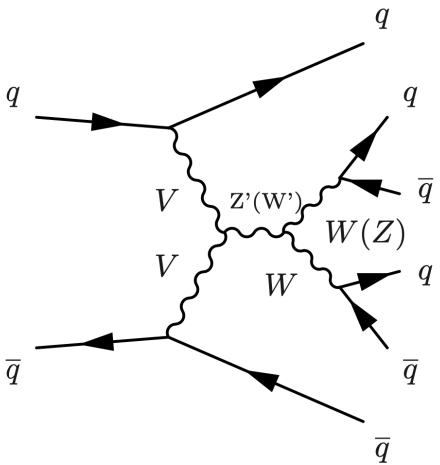
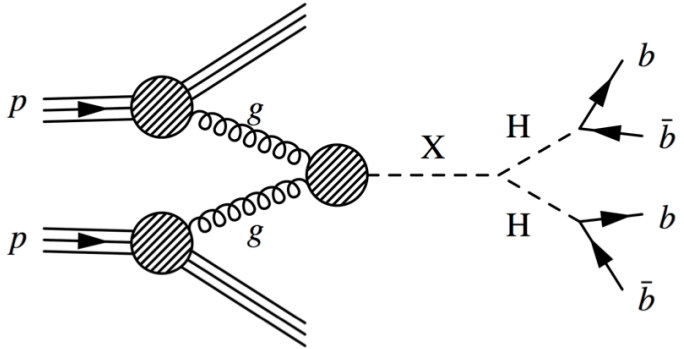
Searches for heavy resonances in diboson final states at CMS

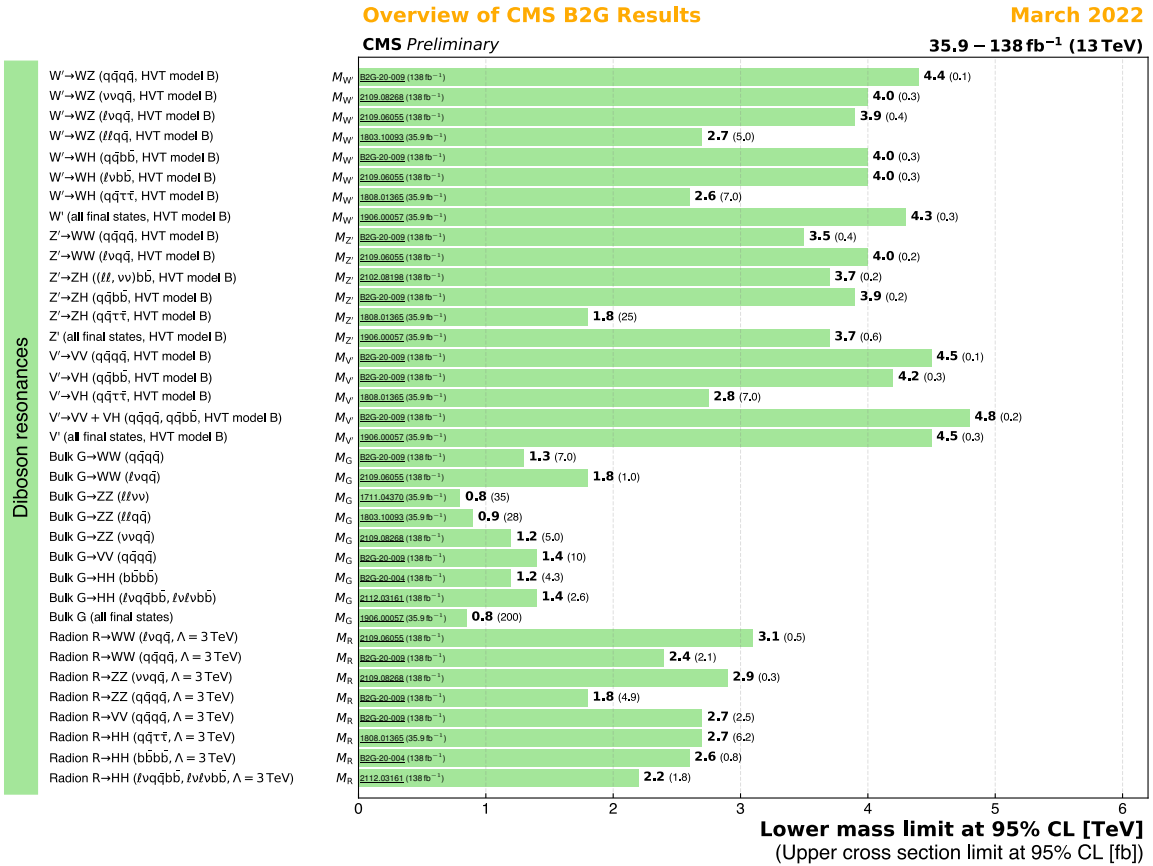
Irene Zoi on behalf of the CMS Collaboration

PHENO 2022





Searches for Diboson resonances in CMS



- Very active sector!
- Allows to probe a wide range of BSM models
  - Warped extra dimension
    Lisa Randall and Raman Sundrum. "A Large mass hierarchy from a small extra dimension". [Phys. Rev. Lett. 83 (1999)3370]
    - Spin-0 radion
    - Spin-2 bulk graviton
  - Heavy Vector Triplet (HVT)
    Duccio Pappadopulo et al. "Heavy Vector Triplets: Bridging Theory and Data". [JHEP 09 (2014)060]
    - Spin-1 W'/Z'
- In this talk: focus on new results since Pheno2021

Fermilab

In this talk:

Full Run2 data: 137-138 fb^{-1}

	ID & Links	Topology	X mass range [TeV]	Spins	Released
	CMS-PAS-B2G-21-001	VBF nonres→ HH→ 4b	-	-	July 2021
	CMS-B2G-20-013	X/nonres → ZZ/ZW/ZH→ llqq	0.45 - 1.8	1/2	July 2021
	CMS-B2G-21-002	W_{kk} → WR → WWW had	W_{kk}:1.5 - 5 R: 6-90% W_{kk}	W_{kk}: 1 R: 0	July 2021
⭐	CMS-PAS-B2G-20-004	X→ HH→ 4b	1 - 3	0/2	July 2021
⭐	CMS-B2G-20-003	X→ ϕϕ→ 4b	X: 1 - 3 ϕ: 25-100 GeV	X=0 ϕ=0	July 2021
⭐	CMS-B2G-20-007	X→ HH→bbWW/bbττ	0.8 - 4.5	0/2	July 2021
⭐	CMS-PAS-B2G-21-003	X→ YH→ 4b	X: 0.9 - 4 Y: 60-600 GeV	X=0 Y=0	November 2021
	CMS-PAS-B2G-22-003	nonres→ HH→ 4b (w/VBF)	-	-	March 2022
⭐	CMS-PAS-B2G-20-009	X→ VV/VH all-jets (w/VBF)	1.3 - 6	0/1/2	March 2022

⭐Covered Worth a mention

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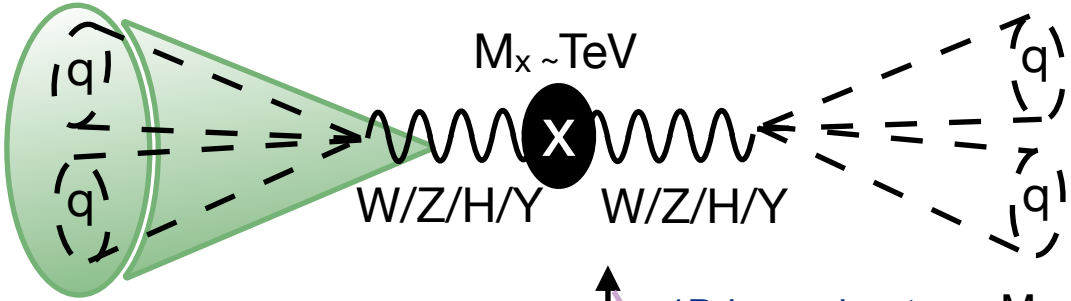
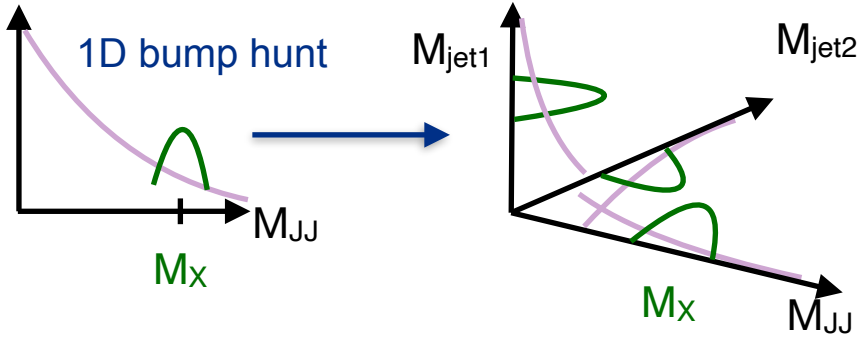
Common strategies and challenges

Jet tagging



Multidimensional analyses

- Low level taggers
  - Nsubjettiness [arXiv:1011.2268]
- Many ML-based taggers
  - DeepJet [JINST 15 (2020) P12012]
  - Double-b [JINST 13 (2018) P05011]
  - DeepAK8 [JINST 15 (2020) P06005]
  - ParticleNet [Phys. Rev. D 101 (2020) 056019]



- Multidimensional bump hunts
- Take into account correlation M_{jet} vs M_{JJ}
- Especially challenging for Y with unknown mass

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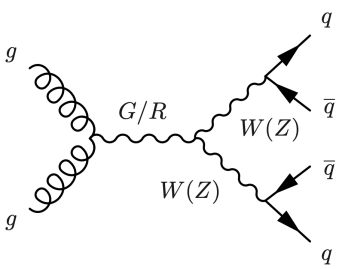
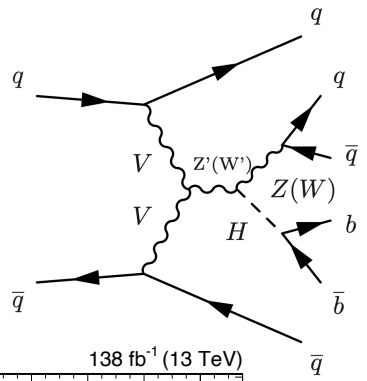
X → VV/VH→all-jets (w/VBF) boosted

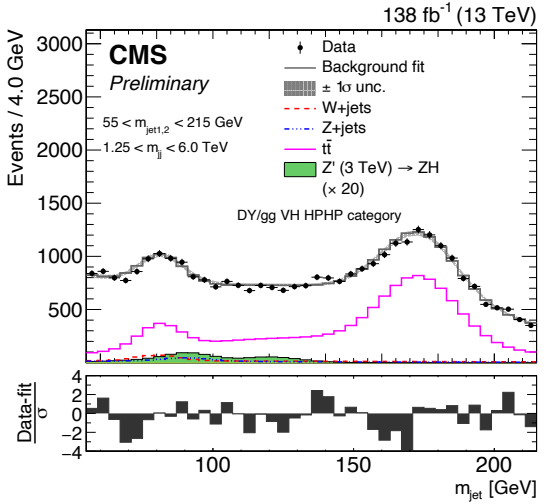
X: 1.3 - 6 TeV

CMS-PAS-B2G-20-009

- X : Spin-0,2 (extra dimension) or Spin-1 (HVT)
  - WW/WZ/ZZ/WH/ZH
- Jet tagging with DeepAK8 V→qq & Z/H→bb
- 3D bump hunt in M_{jet1}, M_{jet2} and M_{jj}
- Data-driven background estimation from templates based on simulation
- Main background QCD (gaussian kernel)
  - 1D for M_{jj}, 2D for M_{jet1} & M_{jet2}
- Other backgrounds ttbar and V+jets
  - 1D for M_{jj}, CB or Gaussians for M_{jet}
- Signal parametrized with dCB







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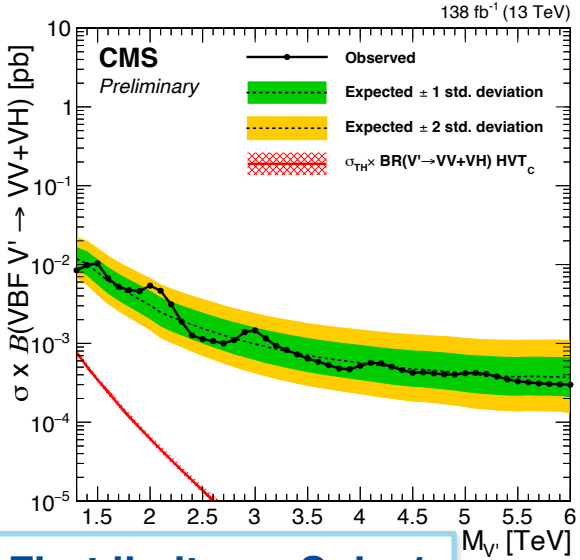
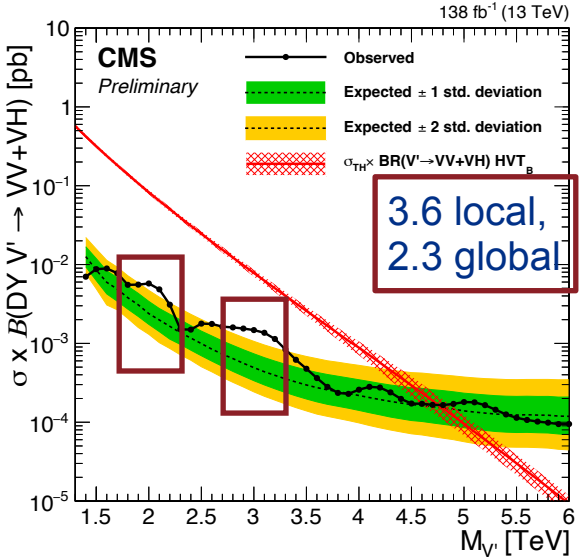
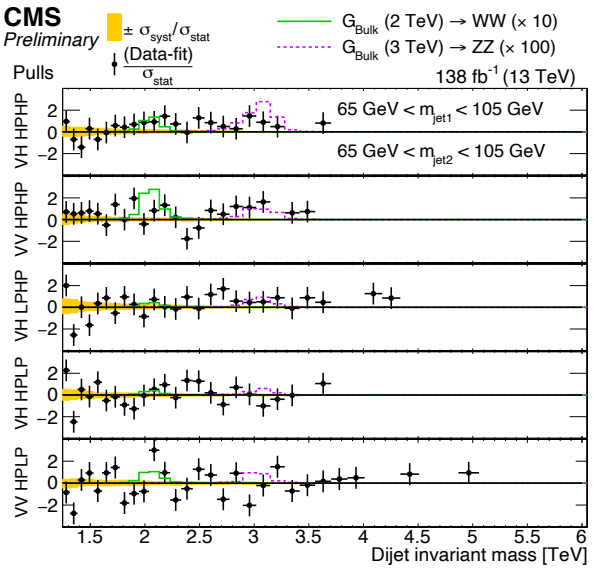
X → VV/VH→all-jets (w/VBF) boosted

CMS-PAS-B2G-20-009

- Categories improve sensitivity on 16 signal hypotheses:
  - DY/gg or VBF production
  - 5 tagging categories based on type/purity







First limits on Spin-1 with VBF in all-hadronic final state

Most stringent limits on Spin-1 (4.8 TeV)

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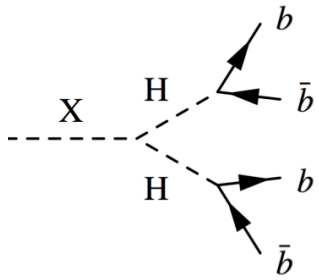
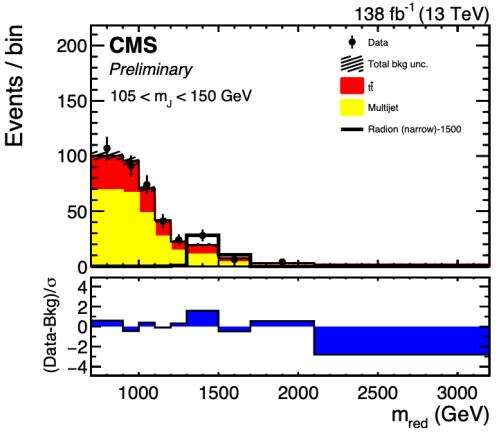
X → HH → 4b with large area jets

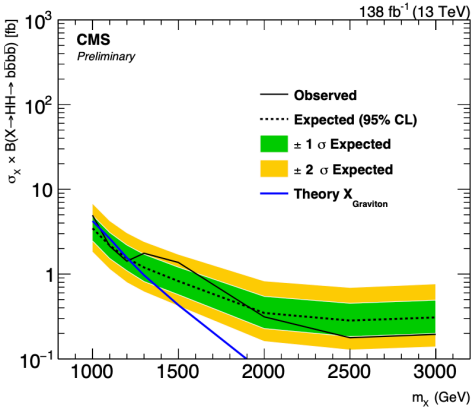
CMS-PAS-B2G-20-004



- 1 H merged & 1 H merged or resolved*
  - Improves sensitivity for $1 < M_X < 2$ TeV
- Jet tagging:
  - merged: DeepAK8, resolved: DeepJet
- Main backgrounds: QCD and tt+jets, estimated from data with help from simulation in "2D-Alphabet" method
- 2D Likelihood fit of (m_{JH}, m_{red}),
  - m_{red}: ~10% better dijet mass resolution
    - Merged: $m_{JJ} - (m_J - m_H) - (m_{J_2} - m_H)$
    - Resolved: $m_{Jjj} - (m_J - m_H) - (m_{JJ}(j_1, j_2) - m_H)$

X: 1 - 3 TeV





Spin-0 in backup

*both merged [Phys. Lett. B 781 (2018) 244] or both resolved [JHEP 08 (2018) 152]

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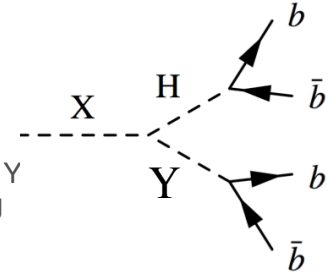
X → YH → 4b boosted

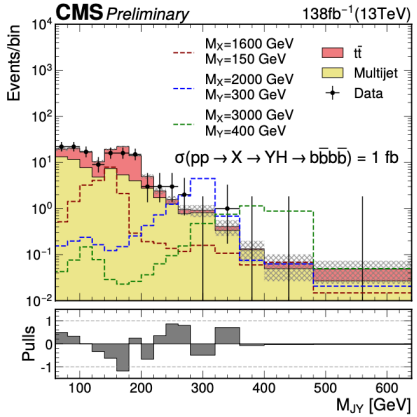
X: 0.9 - 4 TeV
Y: 60-600 GeV

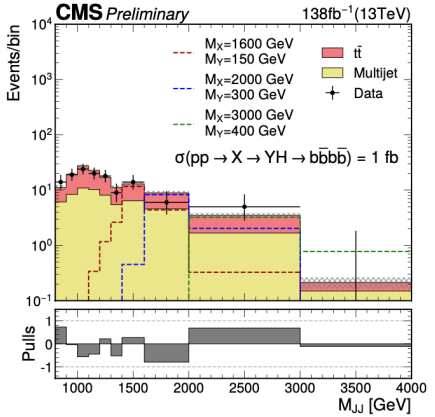
CMS-PAS-B2G-21-003

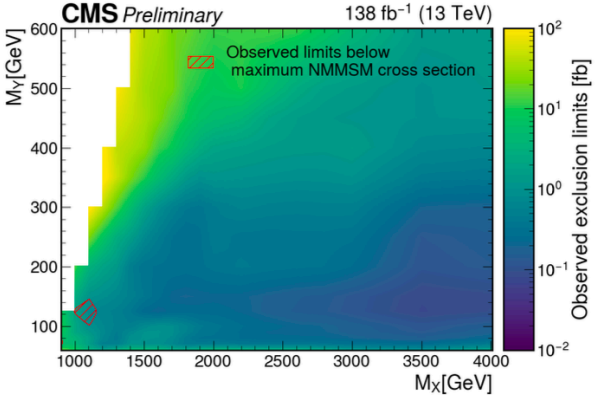
- In next-to-MSSM, X= H' and Y=H_s

  [Phys. Rept. 496 (2010) 1, Int. J. Mod. Phys. A 25 (2010) 3505]
- H-jet $110 < M_J^H < 140$ GeV,
  Y-jet $M_J^Y > 60$ GeV
- 2D bump hunt in M_{JJ} and M_J^Y
- bb tagging with ParticleNet
- Main backgrounds
  - QCD multijet: Data-driven using a pass-fail ratio method
  - ttbar: from simulations with corrections obtained from a semileptonic control region









Limits are 2x better than for X→HH→ 4b

Most stringent cross-section limits

Extends limit ranges of NMSSM scalars

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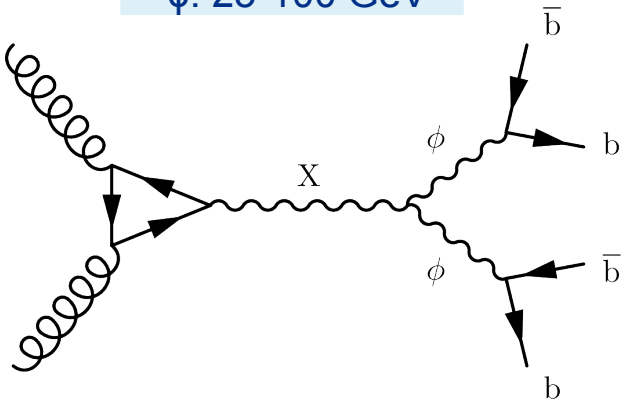
X → ϕϕ → 4b boosted

CMS-B2G-20-003

- Extended Higgs sector with 2 new scalars:
  - for $m_X > 2m_\phi$, X → $\phi\phi$ is the dominant decay
  - ϕ couples to fermions similarly to H
- double-b tagger algorithm
- Bump hunt in 2D: average jet mass $\hat{m}$ & dijet mass M_{jj}
- Main backgrounds:
  - QCD ("ABCD"-like estimate)
  - ttbar (simulation + corrections in data CR)
- Signal modeled with a multivariate normal distribution
  - Mean and width of $\hat{m}$ and M_{jj} + correlation

X: 1 - 3 TeV
ϕ: 25-100 GeV



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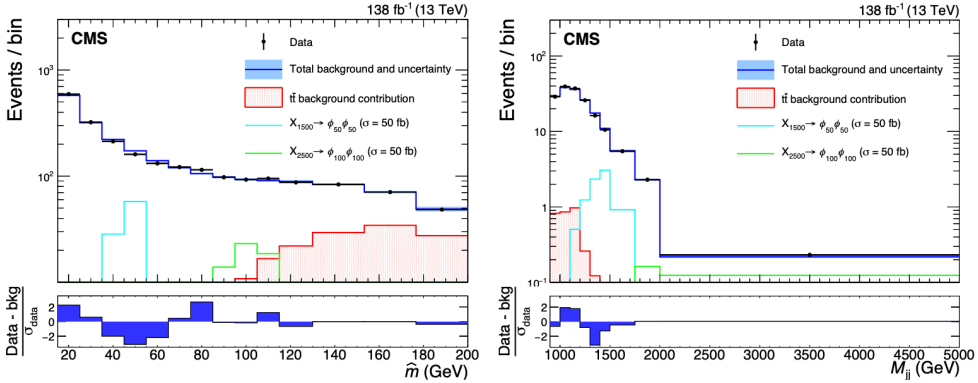
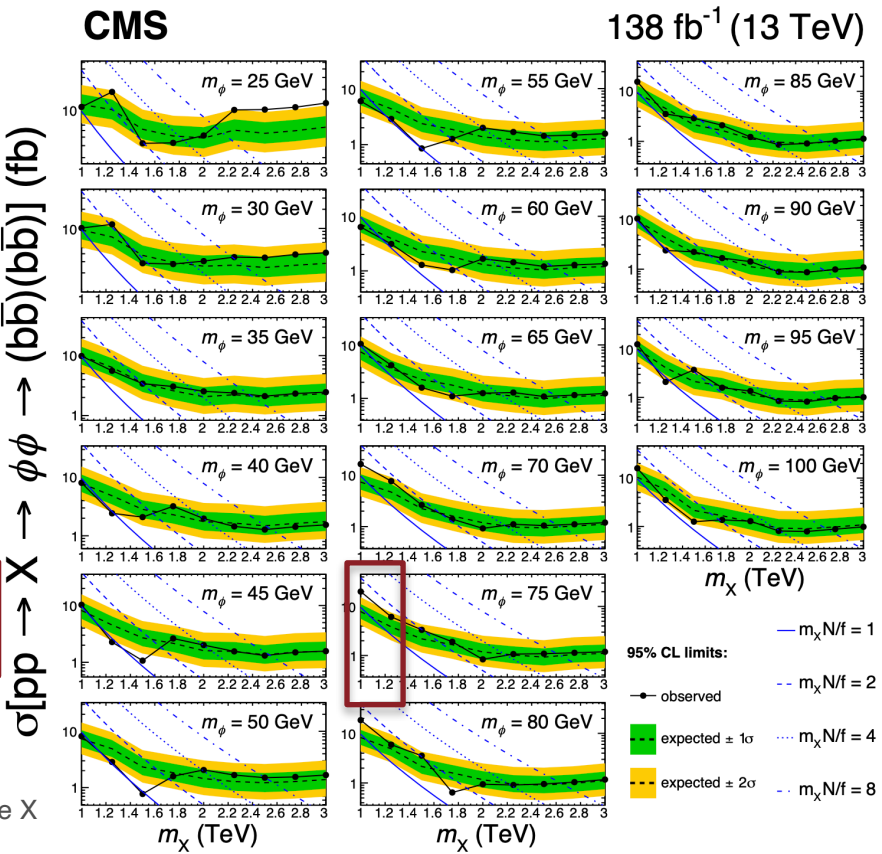
X → ϕϕ → 4b boosted

CMS-B2G-20-003





First result with this signature!!

3.1 local,
1.3 global

N flavors of quarks that receive all their mass from the X
f vacuum expectation value

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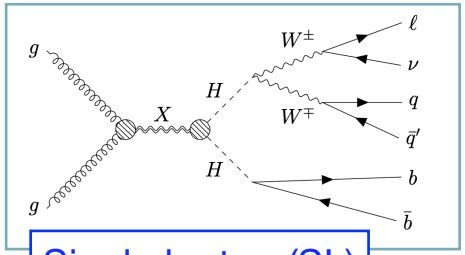
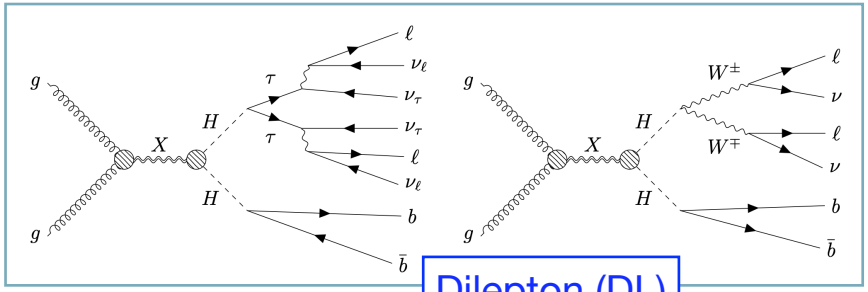
X → HH → bbWW/bbττ with leptons boosted

CMS-B2G-20-007

X: 0.8 - 4.5 TeV



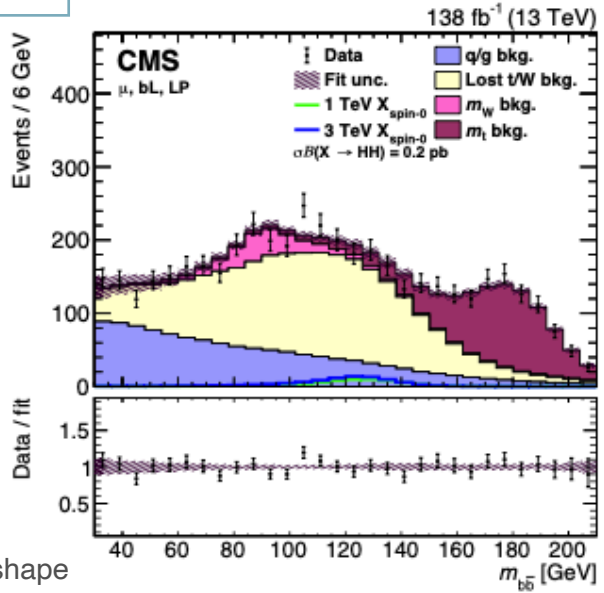
Single lepton (SL)



Dilepton (DL)

- (ℓ = e, μ)

- bb tagging DeepAK8, W→ qq Nsubjettines τ_{21}
- 2D fit of the m_{bb} and m_{HH}
- Reconstruction of the H → WW/ττ:
  - SL: sum of the 4-momenta of p_ν, qq-jet and ℓ
  - DL: $p_H = p_{\ell\ell} + p_{inv}$, with $m_{inv} = 55$ GeV and $\theta_{inv} = \theta_{\ell\ell}$
- Main background is ttbar
  - SL: W(lep)+jets & QCD
  - DL: Z/gamma+jets



*Background splitted by components with similar m_{bb} shape

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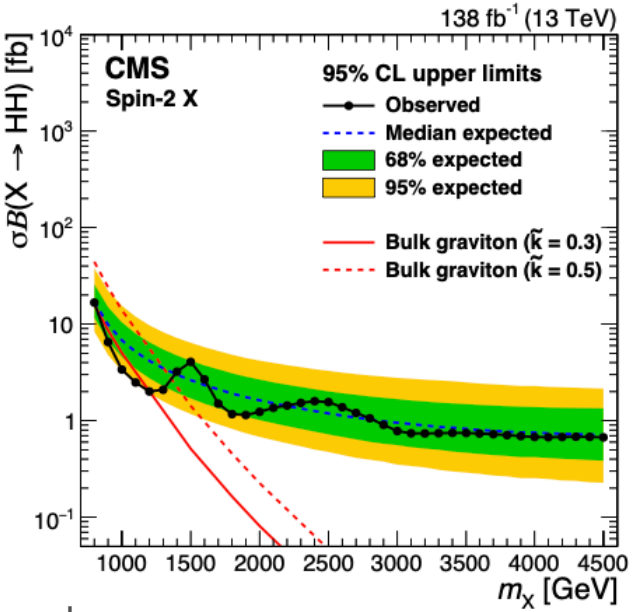
X → HH → bbWW/bbττ with leptons

CMS-B2G-20-007

- Categories:
  - 8 SL: e/μ + loose/tight bb tagging
    + LP/HP in H→ WW reconstructions
  - 4 DL: same/opposite flavor leptons
- 2D templates from simulation:
  - Background: 2D for m_{bb} & 1D for m_{HH}
    - m_{bb} modelled differently for resonant/nonresonant components
  - Signal: double sided Crystall Balls (dCB)
    - For m_{HH} an additional linear component accounts for the dependence on m_{bb}
  - The normalizations from simulation are used as the initial values for the fit to data.



Most sensitive upper limits for X → HH production with leptons!!

Spin-0 in backup

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Summary

- Many new results!
- Exploiting HH with H→ bb and similar channels
- Jet substructure crucial
  - Many ML based taggers for boosted regime of V/H→ qq/bb
  - Key to improved sensitivity!
- Multidimensional bump hunts: 1D, 2D & 3D
  - Tagger decorrelation
- Combinations and Run3 @ 13.6 TeV are around the corner

More to come!!

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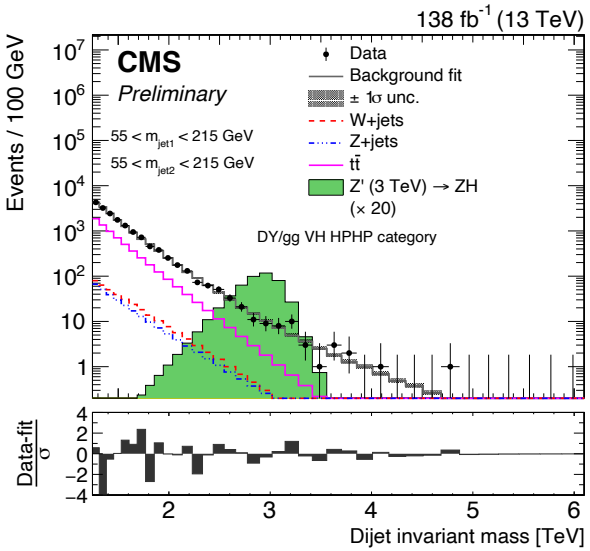
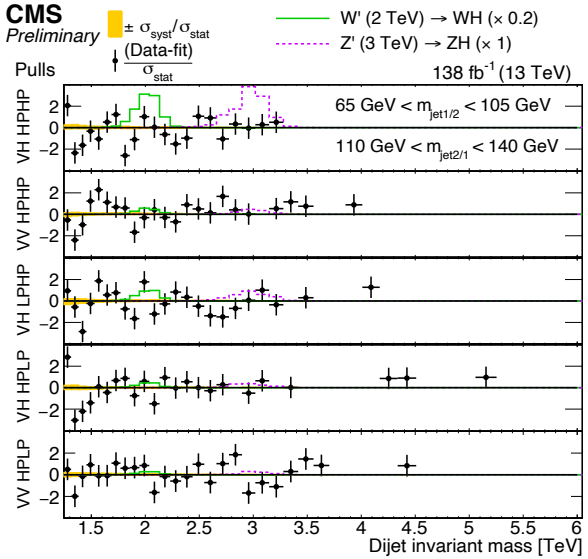
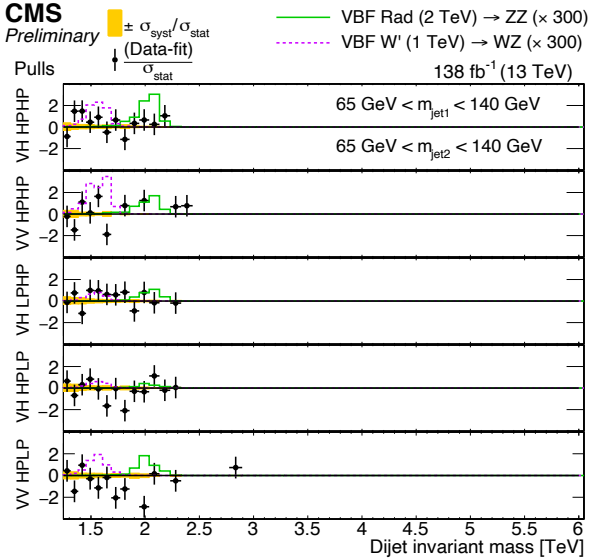
Additional material

X → VV/VH→all-jets (w/VBF) boosted

CMS-PAS-B2G-20-009





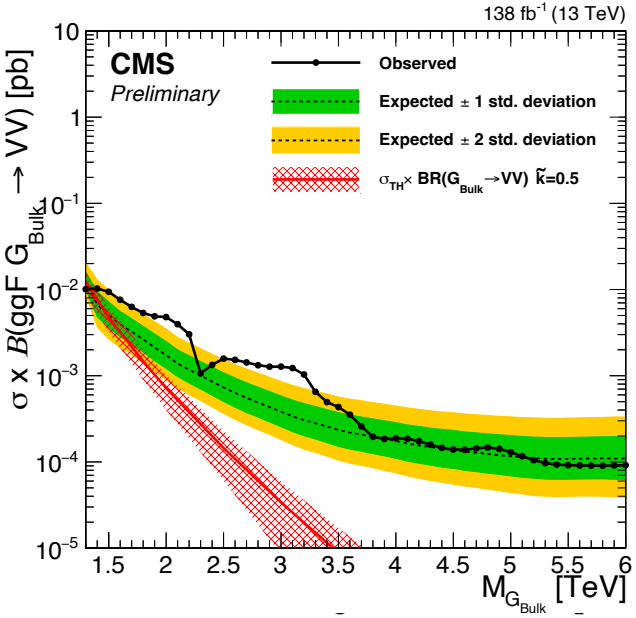


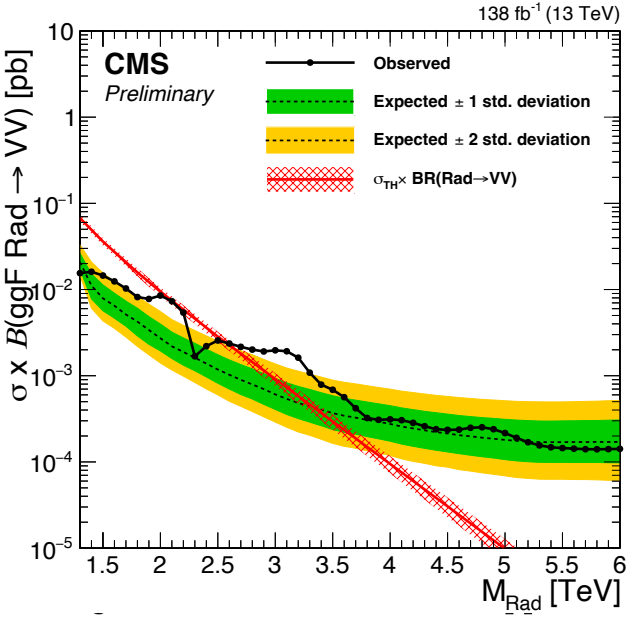
Go back to talk

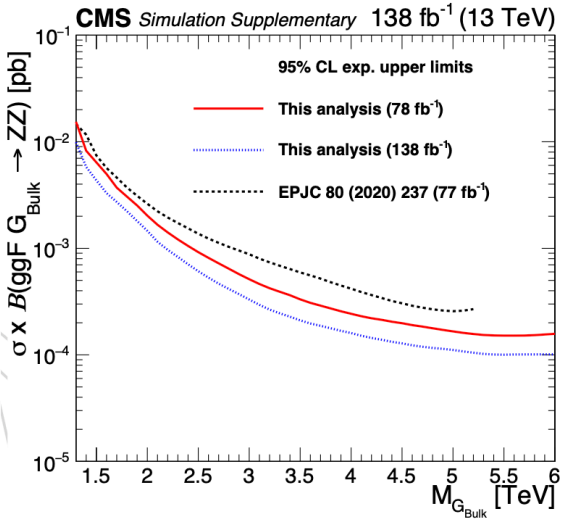
Event category	VBF	$m^{AK8}_{jet1/2}$ and $m^{AK8}_{jet2/1}$ tags
VBF VH HPHP	pass	(5% $q\bar{q}$ or 2% $b\bar{b}$) and 2% $b\bar{b}$
VBF VV HPHP	pass	5% $q\bar{q}$ and 5% $q\bar{q}$
VBF VH LPHP	pass	(20% $q\bar{q}$ or 10% $b\bar{b}$) and 2% $b\bar{b}$
VBF VH HPLP	pass	5% $q\bar{q}$ and 10% $b\bar{b}$
VBF VV HPLP	pass	5% $q\bar{q}$ and 20% $q\bar{q}$
DY/gg VH HPHP	fail	(5% $q\bar{q}$ or 2% $b\bar{b}$) and 2% $b\bar{b}$
DY/gg VV HPHP	fail	5% $q\bar{q}$ and 5% $q\bar{q}$
DY/gg VH LPHP	fail	(20% $q\bar{q}$ or 10% $b\bar{b}$) and 2% $b\bar{b}$
DY/gg VH HPLP	fail	5% $q\bar{q}$ and 10% $b\bar{b}$
DY/gg VV HPLP	fail	5% $q\bar{q}$ and 20% $q\bar{q}$

X → VV/VH→all-iets (w/VBF) boosted

CMS-PAS-B2G-20-009







Model		Observed limit (TeV)	Expected limit (TeV)
Radion DY/gg	VV	2.7	3.4
HVT model B, W'	WZ / WH	4.4 / 4.0	4.3 / 4.3
HVT model B, Z'	WW / ZH	(1.3–3.1, 3.3–3.5) / 3.9	3.8 / 3.8
HVT model B, V'	VV+VH / VV / VH	4.8 / 4.5 / 4.2	4.8 / 4.5 / 4.5
G_{bulk} ($\tilde{\kappa} = 0.5$) DY/gg	VV	1.4	1.5

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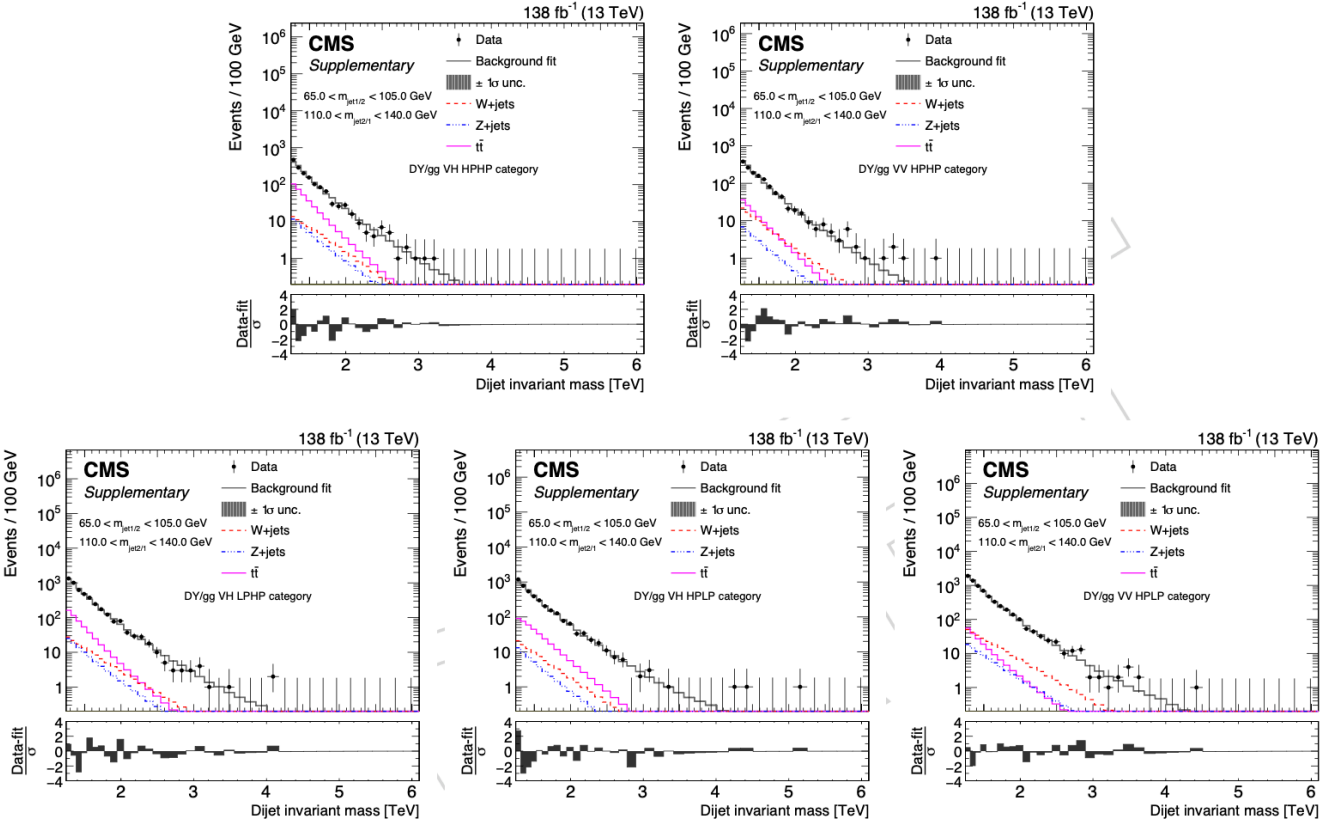
X → VV/VH→all-jets (w/VBF) boosted

CMS-PAS-B2G-20-009



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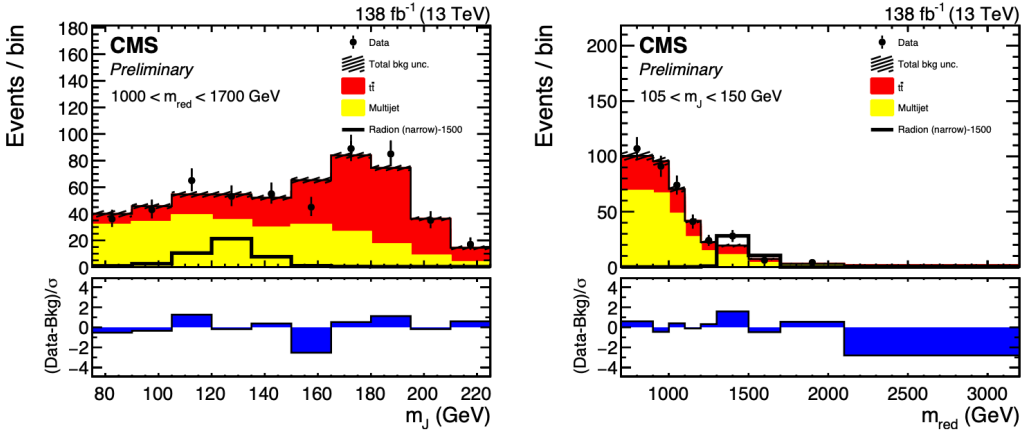
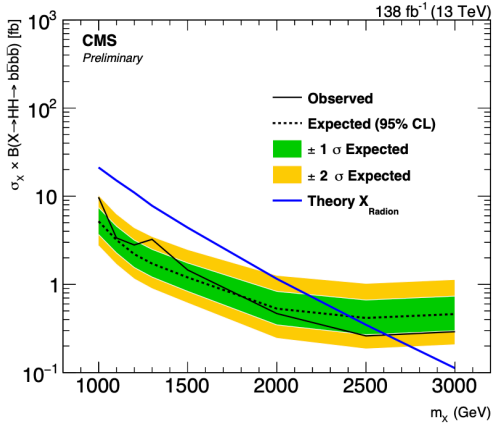
X → HH → 4b with large area jets

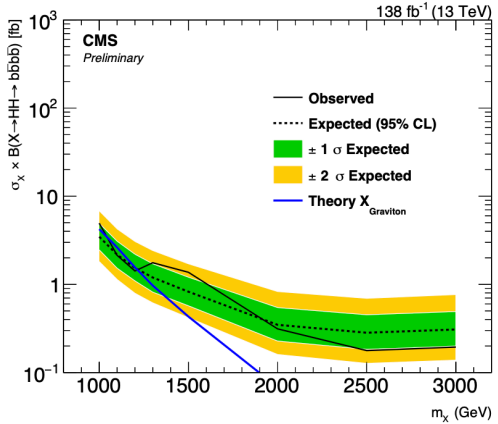


- fluctuations caused by jet energy and mass resolutions are mitigated, leading to 8-10% improvement in the dijet mass resolution

$$m_{\mathrm{red}} \equiv \begin{cases} m_{\mathrm{JJ}} - (m_{\mathrm{J}} - m_{\mathrm{H}}) - (m_{\mathrm{J}_2} - m_{\mathrm{H}}) \\ m_{\mathrm{Jjj}} - (m_{\mathrm{J}} - m_{\mathrm{H}}) - (m_{\mathrm{JJ}}(\mathrm{j}_1, \mathrm{j}_2) - m_{\mathrm{H}}) \end{cases}$$

Go back to talk





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QCD multijet estimation in B2G-20-004 (HH) & B2G-21-003 (HY)

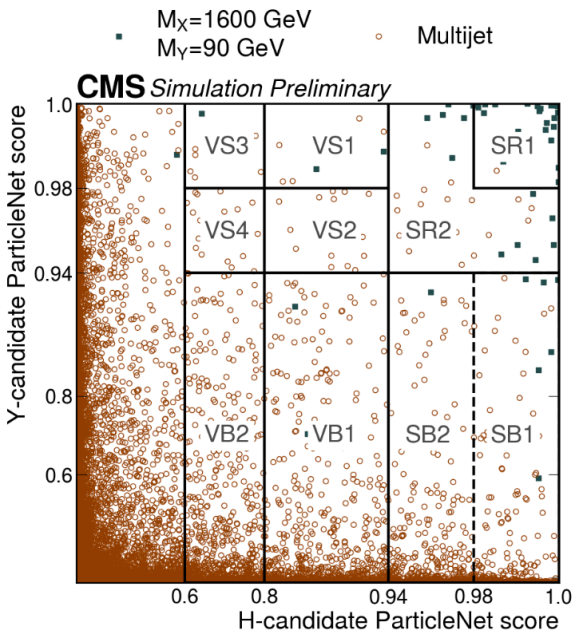
- Event passing the tagging requirement: $n_{pass} = n_{fail} \times R^{MC}_{p/f} \times R_{ratio}$
  - R_{ratio} is the ratio of $R_{p/f}$ in data and simulation and it is smooth and easier to estimate than $R_{p/f}$ in data
  - R_{ratio} surface parameterized by the product of two one-dimensional polynomials with coefficients determined from the fit to data
- HH:
  - R_{ratio} and $R_{p/f}$ are a function of m_J and m_{red}
  - To reduce the effect of statistical fluctuations on the calculation of $R^{MC}_{p/f}$ in QCD multijet simulation, the pass and fail distributions are smoothed by using an adaptive kernel density estimate (KDE)
- HY
  - R_{ratio} and $R_{p/f}$ are a function of m_{JY} and m_{JJ}
  - For $R_{p/f}$, the smoothing method cannot be applied because of the requirement on m_{JH}
    - Adaptation of the above calculation using an initial $R_{p/f}(m_{JY})$ estimated from data sidebands: $R_{p/f} = R^{init} \times R_{ratio}$

X → YH → 4b boosted

X: 0.9 - 4 TeV
Y: 60-600 GeV

CMS-PAS-B2G-21-003

- Main uncertainties on signal: ParticleNet SF, jet mass scale, jet energy scale and resolution, jet mass resolution
- Main uncertainties on bkg: tt norm, top pt, modeling Rp/f
- joint likelihood of the M_{JJ}–M_J^Y distributions in the hadronic (signal and sideband) regions in both the SR1 and the SR2 categories along with the M_J^t distributions in the semileptonic regions in the tight and loose categories
- Plots are for SR1, pulls = (observed events–expected events)/ sqrt($\sigma 2_{obs} + \sigma 2_{exp}$)



Go back to talk

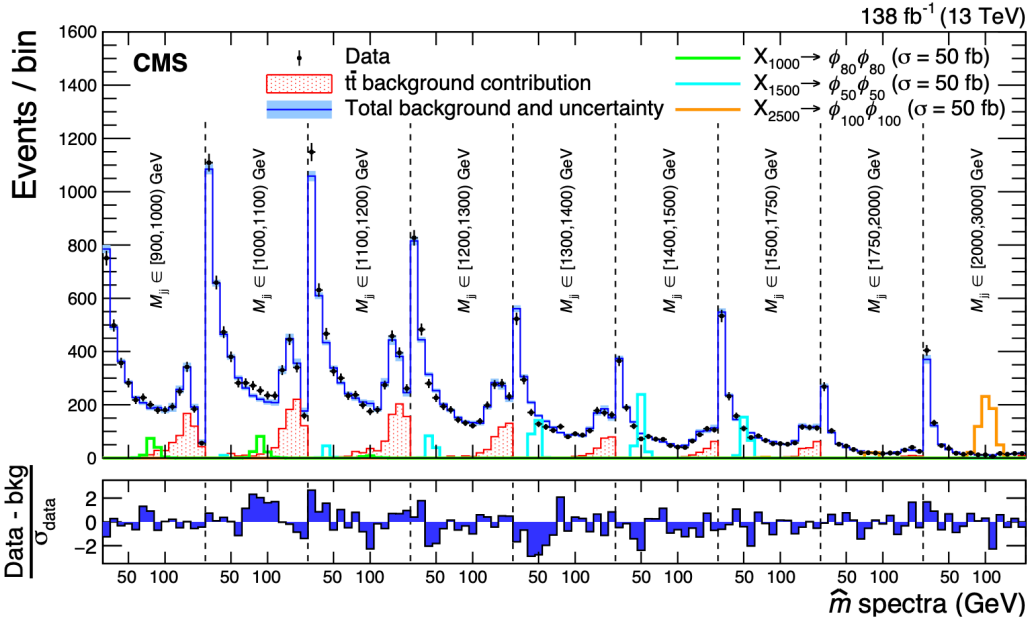
Side band and validation regions for QCD multijet

Fermilab

X → ϕϕ → 4b

CMS-B2G-20-003

	m_{asym}	$\lvert\Delta\eta\rvert$	$D_{j_1}^{bb}$
Tight search region	<0.1	<1.5	>0.8
Loose search region	$[0.1, 0.25]$	<1.5	>0.8
Tight $\lvert\Delta\eta\rvert$ sideband	<0.1	>1.5	>0.8
Loose $\lvert\Delta\eta\rvert$ sideband	$[0.1, 0.25]$	>1.5	>0.8
Tight double-b sideband	<0.1	<1.5	$[-0.8, 0.3]$
Loose double-b sideband	$[0.1, 0.25]$	<1.5	$[-0.8, 0.3]$

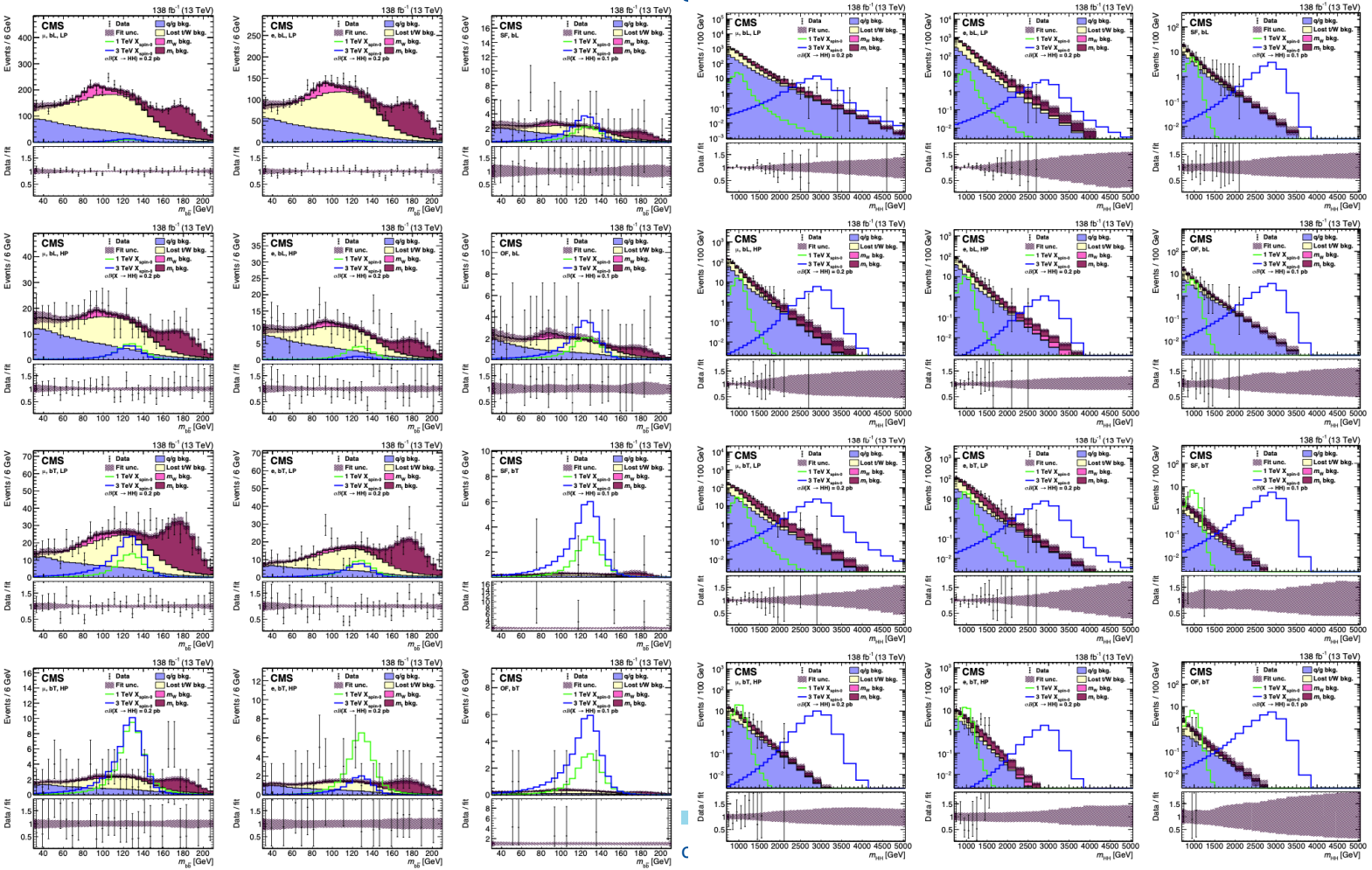


Go back to talk

Fermilab

X → HH → bbWW/bbττ with leptons

CMS-B2G-20-007



Fermilab

X → HH → bbWW/bb$\tau\tau$ with leptons

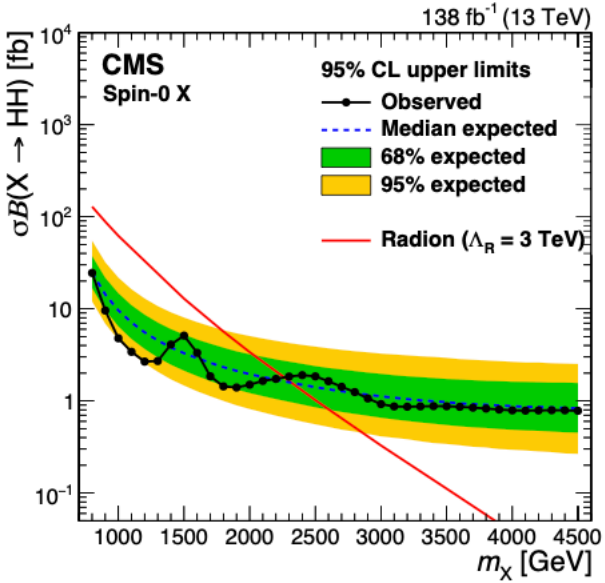
CMS-B2G-20-007

Table 1: The SL channel event categorization and corresponding category labels. All combinations of the two lepton flavors, two $b\bar{b}$ jet tagging, and two H → WW* decay purity selections are used to form eight independent event categories. The lower τ_2/τ_1 working point is 0.55 (0.45) in 2016 (2017–2018).

Categorization type	Selection	Label
Lepton flavor	Electron	e
	Muon	μ
$b\bar{b}$ jet tagging	$0.8 < D_{Z/H\to b\bar{b}} < 0.97$	bL
	$D_{Z/H\to b\bar{b}} > 0.97$	bT
H → WW* purity	$0.45(0.55) < \tau_2/\tau_1 < 0.75$ or $2.5 < D_{\ell\nu q\bar{q}'} < 11.0$	LP
	$\tau_2/\tau_1 < 0.45(0.55)$ and $D_{\ell\nu q\bar{q}'} < 2.5$	HP

Table 2: The DL channel event categorization and corresponding category labels. All combinations of the two lepton flavors and two $b\bar{b}$ jet tagging selections are used to form four independent event categories.

Categorization type	Selection	Label
Lepton flavor	Two electrons or two muons	SF
	One electron and one muon	OF
$b\bar{b}$ jet tagging	$0.8 < D_{Z/H\to b\bar{b}} < 0.97$	bL
	$D_{Z/H\to b\bar{b}} > 0.97$	bT



Bkg. category	Dominant SM processes	Resonant in $m_{b\bar{b}}$	Num. of particle-level quarks
m_t	$t\bar{t}$	top quark mass	3 from top quark
m_W	$t\bar{t}$	W boson mass	2 from W boson
lost-t/W	$t\bar{t}$	No	1 or 2
q/g	V+jets and QCD multijet	No	0

- within $\Delta R < 0.8$ of the bb jet axis

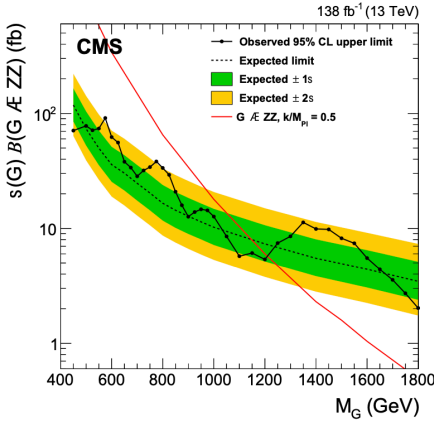
Fermilab

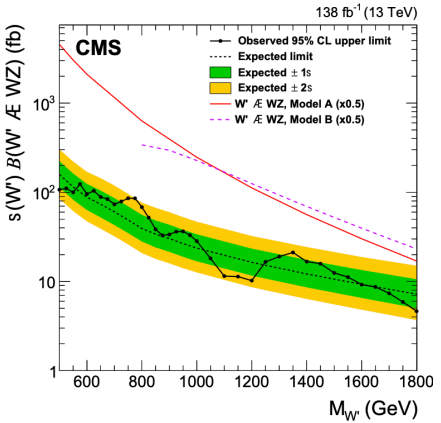
X→ ZV→ ℓℓqq in semileptonic final states

CMS-B2G-20-013

(& ALP nonresonant ZZ/ZH)

- Z→ ℓℓ (ℓ = e, μ) & Z/W/H→qq merged/resolved, b-tagged/ untagged categories
- M_X = 450 - 1800 GeV
- Main background Z+jets (normalization from SB - based on mjj or MJ) in final fit, shape from MC+correction)
- Other bkg: dilepton that do not contain a leptonic Z boson decay (from simulation) & ZV (from simulation)
- Main uncertainties: bkg shape
- Combined ML fit in the MZV /M ZH distribution simultaneously in all categories
- A WED bulk graviton is excluded up to masses of 1200 (expected 1150) GeV for $\kappa = 0.5$.

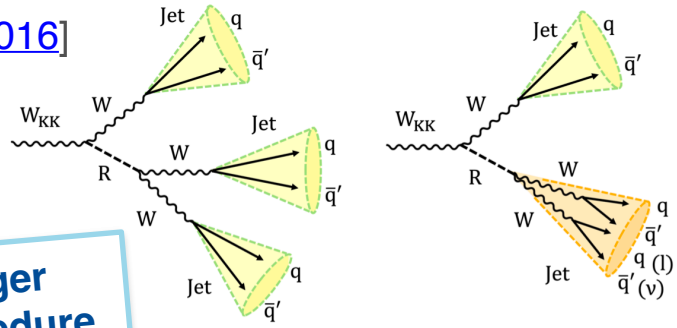




$W_{kk} \rightarrow WR \rightarrow W(qq)WW(\ell\nu qq/4q/3q)$ boosted

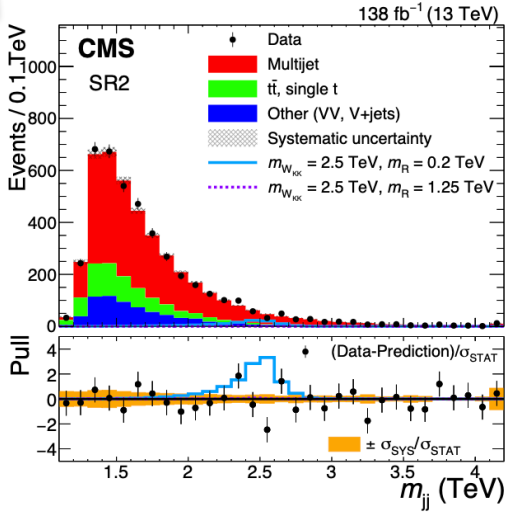
CMS-B2G-21-002

- Extended warped extra dimensions: two branes [JHEP 01 (2017) 016]
  - Only EW gauge fields can propagate in the extended bulk
- R→ WW→ $\ell\nu$qq/4q/3q, (ℓ = e, μ)
- Jet tagging: DeepAK8 [JINST 15 (2020) P06005], deep-W and deep-WH
- For R→ WW→ $\ell\nu$qq:
  jet containing an energetic, charged, nonisolated ℓ
- sensitive to R→WV/VVV/Vt/VH/VX
- 6 SR based on #of jets and jet masses range (backup)
- Main backgrounds: QCD 60-80%, ttbar, single top, W+Jets, etc
  - QCD estimated from data CR, others from simulation
- Bump hunt in m_{jj} or m_{jjj}



dedicated tagger calibration procedure

W_{kk}:1.5 - 5 TeV
R: 6-90% W_{kk}

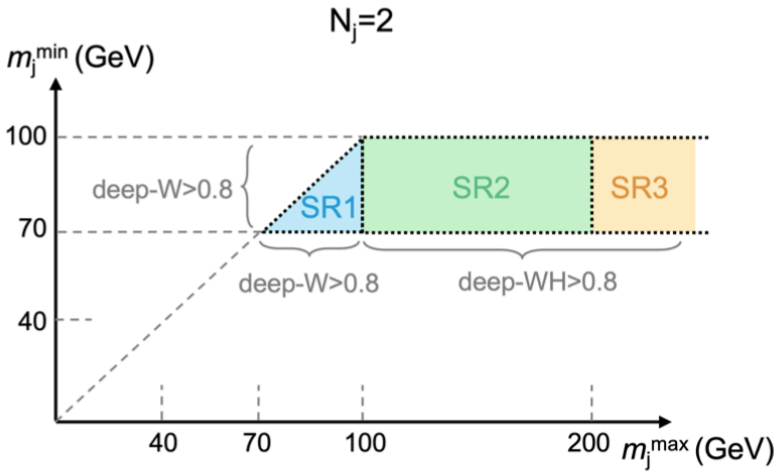


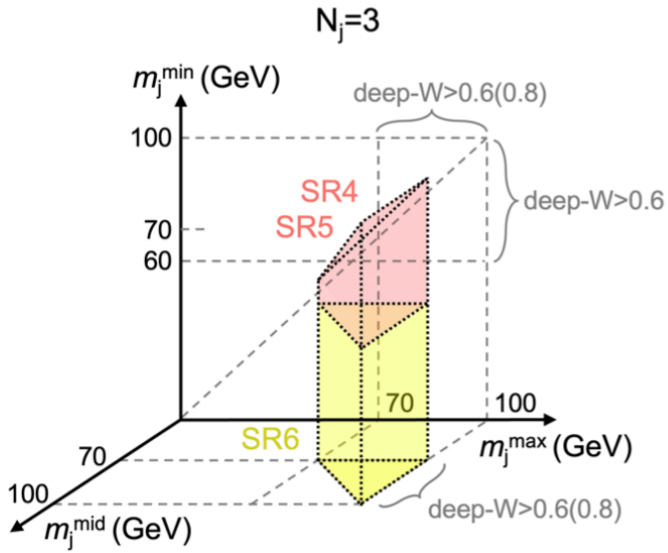
Fermilab

$W_{kk} \rightarrow WR \rightarrow WWW$ in boosted hadronic final states

CMS-B2G-21-002

Region	N_j	m_j^{max} (GeV)	m_j^{mid} (GeV)	m_j^{min} (GeV)	Jet tagging conditions
SR1	2	70–100	—	70–100	Both with deep-W $>$ 0.8
SR2	2	100–200	—	70–100	Higher with deep-WH $>$ 0.8, lower with deep-W $>$ 0.8
SR3	2	$>$200	—	70–100	Higher with deep-WH $>$ 0.8, lower with deep-W $>$ 0.8
SR4	3	70–100	70–100	60–100	All three with deep-W $>$ 0.6
SR5	3	70–100	70–100	60–100	Exactly two with deep-W $>$ 0.6
SR6	3	70–100	70–100	0–60	Two highest with deep-W $>$ 0.8



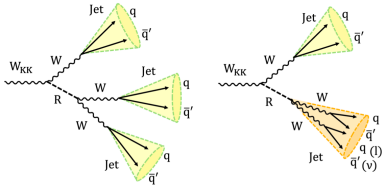


- ST (sum jet and pt miss) > 1.3 TeV: better signal separation for cases with leptons
- $1.5 \leq m_{W_{KK}} \leq 5.0$ TeV, m_R 6-90% of $m_{W_{KK}}$. Merged: $m_R \leq 0.2\ m_{W_{KK}}$

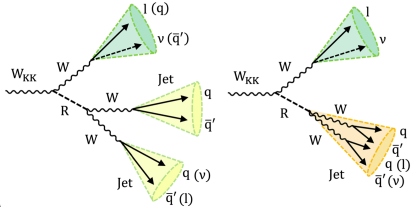
$W_{kk} \rightarrow WR \rightarrow W(qq)WW(\ell\nu qq/4q/3q)$ boosted

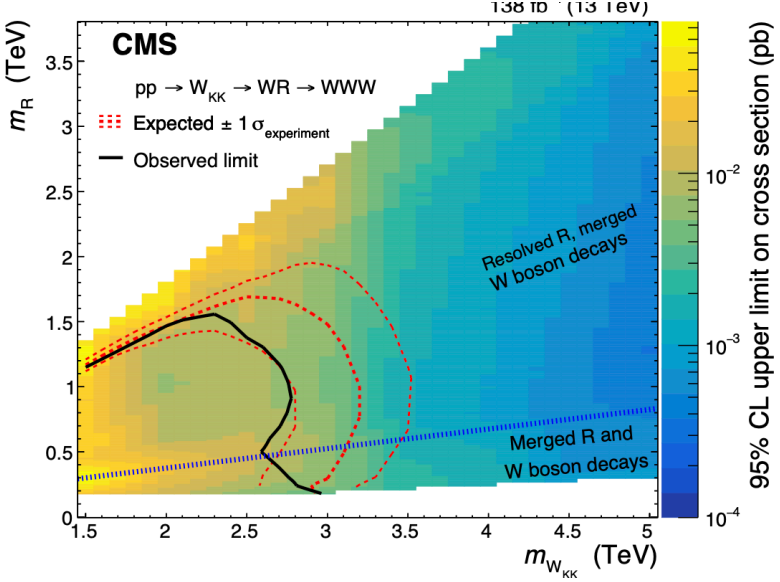
CMS-B2G-21-002

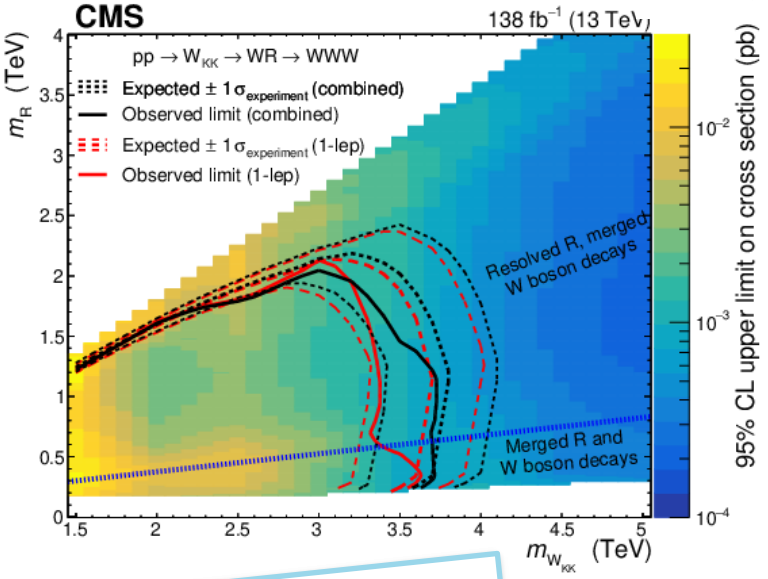
This analysis



Recently combined with the semi-leptonic [CMS-B2G-20-001]







First WW fatjet tagging!

First results with this signature and model!!

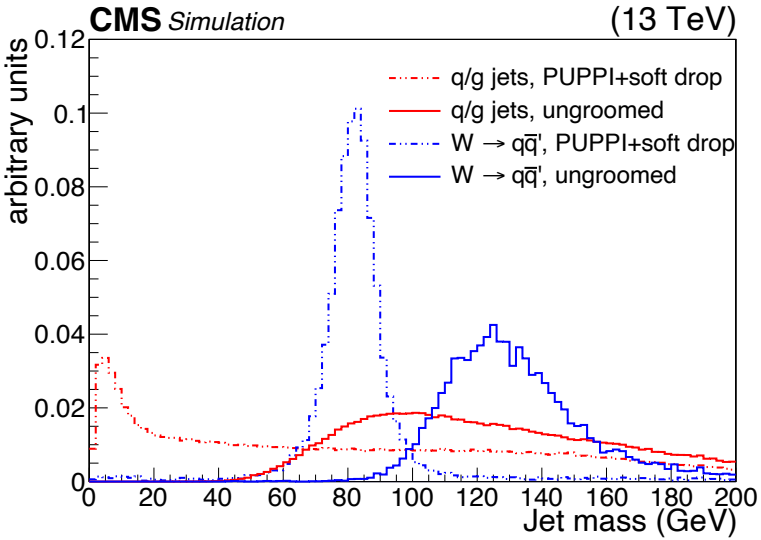
Fermilab

Softdrop

[JHEP 05 (2014)146]

- Soft drop: reduce the jet contamination from initial state radiation, underlying event and pileup

Soft drop condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$



[B2G-17-001]

1. Jet j clustered with CA
2. Decluster last step and obtain j1 and j2
3. Check if soft drop condition is satisfied

Yes → j is the final SD jet

No → decluster jet with higher p_T, remove the other, Repeat

Fermilab

Nsubjettiness

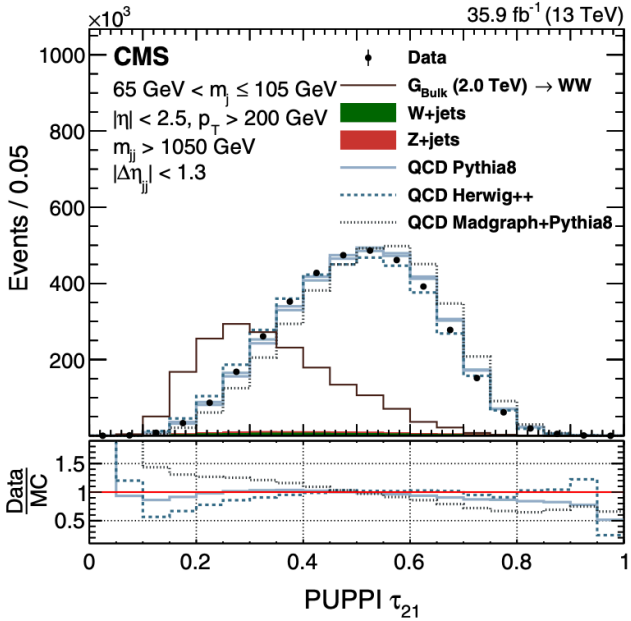
[arXiv:1011.2268]

- N-subjettiness τ_N tells how likely a jet has *N* subjets

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\,\min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\} \qquad d_0 = \sum_k p_{T,k} R$$

N = identified subjets
k = jet constituents

[B2G-17-001]



- $\tau_N \sim 0$: N subjets likely
- $\tau_N >> 0$: more than N subjets likely

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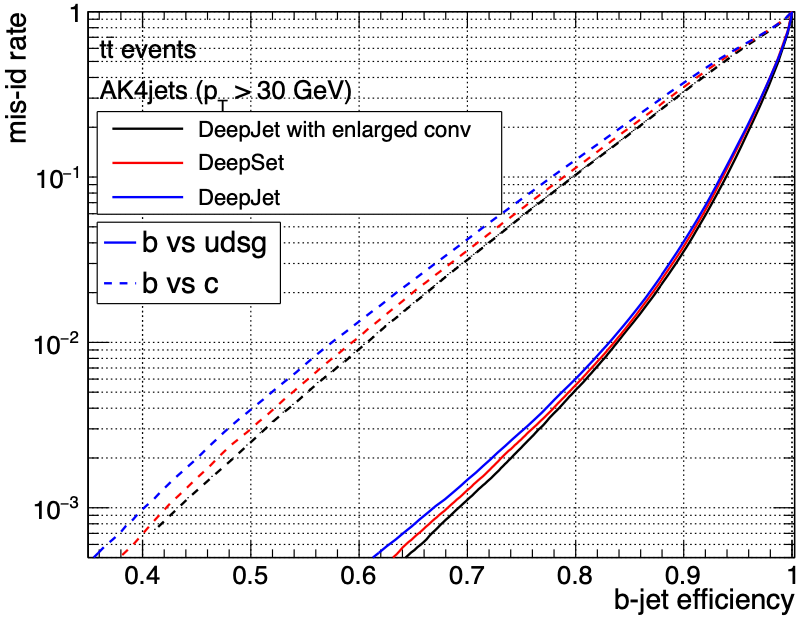
DeepJet

[JINST 15 (2020) P12012]

- Deep neural network algorithm
  - 16(8) properties of up to 25 charged (neutral) particle-flow jet constituents
  - 12 properties of up to 4 secondary vertices associated with the jet



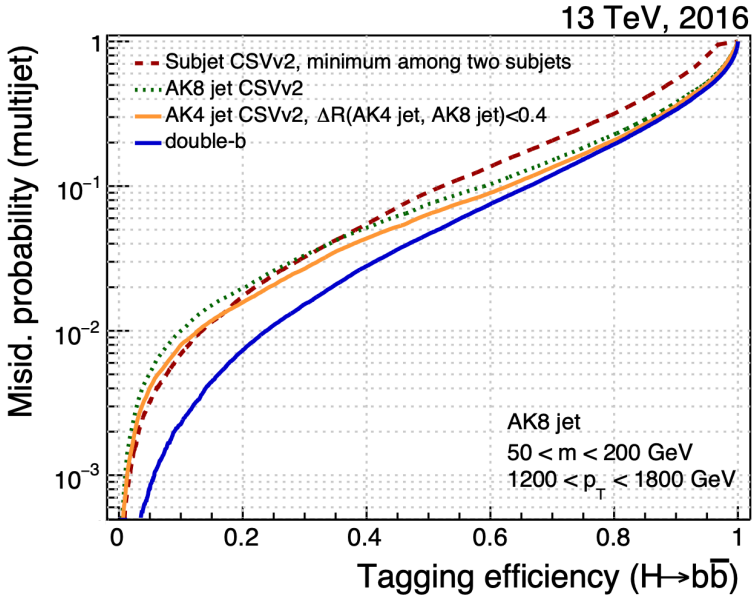
Fermilab

Double-b tagger

[JINST 13 (2018) P05011]

- Combines tracking and vertexing information in a boosted decision tree with 27 input observables

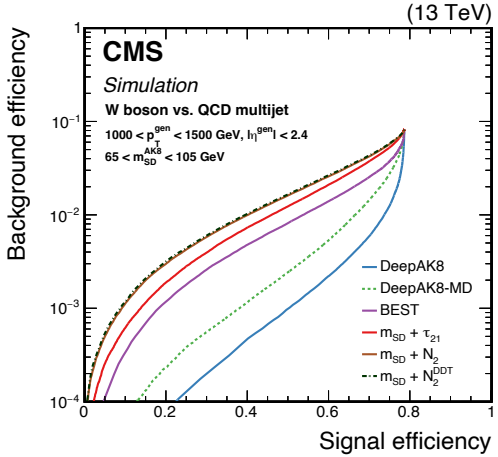
- No strong correlations in double-b tagger versus m_{SD} or p_T in QCD background

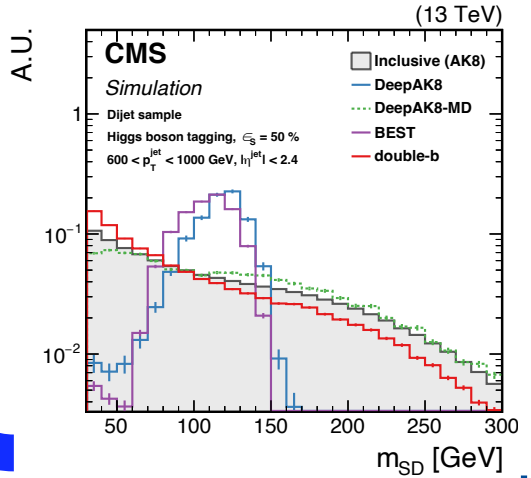


DeepAK8

[JINST 15 (2020) P06005]

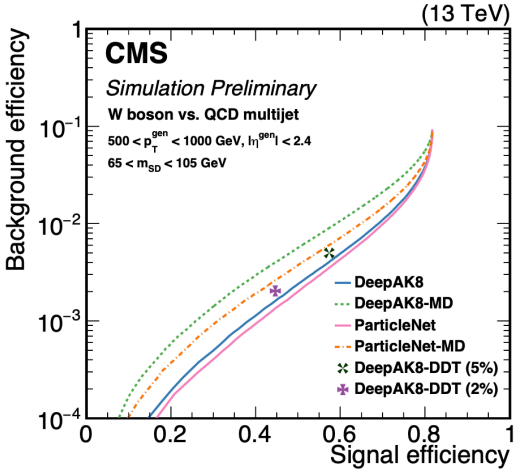
- Multiclass (W/Z/H/t/other) classifier to identify hadronically decaying particles
  - sub-categories for the decay modes (e.g. $Z \rightarrow bb$)
- Inputs:
  - *particle list* contains 100 jet constituent particle (p_T, energy deposit, charge, the angular separation between the particle and the jet axis or the subjet axes, etc.)
  - *secondary vertex list,* up 7 SVs (15 variables)
- Customized Deep Neural Network (DNN)
- Mass decorrelation obtained with adversarial training approach





ParticleNet [Phys. Rev. D 101 (2020) 056019]

- Customized neural network architecture based on the particle cloud representation→ jet as an unordered set of particles
- Uses a permutation-invariant graph neural network architecture
- In CMS:
  - multi-class tagger for t/W/Z/H tagging
  - same inputs as DeepAK8 (PF candidates/secondary vertices)
  - significant performance improvement
  - Mass decorrelation obtained with training using a dedicated signal sample with flat mass spectrum: $m_X \in [15, 250]$ GeV



[CMS-DP-2020-002]