Boosting searches for new physics using jets and jet substructure at the energy frontier

Exploring the Physics Frontier with Circular Colliders
Aspen Winter 2015

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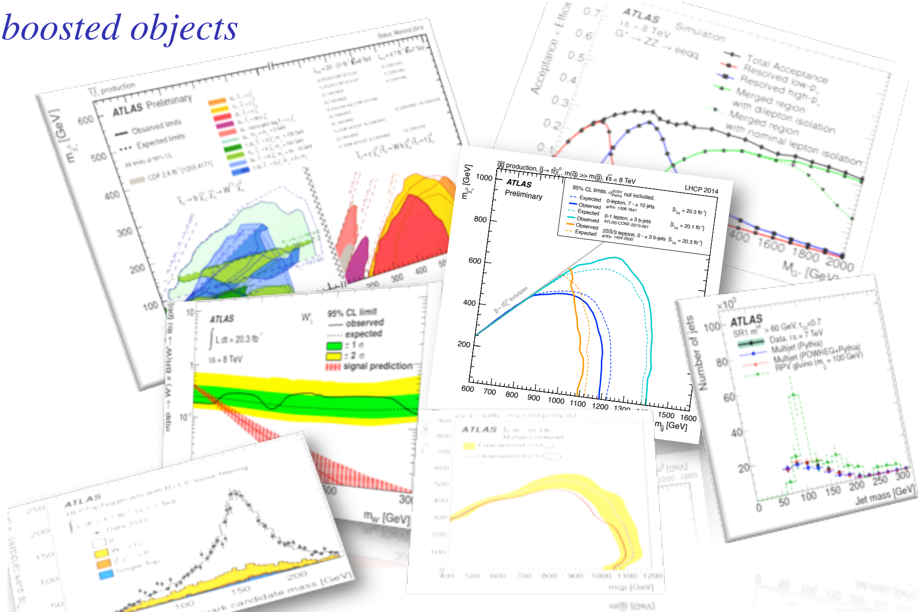
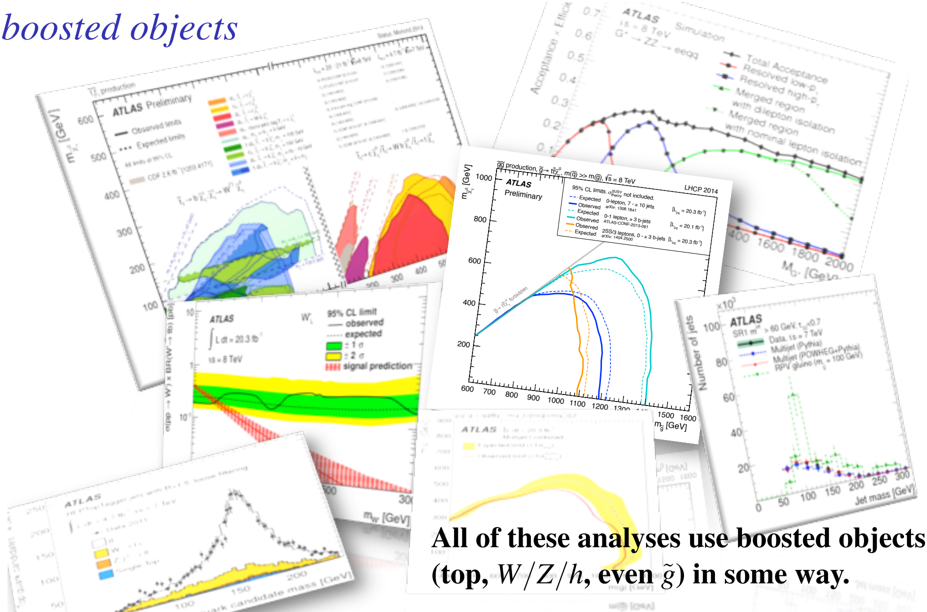
Roadmap

Outline

Run I of the LHC saw an unprecedented evolution in boosted objects



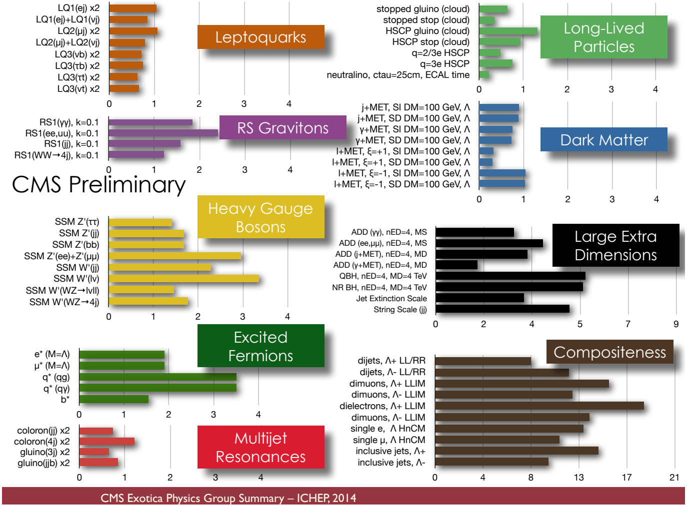
Run I of the LHC saw an unprecedented evolution in boosted objects



All of these analyses use boosted objects (top, $W/Z/h$, even $\tilde{g}$) in some way.

We have already reached the TeV scale

Limits on massive particles that decay to $W/Z/t/h$ are at or above the TeV-scale...and have been for some time.



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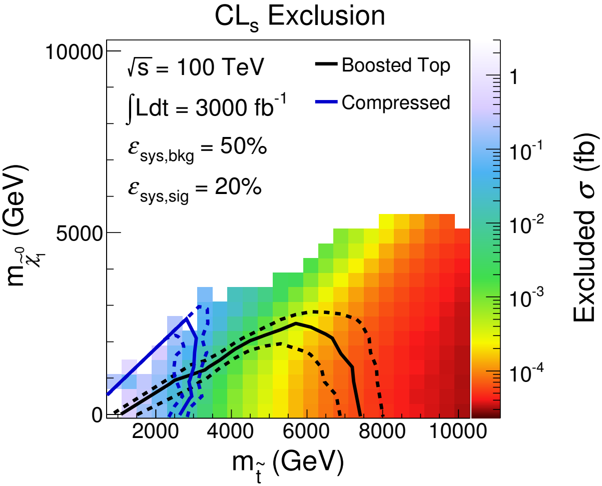
Limits on massive particles that decay to $W/Z/t/h$ are at or above the TeV-scale...and have been for some time.

Extra dimensions	ADD $G_{KK}+g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n=2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e,\mu$	–	–	20.3	M_S 5.2 TeV	$n=3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	1 e,μ	1 j	–	20.3	M_{th} 5.2 TeV	$n=6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n=6$	to be submitted to PRD
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n=6$, $M_D=1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n=6$, $M_D=1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK}\to\ell\ell$	2 e,μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl}=0.1$	1405.4123
	RS1 $G_{KK}\to WW\to\ell\nu\ell\nu$	2 e,μ	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl}=0.1$	1208.2880
	Bulk RS $G_{KK}\to ZZ\to\ell\ell qq$	2 e,μ	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK}\to HH\to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK}\to t\bar{t}$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	2 e,μ	–	–	5.0	$M_{KK}\approx R^{-1}$ 4.71 TeV		1209.2535
	UED	2 γ	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z'\to\tau\tau$	2 τ	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W'\to WZ\to\ell\nu\,\ell'\ell'$	3 e,μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W'\to WZ\to qq\ell\ell$	2 e,μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R\to t\bar{b}$	1 e,μ	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R\to t\bar{b}$	0 e,μ	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
Heavy quarks	Vector-like quark $TT\to Ht+X$	1 e,μ	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT\to Wb+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT\to Zt+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB\to Zb+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB\to Wt+X$	2 e,μ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}^0_1$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}^\pm_1$)=2 m($\tilde{\chi}^0_1$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}^0_1$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}^0_1$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}^\pm_1$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to t\tilde{\chi}^0_1$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1403.5222
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}^0_1$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}^0_1$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}^0_1$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600

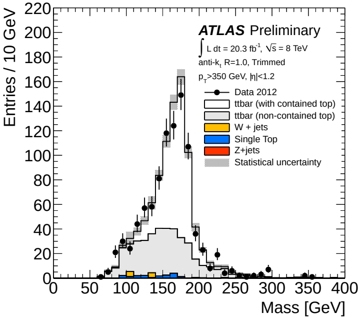
*At 100 TeV, boosted objects are **ubiquitous***



Cohen, D'Agnolo, Hance, Lou, Wacker (arXiv:1406.4512)

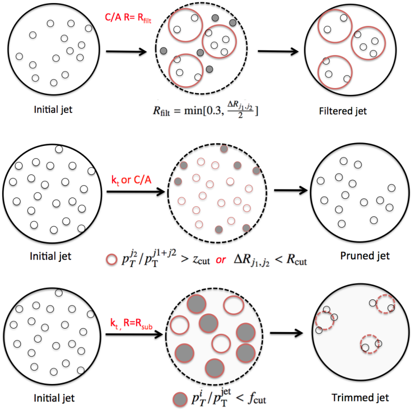
Deployment of a new set of tools for SM and BSM physics

An enormous set of tools has been deployed by both collaborations to maximize our sensitivity to new physics, and to study old physics in new ways.



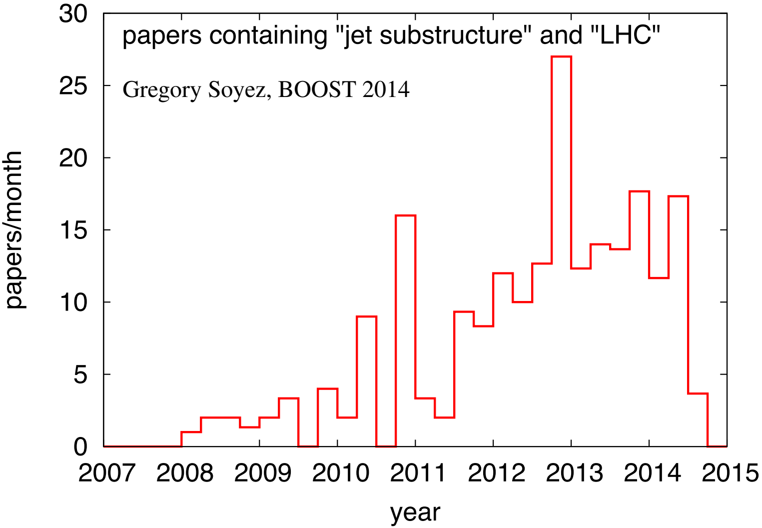
Jet $p_T > 350$ GeV and 3 k_t subjets

ATLAS-CONF-2013-084

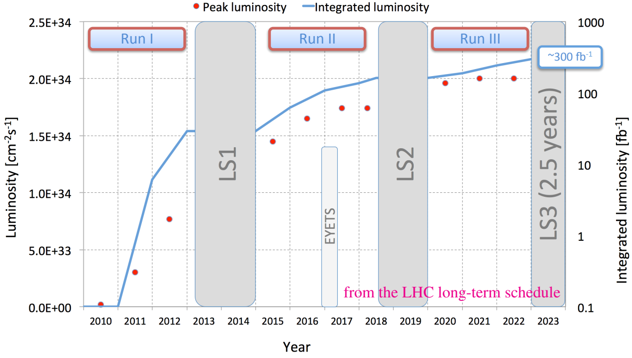


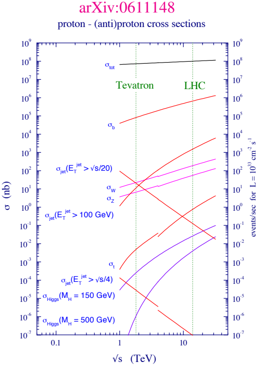
arXiv:1306.4945

"If you ain't boostin', you ain't livin" – Nhan Tran, FNAL (Experimental Summary at BOOST 2014)



This trend will continue and we must be prepared



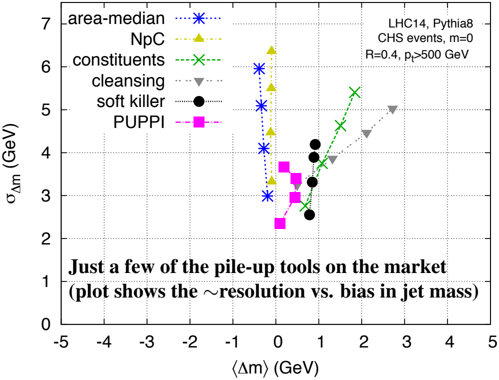


Collider & phase process & energy, integrated luminosity	Tevatron run II $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV $\mathcal{L} = 10$ fb^{-1}	LHC Run I pp at $\sqrt{s} = 8$ TeV $\mathcal{L} = 20$ fb^{-1}	LHC Run II pp at $\sqrt{s} = 13$ TeV $\mathcal{L} = 100$ fb^{-1}	LHC Run III $\sqrt{s} = 13$ TeV $\mathcal{L} = 200$ fb^{-1}	HE-LHC pp at $\sqrt{s} = 33$ TeV $\mathcal{L} = 300$ fb^{-1}
Inclusive $t\bar{t}$ production	6×10^4	4×10^6	6.7×10^7	1.3×10^8	1.4×10^9
Boosted production	23	6×10^4	1.7×10^6	3.5×10^6	7.1×10^7
Highly boosted	0	500	3.7×10^4	7.3×10^4	3.9×10^6

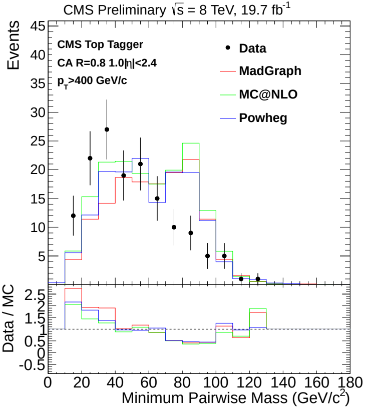
Table adapted from BOOST 2012 Report (arXiv:1311.2708): calc. w/ MCFM. Yields for boosted tops ($M_{t\bar{t}} > 1$ Tev) and highly boosted tops ($M_{t\bar{t}} > 2$ TeV) given in the 2nd and 3rd row.

The challenges we will face

G. Soyez, Pile-up workshop @ CERN



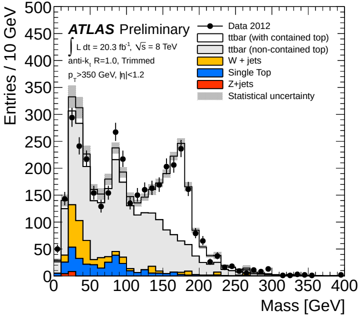
CMS-PAS-JME-13-007

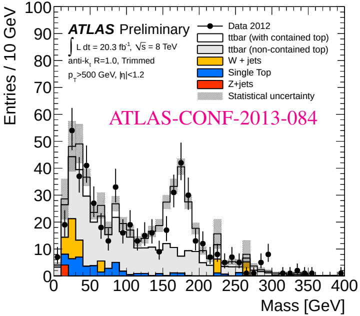


- We have many tools to mitigate pile-up, but the increases in instantaneous luminosity are nonetheless very difficult to cope with.
- Good modeling of complex observables by Monte Carlos is very important and more unfolded measurements may be the key to improvements here.

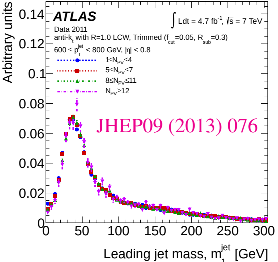
Outline

Commissioning boosted object tools at 13 TeV





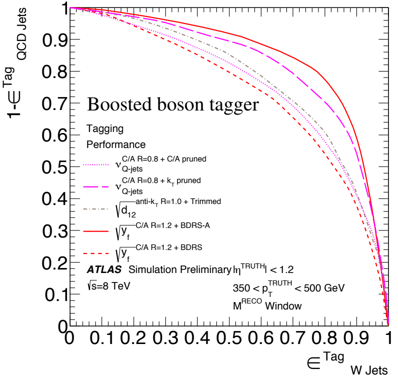
- During the majority of 2015, we generally expect similar operating conditions as in Run I, except for bunch spacing.
- Need to demonstrate performance for signal and background early, and likely use similar working points for top tagging as in Run I.



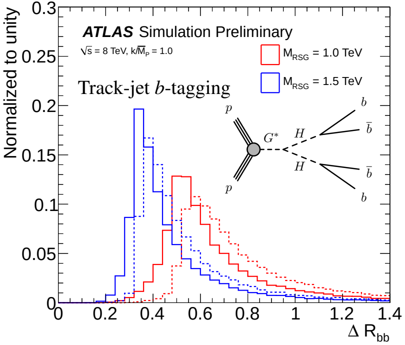
Early Run II extensions for Run I boosted analyses

Two advances made near the end of Run I are likely to be adopted early-on in Run II.

ATL-PHYS-PUB-2014-004

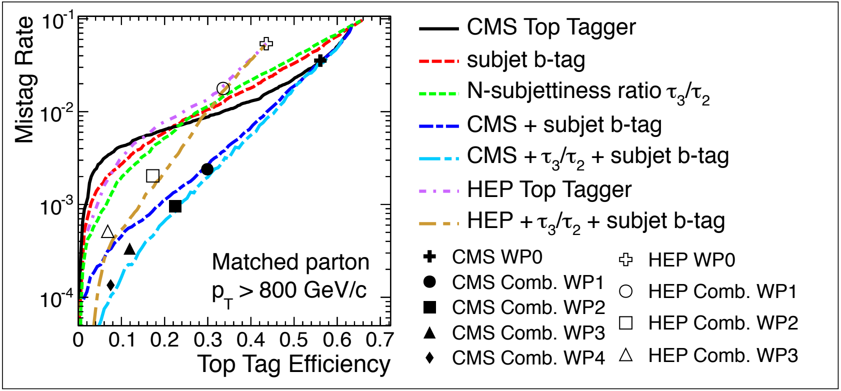


ATL-PHYS-PUB-2014-013



- **LEFT:** Optimized boson tagging using very large parameter space
- **RIGHT:** Track-jet-based *b*-tagging with very small radii. Now have the ability to define *b*-tagged objects independent of the calorimeter and then associated to a given calorimeter-based jet definition *post facto*

Using specialized b-tagging for boosted objects (II)



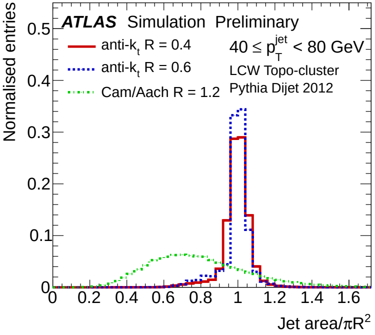
CMS-JME-13-007 (also Ferencek at BOOST 2014)

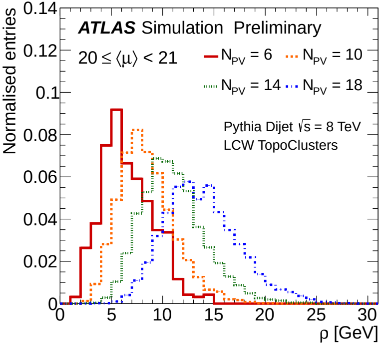
- Subjet *b*-tagging an integral part of boosted top tagging algorithms in CMS
- CMS *b*-tagging for boosted topologies commissioned at 8 TeV and analyses exploiting subjet *b*-tagging now public

Outline

Area-based pile-up subtraction for jet kinematics

ATLAS-CONF-2013-083

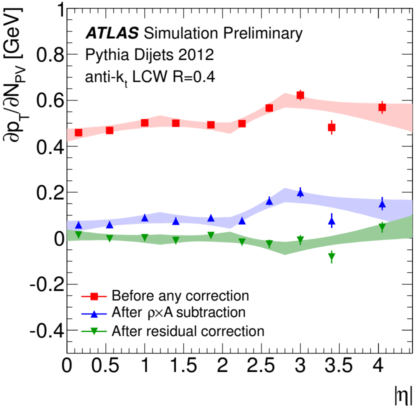


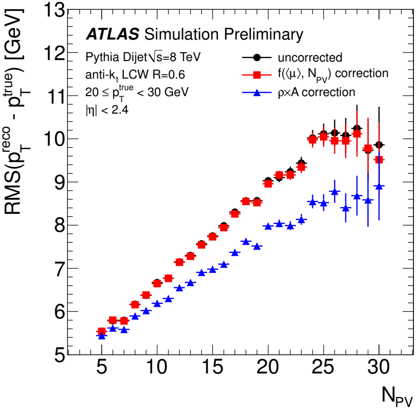


- Both CMS and ATLAS implement the so-called 'area-based' pile-up subtraction
- This is independent of the jet algorithm, and can thus also be applied to subjets if appropriate
  - *Spoiler alert: it will be!*

Area-based pile-up subtraction for jet kinematics

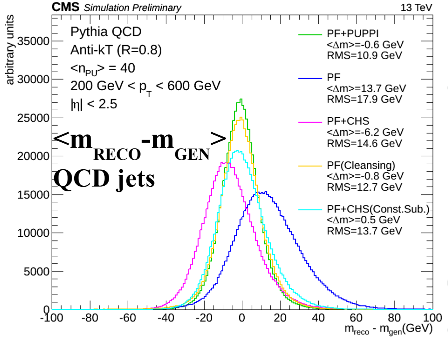
ATLAS-CONF-2013-083

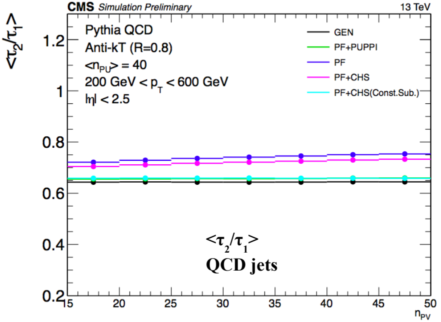




- Reduces the dependence on pile-up significantly (*it better!*)
- Also reduces the impact on the jet resolution
- This is the default mode of pile-up mitigation on the jet 4-vector for Run II (being implemented in the trigger as well!)

Constituent-level pile-up subtraction





- CMS performed an excellent and comprehensive study of new **constituent-level pile-up subtraction** algorithms
- From "simple" (e.g. CHS) to "complex" (e.g. PUPPI), and maximum tracking information (e.g. PUPPI) to no tracking information (e.g. constituent subtraction)

PileUp Per Particle Id

Bertolini, Harris, Low, Tran (arXiv:1407.6013)

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General Idea of the Algorithm

- Use the Jets without Jets paradigm
  - For each particle draw a cone around it
- In each particle cone
  - Compute metric α
    - Distinguishes particle from hard scatter from PU
  - Calculate median α and α_{RMS} over an event for PU
    - Average over all particles associated to another vertex
- Compute a weight that a particle is from pileup
- Reweight particles and re-interpret the event

- I view this more as a way to customize the inputs to the jet reconstruction

PUPPI in CMS

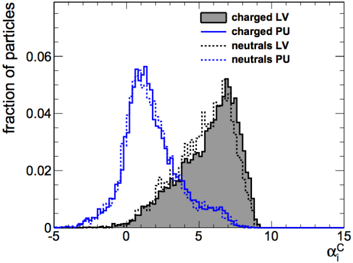
Viola Sordini at BOOST 2014

Operates on the inputs to jet clustering (here PF candidate particles) [arXiv:1407.6013]

• A discriminating variable α is defined :

$$\alpha_i = \log \sum_{j \in Ch,PV} \left(\frac{p_{T,j}}{\Delta R_{ij}} \right)^2 \Theta(R_0 - \Delta R_{ij}) \quad \text{for } |\eta| < 2.5$$

$$\begin{cases} \alpha_i = \log \sum \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij}) \\ \alpha_i = \log \sum p_{T,j} \Theta(R_0 - \Delta R_{ij}) \end{cases} \quad \text{for } |\eta| \geq 2.5$$



• The distribution for charged PU particles is used as template for the distribution for all PU particles

• For each neutral particle, a χ^2 variable is constructed (for $|\eta| \geq 2.5$, sum the two χ^2)

$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{PU})^2}{RMS_{PU}^2}$$

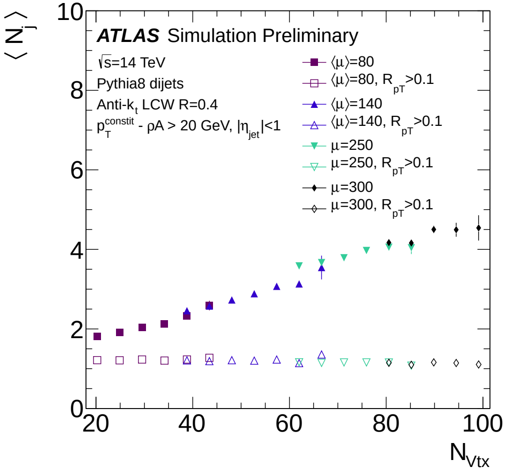
- I view this more as a way to customize the inputs to the jet reconstruction, which is extremely important

How do these approaches scale as we move into the future?

ATLAS ECFA Studies on pile-up suppression

- The mean number of jets with pile-up-corrected $p_T > 20$ GeV and $|\eta| < 1$ per event vs. N_{PV}
- For the curves with open markers, tracking information was used to suppress pileup jets, by imposing the same $R_{p_T} > 0.1$

$$R_{p_T} = \frac{\sum p_T^{track}(PV0)}{p_T^{jet}}$$

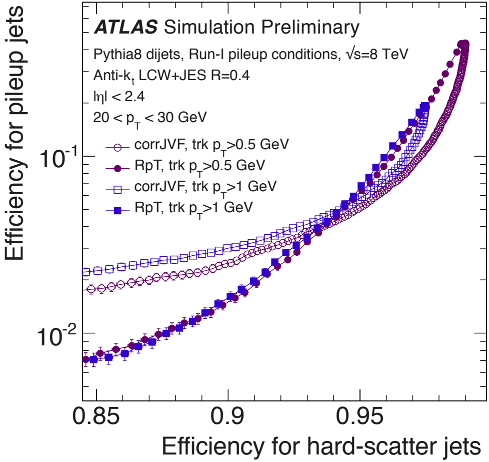


How do these approaches scale as we move into the future?

ATLAS ECFA Studies on pile-up suppression

- Hard-scatter jets are matched within $\Delta R < 0.3$ to a truth jet with $p_{\mathrm{T}} > 10$ GeV, whereas pileup jets are required to have a minimal $\Delta R > 0.6$ from any truth jet with $p_{\mathrm{T}} > 4$ GeV.

$$R_{p_{\mathrm{T}}} = \frac{\sum p_{\mathrm{T}}^{\mathrm{track}}(PV0)}{p_{\mathrm{T}}^{\mathrm{jet}}}$$



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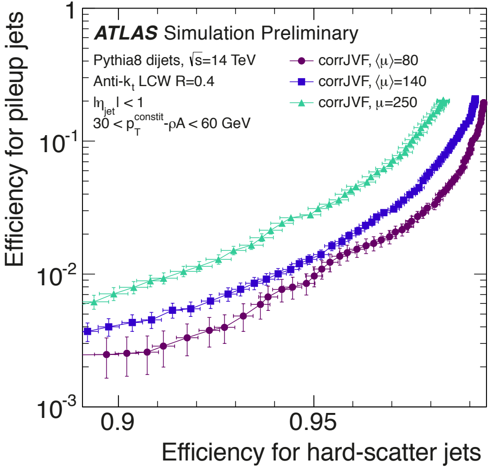
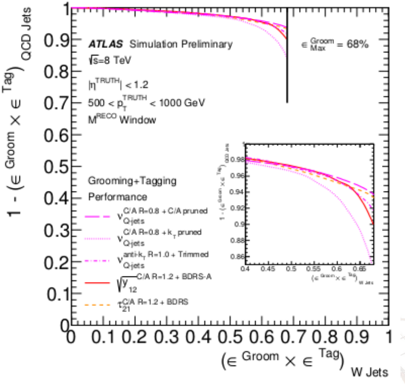
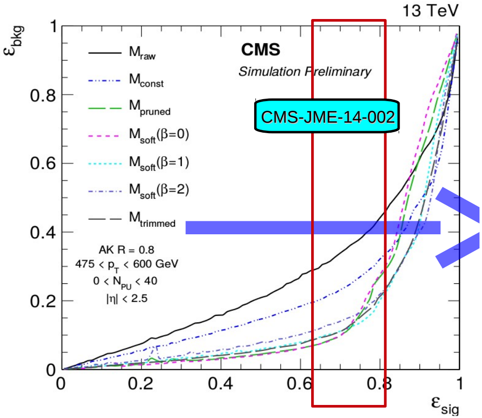


Outline

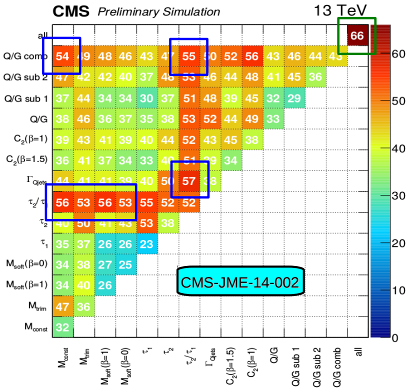
Incorporating new observables for new taggers

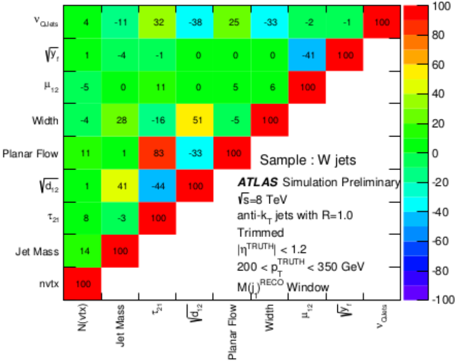




- Both collaborations are now doing very comprehensive *scans* of tagging observables for bosons
- Incorporating multiple mass definitions simultaneously

Multivariate combinations for W tagging



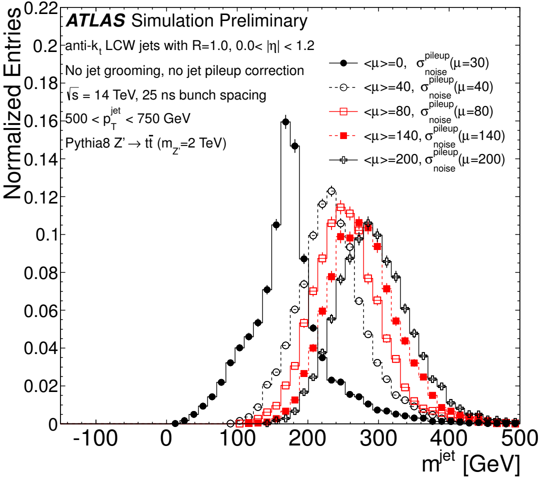


- Now starting to incorporate many variables (some are already "composite" observables, e.g. *QG*-likelihood)
- Linear correlation coefficients (see ATLAS) are useful, but need to be honest about their limitations
- Similarly, need to be honest about the degree to which these complex combinations are necessary

Boosted top tagging and pile-up at very high luminosity

High pile-up scenarios for top tagging

- The anti-k_t $R = 1.0$ jet mass distribution in $Z' \to t\bar{t}$ events where the mean number of interactions per bunch crossing ($\langle\mu\rangle$) is 40, 80, 140, and 200.
- The pileup correction is made to the subjets only, before their pT fraction is calculated.
- When both trimming and jet 4-vector pileup subtraction are applied, the jet mass distribution is stable even at $\langle\mu\rangle$ =200.



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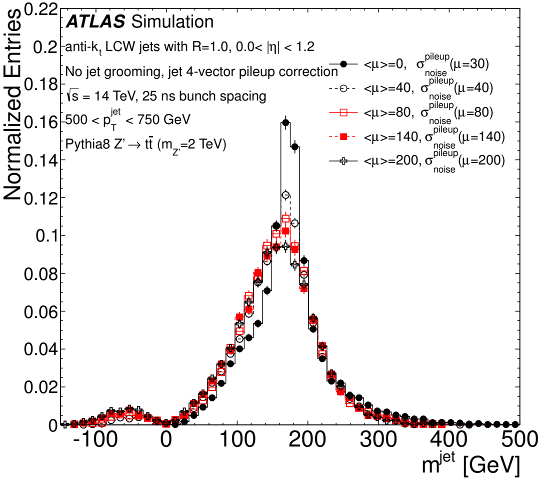

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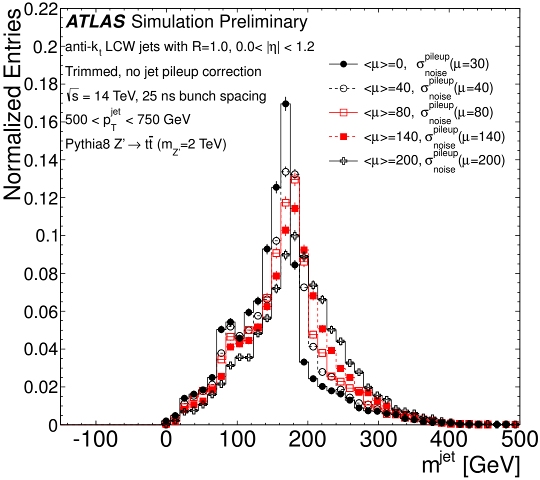

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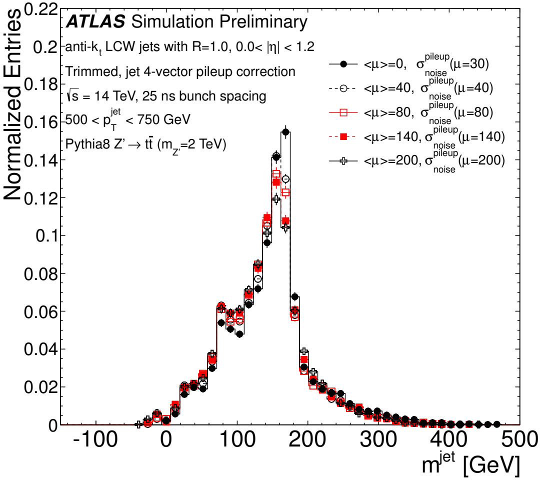
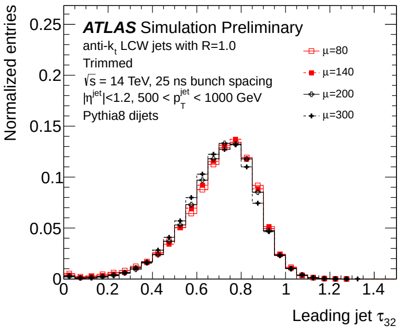
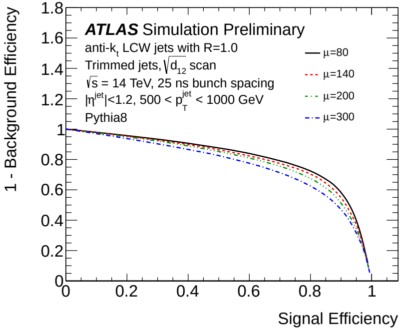


Tagging tops with substructure

ATLAS ECFA Studies on top tagging





- The pile-up suppression uses the event-by-event median p_T density (ρ) and the jet area.
- The pile-up correction is made to the subjets only before their pT is calculated for the trimming procedure.

Outline

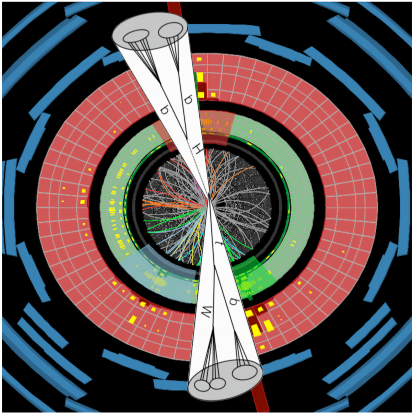
Conclusions and outlook

- **Pile-up mitigation:**
  - We are at the point where the experimental techniques to mitigate pile-up are extremely advanced
  - Collaborations will be testing these techniques at the LHC in the coming years
  - Adapting these techniques to the needs and constraints of new detectors and new technologies for future colliders will be the primary hurdle, not the methods themselves
- **Jet definitions:**
  - Wide variety of jet definitions available, and dynamically defined sizes and grooming parameters will become relatively commonplace
  - This will be relevant for wide dynamic range searches even for very early in Run II
  - Grooming is invaluable for $W/Z/h/t$ tagging and will need to be considered in any future collider detector study and optimization
- **Jet tagging:**
  - Very complex approaches are available, as well as very simple, yet effective, ones
  - Expect multivariate taggers to be commissioned by LHC experiments soon
  - Still need "simple" taggers for cross-checks, easy background/sideband estimates
  - *b*-tagging *will* be involved in almost all searches

The last few years have seen a dramatic increase in the level to which we are able to exploit the hadronic final state to perform precision physics at the energy frontier by treating a jet as much **more** than just a fixed 4-vector surrogate for a parton.

Looking ahead

- These techniques will play a critical role in first Run II analyses
- SUSY, Exotics, Higgs (SM+Exotic) will make use of these taggers as we progress higher in the energy frontier
- At even higher instantaneous luminosities, the complex techniques now available for input-level pile-up mitigation will be come crucial



2015? 2045?

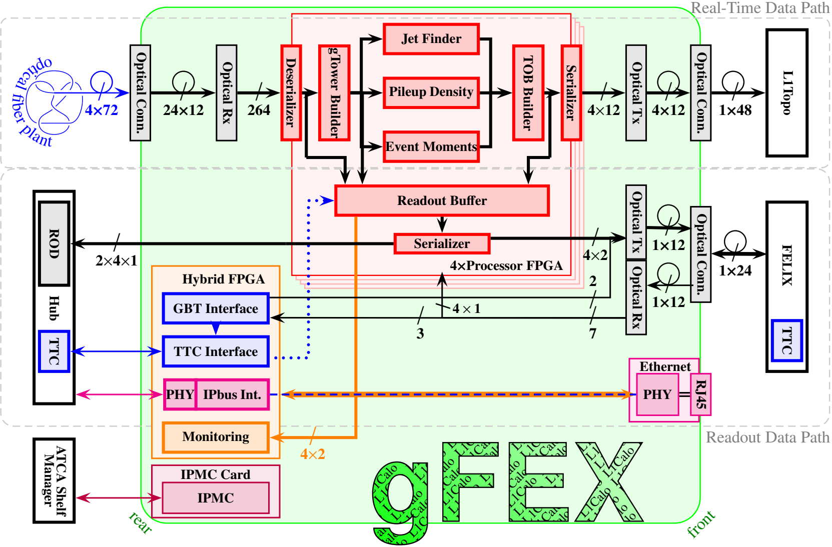
Thank you!

Outline

Additional Material

Outline

6 *Backup slides and additional information*
- Triggering on boosted objects in Run III
- Track-jet based *b*-tagging
- Caveats and pitfalls to watch out for

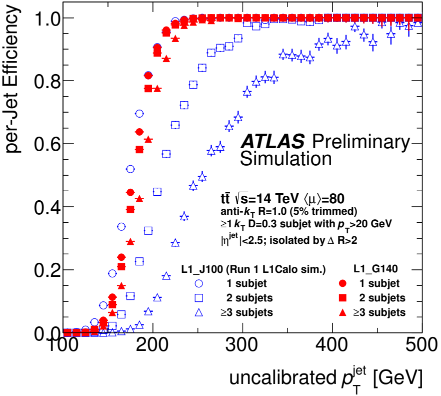


The entire calorimeter on a single board!

Triggering on boosted objects in Run III

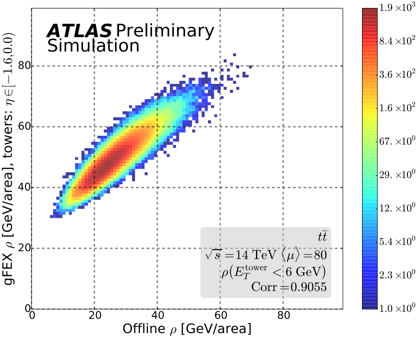
Level-1 fat jet trigger: **global feature extraction (gFEX)**

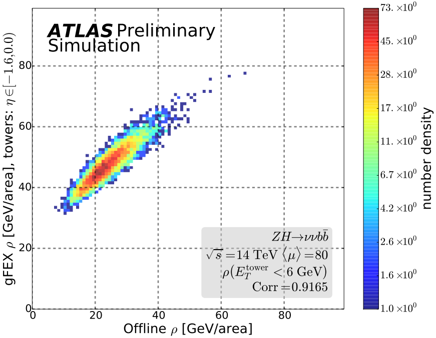
- **Signal: boosted top quarks**
  - Build **gFEX jets (in red)** from seeds
  - Seed threshold: $E_T > 15$ GeV
  - Sum gTowers in $\Delta R < 1.0$ (noise cut: $E_T > 3$ GeV)
- **Compare to Run I** (open markers)
  - Efficiency for Run I trigger **depends on the subjet multiplicity**
  - Worsening efficiencies for QCD jet $\rightarrow$ *W* jet $\rightarrow$ top jet
  - gFEX efficiency *does not depend on the jet structure*



gFEX efficient despite significant jet substructure!

Level 1 pile-up subtraction for boosted tops and bosons





- ρ calculation at Level 1 is independent of hard scattering process, as it should be
- Subtraction improves turn-on and allows for subjet tagging at Level 1

Track-jet based b-tagging for Run II

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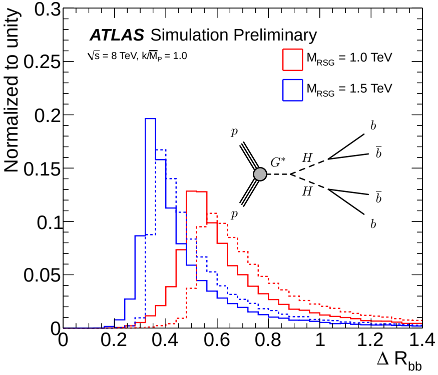

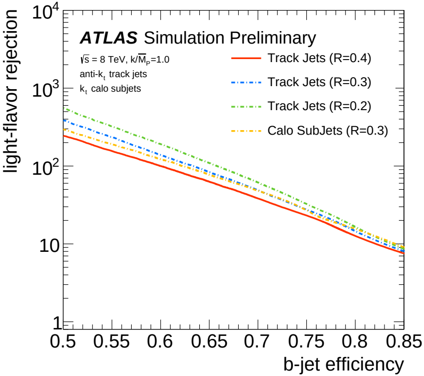

- Specifically developed for the graviton$\rightarrow$ HH $\rightarrow 4b$ search, but has significant implications for top & top-like final states.
- Now have the ability to define b-tagged objects independent of the calorimeter and then associated to a given calorimeter-based jet definition *post facto*

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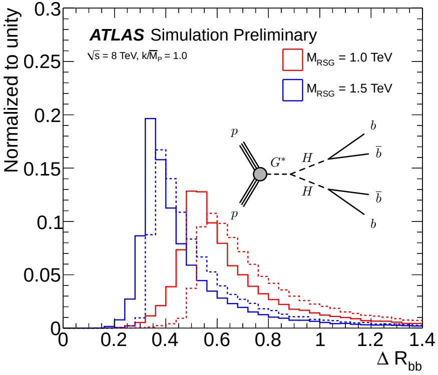

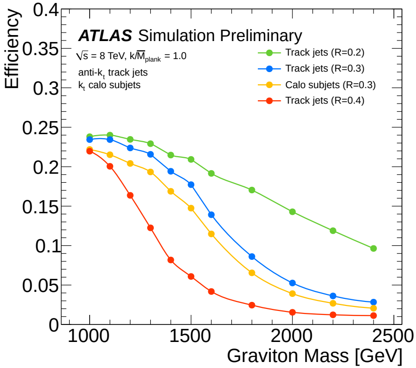

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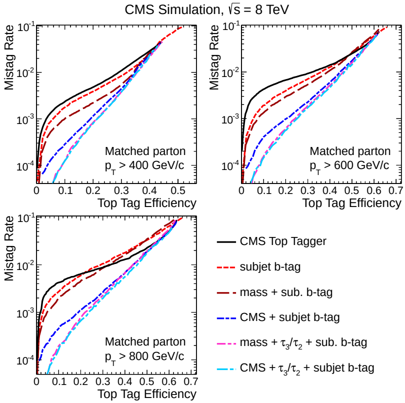
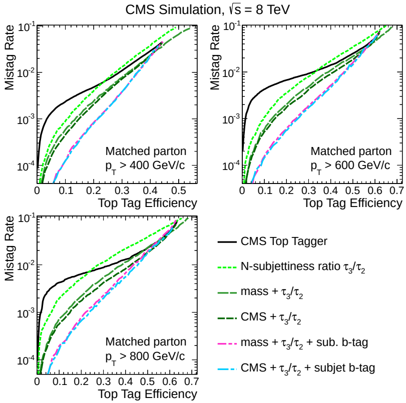
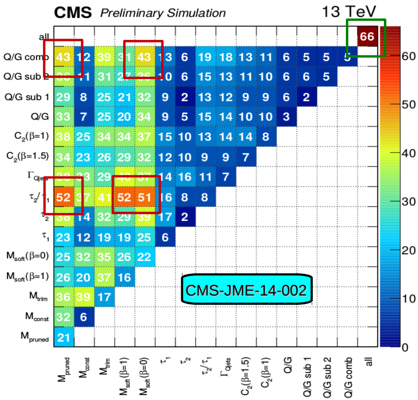
Complex taggers compared to "simple" taggers (II)





- See identical performance with a cut on τ_{32} + cut on mass + cut on *b*-tagging as using full CMSTopTagger

"Best" performance vs. "realistic" performance



- Try to improve the single variable performance by means of **pairs combination**
- Do this in two independent pileup bins

Best Performance

Performance is estimated as **$1/\varepsilon_{back}$ for ε_{sig} = 50 %**

- **Pair → pruned** or **soft drop** mass combined with **τ_2/τ_1** or **subjet Q/G combination**

Performance still far from what you get combining all the observables

- The difference between "best" in boxes, and "second best" (e.g. rejection factor 41 vs. 52) is **0.4%**.
- This is **not** an observable difference, and if we take such arguments literally, we may find ourselves in a corner.
- We should develop a threshold for improvement that requires that the complexity needed for that improvement be outweighed by the significance of the gain

Complex taggers compared to "simple" taggers (I)