Jet Substructure Measurements at CMS

Dennis Schwarz

on behalf of the CMS Collaboration

BOOST 2019

Universität Hamburg

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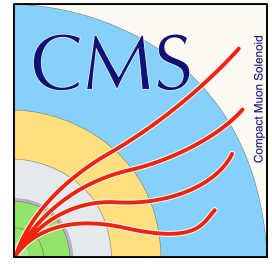
GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung



CLUSTER OF EXCELLENCE

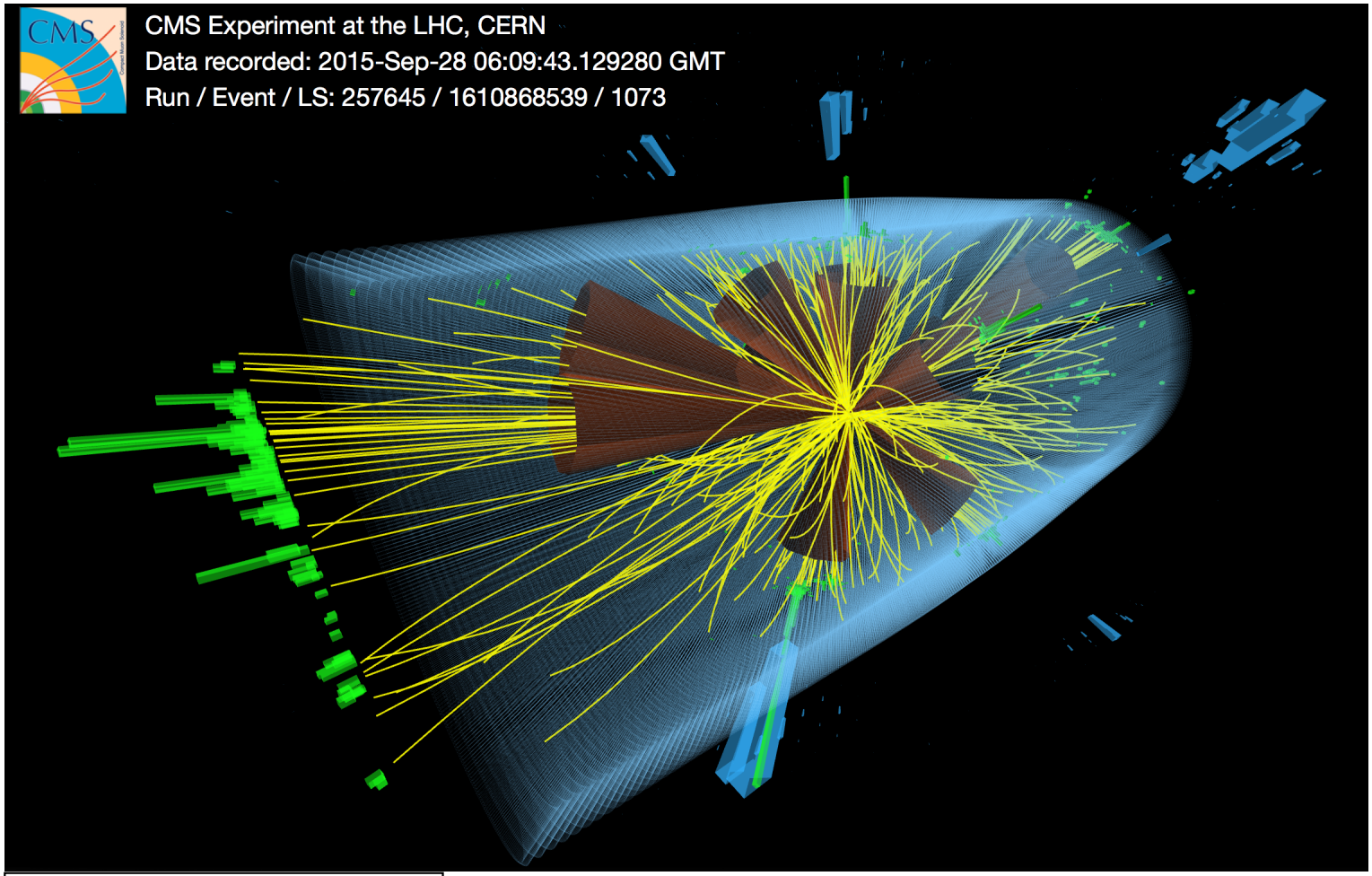
QUANTUM UNIVERSE

PIER

Partnership of
Universität Hamburg and DESY

Jets at LHC

LHC produces **lots** of jets but what is their origin?



Mc Cauley, Thomas,
CMS-PHO-EVENTS-2015-009

Substructure

Outline

- measuring jet mass in dijet events

  [CMS Collaboration, JHEP 11 (2018) 113]

- measuring jet mass in boosted top quark decays

  [CMS Collaboration, CMS-PAS-TOP-19-005] ⟵ **new for BOOST!**

- using substructure in searches for anomalous couplings

  [CMS Collaboration, CMS-SMP-18-008] ⟵ **new**

  [CMS Collaboration, CMS-PAS-SMP-18-006] ⟵ **new**

substructure variables in non-boosted $t\bar{t}$

[CMS Collaboration, Phys. Rev. D 98 (2018) 092014] available in HepData and Rivet

Substructure Measurements

Measuring Jet Mass in Dijet Events

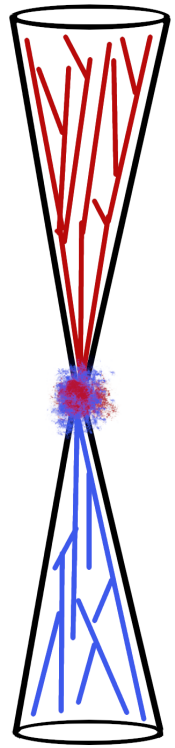
[CMS Collaboration, JHEP 11 (2018) 113]

- **aim:** differential cross section as function of m_{jet}
- di-jet events
- measurement performed with and without soft drop
- covering large range in p_T

- important input for understanding of QCD
- crucial test for MC generators

Jets

anti-k_T, $R = 0.8$, CHS



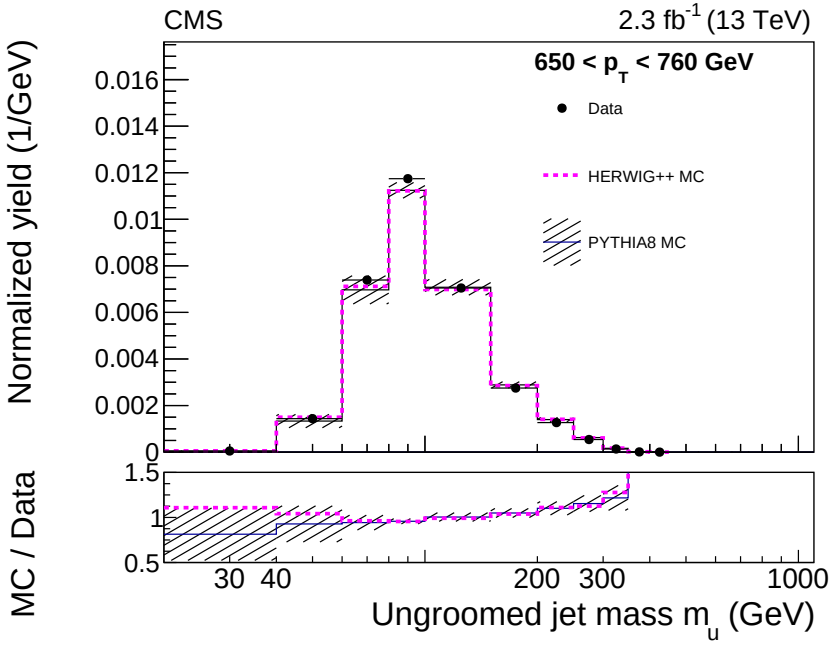
MC generators

- PYTHIA 8.212, CUETP8M1 tune
- Herwig++ 2.7.0, CUETHS1 tune
- POWHEG 2.0 + PYTHIA 8, CUETP8M1 tune

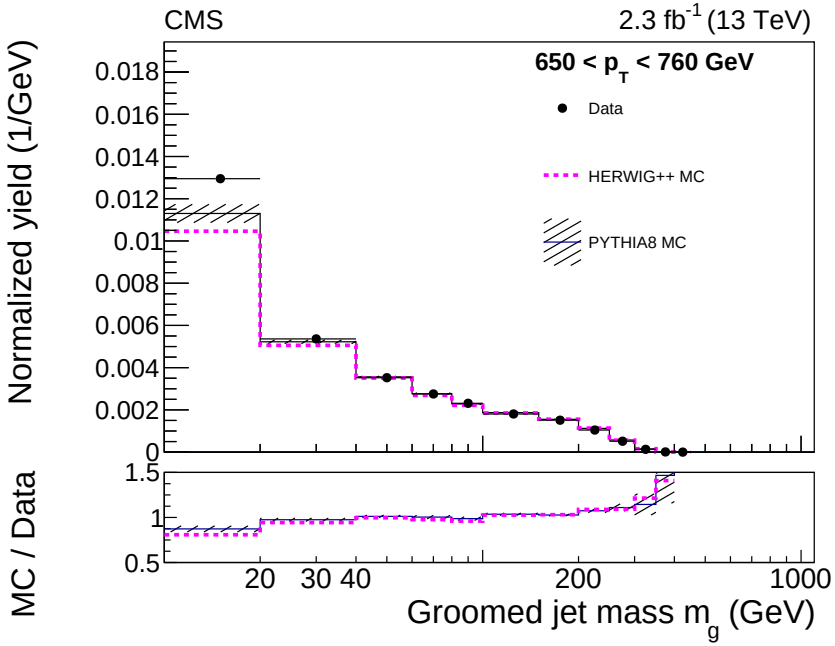
Measuring Jet Mass in Dijet Events

[CMS Collaboration, JHEP 11 (2018) 113]

ungroomed



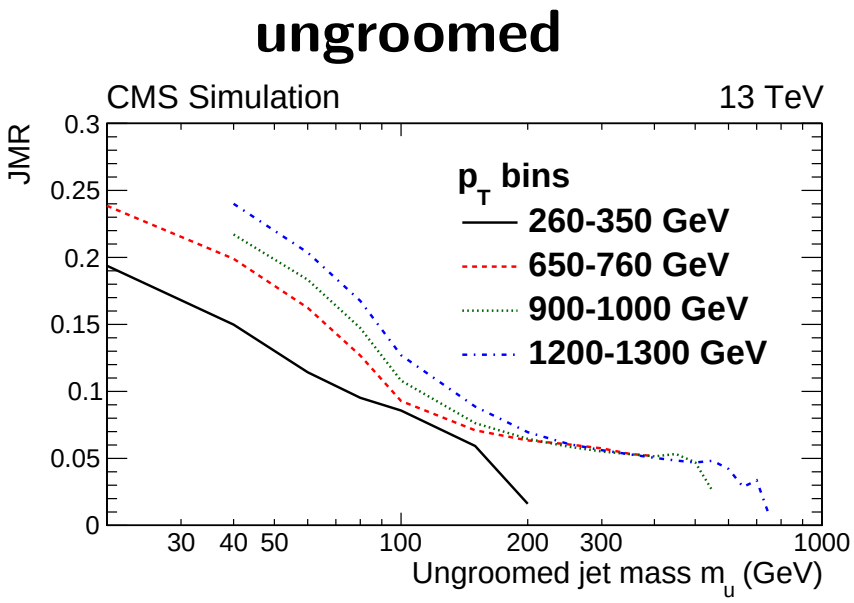
soft drop

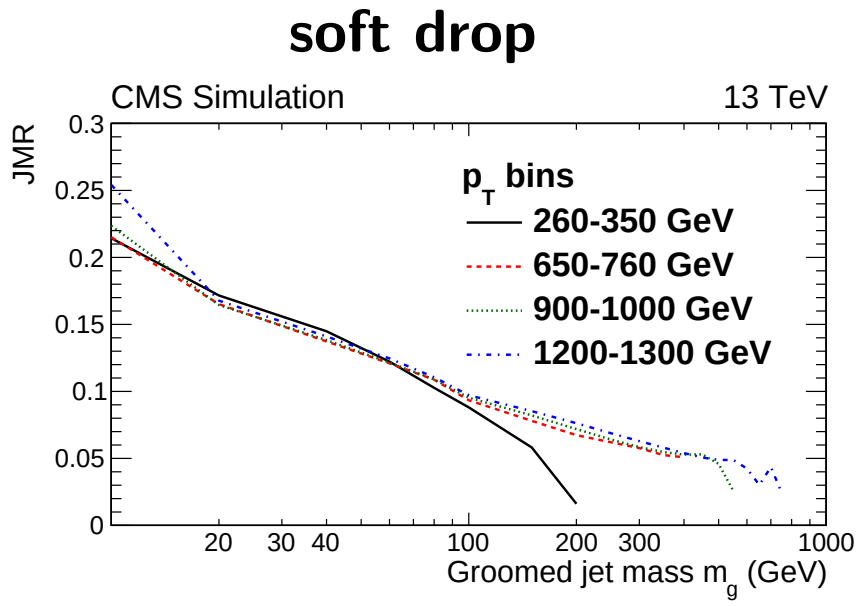


- data/MC comparison prior to unfolding
- falling m_{jet} after soft drop (suppress Sudakov peak)

Measuring Jet Mass in Dijet Events

[CMS Collaboration, JHEP 11 (2018) 113]

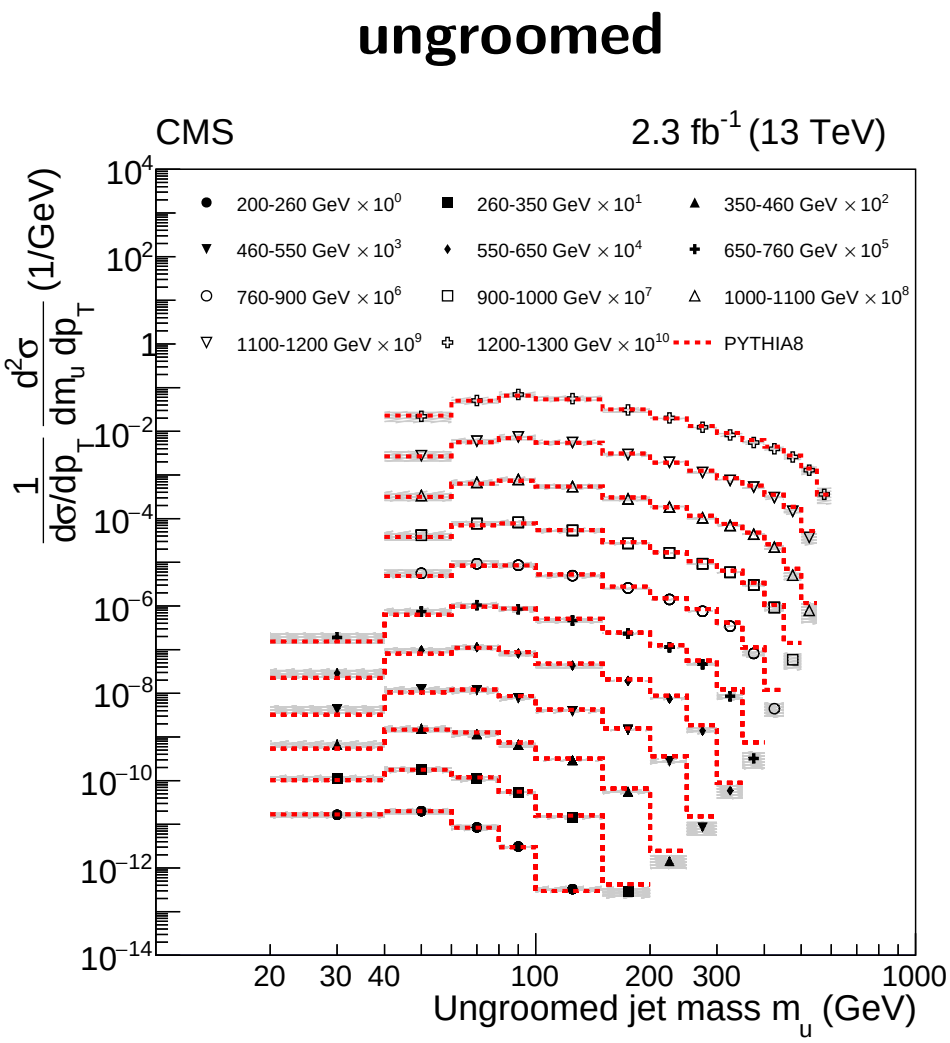




- jet mass resolution $= \mathrm{RMS}\left[\frac{m_{\mathrm{rec}}}{m_{\mathrm{rec}}}\right]$
- stable resolution after soft drop

Measuring Jet Mass in Dijet Events

[CMS Collaboration, JHEP 11 (2018) 113]

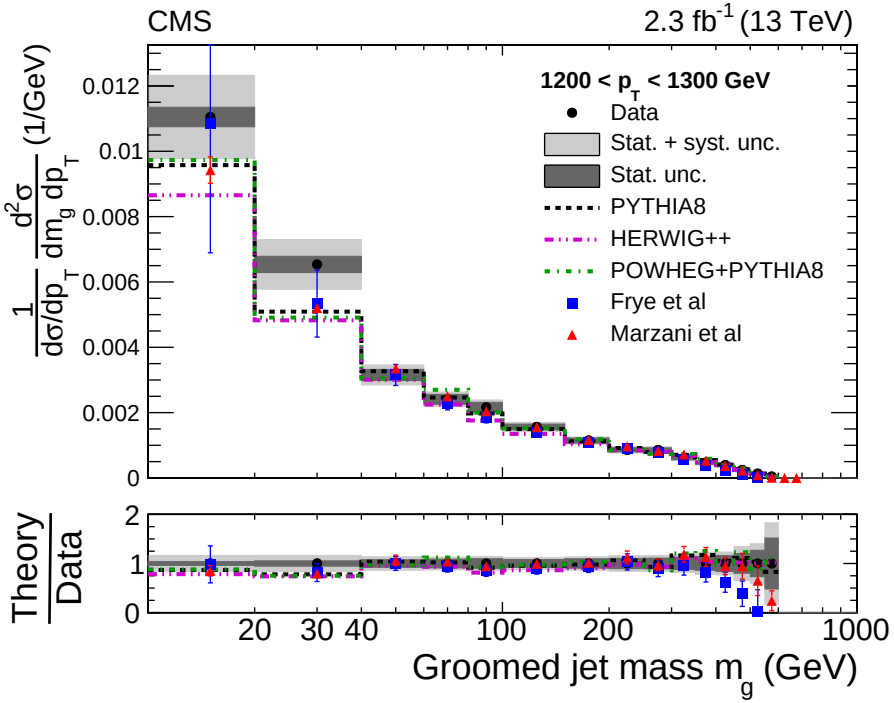


- unfolded measurement
- covering huge p_T range (200 to 1300 GeV)
- overall good agreement with prediction
- low m_{jet} region not accessible without grooming
- dominating uncertainties: jet mass scale and resolution, pileup

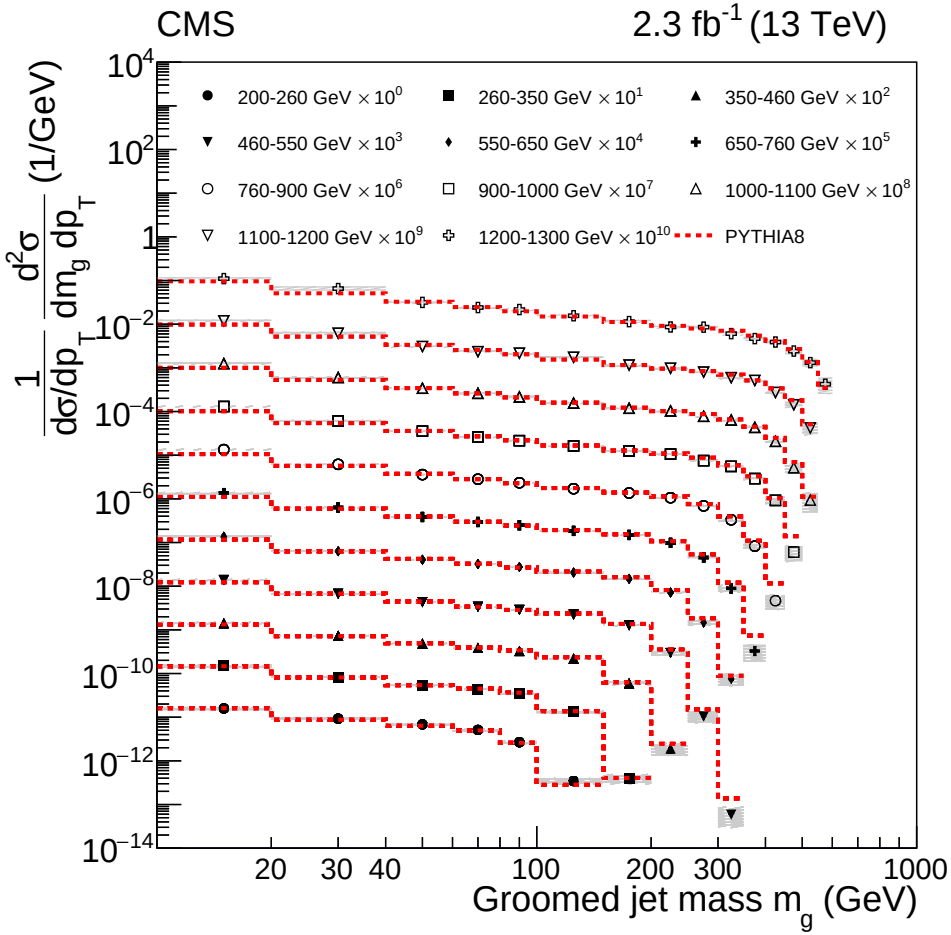
Measuring Jet Mass in Dijet Events

[CMS Collaboration, JHEP 11 (2018) 113]

- after grooming
- overall good agreement with prediction
- pileup not an issue
- compare to calculations!



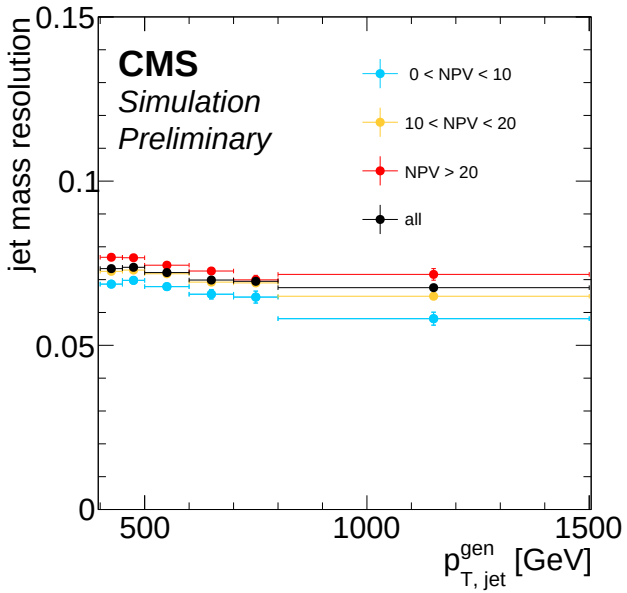
soft drop



Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]

- **aim:** differential $t\bar{t}$ cross section as function of m_{jet}
- boosted $t\bar{t}$ in lepton+jets (jet with $p_T > 400$ GeV)
- novel use of XCone (CHS)
- m_{jet} resolution comparable to AK8, stable against pileup



XCone [I. W. Stewart, F. J. Tackmann, J. Thaler, C. K. Vermilion and T. F. Wilkason, JHEP 1511 (2015) 072]

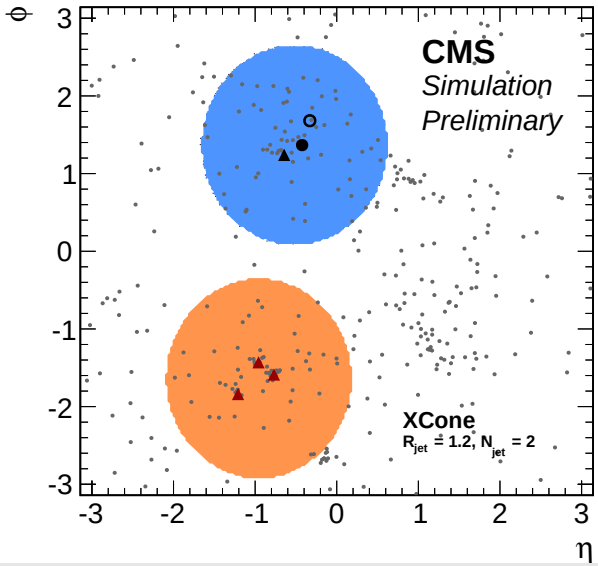
- exclusive jet algorithm $\rightarrow$ returns exactly N jets
- jet axes found by minimizing N-jettiness
- cluster particles inside R around axes

2-step clustering using XCone

[CMS Collaboration, CMS-PAS-TOP-19-005]

set-up for lepton+jets $t\bar{t}$ idea from: [J. Thaler and T. F. Wilkason, JHEP 1512 (2015) 051]

1. find 2 jets with large radius



2-step clustering using XCone

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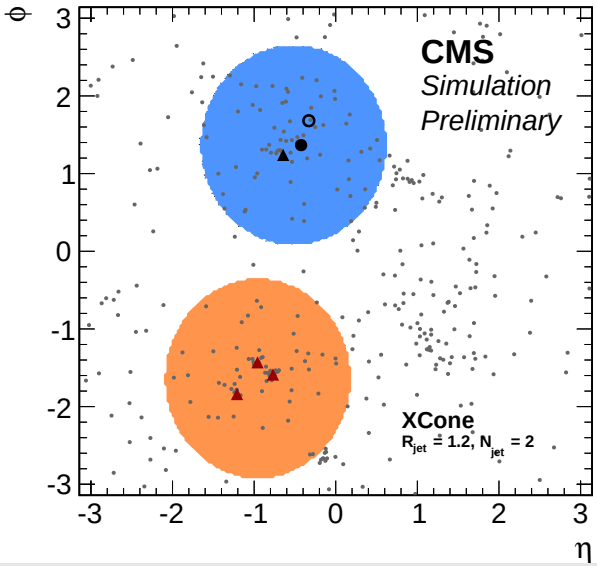
set-up for lepton+jets $t\bar{t}$ idea from: [J. Thaler and T. F. Wilkason, JHEP 1512 (2015) 051]

1. find 2 jets with large radius
2. calculate ΔR(lep, jet) for both jets



2-step clustering using XCone

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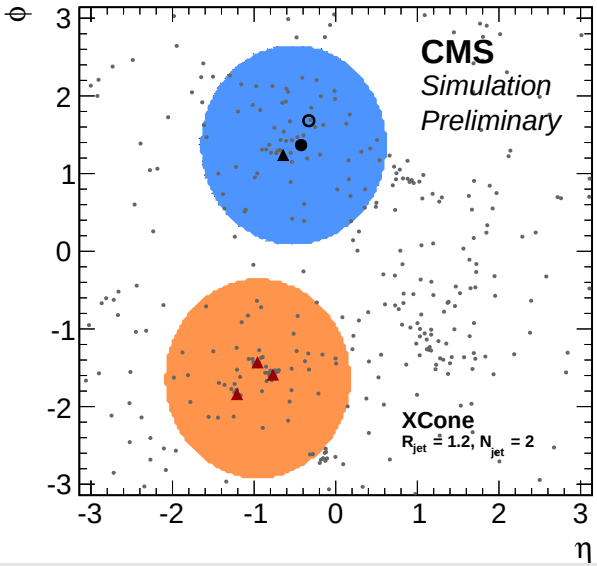
1. find 2 jets with large radius
2. calculate ΔR(lep, jet) for both jets
3. lowest $\Delta R \rightarrow$ leptonic jet; other $\rightarrow$ hadronic jet



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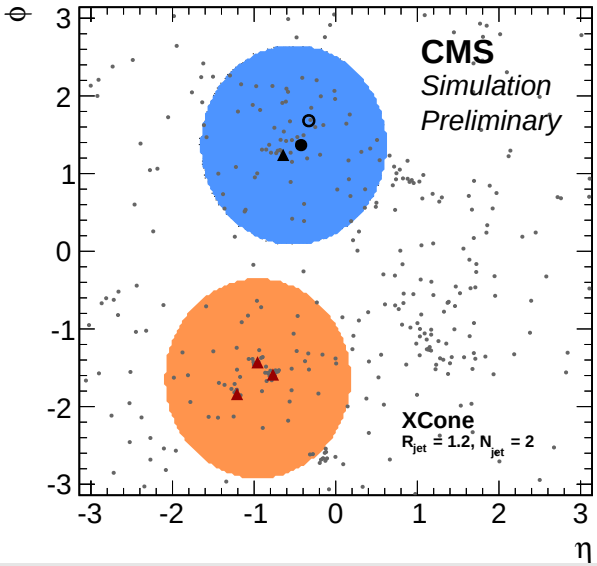
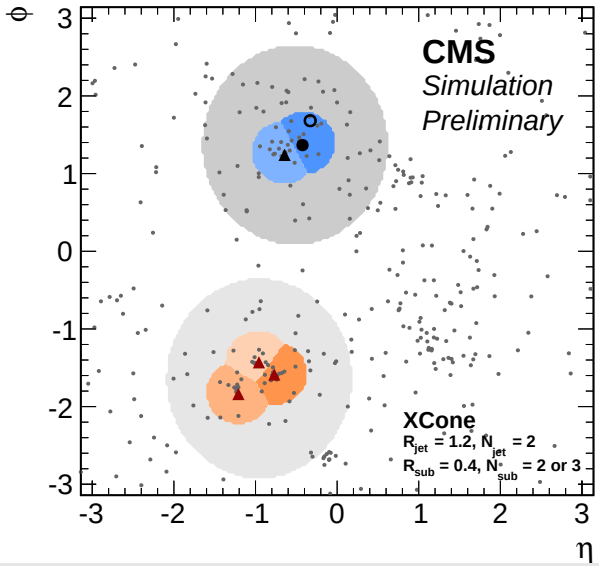
4. find subjets: 3 in hadronic jet, 2 in leptonic jet





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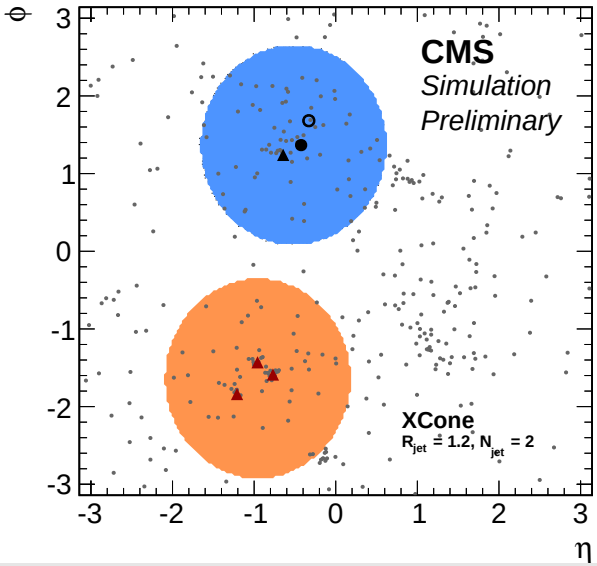
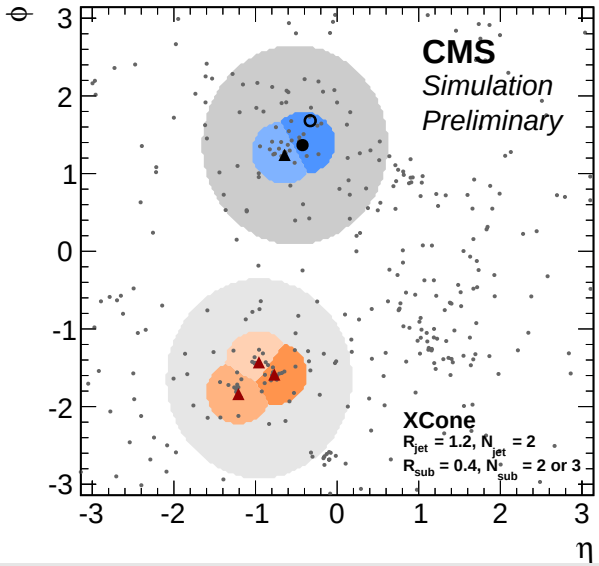
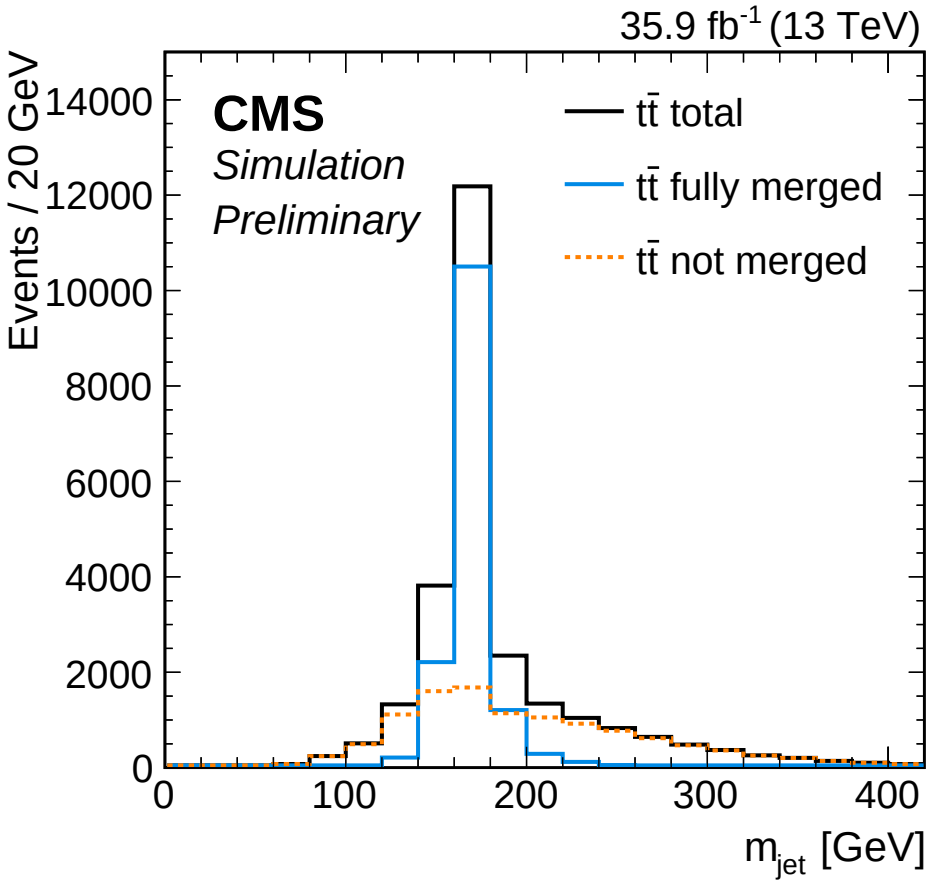
2. calculate ΔR(lep, jet) for both jets
3. lowest $\Delta R \rightarrow$ leptonic jet; other $\rightarrow$ hadronic jet
4. find subjets: 3 in hadronic jet, 2 in leptonic jet
5. combine subjets to final jet





Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]



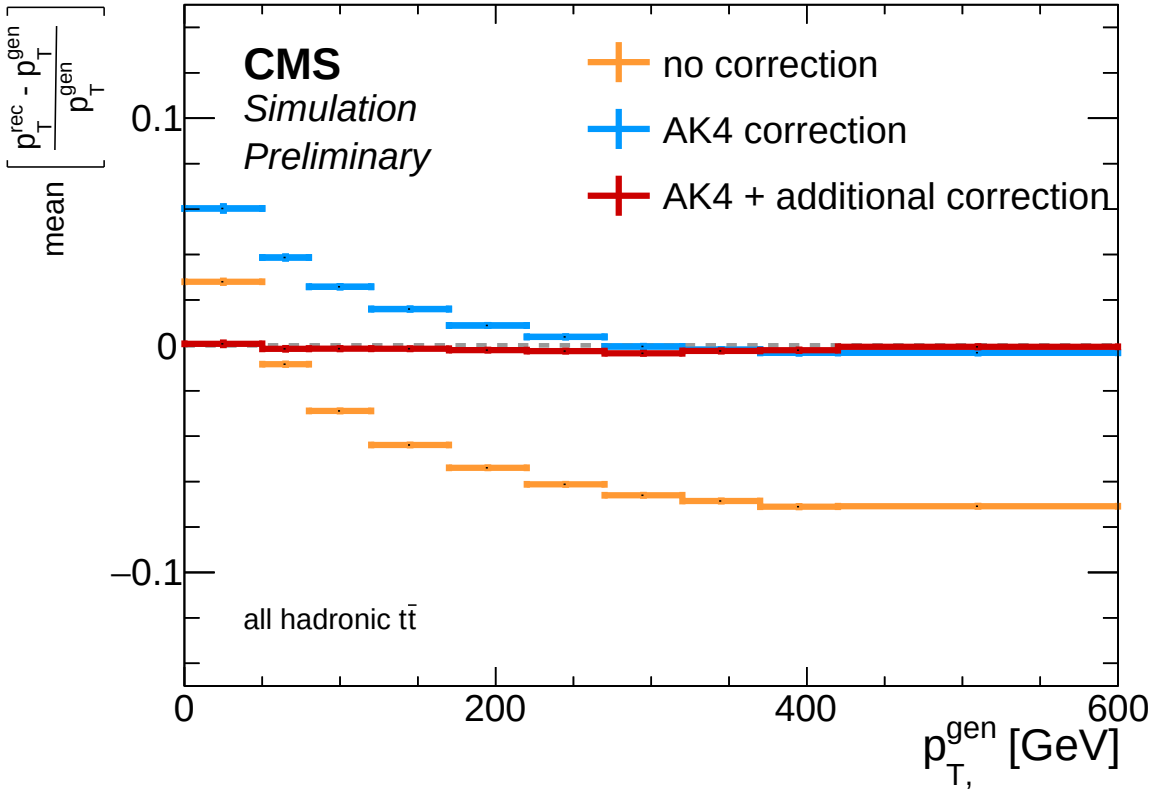
- particle level
- narrow peak
- large 'merged' fraction
- very good XCone performance

merged: decay products inside jet

Measuring Jet Mass in $t\bar{t}$

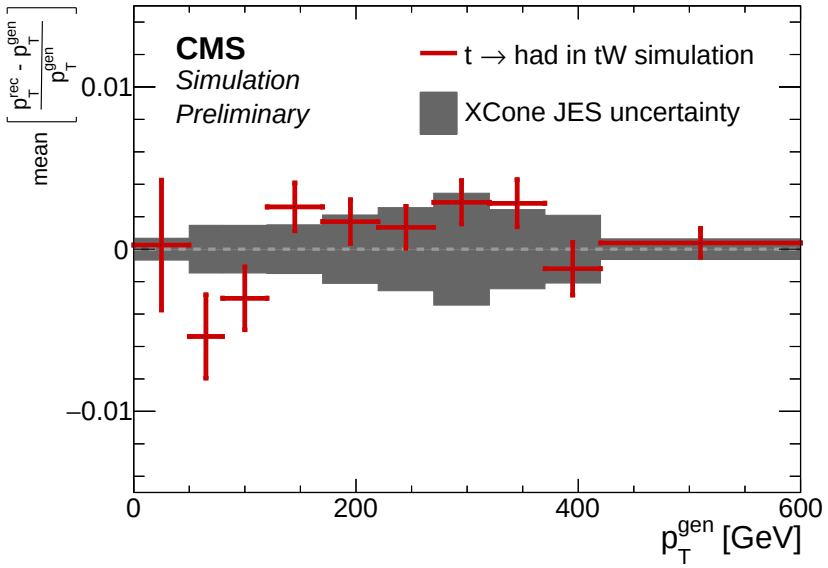
[CMS Collaboration, CMS-PAS-TOP-19-005]

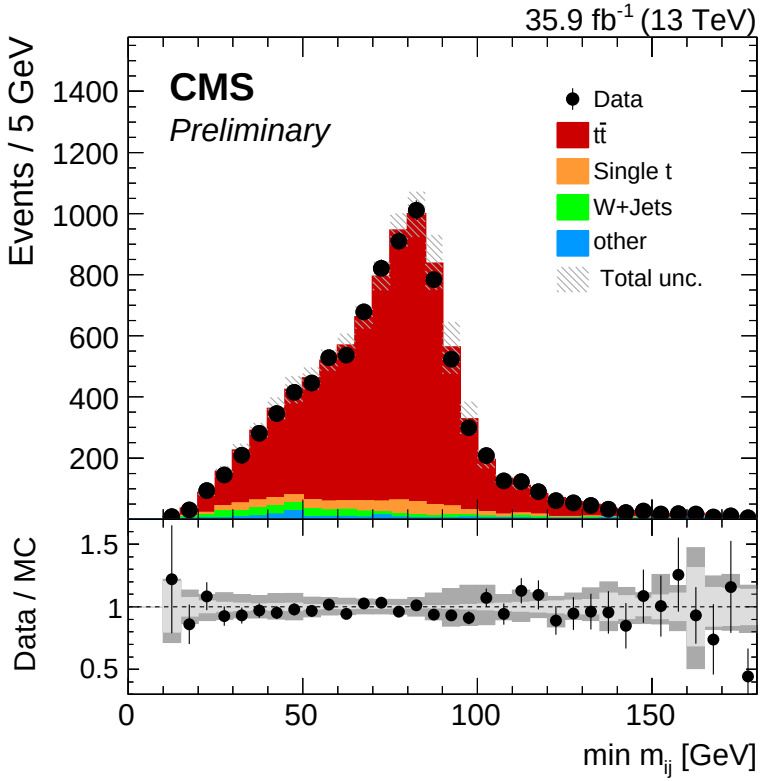
- no jet calibration for XCone so far
- idea: AK4 calibration + additional correction
- correction derived in all hadronic $t\bar{t}$
- correction applied dependent on p_T and η of subjets



Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]

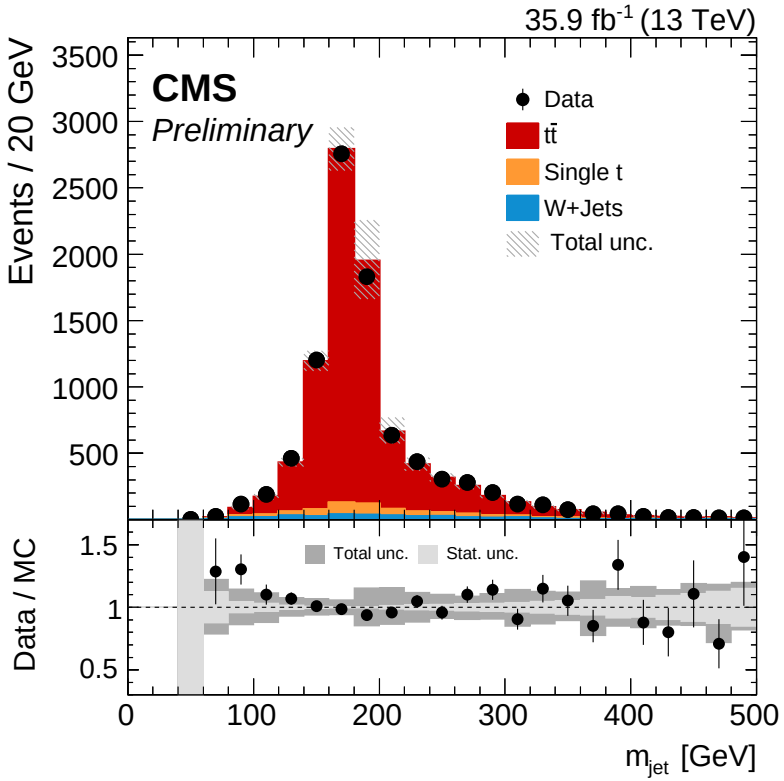


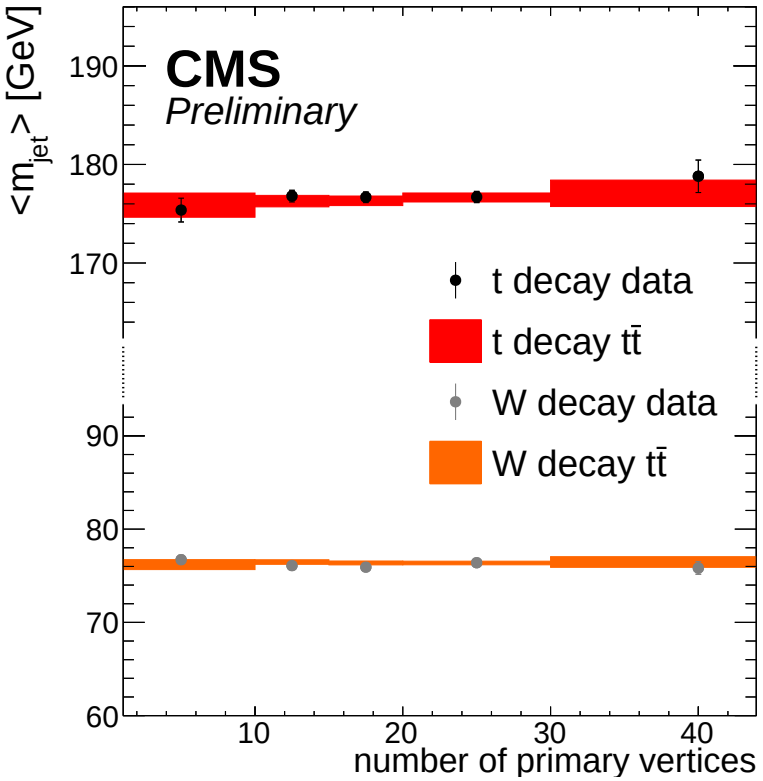


- closure in tW after correction
- cross check in W reconstruction

Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]

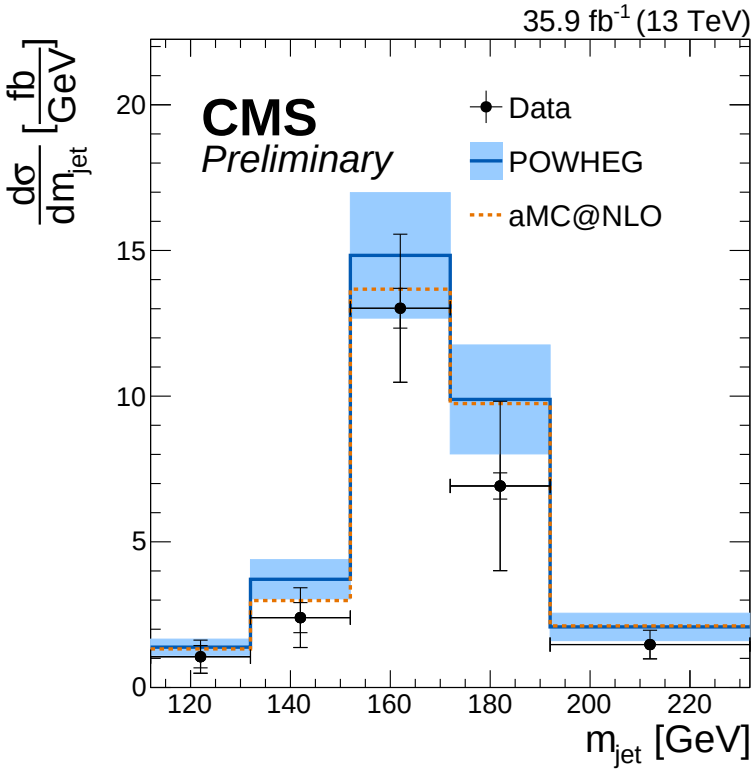


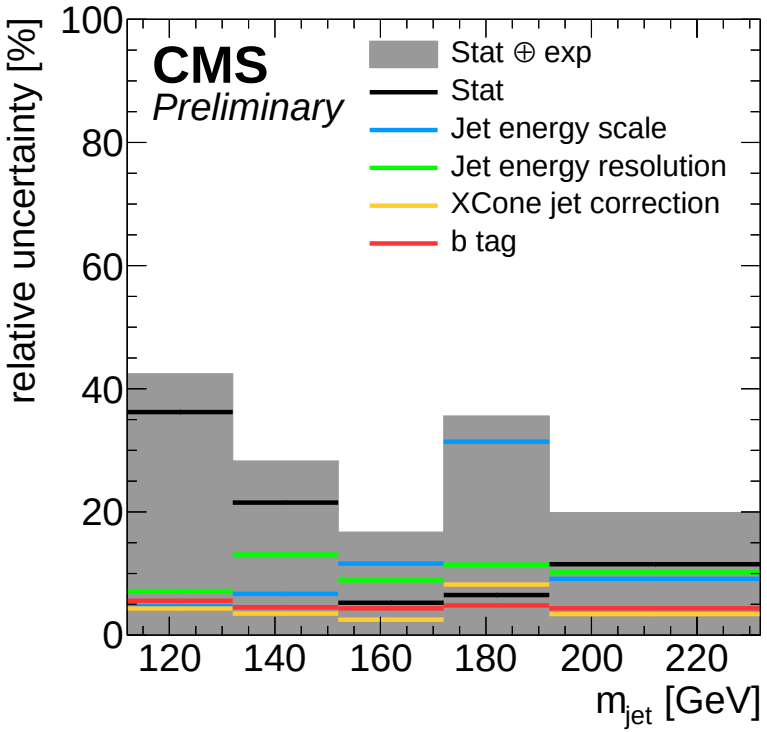


- narrow peak on detector level
- m_{jet} stable against pileup

Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]





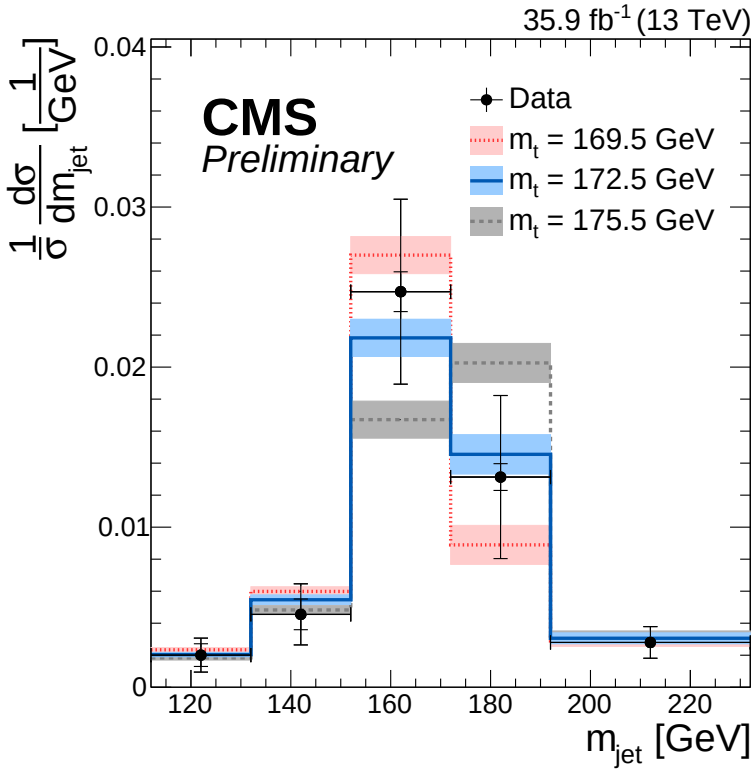
- unfolded distribution
- smaller cross section in data than MC
- dominant uncertainty: jet energy scale

Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]

another feature of substructure measurement:

- normalized distribution sensitive to m_t
- offers an orthogonal measurement of m_t
- advantage: possible comparison with analytical calculations



$$m_t = 172.56 \pm 0.44(\text{stat}) \pm 1.57(\text{exp}) \pm 1.55(\text{model,unfold}) \pm 1.02(\text{theo}) \text{ GeV}$$

$$m_t = 172.56 \pm 2.47(\text{total}) \text{ GeV}$$

8 TeV result:
$\Delta m_t = \pm 9$ GeV
Eur. Phys. J. C 77 (2017) 467

Substructure as a Tool

Using Jet Substructure - Search for aTGC

[CMS Collaboration, CMS-SMP-18-008]

- **aim:** search for anomalous triple gauge couplings
- leptonically decaying W
- hadronically decaying V (Z or W)
- sensitive variable (high) m_{WV}
- V and W are boosted

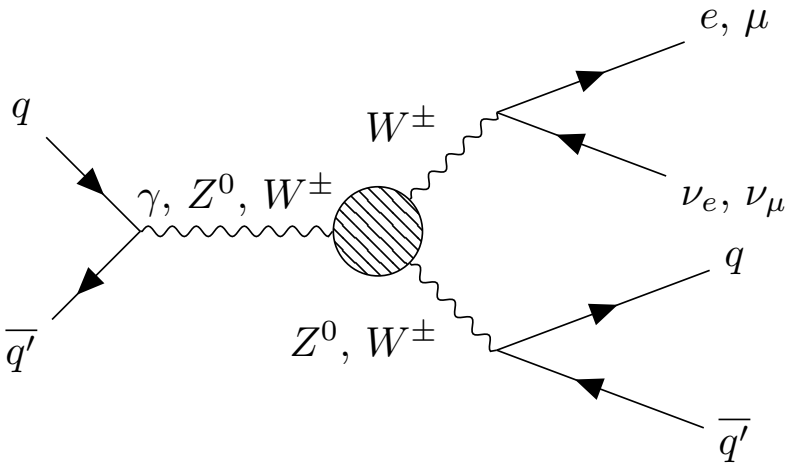
$\rightarrow$ W reconstructed from lepton + p_T^{miss}

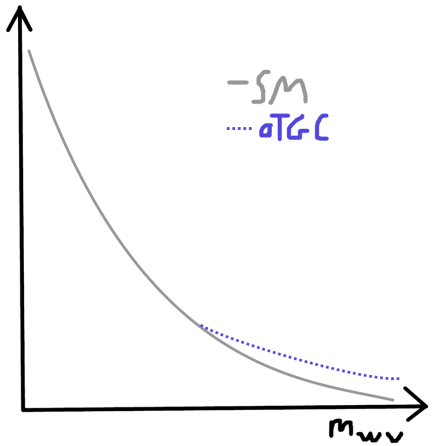
$\rightarrow$ V reconstructed with single jet

- jet identification with τ_{21} and soft drop mass

Jets

anti-k_T, $R = 0.8$, PUPPI

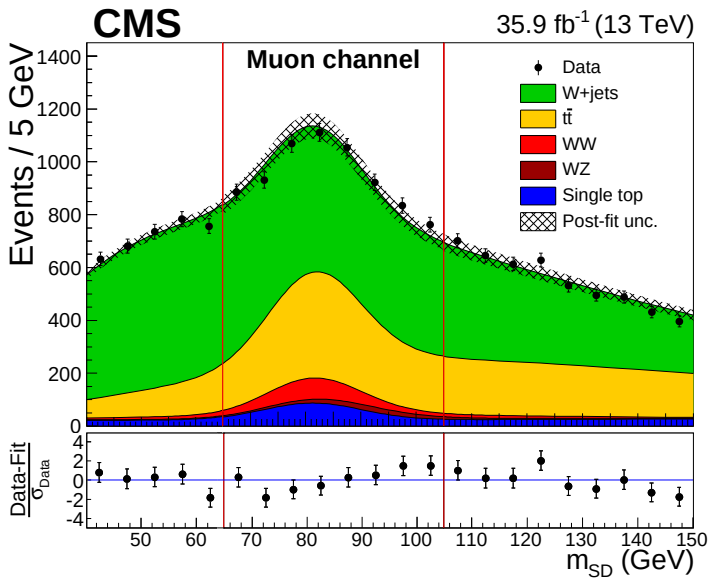


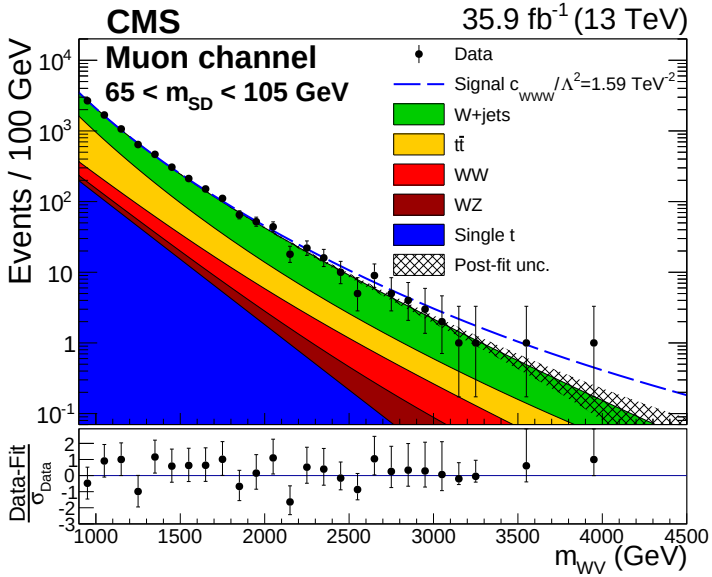


Using Jet Substructure - Search for aTGC

[CMS Collaboration, CMS-SMP-18-008]

- control and signal regions defined by SD mass
- two-dimensional fit in (m_{SD}, m_{WV})
- W+jets contribution suppressed
- sensitivity in tails
- no excess observed





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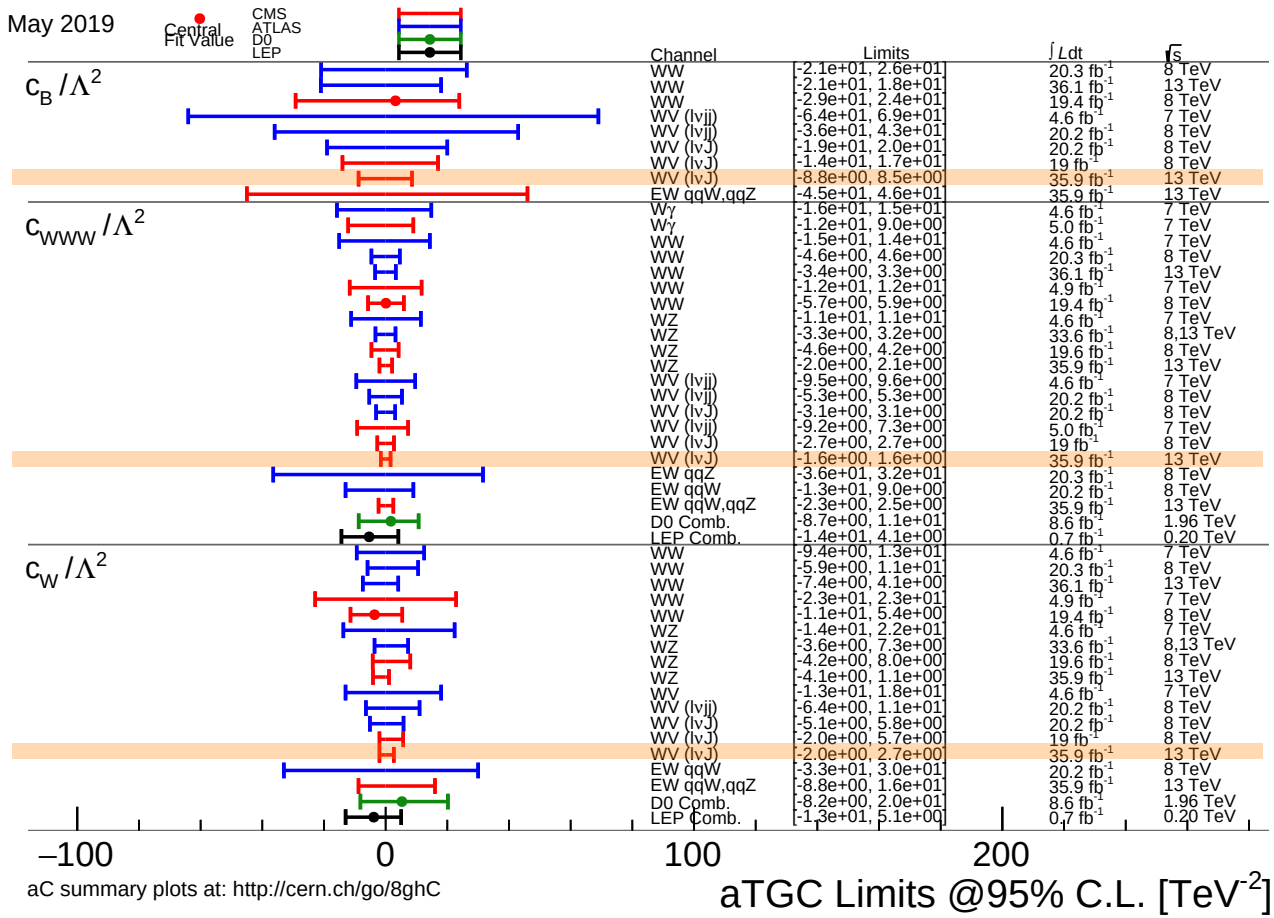
[CMS Collaboration, CMS-SMP-18-008]



$$\delta\mathcal{L} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}\left[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}\right] + \frac{c_W}{\Lambda^2}\left(D_\mu\Phi\right)^\dagger W^{\mu\nu}\left(D_\nu\Phi\right) +$$

$$\frac{c_B}{\Lambda^2}\left(D_\mu\Phi\right)^\dagger B^{\mu\nu}\left(D_\nu\Phi\right)$$

$\rightarrow$ Most stringent limits on aTGC parameters!

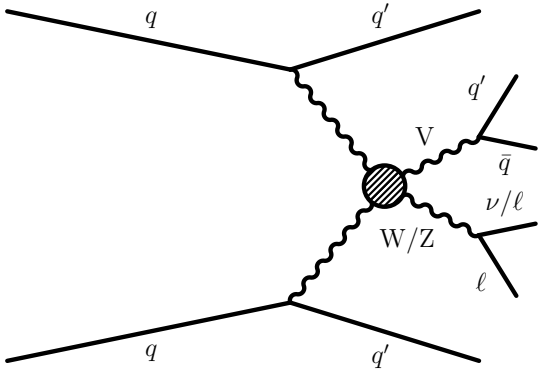
Using Jet Substructure - Search for aQGC

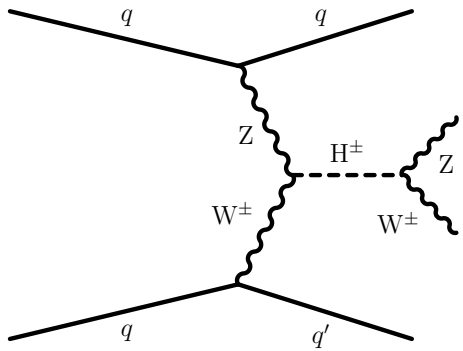
[CMS Collaboration, CMS-SMP-18-006]

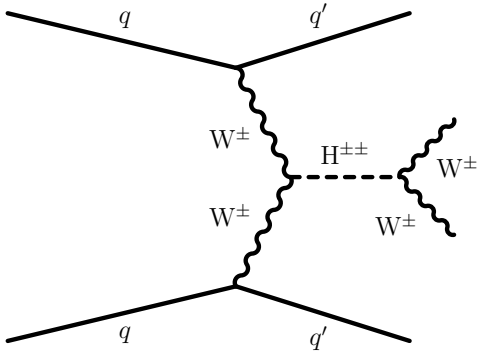
- **aim:** search for anomalous quartic gauge couplings
- also sensitive to charged Higgs models
- VBF $\rightarrow$ forward jets ($\Delta\eta_{jj} > 4.0$)
- 'tag' with leptonic boson decay
- other boson decays hadronically $\rightarrow$ single boosted jet
- sensitive variable (high) M_{ZV} or M_{WV}
- jet identification with τ_{21} and soft drop mass

Jets

anti-k_T, $R = 0.8$, CHS

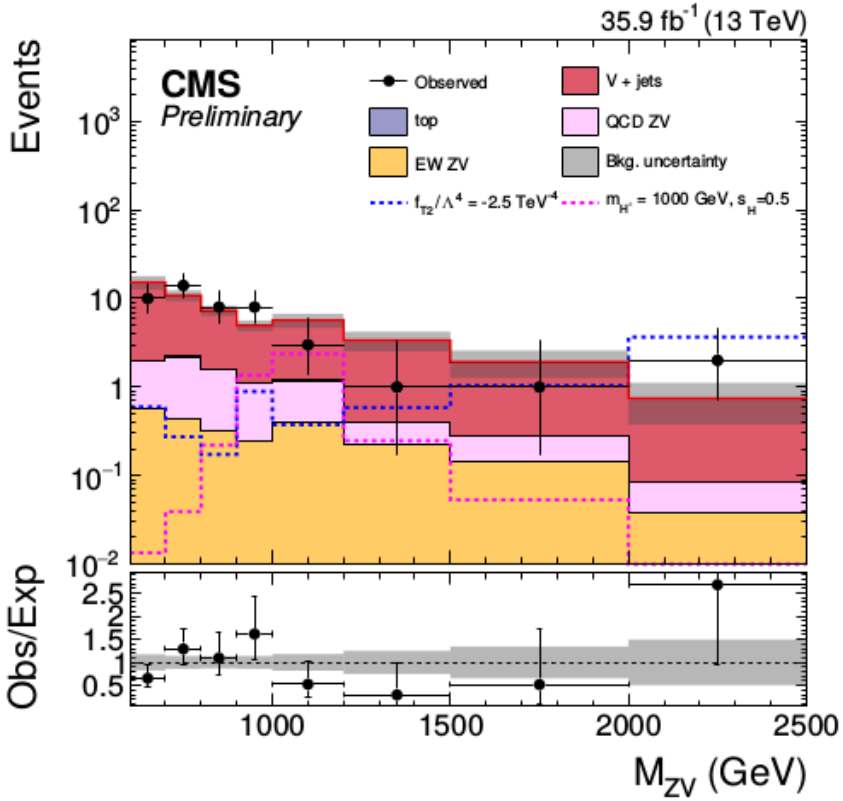


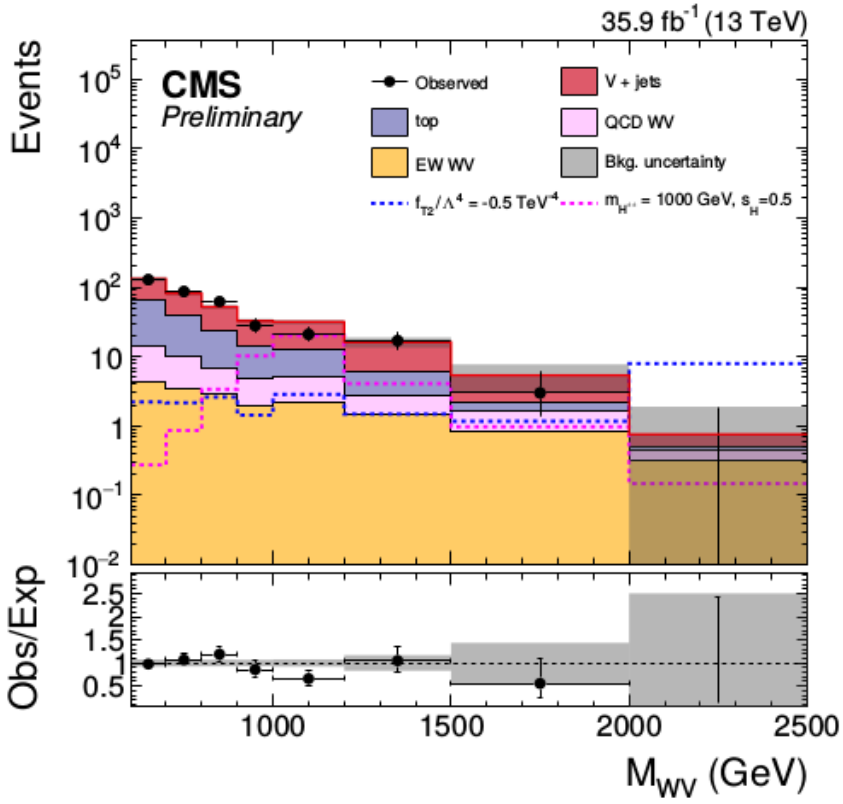




Using Jet Substructure - Search for aQGC

[CMS Collaboration, CMS-SMP-18-006]



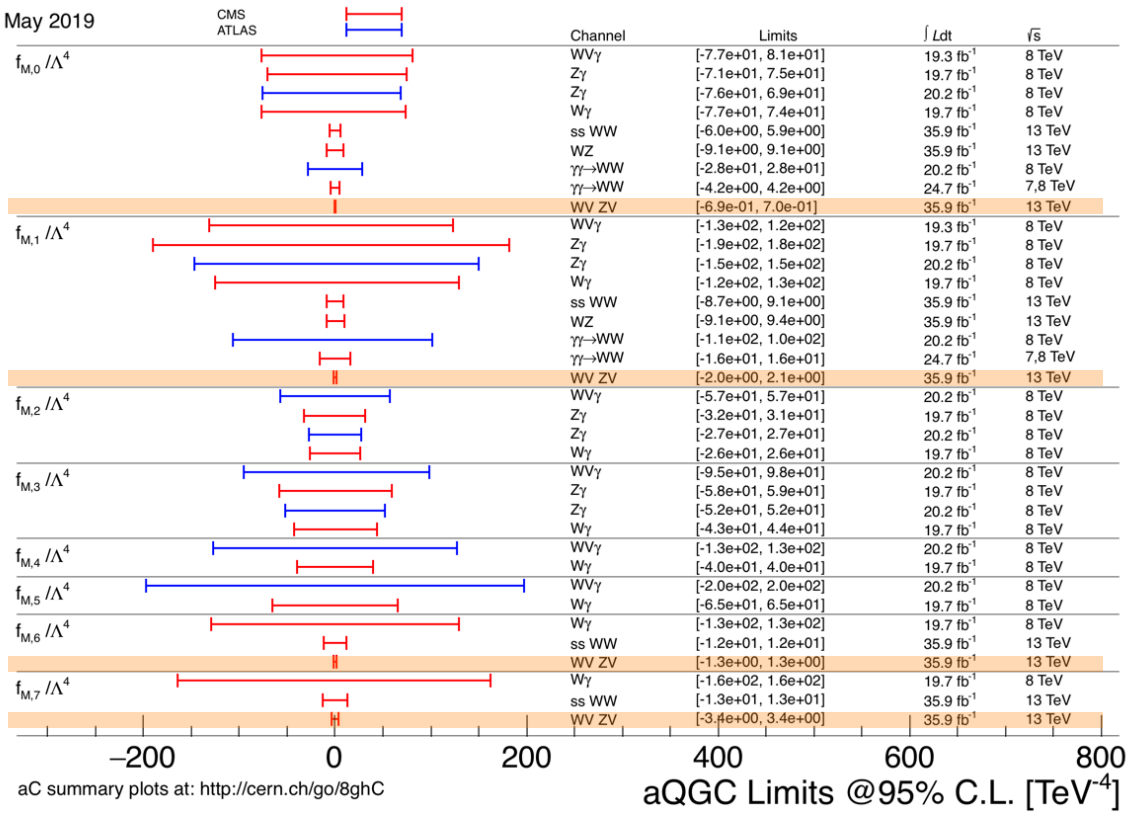


- crucial to cover high masses where bosons are boosted
- no excess observed

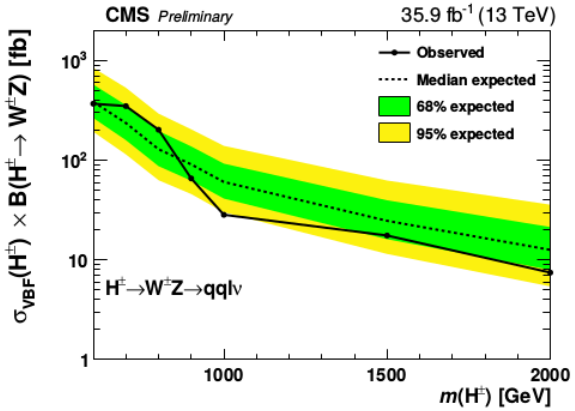
Using Jet Substructure - Search for aQGC

[CMS Collaboration, CMS-SMP-18-006]

Most stringent limits on aQGC parameters!



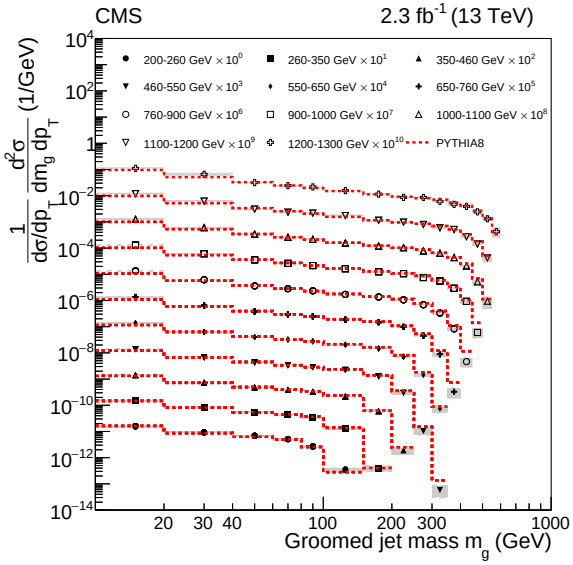
(only limits on $f_{M,i}$ shown here)



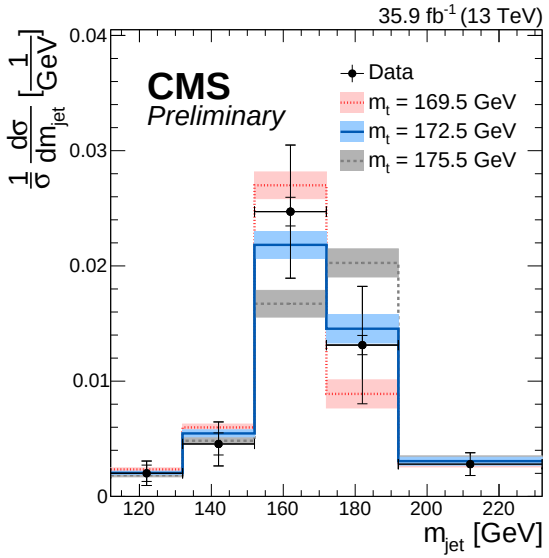
Exclusion limits on charged Higgs production in various final states!

Summary

- anomalous couplings
  - most stringent limits on aTGC and aQGC
  - substructure crucial making boosted topologies accessible



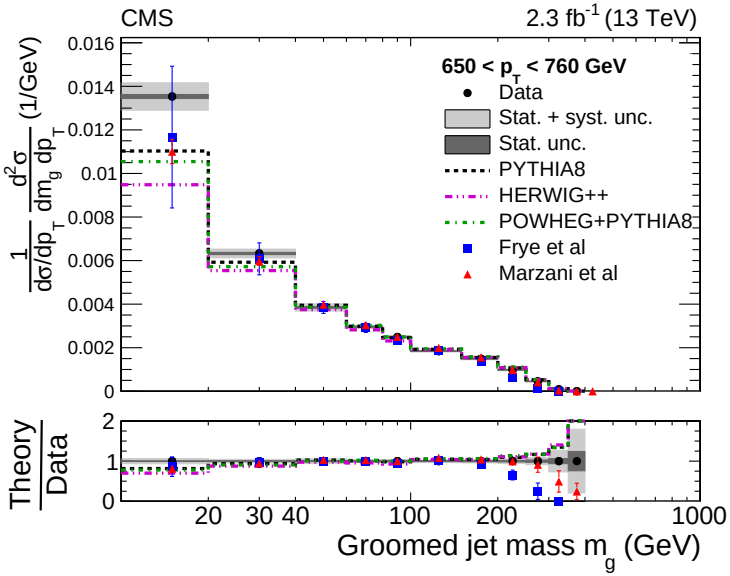
- measurements of substructure
  - substructure measurements help to understand QCD
  - important input to calculations
  - m_t measurement as an orthogonal approach

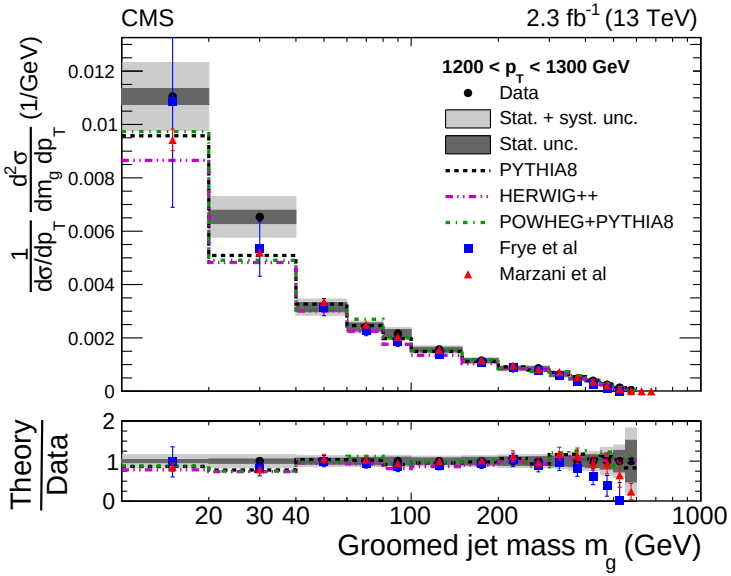


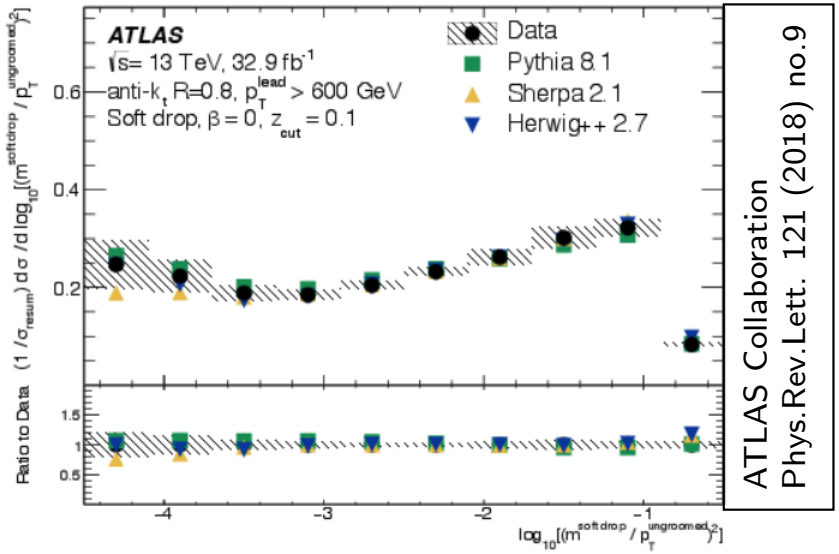
Additional Material
(jet mass in dijet events)

Measuring Jet Mass in Dijet Events

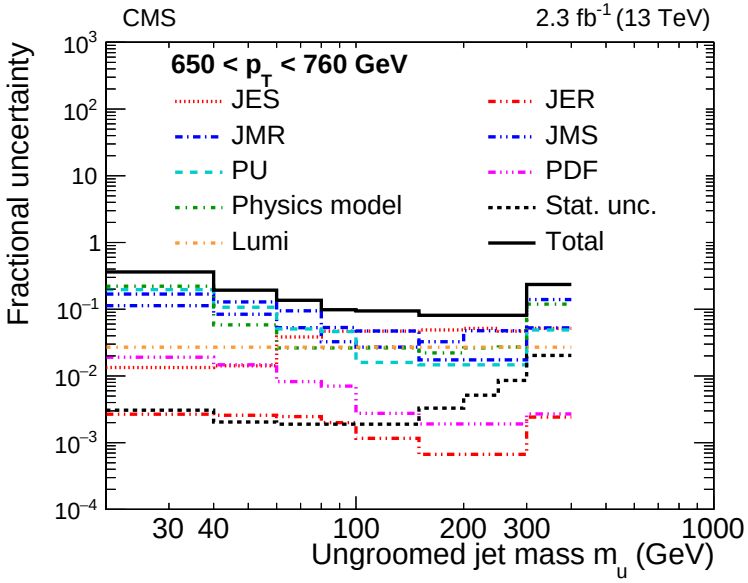
[CMS Collaboration, JHEP 11 (2018) 113]

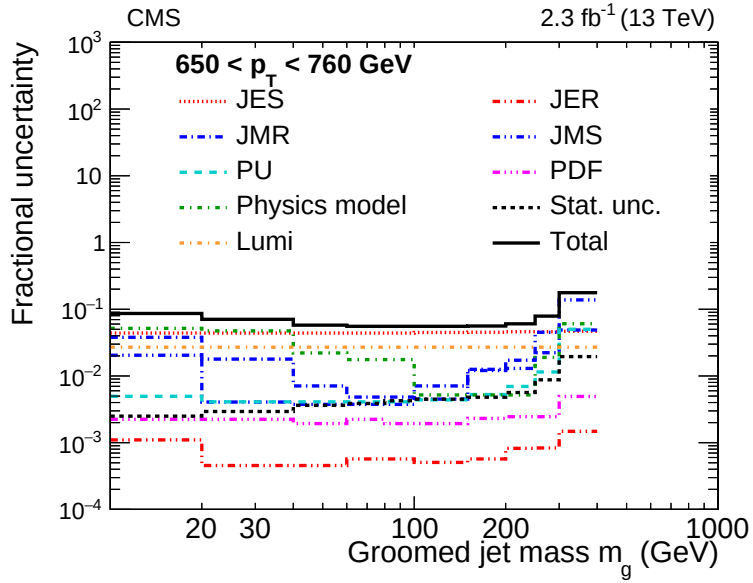




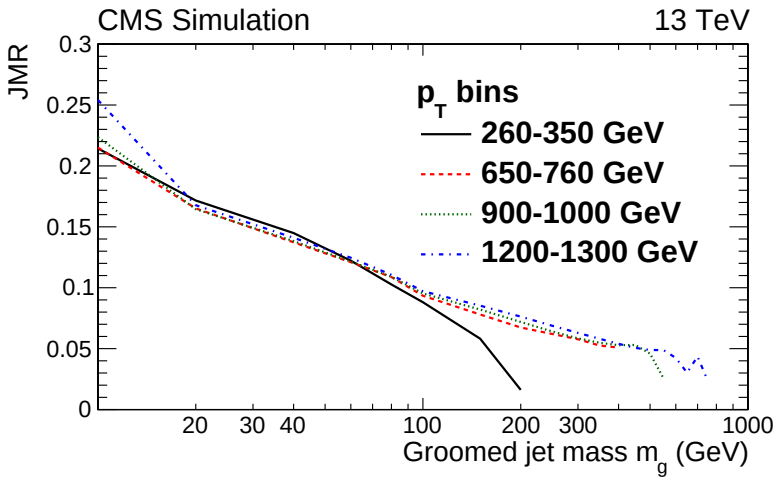


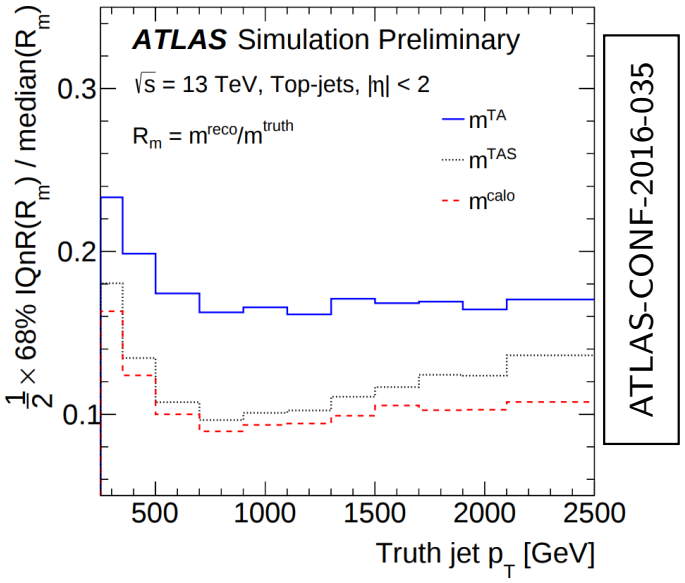
Uncertainties





Jet Mass Resolution

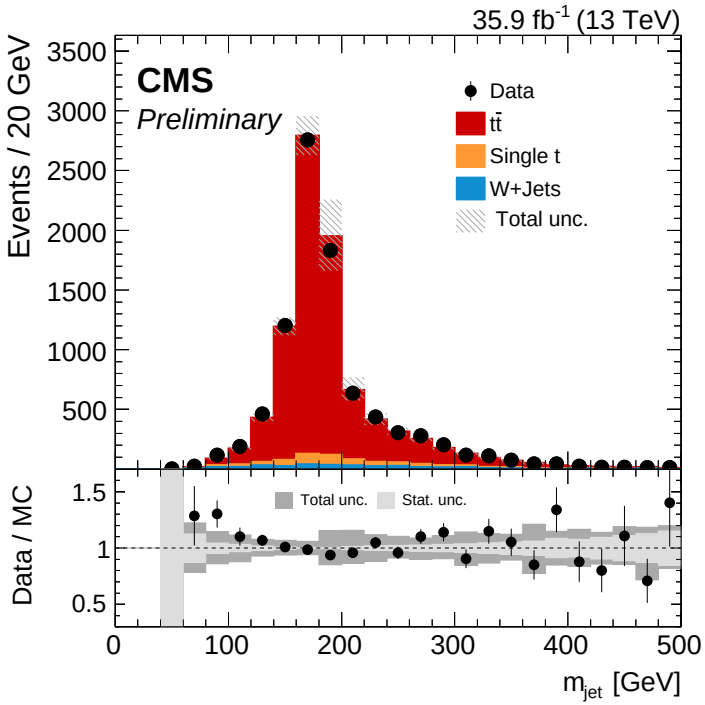


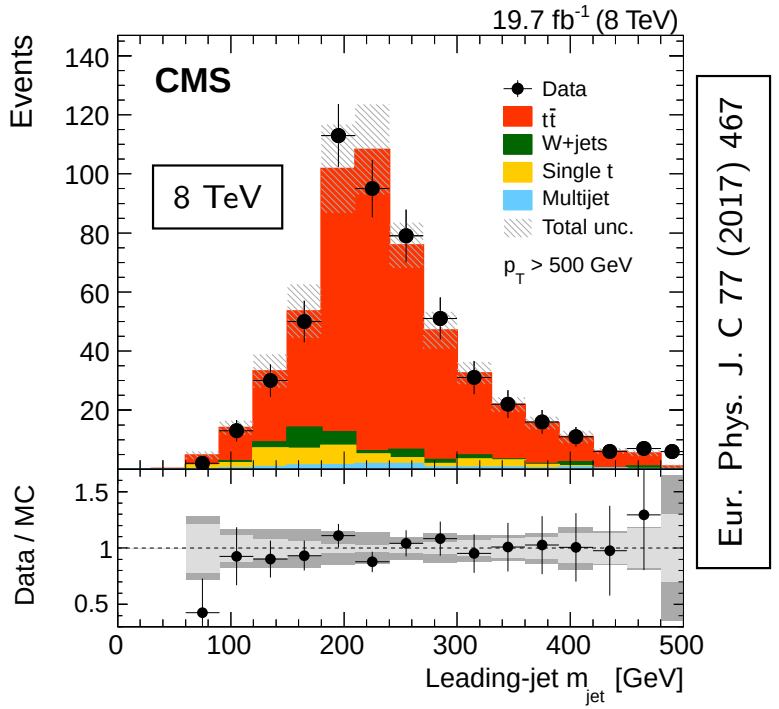


Additional Material
(jet mass in $t\bar{t}$)

Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]



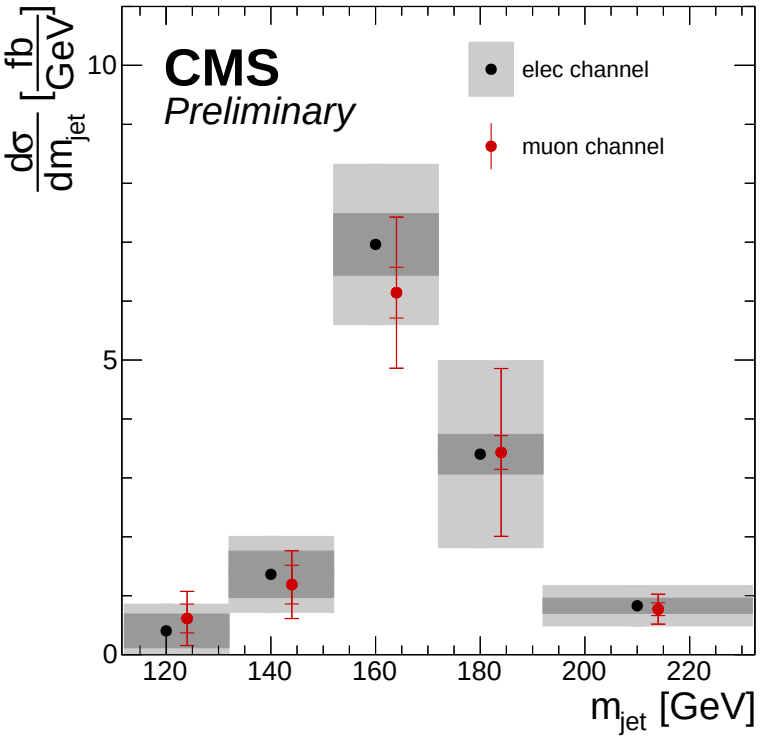


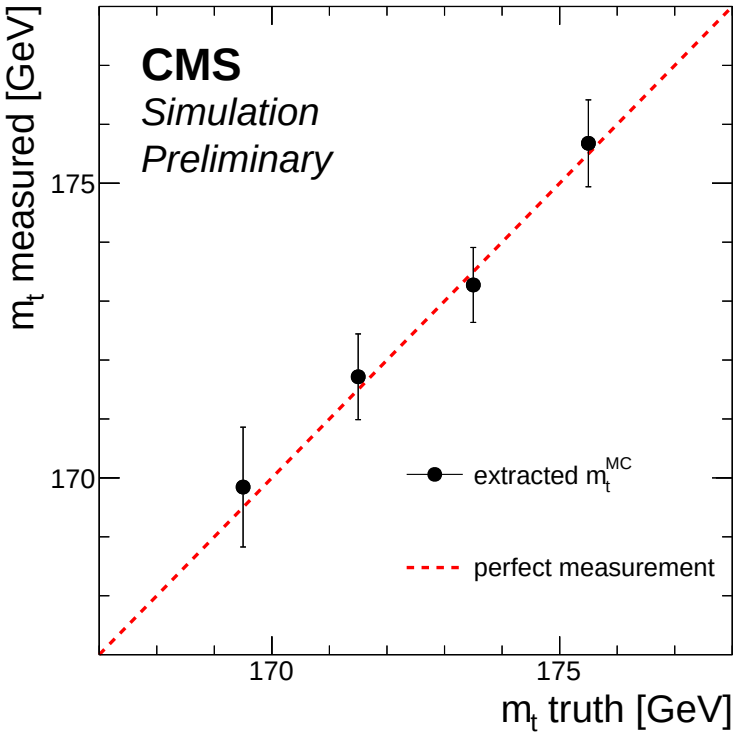
improvement

- better statistics
- no mass shift
- less pile-up effects
- better resolution

Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]



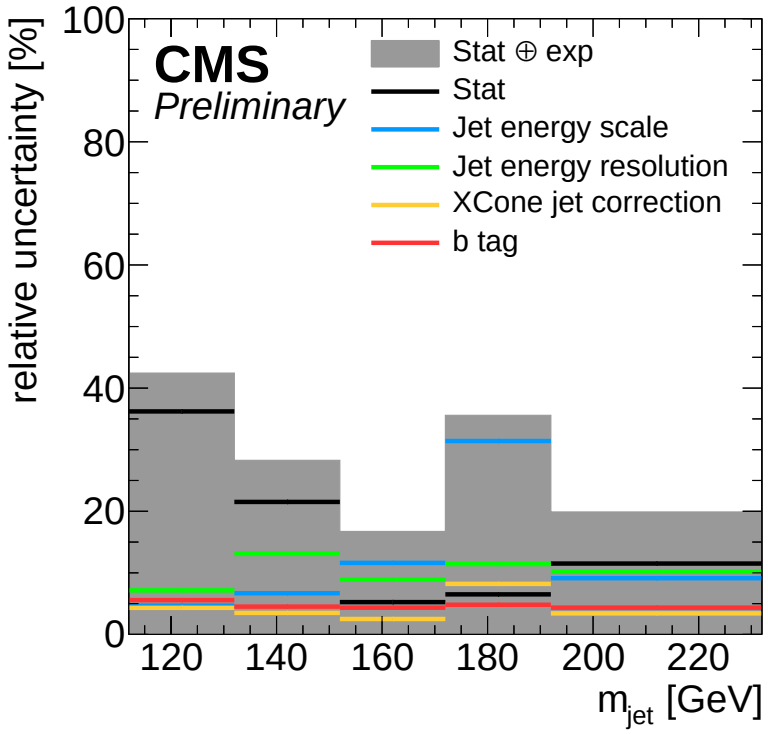


- muon and electron channel compatible
- closure test on mass extraction

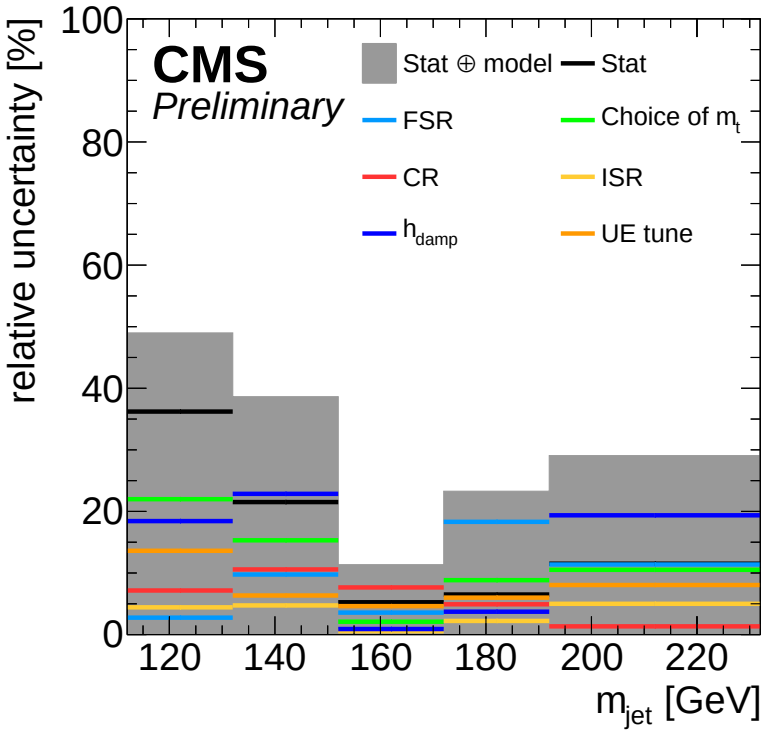
Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]

exp. uncertainties



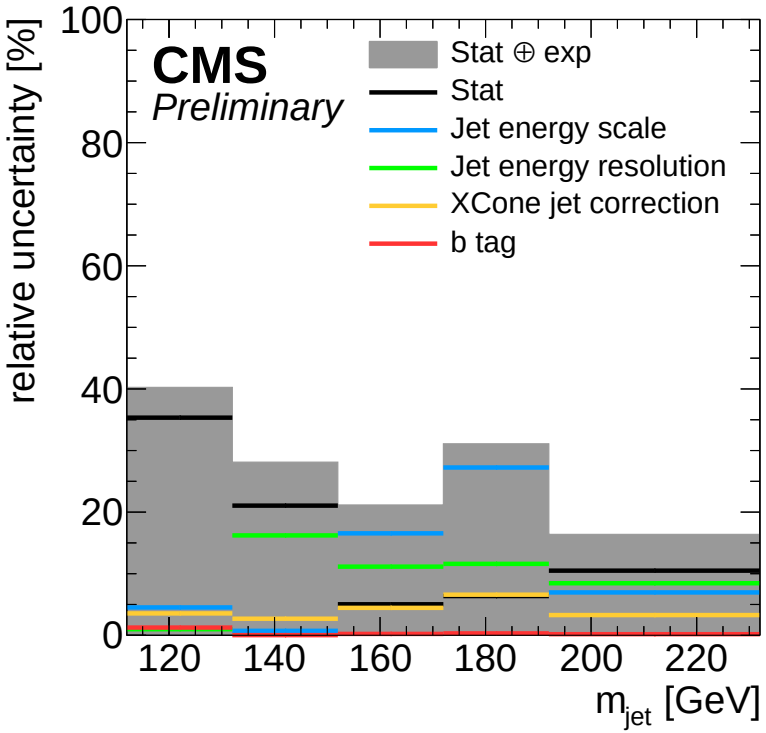
model uncertainties



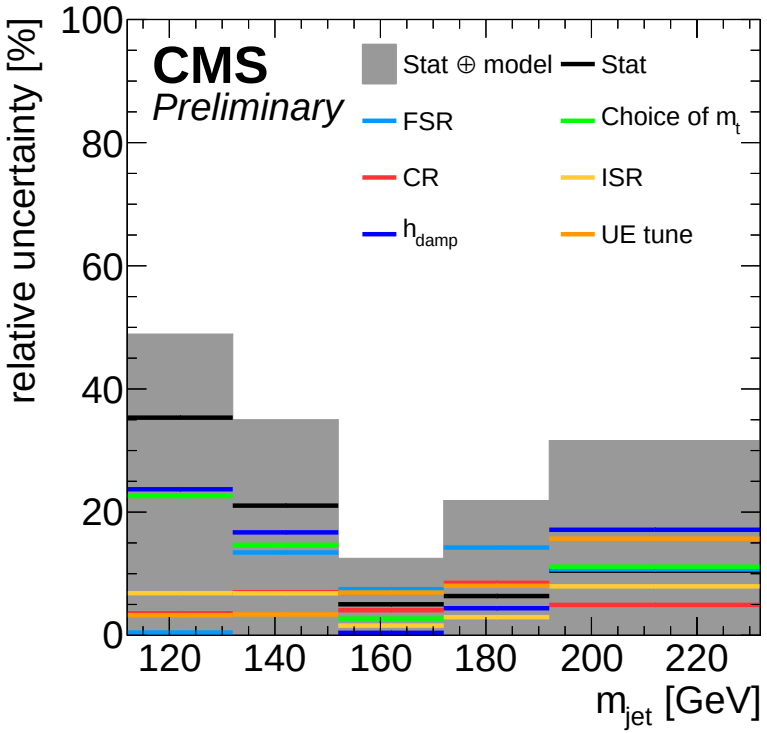
Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, CMS-PAS-TOP-19-005]

exp. uncertainties
(normalized)



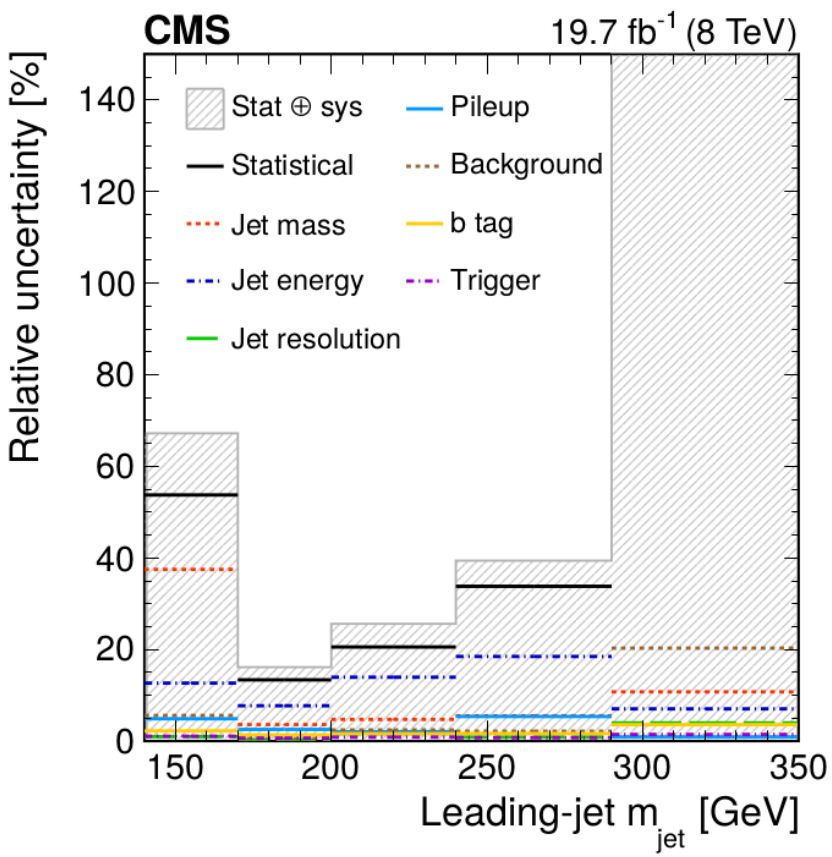
model uncertainties
(normalized)



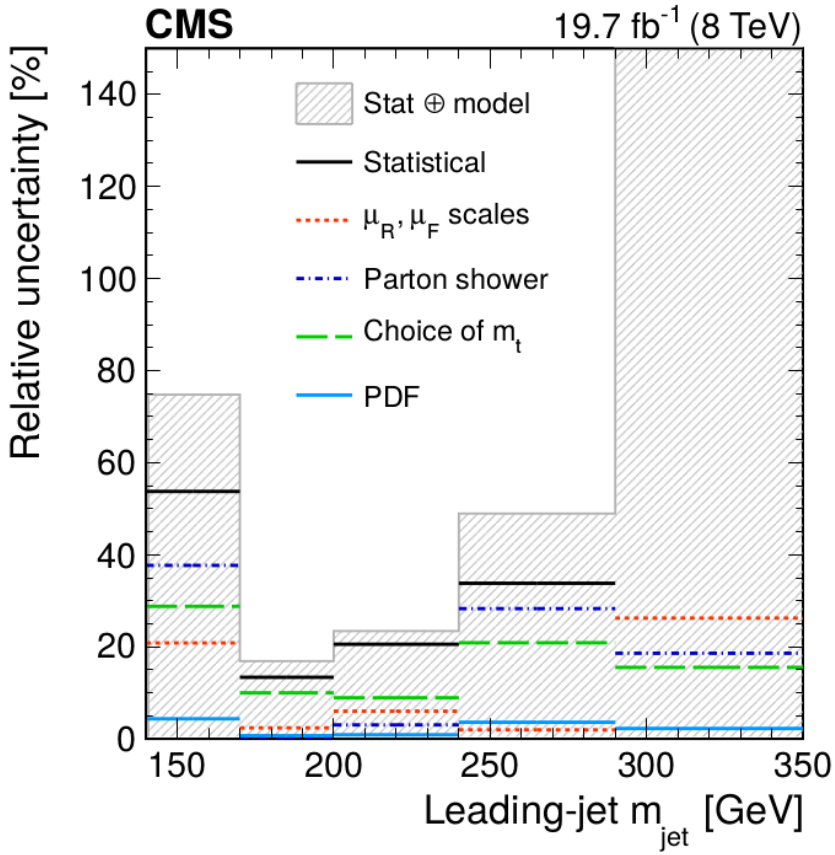
Measuring Jet Mass in $t\bar{t}$

[CMS Collaboration, Eur. Phys. J. C 77 (2017) 467]

exp. uncertainties



model uncertainties

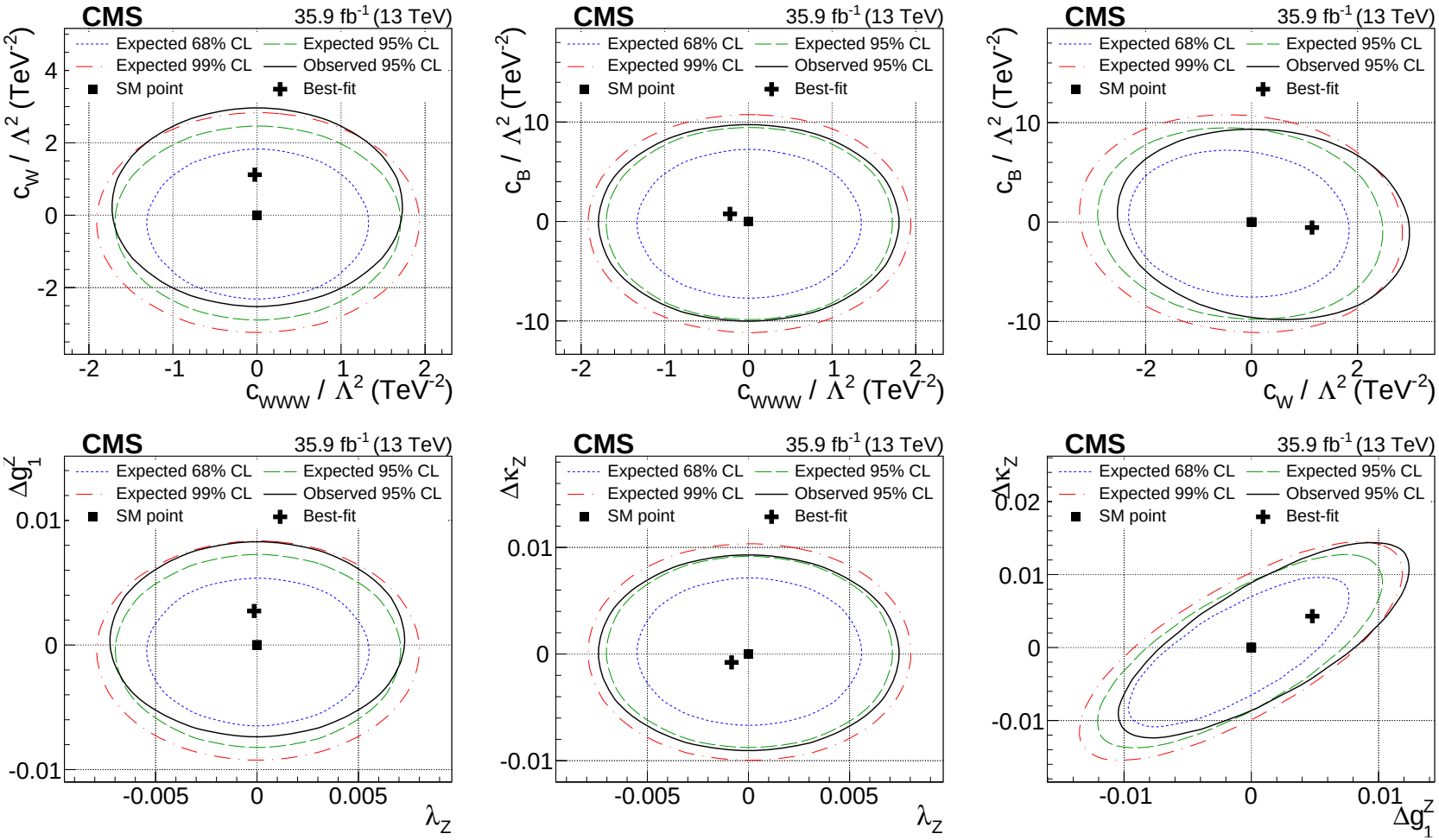


Additional Material
(aTGC)

Using Jet Substructure - Search for aTGC

[CMS Collaboration, CMS-SMP-18-008]

limits on aTGC parameters



normalization uncertainties [%]

	Electron channel				Muon channel			
Uncertainty source	$t\bar{t}$	Single t	WW	WZ	$t\bar{t}$	Single t	WW	WZ
PDF	2.79	0.22	1.93	2.44	2.71	0.25	1.78	2.54
μ_R, μ_F	17.99	0.94	5.77	4.82	17.74	1.06	5.99	4.26
Luminosity	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Pileup	0.59	0.29	0.90	1.40	0.40	0.41	0.82	0.67
V tag	14	14	14	14	14	14	14	14
b tag	1.05	0.85	0.04	0.08	1.04	0.84	0.03	0.08
b mistag	0.04	0.05	0.02	0.04	0.05	0.05	0.03	0.04
Jet energy scale	4.41	4.94	4.26	2.44	3.54	2.97	3.75	2.50
Jet energy resolution	1.79	3.44	1.85	2.69	0.85	0.91	0.62	2.92
Lepton energy scale	0.80	1.45	1.53	0.94	0.68	1.14	1.72	1.19
Lepton energy resolution	0.26	1.22	0.11	0.21	0.02	0.27	0.14	0.33
Lepton ID	2.12	2.22	2.30	2.26	1.81	2.04	2.55	2.42
p_T^{miss}	0.91	1.50	1.01	0.64	0.59	0.99	0.24	0.17
Total	23.74	15.84	16.44	15.91	23.30	14.85	16.31	15.80

Additional Material
(aQGC)

Using Jet Substructure - Search for aQGC

[CMS Collaboration, CMS-SMP-18-006]

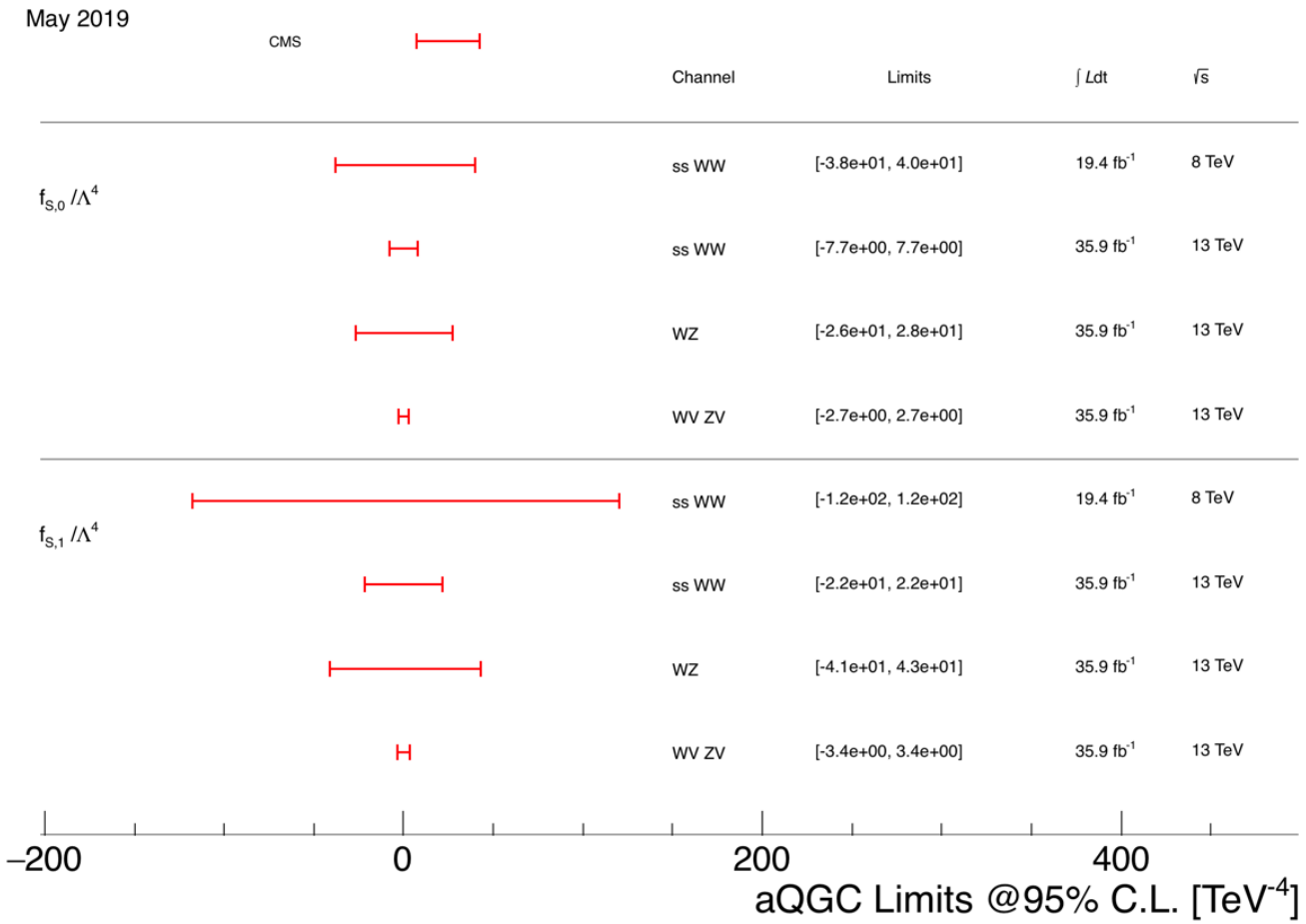
	Observed (TeV^{-4})
f_{S0}/Λ^4	$[-2.7, 2.7]$
f_{S1}/Λ^4	$[-3.4, 3.4]$
f_{M0}/Λ^4	$[-0.69, 0.70]$
f_{M1}/Λ^4	$[-2.0, 2.1]$
f_{M6}/Λ^4	$[-1.3, 1.3]$
f_{M7}/Λ^4	$[-3.4, 3.4]$
f_{T0}/Λ^4	$[-0.12, 0.11]$
f_{T1}/Λ^4	$[-0.12, 0.13]$
f_{T2}/Λ^4	$[-0.28, 0.28]$

Most stringent limits on aQGC operators!

Using Jet Substructure - Search for aQGC

[CMS Collaboration, CMS-SMP-18-006]

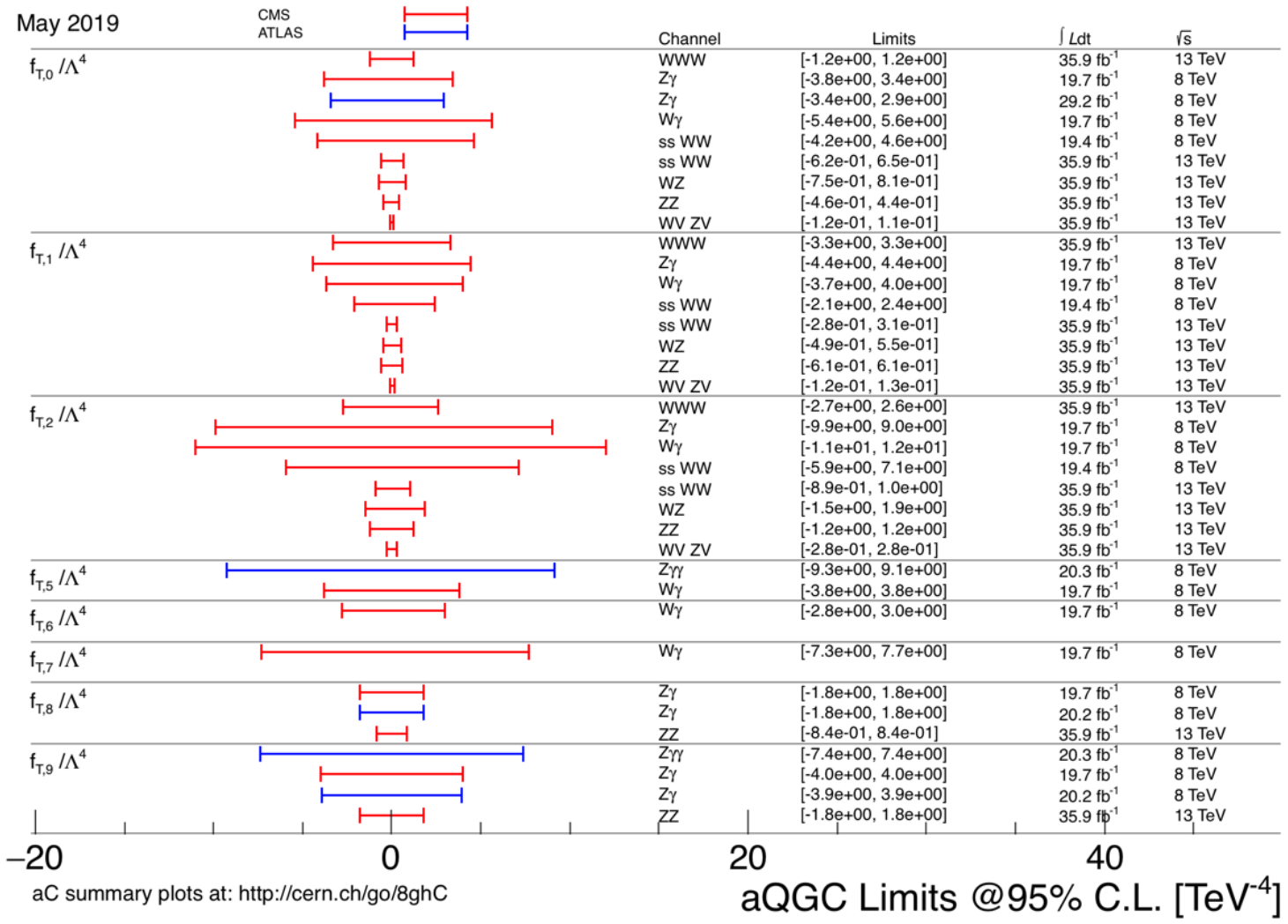
Limits on $f_{S,i}$



Using Jet Substructure - Search for aQGC

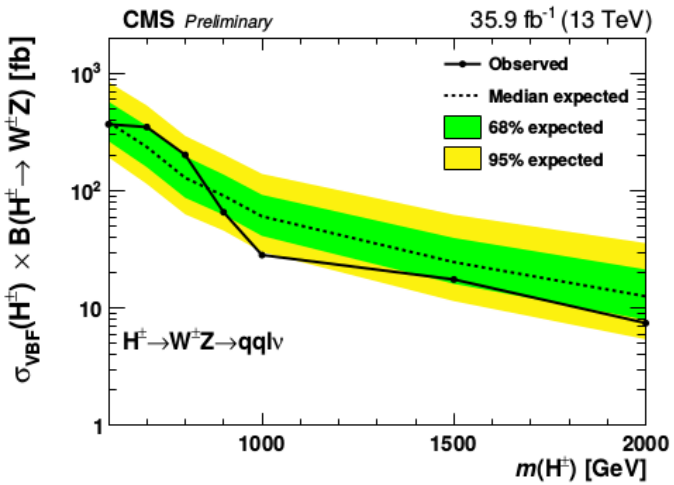
[CMS Collaboration, CMS-SMP-18-006]

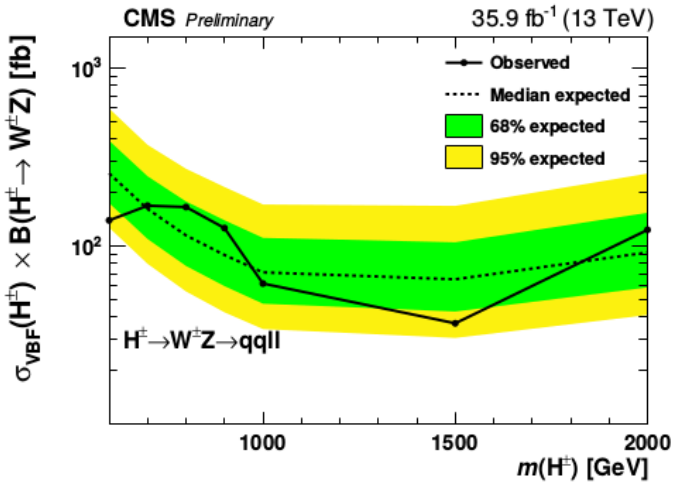
Limits on $f_{T,i}$

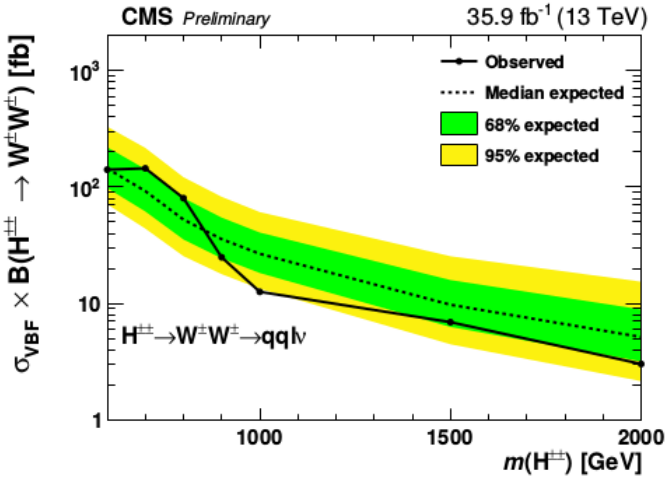


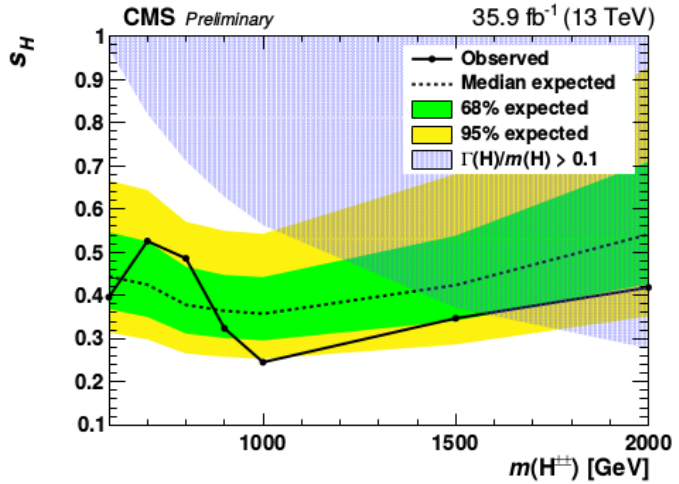
Using Jet Substructure - Search for aQGC

[CMS Collaboration, CMS-SMP-18-006]









Exclusion limits on charged Higgs production in various final states! (charged Higgs predicted by Georgi-Machacek model, $H^{\pm}$, $H^{\pm\pm}$ degenerated in mass)

Using Jet Substructure - Search for aQGC

[CMS Collaboration, CMS-SMP-18-006]

relative uncertainties

Source	Shape	Signal (%)	V+jets (%)	SM EW (%)	QCD VV (%)	Top quark (%)
Renorm./fact. scales	✓	11–22	—	11–22	32–38	—
PDF	✓	7–17	—	4–17	5–9	—
Jet momentum scale	✓	2–13	—	1–17	1–20	5–20
V jet selection		8.0	—	8.0	8.0	—
GM model EW		7.0	—	—	—	—
Bkg. normalization		—	7 (16)	—	—	5.0
V+jets shape	✓	—	5–200	—	—	—
Integrated luminosity		2.5	—	2.5	2.5	—
Lepton efficiency		2.2 (2.8)	—	2.2 (2.8)	2.2 (2.8)	—
Lepton momentum scale	✓	0.5–3.5	—	0.5–3.5	1.5–7.5	1.0–5.0
b quark jet efficiency		2.0	—	2.0	2.0	3.0
Jet/$p_{\mathrm{T}}^{\mathrm{miss}}$ resolution		4.0	—	3.0	2.0	—
Pileup modeling		4.0	—	4.0	4.0	—
Limited MC event count	✓	1–2	—	6–20 (12–39)	7–49 (17–57)	5–50 (3–70)