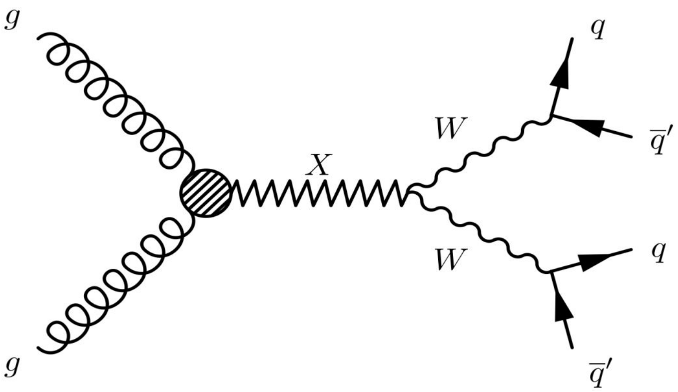
New results from searches with highly boosted Higgs and vector bosons

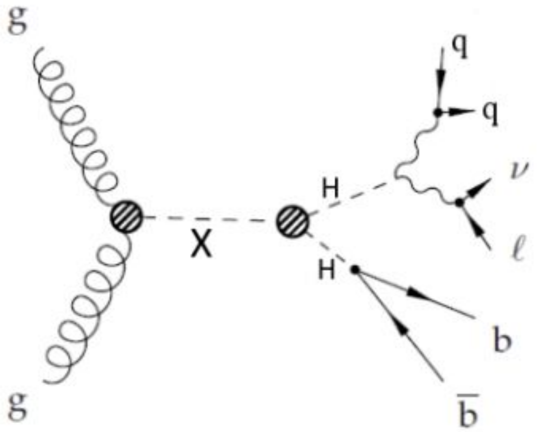
July 25th, 2019

Qiang Li PKU

BOOSTON 2019

Resonance Searches with Boosted H/V Jet



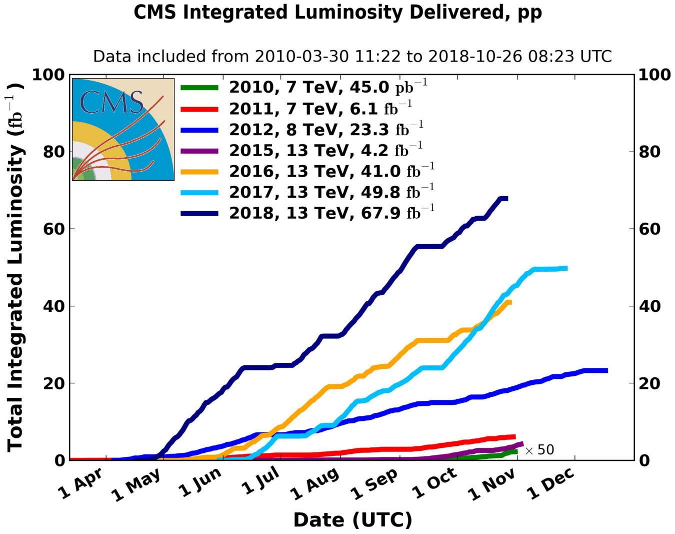


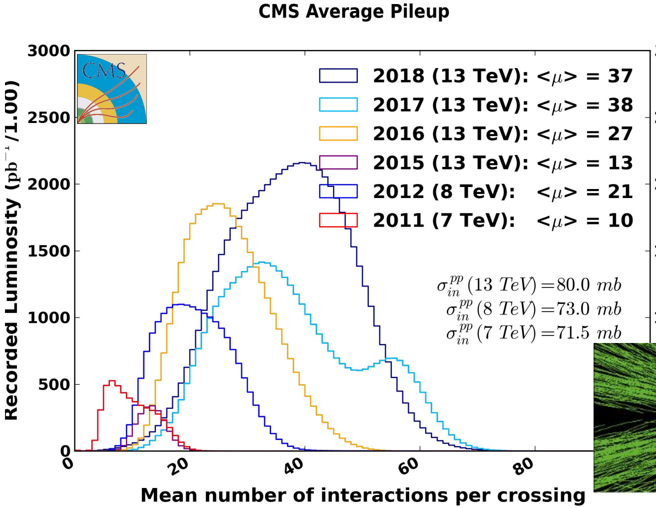
- **VV, VH, HH resonance motivated in many BSM models**
  Bulk Extra Dimension, Composite Higgs, Little Higgs
  Spin-0 Radion/Higgs; Spin-1 W'/Z'; Spin-2 Gravitons

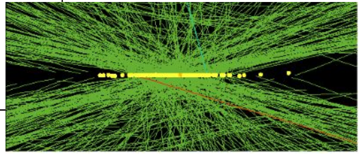
- **Hadronically decayed V/H: High rates, reconstructable spectrum**
  Huge QCD/Wjets bkg, data-driven estimation

- **Highly boosted V/H: Grooming, substructure and/or b-tagging**
  TTbar control Region, Scale Factor

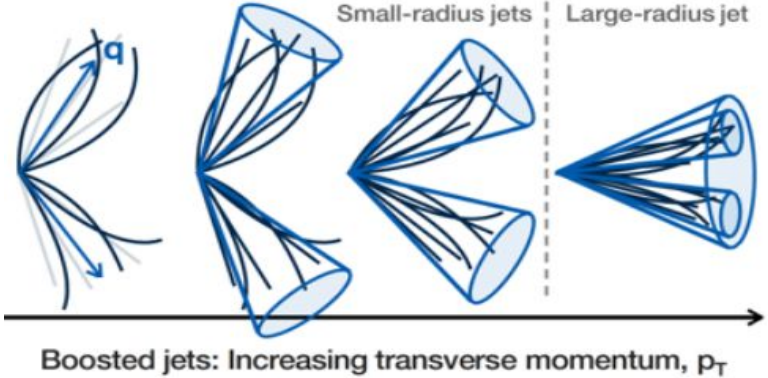
Citius, Altius, Fortius







$$\Delta R_{ij} \sim \frac{m}{p_T}\frac{1}{\sqrt{z(1-z)}} \sim \frac{2m}{p_T}$$



Novel Reco.
Deeper Digging

see e.g. 1302.0260

Pileup Mitigation, Softdrop

PUPPI (PileUp Per Particle Id): based on PF paradigma general framework that determines, per particle, weight for how likely a particle is from PU

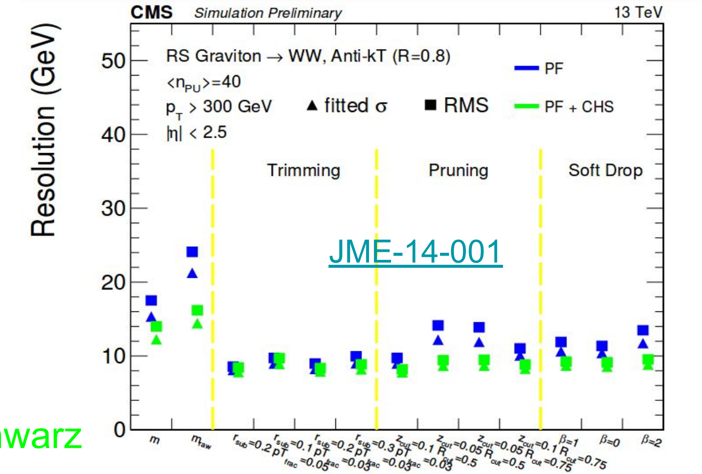
$$\alpha_i = \log \sum_{\substack{j \in Ch,PV \\ j \neq i}} \left(\frac{p_{T,j}}{\Delta R_{ij}} \right)^2 \Theta(R_0 - \Delta R_{ij})$$

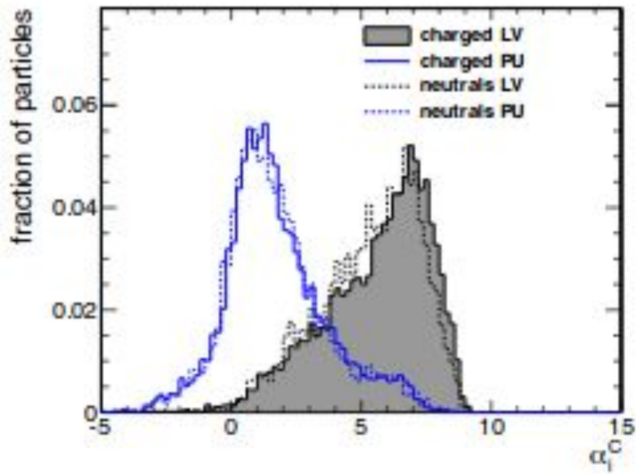
evaluated for each particle i, looking at all the charged particle j from PV within R0

$$\alpha_i = \log \sum_{j \neq i} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij})$$

Forward region use all pf-Inputs since no tracking vertex constraint

More from Anna Benecke and Dennis Schwarz





- Undo last stage of C/A clustering, label subjets j1,j2
- If :

$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$$

then j is soft dropped
else redefine j to be the harder, and iterate

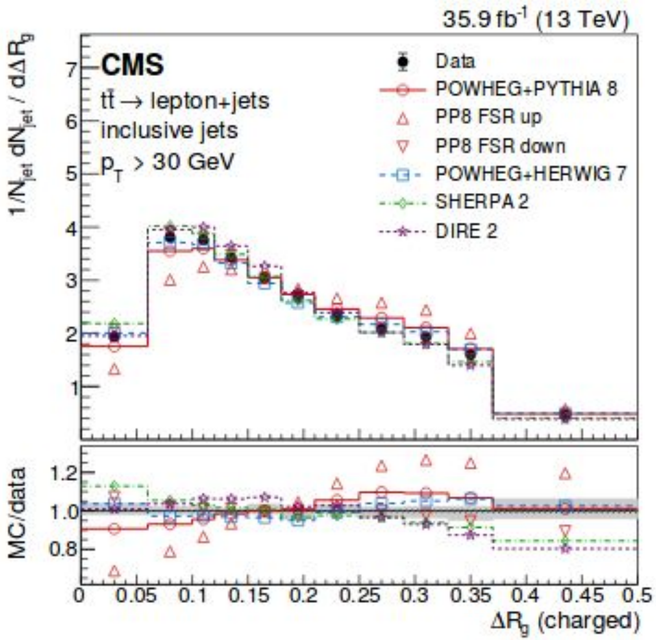
CMS: R0=0.8; beta=0; zcut=0.1

- Recovers (modified) mass drop BDRS tagger for beta=0
  - This case always removes soft radiation entirely (hence the name)

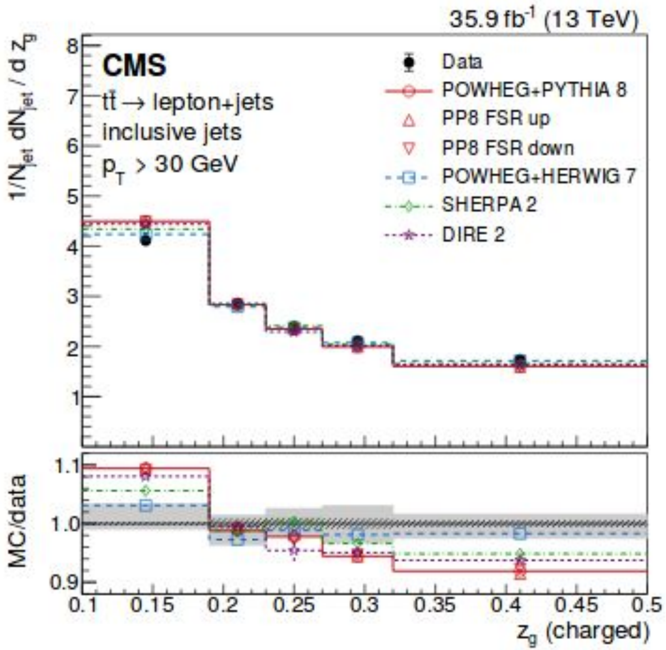
Validation in tt events

Phys. Rev. D 98, 092014 (2018)

Soft-drop observables, unfolded to particle level



More from Dennis Schwarz

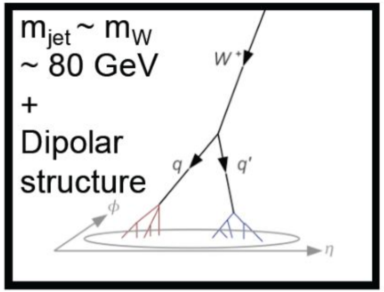


angle between the groomed subjets

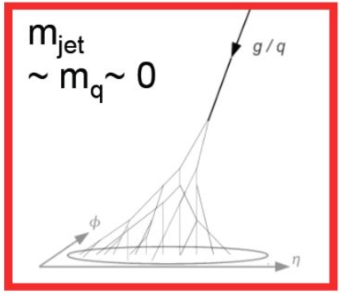
groomed momentum fraction PT_{j2}/PT_{j0}

Substructure tagging: mass decorrelation

SIGNAL



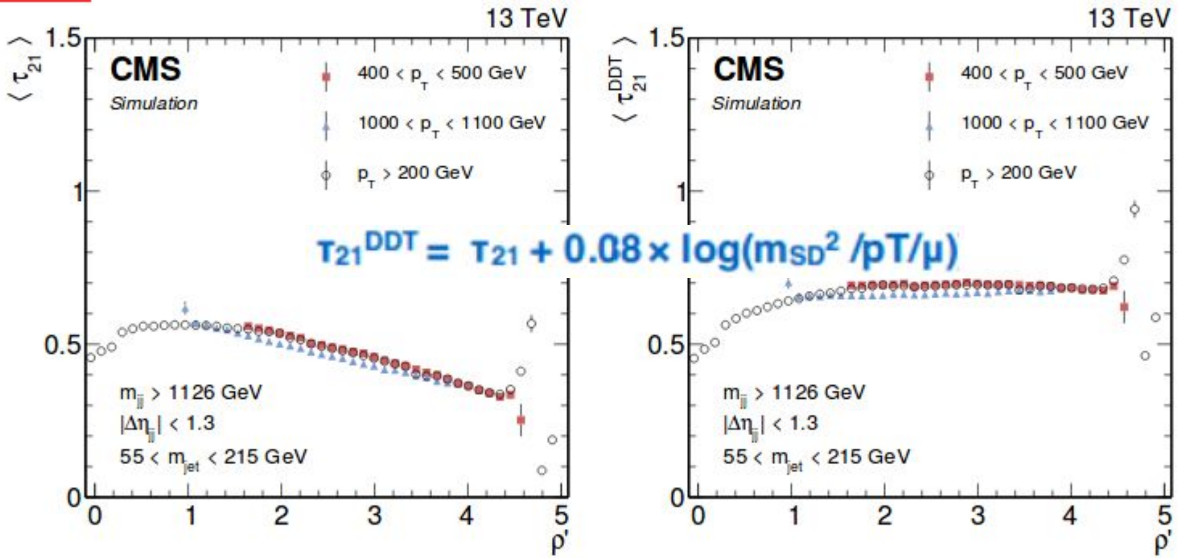
BACKGROUND



N-subjettiness: How likely is a Jet to have "N" subjets

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

T21 variable shows a dependence on the jet pT-scale as well as the jet mass. This particularly affects the monotonically falling behaviour of the nonresonant background distributions.



$$\tau_{21}^{DDT} = \tau_{21} + 0.08 \times \log(m_{SD}^2 / pT/\mu)$$

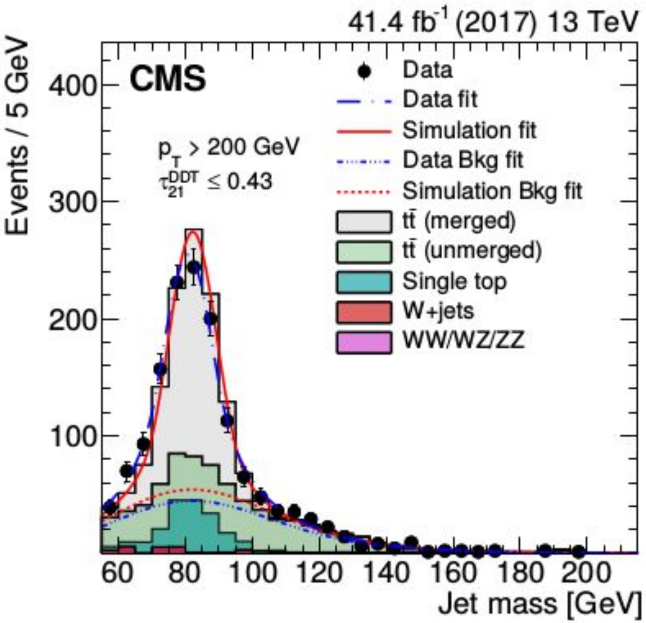
Designing De-correlated Taggers (DDT)

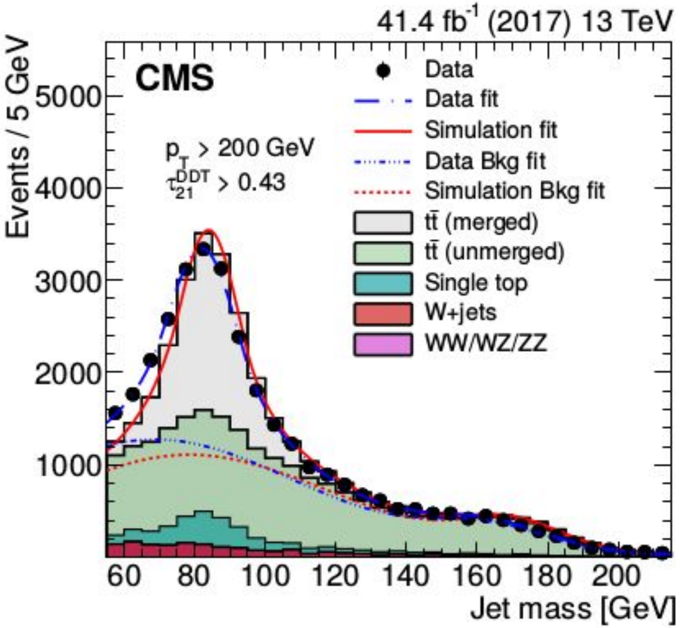
Boosted Technique: Calibration

Extract scale factor, mass scale, and resolution from fit in TTbar Control Region

Pass

$\tau_{21}^{DDT} < 0.43$



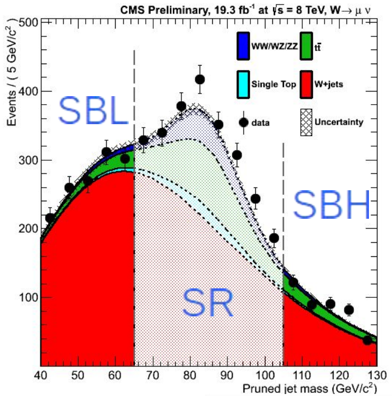


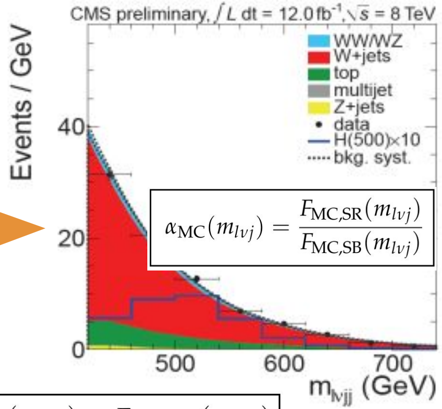
Fail

$\tau_{21}^{DDT} < 0.43$

	m [GeV]	σ [GeV]	W-tagging efficiency
2017			
$\tau_{21}^{DDT} < 0.43$			
Data	80.8 ± 0.4 (stat)	7.7 ± 0.4 (stat)	0.060 ± 0.006 (stat)
Simulation	82.2 ± 0.3 (stat)	7.1 ± 0.3 (stat)	0.070 ± 0.005 (stat)
Data/simulation	0.983 ± 0.007 (stat+syst)	1.08 ± 0.08 (stat+syst)	0.96 ± 0.12 (stat+syst)

Background Estimations: alpha and 2/3D

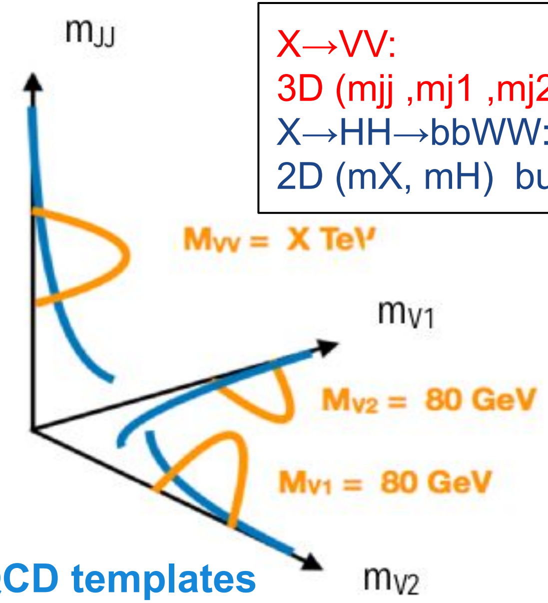




$$\alpha_{\mathrm{MC}}(m_{lvj}) = \frac{F_{\mathrm{MC,SR}}(m_{lvj})}{F_{\mathrm{MC,SB}}(m_{lvj})}$$

$$F_{\mathrm{data,SR}}(m_{lvj}) = \alpha_{\mathrm{MC}}(m_{lvj}) \times F_{\mathrm{data,SB}}(m_{lvj})$$

X→VV:
3D (mjj ,mj1 ,mj2) bump-hunt
X→HH→bbWW:
2D (mX, mH) bump-hunt



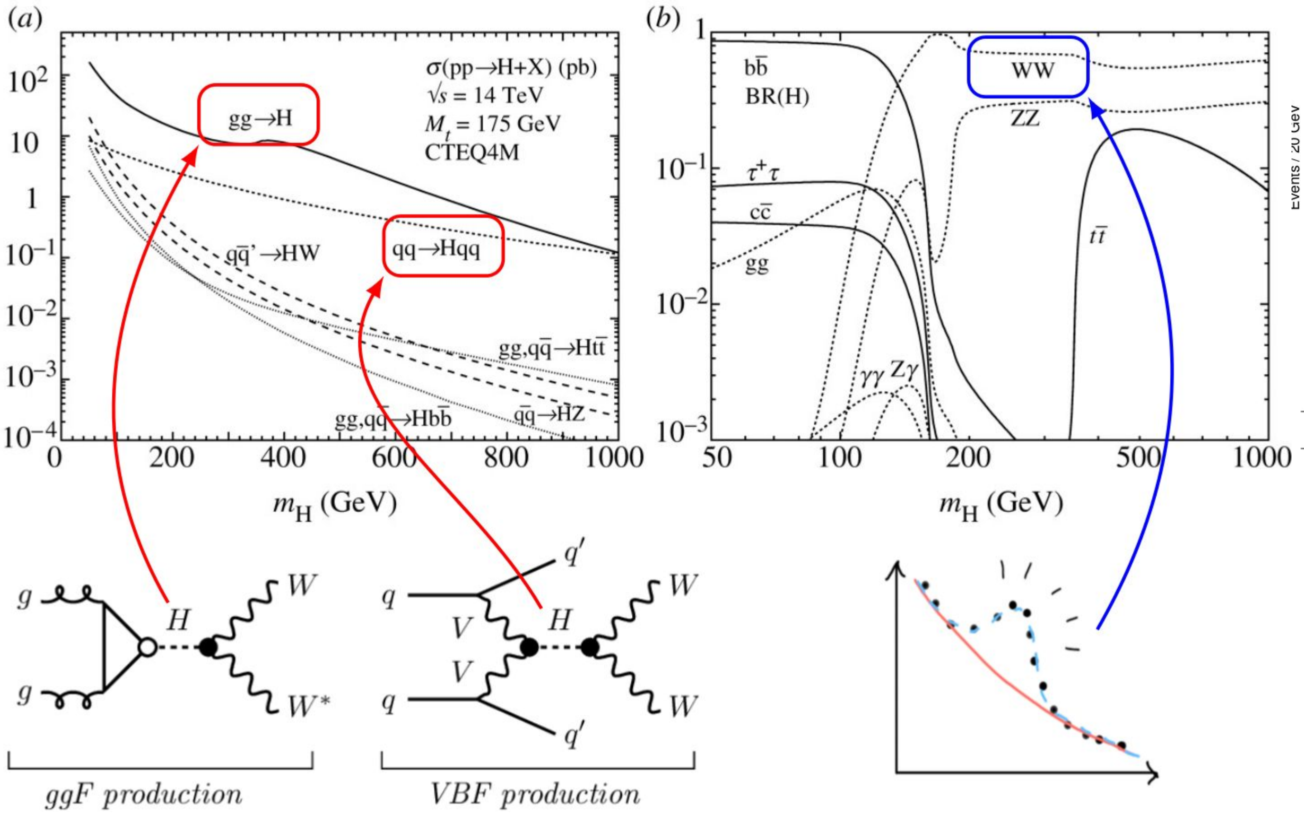
Forward folding kernel approach to ensure smooth QCD templates
- 3D templates derived from MC
- Particle-level evts smeared using detector resolution
- same procedure for resonant bkg. (W/Z)

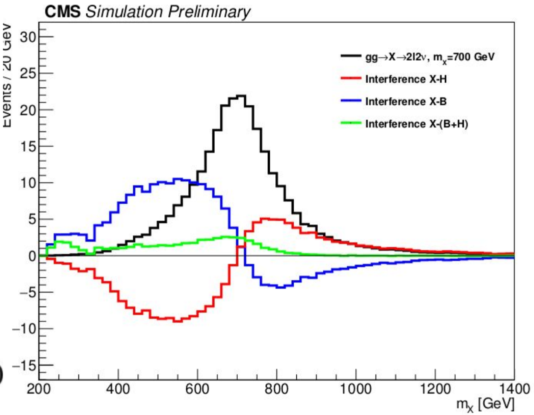
$$P(m_{jj}, m_{jet1}, m_{jet2}) = P_{VV}(m_{jj}) \times P_{cond,1}(m_{jet1}|m_{jj}) \times P_{cond,2}(m_{jet2}|m_{jj})$$

- Each event contributing to a 1D/2D gaussian kernel defined by detector scale and resolution.

Heavy Higgs→ WW 2016 HIG-17-033

High mass SM-like Higgs states predicted in many BSM models: 2HDM and Electroweak Singlet





Interference with WW continuum and h(125) considered

Heavy Higgs→ WW 2016

Di-leptonic channel:

Different-Flavor

– 0 /1/2 jets

– 2 jet VBF (mjj > 500 GeV, Δηjj > 3.5)

Same-Flavor Only VBF category

Cut on mTH, MET …

Major backgrounds :

WW,DY and Top from data-driven

Semi-leptonic channel

Boosted

$65 \leq m_{SD} \leq 105$ GeV

$\tau_2 / \tau_1 \leq 0.4$, $P_{TW} / m_{WW} > 0.4$ or 0.35

Resolved

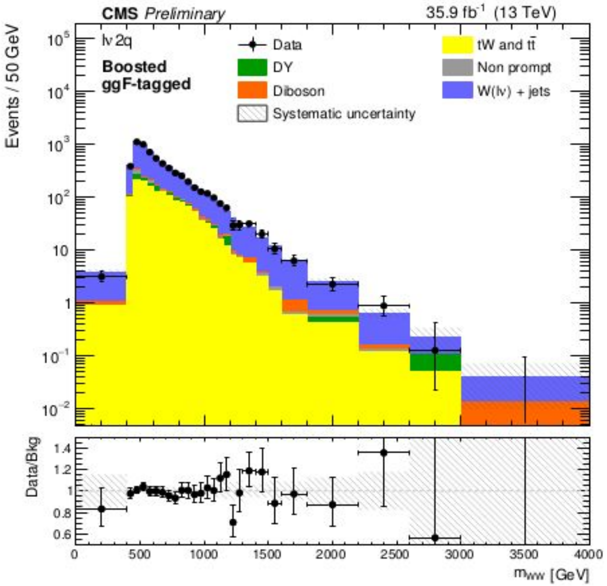
$65 \leq m_{jj} \leq 105$ GeV

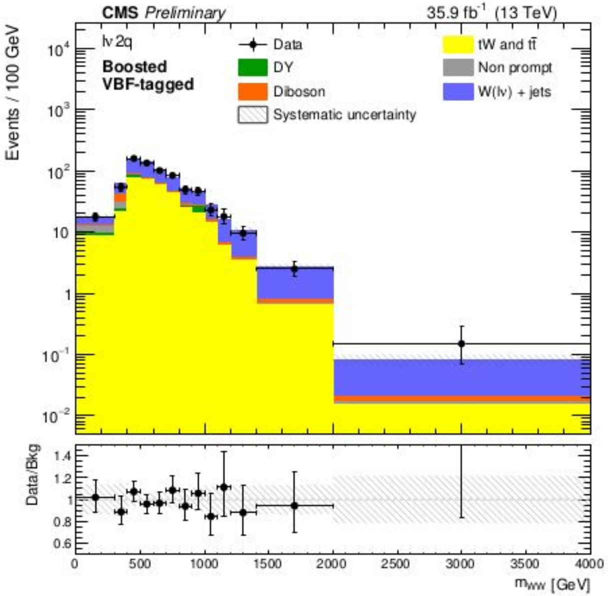
VBF || ggF tagged/untagged

MELA assisted

Major backgrounds :

W+Jets and Top from data-driven estimates





Validation in Sideband:

$40 \leq m_{SD}$ $(m_{jj}) \leq 250$ GeV

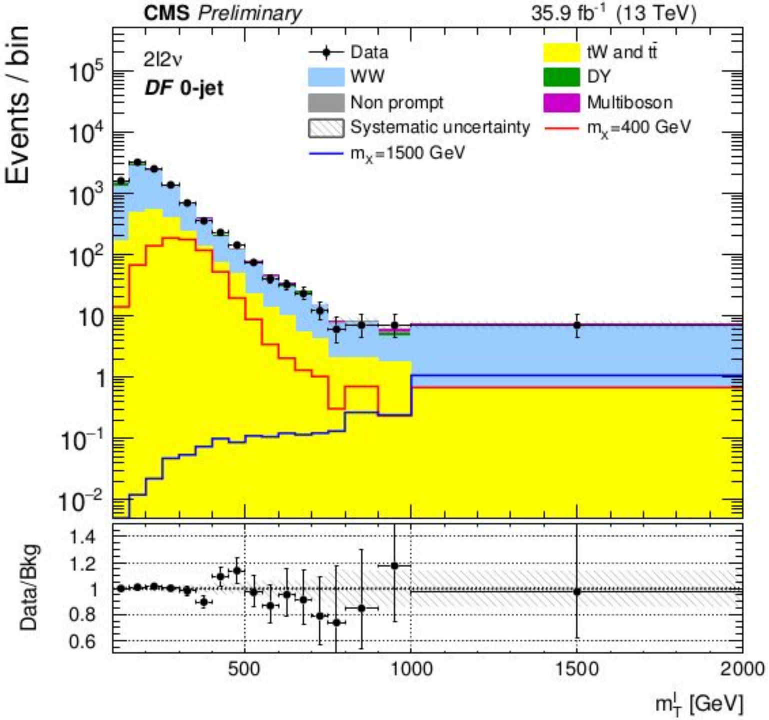
&& out side signal region

With W+jets and top normalizations floating

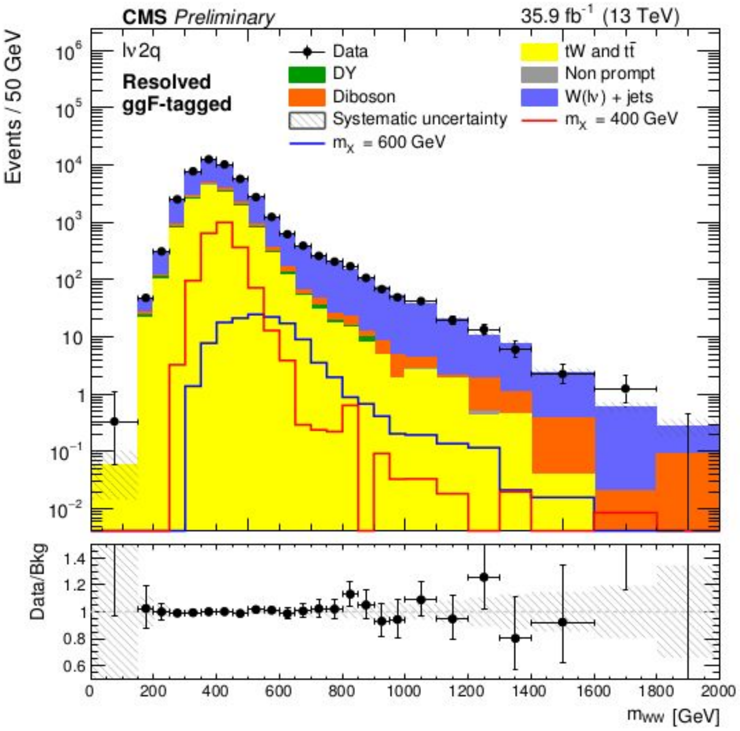
Heavy Higgs→ WW 2016

Di-leptonic channel:
Higgs Visible mass

$$m_T^I = \sqrt{(p_{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_{\ell\ell} + \vec{p}_T^{\text{miss}})^2}.$$

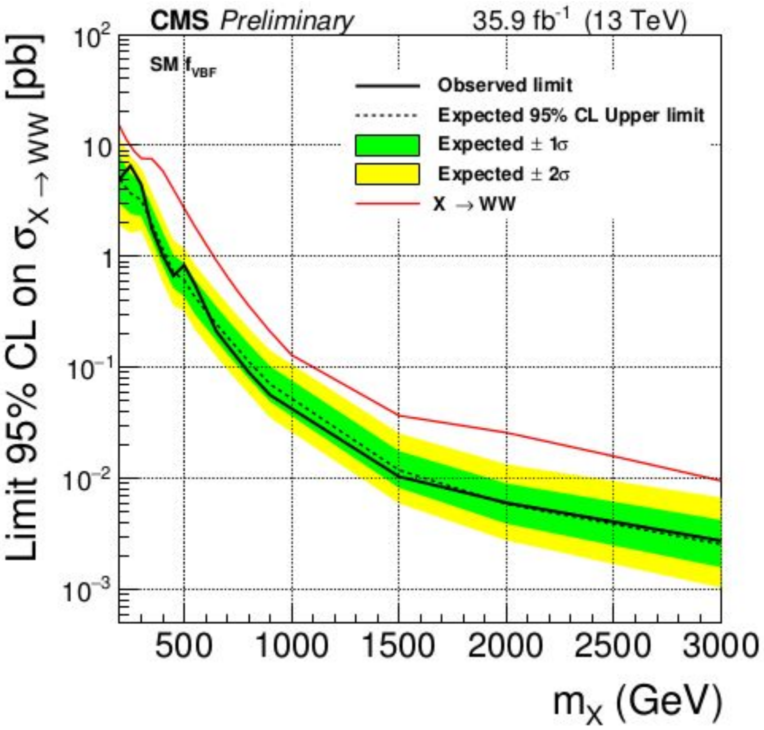


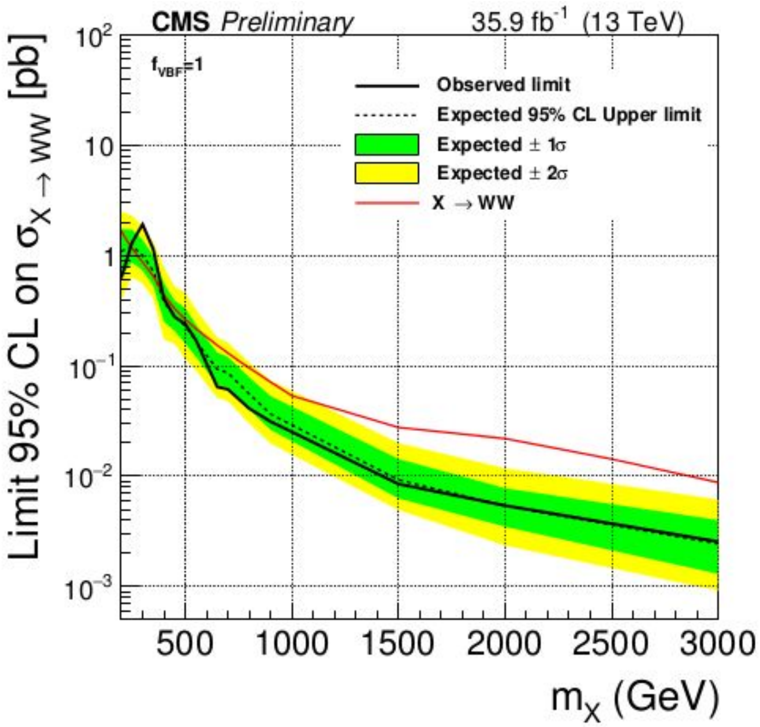
Semi-leptonic channel
Reconstructed m_{WW}



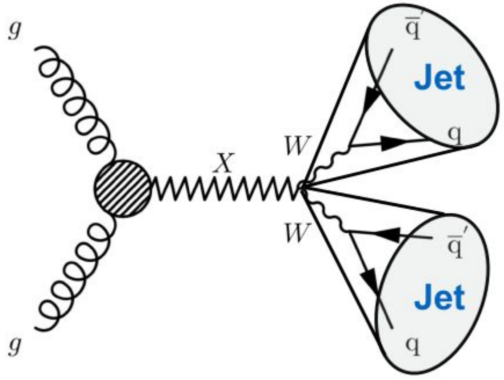
Heavy Higgs→ WW 2016

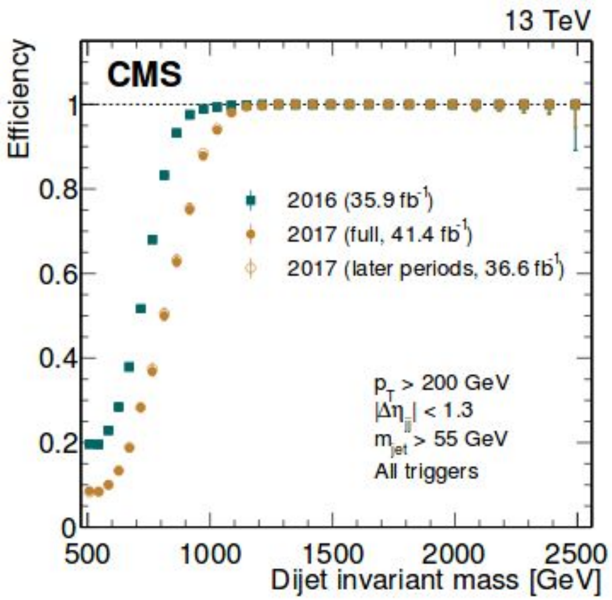
- No excess observed. Upper limit is set at 95% CL on cross section times branching fraction, with different values of the VBF fraction.
- Interpretations on MSSM and 2HDM scenarios are also given.

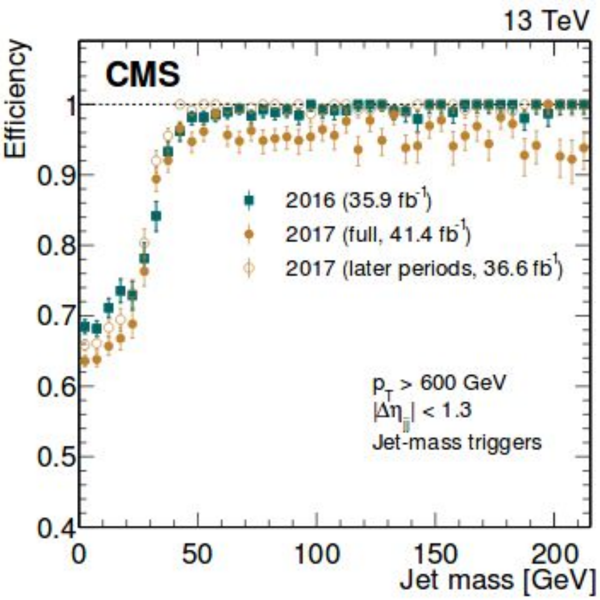


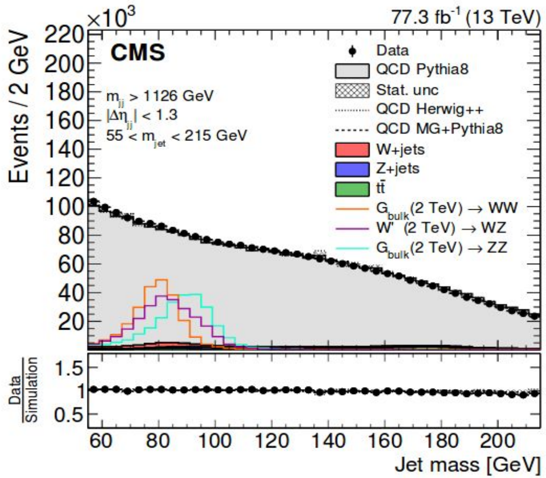


X→ VV 2016+2017 submitted to EPJC









At least 2 AK8 jets (R=0.8)

pT >200 GeV, 55GeV<m_{SD}<215GeV

two jets are labelled at random to avoid possible bias

$|\Delta\eta_{JJ}|$<1.3, m_{JJ} > 1126 GeV

X→ VV 2016+2017

QCD multijet:

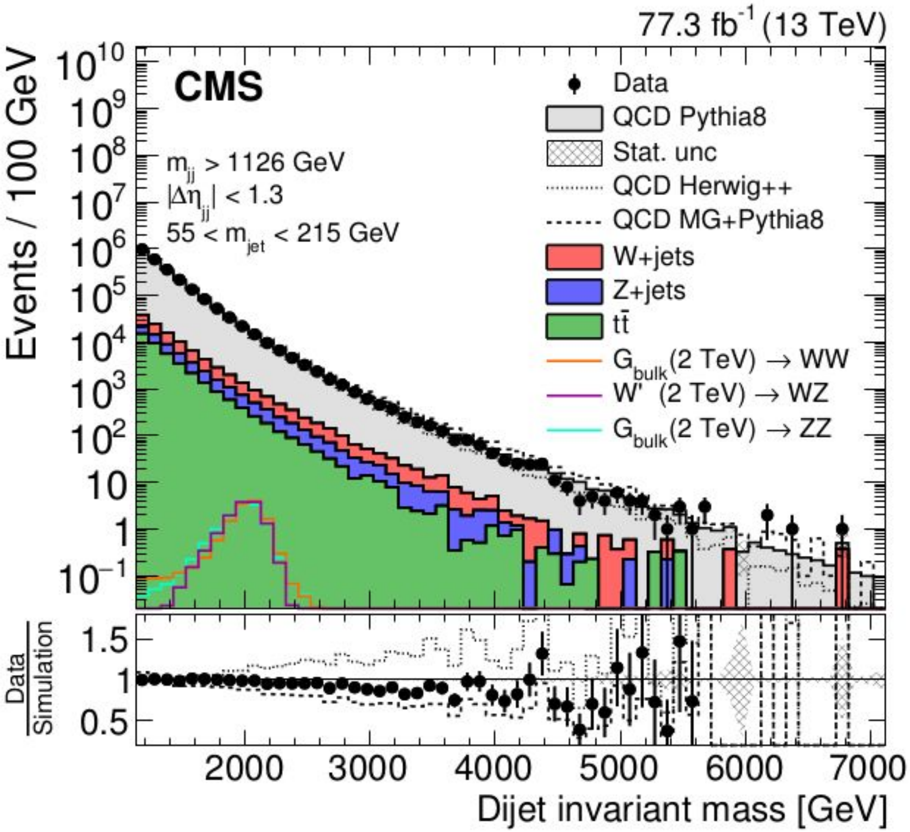
- PYTHIA only
- MADGRAPH MLM + PYTHIA
- POWHEG+PYTHIA ,
- POWHEG+HERWIG ++ 2.7.1

TOP Pair:

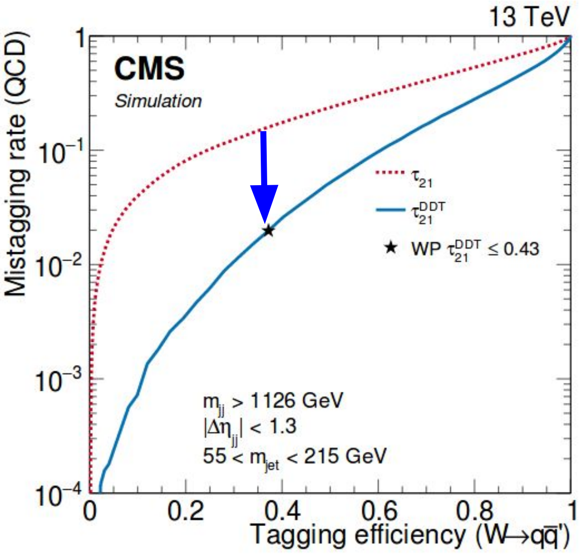
- POWHEG NLO+PYTHIA ,
- MADGRAPH MLM + PYTHIA
- Further reweighting on top quark PT to DATA

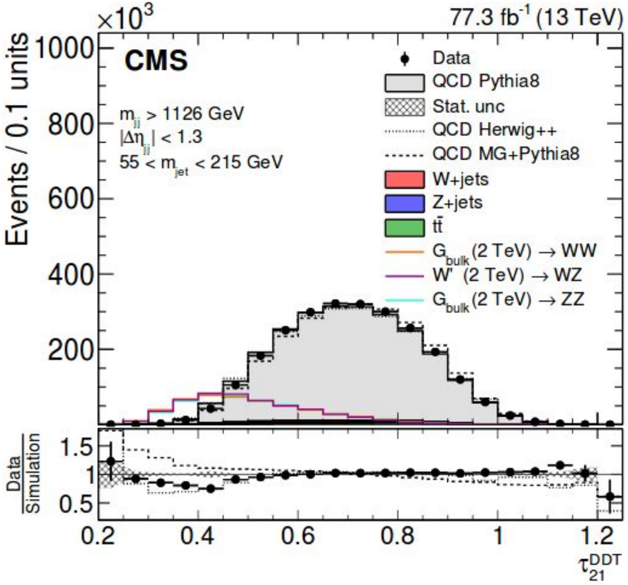
W/Z+Jets:

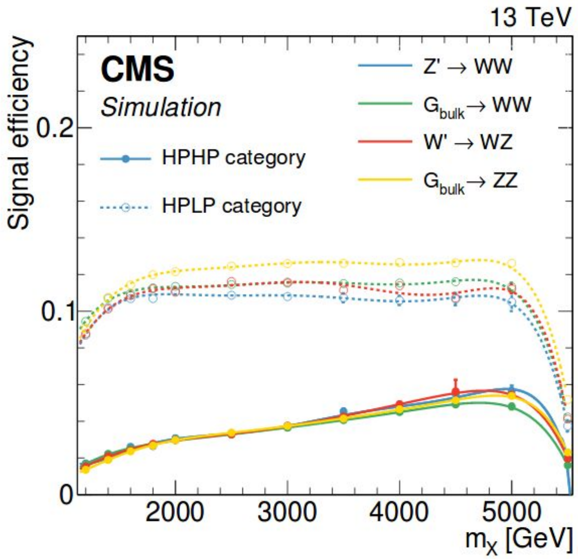
- MADGRAPH MLM + PYTHIA
- PT Dependent NLO QCD/EWK included



X→ VV 2016+2017







HPHP: both jets $0 < \tau_{21}^{DDT} \leq 0.43$,

HPLP: one jet satisfy $0.43 < \tau_{21}^{DDT} \leq 0.79$.

X→ VV 2016+2017

Signal modelling:

three uncorrelated functional shapes $$P_{\mathrm{sig}}(m_{\mathrm{jj}}, m_{\mathrm{jet1}}, m_{\mathrm{jet2}}|\bar{\theta}^{\mathrm{s}}(m_{\mathrm{X}})) = P_{\mathrm{VV}}(m_{\mathrm{jj}}|\bar{\theta}_1^{\mathrm{s}}(m_{\mathrm{X}}))\, P_{\mathrm{j1}}(m_{\mathrm{jet1}}|\bar{\theta}_2^{\mathrm{s}}(m_{\mathrm{X}}))\, P_{\mathrm{j2}}(m_{\mathrm{jet2}}|\bar{\theta}_3^{\mathrm{s}}(m_{\mathrm{X}})).$$

QCD multijet: forward-folding kernel approach

3D templates built from simulation

$$P_{\mathrm{QCD}}(m_{\mathrm{jj}}, m_{\mathrm{jet1}}, m_{\mathrm{jet2}}|\bar{\theta}) = P_{\mathrm{VV}}(m_{\mathrm{jj}}|\bar{\theta}_1^{\mathrm{QCD}})\, P_{\mathrm{cond,1}}(m_{\mathrm{jet1}}|m_{\mathrm{jj}}, \bar{\theta}_2^{\mathrm{QCD}})\, P_{\mathrm{cond,2}}(m_{\mathrm{jet2}}|m_{\mathrm{jj}}, \bar{\theta}_3^{\mathrm{QCD}}).$$

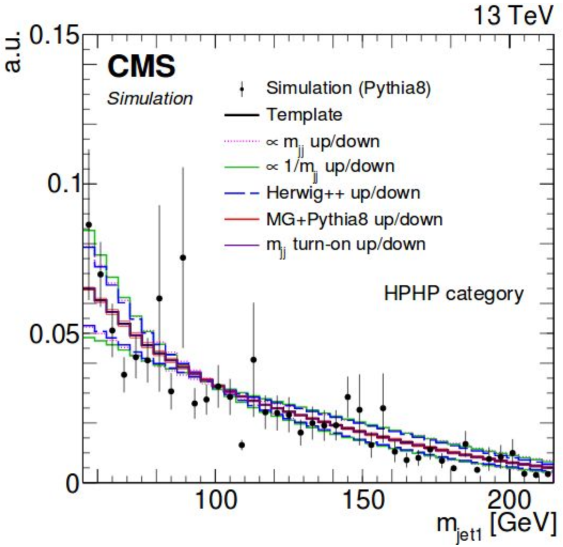
Jet mass is correlated with transverse momentum (and therefore m_{jj})

W/Z+jets (and TTbar+VV):

resonant part treat like and correlate with signal

non-resonant component treated like QCD multijets

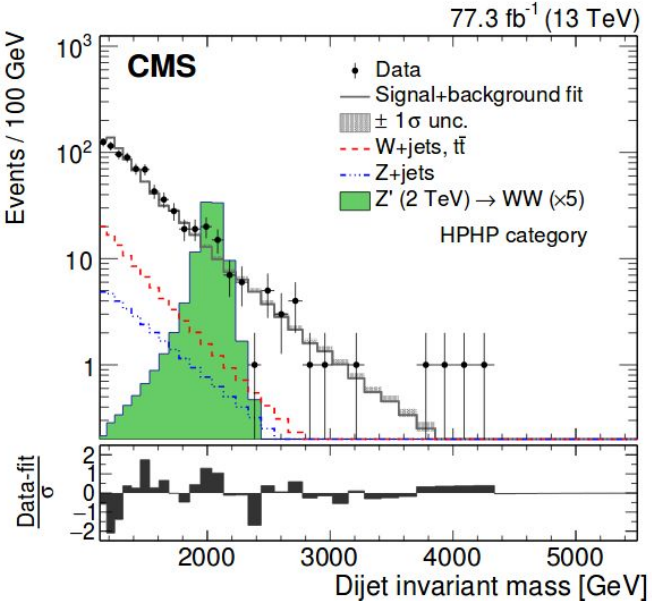
$$P_{\mathrm{V+jets}}\left(m_{\mathrm{jet1}}, m_{\mathrm{jet2}}, m_{\mathrm{jj}}|\bar{\theta}\right) = 0.5\left(P_{\mathrm{VV}}(m_{\mathrm{jj}}|\bar{\theta}_1)\, P_{\mathrm{res}}(m_{\mathrm{jet1}}|\bar{\theta}_2)\, P_{\mathrm{nonres}}(m_{\mathrm{jet2}}|\bar{\theta}_3)\right) + 0.5\left(P_{\mathrm{VV}}(m_{\mathrm{jj}}|\bar{\theta}_1)\, P_{\mathrm{res}}(m_{\mathrm{jet2}}|\bar{\theta}_2)\, P_{\mathrm{nonres}}(m_{\mathrm{jet1}}|\bar{\theta}_3)\right).$$

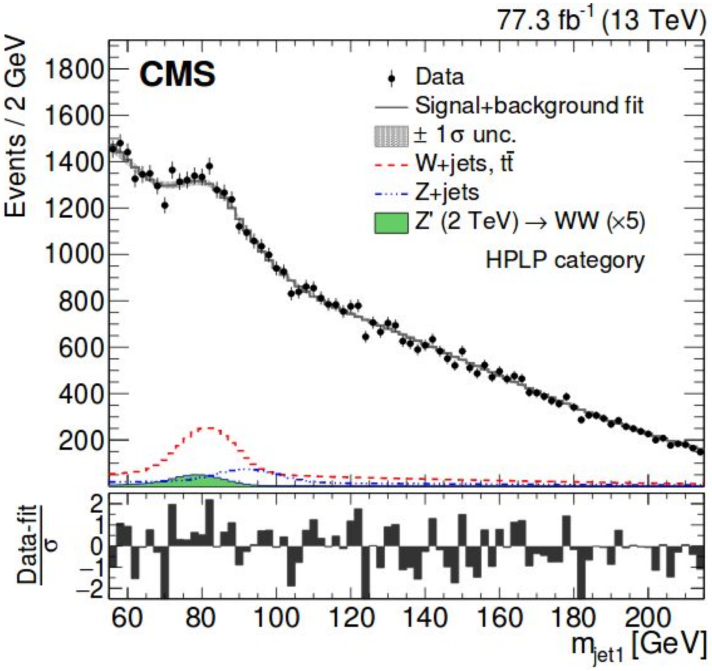


several systematic variations accounted for:

- alternate shapes as shape nuisance parameter
- Including comparison between Pythia8 and Herwig++

X→ VV 2016+2017

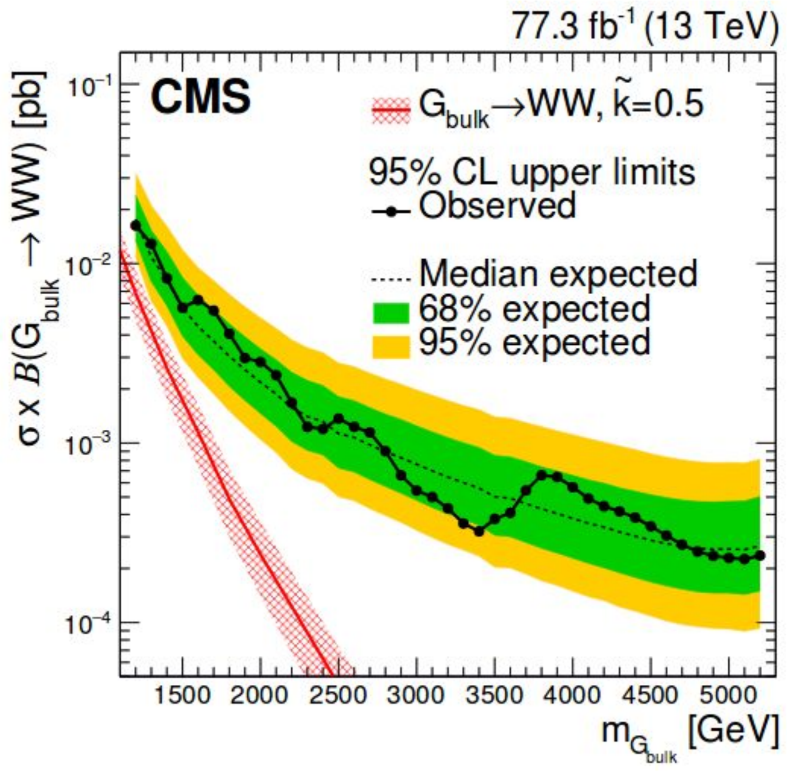


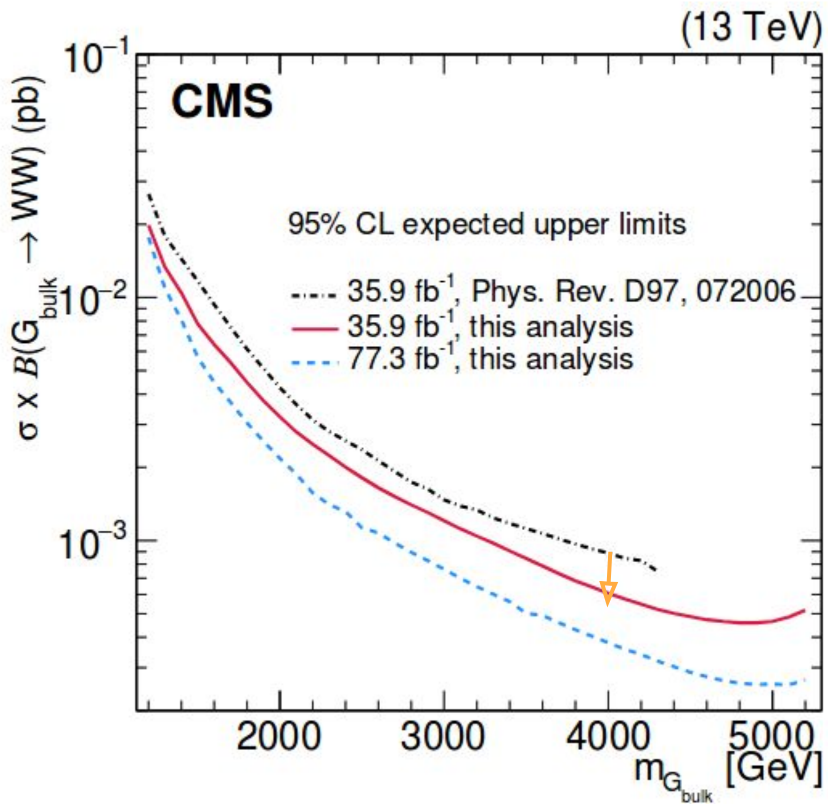


No significant excess over background expectation observed

SM V->qq peak visible:
constrain jet mass scale and resolution
Extracted V+jets cross sections compatible with the SM expectations.

X→ VV 2016+2017



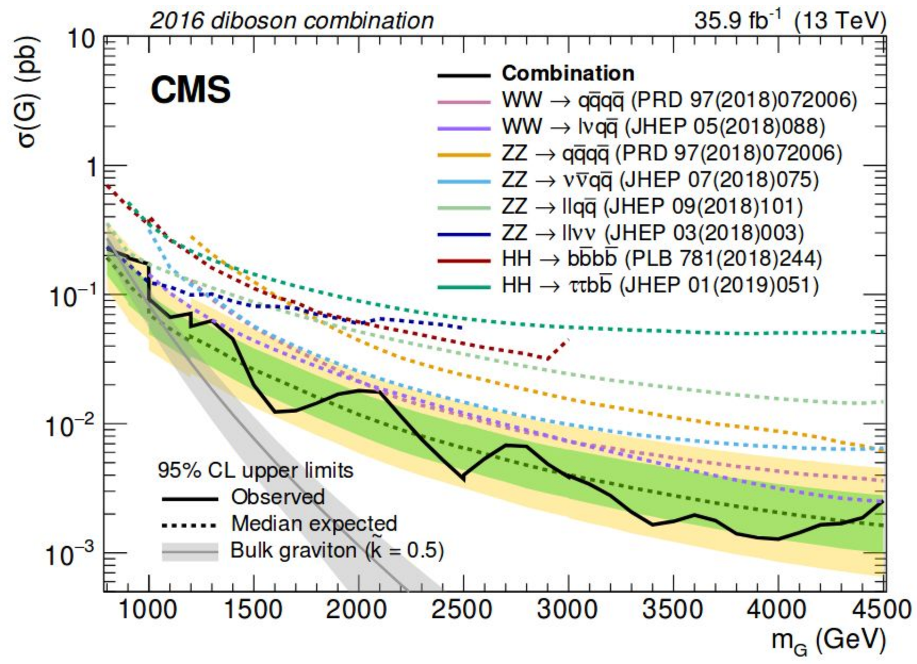


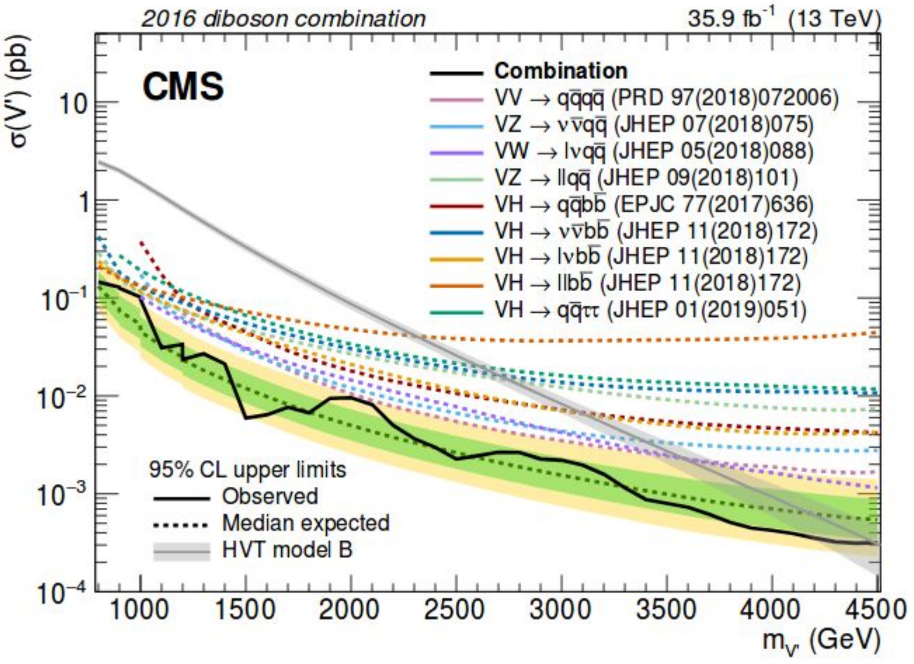
20-30% improvement with respect to the previous method

Di-boson 2016 combination [Submitted to PLB]

Combination of all VV/VH analyses of 2016 data for spin-0, spin-1, and spin-2 interpretations

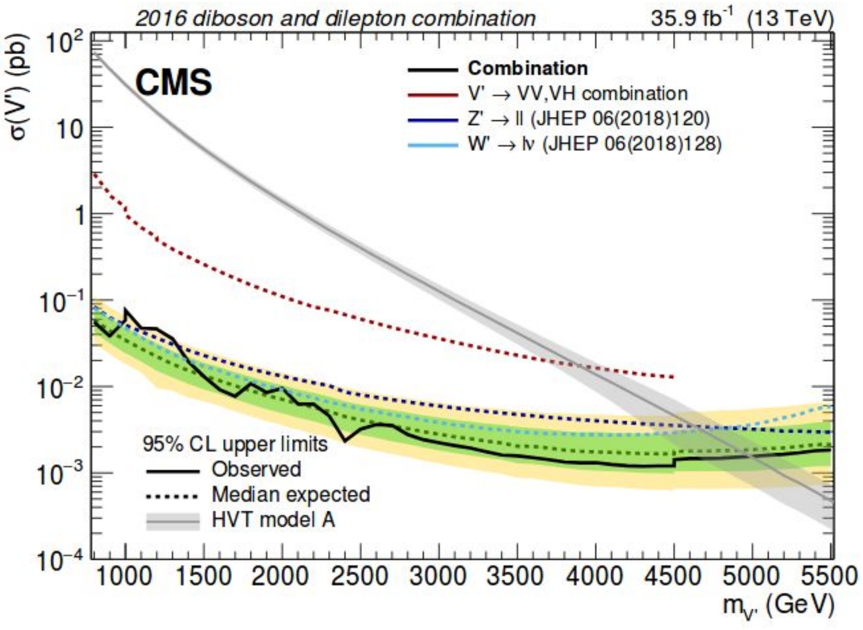
- Large gain in statistical combination

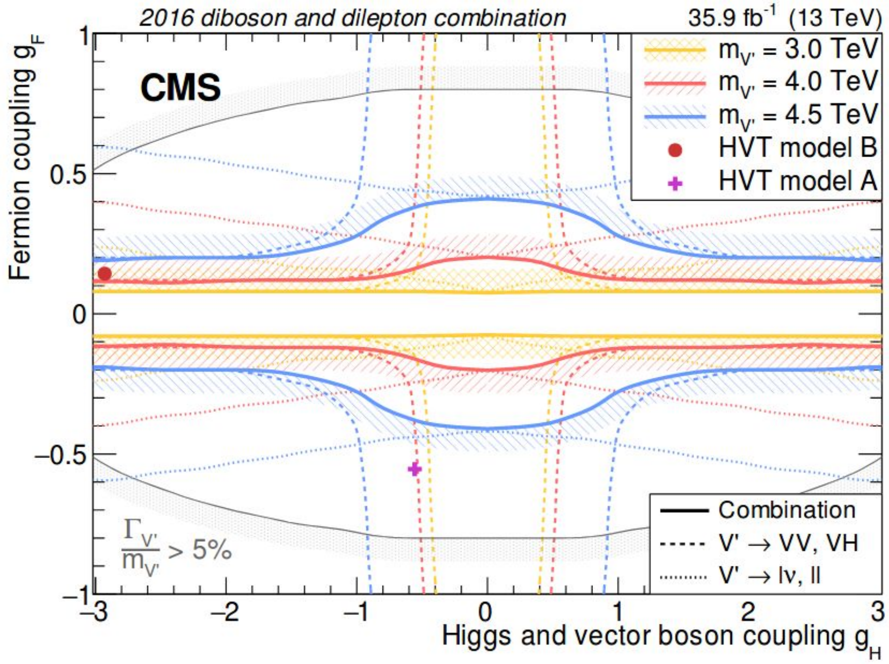




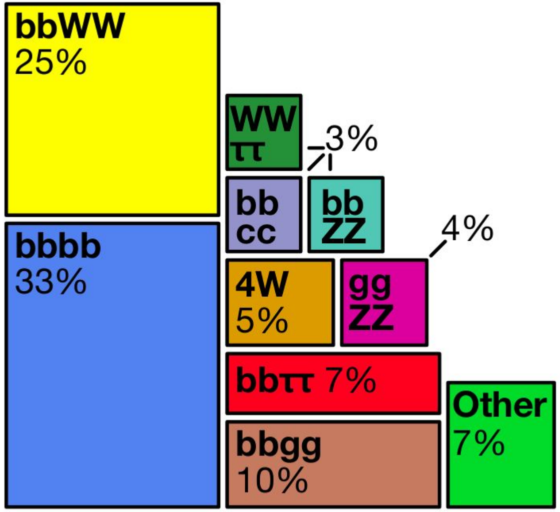
Di-boson 2016 combination

Included for the first time searches with only leptons in the final state: Z'→ll, W'→lν
- enlarge excluded region of the parameter space

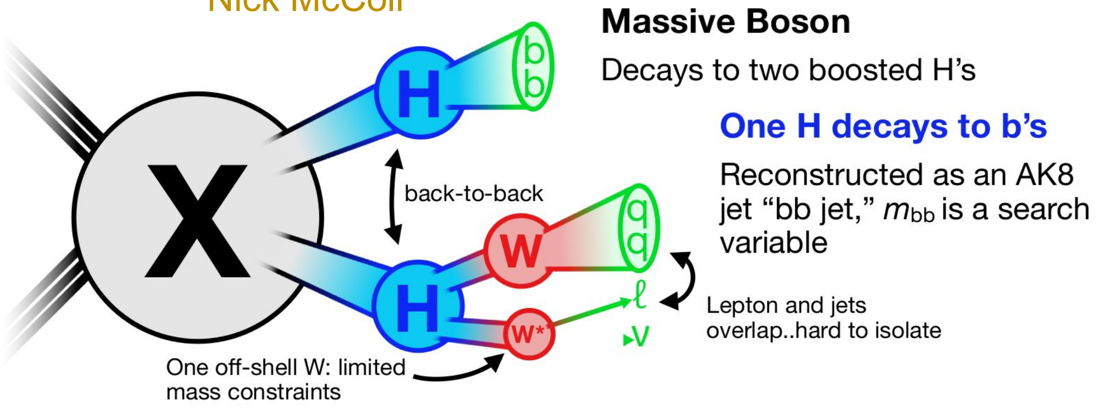




X→HH→bbWW 2016 submitted to JHEP



Nick McColl



Event categorization:

- W→qq: n-subjettiness
- H→bb: sub-jet b-tagging (CSV)

Categorization type	Selection	Category label
Lepton flavor	Electron	e
	Muon	μ
$b\bar{b}$ jet subjet b tagging	One medium	bL
	One medium and one loose	bM
	Two medium	bT
$q\bar{q}'$ jet substructure	$0.55 < q\bar{q}'\ \tau_2/\tau_1 < 0.75$	LP
	$q\bar{q}'\ \tau_2/\tau_1 < 0.55$	HP

Challenging lepton-in-jet reconstruction:

- pT dependent cone isolation

$$\Delta R_{\text{iso}} = \begin{cases} 0.2, & p_T < 50\,\text{GeV}, \\ 10\,\text{GeV}/p_T, & 50 < p_T < 200\,\text{GeV}, \\ 0.05, & p_T > 200\text{ GeV}, \end{cases}$$

- lepton subtraction from the AK8 jet

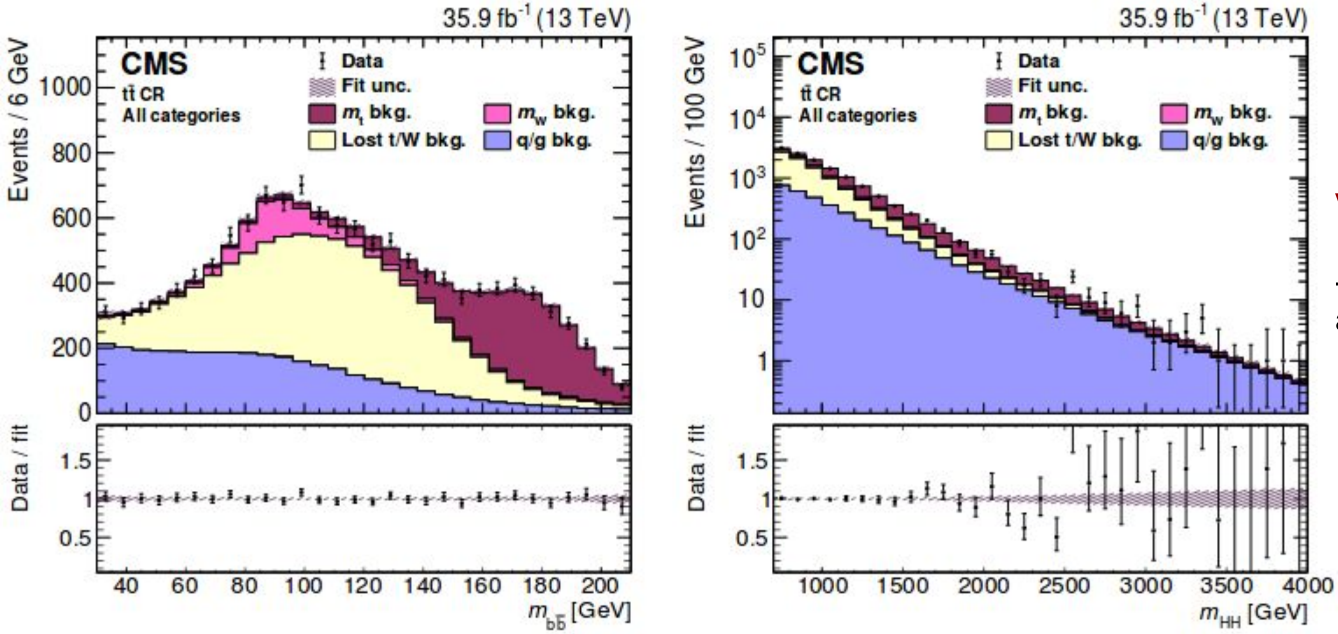
X→HH→bbWW 2016

Background divided into 4 categories with gen-information:

Bkg. category	Dominant SM process(es)	Resonant in $m_{b\bar{b}}$	Num. of gen.-level quarks
m_t	$t\bar{t}$	Yes (near m_t)	3 from t
m_W	$t\bar{t}$	Yes (near m_W)	2 from W
Lost t/W	$t\bar{t}$	No	1 or 2
q/g	W+jets and multijet	No	0

Within ΔR<0.8 of the bb jet axis.

background estimation with 2D fit of m_{bb} and m_{HH}: Non-parametric fit with KDE



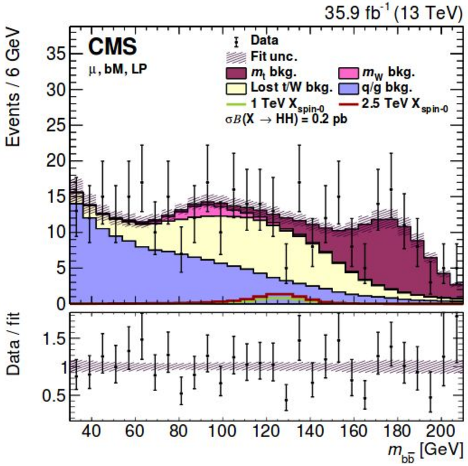
Validated in TTbar and q/g CR

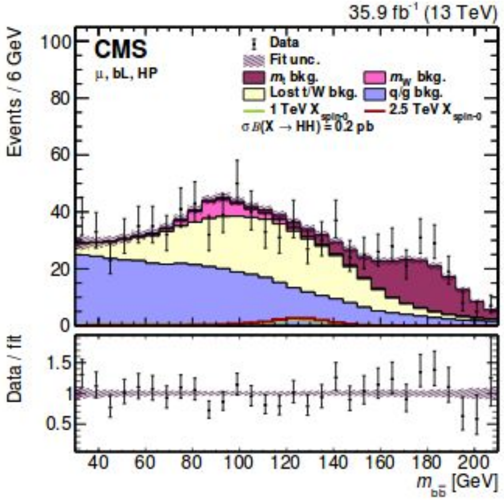
- Data vs MC differences encoded as shape systematics

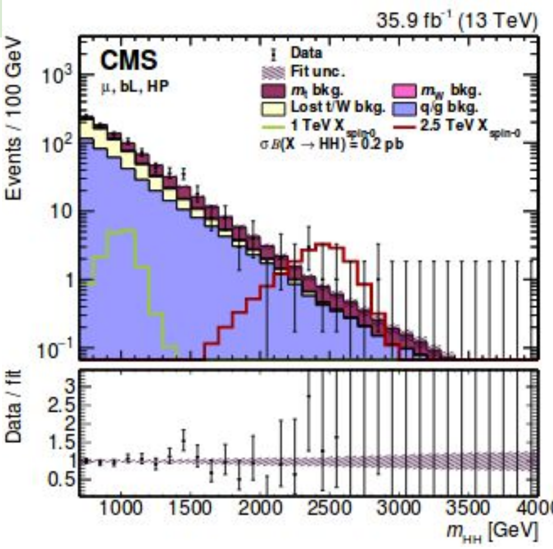
X→HH→bbWW 2016

Background estimation with 2D fit of m_{bb} and m_{HH} in SR region

Alternative background template included as shape uncertainties







Luminosity	Y	Signal
PDF and scales	Y	Signal
Trigger	Y	Signal
Lepton selection	Y	Signal
Jet energy scale	Y, m_{HH}	Signal
Jet energy res.	Y, m_{HH}	Signal
Unclustered energy	Y, m_{HH}	Signal
$b\bar{b}$ jet b tagging	Y	Signal
AK4 jet b tagging veto	Y	Signal
$q\bar{q}'$ τ_2/τ_1 HP:14% LP:33%	Y	Signal
$q\bar{q}'$ τ_2/τ_1 extrapolation	Y	Signal

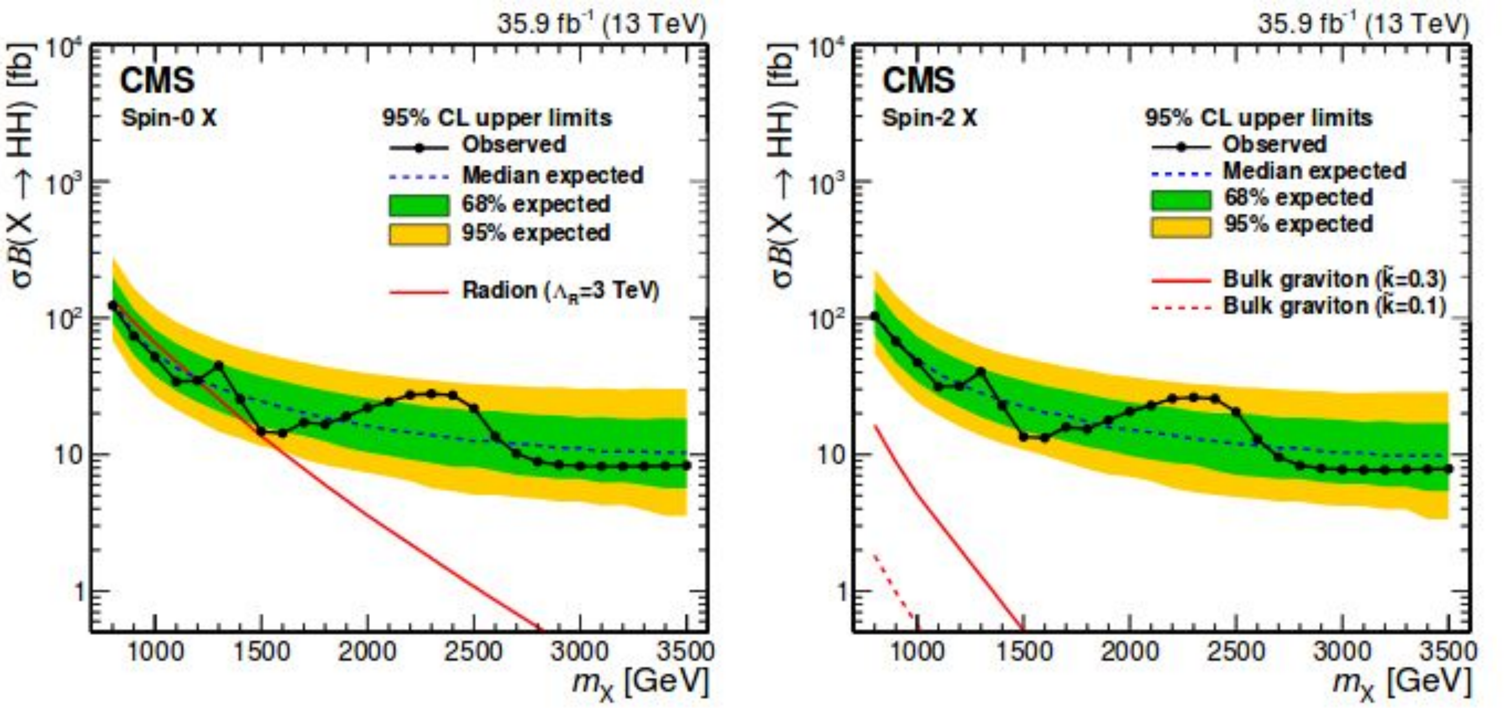
Signal modelled with conditional probabilities

(double CB + exp)

$$P_{\text{signal}}(m_{b\bar{b}}, m_{HH}|m_X) = P_{HH}(m_{HH}|m_{b\bar{b}}, m_X, \theta_1)P_{b\bar{b}}(m_{b\bar{b}}|m_X, \theta_2).$$

X→HH→bbWW 2016

Set limits on spin-0 and spin-2 resonances with similar sensitivity as HH→4b final state



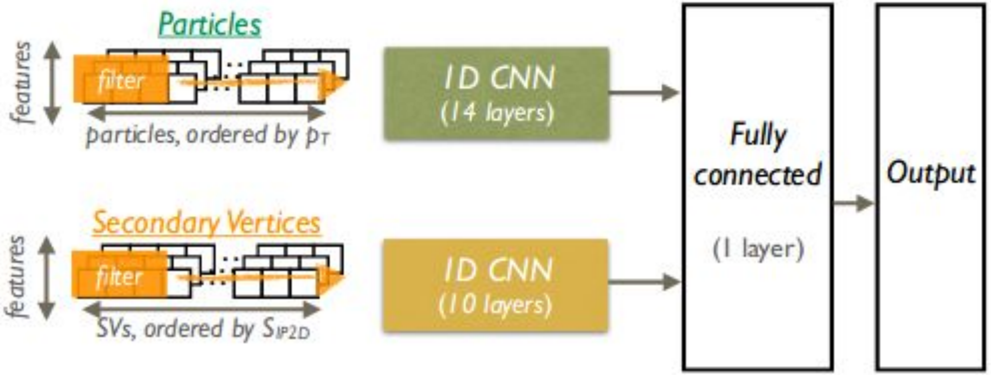
Summary

Rich results from CMS on searches with boosted bosons, although no obvious anomaly.
For more results not covered in this talk see CMS EXO and B2G pages

Long road ahead with fun and possible surprise!

- Full Run2 with 137fb-1
- multi-dimensional fit or multi-regions
- A grand combination with and beyond VV/VH
- Advanced tagger, new topology

Details from Meenakshi Narain



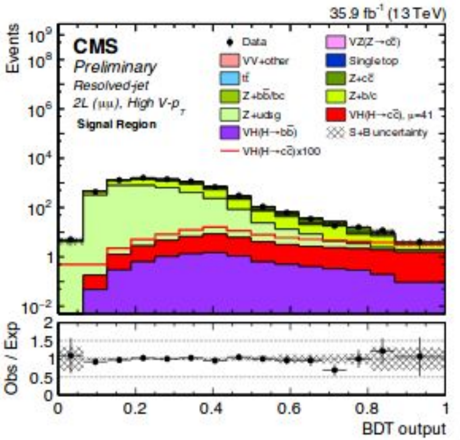
e.g. Hcc tagger
applied successfully in
first CMS result on VH, H→cc
CMS-PAS-HIG-18-031

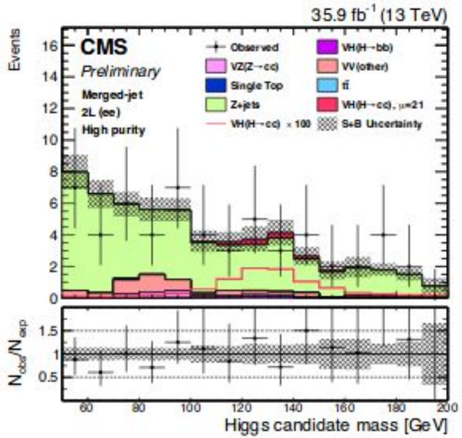
First CMS result on VH, H→cc: a slide from EPS-HEP2019

DIRECT SEARCH H→cc

First direct H→cc search in CMS target the VH production

- Three exclusive channels to capture V decay modes
  0, 1, and 2 leptons (Z→νν, W→ℓν, and Z→ℓℓ)
- Two approaches to explore the H→cc decay topology
  resolved (two jets R=0.4), merged (one large-R jet R=1.5)
- Advanced charm-tagging techniques exploited





	obs(exp) UL on σ/σ_{SM}
ATLAS VHcc (36/fb Run2)	110(150)(*)
CMS VHcc (36/fb Run2)	70(37)

Results are significantly improved

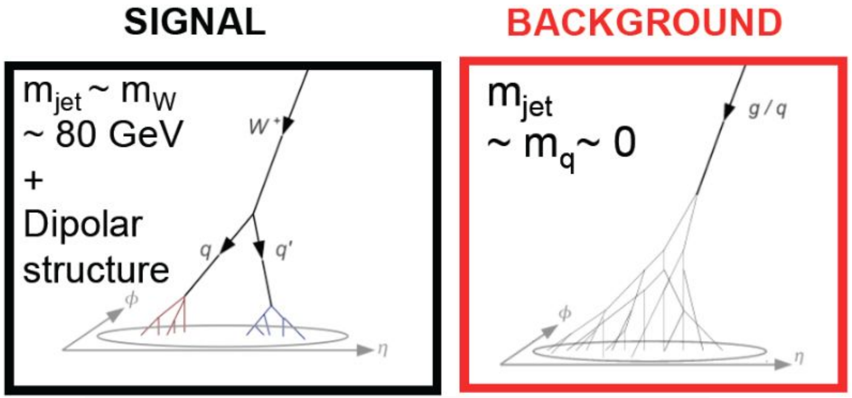
HL-LHC prospects UL on $\sigma/\sigma_{SM} < 6.3$
in the absence of syst unc.
by extrapolating ATLAS Run2 results

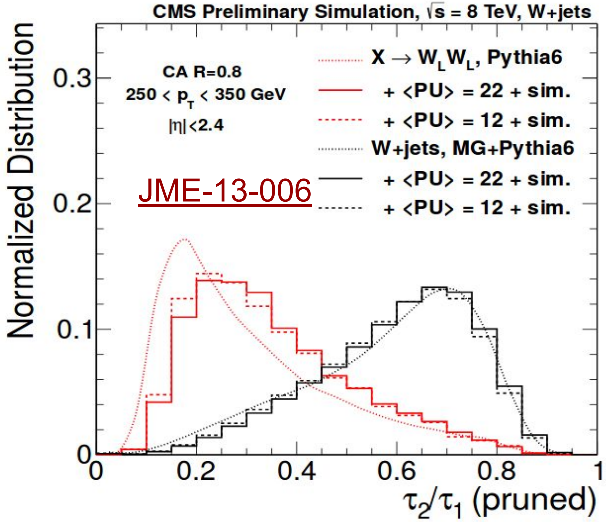
(*) only Z→ℓℓ + H→cc channel analysed

Rare decays/production

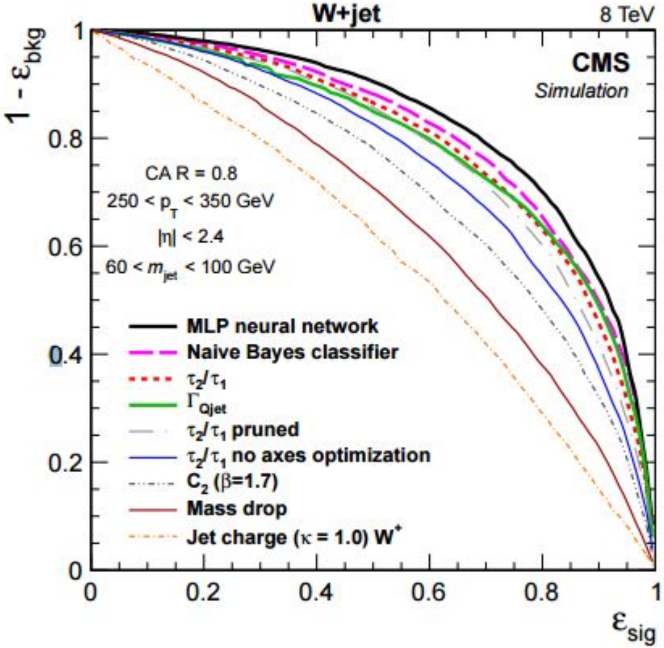
Backup

Substructure: tagging





[JME-13-006]



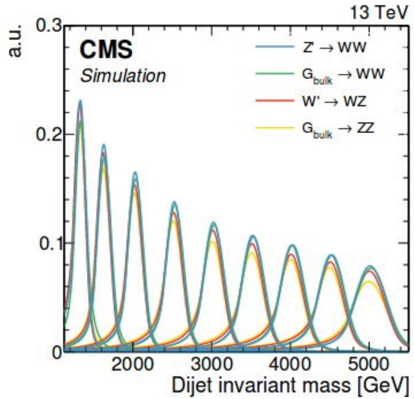
N-subjettiness: How likely is a Jet to have "N" subjets

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

X→ VV 2016+2017 submitted to EPJC

Table 1: The W jet mass peak position (m) and resolution (σ), and the W-tagging efficiencies, as extracted from top quark enriched data and from simulation, together with the corresponding data-to-simulation scale factors. The uncertainties in the scale factors include systematic uncertainties estimated as described in Ref. [62].

	m [GeV]	σ [GeV]	W-tagging efficiency
		2016	
$\tau_{21}^{DDT} < 0.43$			
Data	82.0 ± 0.5 (stat)	7.1 ± 0.5 (stat)	0.080 ± 0.008 (stat)
Simulation	80.9 ± 0.2 (stat)	6.6 ± 0.2 (stat)	0.085 ± 0.003 (stat)
Data/simulation	1.014 ± 0.007 (stat+syst)	1.09 ± 0.09 (stat+syst)	0.94 ± 0.10 (stat+syst)
$0.43 < \tau_{21}^{DDT} < 0.79$			
Data			0.920 ± 0.008 (stat)
Simulation			0.915 ± 0.003 (stat)
Data/simulation			1.006 ± 0.009 (stat+syst)
		2017	
$\tau_{21}^{DDT} < 0.43$			
Data	80.8 ± 0.4 (stat)	7.7 ± 0.4 (stat)	0.060 ± 0.006 (stat)
Simulation	82.2 ± 0.3 (stat)	7.1 ± 0.3 (stat)	0.070 ± 0.005 (stat)
Data/simulation	0.983 ± 0.007 (stat+syst)	1.08 ± 0.08 (stat+syst)	0.96 ± 0.12 (stat+syst)
$0.43 < \tau_{21}^{DDT} < 0.79$			
Data			0.935 ± 0.006 (stat)
Simulation			0.932 ± 0.005 (stat)
Data/simulation			1.003 ± 0.008 (stat+syst)



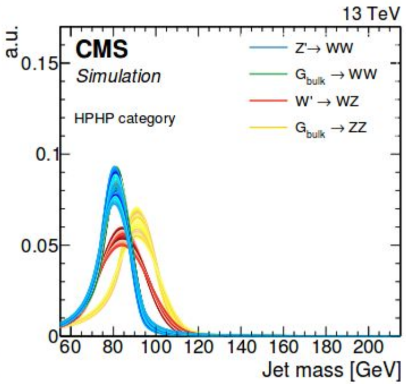
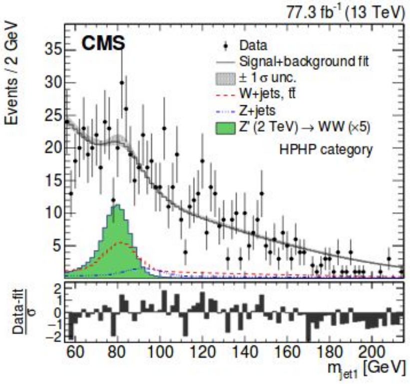
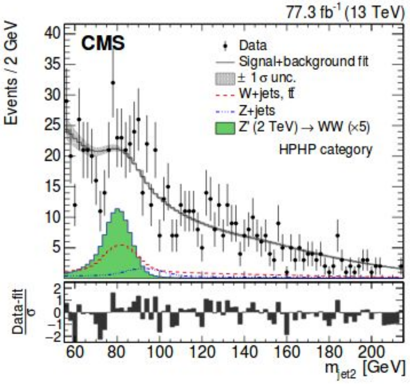


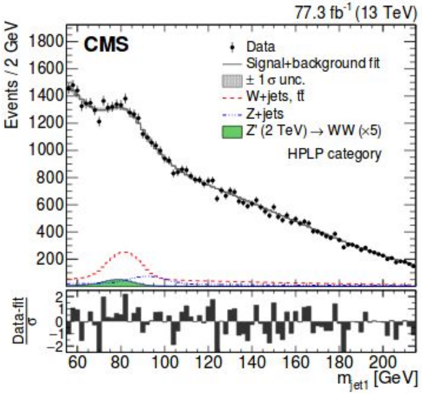
Table 2: Summary of the systematic uncertainties and the quantities they affect. Numbers in parentheses correspond to uncertainties for the 2016 analysis if these differ from those for 2017. Dashes indicate shape variations that cannot be described by a single parameter, and are discussed in the text.

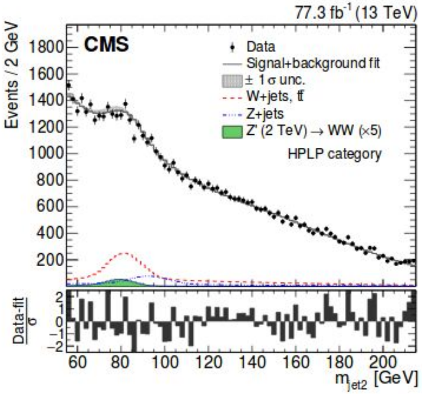
Source	Relevant quantity	HPHP unc. (%)	HPLP unc. (%)
PDFs	Signal yield	3	
W boson tagging efficiency	Signal + V+jets yield	25 (21)	13 (11)
W boson tagging p_T dependence	Signal + V+jets yield	8–23	9–25
Integrated luminosity	Signal + V+jets yield	2.3 (2.6)	
QCD normalization	Background yield	50	
W+jets normalization	Background yield	20	
Z+jets normalization	Migration	20	
PDFs	Signal m_{jj}/m_{jet} mean and width	<1	
Jet energy scale	Signal m_{jj} mean	2	
Jet energy resolution	Signal m_{jj} width	5	
Jet mass scale	Signal + V+jets m_{jet} mean	2	
Jet mass resolution	Signal + V+jets m_{jet} width	8	
QCD HERWIG++	QCD shape	—	
QCD MADGRAPH+PYTHIA8	QCD shape	—	
p_T variations	QCD shape	—	
Scale variations	QCD shape	—	
High-m_{jet} turn-on	QCD shape	—	
p_T variations	V+jets m_{jj} shape	—	

X→ VV 2016+2017 submitted to EPJC

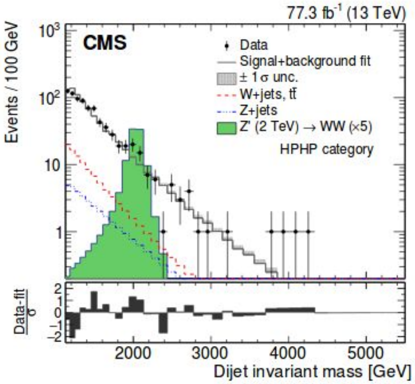


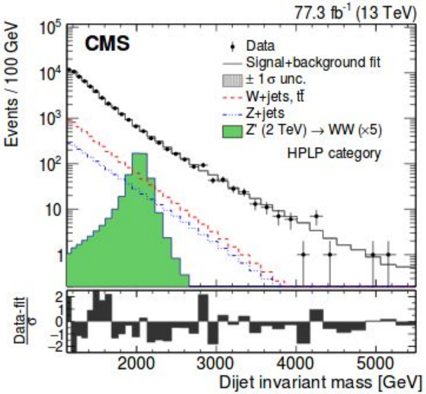






HPHP



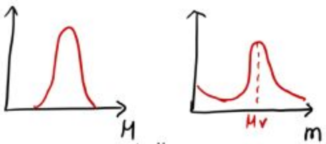


HPLP

WV with 2D

JHEP 05 (2018) 088

Background estimation



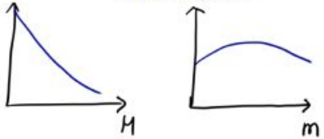
Signal peaks in both m_{WV} and m_{jet}

$$P_{sig}(m_{WV}, m_{jet}|\theta(M_X)) = P_{WV}(m_{WV}|\theta_1(M_X)) \times P_j(m_{jet}|\theta_2(M_X))$$

- Fit both dimensions

double crystal-ball functions, for LP additional exponential is used for m_{jet} mass tail

- Interpolate using polynomials as a function of the resonance mass hypothesis (M_X)



Non-resonant background: W+jets

Conditional probability of m_{WV} as function of m_{jet}:

$$P_{W+jets}(m_{WV}, m_{jet}) = P_{WV}(m_{WV}|m_{jet}, \theta_1) \times P_j(m_{jet}|\theta_2)$$

- P_{WV} templates created using kernel method starting from particle level, clustering as for reconstructed jets
- Determine scale and resolution as function of true jet p_T (encode uncertainties by varying those)
- Populate templates as sums of 2D gaussian templates in bins of m_{jet}
- Smoothen mWV from 2.5 TeV as function of mWV fitting exponential from 2 TeV to avoid empty bins

WV with 2D

JHEP 05 (2018) 088

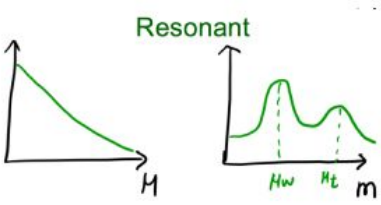
Background estimation

Resonant background: W+V

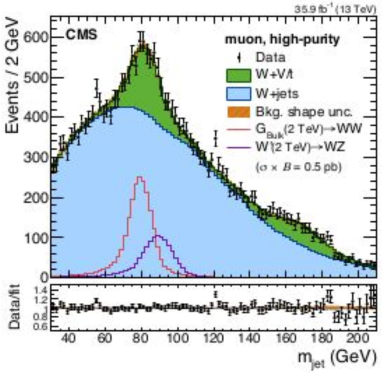
Conditional probability of m_{WV} as function of m_{jet}:

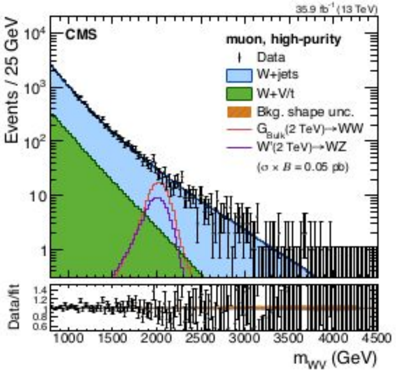
$$P_{W+V}(m_{WV}, m_{jet}|\theta) = P_{WV}(m_{WV}|\theta_1) \times P_j(m_{jet}|\theta_2(m_{WV}))$$

- P_{WV} templates created using kernel method as for W+jets (1D)
- Smoothen m_{WV} from 1.2 TeV as function of m_{WV} fitting exponential
- m_{jet} template described by W and top mass peaks



HP muon





arXiv:1802.09407

Di-boson 2016 combination Submitted to PLB

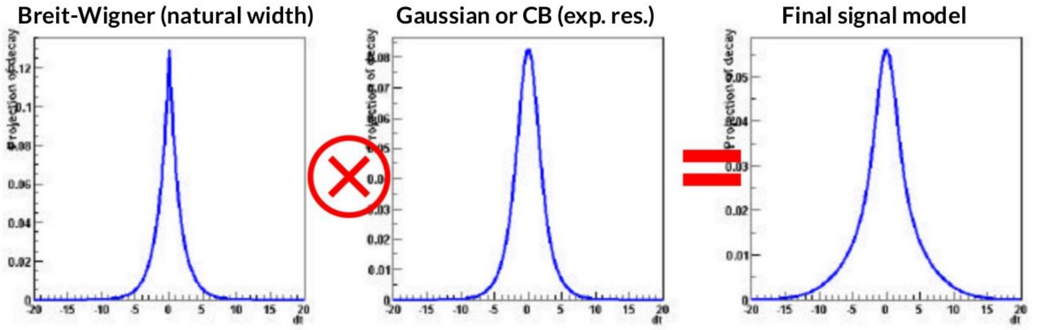
Table 1: Summary of the main selections that guarantee the exclusivity between individual final states. The symbol ℓ represents an electron or a muon; τ leptons are considered separately. The AK4 b jets are additional b tagged AK4 jets that do not geometrically overlap with AK8 jets. The symbol "—" implies that no selection is applied.

Ref.	Channel	Final state	ℓ	τ_h	AK8 jets	AK8 jet mass	AK4 b jets
[1]	WW, WZ, ZZ	$q\bar{q}q\bar{q}$	veto	—	2	$2\,[m_W, m_Z]$	—
[2]	WZ, ZZ	$\nu\nu q\bar{q}$	veto	veto	1	m_V	veto
[3]	WW, WZ	$\ell\nu q\bar{q}$	1	—	1	m_j shape$/[m_W, m_Z]$	veto
[4]	WZ, ZZ	$\ell\ell q\bar{q}$	2	—	1	m_V	—
[5]	ZZ	$\ell\ell\nu\nu$	2	—	—	—	—
[6]	WH, ZH	$q\bar{q}b\bar{b}$	veto	veto	2	$[m_W, m_Z], m_H$	—
[7]	ZH	$\nu\nu b\bar{b}$	0	veto	1	m_H	veto
[7]	WH	$\ell\nu b\bar{b}$	1	veto	1	m_H	veto
[7]	ZH	$\ell\ell b\bar{b}$	2	veto	1	m_H	—
[8]	WH, ZH	$q\bar{q}\tau\tau$	—	2	1	$[m_W, m_Z]$	veto
[8]	HH	$\tau\tau b\bar{b}$	—	2	1	m_H	veto
[9]	HH	$b\bar{b}b\bar{b}$	—	—	2	$2\,m_H$	—
[10]	HH	$b\bar{b}b\bar{b}$	—	—	1	m_H	2
[19]	$\ell\nu$		1	—	—	—	—
[20]	$\ell\ell$		2	—	—	—	—

	Correlation	Type	Variation	$q\bar{q}q\bar{q}$ [1]	$\nu\nu q\bar{q}$ [2]	$\ell\nu q\bar{q}$ (2D fit) [3]	$\ell\ell q\bar{q}$ [4]	$\nu\nu\ell\ell$ [5]	$q\bar{q}b\bar{b}$ [6]	$(\nu\nu, \ell\nu, \ell\ell)b\bar{b}$ [7]	$(q\bar{q}, b\bar{b})\tau\tau$ [8]	$b\bar{b}b\bar{b}$ [9] [10]	$\ell\nu$ [19]	$\ell\ell$ [20]
Bkg. modeling	no	shape	—	f	b	f	b	b	f	b	b	b	b	b
Bkg. normalization	no	yield	2–30%	f	b	f	b	b	f	b	b	b	b	b
Jet energy scale	yes	yield, shape	1–2%	s	s	s, b	s	—	s	s	s	s	—	—
Jet energy resolution	yes	yield, shape	3–7%	s	s	s, b	s	—	s	s	s	s	—	—
Jet mass scale	yes	yield, migr.	1–36%	s	s	s, b	s	—	s	s	s	s	—	—
Jet mass resolution	yes	yield, migr.	5–25%	s	s	s, b	s	—	s	s	s	s	—	—
Jet triggers	yes	yield	1–15%	s	—	—	—	—	s	—	—	s	—	—
e, μ id., iso., trigger	yes	yield, shape	1–3%	—	—	s	s	s, b	—	s	s	—	s, b	s, b
e, μ scale and res.	yes	yield, shape	1–6%	—	—	s	s	s, b	—	s	—	—	s, b	s, b
τ_h reco., id., iso.	yes	yield	6–13%	—	s	—	—	—	—	s	s	—	—	—
τ_h energy scale	yes	yield, shape	1–5%	—	—	—	—	—	—	—	s	—	—	—
τ_h high-p_T extr.	yes	yield, shape	18–30%	—	—	—	—	—	—	—	s	—	—	—
p_T^{miss} scale and res.	yes	yield	1–2%	—	s	s	—	s, b	—	s	s	—	s, b	—
p_T^{miss} triggers	yes	yield	1–2%	—	s	—	—	—	—	s	s	—	—	—
b quark identification	yes	yield, migr.	1–9%	—	s	s, b	—	—	s	s	s	s	—	—
τ_{21} identification	yes	yield, migr.	11–33%	s	s	s, b	s	—	s	—	s	s	—	—
τ_{21} high-p_T extr.	yes	yield, migr.	2–40%	s	s	s, b	s	—	s	—	s	s	—	—
m_H selection	yes	yield	6%	—	—	—	—	—	s	s	s	s	—	—
Pileup	yes	yield	1–2%	s	s	—	s	—	s	s	s	s	s, b	—
Luminosity	yes	yield	2.5%	s	s	s	s	s, b	s	s	s	s	s, b	s, b
PDF and QCD accept.	yes	yield	1–2%	s	—	s	s	s, b	s	s	s	s	—	s, b
PDF and QCD norm.	yes	yield	2–78%	t	t	t	t	t, b	t	t	t	t	t, b	t, b

Future: combination

- In 2016, both ATLAS and CMS neglected non-narrow interpretations
- One of the most common questions at workshops and conferences
- A rigorous treatment is complex and time-consuming (interference effects, ….)
- Proposal for a “feasible” scan of the width:
  - Preferably use **parametric signal shapes** (convenient because parameter interpolation)
  - **Convolute** signal PDF with a **Breit-Wigner** function with **0% width**
  - The width can be set externally (e.g. by a line in the datacard with combine) to any value
  - A single set of datacards can be used for multiple widths
  - All parameters set to constant, and relaxed only if necessary (e.g. fit non-narrow bumps)



The flexibility of the HVT model can be used to probe “extreme” scenarios:

1. **Model A**: “SM-like” V’ production through qq’, decay predominantly to qq’ or ll’
2. **Model B**: boson-enhanced couplings, production through qq’, decay to VV and VH
3. **Model C**: fermiophobic V’, produced through VBF, decay to VV and VH
4. **Model D**: V’ couple predominantly to third generation quarks and leptons

Model C and D not in the original HVT paper, defined by us (experimentalists)

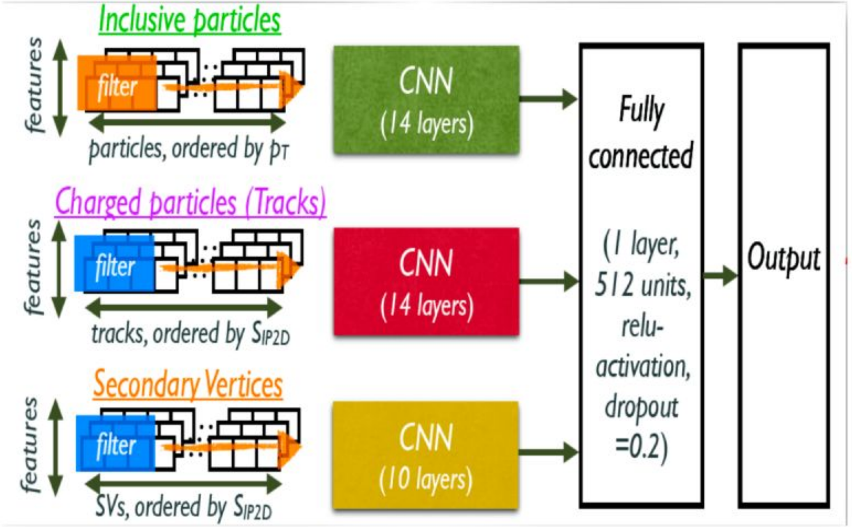
Alberto Zucchetta

Future: Deep AK8

DeepAK8

CMS-DP-2017-049
10.1007/JHEP10(2017)005

- Deep AK8 takes advantage of this additional information
  - Includes particle and detector-level quantities (tracking, vertex formation)
  - Individual jet constituents as inputs
- Uses convolutional NNs to take advantage of nearby correlations



Many output categories!

Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)