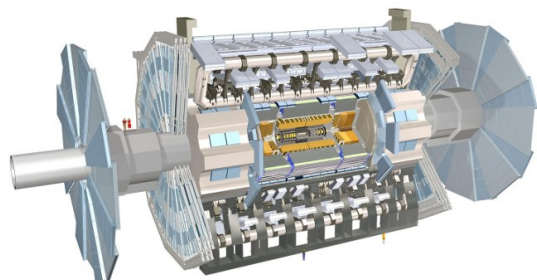
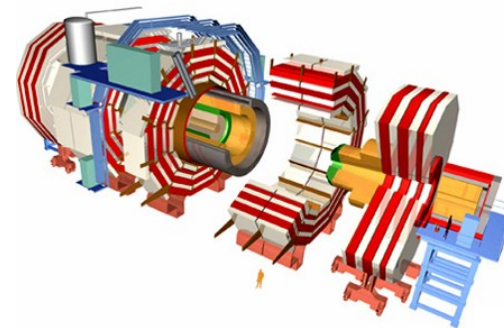


Jets and jet substructure after LHC Run 1



Emily Thompson
Columbia University

on behalf of ATLAS and CMS



BOOST'14 @ LONDON – AUGUST 18, 2014

- Outline:

- A brief Run1 history, and what have we learned
- Putting jet substructure techniques to use
- Run2 and beyond!

Introduction

- BOOST workshop, a history.

- *1 A Look Back at the Experimental Progression of Substructure at BOOST*

(from David Miller's
summary talk last year)

- BOOST 2010: These aren't your daddy's jets
- BOOST 2011: "First" data
- BOOST 2012: Kids in a candy store
- BOOST 2013: Bringing substructure into the mainstream

- Theme of Run1:

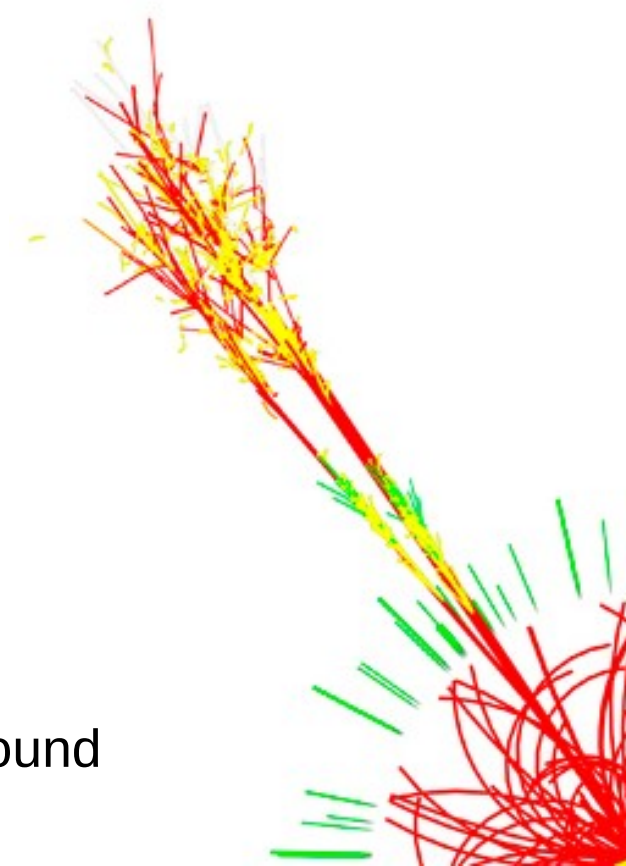
- Validating, calibrating and exploiting jet substructure

- BOOST 2014: Getting ready for Run2!

...wait, are we ready??

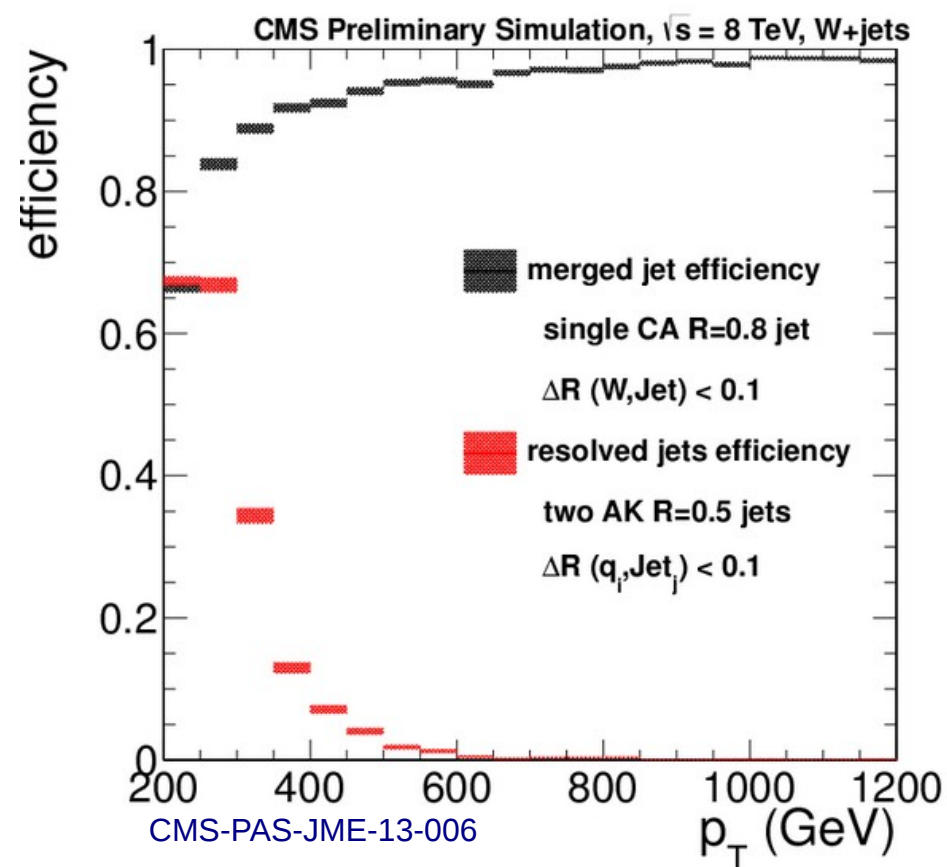
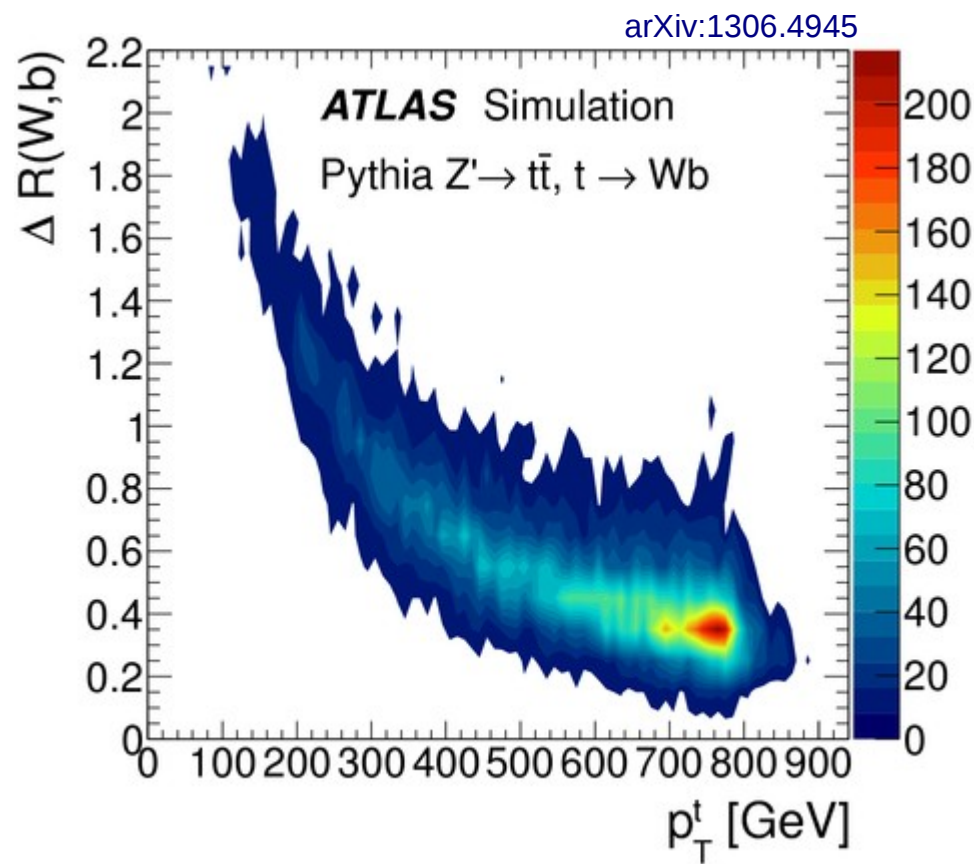
- Go back and ask...what does "boost" mean?

- High p_T
- Dense environments
- Tagging boosted objects over a light quark/gluon background



Where we started...

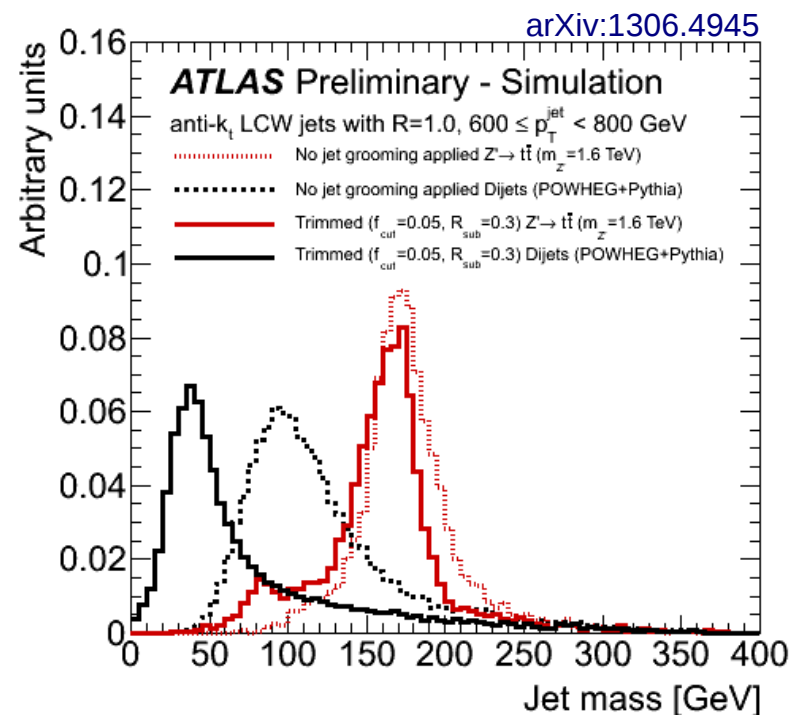
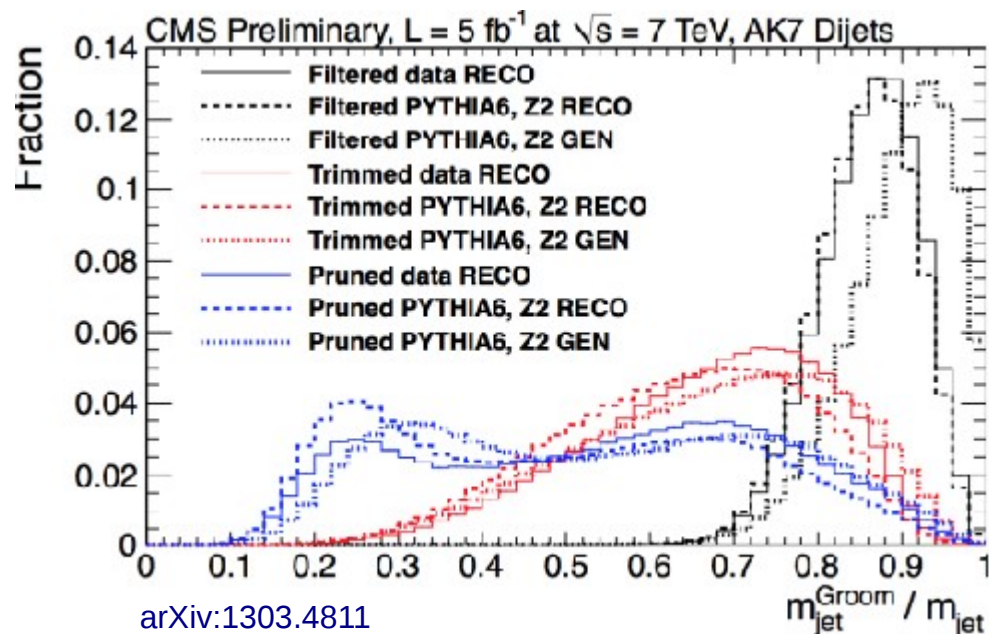
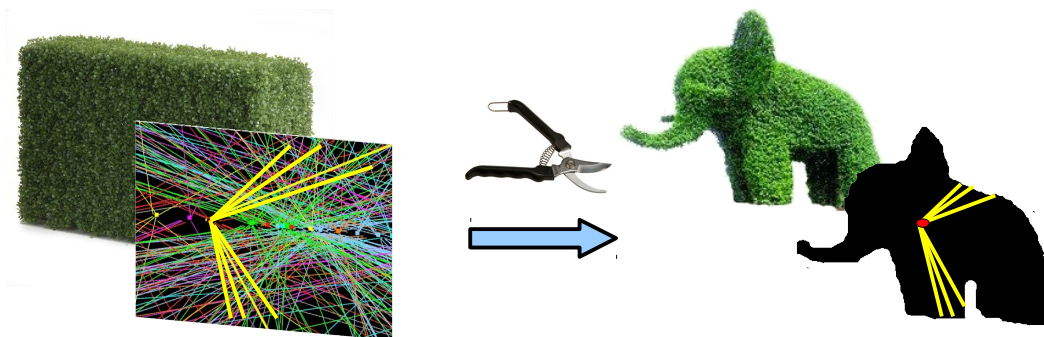
- We knew that new techniques would have to be developed to understand hadronic final states at the LHC
- Needed to convince ourselves it would work, especially in the presence of extreme pileup



Where we started...

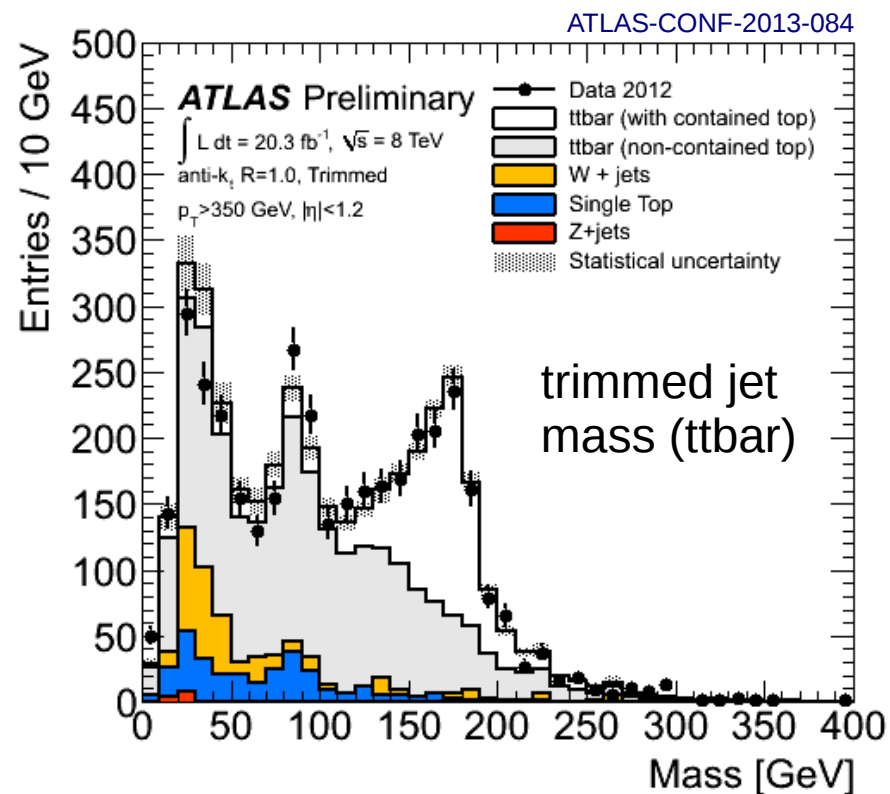
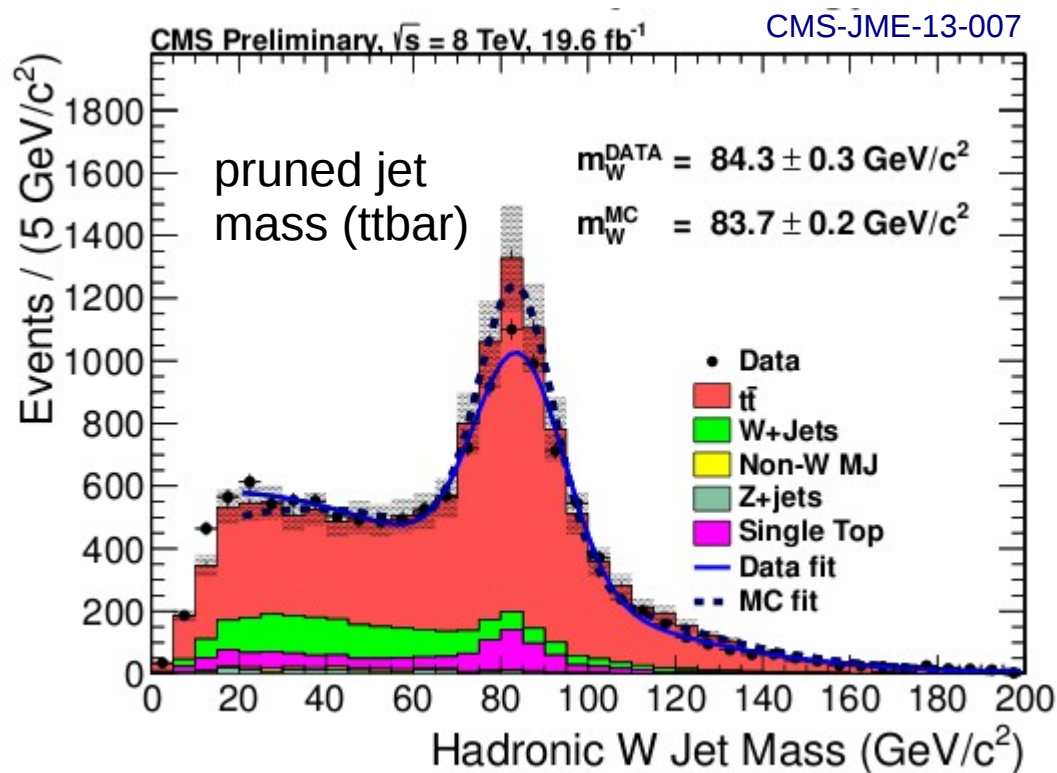
- Pileup mitigation...the three amigos! Trimming, Filtering, Pruning

- They do it all...use mass to tag a boosted object, maybe with some jet shapes, after performing grooming to remove pileup + UE



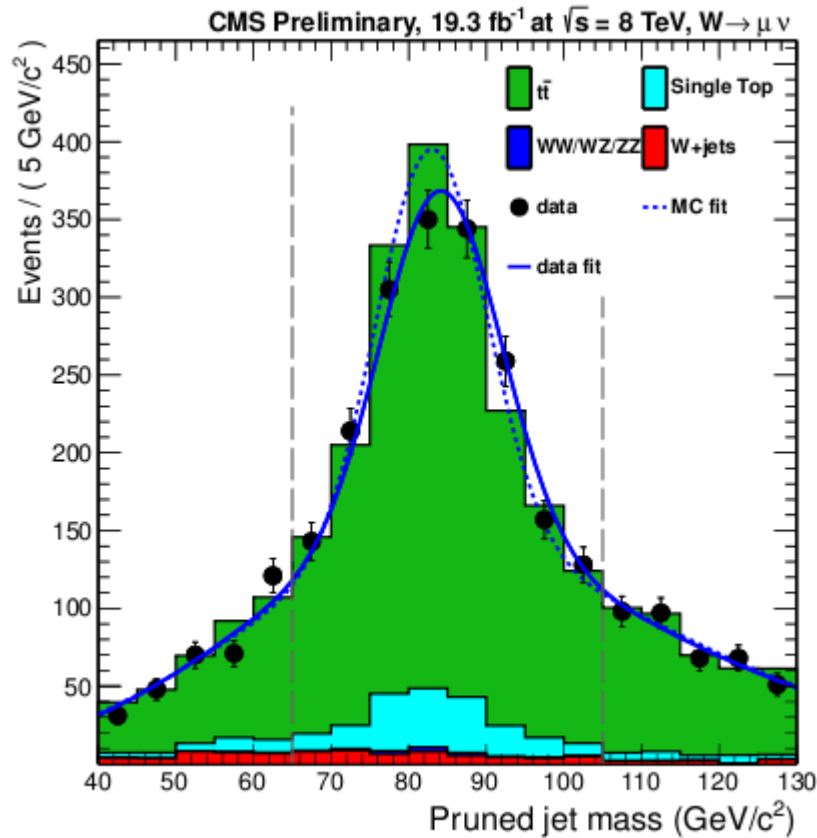
Where we started...

- Pileup mitigation...the three amigos! Trimming, Filtering, Pruning
 - They do it all...use mass to tag a boosted object, maybe with some jet shapes, after performing grooming to remove pileup + UE
- And we compared them in data! Things looked pretty good in 20 fb⁻¹

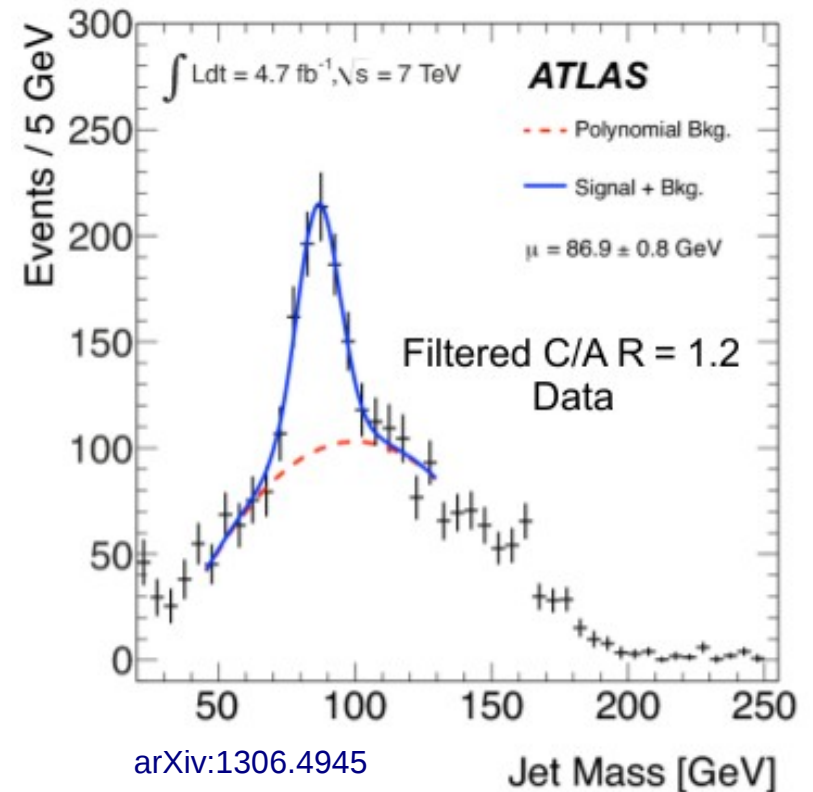
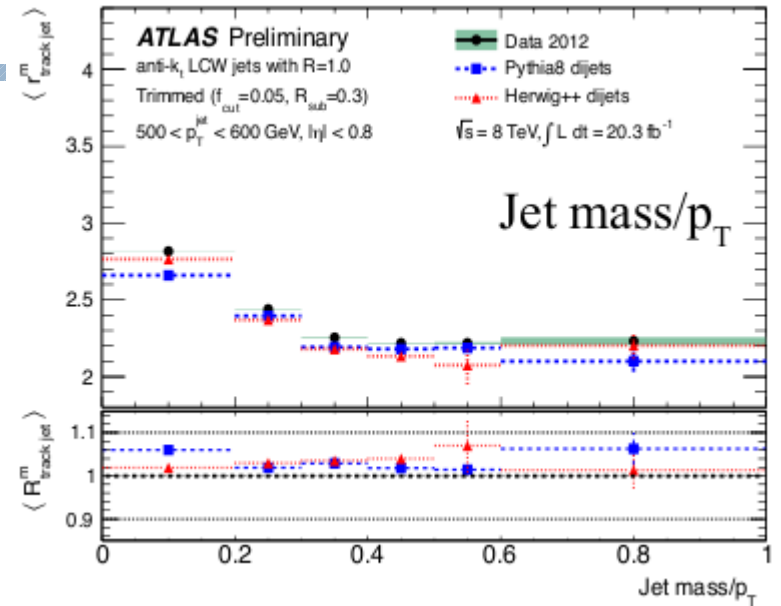


Where we started...

- Grooming works on on uncalibrated substructure components (ie: subjet pT), but we needed to show that we could successfully calibrate on “global” jet scale (ie: jet mass, pT)...

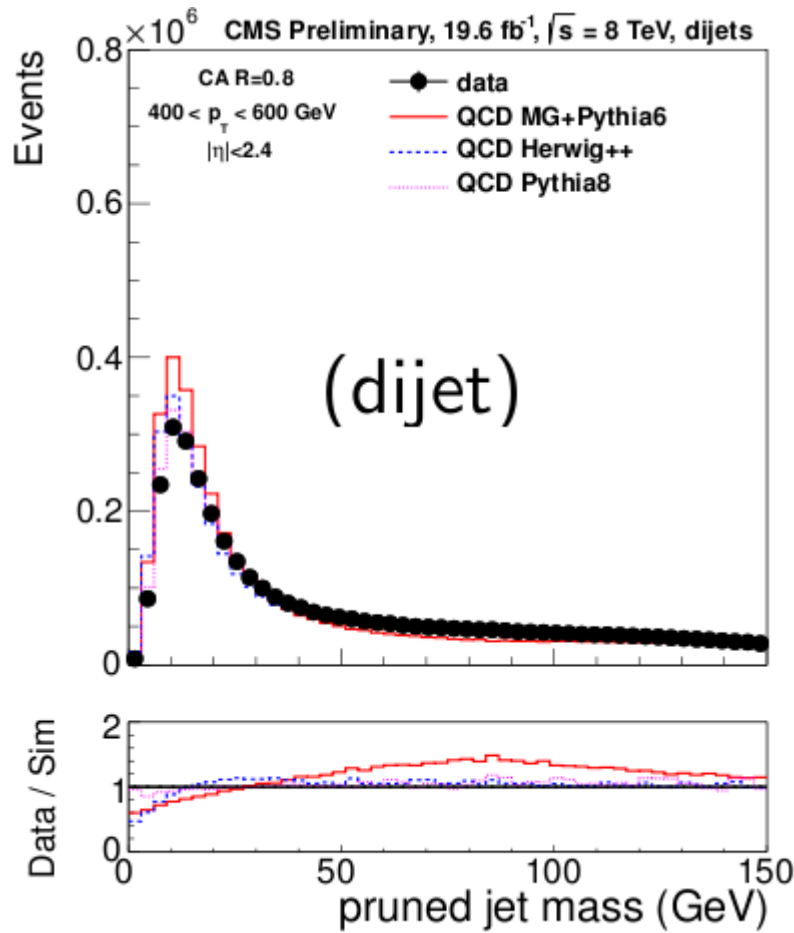


CMS-PAS-JME-13-006

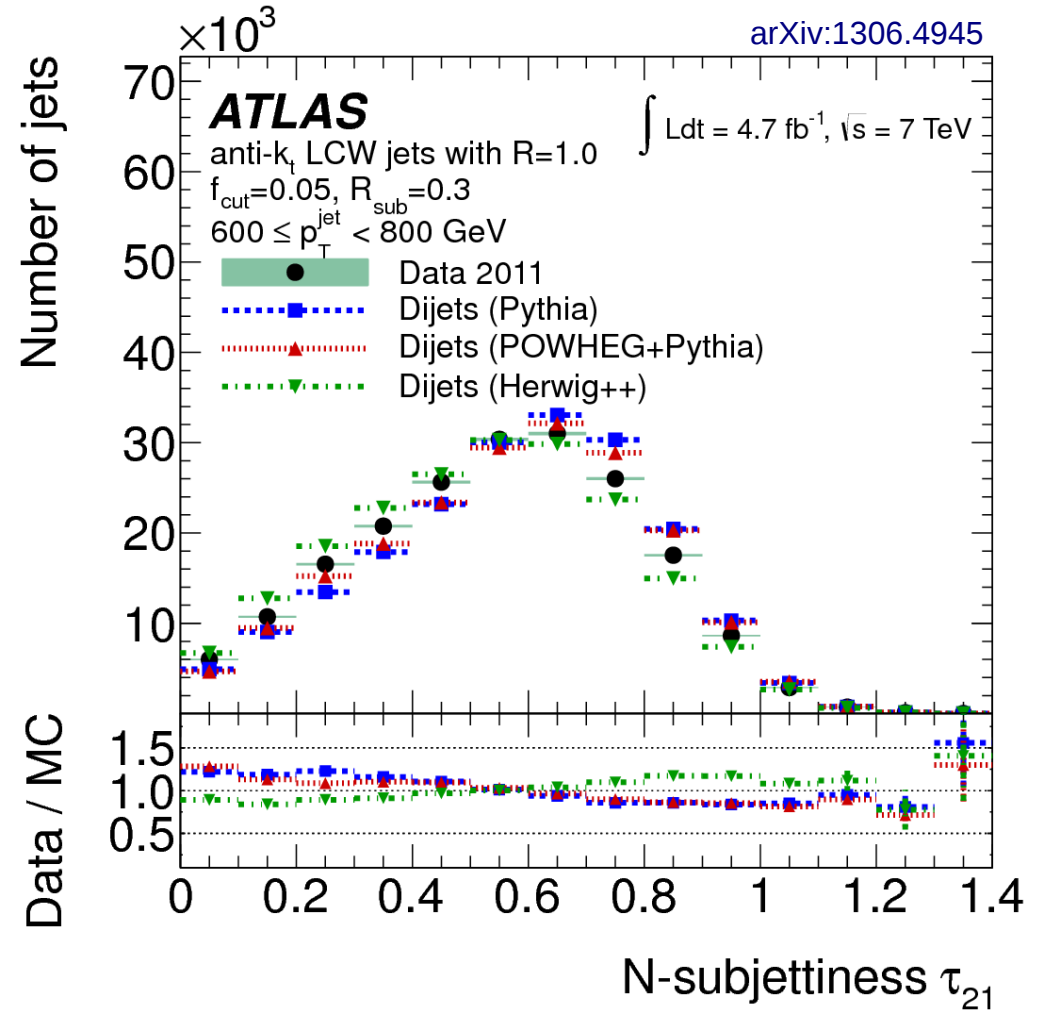


Where we started...

- ...but don't forget the generators! Large differences seen depending on what kind of parton showering was chosen

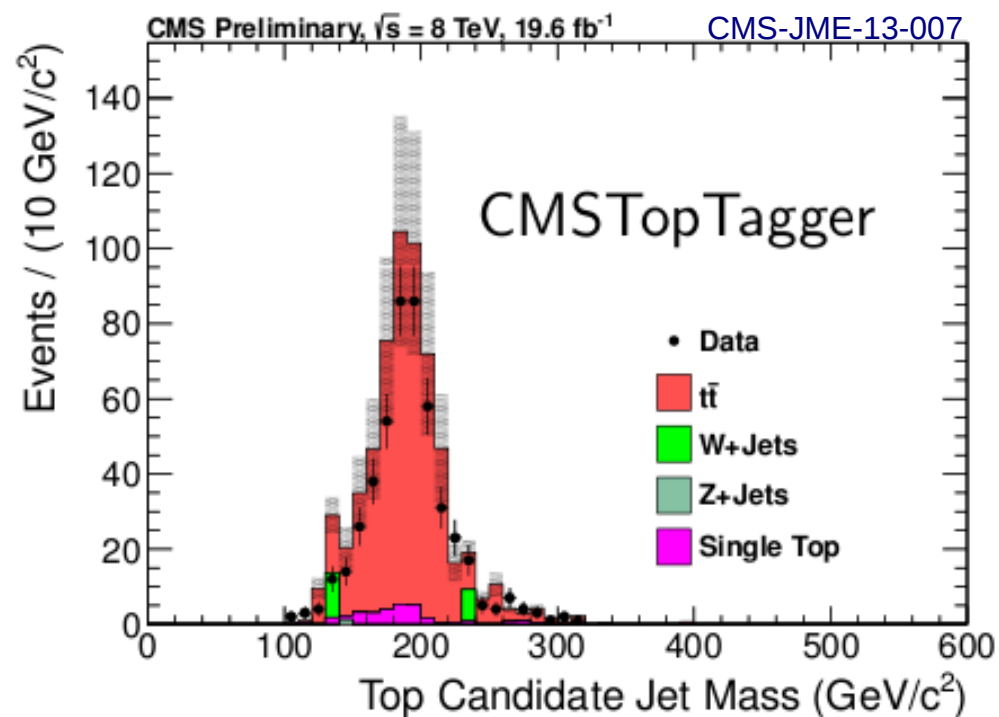
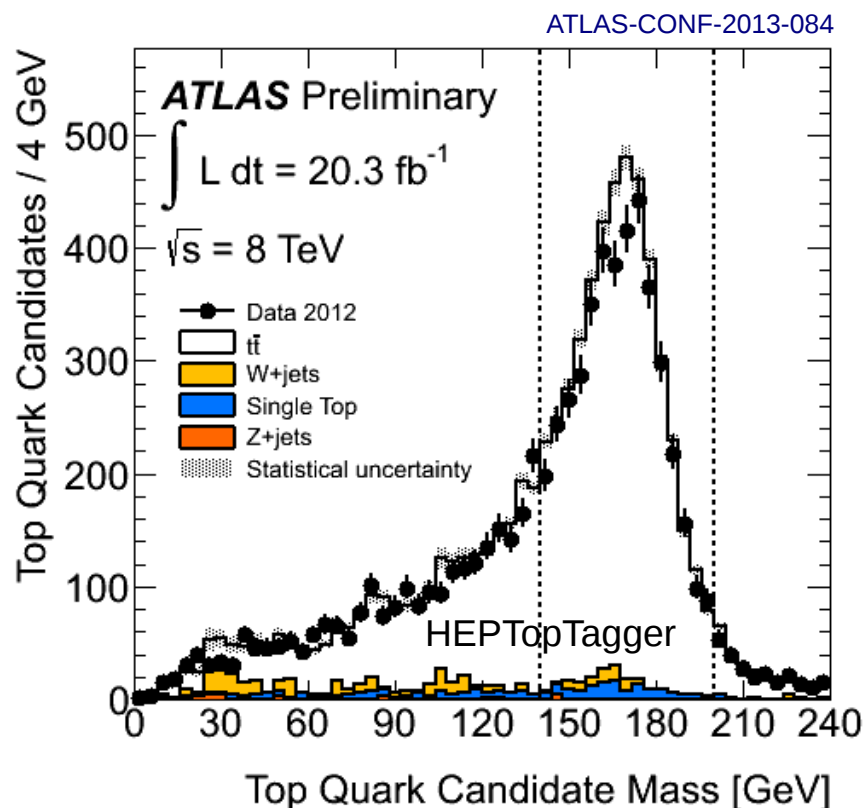


CMS-PAS-JME-13-006

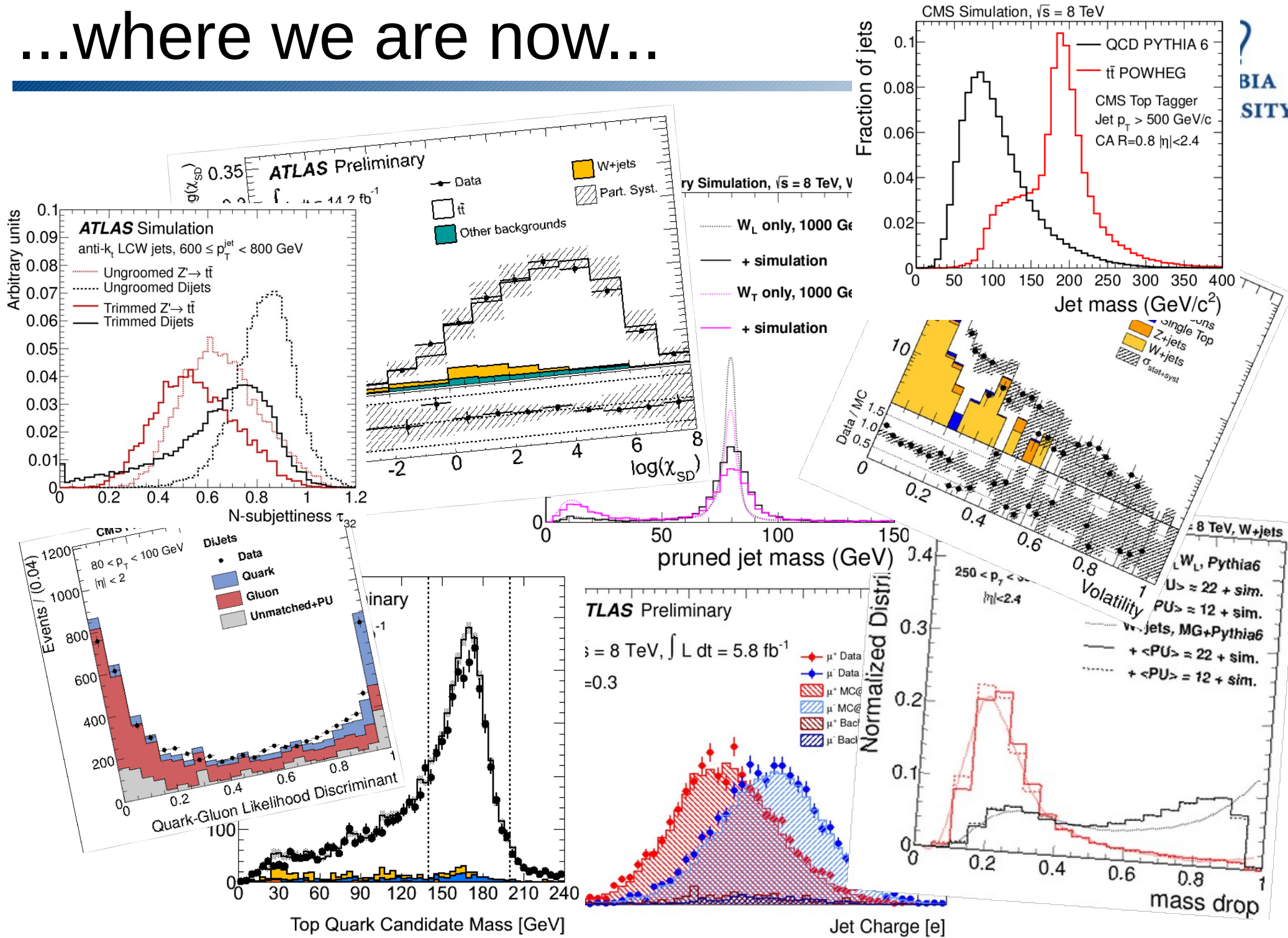


...where we are now...

- Along came advanced tagging: “grooming++”
 - Tagging+grooming all in one!
 - eg: HEPTopTagger, shower deconstruction, CMS top tagger, MVA-based tagging...

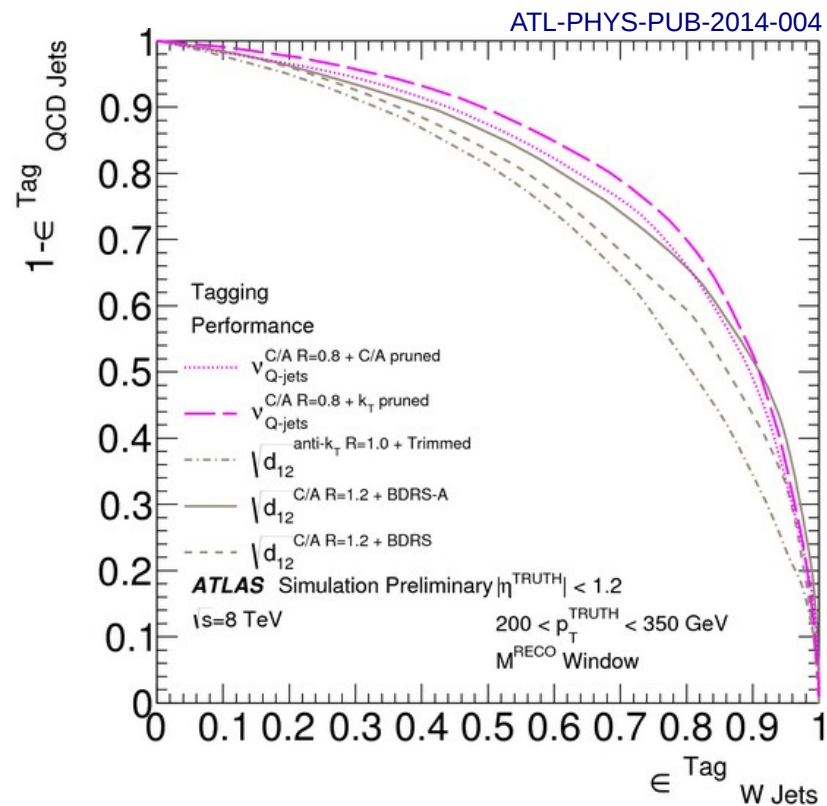
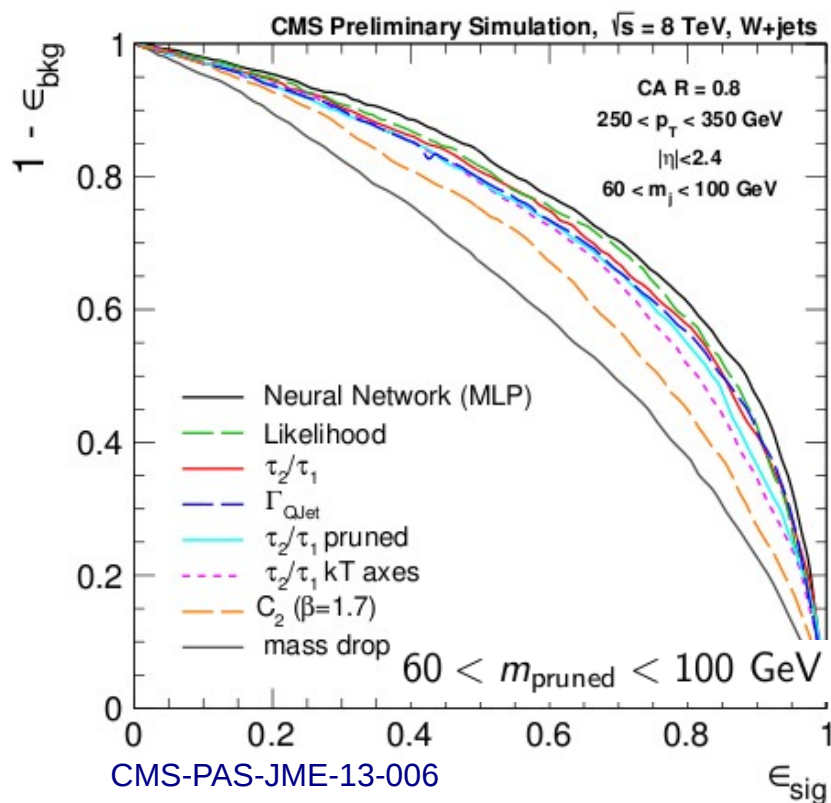


...where we are now...



...where we are now...

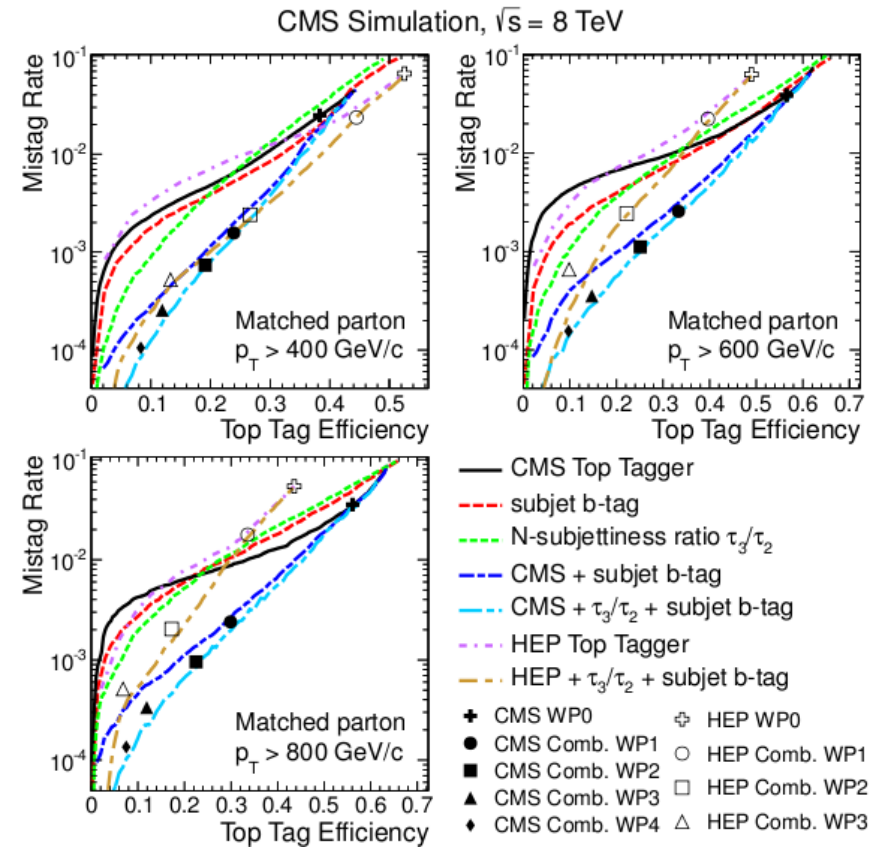
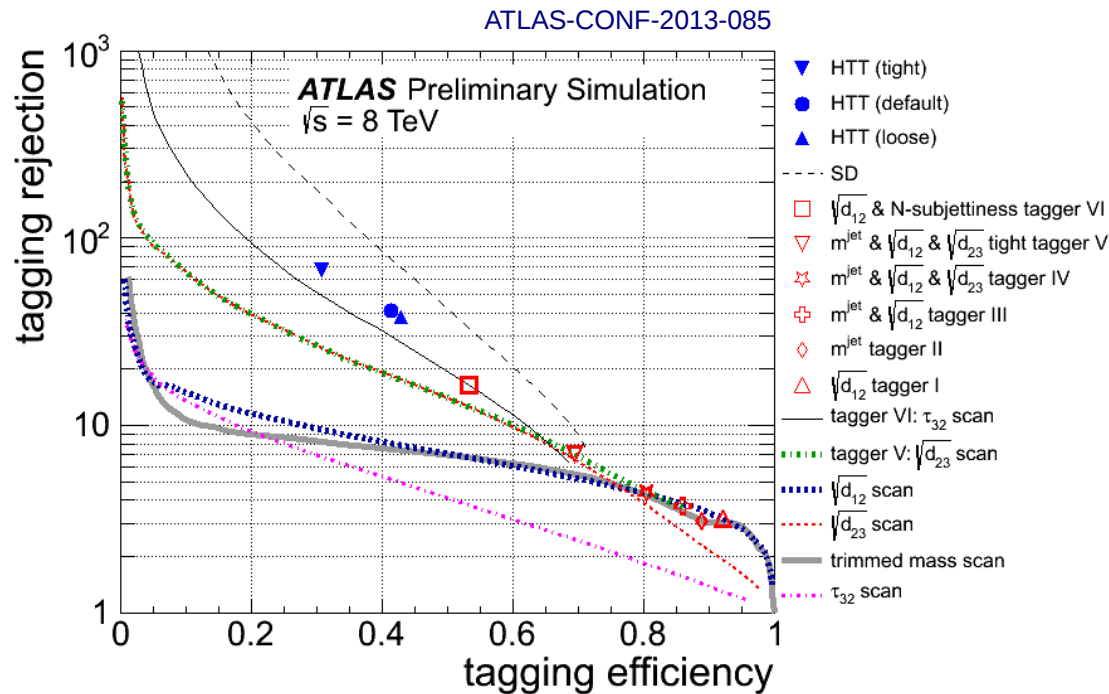
- More rigorous comparisons to focus on just a few taggers, before we move on to Run2
- Caveat: need to add systematics to these curves!
 - This is non trivial! Correlations also need to be properly taken into account



2-pronged “W” tagging

...where we are now...

- More rigorous comparisons to focus on just a few taggers, before we move on to Run2
- Caveat: need to add systematics to these curves!
 - This is non trivial! Correlations also need to be properly taken into account

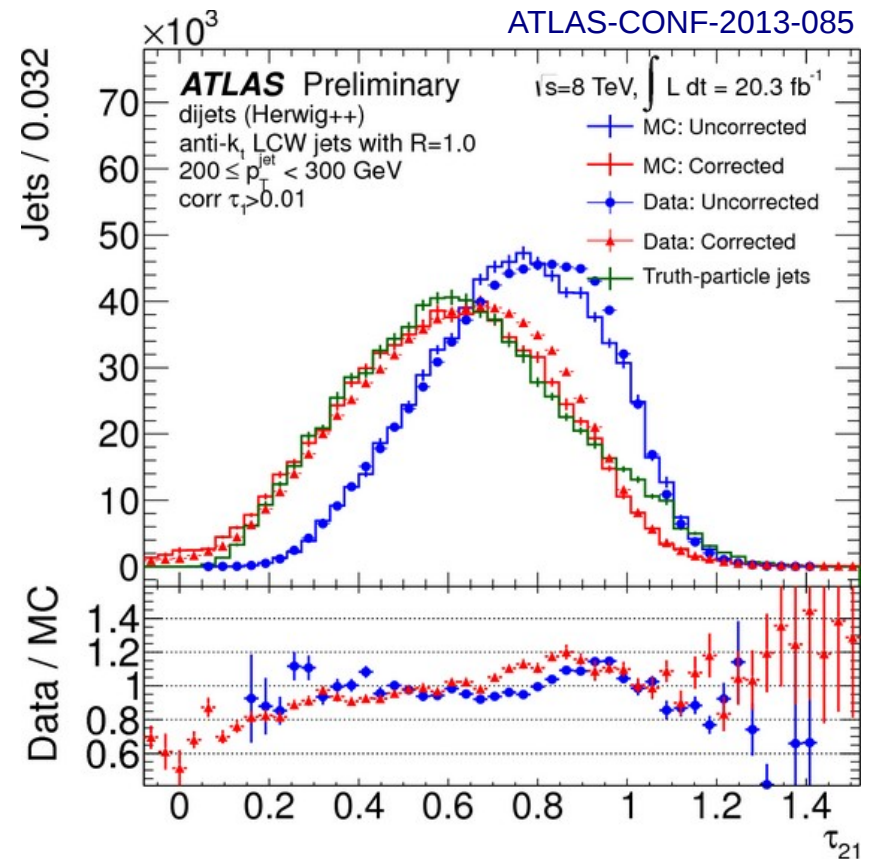
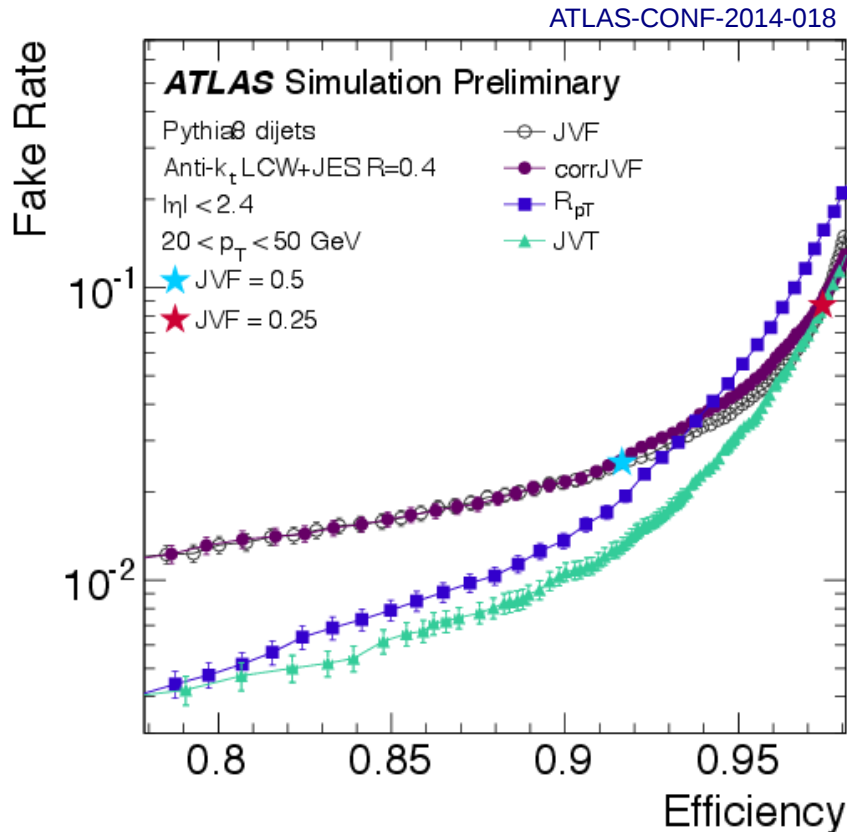


CMS-JME-13-007

3-pronged "top" tagging

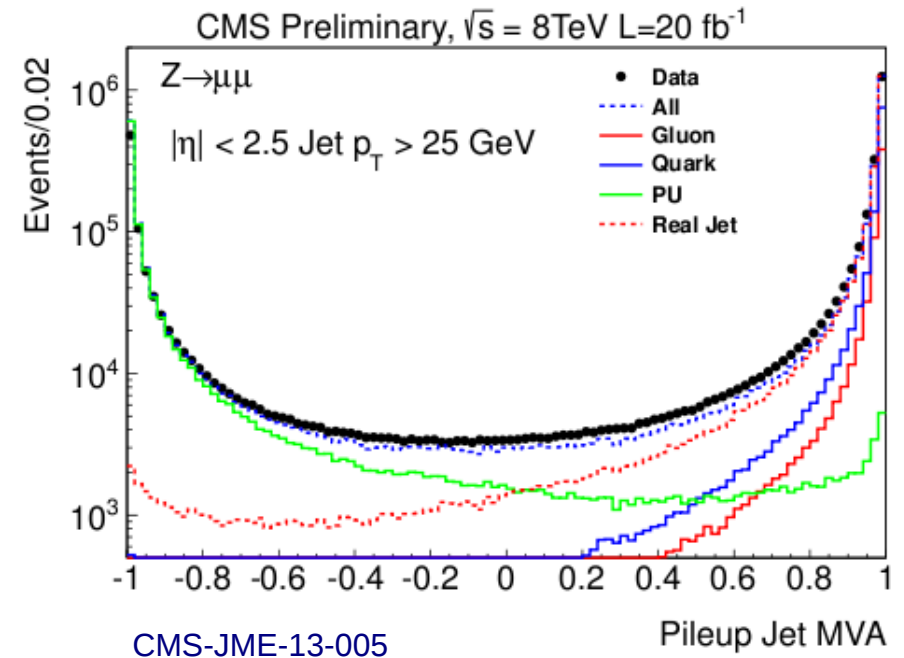
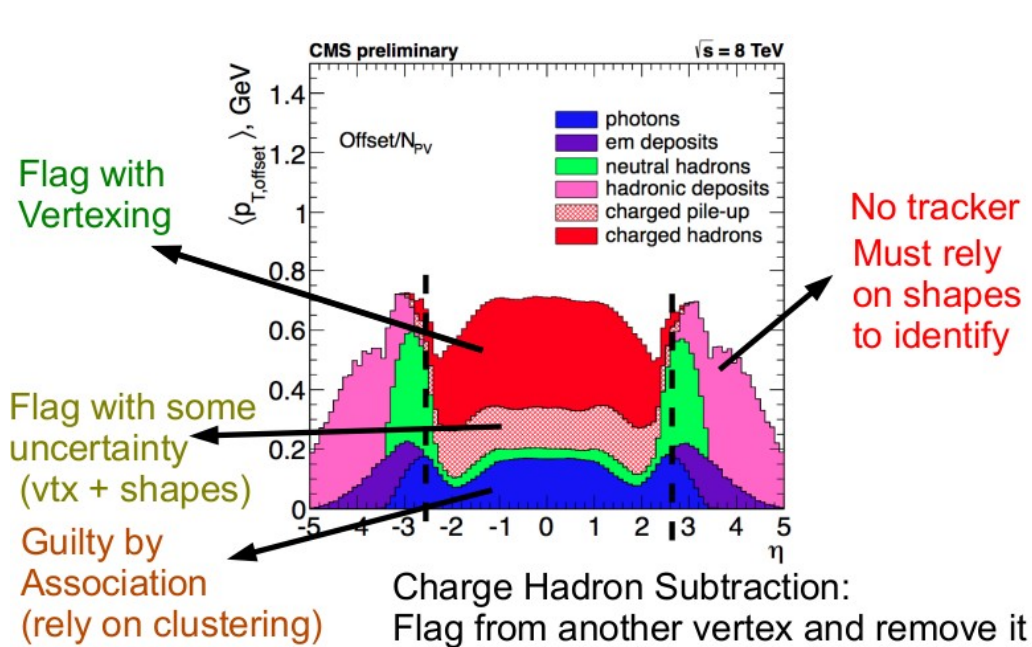
...where we are now...

- Pileup suppression: different approaches from the two experiments:
 - ATLAS: jet vertex fraction, jet areas correction and jet shapes subtraction work well...the latter can help “ease” the task of unfolding to particle level
 - CMS: PFlow reconstruction coupled with charged hadron subtraction...large effort to commission track-based pileup jet ID (already used in analyses)



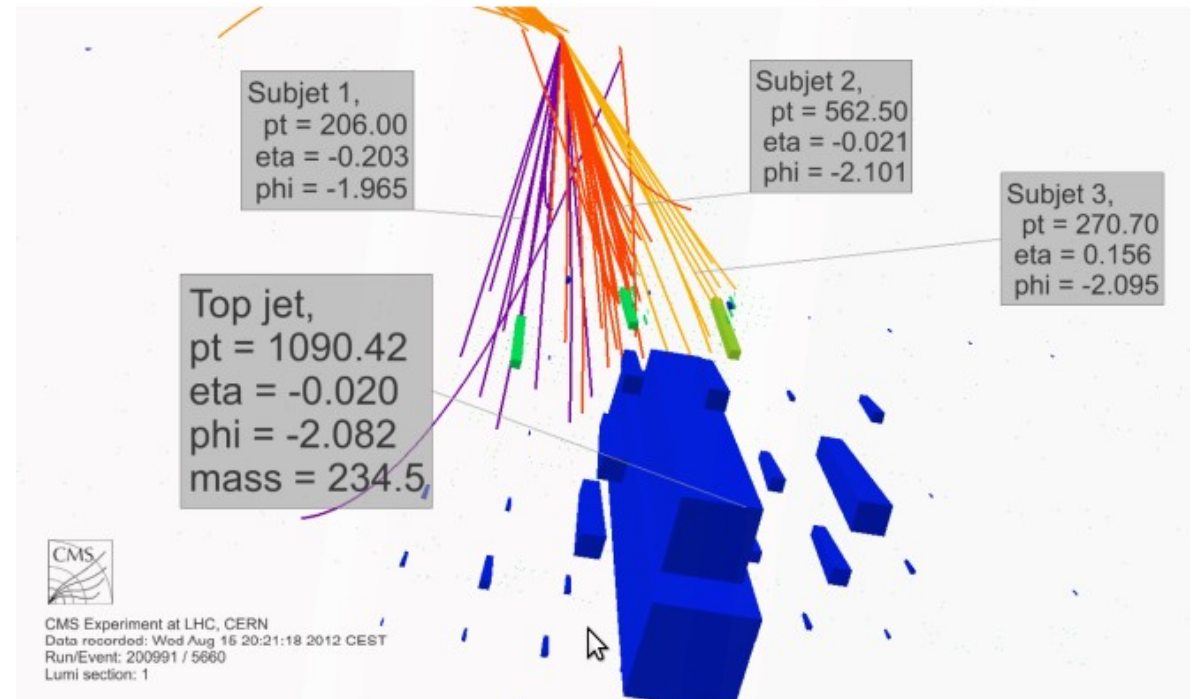
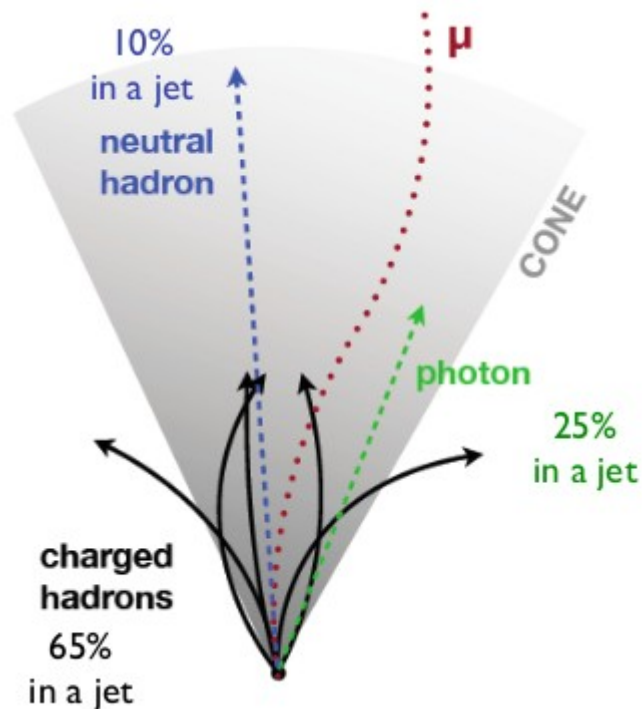
...where we are now...

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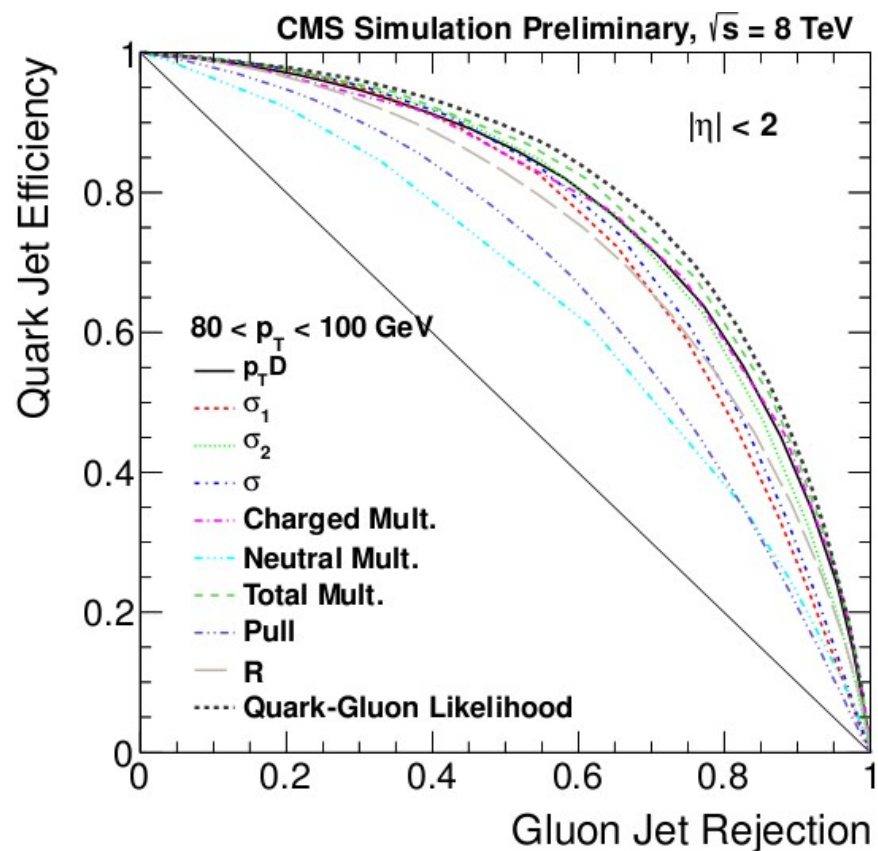
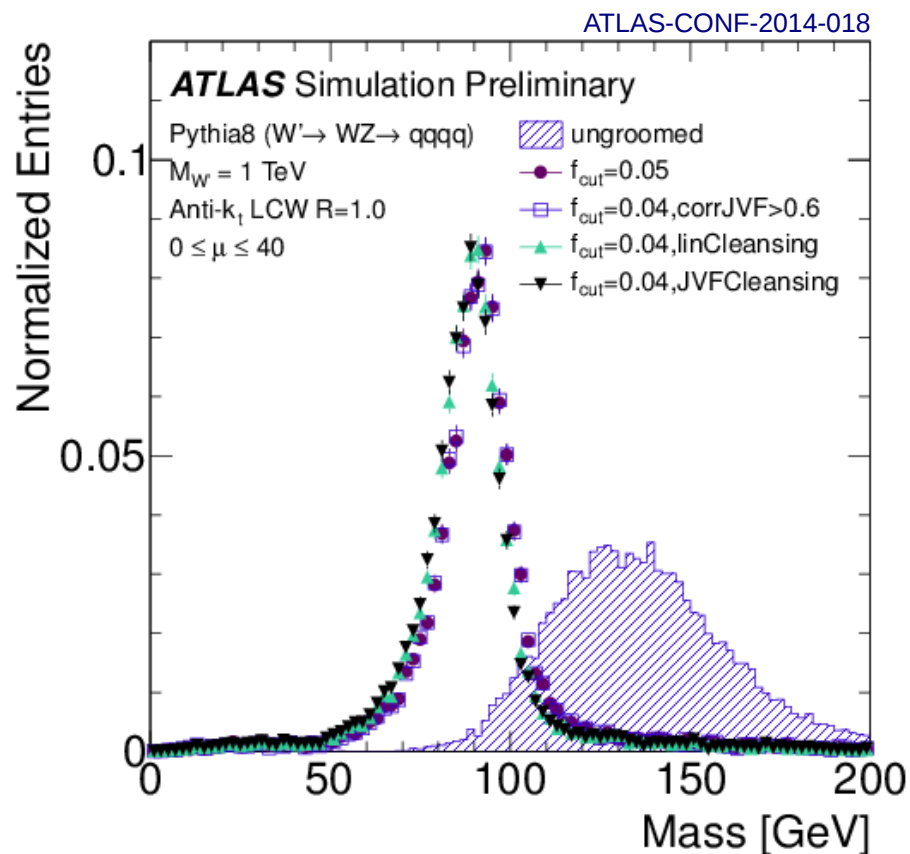
Tracking in jet substructure

- Use of tracking in substructure: eg: CMS particle flow
 - Combines tracking and calorimeter information, where individual pflow objects are used as inputs to jet finding: ideal for jet substructure!
 - Directly removes up to 60% of charged pileup tracks
 - Relies on high granularity and resolution of ECAL and high magnetic field to separate individual showers...only limitation is being able to understand the overlap between showers



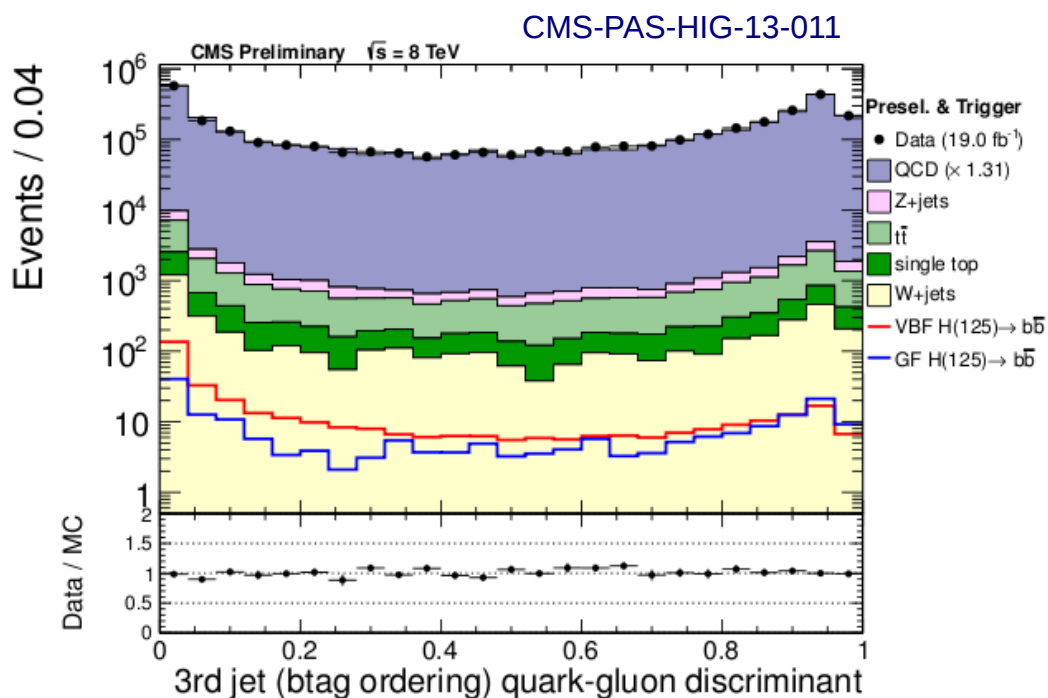
Tracking in jet substructure

- other examples: Jet charge, q/g , track-based trimming...

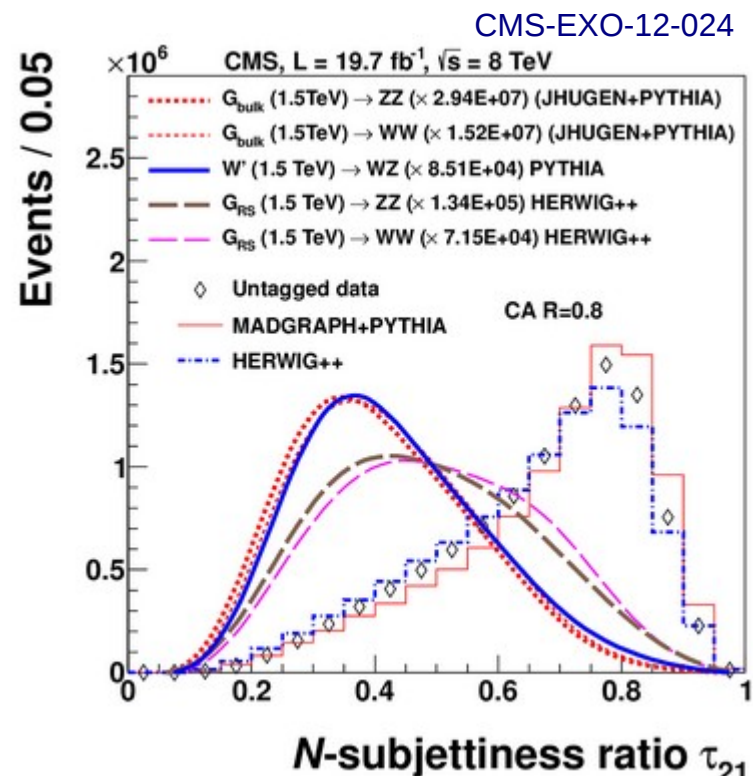


Putting the techniques to use

- In the end, only one thing matters...are the new techniques improving the sensitivity to new physics/providing a better measurement than could have been done with traditional jet algorithms?



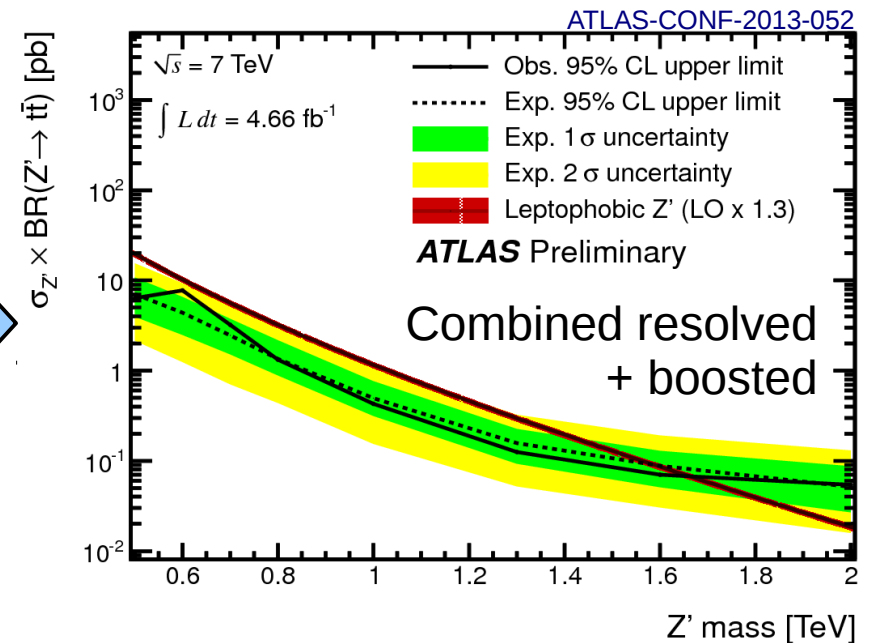
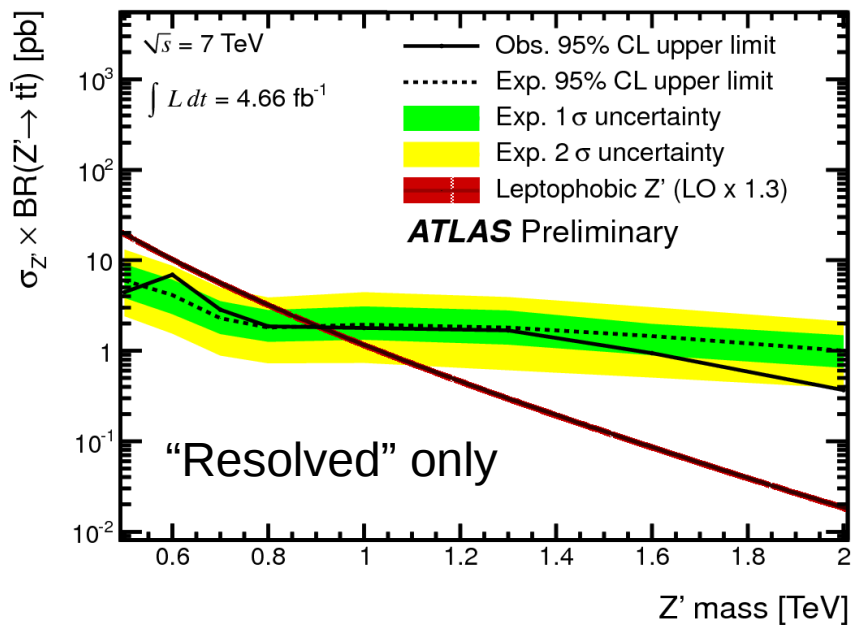
VBF → Vh(bb)



X → VV → qq qq

Putting the techniques to use

- In the end, only one thing matters...are the new techniques improving the sensitivity to new physics/providing a better measurement than could have been done with traditional jet algorithms?



$Z' \rightarrow t\bar{t}$ (semi-lep), 7 TeV

“boosted” employed simple trimmed $R=1.0$ jet with $\sqrt{d_{12}}$ cut

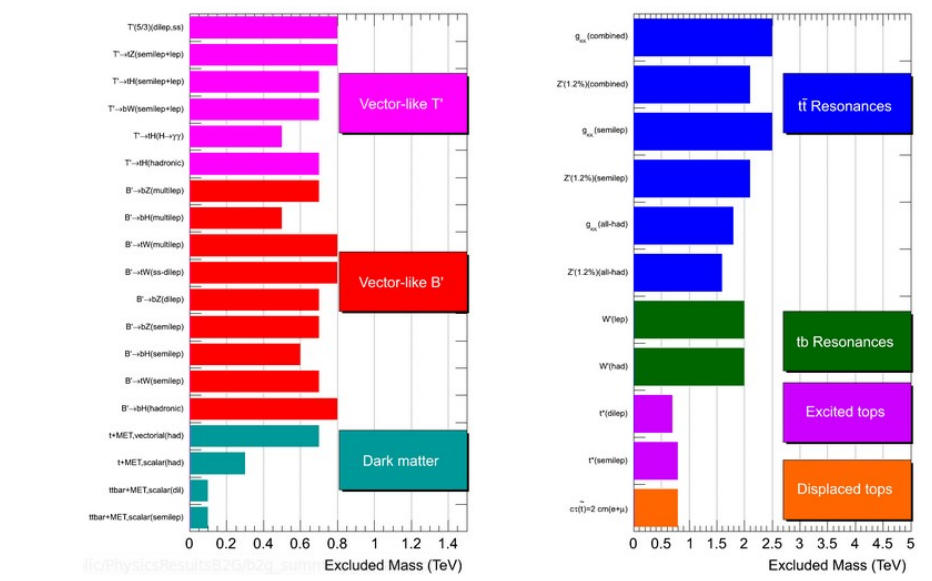
Putting the techniques to use

ATLAS Exotics Searches* - 95% CL Exclusion
 Status: ICHEP 2014

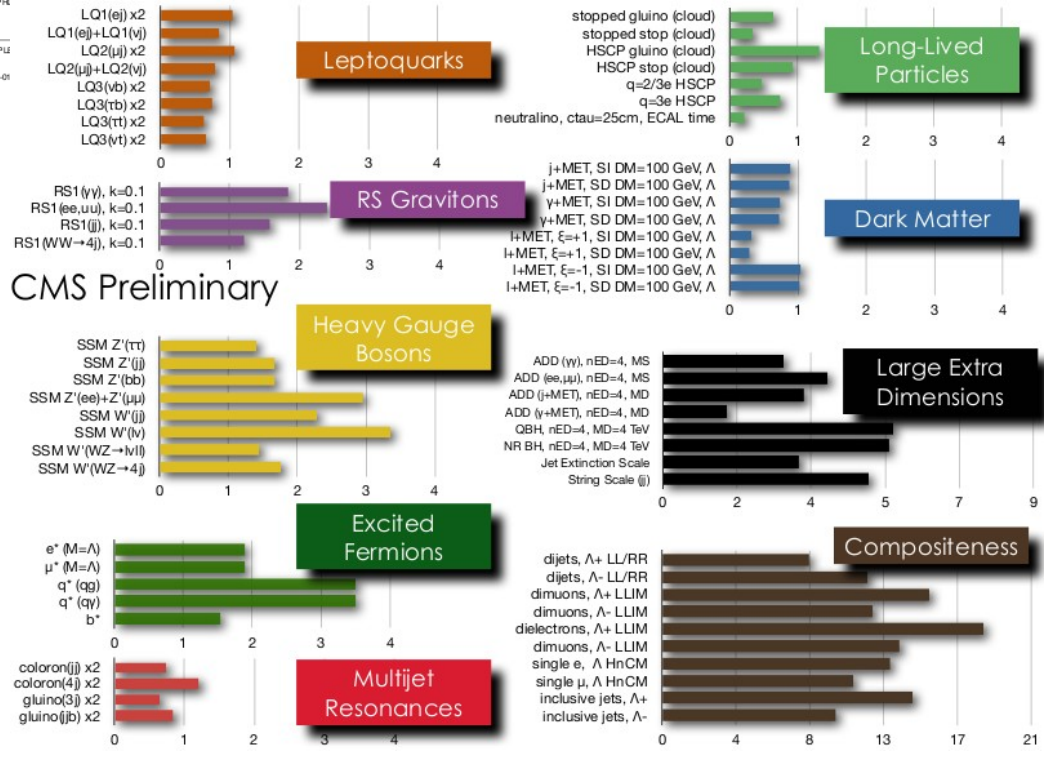
ATLAS Preliminary
 $\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8 \text{ TeV}$

Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
ADD $G_{KK} + g/q$	-	1-2	Yes	4.7	M_{KK} 4.37 TeV	n=2 1210.4491	
ADD non resonant $\ell\ell$	$2e, \mu$	-	-	20.3	M_{KK} 5.2 TeV	n=3 HLZ ATLAS-CONF-2014-030	
ADD QBH $\rightarrow \ell q$	$1e, \mu$	1j	-	20.3	M_{KK} 5.2 TeV	1311.2006 n=6	
ADD QBH	-	2j	-	20.3	M_{KK} 5.82 TeV	to be submitted to PRD	
ADD BH high M_{KK}	2μ (SS)	-	-	20.3	M_{KK} 5.7 TeV	1308.4075 n=6, $M_{KK} = 1.5 \text{ TeV}$ non-rot BH	
ADD BH high Σp_T	$\geq 1e, \mu$	$\geq 2j$	-	20.3	M_{KK} 5.2 TeV	1405.4054 n=6, $M_{KK} = 1.5 \text{ TeV}$ non-rot BH	
RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	M_{KK} 2.88 TeV	1405.4123 $k/\bar{M}_{KK} = 0.1$	
RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$	$2e, \mu$	Yes	4.7	4.7	G_{KK} mass 1.23 TeV	1208.2880 $k/\bar{M}_{KK} = 0.1$	
Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell\ell q\bar{q}$	$2e, \mu$	2j/1j	-	20.3	G_{KK} mass 738 GeV	ATLAS-CONF-2014-039 $k/\bar{M}_{KK} = 1.0$	
Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	-	4b	-	19.5	G_{KK} mass 590-710 GeV	ATLAS-CONF-2014-005 $k/\bar{M}_{KK} = 1.0$	
Bulk RS $G_{KK} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1j/2j$	Yes	14.3	G_{KK} mass 2.0 TeV	ATLAS-CONF-2013-052 BR = 0.925	
S^1/Z_2 ED	$2e, \mu$	-	-	5.0	$M_{KK} = R^2$ 4.71 TeV	1209.2535	
UED	2γ	Yes	4.8	4.8	Compact scales R^{-1} 1.41 TeV	ATLAS-CONF-2012-072	
SMM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	Z' mass 2.9 TeV	1405.4123	
SMM $Z' \rightarrow \tau\tau$	2τ	-	-	19.5	Z' mass 1.9 TeV	ATLAS-CONF-2013-066	
SMM $W' \rightarrow \ell\nu$	$1e, \mu$	-	-	20.3	W' mass 3.28 TeV	ATLAS-CONF-2014-017	
EGM $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$	$3e, \mu$	Yes	20.3	20.3	W' mass 1.30 TeV	1408.4499	
EGM $W' \rightarrow WZ \rightarrow q\ell\ell\ell$	$2e, \mu$	2j/1j	-	20.3	W' mass 1.30 TeV	ATLAS-CONF-2014-039	
LRSM $W'_\mu \rightarrow \ell\bar{\nu}$	$1e, \mu$	2b, 0-1j	Yes	14.3	W' mass 1.84 TeV	ATLAS-CONF-2013-050	
LRSM $W'_\mu \rightarrow \ell\bar{b}$	$0e, \mu$	$\geq 1b, 1j$	-	20.3	W' mass 1.77 TeV	to be submitted to EPJ C	
CI $q\ell q\ell$	-	2j	-	4.8	A 7.6 TeV	1210.1718 q = +1	
CI $q\ell\ell\ell$	$2e, \mu$	-	-	20.3	A 21.5 TeV	ATLAS-CONF-2014-030 $\eta_\mu = -1$	
CI $u\ell\ell\ell$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	14.3	A 3.3 TeV	ATLAS-CONF-2013-051 C = 1	
EFT D5 operator (Dirac)	$0e, \mu$	1-2j	Yes	10.5	M 7.31 GeV	ATLAS-CONF-2012-147 at 90% CL for $m(\chi) < 80 \text{ GeV}$	
EFT D9 operator (Dirac)	$0e, \mu$	1j, $\leq 1j$	Yes	20.3	M 2.4 TeV	1309.4017 at 90% CL for $m(\chi) < 100 \text{ GeV}$	
LQ	Scalar LQ 1 st gen	$2e, \mu \geq 2j$	-	1.0	LQ mass 660 GeV	$\beta = 1$ 1112.4028	
Scalar LQ 2 nd gen	$2\mu, \geq 2j$	-	1.0	1.0	LQ mass 685 GeV	$\beta = 1$ 1203.3172	
Scalar LQ 3 rd gen	$1e, \mu, 1\tau, 1b, 1j$	-	4.7	4.7	LQ mass 534 GeV	$\beta = 1$ 1303.0536	
Vector-like quark $TT \rightarrow Ht + X$	$1e, \mu, \tau$	$\geq 2b, \geq 4j$	Yes	14.3	T mass 790 GeV	T in (TB) doublet ATLAS-CONF-2013-018	
Vector-like quark $TT \rightarrow Wb + X$	$1e, \mu, \tau$	$\geq 1b, \geq 3j$	Yes	14.3	T mass 670 GeV	isospin singlet ATLAS-CONF-2013-030	
Vector-like quark $TT \rightarrow Zt + X$	$2/2/3e, \mu$	$\geq 2/2/1b$	-	20.3	T mass 735 GeV	T in (TB) doublet ATLAS-CONF-2014-036	
Vector-like quark $BB \rightarrow Zb + X$	$2/2/3e, \mu$	$\geq 2/1b$	-	20.3	B mass 755 GeV	B in (B) doublet ATLAS-CONF-2014-036	
Vector-like quark $BB \rightarrow Wt + X$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	14.3	B mass 730 GeV	B in (TB) doublet ATLAS-CONF-2013-051	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1γ	1j	-	20.3	q^* mass 3.5 TeV	only u^* and d^* , $A = m(q^*)$ 1309.3230
Excited quark $q^* \rightarrow qg$	-	2j	-	20.3	q^* mass 4.09 TeV	only u^* and d^* , $A = m(q^*)$ to be submitted to PRF	
Excited quark $b^* \rightarrow Wt$	1 or 2 $e, \mu, 1b, 2j$ or 1j	Yes	4.7	4.7	b^* mass 870 GeV	left handed coupling 1301.1583	
Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	-	-	13.0	ℓ^* mass 2.2 TeV	1308.1364	
Other	LSTC $\alpha\gamma \rightarrow W\gamma$	$1e, \mu, 1\gamma$	Yes	20.3	α mass 960 GeV	to be submitted to PLF 1203.5420	
LRSM Majorana ν	$2e, \mu, 2j$	-	2.1	2.1	N^* mass 1.5 TeV	ATLAS-CONF-2013-011 $m(M_N) = 2 \text{ TeV}$, no mixing $ V_{12} =0.05, V_{13} =0.083, V_{23} =0$ Dirac production, BR($H^+ \rightarrow \ell\nu$)=1 Dirac production, $g = 4e$ Dirac production, $g = \text{lego}$ 1210.5070 1301.1572 1207.6411	
Type III See saw	$2e, \mu$	-	5.8	5.8	N^* mass 240 GeV		
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	-	4.7	4.7	$H^{\pm\pm}$ mass 409 GeV		
Multi-charged particles	-	-	-	4.4	$H^{\pm\pm}$ mass 490 GeV		
Magnetic monopoles	-	-	-	2.0	$monopoles$ mass 962 GeV		

CMS Searches for New Physics Beyond Two Generations (B2G) 95% CL Exclusions (TeV)

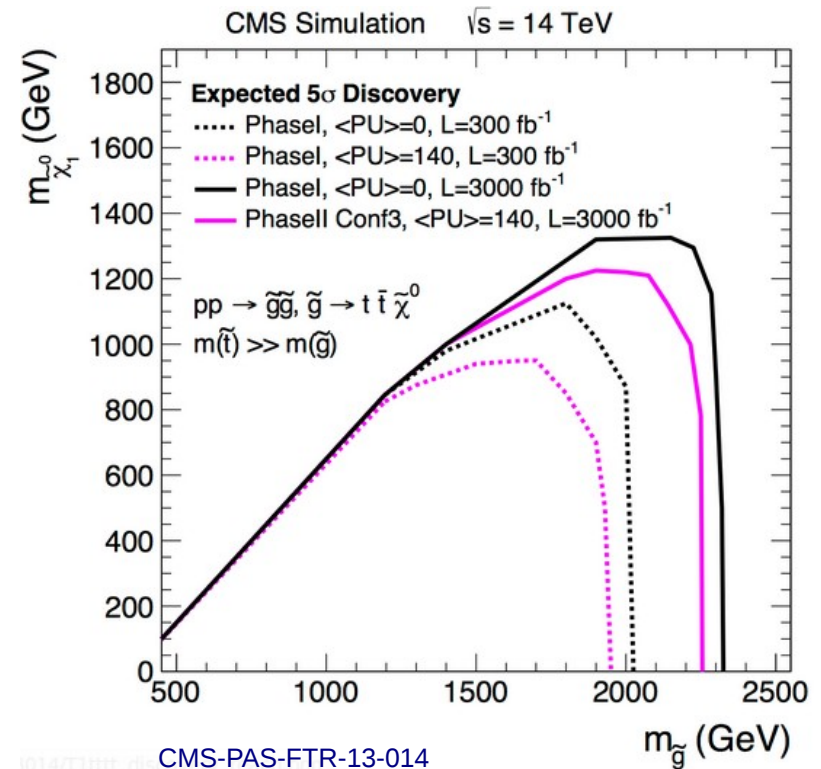
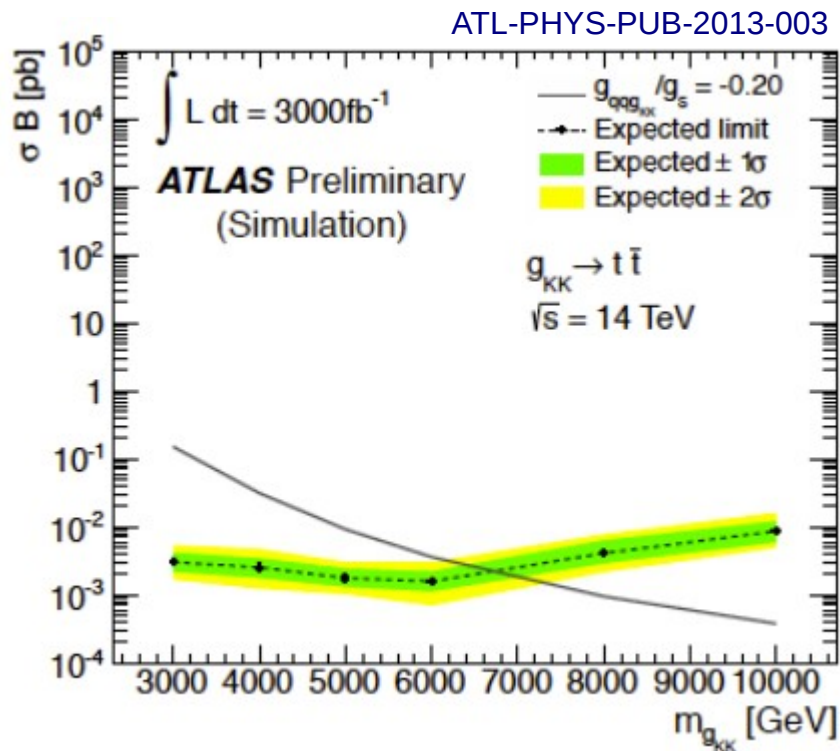


* only a selection shown!

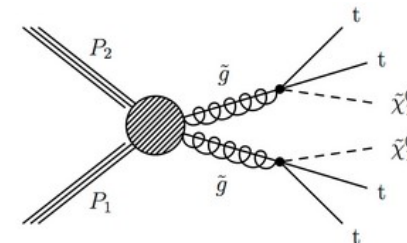


On to Run2...and beyond!

- You can't do physics in Run2 without BOOST
- Any objects with $p_T > \sim 500$ GeV are going to need jet substructure techniques in order to extend discovery reach for new particles into the multi-TeV region

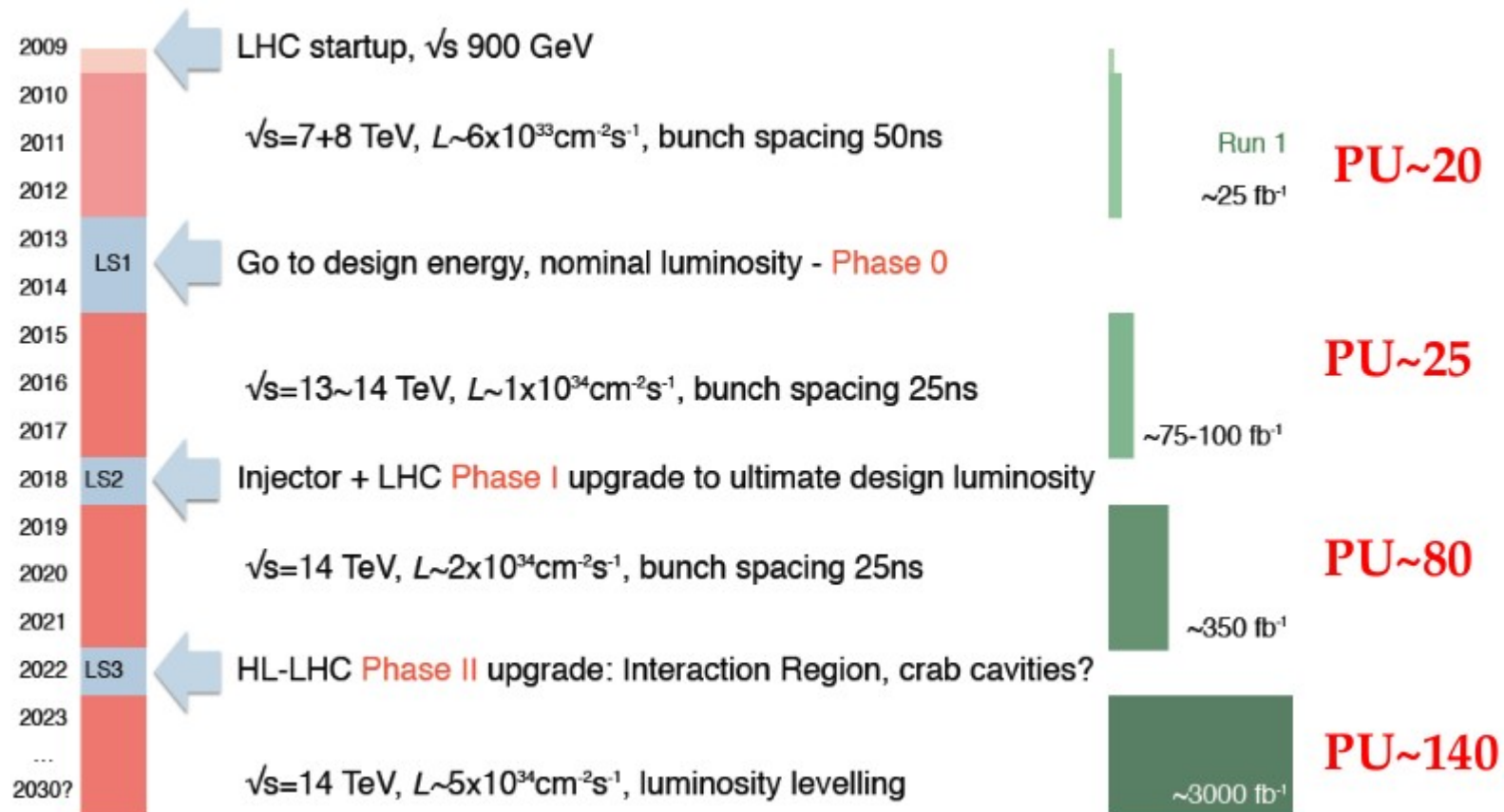


X \rightarrow ttbar resonance



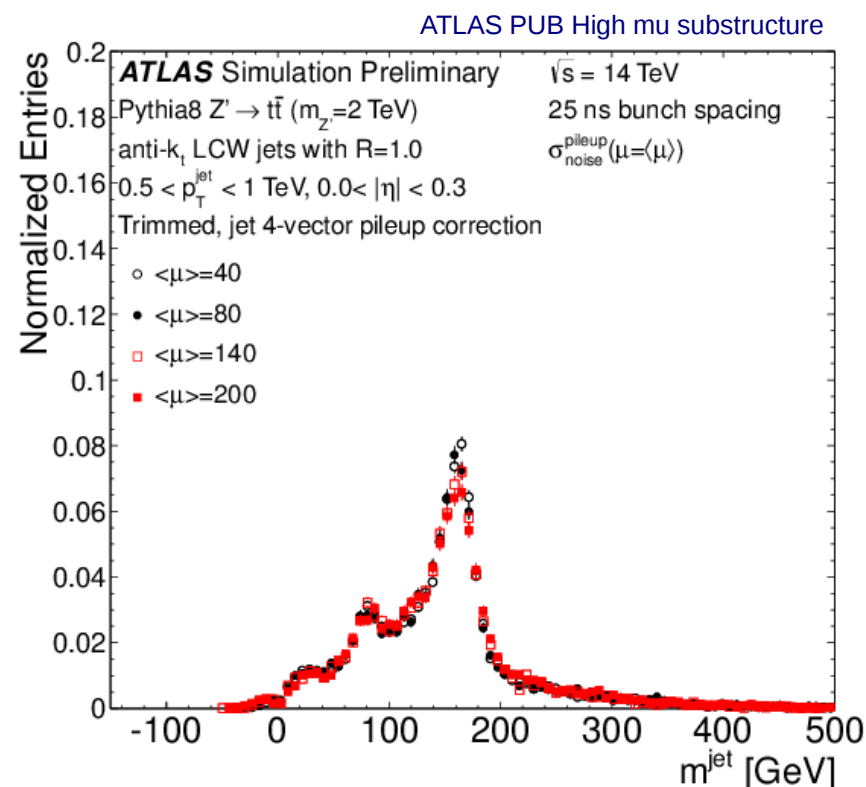
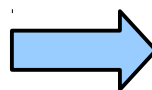
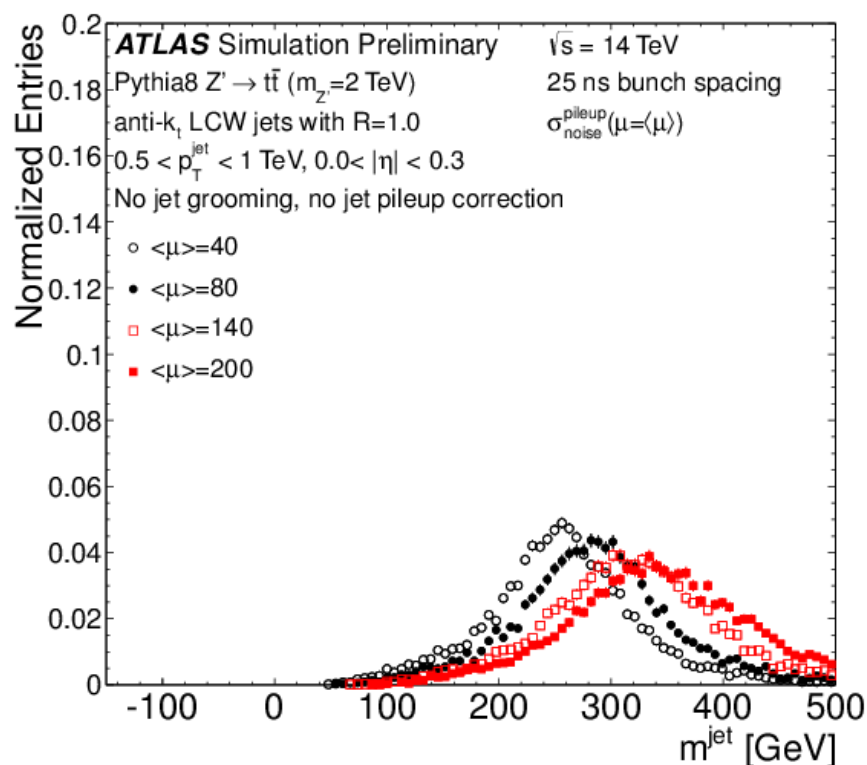
On to Run2...and beyond!

- You can't do physics in Run2 without BOOST
 - Any objects with $p_T > \sim 500$ GeV are going to need jet substructure techniques in order to extend discovery reach for new particles into the multi-TeV region
- Can we handle it?



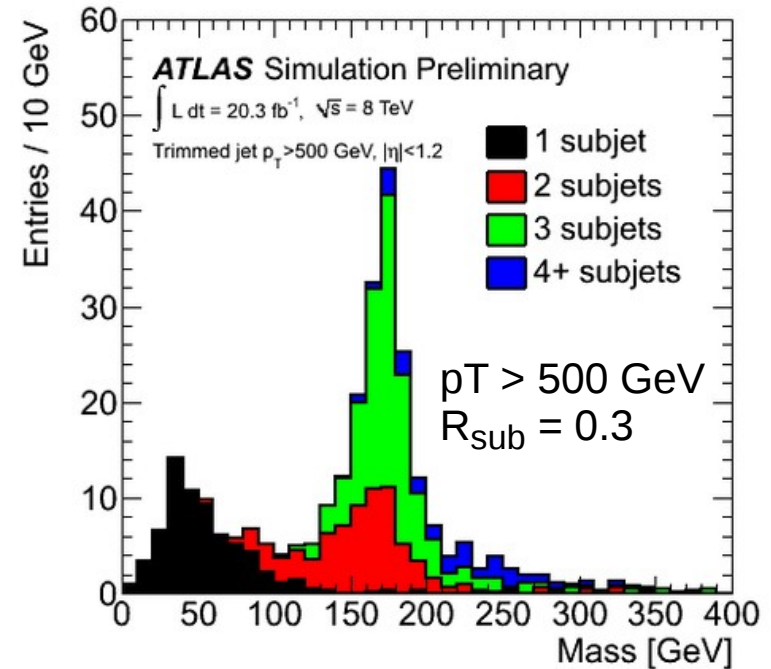
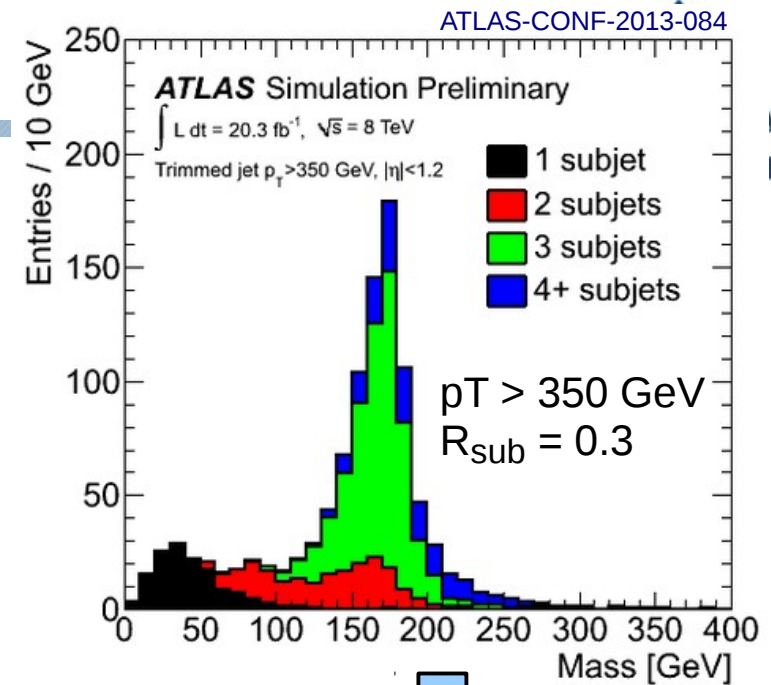
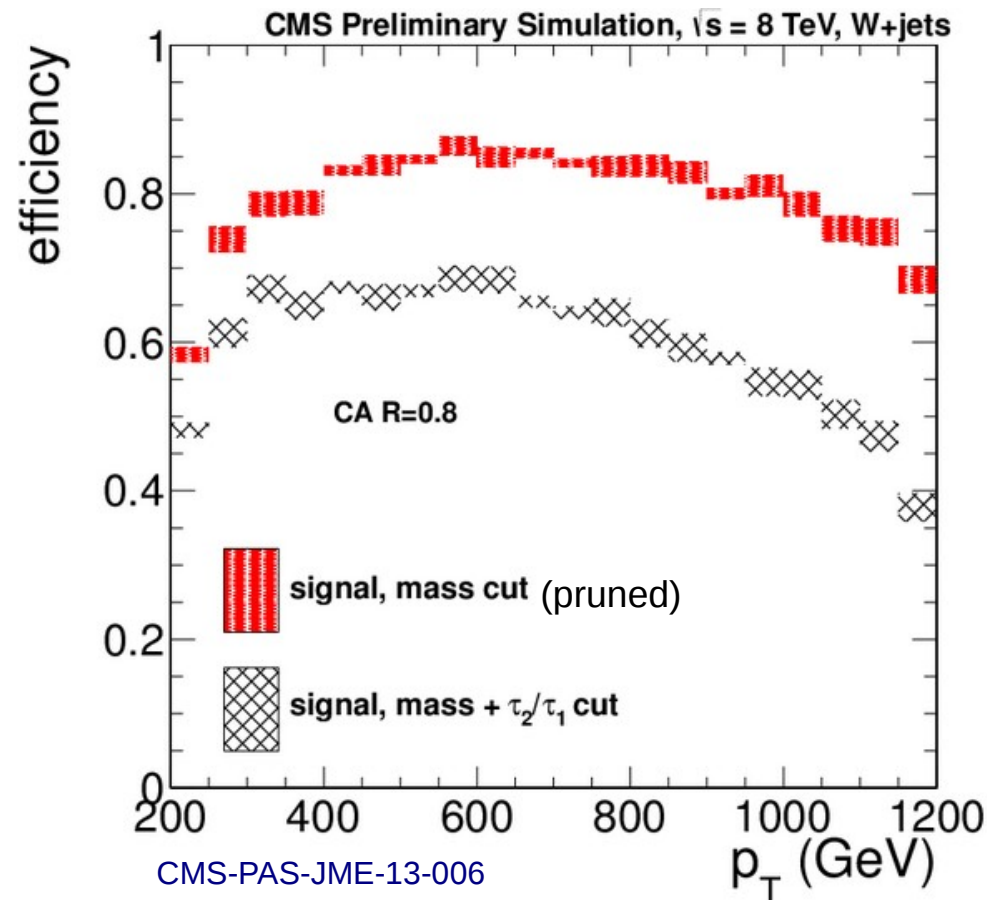
Pileup mitigation

- Our current strategies actually do surprisingly well (at least in simulation!)
- You can't have enough pileup mitigation...we'll never be "done" on this front



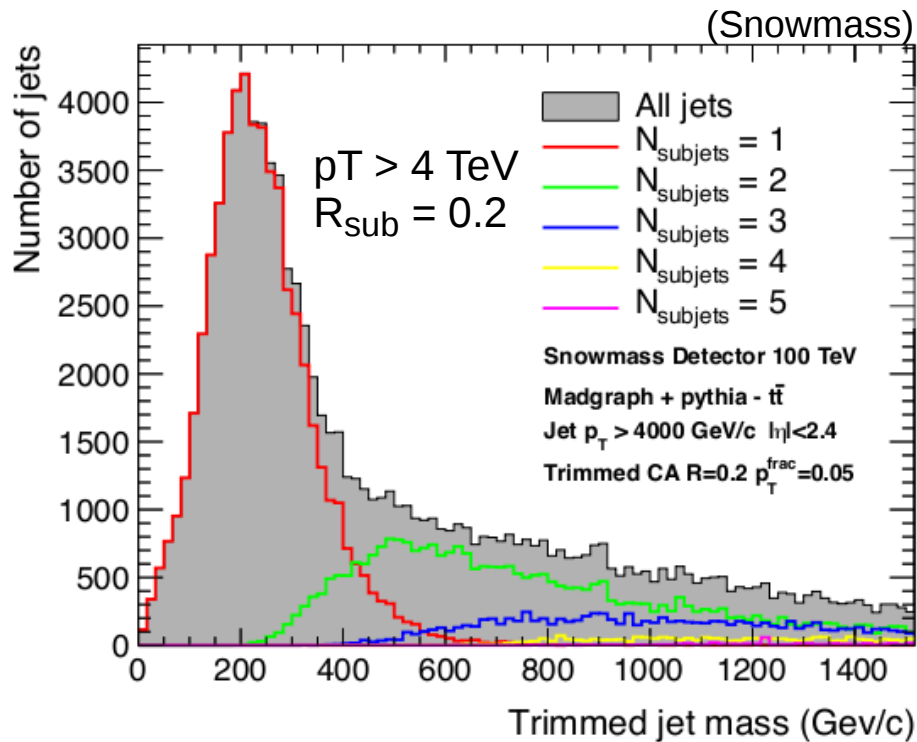
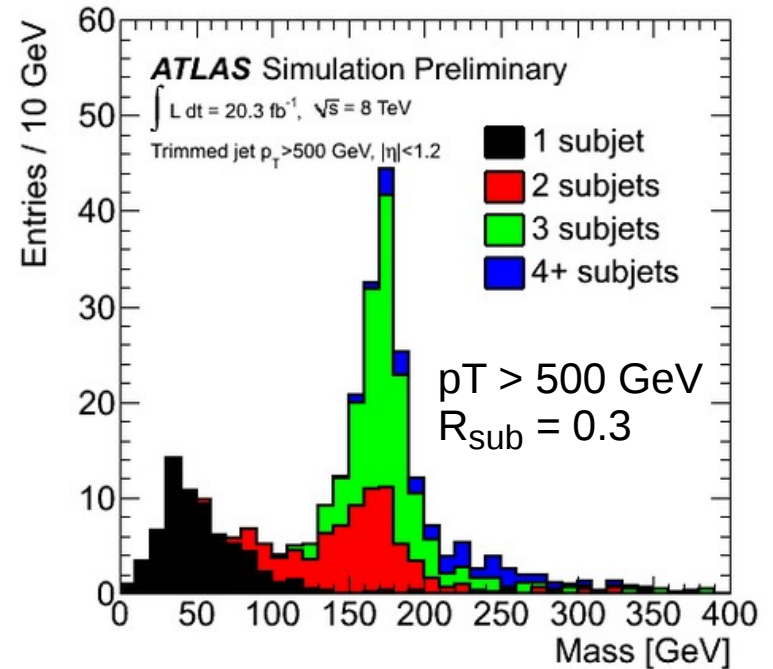
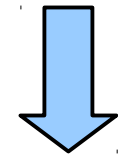
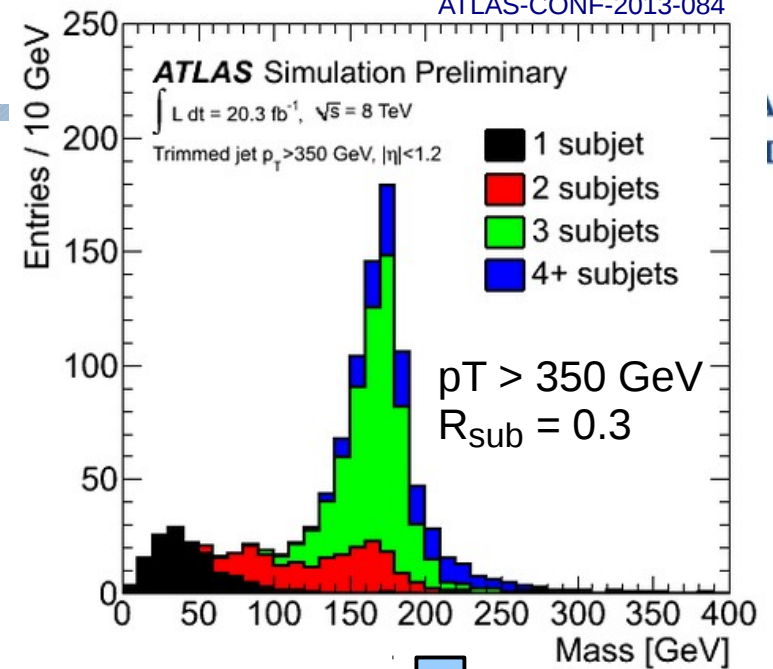
Re-optimization

- Entering the extreme substructure regime
- Retuning grooming parameters for Run2:
 - At really high boost, subjects with current parameters start to merge



Re-optimization

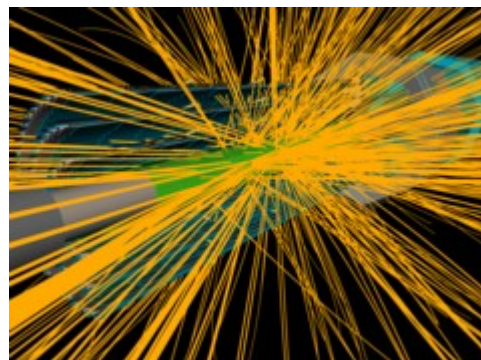
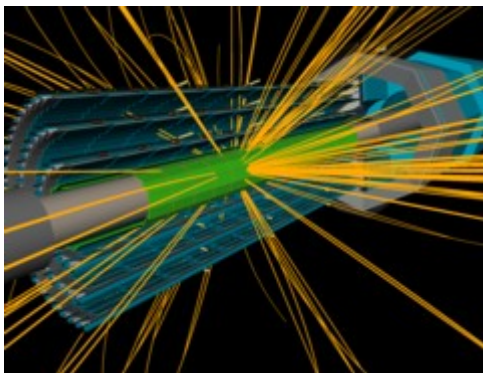
- Entering the extreme substructure regime
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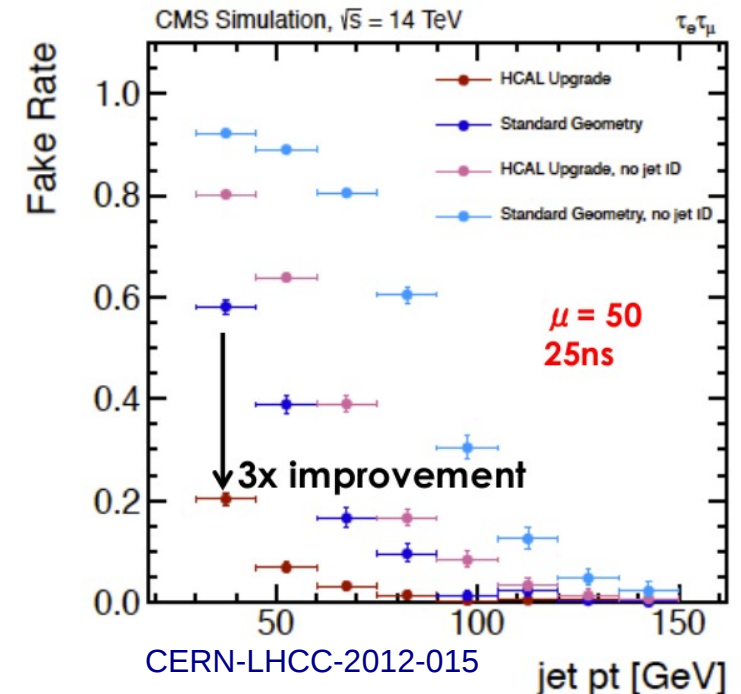
(ok..maybe a *bit* extreme to worry about right now...)

Re-optimization

- Substructure scale: how low can you go?
 - At some point, you're limited by calo granularity...and substructure scale is on the order of cells/clusters
 - Might try jet reconstruction with ecal-only to improve angular resolution.
 - Also take a look at more track based measurements
- Detector upgrades will include tracker and calorimeter improvements
 - ATLAS phase 0: new IBL layer (extra pixel layer)
 - CMS phase 1: new pixel tracker, HCAL with finer longitudinal segmentation

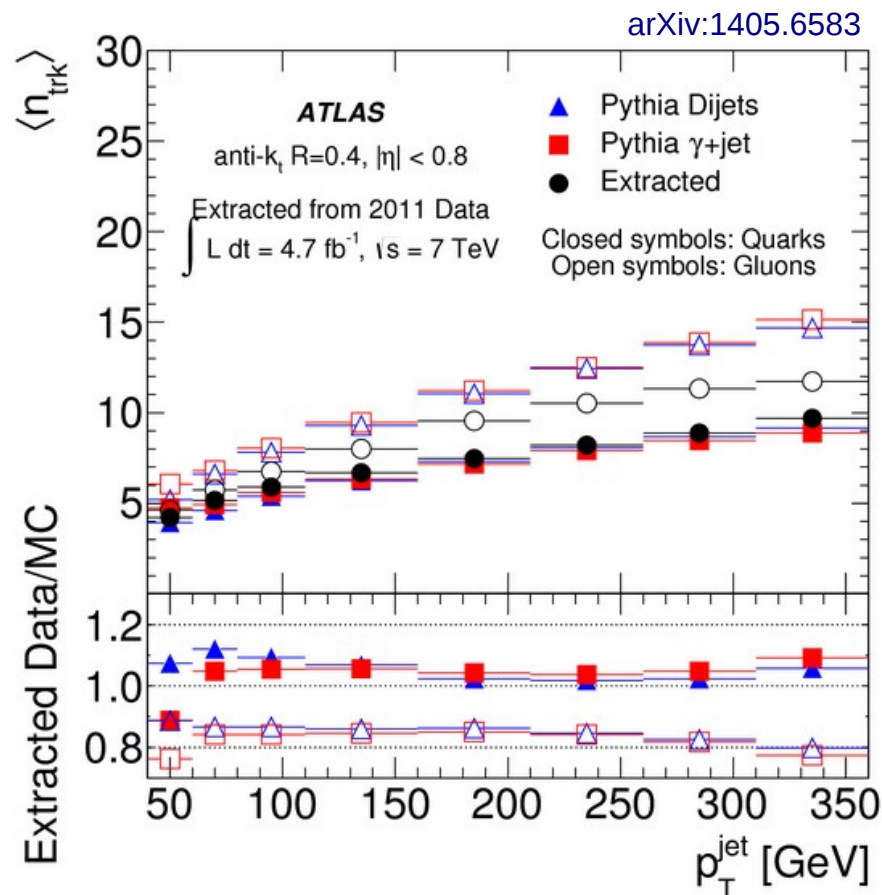
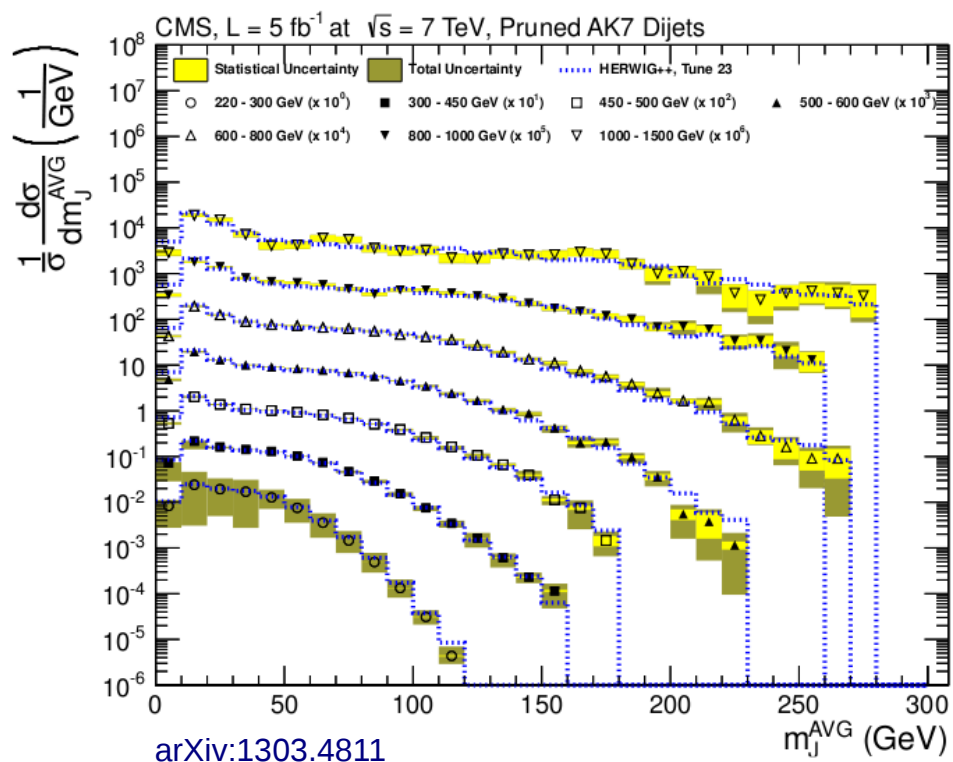


all tracks in dijet event with $p_T > 0.5$ GeV and more than 1 Pixel+IBL cluster



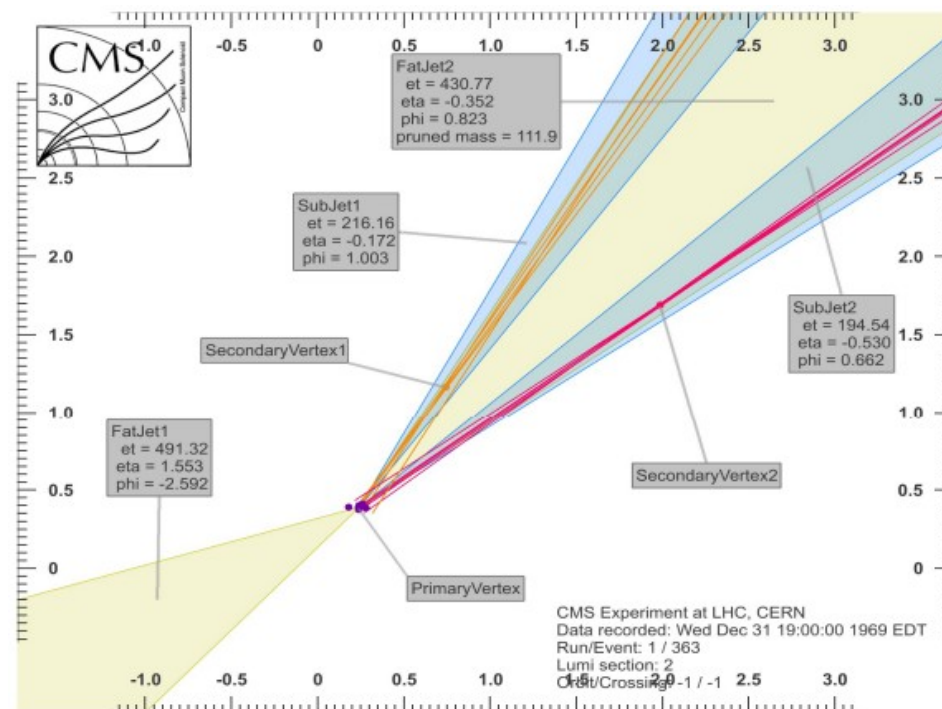
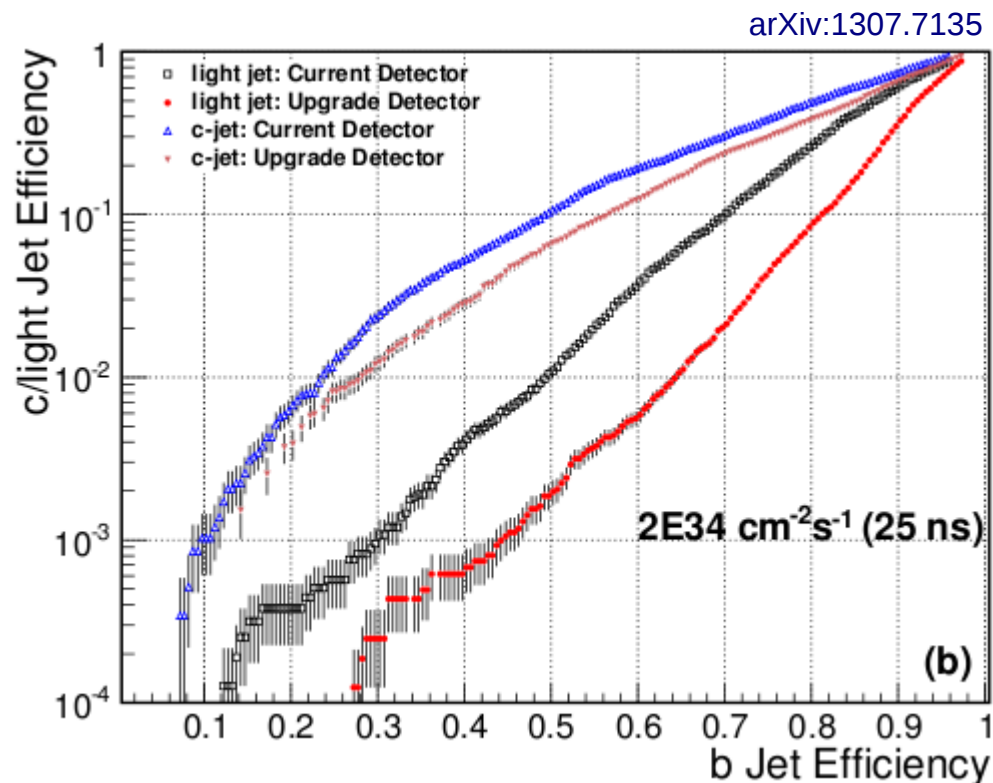
Don't forget those generators!

- One piece missing from us: measurements from jet mass and other shapes have not yet been fed back into generators for tuning
 - Generator modeling is already a limiting systematic for many searches
 - Also high p_T differential cross sections of boosted objects (ttbar, $Z \rightarrow bb$, etc)
 - Correcting back to the particle level is very challenging!



B-tagging in jet substructure

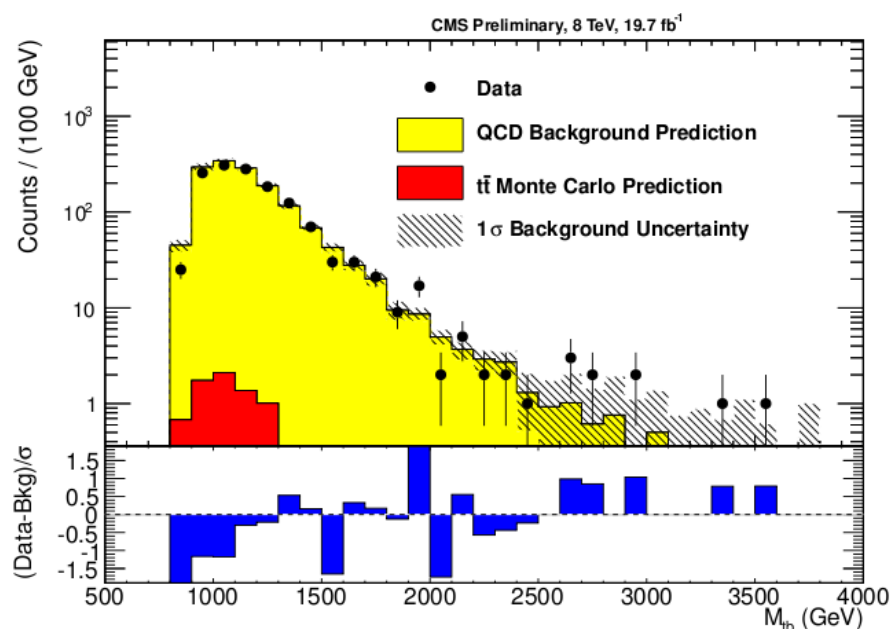
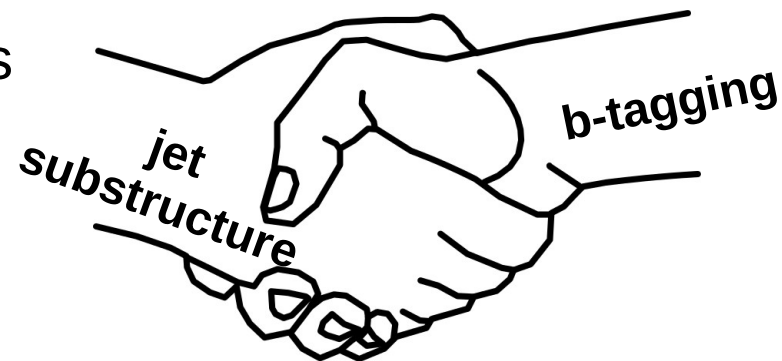
- Last comment: B-tagging was really only seriously brought up last year for the first time (see Ivan Marchesini's talk from BOOST'13)



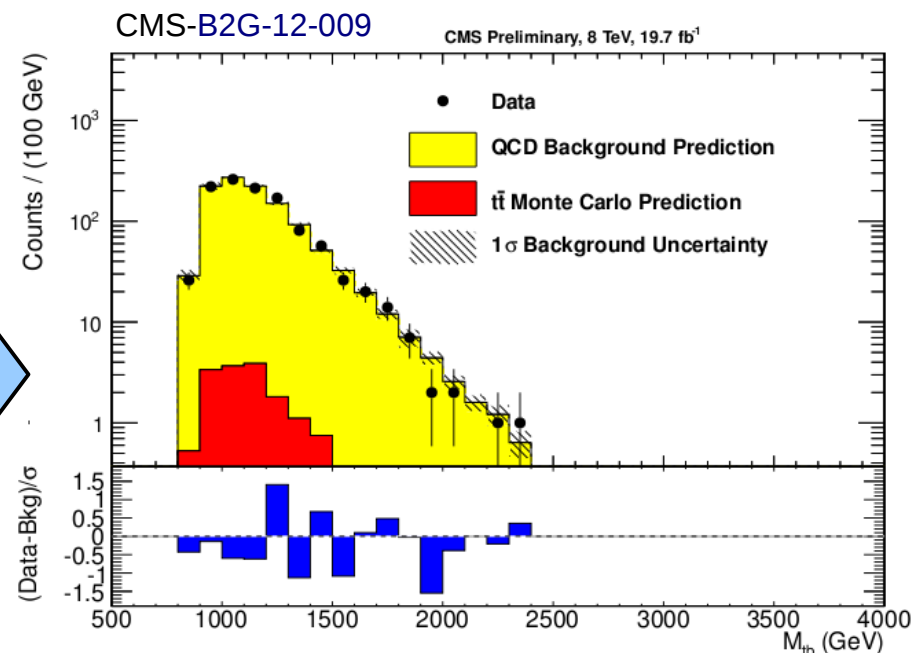
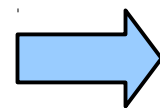
boosted higgs \rightarrow bb (MC)

B-tagging in jet substructure

- B-tagging subjets: integrating b-tagging and substructure techniques in boosted topologies
- eg: CMS $W' \rightarrow tb$ resonance



after top candidate selection

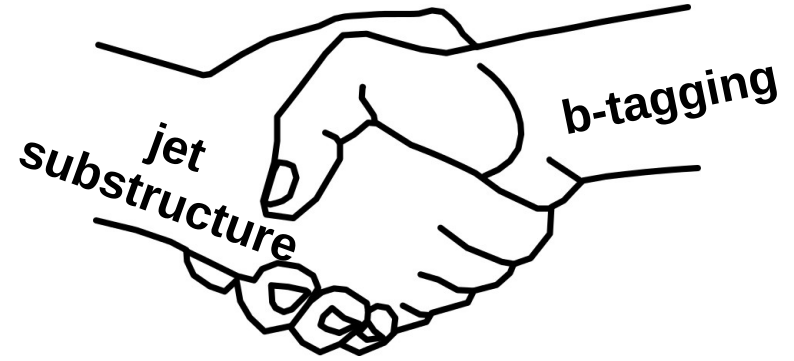
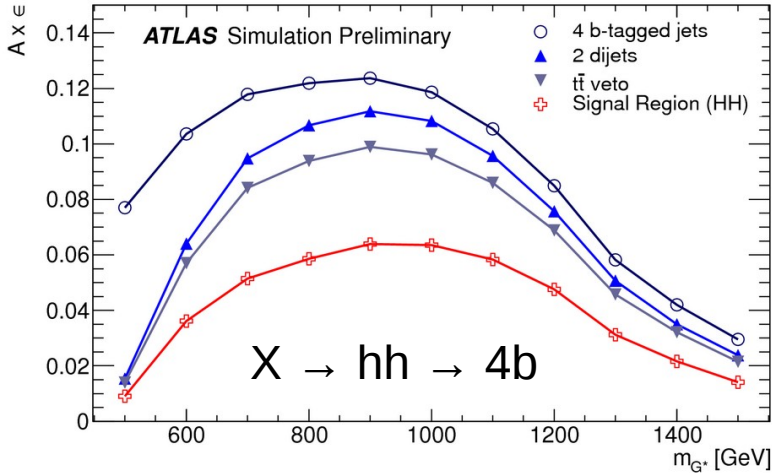


after top candidate selection
+ subjet btagging requirement

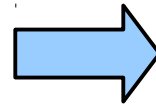
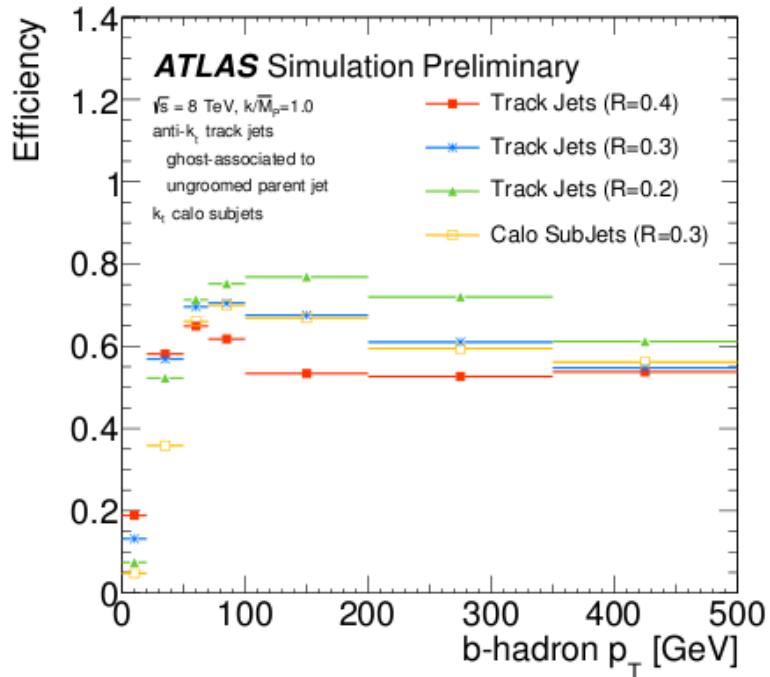
B-tagging in jet substructure

- Further improvements can be gained...

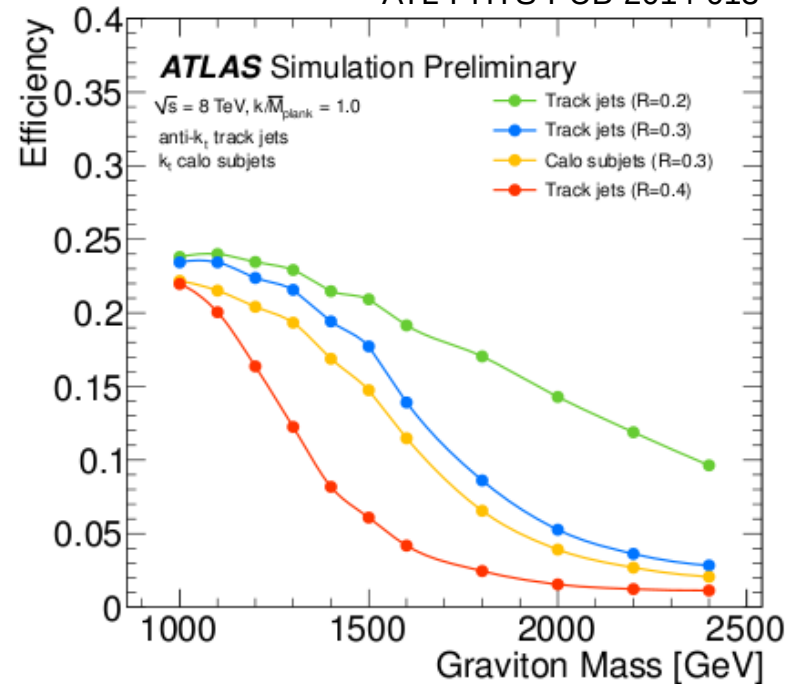
ATLAS-CONF-2014-005



Resolved analysis loses efficiency where b-tagged $R=0.4$ jets begin to merge



ATL-PHYS-PUB-2014-013



In conclusion...

- Can't do Run2 without boosted techniques! Questions to ask going in:
 - What are the optimal taggers? Need to do proper comparisons with systematics
 - How will we define the uncertainties on W and Top tagging efficiency? Using in-situ techniques on the global jet or by propagating individual substructure uncertainties? How can these be improved?
 - Can we improve pileup mitigation? ie: for the jet 4-vector and internal shapes
 - What else can we do with tracking? Where does this break down?
 - How well do things improve when we feed measurements back to generators?
- Ultimate question: If we see evidence of new physics, how do we convince the world (and ourselves) that we're right, and that its not a feature of a tagger? how do you understand the tails?
- Looking forward to a great workshop!

