Using Jet Substructure with ATLAS

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On Behalf of ATLAS Collaboration

Outline

- Physics motivation for investigating jet substructure?
- Quick introduction to substructure jet algorithms
  (more from Michael Spannowsky & Steve Ellis later today)
- ATLAS Results
  - Top
  - SUSY
  - Higgs
- Summary & Outlook

New Physics @ LHC

- Many physics models predict TeV-scale resonances.
  - If decay products are high p_T isolated leptons our challenge is simplified. $Z' \rightarrow \ell\ell$
- Several of these resonances preferentially decay to hadronic final states.
  - Example: RS with all particles in the bulk $\Rightarrow$ $g_{KK} \rightarrow t_R \bar{t}_L$
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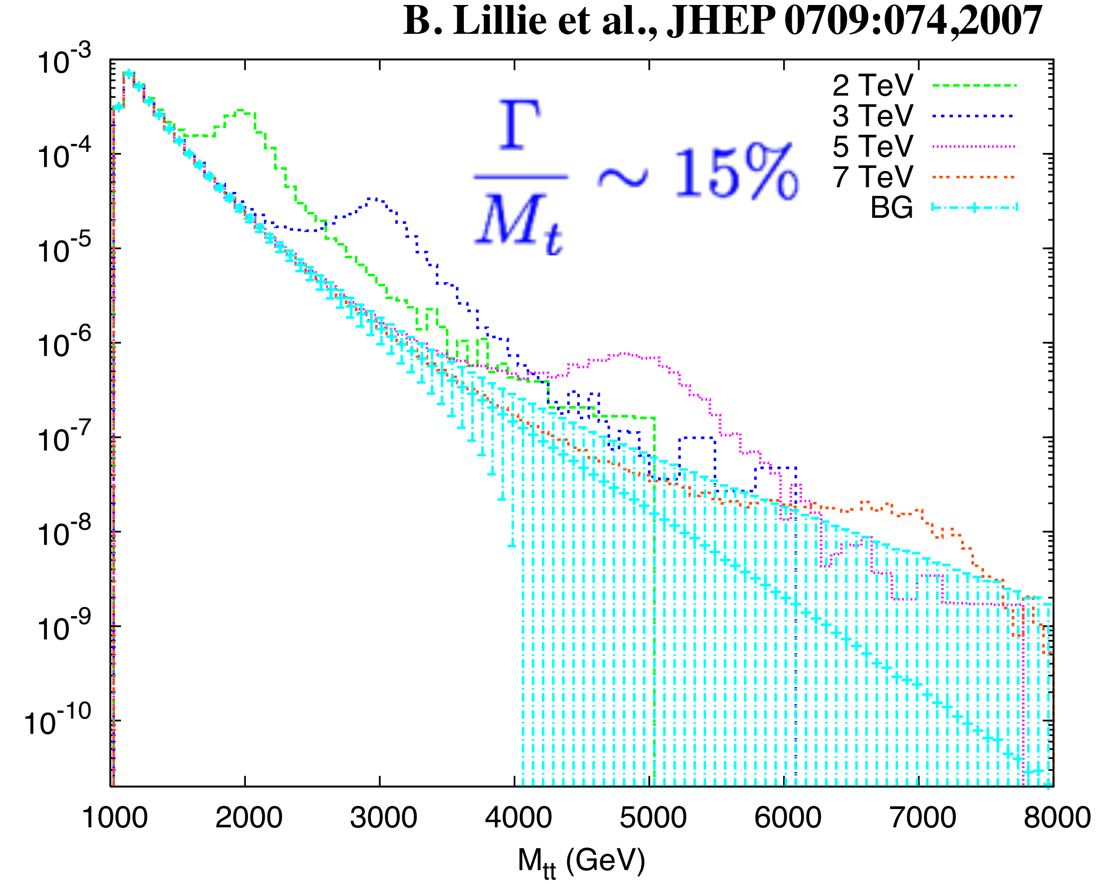
- Top quarks are highly boosted as are its daughter particles (t → Wb)
  - Leptonic W decay ⇒ lepton falls within b-jet
  - Hadronic W decay ⇒ ΔR(q,b) & ΔR(q,q') < R_{cone}

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



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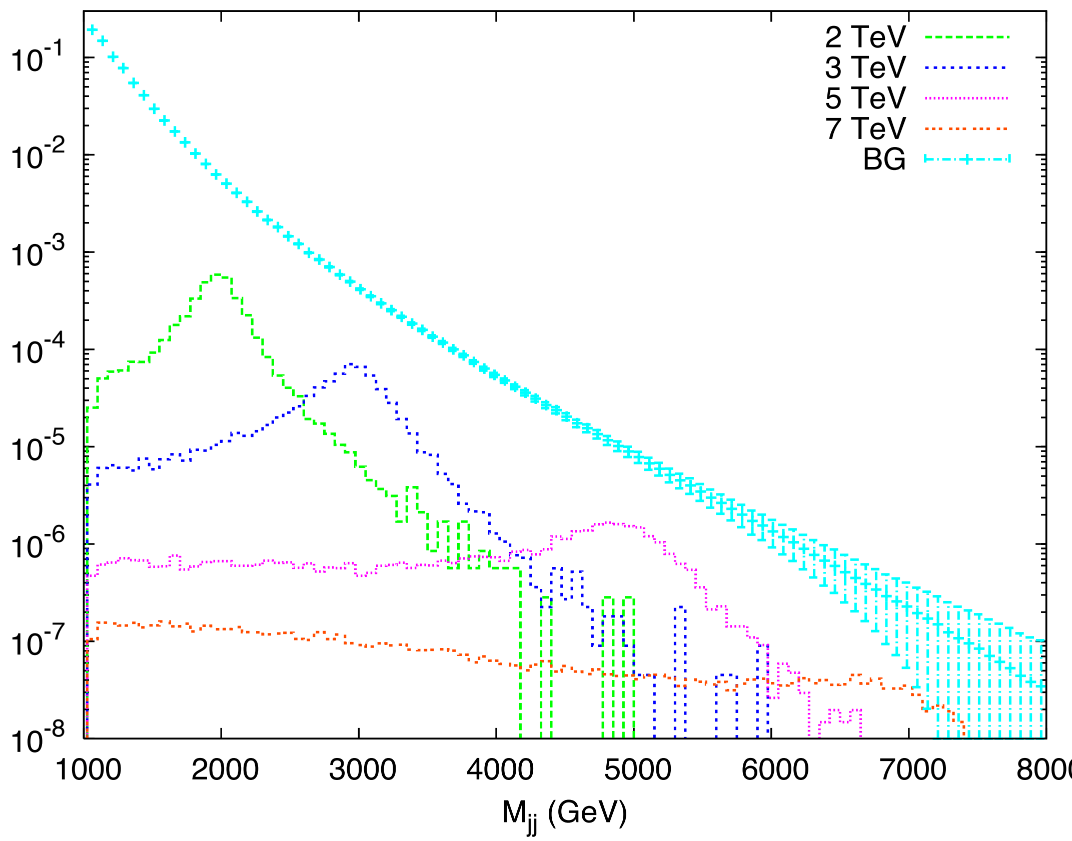

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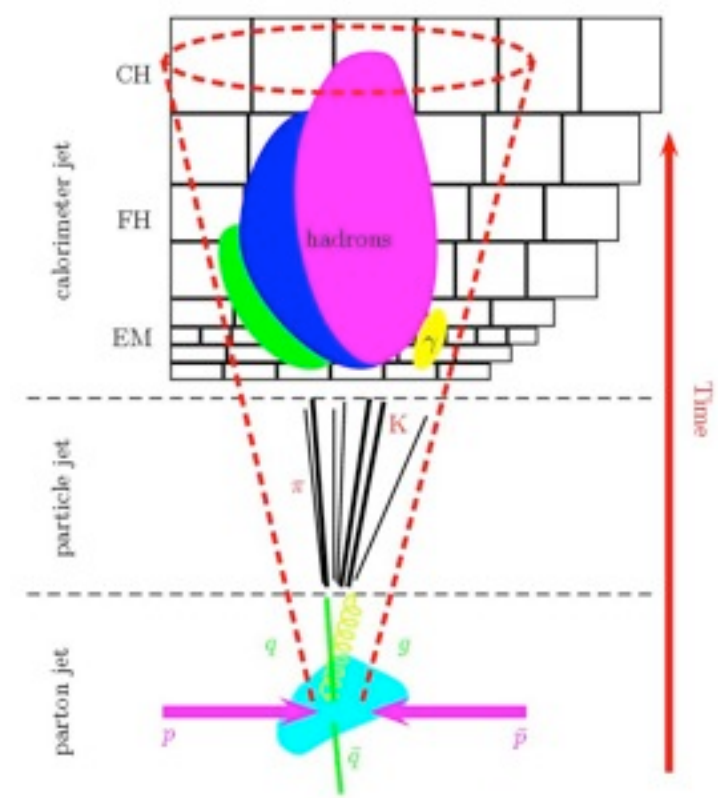
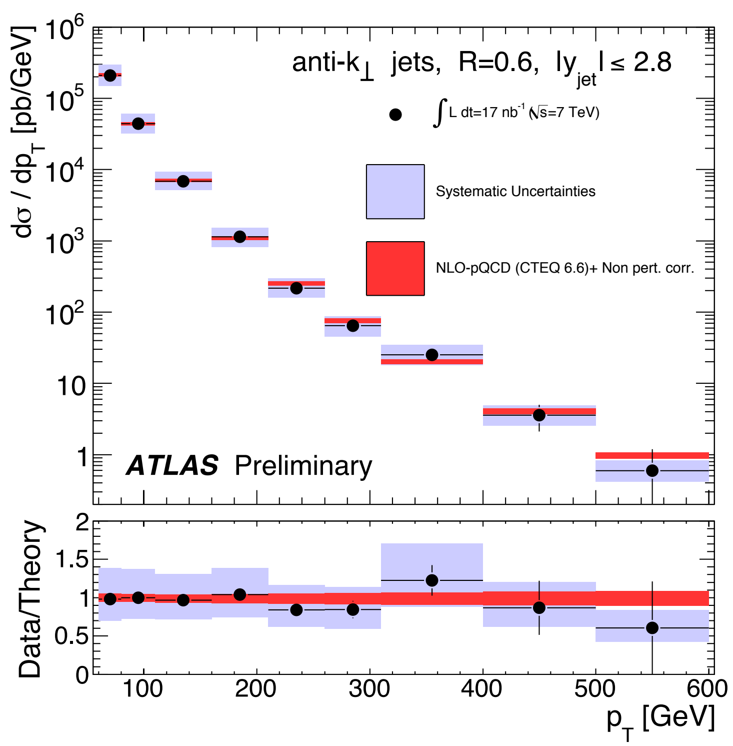
- Resonances are very wide
- Top quarks are highly boosted as are its daughter particles ($t \to Wb$)
  - Leptonic W decay ⇒ lepton falls within b-jet
  - Hadronic W decay ⇒ $\Delta R(q,b)$ & $\Delta R(q,q') < R_{cone}$
- $t\bar{t}$ signal starts to look a lot like QCD multijet background.

Hadronic Final State Analysis

- Analysis of events with hadronic final state.
  - Cluster calorimeter energy with a cone called a jet and correct jet energy back to parton/particle-level.



- Can now ask about p_T, y, etc...



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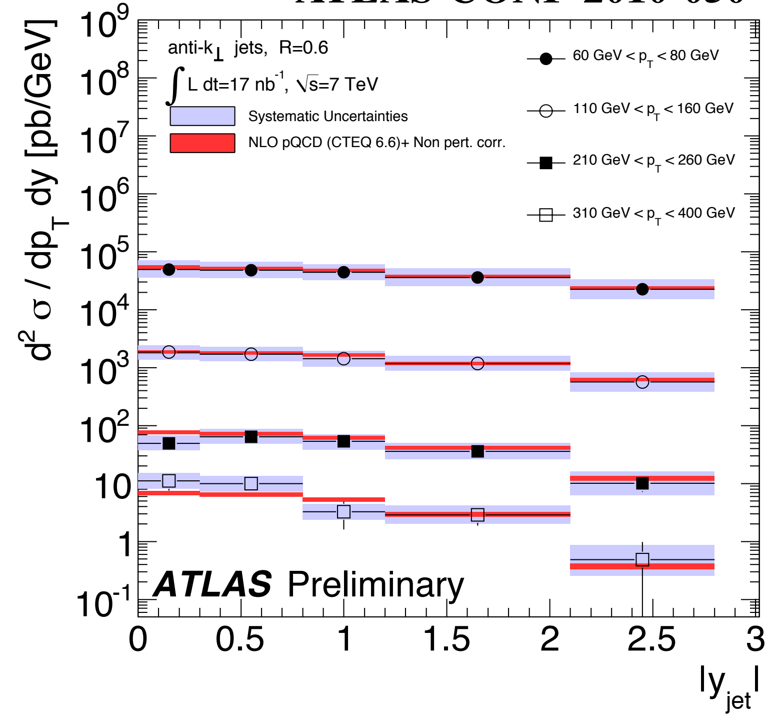


- Unfortunately p_T won't help us with $g_{KK} \to t_R \bar{t}_L$.

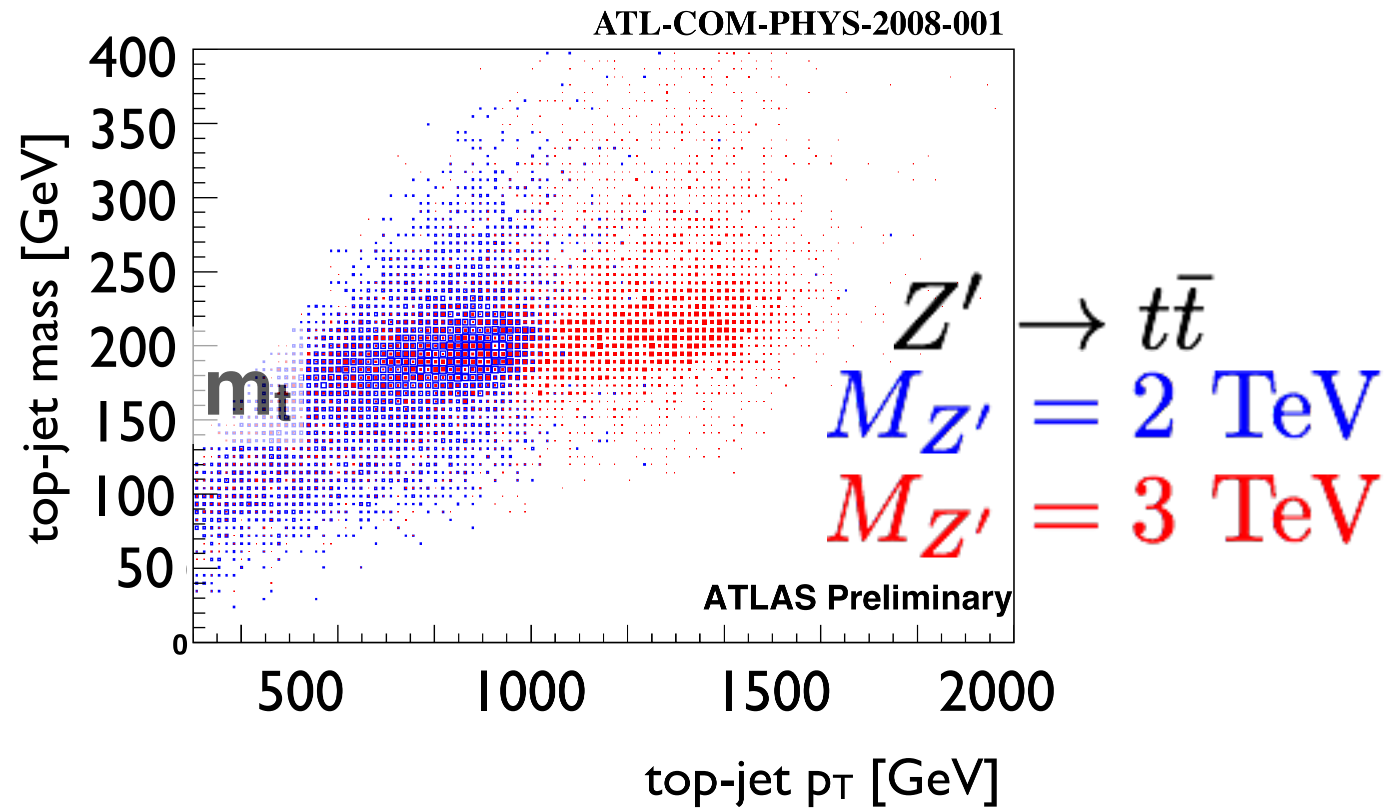
$$\sigma_{jj}(\ p_T > 500\ \text{GeV}\ ) \gg \sigma_{g_{KK}\to t\bar{t}}(\ p_T > 500\ \text{GeV}\ )$$

Moving Beyond Jet P_T

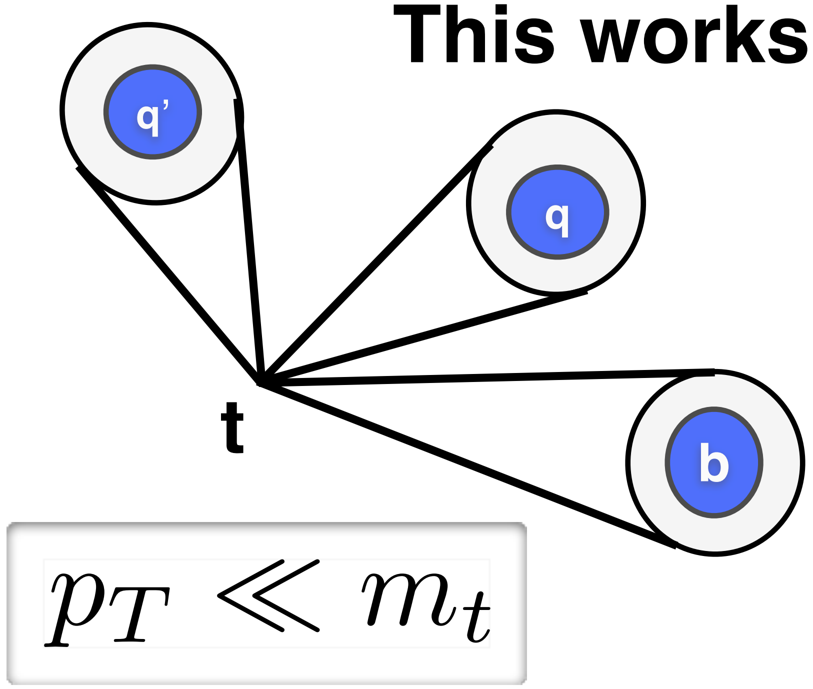
- What about the jet mass since top is much heavier compared to other hadrons?
  - Does M_{jet} equal M_{top}?

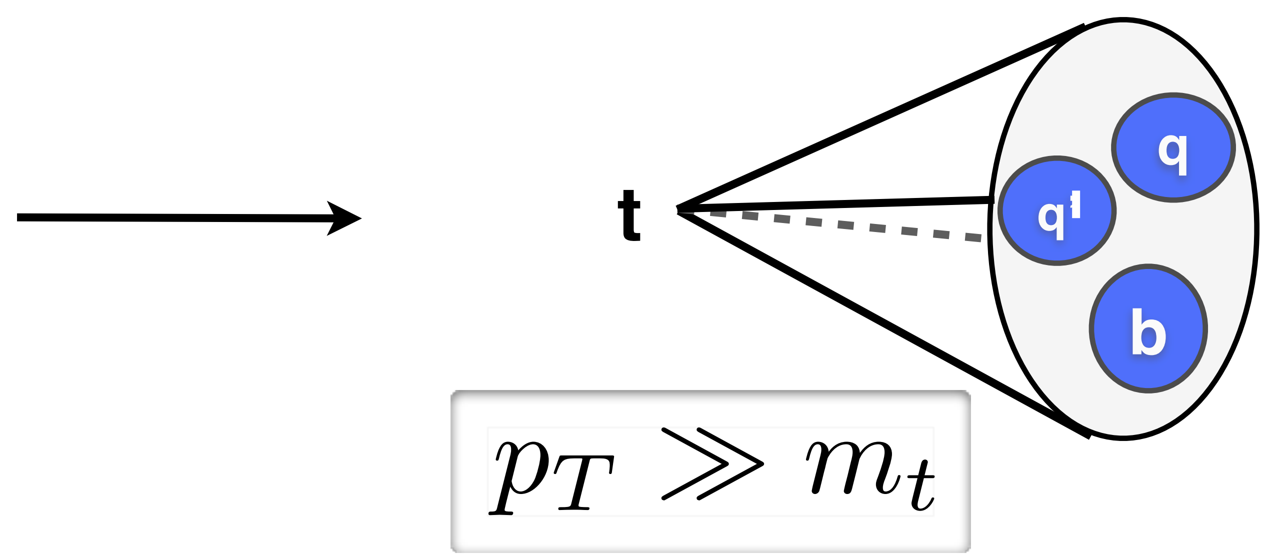
$$M_j = \sqrt{\sum_i E_i - \sum_i \vec{p_i}}$$

- Jet mass seems to be a good discriminator of top-jets and light-jets once the top-jet p_T > 500 GeV.



This works only works for highly boosted jets

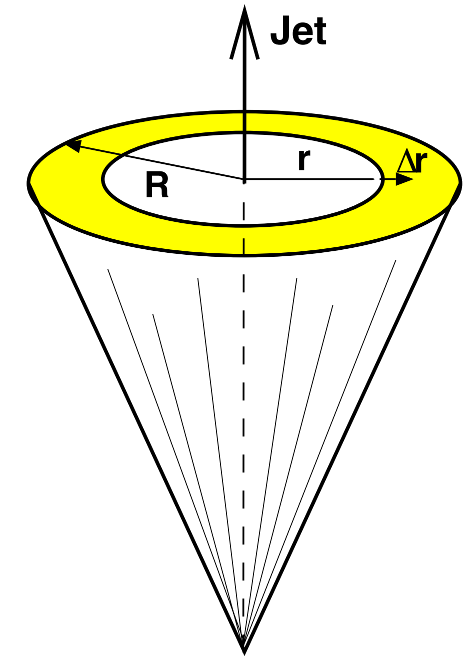




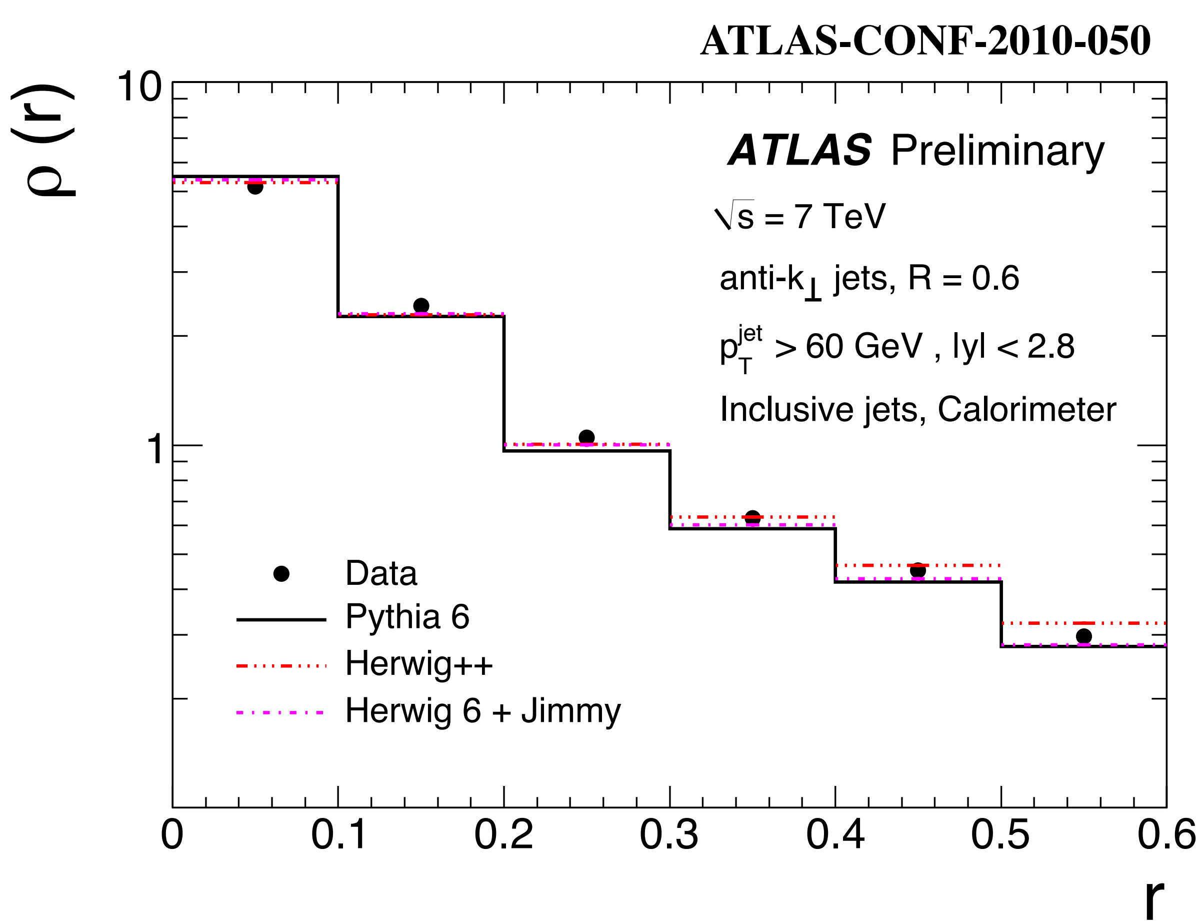
Moving Beyond Jet Mass

- A related quantity is the jet size (width) defined as

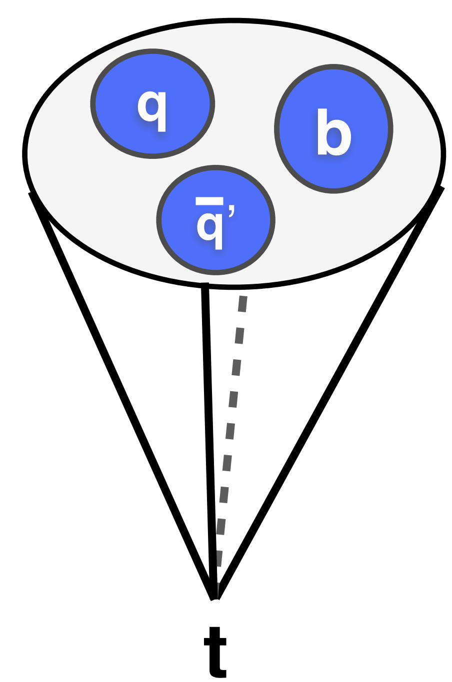
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N}\sum_{jets}^{N}\frac{p_T(r-\frac{\Delta r}{2}, r+\frac{\Delta r}{2})}{p_T(0,R)} \quad , \; 0 < r < R$$



- Expect highly boosted objects to be more collimated (narrow).

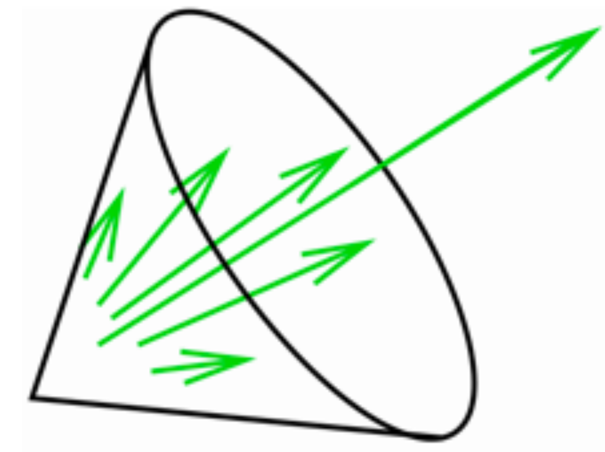


- Still these quantities based on entire jet (all constituents)
- What if jet actually has two or more "hard" constituents?
  - Will show up in mass and ρ, but resolution will be poor.

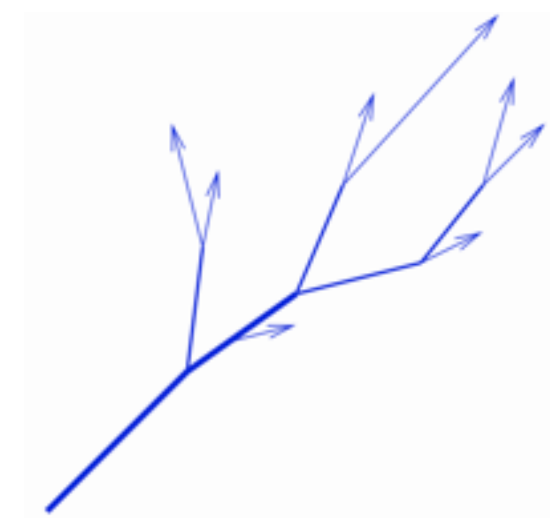


Looking For Jet Substructure

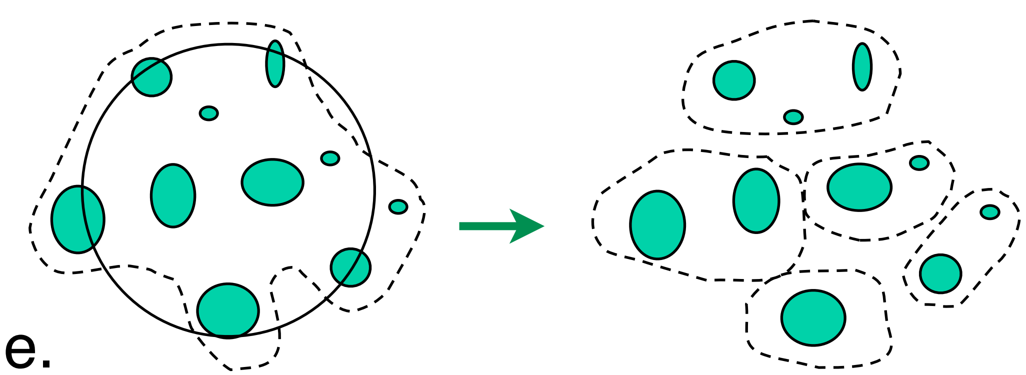
- Using cone-jets we lose information about the clusters that make up the jet.
  - Look for sum of energy above threshold in η-ϕ space.



- Another method is to combine clusters based on on their energy, p_T, or angle with respect to other clusters.
  - Also keep record of cluster ordering.



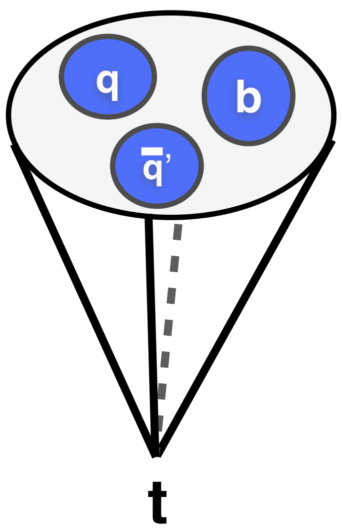
- k_T / CA (Cambridge-Aachen) Algorithms:
  - k_T merges clusters in order of smallest relative momentum until cutoff reached.
  - CA merges clusters in order of smallest relative angle until all mergers are separated by cutoff angle.

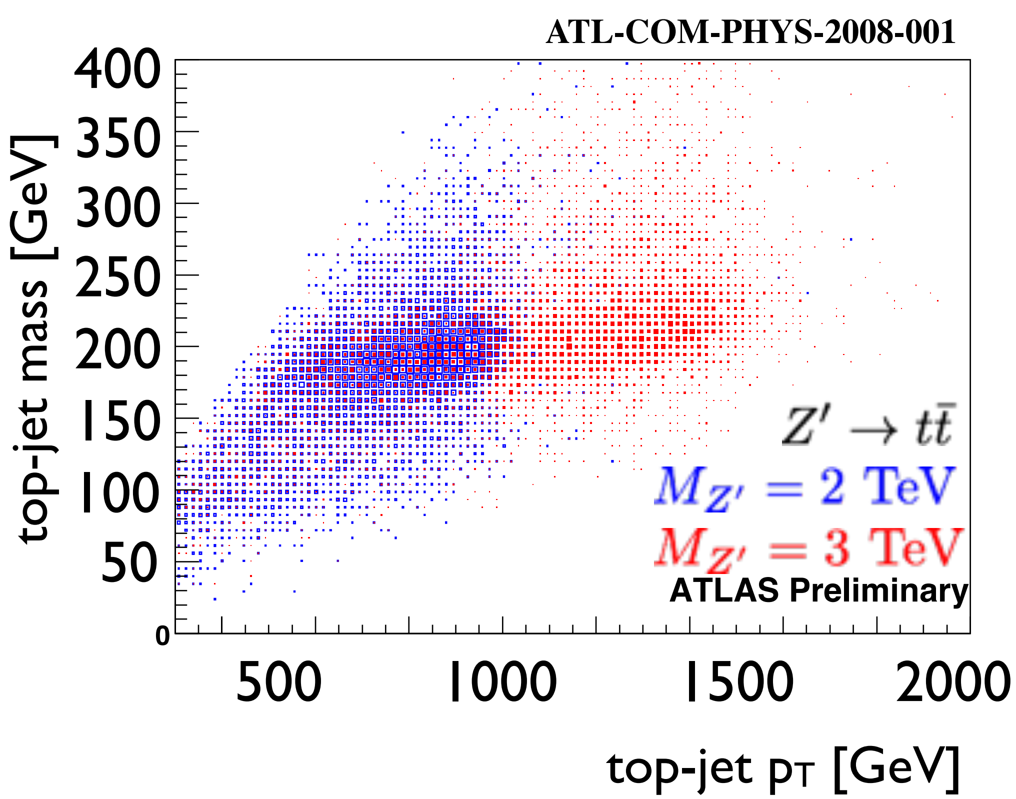


Ordering Scales For Top Decay

- Use k_T / CA ordering to unwrap the jet

- If looking at entire jet, still expect bump in jet-mass distribution.





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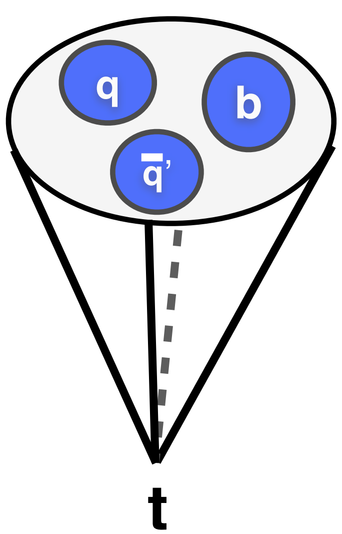
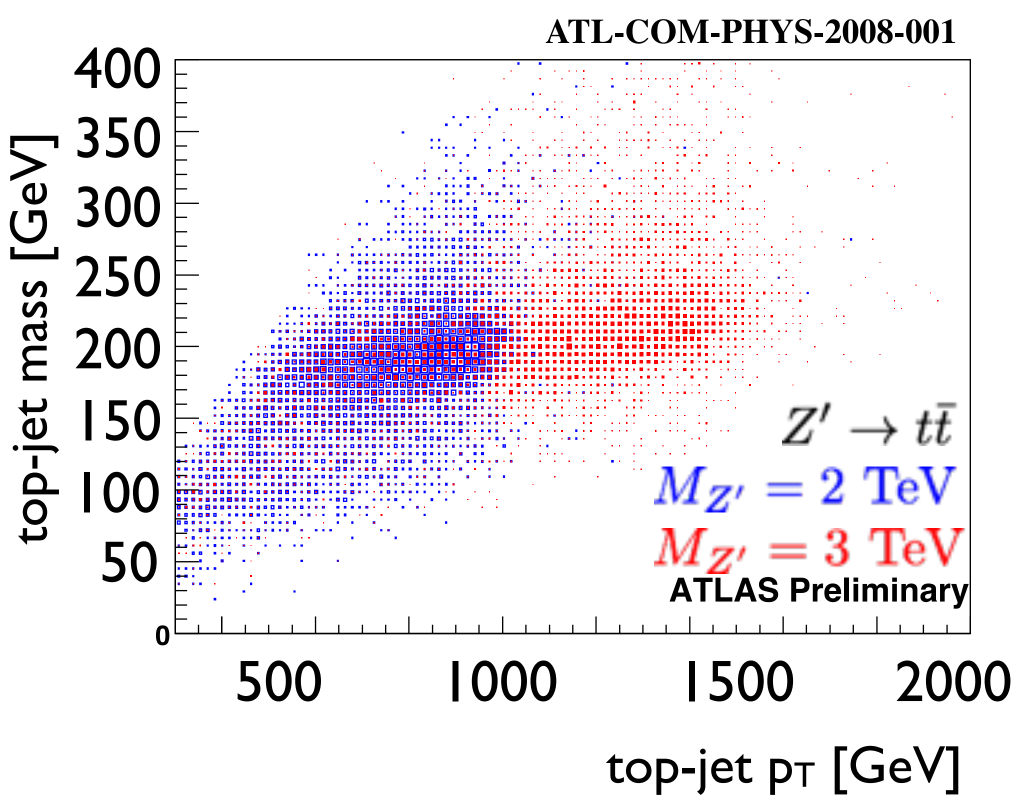
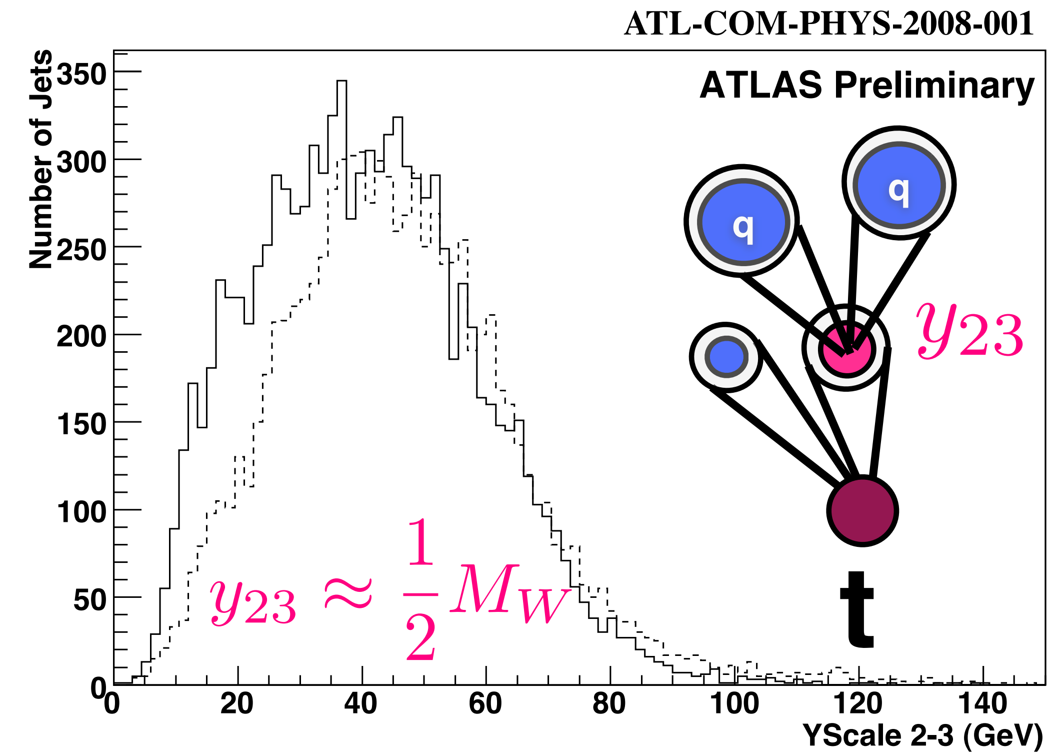
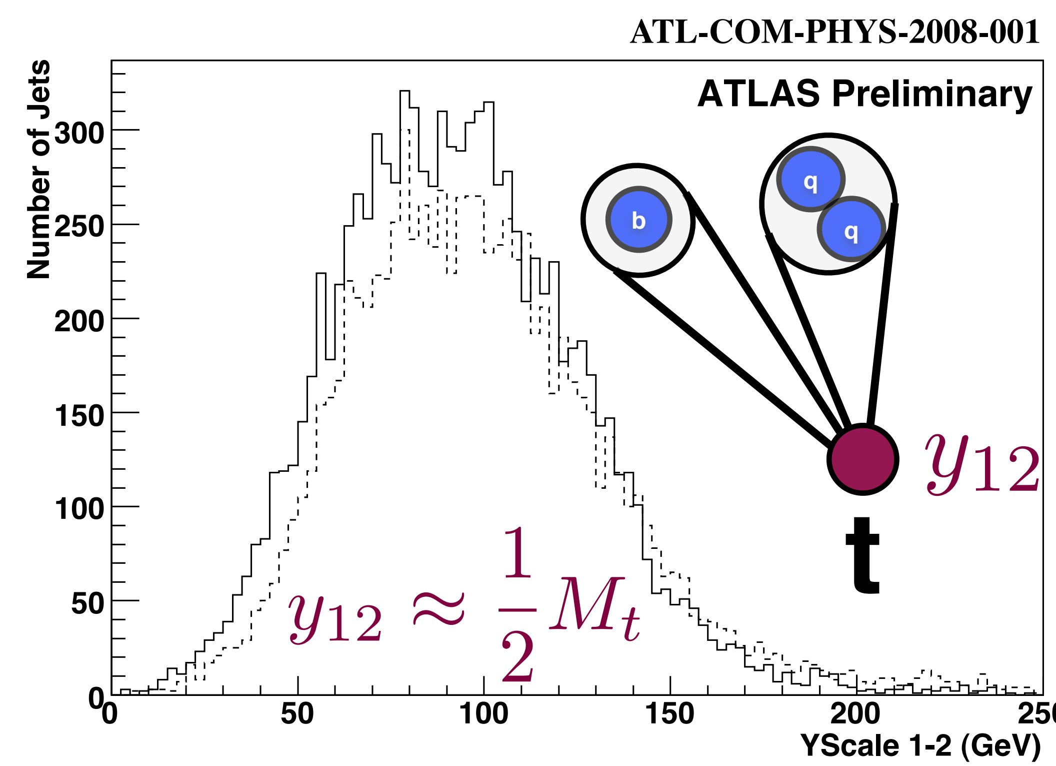




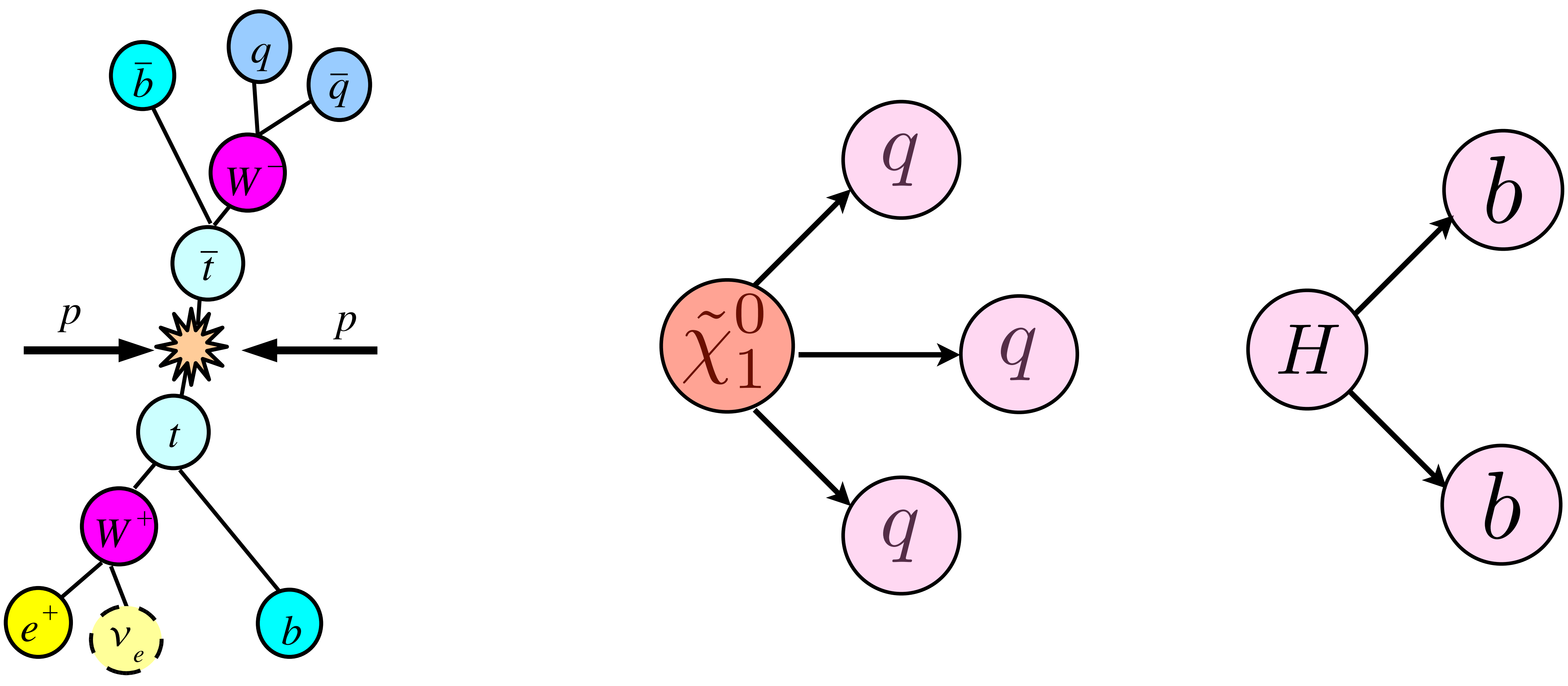
- If we look at k_T splitting scales, we also see the 2nd-to-last splitting (y_{23}: W → qq) and last splitting (y_{12}: t → Wb)





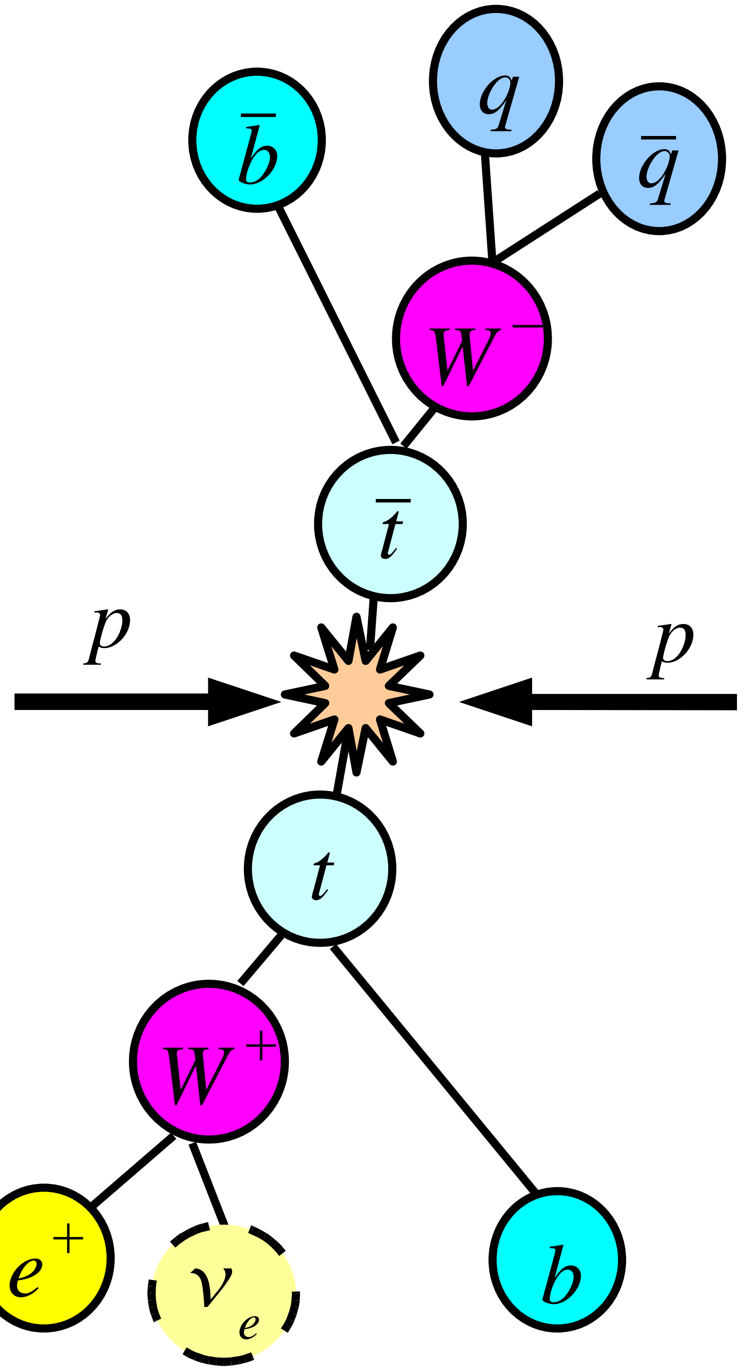
ATLAS applies this technique in the following analyses

(a) (b) (c)



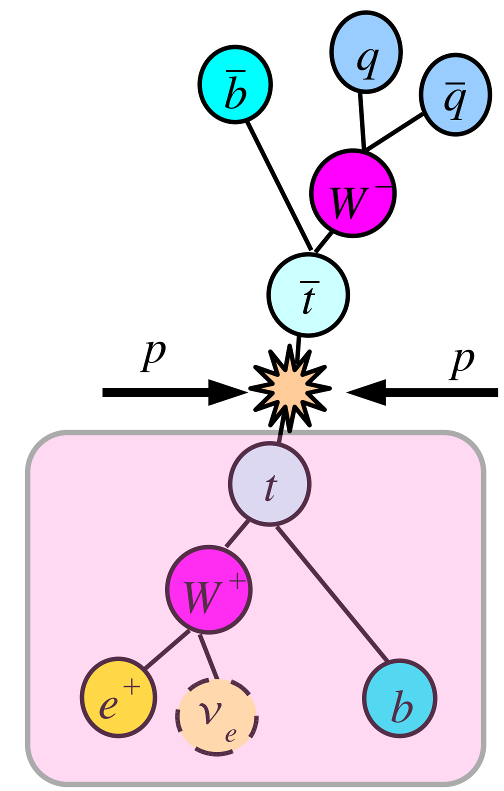
$t\bar{t}$ Resonance

- As seen earlier top pairs may be produced through g_{KK} or other intermediary resonances.
- One possibility is $pp \to Z' \to t\bar{t}$.
  - Narrow spin-1 resonance (color singlet).
- If M(Z′) > 1 TeV then tops are highly boosted.
  - As before, standard reconstruction fails.
- Study semileptonic $t\bar{t}$ (lepton+jets) decay channel.
  - Mix of branching ratio and combinatorics.
- Much of analysis inspired by work of *Thaler & Wang [JHEP 07 (2008) 092]*



Leptonic Top-Jet Selection

- Require electron or muon with $p_T > 20$ GeV
  - Muon require track match and $|\eta| < 2.5$ and electrons require *medium* shower shape and $|\eta| < 2.5$ excluding crack region.



- Require jet with pT > 200(300) for muon(electron) events and $\Delta R(\ell,\ \mathrm{jet}) < 0.6$
  - Call nearest jet the b-jet from top decay.

- Define visible mass fraction for leptonic top decay & lepton momentum w.r.t nearest jet.

$$x_\ell \equiv 1 - \frac{m_b}{m_{b+\ell}}$$

$$y_\ell \equiv p_{\ell\perp b} \times \Delta R(\ell, b)$$

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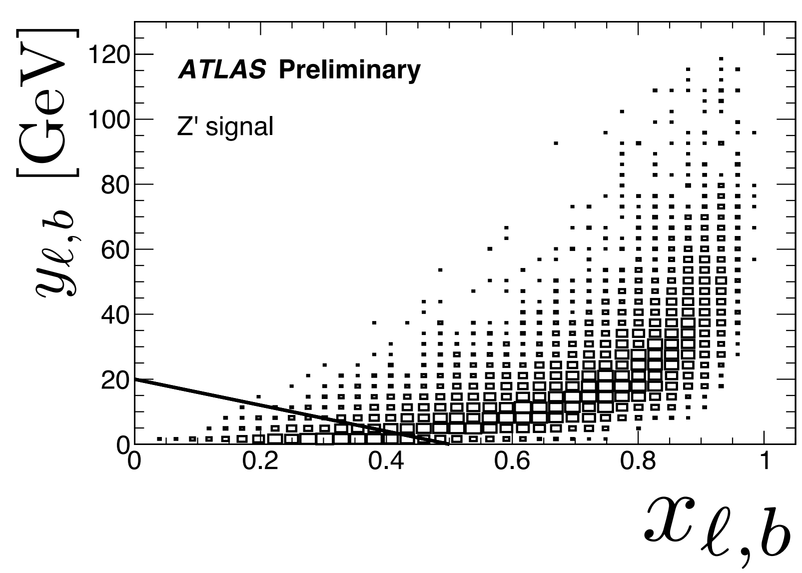
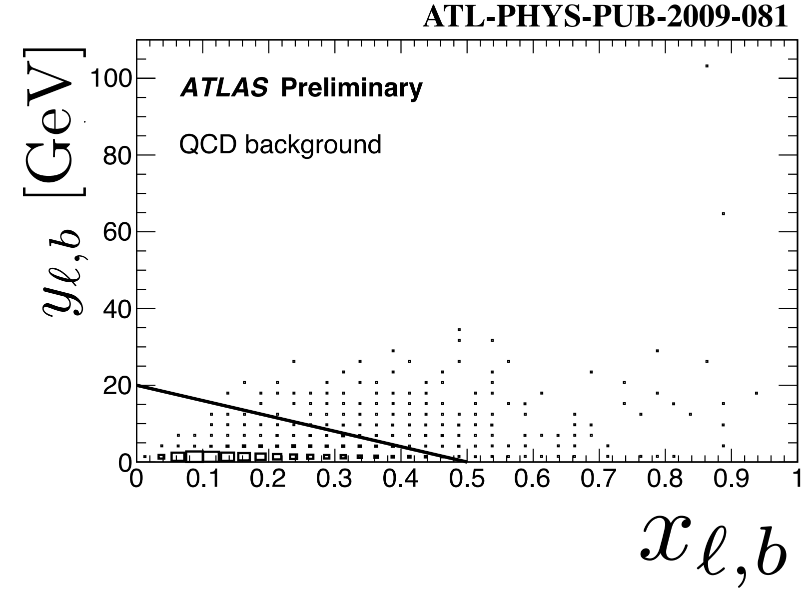
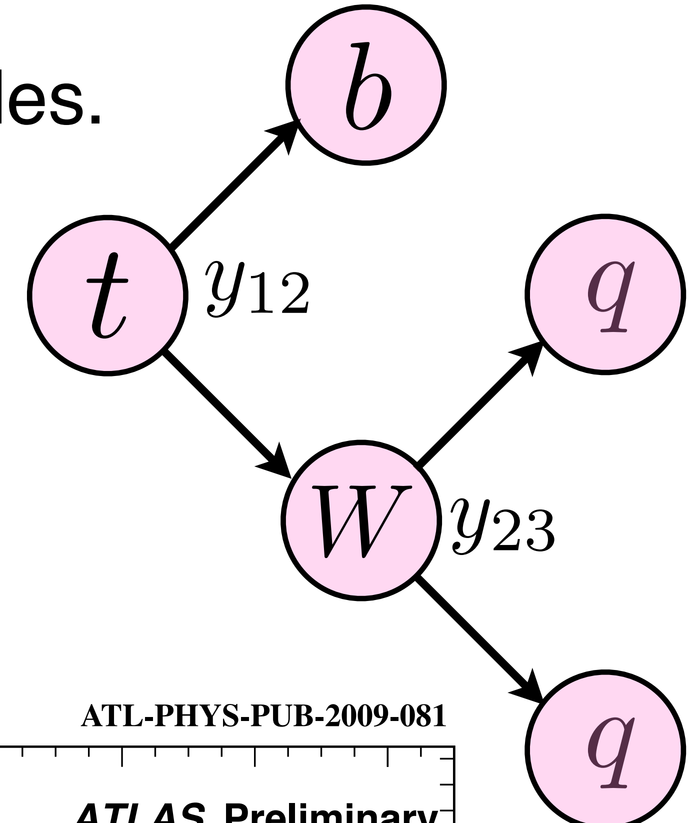




- Make triangle cut to remove much of combinatoric and QCD background.

Hadronic Top-Jet Selection

- Require top-jet with p_T > (200)300 GeV ⇒ collimated decay
- "Unfold" jet clustering. Use last three k_T splitting scales.
  - y_{12} should represent t → Wb decay
  - y_{23} should represent W → qq decay
  - y_{34} should represent hardest hadronic fragmentation.



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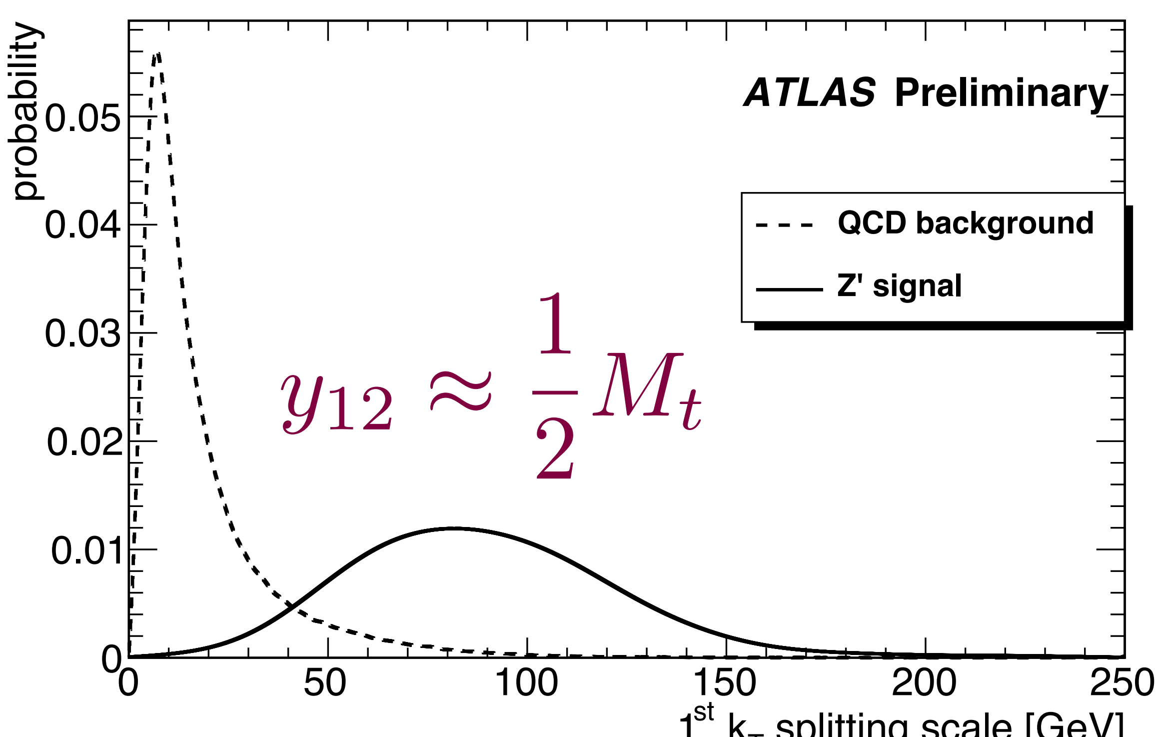
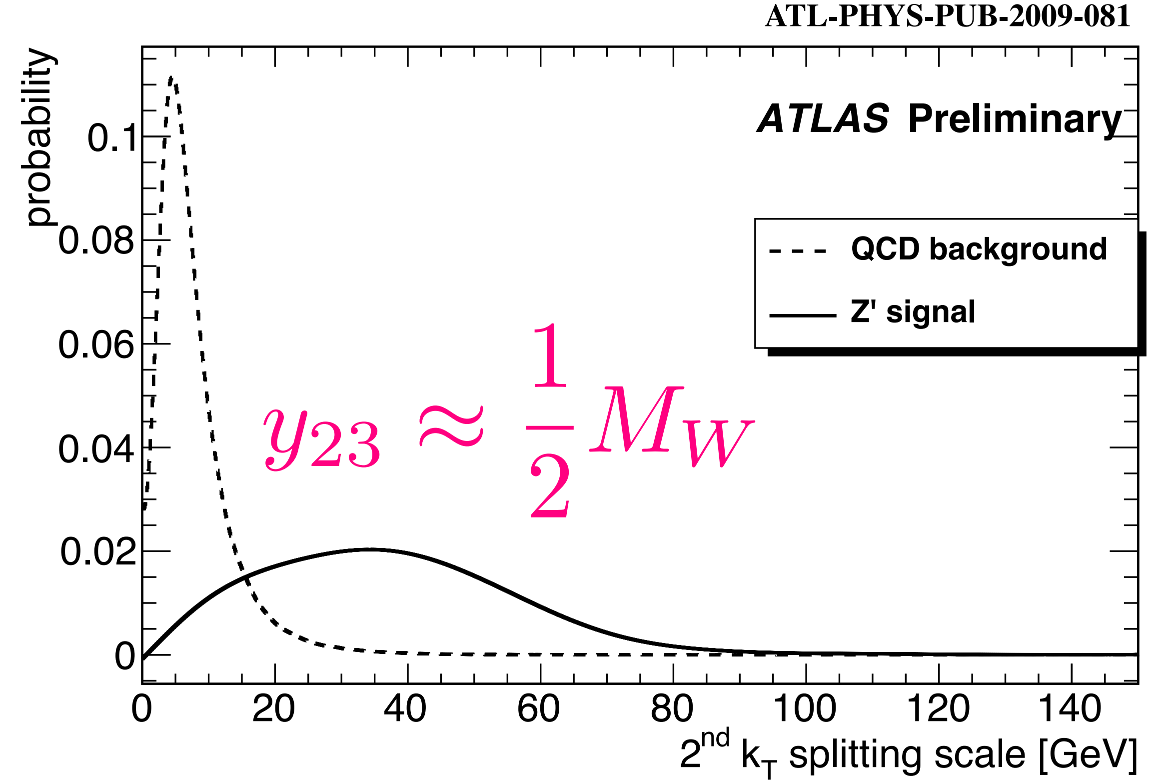


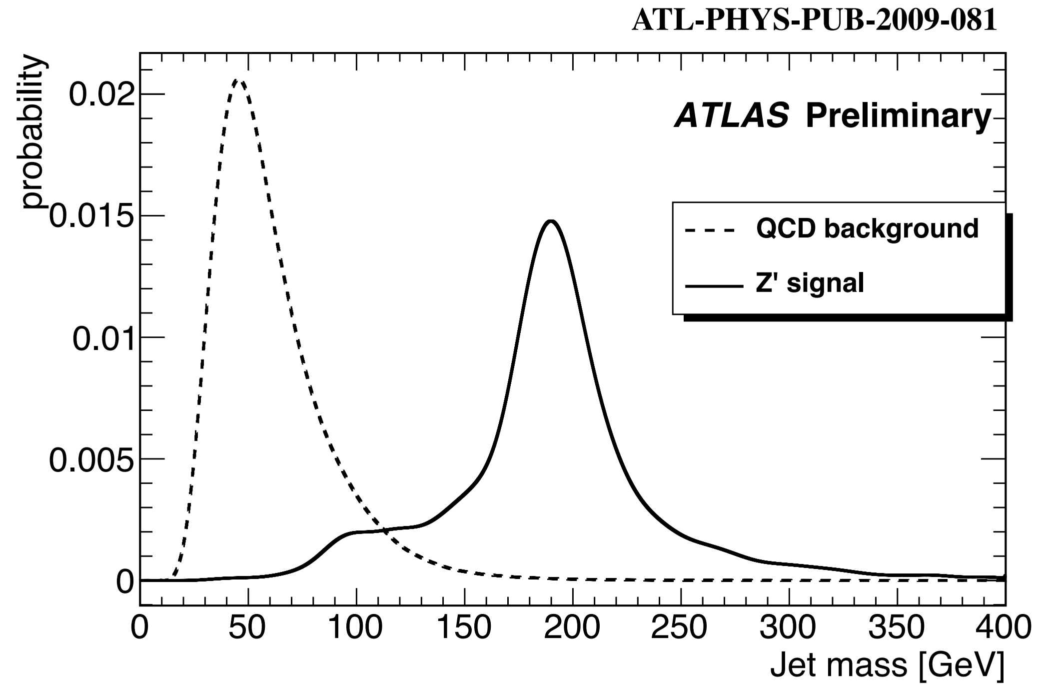


Isolating Z′ → $t\bar{t}$ Signal

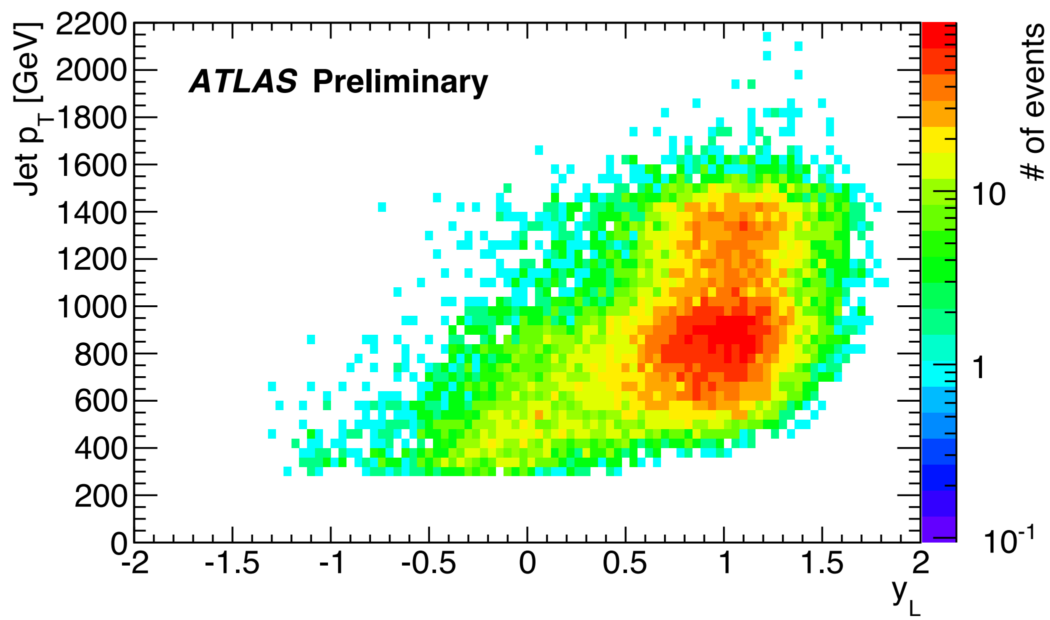
- Construct likelihood to distinguish signal from background.
  - Create PDFs for y_{12}, y_{23}, y_{34}, and jet mass

$$L_{S(B)}(i) = \prod_{k=1}^{n_{var}} p_{S(B),k}(x_k(i))$$

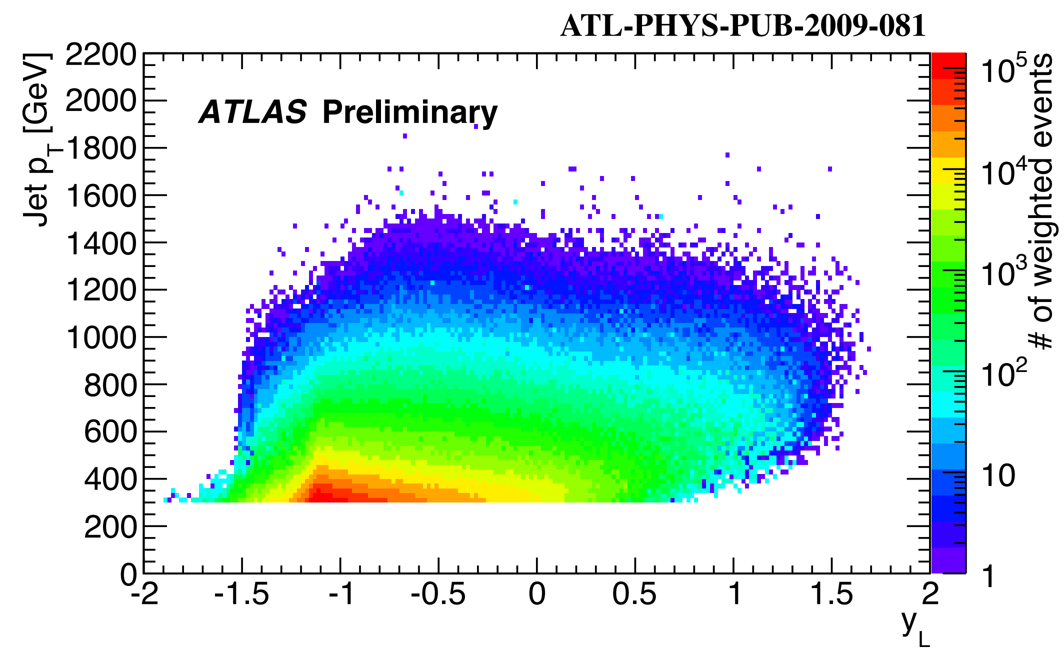
$$y_L(i) = \frac{\ln\left(L_S(i)/L_B(i)\right)}{15}$$



- Likelihood for signal and QCD background.



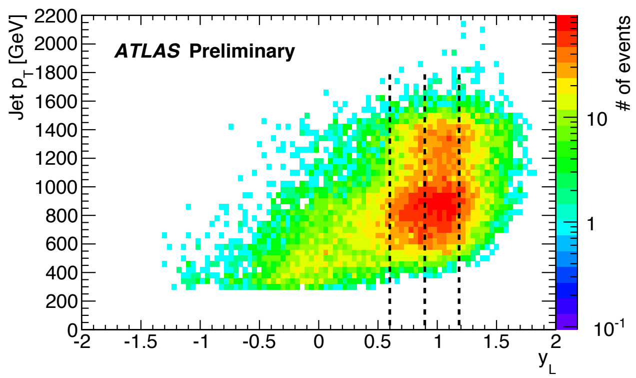
Signal



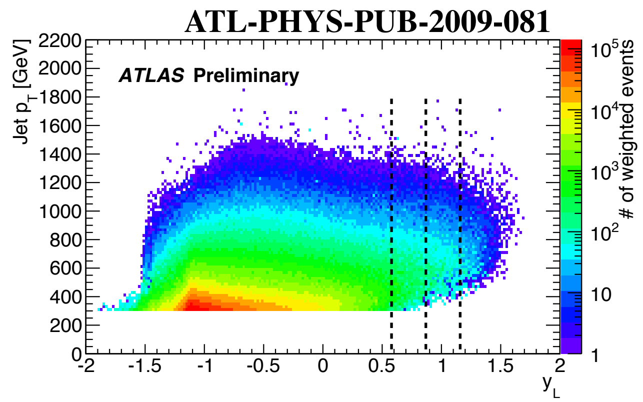
Background

Results For Z′ → $t\bar{t}$

- Results presented for cuts on the likelihood output.
  - Cut @ $y_L > 0.6, 0.9, 1.2$



Signal



Background

$m = 2$ TeV	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
QCD multijet	1.9 ± 0.5	0.7 ± 0.2	0.16 ± 0.04
SM $t\bar{t}$	$21.9 \pm 1.0 \pm 3.9$	$14.2 \pm 0.9 \pm 2.6$	$4.0 \pm 0.5 \pm 0.7$
Total	23.8 ± 4.1	14.9 ± 2.8	4.2 ± 0.9
$m = 3$ TeV	$y_L > 0.6$	$y_L > 0.9$	$y_L > 1.2$
QCD multijet	0.5 ± 0.2	0.2 ± 0.1	0.07 ± 0.03
SM $t\bar{t}$	$2.9 \pm 0.1 \pm 0.5$	$1.8 \pm 0.1 \pm 0.3$	$0.7 \pm 0.1 \pm 0.1$
Total	3.4 ± 0.6	2.0 ± 0.3	0.8 ± 0.2

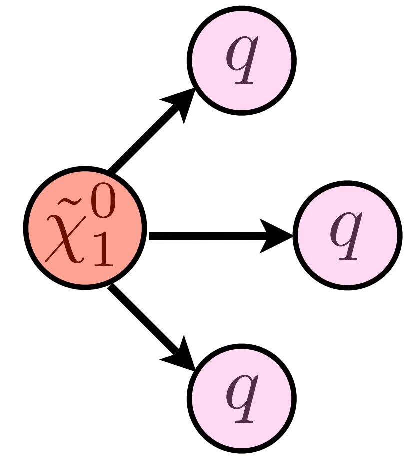
- 95% confidence level limits for 3 cuts on likelihood (σ x BR(Z′→tt)).

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

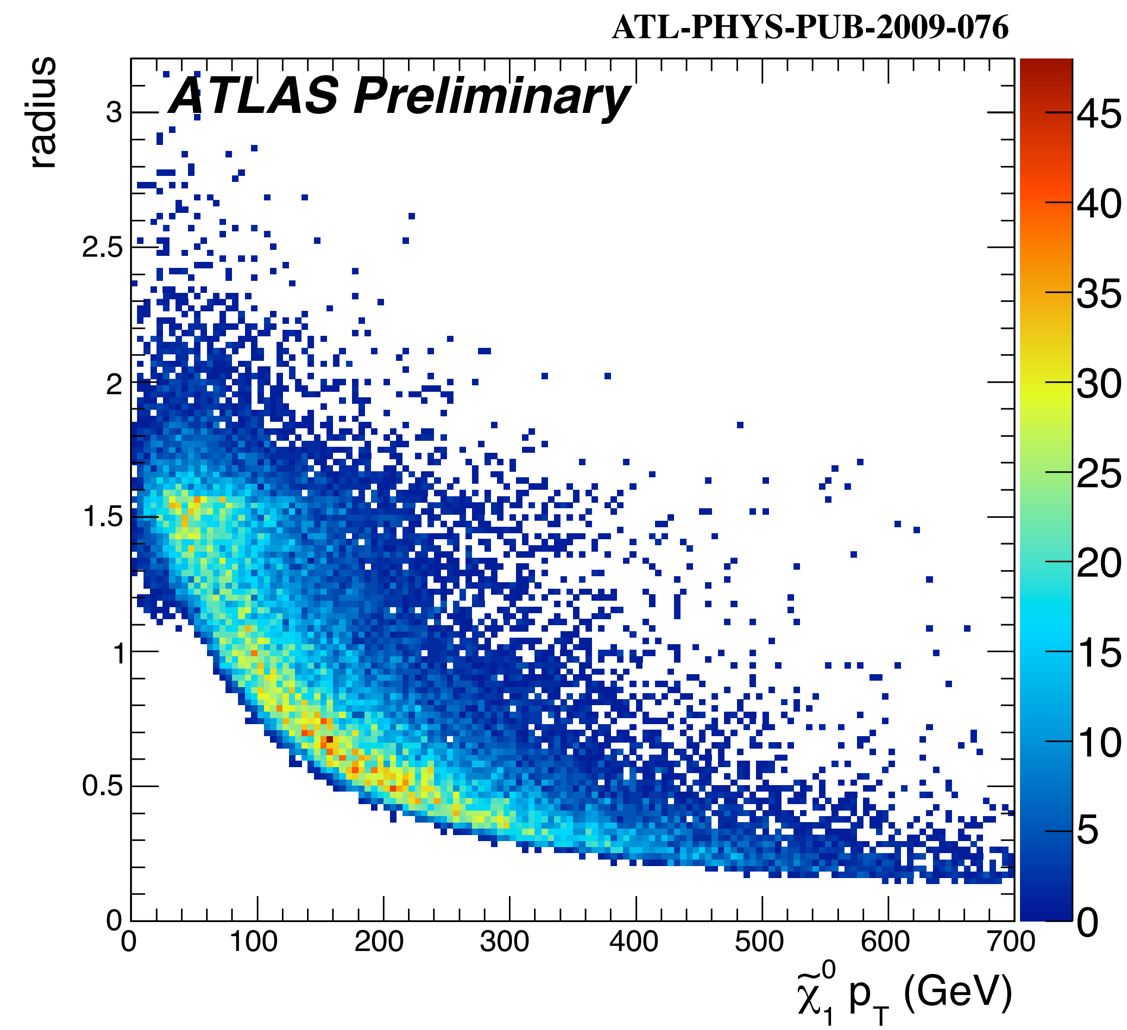
- Analysis assumes √s = 14 TeV with 1 fb^{-1}.
- Still more data required for discovery or evidence of > 3σ.

R-Parity Violating SUSY

- Search for R-parity violating SUSY with baryon number violation ($\lambda'' \neq 0$) through 3-jet neutralino decays.
  - Analysis inspired by recent work of Butterworth *et al*. (**Phys.Rev.Lett.103:241803,2009**)



- mSUGRA benchmark point SPS1a chosen as baseline signal.
  - Key features: light neutralino (96.1 GeV) and high cross section (17.4 pb @ √s = 14 TeV).

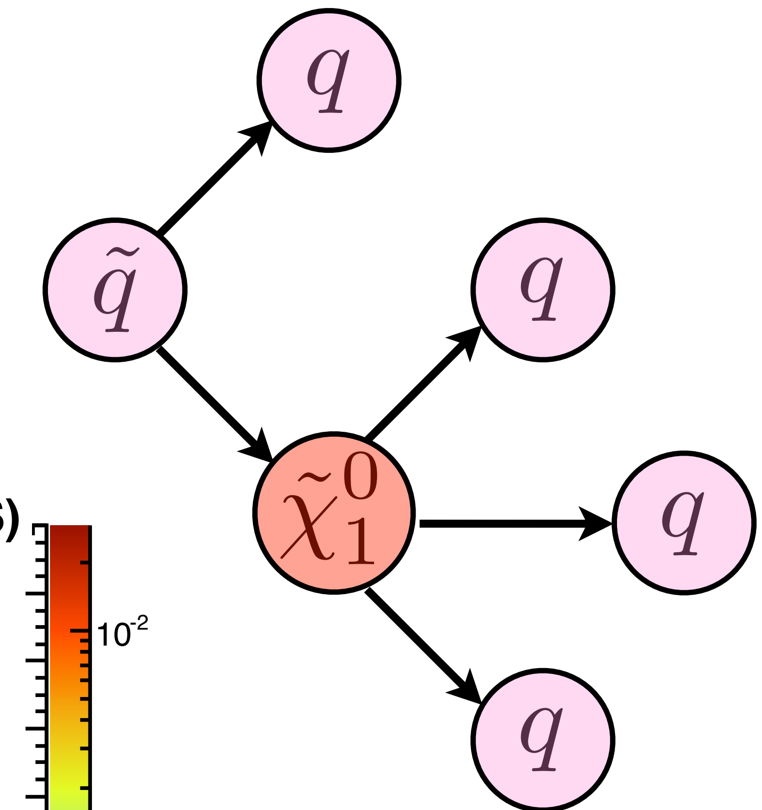


- High QCD multijet rate usually limits RPV searches to use slepton decay.

- Analysis assumes highly boosted $\tilde{\chi}_1^0$ whose hadronic decay will produce 3 collimated jets.
  - Look for high p_T jet with 3 sub-jets

Boosted Jet Selection for RPV SUSY

- Require two jets with p_T > 275 GeV (highly boosted $\tilde{\chi}_1^0$ candidates)
- 40% of $\tilde{\chi}_1^0$ result from squark decay (require two more jets with p_T > 135 GeV)
- $\tilde{\chi}_0^1 \rightarrow qqq$ will have two decay vertices (two scales)
  - Make triangle cut in 2D plane of last (y_1) and second-to-last (y_2) splitting scale.
  - Expect S:B = 1/3 with dijets as dominant background.



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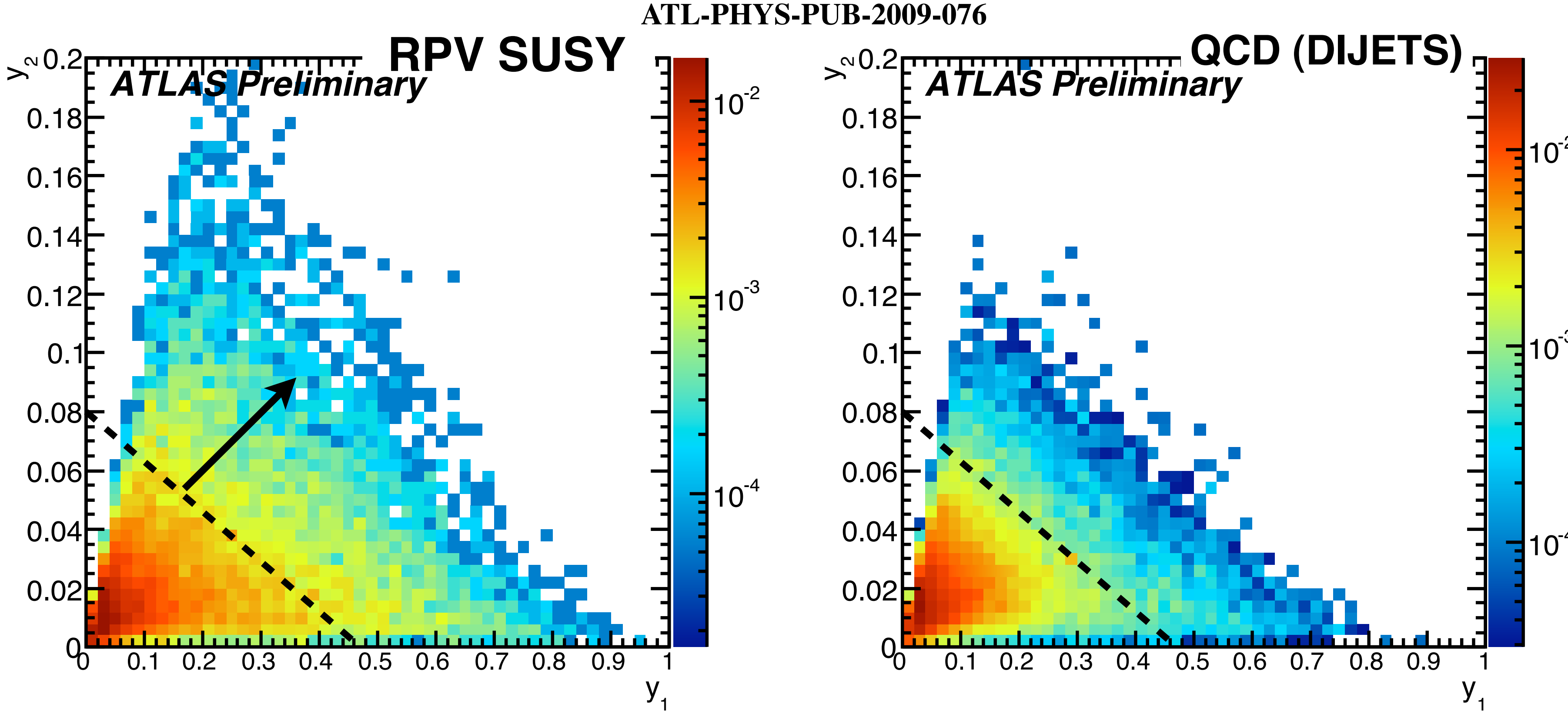
$$y_2 = \frac{1}{m_{\text{jet}}} \min(p_{T,2}^2\ ,\ p_{T,3}^2) \frac{(\Delta R)^2}{R^2}$$



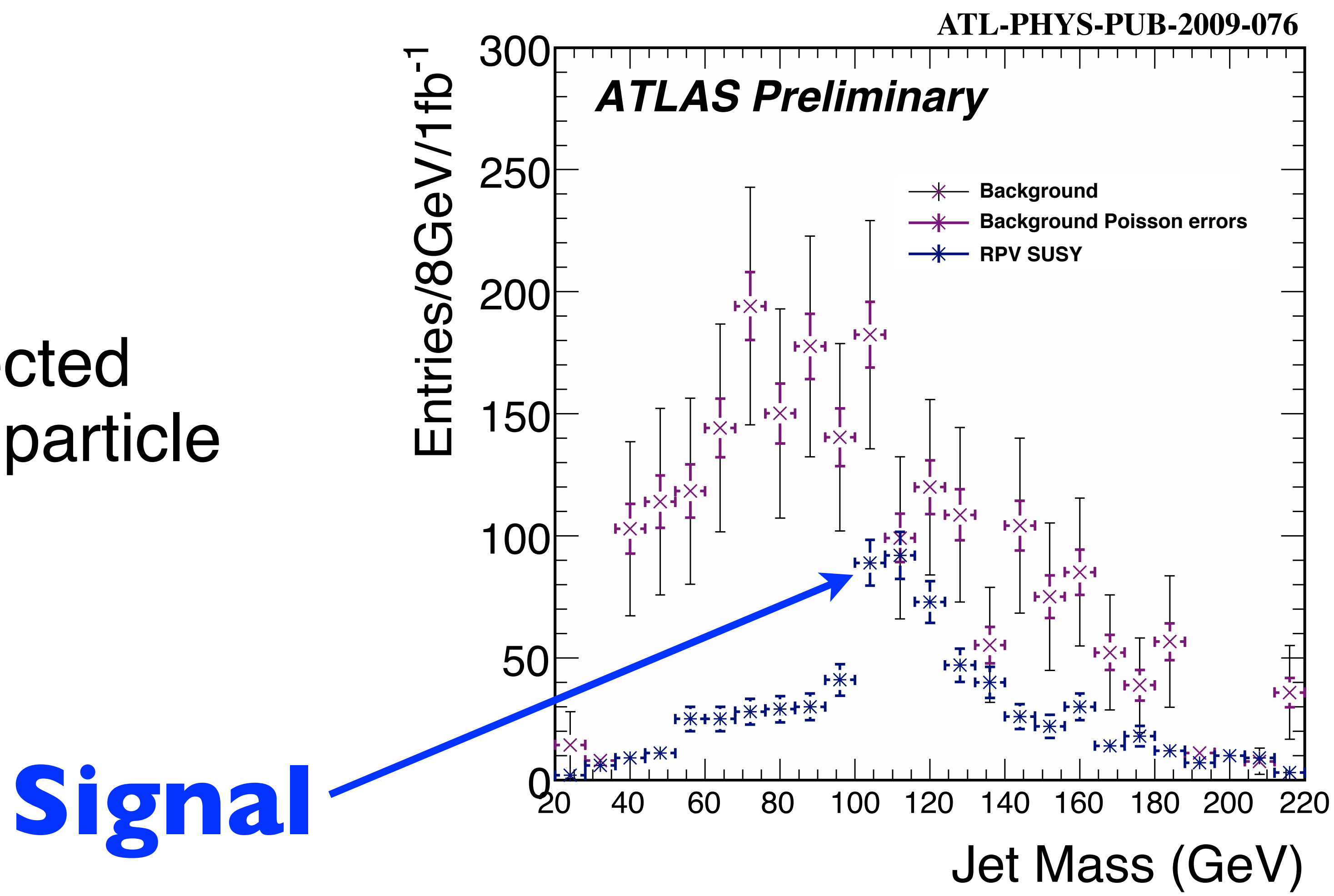
$$y_1 = \frac{1}{m_{\text{jet}}} \min(p_{T,1}^2\ ,\ p_{T,2}^2) \frac{(\Delta R)^2}{R^2}$$

Expected Results for RPV SUSY

- Inspect jet mass distribution for bump in falling background.

- Background shape and normalization is largest uncertainty (using MC).
  - Expect to reduce this uncertainty using data to model the background.

- Analysis technique expected to work for any massive particle decaying to 3 subjets.

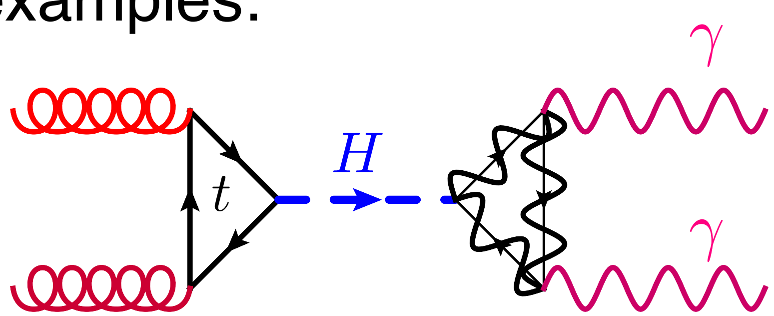


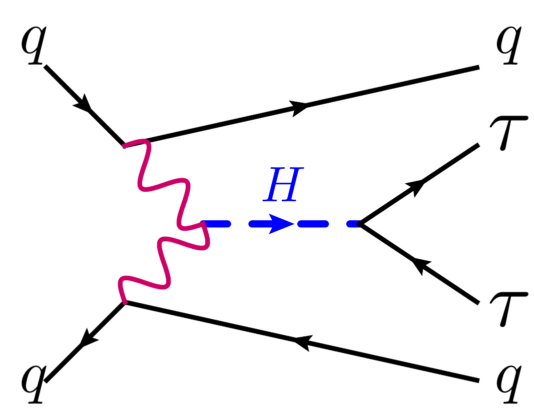
- Important: Allows $\tilde{\chi}_1^0$ search without leptons in the final state.

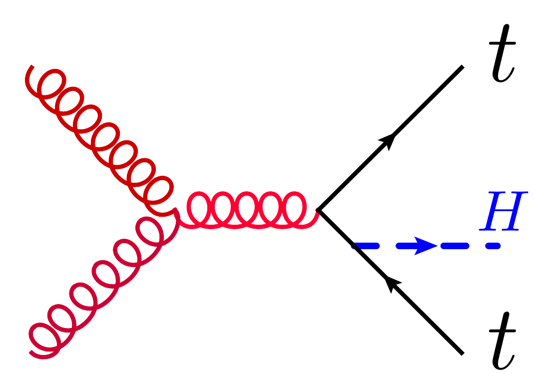
Recovering $H \rightarrow b\bar{b}$ At The LHC

- Low mass Higgs ($M_H \approx 120$ GeV) searches are challenging at the LHC.
  - Increased $b\bar{b}$ backgrounds w.r.t Tevatron + pp vs $p\bar{p}$.
  - Tevatron searches in $WH \rightarrow l\nu bb$ and $ZH \rightarrow ll(\nu\nu)bb$ not as powerful at LHC.

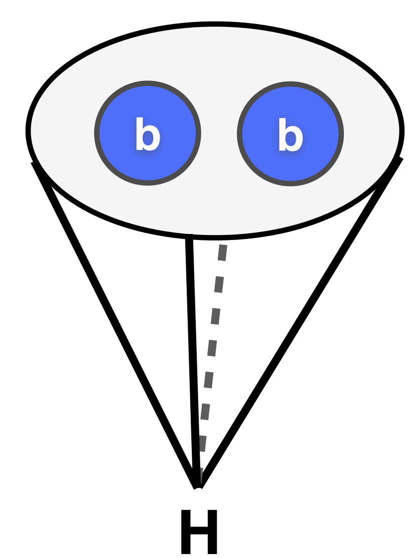
- Current strategy merges several production modes all with low rates.
  - examples:







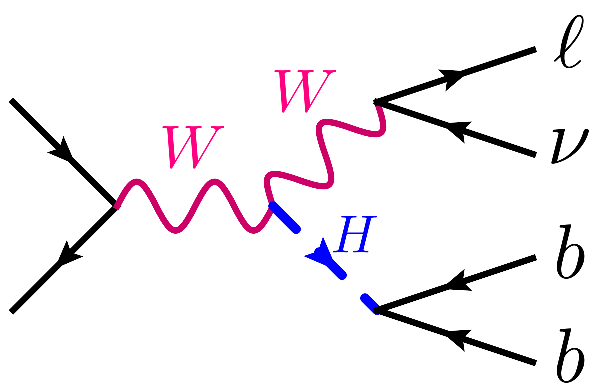
- Recent paper by *Butterworth et al.* [Phys. Rev. Lett. 100, 242001 (2008)] suggest that $H \rightarrow b\bar{b}$ measurement may still be possible at LHC.



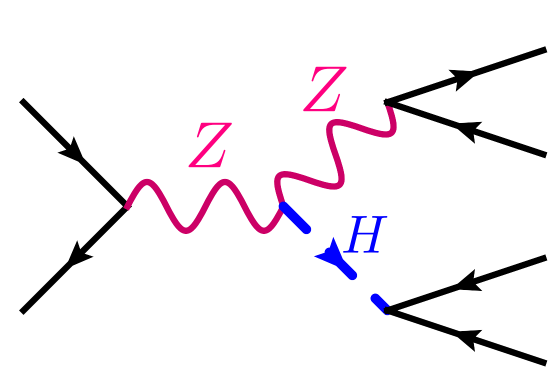
- Idea: Look for boosted Higgs decaying to single $b\bar{b}$-jet.

Boosted Higgs-Jet Analysis

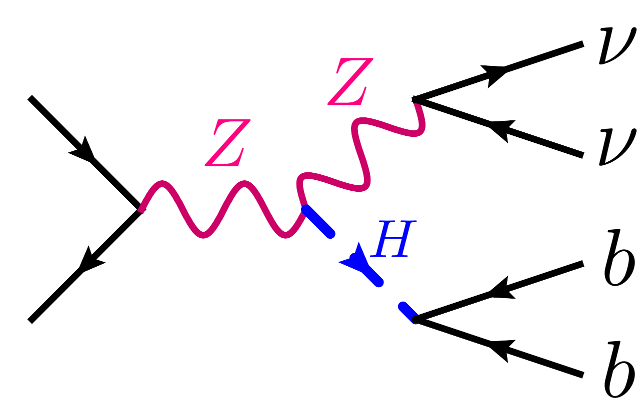
- A boosted Higgs ($p_T \gg m_H$) requires recoiling from another boosted object.
- Look for W+H and Z+H in three decay channels.



$p_T(l) > 30$ GeV
$E_T^{miss} > 30$ GeV
$p_T(W) > 200$ GeV

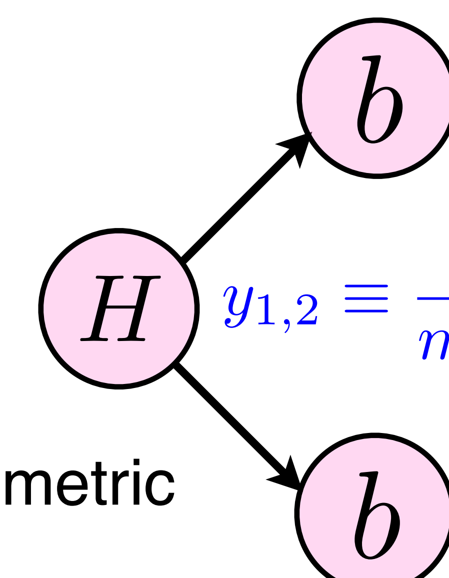


$p_T(l_1)(l_2) > 25(20)$ GeV
$80 < M_Z < 100$ GeV
$p_T(Z) > 180$ GeV



Veto lepton
$E_T^{miss} > 200$ GeV

- Each channel requires one jet with $p_T(j) > 200$ GeV and $\Delta\Phi(H,V) > 1.2$ rad.
- Look for "mass drop" within the jet using last clustering step (**CA**).
  - Higgs-jet should have two hard subjets that ~ share m_H ($p_T(b) \sim m_H/2$).
  - Background jets tend to have more asymmetric p_T sharing and no large mass drop.

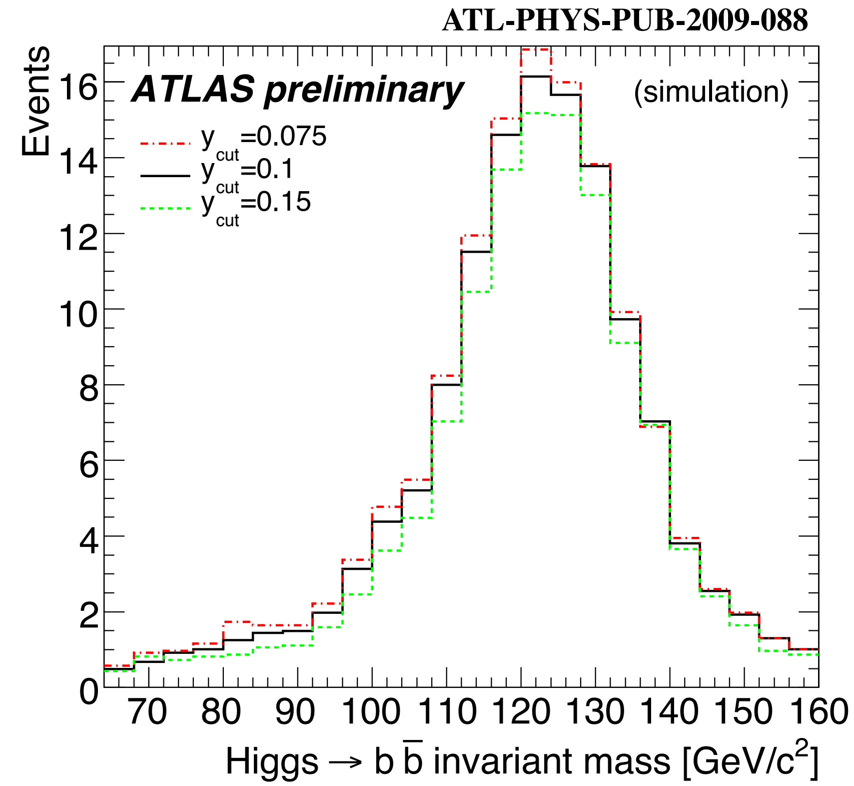


$$y_{1,2} \equiv \frac{1}{m_j^2} \min(p_{T,1}^2, p_{T,2}^2)\Delta R^2 > 0.1$$

$$m_{j1} < \frac{1}{\sqrt{3}} m_j$$

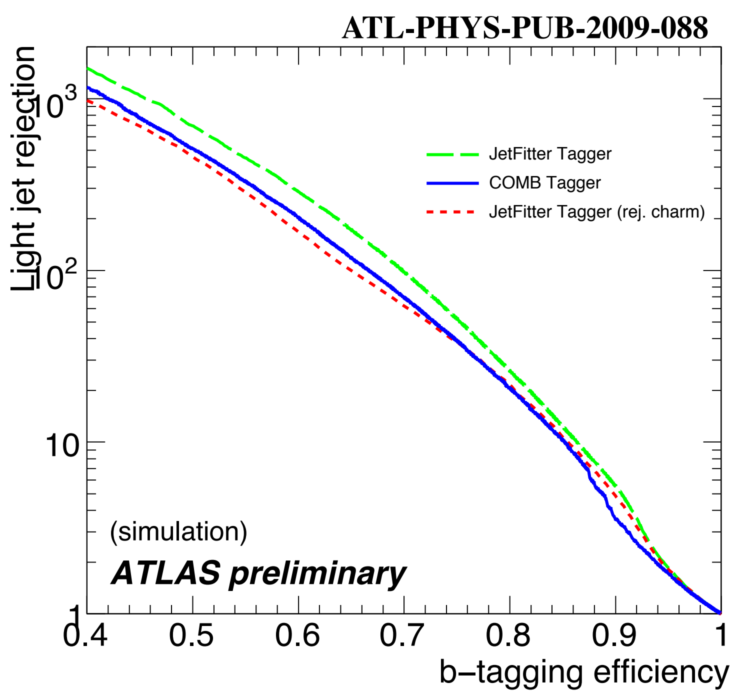
Further Higgs-Jet Analysis

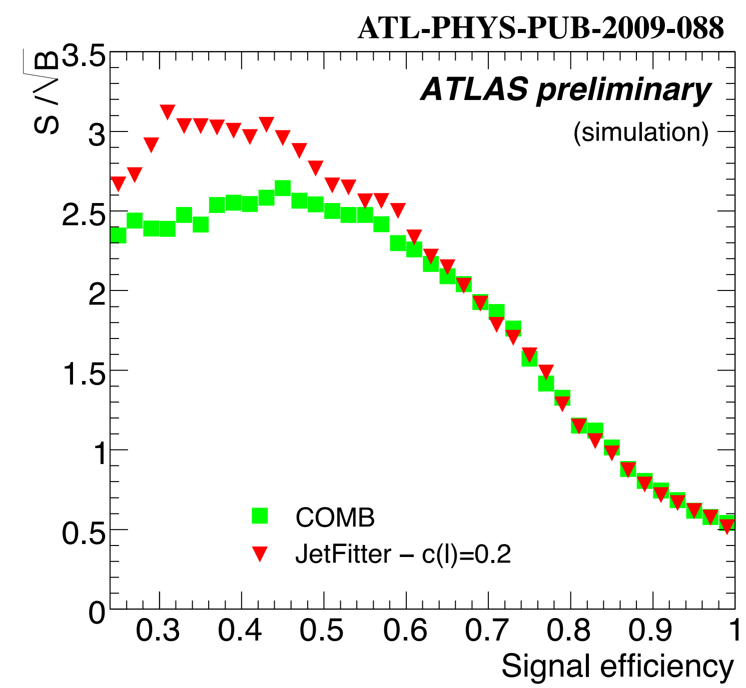
- Effect of mass drop cut and asymmetric p_T sharing cut is quite efficient for signal.



- Further improve mass resolution by rerunning CA on selected jets but with $R = \min(0.3, R_{b\bar{b}}/2)$.
  - Choose two hardest subjects within these newly clustered jets.
  - Helps remove soft QCD radiation ⇒ good for mass resolution.

- Lastly, look for displaced tracks within cone ($\Delta R < 0.4$) of subjects.
  - Scan operating point to maximize significance.





Results for Higgs → $b\bar{b}$

- Results presented for a mass window cut assuming m_H = 120 GeV.
  - S:B ~ 2:3 for lvbb

Channel	signal	t_i	w_i	z_i	$S/\sqrt{B}$
$llb\bar{b}$	5.34	0.98	0.0	11.2	1.5
$l\nu b\bar{b}$	13.5	7.02	12.5	0.78	3.0
$\nu\nu b\bar{b}$	16.3	45.2	27.4	31.6	1.6
Combined					3.7

- Results assume perfect knowledge of signal acceptance and backgrounds after collecting 30 fb^{-1} @ $\sqrt{s}$ = 14 TeV.
  - Flat 10% systematic uncertainty → 3.2σ
  - Flat 15% systematic uncertainty → 3.0σ
- **Diboson resonances** will be seen before Higgs thus providing a standard candle.

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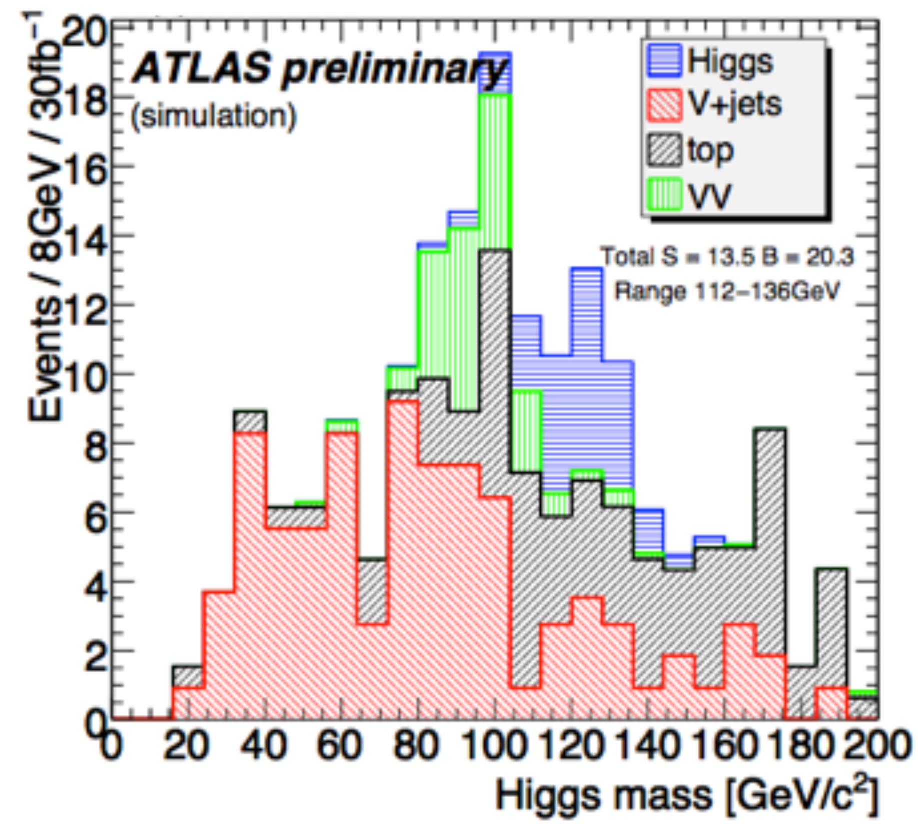
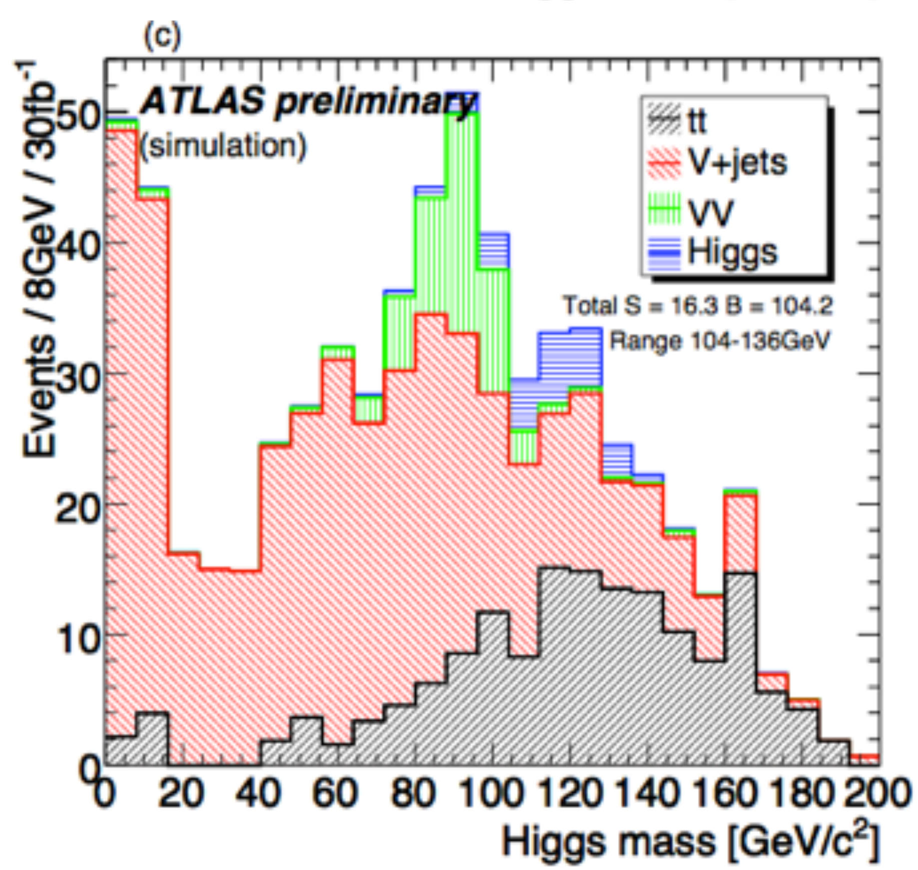
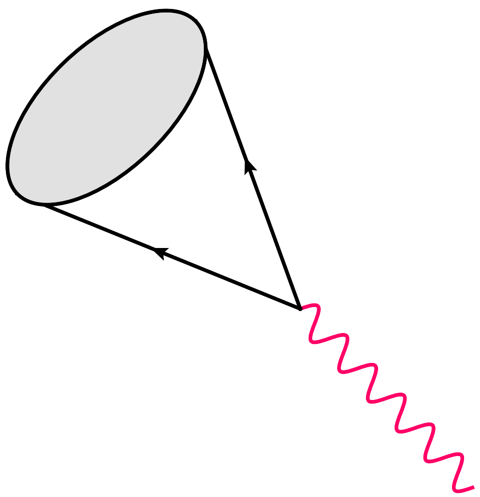


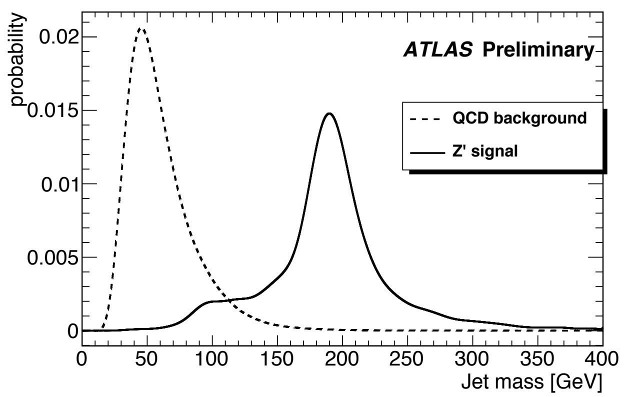


Before We Observe New Physics

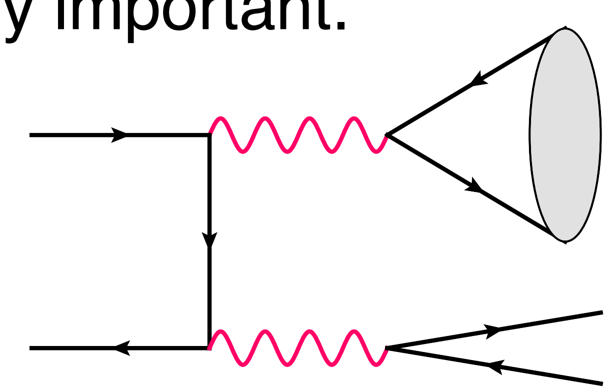
- Only three new physics signatures presented, but many more possibilities.
- Important steps before discovery:
  - Calibration of k_T , k_T^{-1}, and CA jets extremely important. Most analyses depend strongly on JES. Luckily we will produce many dijet and γ/Z + jet events.

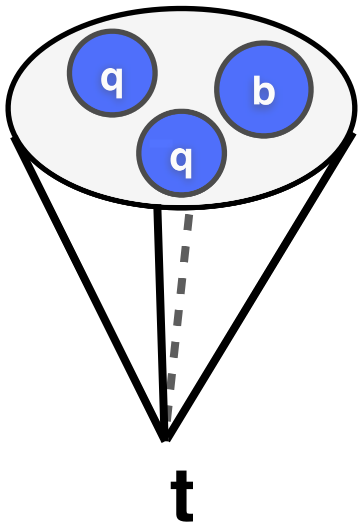


  - Detailed study of jet mass also very important. Most HEP results use jet p_T, η. Few test of jet mass for high jet masses.



  - Measurement of standard candles extremely important. Test standard model predictions for WW,WZ,ZZ, tt for $p_T(t, W, Z) \gg m_{t,W,Z}$ Also important to test MC generators in extreme phase space.

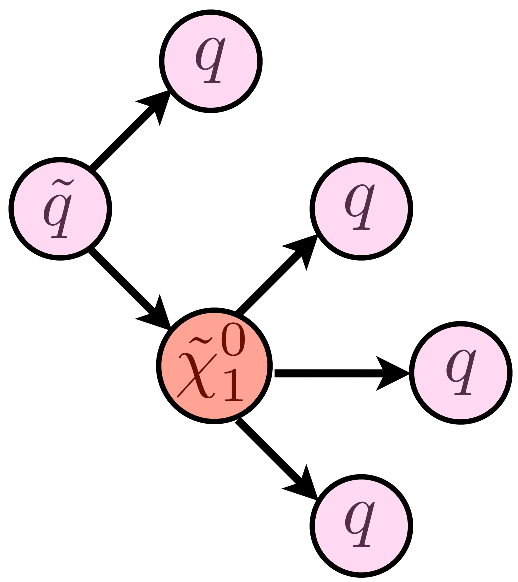




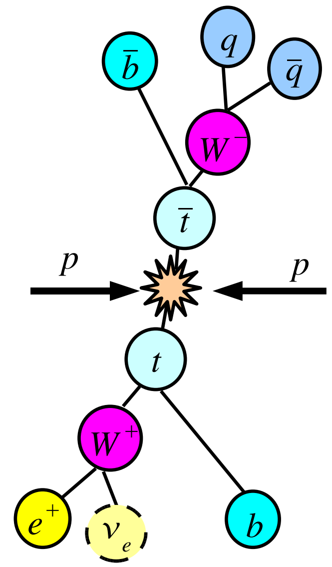
Summary & Outlook

- Many ongoing analyses within ATLAS using jet substructure as tool for isolating new physics signals.

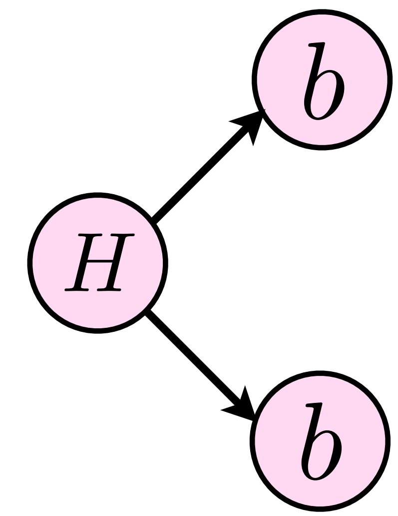
$\tilde{\chi}_0^1 \rightarrow qqq$



$Z' \rightarrow t\bar{t}$



$H \rightarrow b\bar{b}$



- Plenty of work to prove SM signals before claiming new physics.
  - Calibration of new substructure and validation of jet mass
  - Measurement of m_t, m_W, m_Z, σ(tt), σ(VV)
- Extremely active field with strong interplay between theory and experiment.

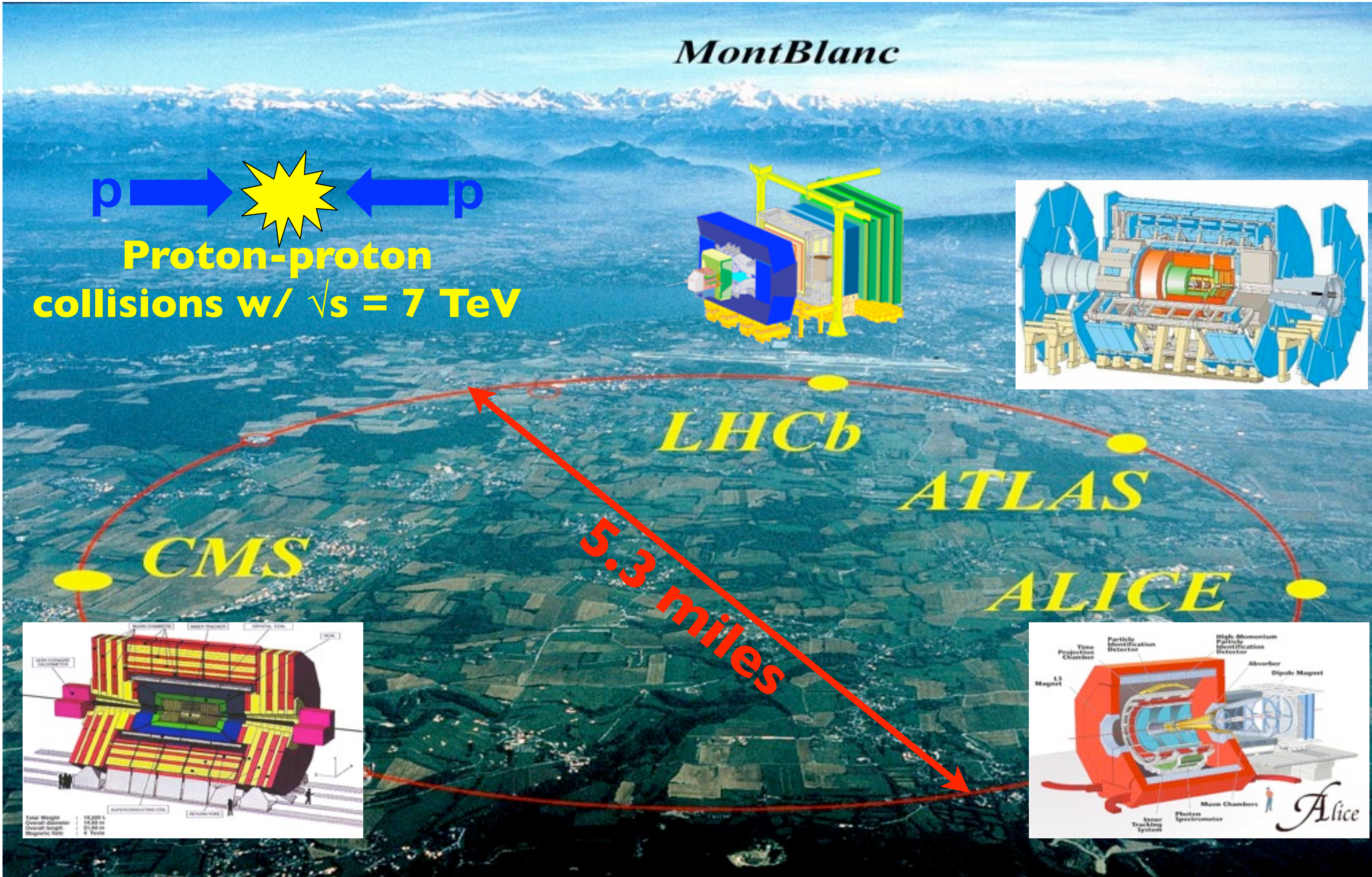
http://www.physics.ox.ac.uk/boost2010

- Analysis of coming year’s dataset will be very valuable for future substructure searches.

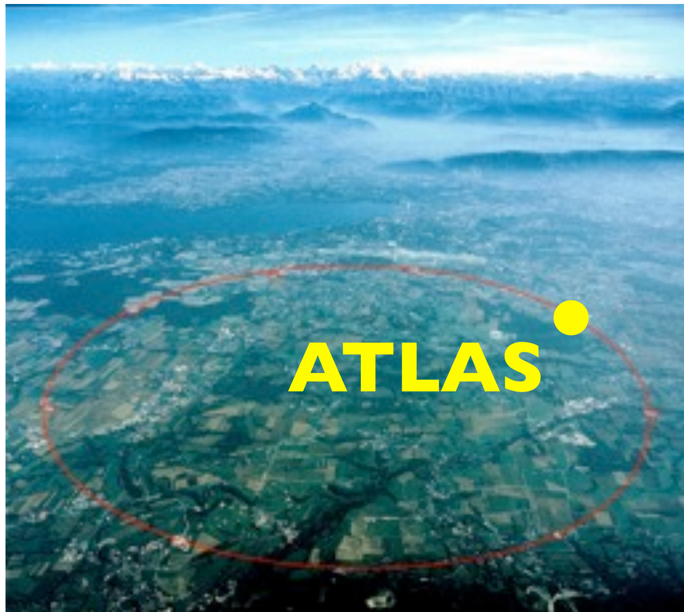
The Large Hadron Collider

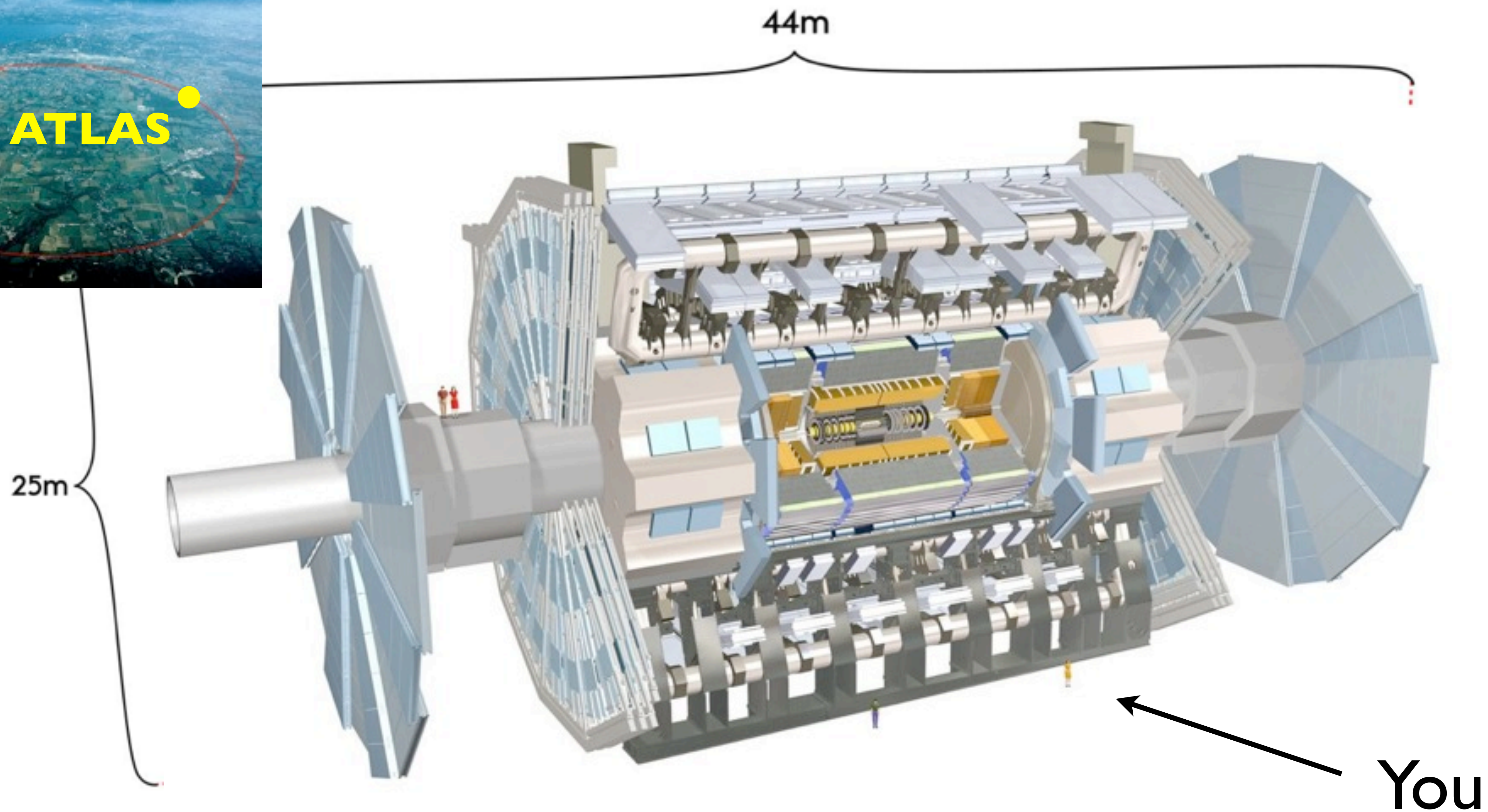
the ATLAS Experiment

BROOKHAVEN NATIONAL LABORATORY



The ATLAS Detector





“Standard” HEP Detector

IP → Tracking Detector → Calorimeter → Muon System