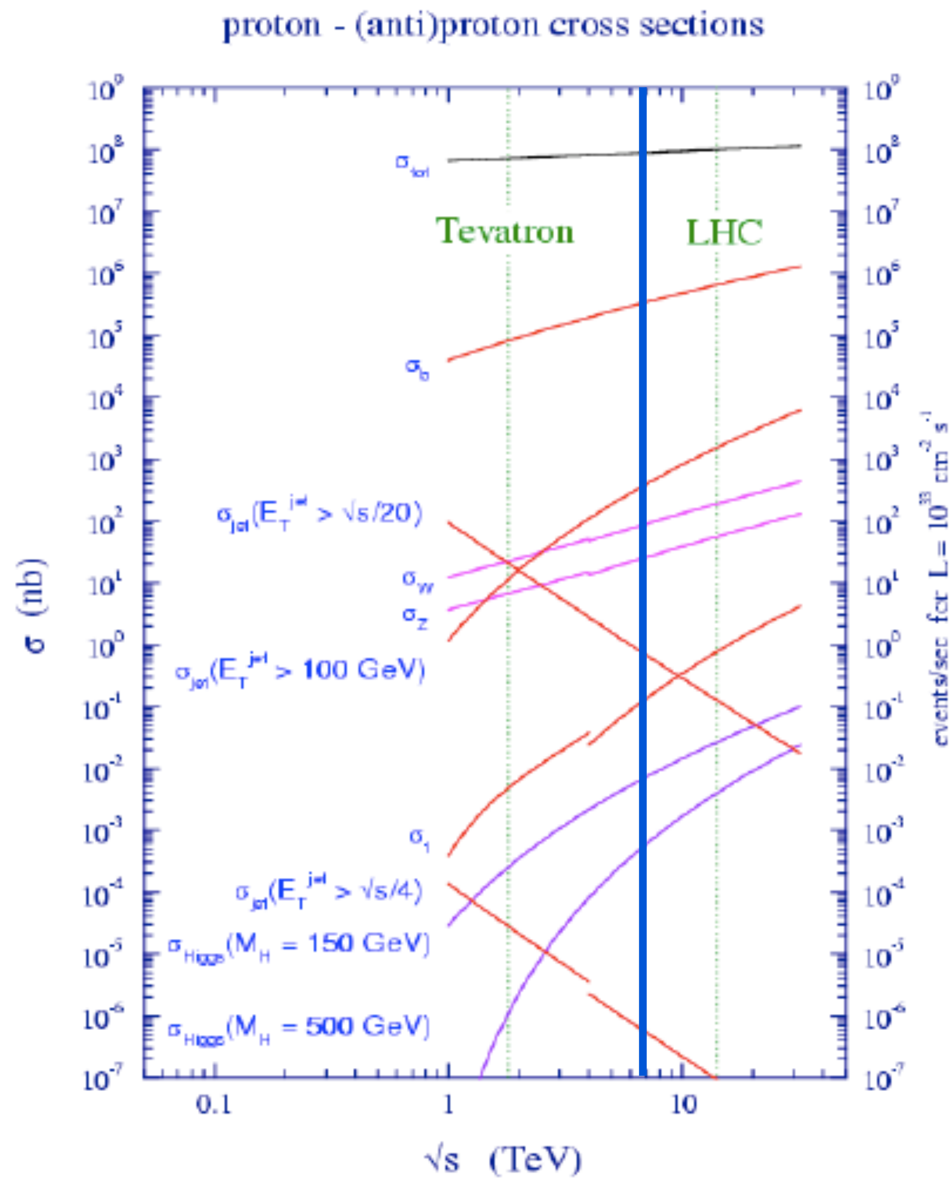
New Physics @ LHC

Physics @ LHC

- LHC opens a new era:
  - Tevatron was mega-W
  - LHC is
    - Giga-W
    - Giga-Z
    - Top factory
    - Higgs mini-factory
    - New physics factory?



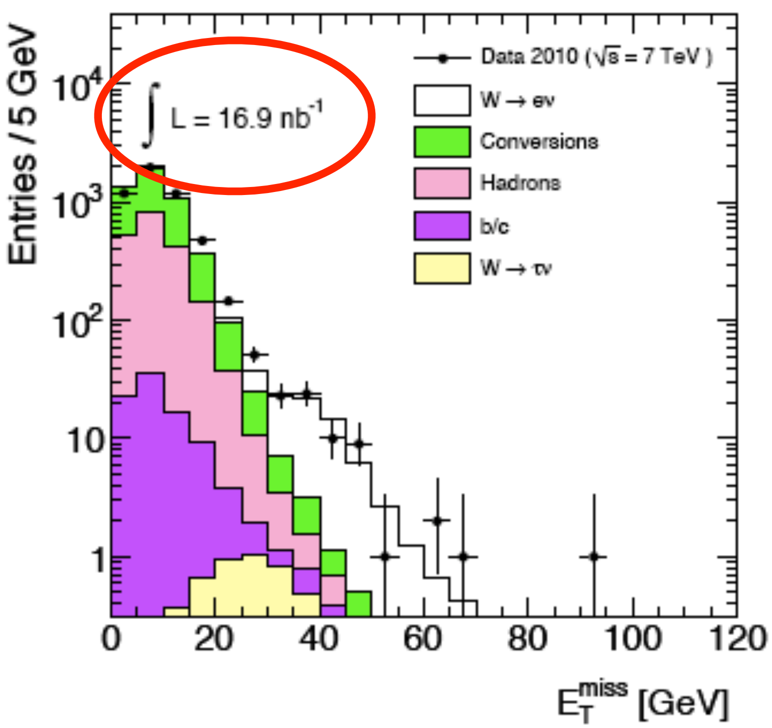
Experimental Searches

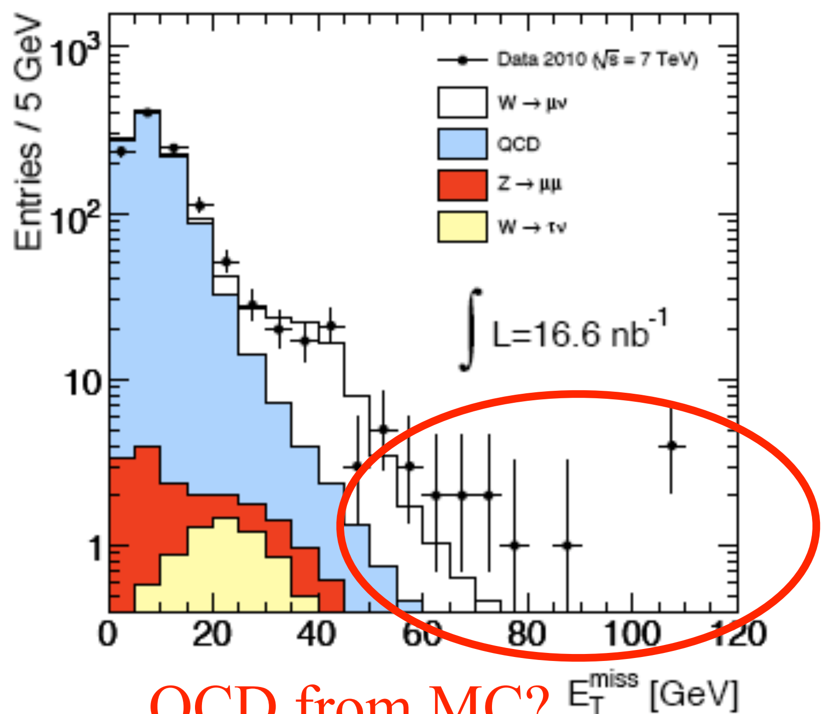
- By final state, so main questions are
  - Does the new physics produce dark matter?
    - Particles we basically know exist and interact weakly at best
    - ➡ Yes: signatures contain missing transverse energy
    - ➡ No: MET not generic signature
  - Are there new interactions?
    - ➡ No: we know how to calculate everything
    - ➡ Yes: strong (resonances) or very weak (long-lived particles)?
- e.g. SUSY is (a,a), technicolor (b,b)....

Missing ET

- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

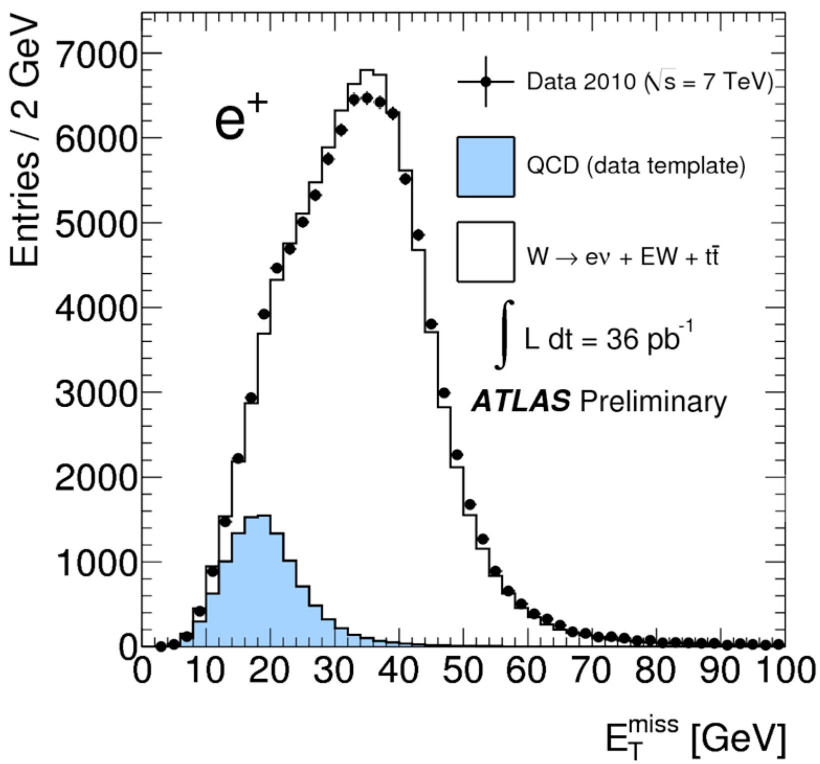
Early 2010

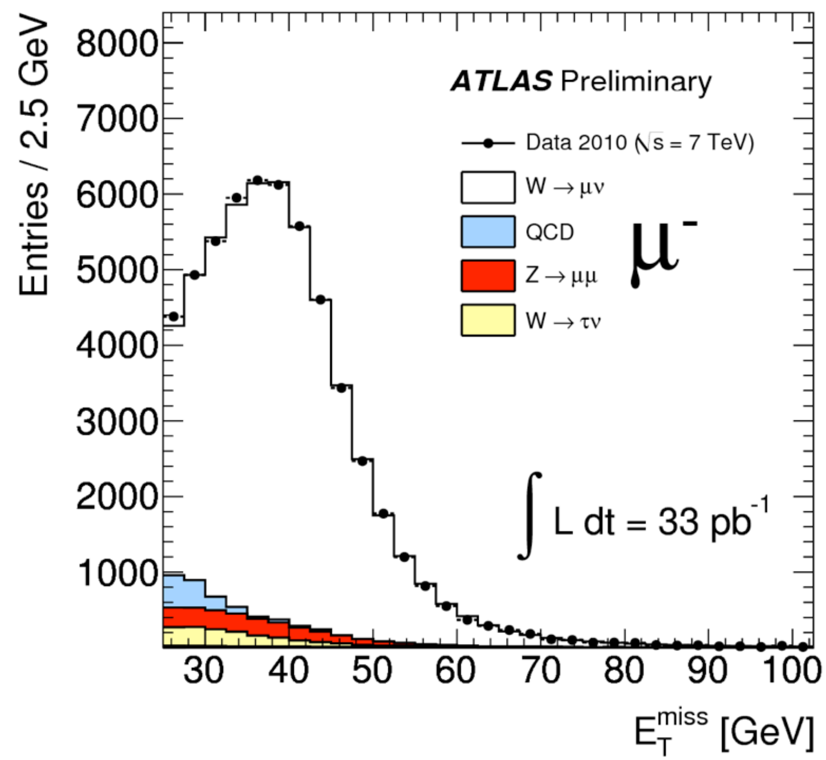




QCD from MC?

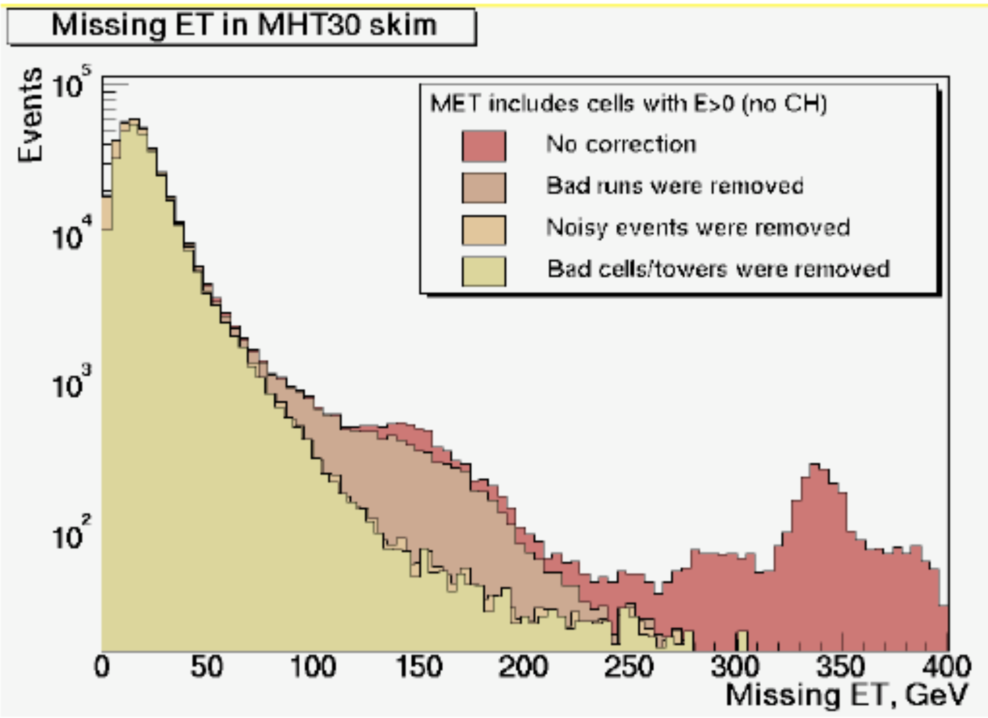
- With more data and QCD evaluated from data





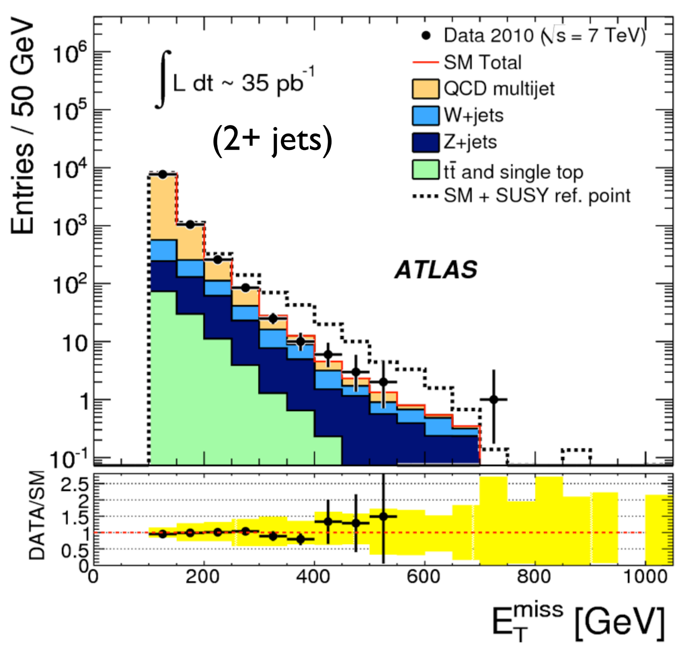
- Already ~200k clean $W \rightarrow \ell\nu$ events in 2010
  - Millions now...

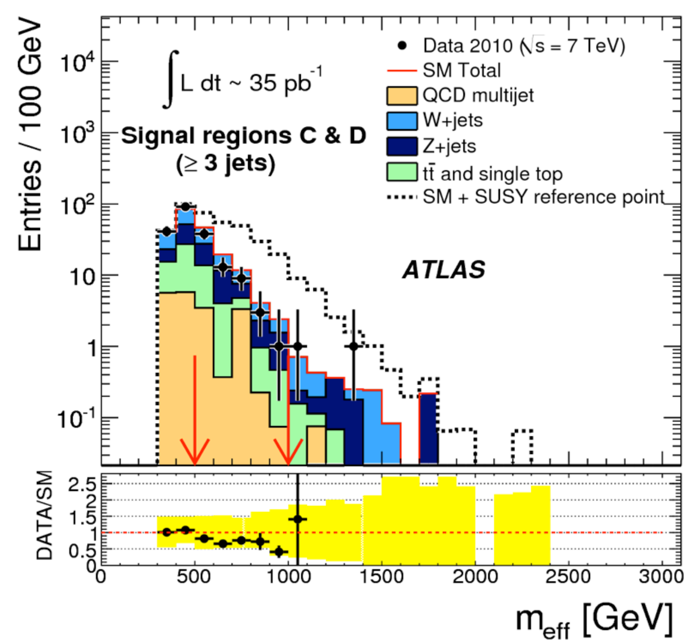
- Analyses using MET are particularly sensitive
  - Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bits)
  - Easy: basic DQ (missing board, etc.)
  - Hard: low frequency
  - Can't spot a 10^{-5} Hz (once a day) effect online or in first pass DQ
    - But can be biggest part of dataset after cuts!
    - Everytime dataset x5, find new source of rare noise...



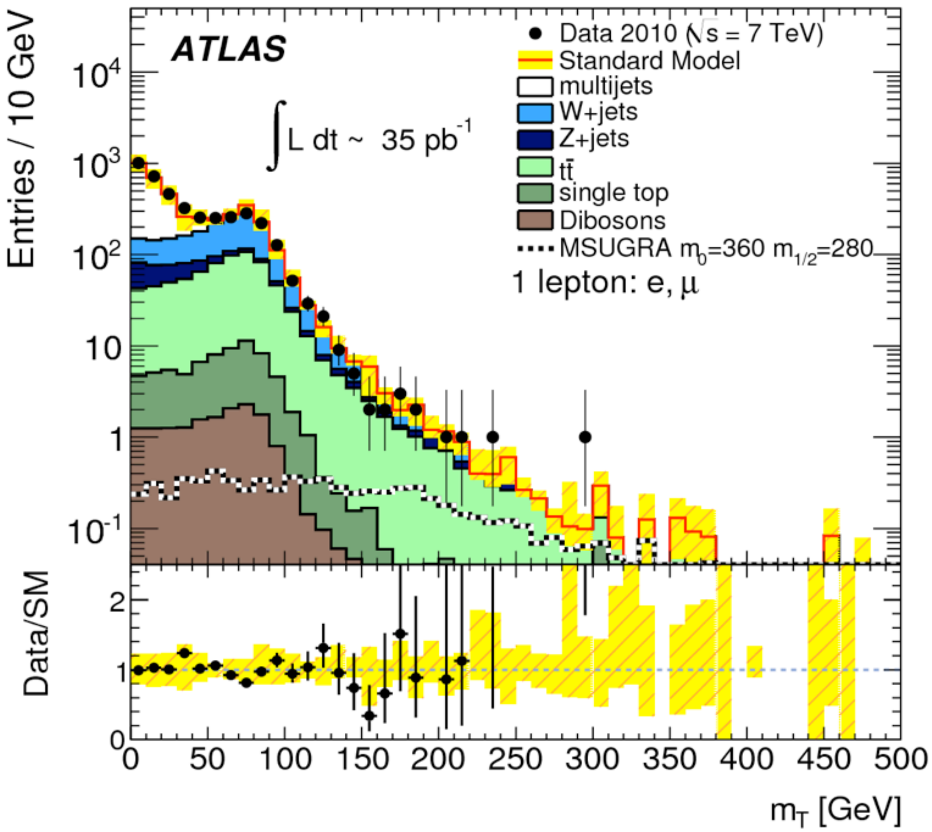
SUSY as a Benchmark

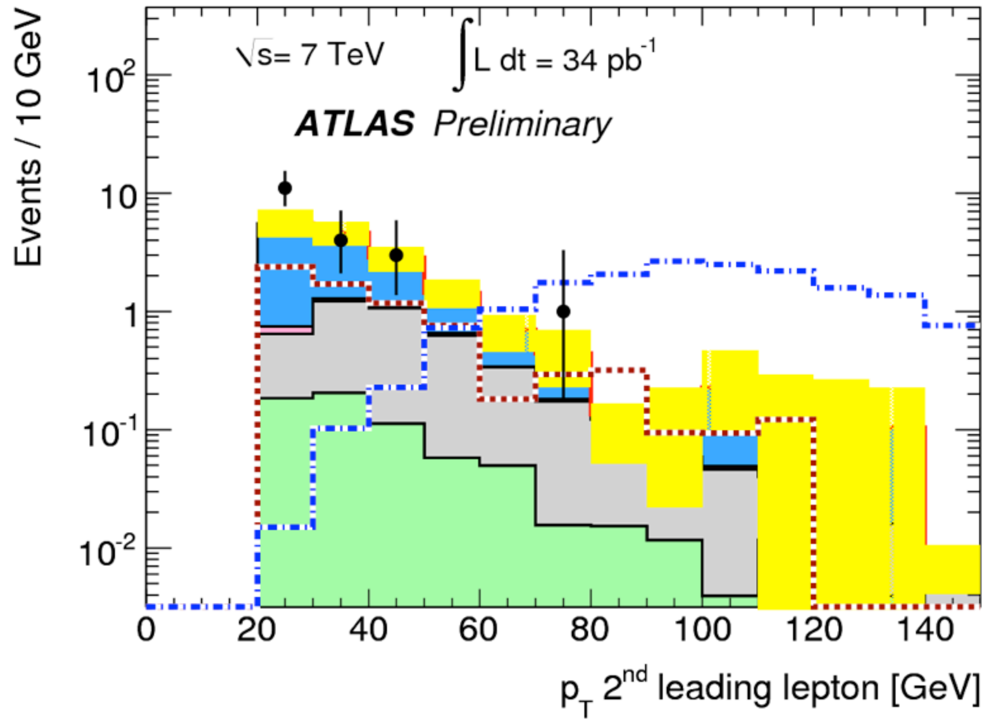
- Hadron collider ⇒ produce squarks and gluinos decaying to jets + MET
  - Optimize jet p_T & MET cuts for different scenarios, since gluinos produce more jets than squarks
    - Use M_{eff} to discriminate, measure of event Q^2



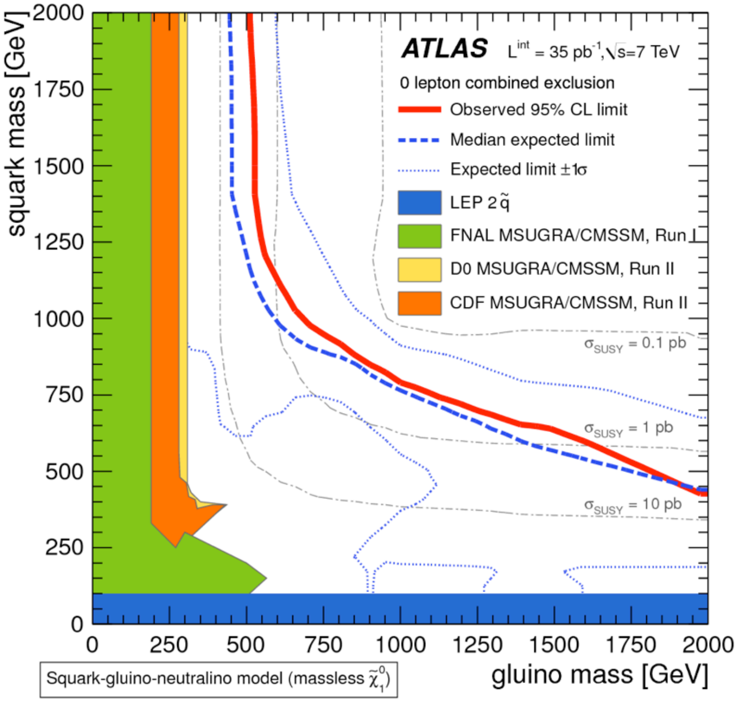


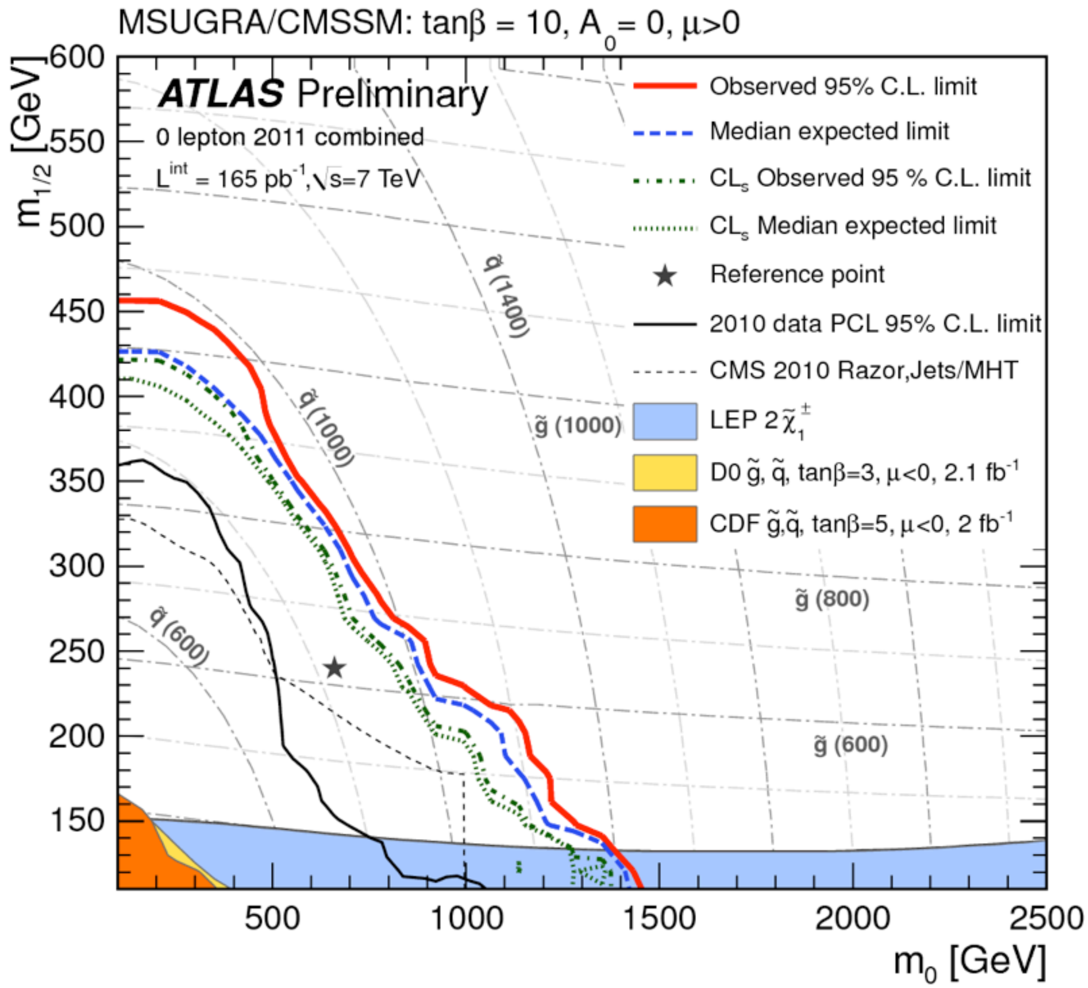
● Leptons can appear in decay chains....





All Praise COM Energy!

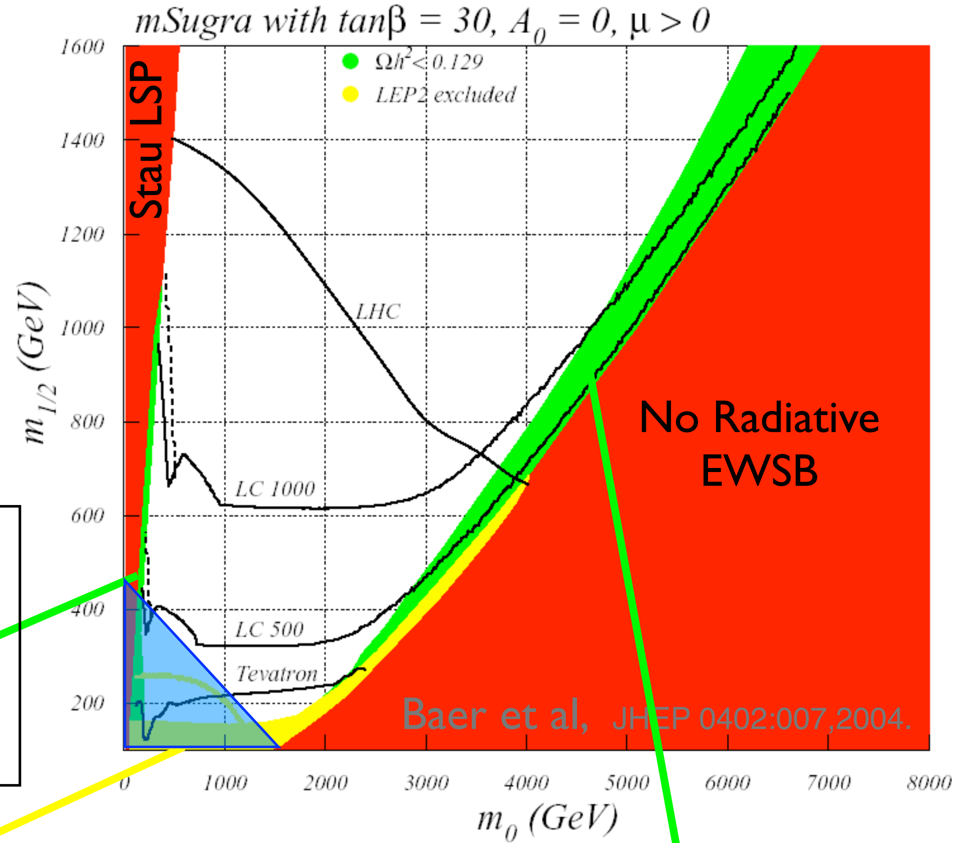




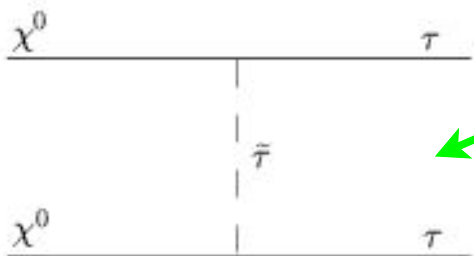
Tevatron blown away....

SUSY In Trouble?

- Can calculate relic LSP density
  - LSP cannot be too heavy, or need an efficient way to annihilate

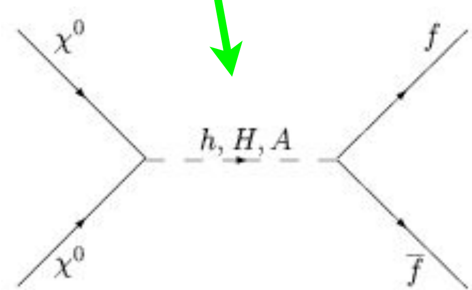


Coannihilation:
LSP and NLSP are almost degenerate



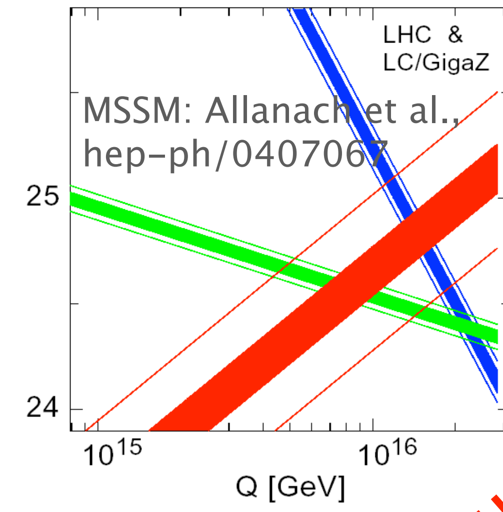
Bulk region:
superpartners are light

Focus points:
neutralino is mostly higgsino;
light charginos,
small mass gaps



Not SUSY?

- SUSY theories (and others with full or partial set of SM-partners) have a number of attractive features
  - "Explanation" for low Higgs mass (and sometimes EWSB)
  - Gauge coupling unification (often)
  - Dark matter candidate (if introduce a new parity, natural in UED, ~ad-hoc in SUSY)
  - No new interactions (often)



- But answering those questions comes at a large cost
  - Many new particles, with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

Dinosaurs on Venus?

A Simple Observation

Higgs and Fermion Masses

- Inside a generation, the more a fermion interacts, the heavier it is
  - (Of course, we don't know that the τ-ν_τ lepton generation doesn't really match up with the d-u quark generation, only hint is b-τ unification I believe)

➡ Pattern suggests fermion masses might be related to a more complex mechanism

  - Indirect relation to interactions? ("Gauge mediation?")
  - Higgs may then only be relevant for VV scattering, relaxing mass constraints, existing limits (no bb!)

Spin & Mass

- Problem with mass is that it allows a particle to change helicity
  - And, of course, since parity is maximally violated in weak interactions, this "breaks the symmetry"
  - Deeper understanding of spin as useful to making progress as a Higgs observation

➡ Scenario of restoration of parity might lead to *understanding* of fermion masses

  - No necessarily strict left-right...

Parity

(or: Step-By-Step)

Parity Restoration: Signals

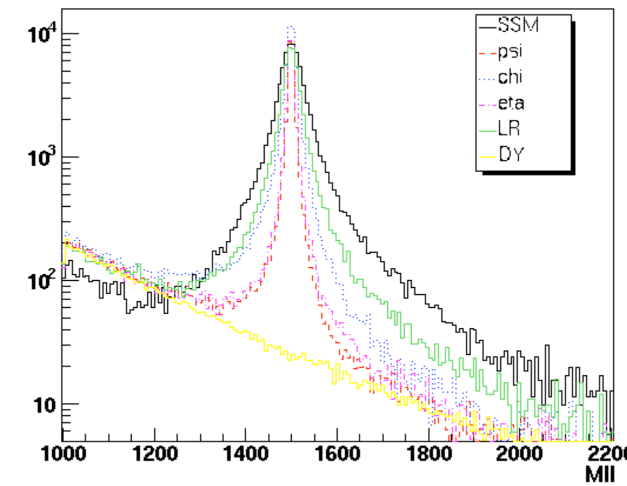
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p_T
  - $t\bar{t}$ decays visible
  - ν_R is presumably heavy, W' may only decay to quarks
    - If ν_R lighter than W'/Z', ν_R decays become important
- Note: many kinds of Z' - recent review by Langacker

arXiv:0801.1345

Z' Production and Decay

- Production from u, d quarks is dominant at Tevatron/LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\varkappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes ν_R heavier

T. Rizzo, hep-ph/0610104



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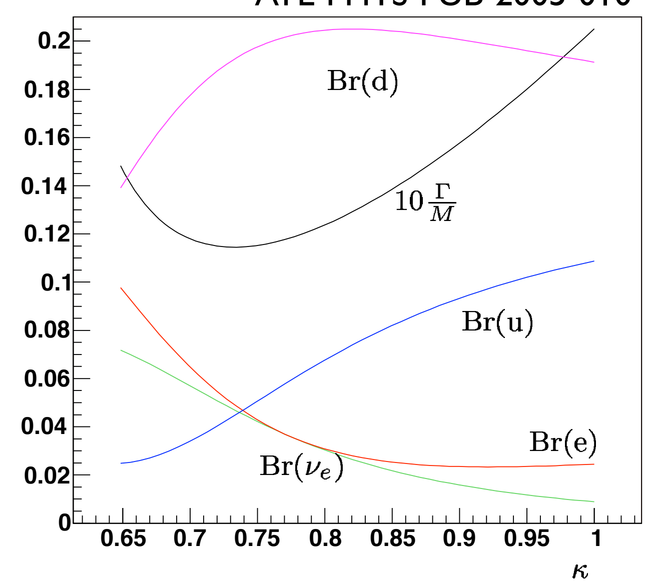
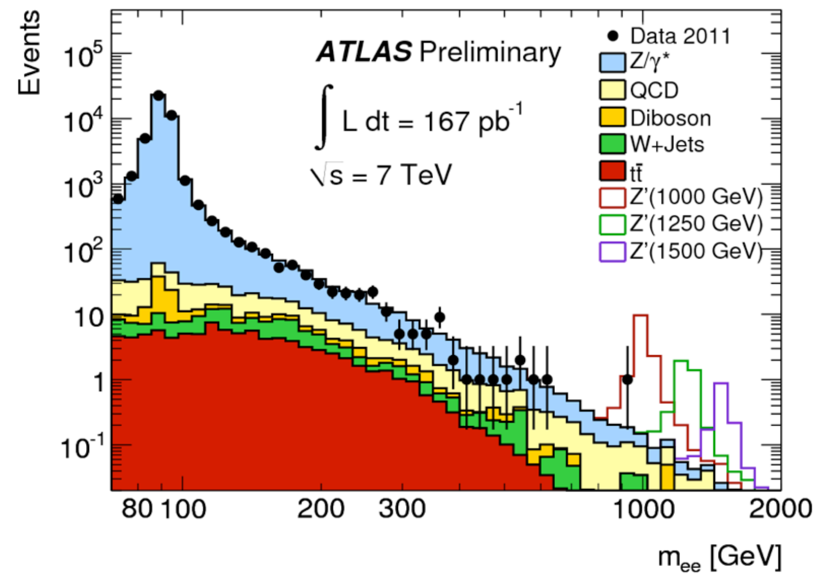
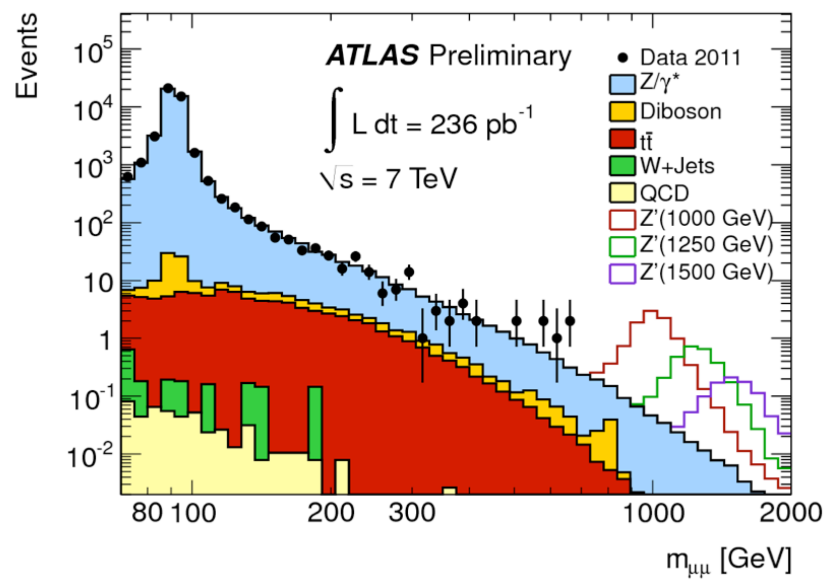


Z' → ee/μμ

- Most promising channels:
  - Backgrounds very low!
  - "Self-calibrating"
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- Extend Tevatron reach already!





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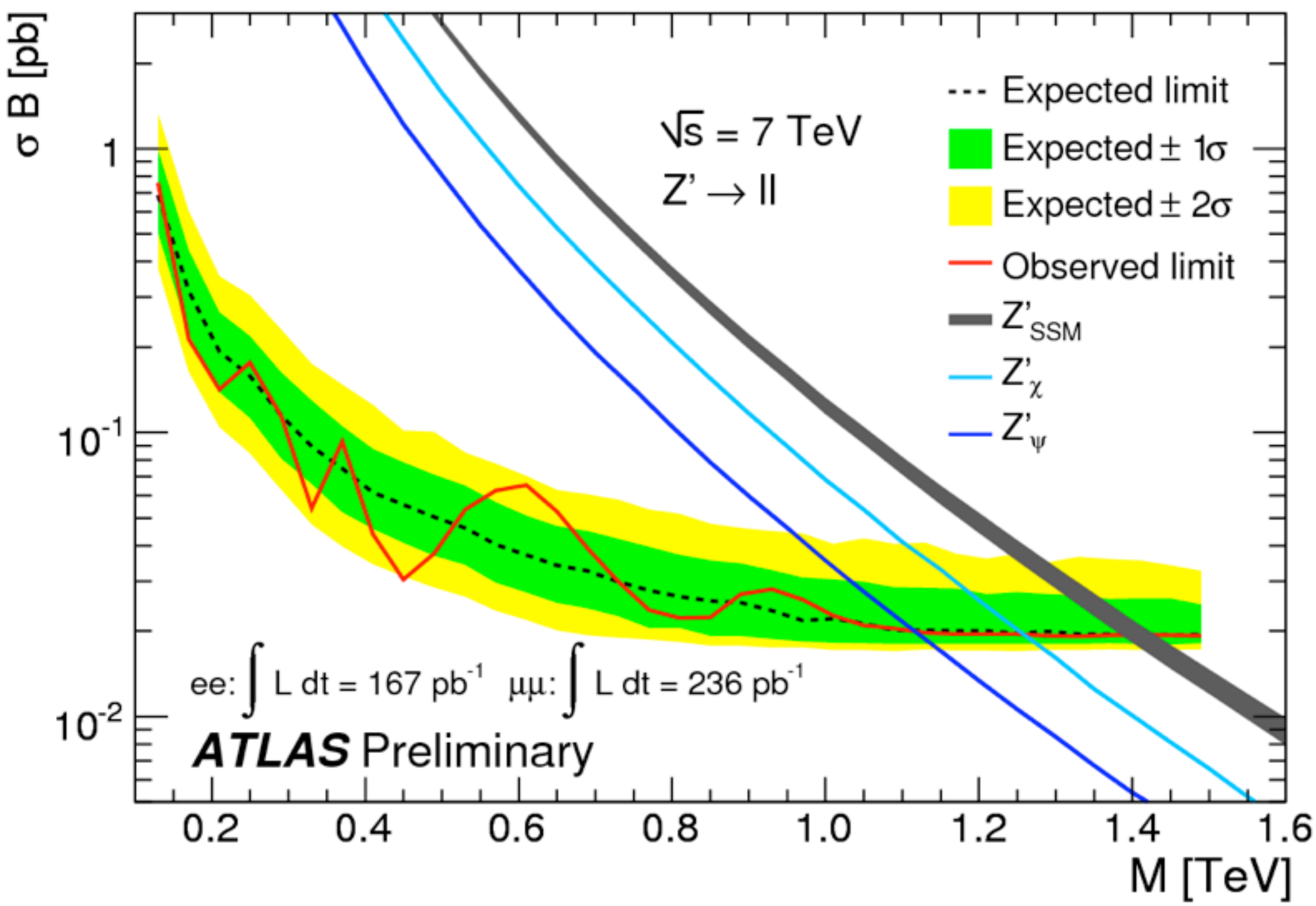
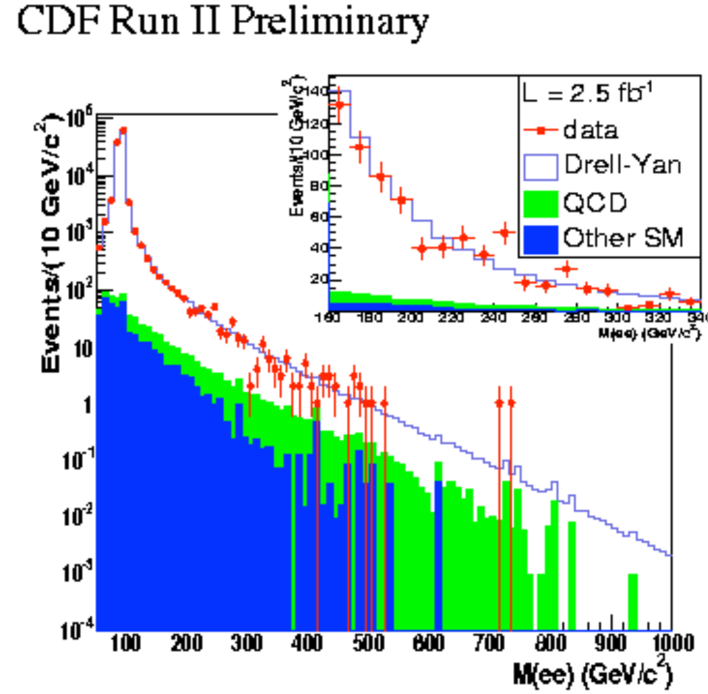
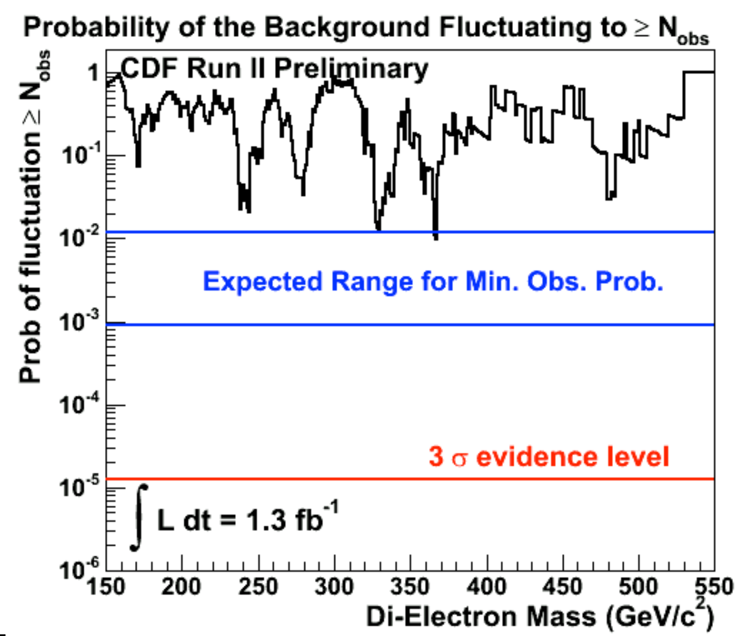


Tevatron limit on Z'_{SSM} ~1 TeV

"Look Elsewhere" Effect

- If search is done by counting experiment in a shifting mass window, need to factor in "look elsewhere" effect (# of windows)
  - Always an excess if look at sufficient distributions…
- Global fit to the (DY) spectrum is another approach
  - Let fit find the mass
  - Shape analysis more sensitive
- Need to run pseudo-experiments!

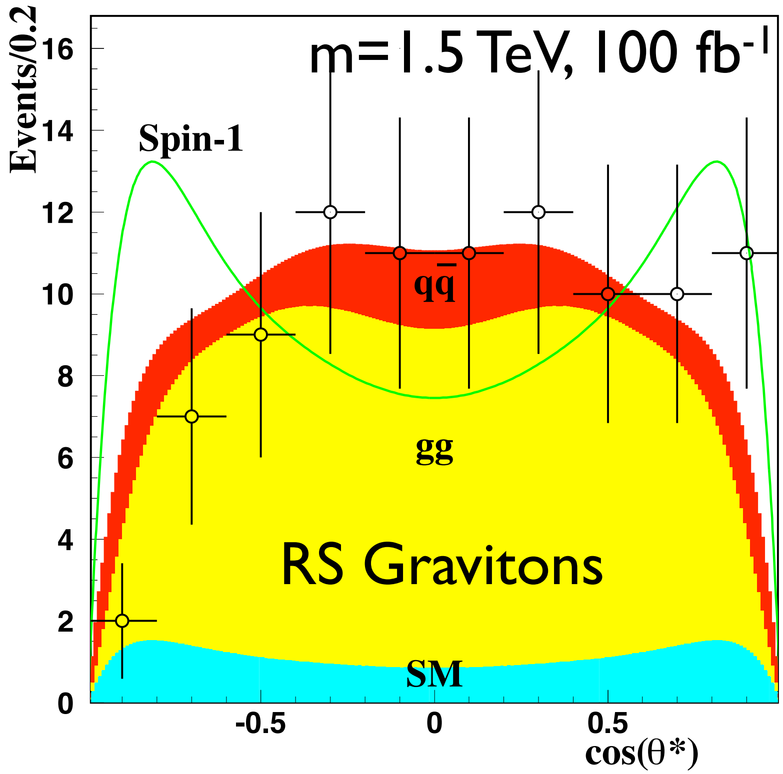




Spin Determination

- Look at angle between lepton and beam direction
  - Spin 1 particles tend to emit leptons closer to beam
- Plot is potentially optimistic: sensitivity is in the forward region where lepton identification not nearly as efficient or pure
  - But for heavy resonances decay products are central…

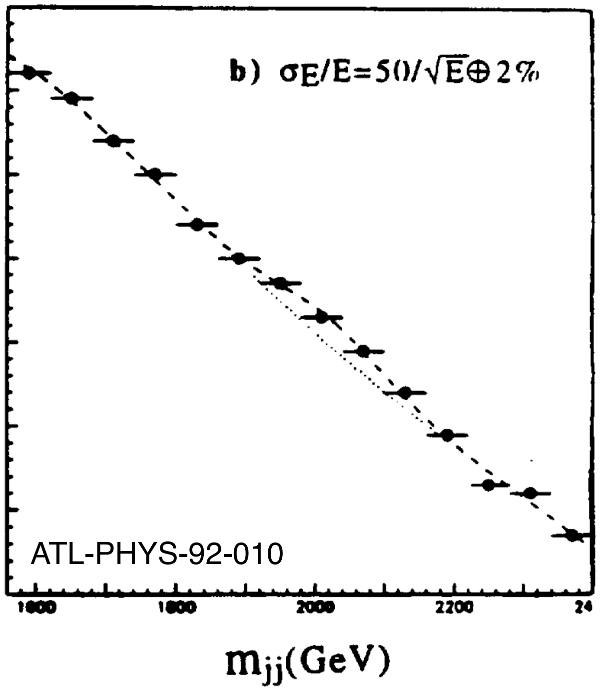
B. Allanach et al, JHEP 0009:019,2000

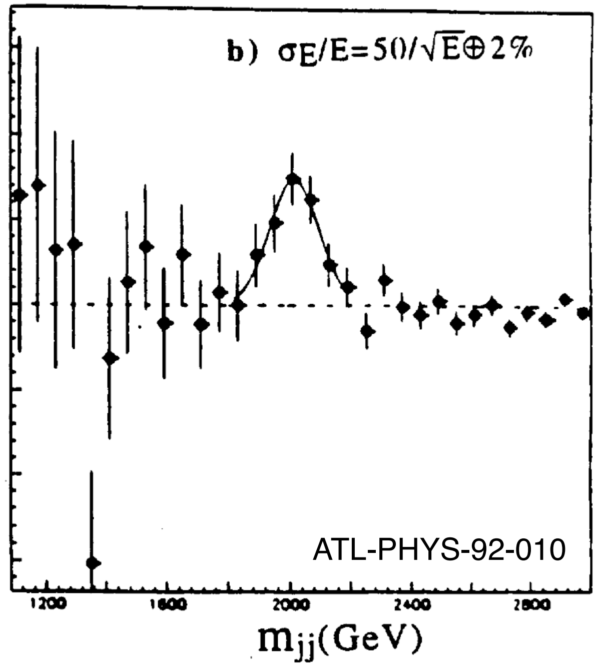


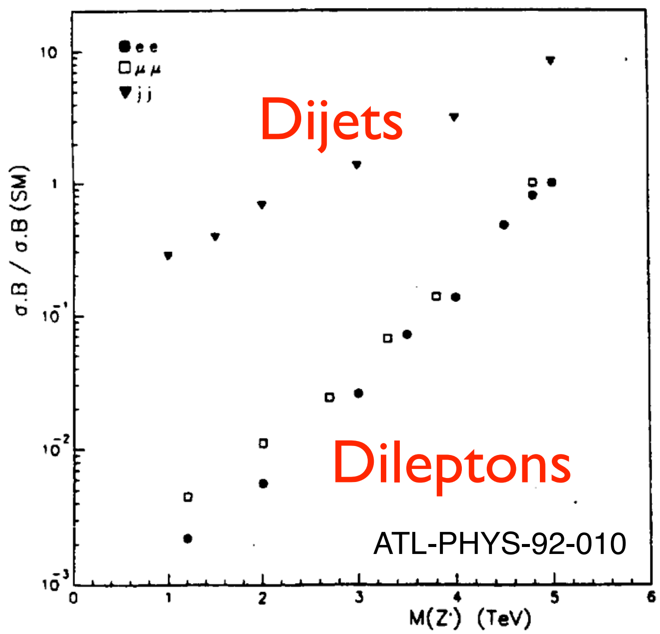
$Z'/W'/q^* \to jj$

- In the dijet channel, the backgrounds are obviously much larger
  - But not necessarily unmanageable: DØ published a Run 1 search for resonances in the dijet channel

(PRD Rapid Comm. {69}, 111101 (2004))



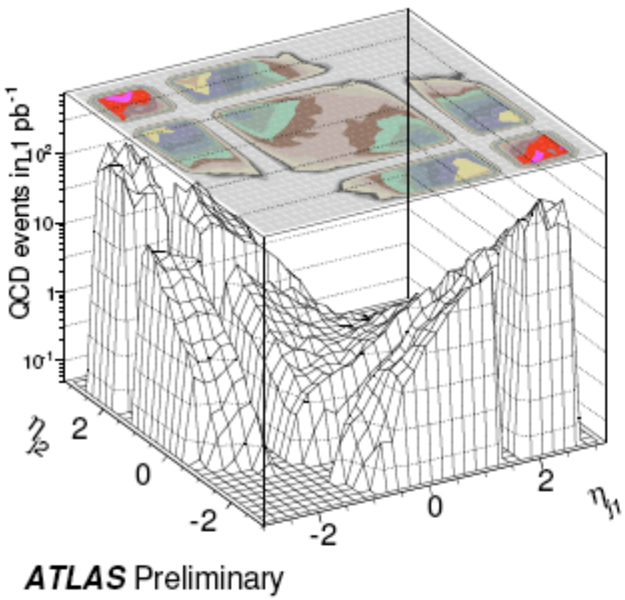


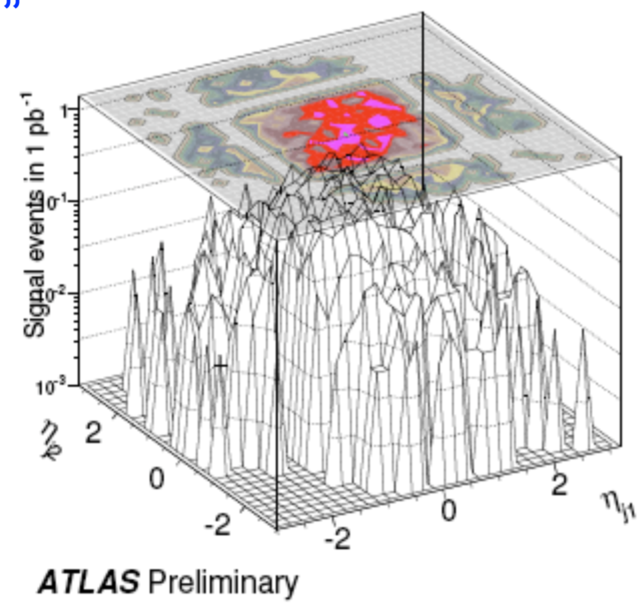


Angles

875 GeV < m_{jj} < 1020 GeV

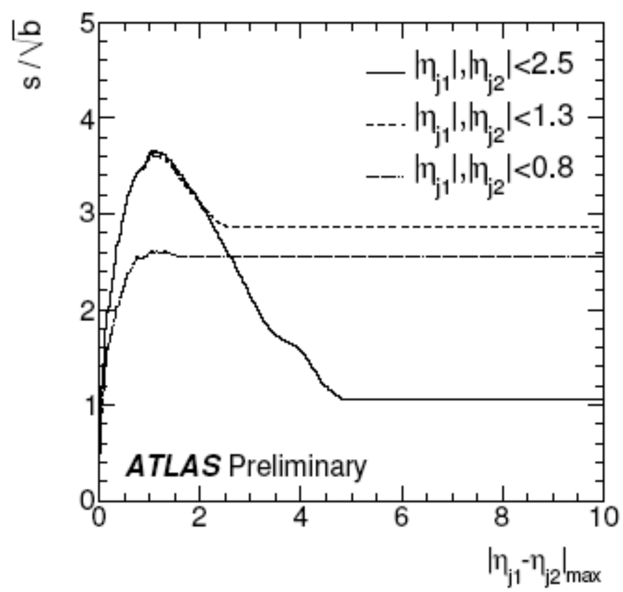
QCD





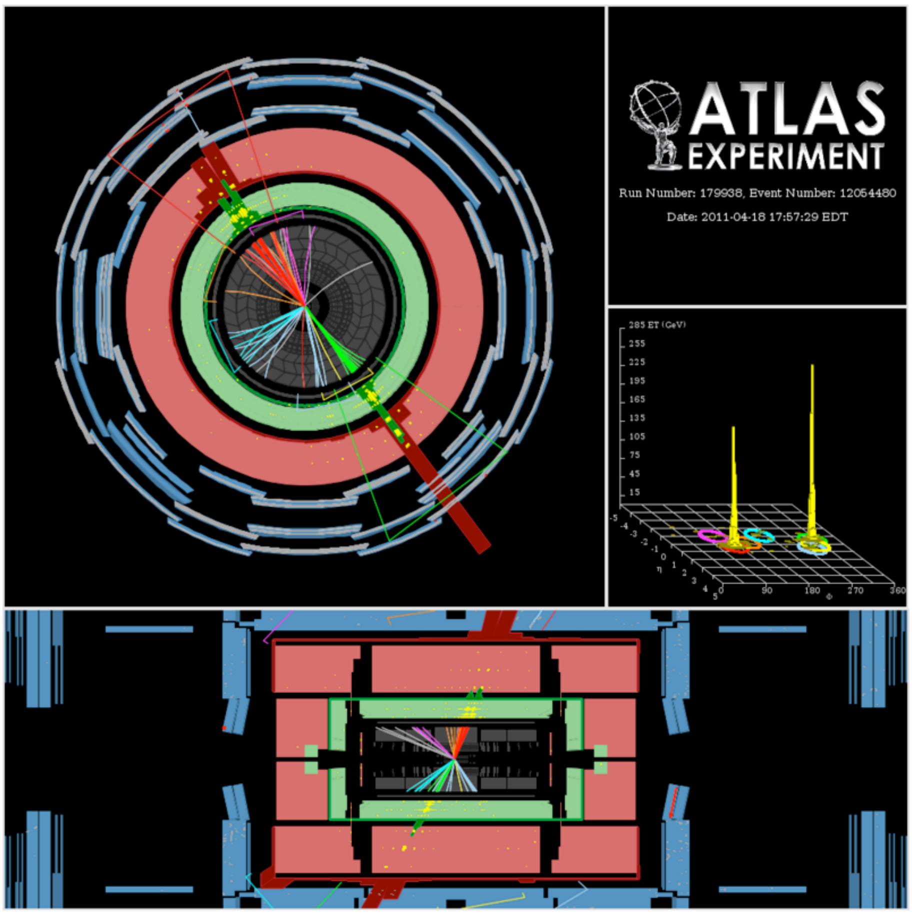
q^*

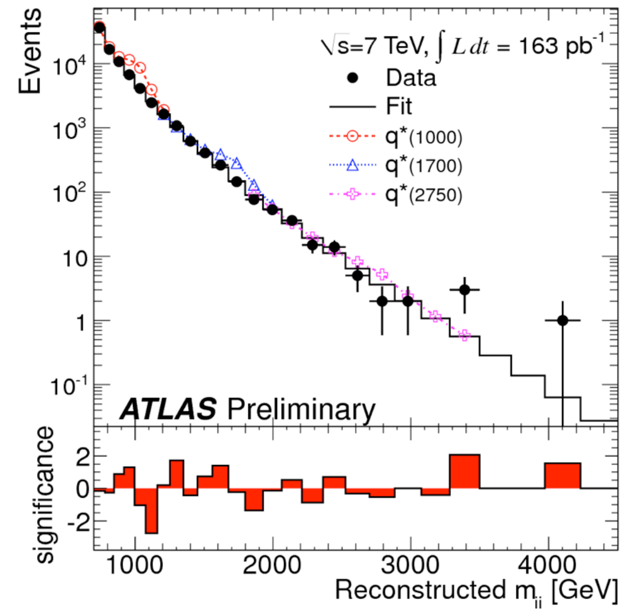
- High mass object → large boost → central
  - But background dominated by QCD "elastic" scatters and larger angle = higher mass

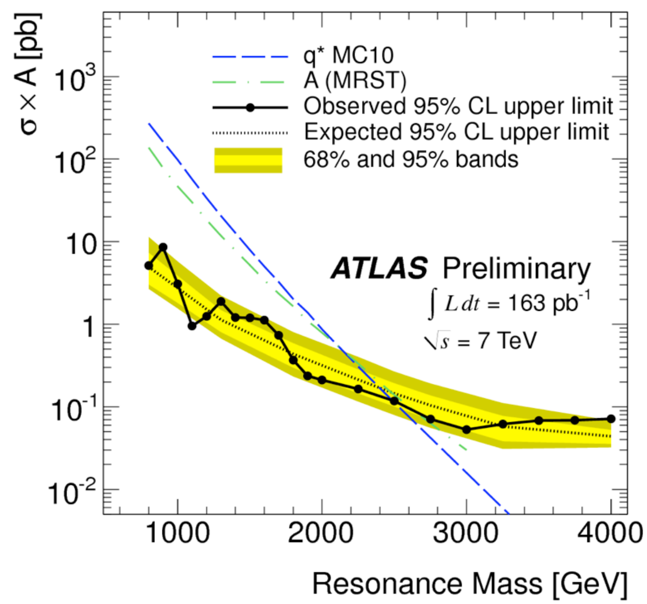


ATLAS Search

- Look for “bump” in m_{jj}
  - No bump, set limit
- Note 4 TeV event!

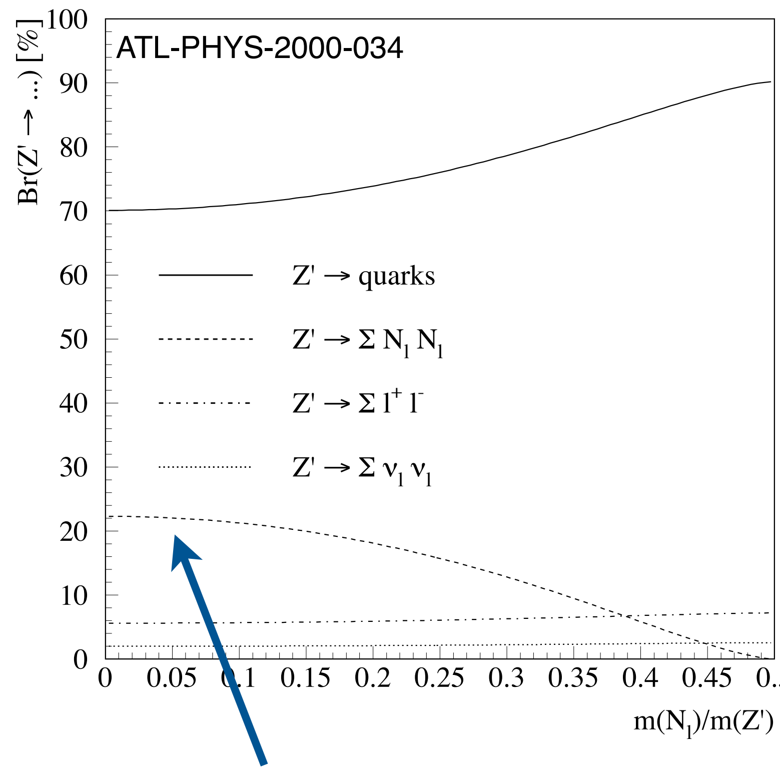






$Z' \rightarrow \nu_R\nu_R$

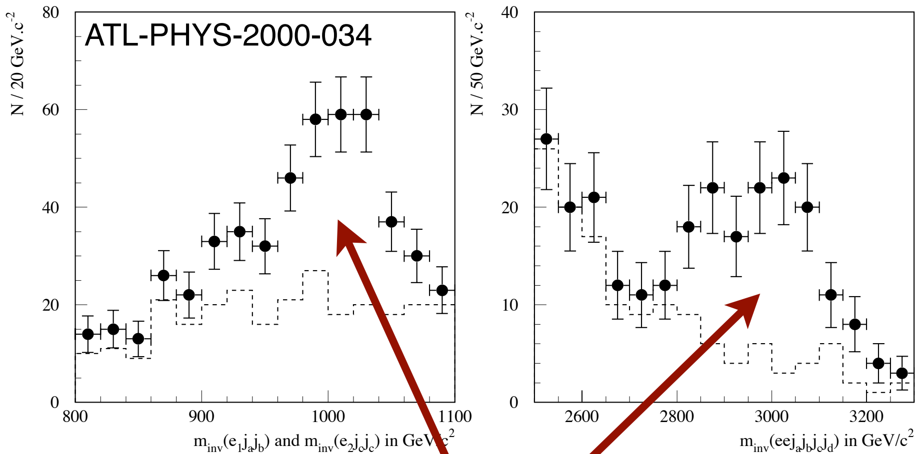
- If ν_R is lighter than m(Z')/2, decay channel opens up
- ν_R subsequently decays to lW_R^* (assuming W_R is heavier than ν_R), leading to signature with two leptons and 4 jets
  - Or other combinations if $m(\nu_R') < m(\nu_R)$, for example more leptons
  - Since ν_R is majorana, can get same-sign leptons!



If ν_R is light, lepton and jets collimated → leptons embedded in merged jets

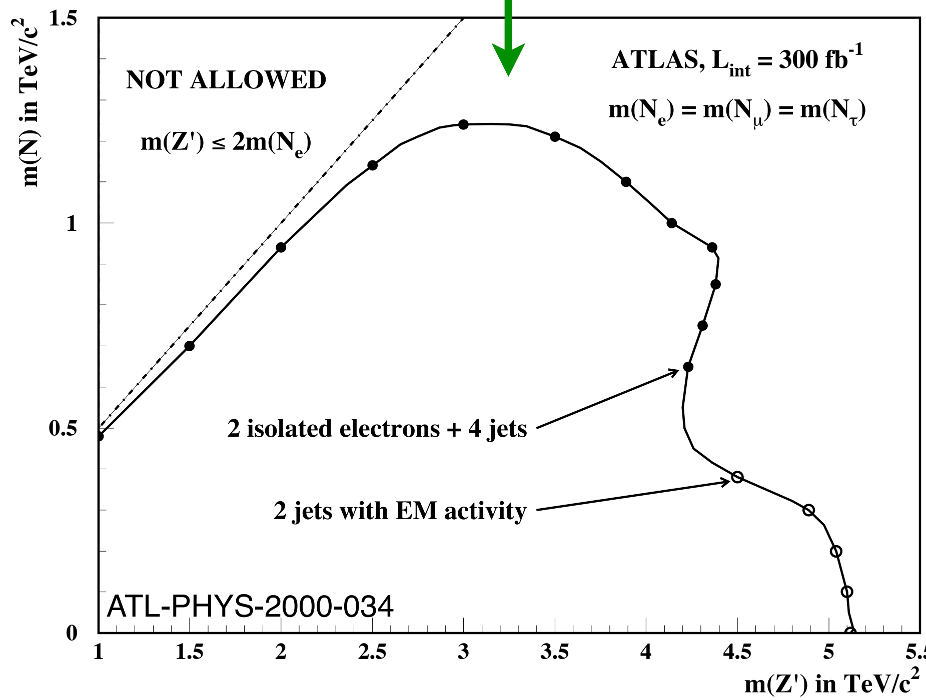
Z' → $\nu_R \nu_R$ (2)

- Backgrounds include $t\bar{t}$, ZZ, ... + jets, but also W_R!



Reconstruction of ν_R (ejj) and Z' (eejjjj) masses

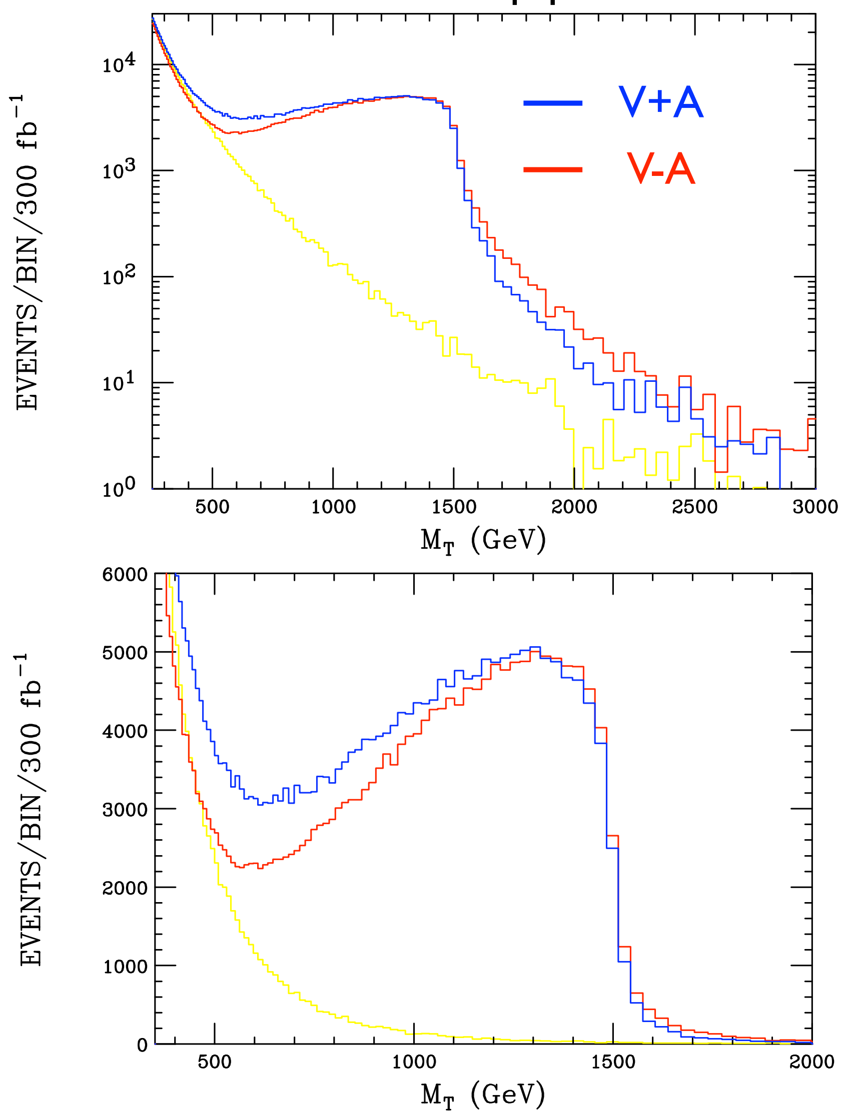
Discovery Potential



W' Production

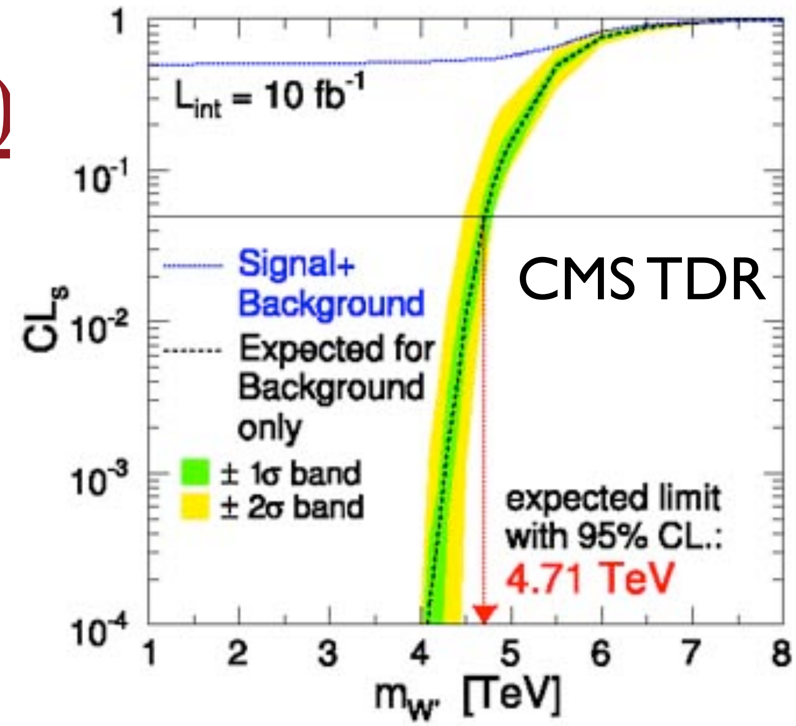
- W' production rate not very dependent on couplings
- But interference with W important (and not in most experimental studies)!
  - Key in identifying W' coupling helicity in fact
- (This plot is for e+MET transverse mass, which may not be a signature)

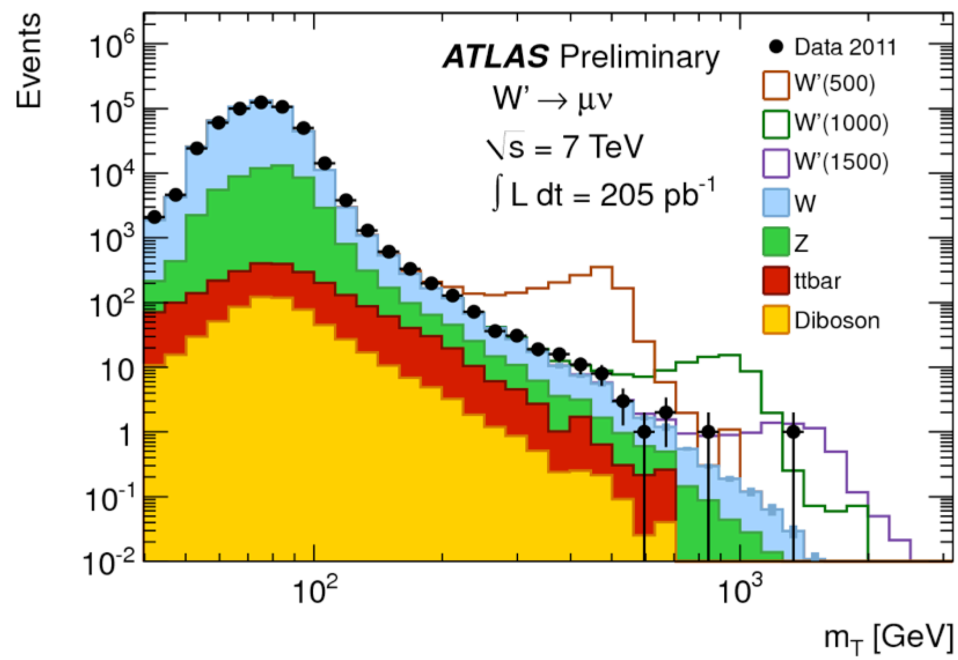
T. Rizzo, hep-ph/0704.0235



W’ → μν(R)

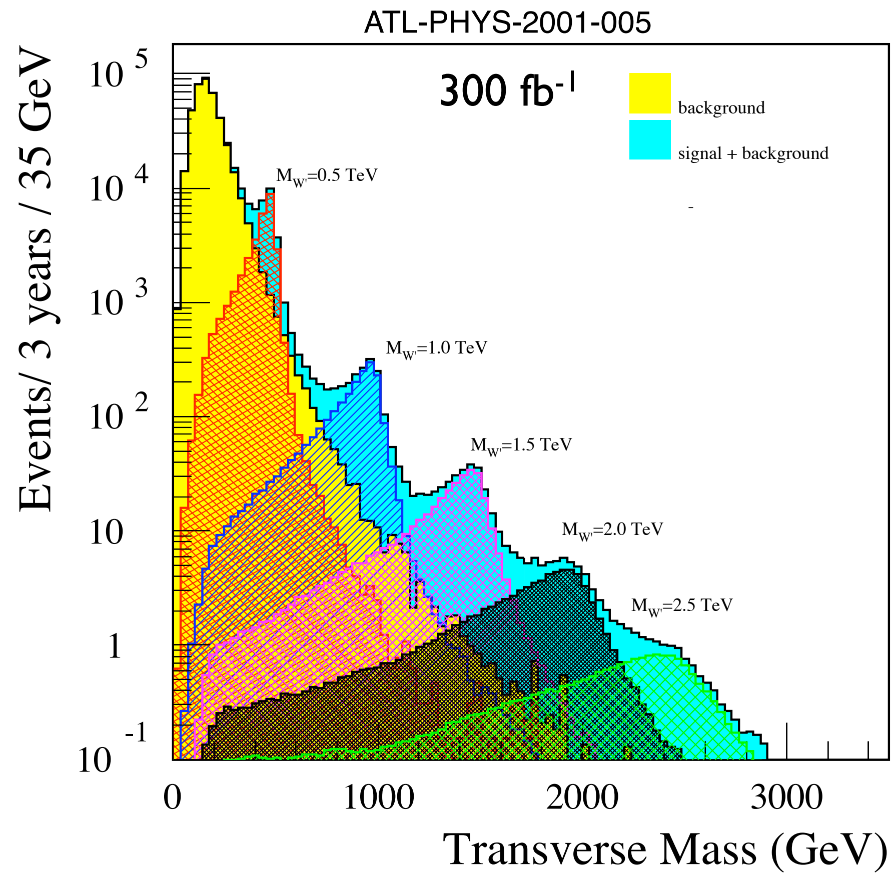
- SSM W’
  - “Standard” M_T plot
- Discovery reach ~4.5 TeV with 10 fb^{-1}
  - Already at ~1.7 TeV
- Similar reach with electrons
  - Note very different resolution effects in electrons vs muons
- Decay does not necessarily exist!





W’ → WZ

- Require at least one of the W, Z to decay leptonically to suppress backgrounds
  - Then use mass constraints to improve S/B further
- Cleanest channel is obviously when both decay leptonically (but BR only 1.4%)
  - LR model study by ATLAS
  - (Also a technicolor signature, probably at lower mass)



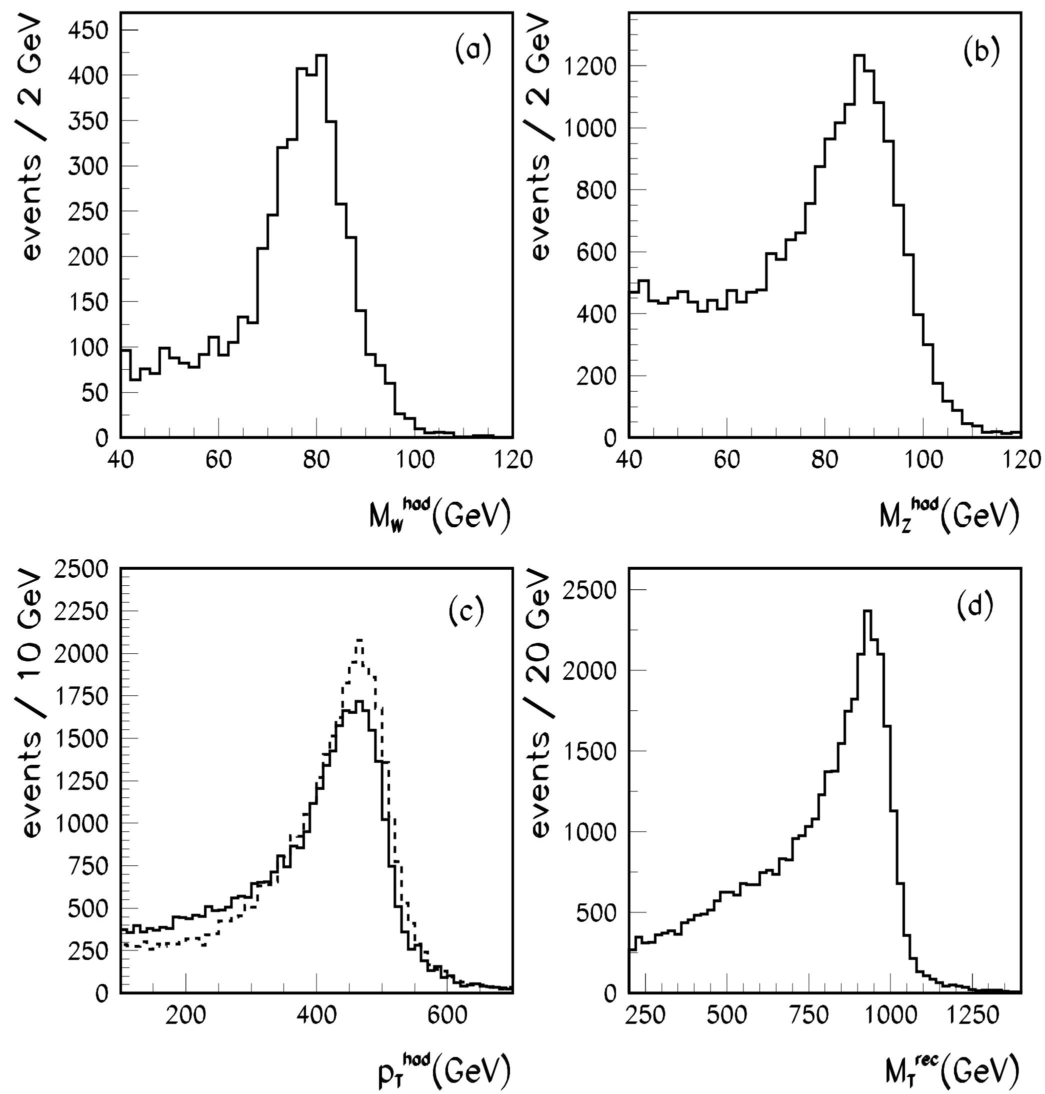
-Trileptons at low mass

-Lepton(s) + jets for high mass reach

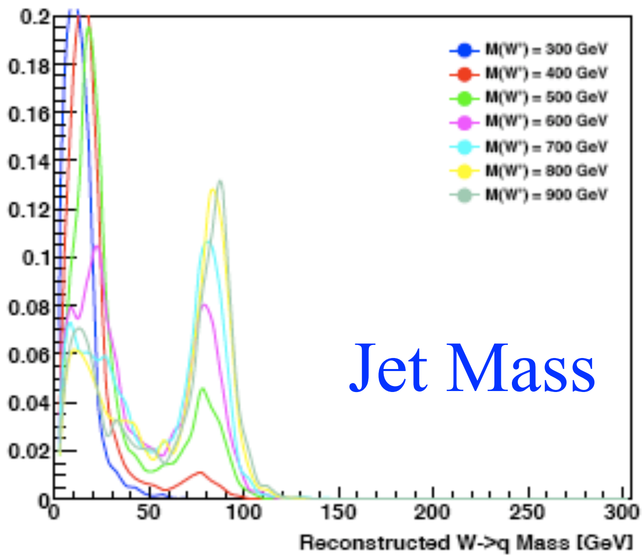
W' → WZ (2)

- If allow one boson to decay hadronically, higher BR (4.6/15%) but higher backgrounds
  - Hadronically decaying boson has large boost, so jets are merged → rely on jet mass
  - W/Z + jets background not well known

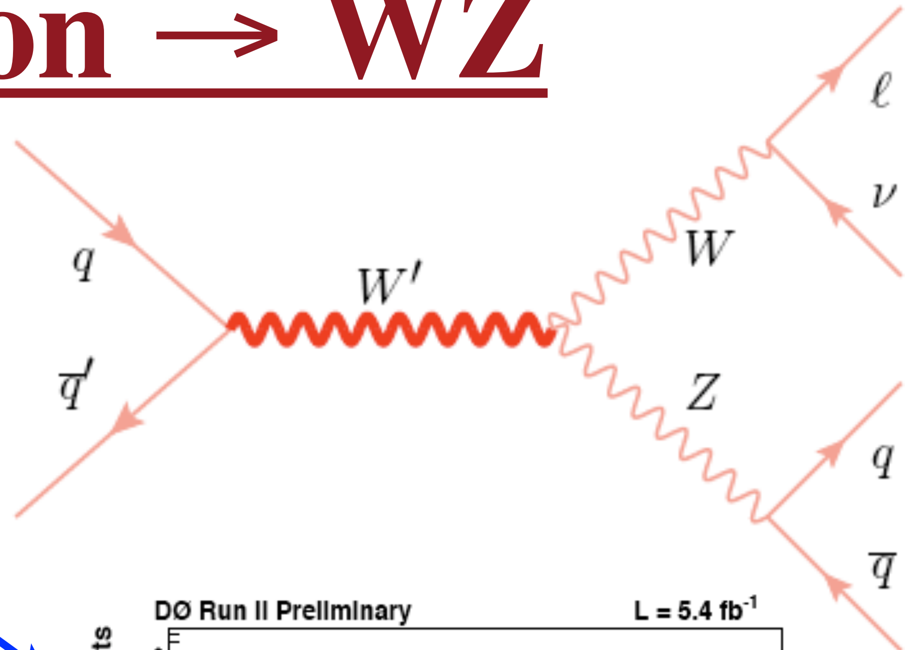
ATL-PHYS-2001-005

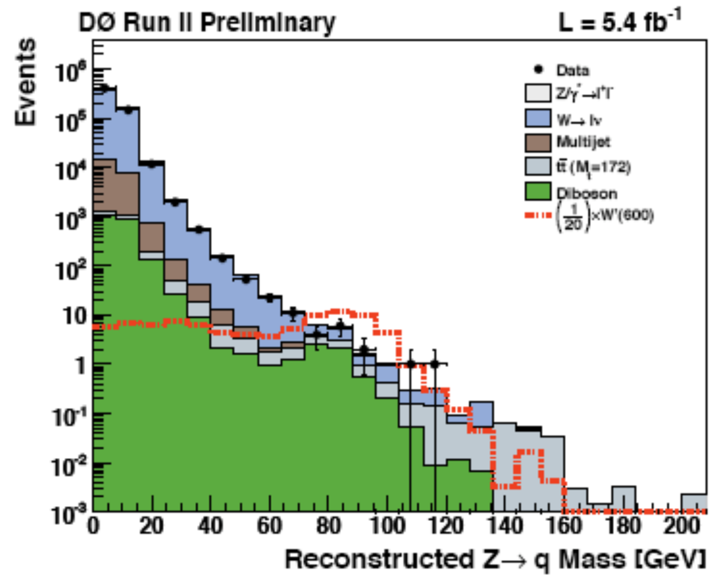


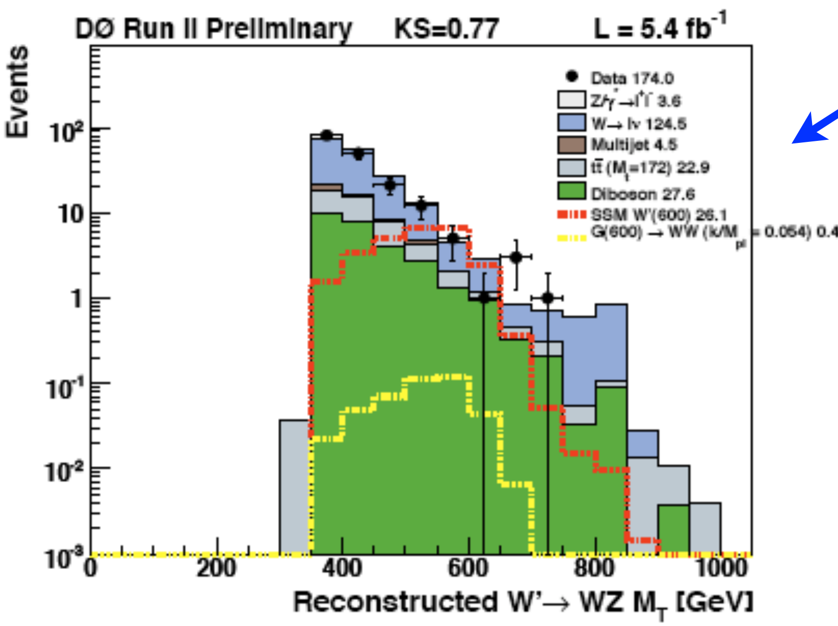
W Excitation → WZ



Jet Mass







Jet mass enhances sensitivity by ~200 GeV to ~750 GeV

DØ, arXiv:1011.6278 [hep-ex]

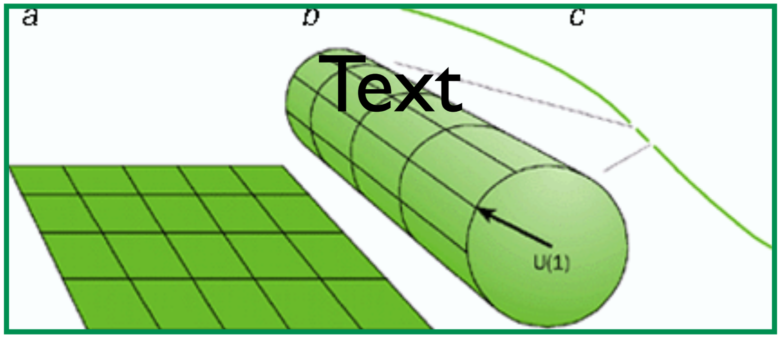
Gravity and Hierarchy

(or: Out of This World?)

Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified

Source: PhysicsWorld

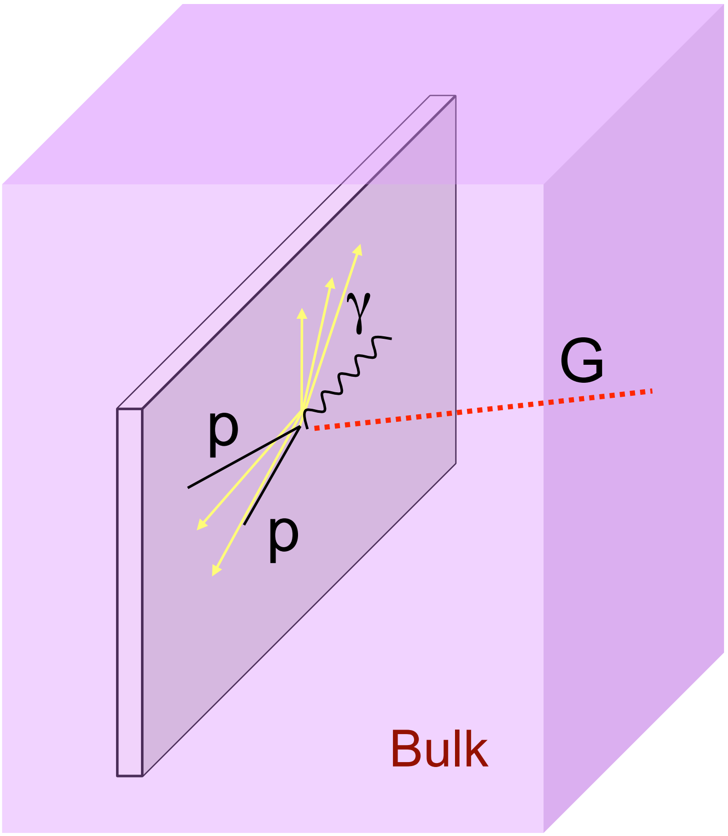


- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In ’90 Antoniadis realized they may be much larger...

Phys.Lett.B246:377-384,1990

"ADD"

- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali):
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"

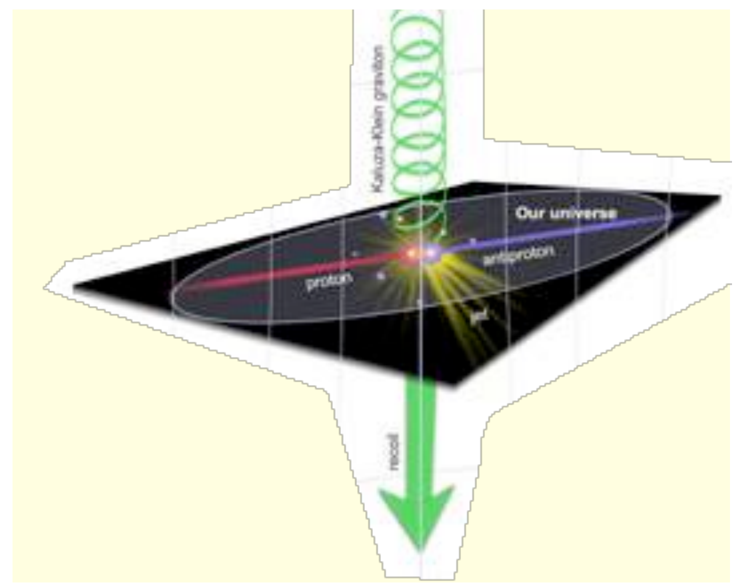


Drawing by K. Loureiro

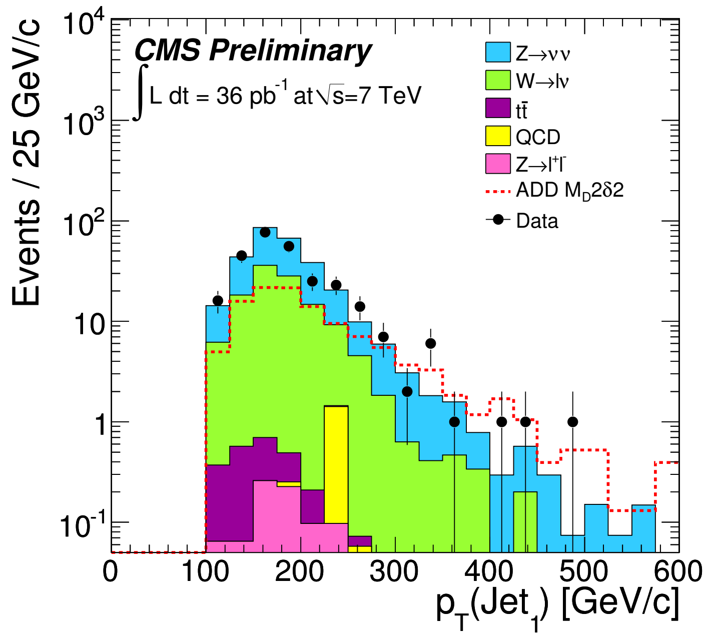
ADD Signatures

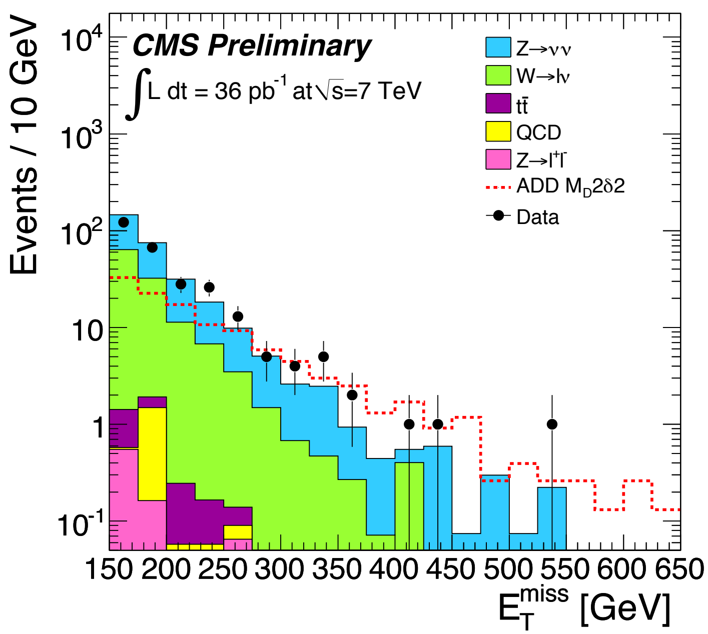
- Edges of extra dimensions identified
  - ➡ Boundary conditions
  - ➡ Momentum along extra dimension is quantified
  - Looks like mass to us
  - Very small separations → looks like continuum
  - Called Kaluza-Klein tower
- Coupling to single graviton very weak, but there are *lots* of them!
  - Large phase space → observable cross-section
    - Impacts all processes (graviton couples to energy-momentum)

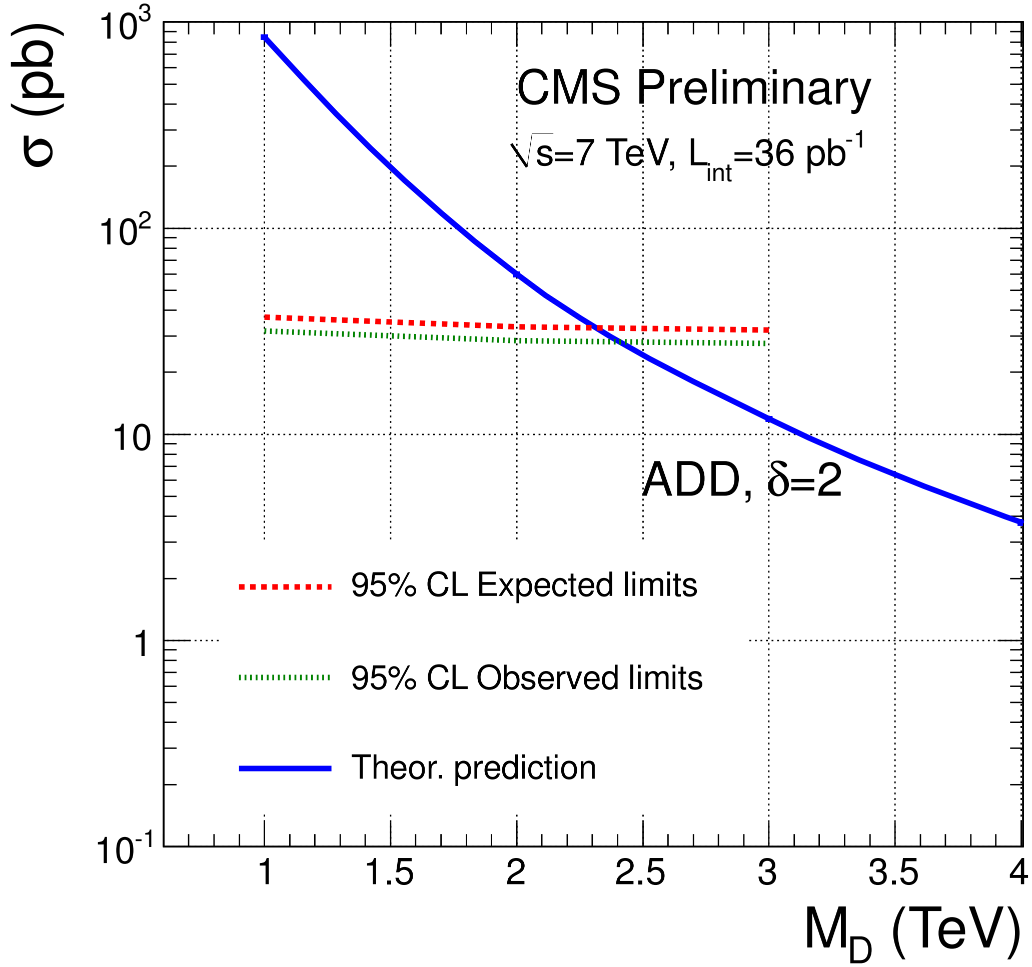
- Consider processes that involve the bulk (i.e. gravitons)
  - Translational invariance is broken
    - ➡ Momentum is not conserved ...
    - ... because graviton disappears in bulk right away
- Look for p p → jet/photon + nothing (i.e. $\not{E}_T$), or deviations in high mass/angular behavior in standard model processes
  - Graviton has spin 2, couples to energy-momentum!
- Limit size of ED at ~2 TeV



Jet + Graviton

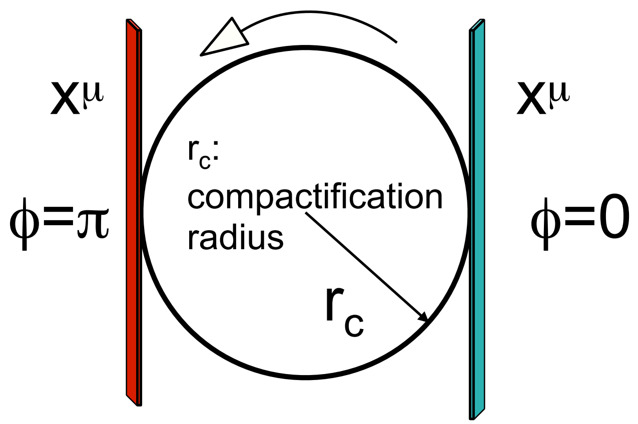


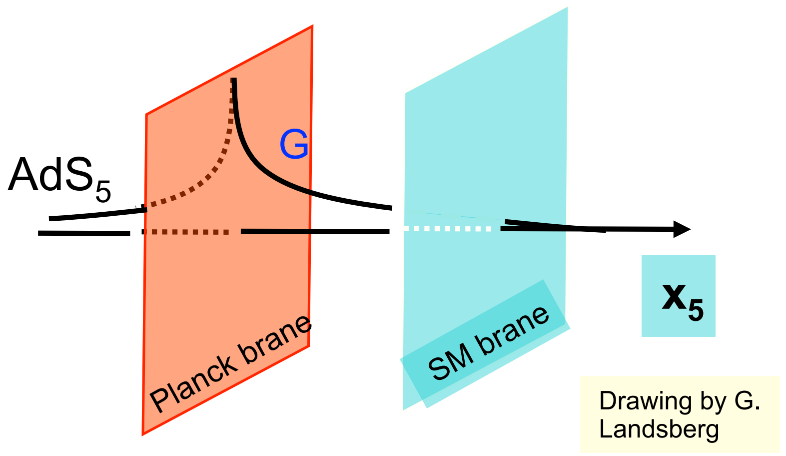




Warped Extra Dimensions

- "Simple" Randall-Sundrum model:
  - SM confined to a brane, and gravity propagating in an extra dimension
  - As opposed to the original ADD scenario, the metric in the extra dimension is "warped" by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)

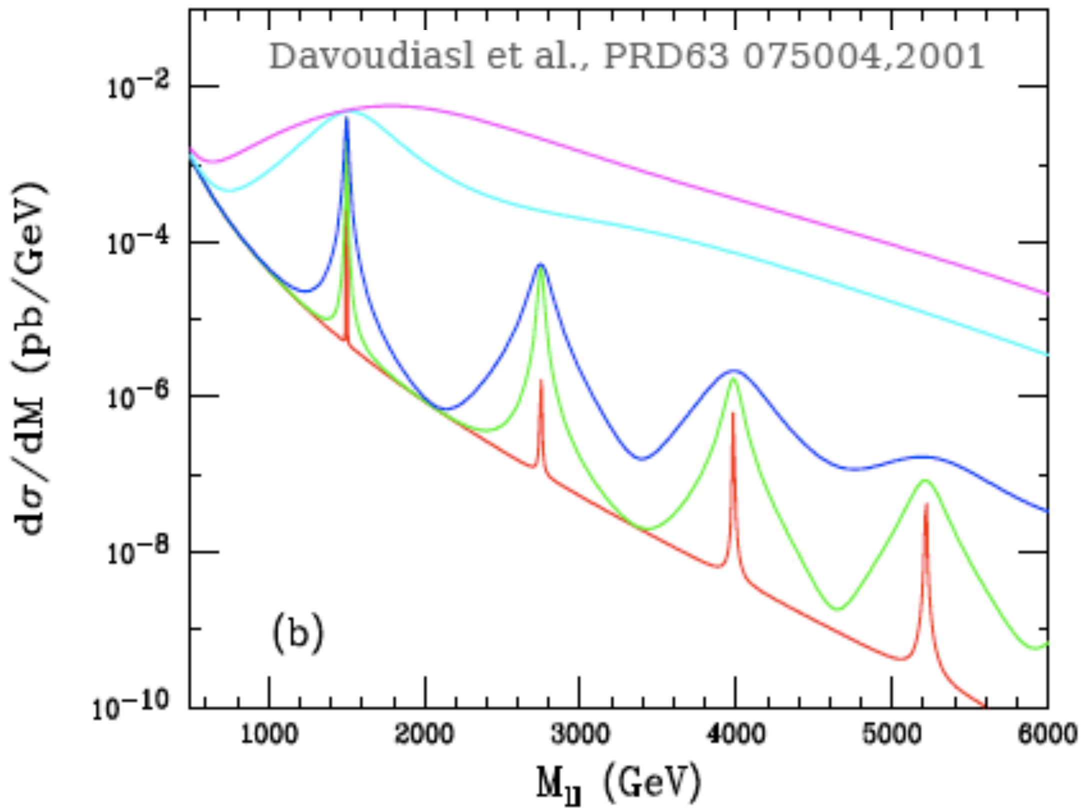




Graviton Excitations

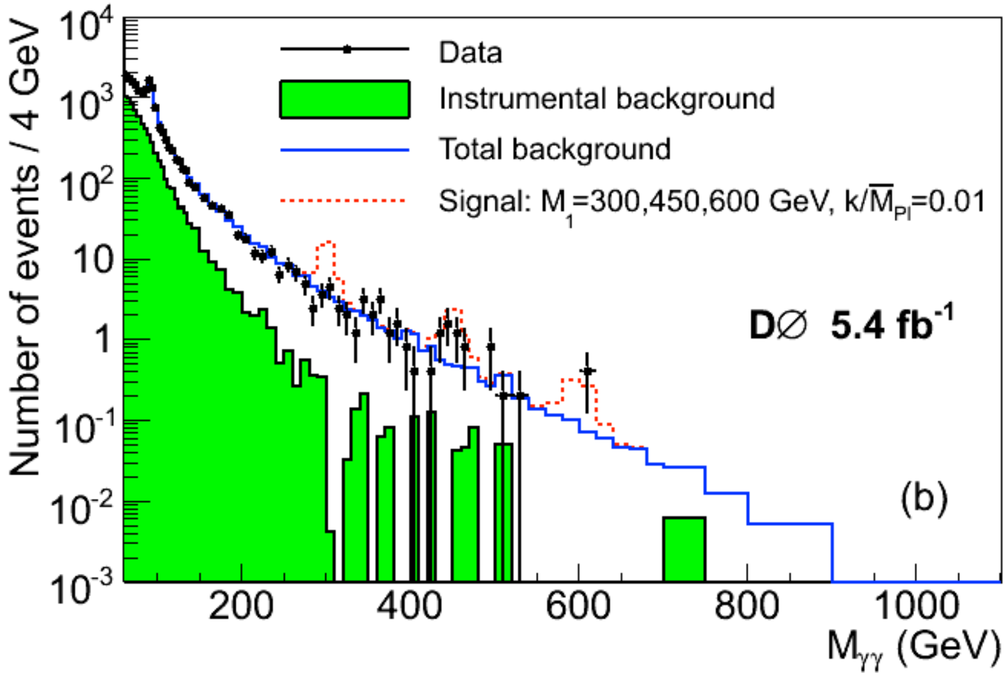
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function
    - ➡ Smoking gun!

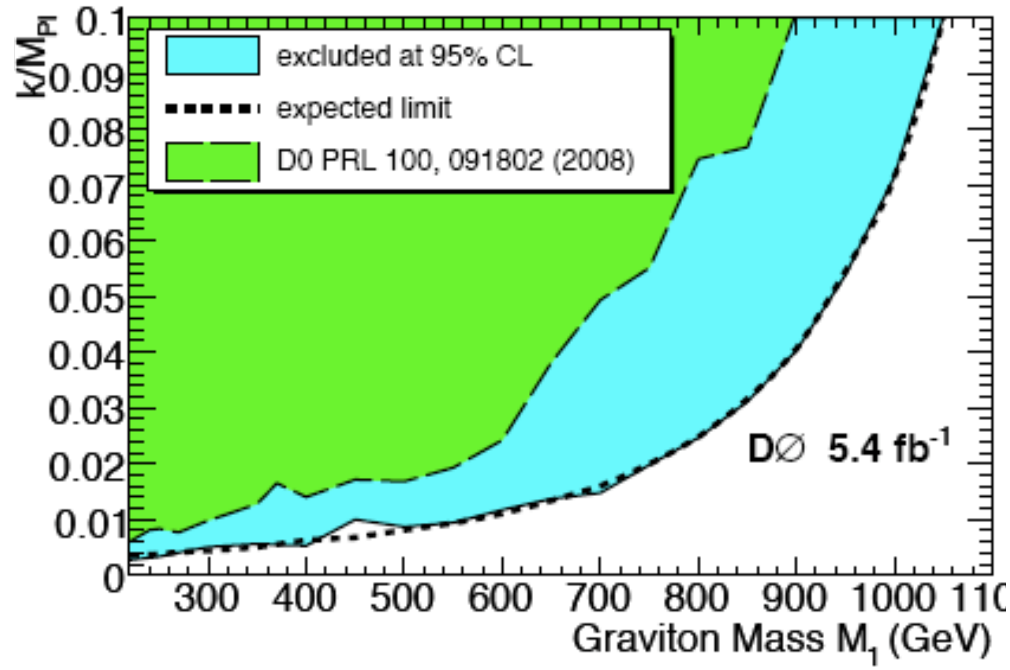
(BRs also different than Z':
e.g. $\gamma\gamma$ allowed)



Dielectrons/Diphotons

DØ, Phys. Rev. Lett. 104, 241802 (2010)

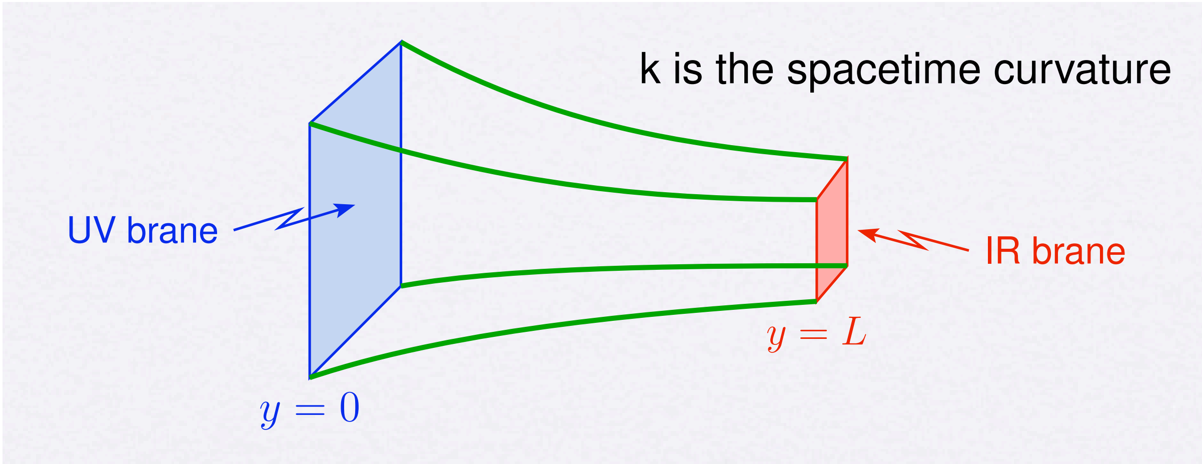




- Separate dielectrons from diphotons:
  - Targeted background rejection yields better limits
  - Diphotons more sensitive

Hierarchies

- Physics on a curved gravitational background:



- Scales depend on position along extra dimensions
  - UV brane scale is $M_{Pl} = 2 \times 10^{18}$ GeV
  - IR brane scale is $M_{Pl}\, e^{-kL} \sim 1$ TeV if $kL \sim 30$
- If were to localize Higgs on IR brane, naturally get EW scale ~ 1TeV (from geometry!)

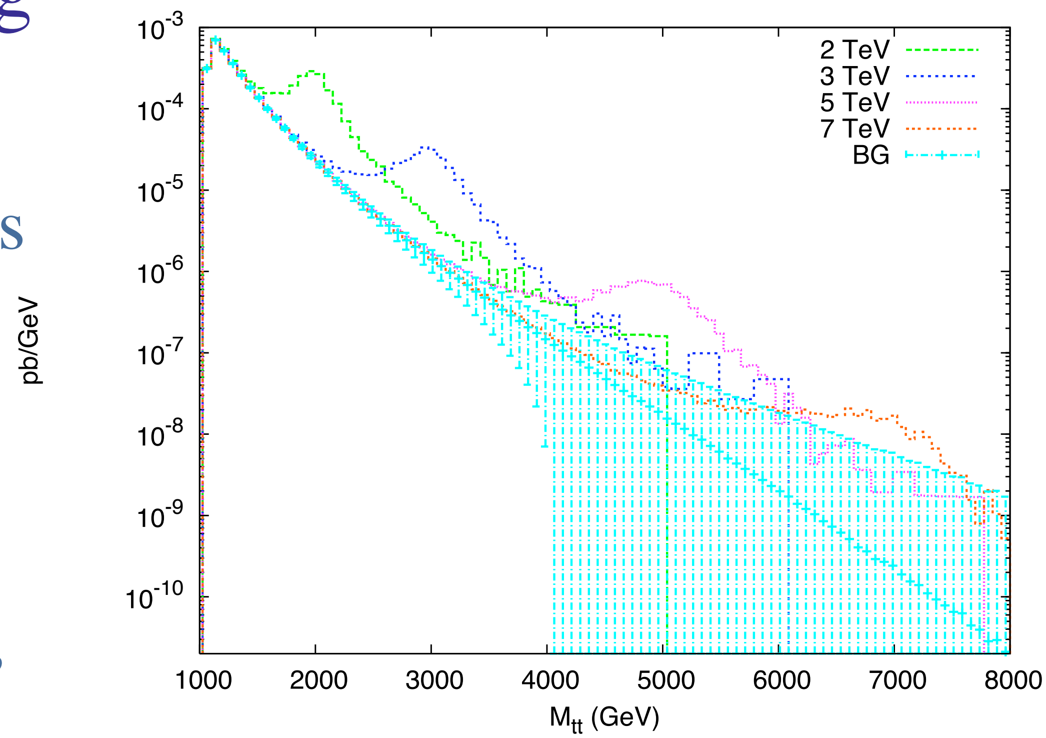
Flavor

- Interesting variation has fermions located along the extra dimension
  - Fermion masses generated by geometry
  - Heavier fermions are closer to IR brane, and gauge boson excitations as well
    - Gauge boson excitations expected to have masses in the 3-4 TeV range (bounds from precision measurements)
    - Couple mainly to top/W/Z (!)
  - Flavor changing determined by overlap of fermion "wave function" in the ED
    - Nice suppression of FCNC etc.

Gauge Boson Excitations

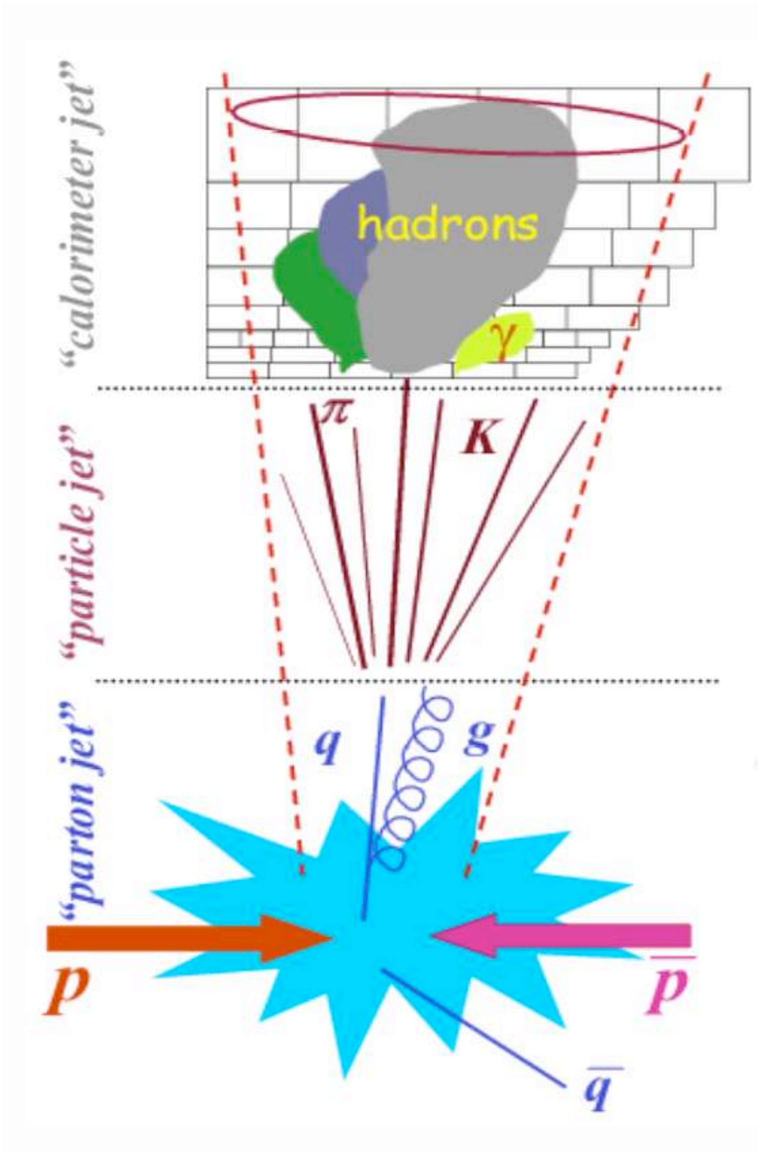
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

B. Lillie et al., JHEP 0709:074,2007



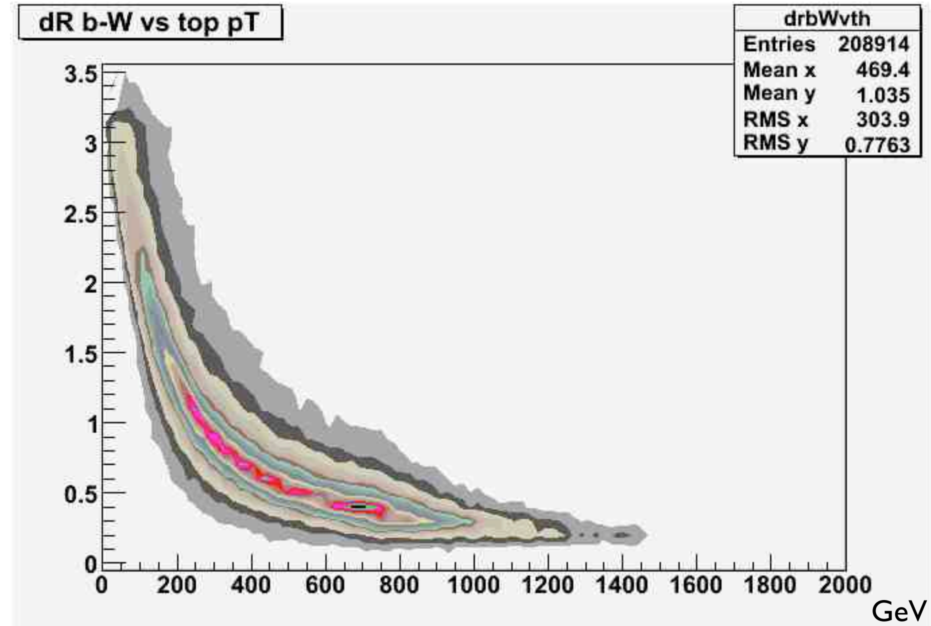
New Experimental Phenomenology

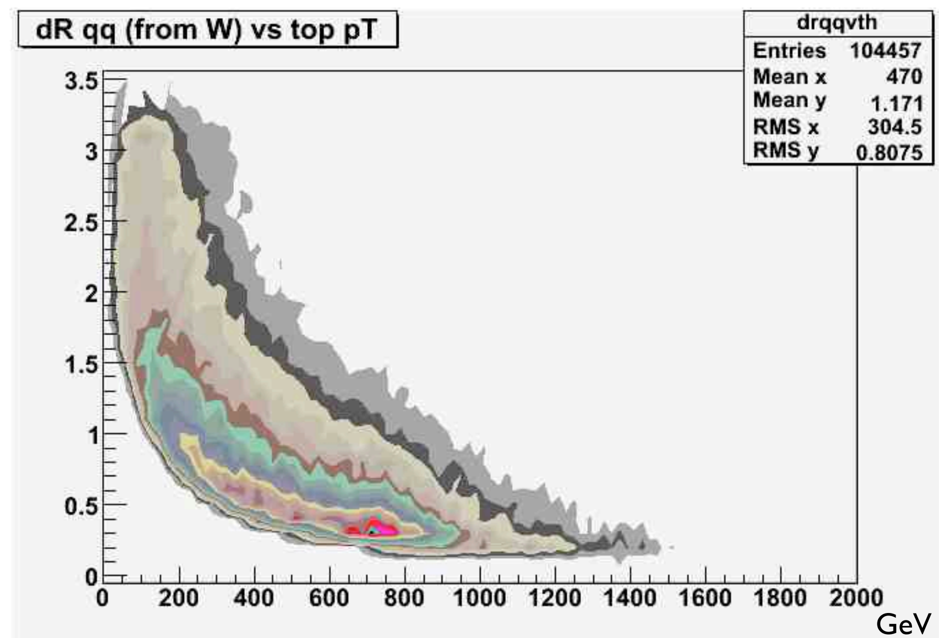
- Possibility to produce heavy resonances decaying to top quarks, W and Z bosons
  - Heavy objects with momentum >> mass
    - Decay products collimated
  - For leptonic W/Z decays, not a big issue since we measure isolated tracks very well
  - But hadronic decays lead to jets, which are intrinsically wide



Top Quark Decays

- Simulated decays:
  - $dR = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$
  - Typical jet radius ~0.5
  - LHC calorimeters have granularity 0.1 x 0.1 or better
- For top p_T > ~300 GeV
  - dR ($q\bar{q}$' from W) < 2 R_{jet}
  - dR (bW) < 2 R_{jet}
    - (No isolated lepton!)

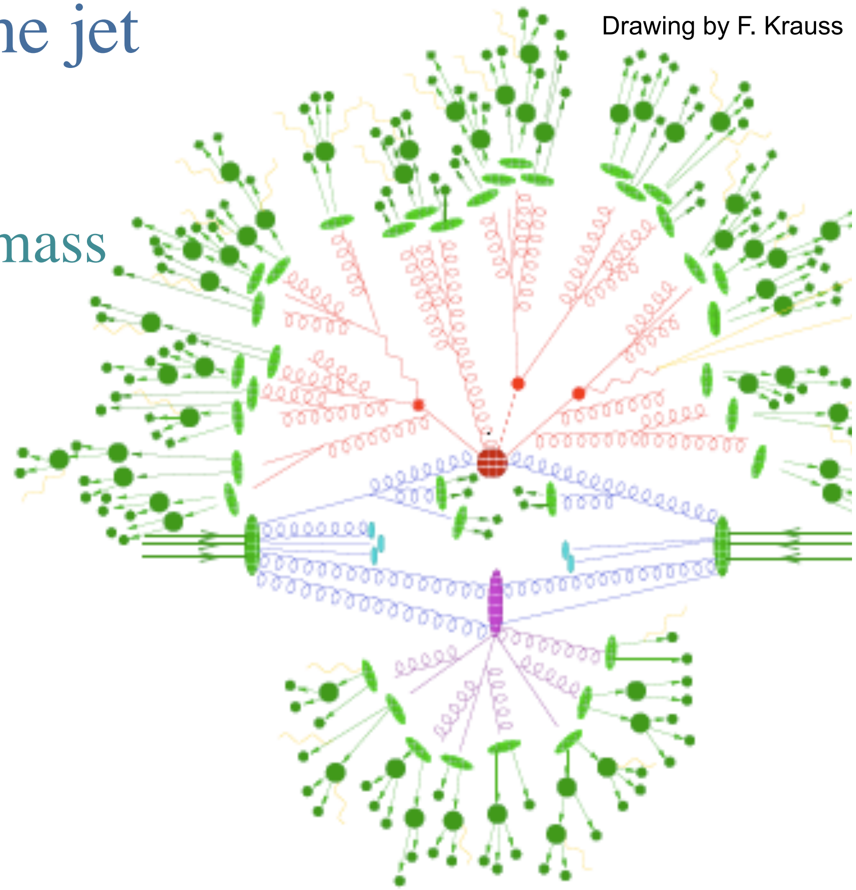




Fully Hadronic Decays

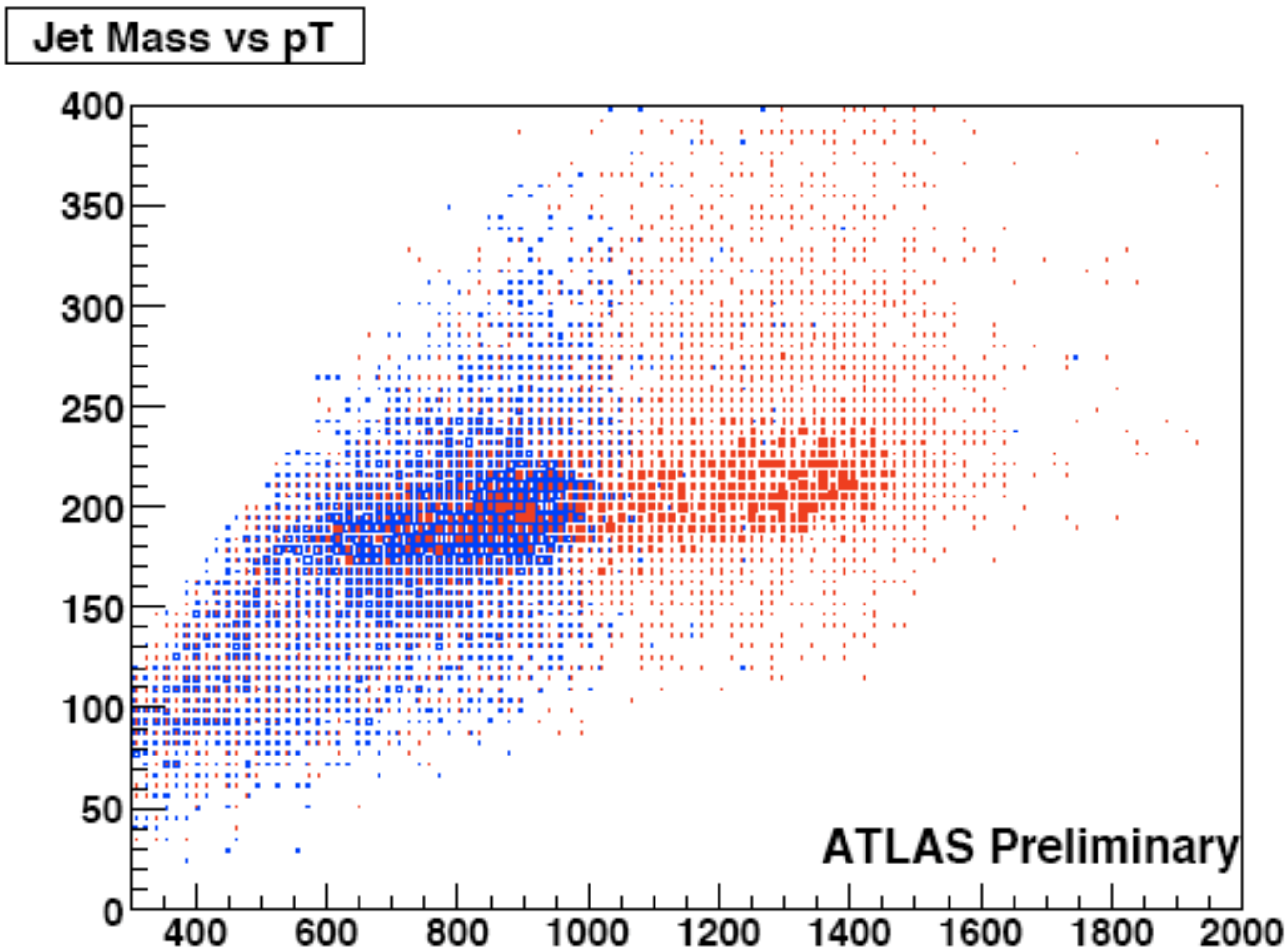
- Decay hadrons reconstructed as a single jet
    - But even if it looks like a single jet, it originates from a massive particle decaying to three hard partons, not one
- If I measured each of the partons in the jet perfectly, I would be able to:
    - Reconstruct the “originator’s” invariant mass
    - Reconstruct the direct daughter partons
- But
    - Quarks hadronize → cross-talk
    - My detector can’t resolve all individual hadrons

Drawing by F. Krauss



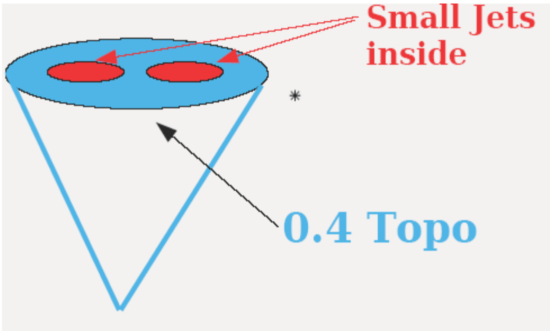
Jet Mass

- Jet mass: invariant mass of all jet constituents
  - In principle, ≥ top quark mass



Subjets

- Jet mass is not sensitive to structure
  - Can't tell whether a jet is isotropic or not
- Expect "blobs" with higher concentration of energy for jets from top/W/Z decays

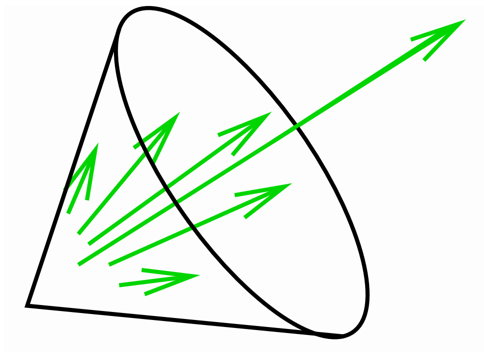


- Multiple ways of exploiting this....
  - Shown here: k_T splitting scales

J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *Phys. Rev.* **D65** (2002) 096014

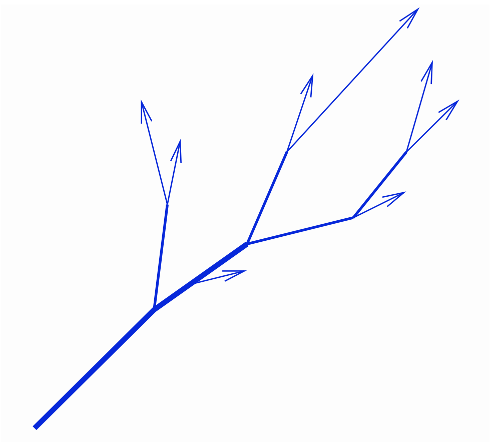
k_T Splitting Scales

- k_T jet algorithm is much better suited to understand jet substructure than cone:
  - Cone maximizes energy in an η x ϕ cone
  - k_T is a "nearest neighbor" clusterer



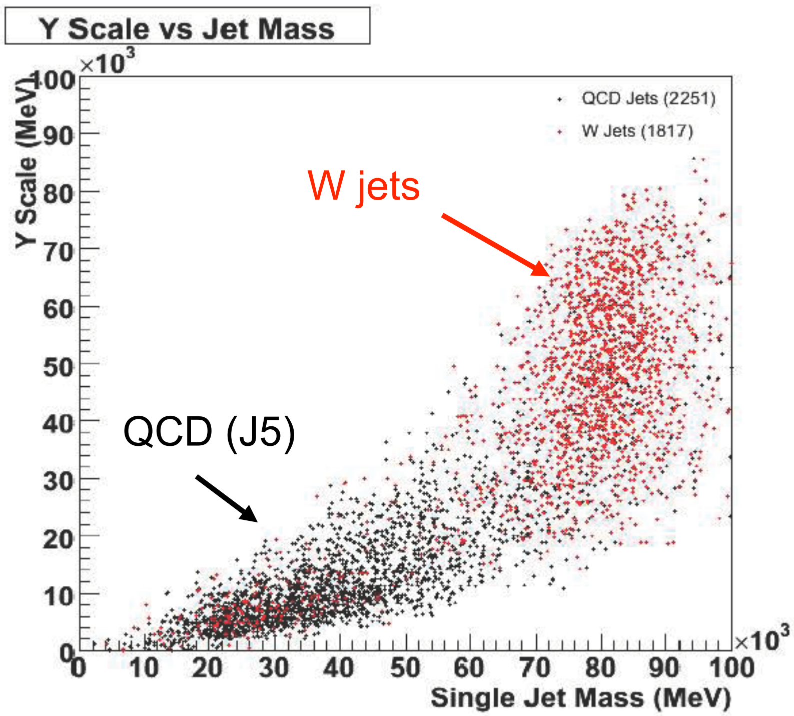
$$y_2 = \min\left(E_a^2, E_b^2\right) \bullet \theta_{ab}^2 / p_{T(jet)}^2$$

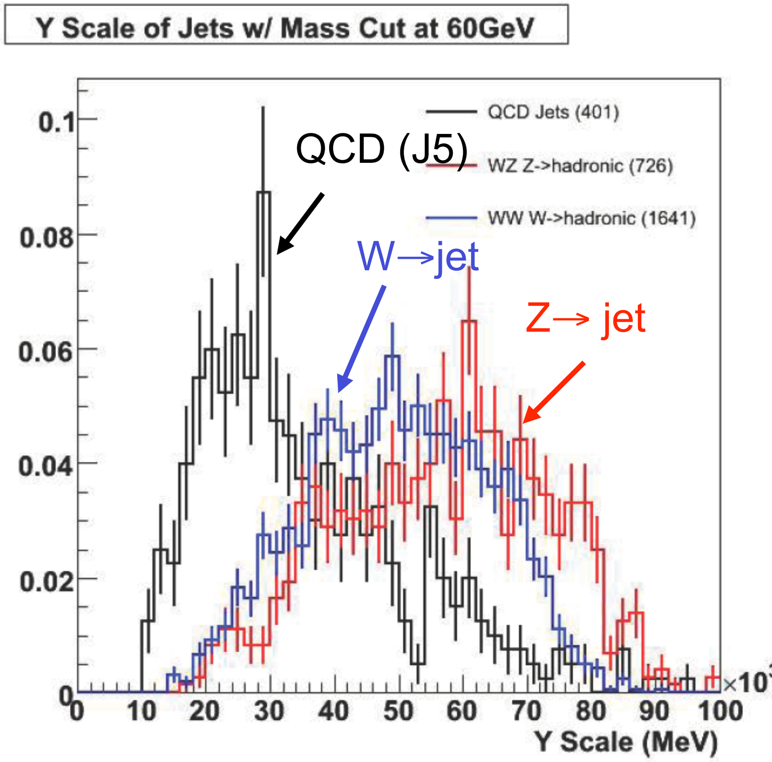
$$Y \text{ scale } = \sqrt{p_{T(jet)}^2 \bullet y_2}$$



- Can use the k_T algorithm on jet constituents and get the (y-)scale at which one switches from 1 → 2 (→ 3 etc.) jets
  - Scale is related to mass of the decaying particle

- Applied to high p_T WW scattering:





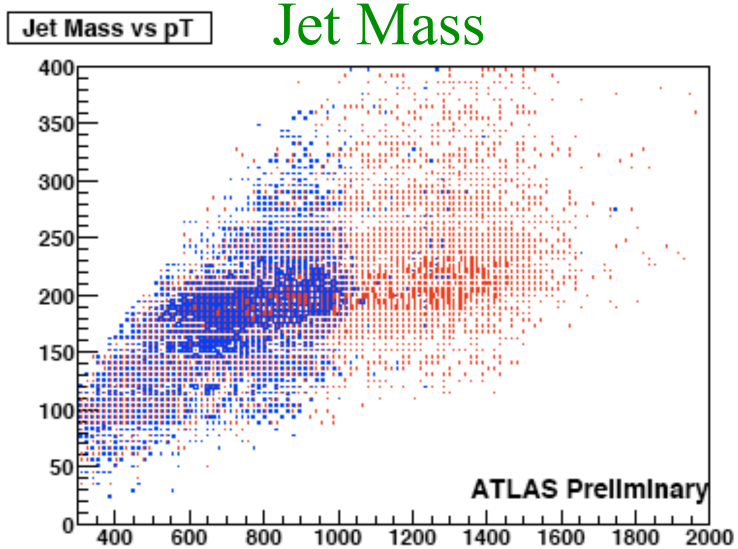
- k_T jet algorithm, with R = 0.5
- Cuts applied : p_T(jet) > 300 GeV,

Techniques also believed to allow recovery of H → bb at LHC!

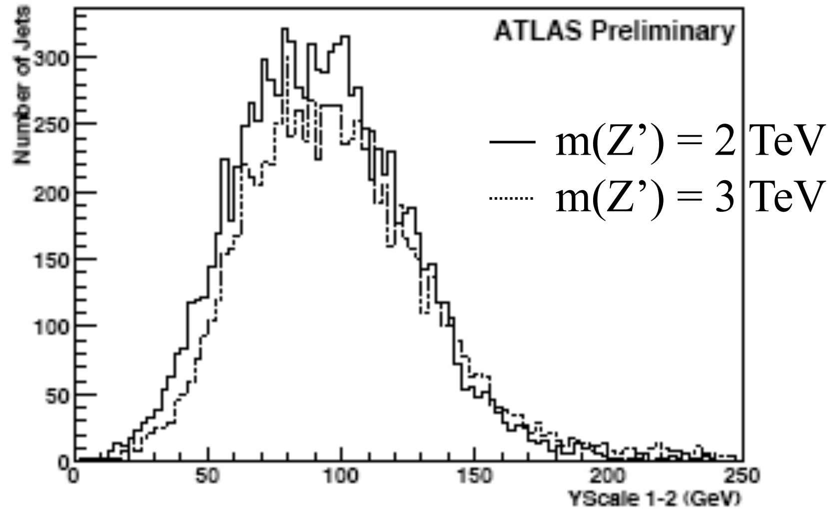
BDRS, Phys.Rev.Lett. 100 (2008) 242001

Now Hadronic Top

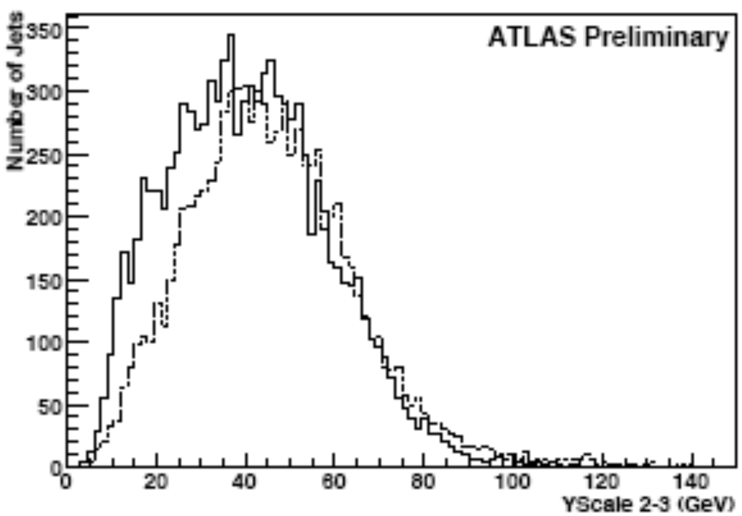
Jet Mass



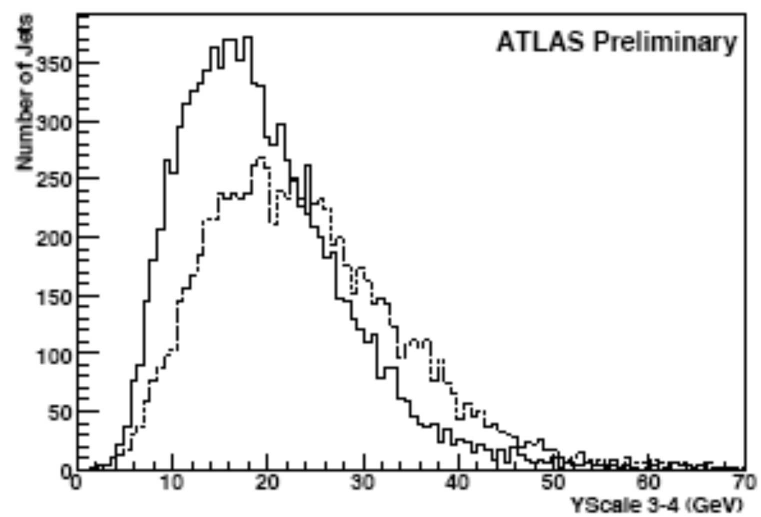
$1 \rightarrow 2$ Jet Scale



$2 \rightarrow 3$ Jet Scale

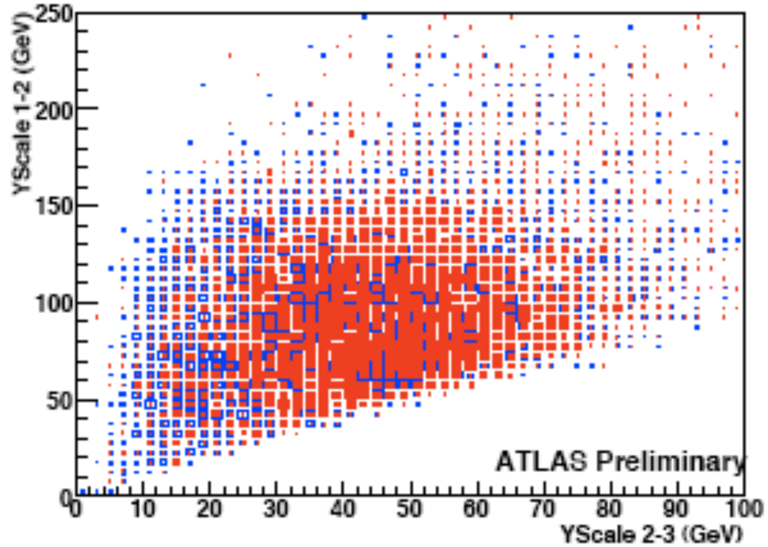


$3 \rightarrow 4$ Jet Scale



Slow p_T Dependence!

- Observations:
  - Variables show slow dependence on top (jet) p_T
  - Only weakly correlated



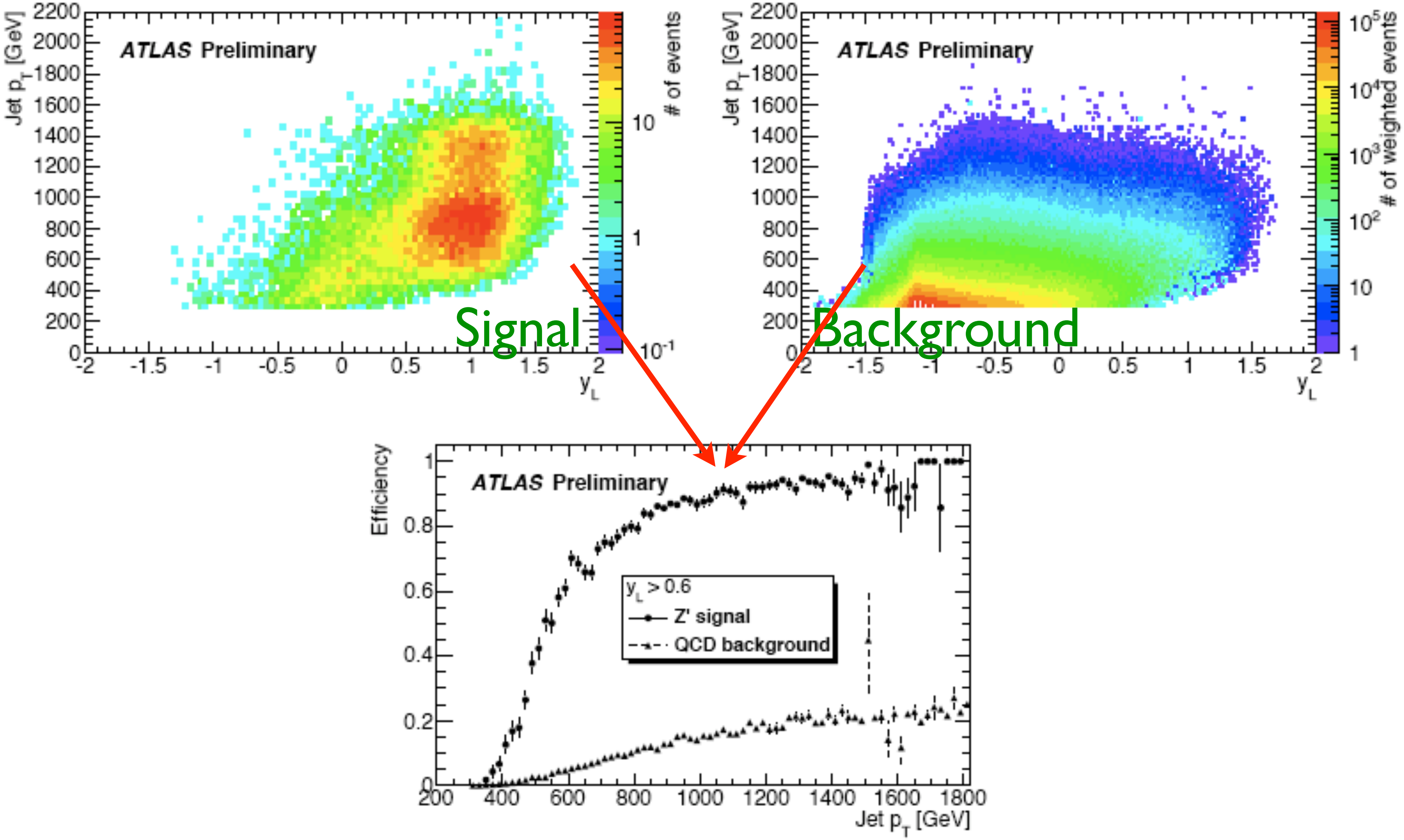
m(Z’) = 2 TeV

m(Z’) = 3 TeV

  - For light jets, all the variables drop off exponentially

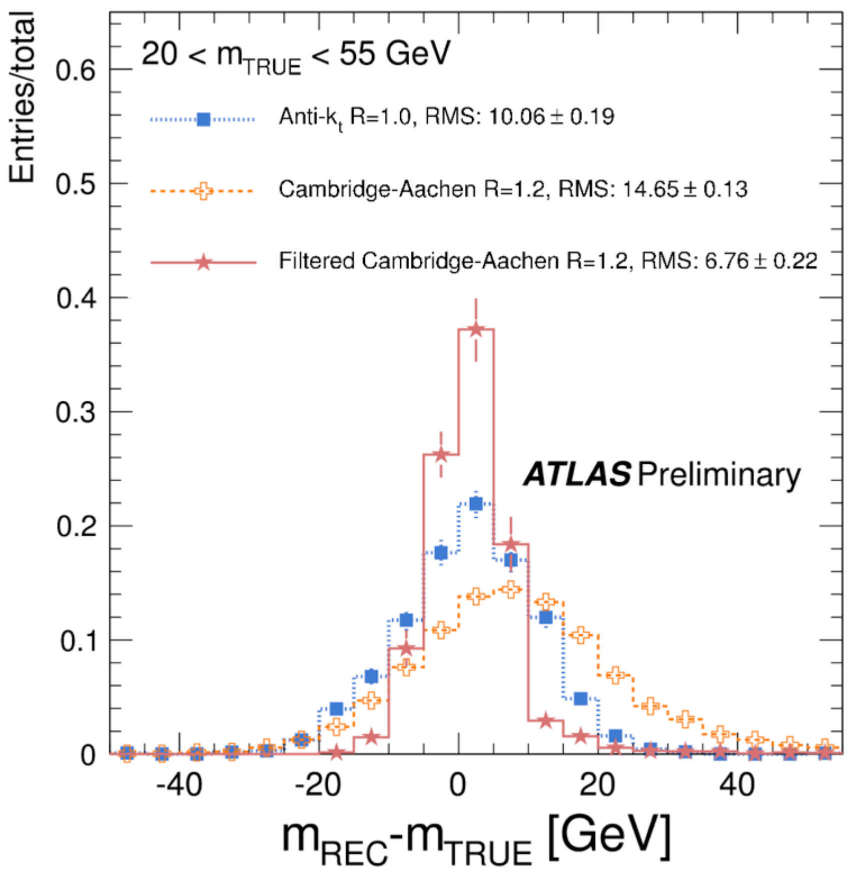
➡ Combine into a likelihood

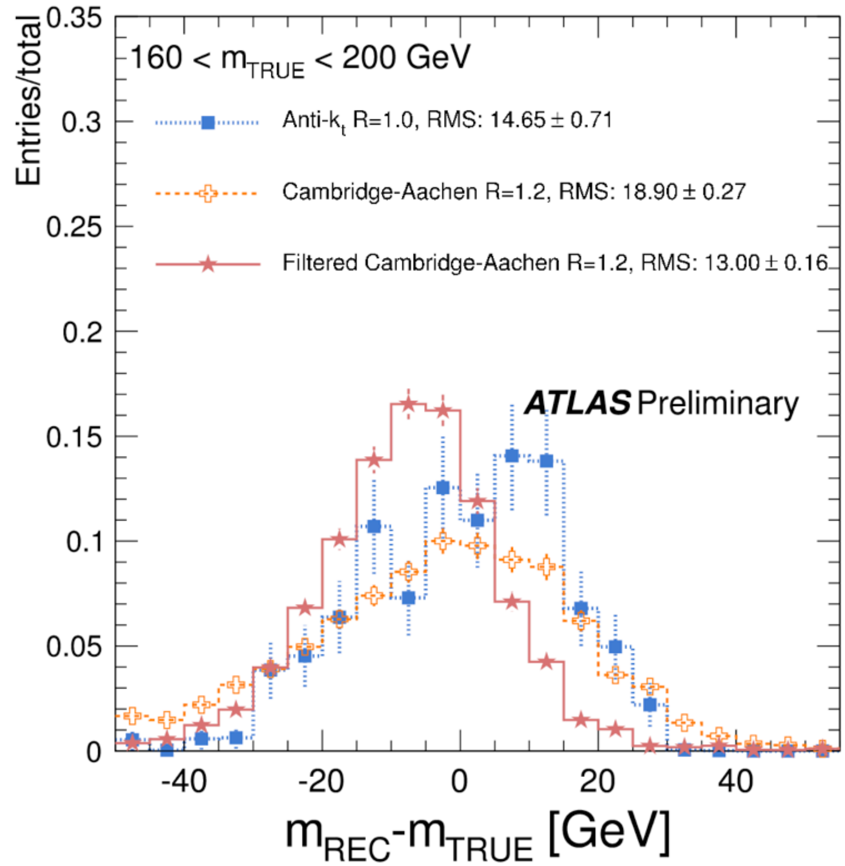
Hadronic Decays: Result

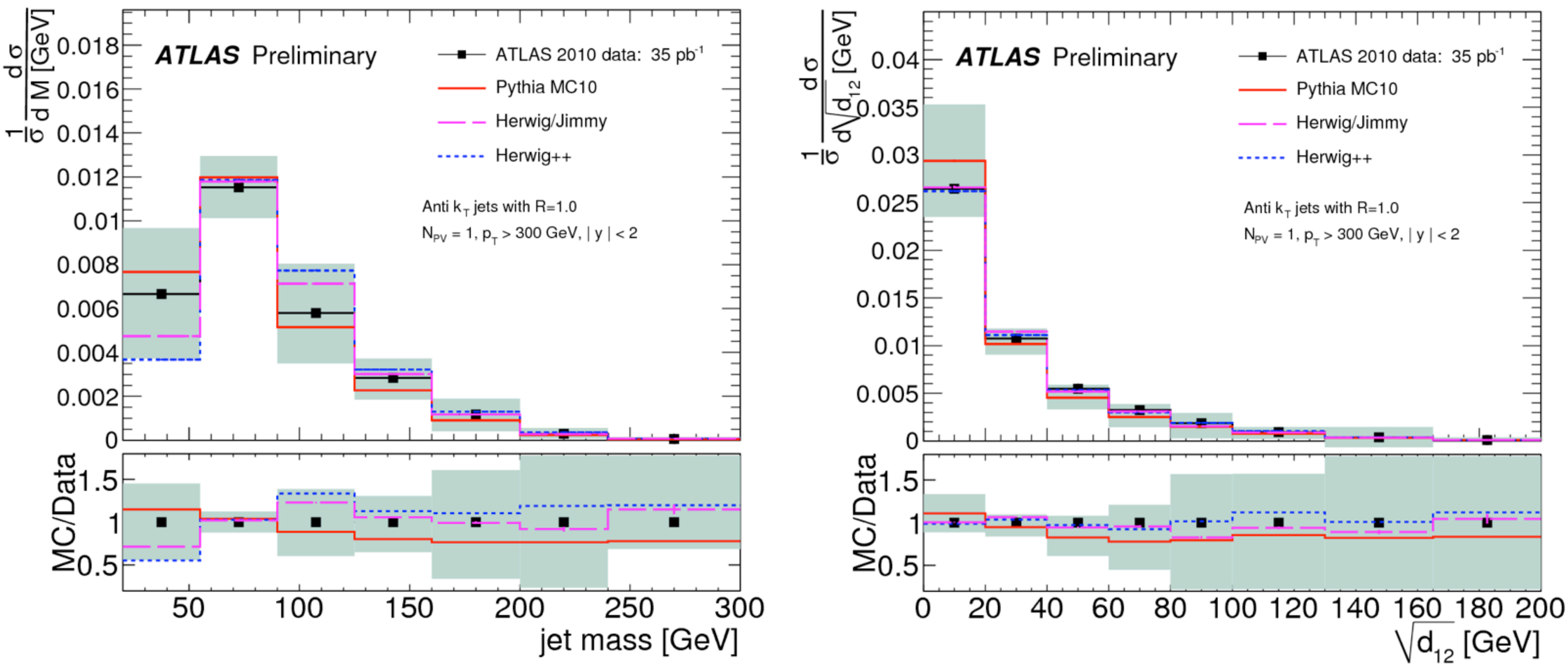


Testing the Variables

- Background studies of MC modeling





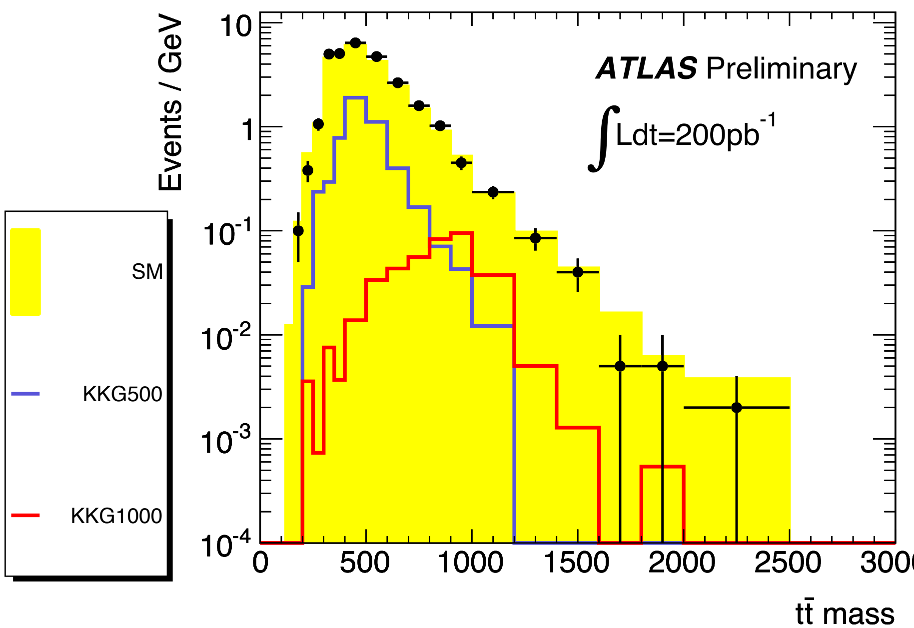

ATLAS Preliminary
ATLAS 2010 data: 35 pb-1
Pythia MC10
Herwig/Jimmy
Herwig++
Anti kT jets with R=1.0
NPV = 1, pT > 300 GeV, | y | < 2
MC/Data
jet mass [GeV]
√d12 [GeV]

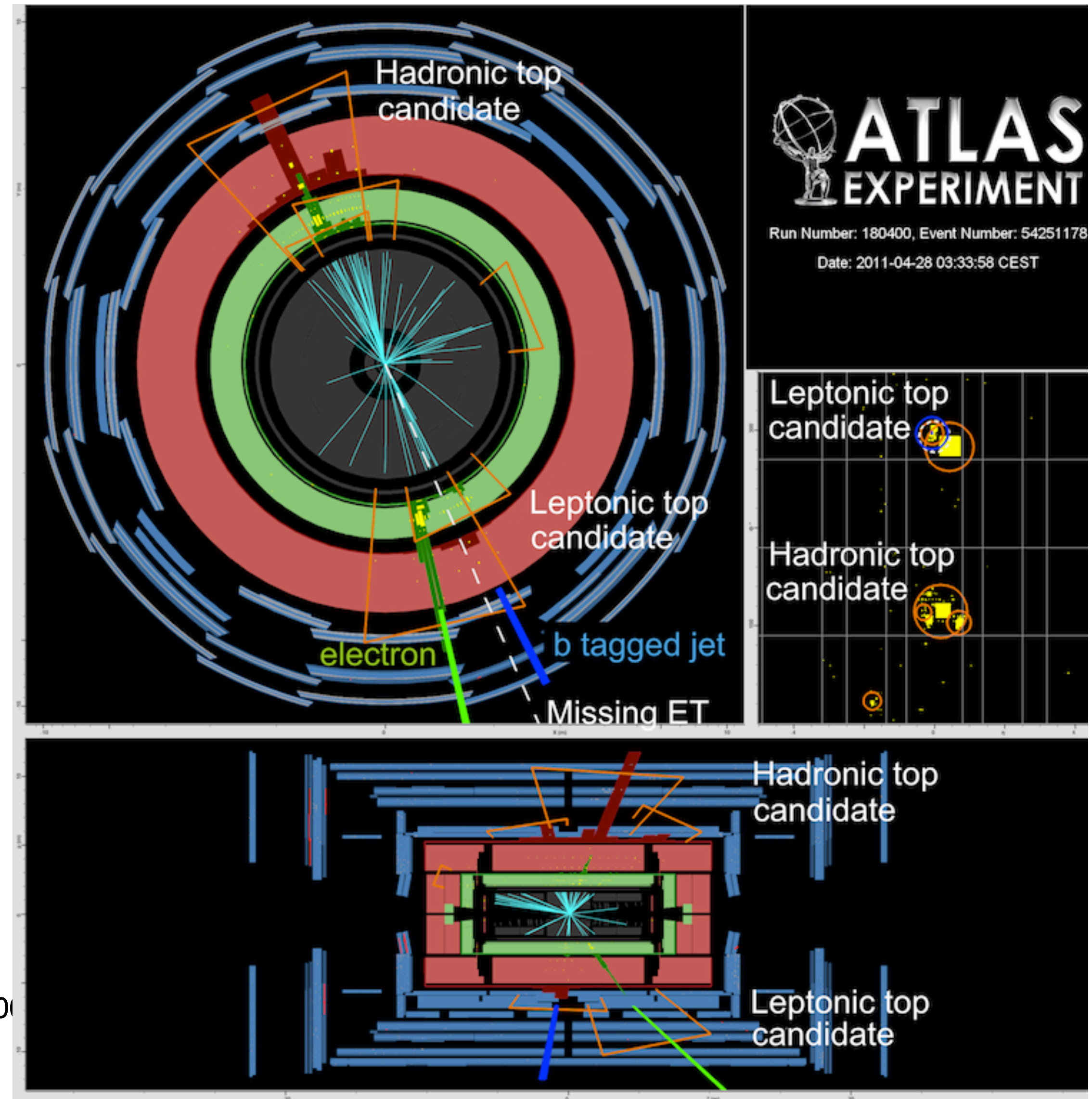
Many More Techniques

- Whole "jet structure" community exists
  - Report of BOOST2010 workshop a very useful resource:
    - **Boosted objects: A Probe of beyond the Standard Model physics, A. Abdesselam et al, Eur.Phys.J. C71 (2011) 1661**
  - Direct comparison of multiple taggers, and "groomers"
  - Since then, more have been developed, and also more extensive non-perturbative calculations of the jet structure
  - Many of the tools available in the fastjet library (Cacciari, Salam, Soyez)
    - http://www.lpthe.jussieu.fr/~salam/fastjet/

High Mass tt Events

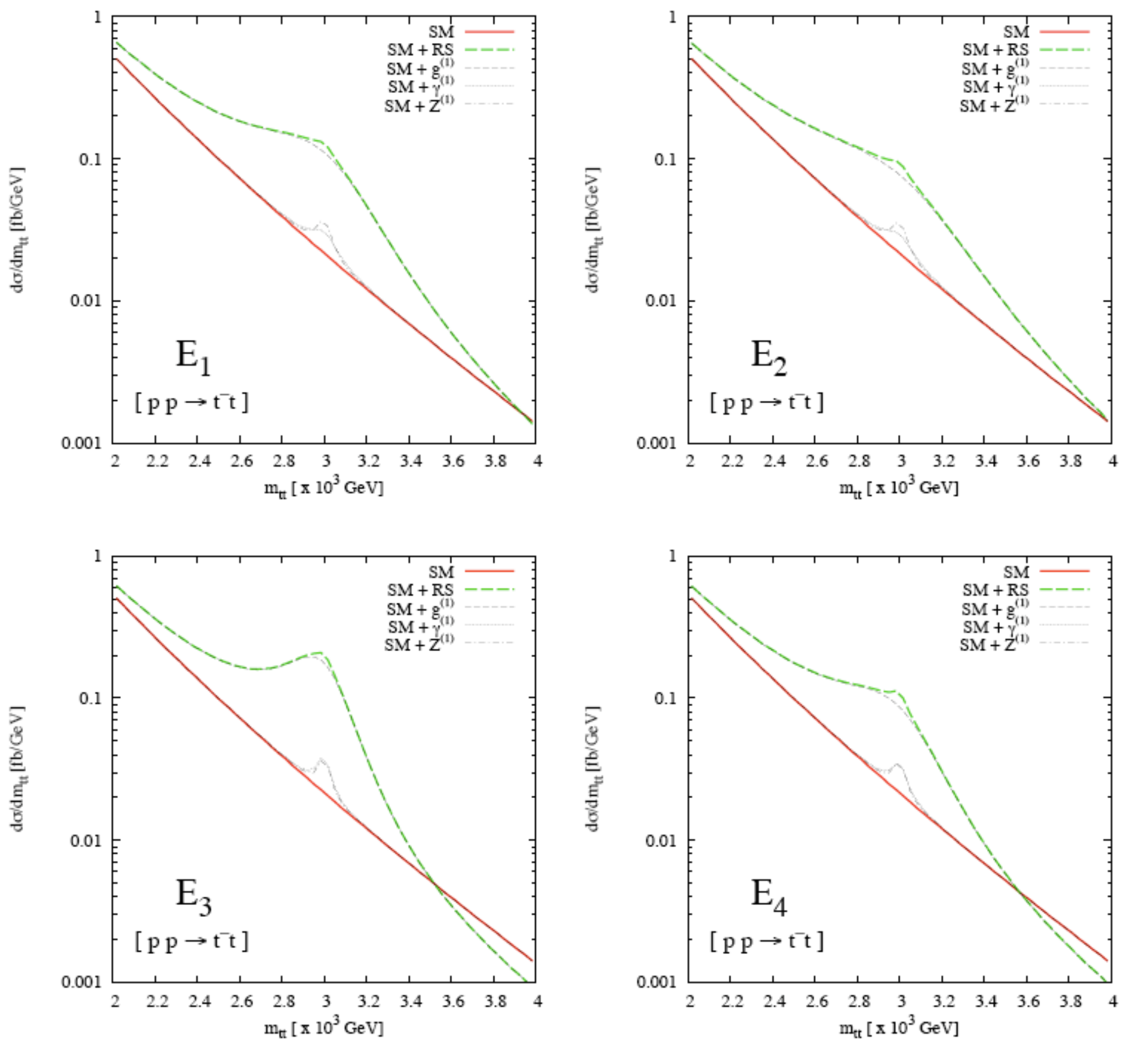
ATLAS and CMS are already observing high mass events with boosted topologies!





- ATLAS ℓ+jets study was used to estimate sensitivity to a specific RS scenario:

Djouadi, Moreau, Singh: Nucl.Phys.B797:1-26,2008



Use ATLAS study, apply efficiencies and smear resonance with ATLAS mass resolution

GB, G. Moreau, R. Singh in Les Houches 2009: arXiv:1005.1229

Signal Model	Integrated Luminosity for 95% C.L. Exclusion (fb^{-1})
E1 + SM	2.5
E2 + SM	5.4
E3 + SM	1.8
E4 + SM	6.7

Too Short

- Many topics not or barely addressed
  - Long-lived particles, can decay halfway or outside detector, or get stuck and decay later...
  - "Quirks"
  - "Lepton jets"
  - RPV SUSY
  - Model-independent searches
  - ...
- Many new models have signatures that exist in other models!

But...

- We do expect to see something new in the next few years
  - Is there a Higgs?
    - Does it generate fermion masses? Does something "material" stabilize its mass? Does that something tell us why the fermion masses are so? Why there are three?
  - No Higgs?
    - More space? New interactions?
- We can hope for a very rich phenomenology which will help understand more than the question of mass
  - Towards Mendeleev's table's physics equivalent

One of my highlights

Why you should be wary of existing background estimates...

GB: "I wonder what the cross section for $t\bar{t} + 6\mathbf{jets}$ is."

FK: "45 Picobarn!"[a]

GB: "Oh!"

To be continued ...

Les Houches 2009

[a] see arXiv:0808.3674 [hep-ph]

Thanks

(and mainly: stay critical of what you're told!)