Substructure: a discovery tool at the LHC

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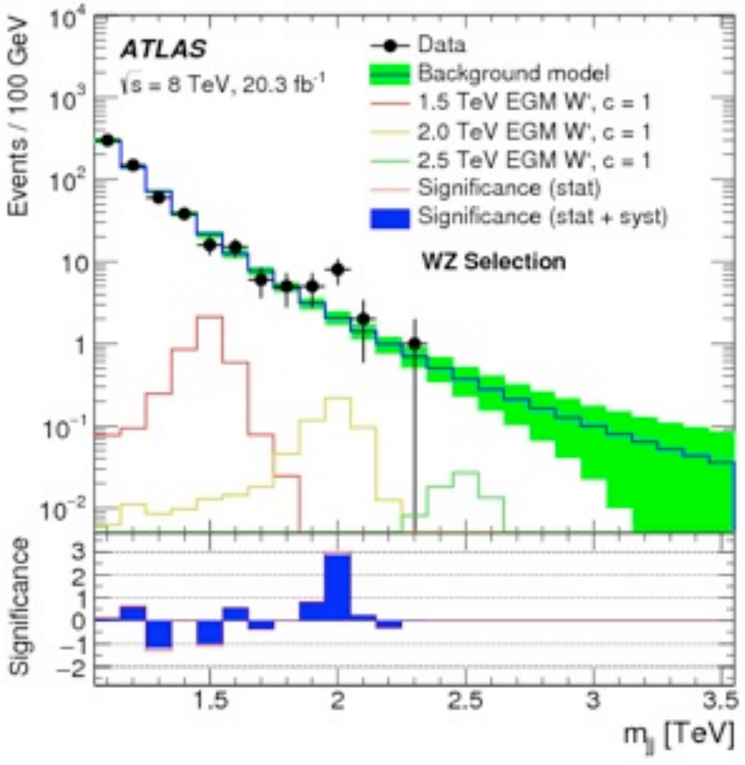
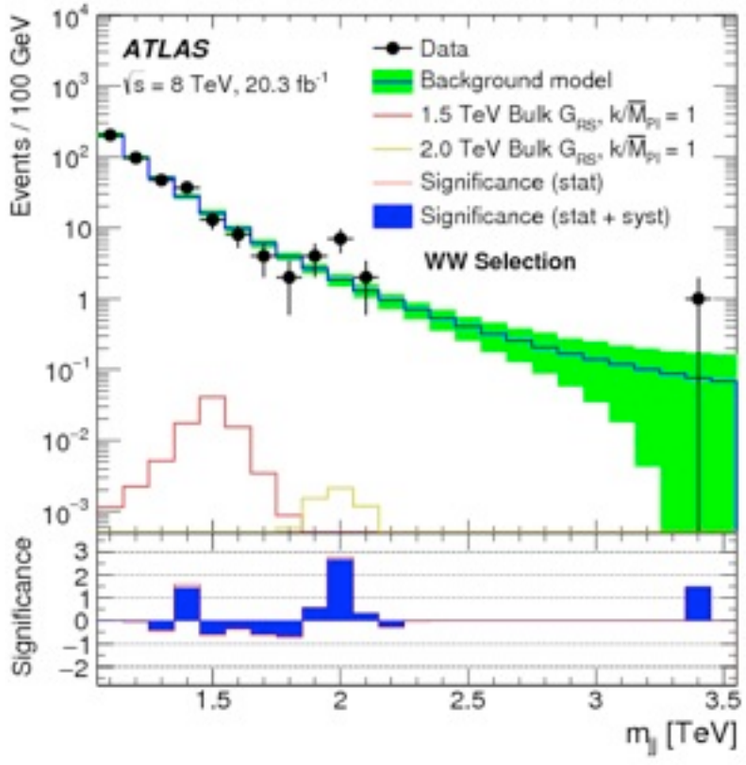
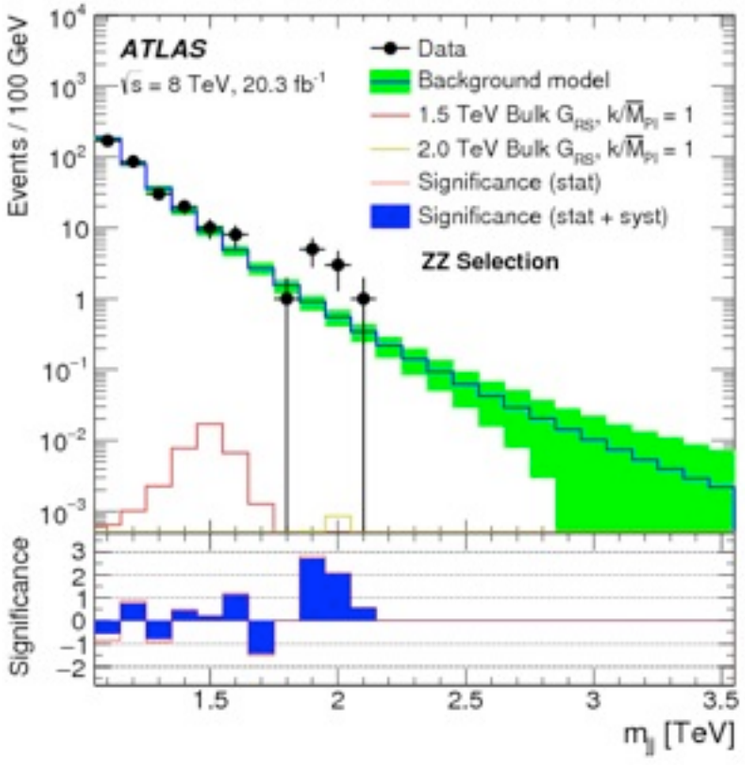
University of Witwatersrand

SAIP Meeting 2015
Port Elizabeth

Search for high mass di-boson resonance



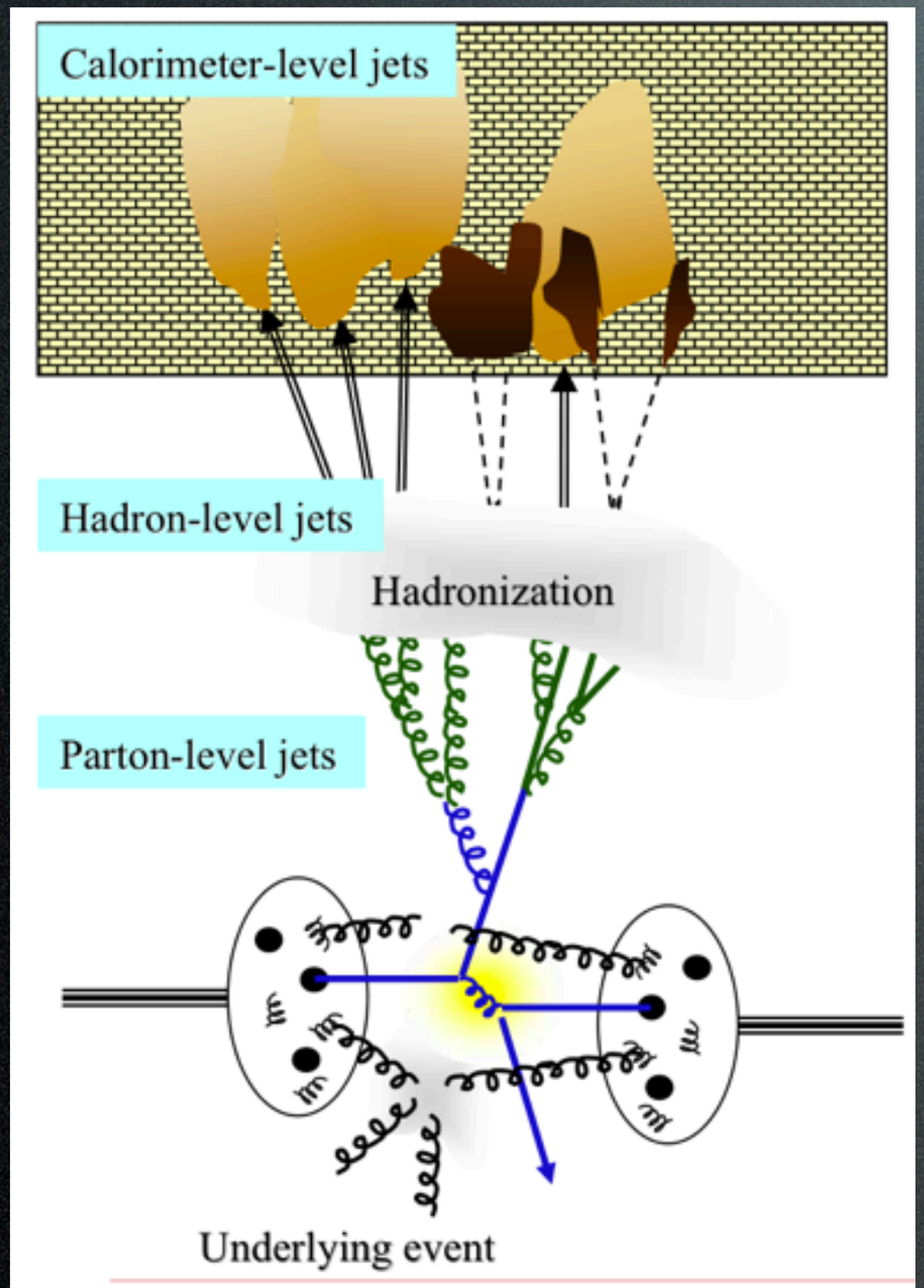




Are they real? How to find out in Run 2?

arXiv:1506.00962 [hep-ex]

Jets



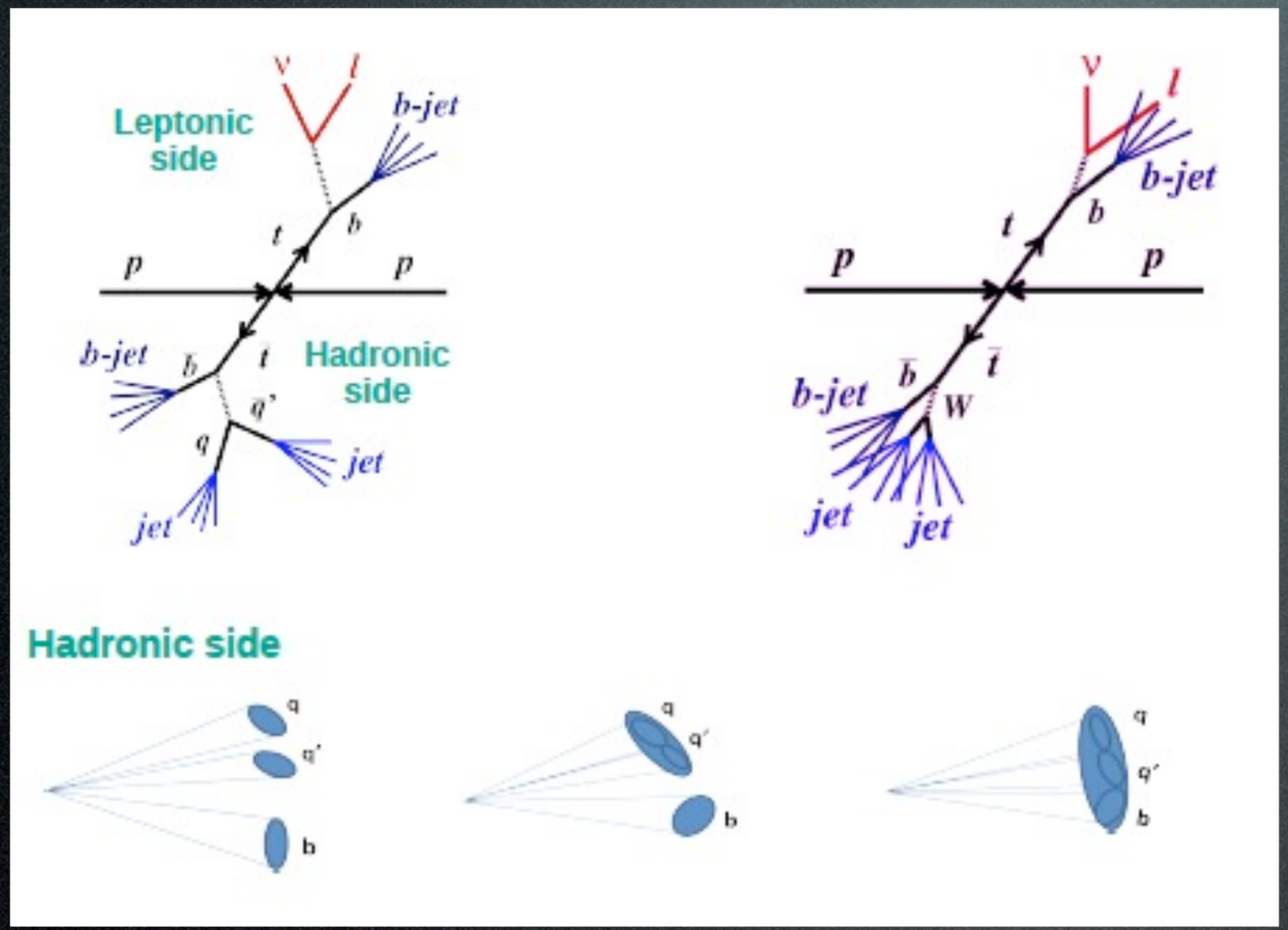
Used as a proxy for (everything coming out from) single quark or gluon originating in hard scatter

As close as we can get to a physical single hard quark or gluon

3

Jet Substructure in Brief

Large radius jets



The angular resolution of the decay products: $\Delta R \approx 2m/p_T$

So for a top quark (of mass 173 GeV) with $p_T > 350$ GeV, we have $\Delta R \sim 1$.

With increasing c.m energy: collimated decay products from boosted heavy particles result in a single massive jet.

So when you take apart a jet, what does it look like?

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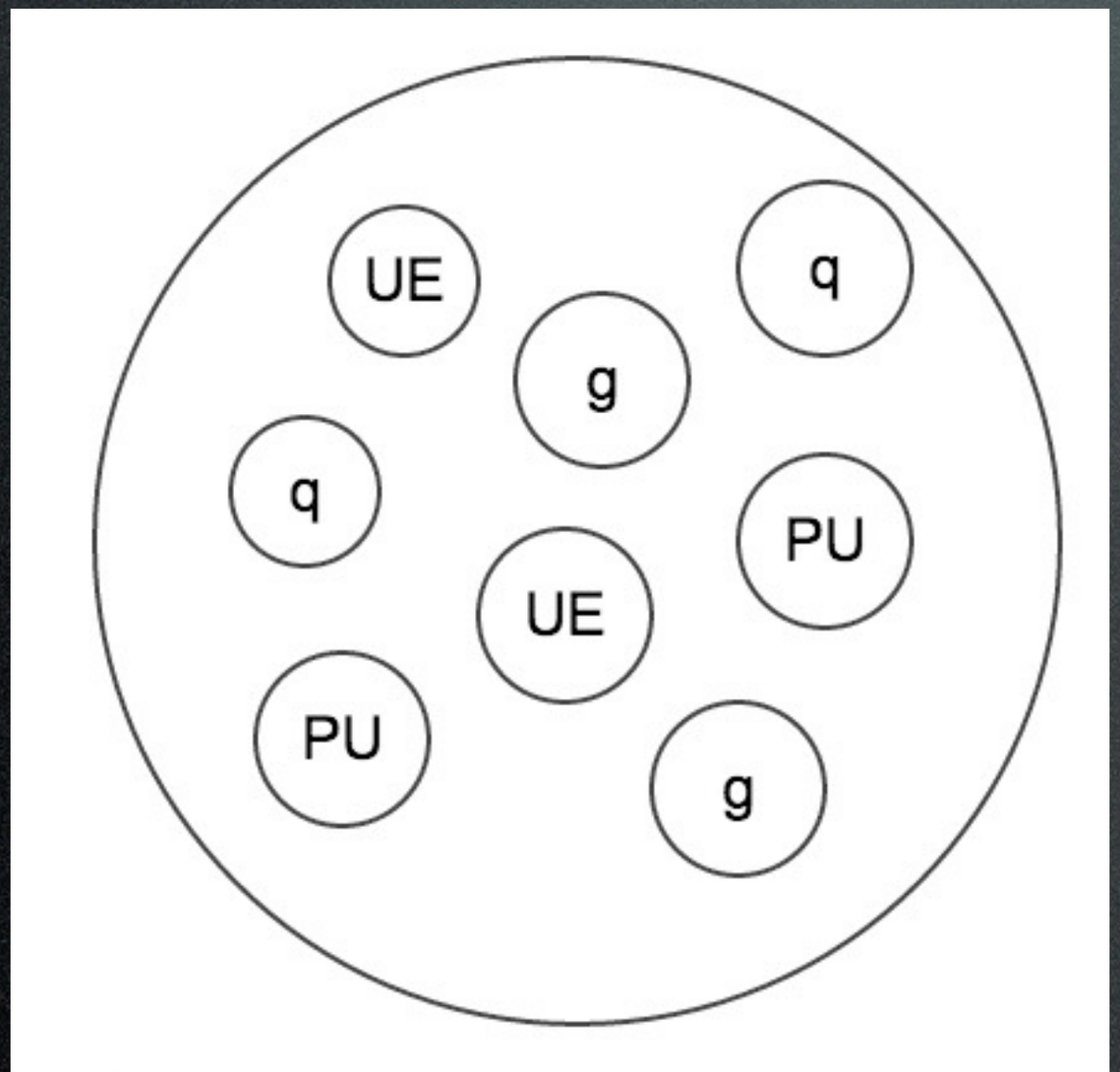


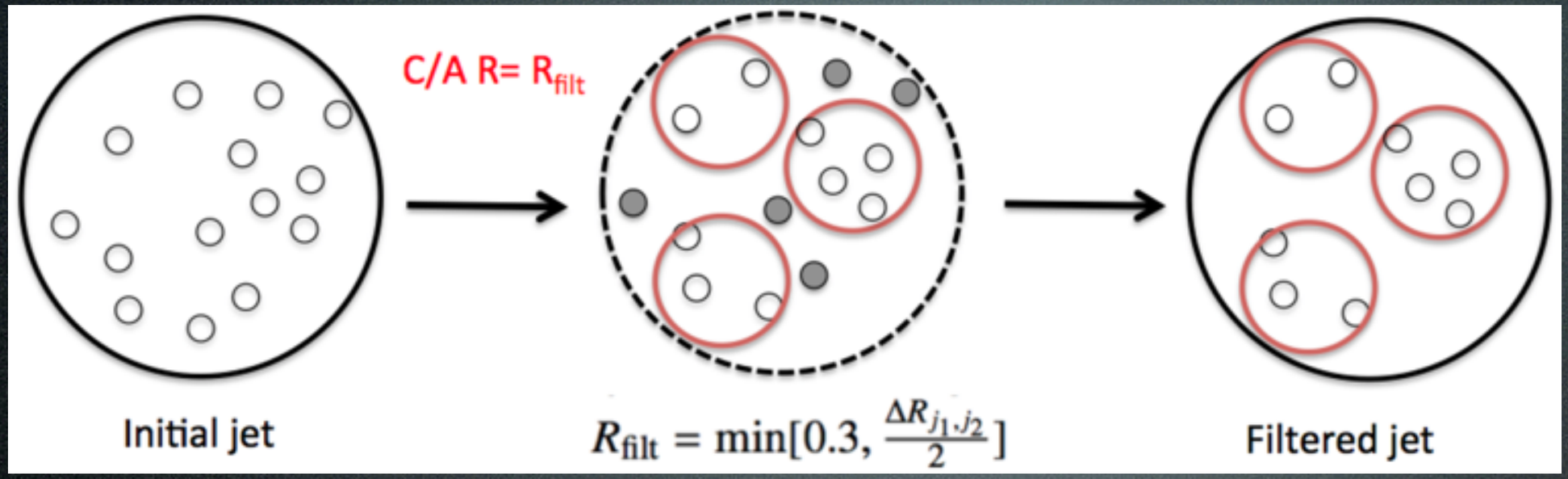
We want to exploit the "substructure" of the large-radius jet to identify original particles

Substructure Techniques

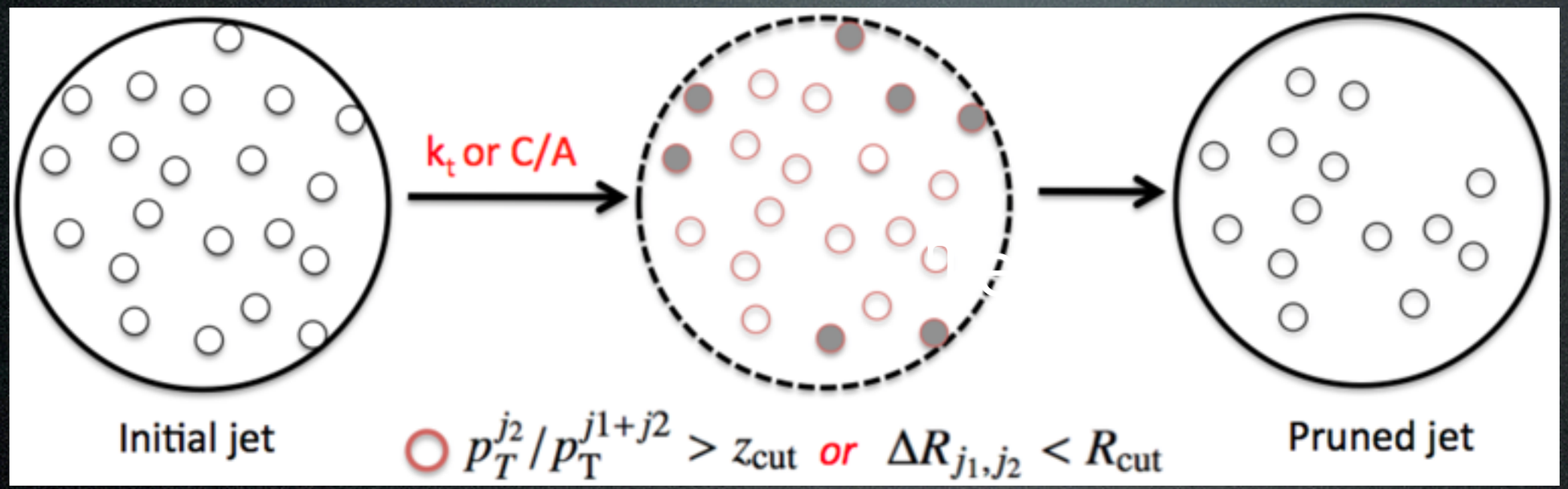
- Jets need to be “groomed”.

The large-radius jets not only include particles coming from the interesting decays, but also from pileup, underlying event ....

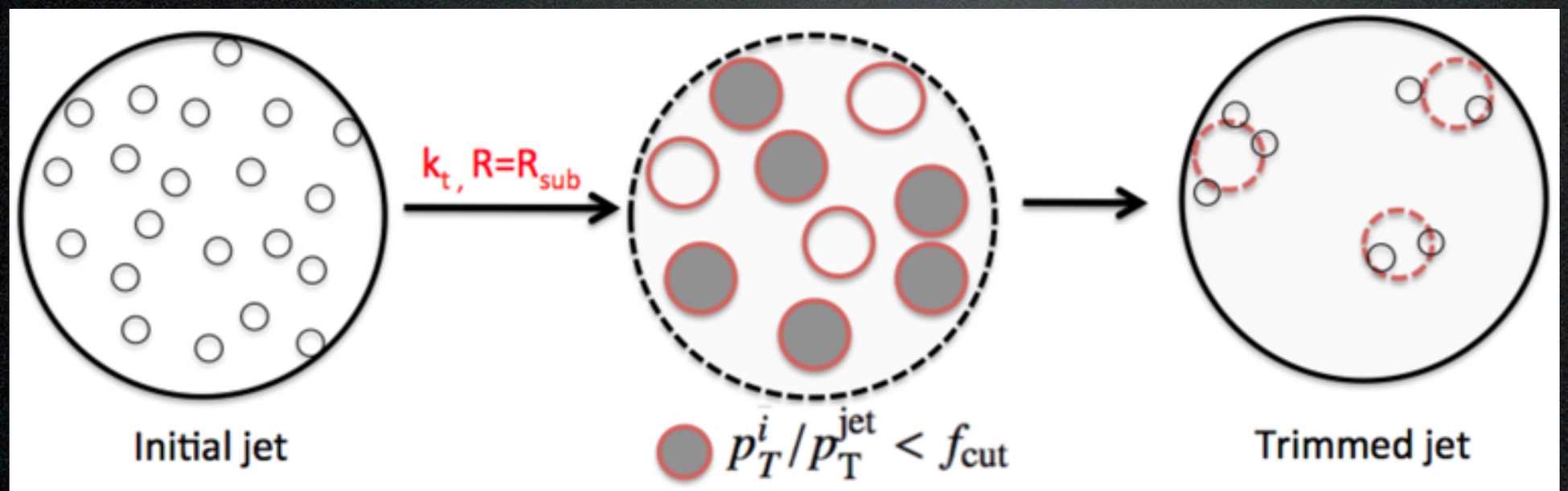
- Need observables which would be sensitive to signal-like or background-like nature of these jets.



Filtering

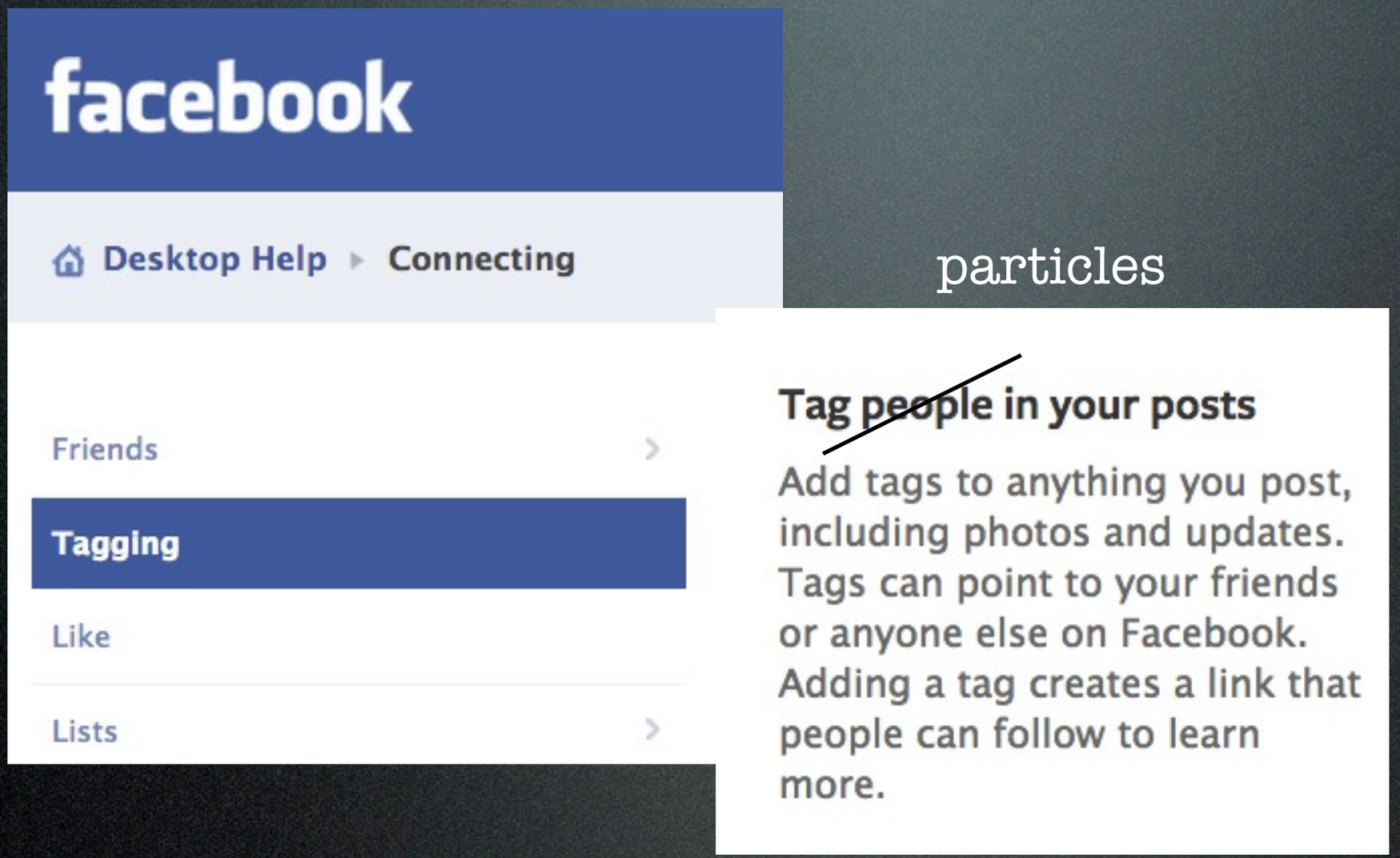


Prunning



Trimming

Tagging Top or Higgs



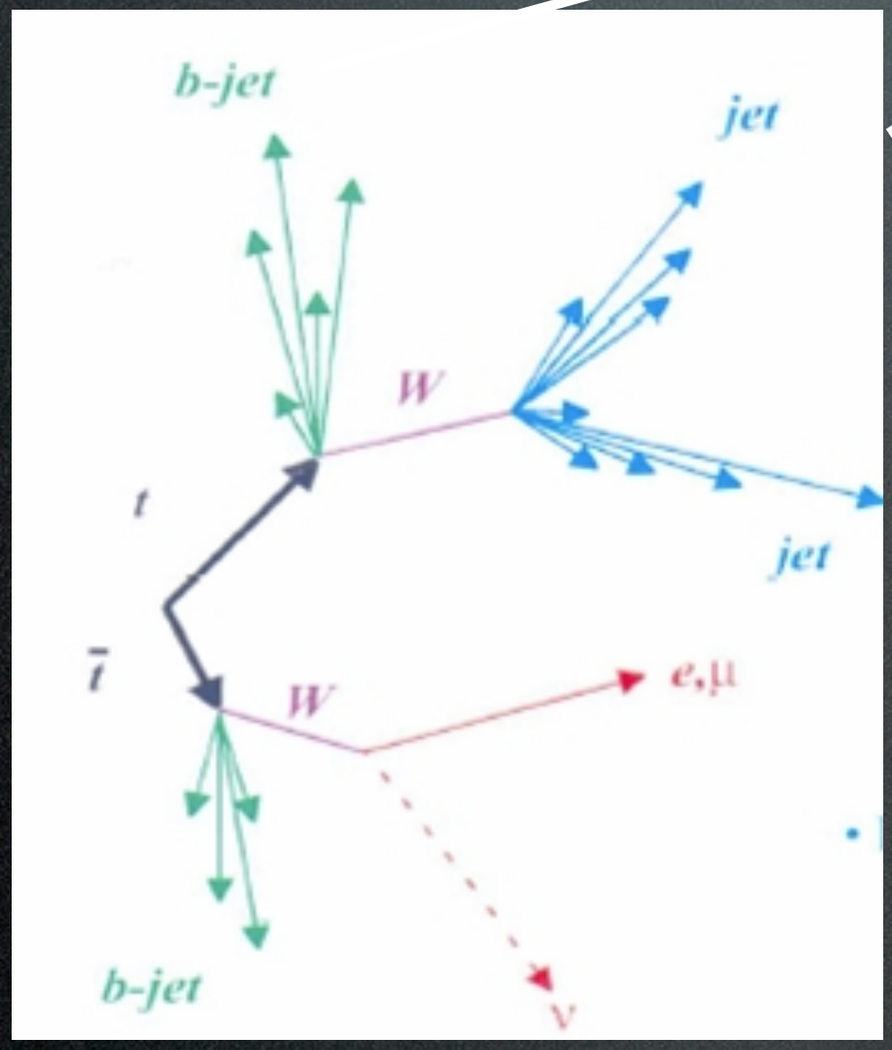
particles

- Target is to identify jets resulting from the decay of top quark or Higgs against jets coming from light quark/gluons.

Playing with the Shower

Recall

Top quark decay:

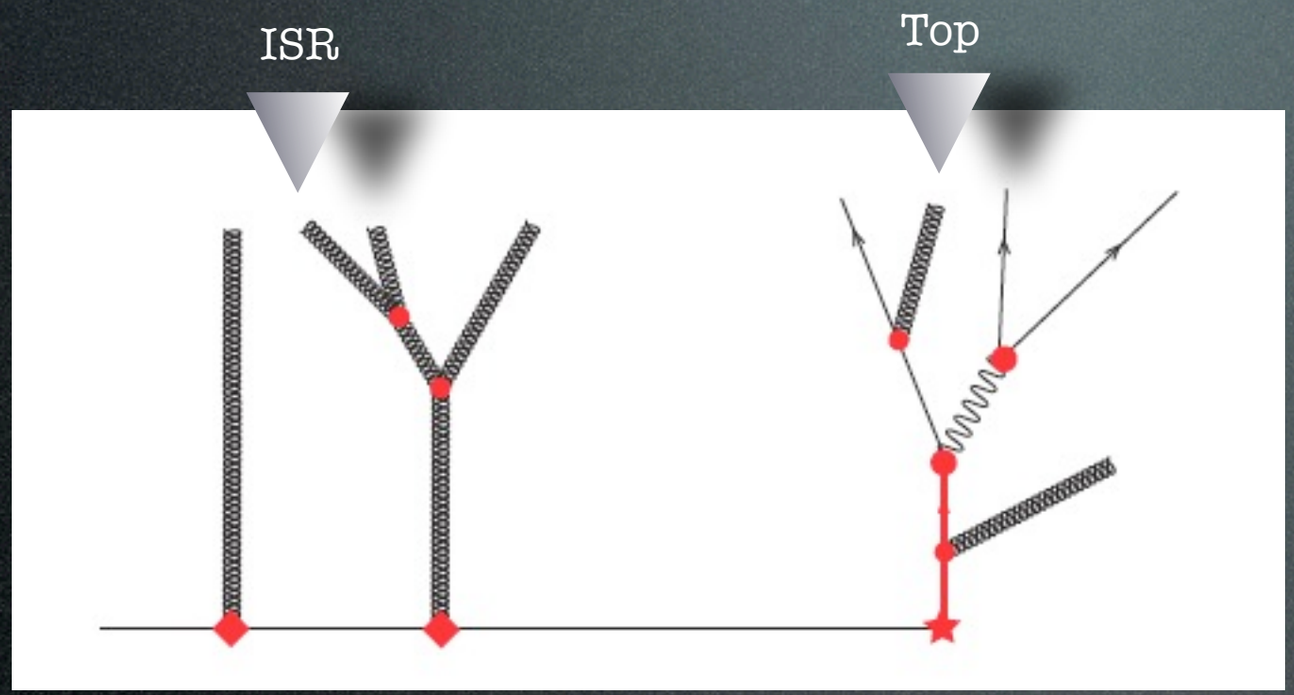


Parton Shower!

Reversing the Shower

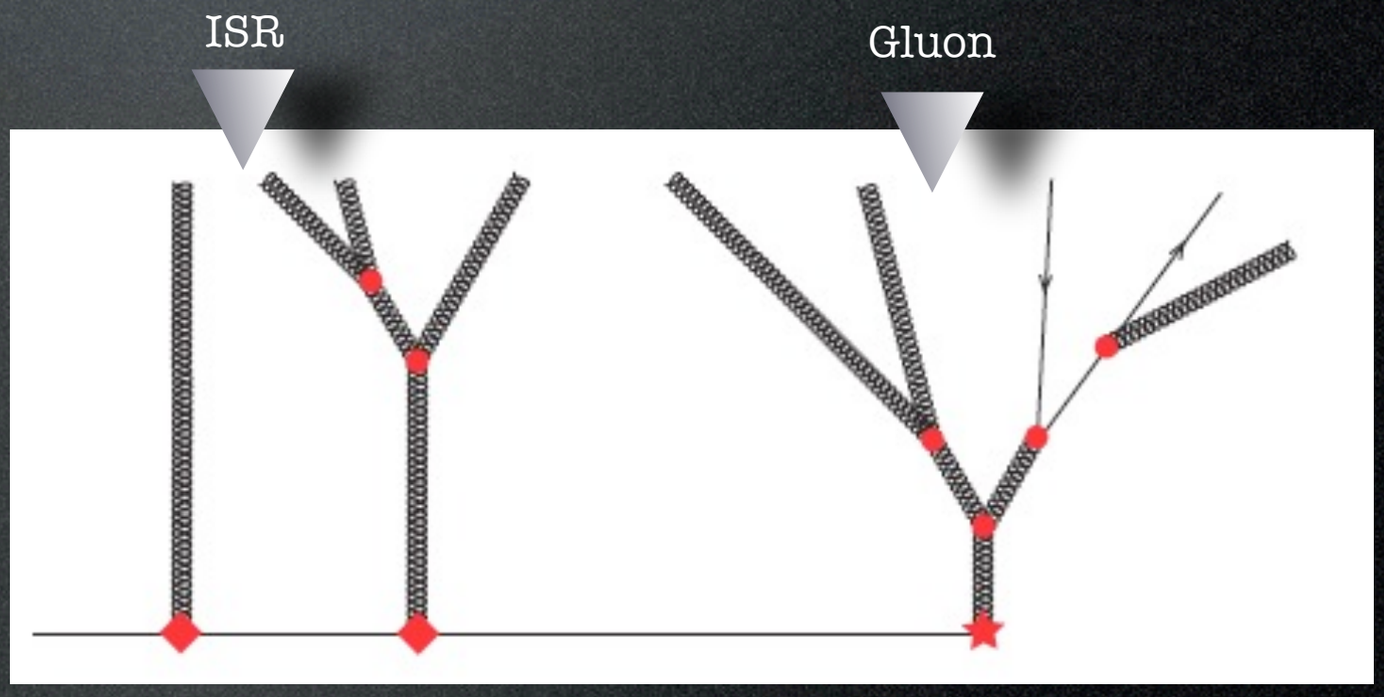
Davison E. Soper, Michael Spannowsky; arXiv:1102.3480, arXiv:1211.3140

Shower Deconstruction



Top quark jet
shower history

vs.

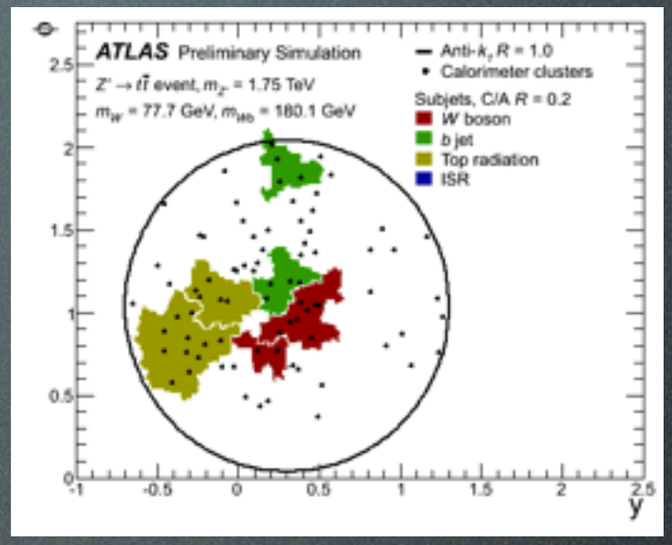


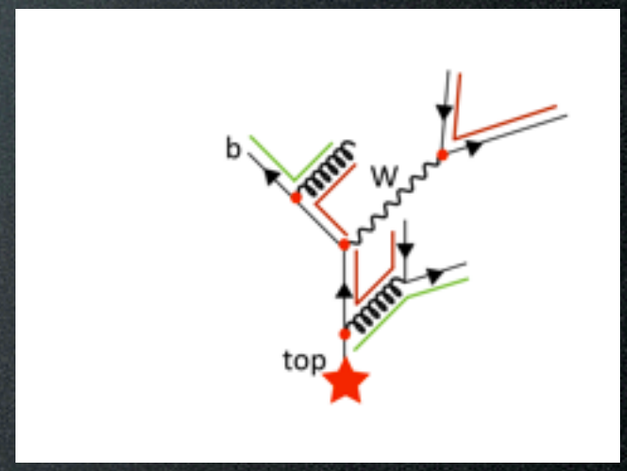
Light quark jet
shower history

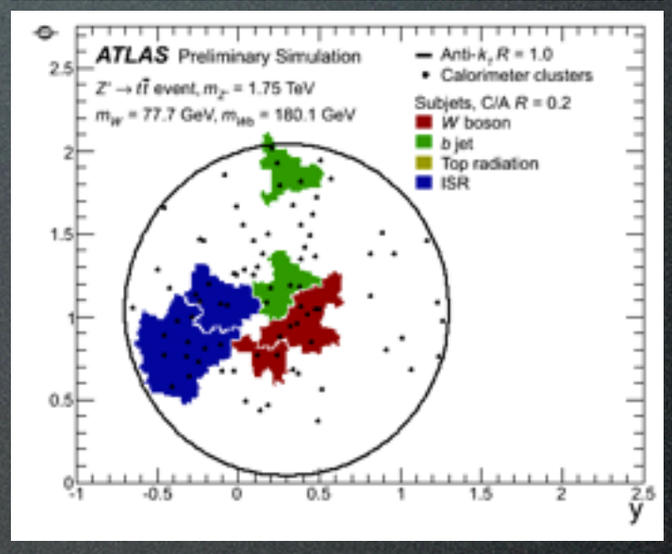
Shower Deconstruction

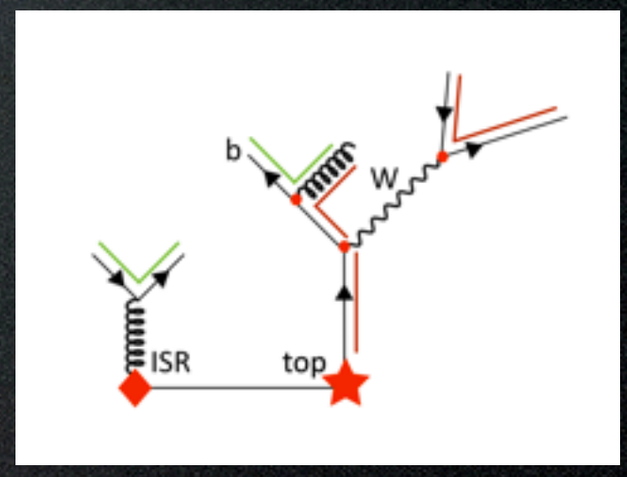
- Decompose the large-radius jet into small radius **sub/microjets.**
- Build all possible shower histories with the microjets.
- Assign probability whether signal-like or background-like.
- A single analytic function:

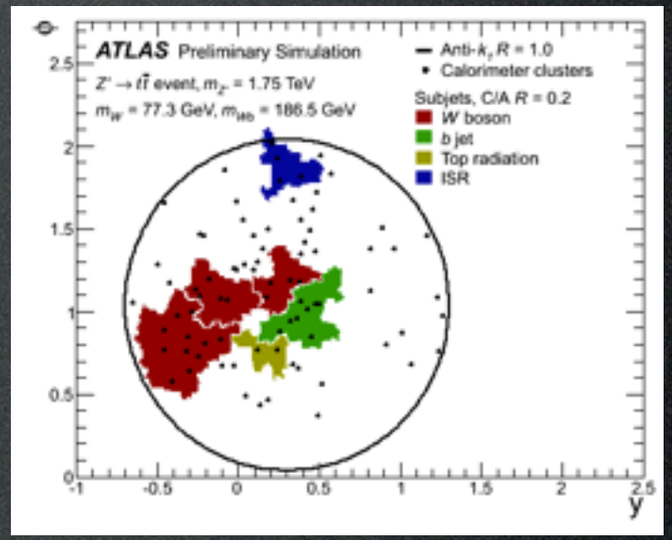
$$\chi(\{p\}_N) = \frac{P(\{p\}_N|\mathrm{S})}{P(\{p\}_N|\mathrm{B})}$$

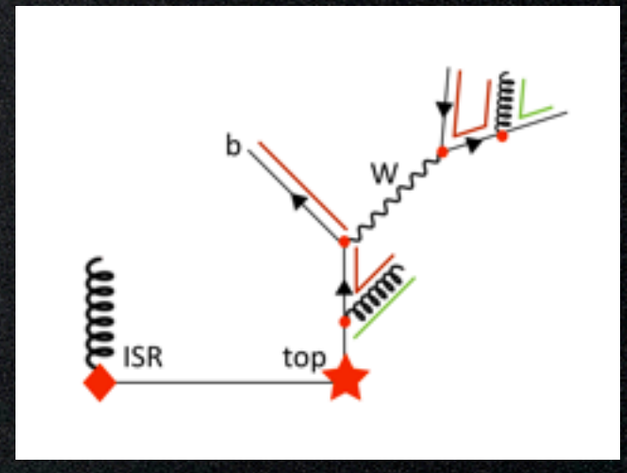












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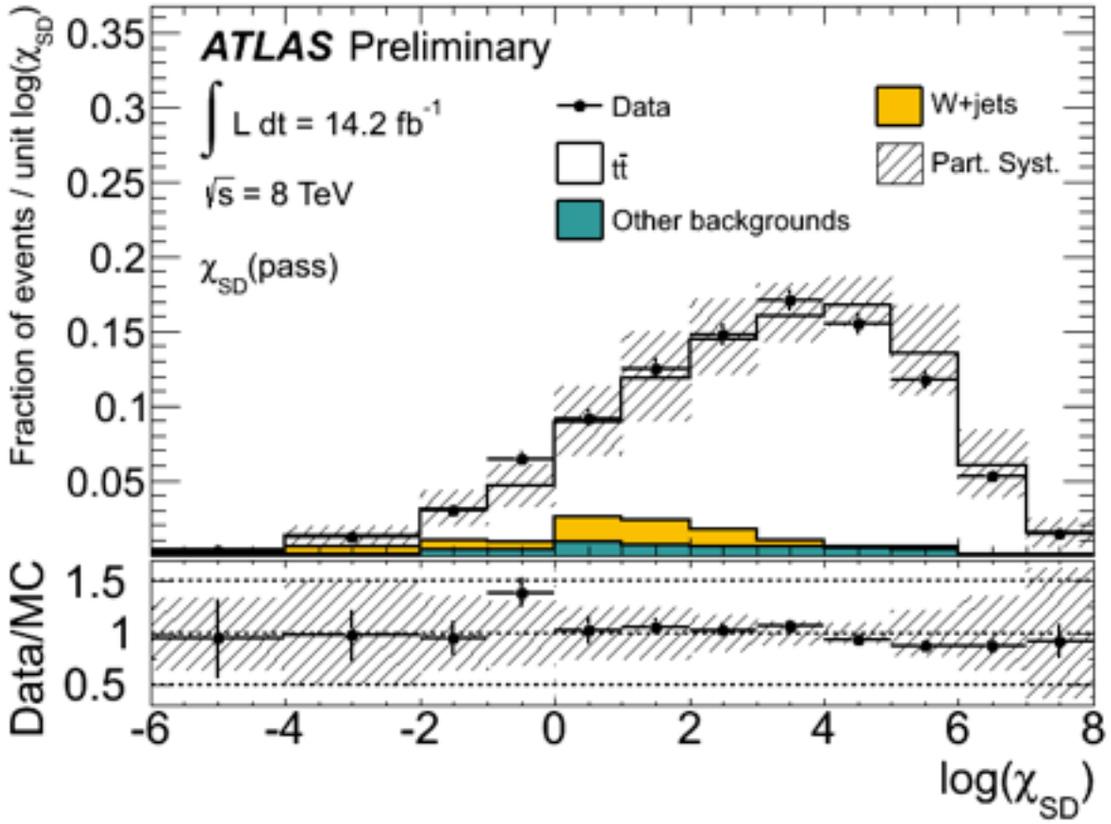
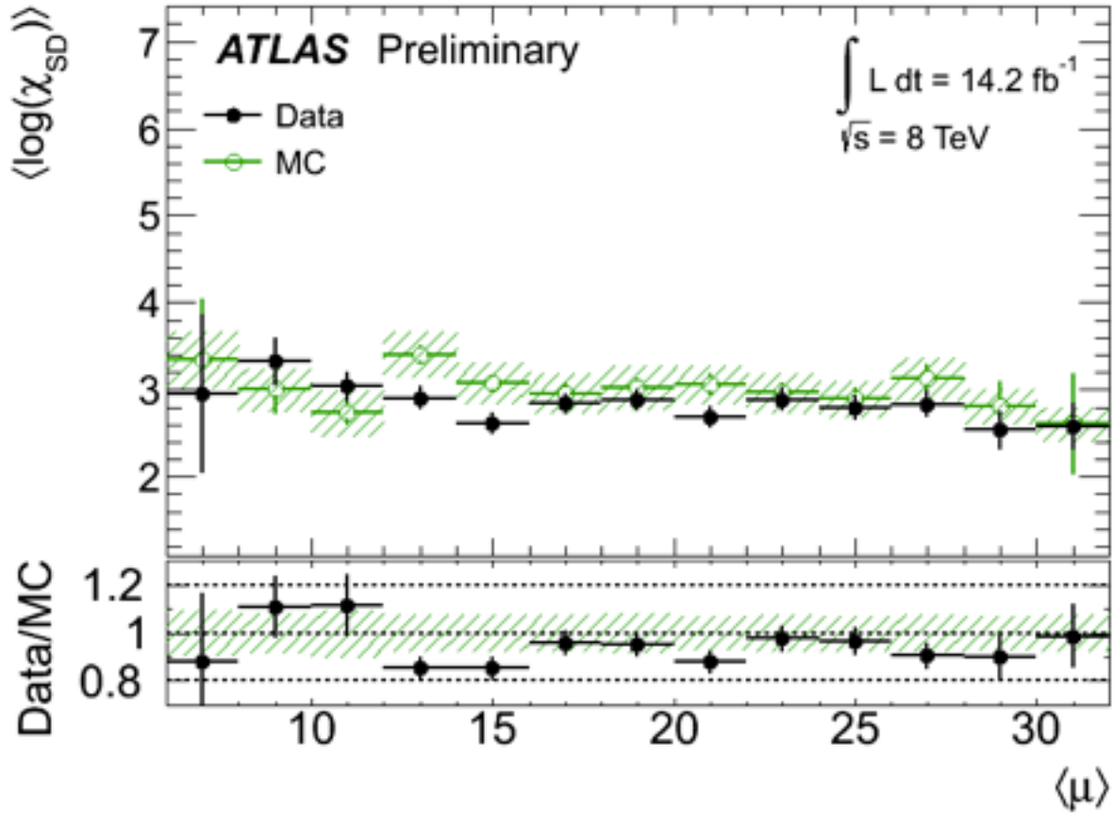
Looking at our Data



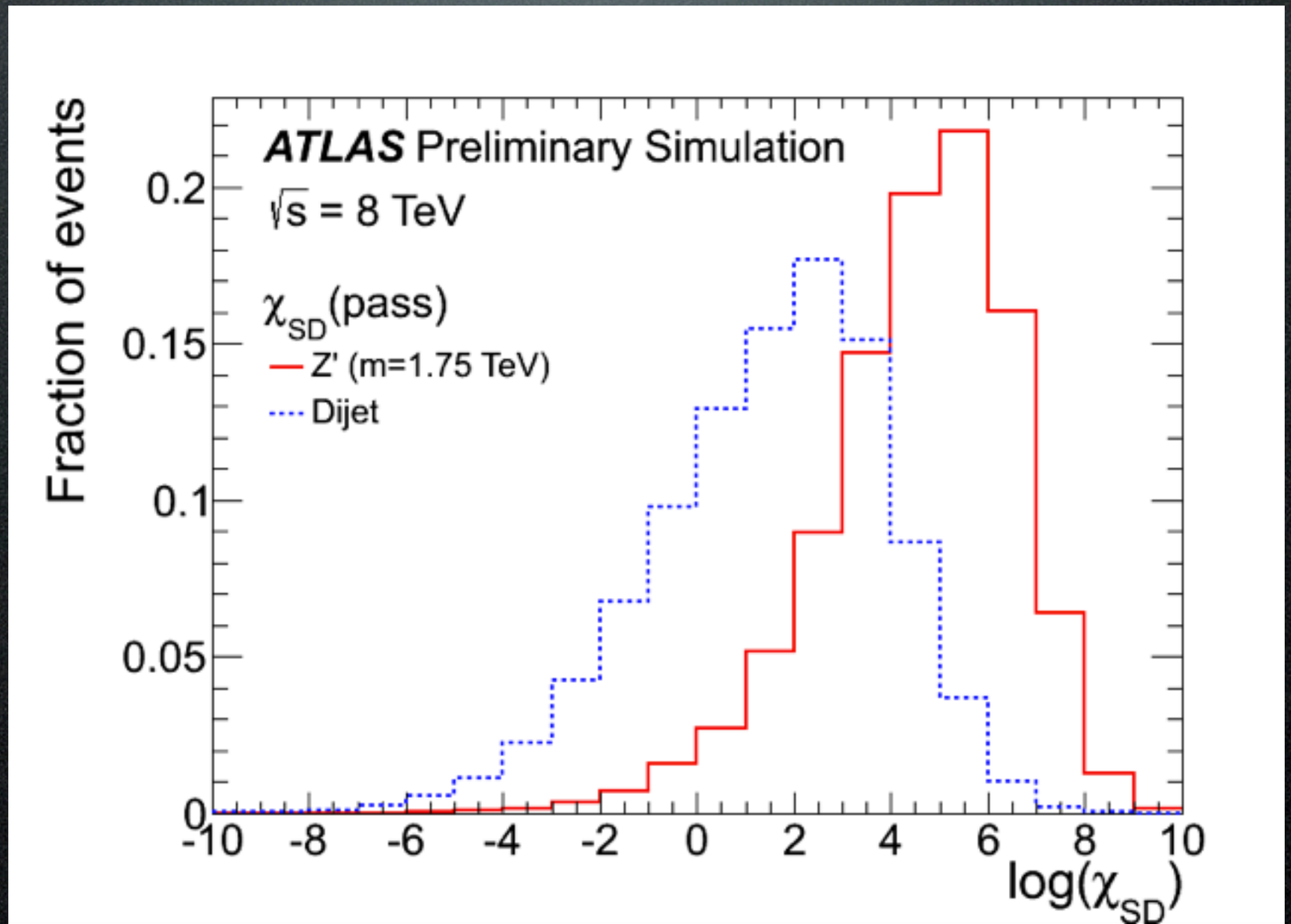
LogChi modelled well by MC



LogChi robust against pileup

ATLAS-CONF-2014-003

Signal and BG Discrimination



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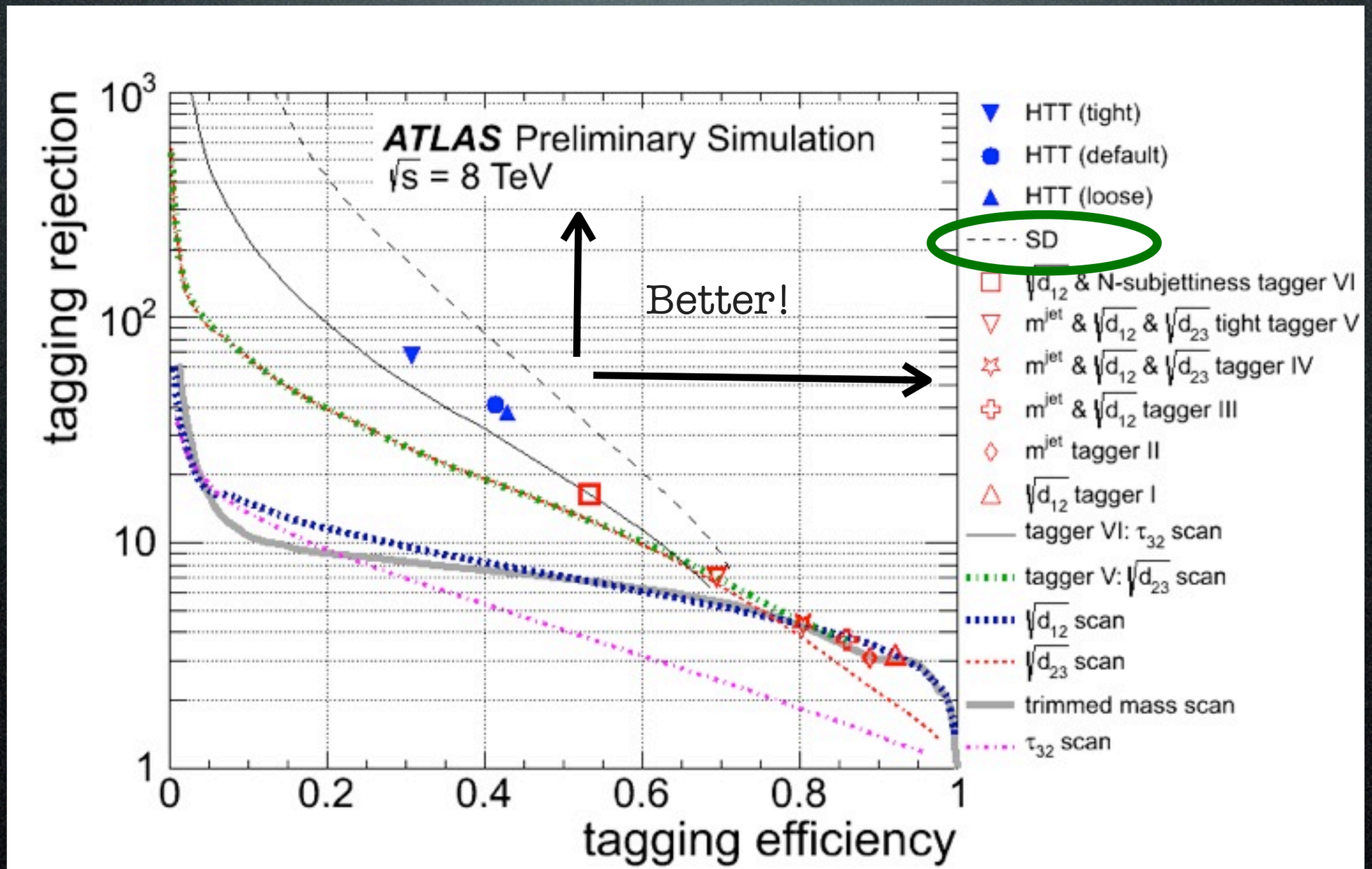
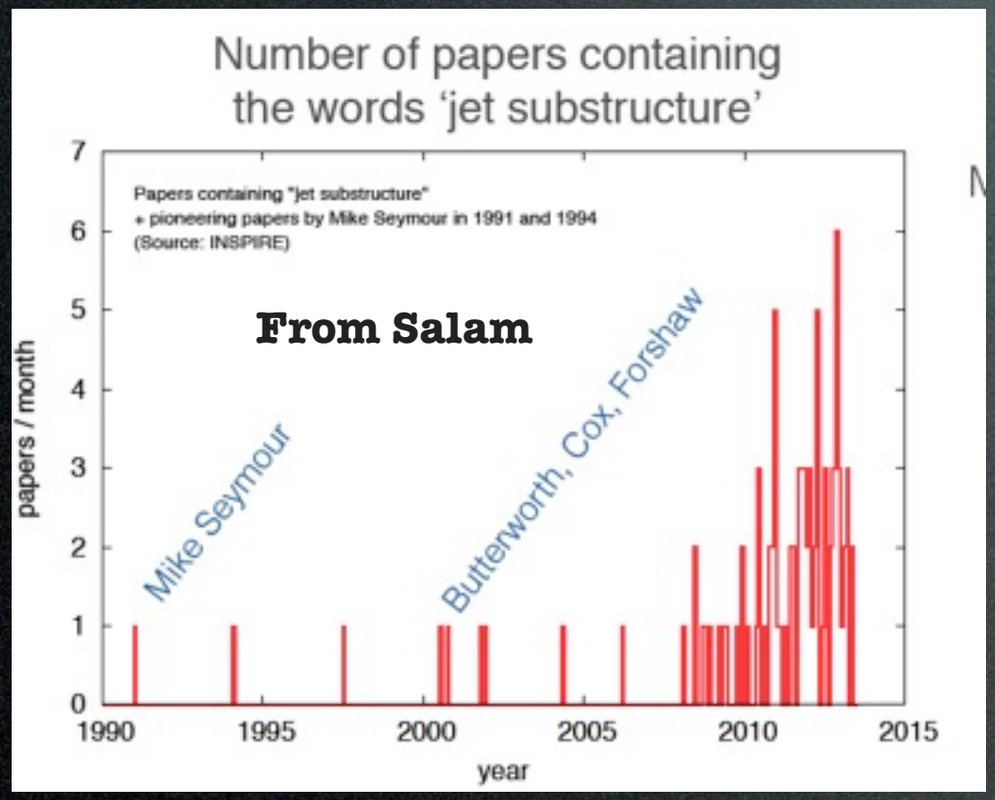
Top-Tagging Comparison



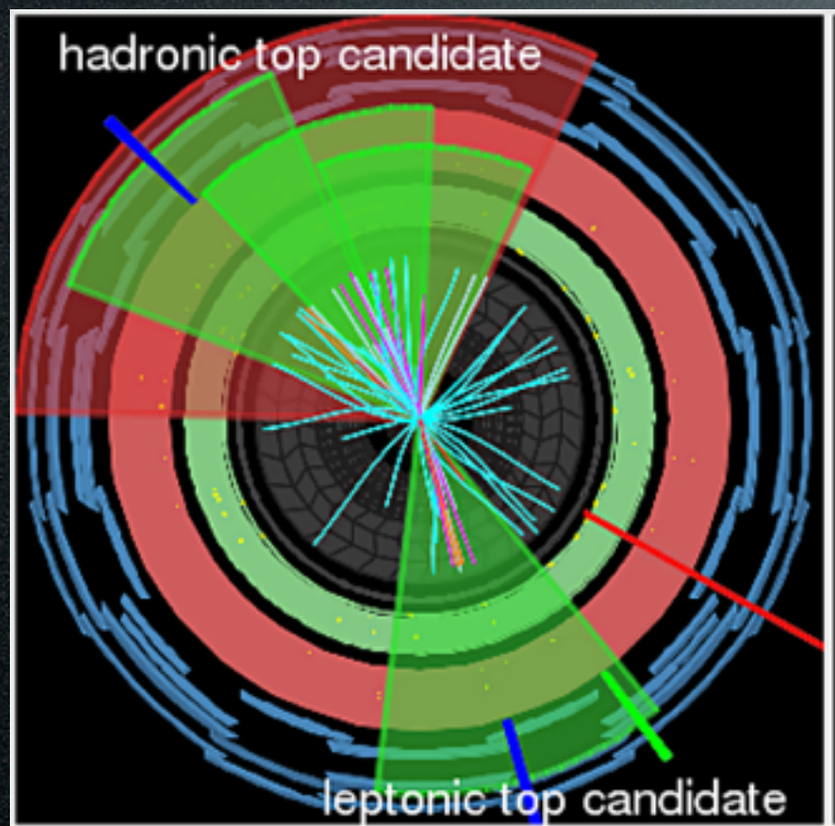
Better top quark finding efficiency at the same rejection of multijets when compared to the HEPTopTagger.

ATLAS-CONF-2014-003

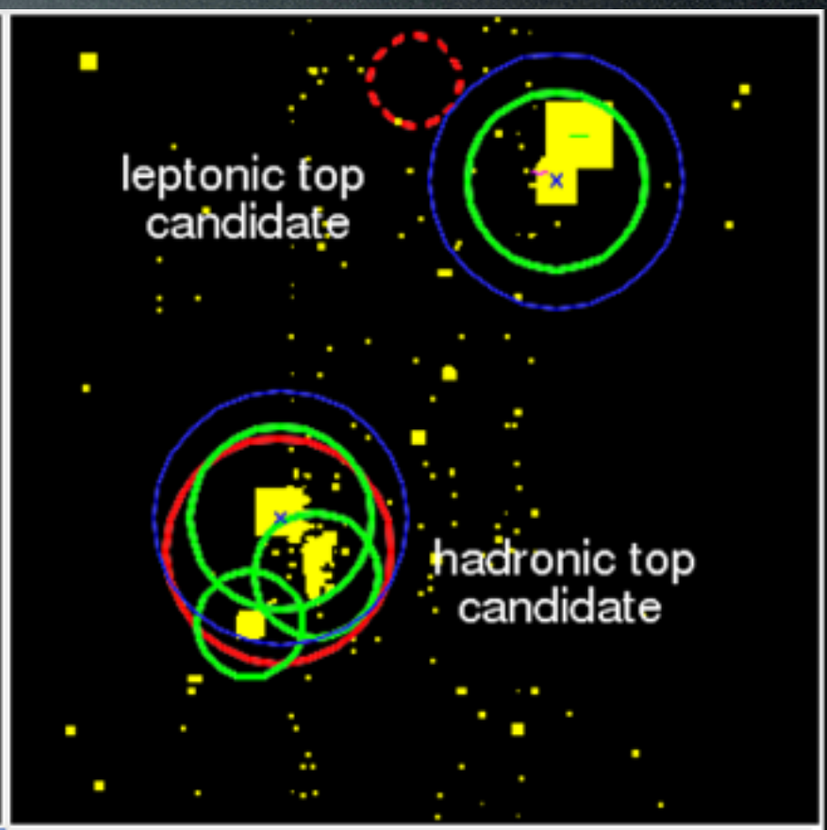
Looking Forward

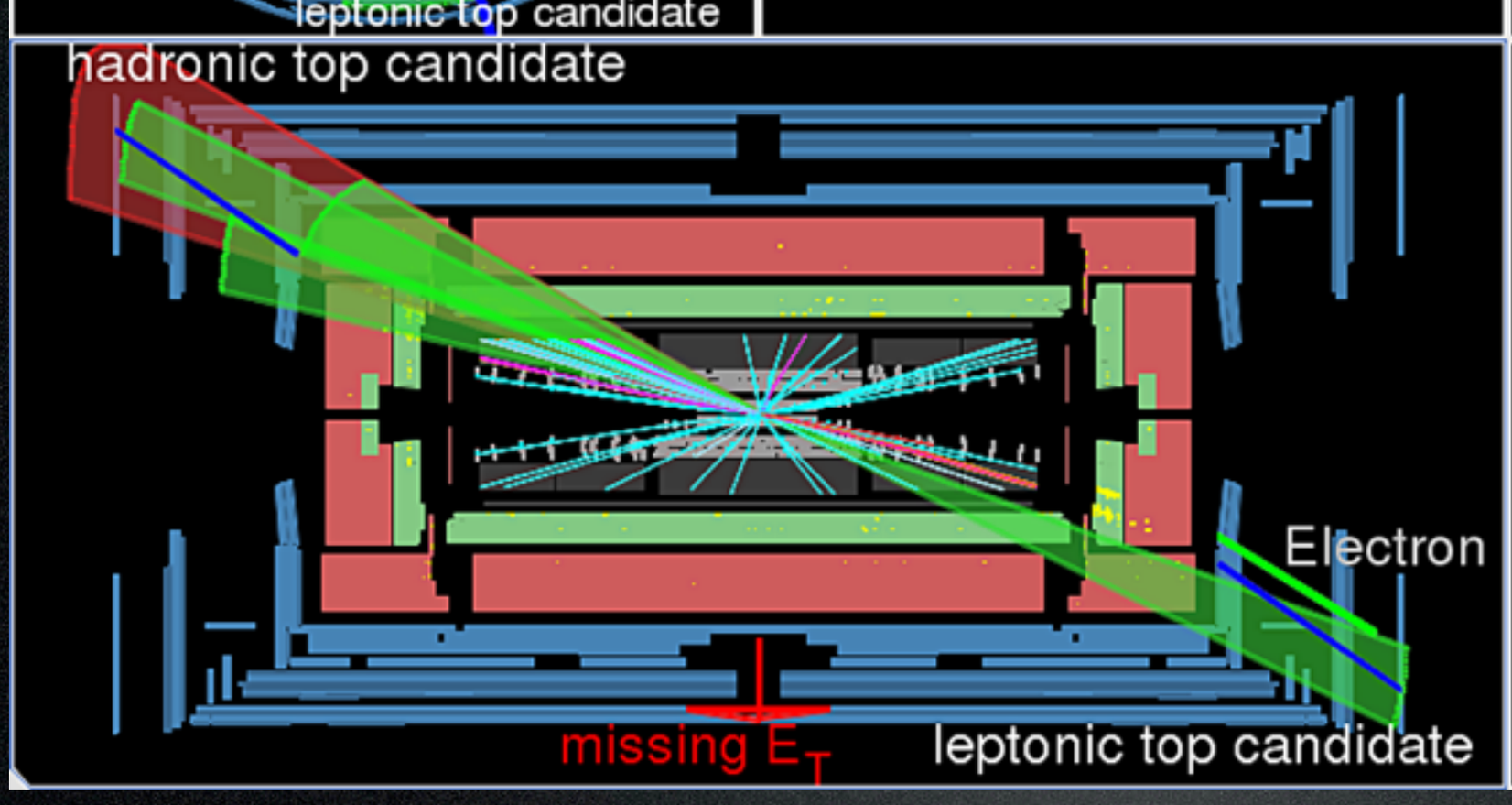


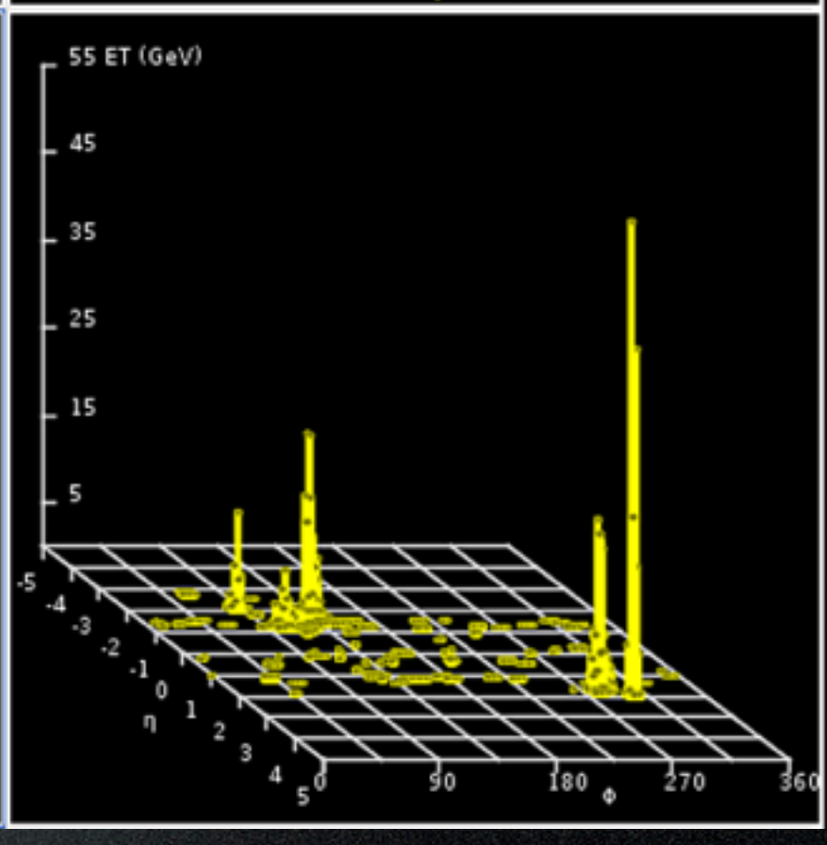
- Jet substructure studies are essential for finding new physics in post-Higgs era in (HL) LHC and ILC.
- Pileup will pose significant challenges
- Many theoretical tools, but commissioning them in experiments needs a lot of effort.
- Shower deconstruction using maximal information approach is extremely promising for many of these searches.


hadronic top candidate
leptonic top candidate


ATLAS
EXPERIMENT
Run Number: 209995, Event Number: 51046560
Date: 2012-09-09 23:10:22 CEST


leptonic top candidate
hadronic top candidate


hadronic top candidate
Electron
missing E_T
leptonic top candidate


55 ET (GeV)
45
35
25
15
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

Supporting Material

Milestones and Prospects

Run 1	Commissioning the tools
Run 2: 100 fb^{-1}	and... Improve precision of top/W/Higgs mass measurements. Exclude/severely constraint many of the new physics models with the higher energy reach
Run 3: 300 fb^{-1}	and... Directly test the coupling of the Higgs boson to fermions
HL-LHC: 3000 fb^{-1}	and... Measure Higgs self coupling Measure vector boson scattering Observe rare Higgs decays

Stephen D. Ellis, Davision E. Soper; arXiv:hep-ph/9305266

Matteo Cacciari, Gavin P. Salam, Gregory Soyez; arXiv:0802.1189

Detour: Jet Clustering

Distance between two input objects

Distance between each input object and beam

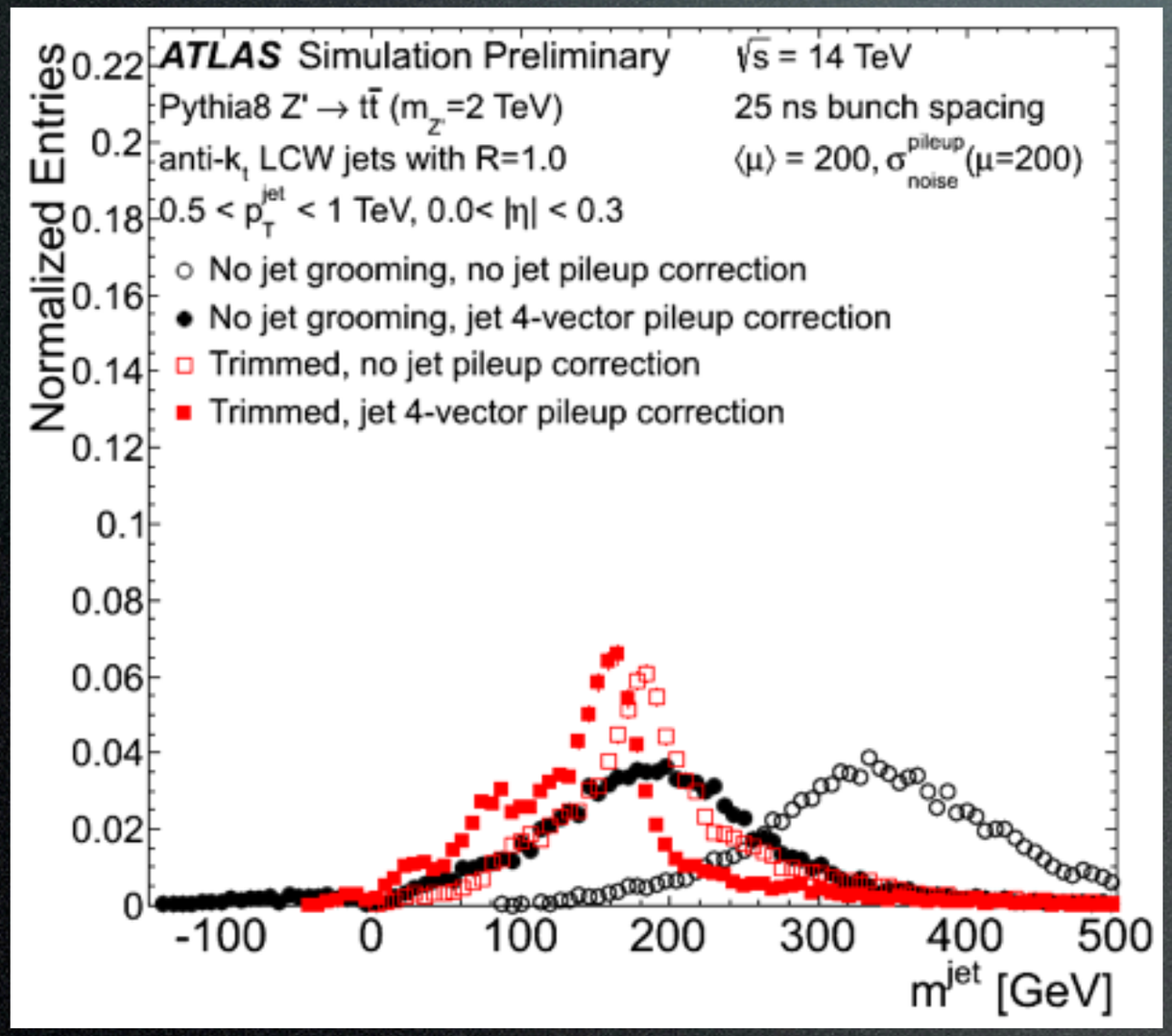
$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

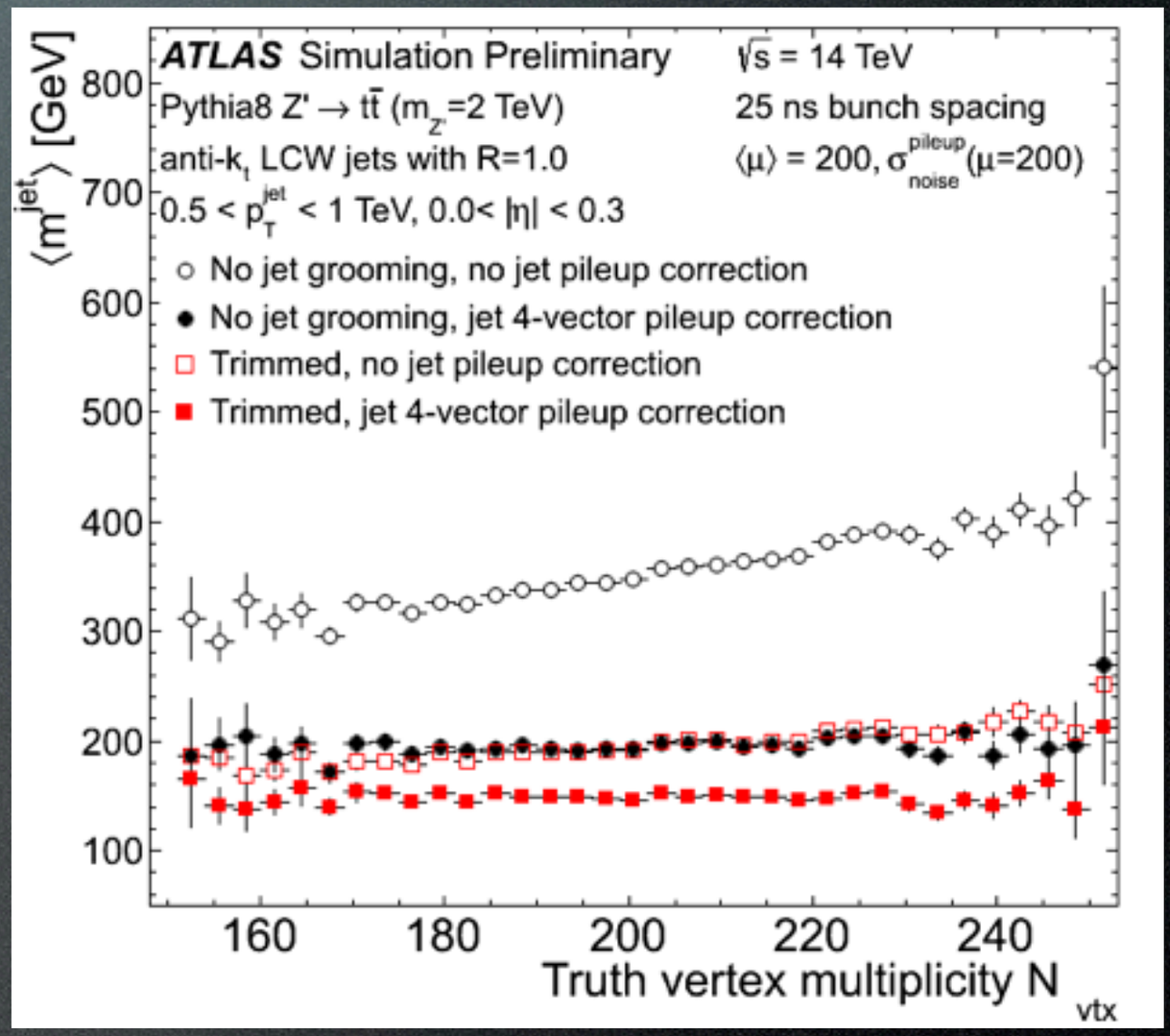
Intrinsic transverse momentum

Fixed “radius” parameter

- Find the smallest of all $\{d_{ij}, d_{iB}\}$
- If this is one of the d_{ij} values, inputs i and j are merged.
- If it is one of the d_{iB} values, i^{th} input is considered a jet.
- Continue till all inputs are merged into jets.

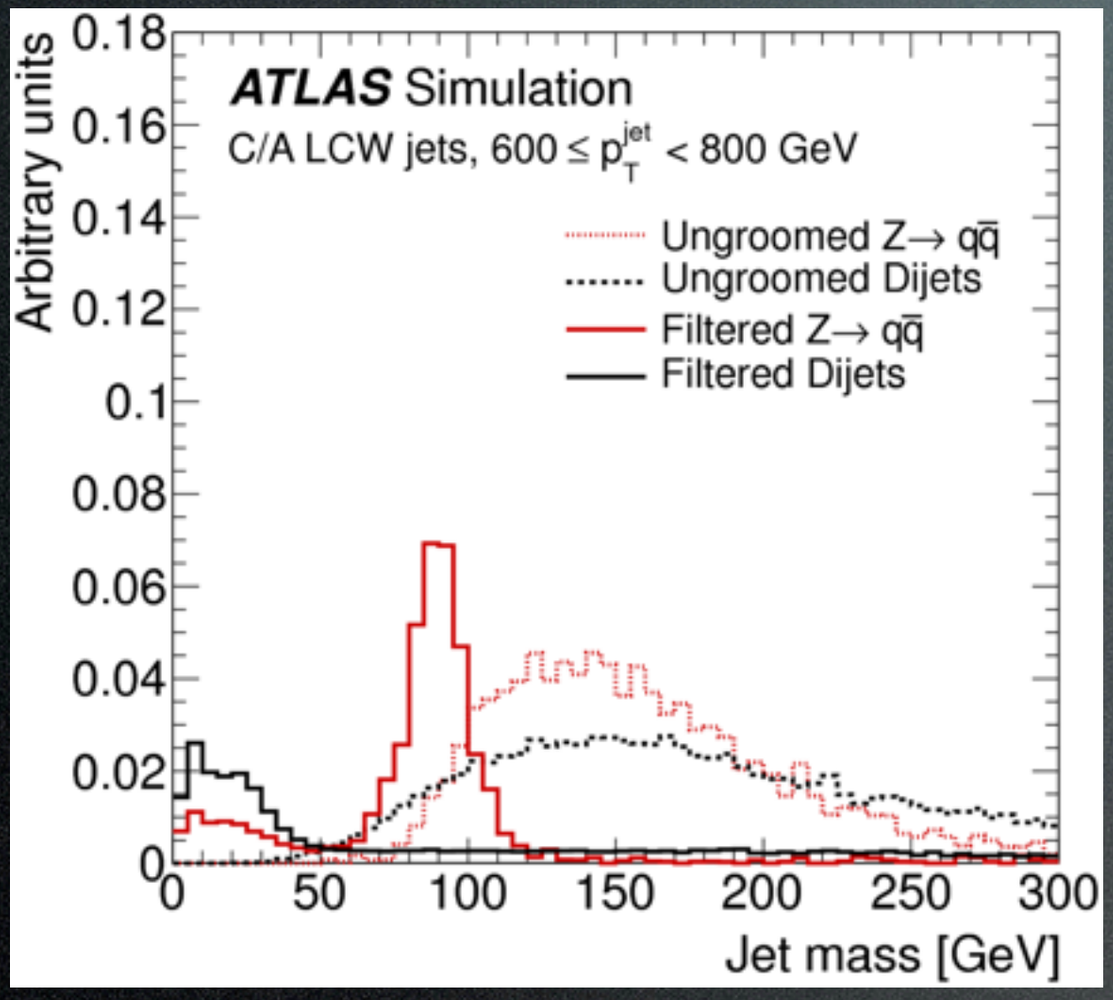
Effect of Grooming on Pileup



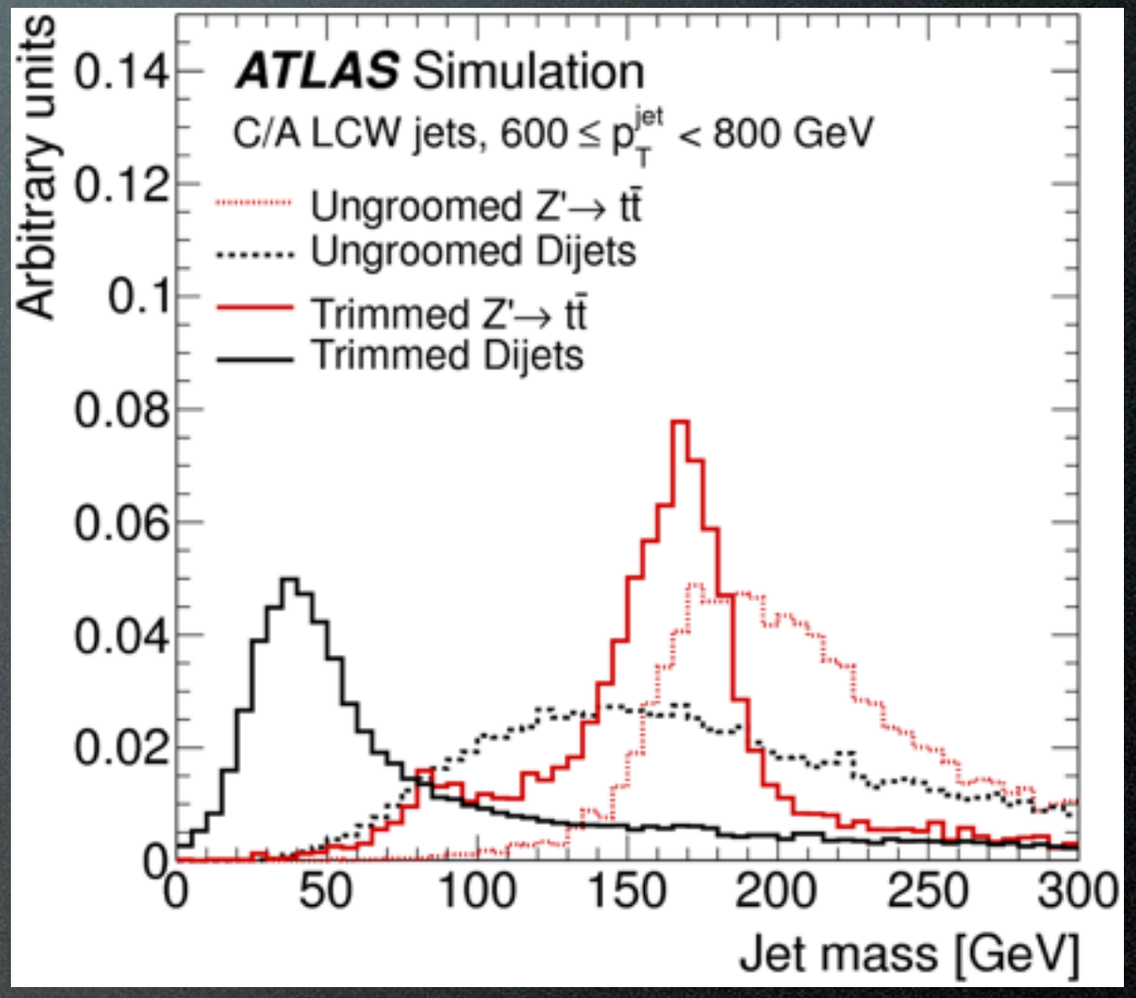


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013HighMuSubstructure

Jet Mass



arXiv:1306.4945v1



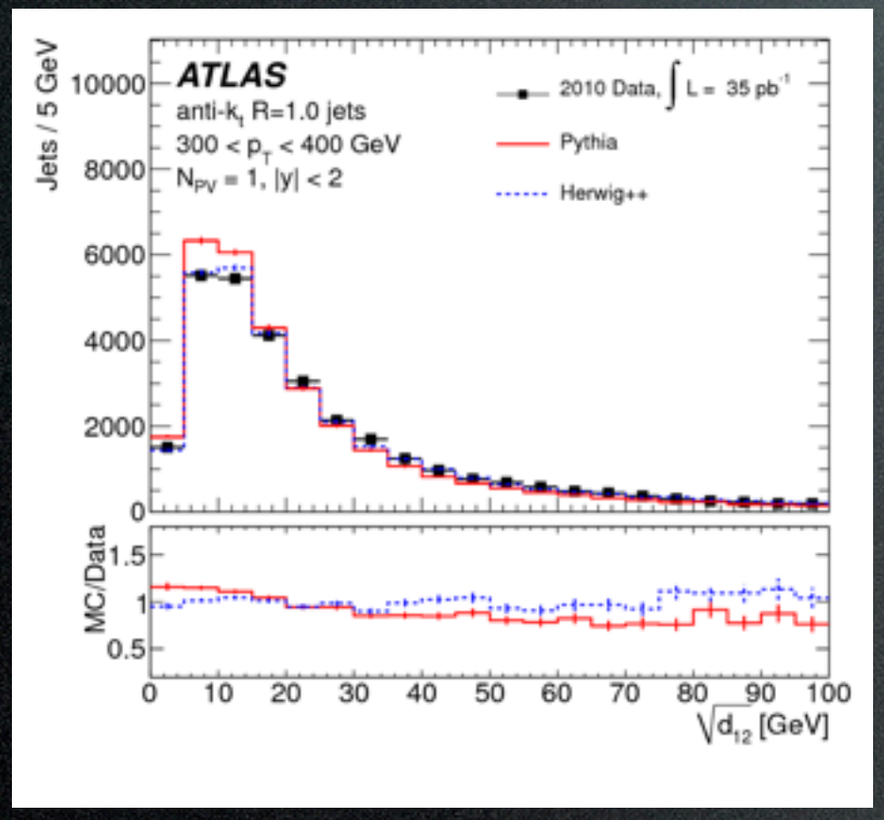
arXiv:1306.4945v1

Clear peak visible after grooming

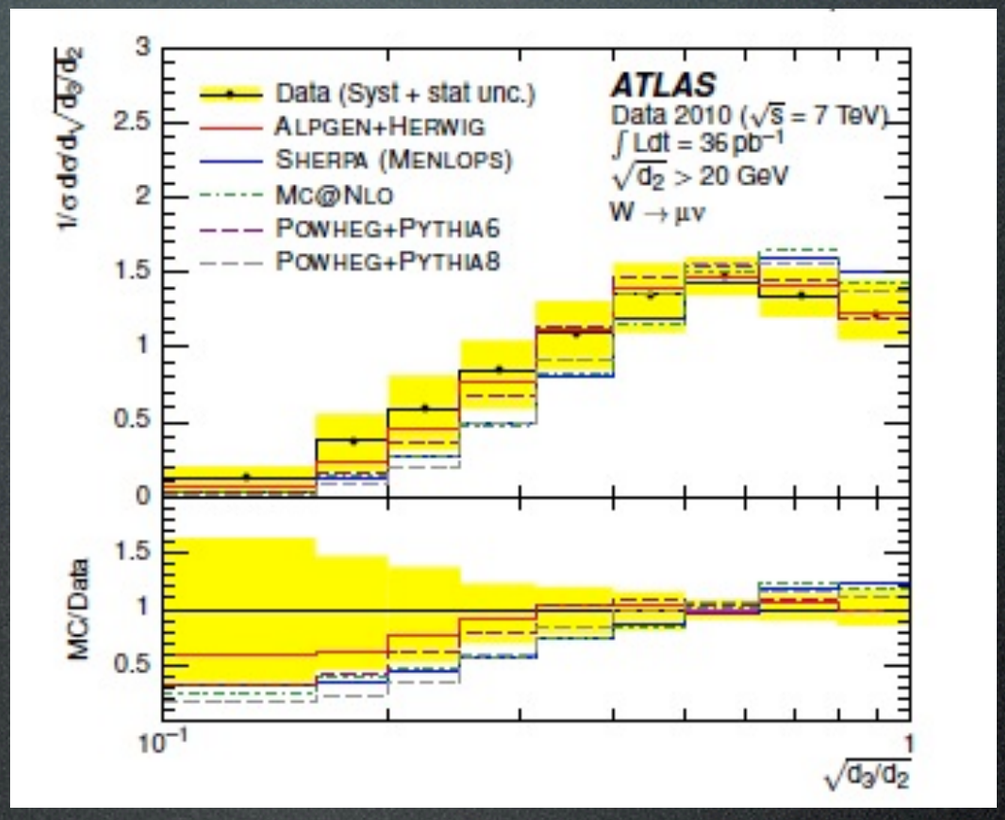
k_t Splitting Scale

$$\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij}$$

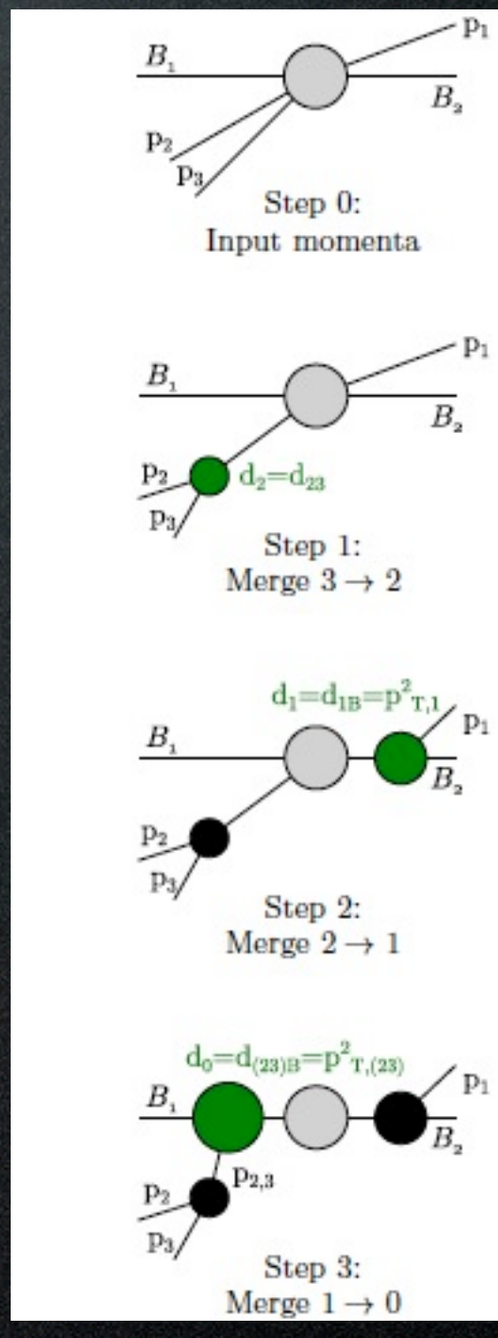
When combining two subjets with k_t algorithm:



arXiv:1203.4606



arXiv:1302.1415



arXiv:1302.1415

Symmetric for heavy particle two body decay

Jesse Thaler and Ken Van Tilburg; arXiv:1011.2268

N-Subjettiness

Quantify the degree to which jet radiation is aligned along specific subjet axes.

$$\tau_N \equiv \frac{1}{d_0} \sum_{k=1}^{M} \left(p_{\mathrm{T},k} \times \underbrace{\Delta R_{\mathrm{min},k}}_{\text{distance to nearest subjet}} \right)$$

$d_0 = R \times$ sum of p_{T} of all constituents

Smaller values: N or less energy deposits

Larger values: more than N energy deposits

No of Subjets: ≤N >N

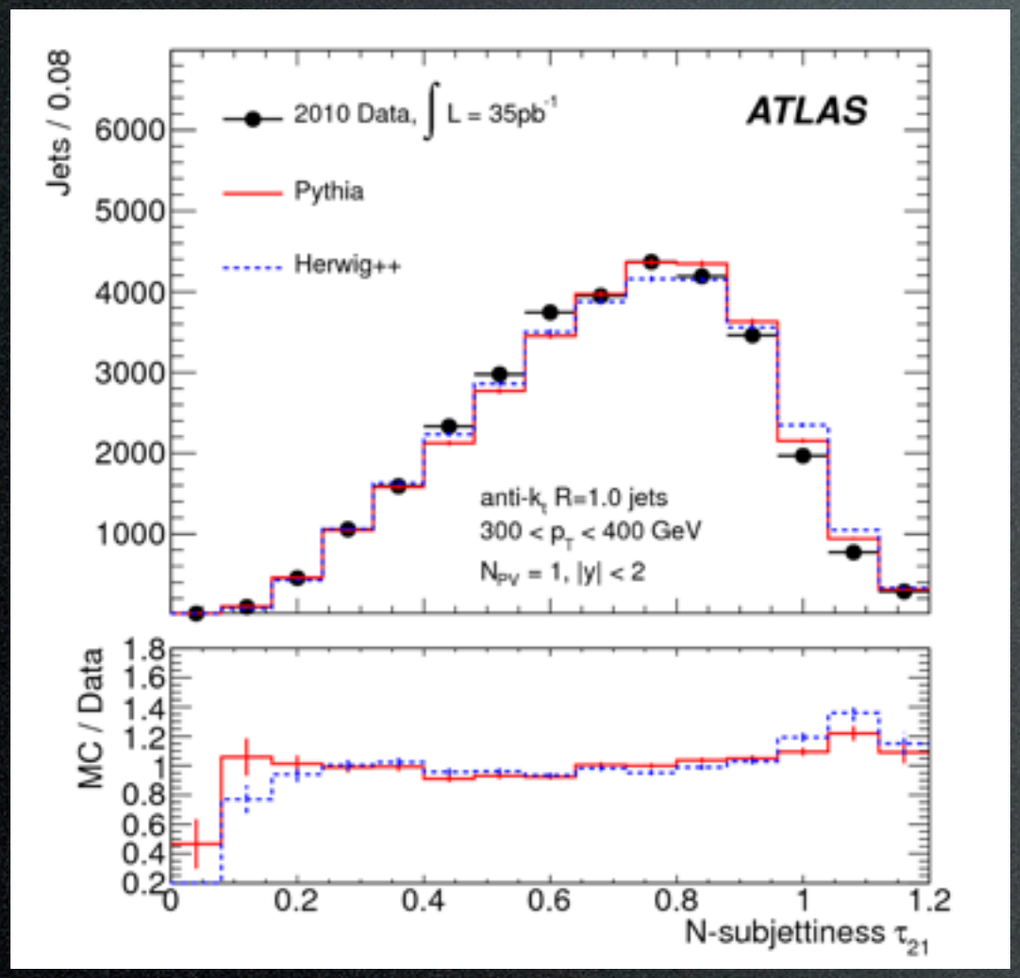
$\tau_N = 0$ $\tau_N = 1$

Calculated by k_t clustering the constituents, and requiring exactly N subjets

N-Subjettiness

The ratio τ_N/τ_{N-1} is used as discriminant

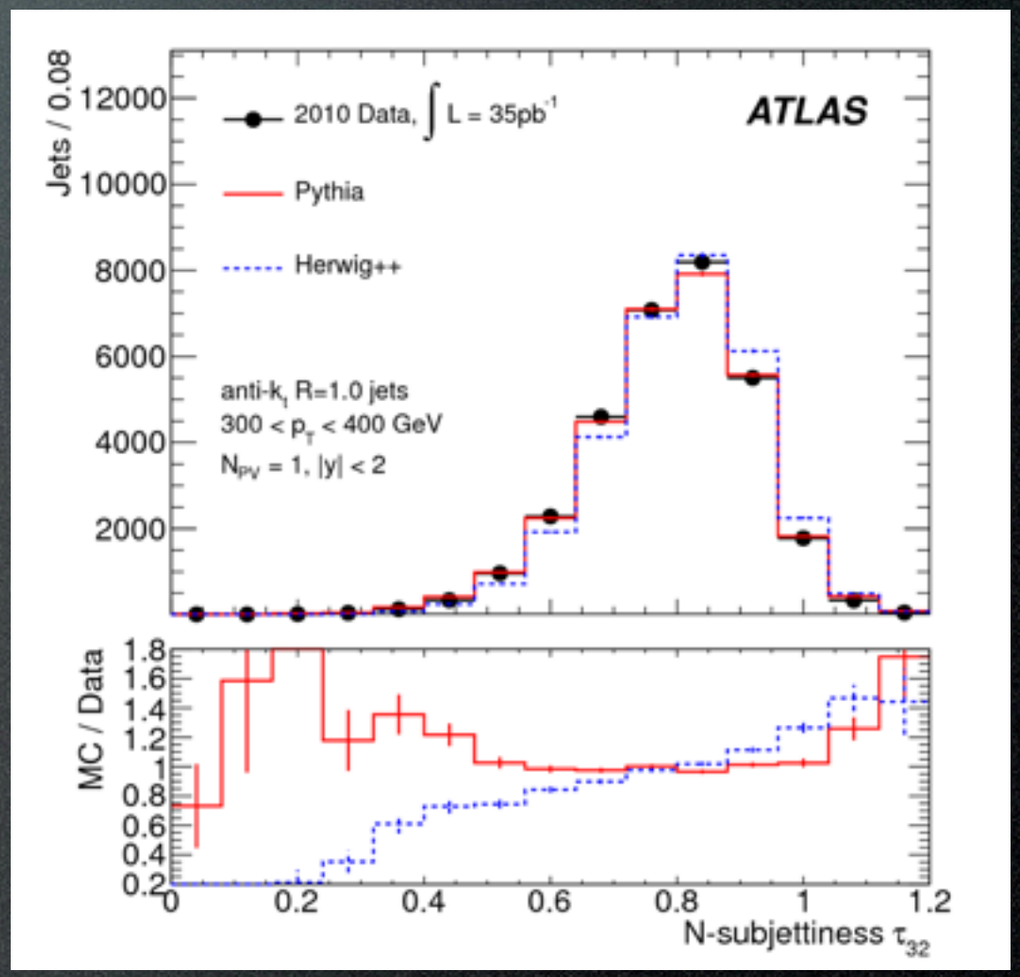
More like 2 subjets than 1



arXiv:1203.4606

W-like ⟷ QCD-like

More like 3 subjets than 2



arXiv:1203.4606

N-Subjettiness

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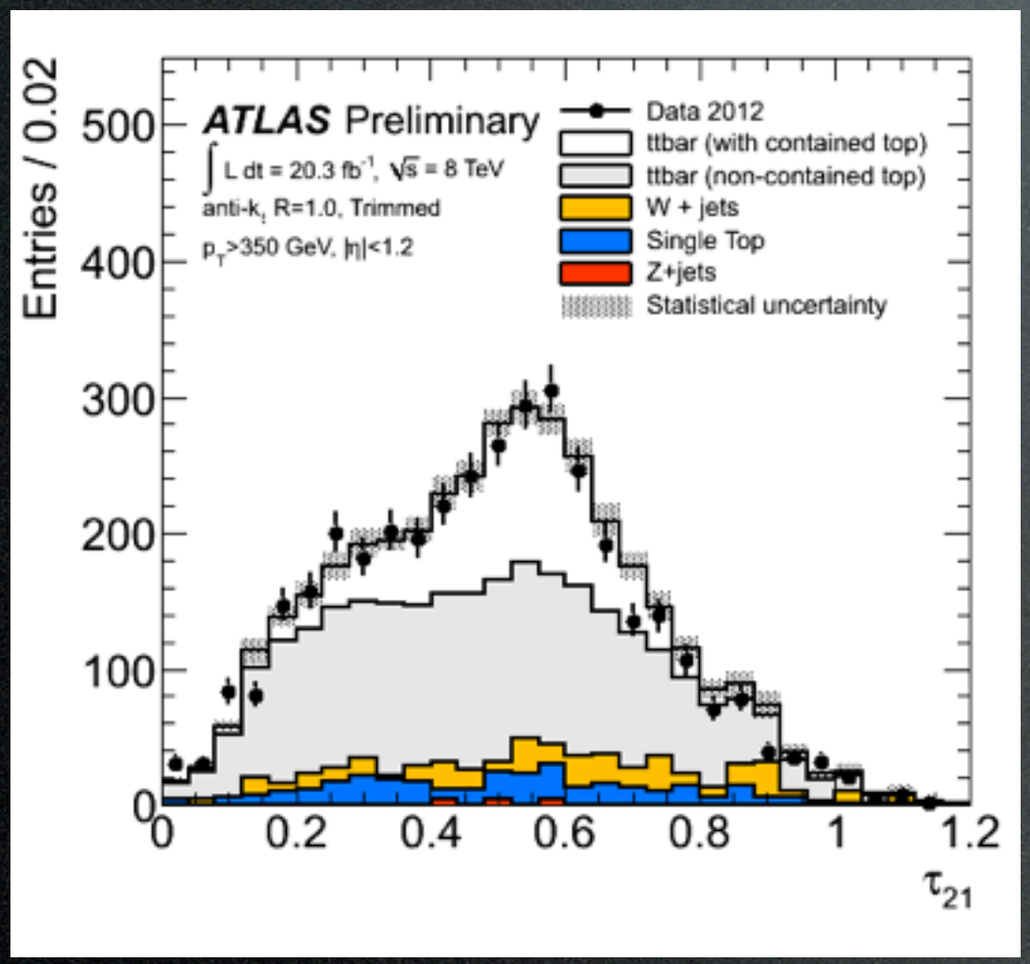
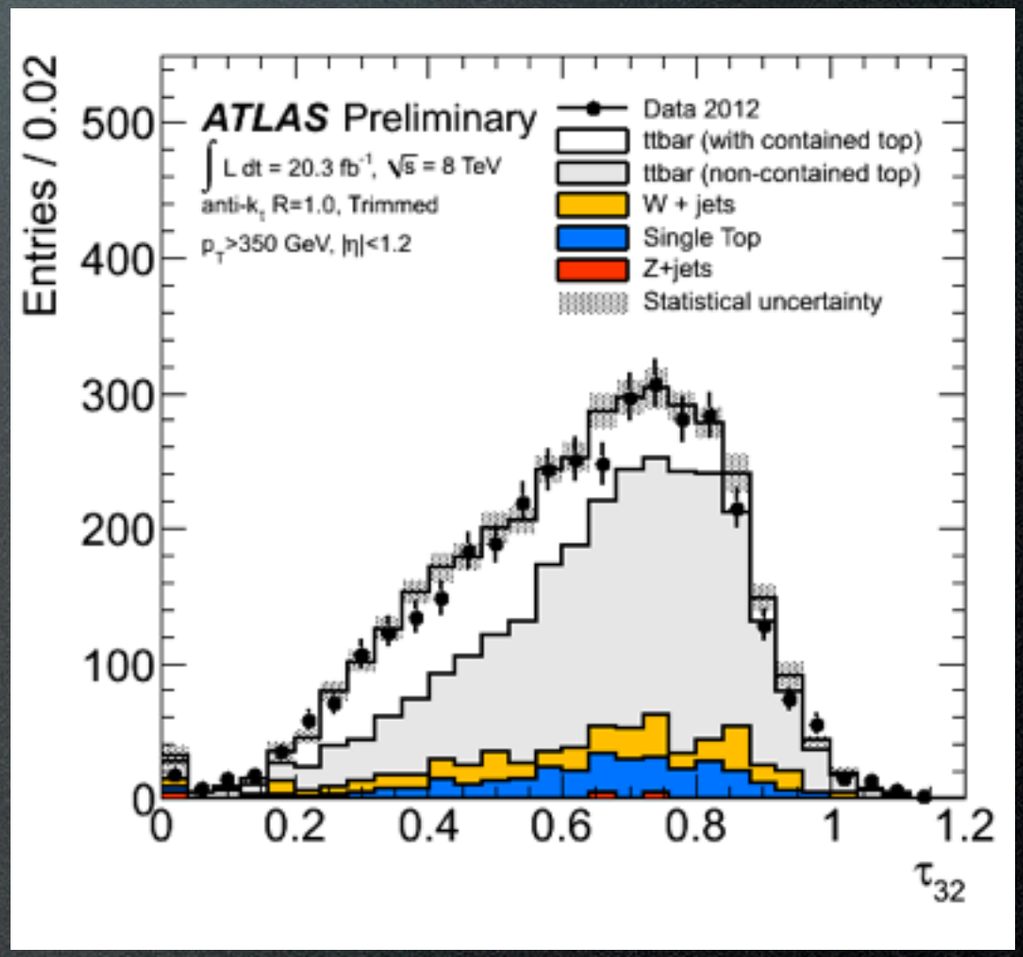


arXiv:1203.4606

More like 3 subjets than 2



arXiv:1203.4606

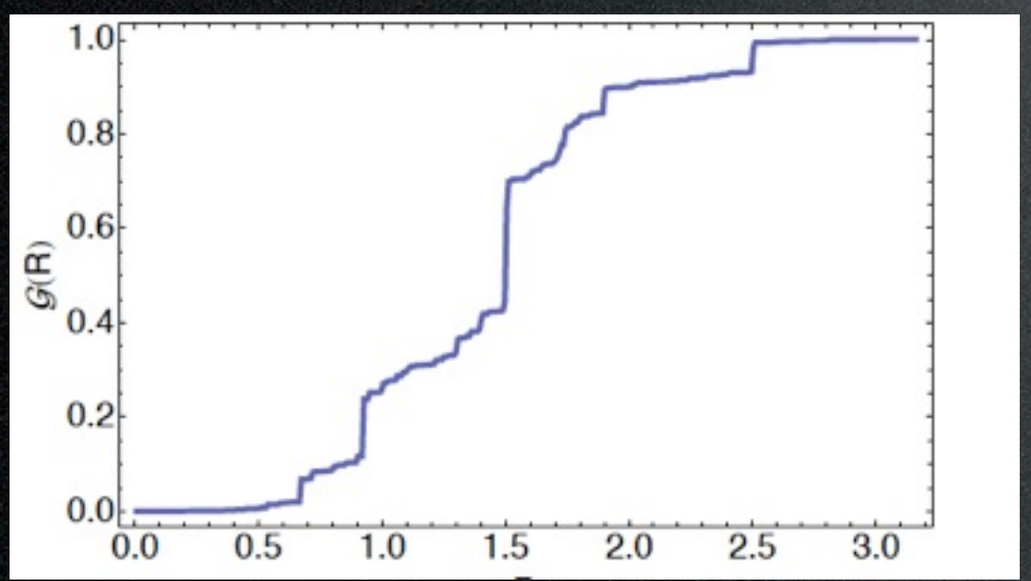
W-like ⟷ QCD-like

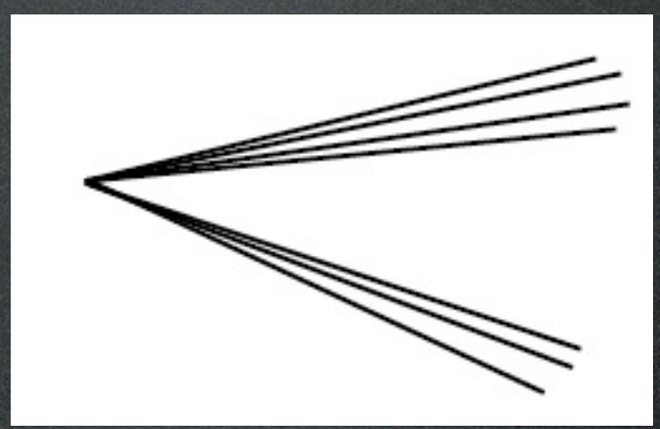
Martin Jankowiak, Andrew J. Larkoski; arXiv:1104.1646

Angular Correlation Function
(or jet substructure without trees)

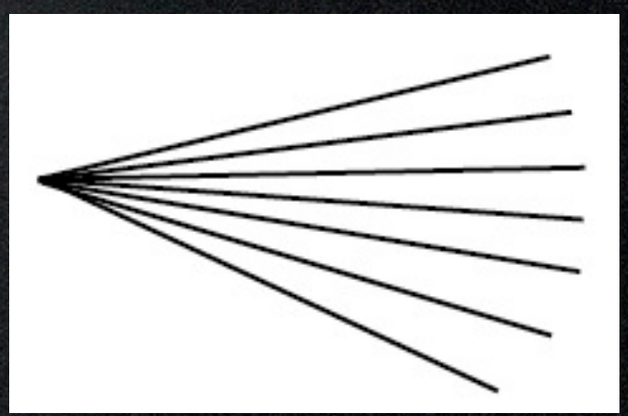
$$\mathcal{G}(R) \equiv \sum_{i \neq j} p_{\perp i} p_{\perp j} \Delta R_{ij}^2 \Theta[R - \Delta R_{ij}]$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$



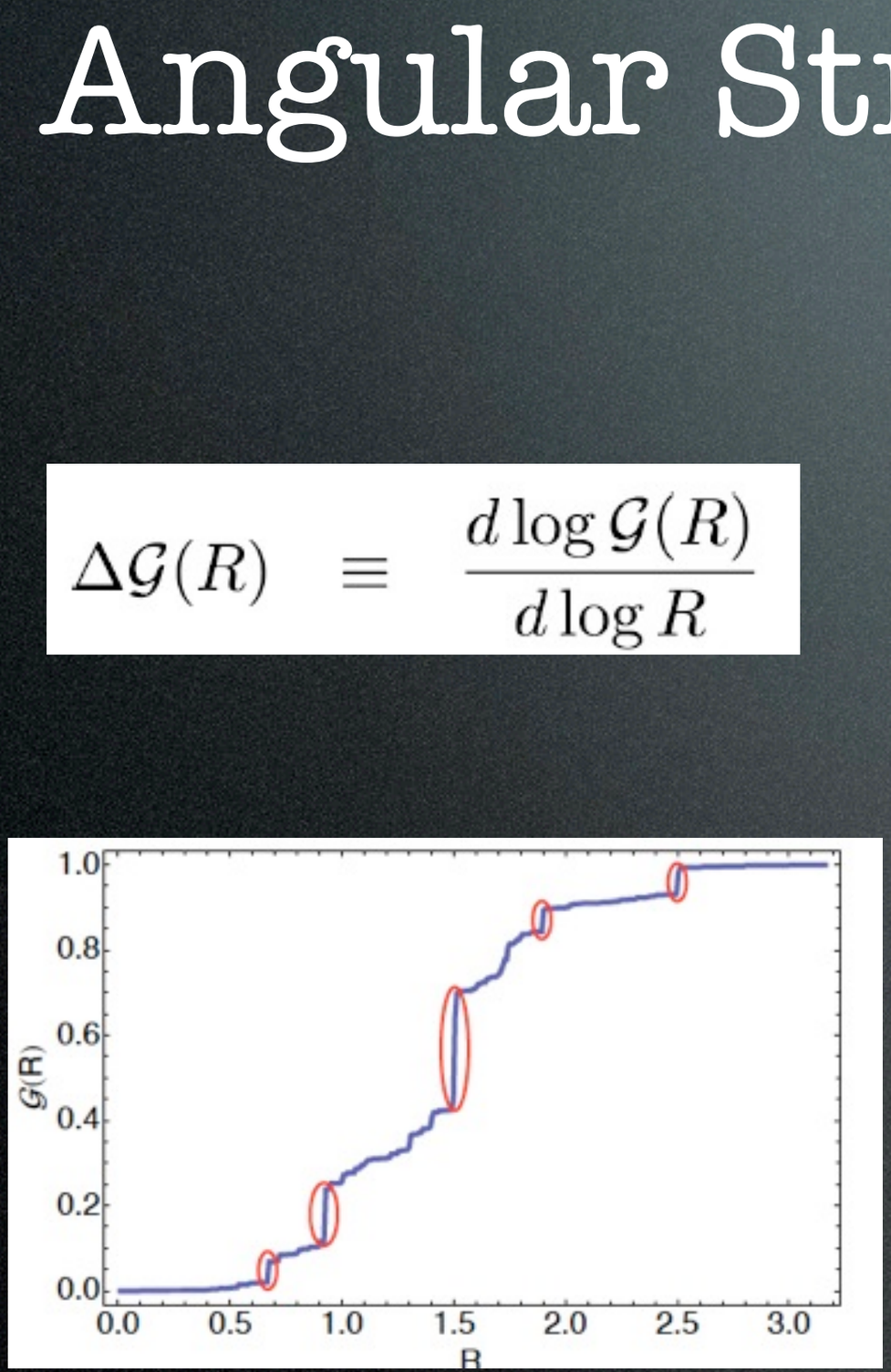


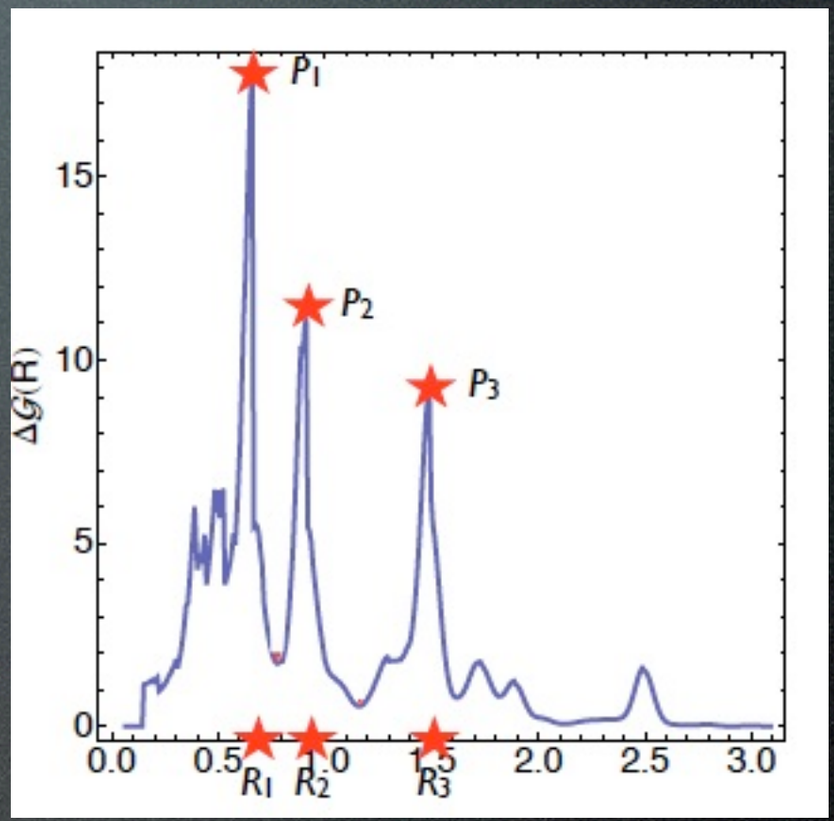
vs.



Angular Structure Function

$$\Delta\mathcal{G}(R) \equiv \frac{d\log\mathcal{G}(R)}{d\log R}$$



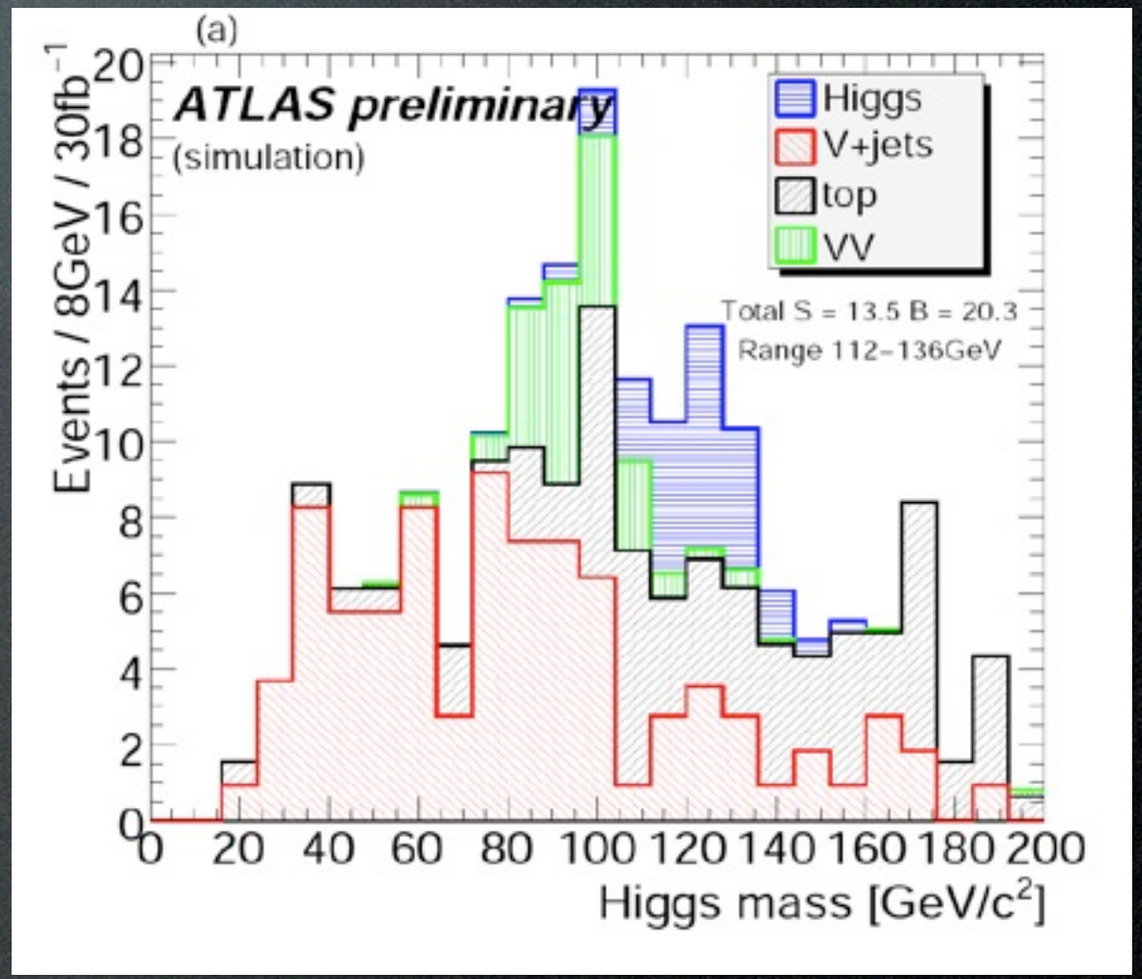


- Location of the peaks
- Height of the peaks
- Number of peaks

J. Butterworth, A. Davidson, M. Rubin, G. Salam; http://arxiv.org/abs/0802.2470

Where it all started: **B**utterworth-**D**avison-**R**ubin-**S**alam Higgs to bb tagger (2008)

- Start with fat (C-A 1.2) boosted ($p_T > 200$) b-tagged jet.
- De-cluster the jet. At each stage, mass drop and symmetric splitting requirement.
- Continue till an interesting splitting has been found.
- Higgs candidate from two hardest b-tagged subjets among the three hardest.



Tilman Plehn, Michael Spannowsky, Michihisa Takeuchi, Dirk Zerwas; arXiv:1006.2833

HEPTopTagger

Browsing through all the branches of jet recombination history

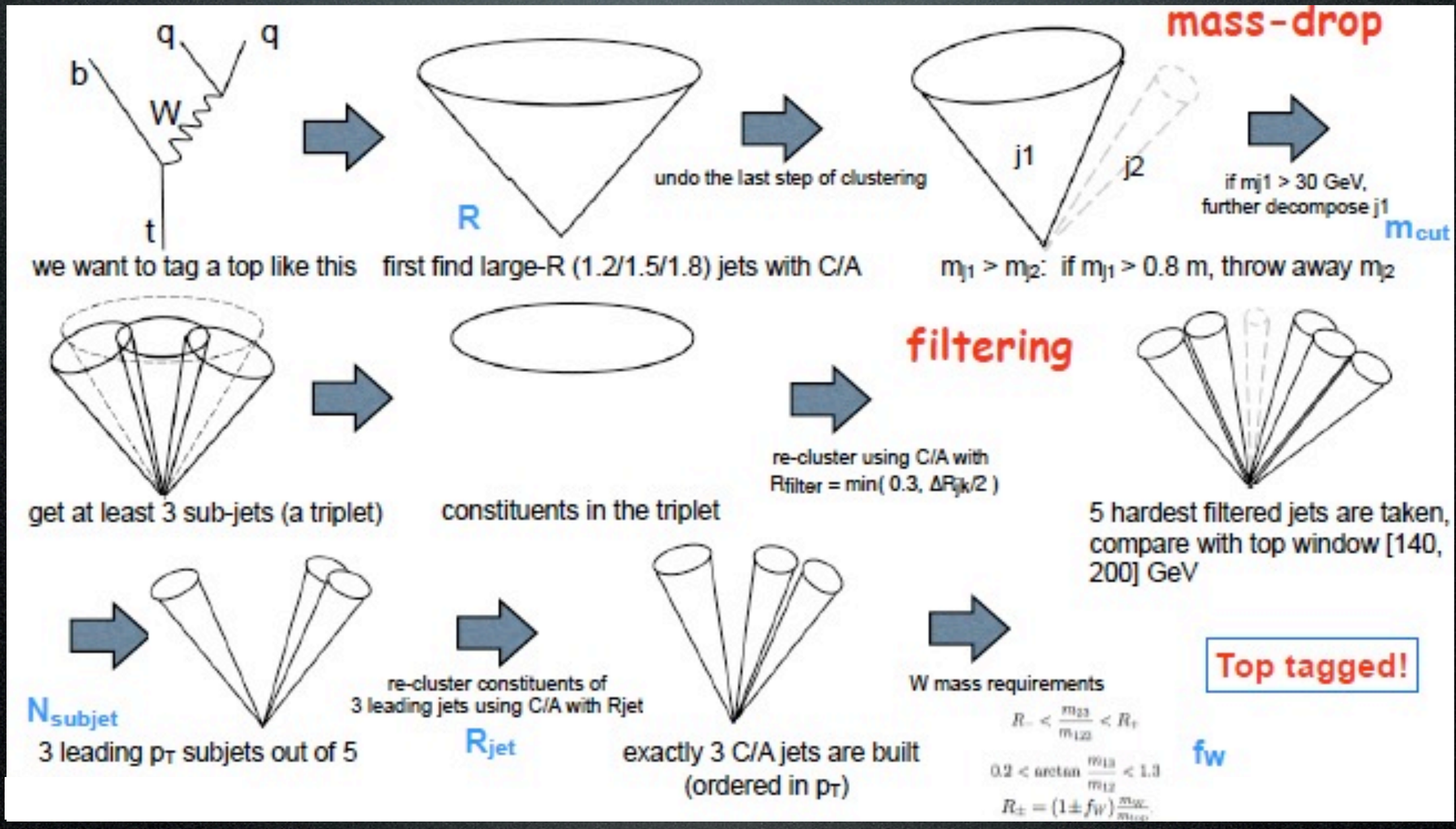
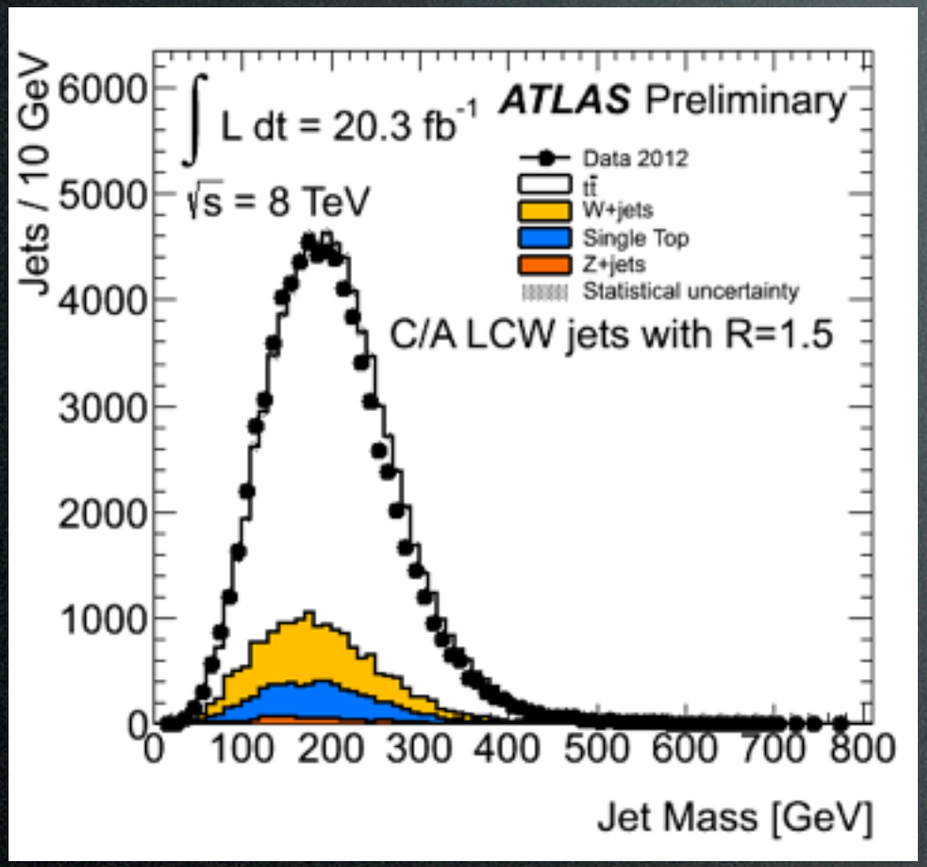
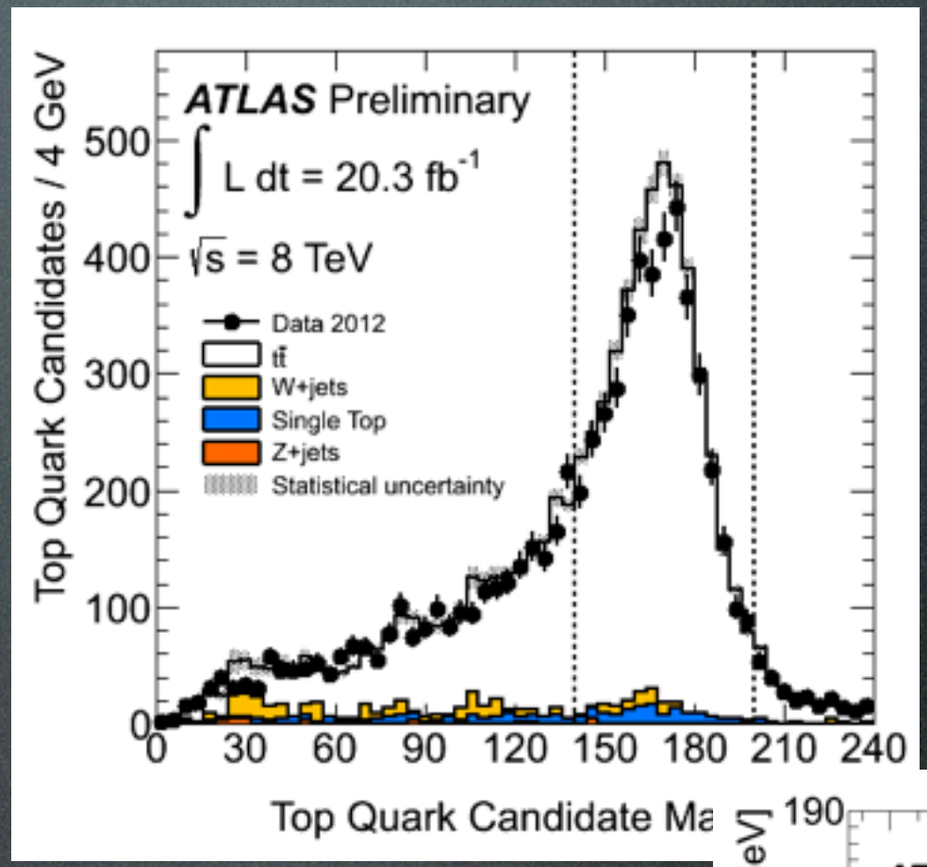


Figure by Xiaoxiao Wang

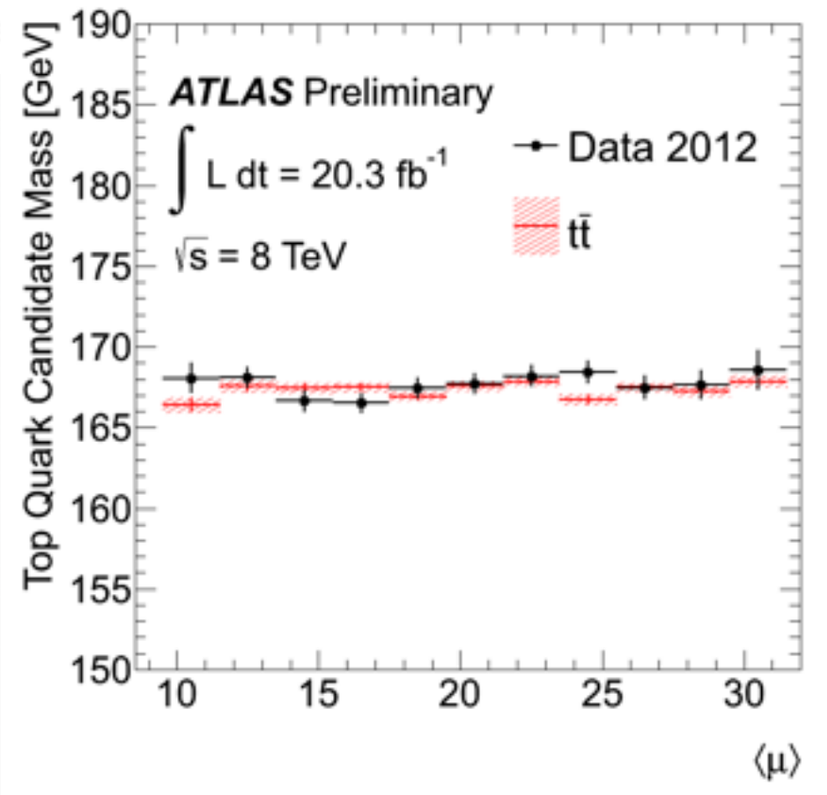
HEPTopTagger Performance





Before and after tagging by HepTopTagger

Pileup resilience



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