

# Experimental Review

Gustaaf Brooijmans

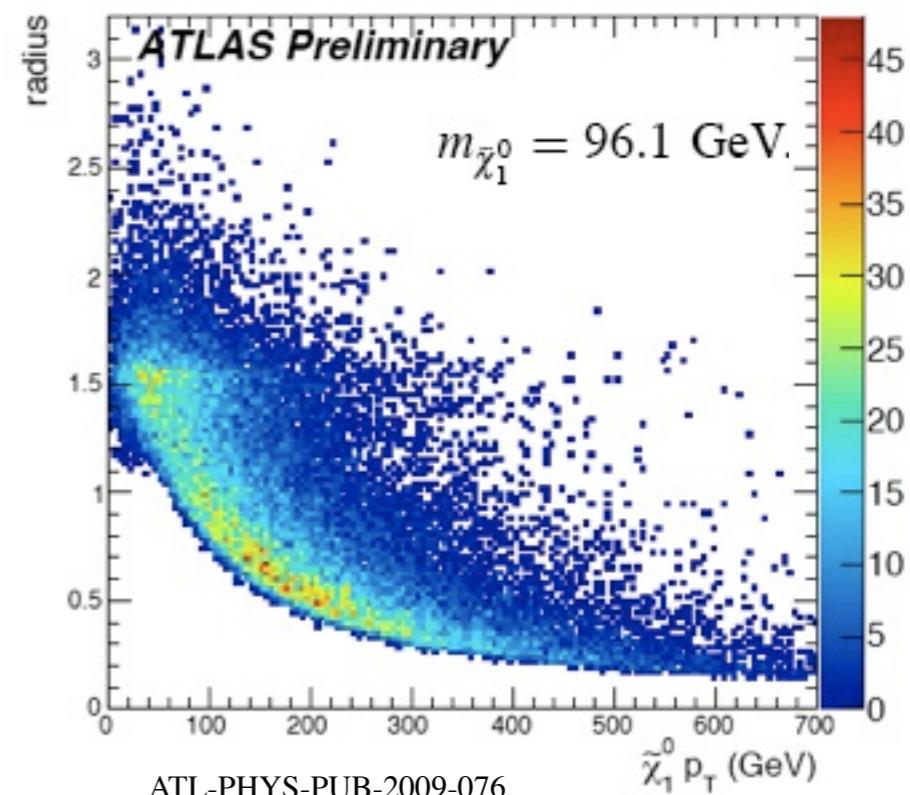
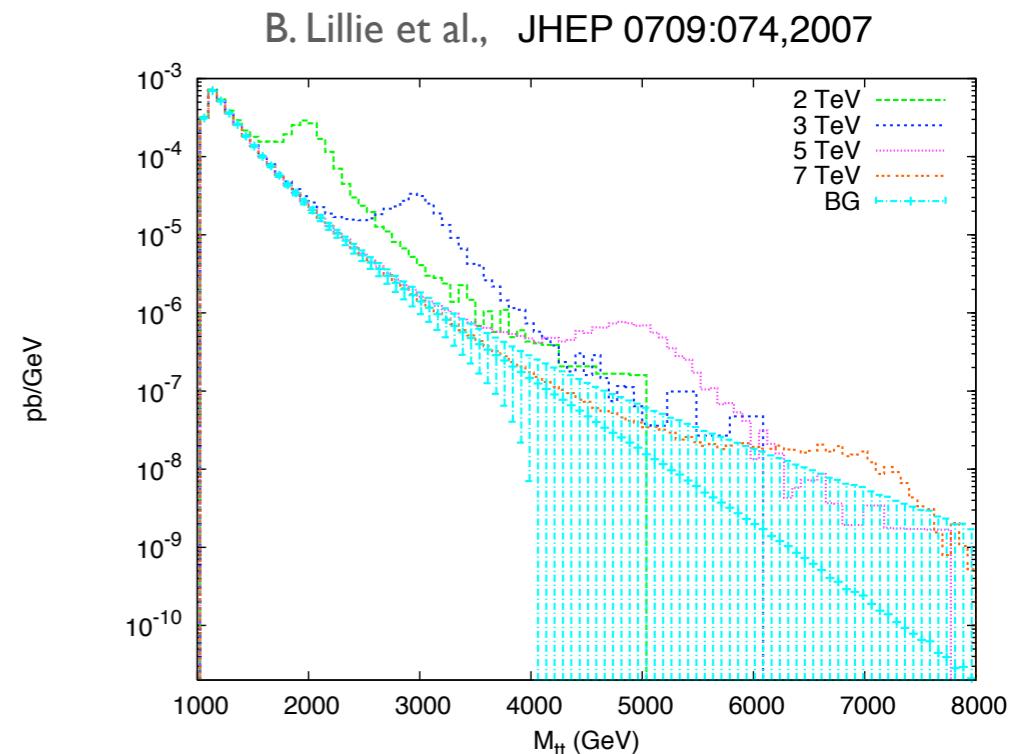


Boost 2010, Oxford, June 22, 2010

- The physics case
- History
  - Jet studies at HERA and the Tevatron
  - Simulation results from LHC
- Early LHC data
- Some notions on the way forward

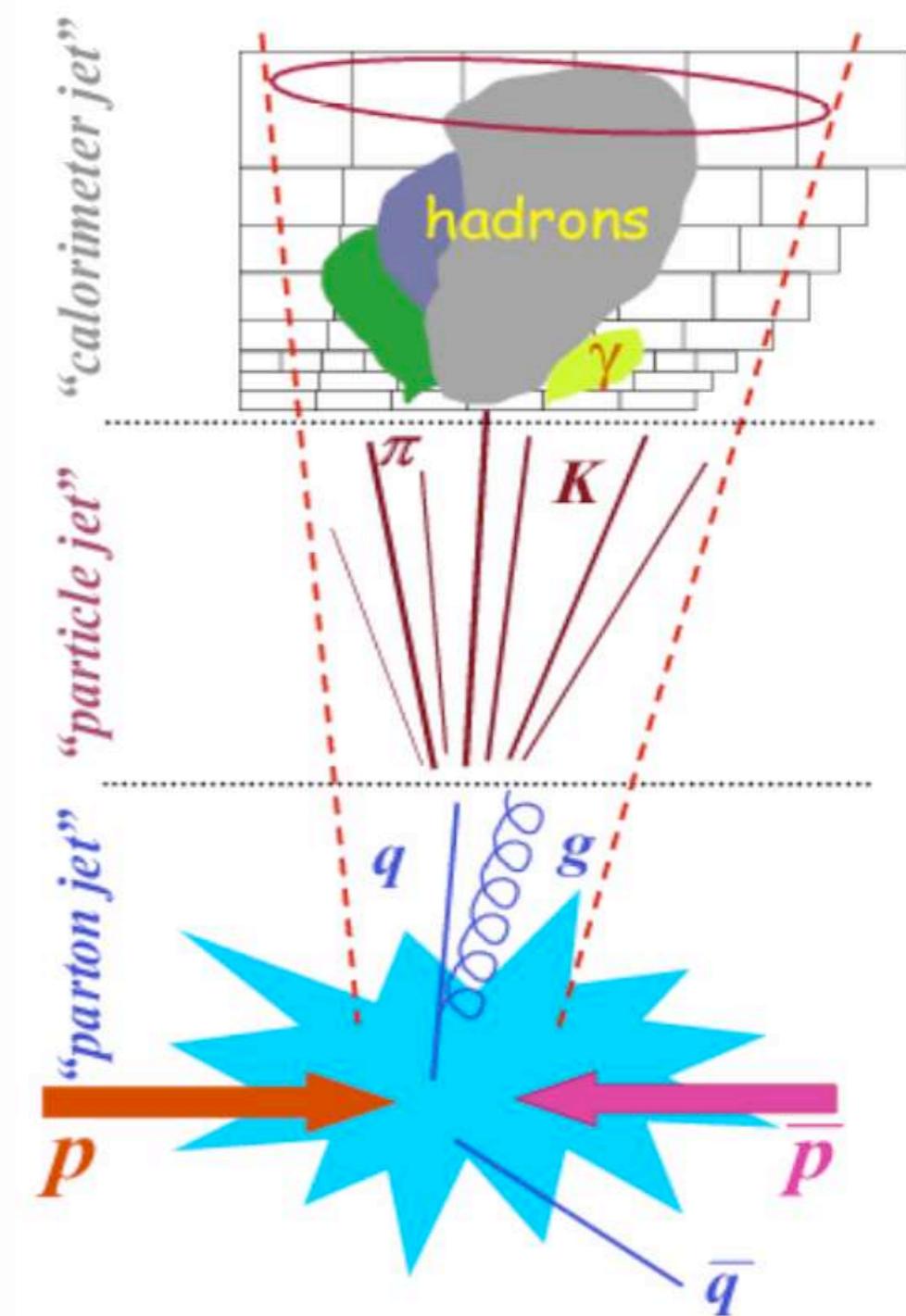
# New Resonances

- In Randall-Sundrum models with all particles in the bulk, excitations of the gauge bosons are very promising channels for discovery
- Couplings to light fermions are small, but large coupling to top,  $W_L, Z_L$  which are produced with  $p \gg m$
- In RPV SUSY, high- $p_T$  LSP can decay to collimated quarks
- High mass WW scattering, ....



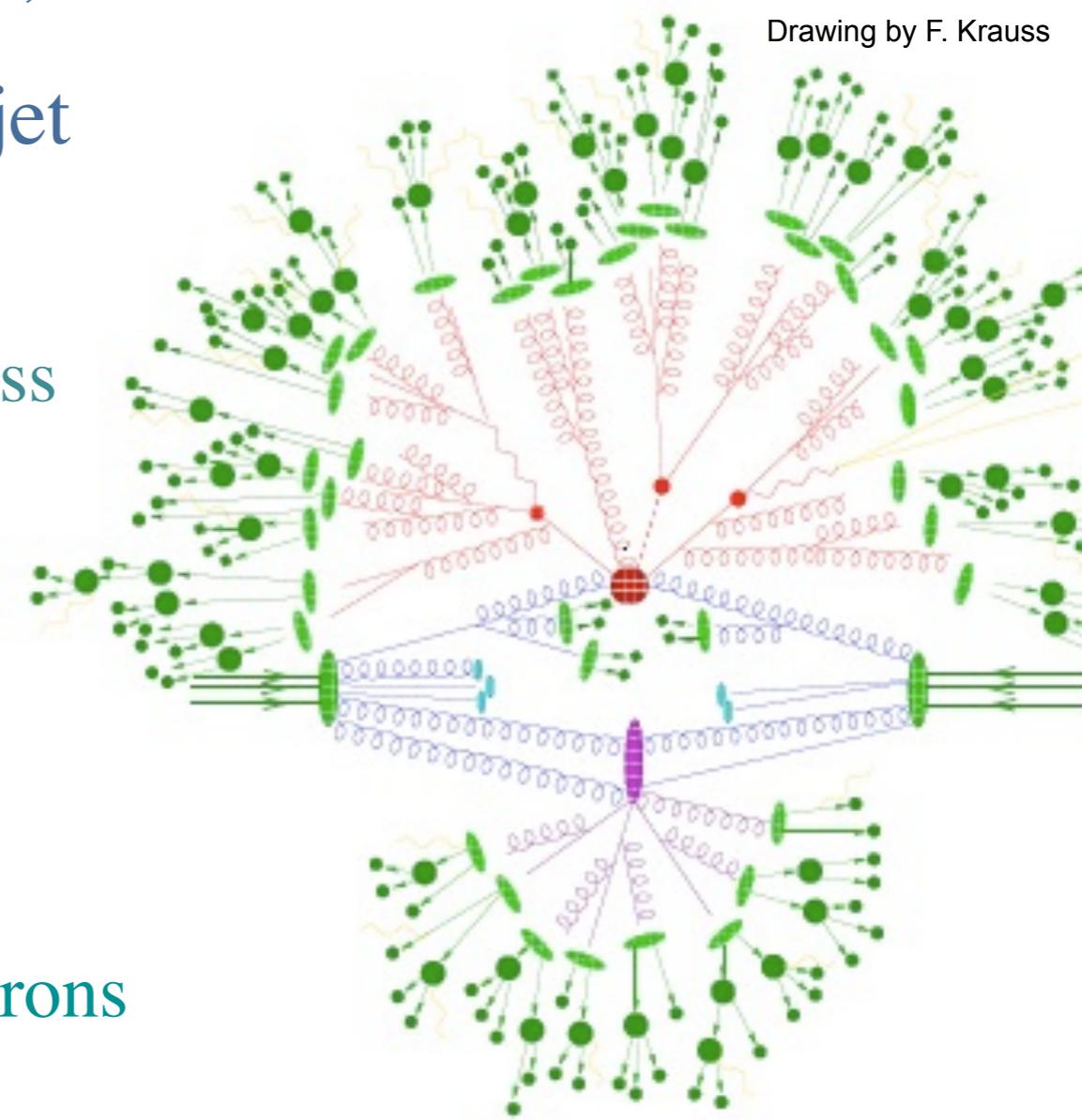
# New Experimental Signature

- Possibility to produce (very) heavy resonances decaying to top quarks, W and Z bosons
- Top/W/Z with momentum  $\gg$  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
  - ... or new light HV particles with  $p \gg m$  decaying to leptons/photons



# Fully Hadronic Decays

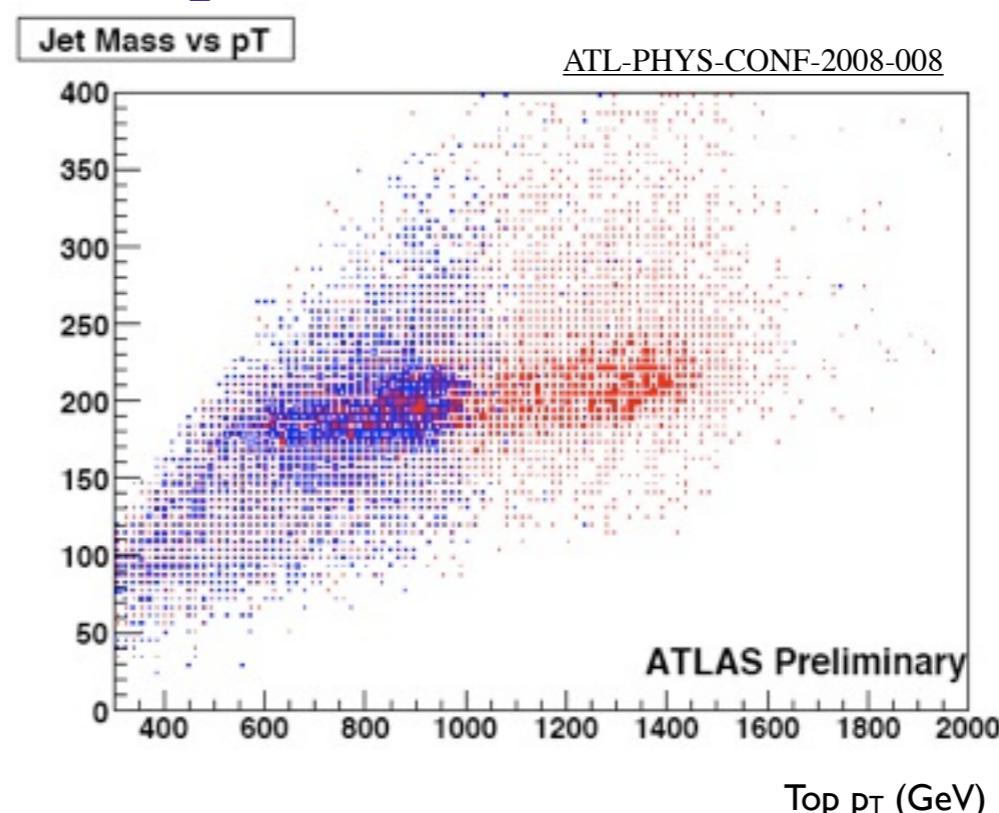
- Decay hadrons reconstructed as a single jet
  - But even if it looks like a single jet, it originates from a massive particle decaying to three hard partons, not one
- If I measured each of the partons in the jet perfectly, I would be able to:
  - Reconstruct the “originator’s” invariant mass
  - Reconstruct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



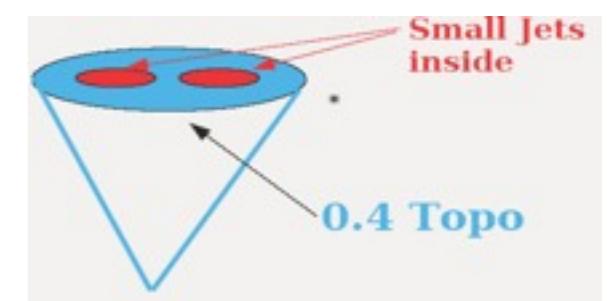
# Jet Mass

- Jet mass: invariant mass of all jet constituents

High  $p_T$  top quarks  
from  $Z'$  ( $m=2,3$  TeV)  
decays



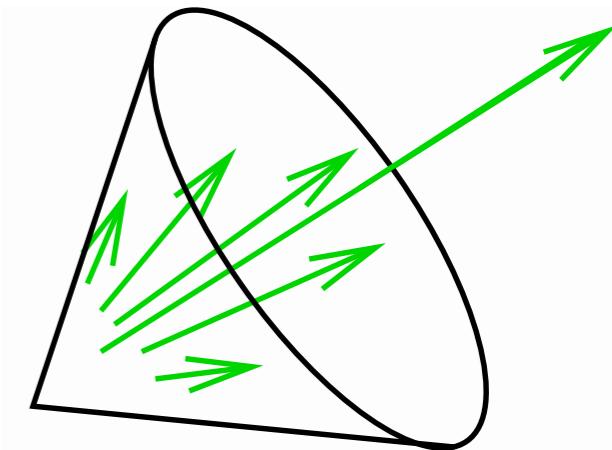
- Jet mass not sensitive to jet structure
  - Multiple techniques to exploit this
  - Typically use recombination jet algos to find “subjets”
    - $k_\perp$  vs Cambridge-Aachen, different criteria to identify subjets



# Splitting Scales

- Recombination algorithms are better suited to understand jet substructure than cone:

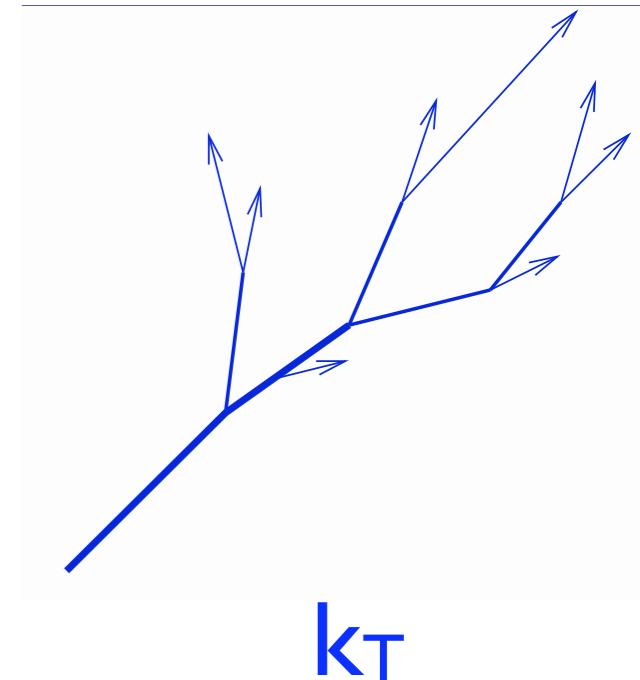
- Cone maximizes energy in an  $\eta \times \phi$  cone
- CA/ $k_T$  are a “nearest neighbor” clusterer



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

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

- Can use the  $k_T$  algorithm on jet constituents and get the (y-)scale at which one switches from  $1 \rightarrow 2 (\rightarrow 3 \text{ etc.})$  jets



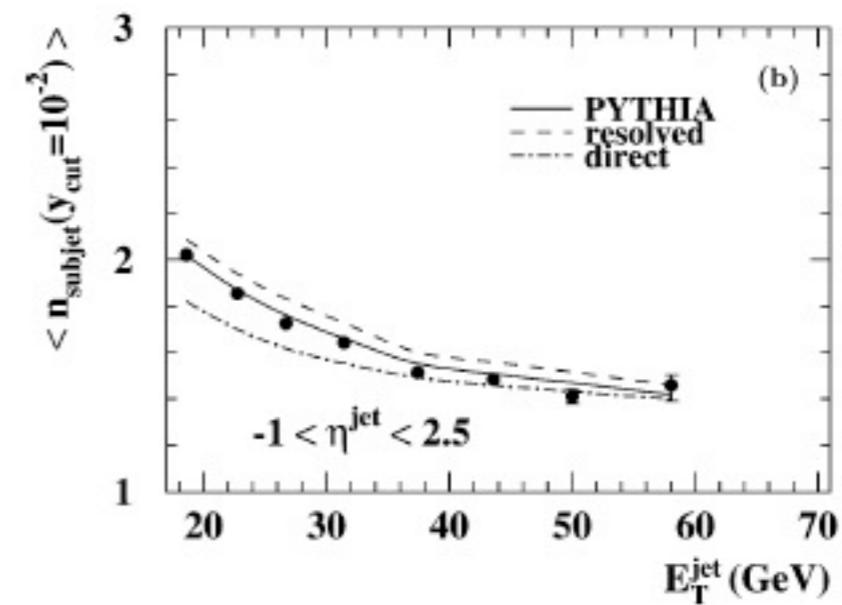
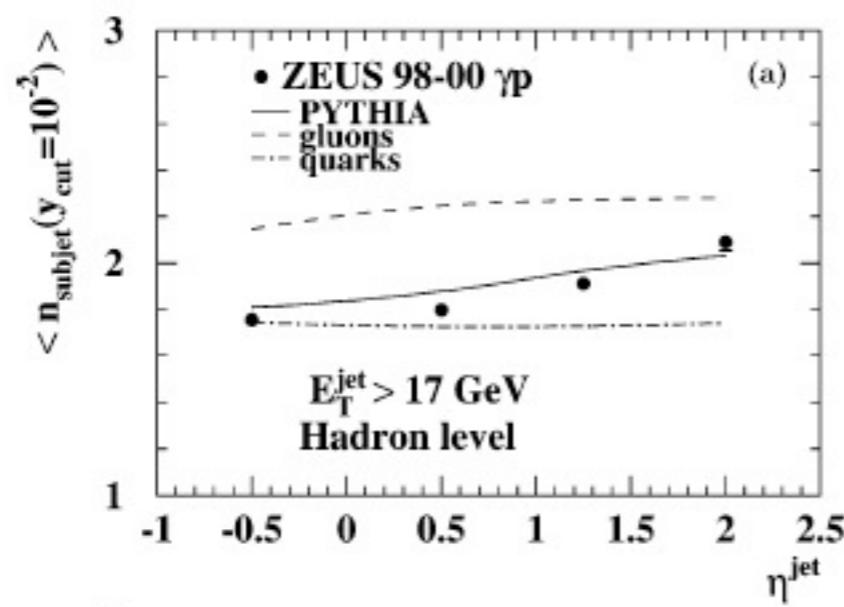
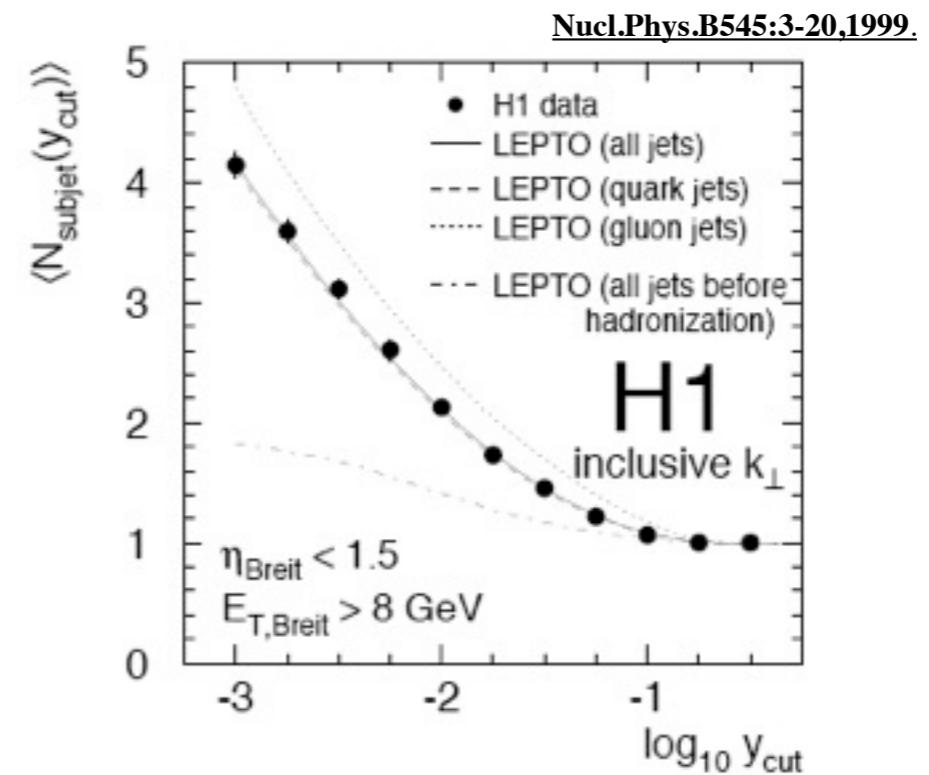
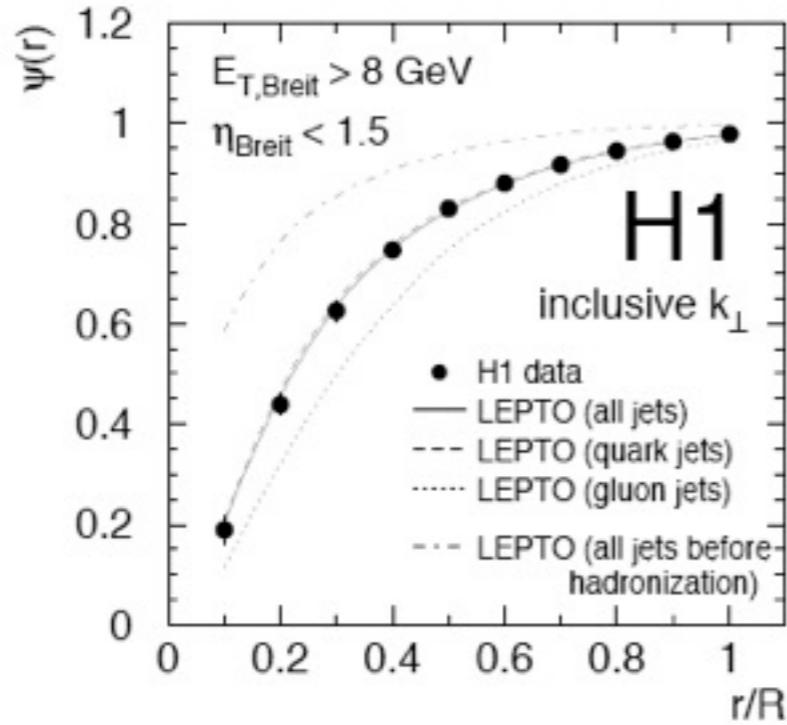
- Scale is related to mass of the decaying particle
- For CA (angular ordering), need ID criteria

# History

- Using jet structure to look for new physics is fairly new
  - Experimental studies mostly started ~2006  
J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *Phys. Rev.* **D65** (2002) 096014
- No data results from LHC yet
  - How reliable is the simulation?
    - For backgrounds in particular
    - (Some results from Tevatron at this meeting)
    - But for Tevatron, at edge of kinematic reach)
  - However, studies of jet structure have been performed for decades....

# “Distant” Past

- Jet shapes and number of subjets

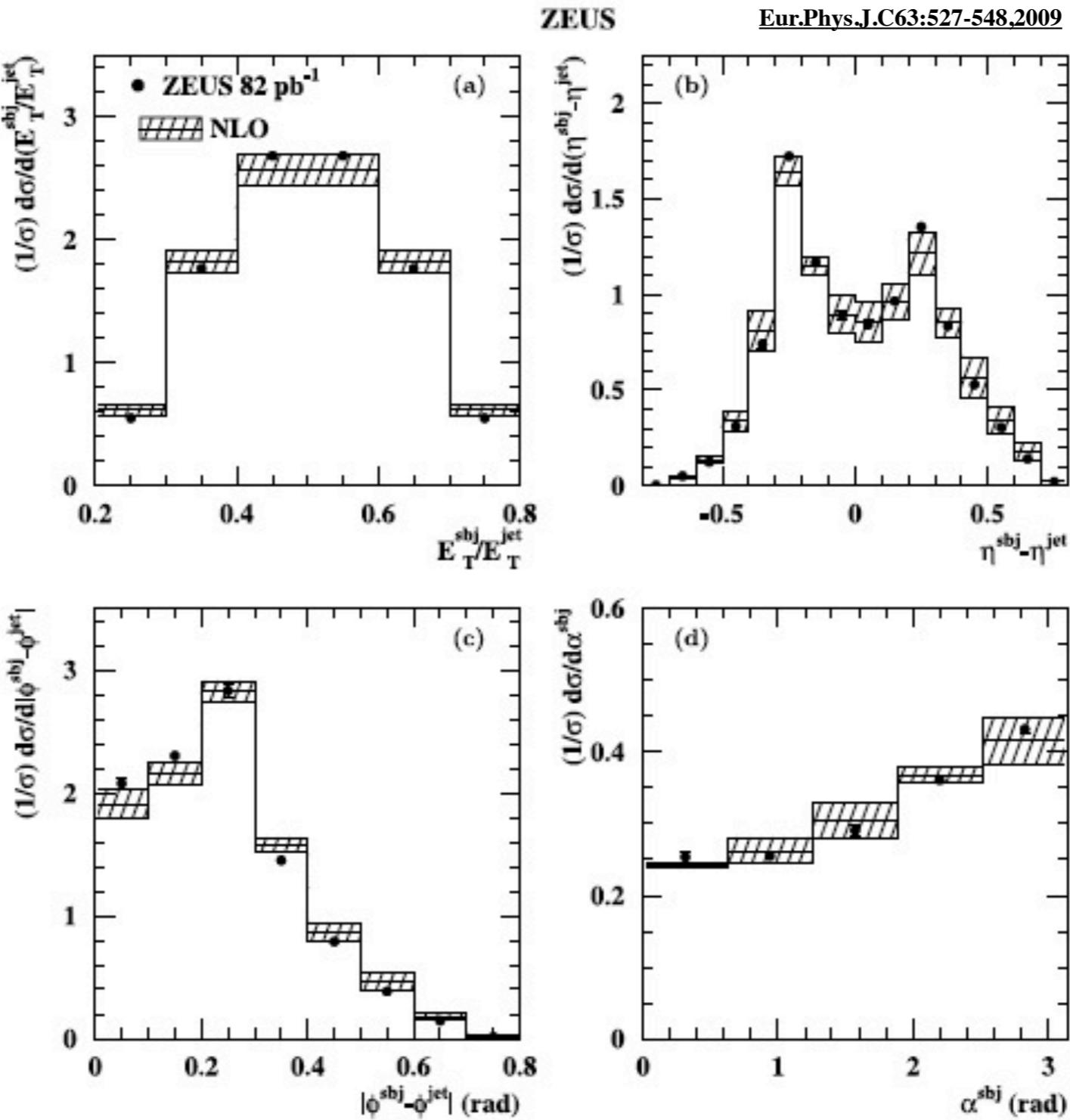


[Nucl.Phys.B545:3-20,1999.](#)

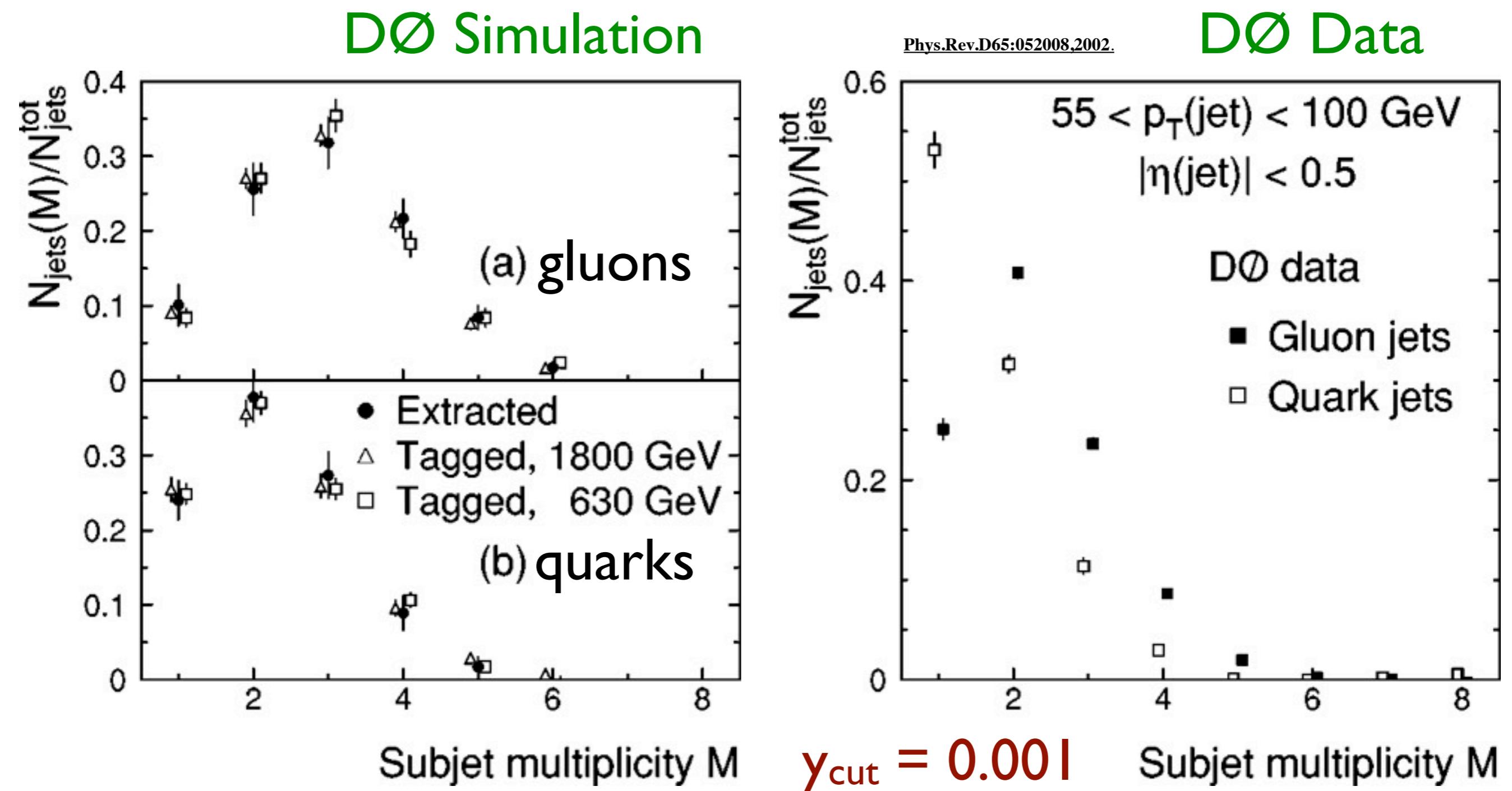
[Nucl.Phys.B700:3-50,2004](#)

# ● Subjet properties

## ● Events with two subjets



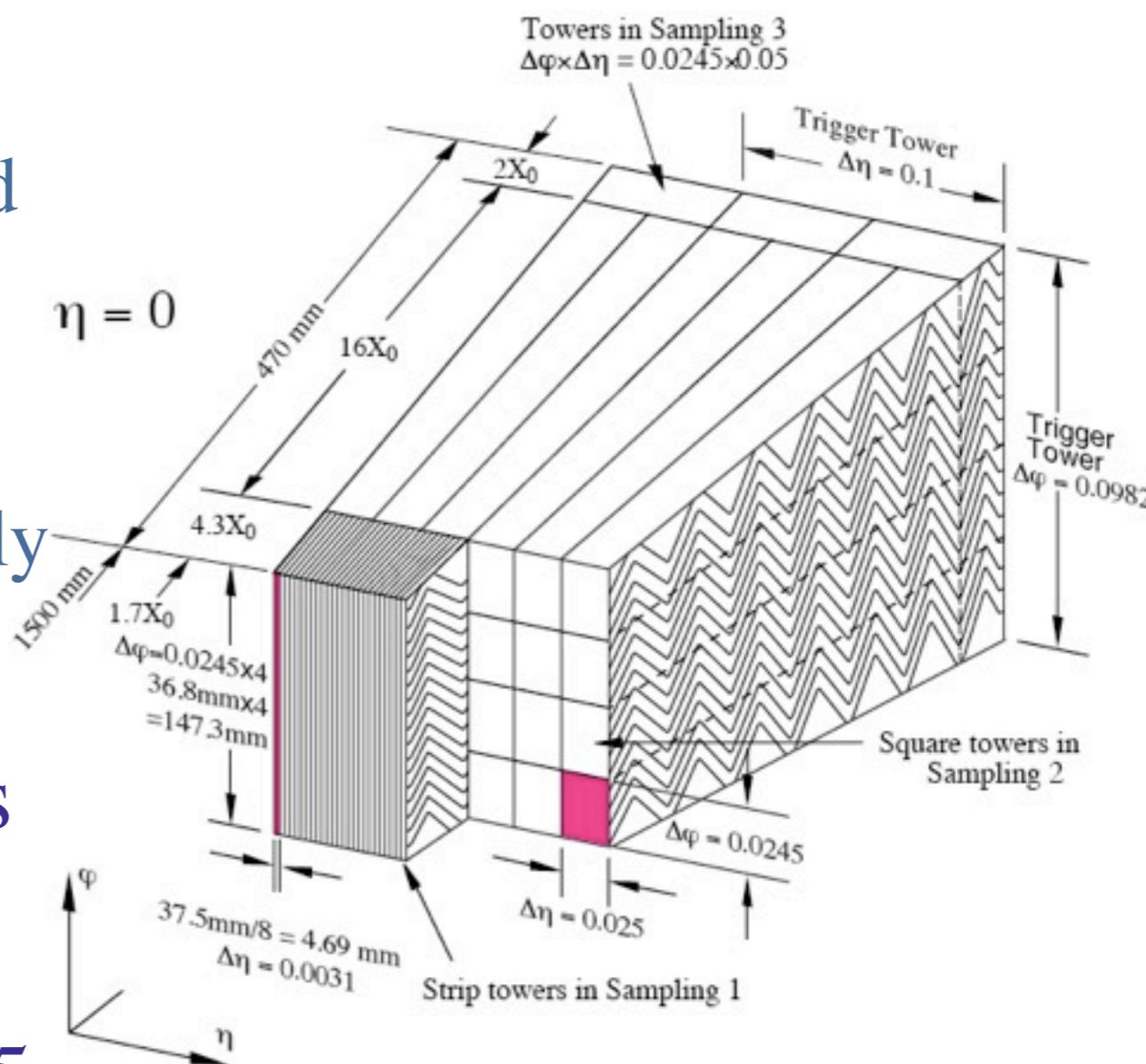
## ● Quarks and gluons



# Modern Calorimeters

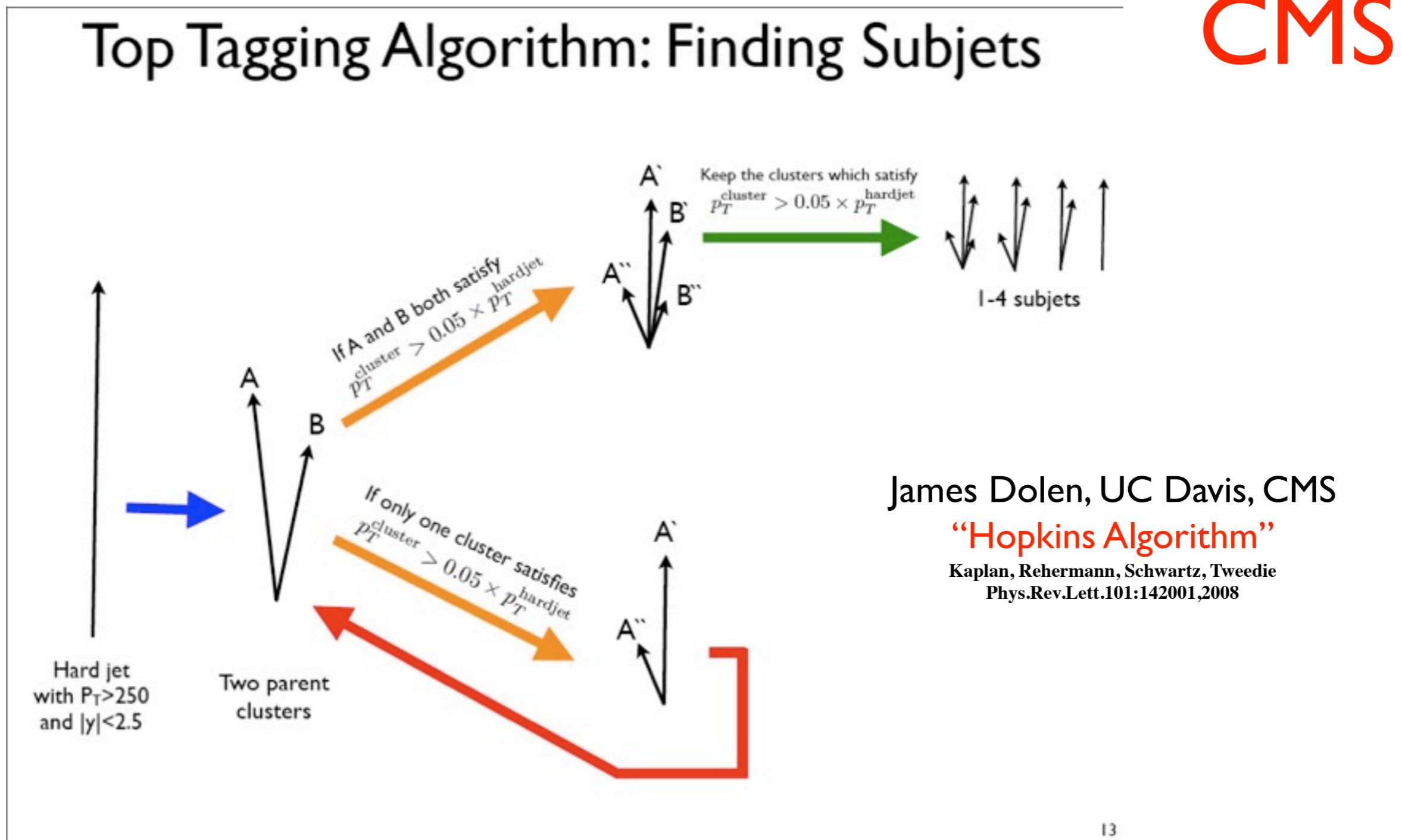
- Jets often deposit ~50% of their energy in EM calorimeters
- ATLAS has most finely segmented EM calorimeter in any hadron collider experiment!
- (CMS has  $0.0175 \times 0.0175$  but only one layer)
- Hadron (“tile”) calorimeter has  $0.1 \times 0.1$  segmentation
- CDF, DØ, H1, ZEUS have 0.05 as finest granularity, mostly 0.1

ATLAS EM Barrel

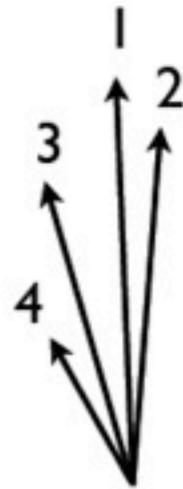


# Recent Past: Boost 09

- First full-simulation studies of subjets to tag tops shown at Boost 2009



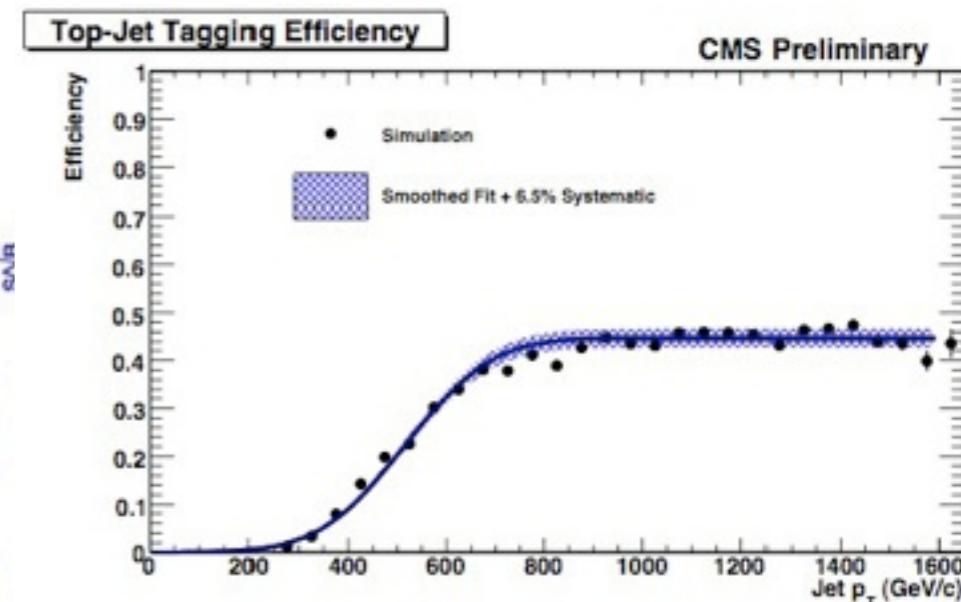
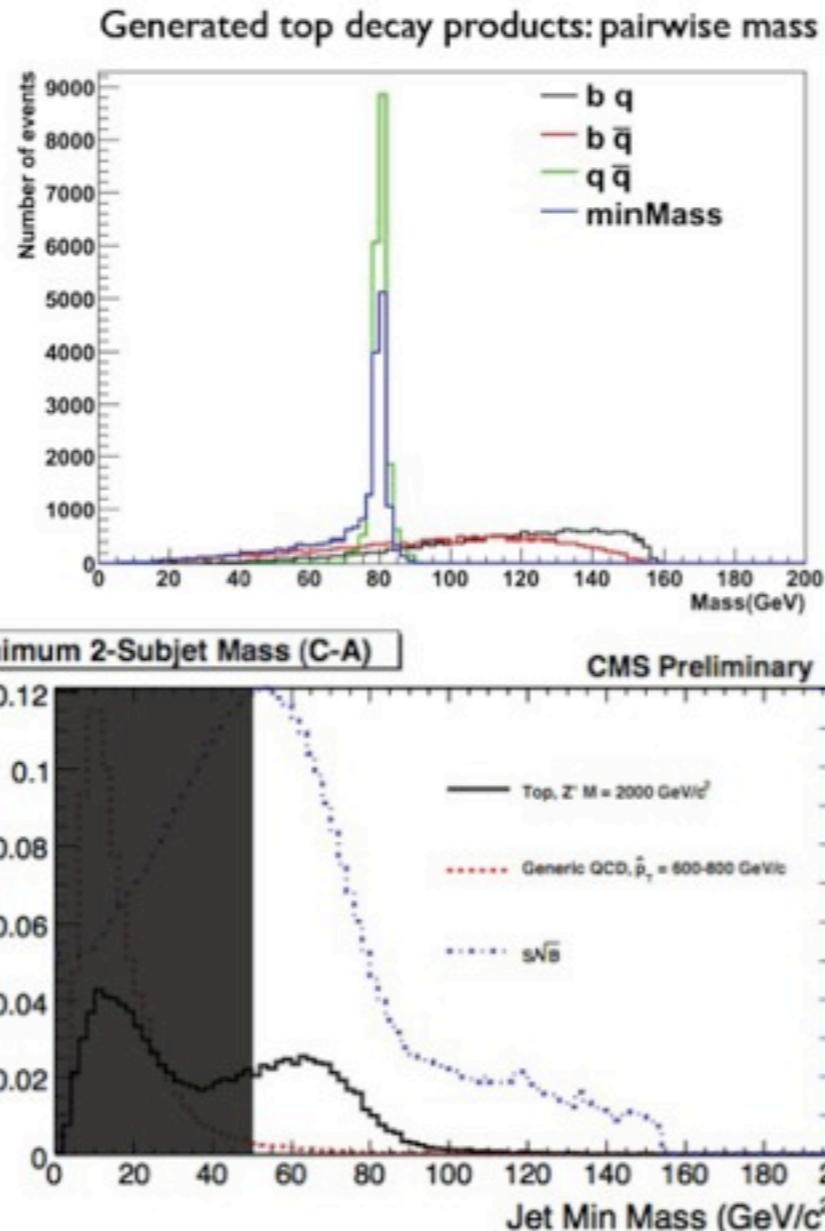
# Minimum 2-Subjet Mass



Jet with three or four subjects

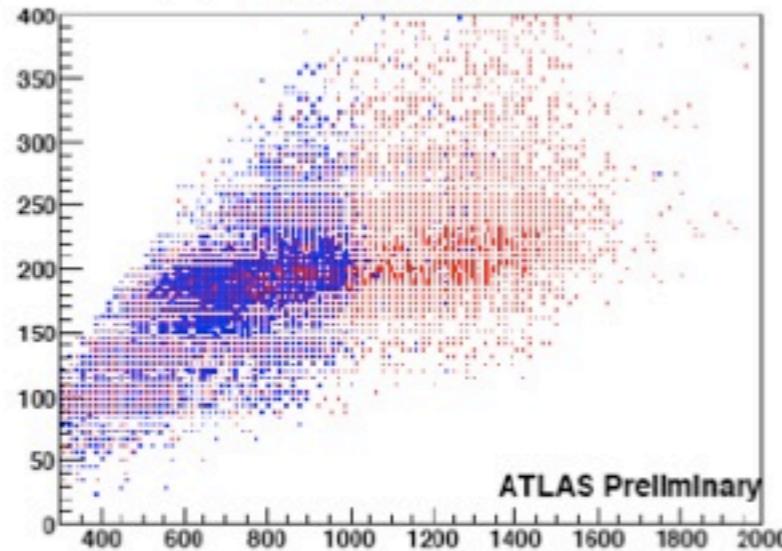
$$m_{ij}^2 = (E_i + E_j)^2 - (p_i + p_j)^2$$

$$\text{MinMass} = \min\{m_{12}, m_{13}, m_{23}\}$$

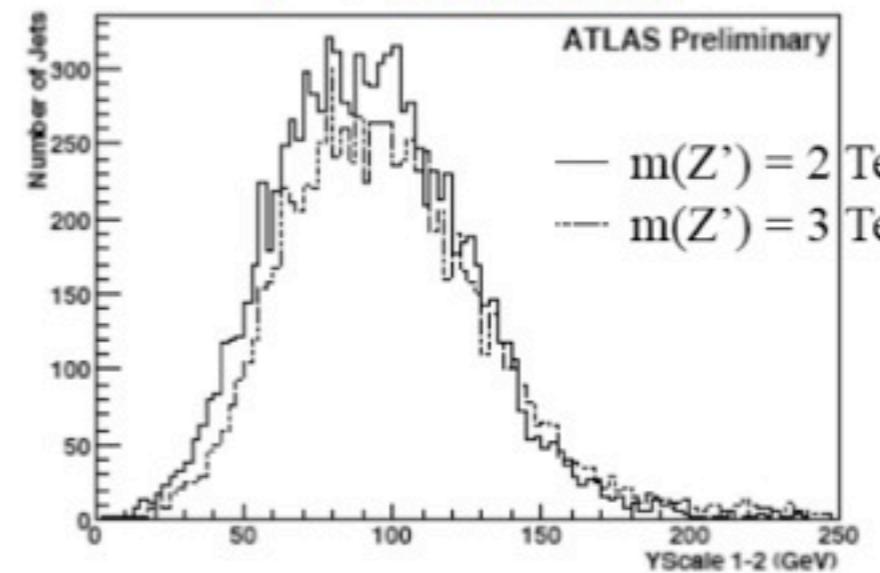


Jet Mass vs pT

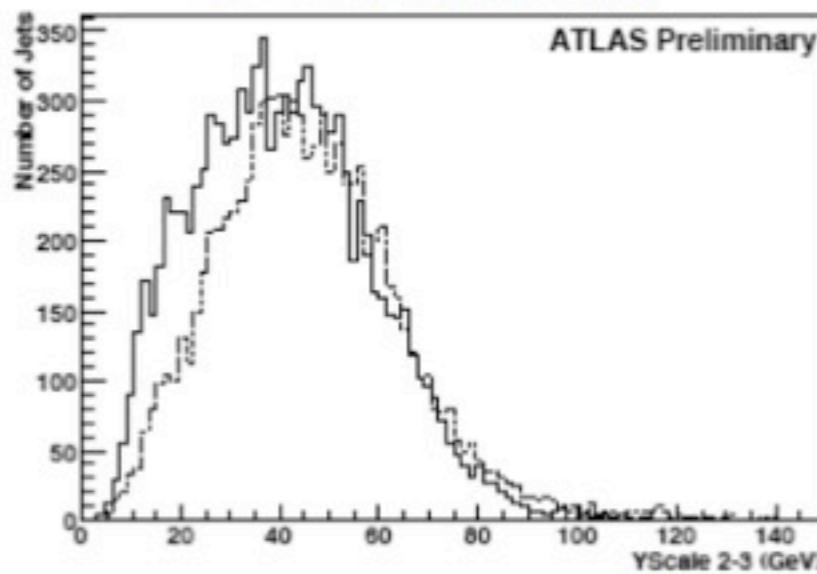
Jet Mass



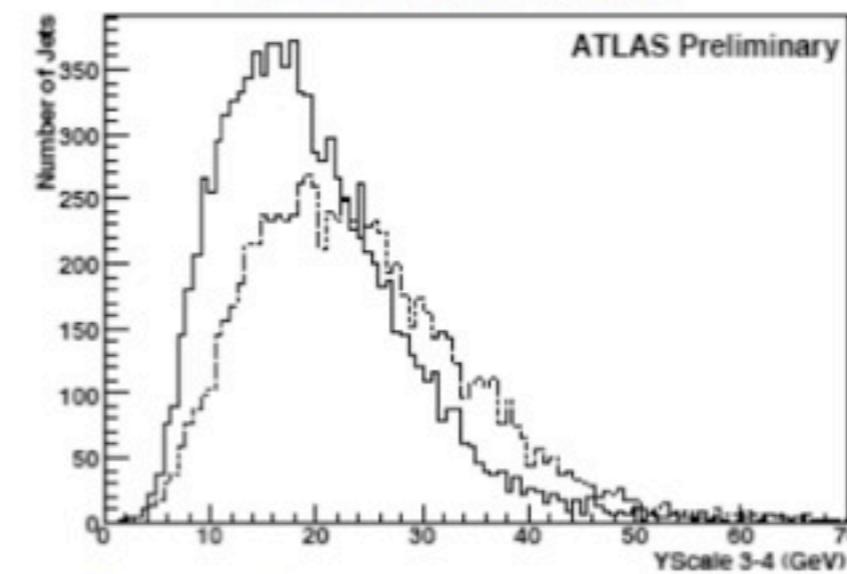
1 → 2 Jet Scale



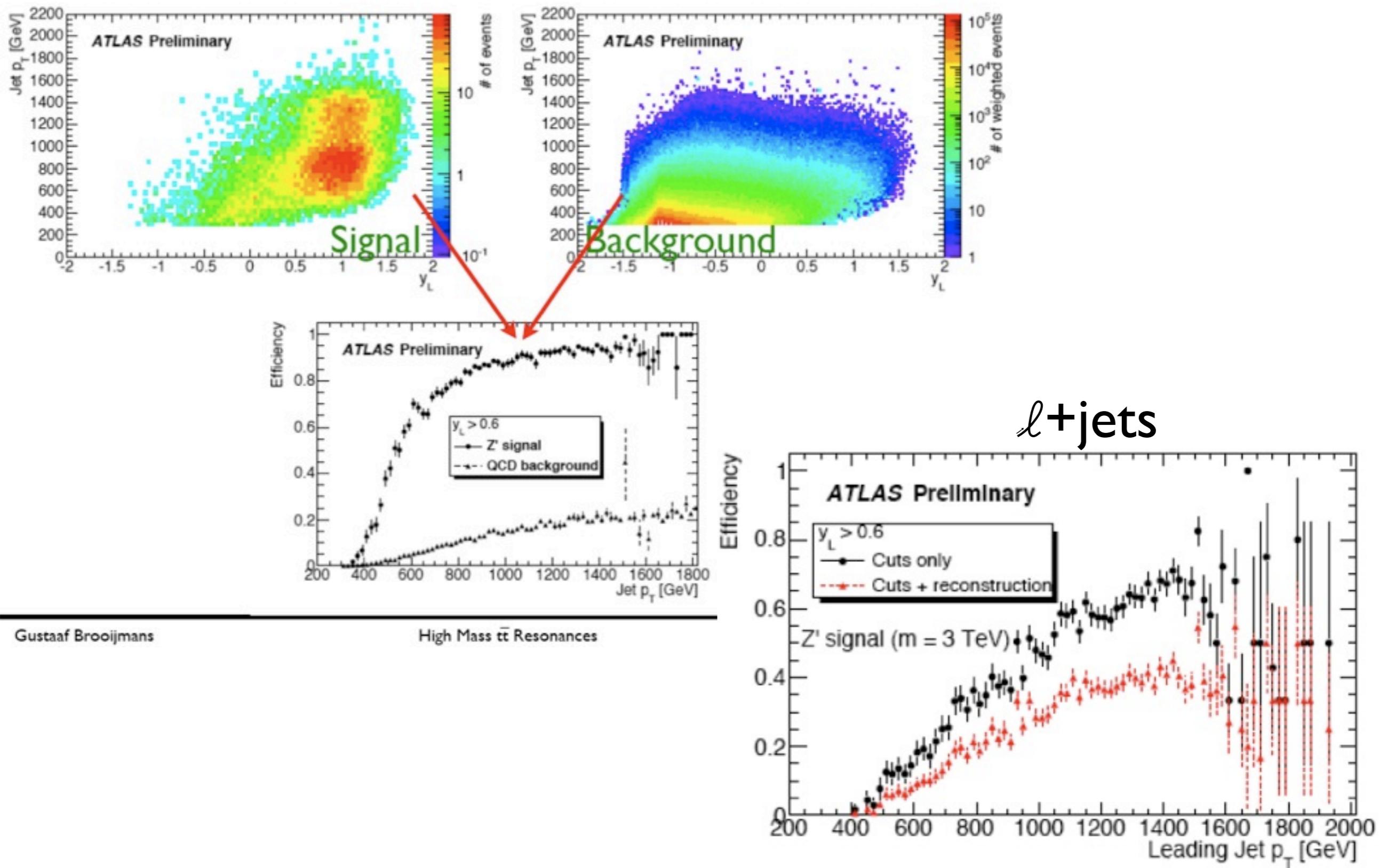
2 → 3 Jet Scale



3 → 4 Jet Scale

ATL-PHYS-CONF-2008-008Slow p<sub>T</sub> Dependence!

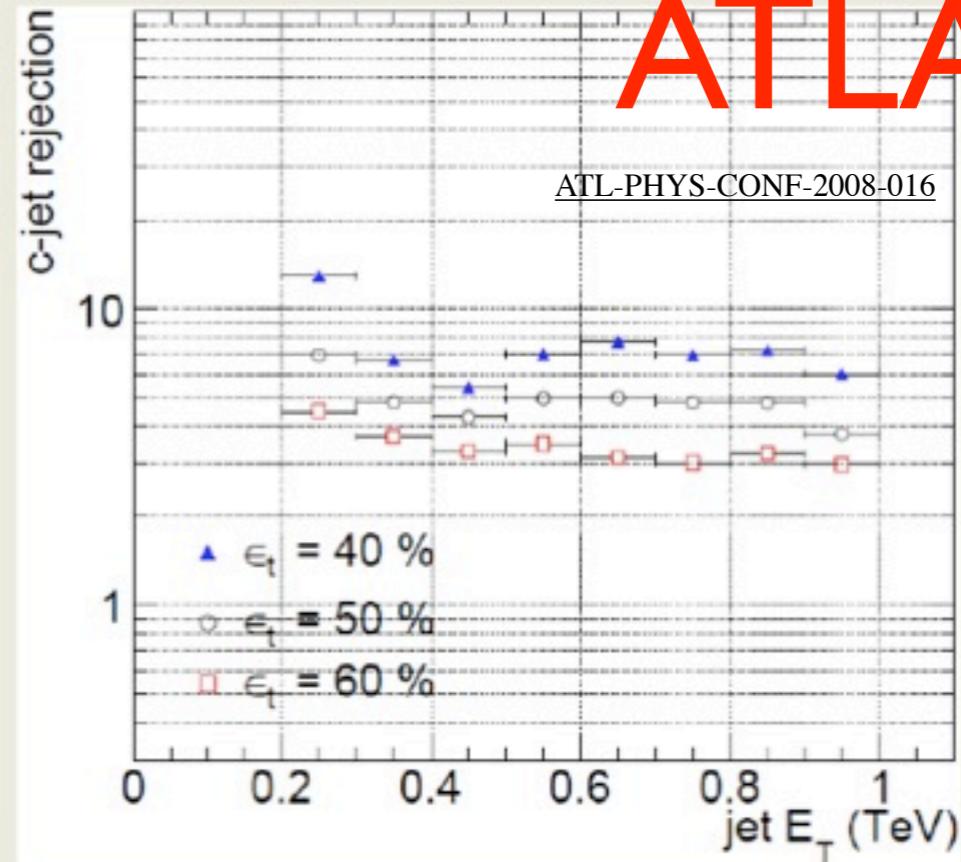
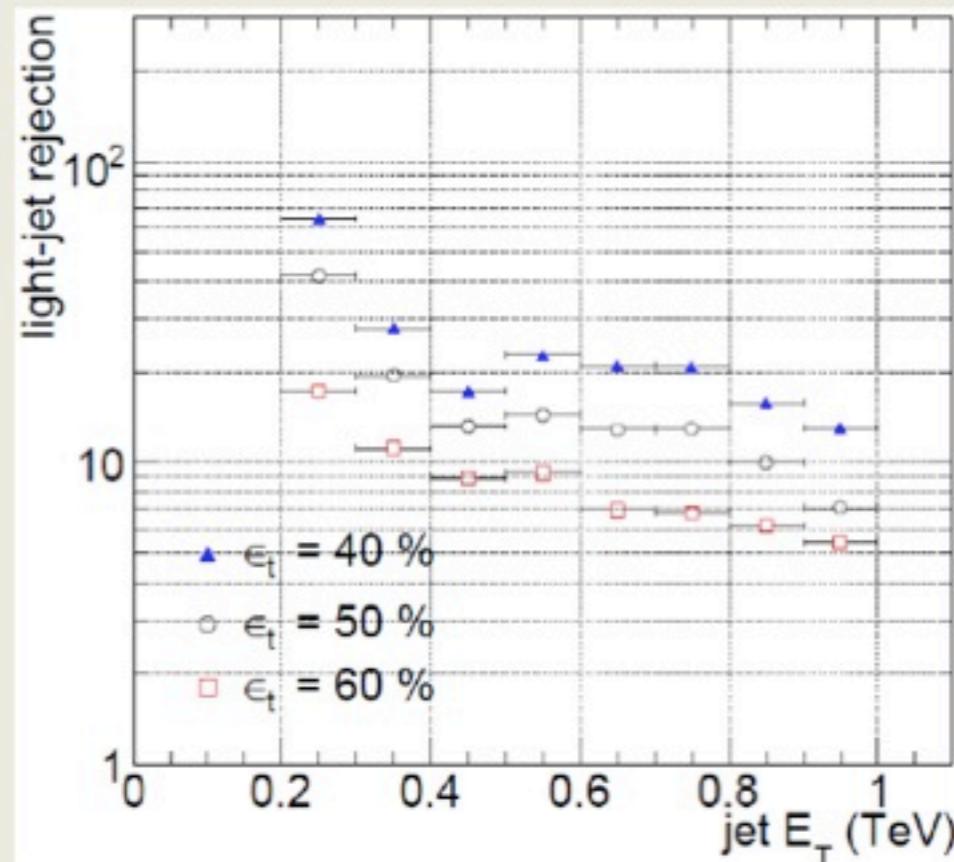
# Hadronic Decays: Result



# • Does b-tagging still work?

TadaAki Isobe, Tokyo, ATLAS

## Top mono-jet tagging performance with the application of b-tagging



ATLAS

- Use IP3D+SV1 algorithm
- In the case of leptonic W decay, tagging performance is comparable with that for normal b-jet
- Light jet rejection power of  $\sim 20$  for 40% efficient high-pT top mono-jet identification (up to  $E_T=800\text{GeV}$ )

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- First real data lepton jets analysis also at Boost 09:

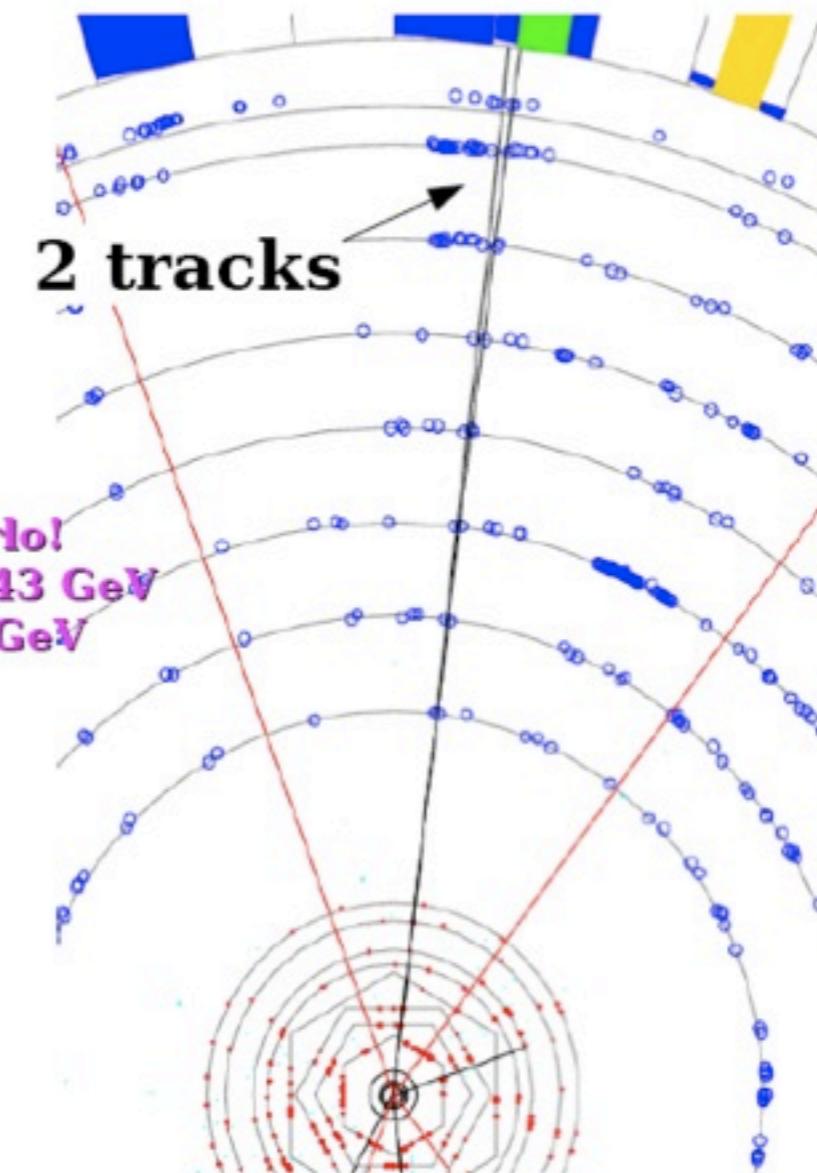
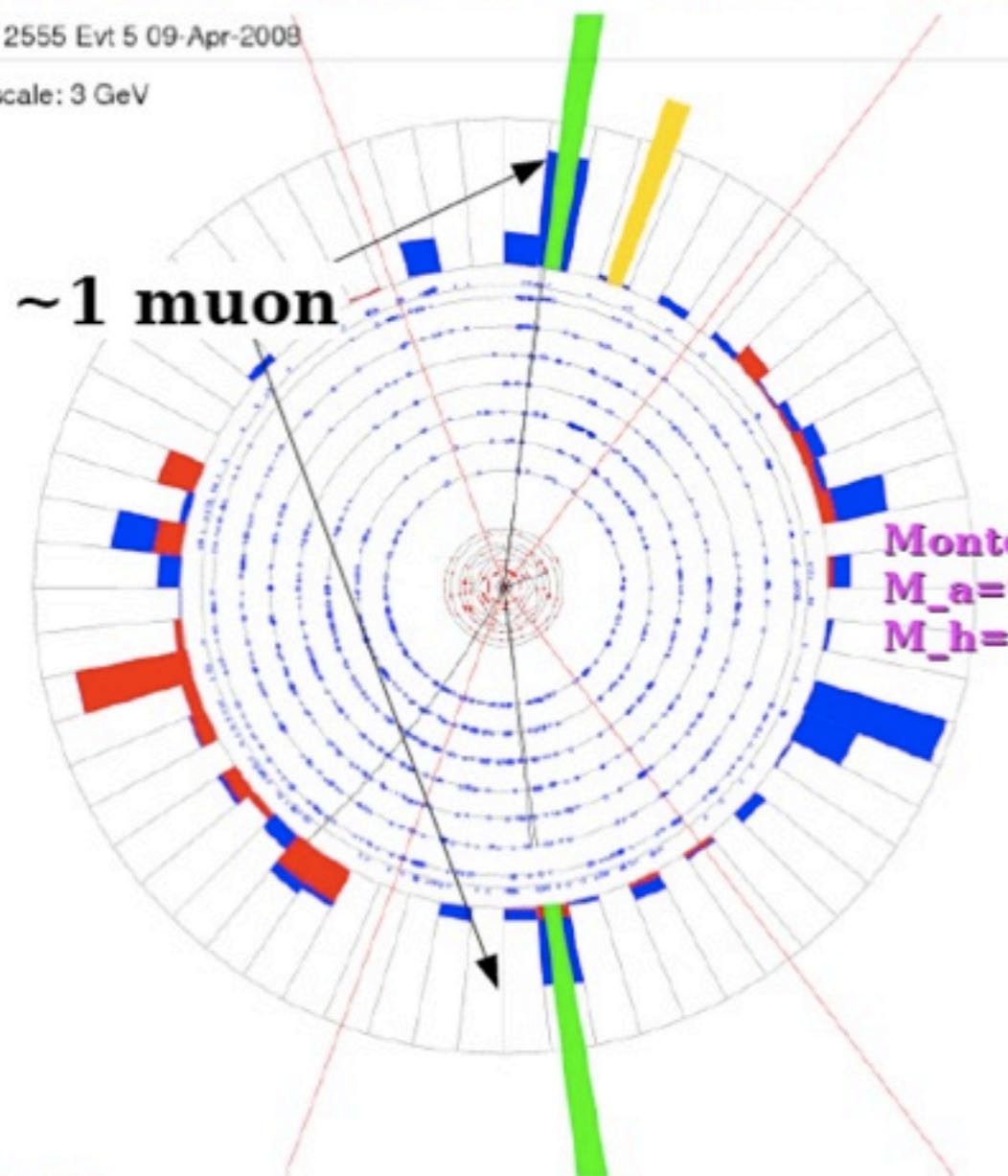
$h \rightarrow aa \rightarrow 4\mu$

Muon pairs can be extremely collinear !

Essentially a search for pairs of (2 muon) **lepton-jets**

[Phys.Rev.Lett.103:061801,2009](#)

DO



**SLAC**  
NATIONAL ACCELERATOR LABORATORY

Andy Haas - 7/9/09

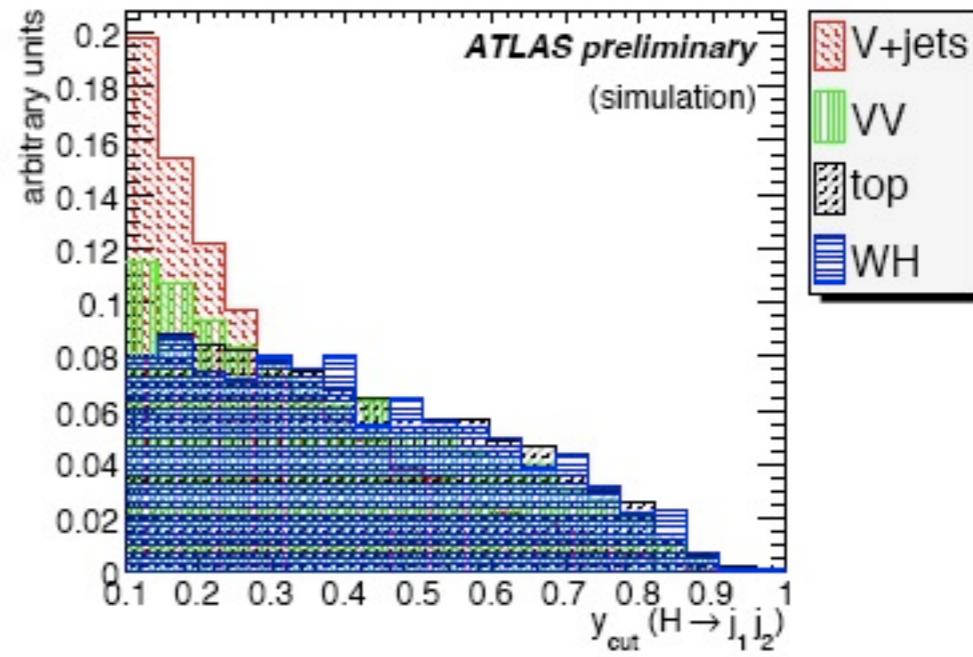
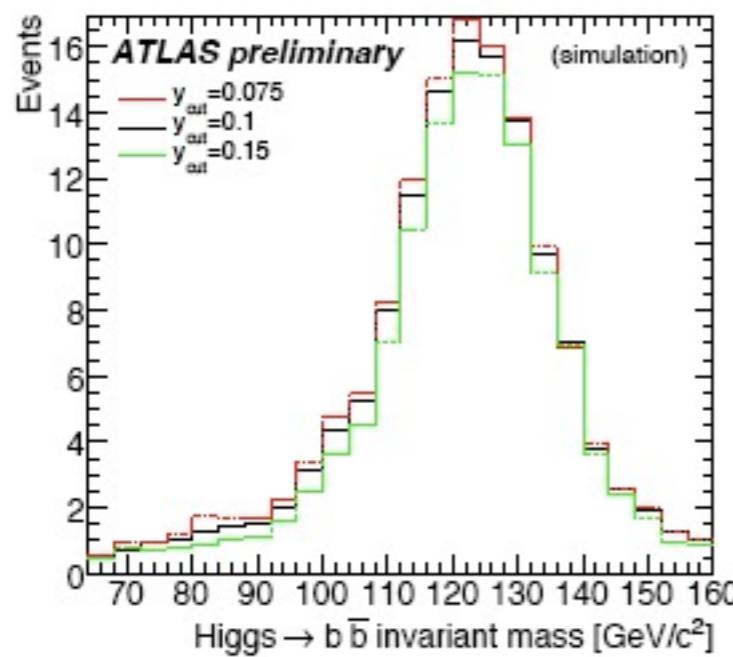
Slide 8

DO

# Since Boost 09

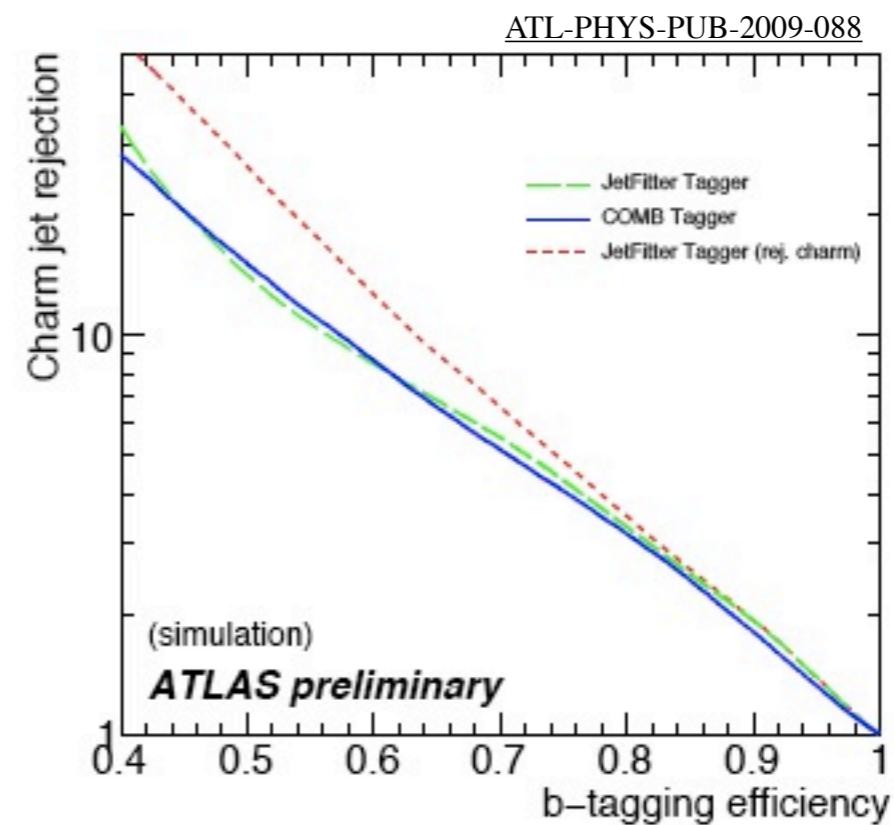
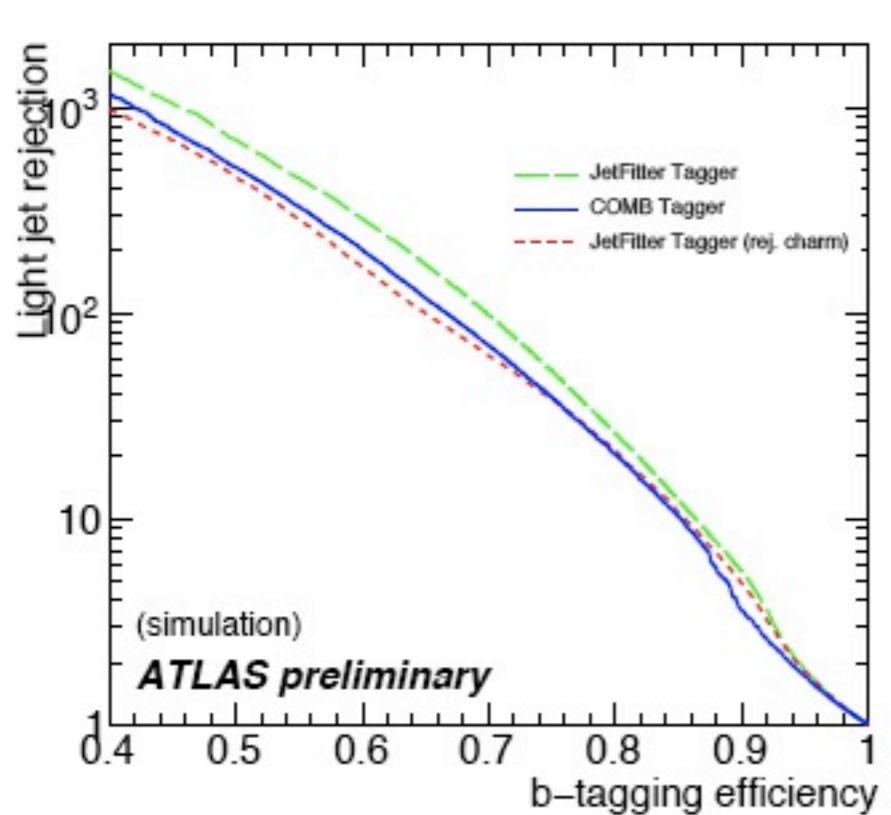
- Expand to other topics: “CA mass-drop” substructure algorithm (Butterworth, Davison, Rubin, Salam: [Phys.Rev.Lett.100:242001,2008](#)) and searches for  $b\bar{b}$  Higgs decays

1. Break the jet  $j$  into two subjets by undoing its last stage of clustering. Label the two subjets  $j_1, j_2$  such that  $m_{j_1} > m_{j_2}$ .
2. If there was a significant mass drop (MD),  $m_{j_1} < \mu m_j$ , and the splitting is not too asymmetric,  $y = \frac{\min(p_{tj_1}^2, p_{tj_2}^2)}{m_j^2} \Delta R_{j_1, j_2}^2 > y_{cut}$ , then deem  $j$  to be the heavy-particle neighbourhood and exit the loop. Note that  $y \simeq \min(p_{tj_1}, p_{tj_2}) / \max(p_{tj_1}, p_{tj_2})$ .
3. Otherwise redefine  $j$  to be equal to  $j_1$  and go back to step 1.

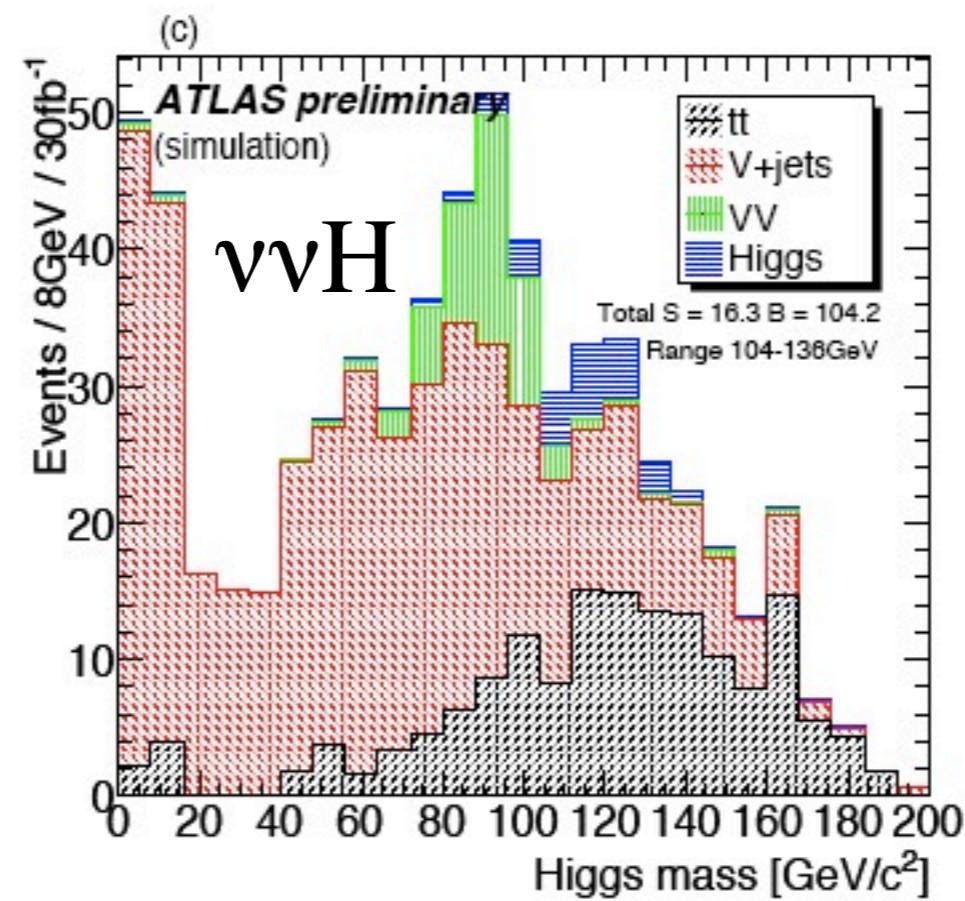
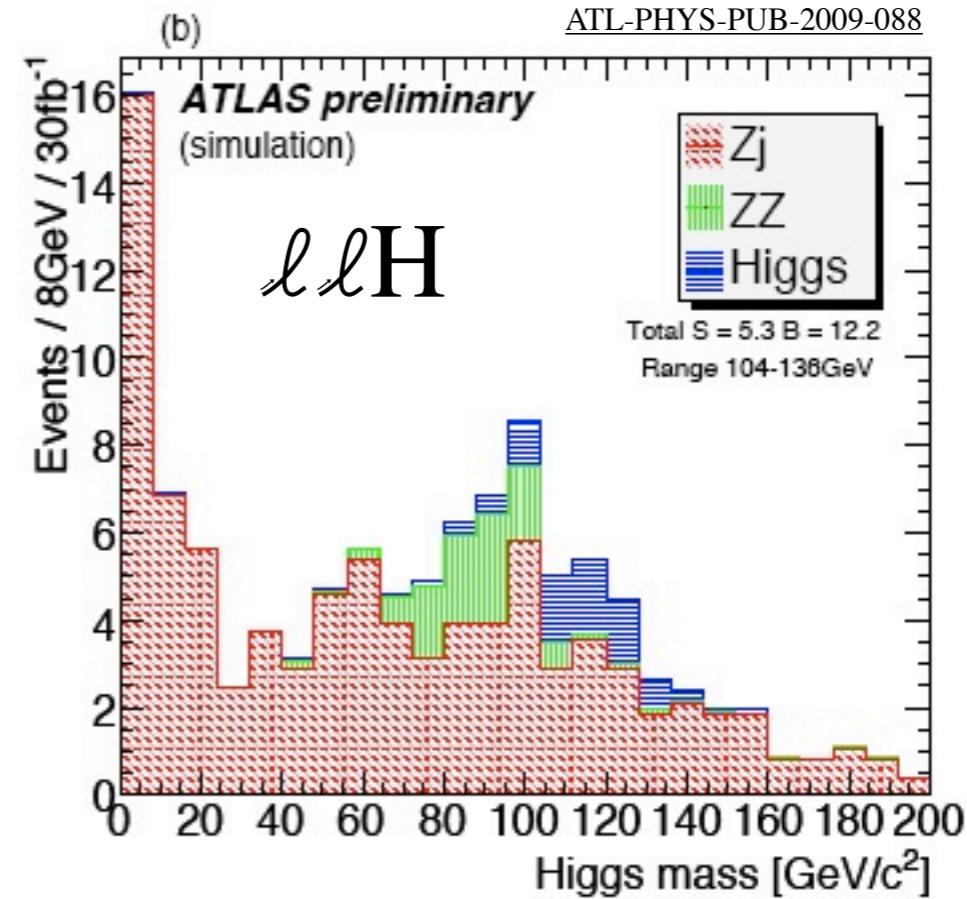
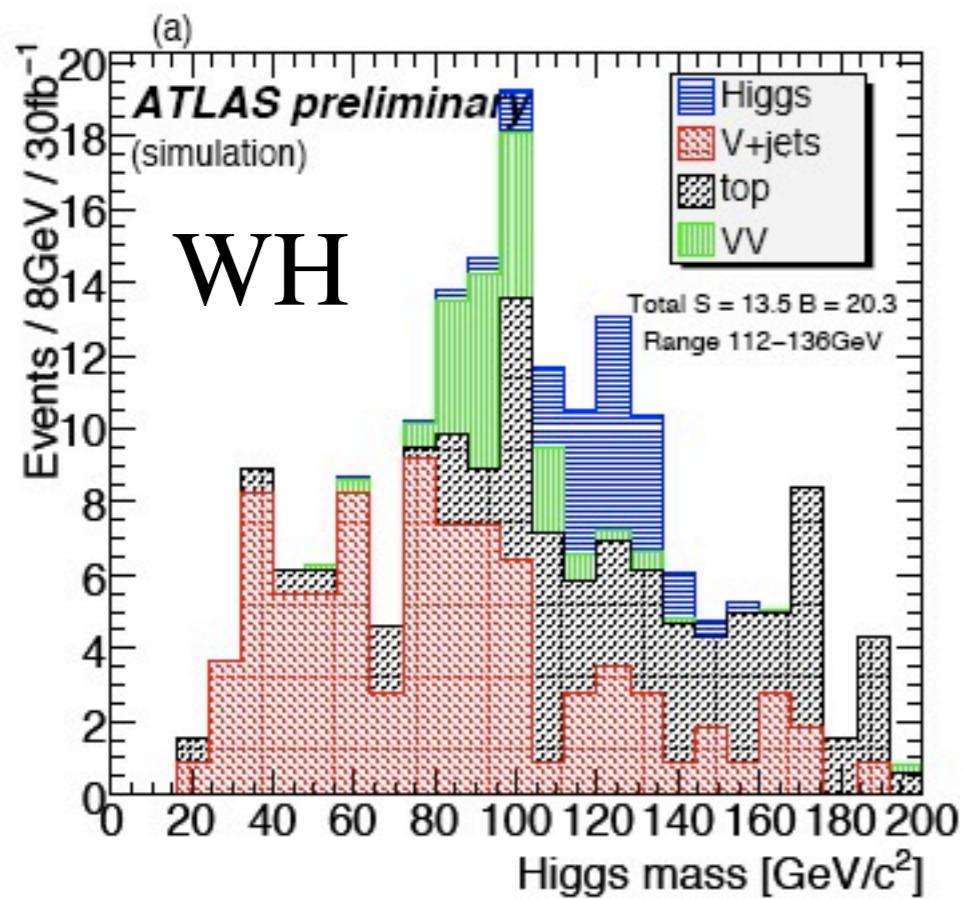


[ATL-PHYS-PUB-2009-088](#)

- b-tagging works very well for jets that pass:



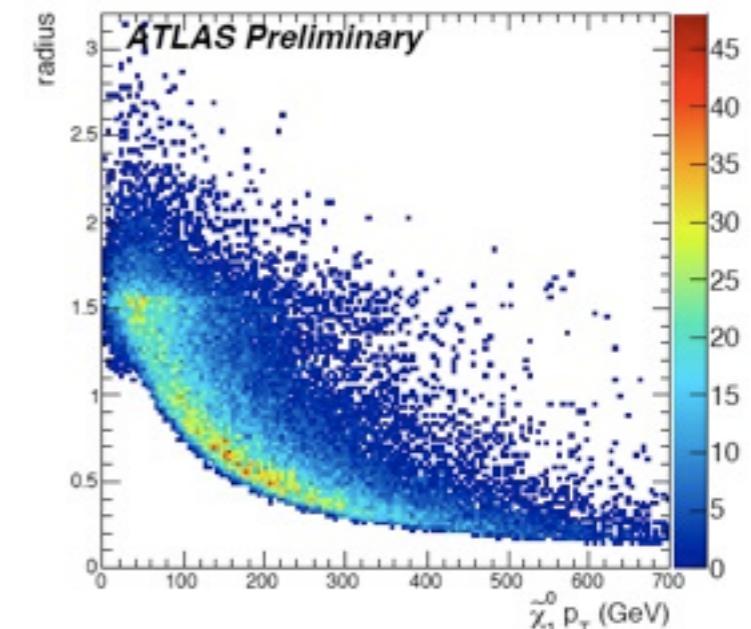
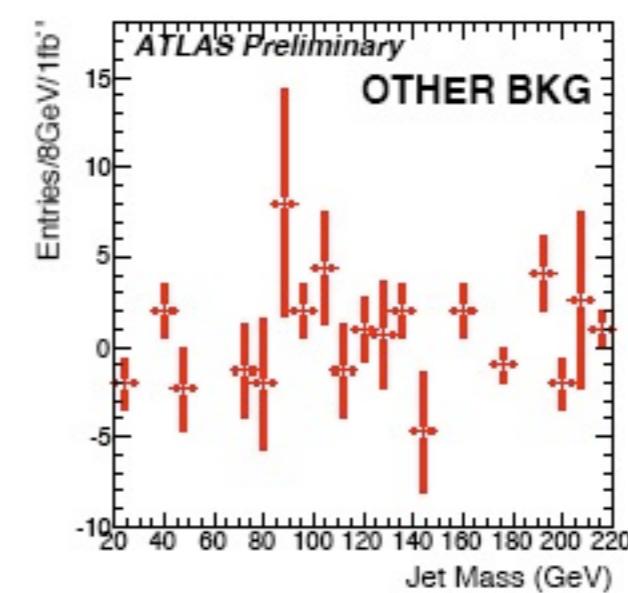
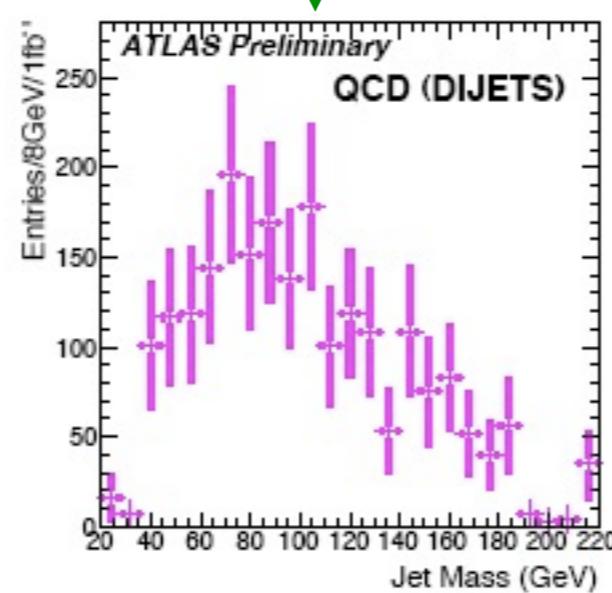
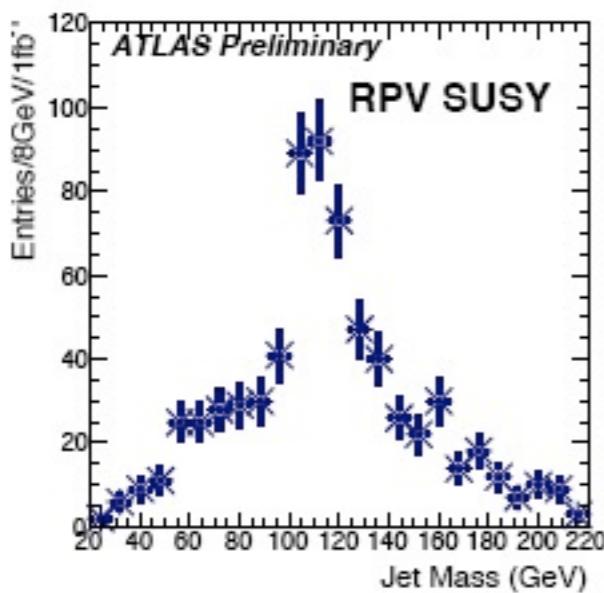
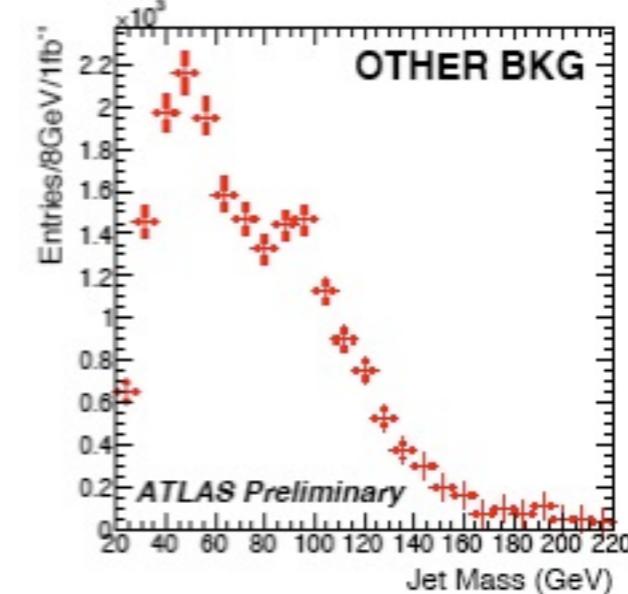
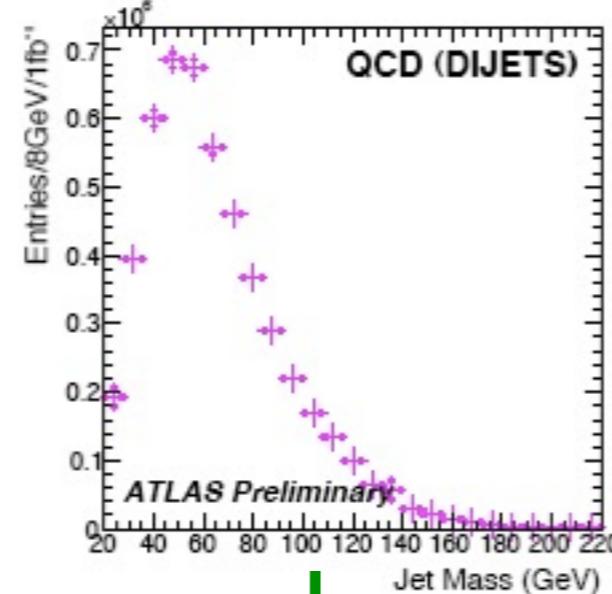
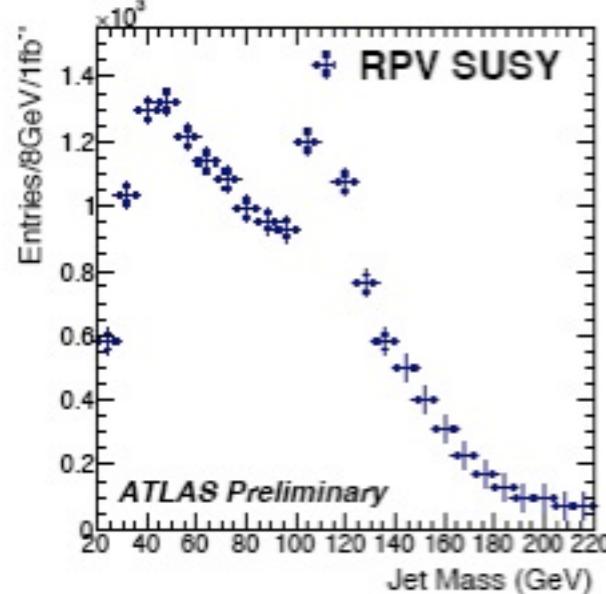
- Here,  $p_T > 200$  GeV, b-tagging only uses tracks within  $\Delta R < 0.4$  of candidate subject
  - Each track can belong to only one subject
  - Don't know that this is completely understood



3+  $\sigma$  with  $30 \text{ fb}^{-1}$ ?

# ● $k_T$ applied to RPV SUSY:

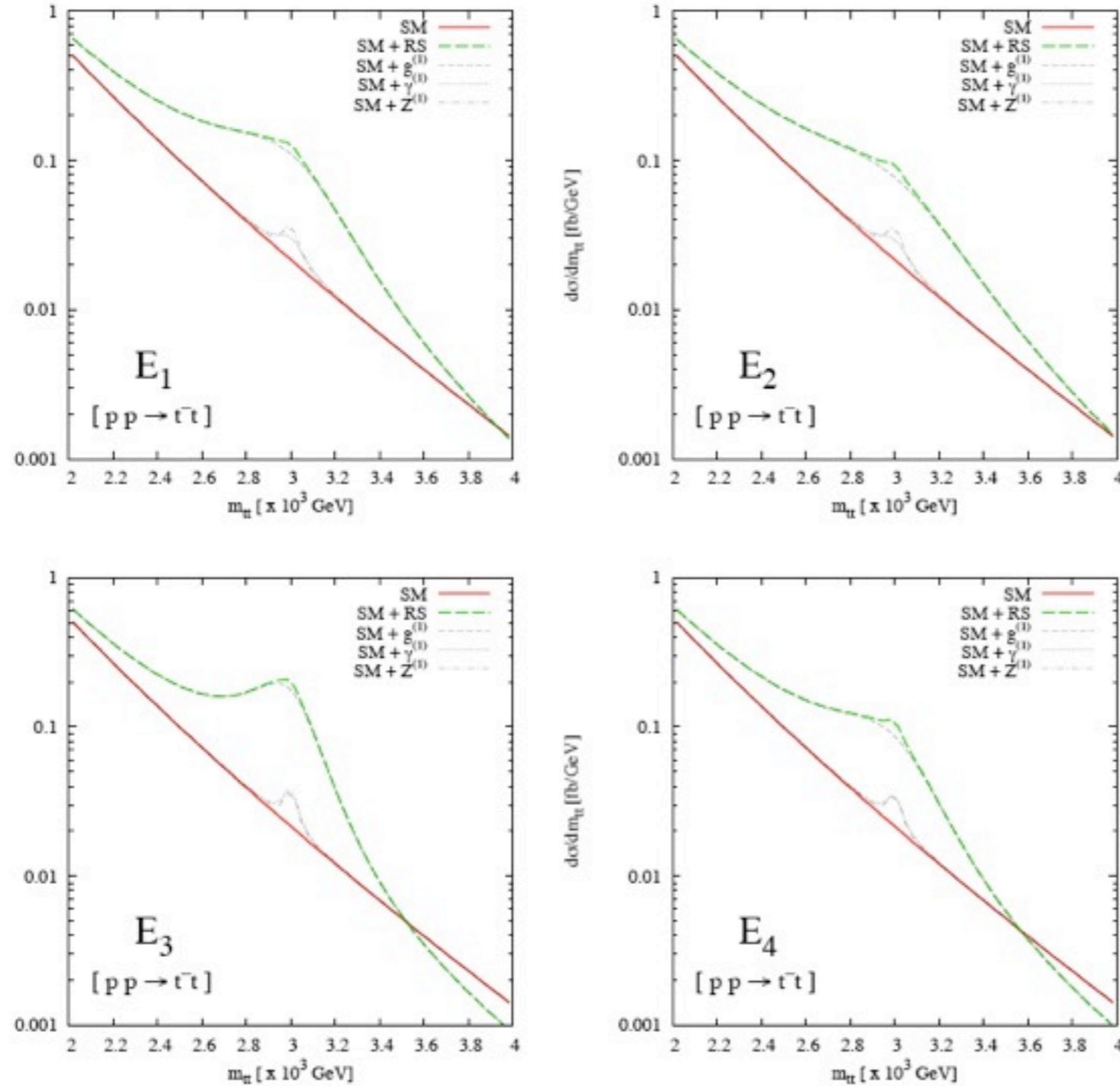
- Ask for two jets with  $p_T > 275$  GeV
- Apply 2-D cuts on splitting scales



[ATL-PHYS-PUB-2009-076](#)

- ATLAS  $\ell + \text{jets}$  result 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](#)

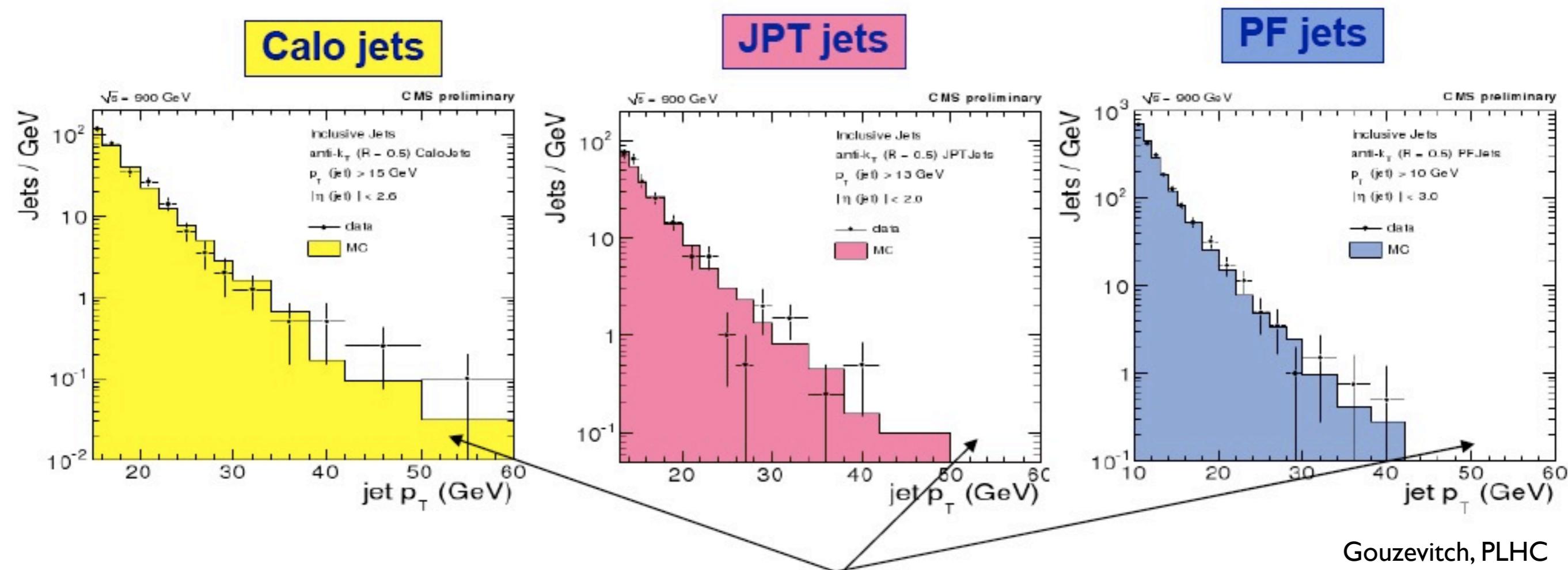


Signal Model	Integrated Luminosity for 95% C.L. Exclusion ( $\text{fb}^{-1}$ )
E1 + SM	2.5
E2 + SM	5.4
E3 + SM	1.8
E4 + SM	6.7

(14 TeV)

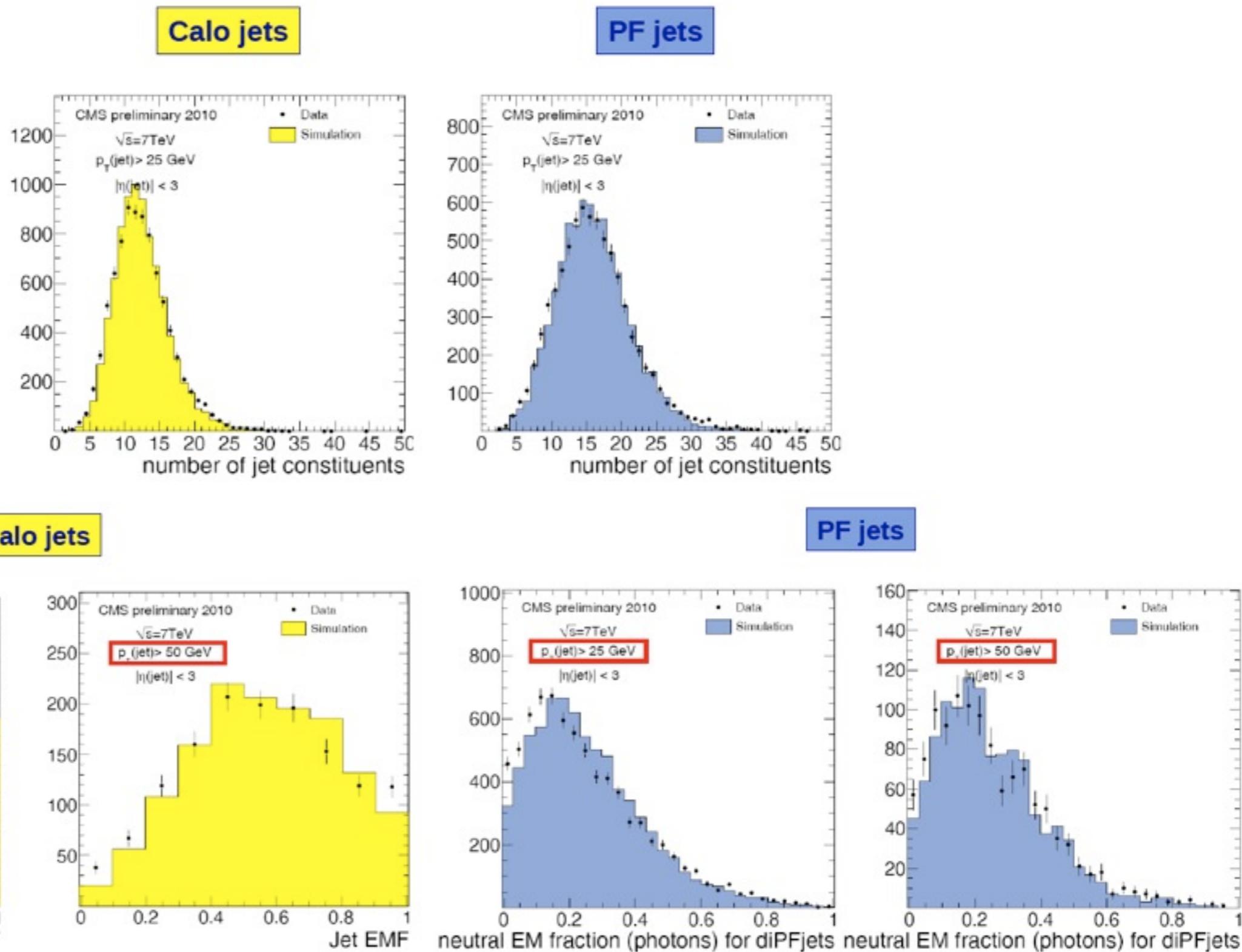
# Now: CMS

- CMS uses “Calo”, “JPT” (replace tower by track if matched) and “PF” (particle flow) jets
- Increase in complexity but better resolution



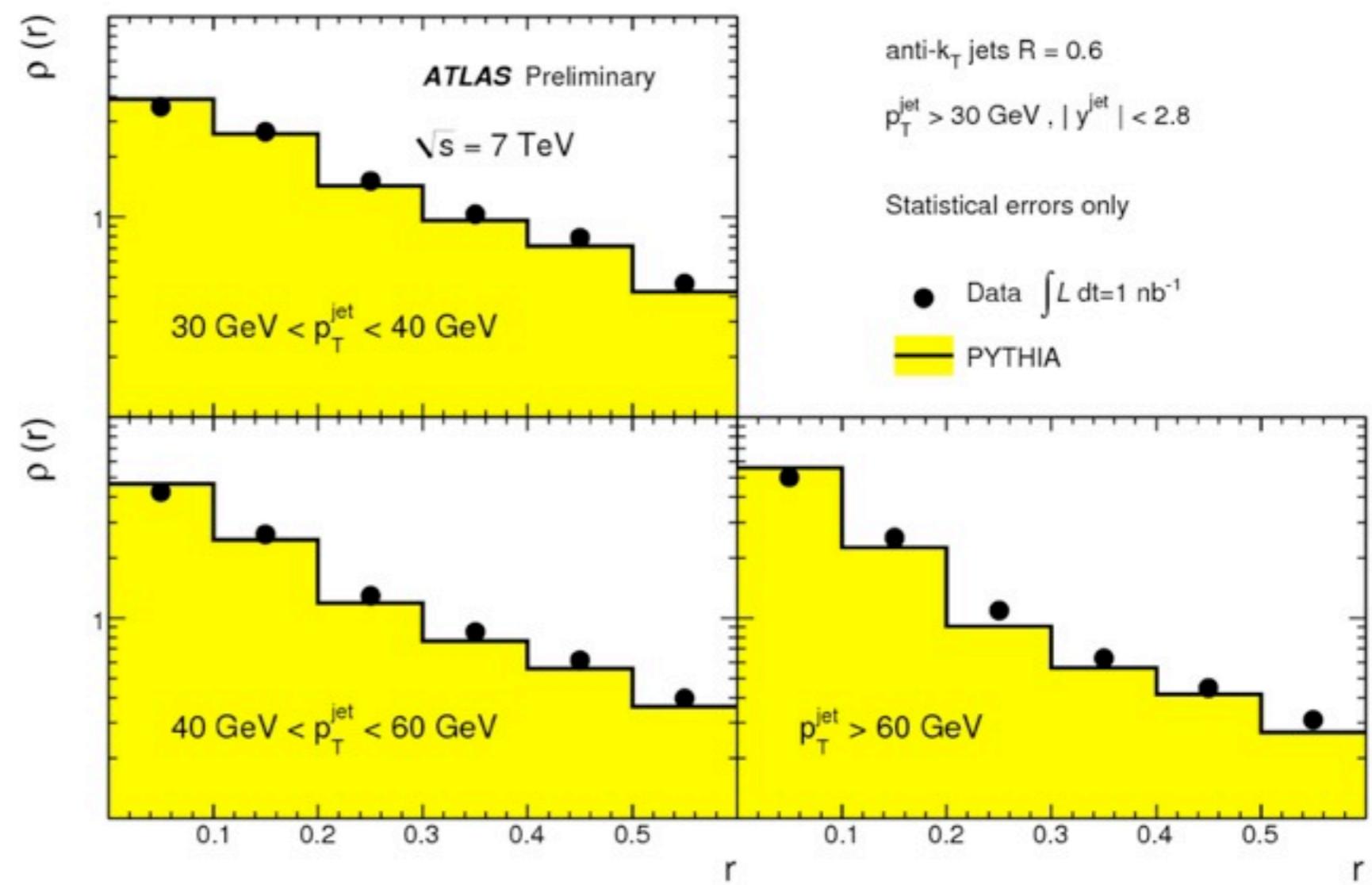
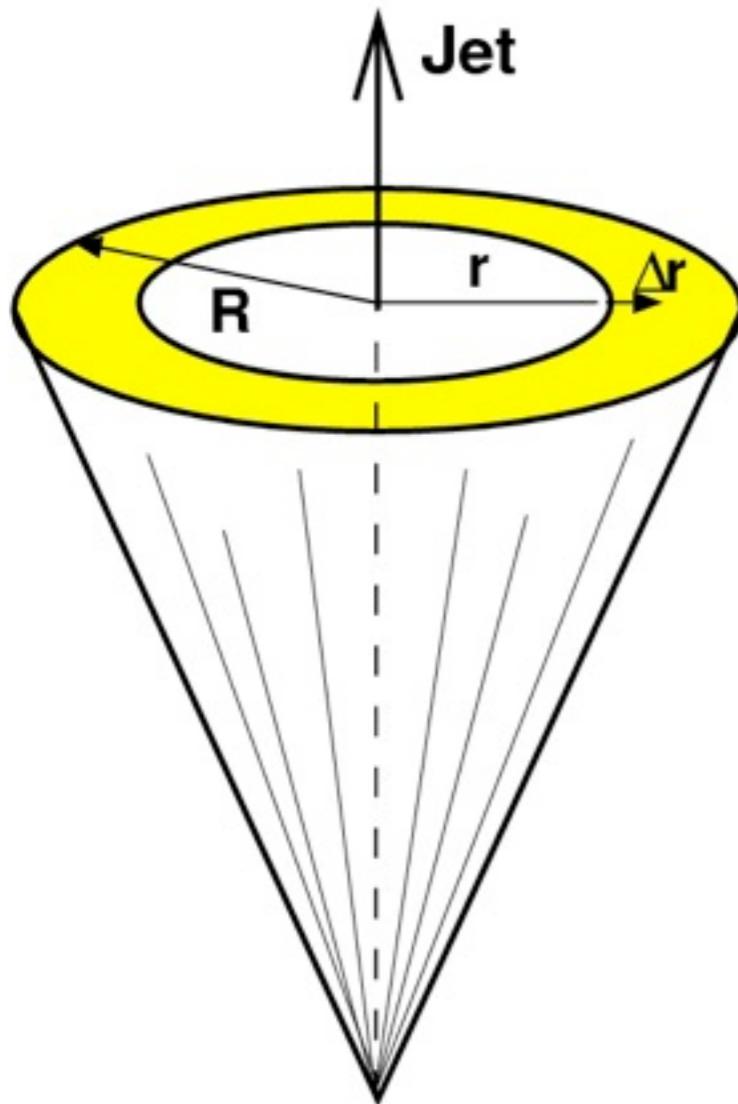
Improving resolution

# ● First look at jet structure

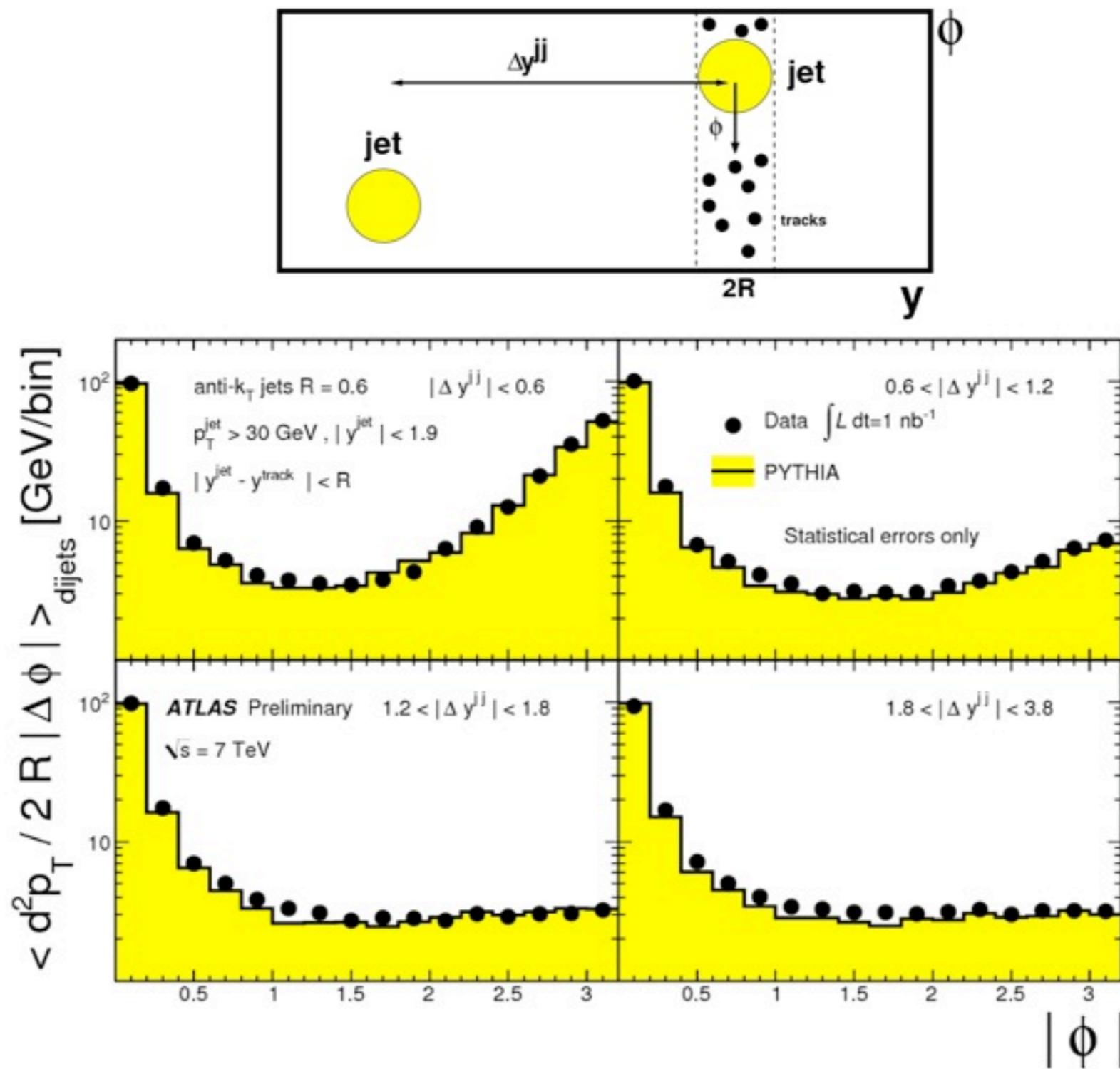


# Now: ATLAS

- Jet shape:  $\rho(r) = \frac{1}{\Delta r} \frac{1}{N_{jet}} \sum_{\text{jets}} \frac{p_T(r - \Delta r/2, r + \Delta r/2)}{p_T(0, R)}, 0 \leq r \leq R$



- Charged particle flow:  $\langle \frac{d^2 p_T}{|d\phi| dy} \rangle_{jets} = \frac{1}{2R|\Delta\phi|} \frac{1}{N_{jet}} \sum_{jets} p_T(|\phi - \Delta\phi/2|, |\phi + \Delta\phi/2|)$



# Future

- “Calibration”
  - Need to establish the validity/efficiency/rejection of these techniques on real data: prerequisite to any new physics search
- W/Z+jets in multijet events
  - Adam Davison
- Hadronic W in tt l+jets events
  - Better S/B?

# Expanding Phase Space

- Phenomenological developments have shown interesting potential
  - Lower  $p_T$  threshold & wider jets
  - See e.g. Michael Spannowsky's talk at Seattle workshop (ttH)  
Plehn, Salam, Spannowsky: [Phys.Rev.Lett.104:111801,2010](#)
    - Can improve over a narrow jets analysis...
    - ... partially due to new variables like “mass drop”?
- How low and wide can we go?
- Do we now have the tools to move to a more “inclusive” analysis of the full event?
- Can these tools help for lepton/photon jets?

# Potential Trouble?

- Pair of objects forming a jet

- $m^2 = p_T^2 dR^2 z (1-z)$

→  $m \sim p_T dR/2$  if momentum is ~evenly shared

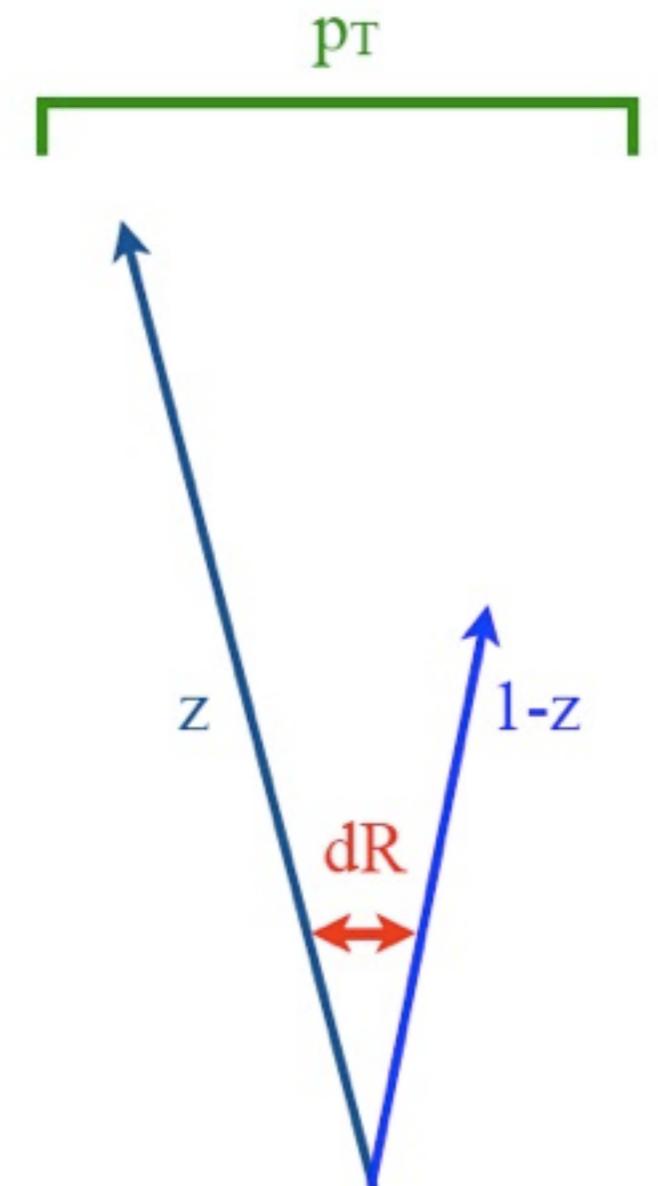
- $p_T \sim 150 \text{ GeV}$ ,  $m \sim 75 \text{ GeV}$

- $2m/p_T = 1 \sim dR$

- Just a little under  $2R$  for anti- $k_T$  0.6

- We will be probing the region where jets “naturally” merge

- Also where matching phase space coverage is tricky for ME generators!



# Conclusions

- Quite a bit of progress in the recent past
- Next year will see first observations in data
  - Emphasis on SM signals is important: W best candidate
  - Signal is in a tricky area for simulation
    - Depends on jet finder
    - What about JES corrections & uncertainties?
- How far can the technique be expanded?
- The future starts here!