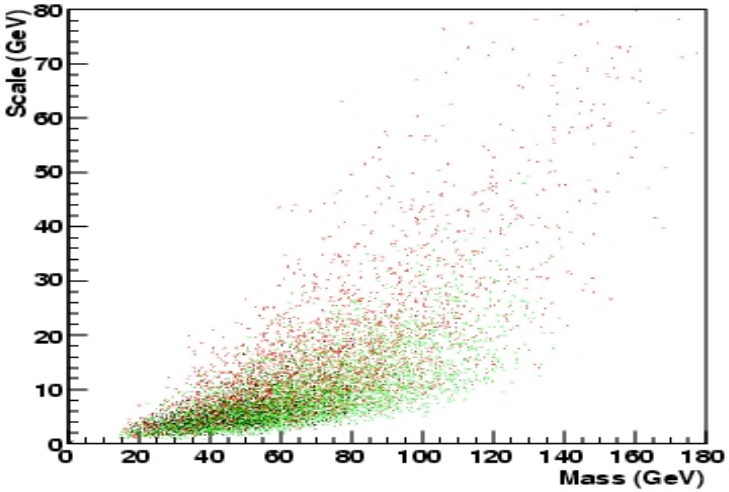
information on the SUSY mass spectrum.

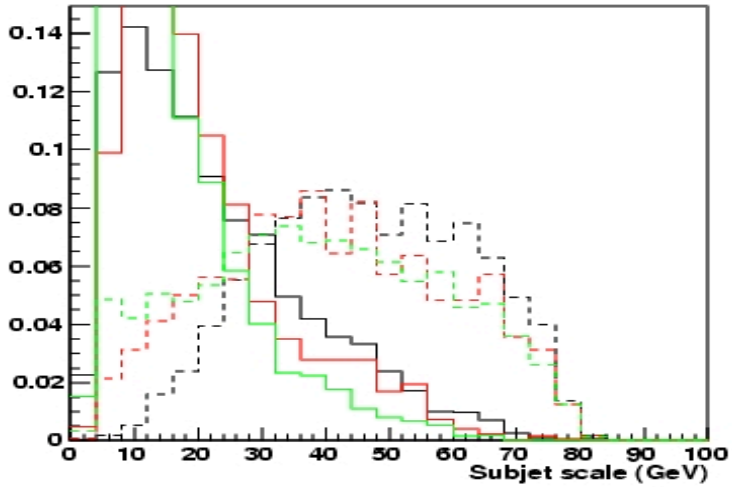
- Similar decay chains exist involving the Higgs or Z.

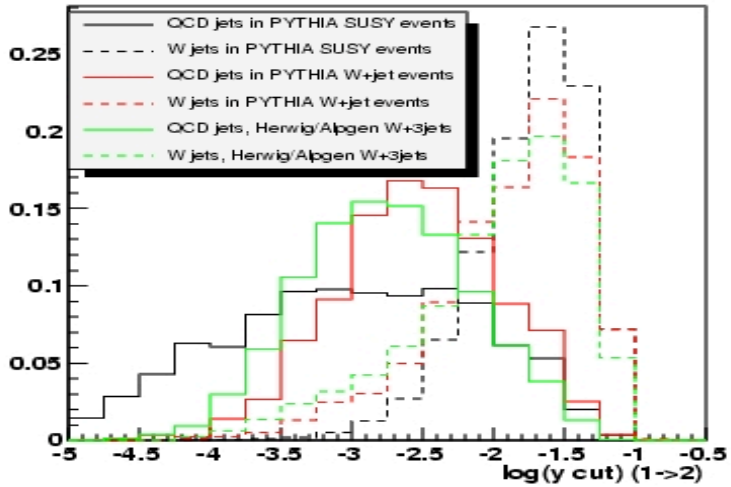
- Try this for benchmark models a, b, g, d *obtained by relaxing GUT scale universality of Higgs mass, or introducing gravitino dark matter candidate.*

QCD Toolkit: SUSY final states





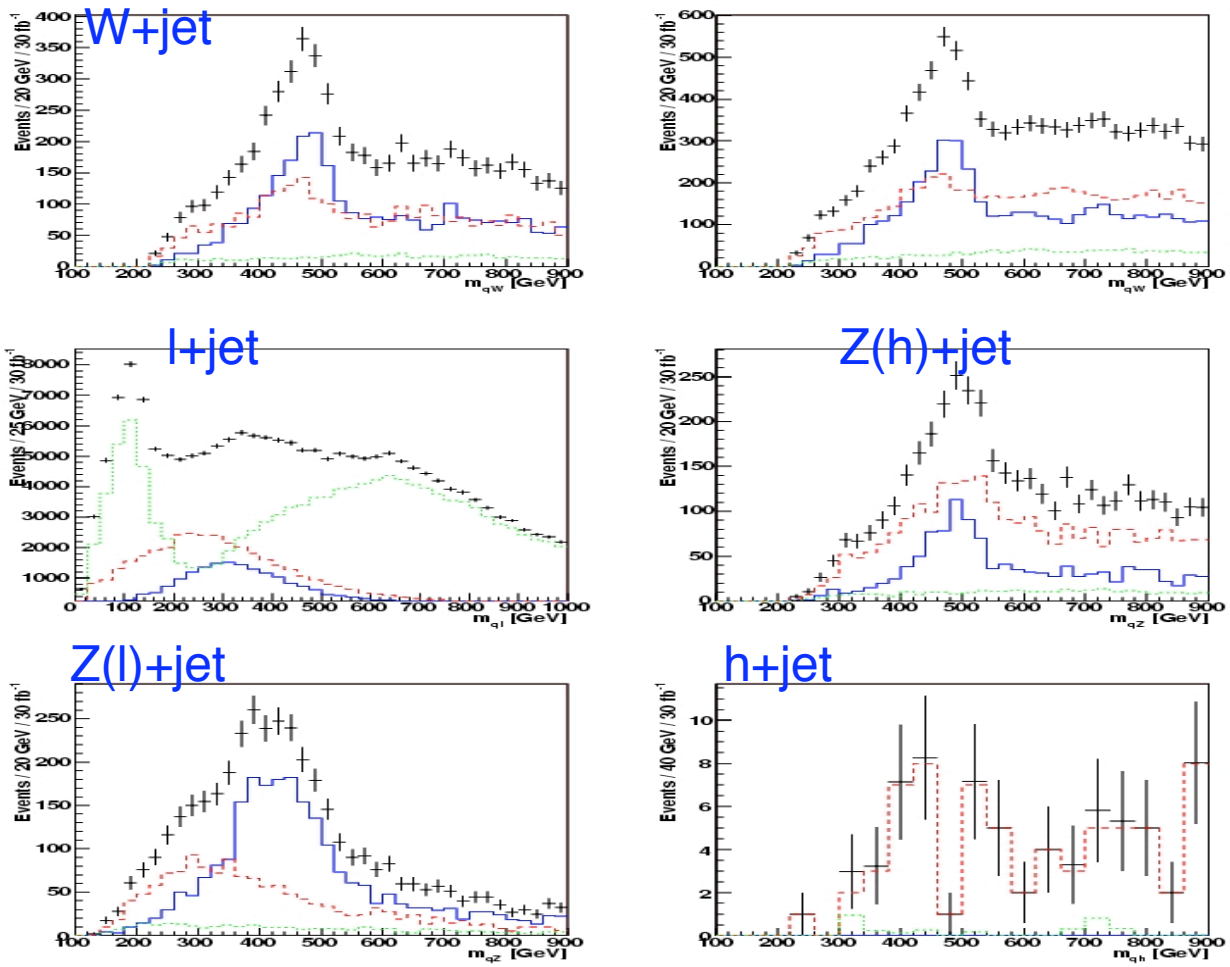




- Dashed lines = W jets
- Solid lines = quark, gluon jets
- SUSY events
- Pythia W+jet
- Alpgen/ Herwig W +jets

JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

SUSY final states



scenario α

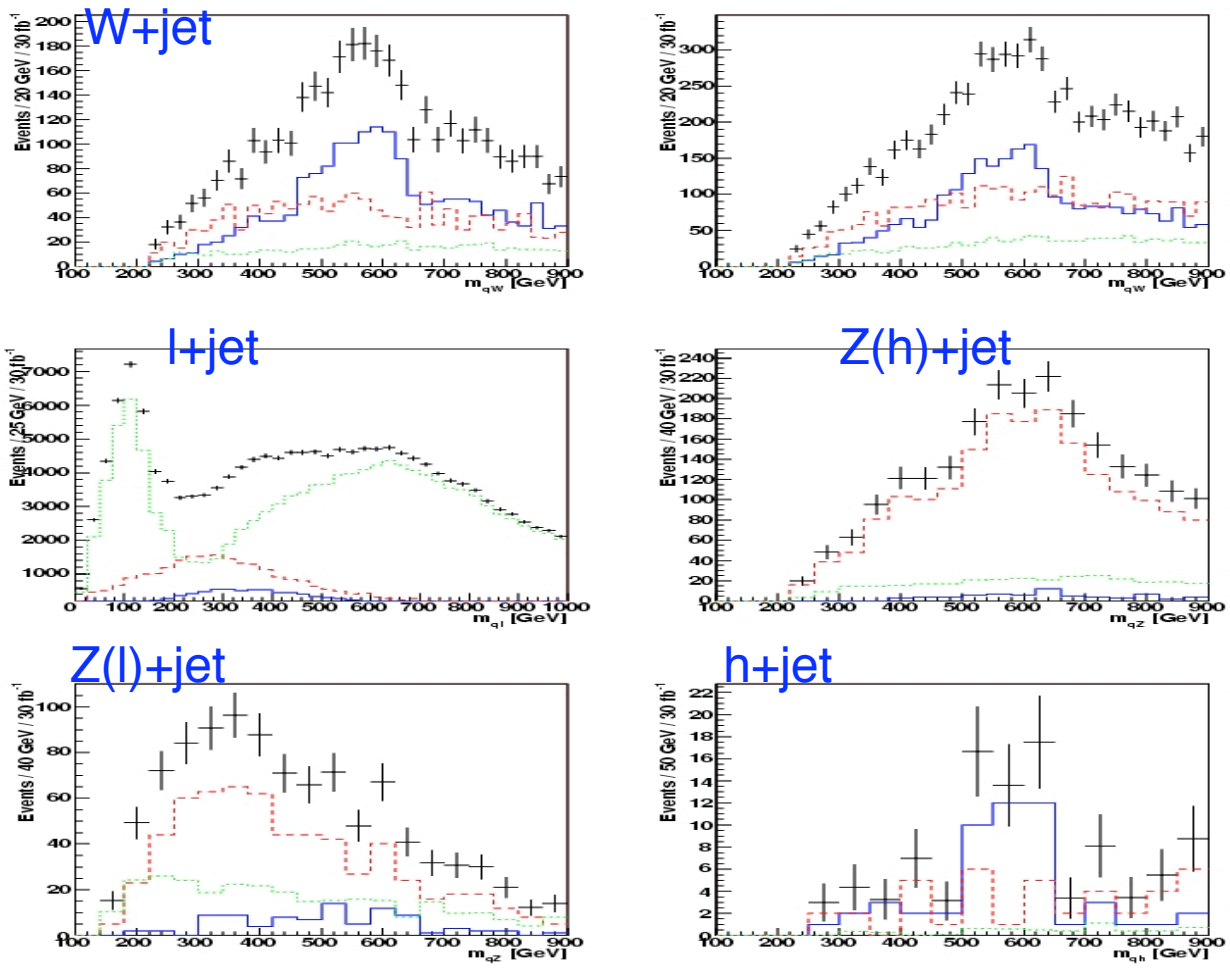
SM background from ttbar, W+jets, Z+jets, WW/ZZ/WZ, QCD.

SUSY background from misidentified decays, especially QCD jets faking hadronic W, Z or h decays.

Signal

JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

SUSY final states



scenario β

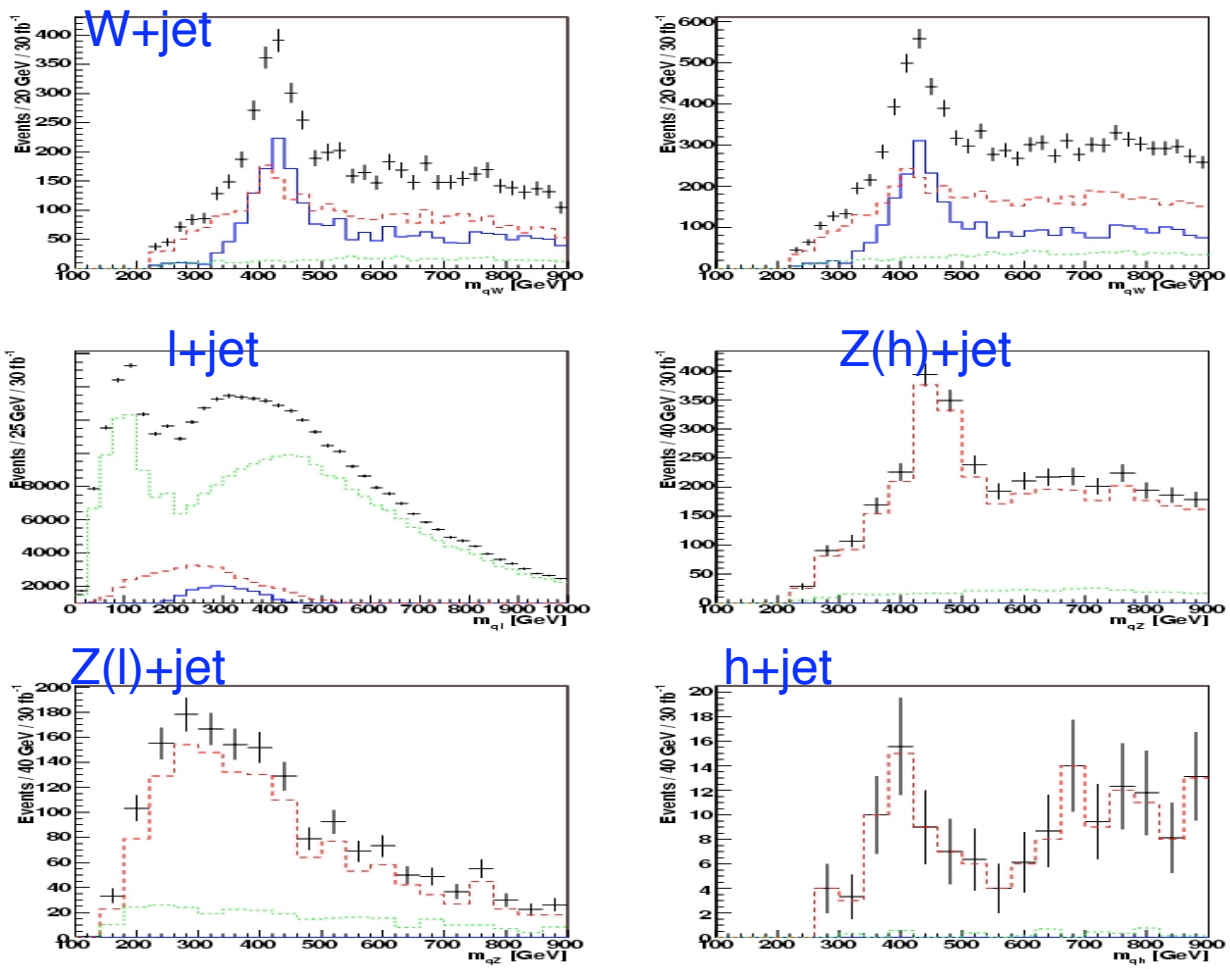
SM background from ttbar, W+jets, Z+jets, WW/ZZ/WZ, QCD.

SUSY background from misidentified decays, especially QCD jets faking hadronic W, Z or h decays.

Signal

JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

SUSY final states



scenario γ

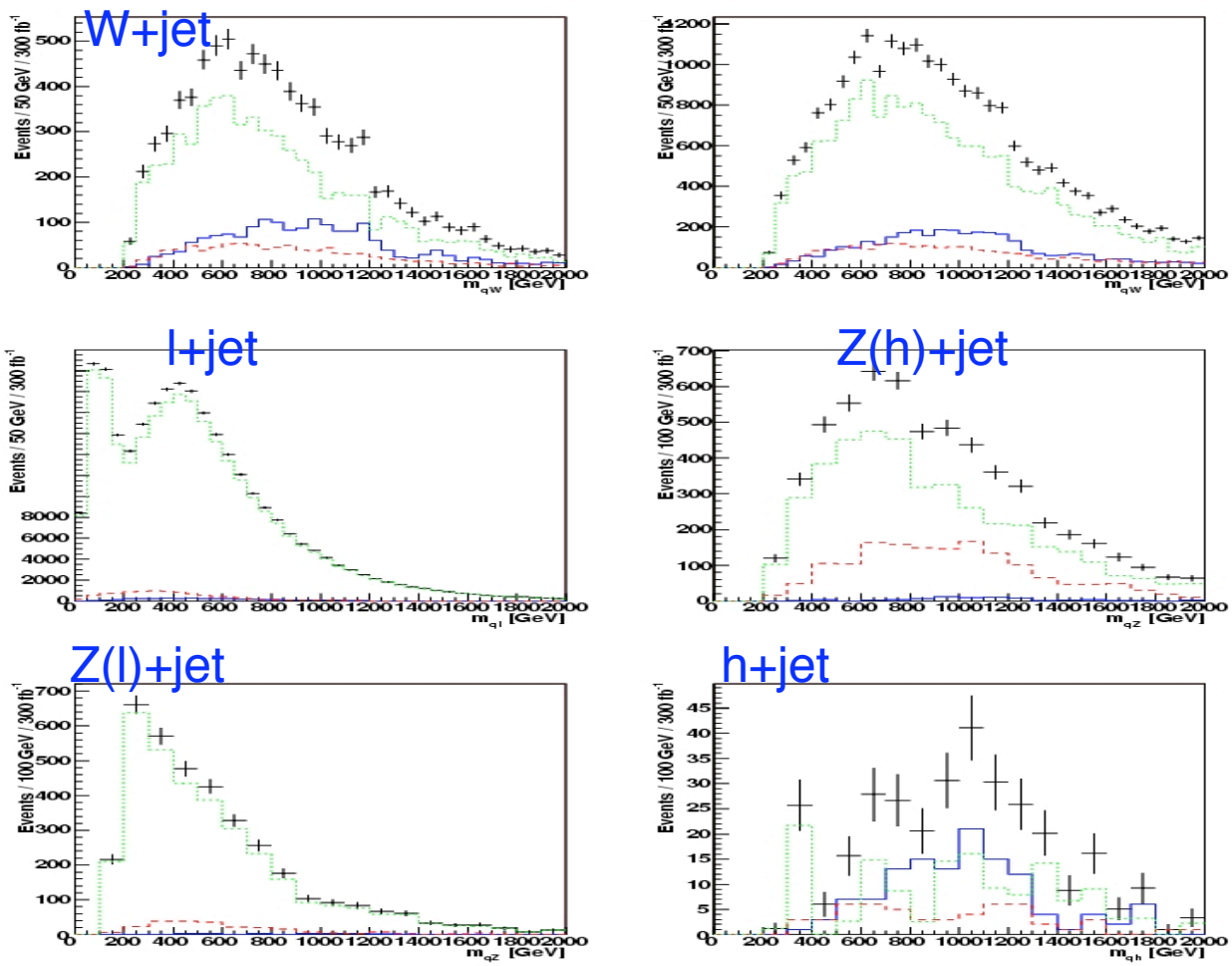
SM background from ttbar, W+jets, Z+jets, WW/ZZ/WZ, QCD.

SUSY background from misidentified decays, especially QCD jets faking hadronic W, Z or h decays.

Signal

JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

SUSY final states



scenario δ

SM background from ttbar, W+jets, Z+jets, WW/ZZ/WZ, QCD.

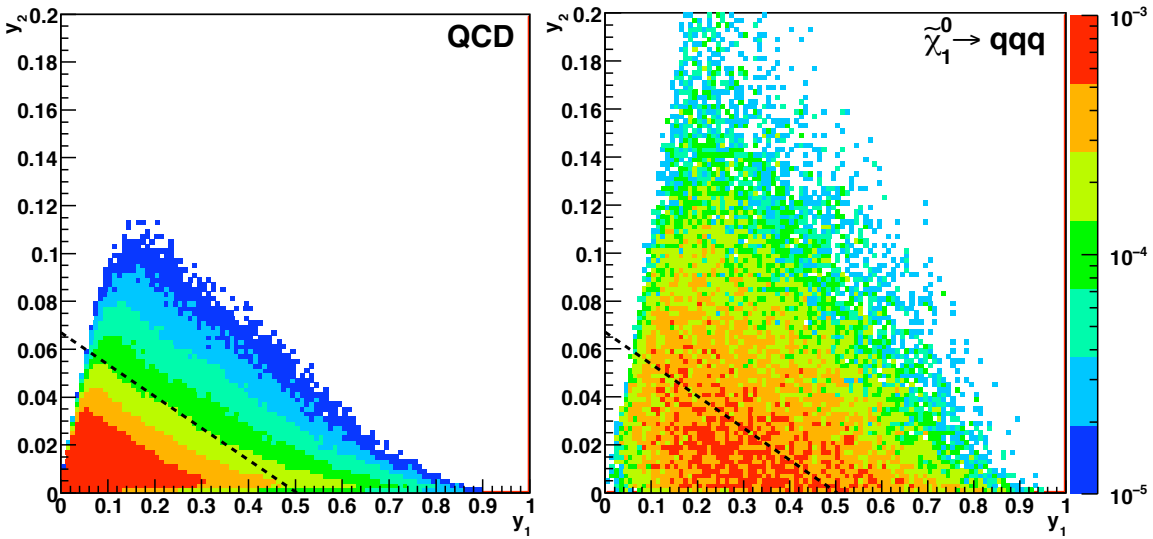
SUSY background from misidentified decays, especially QCD jets faking hadronic W, Z or h decays.

Signal

JMB, J. Ellis, A. Raklev JHEP 0705:033,2007.

Another Example: Baryon-number violating decays

- Three body decay, but with no real intermediate state.
- Two methods tried:
  - First method: as with top analyses, look at the first two k_T y scales

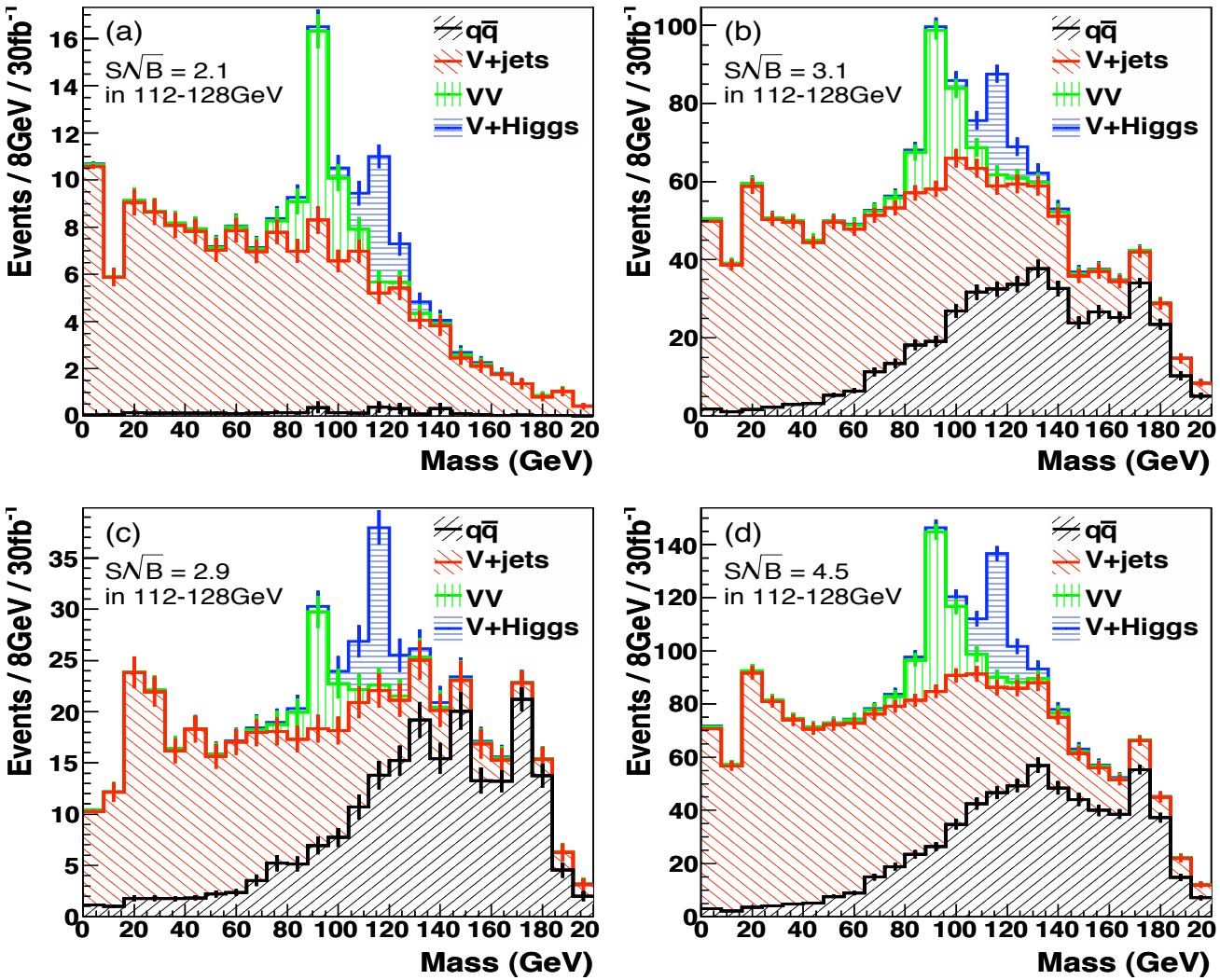


  - Second method: use C/A

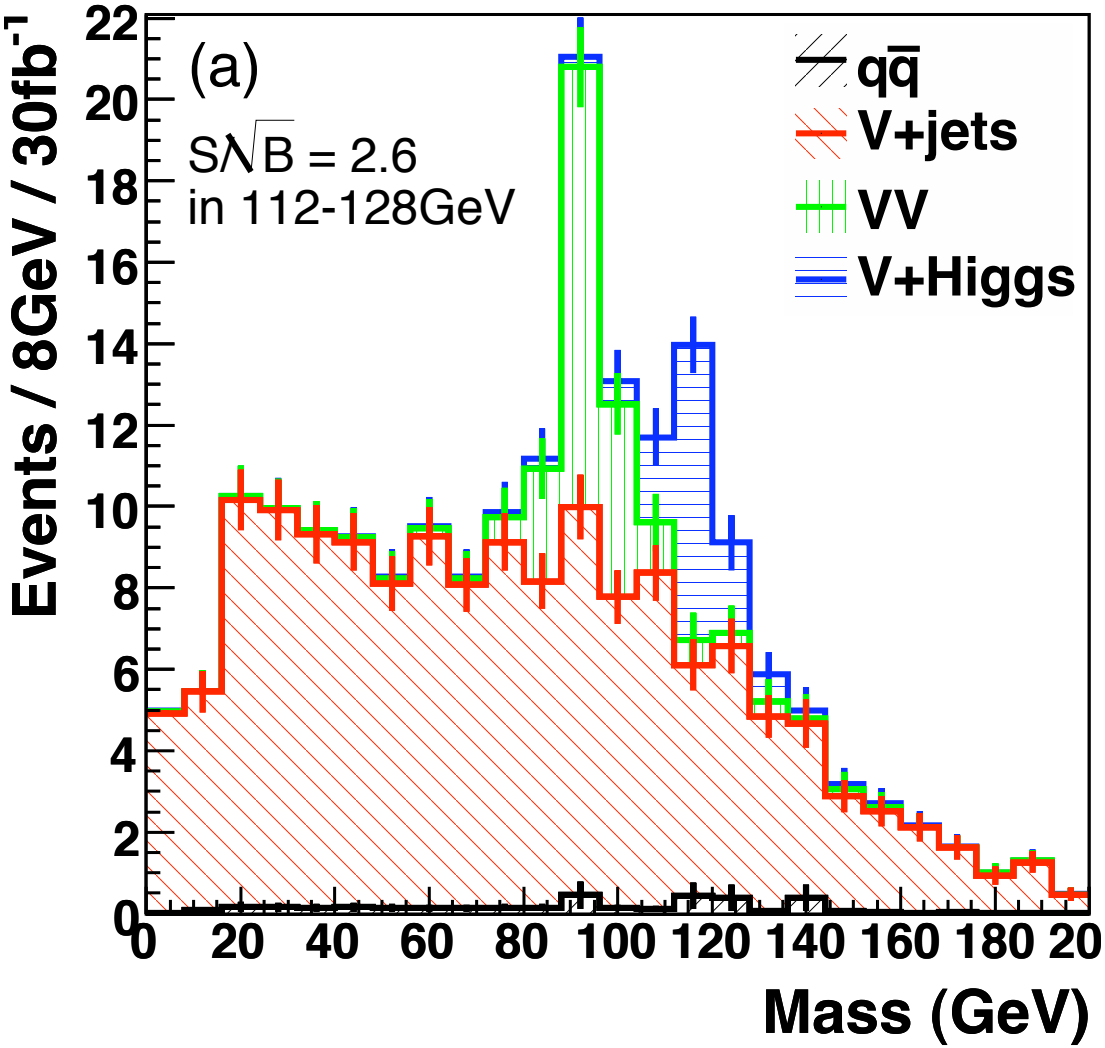
Another Example: Baryon-number violating decays

- Method 2:
  - Recurse through C/A splittings.
  - When you find a very asymmetric one (i.e. QCD like) reject the softer of the two objects.
  - For the remaining (symmetric) splittings, look at the two with the largest JADE-type different $p_{Ti}p_{Tj}\Delta R_{ij}$.
  - If the smaller bc is contained by the larger a(bc), this is a neutralino candidate.
  - Mass is the mass of abc system.

Extra

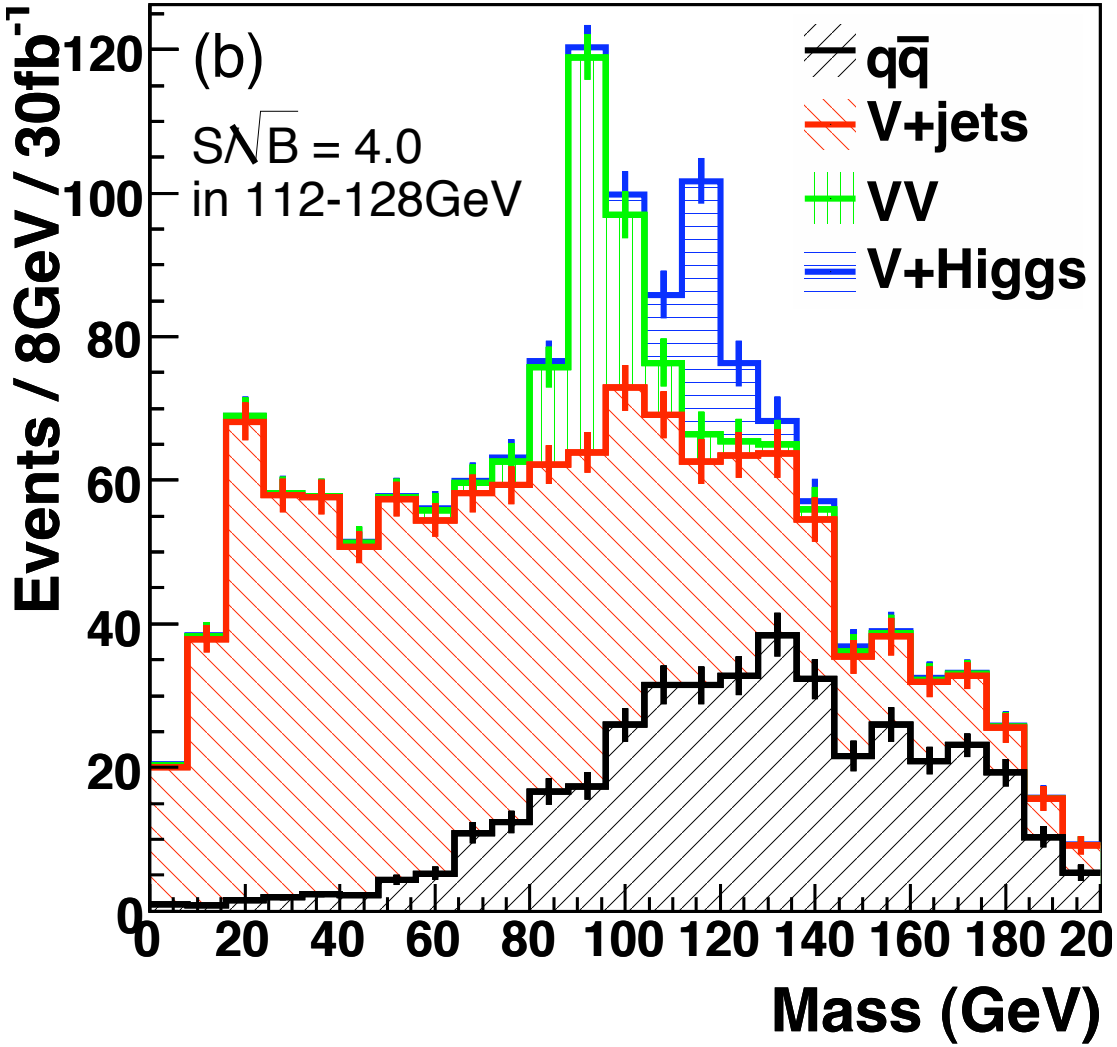

(a)
S√B = 2.1
in 112-128GeV
(b)
S√B = 3.1
in 112-128GeV
(c)
S√B = 2.9
in 112-128GeV
(d)
S√B = 4.5
in 112-128GeV
qq̄
V+jets
VV
V+Higgs
Events / 8GeV / 30fb⁻¹
Mass (GeV)

Leptonic Z case



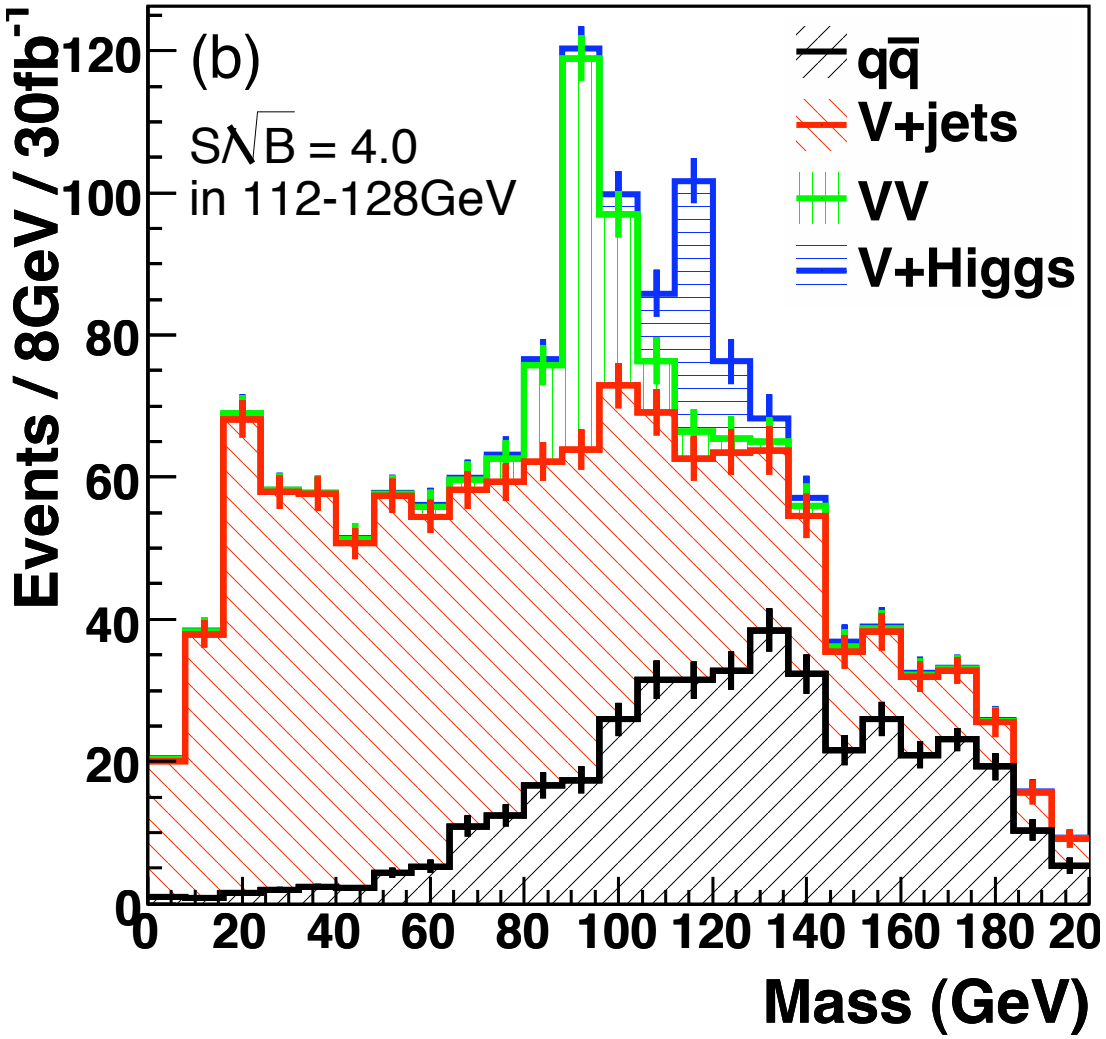
- Common cuts, plus require
  - dilepton mass between 80 and 100 GeV

Z → neutrinos case



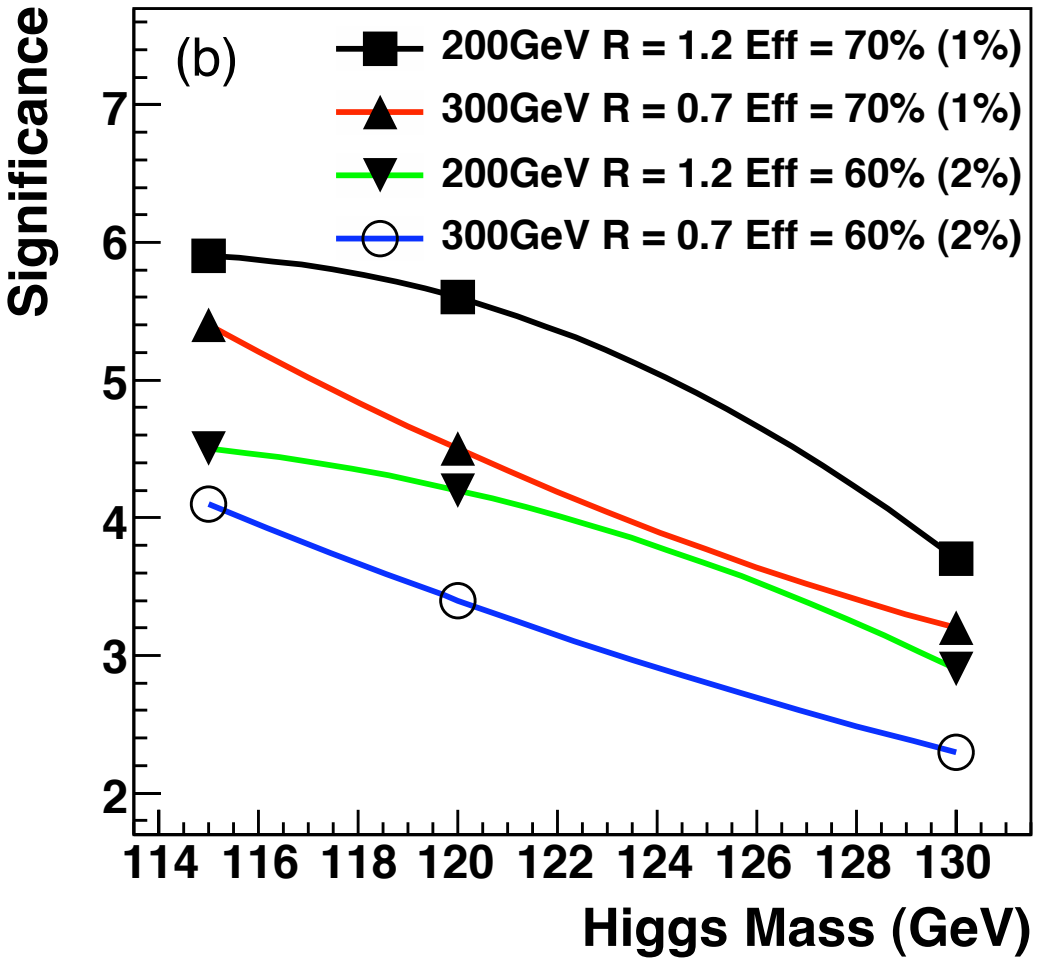
- Common cuts, plus require
  - Missing E_T greater than 200 GeV

Leptonic W case



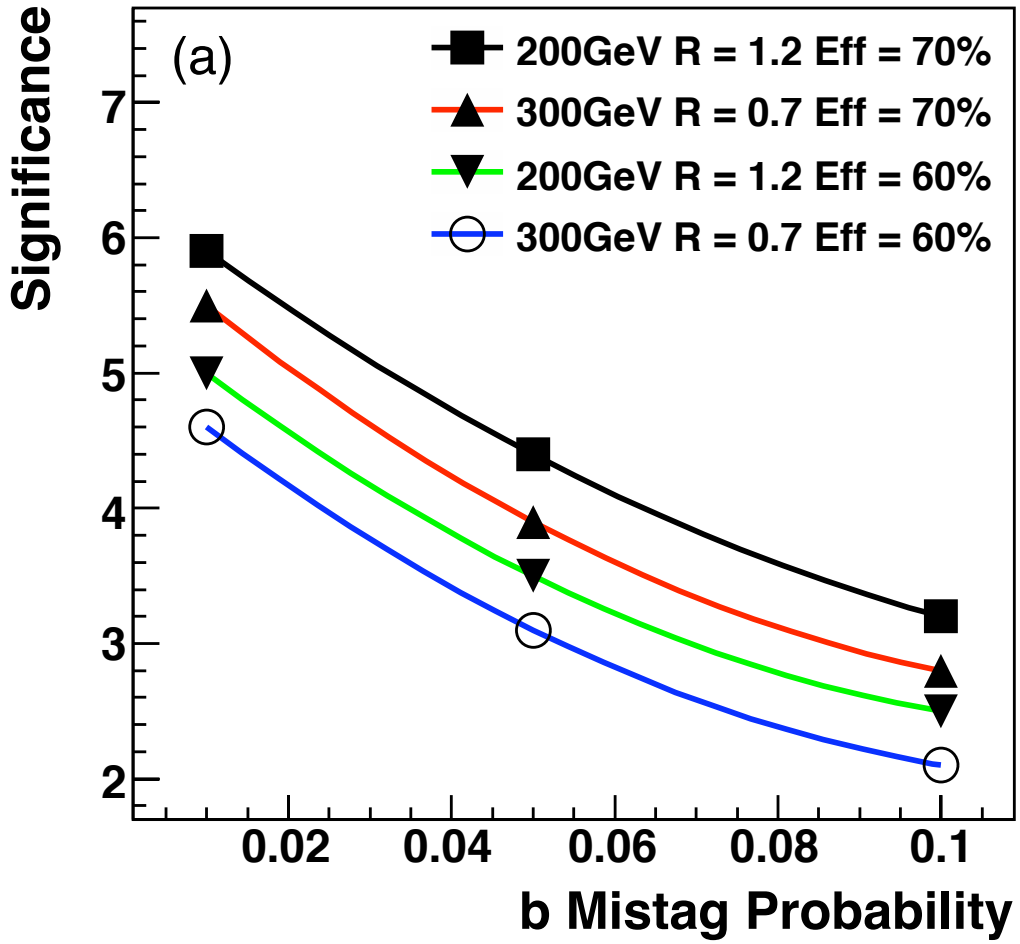
- Common cuts, plus require
  - missing $E_T > 30$ GeV
  - Lepton and missing E_T consistent with a W
  - No extra jets $|\eta| < 3$, $p_T > 30$ GeV

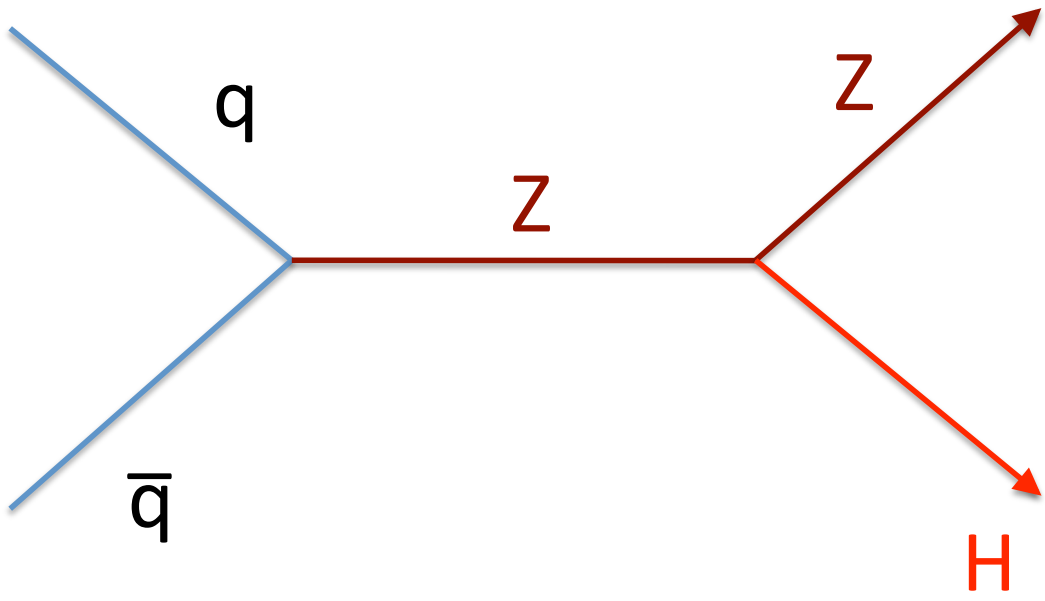
Combined result



- Note excellent Z peak for calibration
- 5.9 σ; potentially very competitive
- Also, unique information on relative coupling of H to Z and W.
- Reasonably good up to about 130 GeV.

Combined result



- Strong dependence of b-tag performance
- Significance about 4.5σ for 60% efficiency/factor 50 rejection
- Also strong dependence on jet mass resolution (not shown)

Higgs + (W or Z)