PURDUE UNIVERSITY CALUMET

ATLAS + CMS: Boosted Topologies

John Stupak III
On behalf of the ATLAS and CMS collaborations

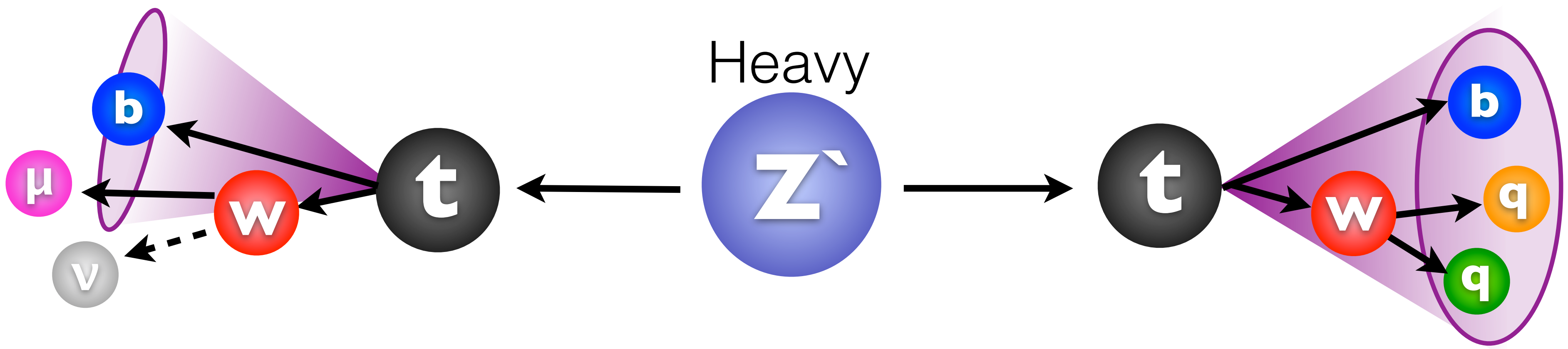
RENCONTRES DE MORIOND 50 since 1966

3/17/15

Introduction

*This talk focuses on hadronic decays of boosted particles

- What is meant by boosted? $p_T \gtrsim 2m$
  - Collimated decay products: $\Delta R \approx 2m/p_T$
  - Non-isolated leptons + challenging/rich hadronic topologies*



Use "fat jet" to capture all daughters

- Why the boosted regime?
  - No sign yet of BSM physics at the LHC → probe higher mass scales
- Hadronic decays often have large BRs
  - Recover significant signal cross section
  - Reject QCD background w/ jet substructure

BR(H → hadrons) ≈ 84%

BR(Z → hadrons) ≈ 70%

BR(W → hadrons) ≈ 68%

Outline

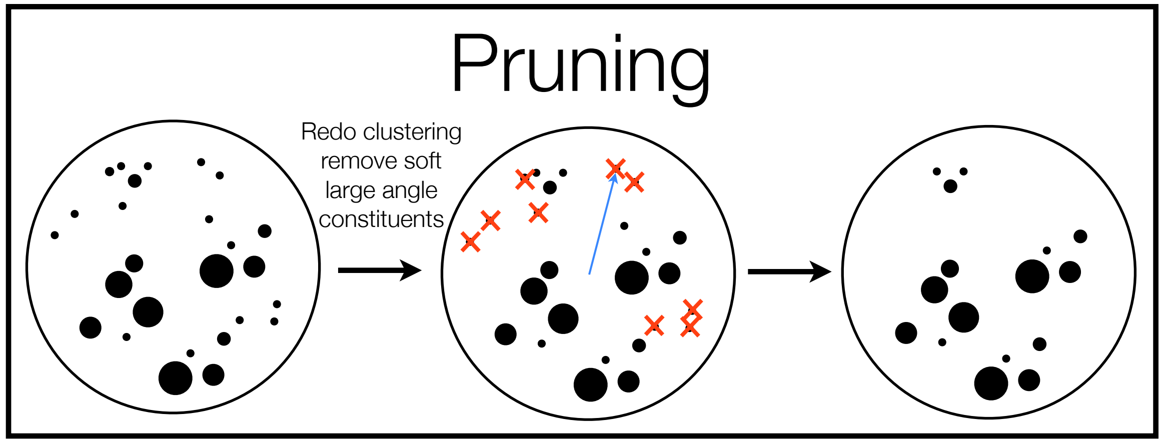
- Jet substructure techniques
  - Grooming
  - Additional substructure
  - Subjet b-tagging
  - V/top/Higgs tagging
- Boosted analyses
  - Fermion+fermion resonances
  - Fermion+boson resonances
  - Diboson resonances
  - SUSY
  - SM measurements
- Run II considerations

Boosted Techniques

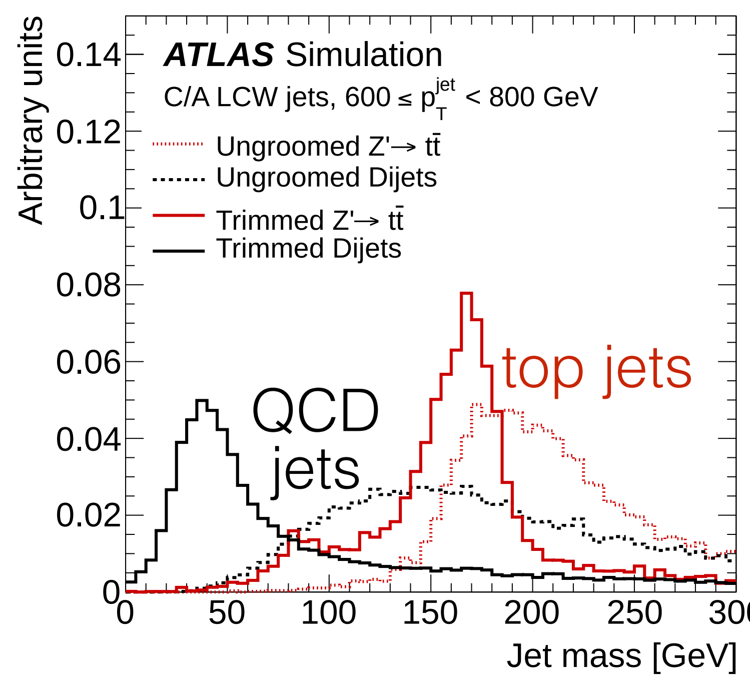
Jet Mass / Grooming

- Jet mass
  - Powerful tool to identify merged jets from heavy particle decays
  - Generated perturbatively for jets from light quarks/gluons (“QCD jets”)
  - Highly sensitive to UE and PU
- Grooming
  - Remove soft / wide angle radiation
  - Examples: pruning, trimming, filtering, …

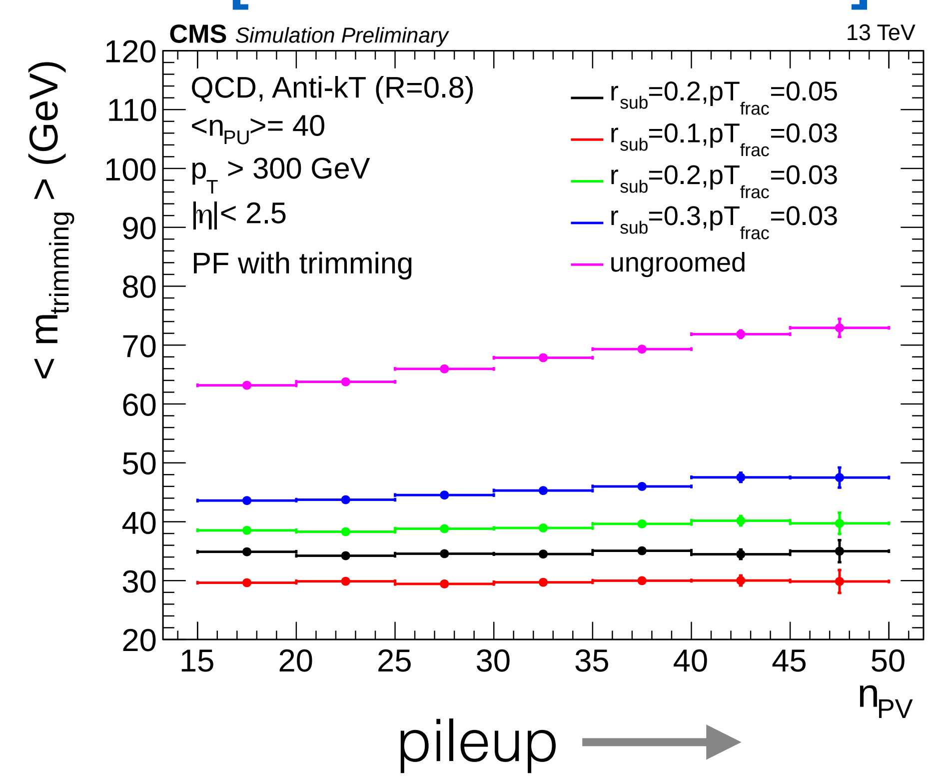
Example:



[ATLAS JHEP 09 (2013) 076]



[CMS PAS JME-14-001]



NB: jet mass resolution insufficient to separate W jets from Z jets

Grooming improves background rejection, energy/mass resolution, and PU stability

Additional Observables

- k_T-splitting scale

$$\sqrt{d_{12}} = \min(p_{T_1}, p_{T_2})\Delta R_{12}$$

Exploit symmetric nature of heavy particle decays

- Mass drop

$$\mu_{1,2} = \frac{\max(m_1, m_2)}{m_{12}}$$

Characterize “clumpyness"

- N-subjettiness

$$\tau_N = \frac{1}{d_0}\sum_k p_{T_k} \times \min(\Delta R_{1k}, \Delta R_{2k}, ..., \Delta R_{Nk})$$

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- Energy correlation functions
- Quark/gluon likelihood
- Jet width $w = \frac{\sum_i \Delta R_{i,\mathrm{jet}} p_{T_i}}{\sum_i p_{T_i}}$
- Jet charge $q = \sum_i q_i \left(\frac{p_{T,i}}{p_{T,\mathrm{jet}}}\right)^\kappa$
- Pull angle $\vec{t} = \sum_i \frac{p_{T,i}|r_i|}{p_{T,\mathrm{jet}}}\vec{r}_i$
- Q-jets volatility

$$\nu_{\mathrm{Q-jets}} = \frac{\sqrt{\langle m^2\rangle - \langle m\rangle^2}}{\langle m\rangle}$$

- Planar flow

$$P = 4 \times \det(I)/\mathrm{Tr}(I)^2$$

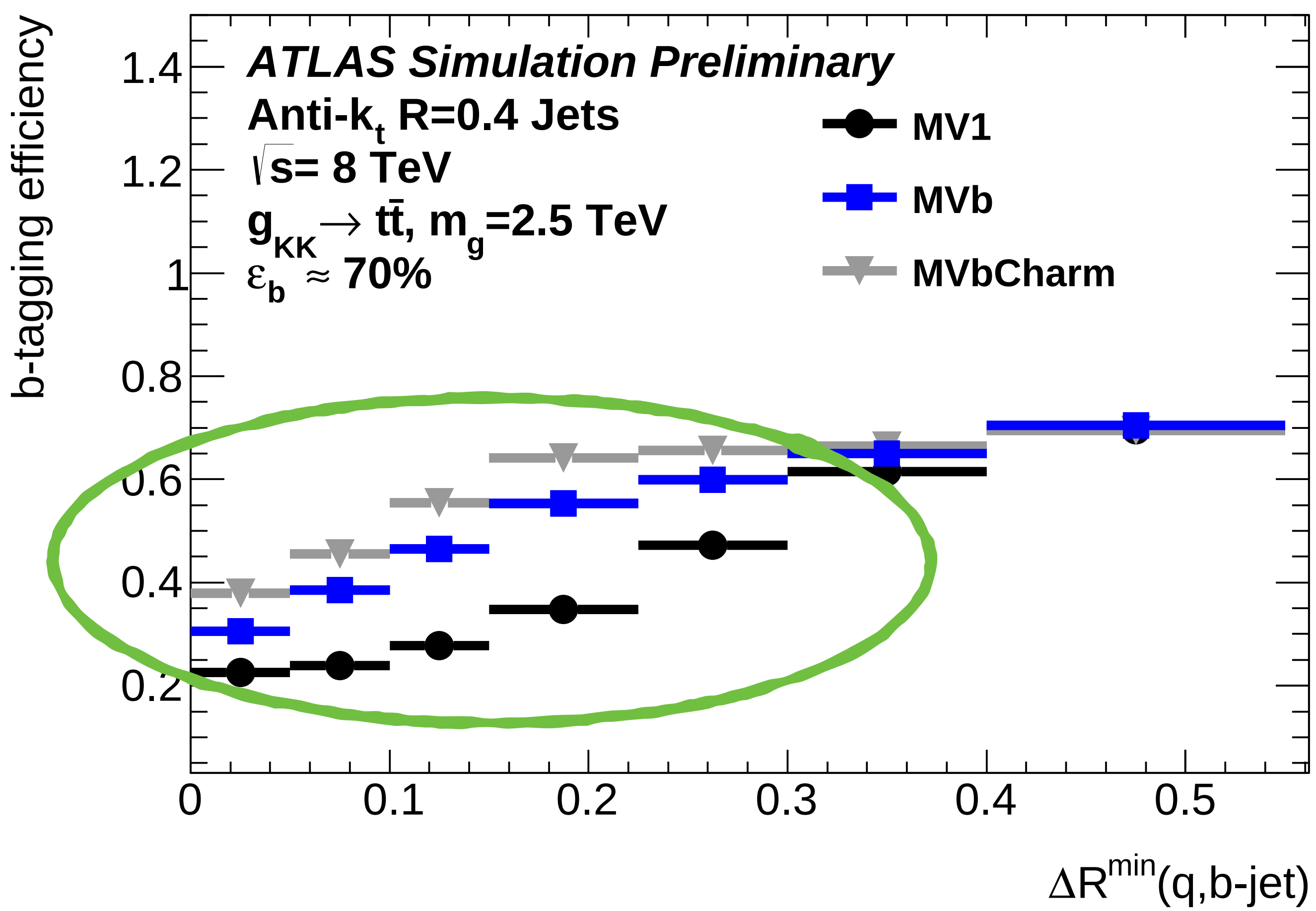
- …

Too many to discuss here

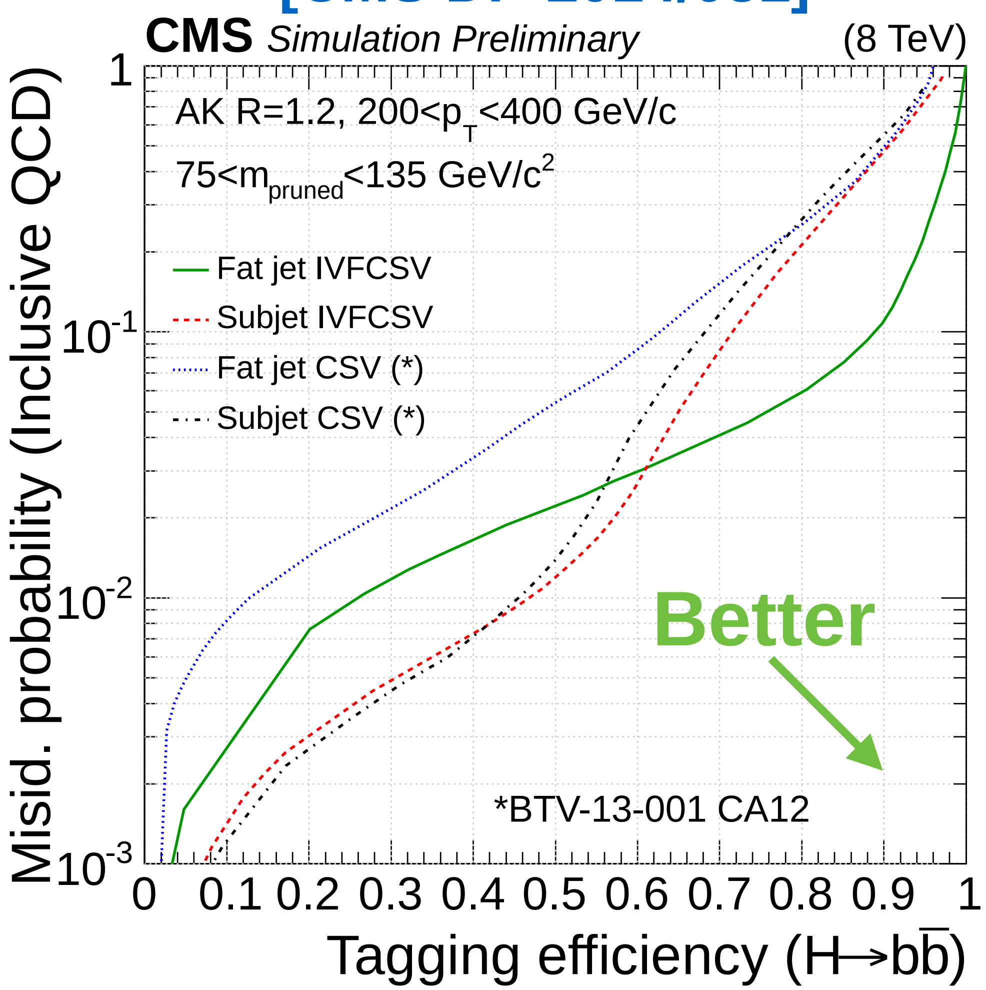
Boosted B-tagging

- Many variables from the previous slide are correlated
  - B-tagging of subjets is largely orthogonal
- Difficult in boosted regime due to density of environment
  - Strong efforts ongoing within both collaborations to further improve performance

[ATL-PHYS-PUB-2014-014]



[CMS DP-2014/031]



V/top/Higgs Tagging

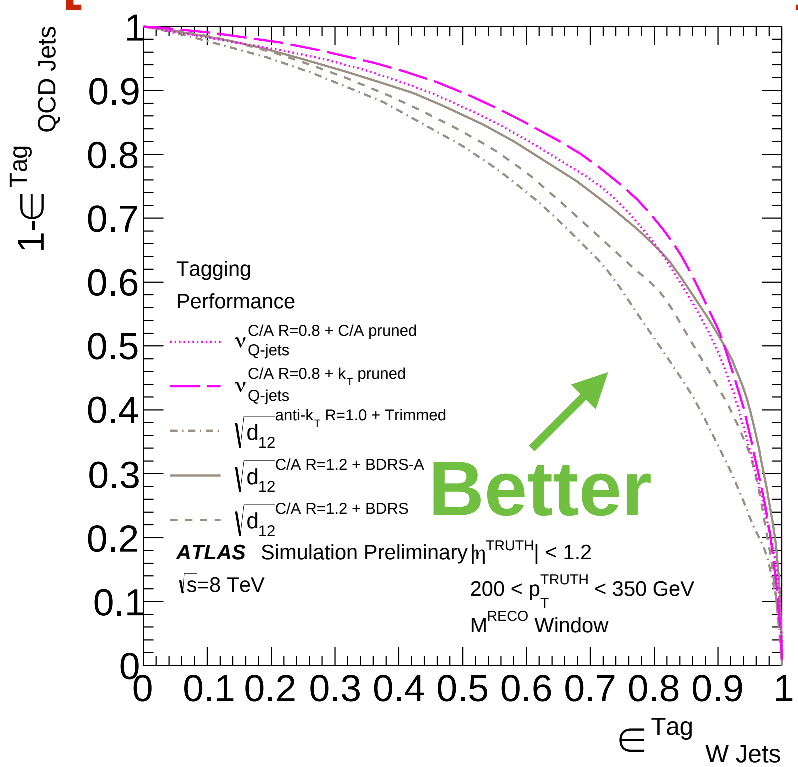
- Putting all available information together
  - Typically groomed mass window + substructure (+ b tagging)
  - Alternatively, groomed mass window can be replaced with a more sophisticated tagging algorithm
    - CMS/HEP Top Tagger, BDRS, …

CMS/HEP Top Tagger

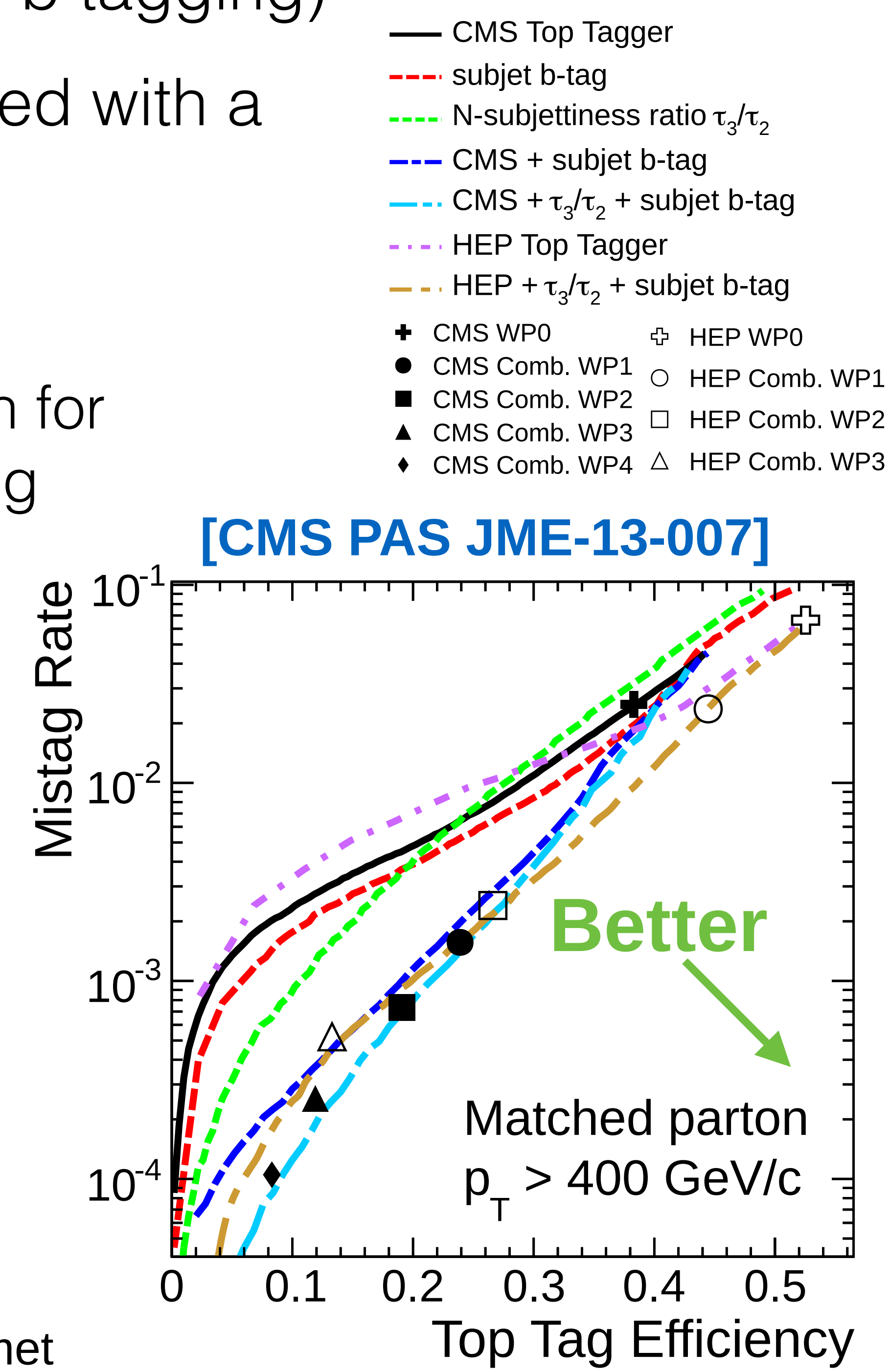
- Groom to find subjets
- Require:
  - $N_{subjets} \geq 3$
  - $m_{jet} \approx m_{top}$
  - $\min(m_{ij}) \approx m_W$ (CMS)
  - $m_{ij} \approx m_W$ (HEP)

See talk by Chris Malena Delitzsch for more details on ATLAS V tagging

[ATLAS PHYS-PUB-14-004]



[CMS PAS JME-13-007]



See talks by Mario Pelliccioni and Eduardo Navarro De Martino

Higgs

- High mass searches
  - $H \rightarrow WW \rightarrow \ell\nu qq$ [CMS PAS HIG-14-008] Brand New!
  - $H \rightarrow ZZ \rightarrow \ell\ell qq$ [CMS PAS HIG-14-007] Brand New!

Fermion+Fermion Resonances

- Z′→tt [CMS PAS B2G-13-008] Brand New!
- Z′→tt [ATLAS CONF-2015-009] Brand New!
- Additional searches in the backup
  - W′→tb [ATLAS arXiv:1408.0886]
  - W′→tb [CMS PAS HIG-14-007]

(Extended gauge sectors, colorons, axigluons, pseudoscalar Higgs, extra dimensions)

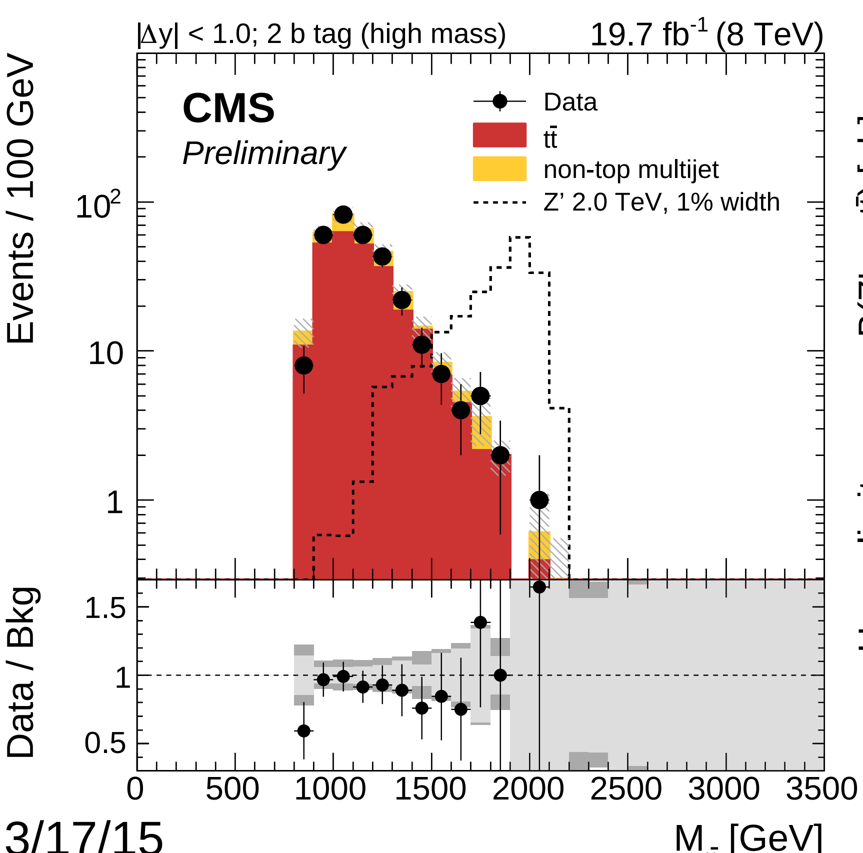
[CMS PAS B2G-13-008]

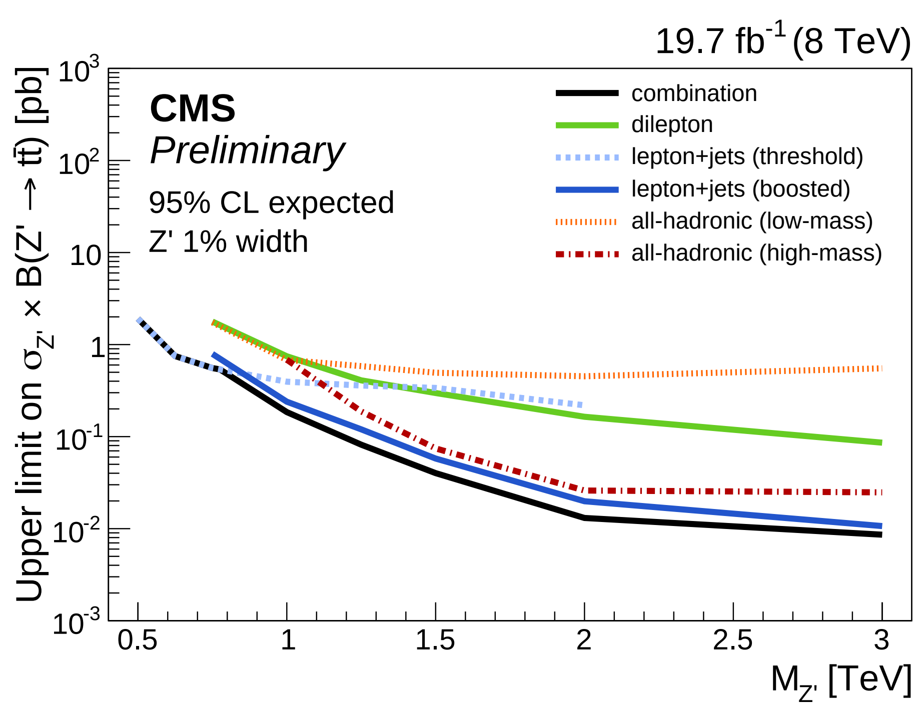
Brand New!

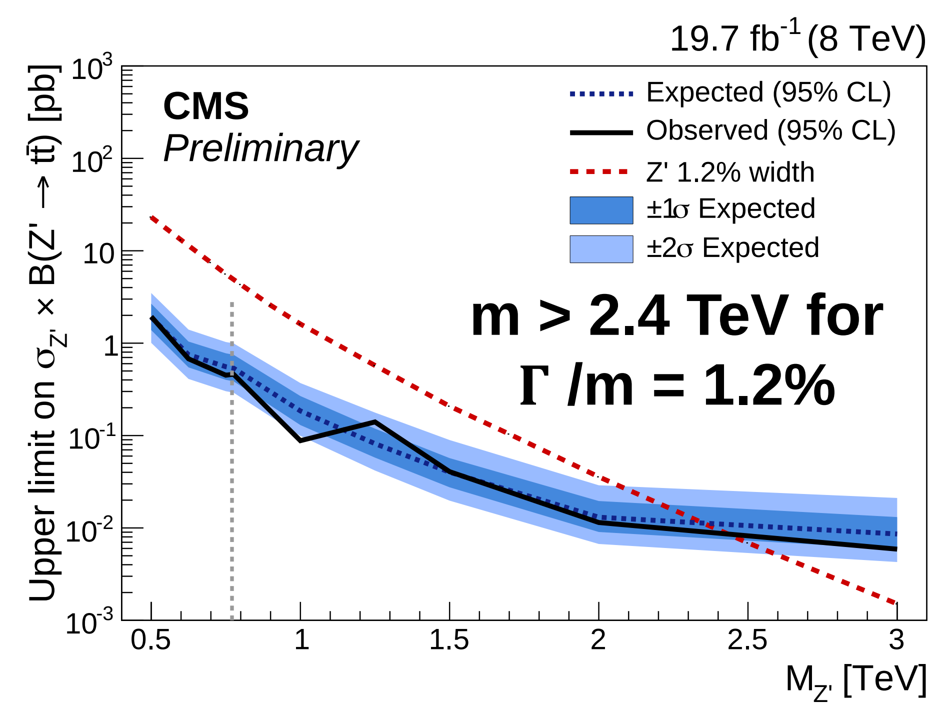
$Z' \rightarrow t\bar{t}$

- Combination of searches for tt resonance in 0,1,2 lepton events
  - Hadronic channel
    - Dijet topology w/ 2 top tags
    - Separate high and low mass optimizations
    - QCD mistag rate measured in data

	Top Tagger	b-tagging	N-subjettiness
Low Mass	HEP (R = 1.5)	sub-jet	
High Mass	CMS (R = 0.8)	sub-jet	$\tau_{32} = \tau_3/\tau_2$





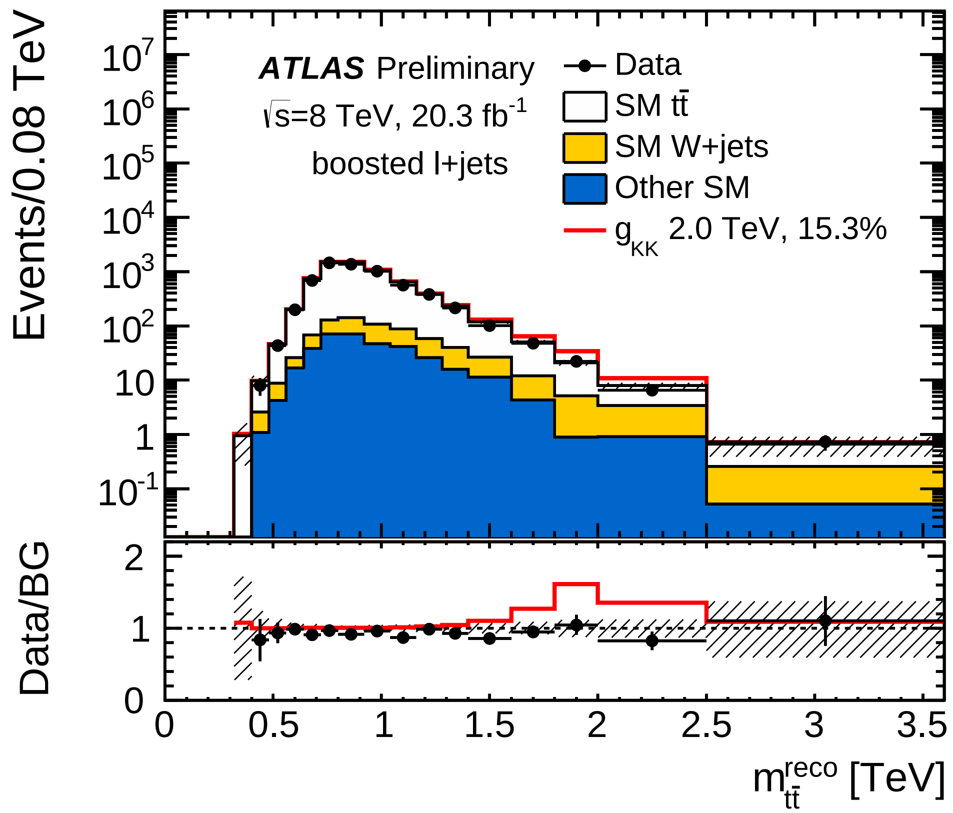


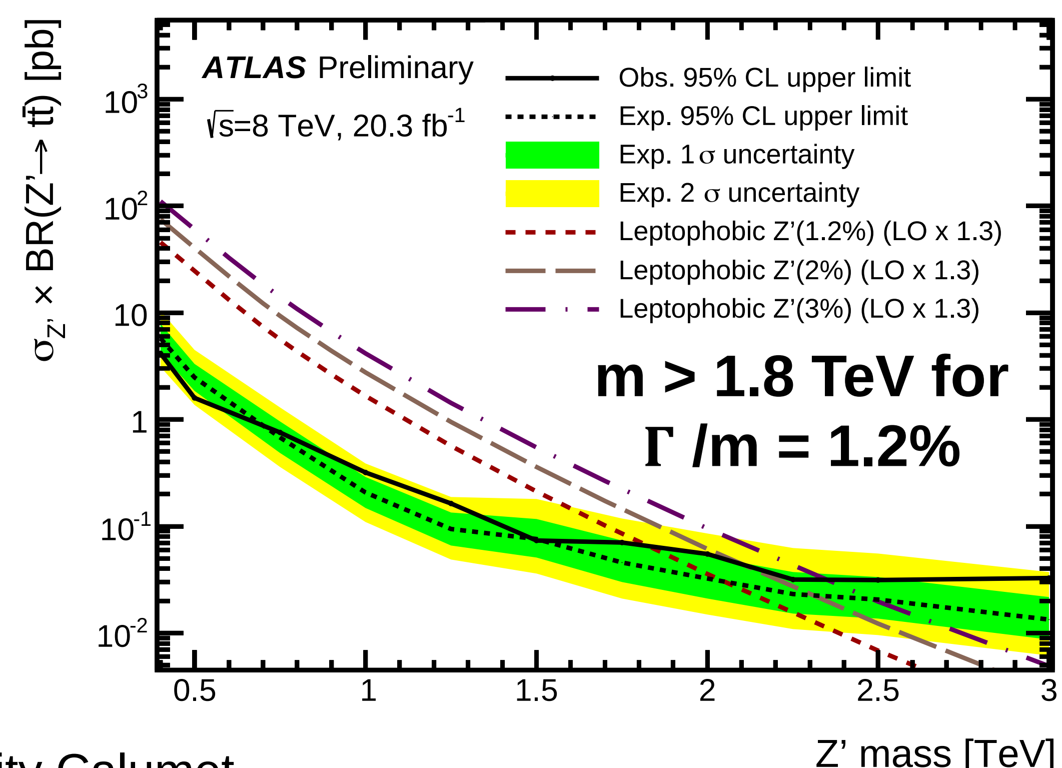
Brand New!

$Z' \rightarrow tt$

[ATLAS CONF-2015-009]

- Lepton + jets (resolved and merged analyses)
  - Merged channel
    - Event selection
      - 1 ℓ (mini-isolation) + ≥1 b jet + ≥1 top jet + MET + m_T
        - Trimmed R=1.0 jet with m > 100 GeV + k_T-splitting scale
    - Categorize events based on ΔR-matching of b-jets to top candidates
    - W+jets normalization and heavy flavor corrections taken from data





Fermion+Boson Resonances

- T′→t(bjj)H(bb) [CMS arXiv:1503.01952] Brand New!
- Additional searches in the backup
  - $\ell^* \to \ell\gamma / \ell Z$ [CMS PAS EXO-14-015] Brand New!
  - B′→bH(bb) [CMS PAS B2G-14-001]

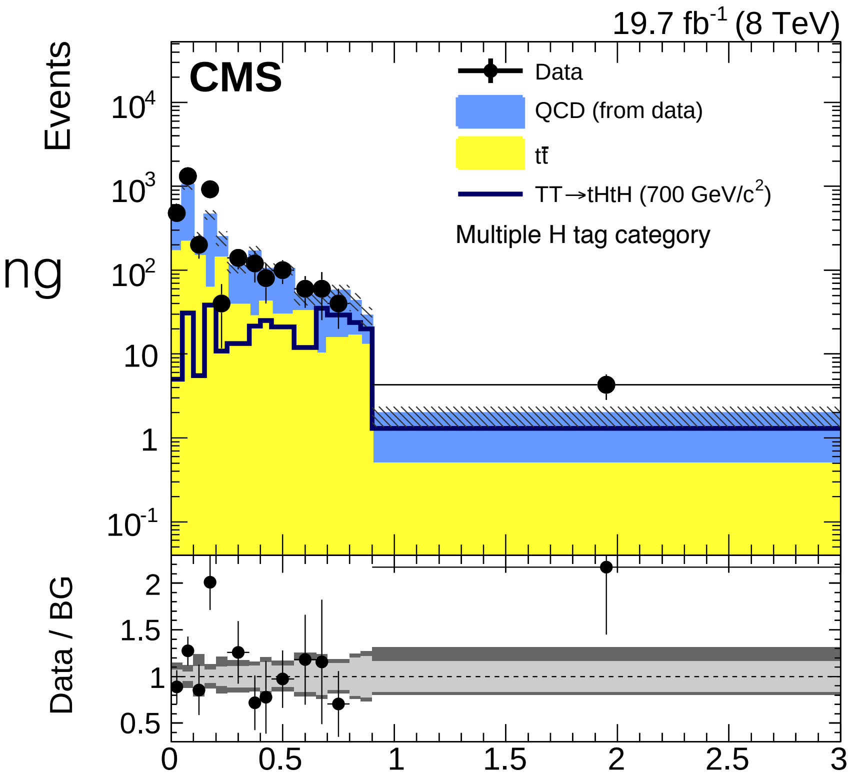
(Little Higgs, extra dimensions, composite Higgs)

Brand New!

$T' \rightarrow t(bjj)H(bb)$

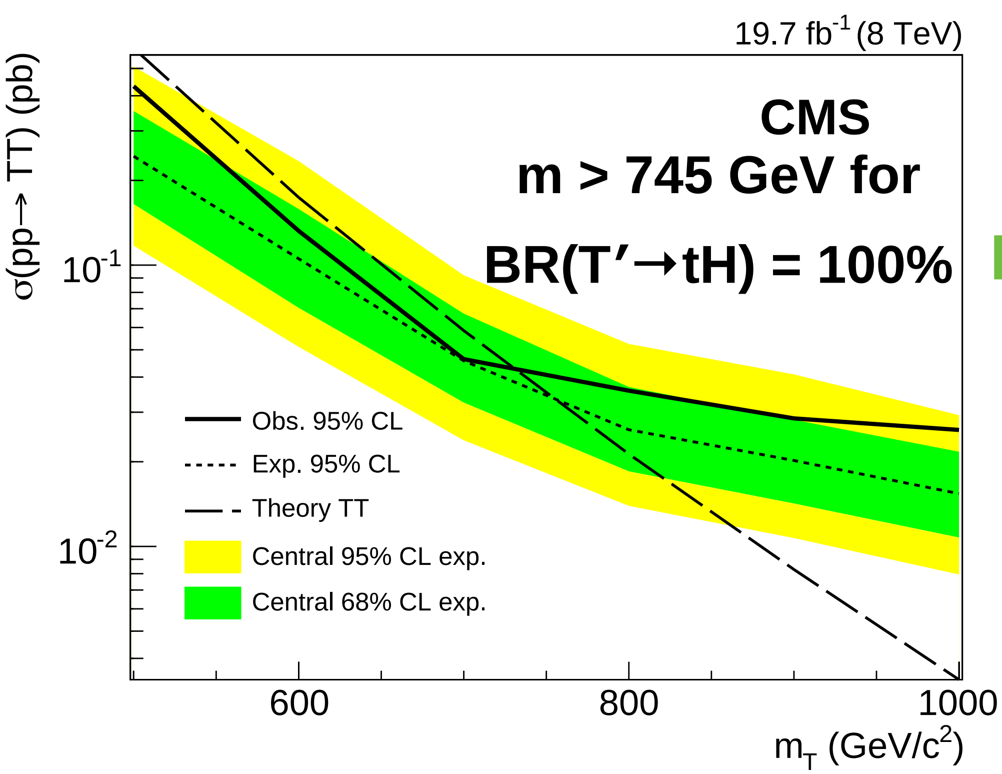
[CMS arXiv:1503.01952]

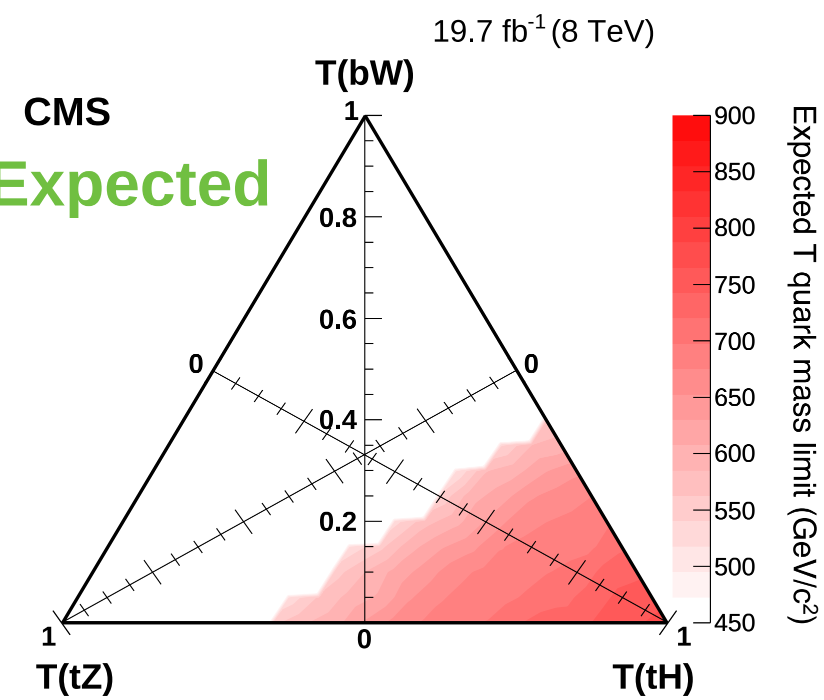
- Search for pair production of tH resonances
  - First vector-like quark search in an all hadronic final state
  - First use of Higgs tagger exploiting substructure + subjet b-tagging
- Require ≥1 top jet and ≥1 Higgs jet
  - Top tag - HEP Top Tagger + subjet b-tag
  - Higgs tag - Filtered R=1.5 jet with m > 60 GeV + double subjet b-tag
    - Efficiencies validated in boosted semileptonic tt data

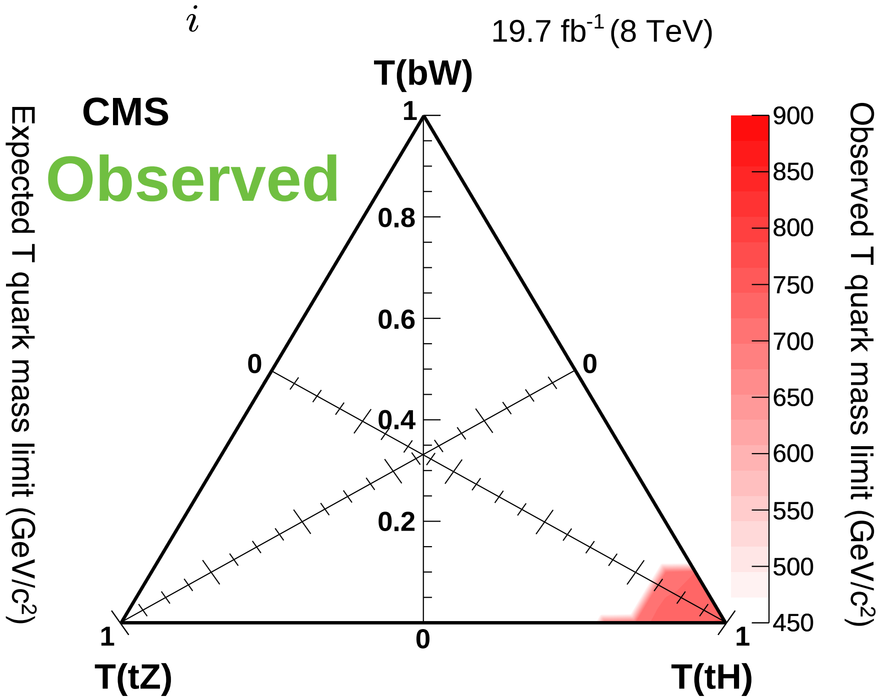


$$H_T = \sum_i p_T^{j_i}$$

Likelihood(H_T, m_{bb})







Diboson Resonances

- V(qq)H(bb/WW) [CMS PAS EXO-14-009] Brand New!
- Z(qq)H($\tau\tau$) [CMS arXiv:1502.04994] Brand New!
- Additional searches in the backup
  - V(qq)W($\ell\nu$) [ATLAS arXiv:1503.04677] Brand New!
  - V(qq)Z($\ell\ell$) [ATLAS EPJC 75:69 (2015)]
  - V(qq)V(qq) [CMS JHEP 08 (2014) 173]
  - V(qq)V($\ell\nu$/$\ell\ell$)[CMS JHEP 08 (2014) 174]

See talk by Katharine Leney

(Little Higgs, composite Higgs, 2HDM)

Brand New!

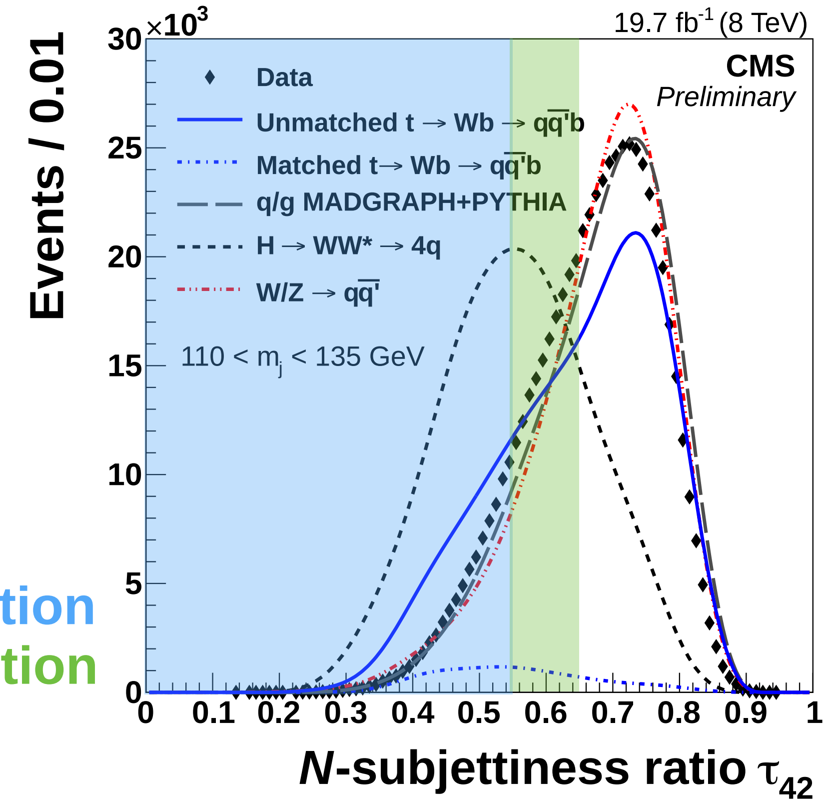
VH Resonance

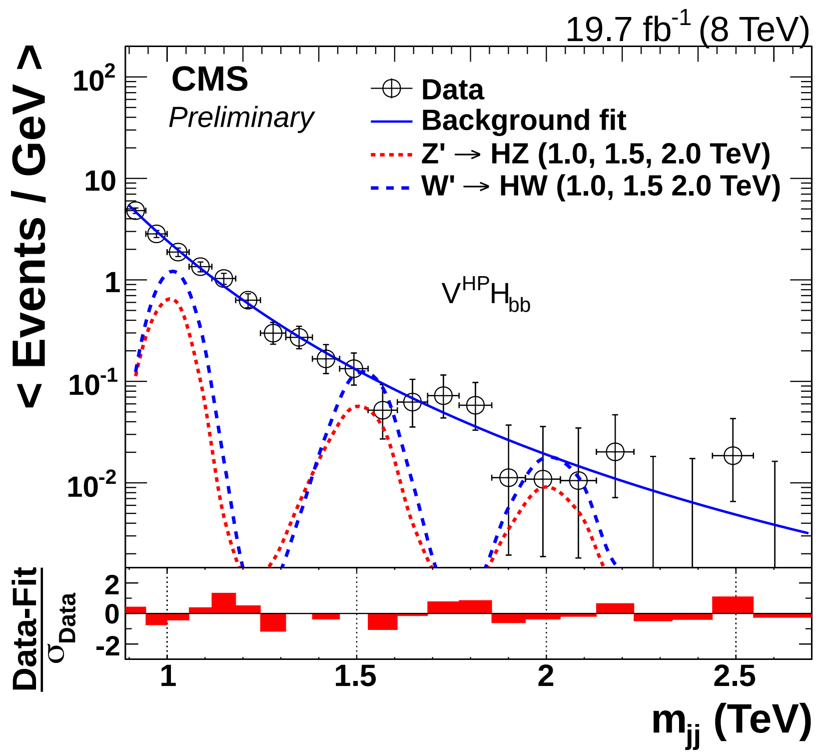
[CMS PAS EXO-14-009]

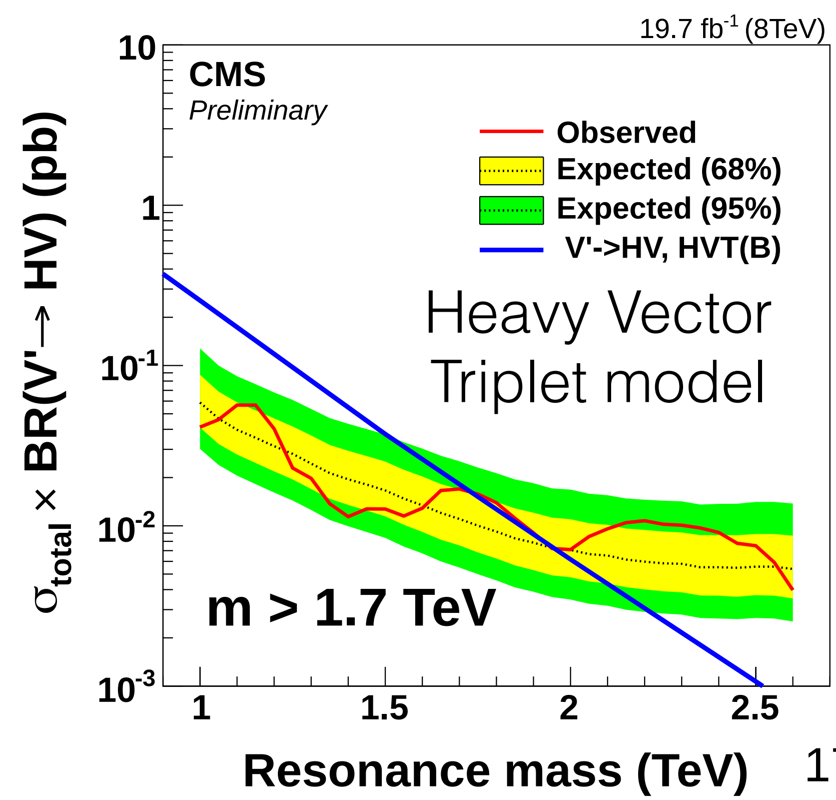
- First search for VH resonance in all hadronic final state
  - With H→bb/H→WW*→4q and V→qq
- First attempt to reconstruct boosted H→4q decays
- Pruned R=0.8 jets used for H→bb/4q and V→qq tagging
  - + N-subjettiness (H→4q: τ_{42}, V→qq:τ_{21})
  - + Sub-jet/fatjet b-tagging (H→bb)
- Categorize events based on H decay mode and H/V purity
- Background model:

$$P(m_{jj}) = \frac{p_0(1 - m_{jj}/\sqrt{s})^{p_1}}{(m_{jj}/\sqrt{s})^{p_2}}$$

High purity selection
Low purity selection







(Little Higgs, composite Higgs, 2HDM)

Brand New!

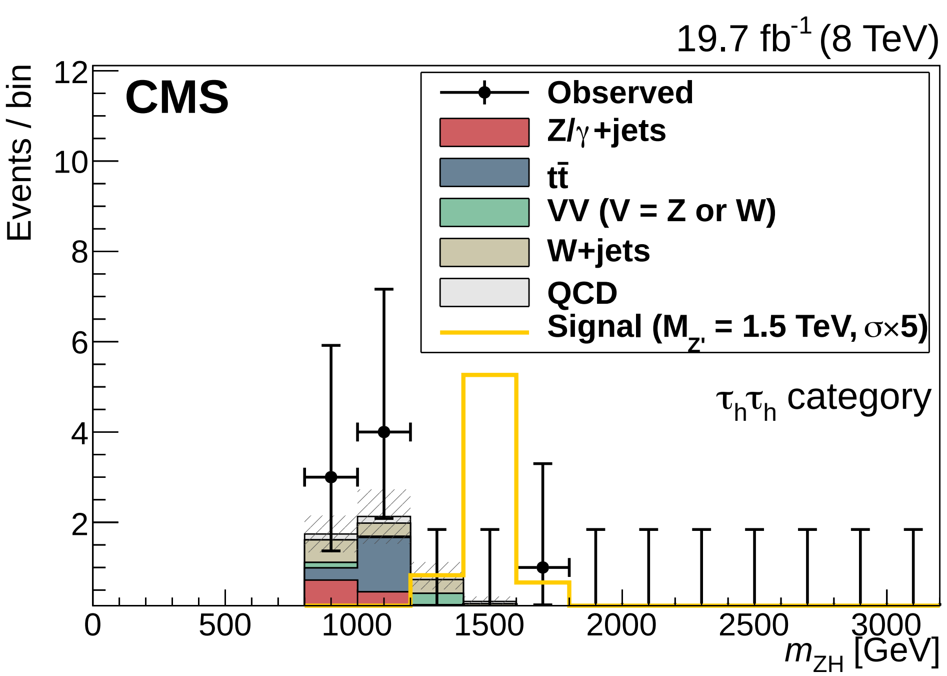
ZH Resonance

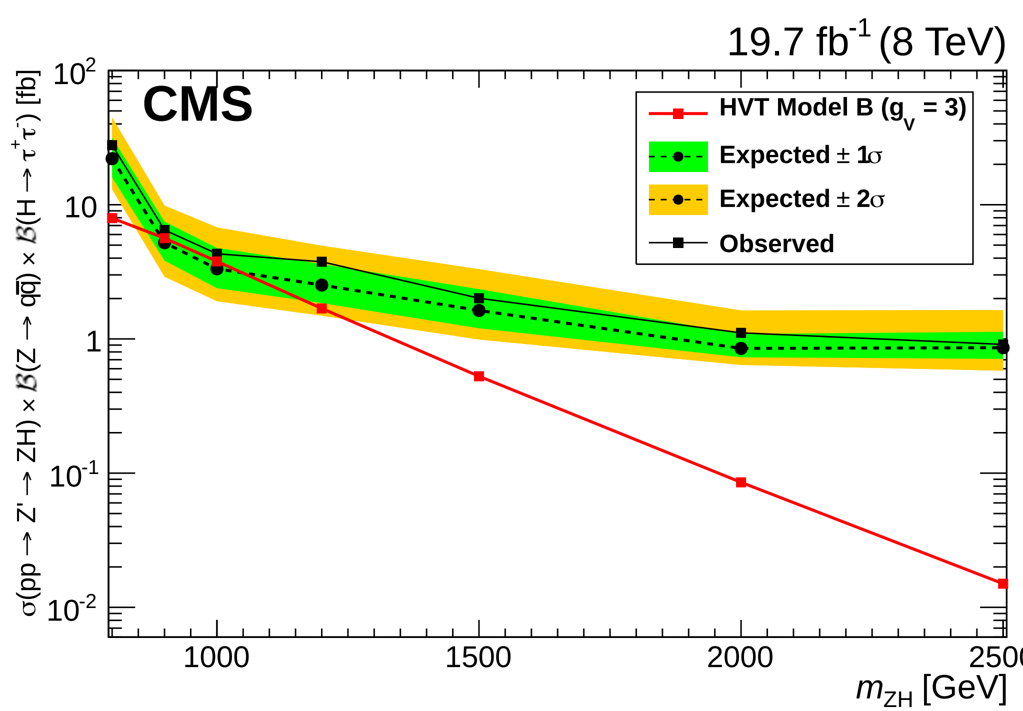
[CMS arXiv:1502.04994]

- Search for boosted Z→qq recoiling against H→$\tau\tau$
    - Consider all possible τ decays: $\tau_e\tau_e$, $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$, $\tau_h\tau_e$, $\tau_h\tau_\mu$, $\tau_h\tau_h$
- Z tagging - Pruned R=0.8 jet with 70 < m < 110 GeV + N-subjettiness
- $\tau_h\tau_h$: Novel reconstruction of boosted H→$\tau\tau$

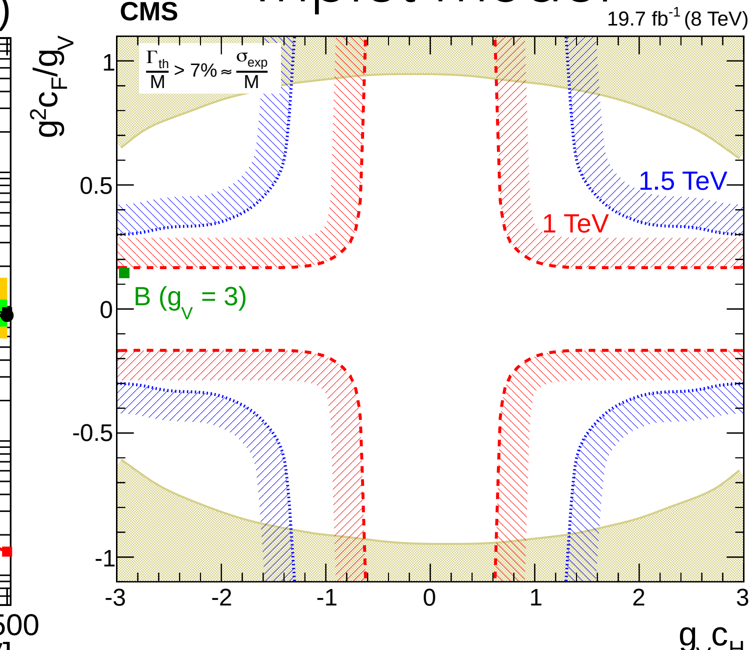
mass drop: $\mu_{1,2} = \frac{\max(m_1, m_2)}{m_{12}}$

    - Pruned (R=0.8) subjets with large mass drop serve as seeds to the “hadron-plus-strips” algorithm
    - Likelihood fit to reconstruct H→$\tau\tau$ from MET and visible daughters (SVfit)
    - 105 < $m_{\tau\tau}$ < 180 GeV





Heavy Vector Triplet model



SUSY

- RPV [ATLAS arXiv:1502.05686] Brand New!
- Additional searches in the backup
  - Stop (all hadronic) [ATLAS JHEP 09 (2014) 015]
  - Stop (single lepton) [ATLAS JHEP 11 (2014) 118]

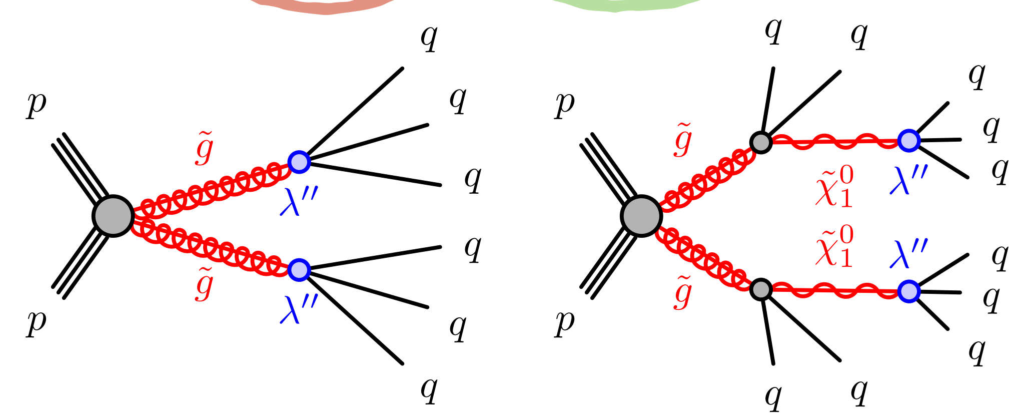
Brand New!

RPV SUSY

[ATLAS arXiv:1502.05686]

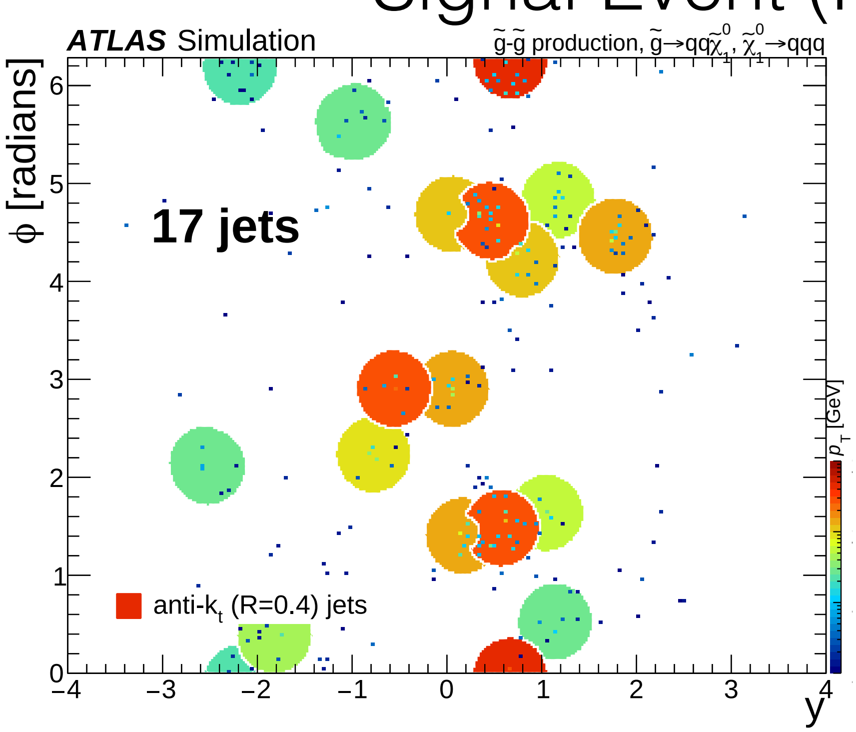
$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

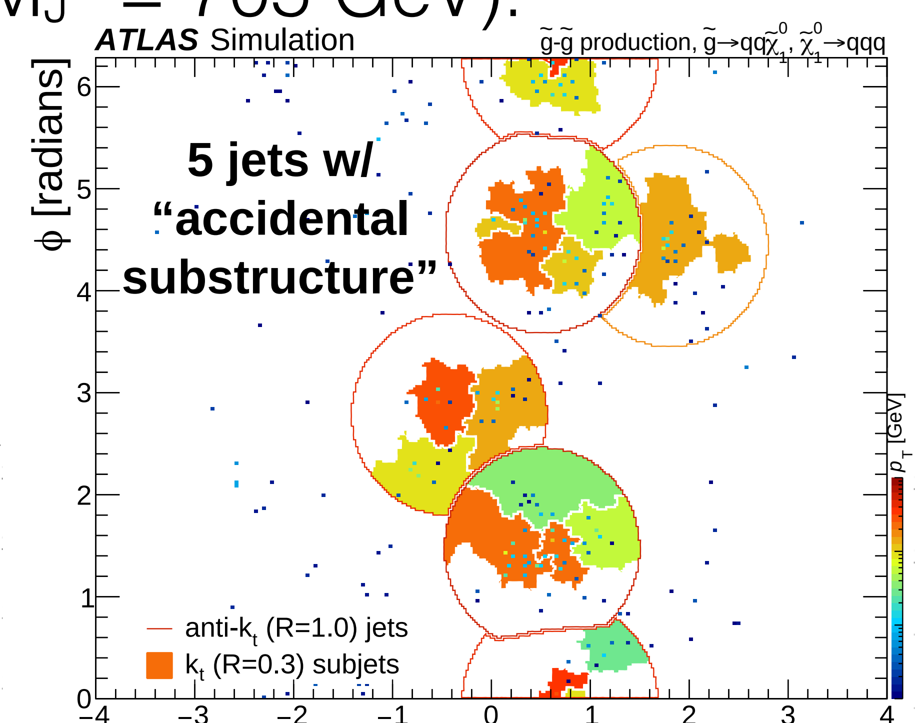
- Jet multiplicity and total-jet-mass based searches
  - Jet counting analysis
    - ≥6/7 jets ⊗ ≥0/1/2 b tags (R=0.4)
  - Total jet mass analysis
    - Relies on "accidental substructure"
      - Trimmed R=1.0 jets formed from unrelated hadronic activity
      - Large masses generated "accidentally"
    - Signal region - 4 fat jets with small $|\Delta\eta_{12}|$

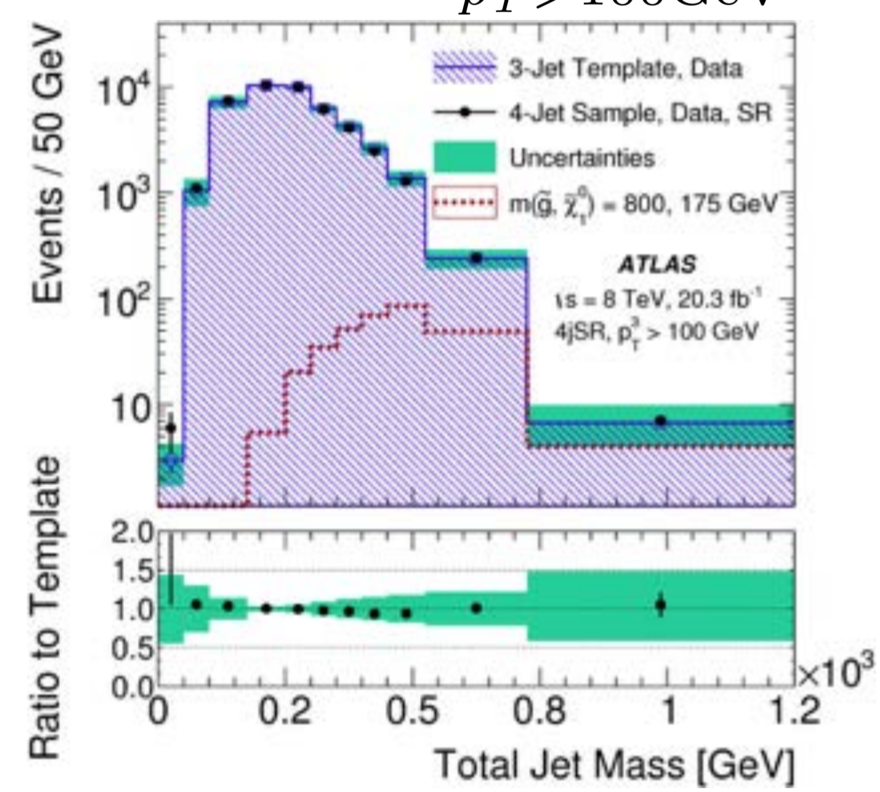


Primary observable: $$M_J^{\Sigma} = \sum_{p_T > 100\mathrm{GeV}}^{4} m_{\mathrm{jet}}$$

Signal Event (M_J^{Σ} = 705 GeV):







Brand New!

[ATLAS arXiv:1502.05686]

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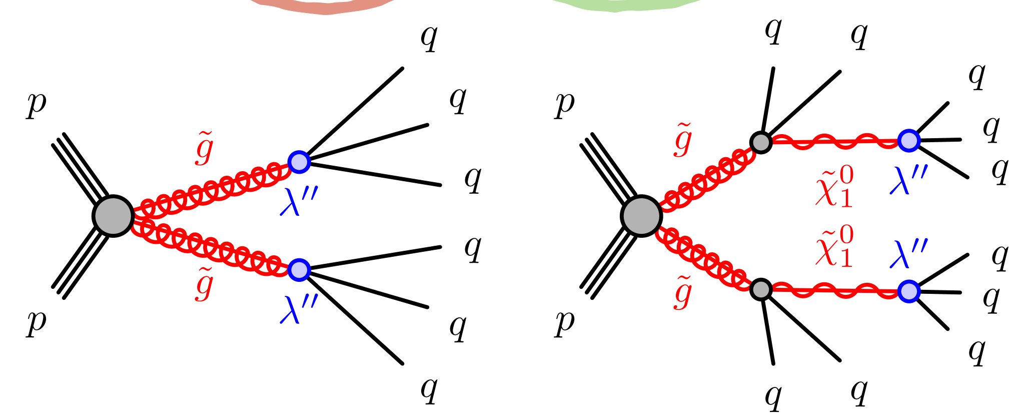

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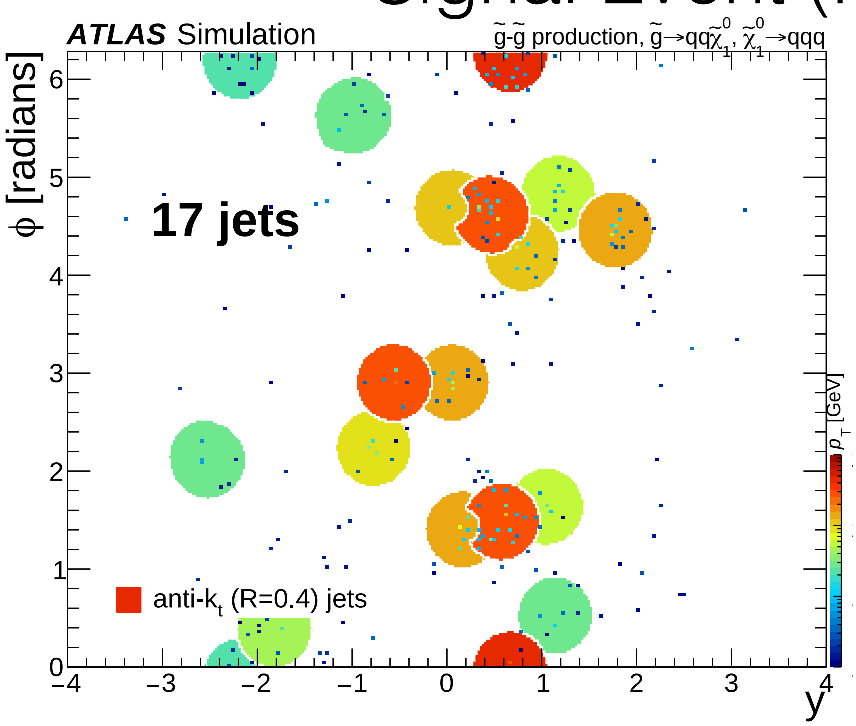
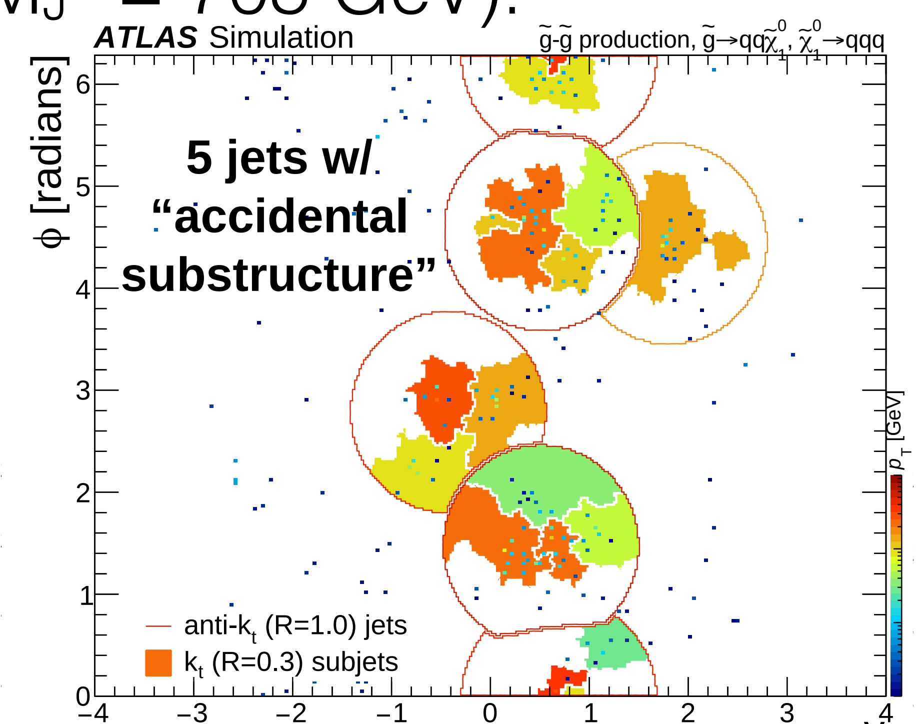
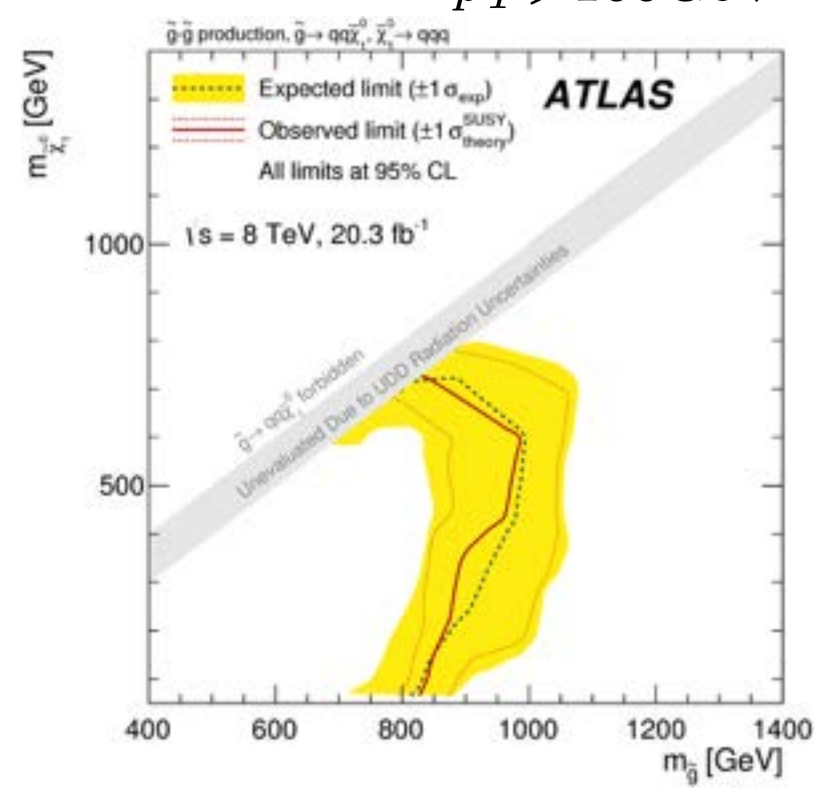






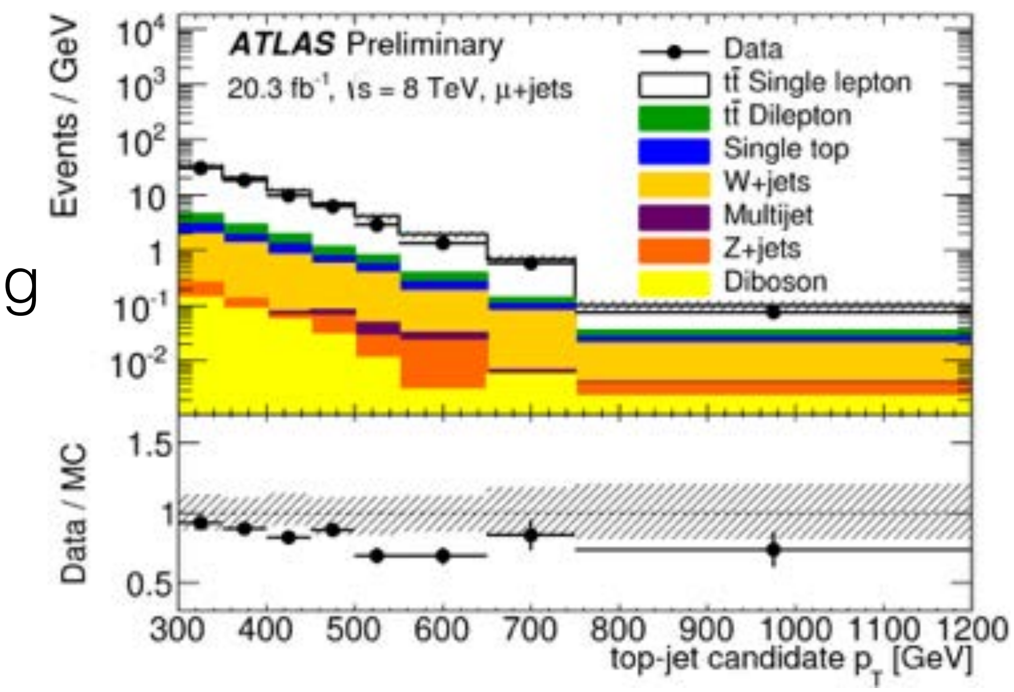
SM Measurements

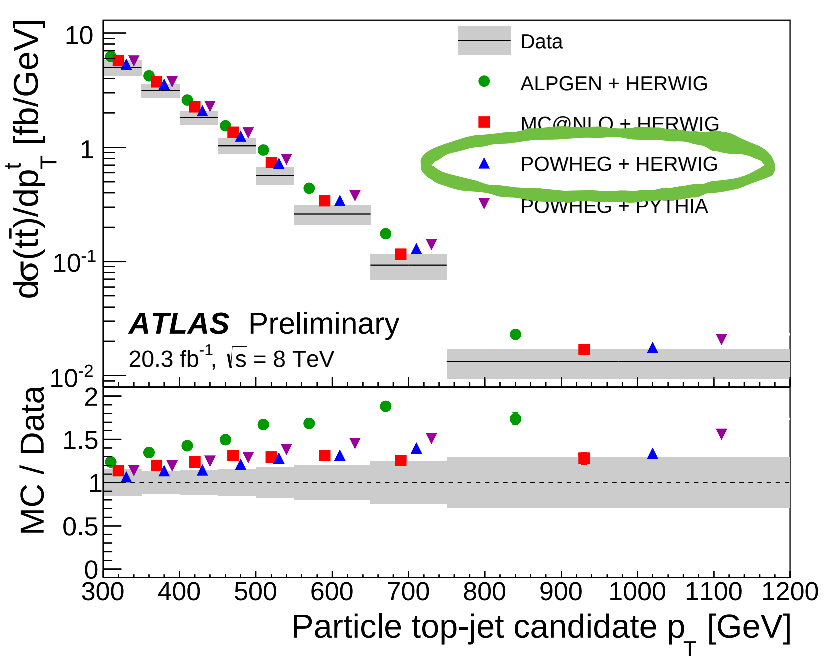
- tt differential cross section [ATLAS-CONF-2014-057]
- V + jets cross section [ATLAS 2014 NJP 16 113013]

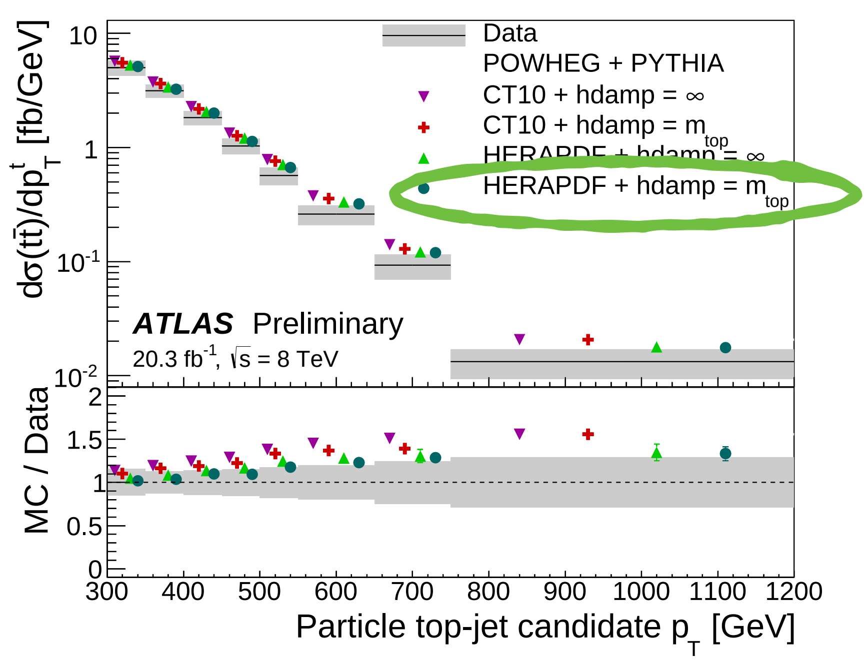
[ATLAS-CONF-2014-057]

Differential tt Cross Section

- Extension of leptonic results with $p_T(t) < 800$ GeV
- Lepton + jets channel
  - Trimmed R=1.0 jets with m > 100 GeV + k_T splitting scale
    - $p_T > 300$ GeV and $|\eta| < 2.0$
- MC predictions overestimate the data, especially at high $p_T(t)$
- Dominated by JES (particle level) and signal modeling (parton level) uncertainties







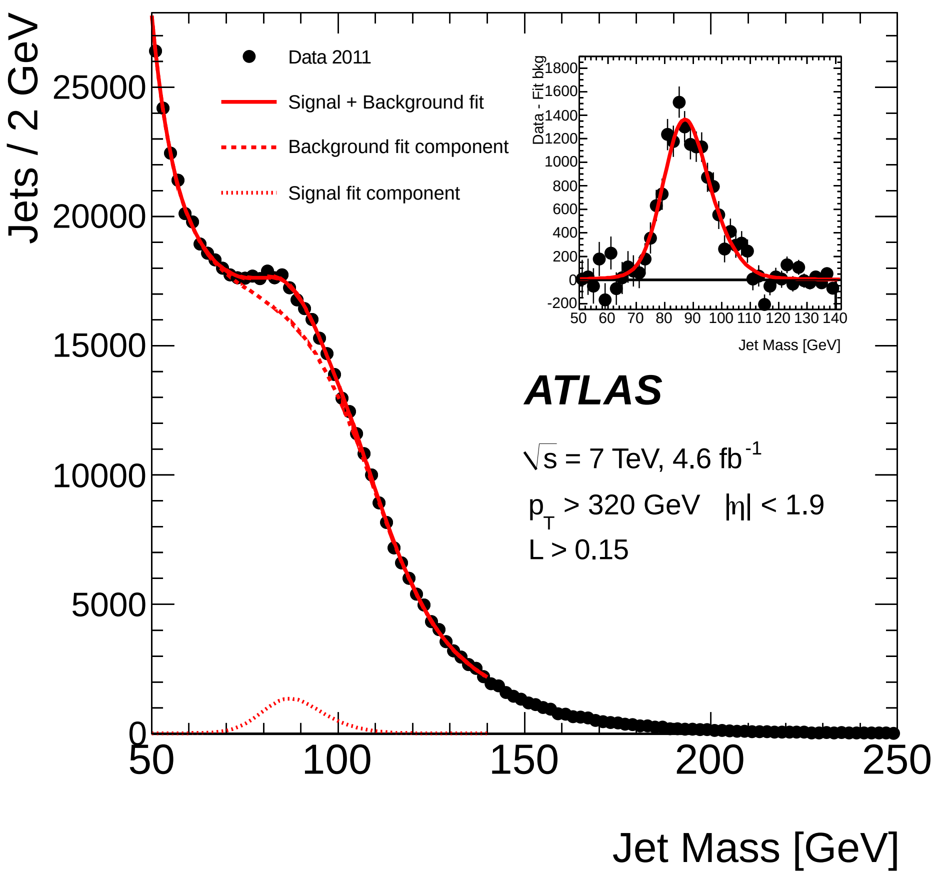
	e+jets	μ+jets
$t\bar{t}$ ℓ+jets	4020 ± 460	3500 ± 400
$t\bar{t}$ dilepton	227 ± 36	210 ± 26
W+jets	263 ± 50	252 ± 48
single top	136 ± 27	134 ± 25
Multijet	91 ± 17	3 ± 1
Z+jets	34 ± 18	14 ± 8
Dibosons	22 ± 11	18 ± 9
Prediction	4790 ± 540	4130 ± 470
Data	4148	3604

~85% purity

[ATLAS 2014 NJP 16 113013]

V + Jets Cross Section

- Challenging measurement extending leptonic result with $p_T(V) < 300$ GeV
  - Based on $L = 4.6\ fb^{-1}$ at $s^{1/2} = 7$ TeV
- R = 0.6 jets with pT > 320 GeV and $|\eta| < 1.9$
  - 50 < m < 140 GeV
  - Likelihood constructed from jet shape variables in the jet rest frame
- Extract V + jets cross section with binned maximum fit to m_{jet}



~20% precision

σ_{W+Z}: 8.5 ± 0.8 (stat) ± 1.5 (syst) pb

MCFM (NLO): 5.1 ± 0.5 pb

Sources	σ_{W+Z}
MC modelling	4.4%
Background pdf	8.8%
Signal pdf	5%
Jet energy scale	3.7%
Jet energy resolution	<1%
Jet mass scale	2.2%
Jet mass resolution	12.6%
$t\bar{t}$ contribution	2.8%
Single-top and diboson contribution	<1%
W and Z relative yield	2.9%
Luminosity	1.8%
Total	18%

[ATLAS 2014 NJP 16 113013]

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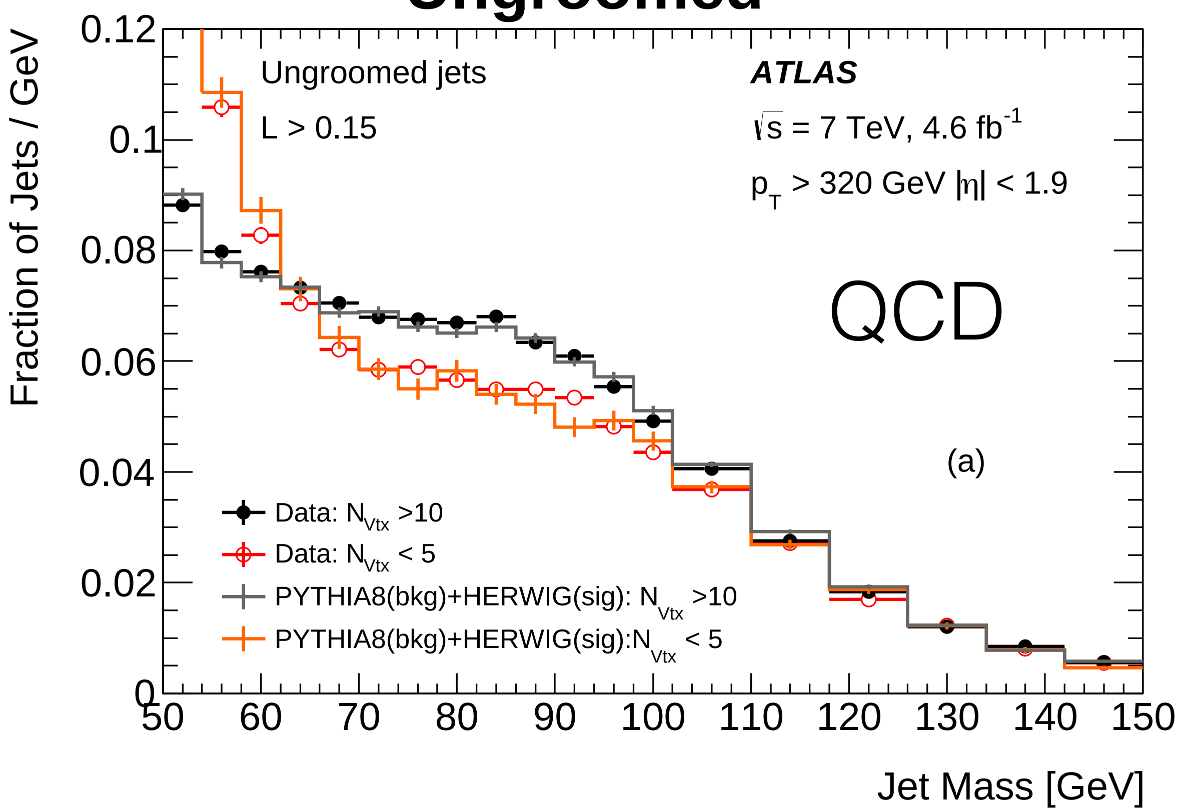
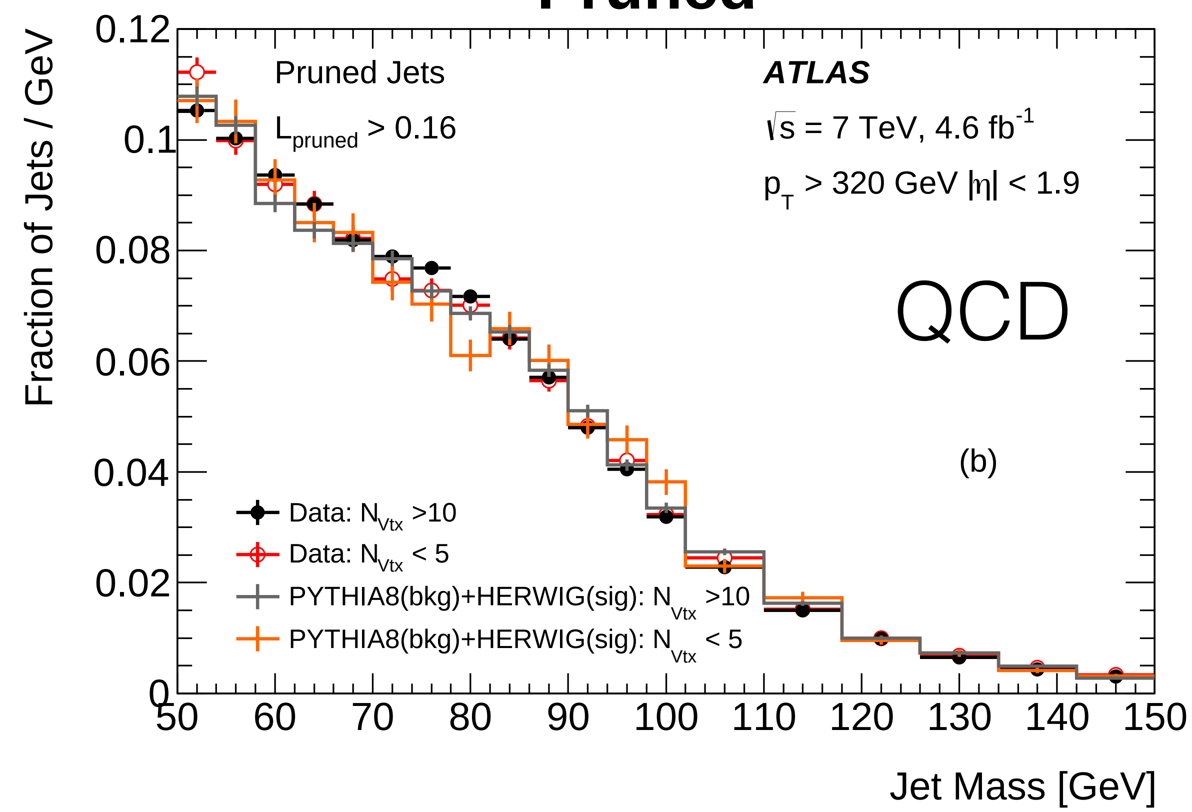
Ungroomed



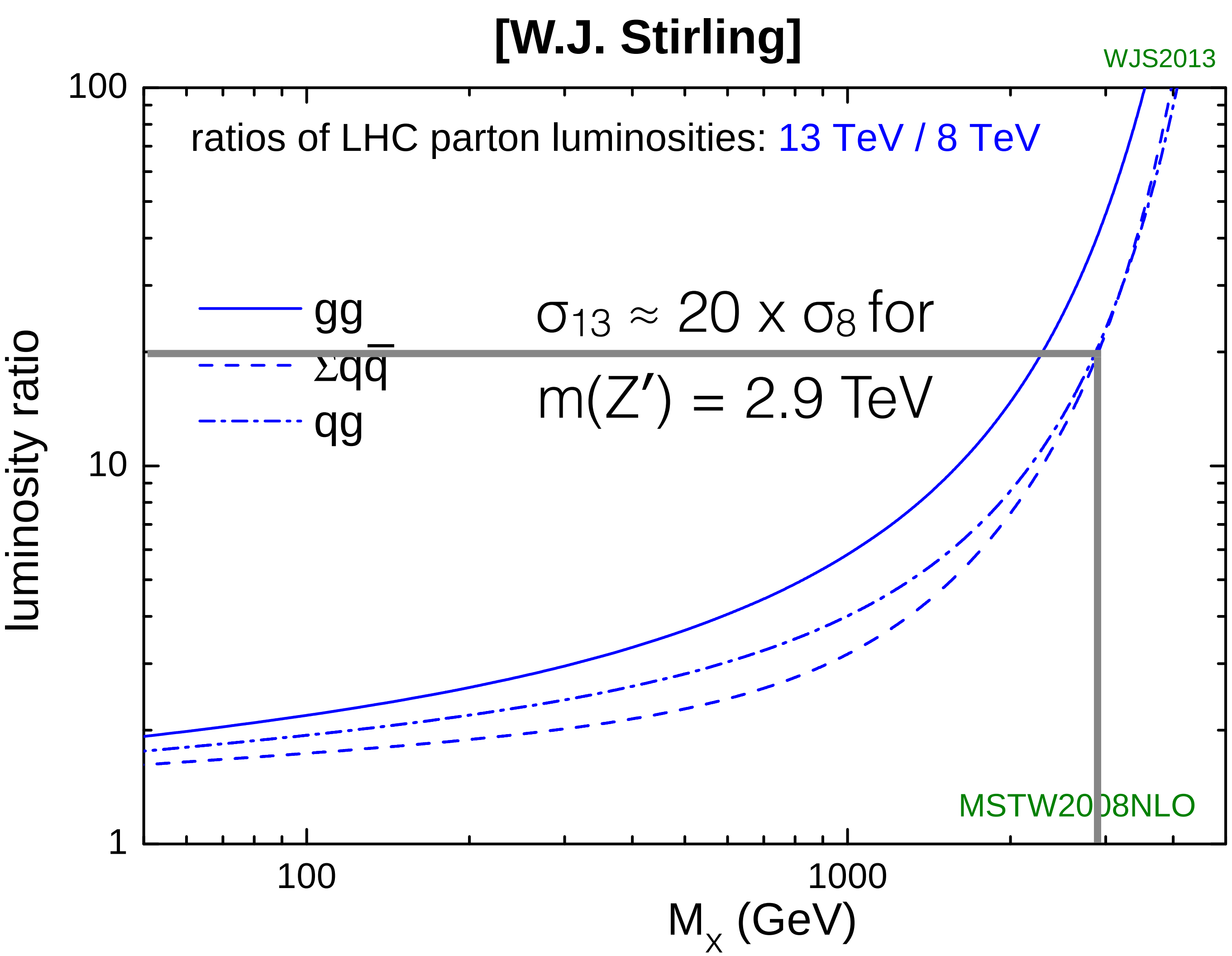
Pruned



Run II Considerations

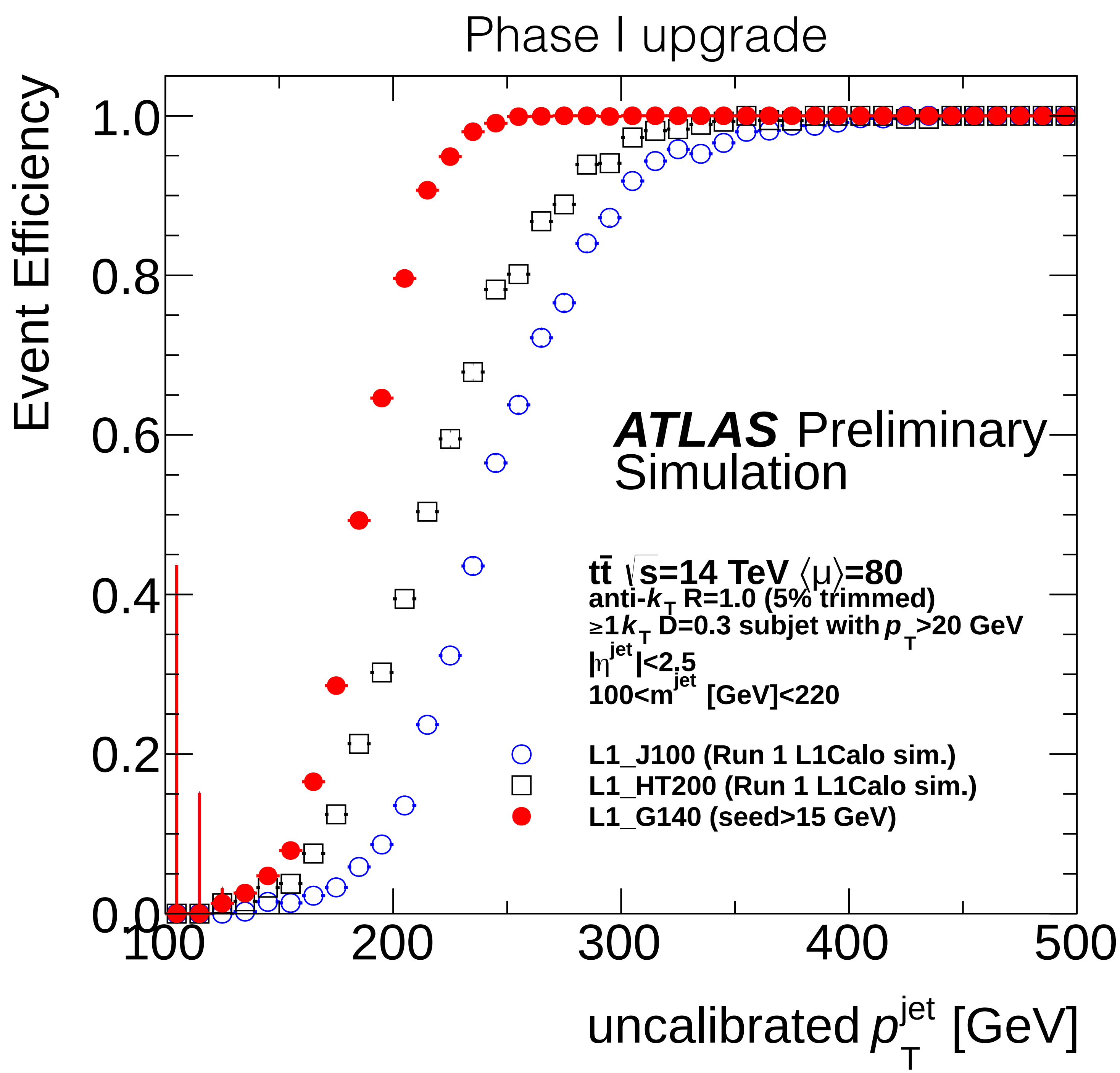
Run II Potential

- With increase to 13 TeV, large increase in cross section for heavy particle production
  - Boosted techniques essential
- New challenges as well
  - Triggering in hadronic final states
  - Pileup mitigation



Trigger

- Triggering will be a serious challenge in Run II, especially for all hadronic analyses
  - Substructure based triggers being deployed which incorporate grooming + mass cut
  - Maybe even something more sophisticated - top tagging?

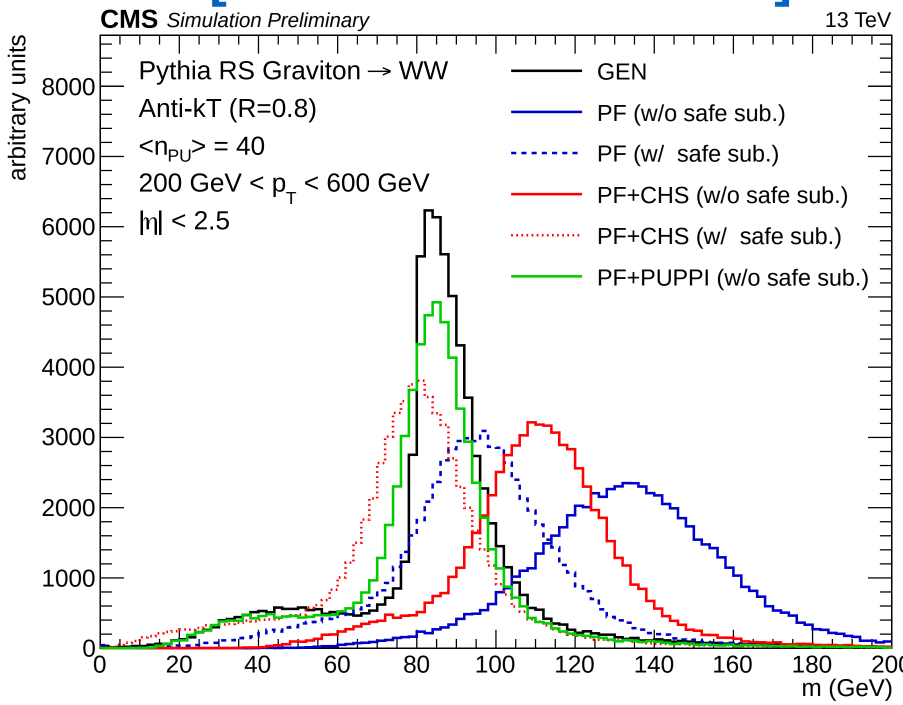


Pileup Mitigation

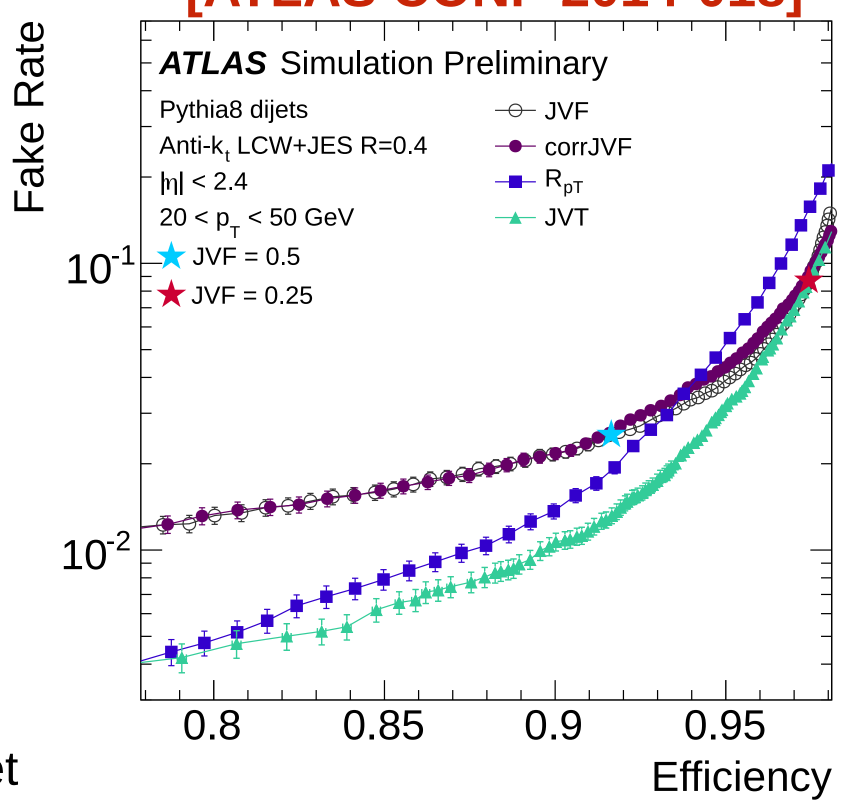
- More extreme pileup expected during Run II (w/ 25ns bunch spacing)
- New techniques being developed to cope
  - Cleansing
  - Constituent subtraction
  - Shape subtraction
  - Soft Killer
  - PileUp Per Particle Identification (PUPPI)
    - Correct for pileup at the particle level
  - Jet vertex tagger / pileup jet ID
    - Likelihoods constructed from tracking information and jet shape variables
  - …

See https://indico.cern.ch/event/306155 for details on these and other methods

[CMS PAS JME-14-001]



[ATLAS CONF-2014-018]



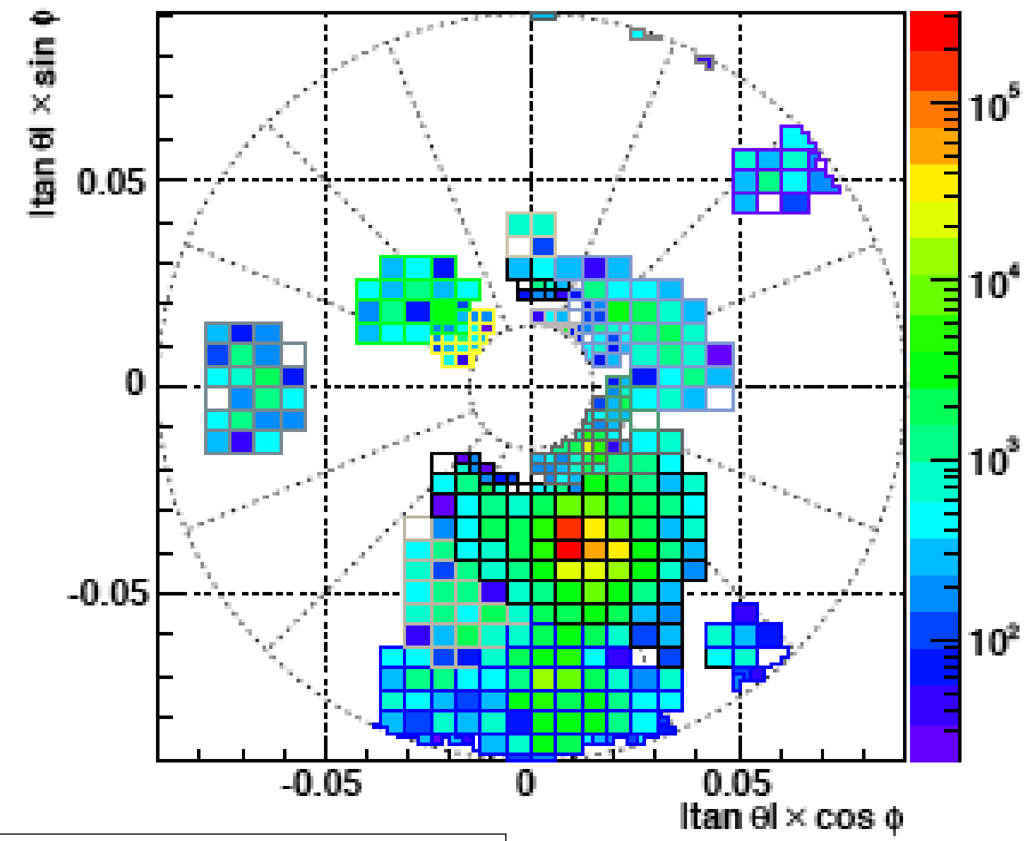
Conclusion

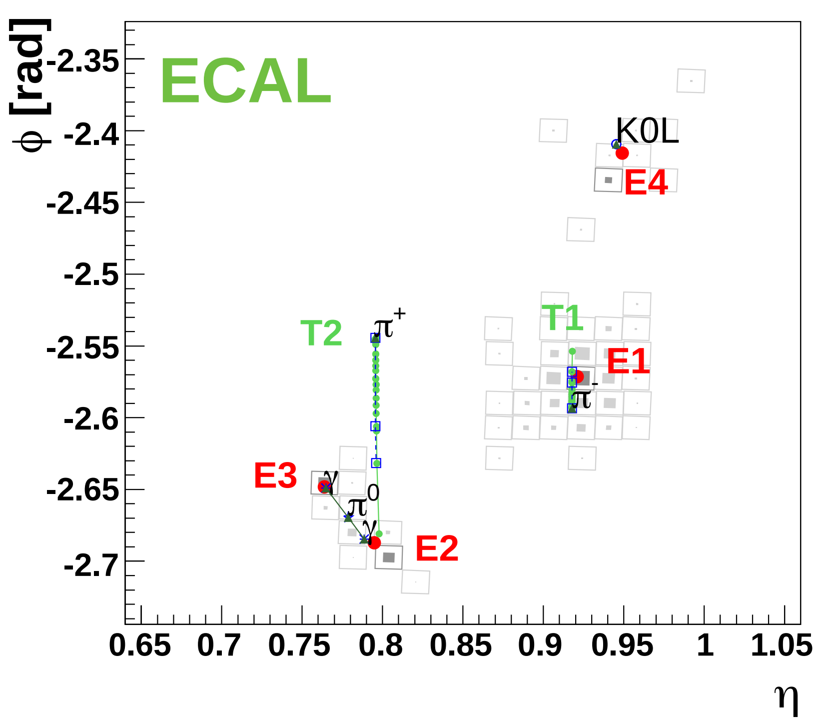
- The boosted regime and jet substructure significantly enhanced the sensitivity to new physics during Run I
  - Many strong analyses published, in addition to those presented here
  - Virtually all physics groups within ATLAS and CMS exploited boosted topologies
- With the increased energy in Run II, the boosted regime will be vital
  - Also many new challenges
    - The community is working hard to mitigate pileup effects and improve existing algorithms to maximize performance

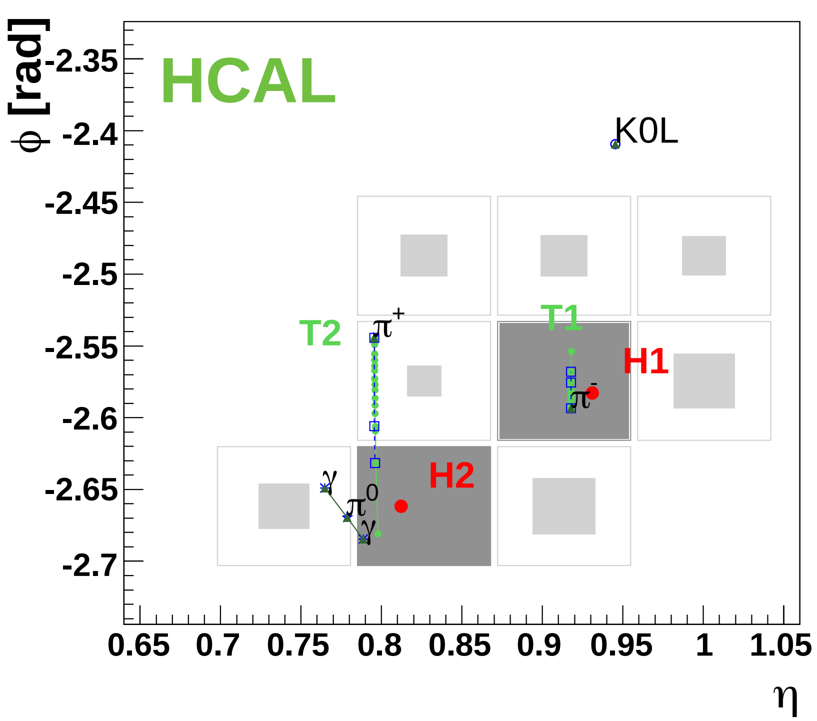
Backup

Jet Constituents

- Inputs to sequential, Iterative clustering algorithms
  - ATLAS - topological clusters
    - 3D clustering with built-in noise and pileup suppression
  - CMS - particle flow + charged hadron subtraction
    - Stable particles (e, μ, γ, $\pi^{\pm}$, π^{0}) reconstructed and identified with an optimized combination of all sub-detectors







Jet Reconstruction

- Jet constituents
  - CMS - particle flow + charged hadron subtraction
    - Reconstruct and identify all particles with an optimized combination of all sub-detectors (e, μ, γ, $\pi_{\pm}$, π_0)
  - ATLAS - topological clusters
    - 3D clustering with built-in noise and pileup suppression
- Sequential, Iterative clustering algorithms
  - Calculate the "distance" between all constituents

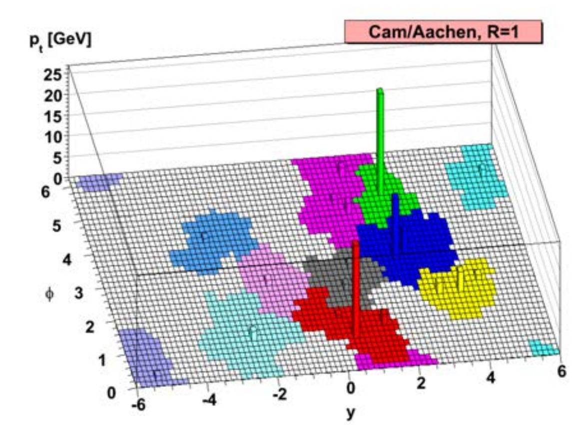
$$d_{ij} = \min(p_{T_i}^{2n}, p_{T_j}^{2n})\Delta R_{ij}^2/R^2$$

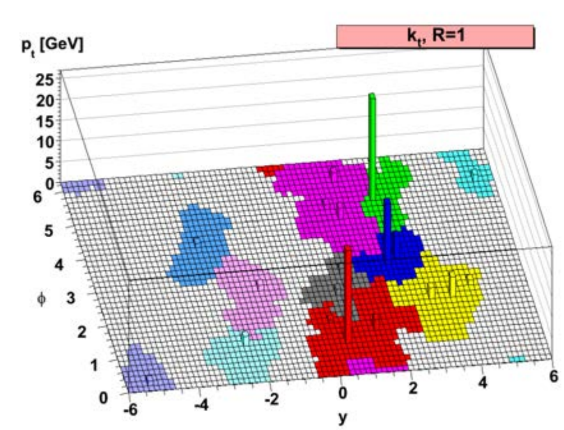
$$d_{iB} = p_{T_i}^{2n}$$

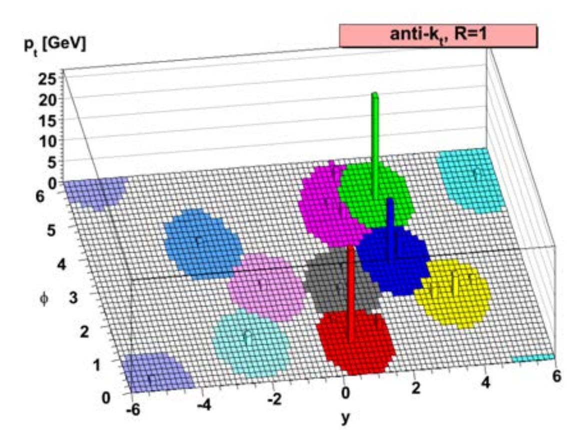
  - Merge nearest constituents
  - If for a given constituent i all $d_{ij} > d_{iB}$, classify i as a jet
  - Repeat until all constituents are clustered

n	Algorithm
1	k_T
0	Cambridge-Aachen
-1	anti-k_T

[JHEP 04 (2008) 063]

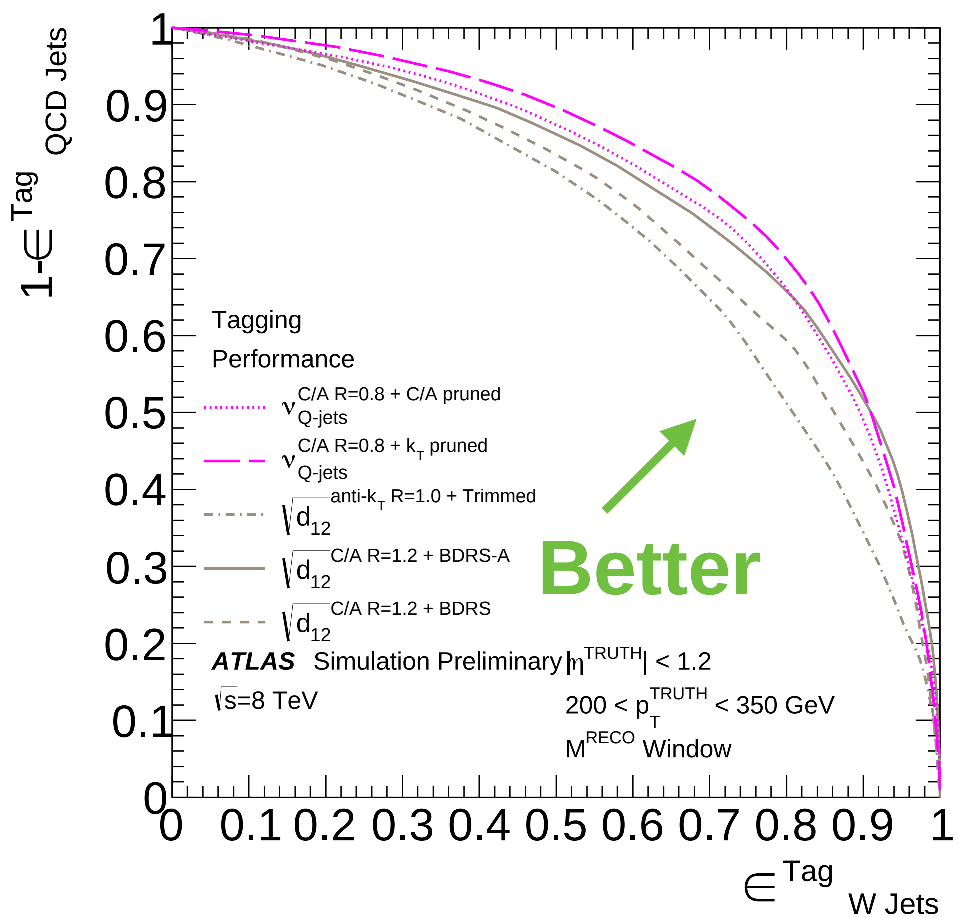


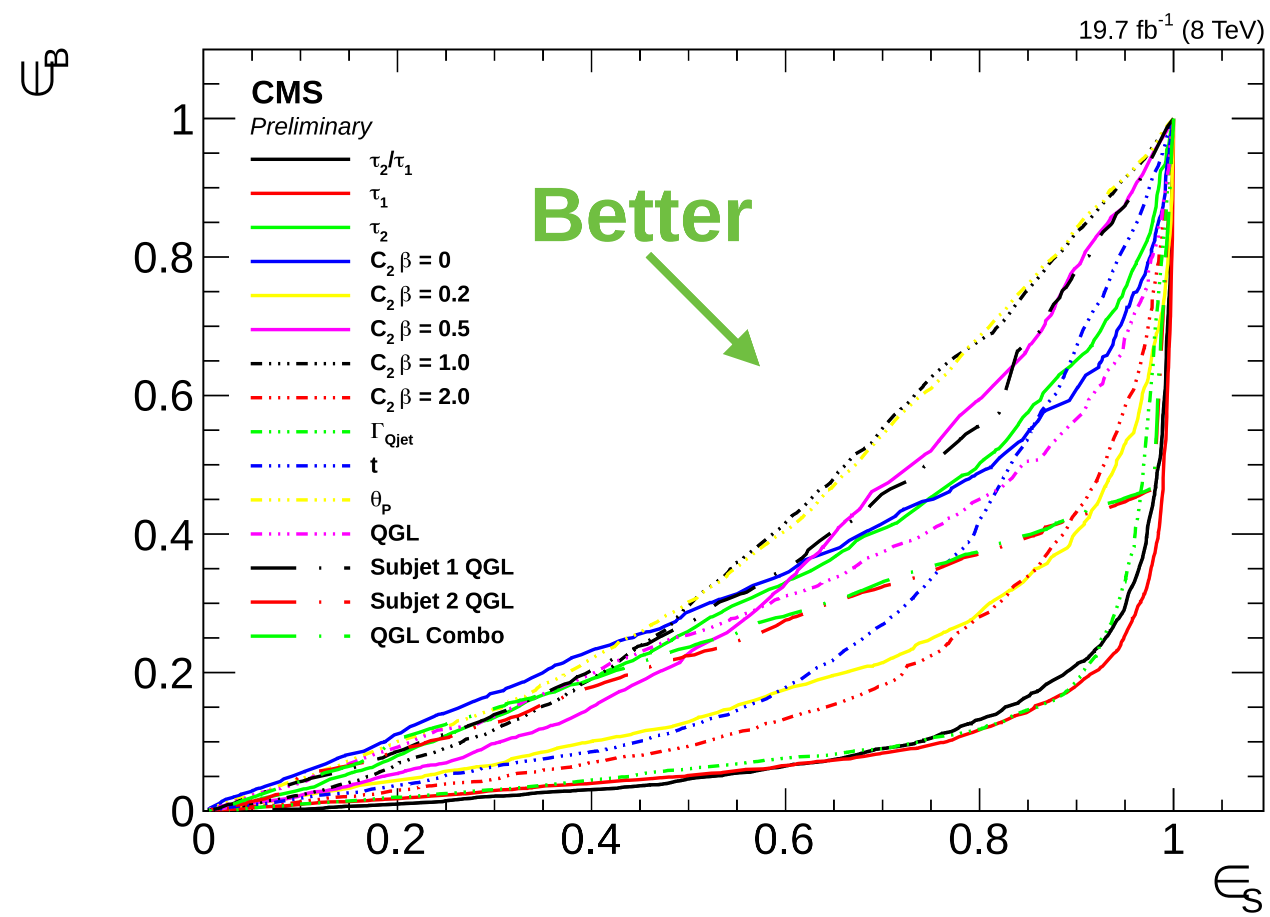




V tagging

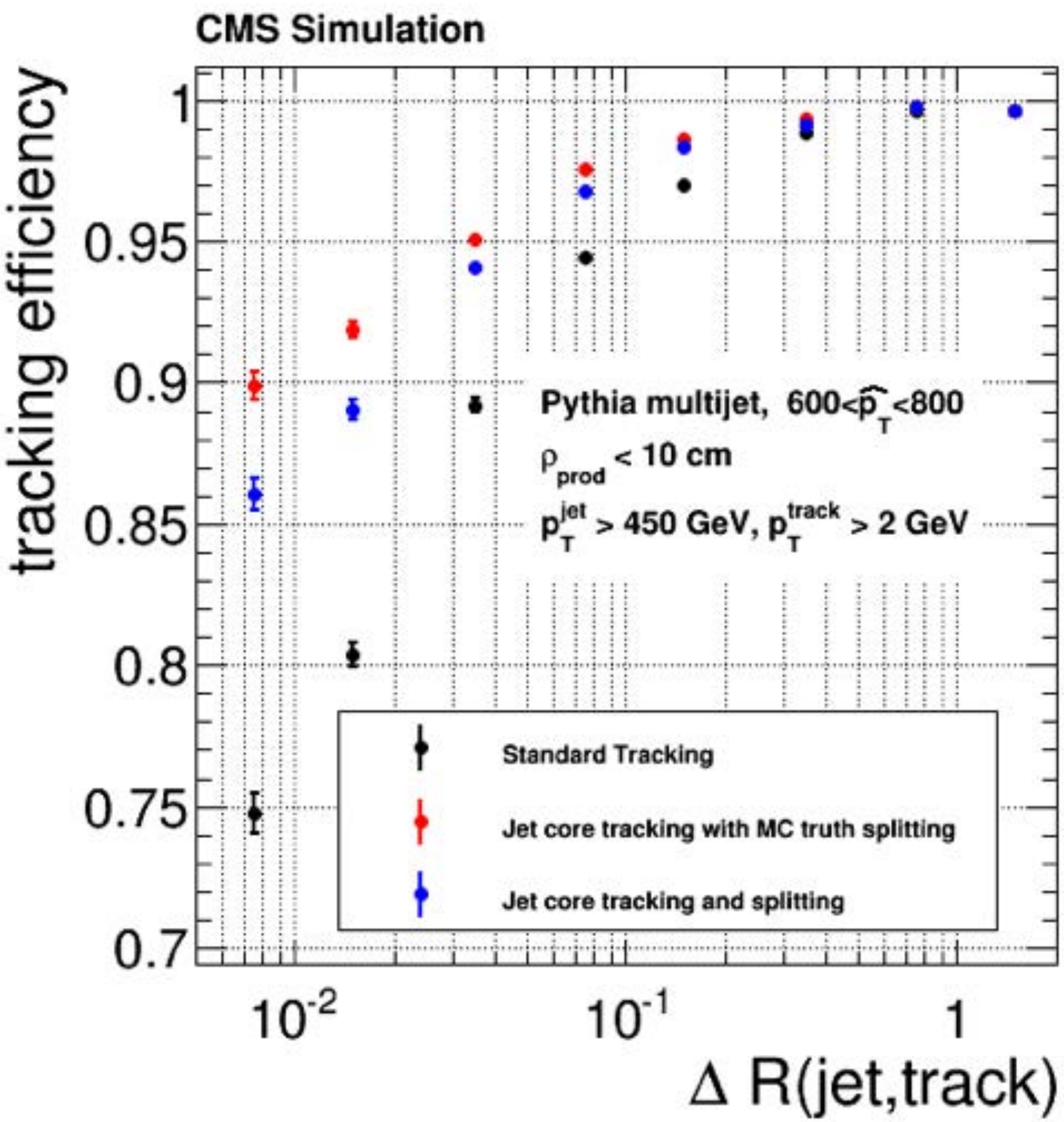
- The combination of grooming and substructure variables to identify hadronic W/Z
- Studied by both ATLAS and CMS
  - Many combinations of jet algo, groomer, and substructure techniques





Jet Core Tracking Improvements

- Additional iterative tracking step targeting the core of jets
  - Pattern recognition is performed testing in parallel a large number of possibilities
- Merged pixel cluster splitter
  - Exploit the information of the jet direction to predict the expected cluster shape and charge



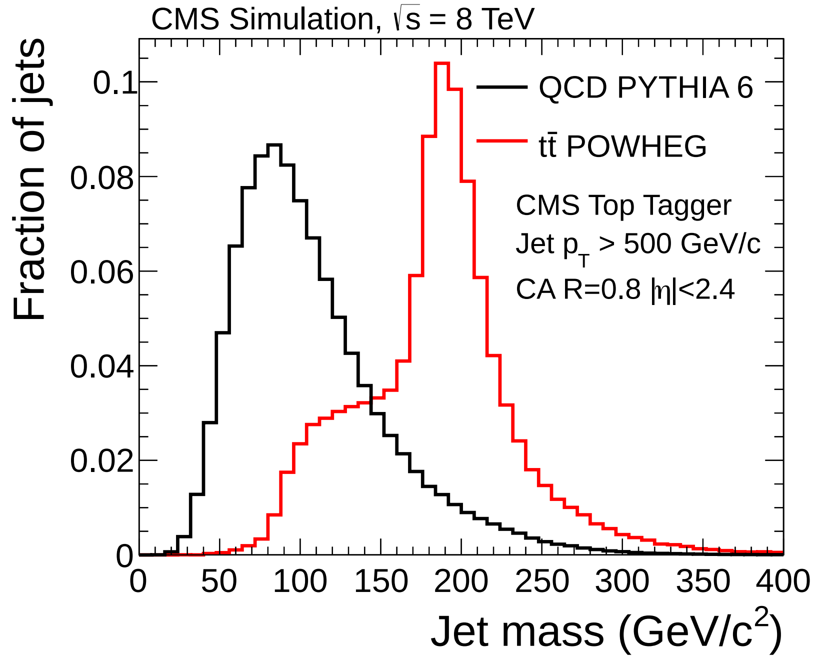
https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighPtTrackingDP

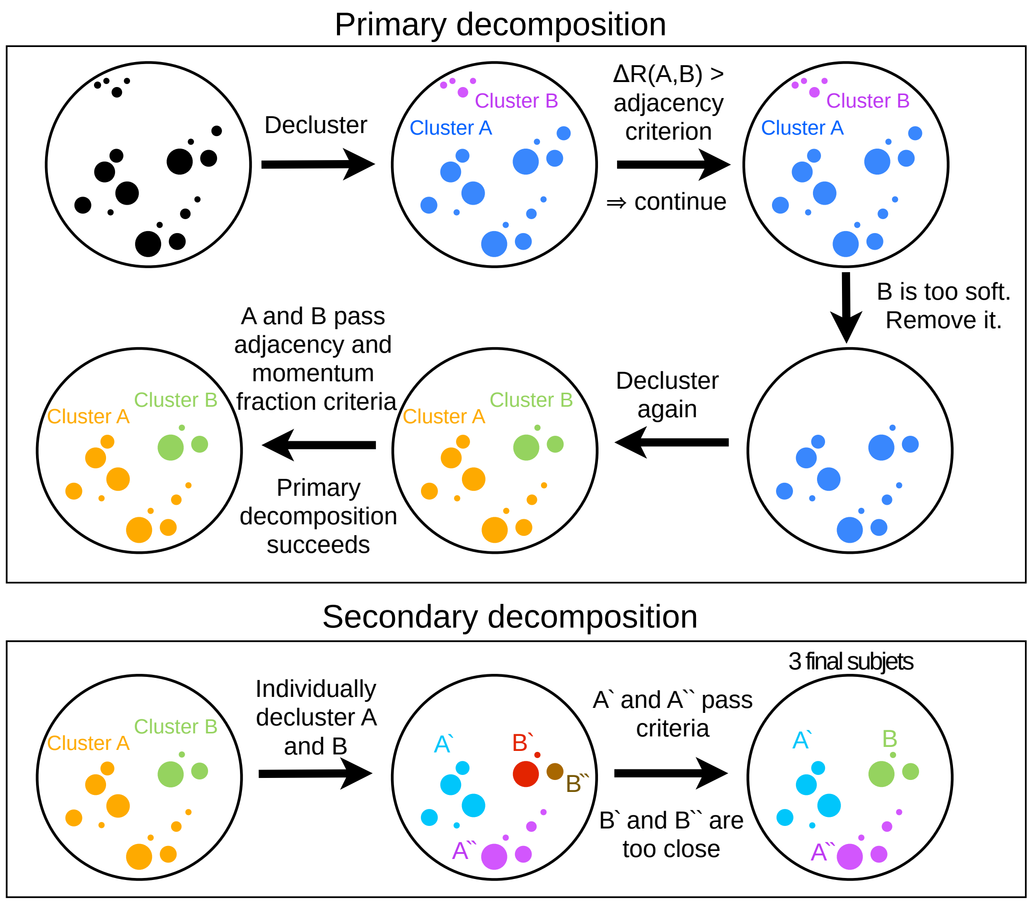
[CMS PAS JME-13-007]

CMS Top Tagger

- Optimized for jets with $p_T \gtrsim 350$ GeV
- CA R=0.8 jets
- Reverse clustering sequence
  - Find ≤4 well-separated, high p_T subjets
- Require:
  - $N_{subjets} \geq 3$
  - $m_{jet} \approx m_{top}$
  - $\min(m_{ij}) \approx m_W$

$$\Delta R_{ij} > 0.4 - 0.0004 \times p_T$$
$$p_T^{cluster} > 0.05 \times p_T^{jet}$$





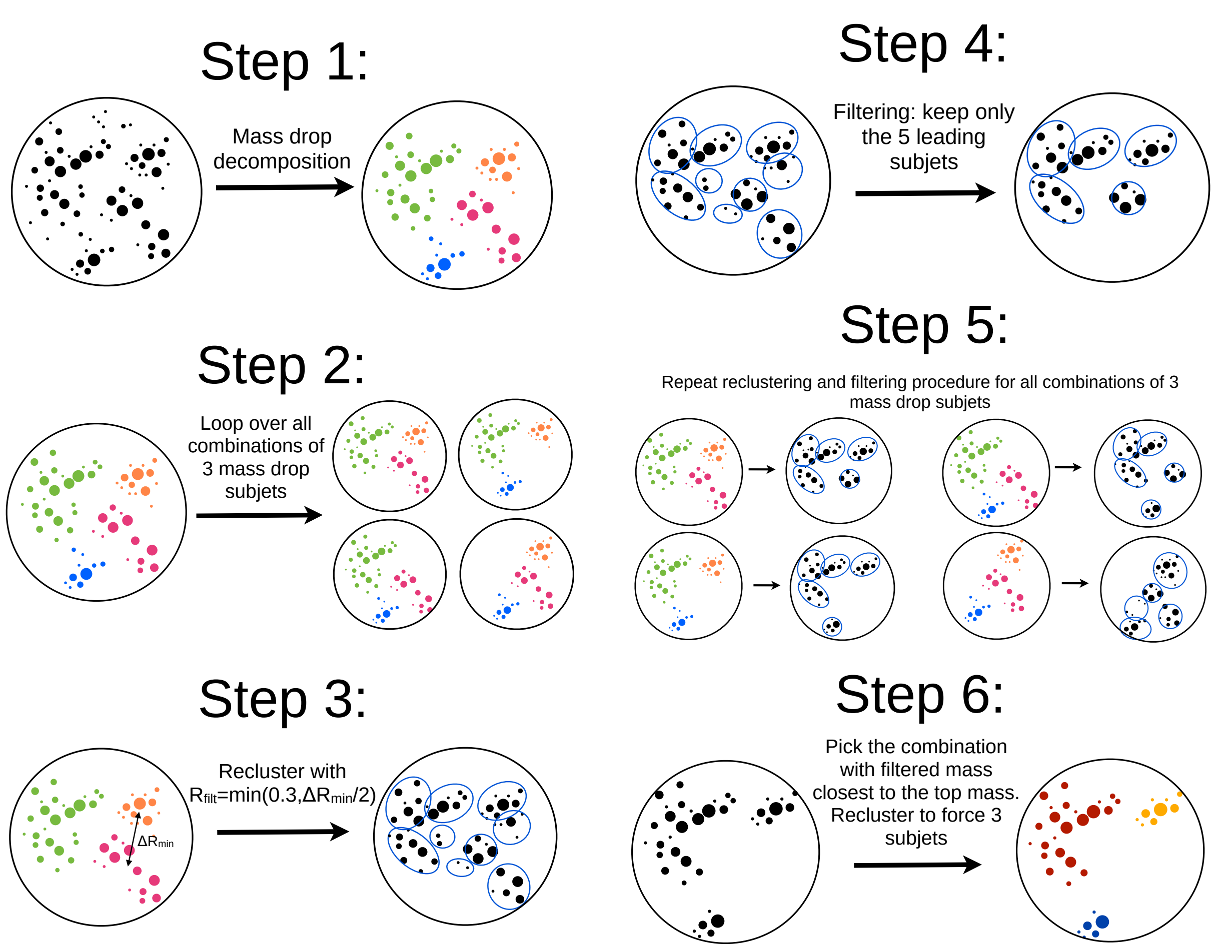
[CMS PAS JME-13-007] [ATLAS CONF-2013-084]

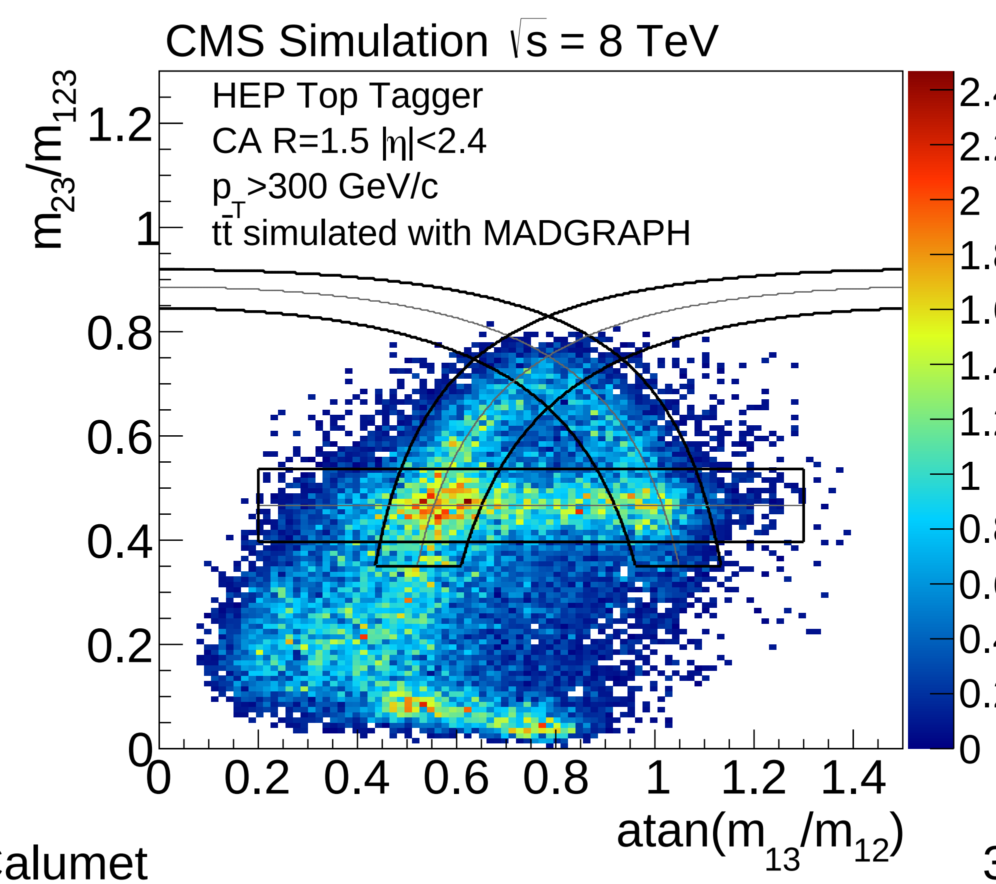
HEP Top Tagger

- Optimized for jets with $p_T \gtrsim 200$ GeV
- CA R=1.5 jets
- Mass drop decomposition + filter

$$\max(m_i, m_j) < 0.8 m_j$$

- Require:
  - $N_{subjets} \geq 3$
  - $m_{jet} \approx m_{top}$
  - $m_{ij} \approx m_W$





(Extended gauge sectors, colorons, axigluons, pseudoscalar Higgs, extra dimensions)

Brand New!

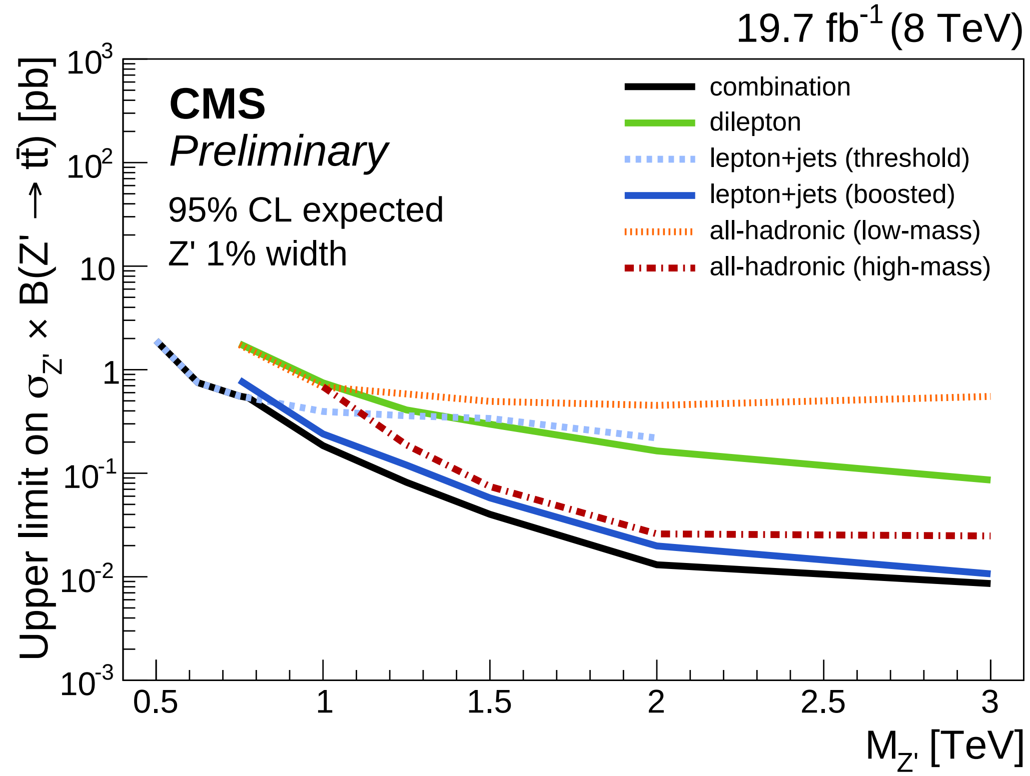
[CMS PAS B2G-13-008]

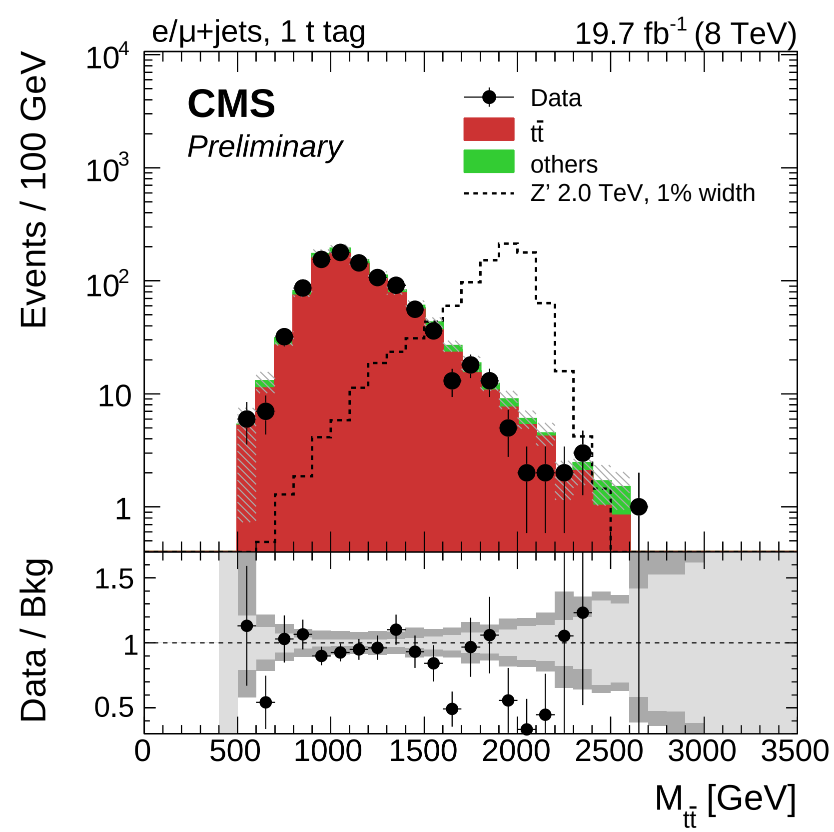
$Z' \rightarrow tt$

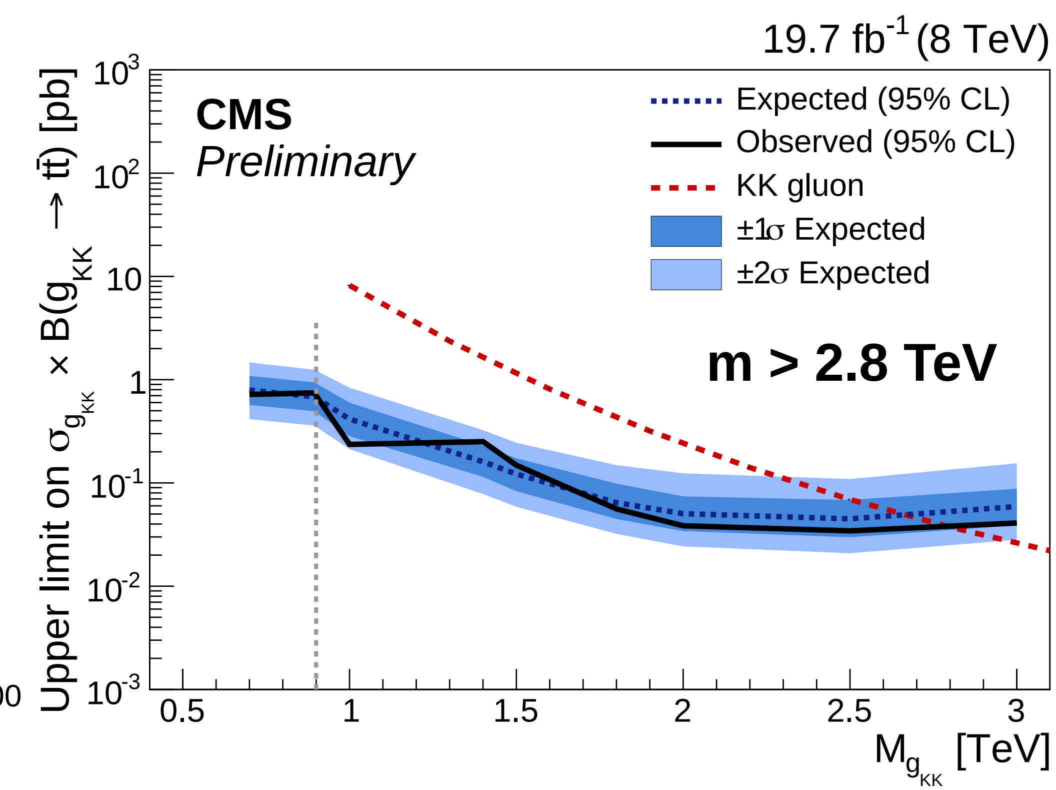
- Semi-leptonic channel (boosted analysis)
  - CMS Top Tagger + N-subjettiness + subjet b-tagging
  - Categorize events based on CMS top-tag and b-jet multiplicity
  - χ^2 based event reconstruction
  - W+jets bkgd
    - Apply SF for top mistag rate from W+jets enriched SB

$$\epsilon_{\text{mistag}}^{\text{data}} = 1.2\%$$

$$\epsilon_{\text{mistag}}^{\text{data}} / \epsilon_{\text{mistag}}^{\text{MC}} = 0.83 \pm 0.21$$



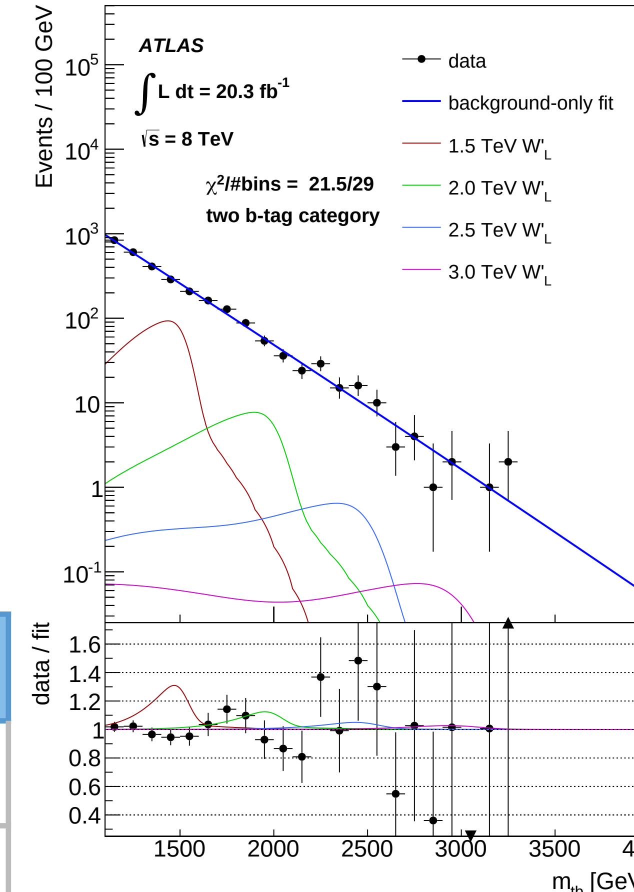




[CMS PAS B2G-12-009] [ATLAS arXiv:1408.0886]

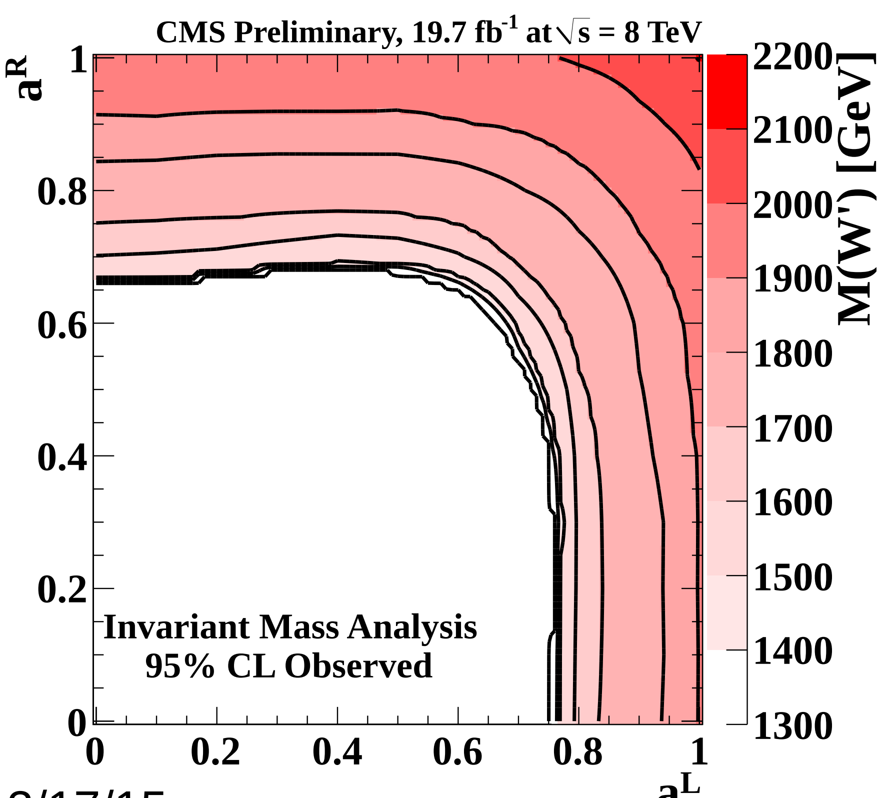
$W' \rightarrow tb$

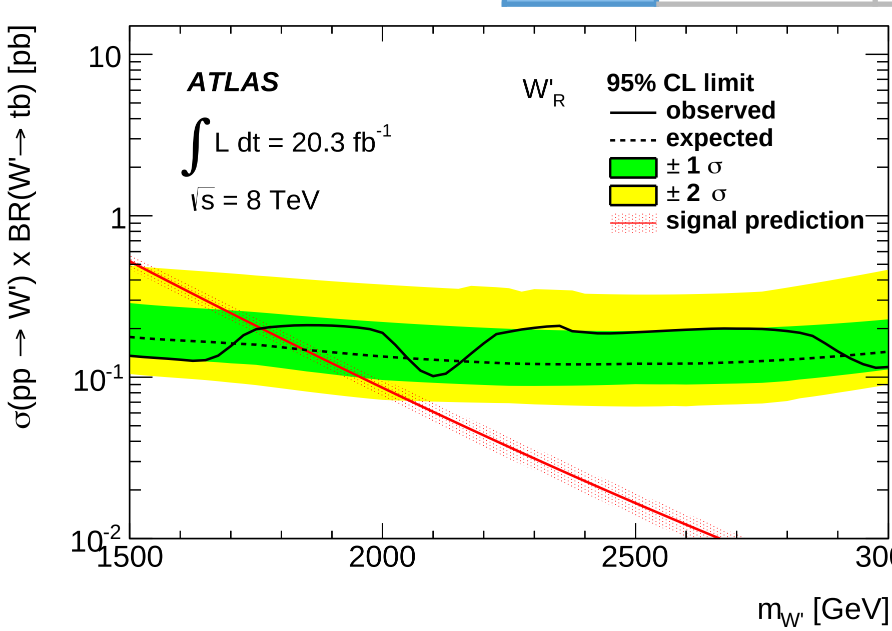
- Search for high mass tb resonance
- Top tagging
  - CMS - CMS top tagger + N-subjettiness + subjet b-tag $\sqrt{d_{12}} = \min(p_{T_1}, p_{T_2})\Delta R_{12}$
  - ATLAS - Trimming + k_T scale + N-subjettiness
- Well separated b jet

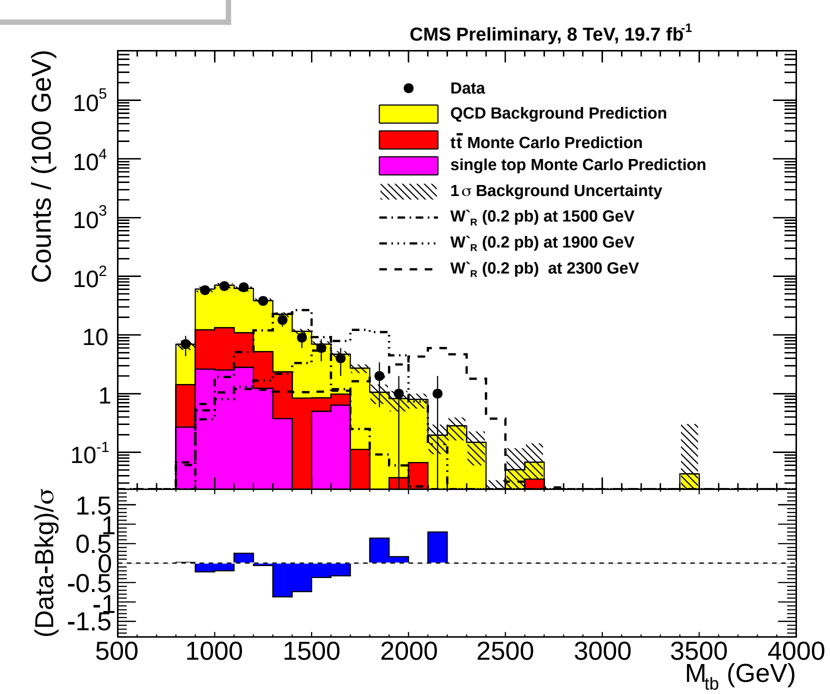


Mass Limits [TeV]

	CMS	ATLAS
W_R	2.02	1.76
W_L	1.94	1.68



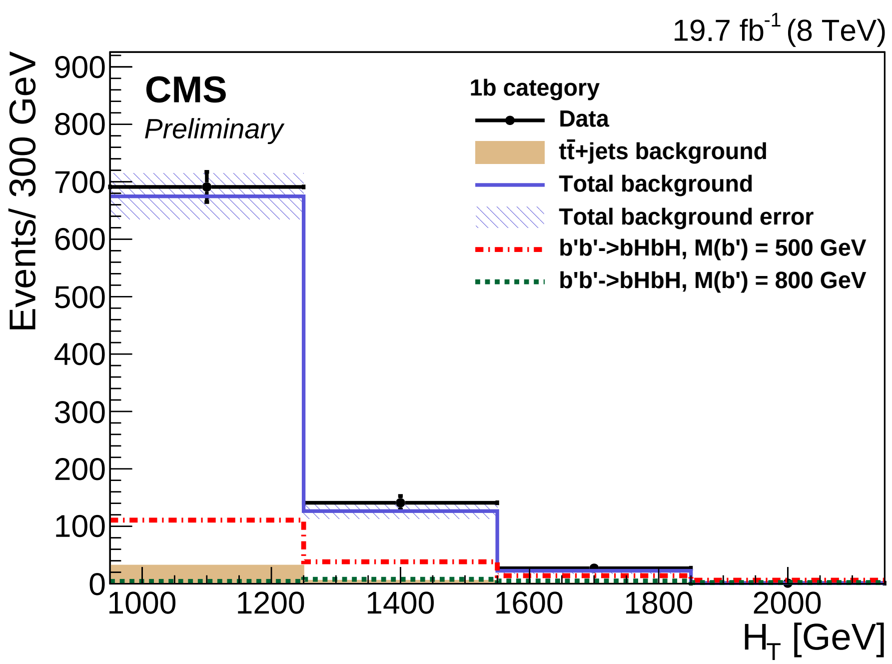


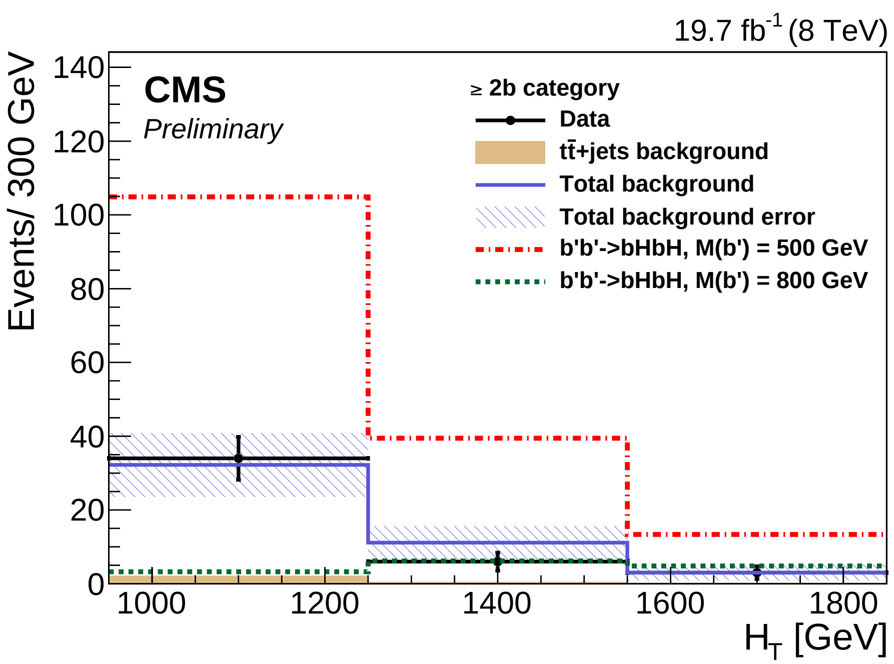


$B' \rightarrow bH(bb)$

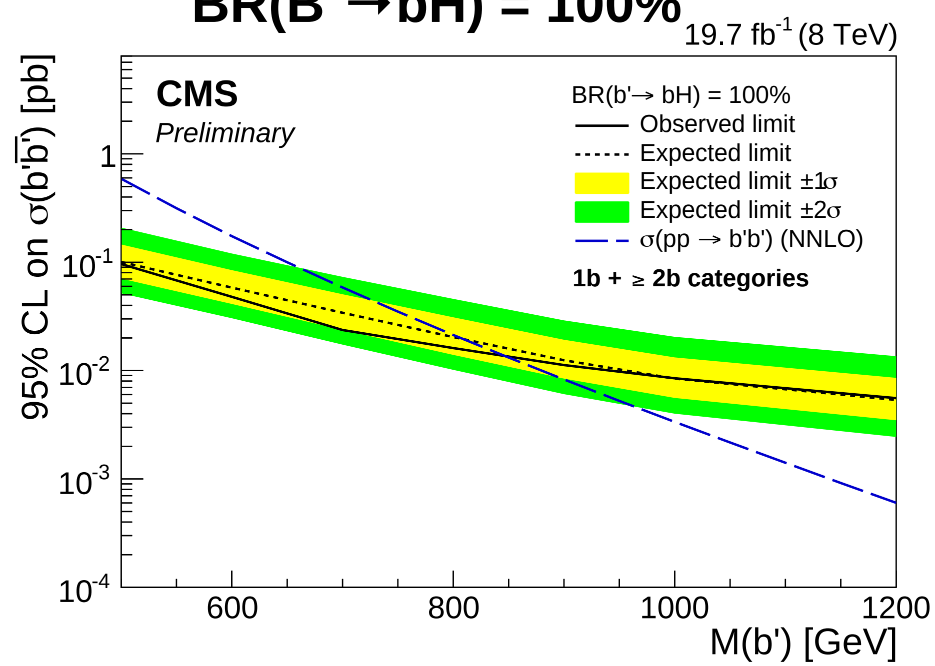
[CMS PAS B2G-14-001]

- Search for pair production of bH resonance
- Higgs tagging - Pruned R=0.8 jet with 90 < m < 140 GeV + N-subjettiness + double subjet b-tag
- Categorize events based on the number of additional b jets
  - Test for presence of signal with H_T





m > 846 GeV for BR($B' \rightarrow bH$) = 100%



$\ell^* \to \ell\gamma / \ell Z$

[CMS PAS EXO-14-015]

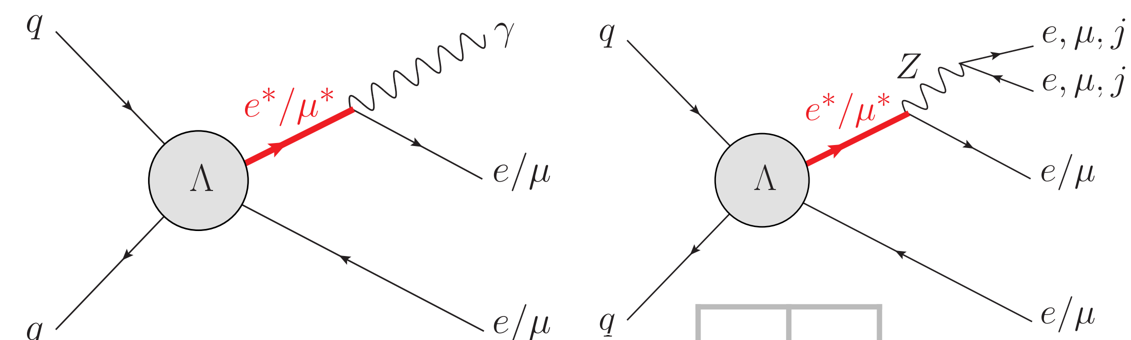
- Search for excited leptons through contact interactions

Production:

$$\mathcal{L}_{CI} = \frac{g_*^2}{2\Lambda^2} j^\mu j_\mu$$

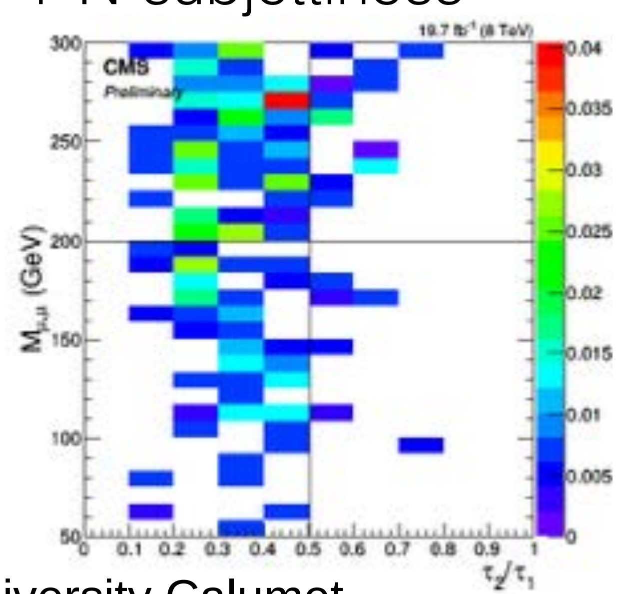
Decay:

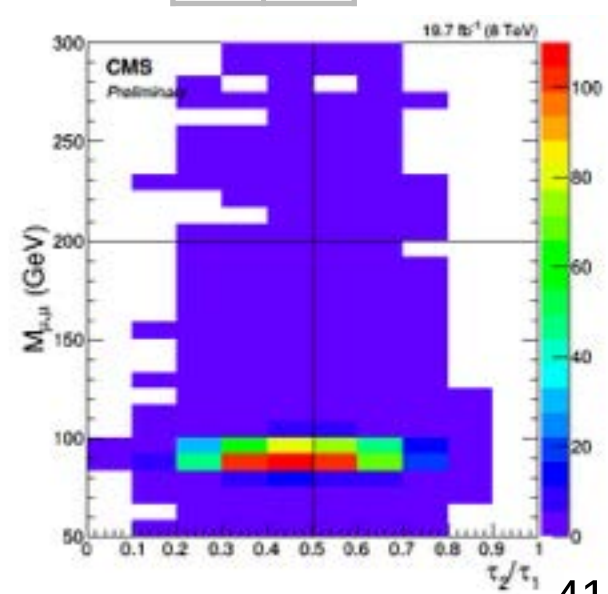
$$\mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left(g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) f_L + h.c.$$



- $2\ell+\gamma$, 4ℓ, and 2ℓ+J final states
- 2ℓ+J search
  - Trigger - double electron or double muon trigger
  - Z tag
    - Pruned R = 0.8 jet with 70 < m < 110 GeV + N-subjettiness
      - Data/MC scale factor of 0.9 ± 0.1
  - $m_{\ell\ell} > 200$ GeV
  - Background modeled with ABCD method
    - $m_{\ell\ell}$ and τ_{21}

A	C
B	D



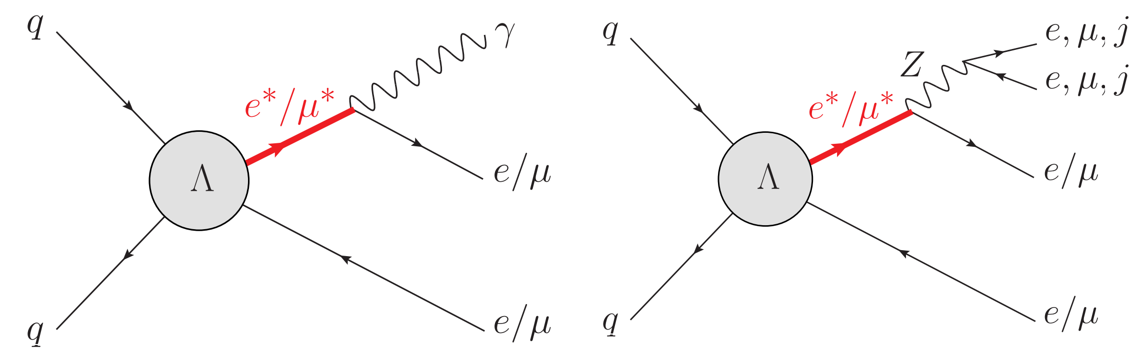


Brand New!

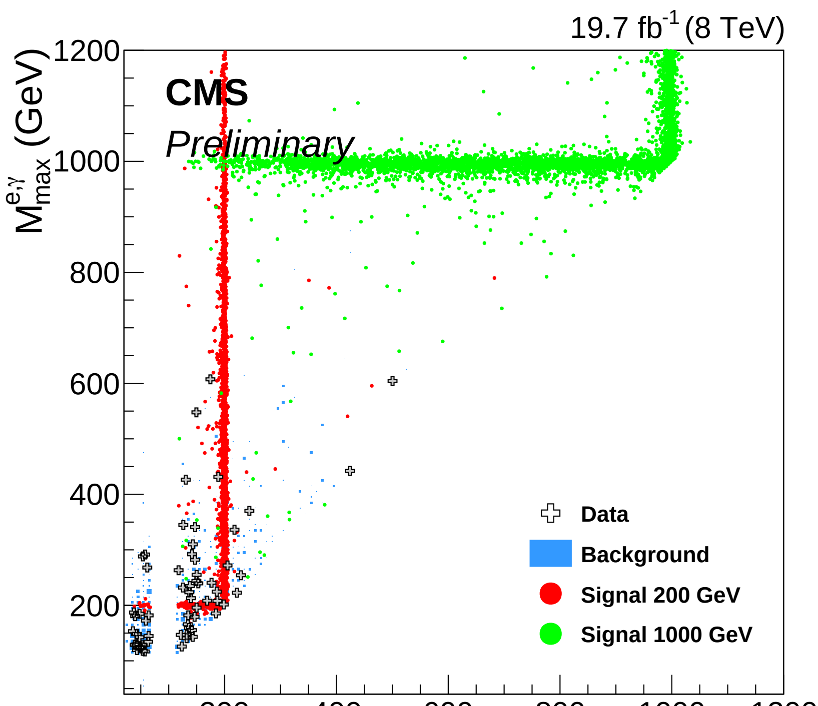
$\ell^* \rightarrow \ell\gamma/\ell Z$

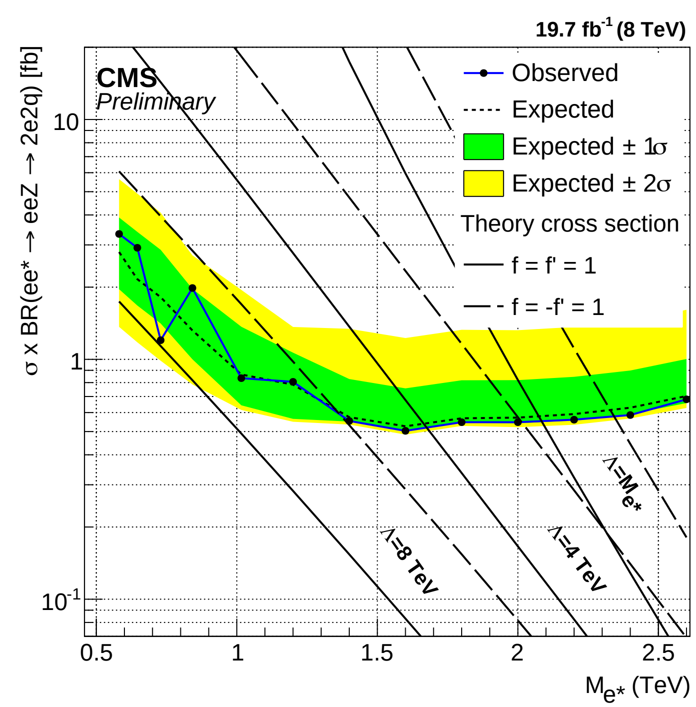
[CMS PAS EXO-14-015]

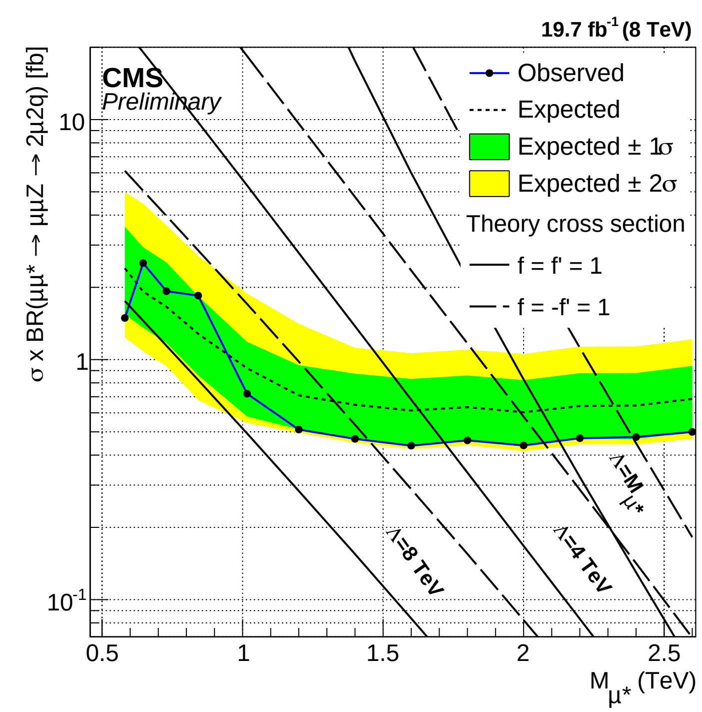
- Search for excited leptons through contact interactions
- 2ℓ+J search
    - Pair Z with remaining leptons to form 2 ℓ^* candidates
    - Apply mass-dependent L-shaped cut



Search channel	$M^*_\ell = \Lambda$, values in TeV f = f′ = 1	f = -f′ = 1
$ee^* \rightarrow ee\gamma$	2.45 (2.45)	-
$ee^* \rightarrow eeZ \rightarrow$2e2j	2.10 (2.10)	2.35 (2.35)
$ee^* \rightarrow eeZ \rightarrow$4e	1.55 (1.55)	1.80 (1.80)
$ee^* \rightarrow eeZ \rightarrow 2e2\mu$	1.60 (1.60)	1.85 (1.85)
$ee^* \rightarrow eeZ \rightarrow 2e2\ell$	1.70 (1.70)	1.95 (1.95)
$\mu\mu^* \rightarrow \mu\mu\gamma$	2.48 (2.40)	-
$\mu\mu^* \rightarrow \mu\mu Z \rightarrow 2\mu 2j$	2.10 (2.05)	2.38 (2.30)
$\mu\mu^* \rightarrow \mu\mu Z \rightarrow 4\mu$	1.65 (1.65)	1.90 (1.90)
$\mu\mu^* \rightarrow \mu\mu Z \rightarrow 2\mu 2e$	1.60 (1.60)	1.85 (1.85)
$\mu\mu^* \rightarrow \mu\mu Z \rightarrow 2\mu 2\ell$	1.75 (1.75)	2.00 (2.00)





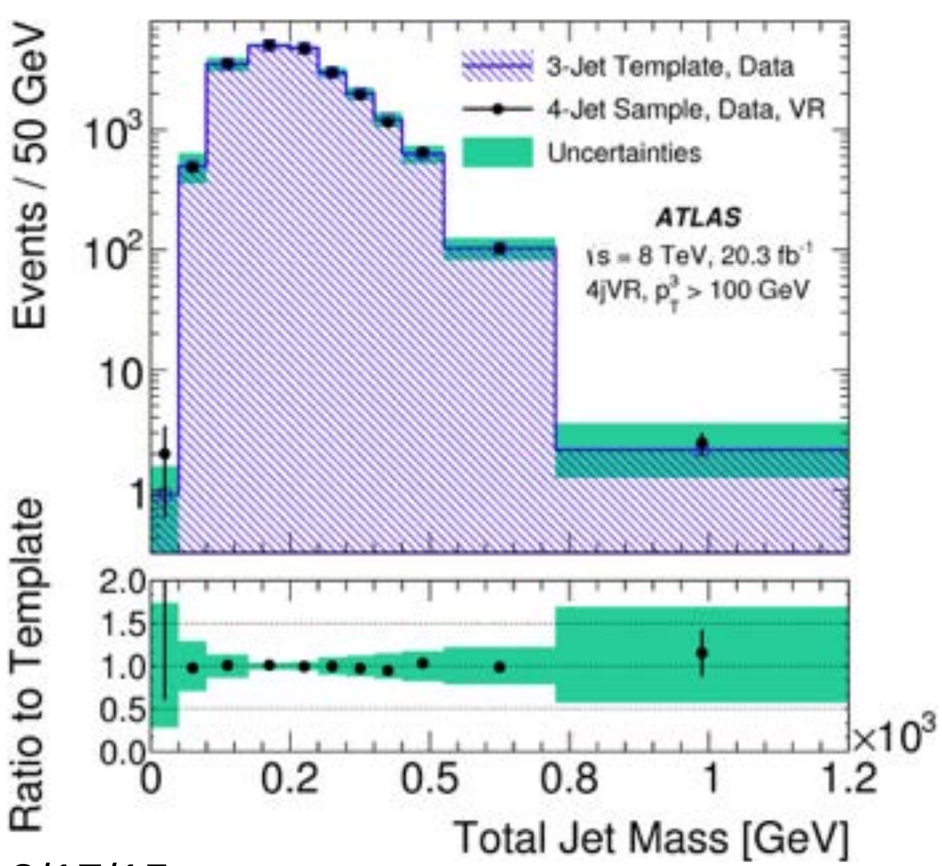


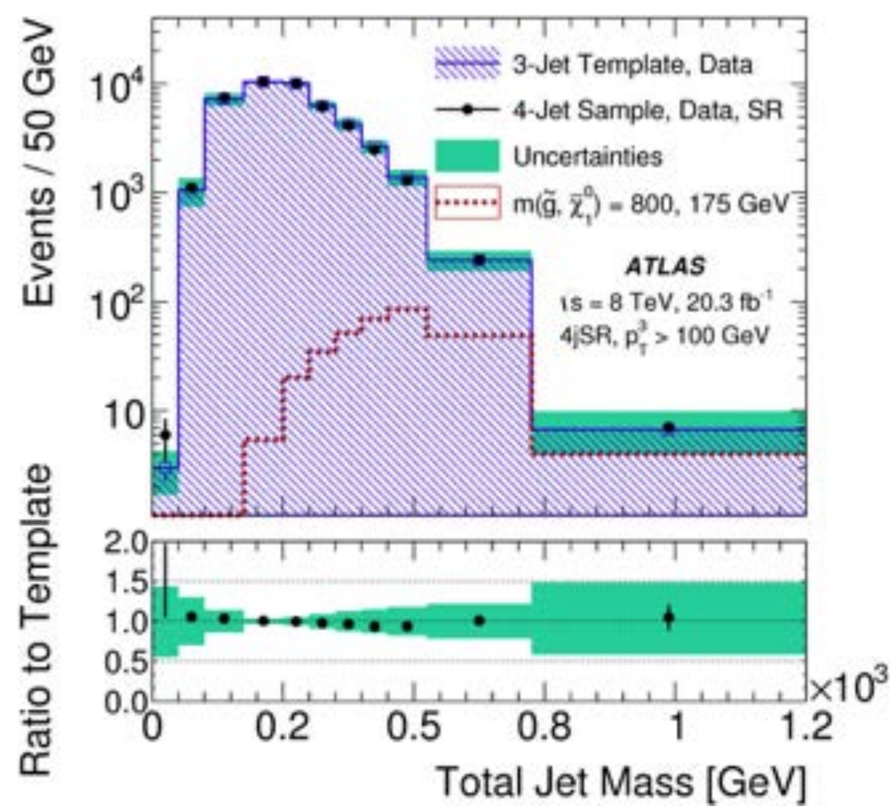
Brand New!

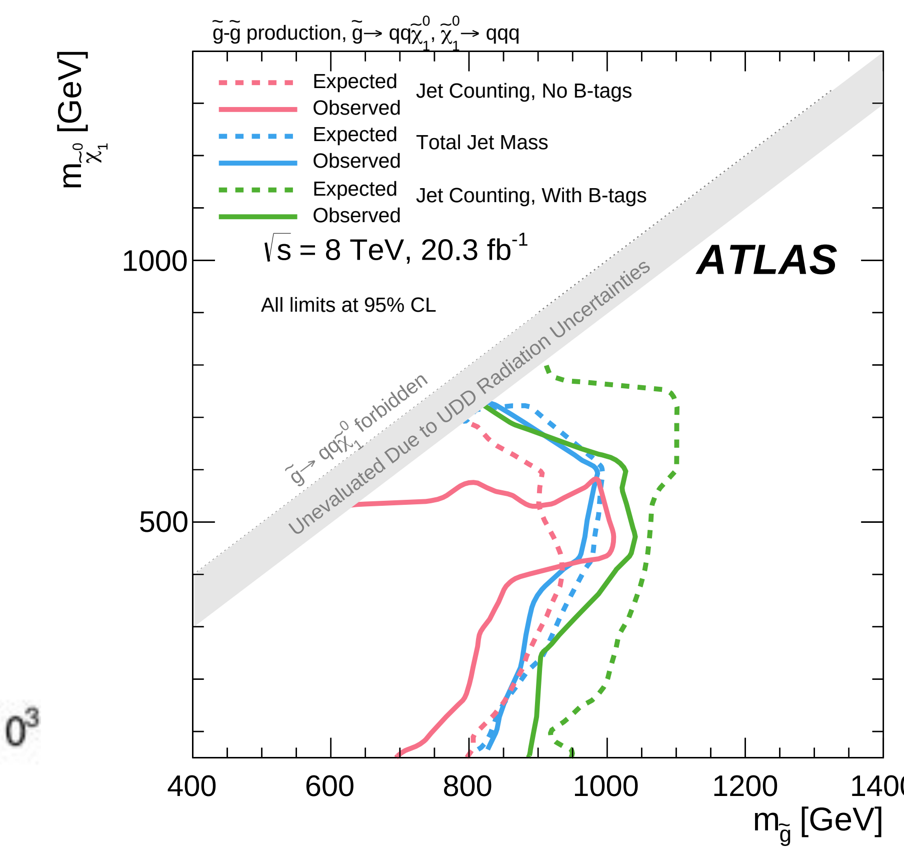
RPV SUSY

[ATLAS arXiv:1502.05686]

- Total jet mass analysis
  - Background modeling - “template method”
    - p_T- and η-dependent m_j probability density functions derived in 3-jet CR
    - Convolve PDFs with data in the SR → m_J^{Σ} background prediction
    - Validate in 4-jet CR with large $|\Delta\eta_{12}|$

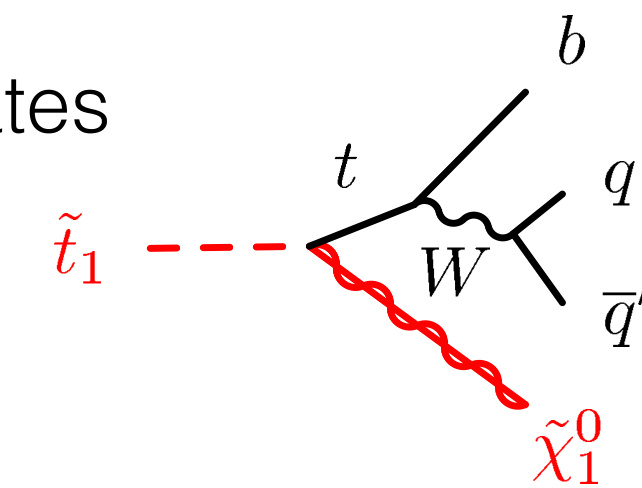




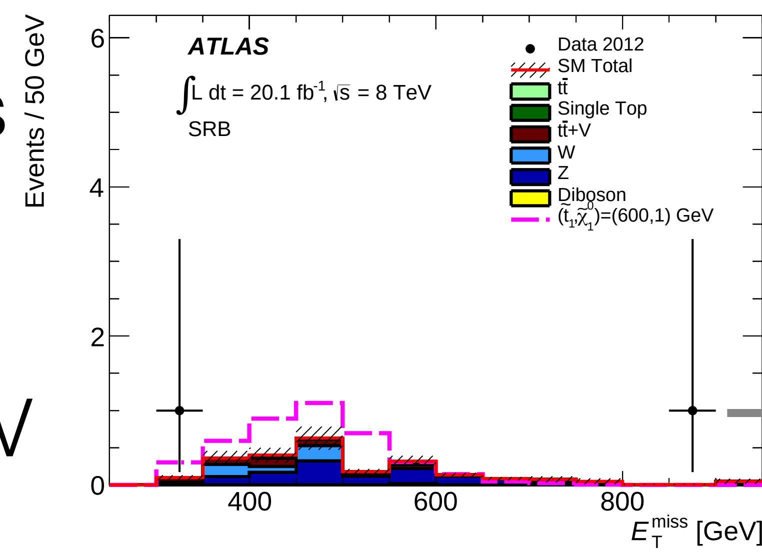


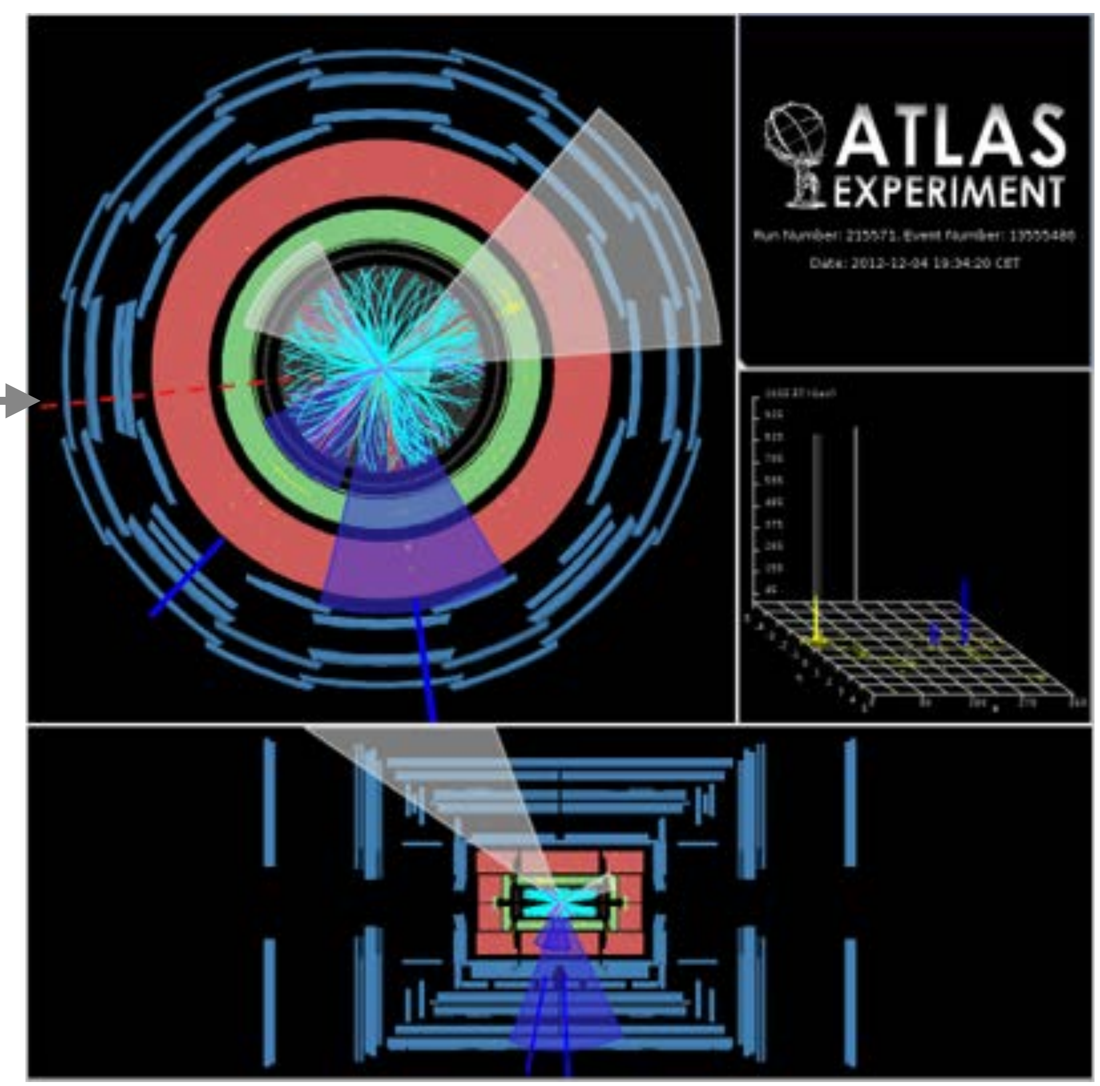
Stop

- Searches in fully hadronic and single lepton final states
  - Each contains 1 SR targeting boosted regime



- Fully hadronic
  - ≥5/6 R=0.4 jets
    - ≥2 b-tagged
  - MET > 150 GeV



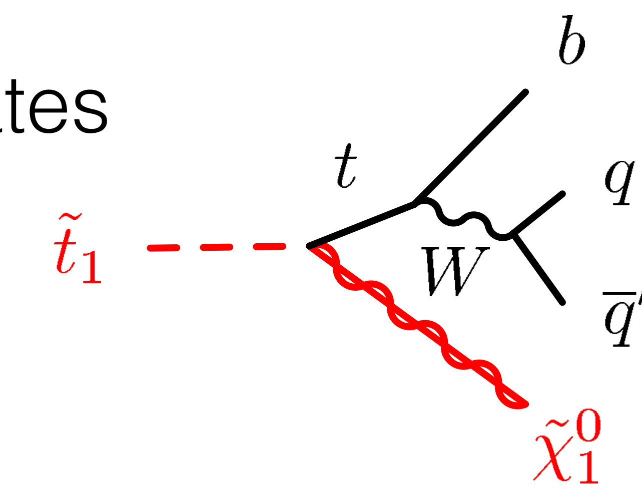


	SRB1	SRB2
anti-k_t $R = 0.4$ jets	4 or 5, $p_T > 80, 80, 35, 35, (35)$ GeV	5, $p_T > 100, 100, 35, 35, 35$ GeV
$\mathcal{A}_{m_t}$	< 0.5	> 0.5
$p^0_{T,\text{jet},\,R=1.2}$	–	> 350 GeV
$m^0_{\text{jet},\,R=1.2}$	> 80 GeV	$[140, 500]$ GeV
$m^1_{\text{jet},\,R=1.2}$	$[60, 200]$ GeV	–
$m^0_{\text{jet},\,R=0.8}$	> 50 GeV	$[70, 300]$ GeV
m_T^{min}	> 175 GeV	> 125 GeV
m_T (jet^3, $\mathbf{p}_T^{\text{miss}}$)	> 280 GeV for 4-jet case	–
$E_T^{\text{miss}}/\sqrt{H_T}$	–	$> 17\sqrt{\ }$ GeV
E_T^{miss}	> 325 GeV	> 400 GeV

[ATLAS JHEP 09 (2014) 015] [ATLAS JHEP 11 (2014) 118]

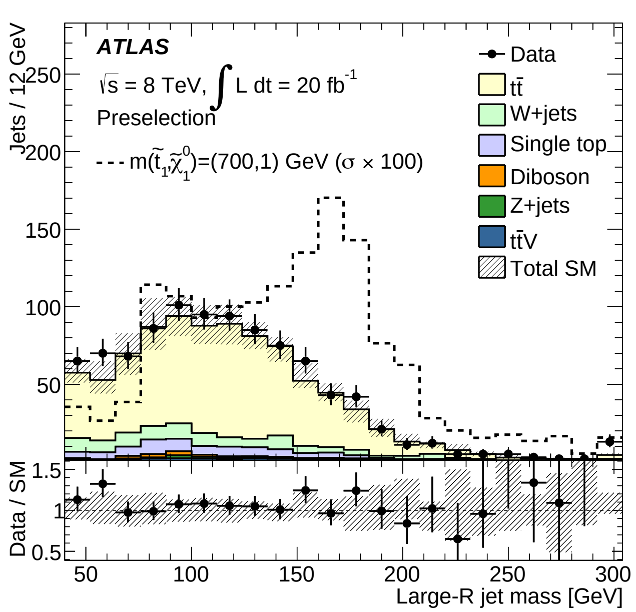
Stop

- Searches in fully hadronic and single lepton final states
  - Each contains 1 SR targeting boosted regime

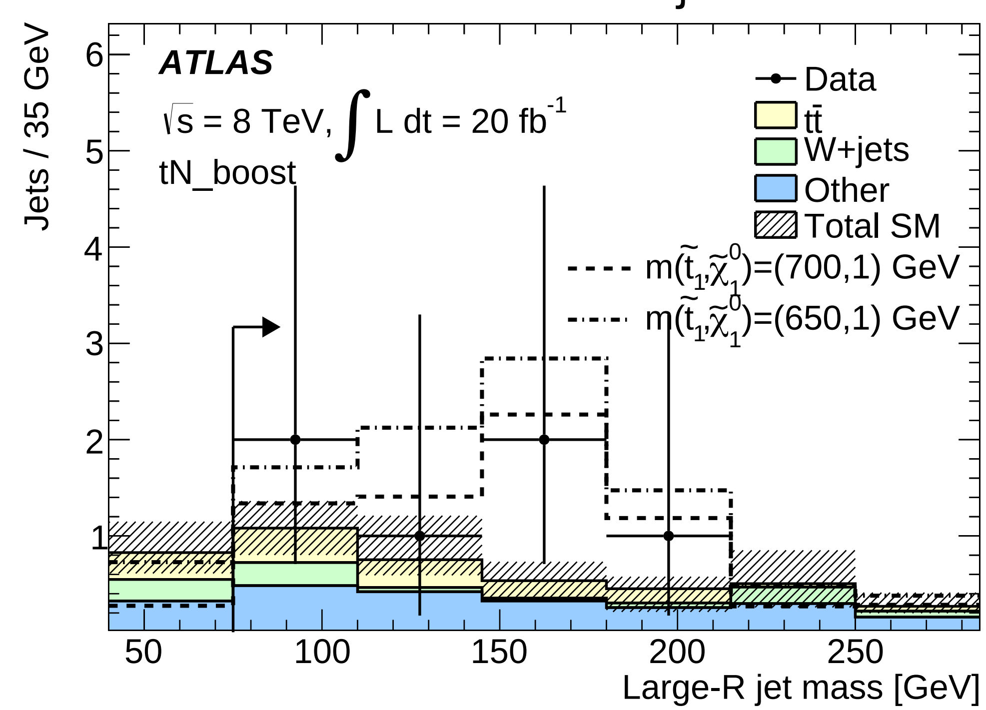


- Single lepton
  - ≥4 R=0.4 jets
    - ≥1 b-tagged
  - MET > 350 GeV

tN_boost	e ε	μ ε
No requirements	100.00%	100.00%
Trigger	95.31%	95.31%
Event DQ	94.07%	94.07%
Lepton (exactly 1 baseline)	33.75%	33.75%
Lepton (exactly 1 signal)	11.41%	11.41%
≥ 4 jets (75, 65, 40, 25) GeV	7.74%	7.74%
$\Delta\phi(\text{jet}_{1,2}, \vec{p}_{\mathrm{T}}^{\,\text{miss}}) > 0.5, 0.3$	7.36%	7.36%
≥ 1 b-tag in 4 leading jets	5.81%	5.81%
$E_{\mathrm{T}}^{\text{miss}} > 315$ GeV	2.92%	2.92%
$m_{\mathrm{T}} > 175$ GeV	2.65%	2.65%
≥ 1 large-R jet, $p_{\mathrm{T}} > 270$ GeV and jet mass > 75 GeV	2.20%	2.20%
$\Delta\phi$ (2nd large$-R$ jet, $\vec{p}_{\mathrm{T}}^{\,\text{miss}}$) > 0.85	2.15%	2.15%
τ veto*	2.02%	2.02%
$\min(\Delta R(\text{signal lepton}, b\text{−jet})) < 2.6$	2.02%	2.02%
topness > 7	1.79%	1.79%
$am_{T2} > 145$ GeV	1.73%	1.73%
$H_{\mathrm{T,sig}}^{\text{miss}} > 10$	1.72%	1.72%



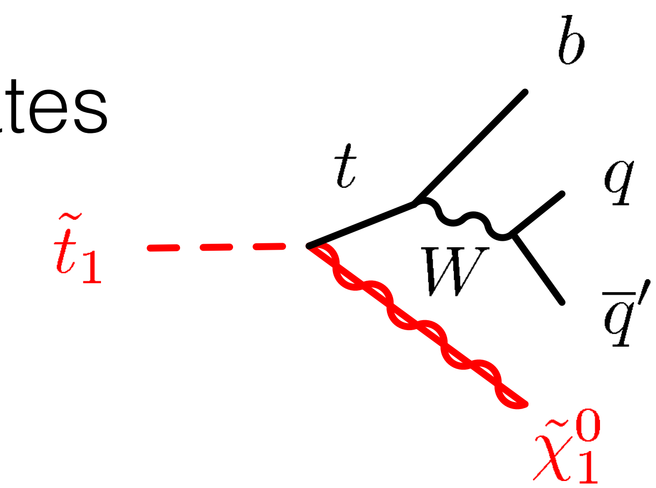
Trimmed R=1 jets



[ATLAS JHEP 09 (2014) 015] [ATLAS JHEP 11 (2014) 118]

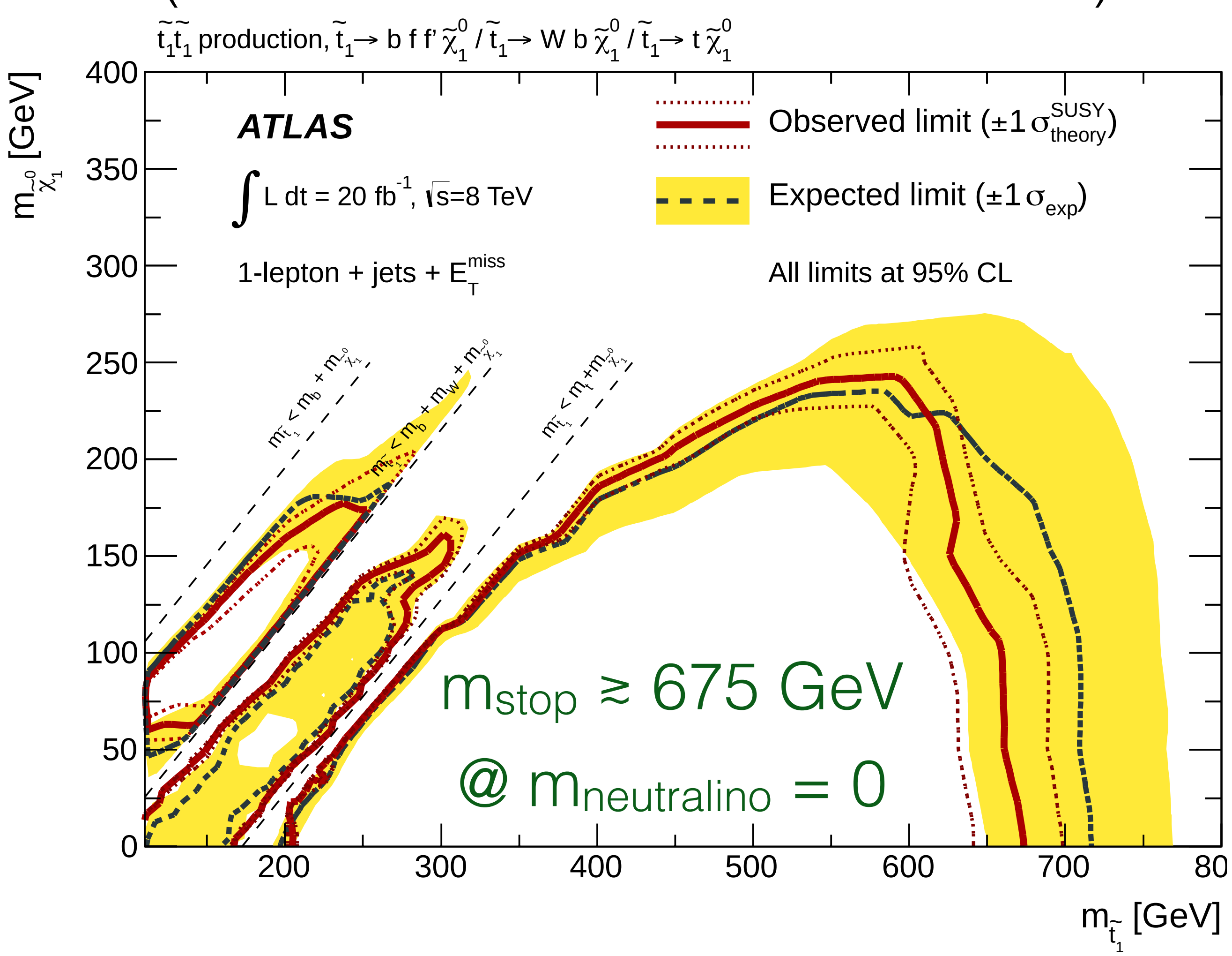
Stop

- Searches in fully hadronic and single lepton final states
  - Each contains 1 SR targeting boosted regime

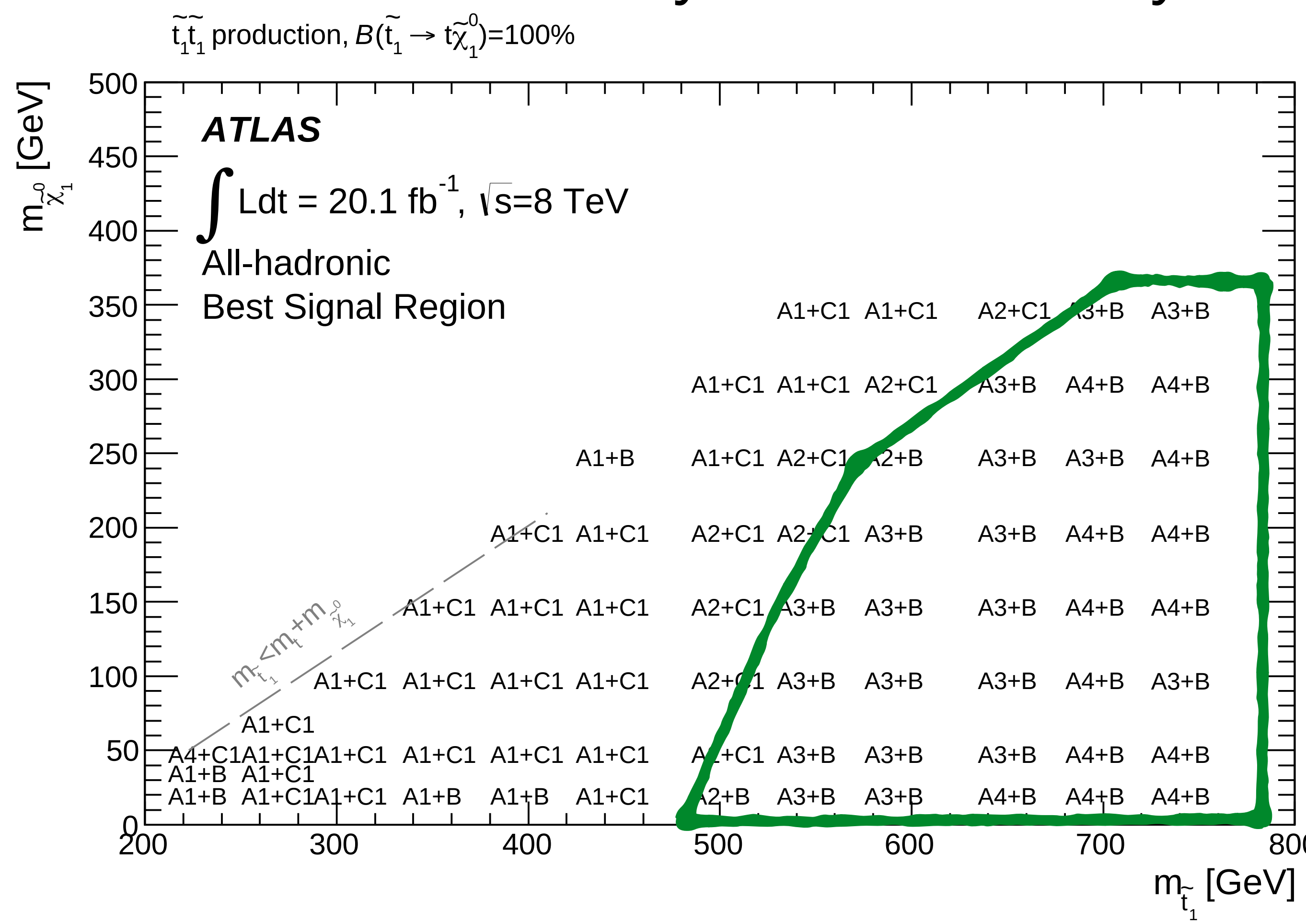


Single lepton analysis

(similar results in hadronic channel)



Hadronic analysis sensitivity



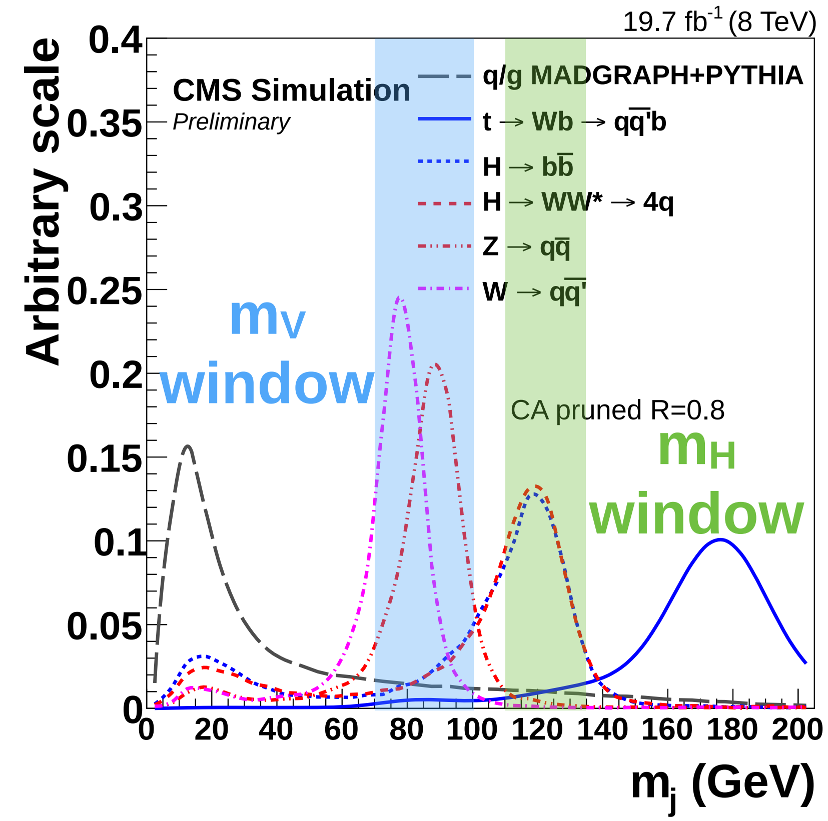
(Little Higgs, composite Higgs, 2HDM)

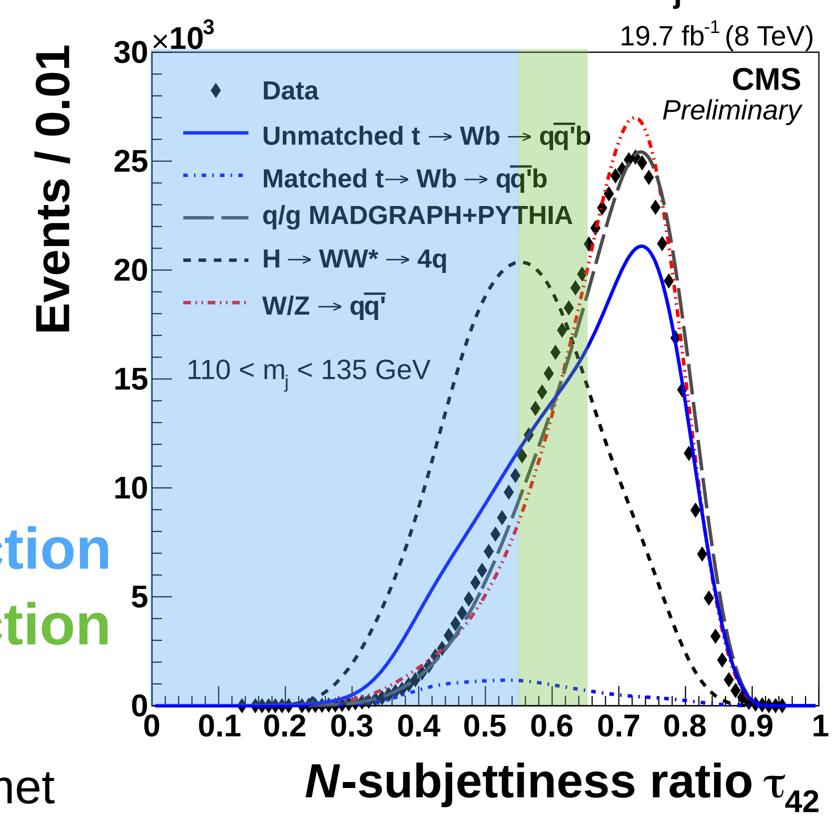
Brand New!

VH Resonance

[CMS PAS EXO-14-009]

- First search for VH resonance in all hadronic final state
  - With H→bb/H→WW*→4q and V→qq
- First attempt to reconstruct boosted H→4q decays
- H_T and dijet mass triggers
- Pruned R=0.8 jets used for H→bb/4q and V→qq tagging
  - + N-subjettiness (H→4q: τ_{42}, V→qq:τ_{21})
  - + Sub-jet/fatjet b-tagging (H→bb)
- Categorize events based on H decay mode and V purity





High purity selection

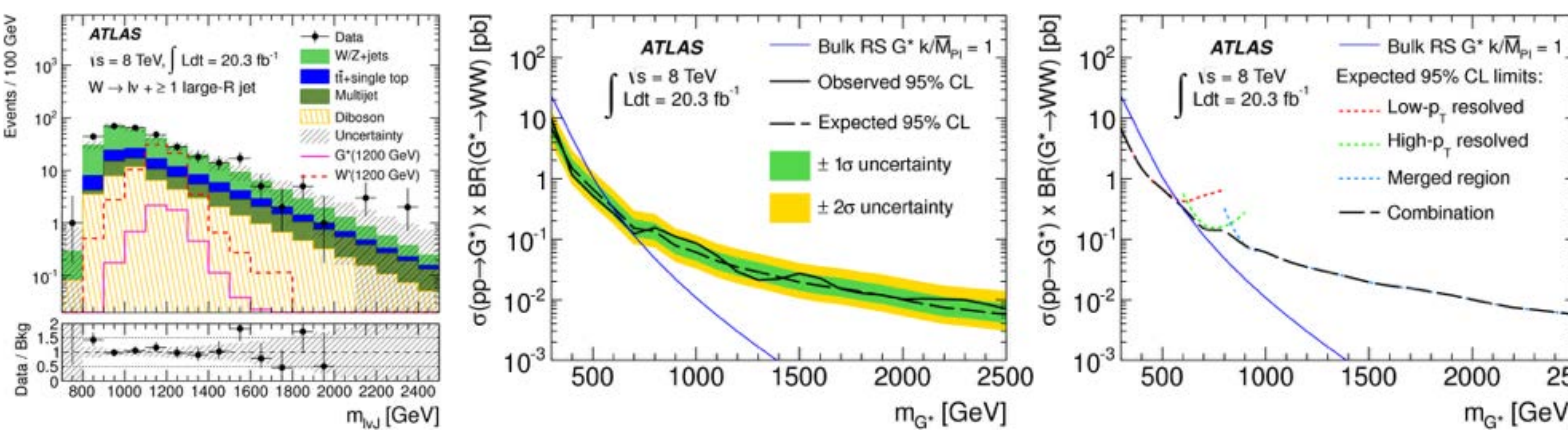
Low purity selection

VW Resonance

Brand New!

[ATLAS arXiv:1503.05677]

- Search in $\ell\nu qq$ final state
  - Low p_T resolved, high p_T resolved, and merged analyses
- Merged channel $\sqrt{y_f} = \min(p_T^{j1}, p_T^{j2})\Delta R_{12}/m_{12} > 0.45$
  - Momentum balance filtered R=1.2 jets with 65 < m < 105 GeV
  - Neutrino p_z determined from W mass constraint

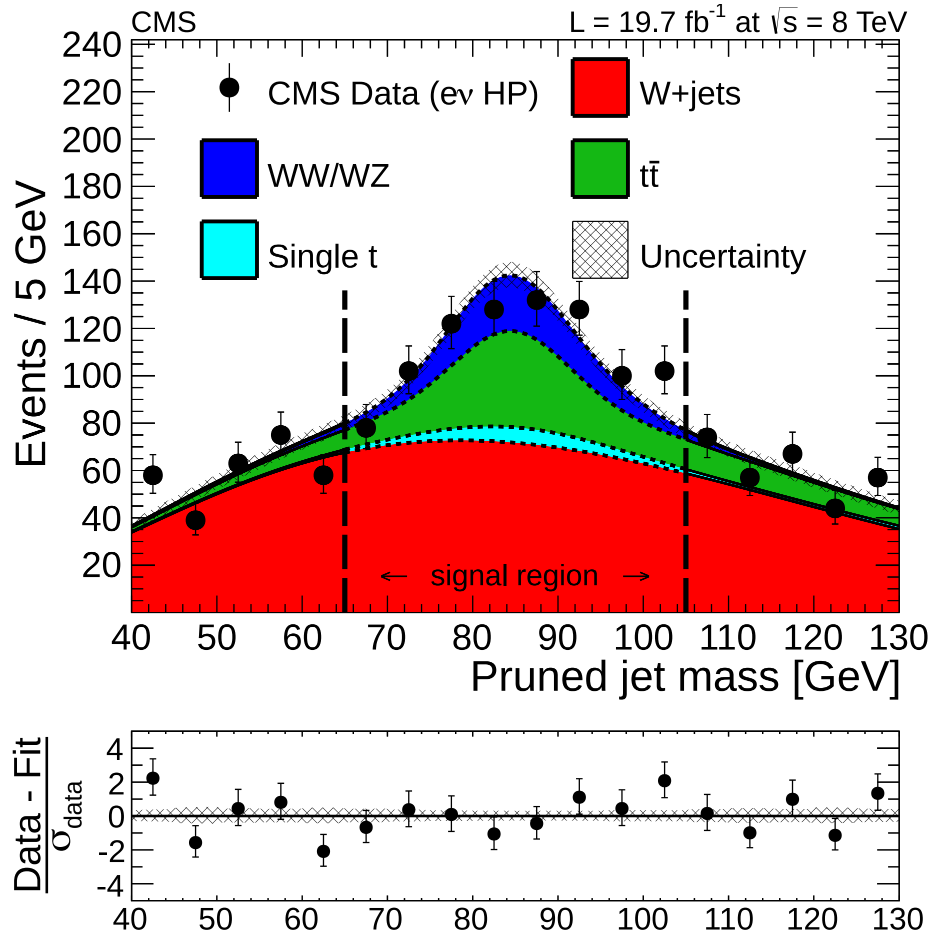


[CMS JHEP 08 (2014) 173] [CMS JHEP 08 (2014) 174] [ATLAS EPJC 75:69 (2015)]

VV Resonance

- Search for VV resonance
  - JJ, $\ell\nu$J, and $\ell\ell$J final states
  - Pruned R=0.8 jets with 70 ≲ m ≲ 105 GeV + N-subjettiness
  - Categorize events based on τ_{21} and single/double tag (JJ)
  - $\ell\ell$J and $\ell\ell$jj final states
  - BRDS-A R=1.2 jets with 70 < m < 110 GeV
- Semileptonic analyses: take normalization and shape of V+jets background from $m_{J/jj}$ sideband (with shape corrections from MC)
- Fully-hadronic: Model multijet background as smoothly falling distribution
- Bump hunt in $m_{JJ}/m_{\ell\nu J}/m_{\ell\ell J}/m_{\ell\ell jj}$

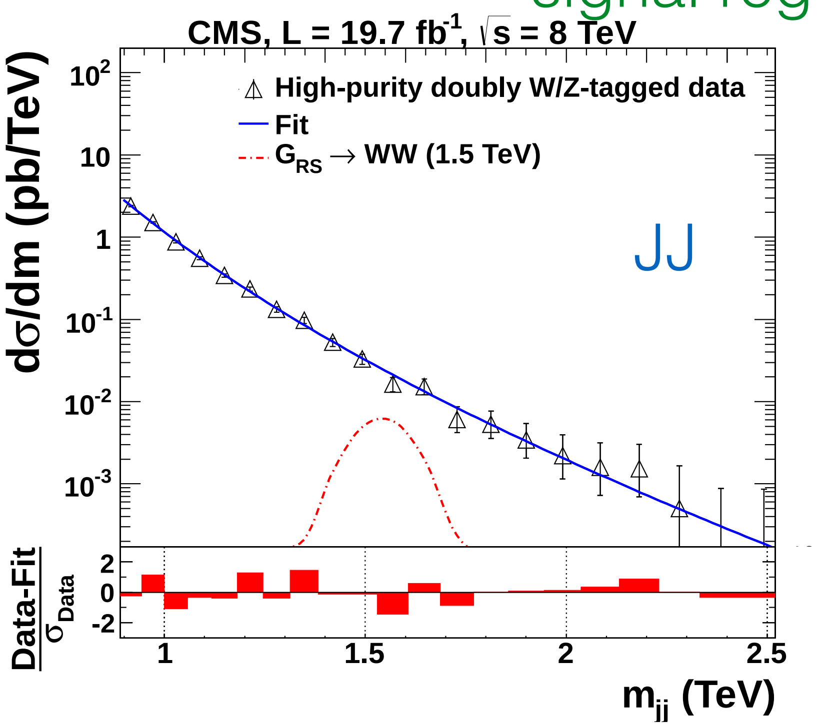
m_J sideband

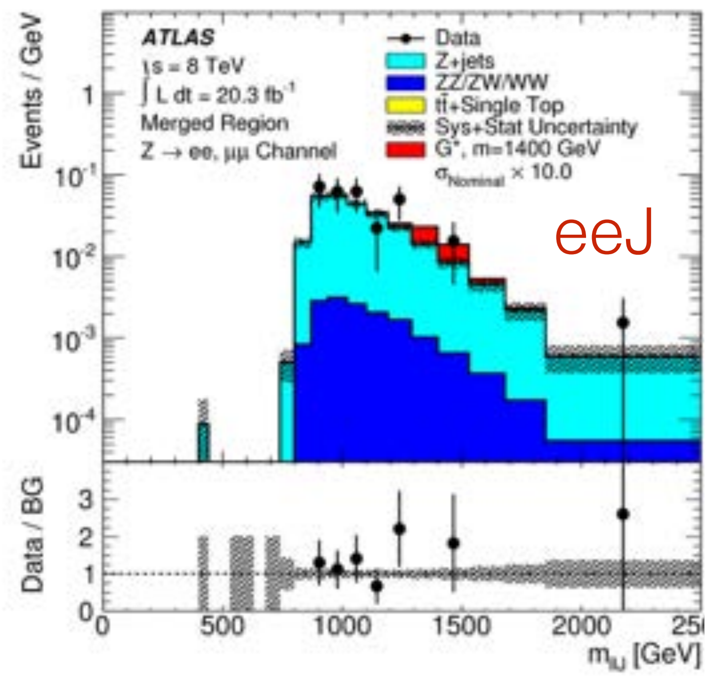


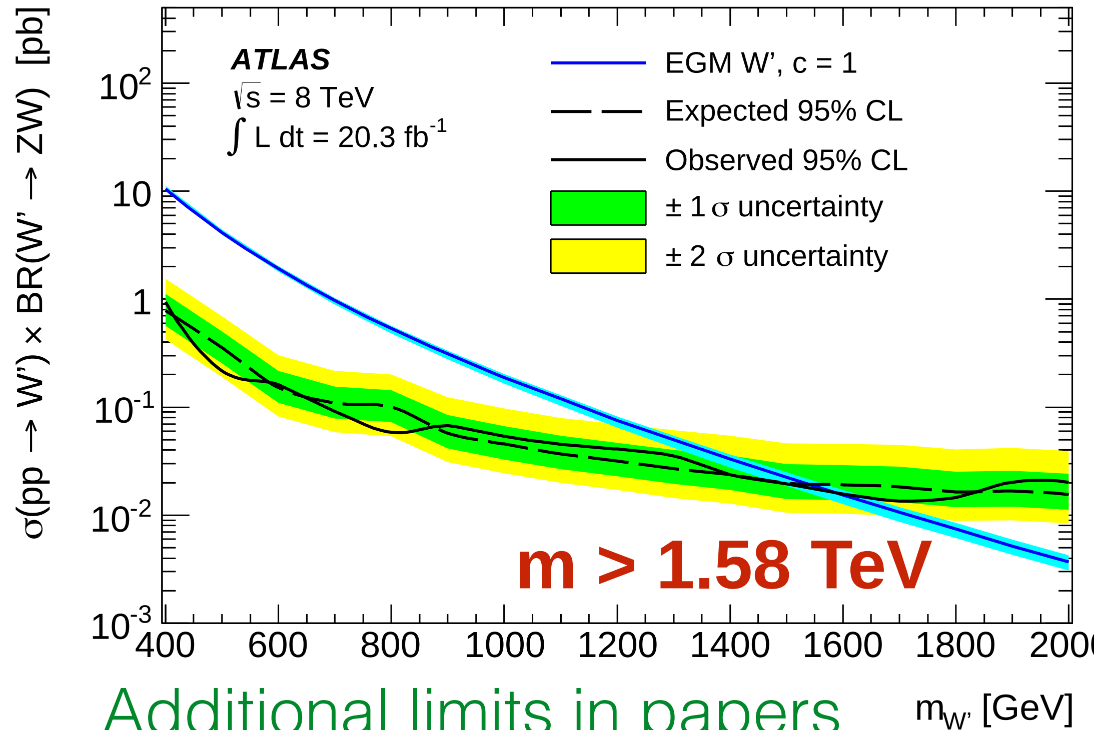
[CMS JHEP 08 (2014) 173] [CMS JHEP 08 (2014) 174] [ATLAS EPJC 75:69 (2015)]

VV Resonance

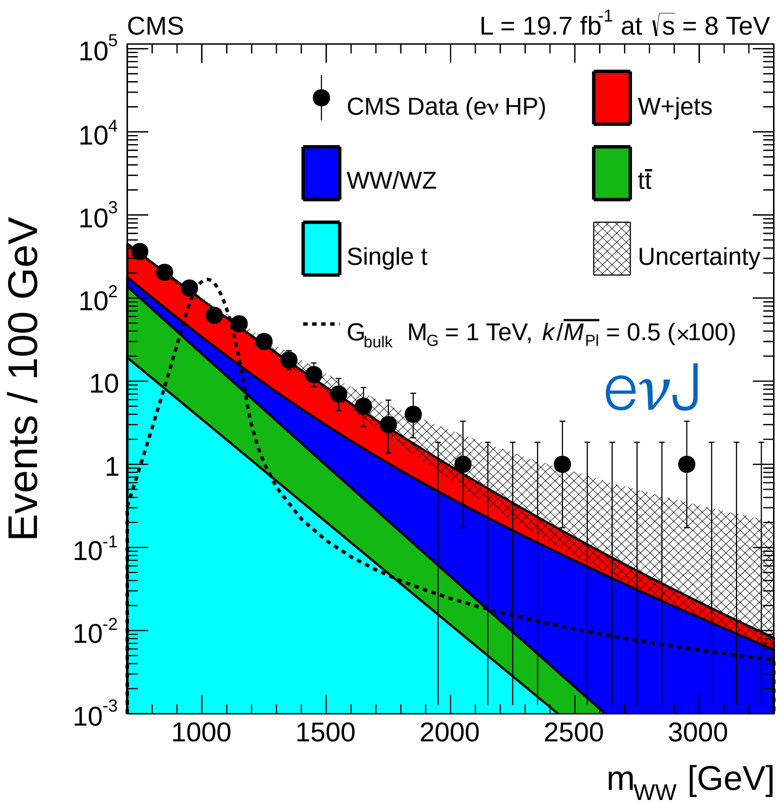
signal region results

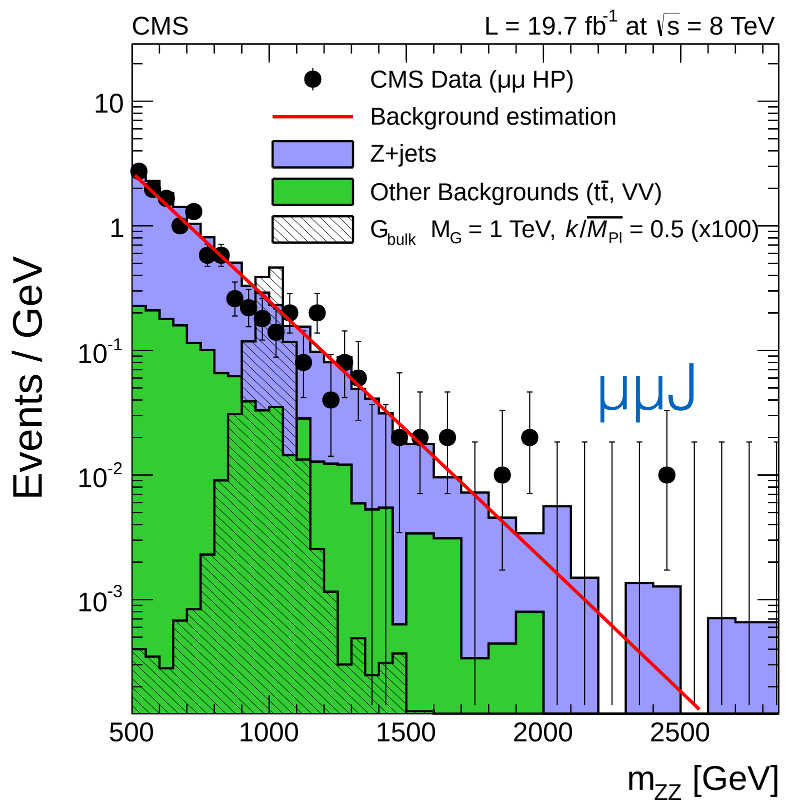


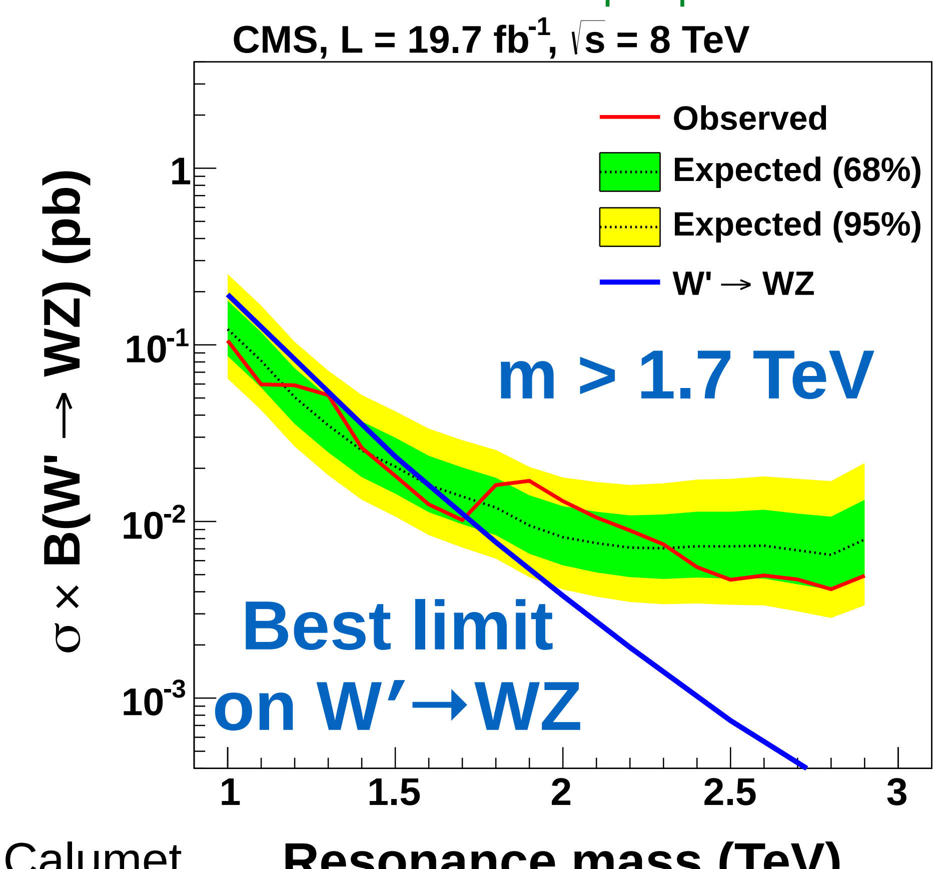




Additional limits in papers







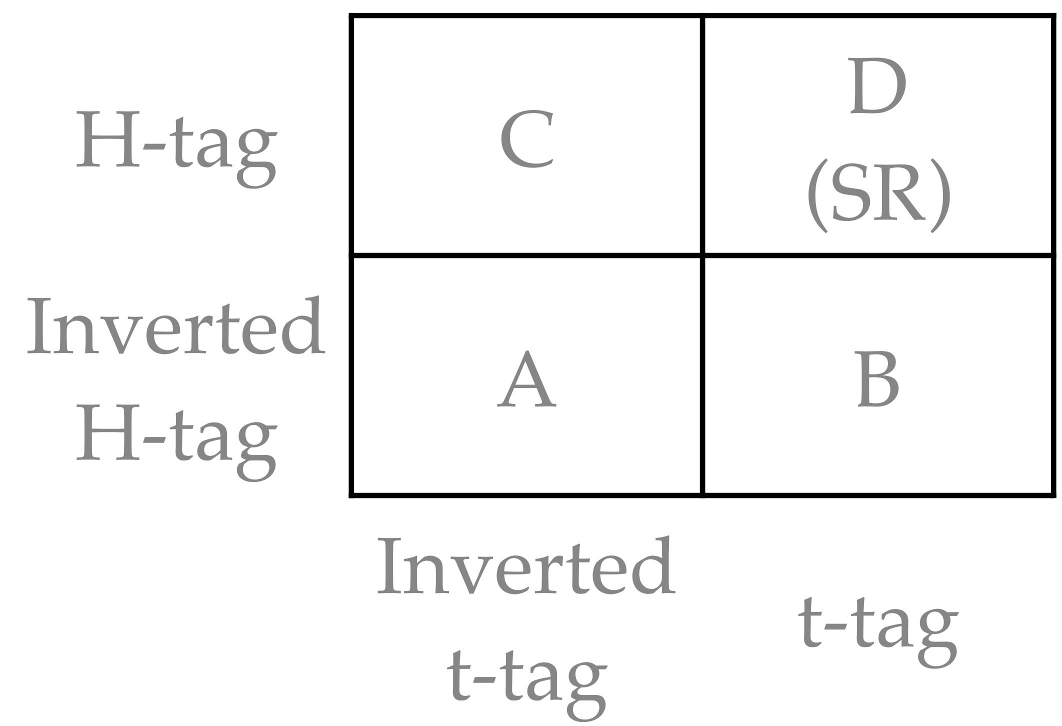
[CMS arXiv:1503.01952]

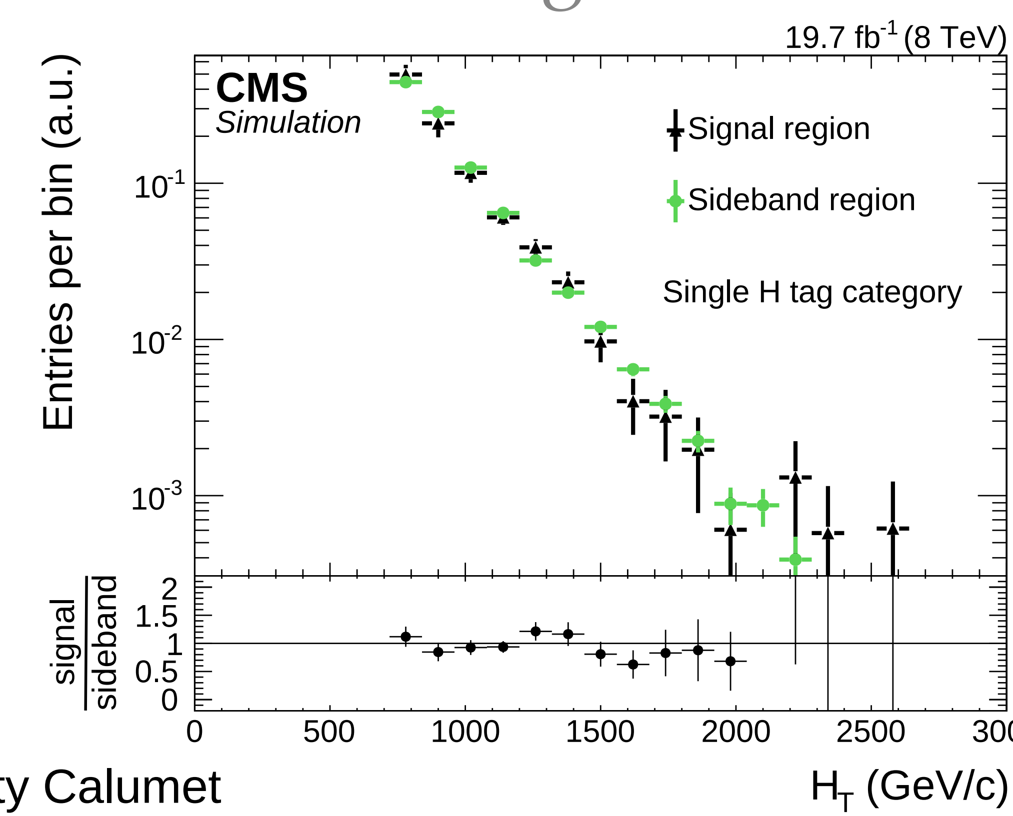
ABCD Method in $T' \rightarrow tH$

- QCD normalization:

$$N_D = N_B \frac{N_C}{N_A}$$

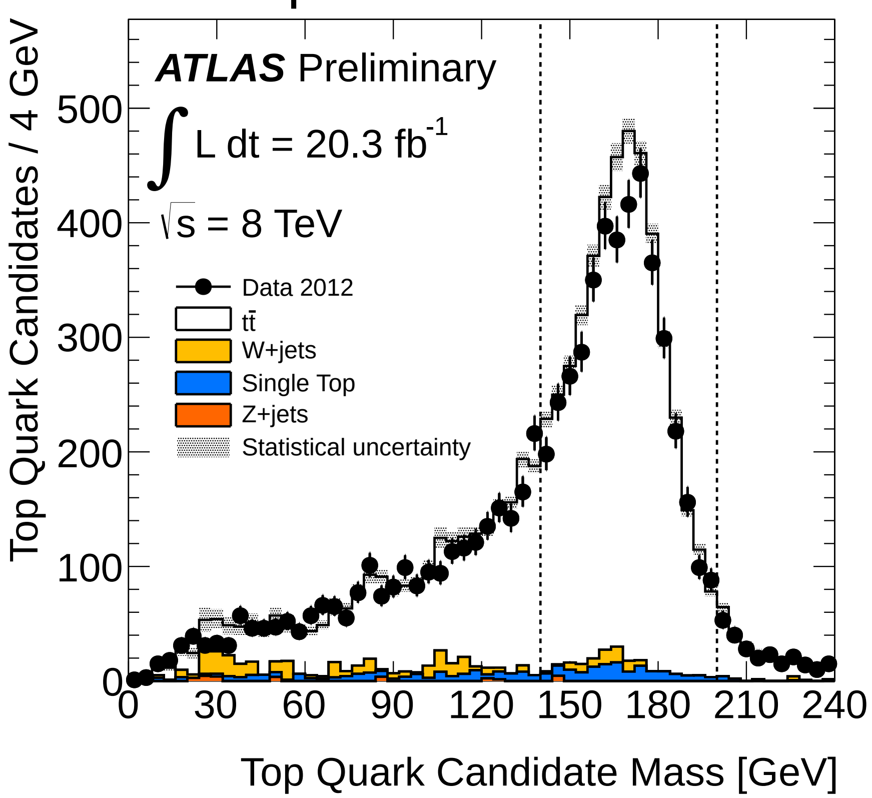
- QCD shape:
  - Taken from region B
- Validated with QCD MC and data

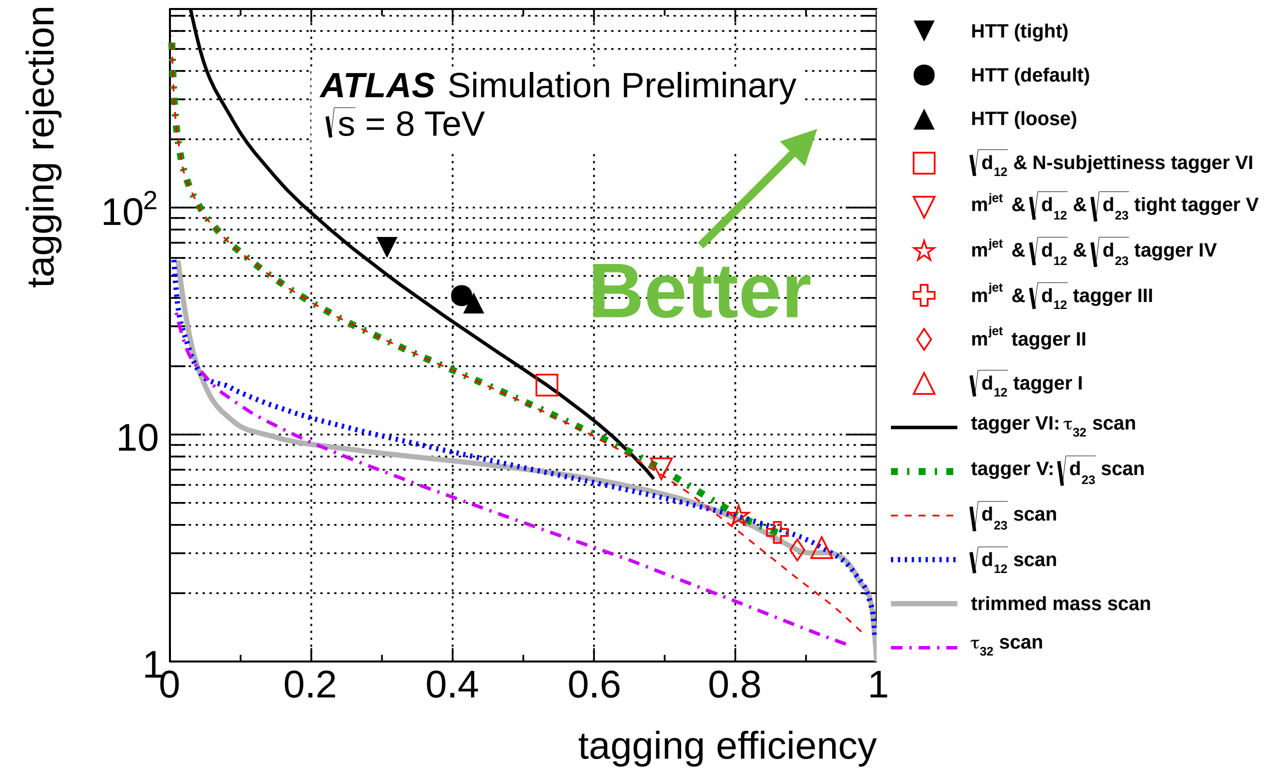




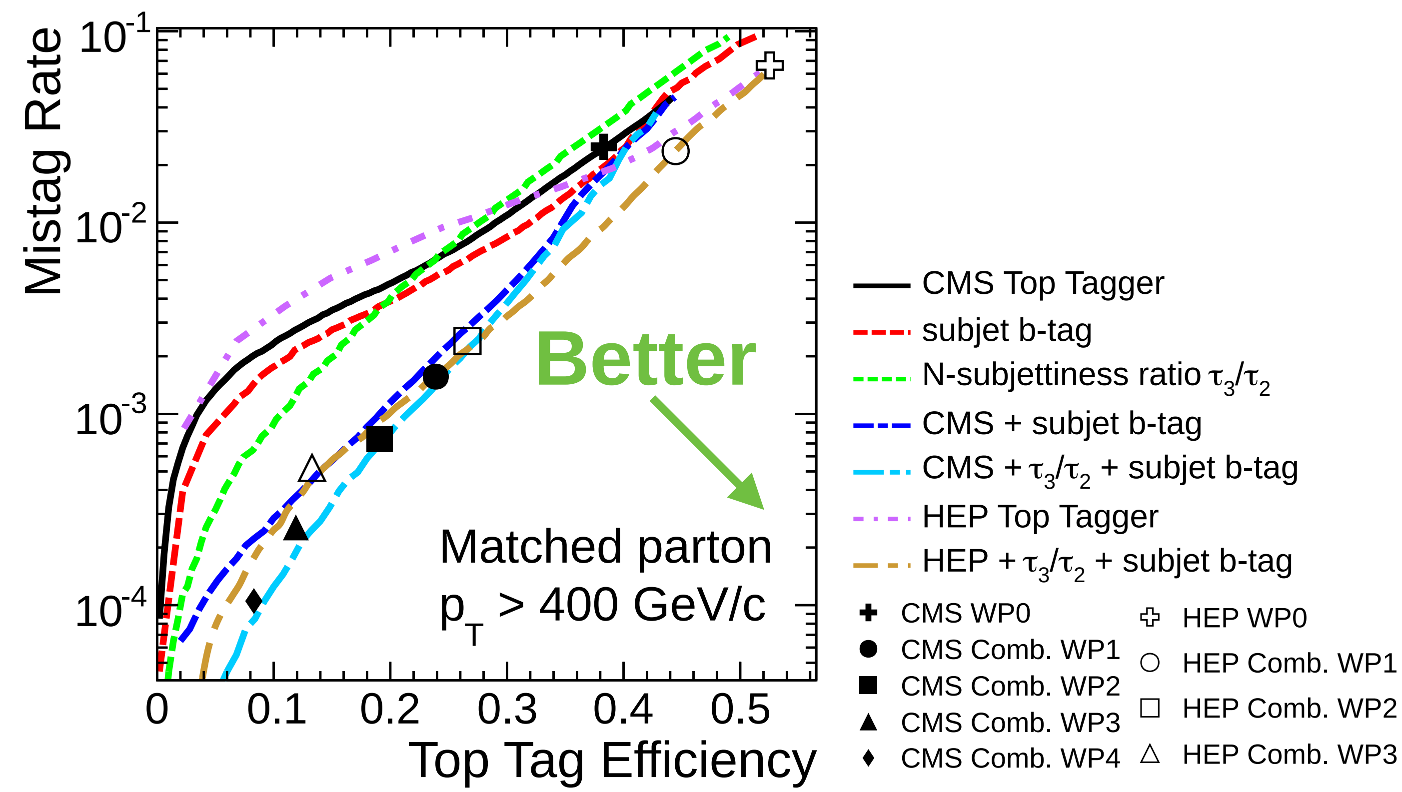
Top Tagging Performance

- Techniques validated in data



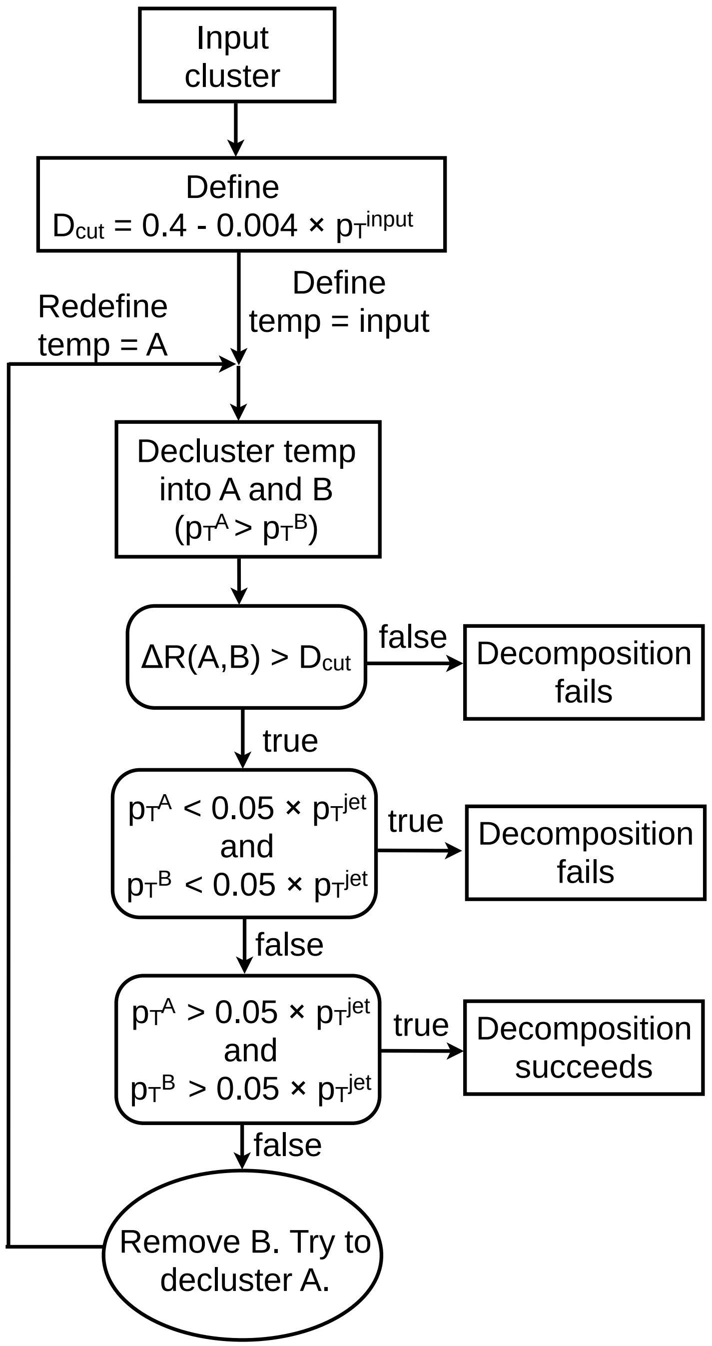


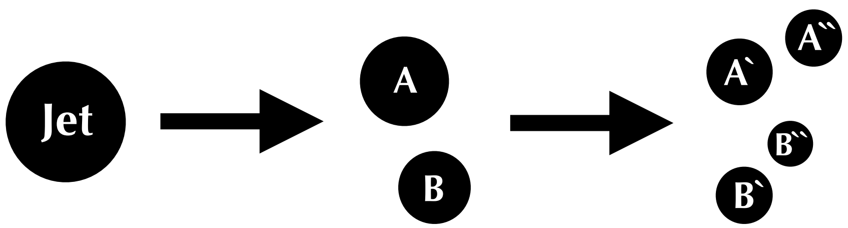
- Optimal performance
  - Obtained by combining tagger with additional jet substructure info
  - Analysis dependent



CMS Top Tagger

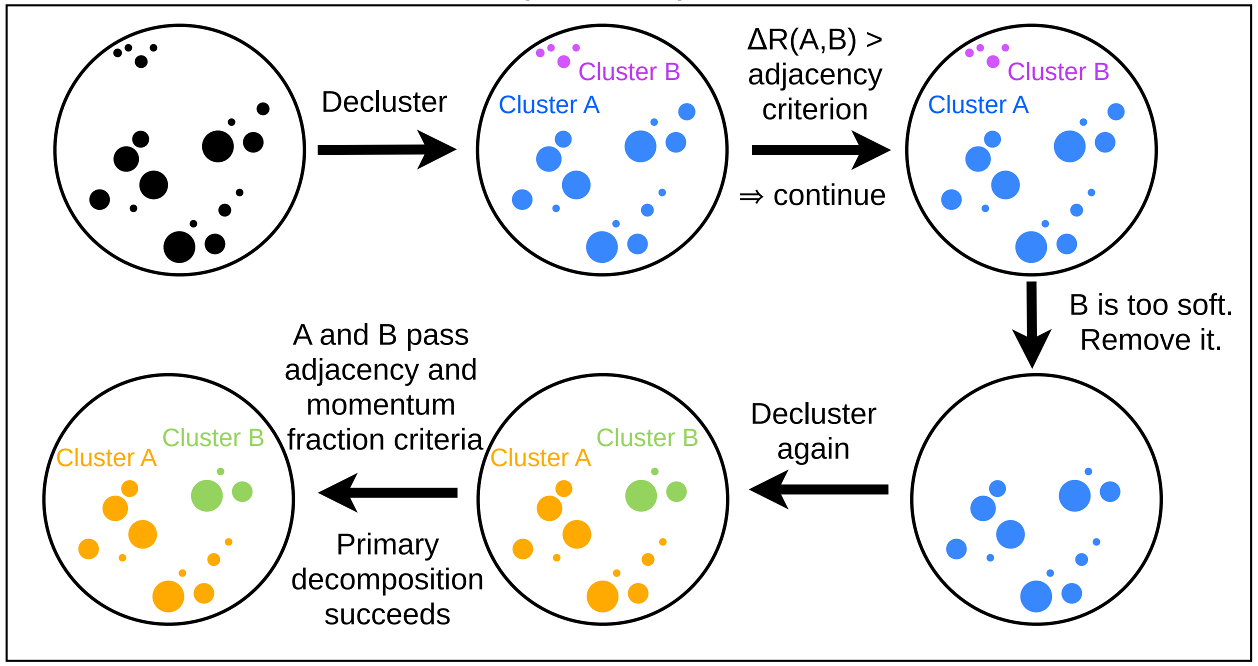
CMS Top Tagger decomposition



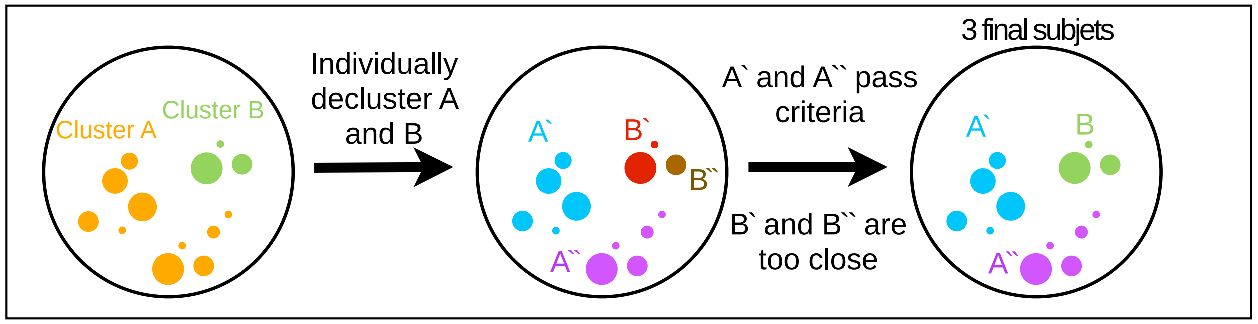


Example: CMS Top Tagger decomposition

Primary decomposition

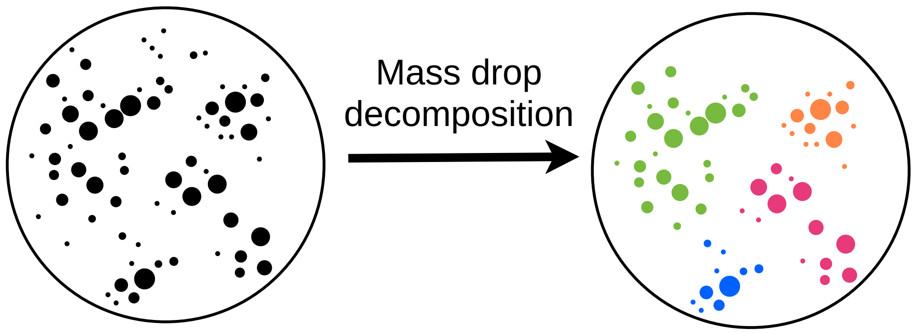


Secondary decomposition

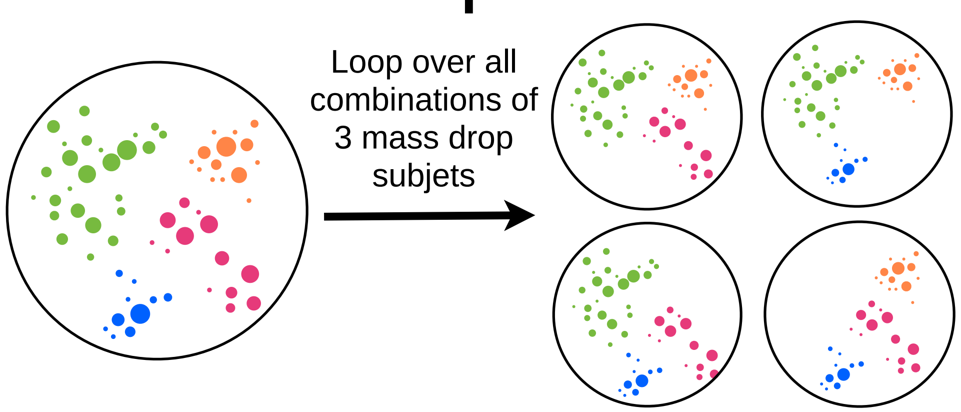


HEP Top Tagger

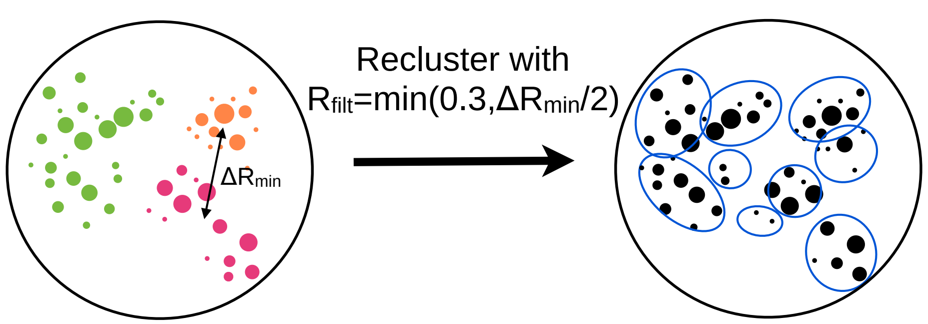
Step 1:



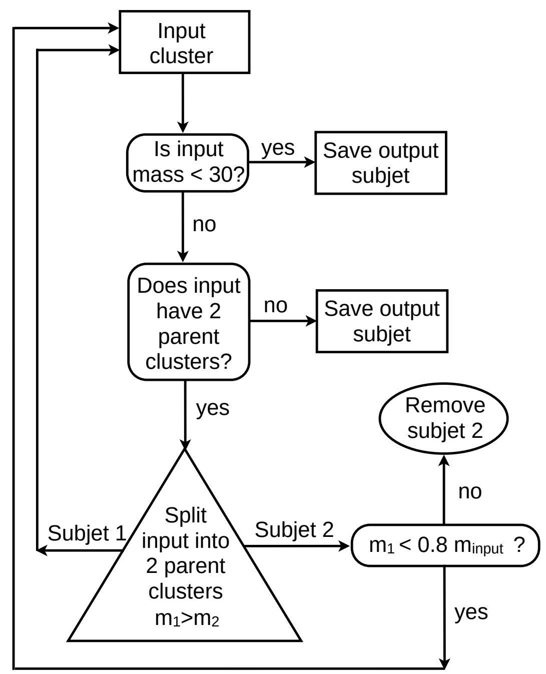
Step 2:



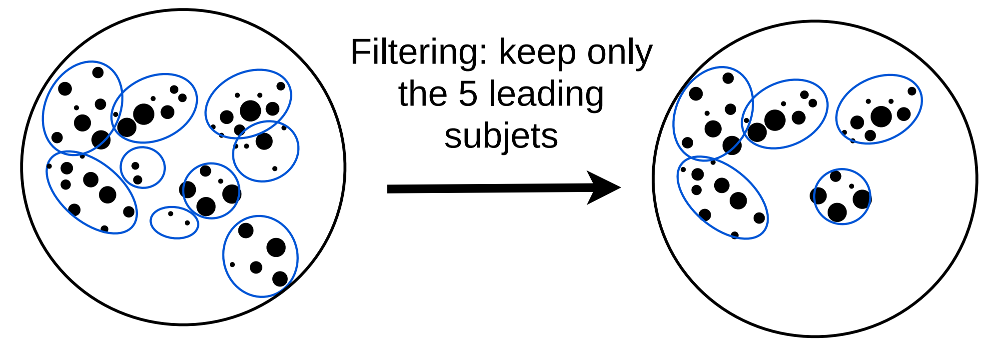
Step 3:



HEP Top Tagger
Mass drop decomposition

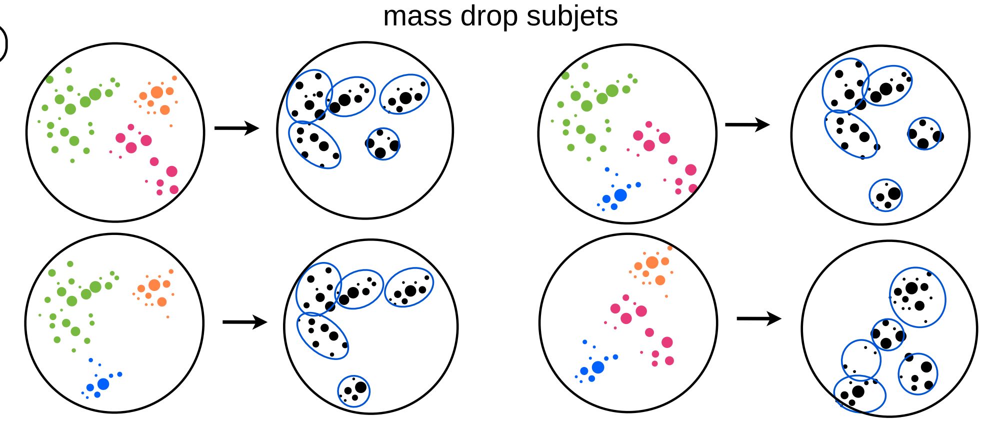


Step 4:

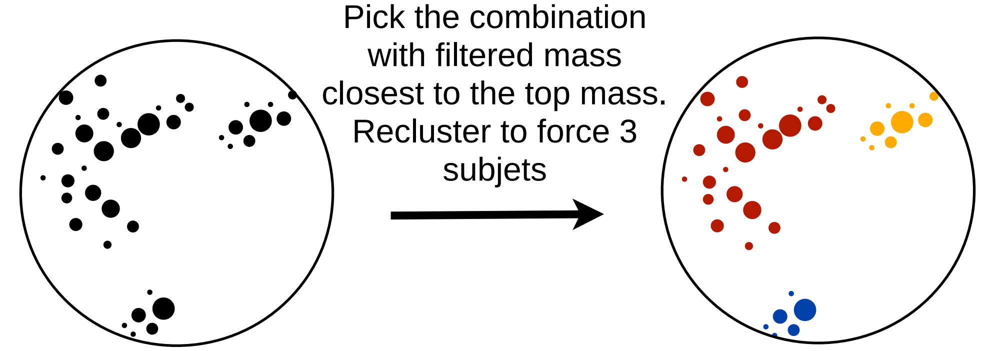


Step 5:

Repeat reclustering and filtering procedure for all combinations of 3 mass drop subjets



Step 6:



HEP Top Tagger

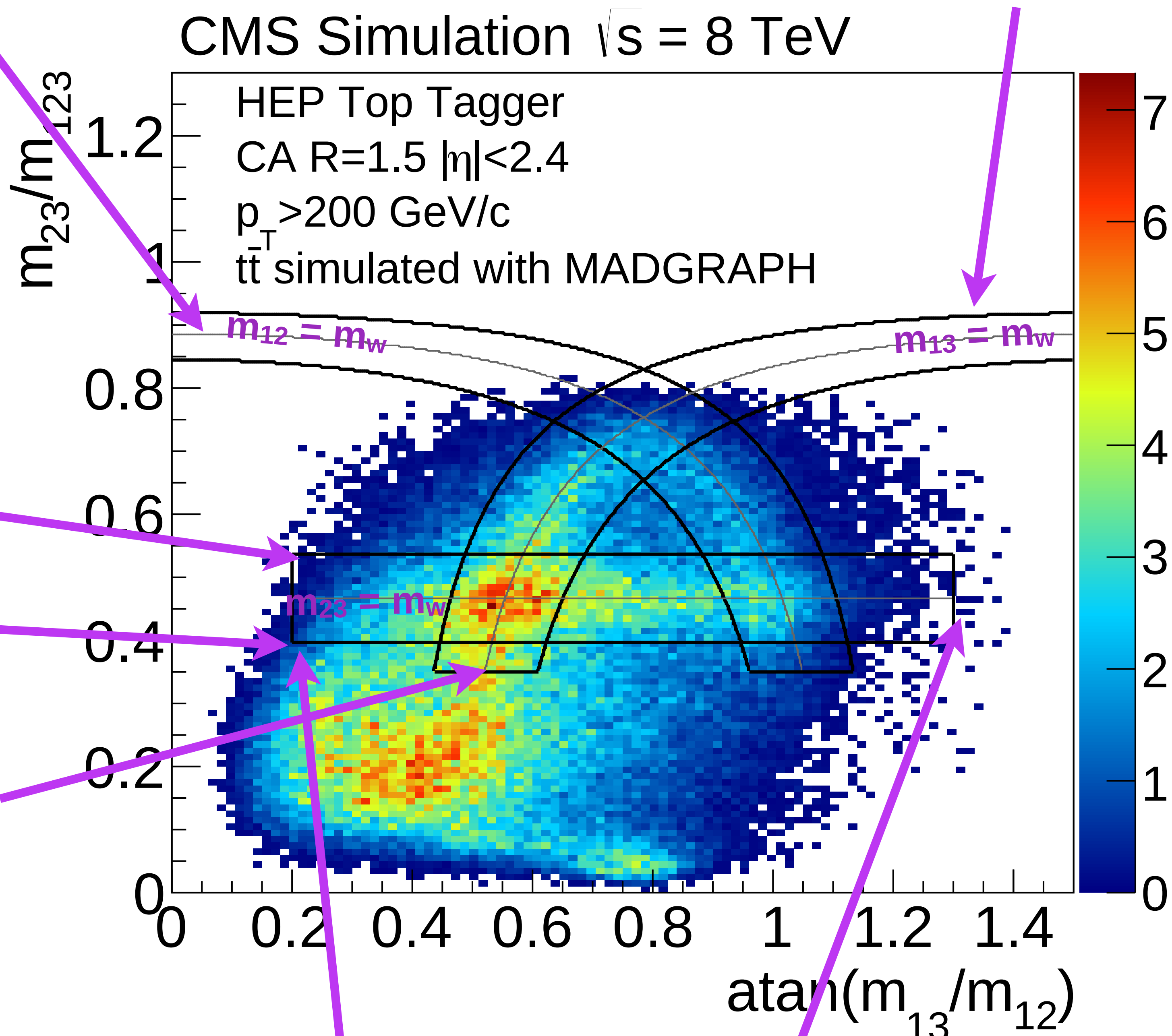
$$R^2_{\min}\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R^2_{\max}\left(1+\left(\frac{m_{12}}{m_{13}}\right)^2\right) \quad R^2_{\min}\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1-\left(\frac{m_{23}}{m_{123}}\right)^2 < R^2_{\max}\left(1+\left(\frac{m_{13}}{m_{12}}\right)^2\right)$$

$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max}$$

$$R_{\max} = (1+f_W)\times m_W/m_t$$

$$R_{\min} = (1-f_W)\times m_W/m_t$$

$$\frac{m_{23}}{m_{123}} > 0.35$$



$$0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

Top Tagging Performance