Breaking the Electroweak Barrier: New Signatures at Hadron Colliders

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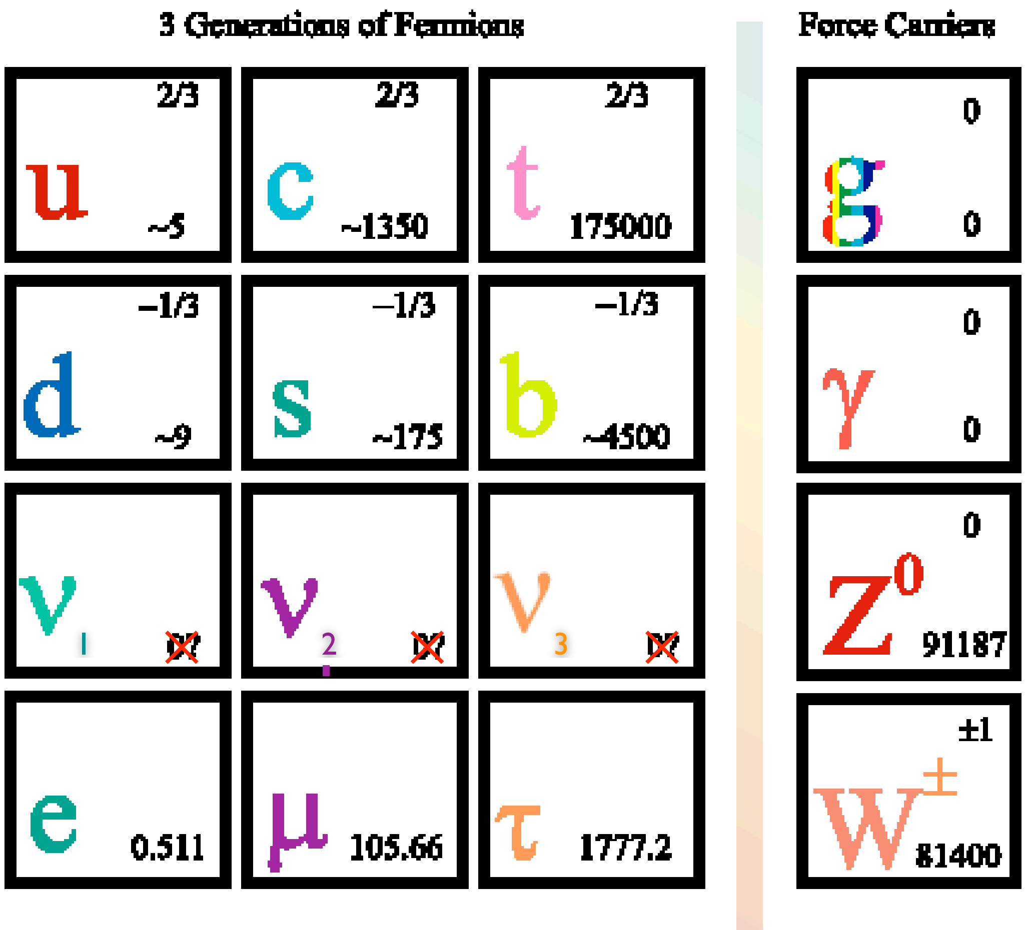
Outline

- The Standard Model: successes and problems
- The tools: colliders and detectors
- Gravity and hierarchy
- High p^T top quark reconstruction
  - Hadronic decays
  - Semileptonic decays
  - Di-top mass
- Conclusions

HEP in 2009



Masses are in MeV

CKM elements:

Observable	Central ± 1 σ
$\|V_{ud}\|$	0.97430 [+0.00019 -0.00019]
$\|V_{us}\|$	0.22521 [+0.00082 -0.00082]
$\|V_{ub}\|$	0.00350 [+0.00015 -0.00014]
$\|V_{cb}\|$	0.04117 [+0.00038 -0.00115]
$\|V_{ud}\|$ (meas. not in the fit)	0.97444 [+0.00028 -0.00028]
$\|V_{us}\|$ (meas. not in the fit)	0.2257 [+0.0011 -0.0011]
$\|V_{ub}\|$ (meas. not in the fit)	0.00350 [+0.00015 -0.00016]
$\|V_{cb}\|$ (meas. not in the fit)	0.04399 [+0.00069 -0.00397]
$\|V_{cd}\|$	0.22508 [+0.00082 -0.00082]
$\|V_{cs}\|$	0.97347 [+0.00019 -0.00019]
$\|V_{td}\|$	0.00859 [+0.00027 -0.00029]
$\|V_{ts}\|$	0.04041 [+0.00038 -0.00115]
$\|V_{tb}\|$	0.999146 [+0.000047 -0.000016]

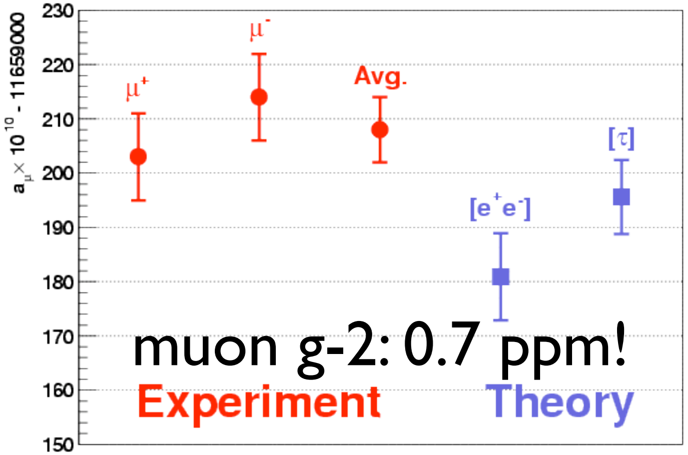
In Words

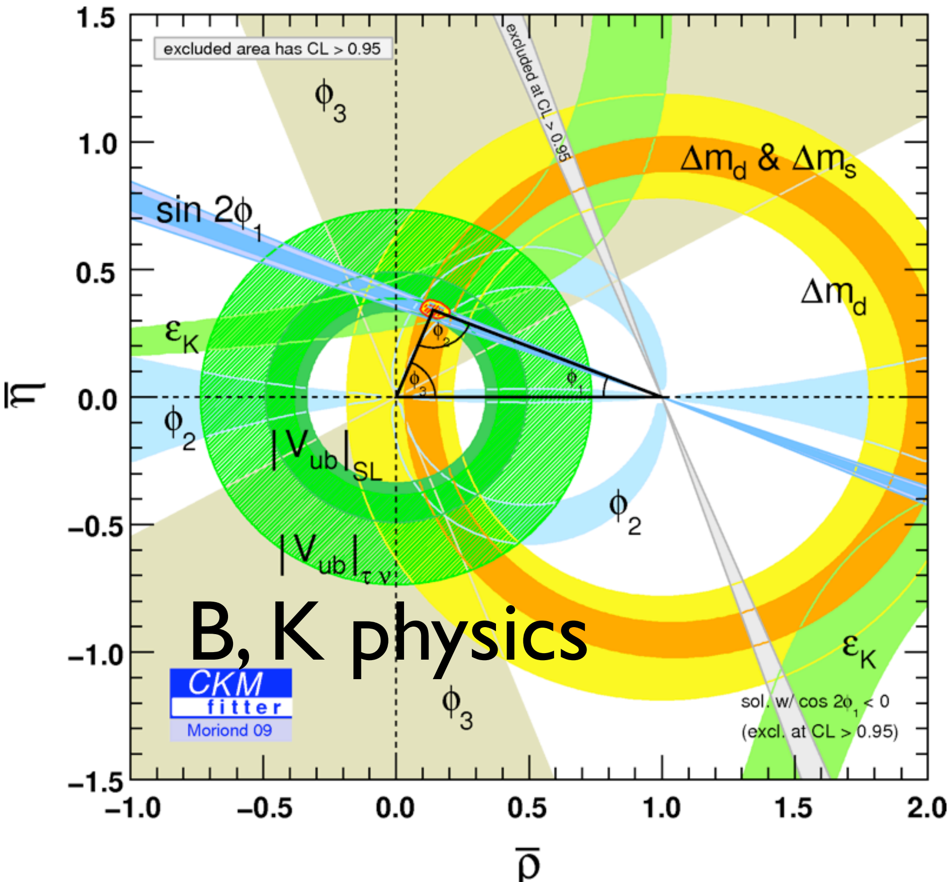
- Matter is built of spin 1/2 particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions
- There appear to be 3 generations of matter particles
- The 4 different matter particles in each generation carry different combinations of quantized charges characterizing their couplings to the interaction bosons
- The matter fermions and the weak bosons have “mass”
- Gravitation is presumably mediated by spin 2 gravitons
- Gravitation is extremely weak for typical particle masses
- There appear to be 3 macroscopic dimensions

About the Standard Model

- It's a theory of interactions:
  - Properties of fermions are inputs
  - Properties of interaction bosons in terms of couplings, propagations, masses are linked:
    - Measuring a few allows us to predict the rest, then measure and compare with expectation
- It's remarkably successful:
  - Predictions verified to be correct at sometimes incredible levels of precision
  - After ~30 years, still no serious cracks

Precision Results





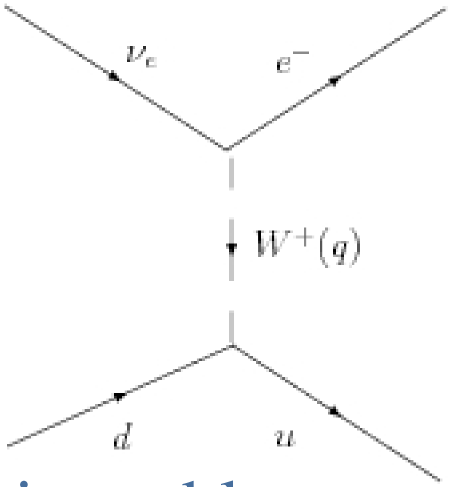
LEP, SLD & Tevatron

Many Fundamental Questions

- What exactly *is* spin? Or color? Or electric charge? Why are they quantified?
- Are there only 3 generations? If so, why?
- Why are there e.g. no neutral, colored fermions?
- What is mass? Why are particles so light?
- Is there a link between particle and nucleon masses?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- …

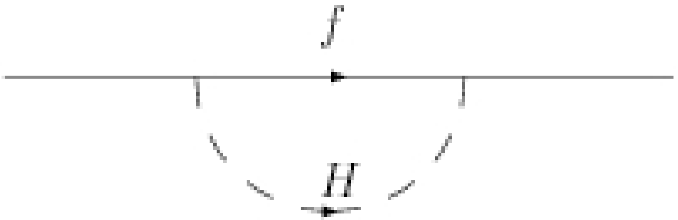
Vector Boson Scattering

- There is in fact one known problem with the standard model:
  - If we collide W's and Z's (not so easy...), the scattering cross-section grows with the center of mass energy, and gets out of control at about 1.7 TeV
- This is similar to "low" energy neutrino scattering:
  - If $q^2 << (M_W)^2$, looks like a "contact interaction", and cross-section grows with center of mass energy
  - But when $q^2 \approx (M_W)^2$, W-boson propagation becomes visible, and "cures" this problem



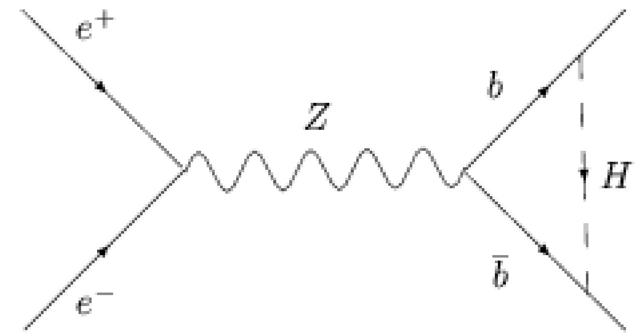
The Higgs Boson

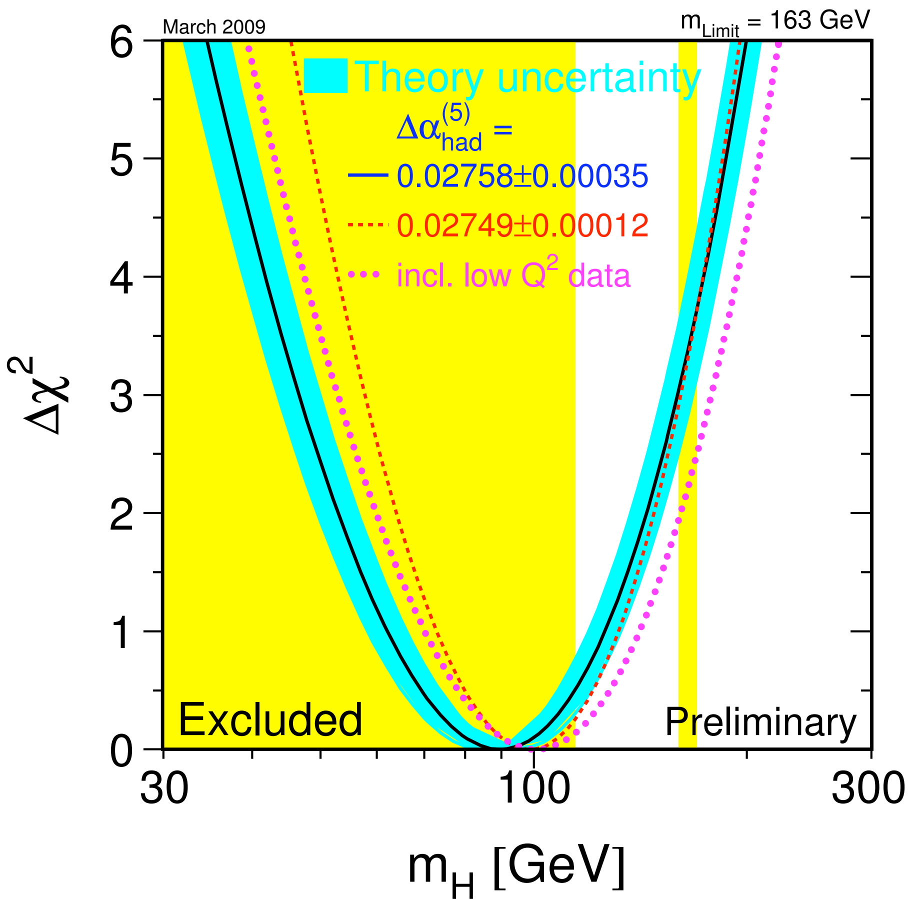
- One way to solve this, is to introduce a massive, spinless particle (of mass < ~1 TeV)
  - Couplings to W and Z are fixed, quantum numbers are known...
  - .... to be those of the vacuum
  - Its mass is unknown, and its couplings to the fermions are unknown.... well, maybe
    - Fermions can acquire mass by coupling to this Higgs boson, so their couplings could be proportional to their masses. This is called the "standard model Higgs"



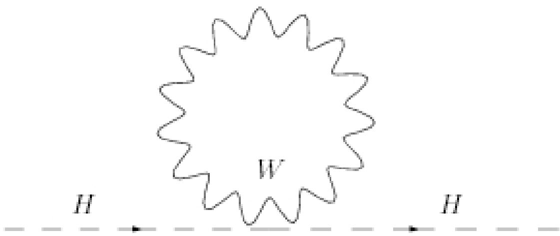
Precision Measurements

- In fact, we can say something about the standard model Higgs mass
  - If the fermions get their masses from the Higgs, we know all couplings and can infer the Higgs mass from precision measurements
  - Result is very sensitive to measured top quark, W boson masses
    - Really wants a "light" Higgs boson

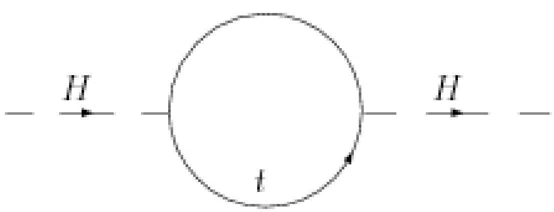




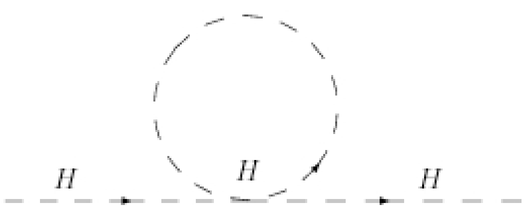
Higgs Mass



$$\frac{1}{16\pi^2} g^2 E^2$$



$$\frac{3}{16\pi^2} y_t^2 E^2$$



$$\frac{1}{16\pi^2} \lambda E^2$$

- Higgs, in fact, also acquires mass from coupling to W's, fermions, and itself!
  - These "mass terms" are quadratically divergent
  - Drive mass to limit of validity of the theory
- So we expect the Higgs mass to be close to the scale where new physics comes in....

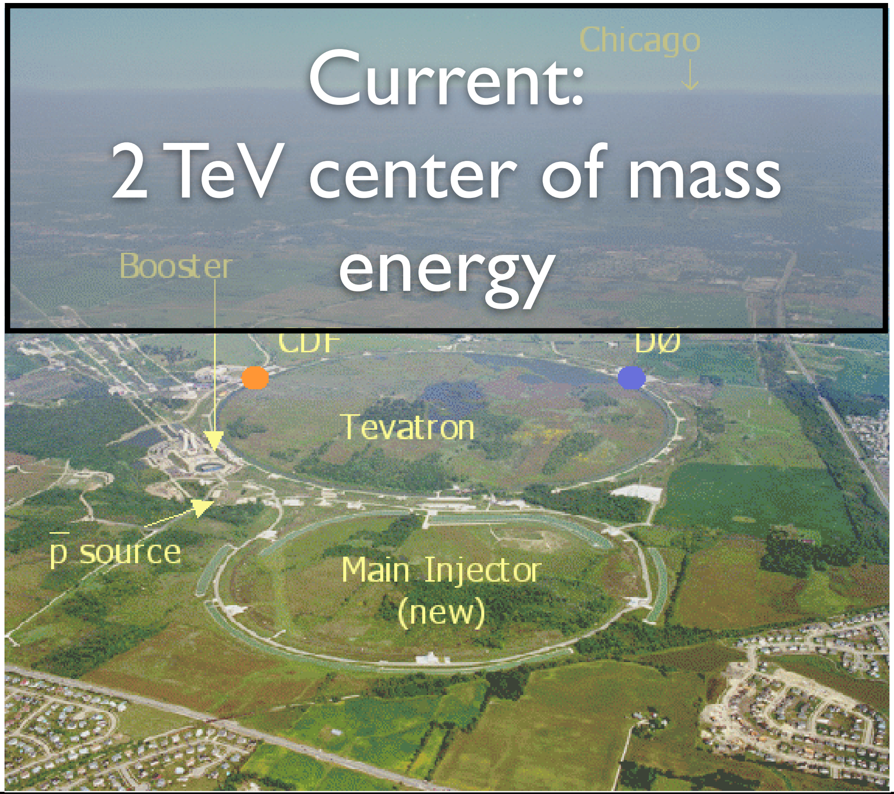
Higgs Drawbacks

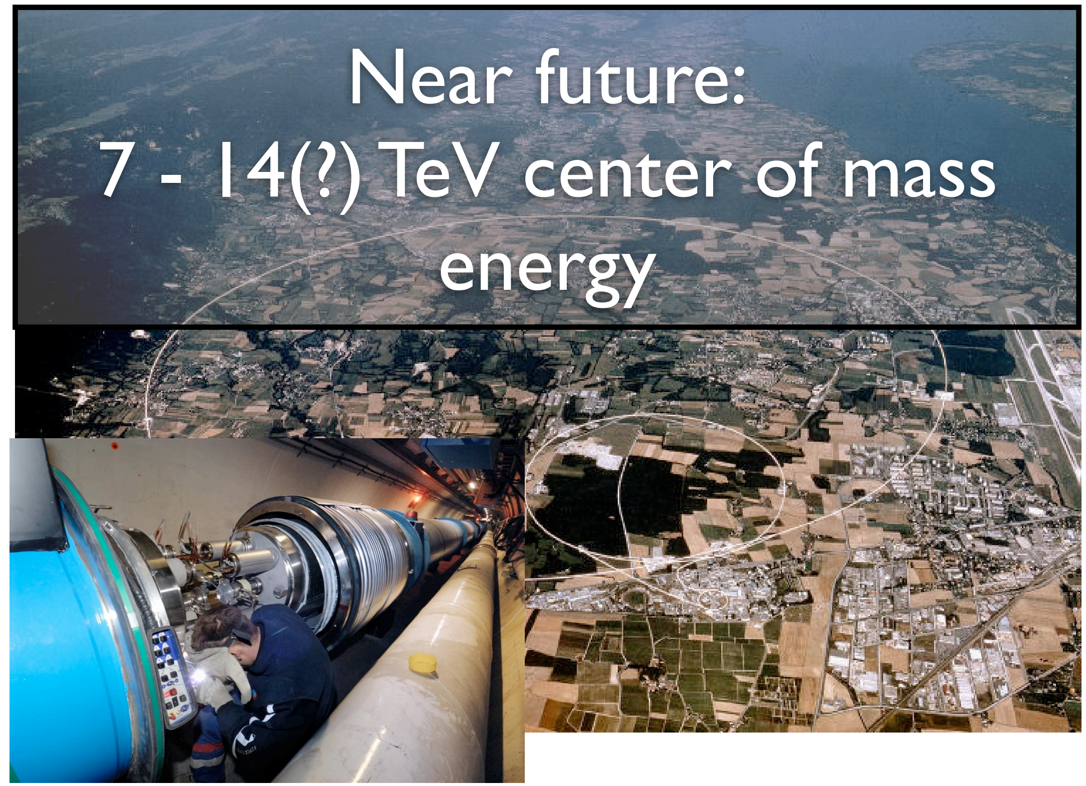
- In principle, with the addition of a Higgs boson around 150 GeV particle physics could be "complete", but fine-tuned (the hierarchy problem)
  - Like Mendeleev's table for chemistry
- But by itself, the Higgs is very unsatisfactory:
  - Why are the couplings to the fermions what they are?
    - Dumb luck (aka landscape)?
  - What is the link to gravity?
  - Why does the Higgs break the symmetry?
  - Why are there 3 generations, dimensions, ...?

The Tools

Colliders

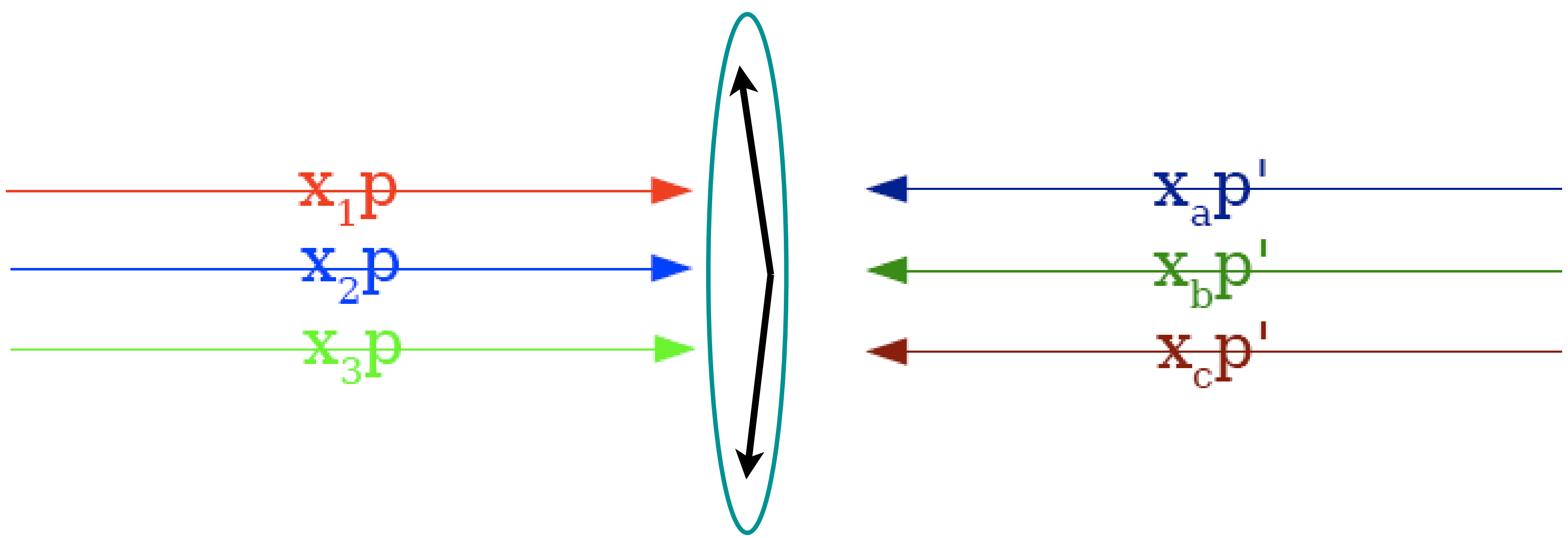
- Hunting for answers:
  - Can study well-understood processes with high precision
  - Or probe at very high energy
    - High energy implies probing of short distances, and (maybe) production of other, massive particles





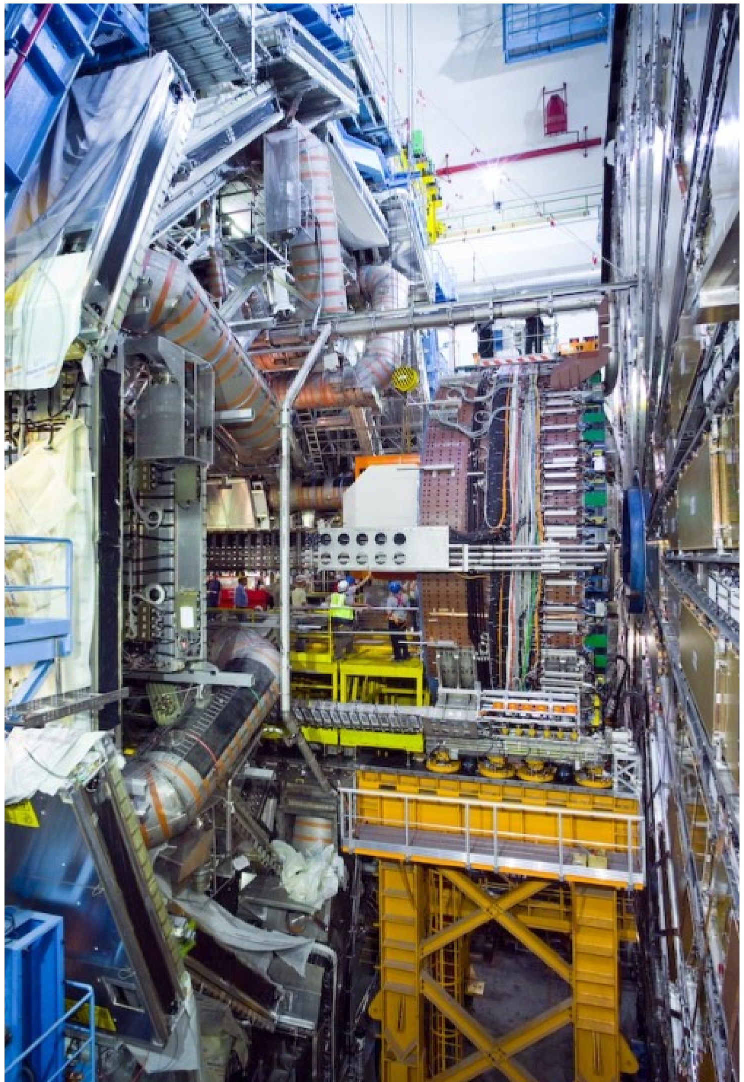
Hadron Colliders

- Incoming longitudinal momentum not known:
  - "Hard interaction" is between one of the quarks and/or gluons from each proton, other quarks/gluons are "spectators"
- Longitudinal boost "flattens" event to a pancake
- We usually work in the plane transverse to the beam

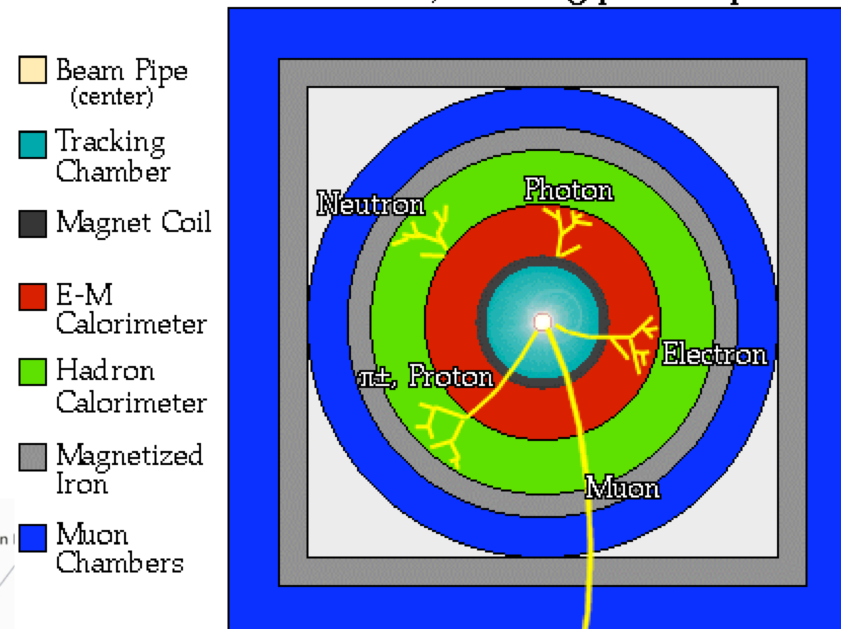


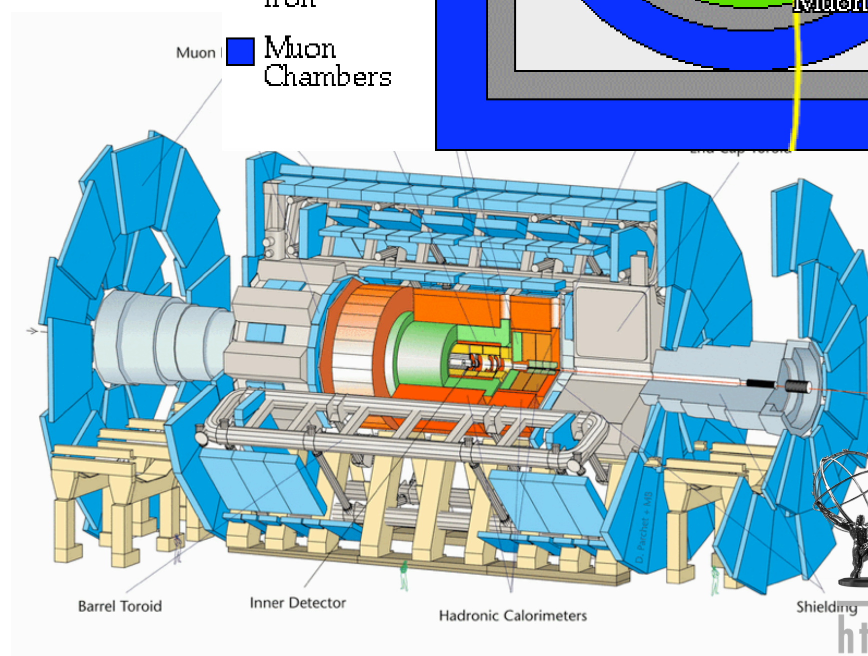
ATLAS

- Make best possible measurement of all particles coming out of collisions



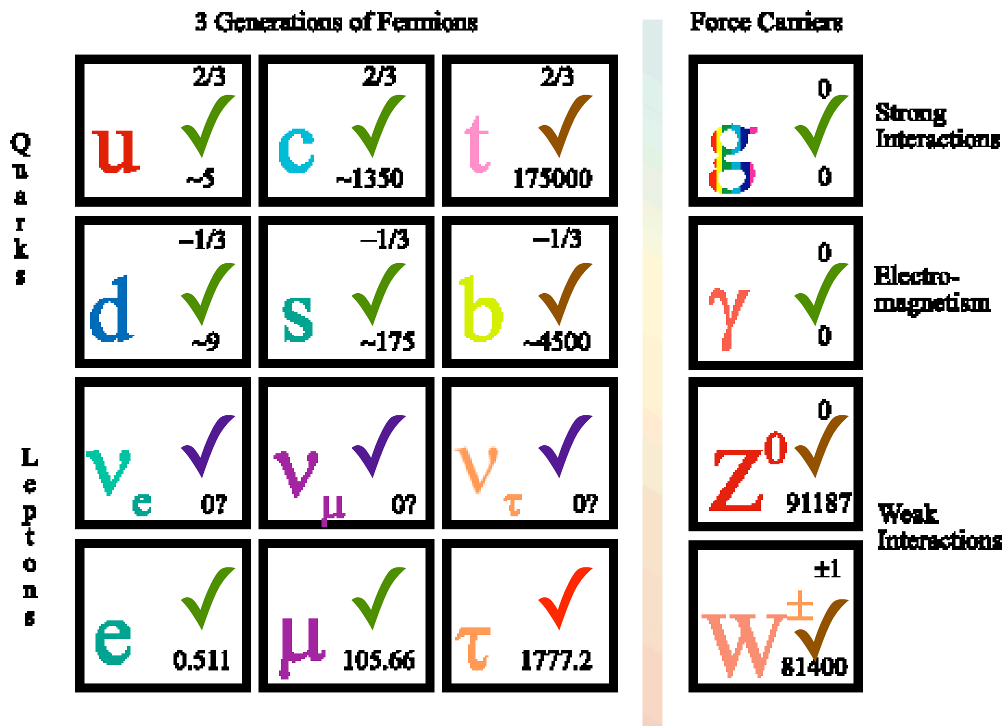
A detector cross-section, showing particle paths





http://atlas.ch

Detecting Particles



Masses are in MeV

✓: Detect with high efficiency

✓: Detect by missing transverse energy

✓: Detect through decays: $t \to Wb$, $W/Z \to$ leptons, ...

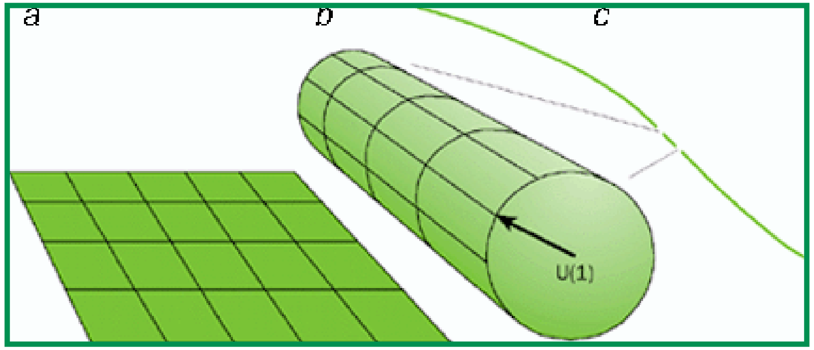
Gravity and Hierarchy

(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

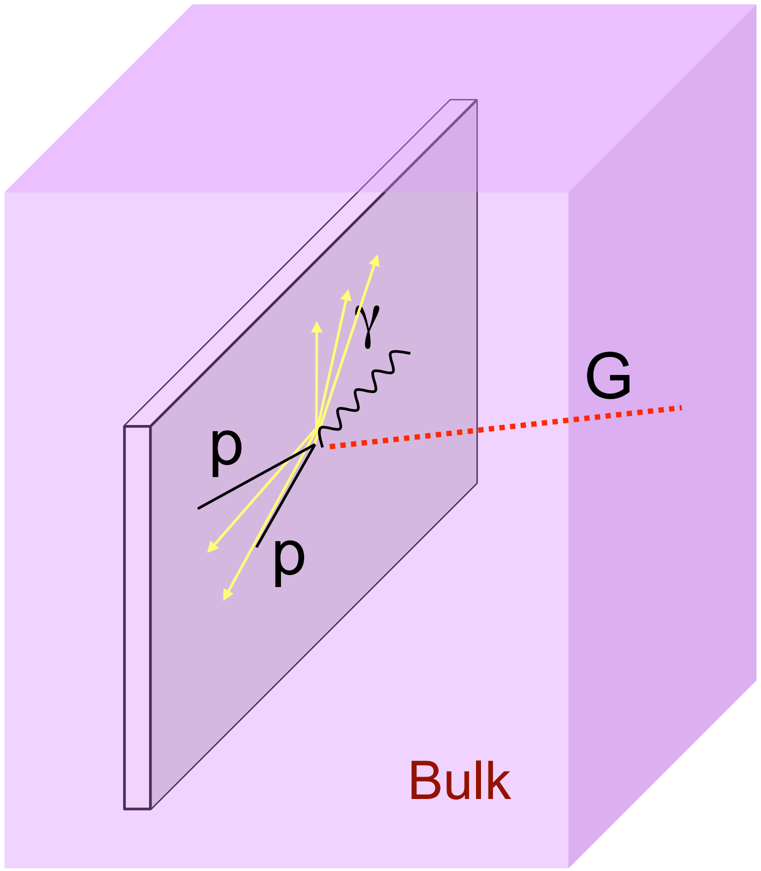


- Radius of compactification usually assumed to close to the observed scale of gravity, i.e. ~10^{18} GeV
  - In ’90 Antoniadis realized they may be much larger...

Phys.Lett.B246:377-384,1990

"ADD"

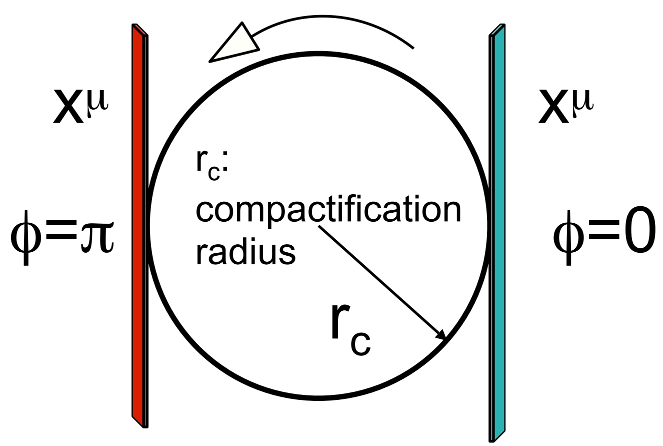
- "Large extra dimension" scenario (developed by Arkani-Hamed, Dimopoulos and Dvali):
  - Standard model fields are confined to a 3+1 dimensional subspace ("brane")
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton "goes through"
    - True scale much lower! No hierarchy problem!

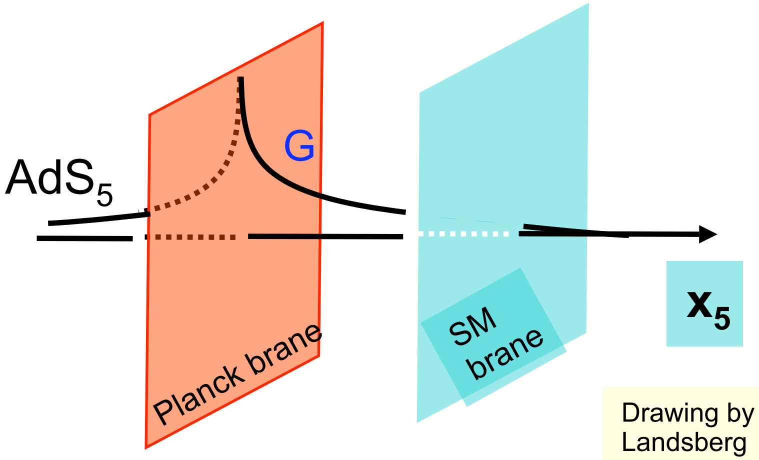


Drawing by K. Loureiro

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)



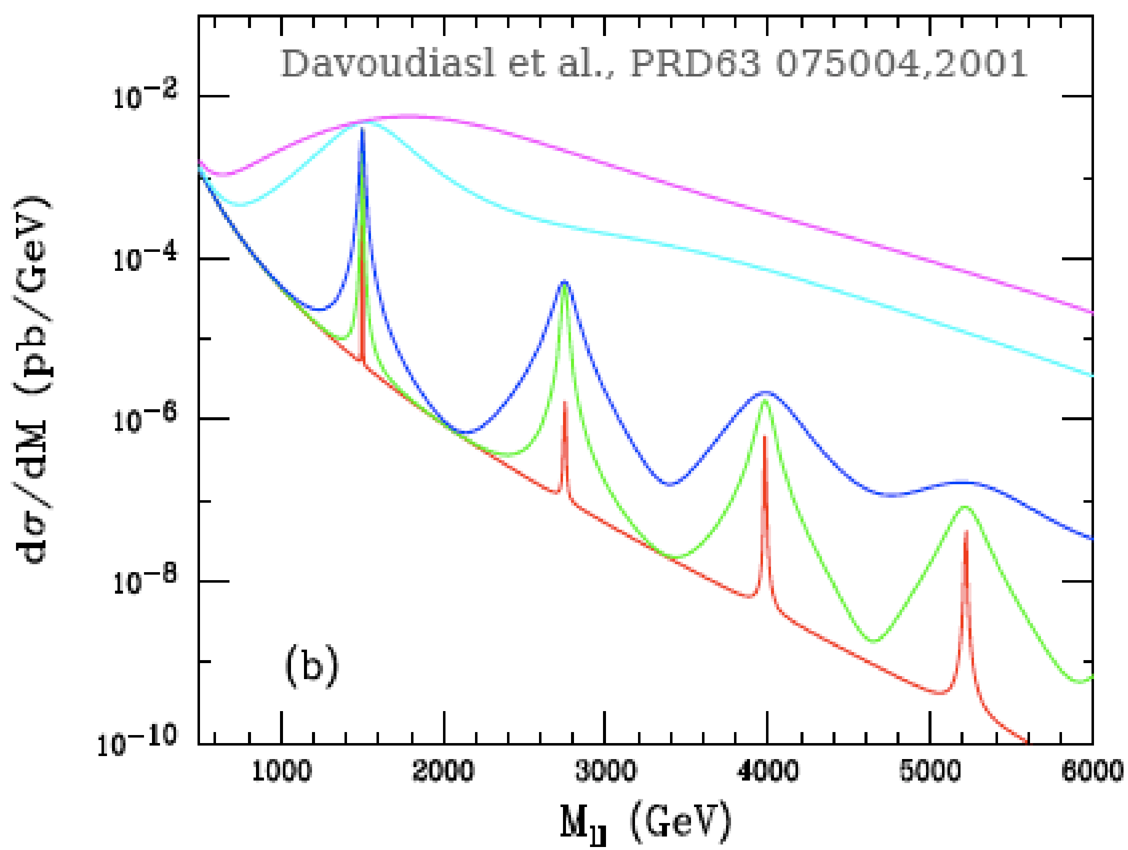


Drawing by G. Landsberg

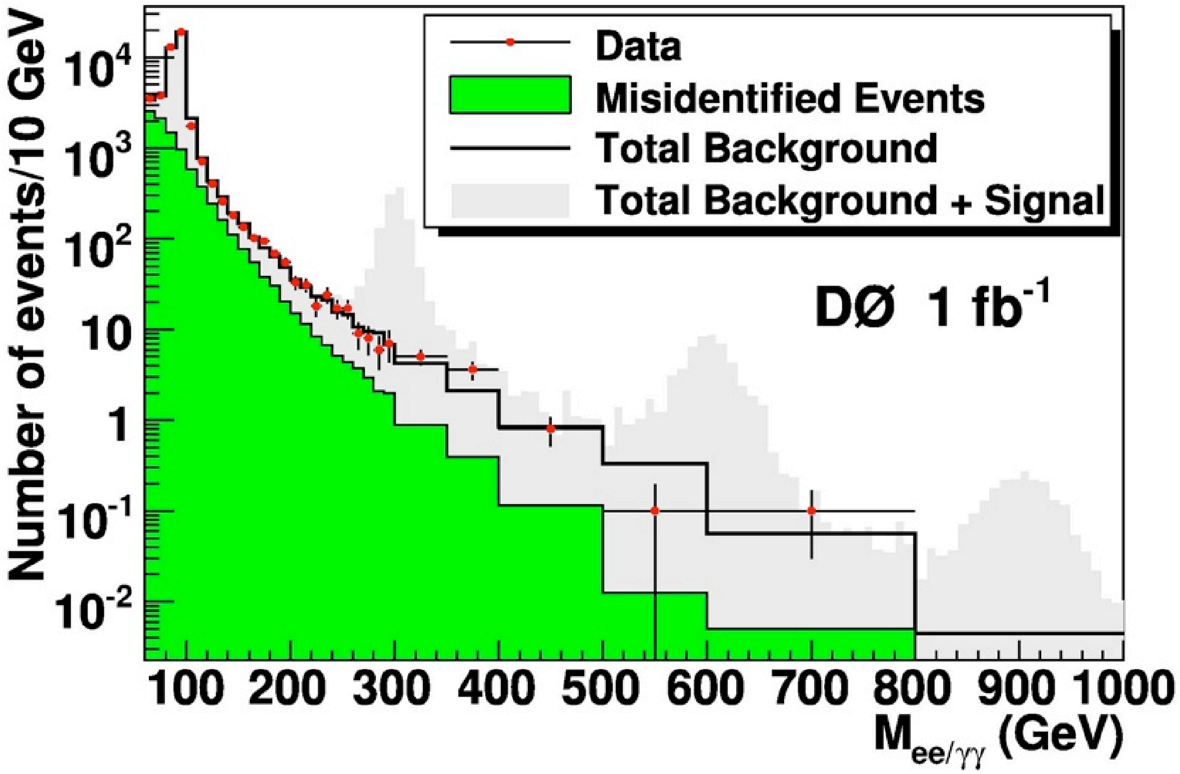
Graviton Excitations

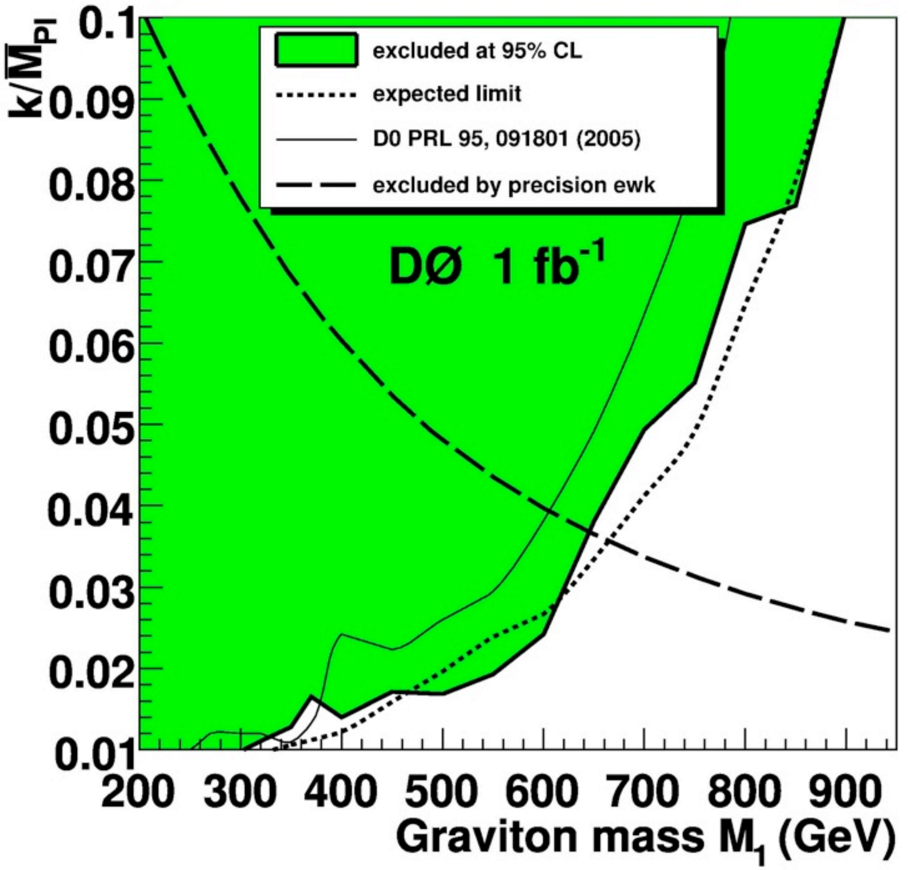
- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function
    - ➡ Smoking gun!

(BRs also different than Z':
e.g. γγ allowed)



Dielectrons/Diphotons

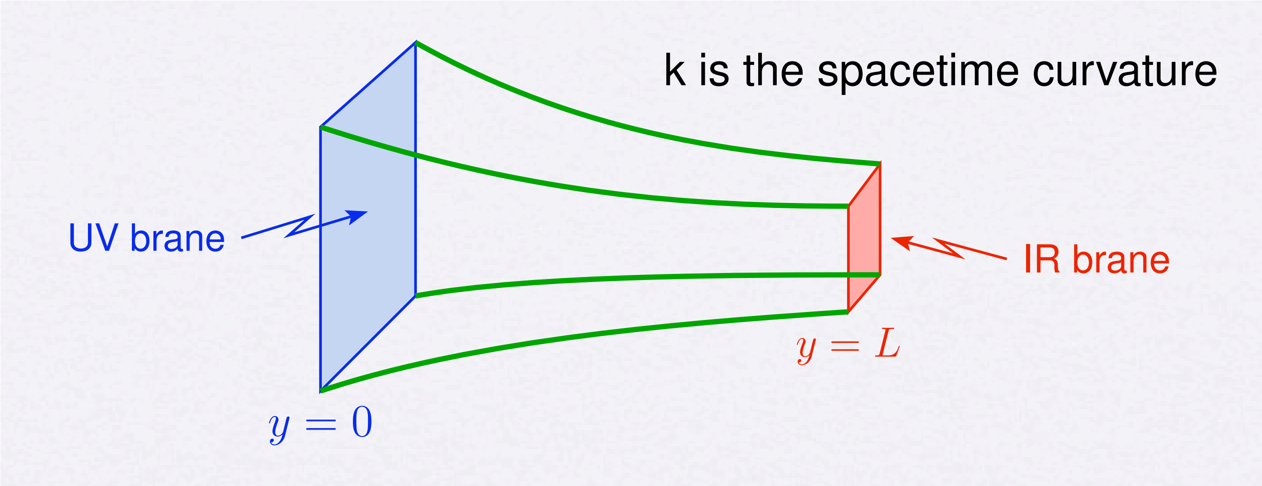




- Single search: no attempt to distinguish electrons from photons...

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 ~ 1 TeV (from geometry!)

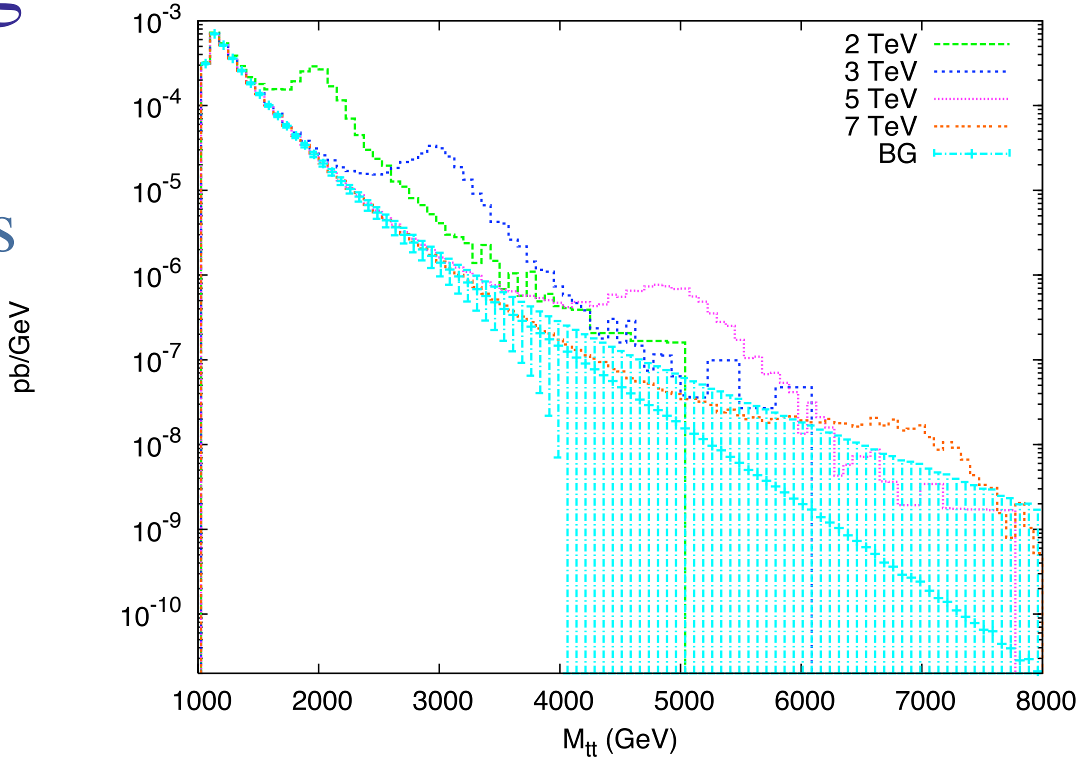
Flavor

- Interesting RS 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 2-4 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

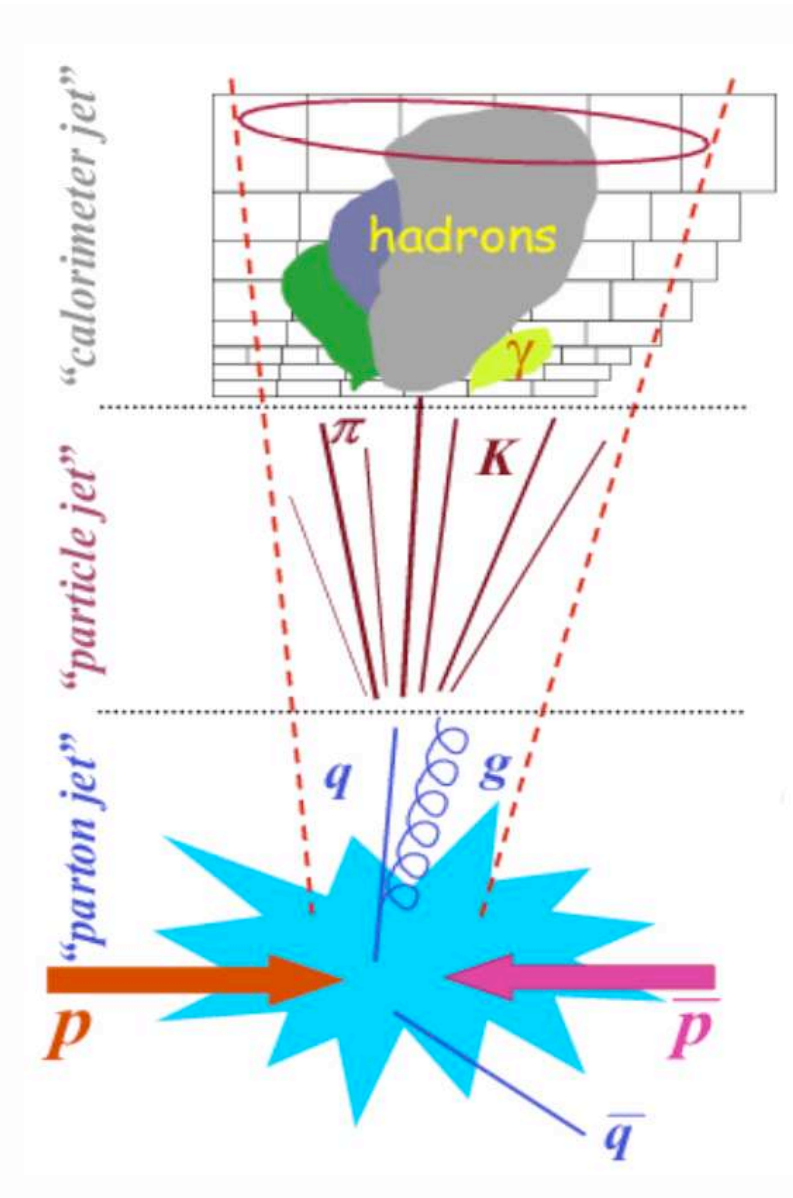
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

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



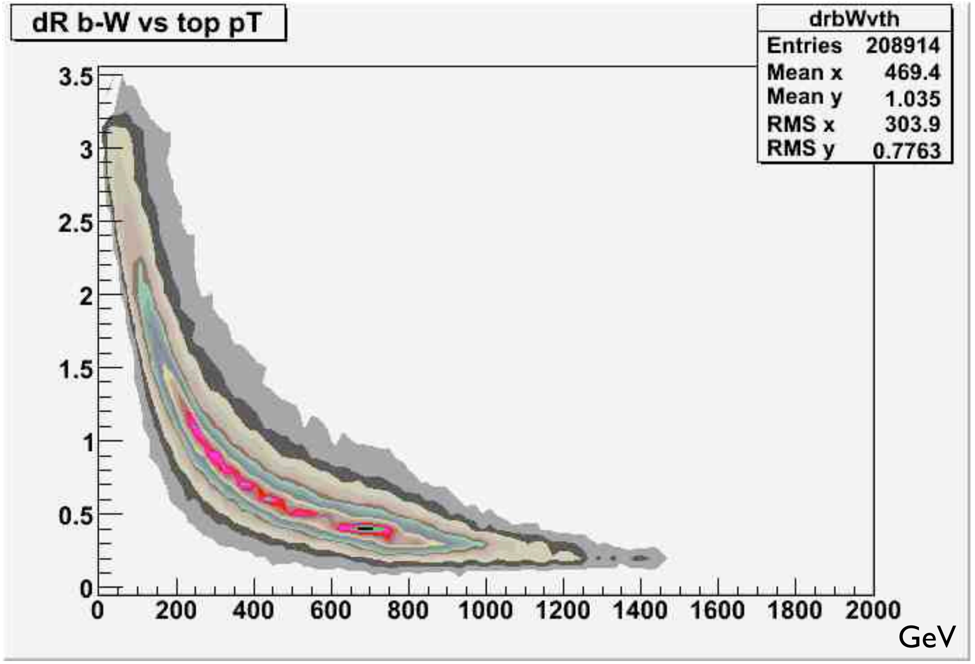
New Experimental Signature

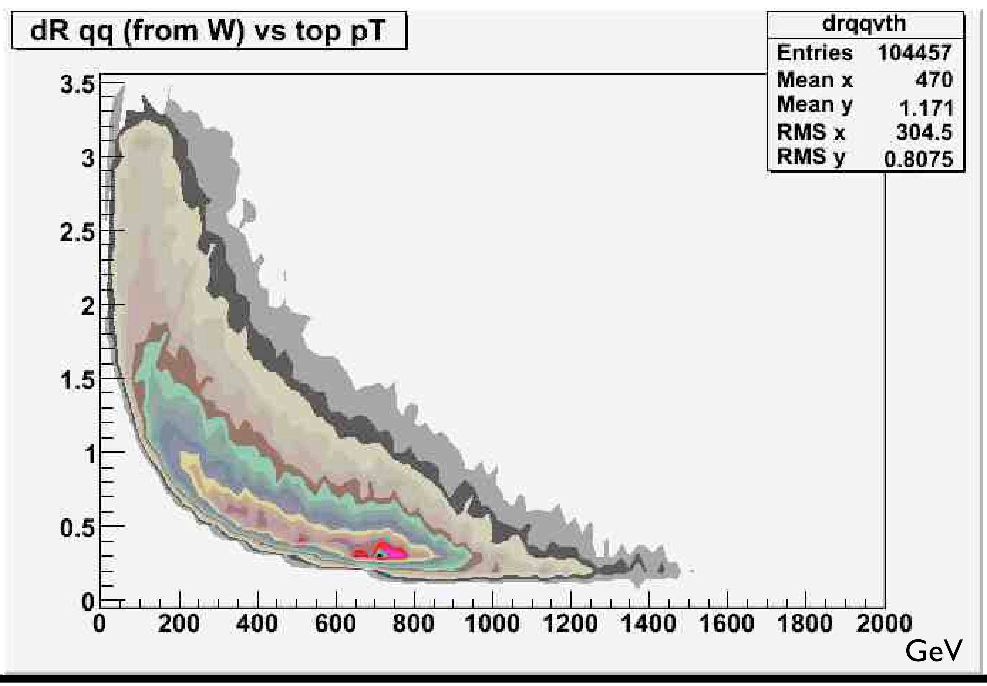
- Possibility to produce (very) heavy resonances decaying to top quarks, W and Z bosons
  - Top/W/Z with momentum >> mass
    - Decay products collimated
  - For leptonic W/Z decays, not a big issue since we measure isolated tracks very well
  - But hadronic decays lead to jets, which are intrinsically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



Top Quark Decays

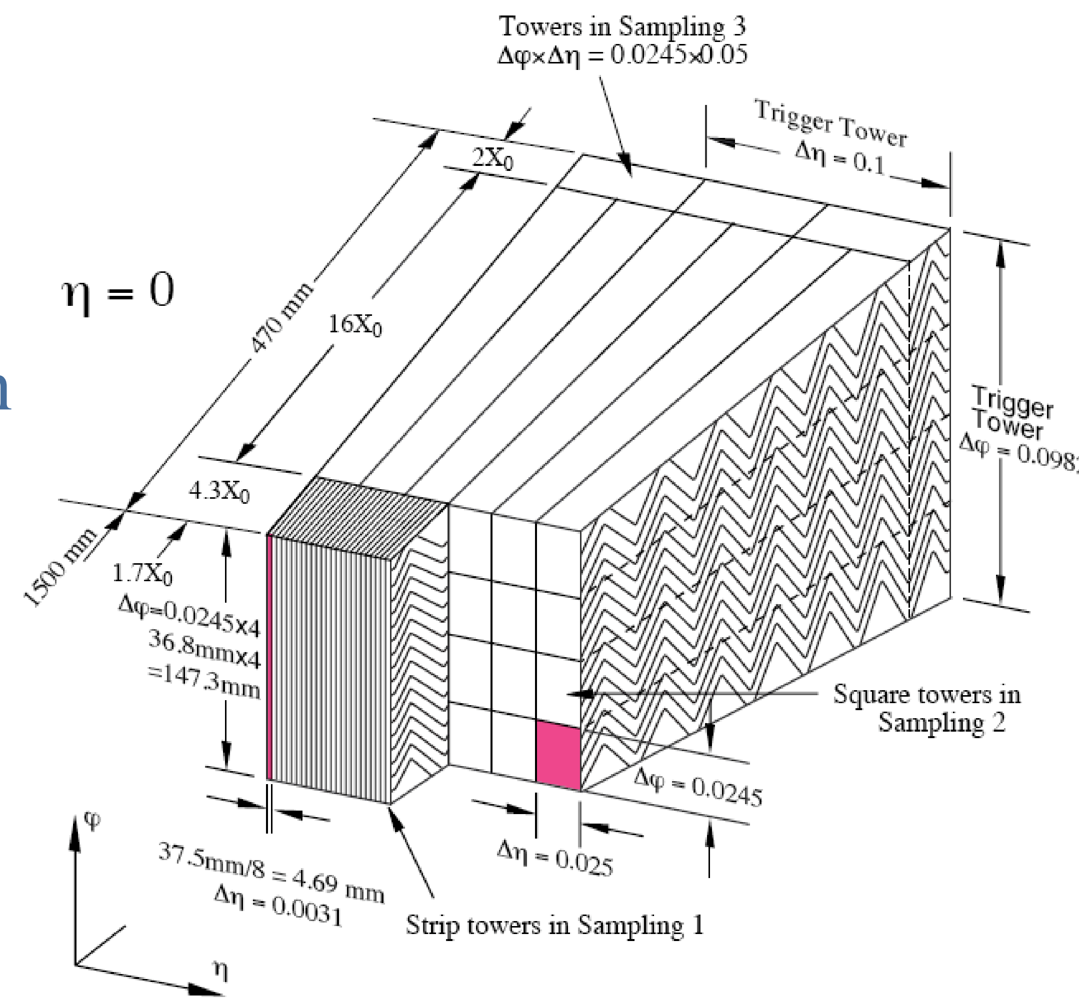
- Simulated decays:
  - $dR = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$
  - Typical jet radius ~0.5
- For top p^T > ~300 GeV
  - dR ($q\bar{q}$' from W) < 2 R_{jet}
  - dR (bW) < 2 R_{jet}
    - (No isolated lepton!)
- But calorimeters have much finer granularity





ATLAS Calorimeters

- Jets deposit almost 50% of their energy in EM calorimeters
  - ATLAS has most finely segmented EM calorimeter in any hadron collider experiment!
  - (CMS has 0.0175 x 0.0175 but only one layer)
- Hadron ("tile") calorimeter has 0.1 x 0.1 segmentation



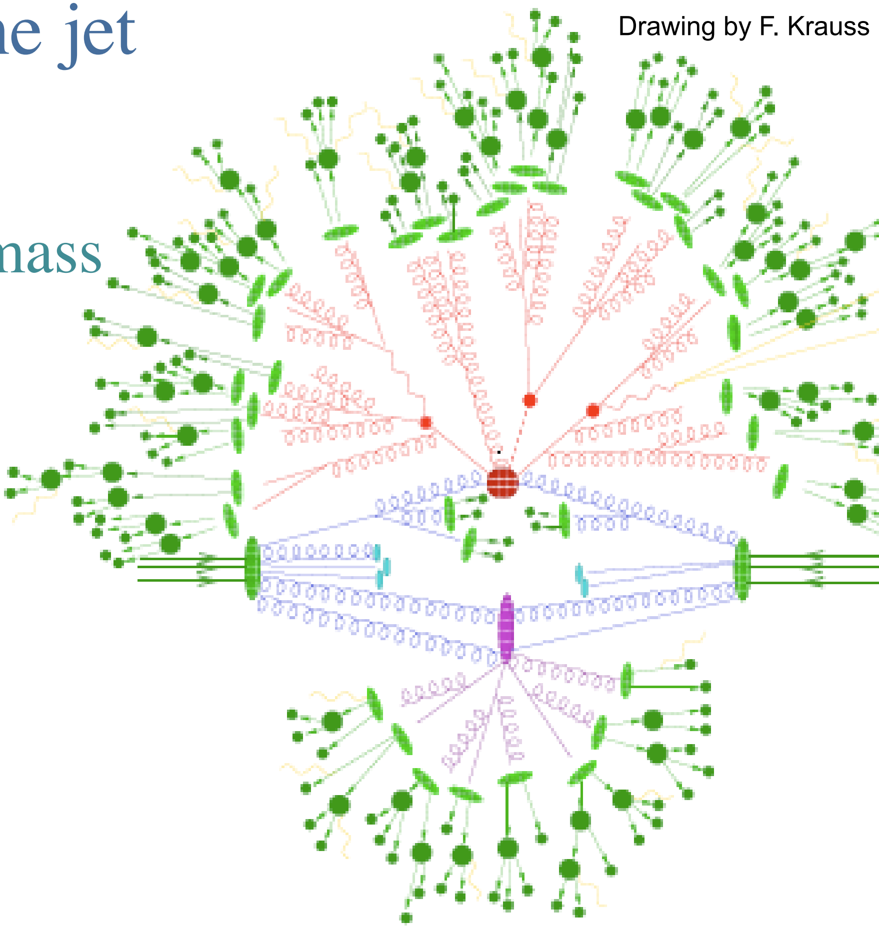
ATLAS Study: Goals & Datasets

- Can we distinguish hadronic & semileptonic decays of high p^T top quarks from light/b jets?
  - Develop tools and evaluate efficiency/rejection
- Use fully simulated samples of:
  - $Z' \rightarrow t\bar{t}$ events with $m(Z') = 2$ and 3 TeV
    - Yields top quarks with 500 GeV $< p^T <$ 1500 GeV
    - (Not many in “transition region”: 200-600 GeV)
  - QCD multijet events with 280 GeV $< p^T <$ 2240 GeV
    - Generated in 3 bins of p^T

Fully Hadronic Decays

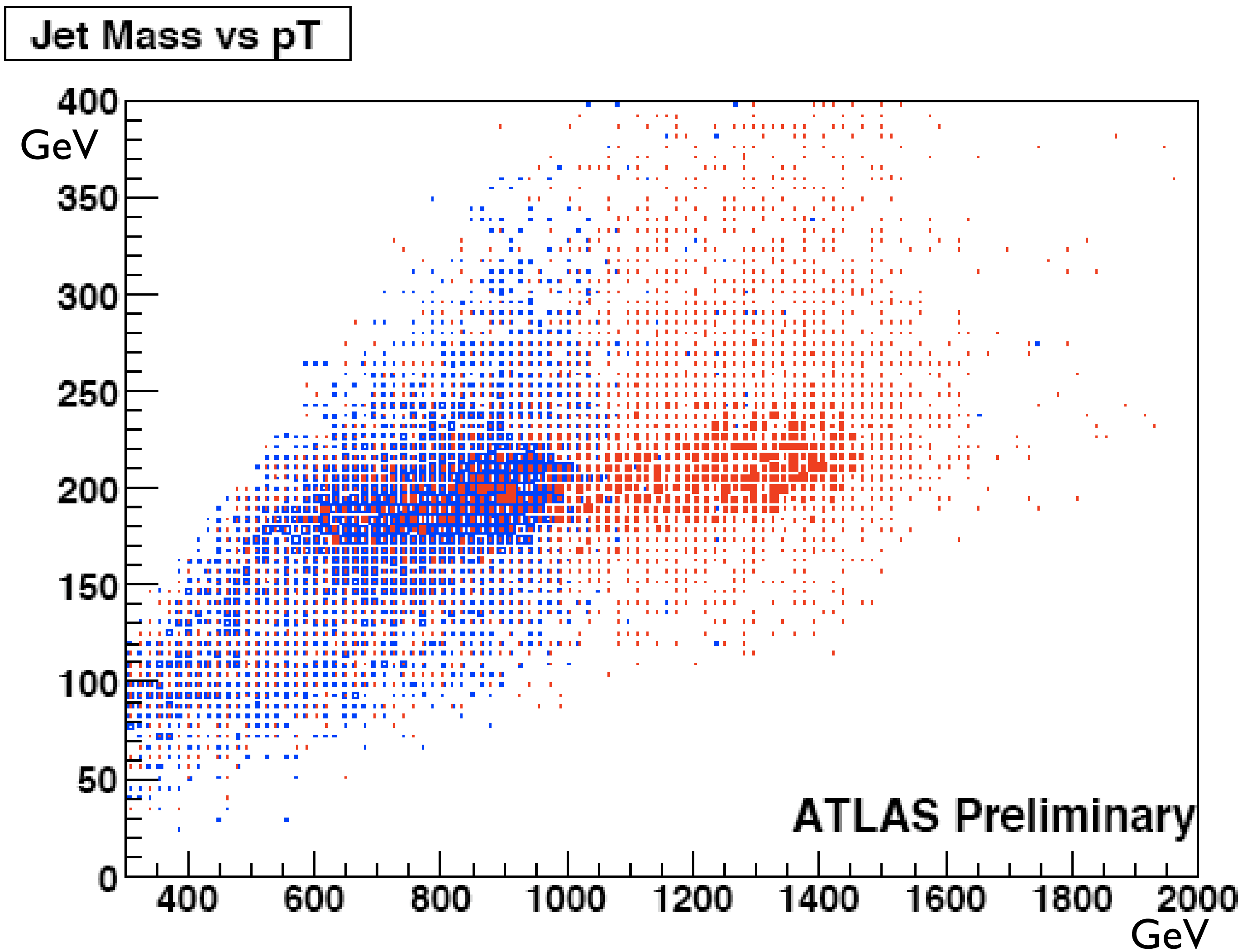
- Decay hadrons reconstructed as a single jet
  - But even if it looks like a single jet, it originates from a massive particle decaying to three hard partons, not one
- If I measured each of the partons in the jet perfectly, I would be able to:
  - Reconstruct the "originator's" invariant mass
  - Reconstruct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

Drawing by F. Krauss



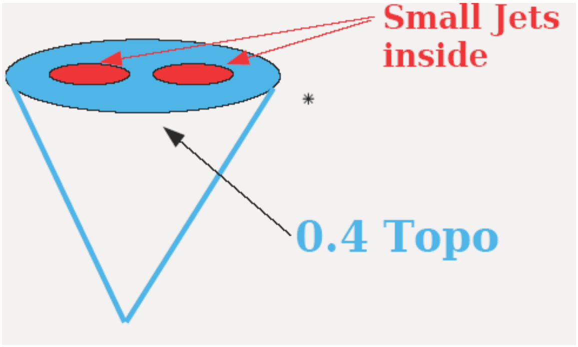
Jet Mass

- 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....
  - This study: $k_\perp$ splitting scales

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

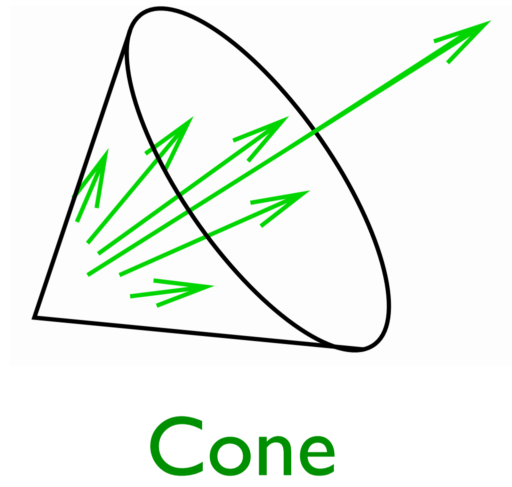
$k_\perp$ Splitting Scales

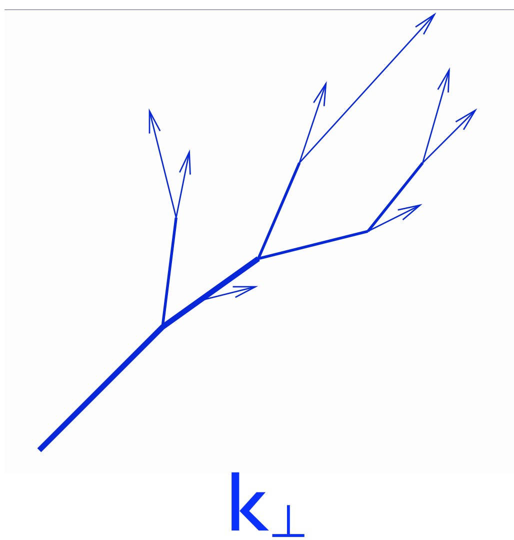
- $k_\perp$ jet algorithm is much better suited to understand jet substructure than cone:
  - Cone maximizes energy in an $\eta \times \phi$ cone
  - $k_\perp$ is a "nearest neighbor" clusterer

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

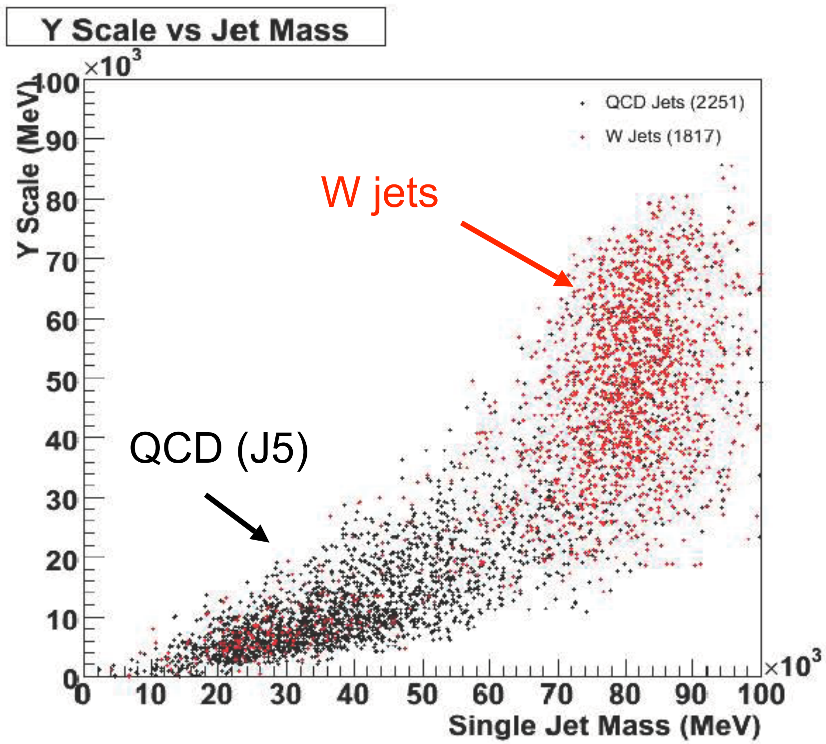
$$Y \text{ scale } = \sqrt{p_{T\,(jet)}^2 \bullet y_2}$$

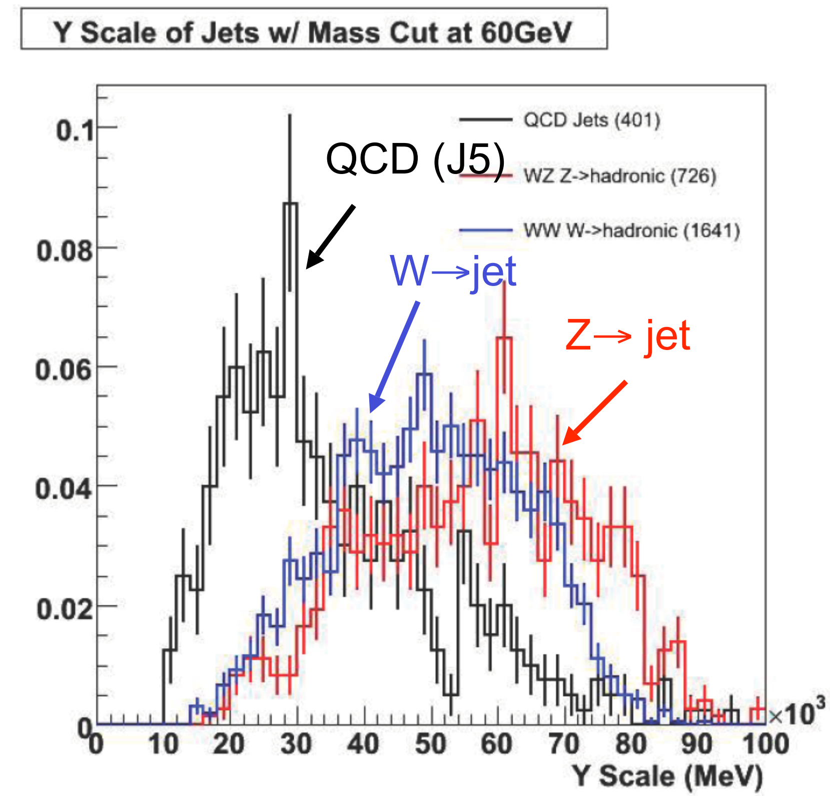
- Can use the $k_\perp$ algorithm on jet constituents and get the (y-)scale at which one switches from 1 → 2 (→ 3 etc.) jets
  - Scale is related to mass of the decaying particle





• Applied to high p^T WW scattering:

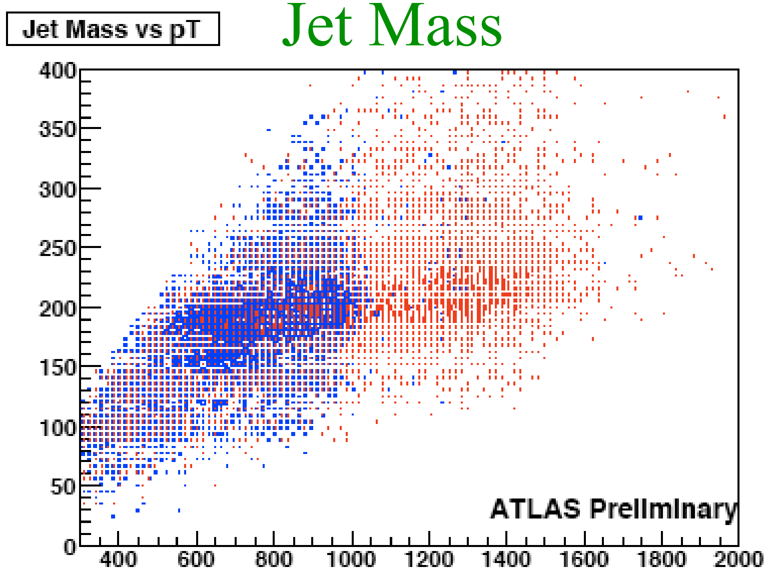




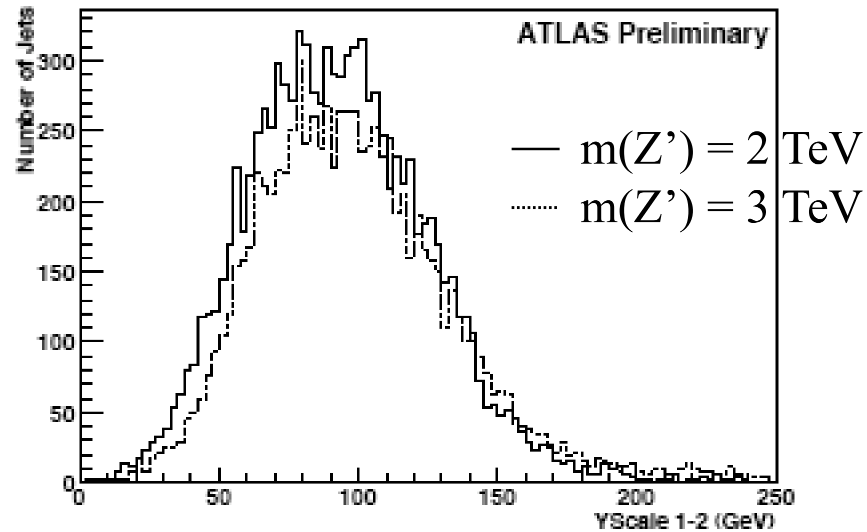
- k_T jet algorithm, with R = 0.5
- Cuts applied : p_T(jet) > 300 GeV,

Variables

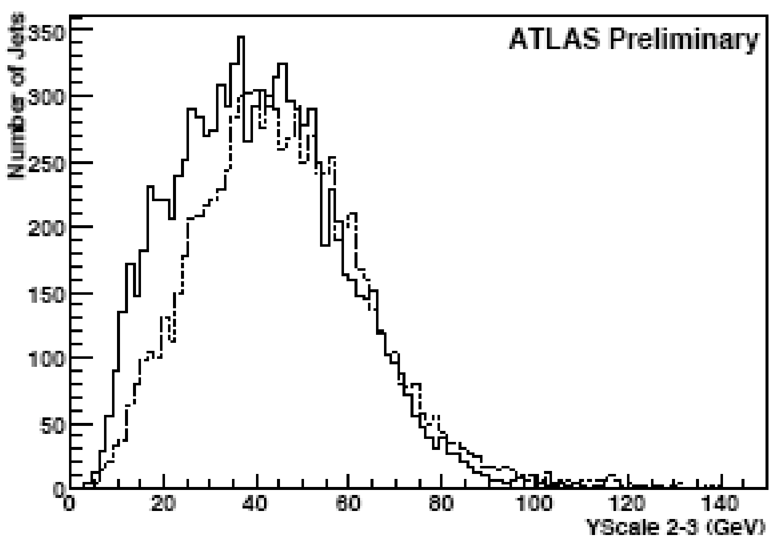
Jet Mass



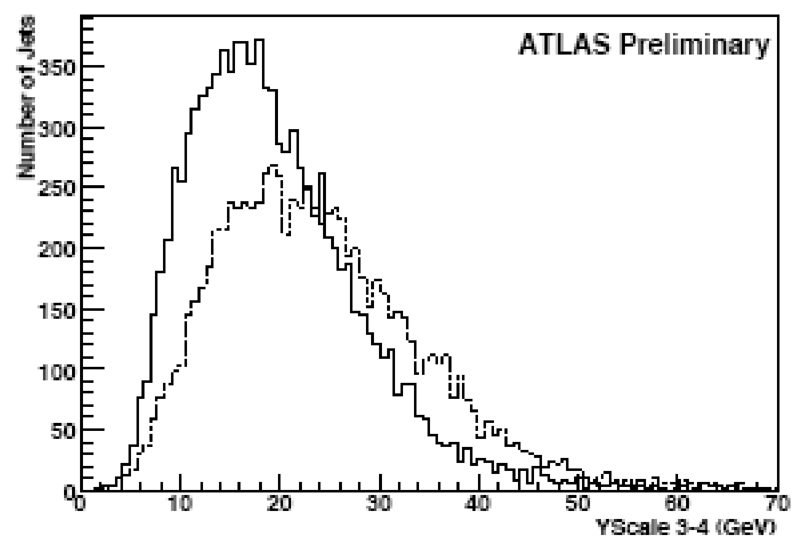
$1 \rightarrow 2$ Jet Scale



$2 \rightarrow 3$ Jet Scale

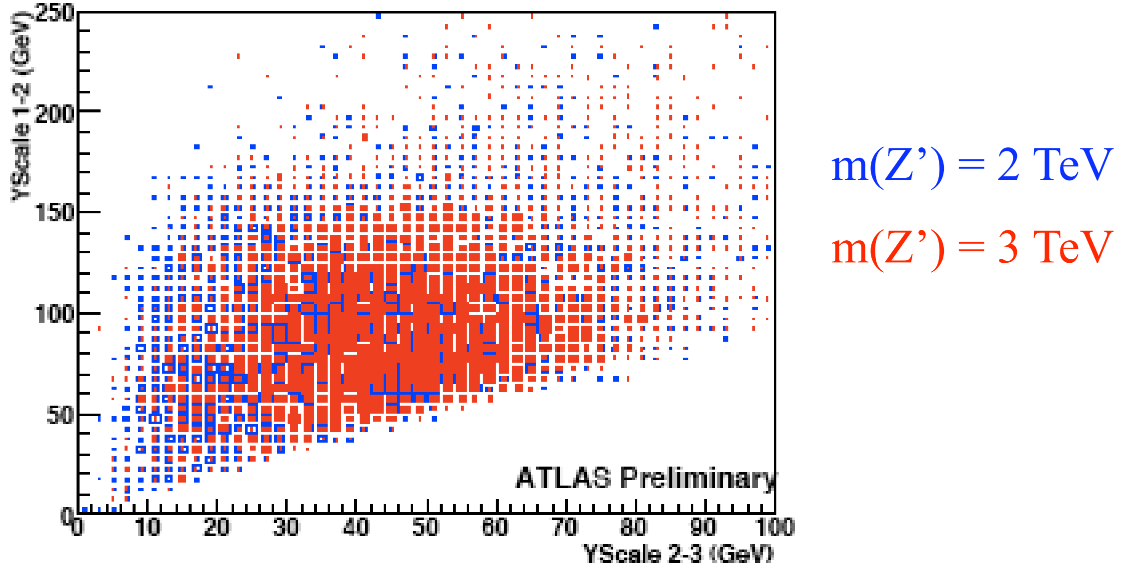


$3 \rightarrow 4$ Jet Scale



Slow p^T Dependence!

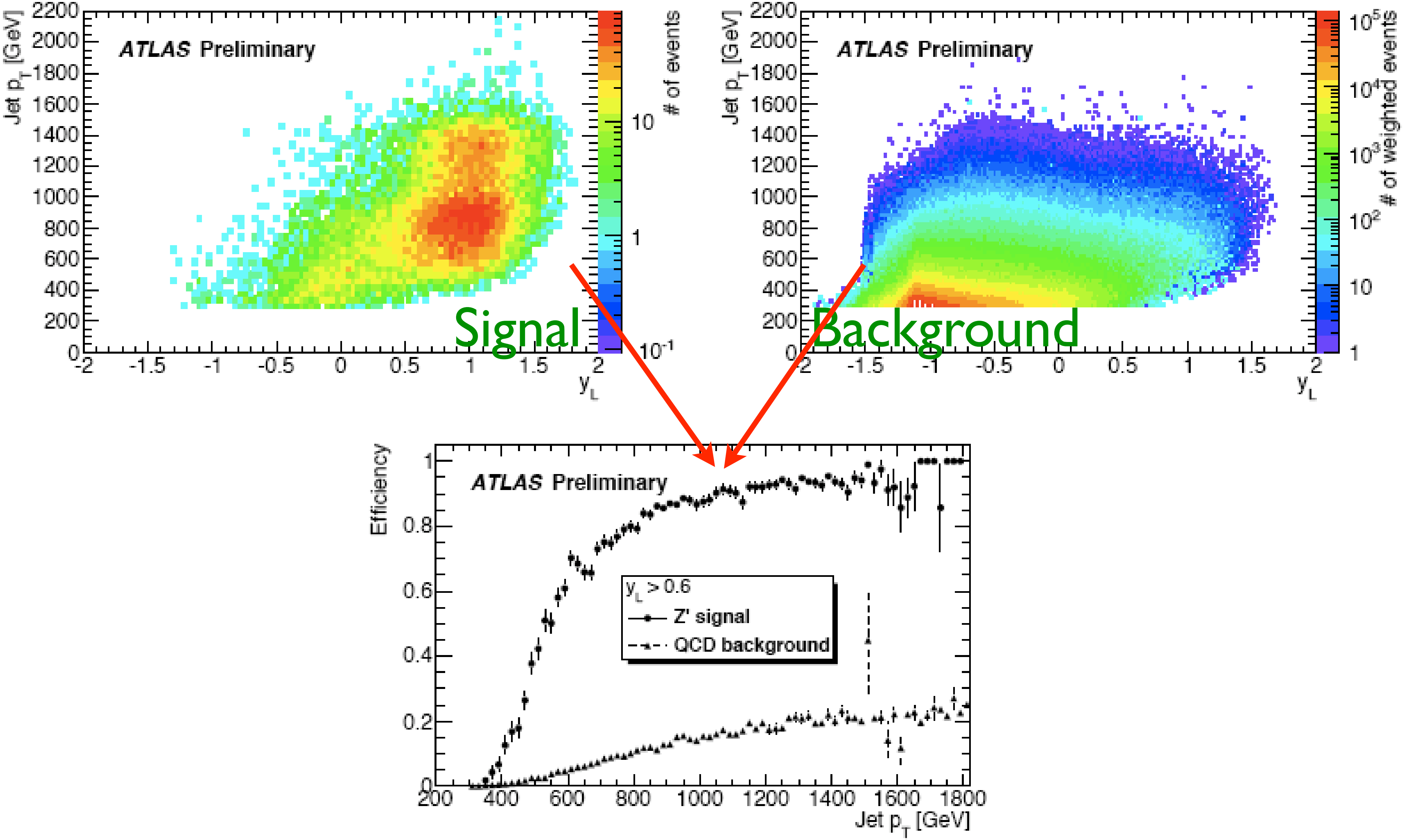
- Observations:
  - Variables show slow dependence on top (jet) p^T
  - Only weakly correlated



  - For light jets, all the variables drop off exponentially

➡ Combine into a likelihood

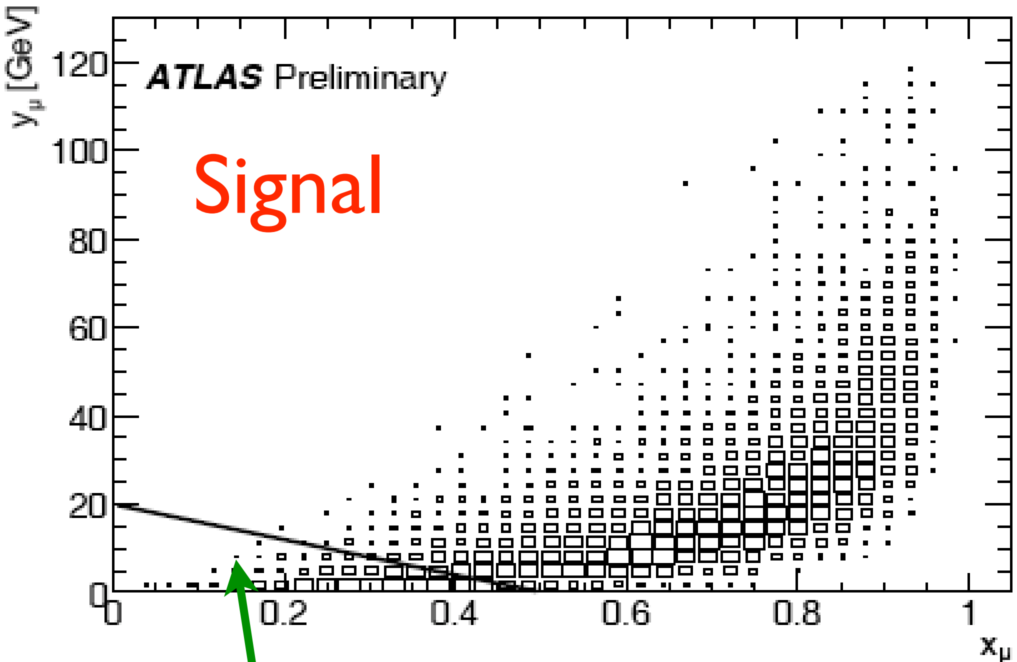
Hadronic Decays: Result

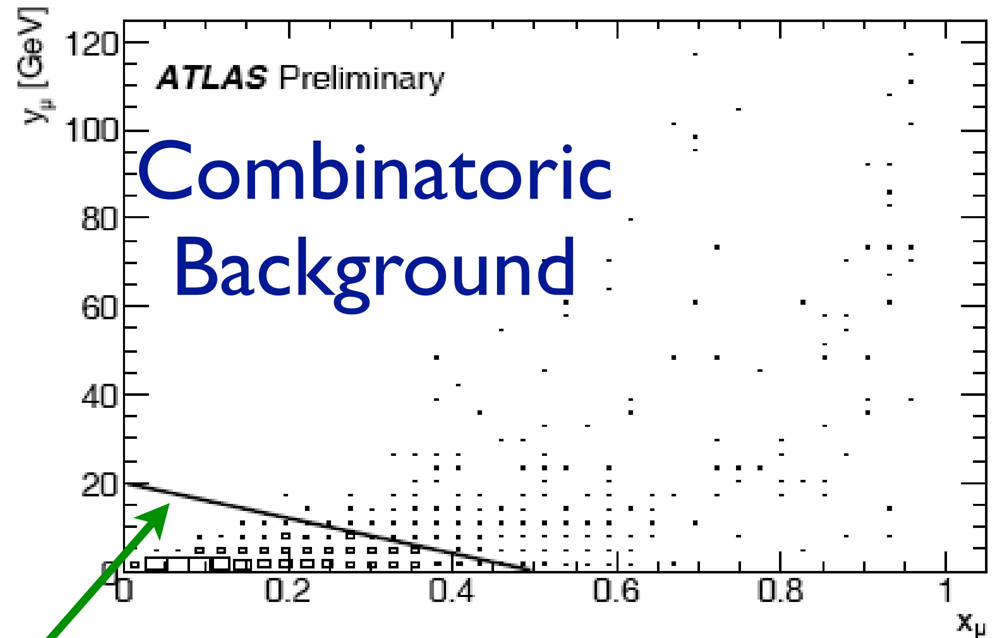


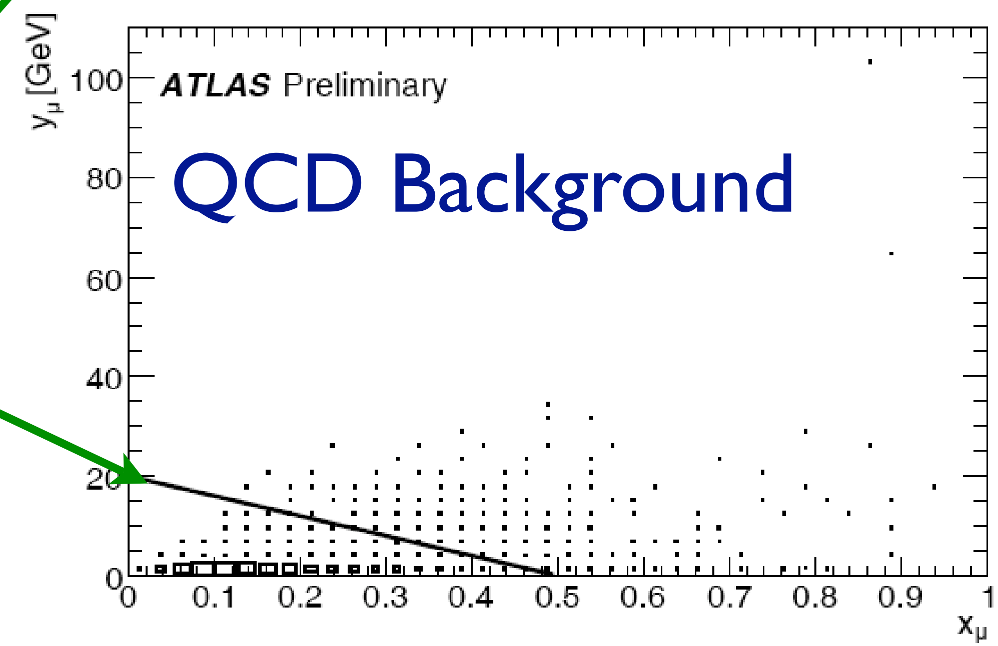
Semileptonic Decays: Muons

- Require a good muon, $p^T > 20$ GeV, $|\eta| < 2.5$, and a $p^T > 200$ GeV jet within ΔR=0.6 (call it "*b*-jet")
- Reduce "fakes" from b/c-decays (or other decays in flight):
  - Isolation not useful (signal muon close to *b* from top decay)
  - Two new variables (better than increase in muon p^T cut):
    - $x_\mu \equiv 1 - m_b^2/m_{visible}^2$ fraction of visible top mass carried by muon*
    - $y_\mu \equiv p_{\mu\perp b} \times \Delta R(\mu, b)$ relative p^T of muon wrt jet
    - (We do **not** use *b*-tagging: we assume the jet close to the lepton comes from a *b* quark so call it that)

*J. Thaler and L.-T. Wang, *JHEP* **07** (2008) 092, arXiv:0806.0023 [hep-ph].

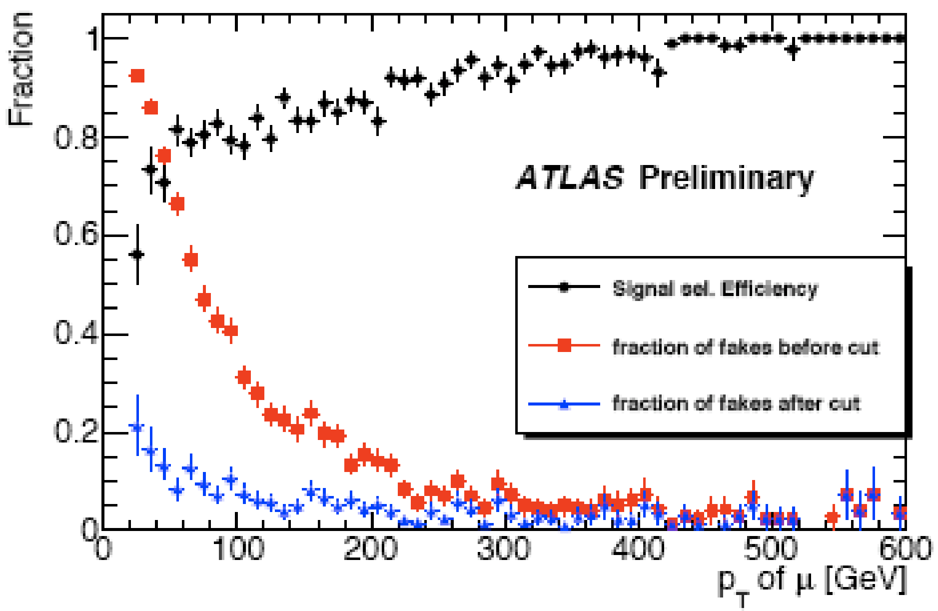


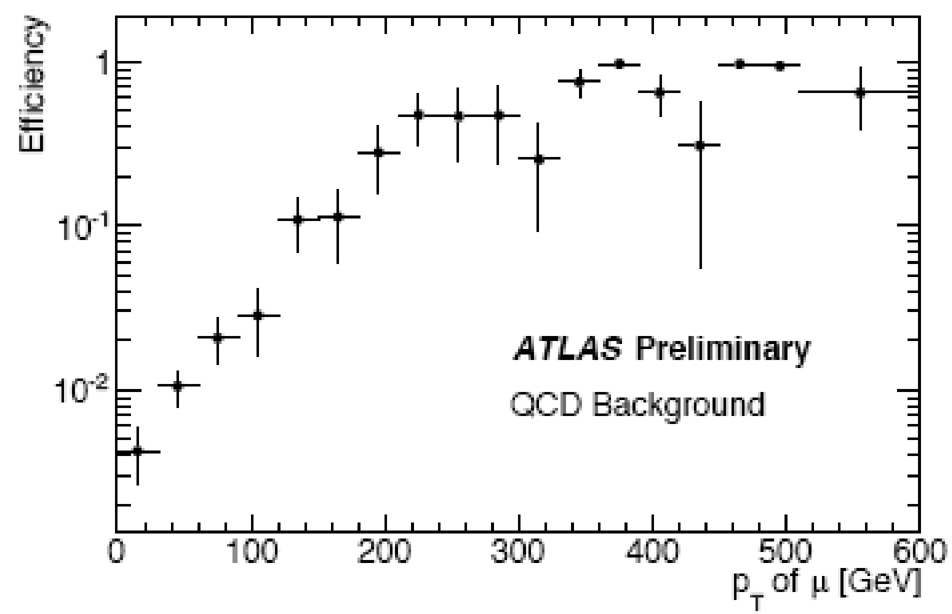




Apply a “diagonal” cut

- "Muonic top" efficiency after preselection (i.e. a good muon was found close to a high-p^T jet)
  - We find *a* muon in 88% of events where the W from top decay yielded a muon of 20 GeV p^T or more

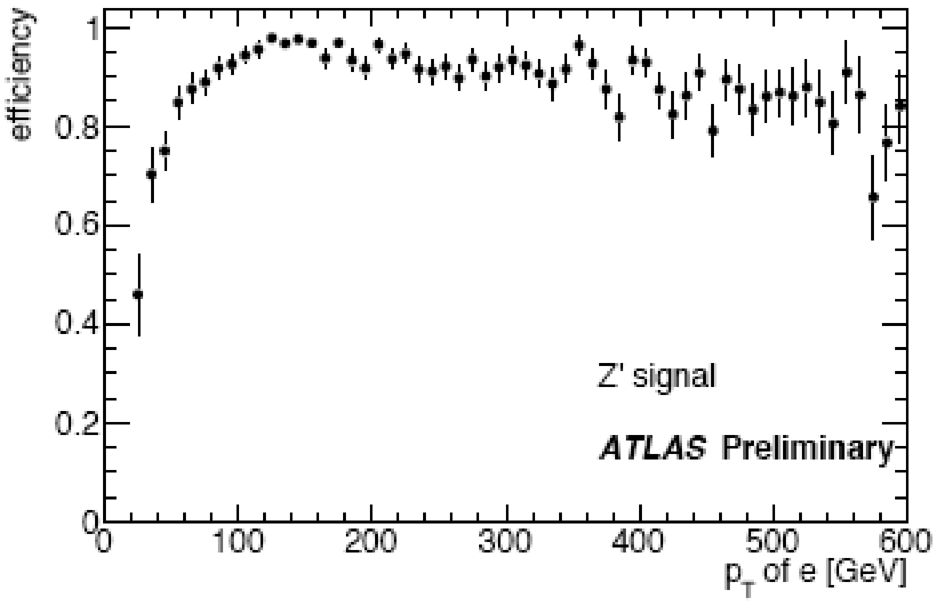


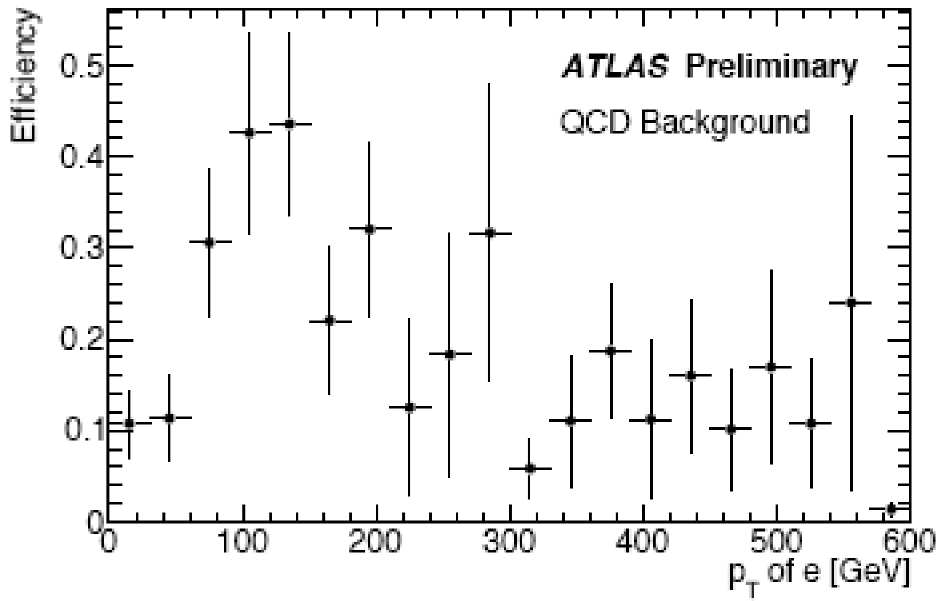


Semileptonic Decays: Electrons

- Trickier, since electron is embedded in the jet, but candidates can be reconstructed with good efficiency thanks to fine calorimeter granularity
  - 57% of events with top $\rightarrow$ e have a well-reconstructed electron
- So, require a good electron ($p^T > 20$ GeV, $|\eta| < 2.5$, excluding cracks), + $p^T > 300$ GeV jet within ΔR=0.6 (also require jet's first $k_\perp$ splitting scale > 10 GeV, i.e. electron component of jet)
  - Subtract the electron 4-momentum from the jet to obtain the "*b*-jet" and define x_e and y_e as in muon case
  - Also define $y'_e \equiv p_{e\perp j} \times \Delta R(e,j)$ (i.e. y_e but without subtracting electron 4-momentum from jet), require that $y'_e > 1$

- For electrons, combinatoric background not an issue
  - Harder to see electrons from *b* decays
- Efficiencies after preselection:



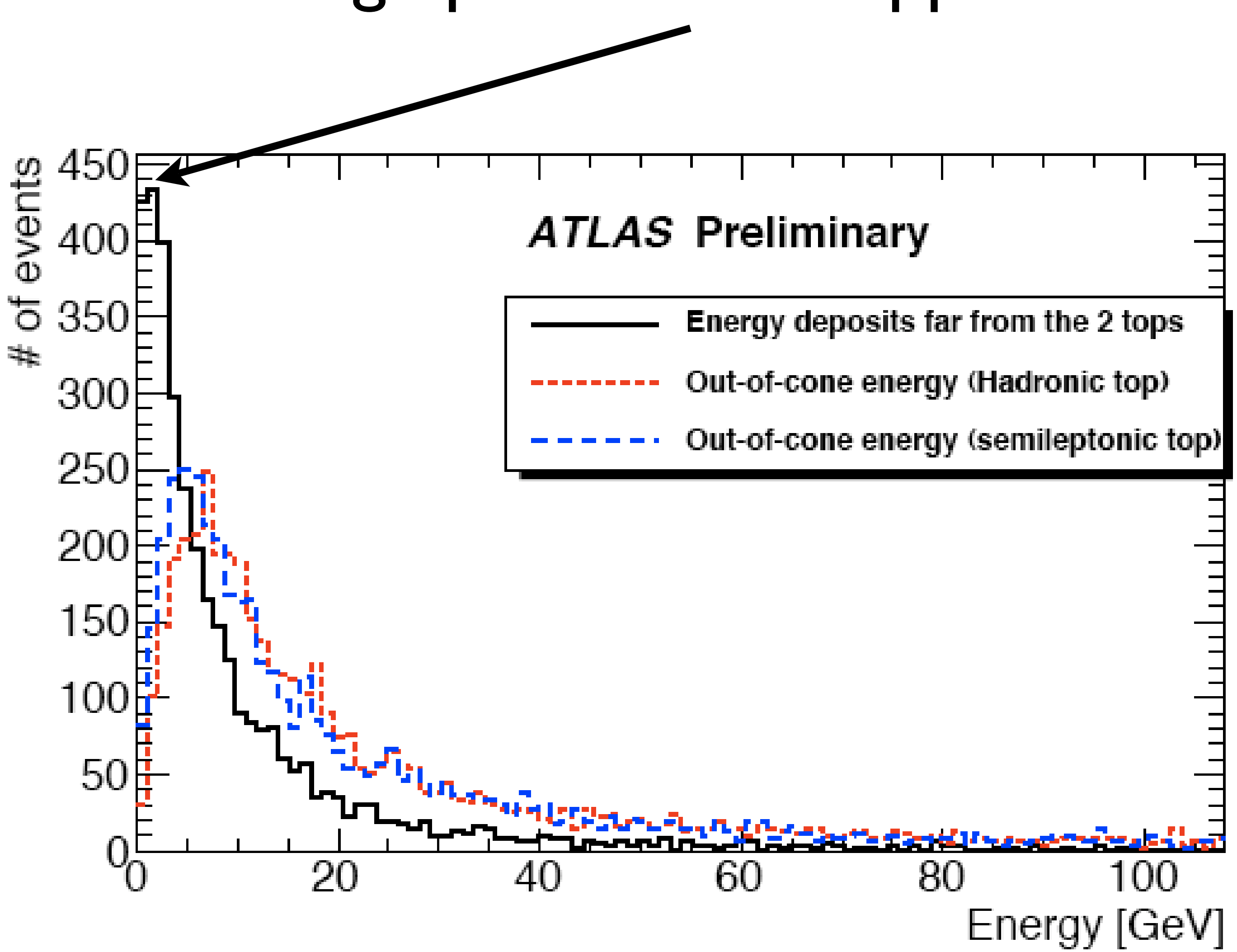


  - Of course, preselection has very large impact on multijet background!

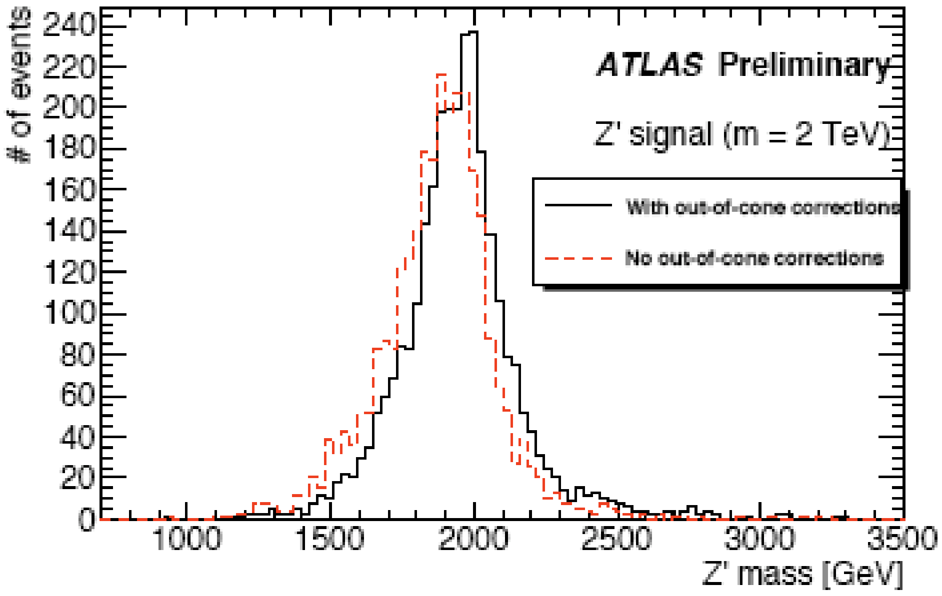
Z' Mass Reconstruction

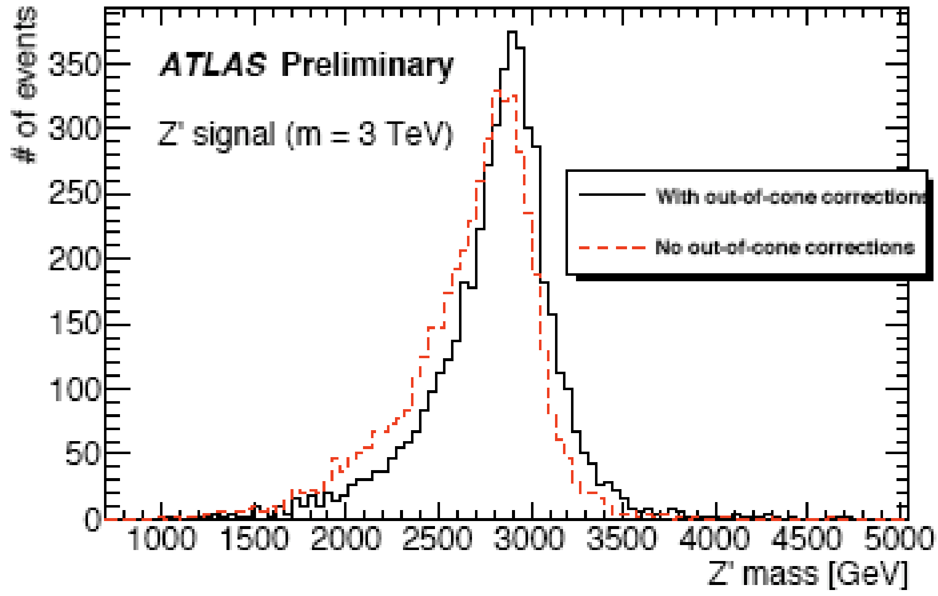
- W mass constraint to determine neutrino p_z (take smallest value, or real part of imaginary solution)
  - Require $\Delta R(\nu,\ell) < 1.0$
- Apply "local" out-of-cone energy correction:
  - Use cone 0.7 "topocluster" jets
  - Add topoclusters in $0.7 < R < 1.2$ to jet
  - Reasonable? Look for energy deposits (in a cone of radius 0.4) far away from top candidates
    - 30% of the time, no topoclusters, rest of the time, energy substantially lower than the local out-of-cone correction.

Large peak at 0 is suppressed



Z' Peaks

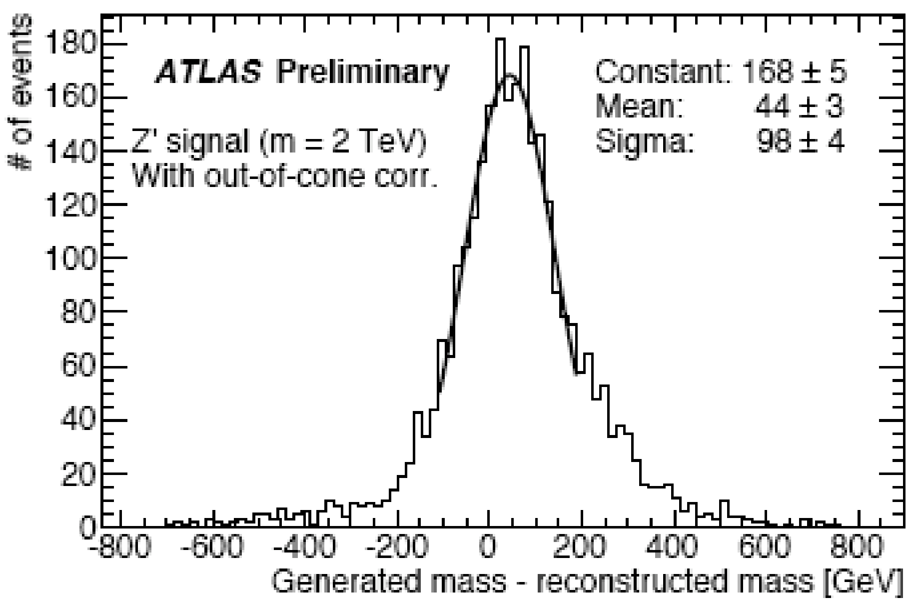


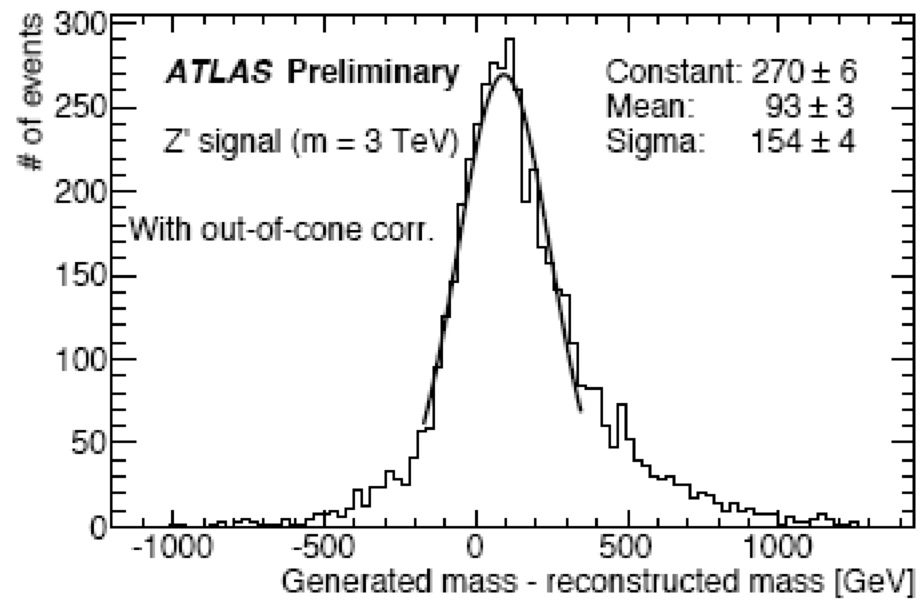


- Correction helps peak, but does not improve tails!
  - As expected if tails come from bad $p_z(\nu)$

Z’ Mass Resolution

- SSM Z’ at this mass narrower than detector/method resolution, but not negligibly so:

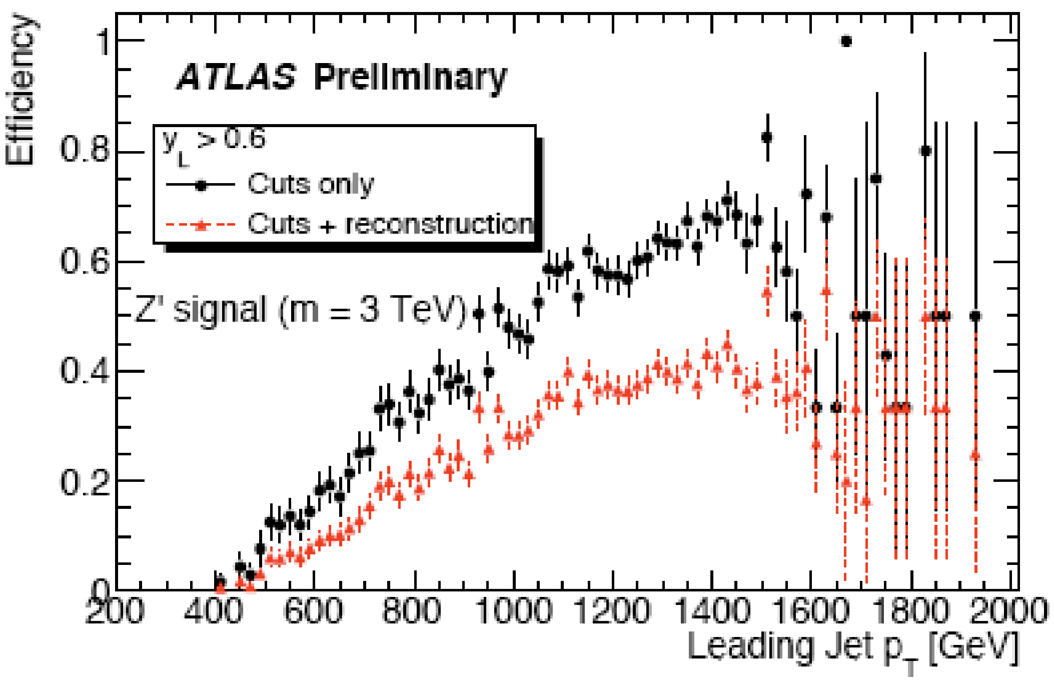


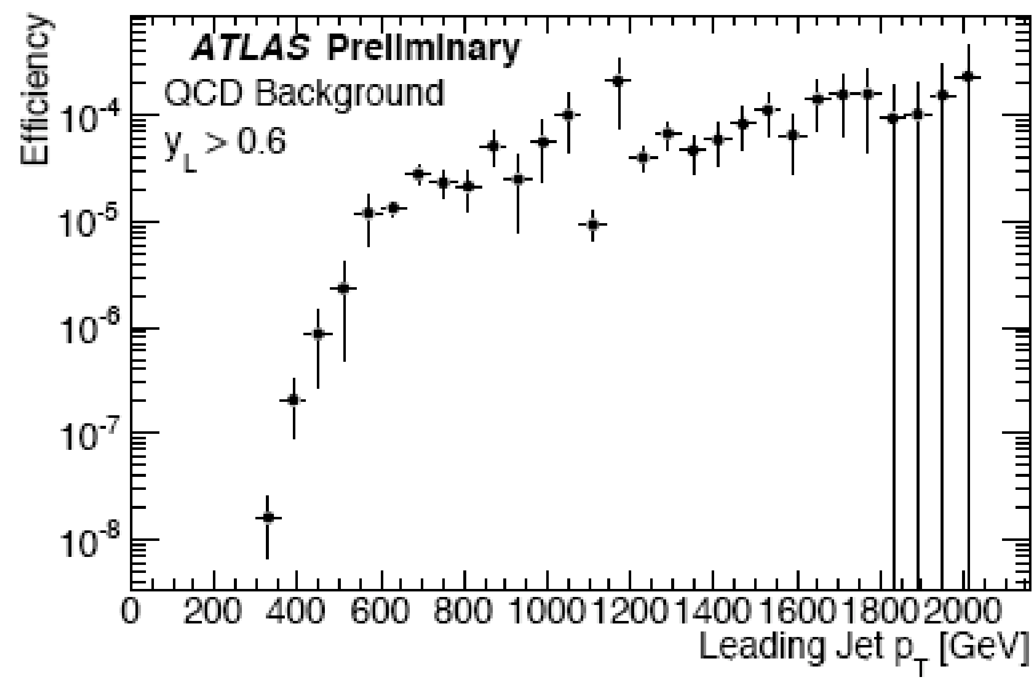


Also still have a substantial offset!

⇒ work to do!

Overall Selection Efficiency





- For multijet background, rate determined by factorizing leptonic and hadronic rejection
  - (Limited MC statistics)

Sensitivity

- Number of events in mass windows [1800,2100] ([2700,3100]) GeV for 2 (3) TeV Z'

Signal Efficiencies

	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
l+jets $Z' \to t\bar{t}$ (2 TeV)	0.094 ± 0.002	0.063 ± 0.002	0.016 ± 0.001
l+jets $Z' \to t\bar{t}$ (3 TeV)	0.136 ± 0.002	0.101 ± 0.002	0.034 ± 0.001

Backgrounds, 1 fb^{-1}

$m = 2$ TeV	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
QCD multijet (J5 + J6 + J7)	1.9 ± 0.5	0.7 ± 0.2	0.16 ± 0.04
SM $t\bar{t}$	$17.1 \pm 0.8 \pm 2.6$	$11.1 \pm 0.7 \pm 1.7$	$3.1 \pm 0.4 \pm 0.5$
Total	19 ± 2.8	11.8 ± 1.9	3.3 ± 0.6
$m = 3$ TeV	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
QCD multijet (J5 + J6 + J7)	0.5 ± 0.2	0.2 ± 0.1	0.07 ± 0.03
SM $t\bar{t}$	$2.3 \pm 0.1 \pm 0.3$	$1.4 \pm 0.1 \pm 0.2$	$0.52 \pm 0.07 \pm 0.08$
Total	2.8 ± 0.4	1.6 ± 0.2	0.6 ± 0.1

(W+jets shown to be much smaller than top)

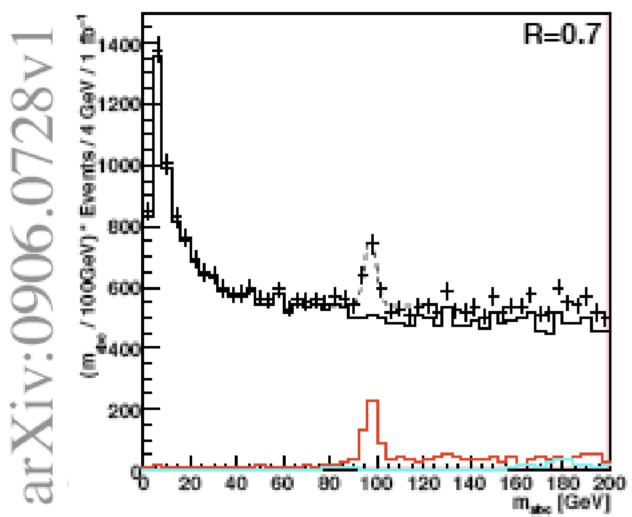
Limits

- Set limits for 1 fb^{-1} of data
  - 15% uncertainty on signal acceptance
  - 10% on luminosity
  - 15% on $t\bar{t}$ background
- 95% CL upper limits on signal cross-section using Bayesian technique

95% C.L. limits on σ x BR($t\bar{t}$) (fb)	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
$m = 2$ TeV	550	650	1400
$m = 3$ TeV	160	180	450

Observations

- For di-top resonances in ℓ+jets, after applying tools described, irreducible background is dominant (as for Z'$\rightarrow \ell\ell$!)
  - Mass resolution becomes key to improvement
- Variety of other techniques on the market
  - E.g. use of Cambridge-Aachen algorithm to search for hard "cores"
    - Tested on RPV SUSY
  - Jet "pruning" **arXiv:0903.5081**



Conclusions

- Measurement of final states with high p^T top quarks may be crucial to search for new physics
- Tested technique based on $k_\perp$ algorithm with promising results for di-top resonances
- Of course, many other scenarios (W'→tb, $T_H \rightarrow tA_H$, ...), and for those more sophisticated techniques may be necessary
  - And ... "transition region"!
- Lots of very interesting work to do!