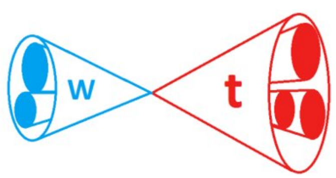
Search for heavy BSM particles coupling to third generation quarks at CMS

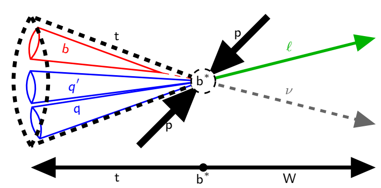
Anna Benecke (UCLouvain)
on behalf of the CMS Collaboration

Introduction

Excited bottom quarks (b*)

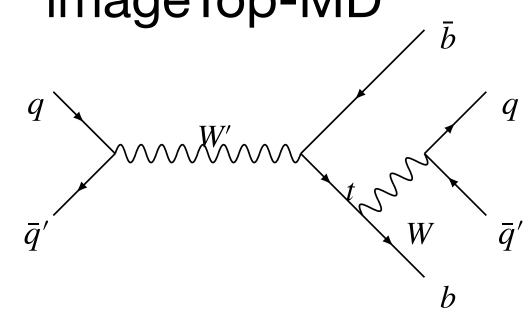
- Combination of all-hadronic and l+jets
- Using PUPPI and HOTVR

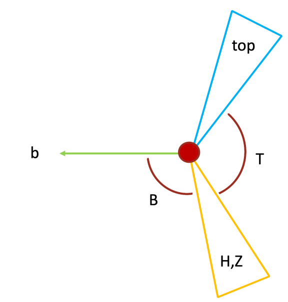




Heavy gauge boson (W')

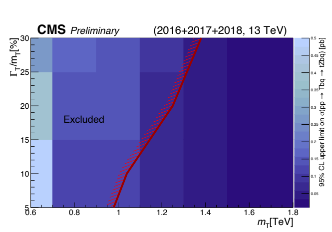
- W' → tb, W' → VLQ+q
- Using PUPPI + DeepAK8-MD and imageTop-MD

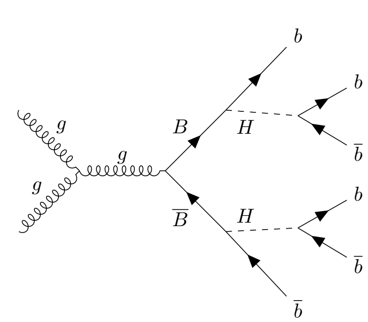




Vector-like quarks (T/B)

- T → tZ($\nu\nu$), BB →6b
- Cover merged, partially merged and resolved regime
- Different widths tested





Disclaimer: I will present recent results of the CMS Collaboration with my personal selection. I will also stress new techniques used in the different analyses

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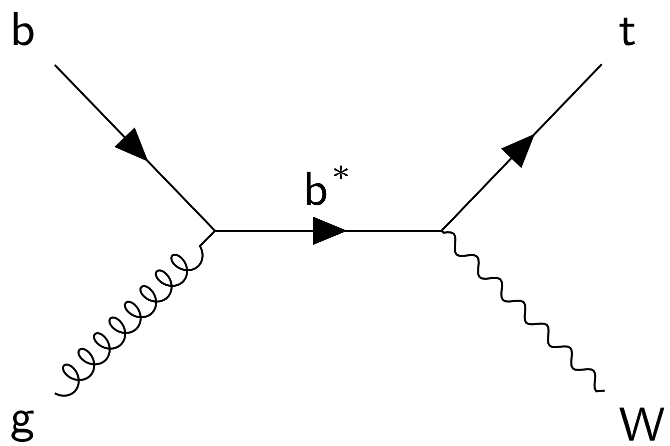
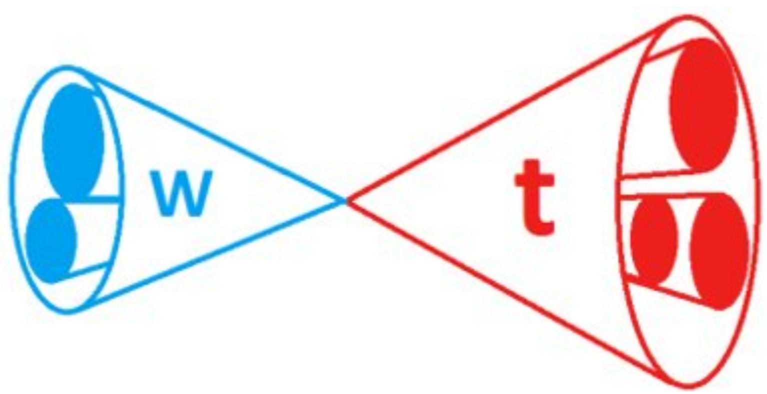
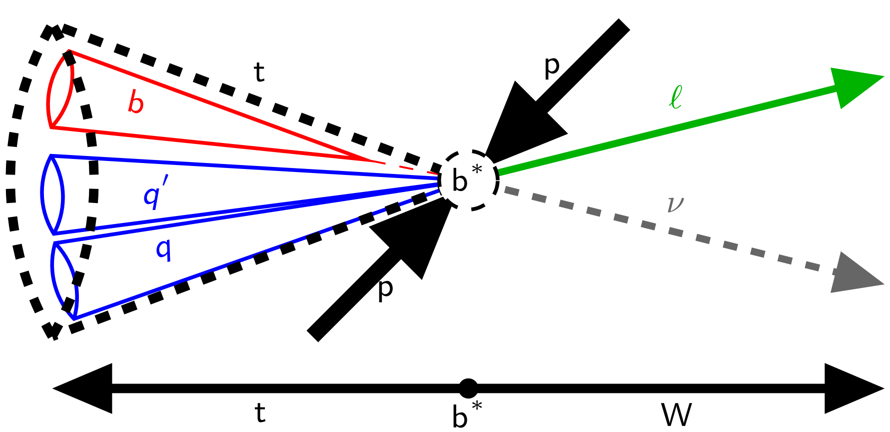




(graphic credit to Lucas Corcodilos)

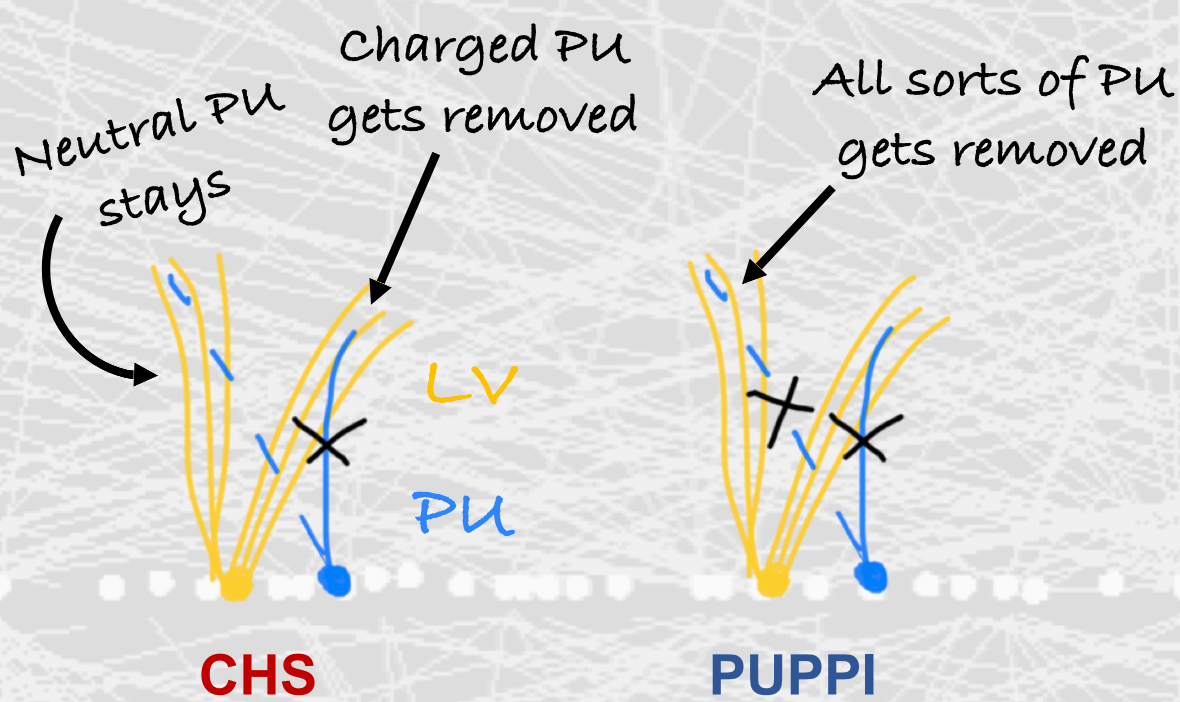


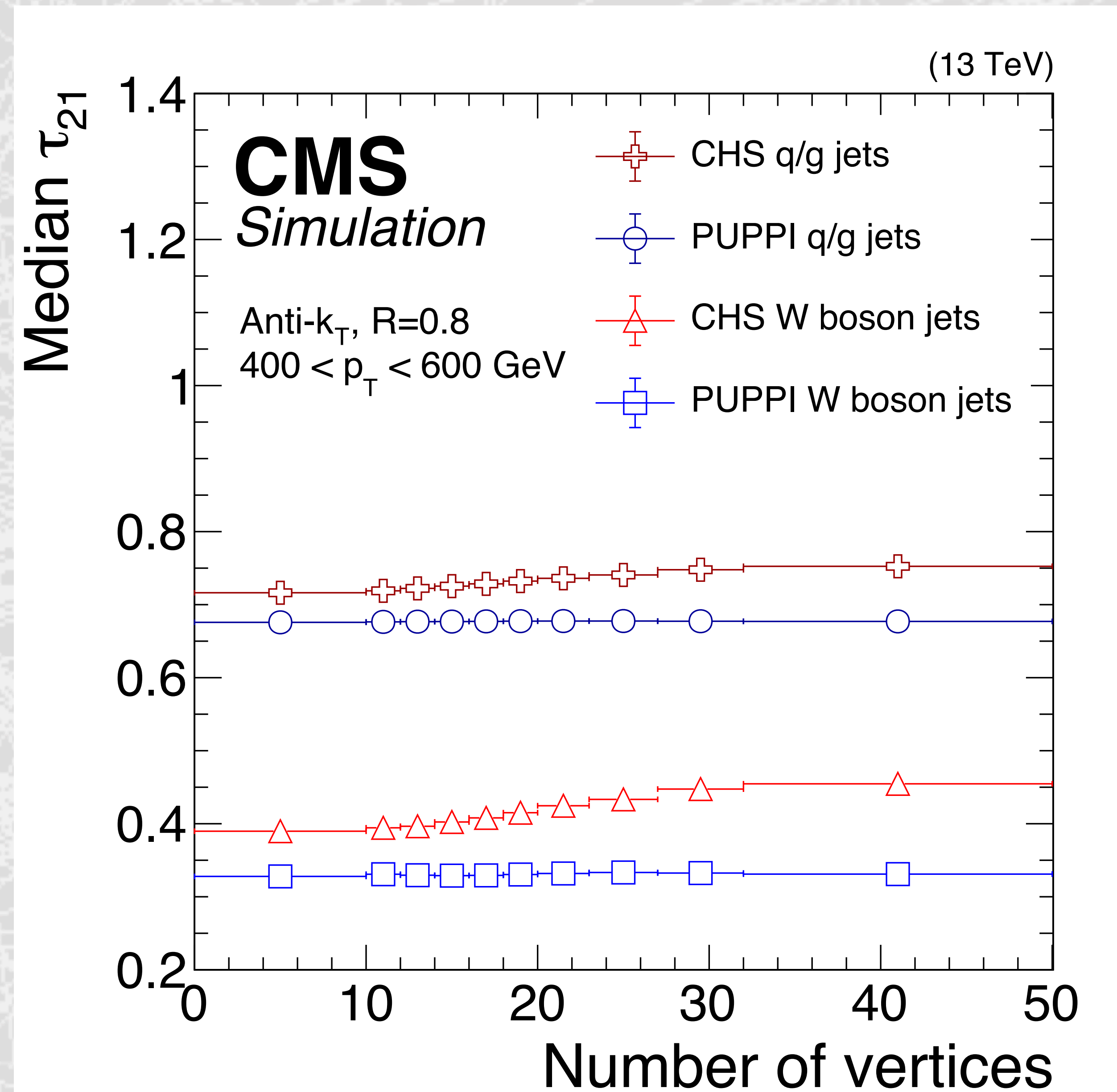
(graphic credit to Alexander Fröhlich)

- Search for b* → tW
- Combination of l+jets (CMS-PAS-B2G-20-010) and all-hadronic (CMS-B2G-19-003) channels
- Sensitive variables: m_t and m_{tW}
- Bkg. estimation from data and simulation using control regions with pass and fail ratio/ transfer function
- Using PUPPI for large-cone jets
- l+jets: using HOTVR to identify the large-cone jet originating from the t quark

Pileup per particle identification (PUPPI)

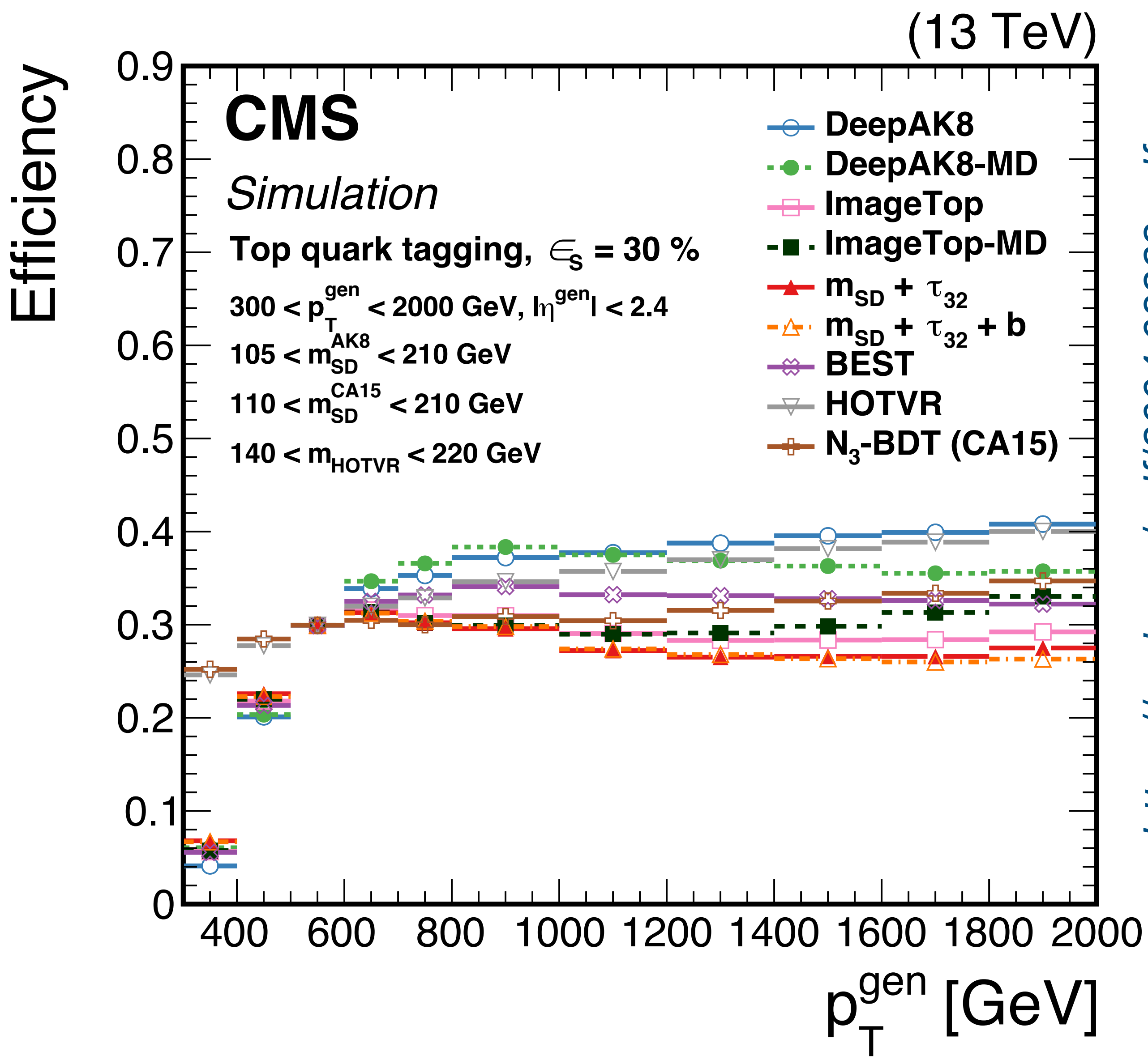
Performance studied in CMS extensively in CMS-JME-18-001



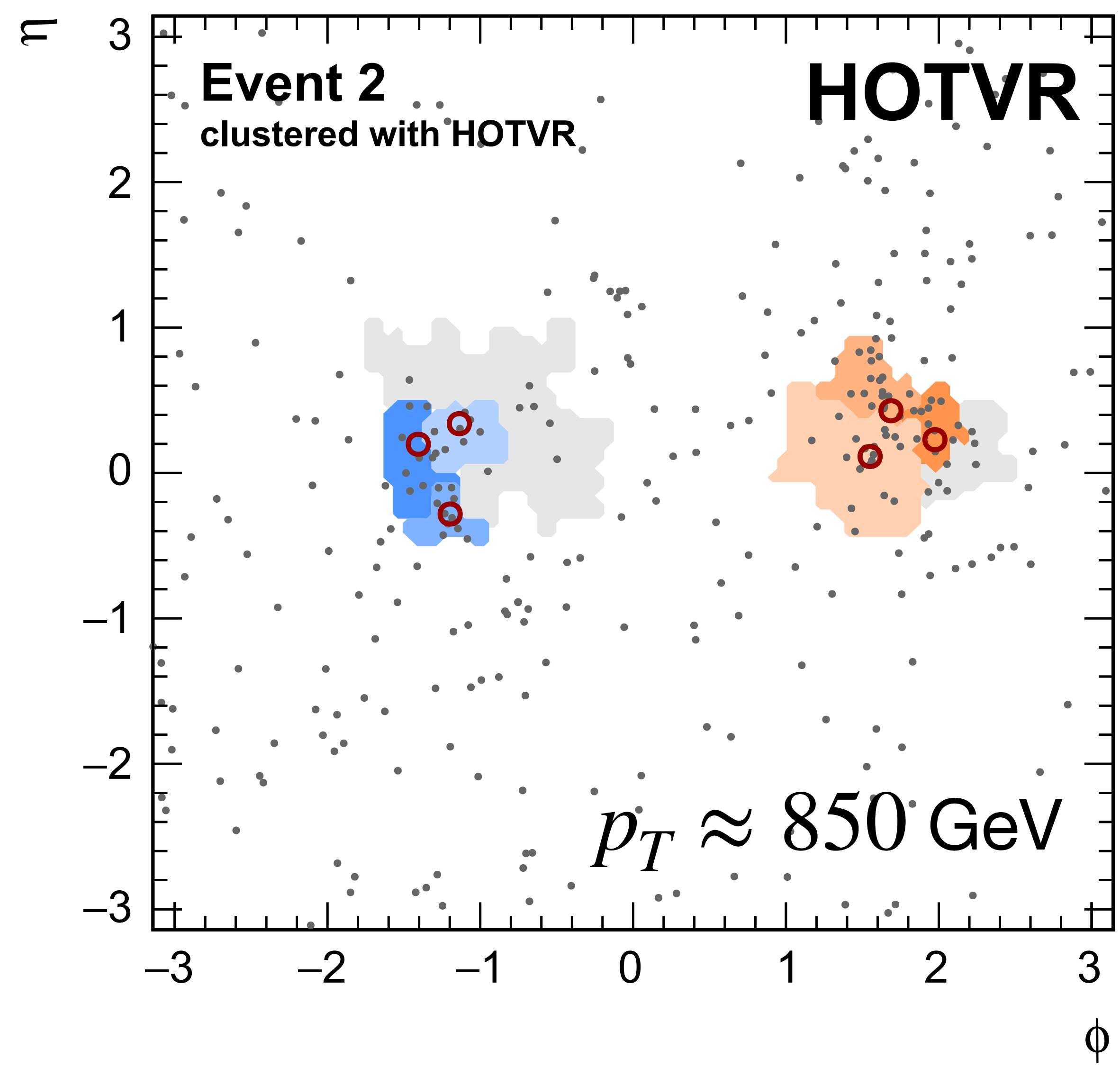


PUPPI has a high pileup stability compared to **CHS**

Heavy object tagging with variable R (HOTVR)



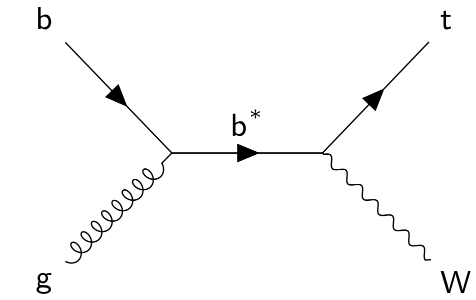
https://arxiv.org/pdf/2004.08262.pdf



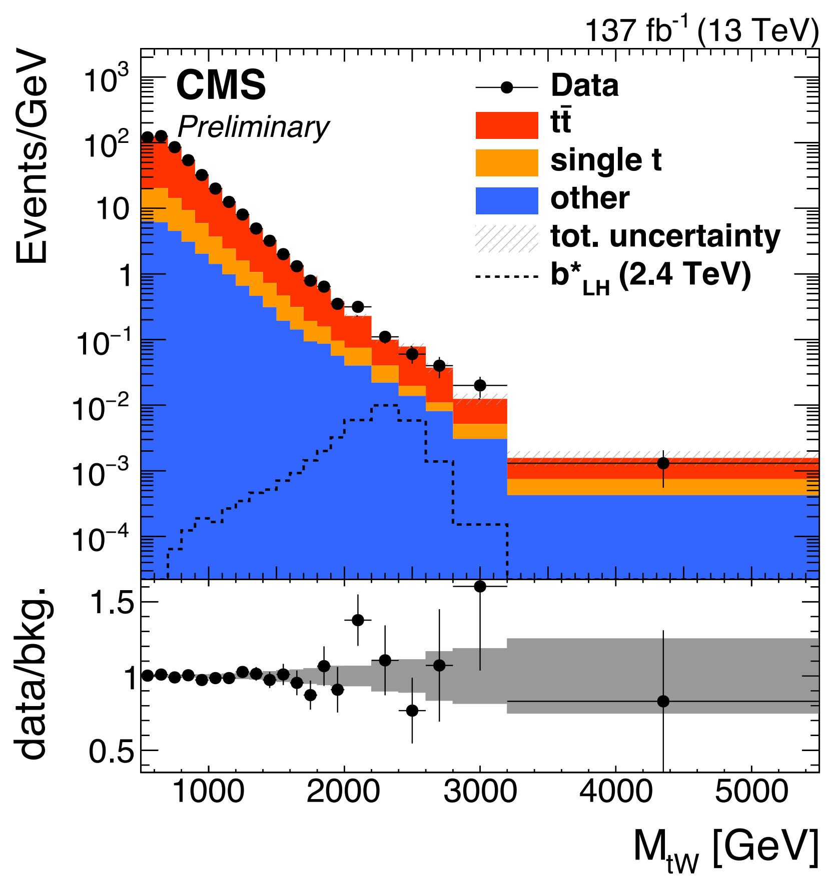
https://arxiv.org/abs/1606.04961

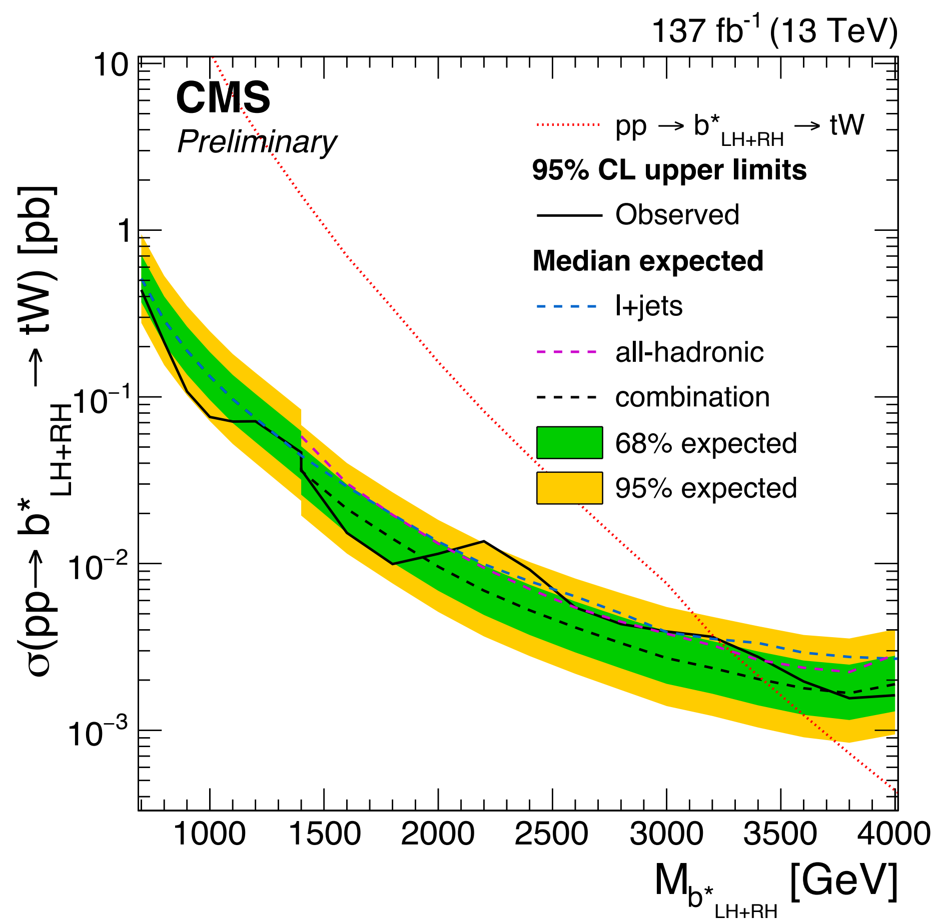
- Classical tagger suffer from inefficiency at low p_T because of cone size
- HOTVR adapts the jet radius to the p_T of the jet

Excited bottom quark (b*)



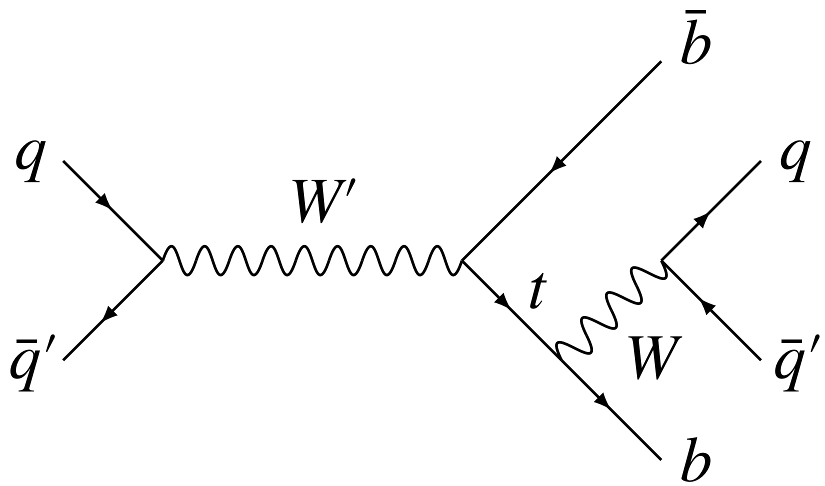
- Combination of l+jets (CMS-PAS-B2G-20-010) and all-hadronic (CMS-B2G-19-003) channel
- Improved by almost a factor two compared to previous results
- Excluded at 95% CL up to 2.95 (LH), 3.03 (RH) and 3.22 TeV (LH+RH)

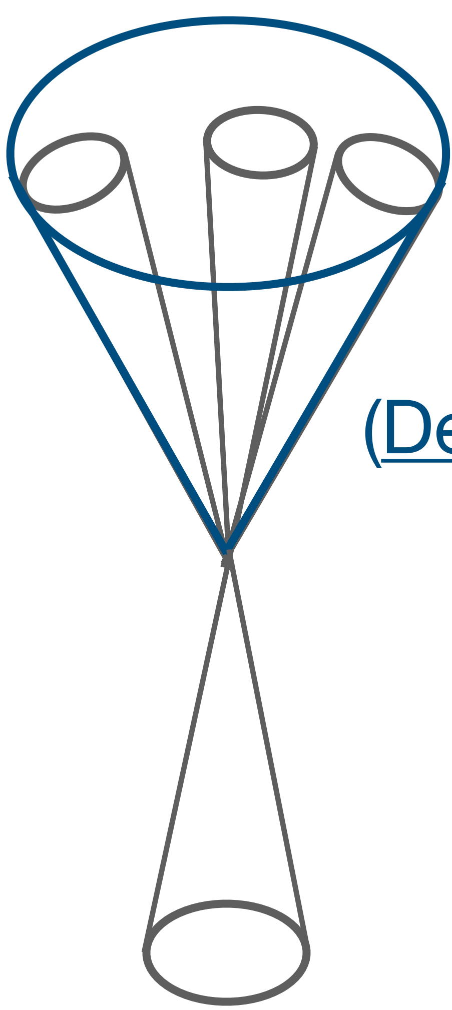




Heavy gauge boson (W’)

CMS-PAS-B2G-20-005

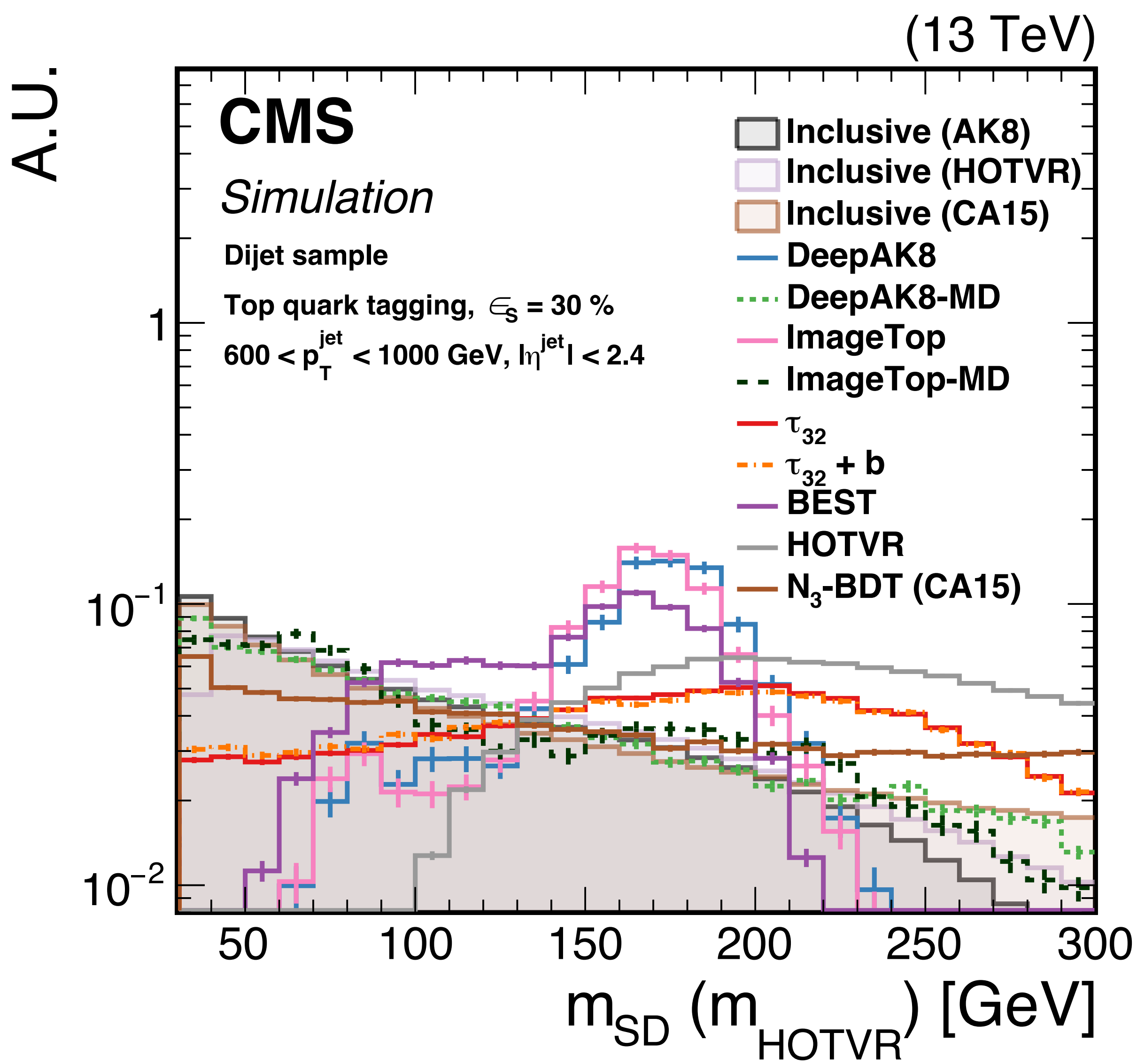




- Search for W’ → tb, all-hadronic
- Back-to-back topology
- Sensitive variable: m_{tb}
- Bkg. estimation from data using control regions with pass and fail ratio
- Using PUPPI + DeepAK8-MD for large-cone jet

DeepAK8-MD

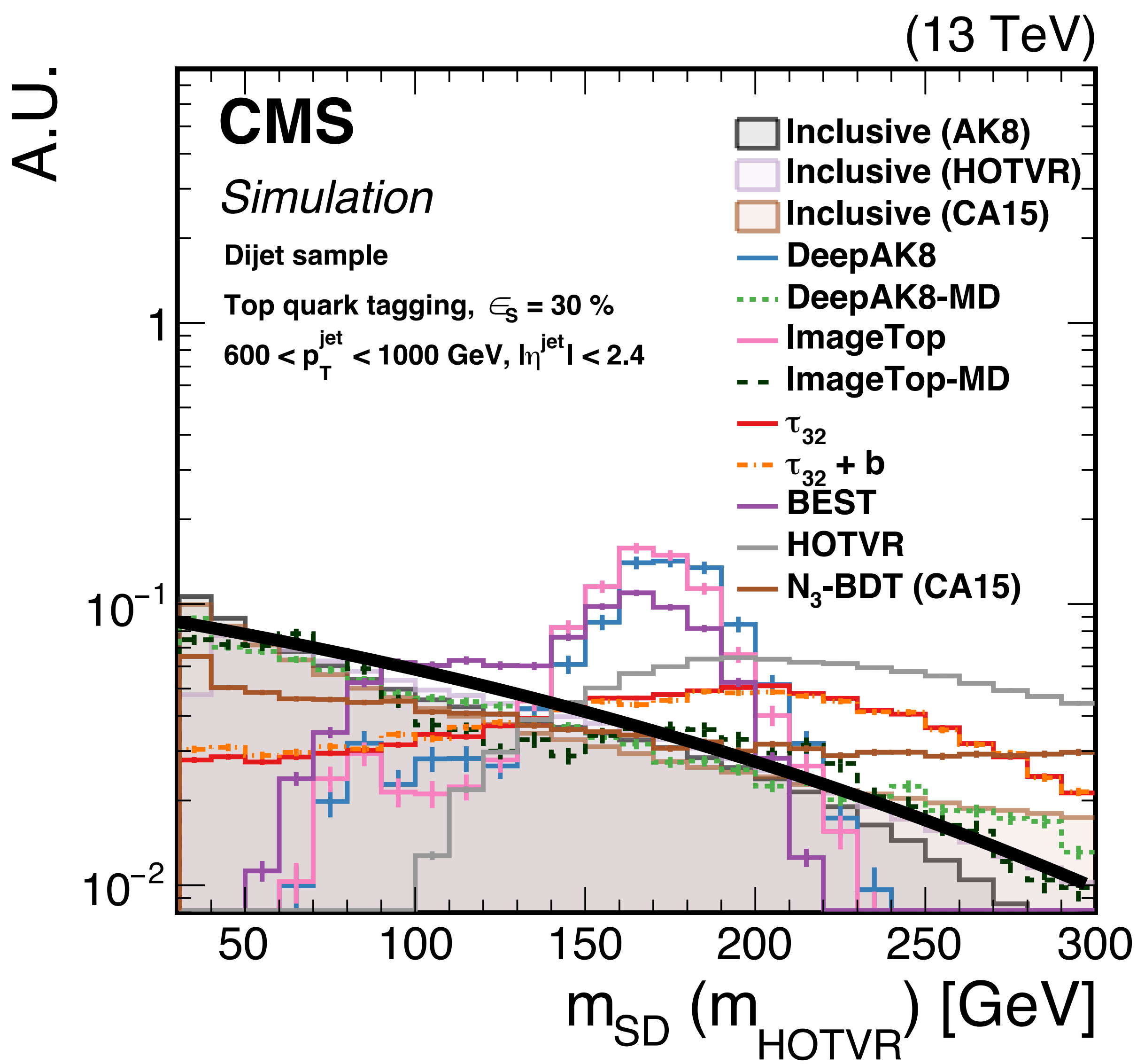
Performance studied in CMS extensively in CMS-JME-18-002



- Deep neural network with 2 input list:
  - Particle list of jet constituents
  - Secondary vertex information
- “tagger” can shape the QCD multijet background
- Challenge when doing a “bump hunt” search
- Mass decorrelation with penalty function

DeepAK8-MD

Performance studied in CMS extensively in CMS-JME-18-002



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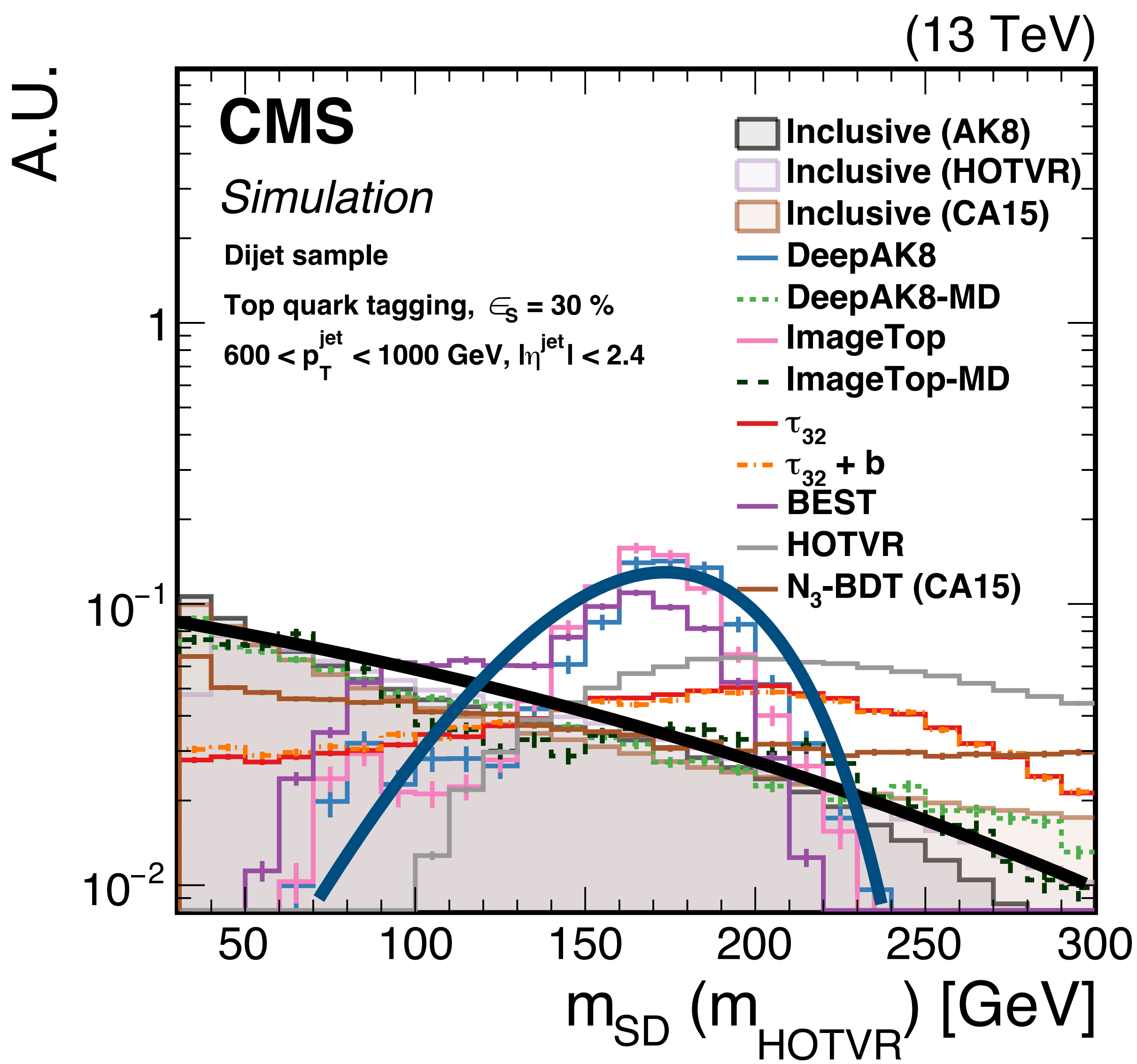

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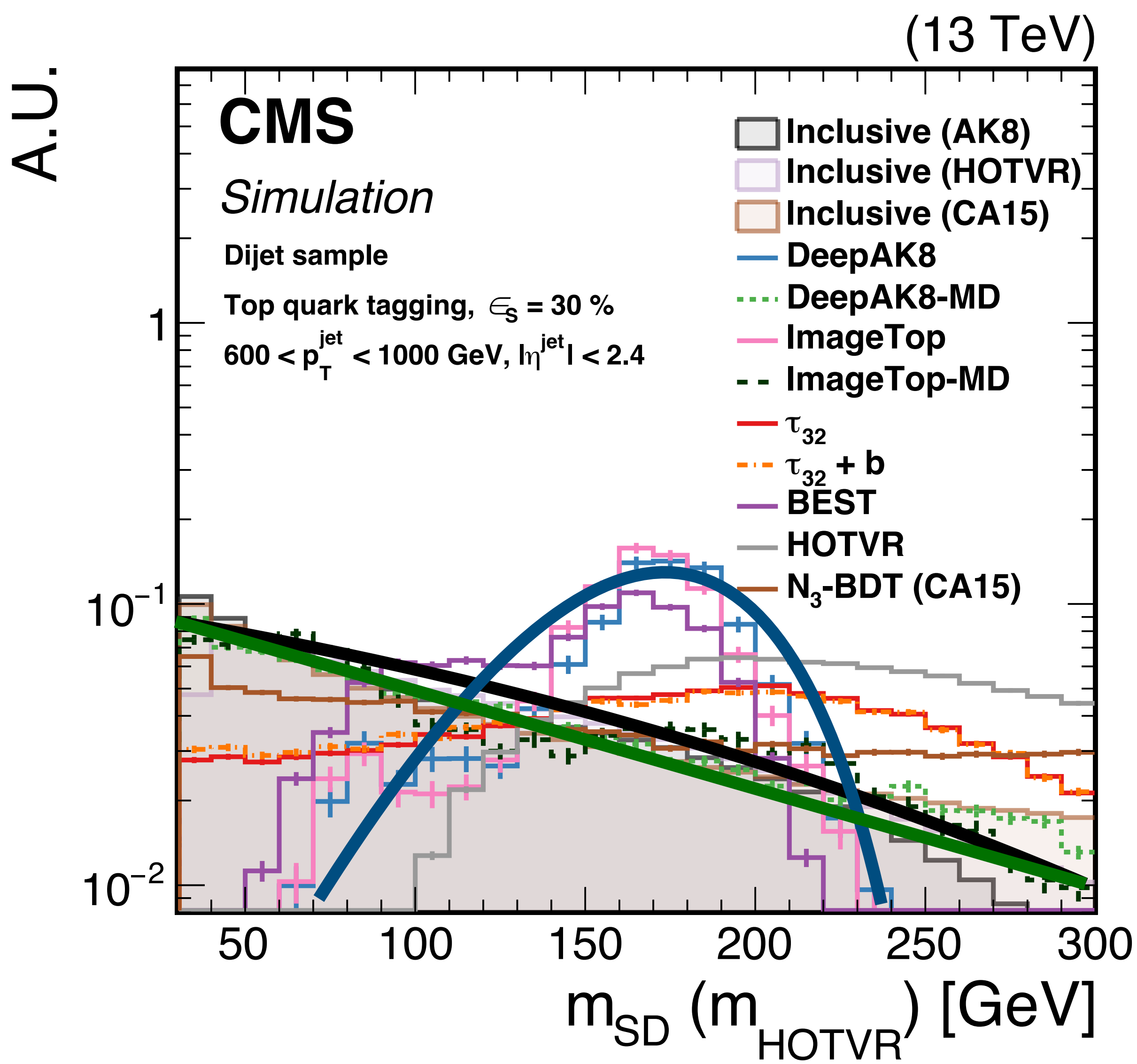

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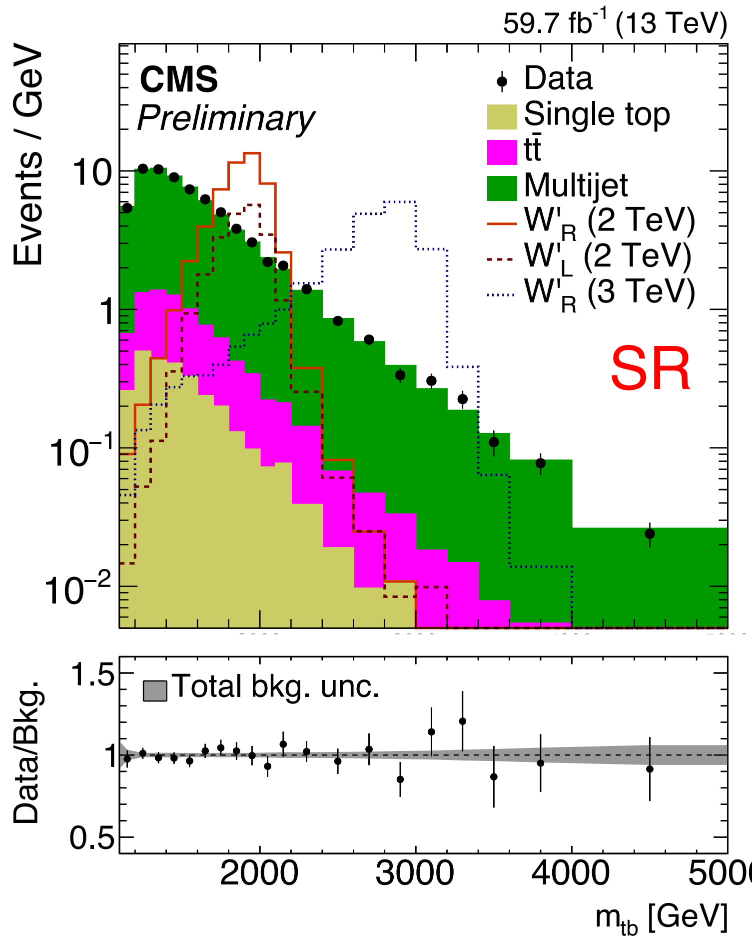
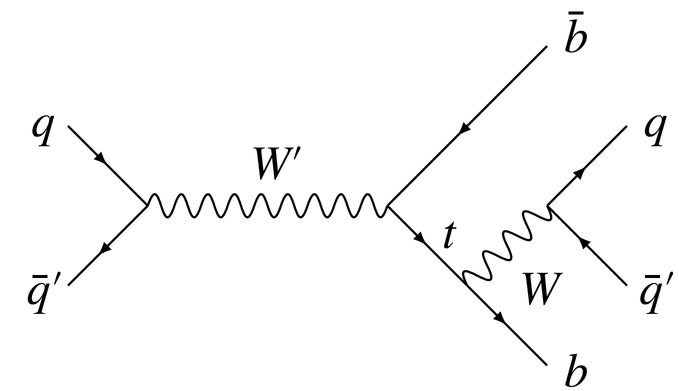
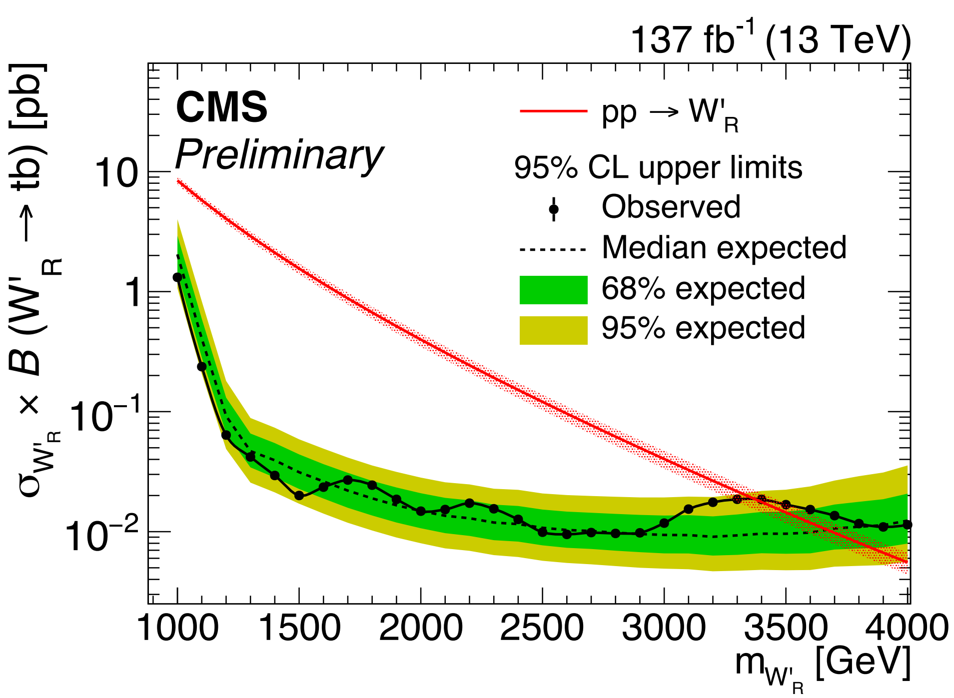
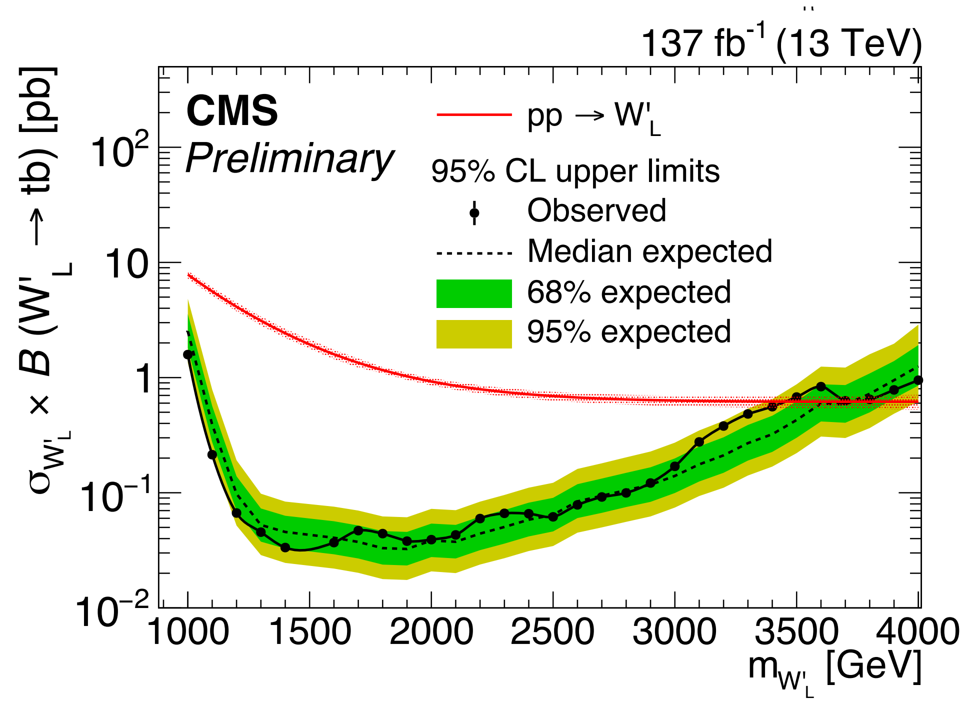
Heavy gauge boson (W’)





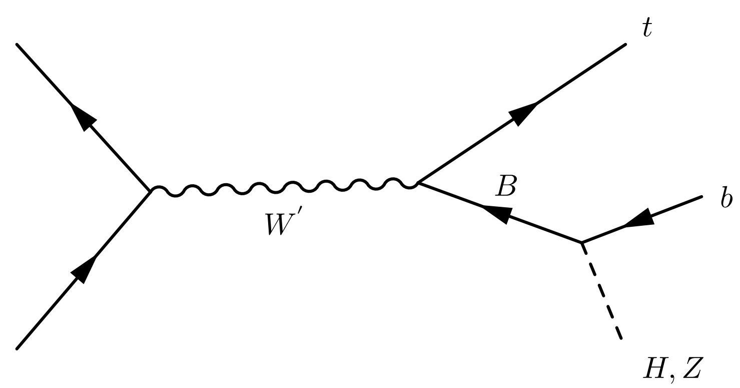
- Search for W’ → tb (CMS-PAS-B2G-20-005)
- Left- and right-handed W’ excluded at 95% CL below 3.4 TeV

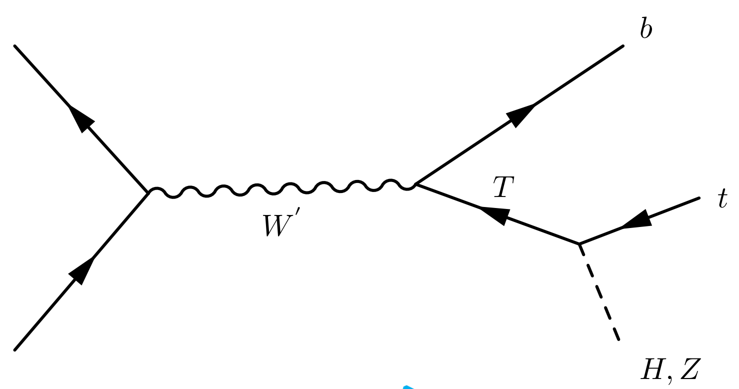


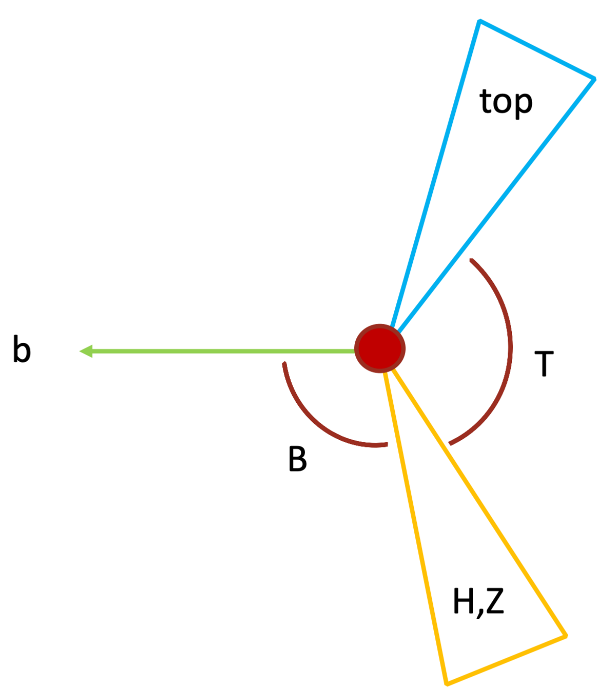


Heavy gauge boson and vector-like quarks (W' and T/B)

CMS-PAS-B2G-20-002





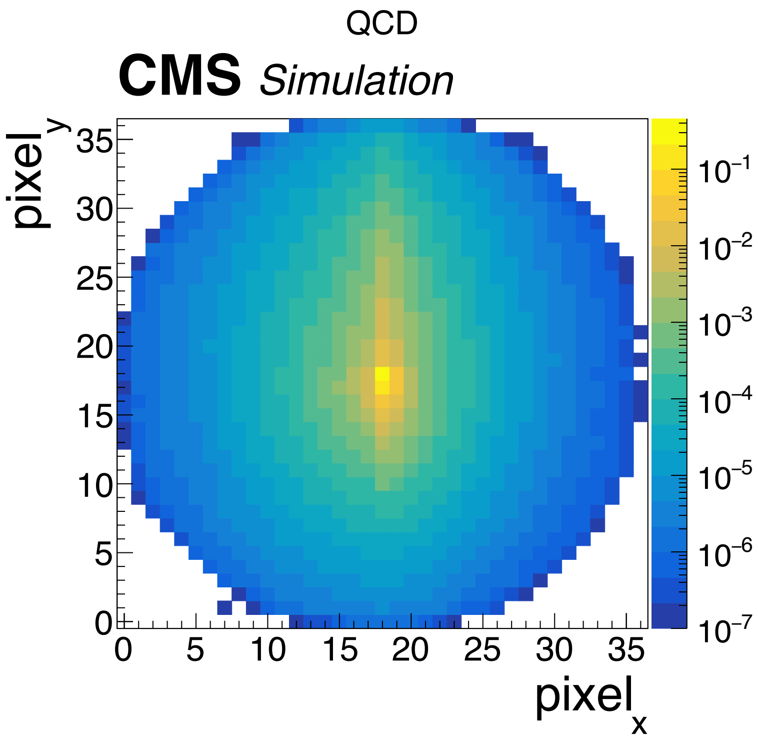


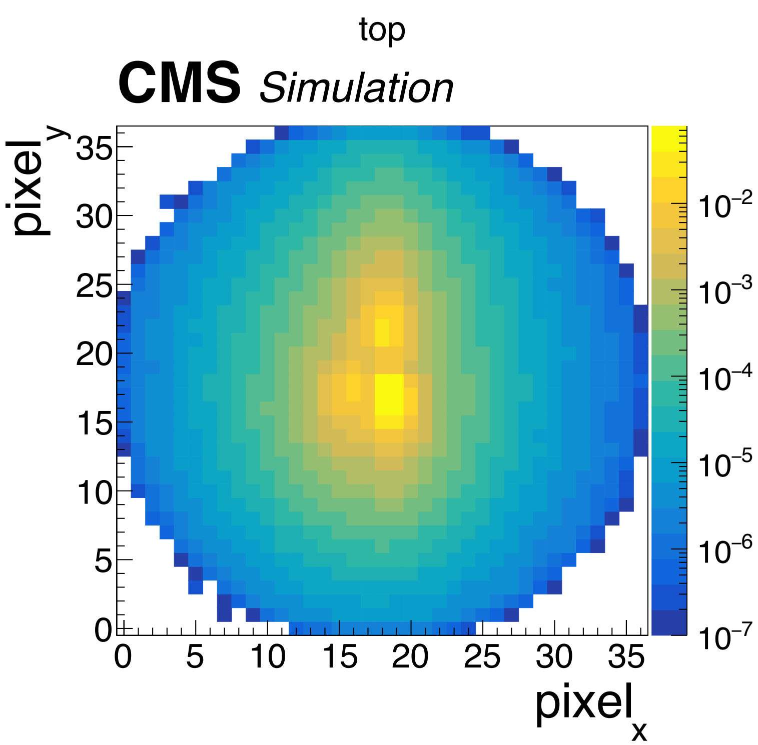
(graphic credit to Kevin C. Nash)

- Search for W' → VLQ + q, all-hadronic
- Sensitive variable: invariant 3 jet mass
- Bkg. estimation from data using control regions with a transfer function
- Using PUPPI for large-cone jets + imageTop-MD

imageTop-MD

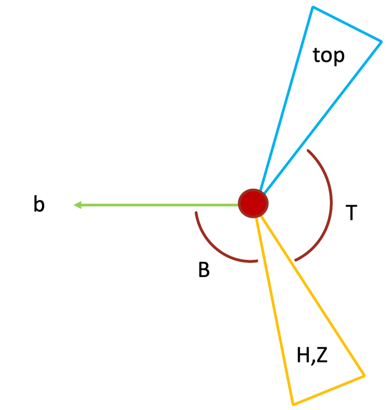
Performance studied in CMS extensively in CMS-JME-18-002



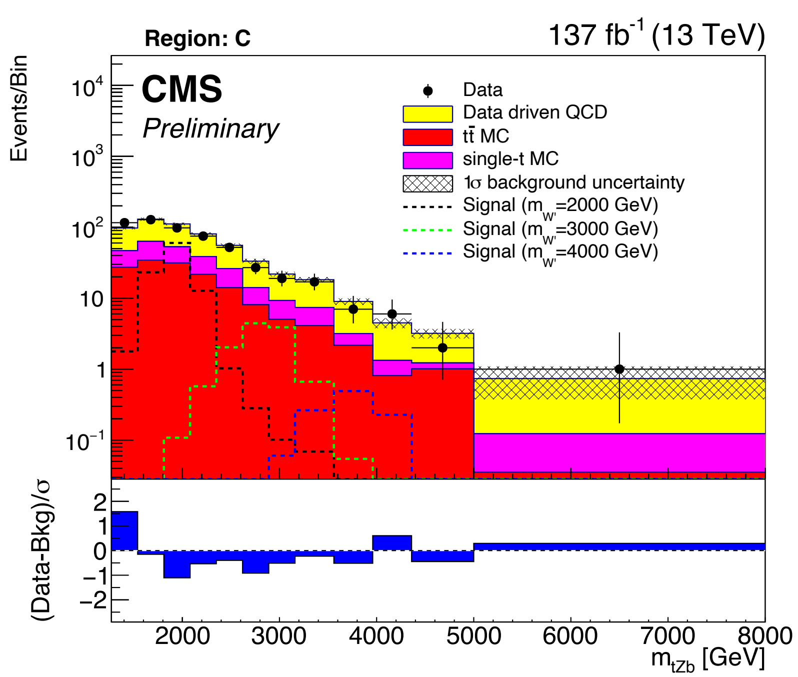


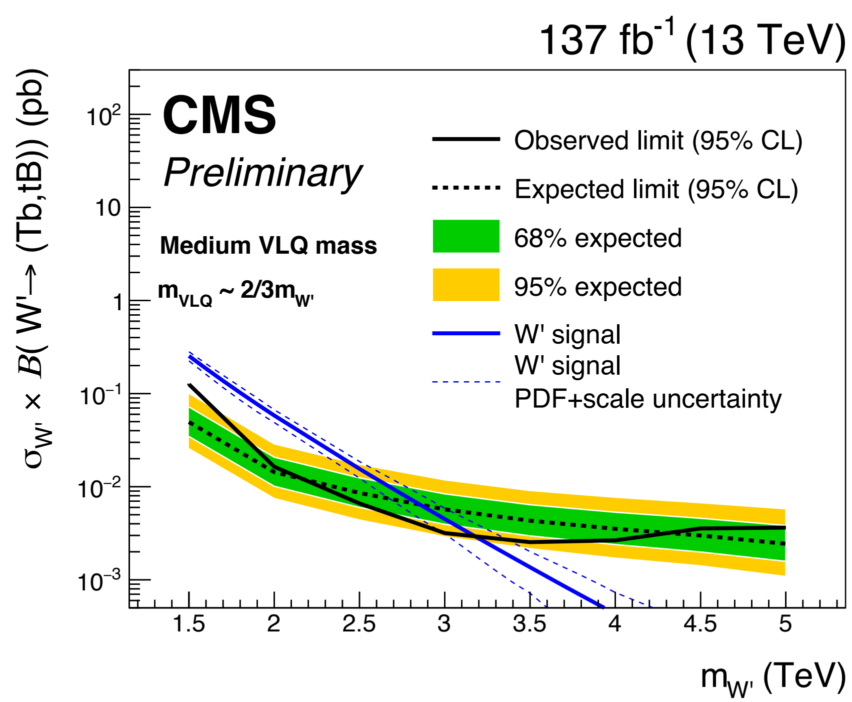
- Pixelizing the energy deposit of a jet
- Image is flipped horizontal and vertical such that energy maxima is in the lower-left corner
- DeepJet b-tagging subjets added
- Decorrelation done by equally shaped p_T distribution of t and QCD sample

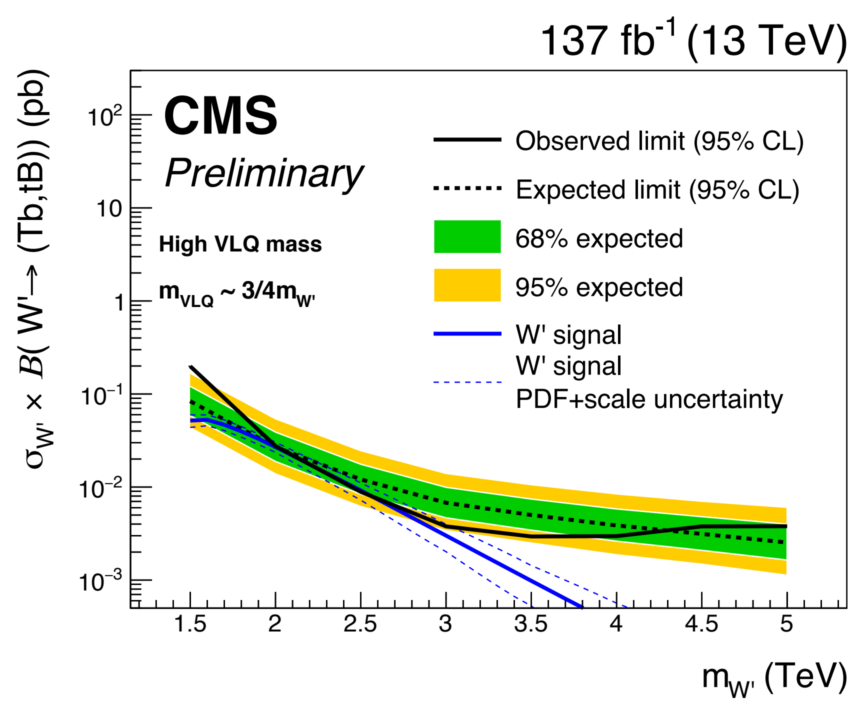
Heavy gauge boson and vector-like quarks (W’ and T/B)



- Search for W’ → VLQ + q, all-hadronic (CMS-PAS-B2G-20-002)
- Almost reached sensitivity to exclude scenarios with $m_{\text{VLQ}} \sim 1/2 m_{W'}$ and $m_{\text{VLQ}} \sim 3/4 m_{W'}$
- Excluded W’ at 95% CL for $m_{\text{VLQ}} \sim 2/3 m_{W'}$ below 3.2 TeV

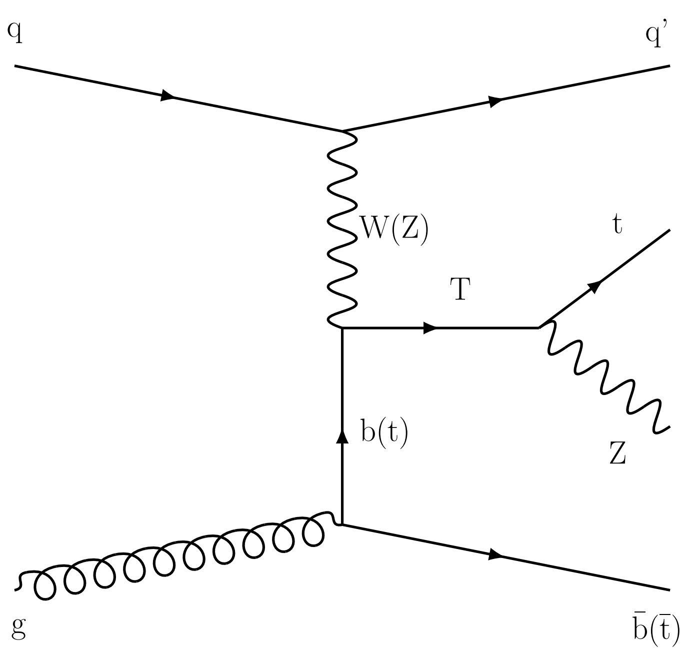




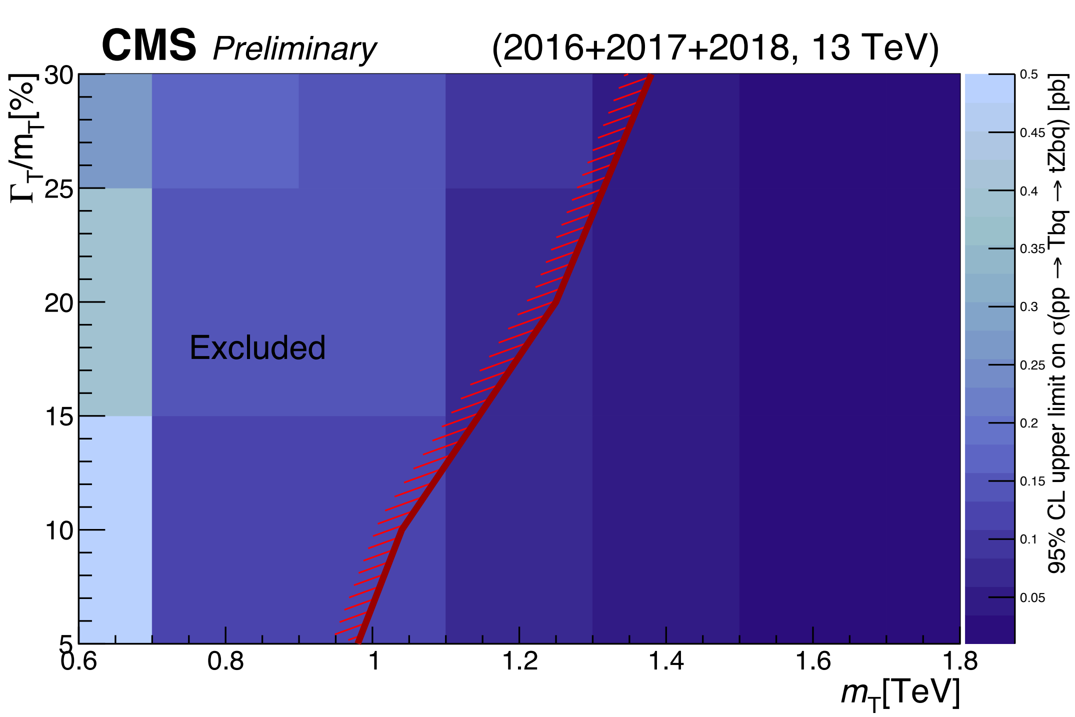


Heavy vector-like t quark partner (T)

<u>CMS-PAS-B2G-19-004</u>

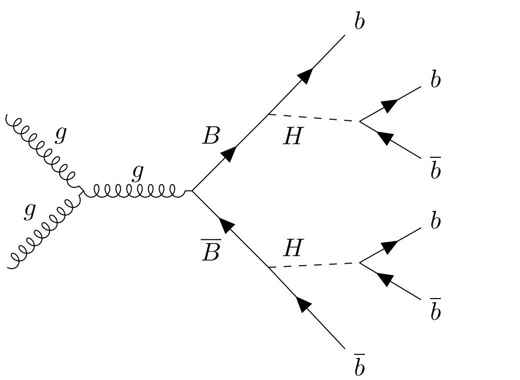


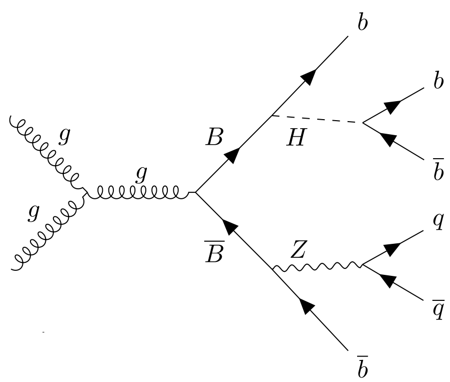
- Search for T → $tZ(\nu\nu)$
- Covering full range of merged, partially merged and resolved top topology
- Test different widths of the VLQ T
- Sensitive variable: transverse mass M_T
- Bkg. estimation from data and simulation using control regions with correction factors
- Using <u>PUPPI</u> for large-cone jets + substructure tagging
- Excluded at 95% CL mass hypotheses between 0.98 and 1.4 TeV depending on the width of the T

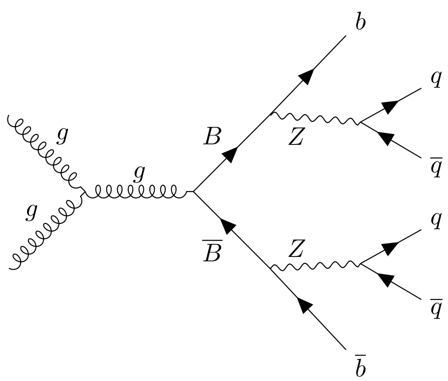


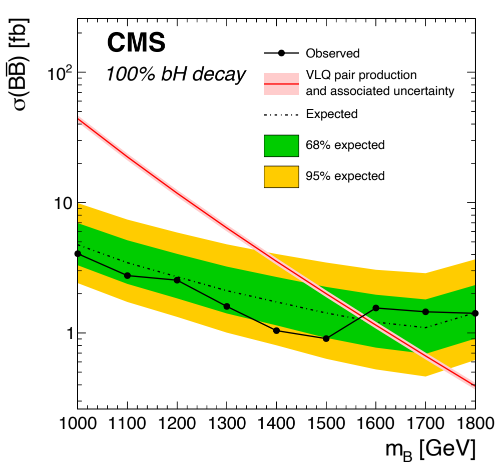
Heavy vector-like b quark partner (B)

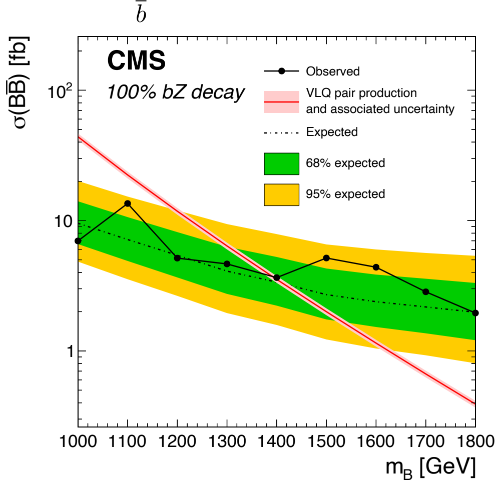
CMS-B2G-19-005

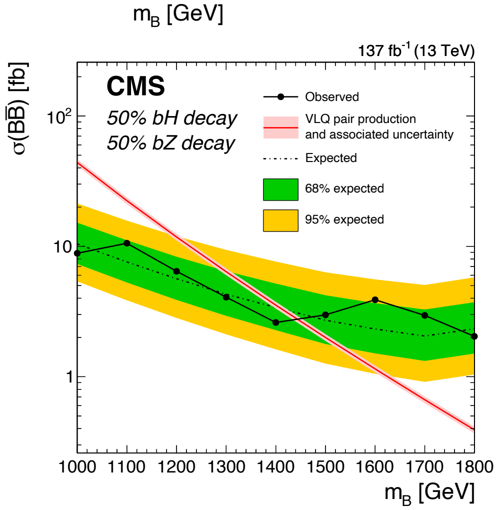








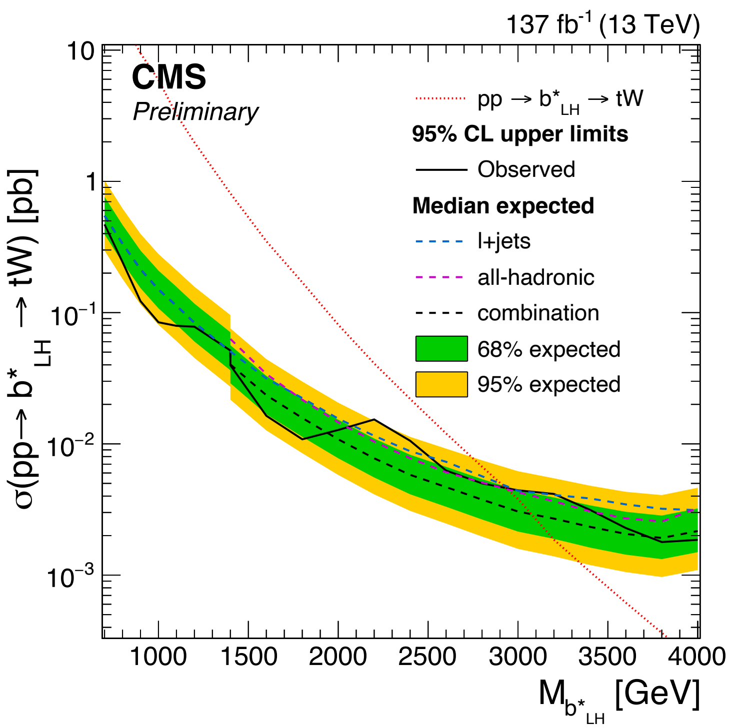


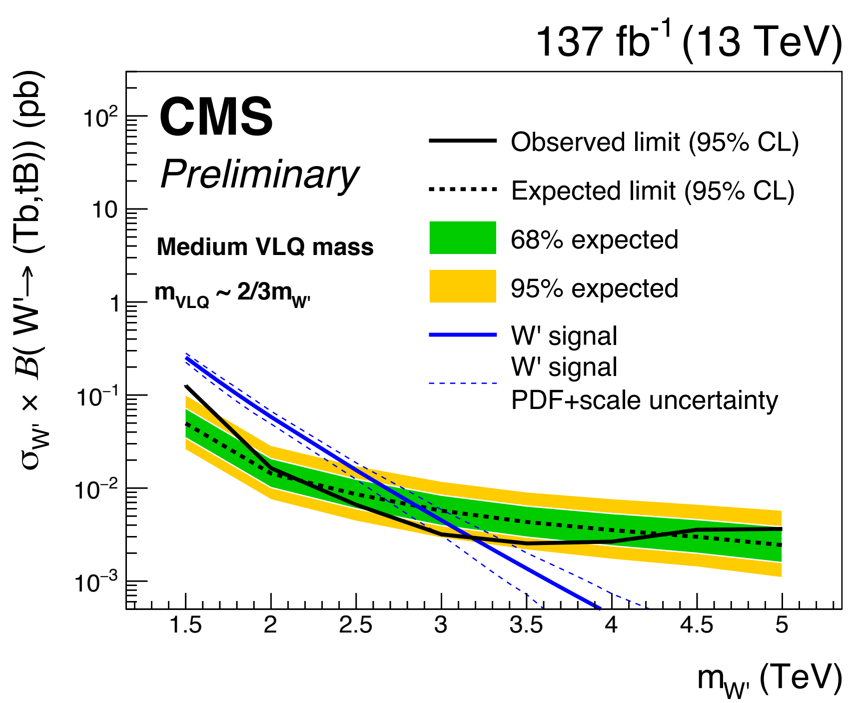


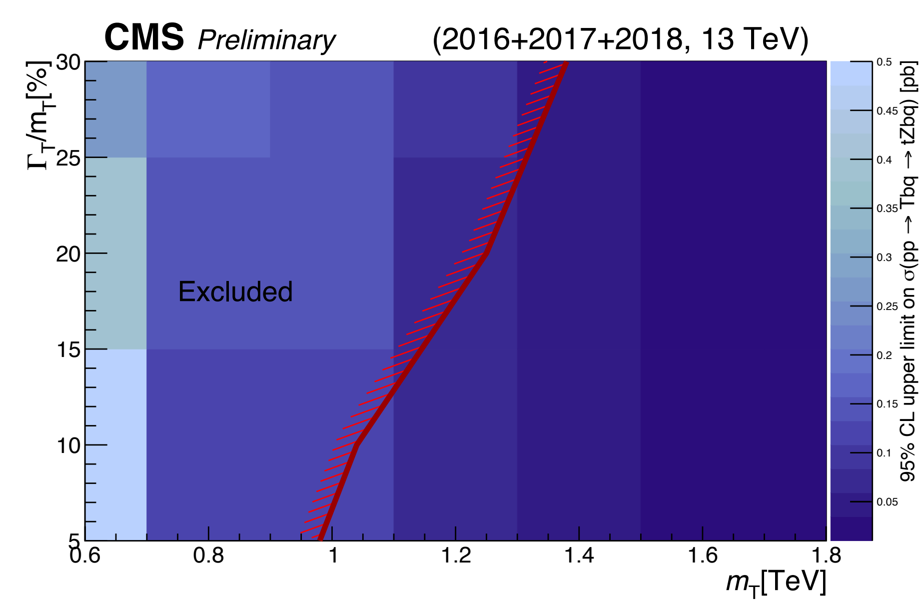
- Search for BB → bZbZ, bHbH, bZbH, all-hadronic, 6 b-jets
- Covering full range of merged, partially merged and resolved H/Z topology
- Sensitive variable: M_{BB}
- Bkg. estimation from data using control regions with a transfer function
- Using PUPPI for large-cone jets + DoubleB
- Using CHS for small-cone jets + DeepJet
- B excluded at 95% CL below 1570 GeV, 1390 GeV and 1450 GeV

Summary

- Using novel substructure techniques allows to probe for extremely heavy resonances
- New tagging techniques increase efficiency while background rejection stays stable
- Novel pileup mitigation technique PUPPI used as standard for large-cone jets
- Several analysis improved significantly with the new techniques







Backup

Search for an excited bottom quark (b*)

Excited bottom quark (b*)

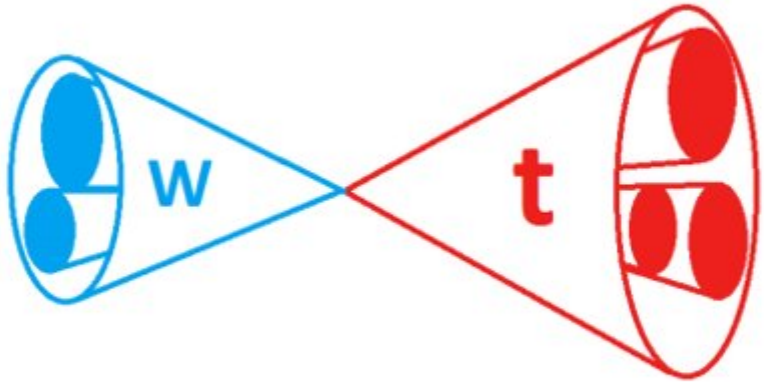
CMS-B2G-19-003

Event selection

- Search for b* →tW, all-hadronic, dijet signature
- $m_{tW} > 1.2$ TeV
- Top tagged: 105 < M_{SD} < 220 GeV, τ_{32} < 0.65, DeepCSV tag
- W tagged: 65 < M_{SD} < 105 GeV, τ_{21} < 0.4 (0.45)
- $|\Delta y| < 1.6$ & $|\Delta\phi| > \pi/2$

QCD estimation with pass and fail control regions

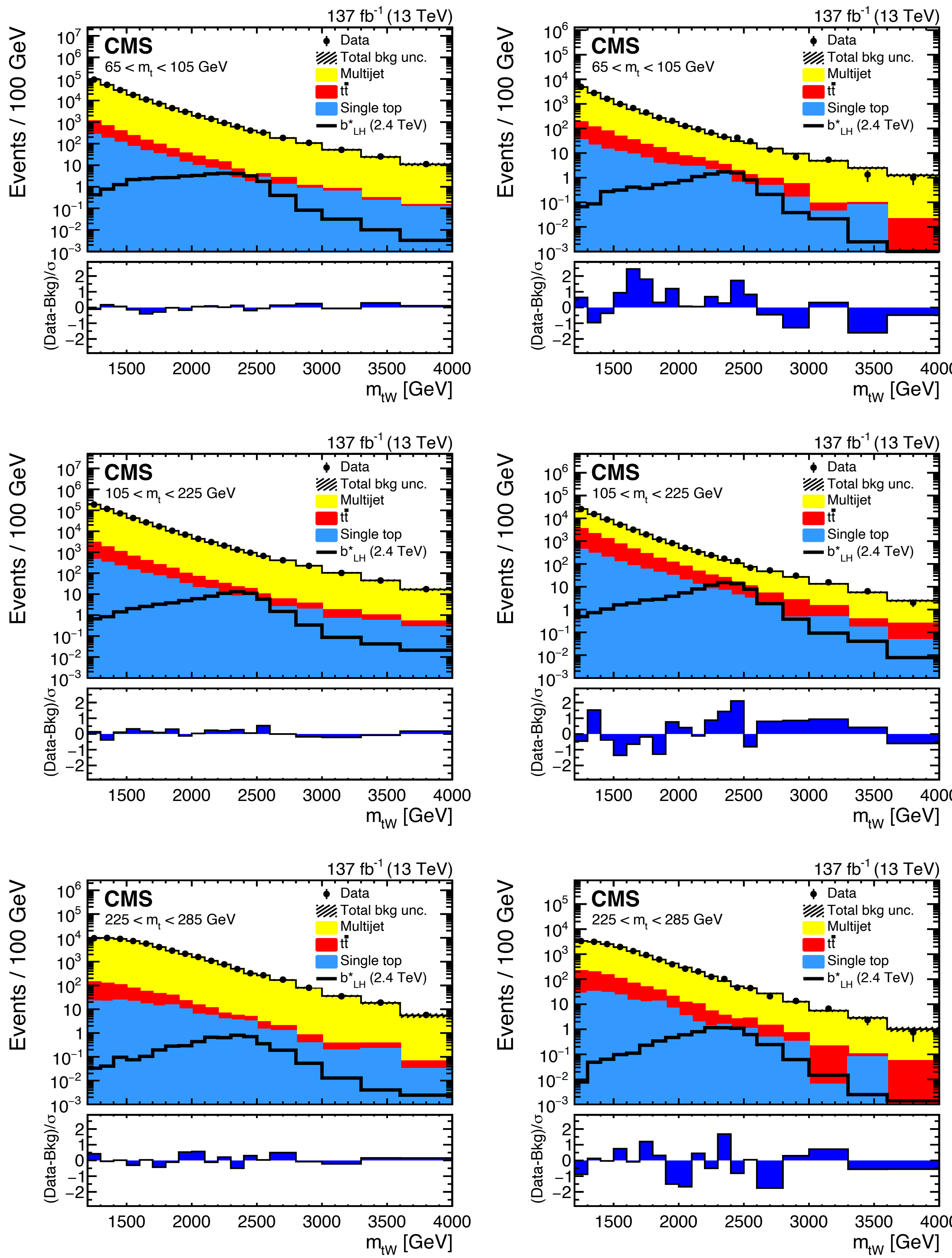
$$n_{\mathrm{P}}^{\mathrm{QCD}}(i) = n_{\mathrm{F}}^{\mathrm{QCD}}(i) R_{\mathrm{P/F}}^{\mathrm{MC}}(m_{\mathrm{t}}, m_{\mathrm{tW}}) R_{\mathrm{ratio}}(m_{\mathrm{t}}, m_{\mathrm{tW}}),$$



(graphic credit to Lucas Corcodilos)

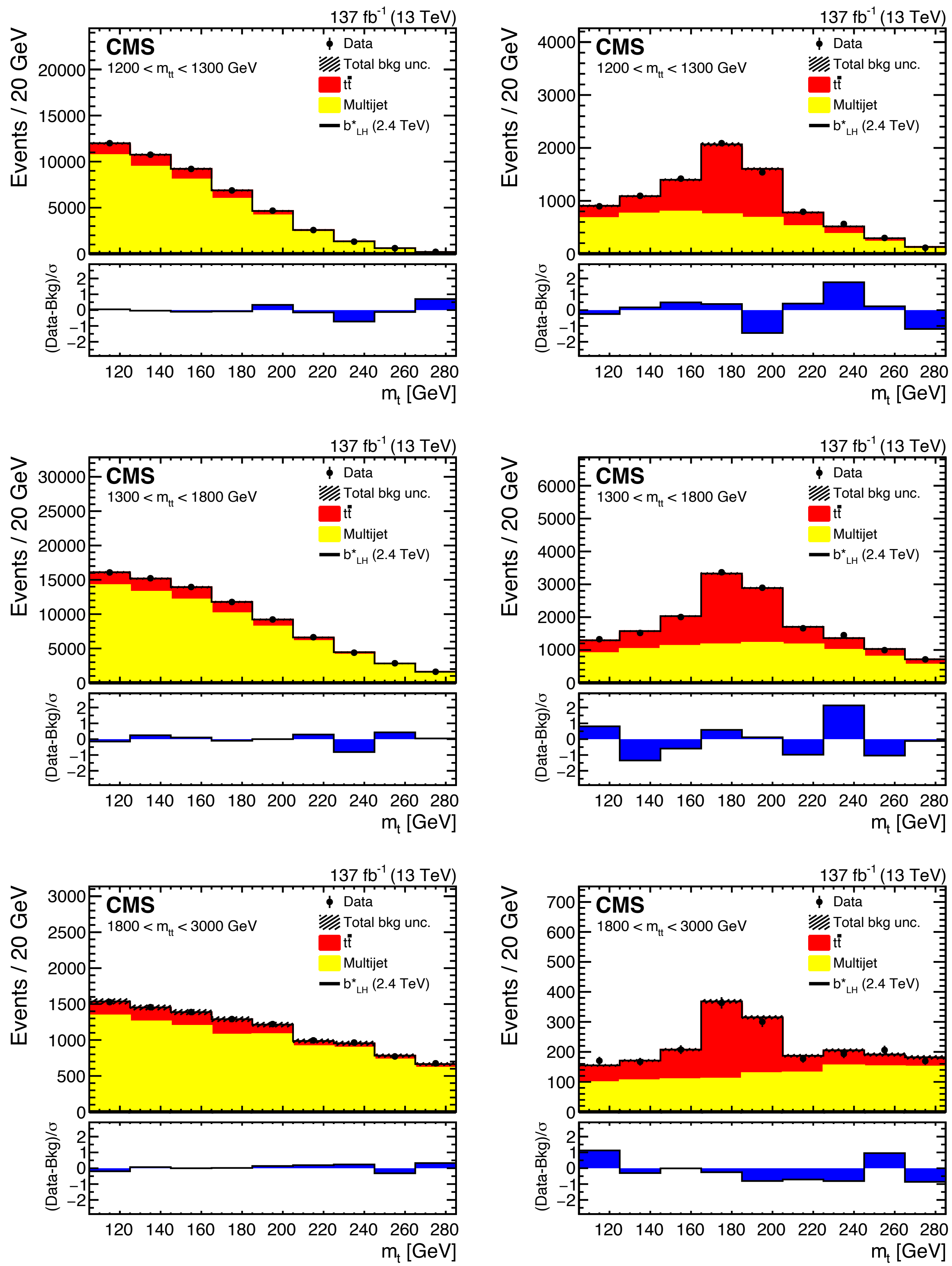
Excited bottom quark (b*)

CMS-B2G-19-003



Excited bottom quark (b*)

CMS-B2G-19-003

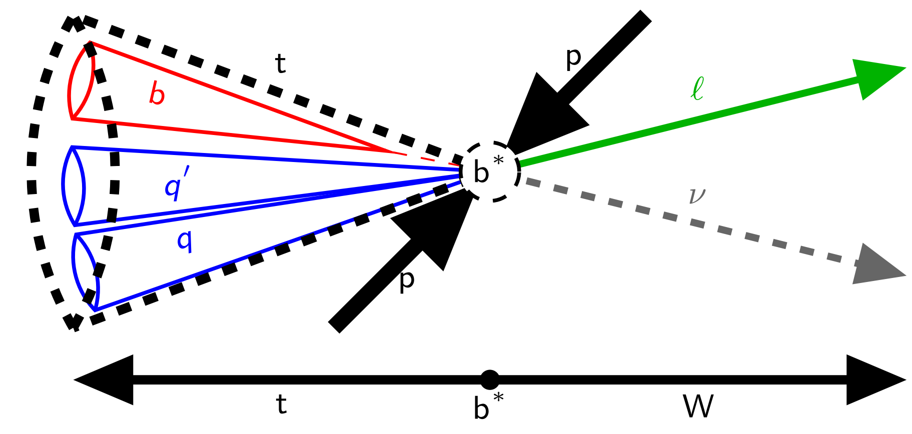


Excited bottom quark (b*)

CMS-PAS-B2G-20-010

Event selection

- Search for b* →tW, l+jets
- Single lepton trigger
- Top tagged: 140 < M_{SD} < 220 GeV, τ_{32} < 0.56
- Split events in 0b, 1b and 2b-tagged category



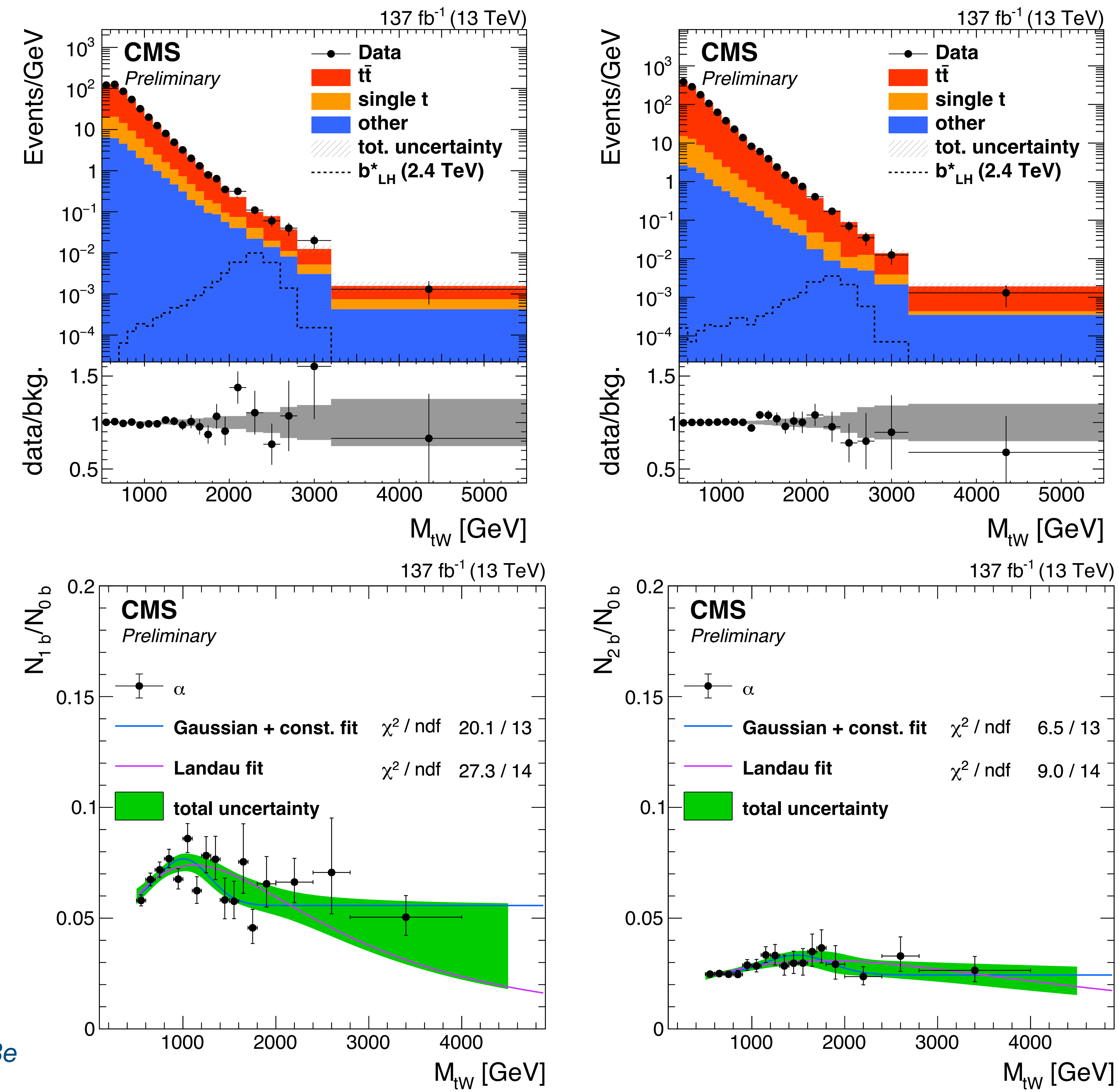
(graphic credit to Alexander Fröhlich)

Background estimation

- Alpha method for all backgrounds except $t\bar{t}$
- $t\bar{t}$ from simulation and CR to constrain normalisation

Excited bottom quark (b*)

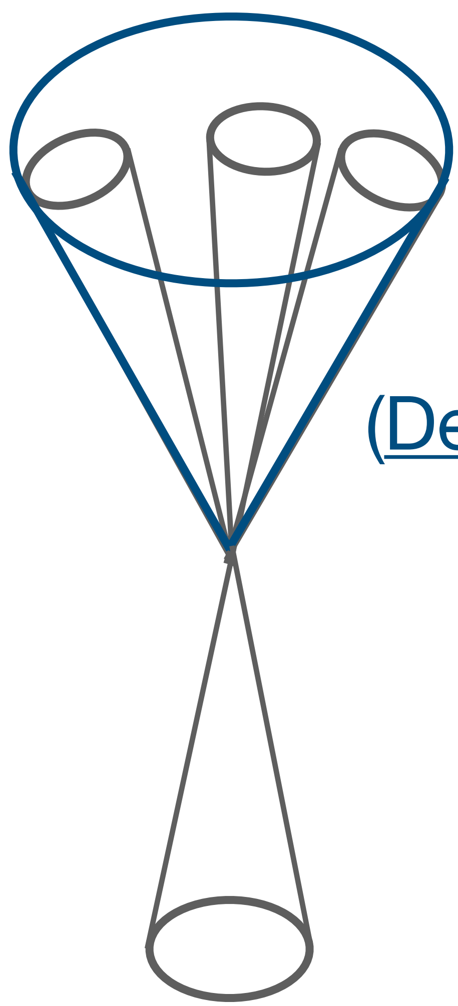
[CMS-PAS-B2G-20-010](#)



Search for a heavy gauge boson (W’)

Heavy gauge boson (W')

CMS-PAS-B2G-20-005



Event selection

- >=1 AK8 jet with p_T > 550 GeV
- >= 1 AK4 jet with p_T > 550 GeV, no overlapping to AK8 jet
- Highest top scored AK8 jet is taken as top candidate
- Highest p_T AK4 jet with $\Delta\phi > \pi/2$ and $\Delta R > 1.2$

Heavy gauge boson (W')

CMS-PAS-B2G-20-005

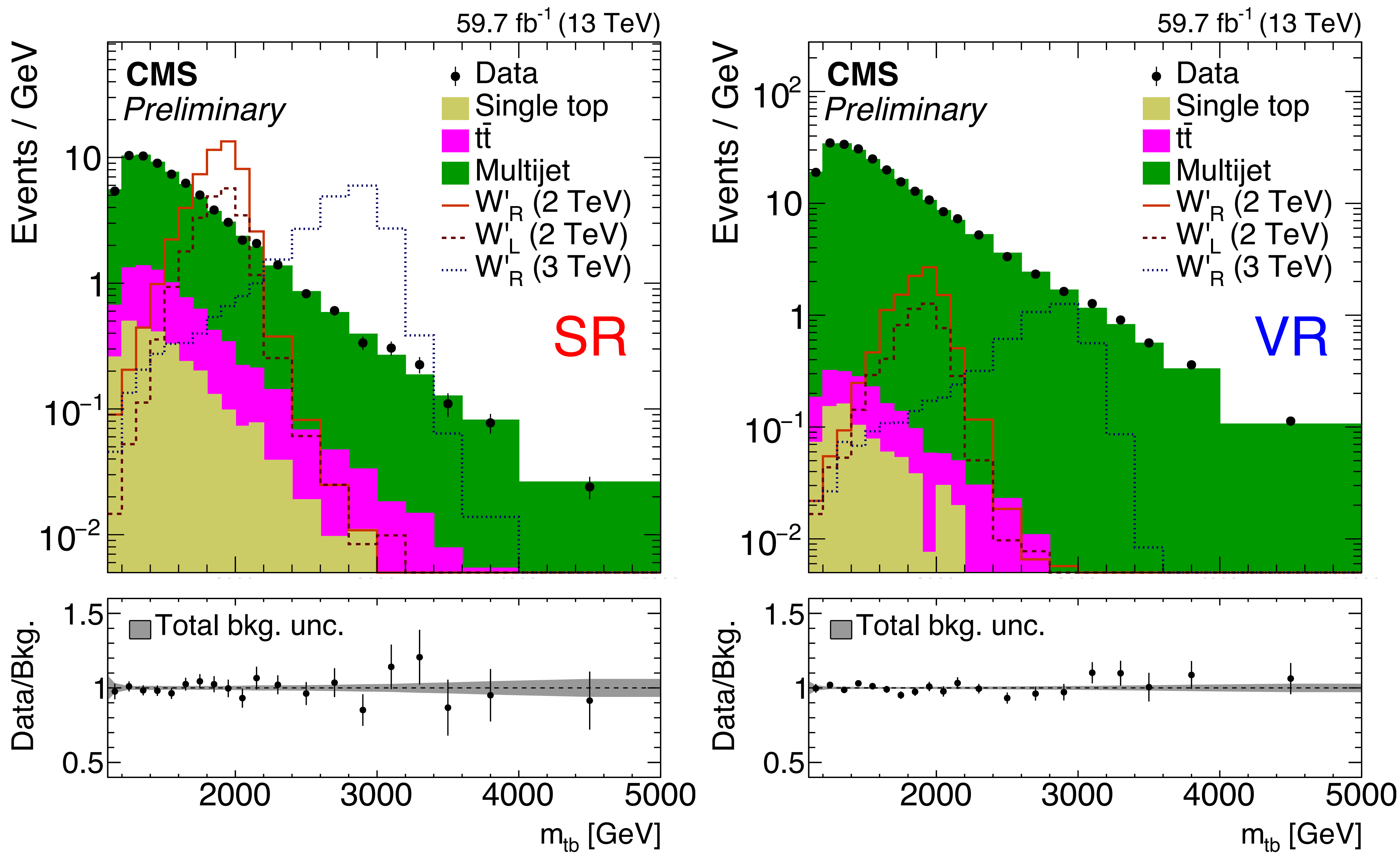
Jet	Variable	SR	VR	CR1	CR2
t	m_{SD}	$\in [105, 210]$ GeV	$\in [105, 210]$ GeV	< 105 GeV	< 105 GeV
t	top quark tagging	pass	fail	pass	fail
b	b tagging	pass	pass	pass	pass
Jet	Variable	SR$'$	VR$'$	CR1$'$	CR2$'$
t	m_{SD}	$\in [105, 210]$ GeV	$\in [105, 210]$ GeV	< 105 GeV	< 105 GeV
t	top quark tagging	pass	fail	pass	fail
b	b tagging	fail	fail	fail	fail

Pass and fail ratio for QCD multijet background estimation

$t\bar{t}$ and ST from simulation

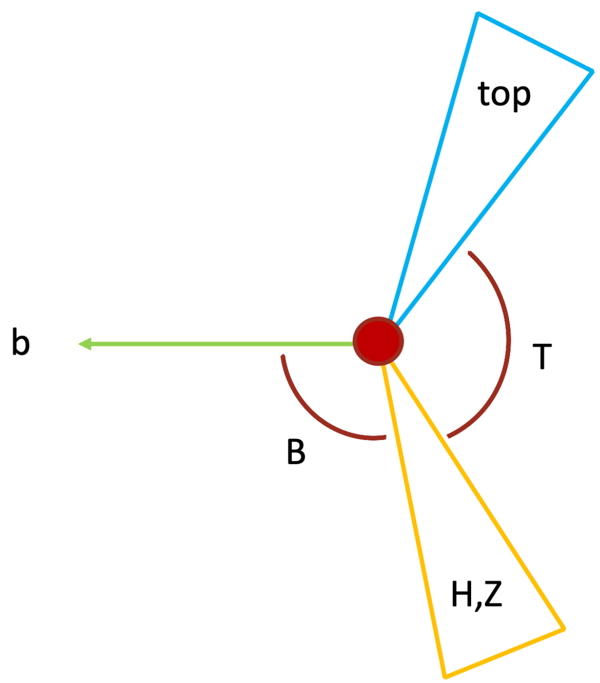
Heavy gauge boson (W')

CMS-PAS-B2G-20-005



Summary

Heavy gauge boson and vector-like quarks (W' and T/B)



CMS-PAS-B2G-20-002

- Top tagged: 140 < M_{SD} < 220 GeV
- H tagged: 105 < M_{SD} < 140 GeV + doubleB
- Z tagged: 65 < M_{SD} < 105 GeV + τ_{21}
- Using PUPPI for large-cone jets + imageTop-MD

Summary

Heavy gauge boson and vector-like quarks (W' and T/B)

CMS-PAS-B2G-20-002

Label	Tag	Discriminator	Mass
Tight	H	$0.6 < \text{Dbtag}$	$105 < m_{\text{SD}}(\text{H}) < 140\,\text{GeV}$
	Z	$\tau_{21} < 0.45$	$65 < m_{\text{SD}}(\text{Z}) < 105\,\text{GeV}$
	t	$0.9 < \text{imageTop}_{\text{MD}}$	$140 < m_{\text{SD}}(\text{t}) < 220\,\text{GeV}$
Medium	H	$0.0 < \text{Dbtag} < 0.6$	$105 < m_{\text{SD}}(\text{H}) < 140\,\text{GeV}$
	Z	$0.45 < \tau_{21} < 0.6$	$65 < m_{\text{SD}}(\text{Z}) < 105\,\text{GeV}$
	t	$0.3 < \text{imageTop}_{\text{MD}} < 0.9$	$140 < m_{\text{SD}}(\text{t}) < 220\,\text{GeV}$
Loose	H	$-1.0 < \text{Dbtag} < 0.0$	$5 < m_{\text{SD}}(\text{H}) < 30\,\text{GeV}$
	Z	$0.6 < \tau_{21} < 1.0$	$5 < m_{\text{SD}}(\text{Z}) < 30\,\text{GeV}$
	t	$0.0 < \text{imageTop}_{\text{MD}} < 0.3$	$30 < m_{\text{SD}}(\text{t}) < 65\,\text{GeV}$

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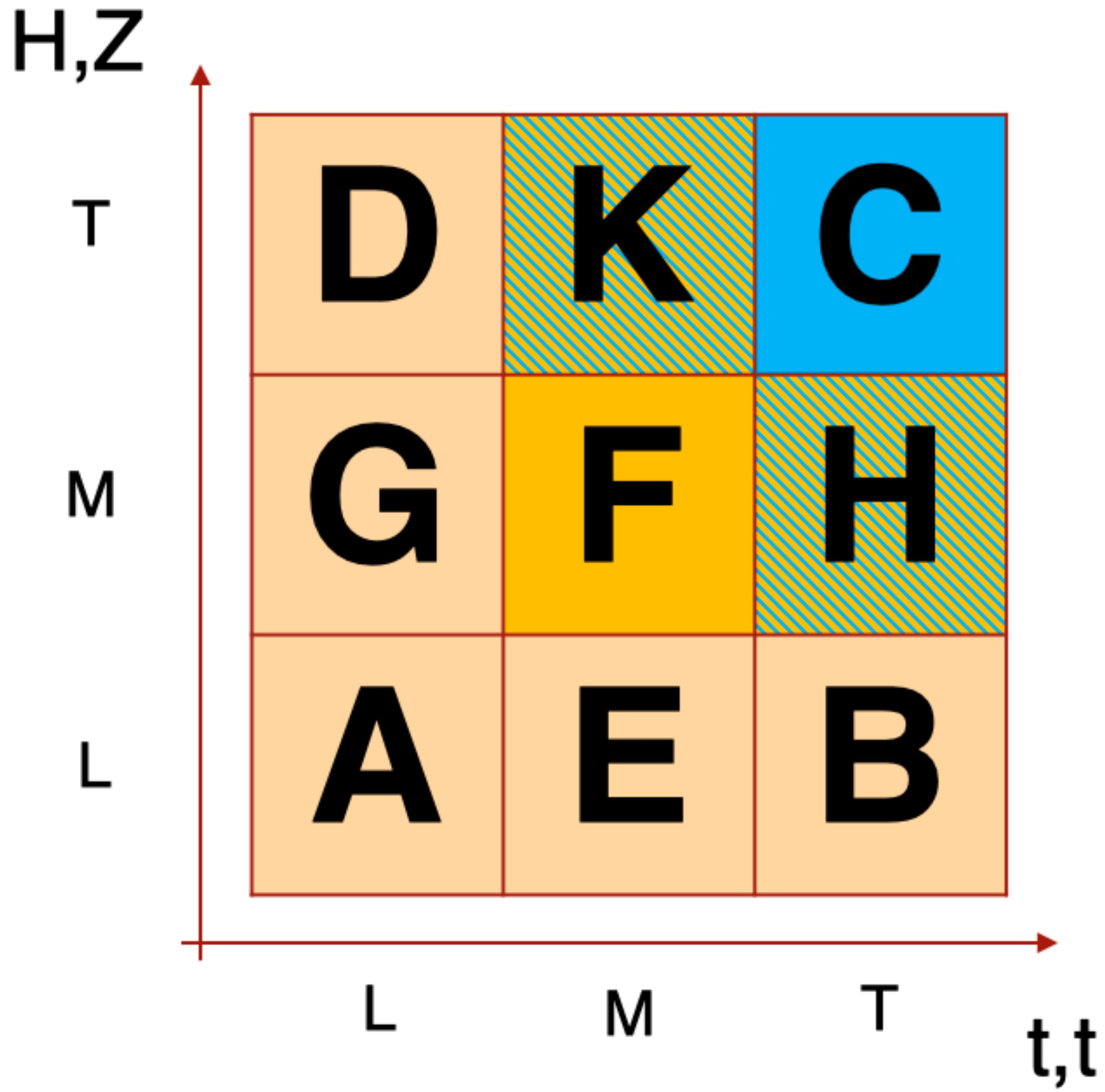
Heavy gauge boson and vector-like quarks (W' and T/B)

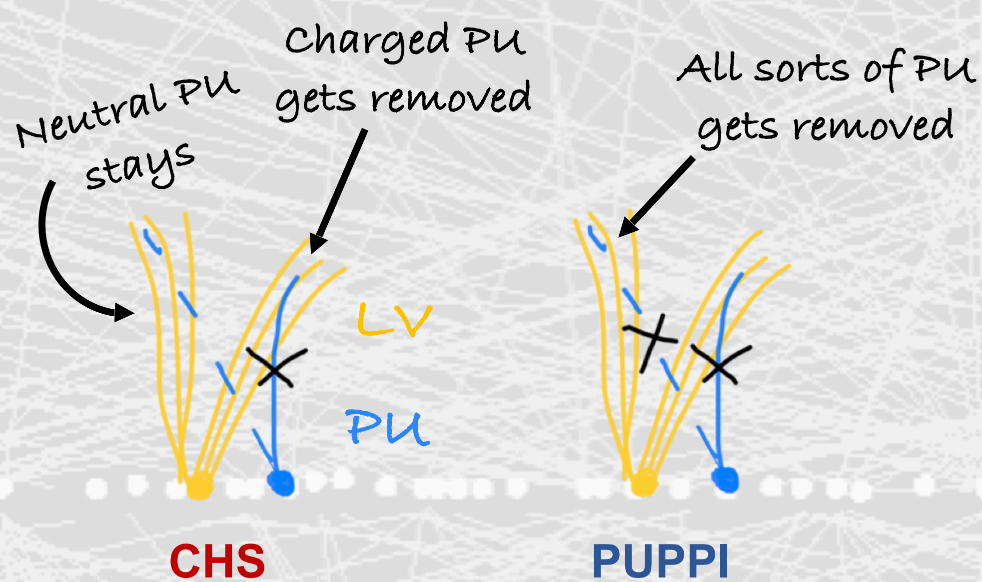
CMS-PAS-B2G-20-002



PUPPI in detail

Pileup per particle identification (PUPPI)

Performance studied in CMS extensively in JME-18-001



1. Define variable α to discriminate pileup from leading vertex

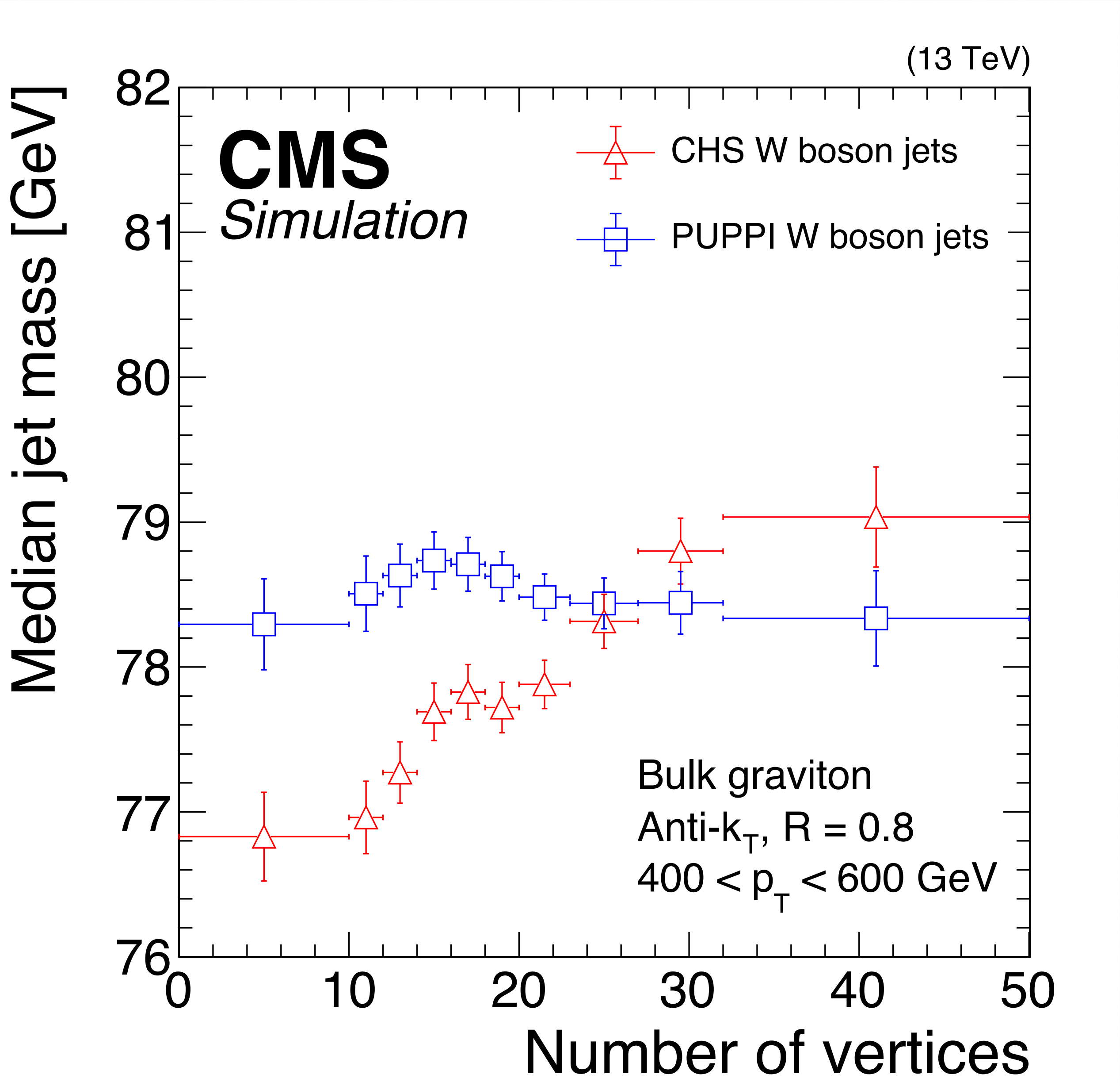
$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{Tj}}{\Delta R_{ij}} \right)^2$$

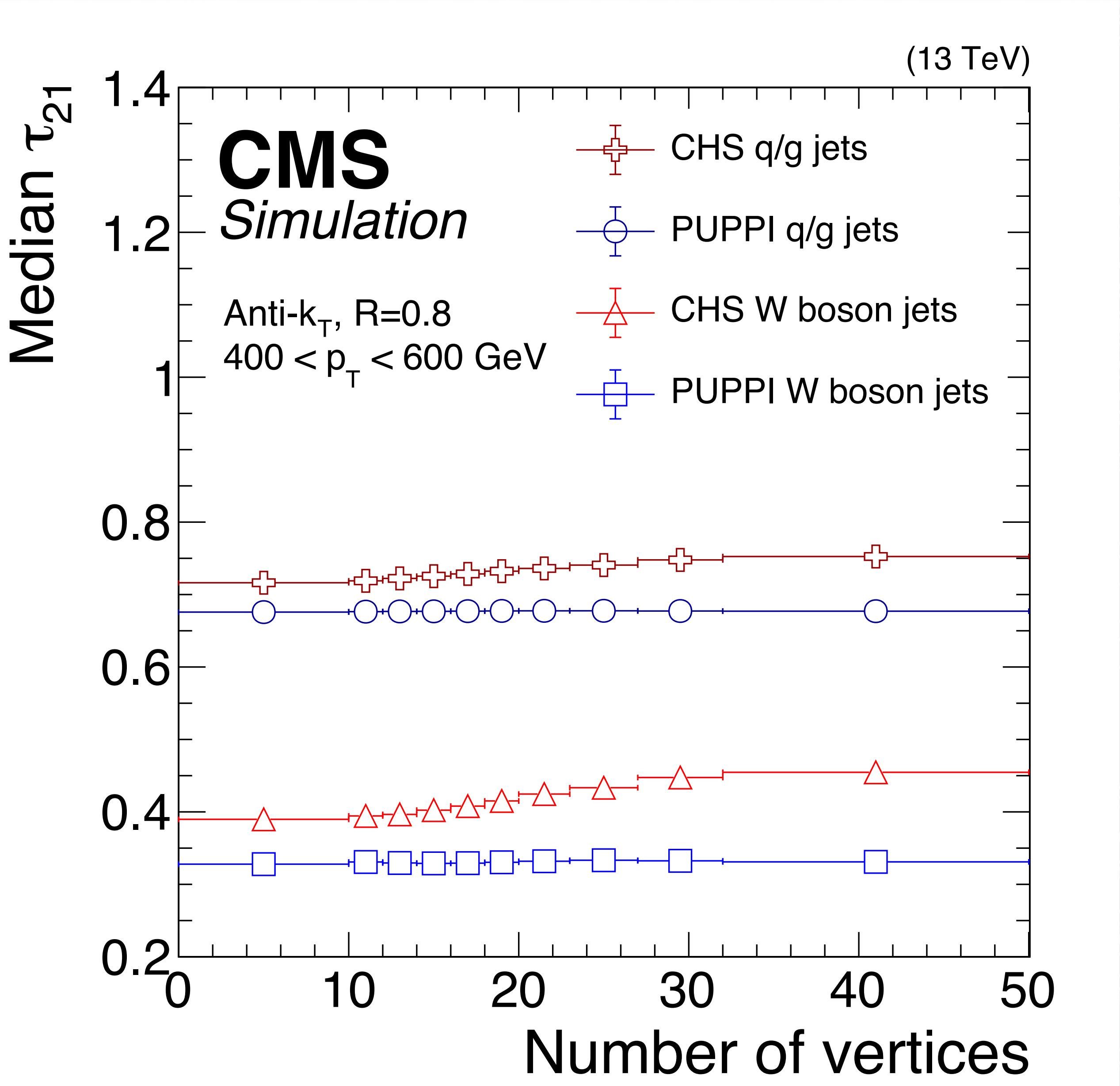
2. Assume charged pileup has the same shape as neutral pileup

3. Use α on an event-by-event basis to calculate a per-particle weight

Pileup per particle identification (PUPPI)

Performance studied in CMS extensively in JME-18-001





PUPPI has a high pileup stability compared to **CHS**

PUPPI in Detail

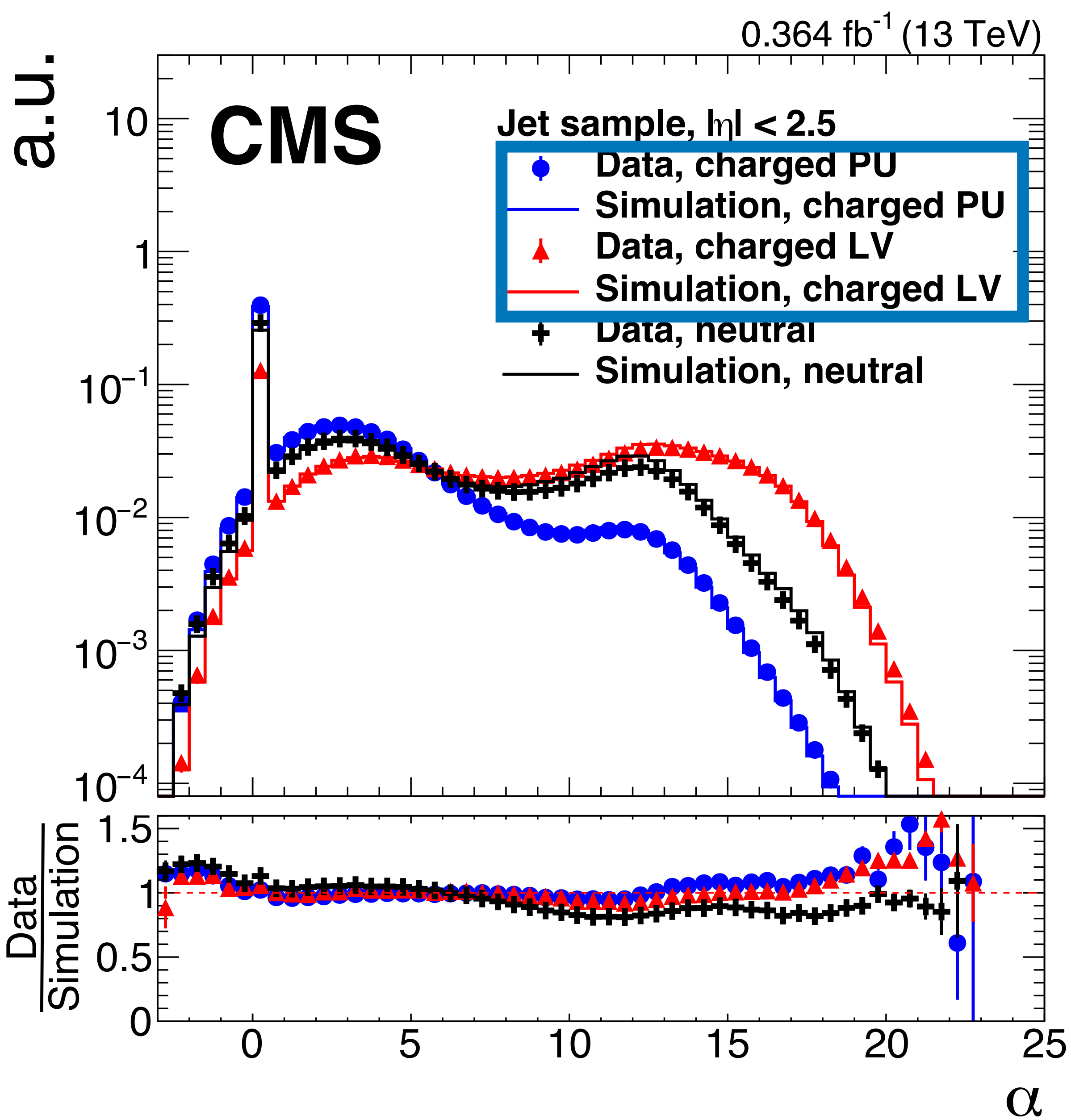
1. Define variable α to discriminate pileup from leading vertex

2. Assume charged pileup has the same shape as neutral pileup

3. Use α on an event-by-event basis to calculate a per-particle weight

1. Define variable α to discriminate pileup from leading vertex

$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{\mathrm{T}j}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles} \end{cases}$$



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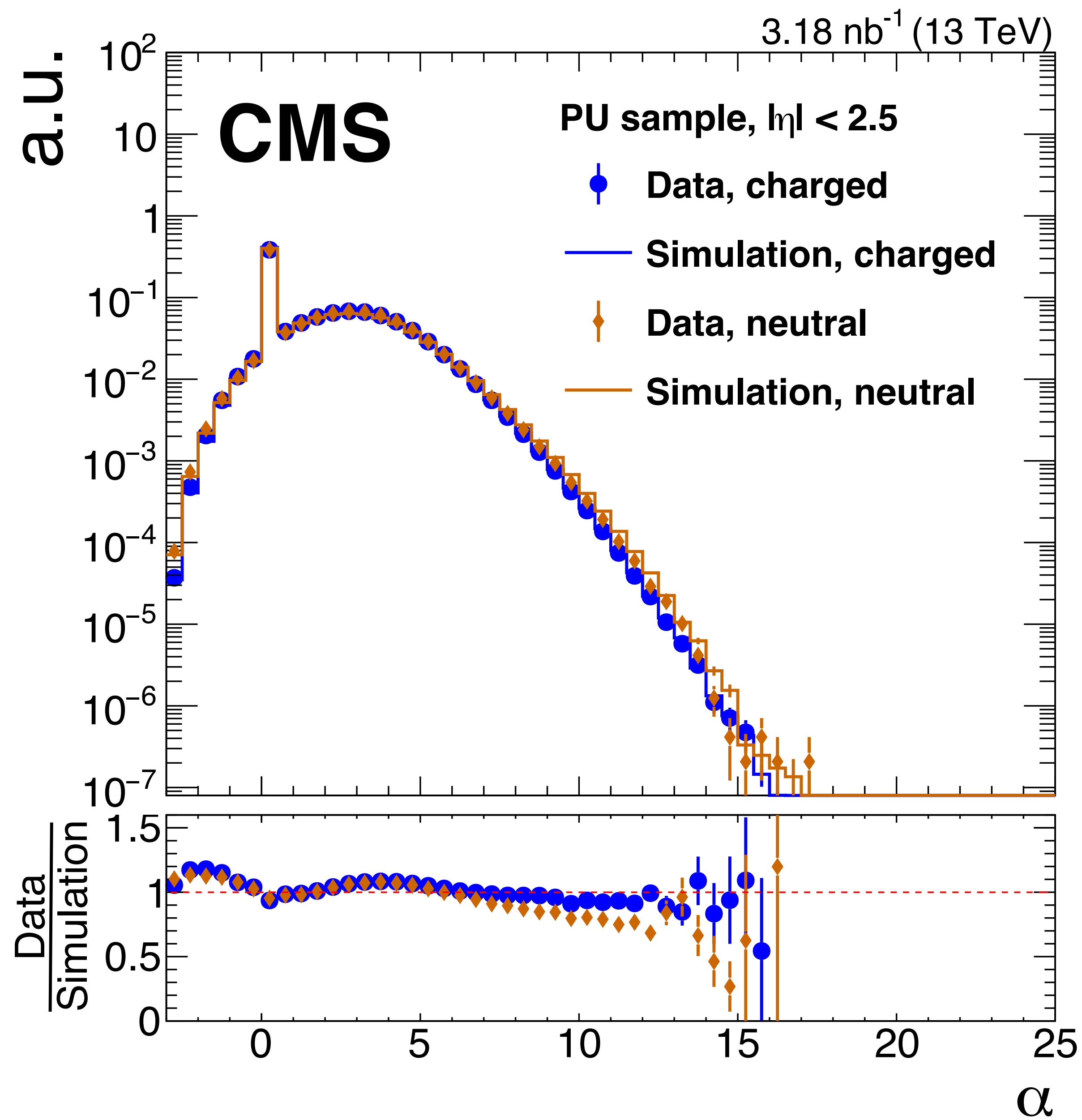
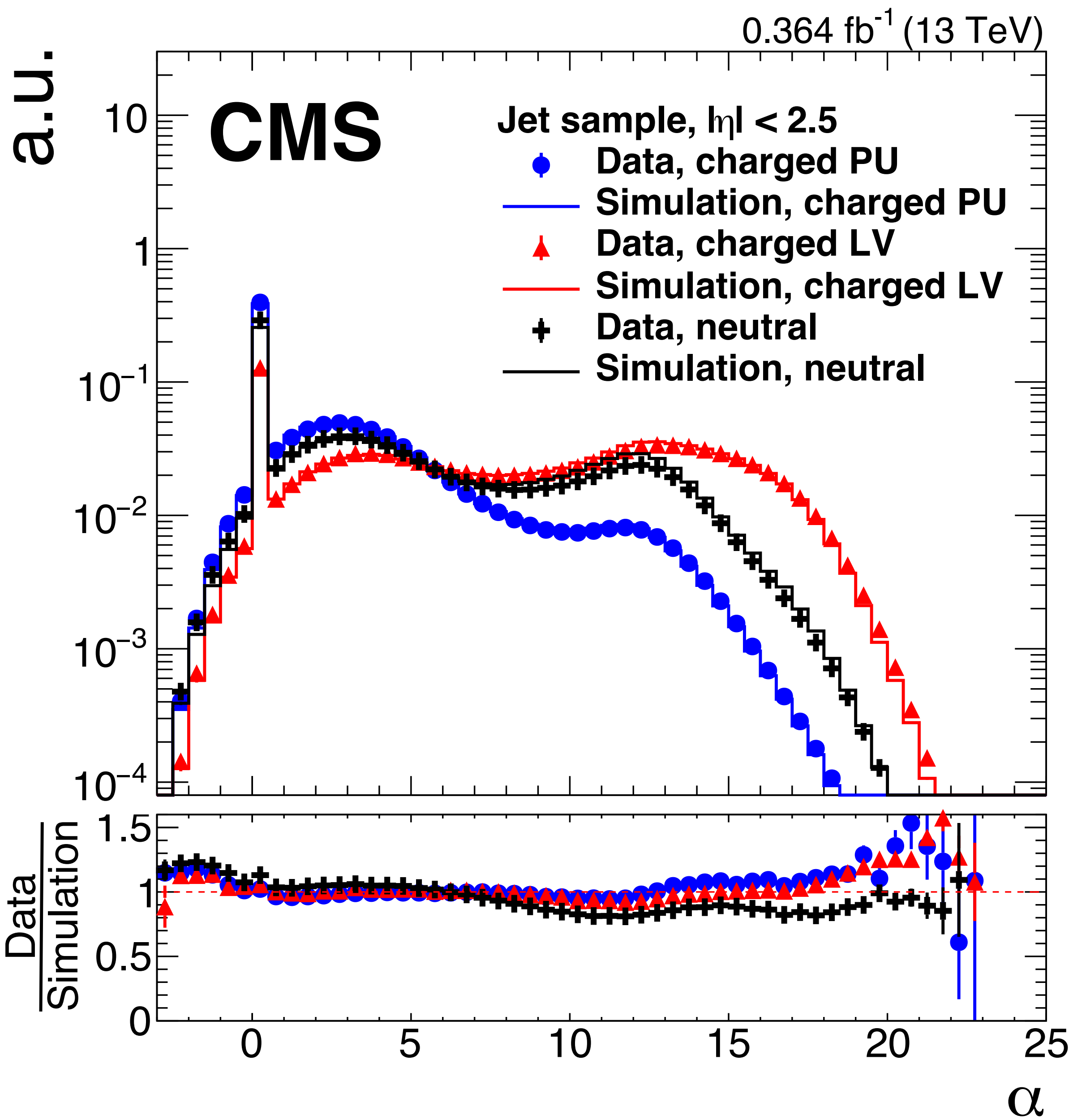


Summary

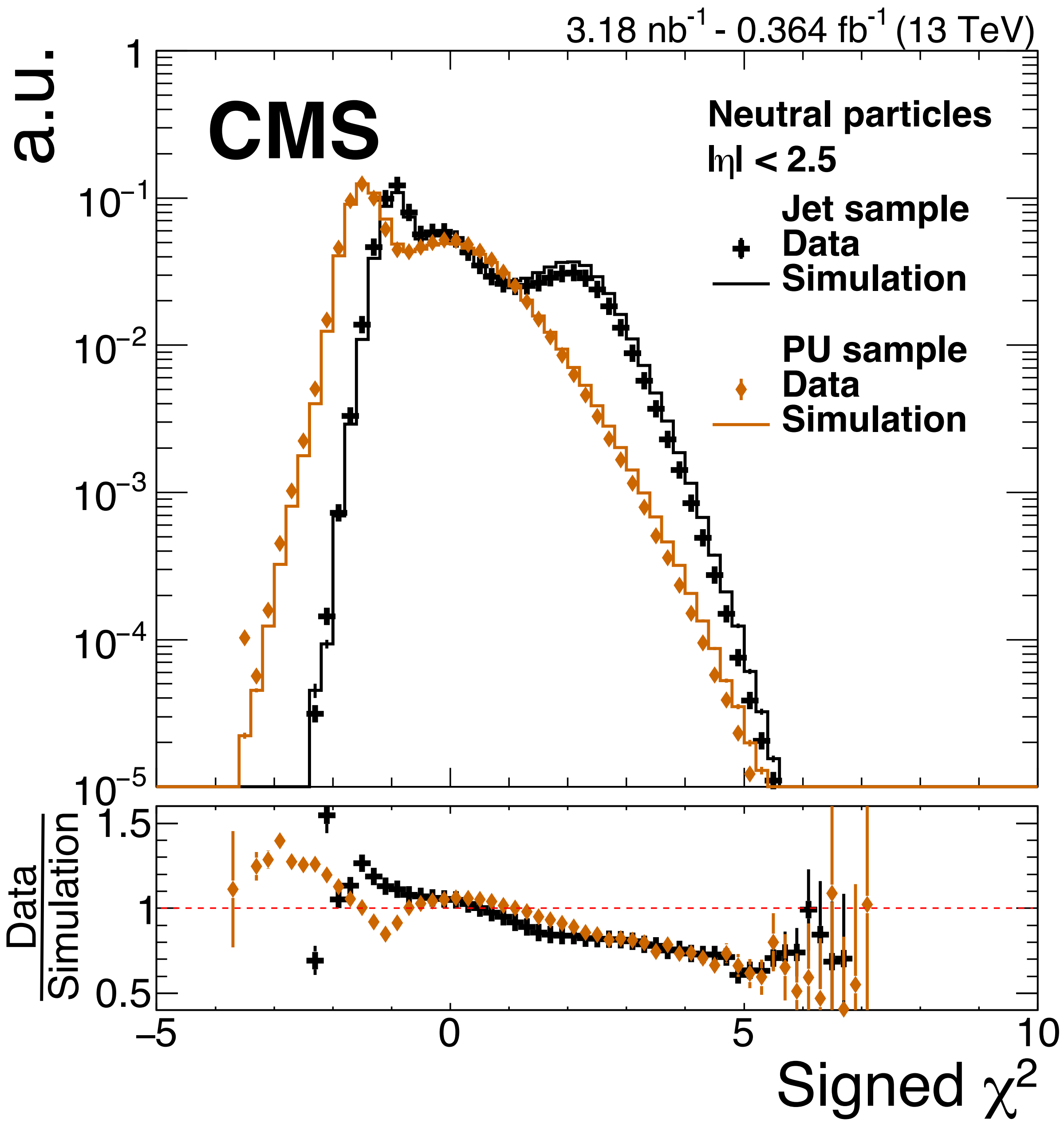
3. Use α on an event-by-event basis to calculate a per-particle weight



1. Calculate Median and RMS of charged PU shape (blue)

$$\bar{\alpha}_{PU},\ RMS_{PU}$$

3. Use α on an event-by-event basis to calculate a per-particle weight



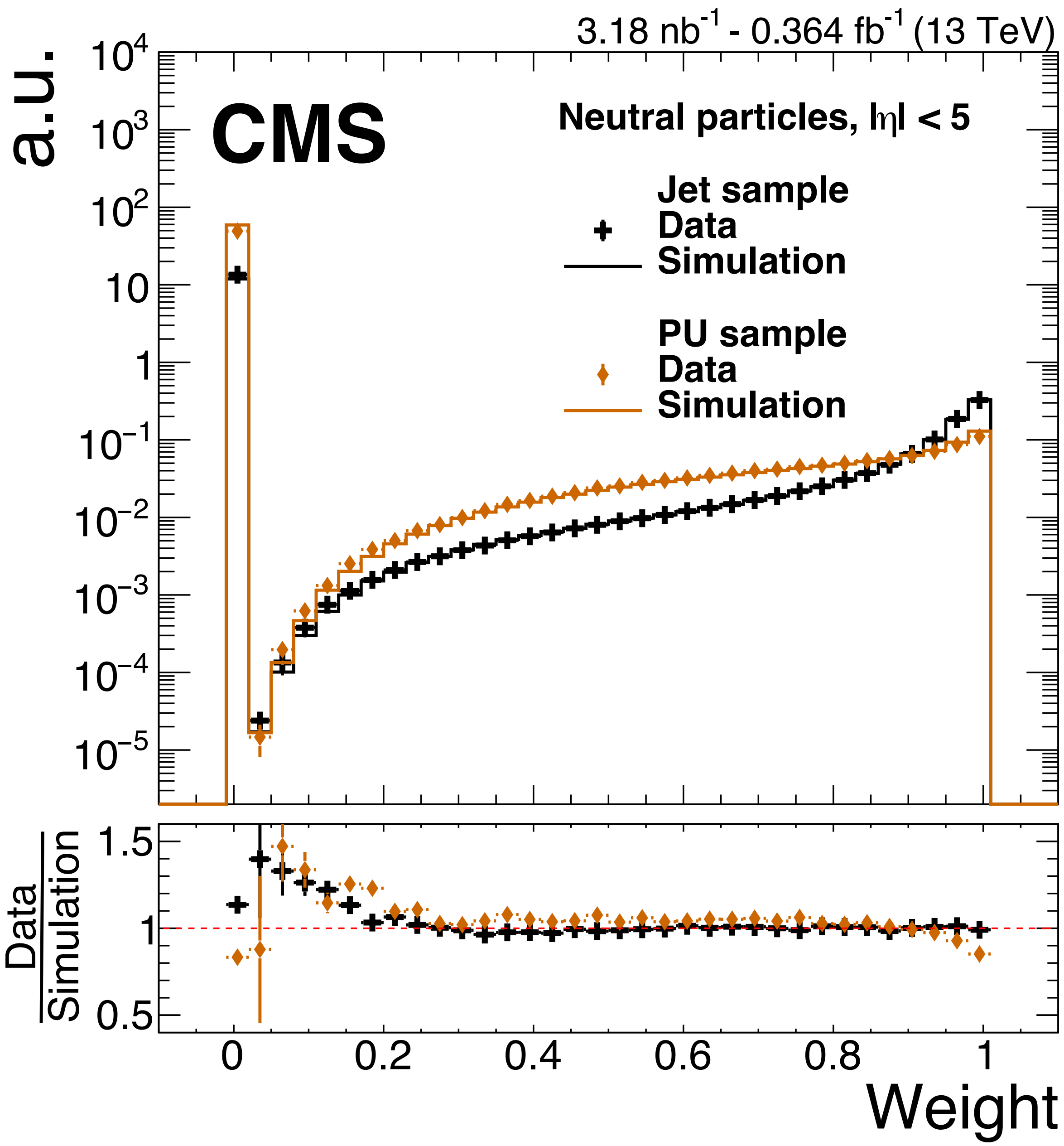
1. Calculate Median and RMS of charged PU shape

$$\bar{\alpha}_{PU},\ RMS_{PU}$$

2. For each particle calculate

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

3. Use α on an event-by-event basis to calculate a per-particle weight



1. Calculate Median and RMS of charged PU shape

$$\bar{\alpha}_{PU},\ RMS_{PU}$$

2. For each particle calculate

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

3. Assign a weight to each particle

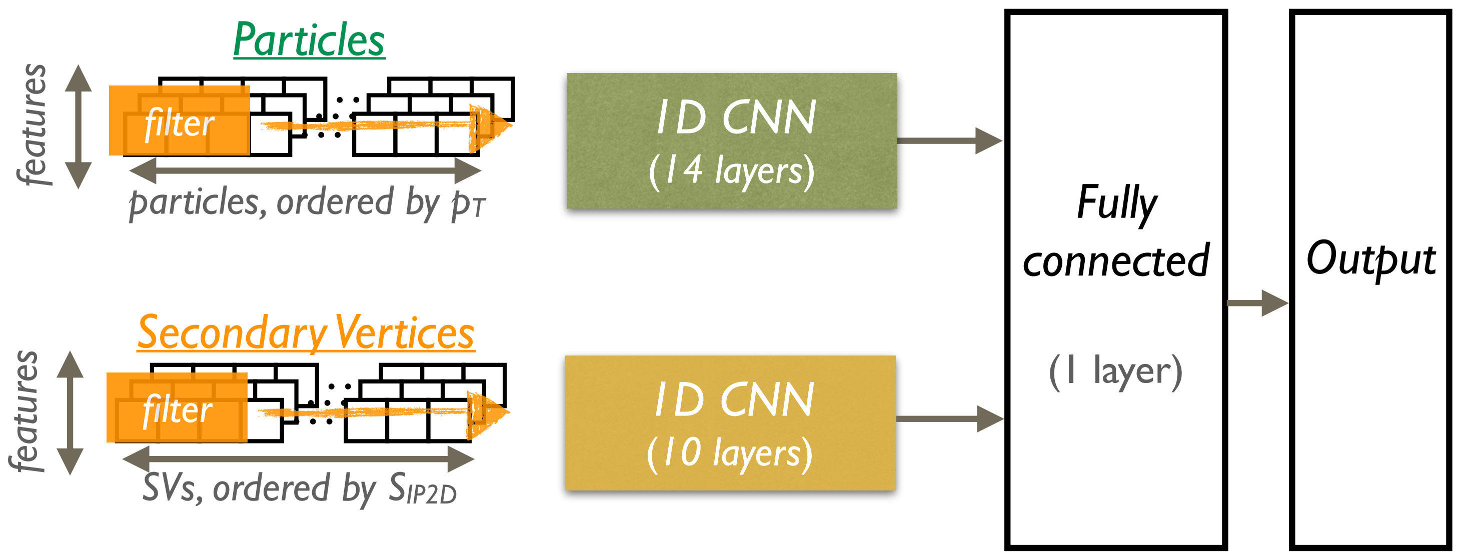
$$w_i = F_{\chi^2, NDF=1}(\chi_i^2)$$

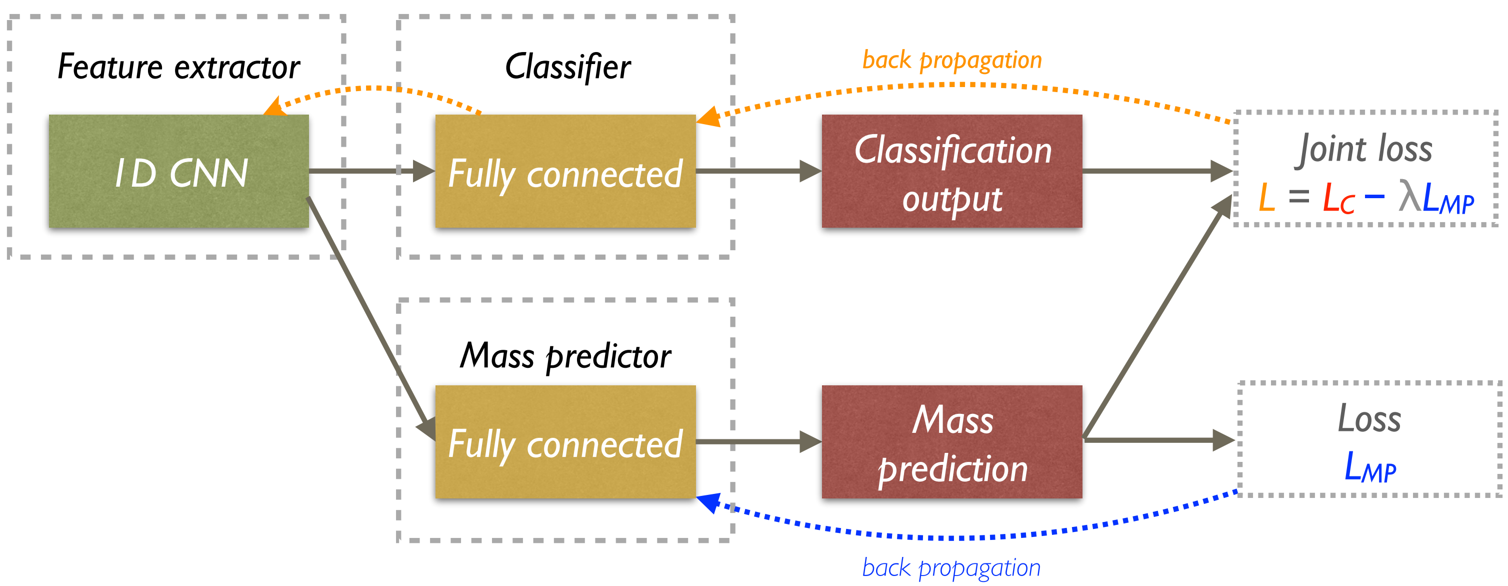
Pileup ⟶ Hard scattering

DeepAK8 in detail

Architecture

Performance studied in CMS extensively in JME-18-002

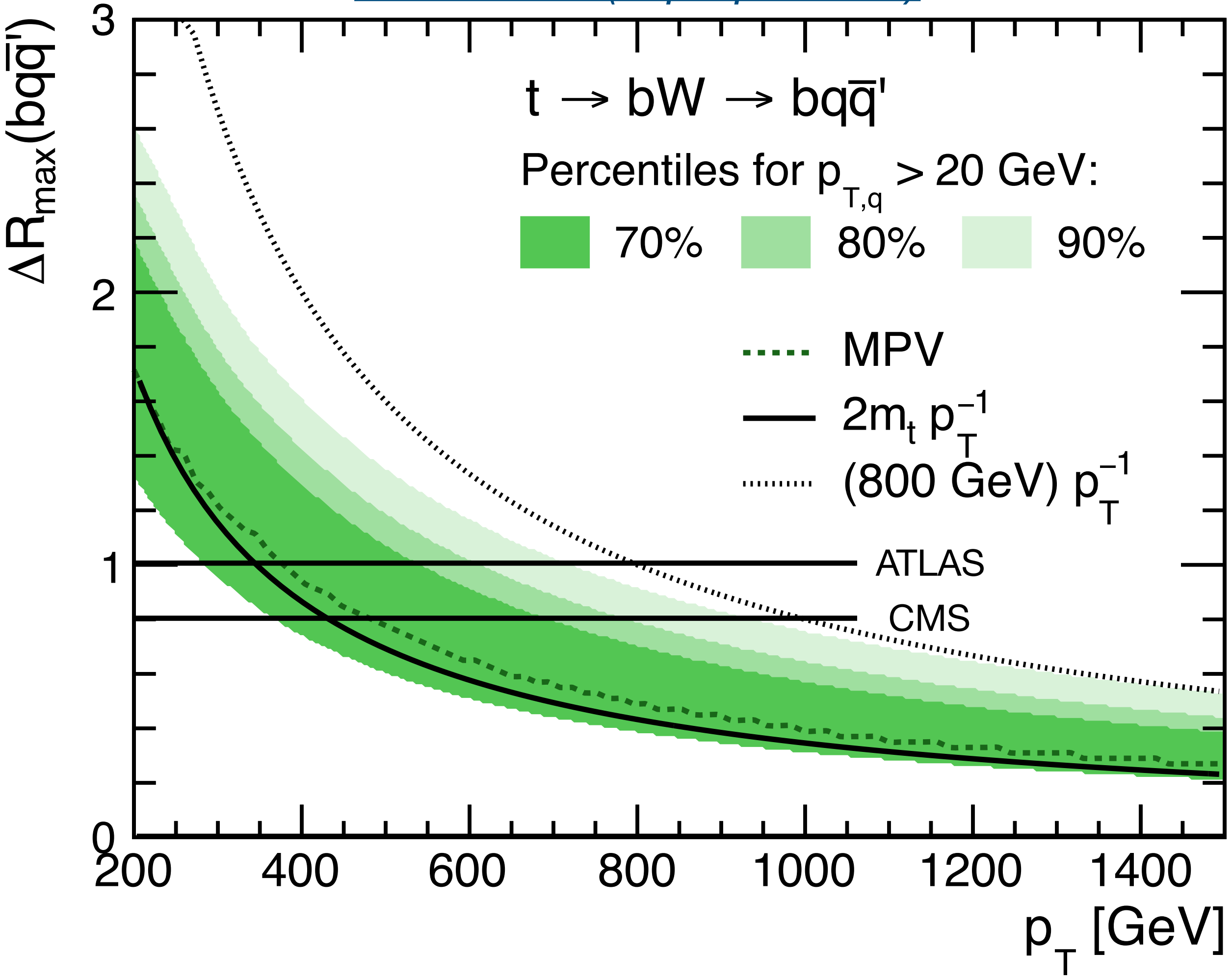


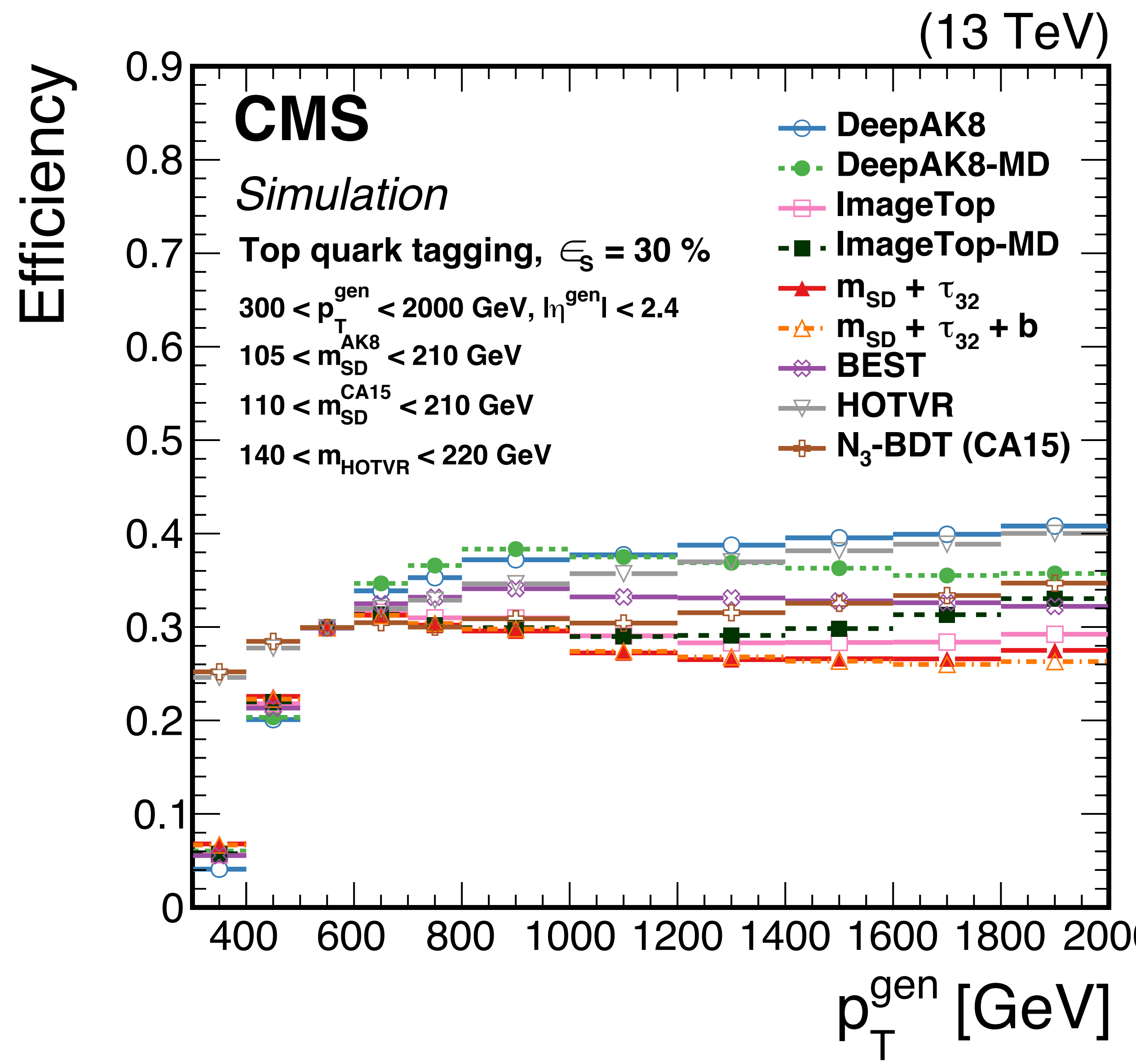


HOTVR in detail

Heavy object tagging with variable R (HOTVR)

Roman Kogler,
The coming of age of jet substructure at the LHC (in preperation)





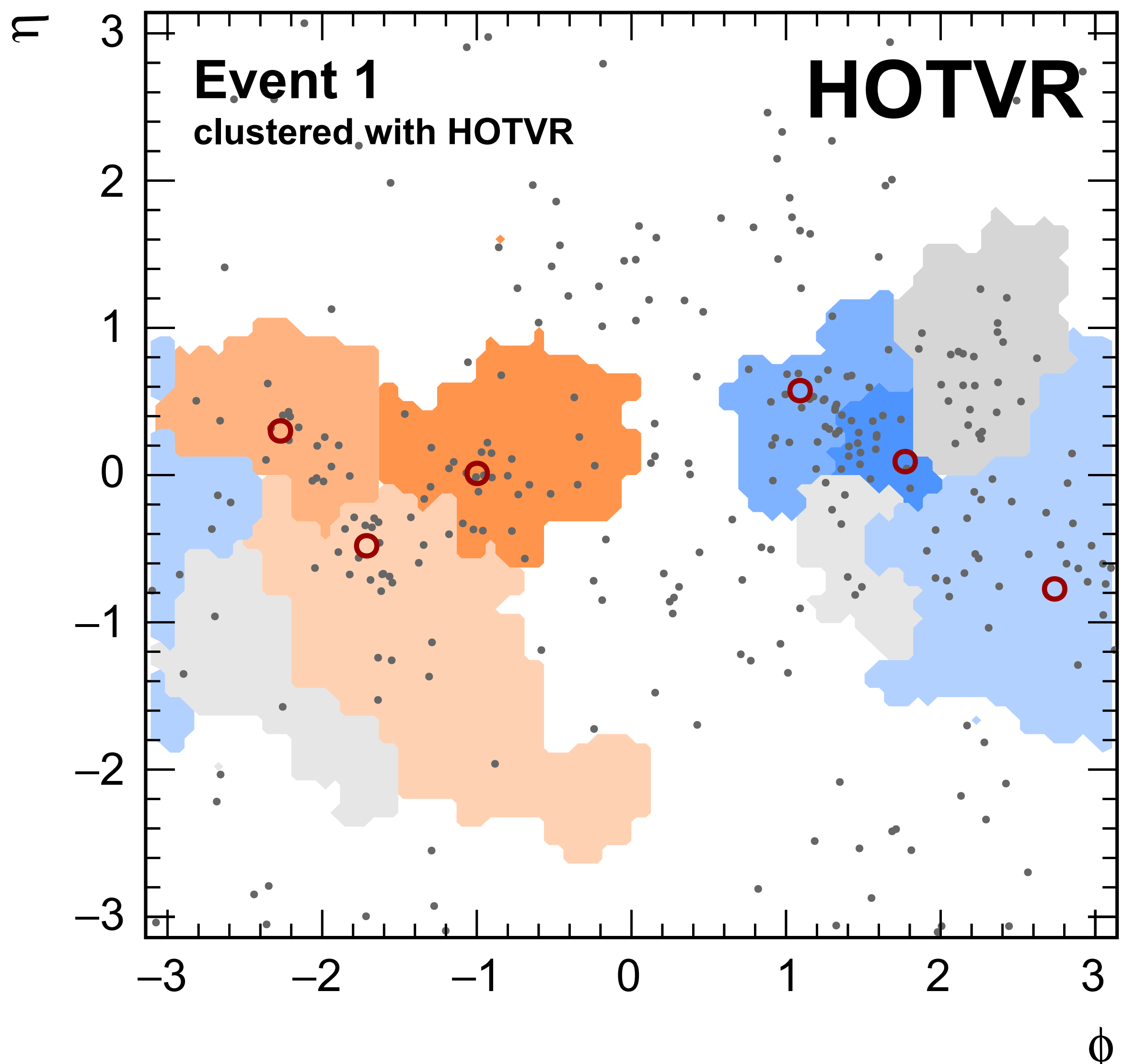
https://arxiv.org/pdf/2004.08262.pdf

- Jet cone is relevant for the "p_T threshold"
- Classical tagger suffer at low p_T

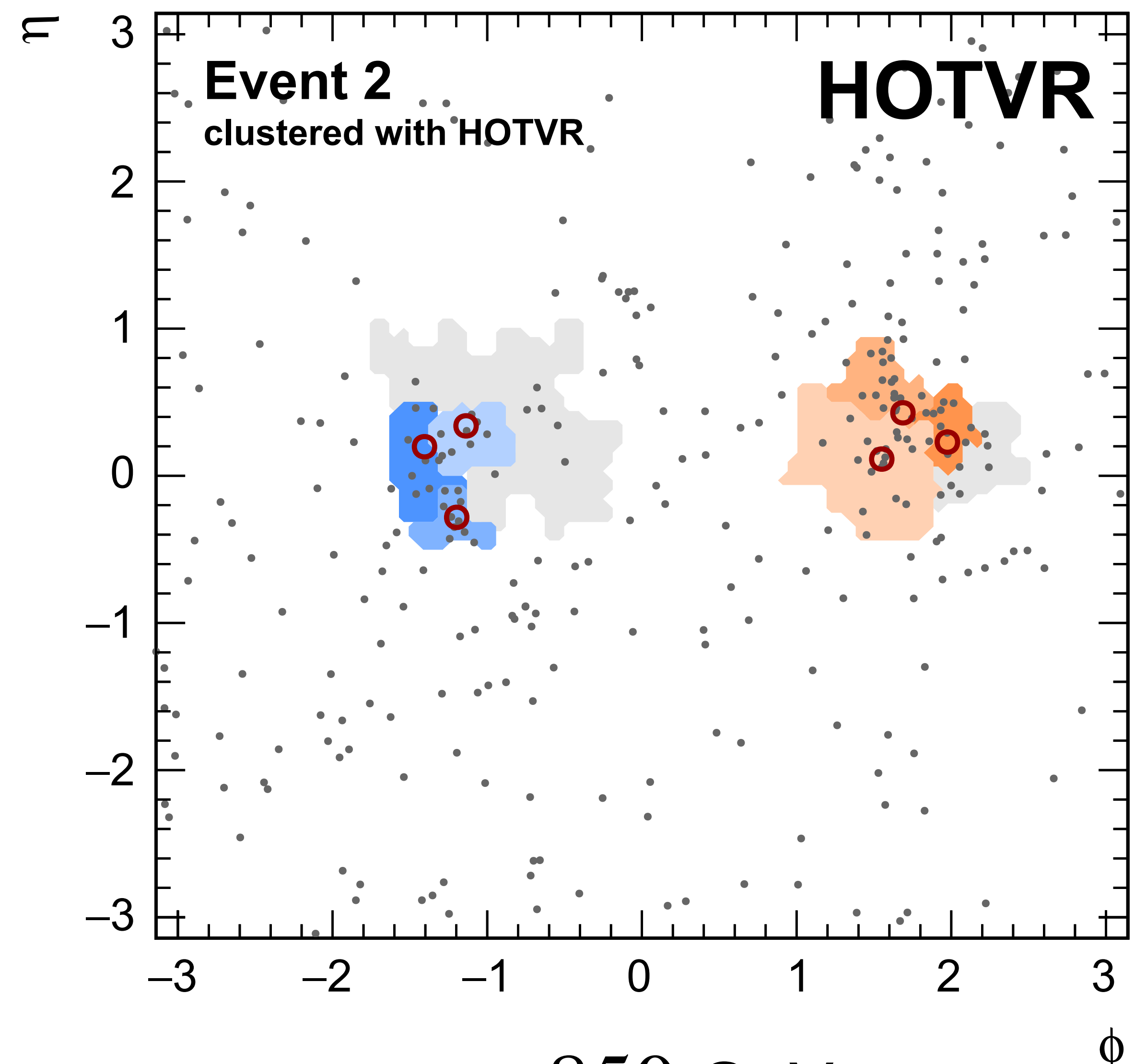
Summary

Heavy object tagging with variable R (HOTVR)

Performance studied in CMS extensively in JME-18-002



$p_T \approx 240$ GeV



$p_T \approx 850$ GeV

https://arxiv.org/abs/1606.04961

HOTVR adapts the jet radius to the p_T of the jet

HOTVR in details

The full HOTVR algorithm can be summarised as follows.

1) If the smallest distance parameter is $d_{i\mathrm{B}}$, store the pseudojet i as jet and remove it from the input list of pseudojets.

2) If the smallest distance parameter is d_{ij} and $m_{ij} \leq \mu$, combine i and j.

3) If the smallest distance parameter is d_{ij} and $m_{ij} > \mu$, check the mass jump criterion $\theta \cdot m_{ij} > \max[m_i, m_j]$.
   a) If the mass jump criterion is not fulfilled, compare the masses of the two pseudojets and remove the one with the lower mass from the input list.
   b) If the mass jump criterion is fulfilled, check the transverse momenta of the subjets i and j.
      i) If $p_{\mathrm{T},i} < p_{\mathrm{T,sub}}$ or $p_{\mathrm{T},j} < p_{\mathrm{T,sub}}$, remove the respective pseudojet from the input list.
      ii) Else, combine pseudojets i and j. Store the pseudojets i and j as subjets of the combined pseudojet. In case i or j have already subjets, associate their subjets with the combined pseudojet.

4) Continue with 1) until the input list of pseudojets is empty.

$$d_{ij} = \min\left[p_{\mathrm{T},i}^{2n}, p_{\mathrm{T},j}^{2n}\right] \Delta R_{ij}^2 ,$$
$$d_{i\mathrm{B}} = p_{\mathrm{T},i}^{2n} R_{\mathrm{eff}}^2(p_{\mathrm{T},i}) ,$$
$$R_{\mathrm{eff}}(p_{\mathrm{T}}) = \frac{\rho}{p_{\mathrm{T}}} .$$

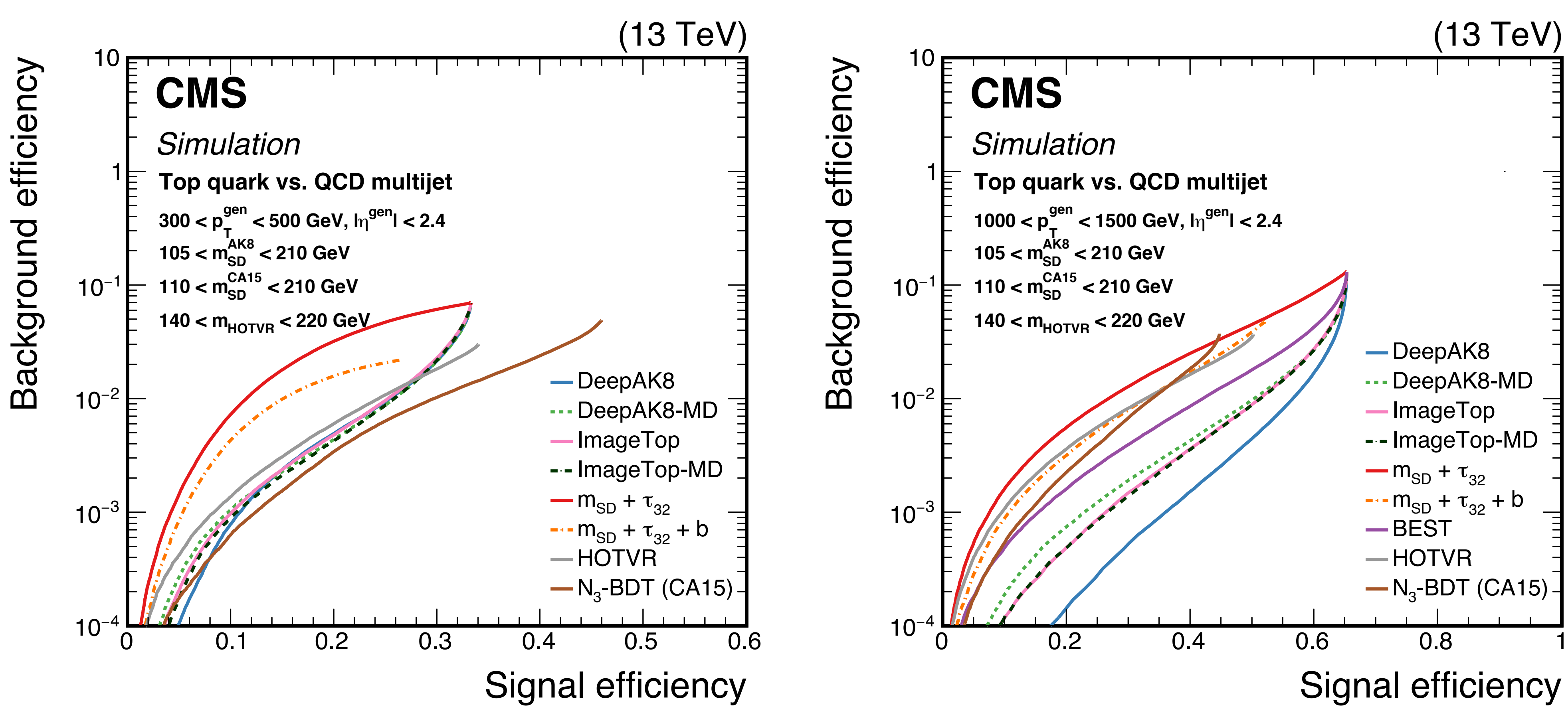
$$R_{\mathrm{eff}} = \begin{cases} R_{\min} & \text{for } \rho/p_{\mathrm{T}} < R_{\min} , \\ R_{\max} & \text{for } \rho/p_{\mathrm{T}} > R_{\max} , \\ \rho/p_{\mathrm{T}} & \text{else} . \end{cases}$$

https://arxiv.org/abs/1606.04961

HOTVR in details

Parameter	Default	Description
$R_{\min}$	0.1	Minimum value of R_{eff}.
$R_{\max}$	1.5	Maximum value of R_{eff}.
ρ	600 GeV	Slope of R_{eff}.
μ	30 GeV	Mass jump threshold.
θ	0.7	Mass jump strength.
$p_{\mathrm{T,sub}}$	30 GeV	Minimum p_{T} of subjets.

Table 1: Parameters of the HOTVR algorithm. The default values are given for the top-tagging mode.



https://arxiv.org/abs/1606.04961

CMS-JME-18-002

ImageTop-MD in detail

ImageTop-MD architecture

Performance studied in CMS extensively in JME-18-002