Boosted technique for Higgs measurement and New Physics Searches

Aug 30th, 2021

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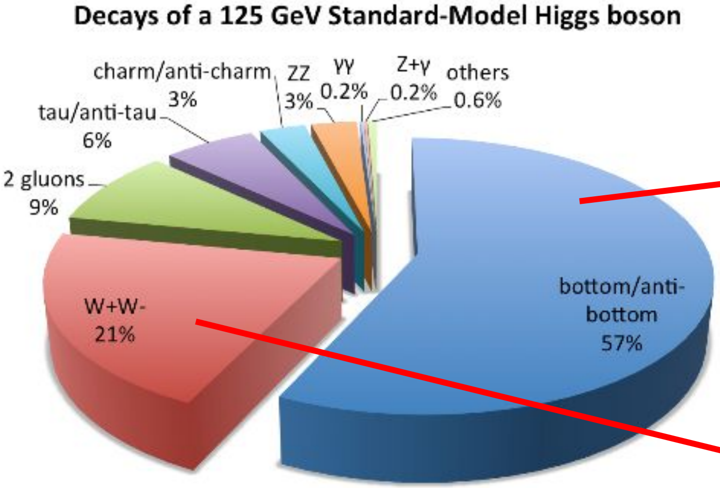
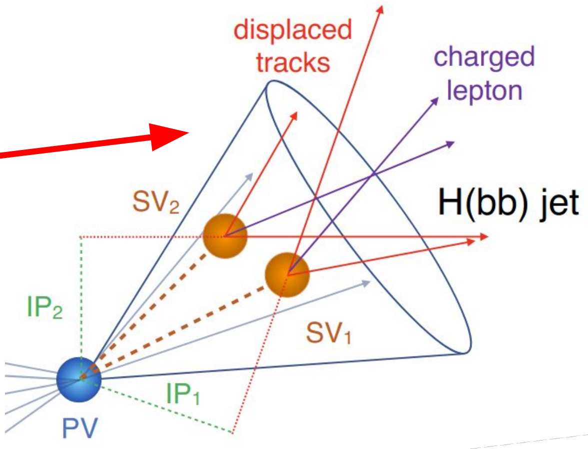
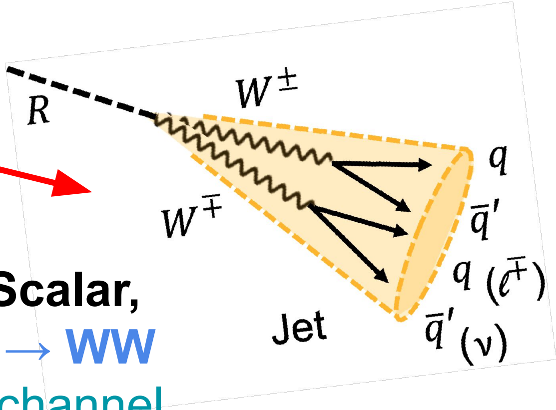
Higgs potential and BSM opportunity

Boosted Higgs







- **High PT Higgs measurement/search**
  - Inclusive search for H→ bb
  - H→ cc (Merged and Resolved)

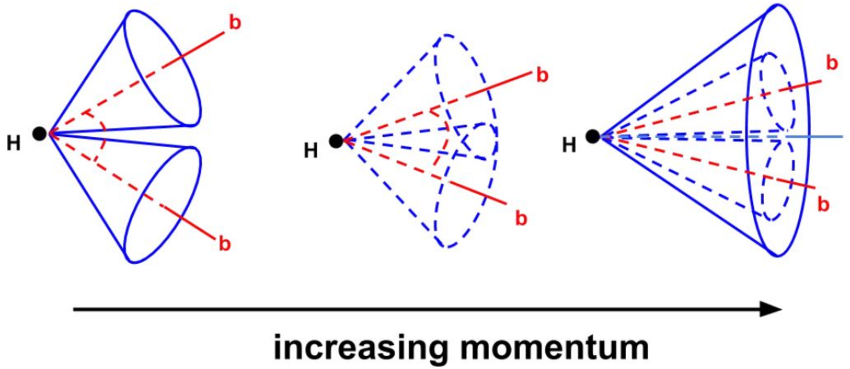
  Covered in Huilin's talk
- **Heavy Resonance decays into Higgs**
  - X → W + H → lν + bb
  - X → H + H → bb + WW

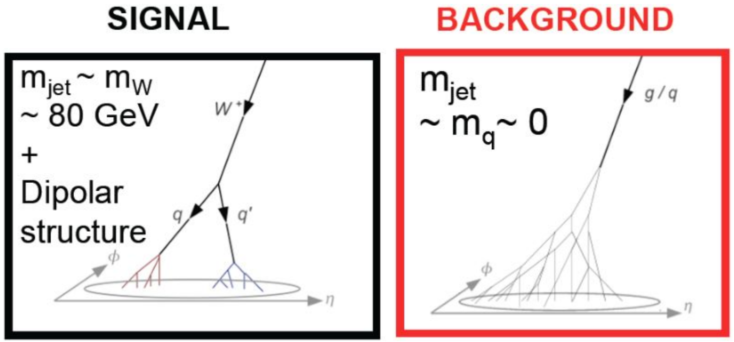
- **X → W + Scalar,**
  Scalar → WW
  - 1-lep channel
  - 0-lep channel

Citius, Altius, Fortius

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

see e.g. [1302.0260]





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

Boosted objects→small angular separation

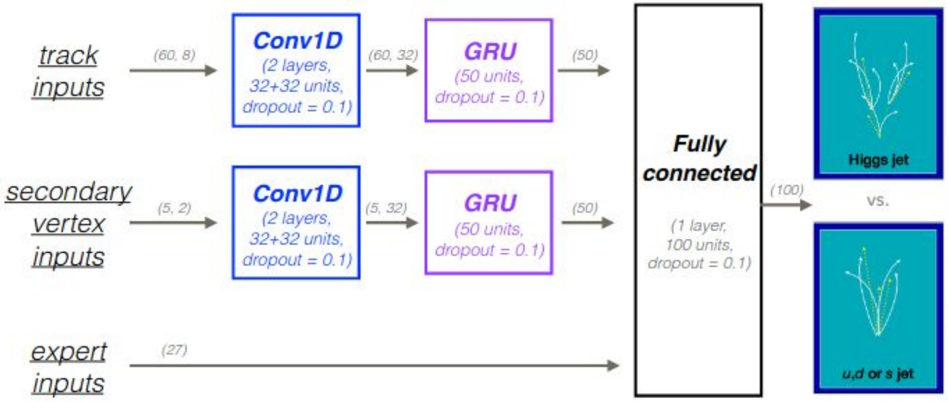
→**merged jets** (W/Z →qq; H →bb....)

- Jets: anti-kt with R = 0.4/0.8 (AK4/AK8)
- Puppi: pile-up mitigation
- Jet grooming, soft drop

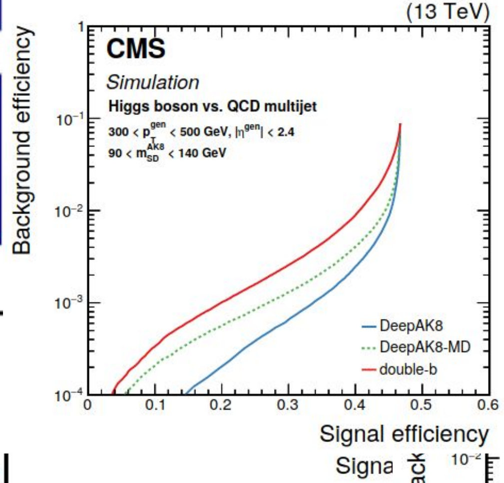
- N-subjettiness:
  - How likely is a Jet to have “N” subjets
  - Designing De-correlated Taggers (DDT)
- (Deep) double-b tagger:
  - discriminate H → bb decays
- DeepAK8 tagger (**more in Huilin’s talk**):
  - multi-class tagger for t/W/Z/H tagging
  - PF candidates and secondary vertices

Deep tagger (DDBT and DeepAK)

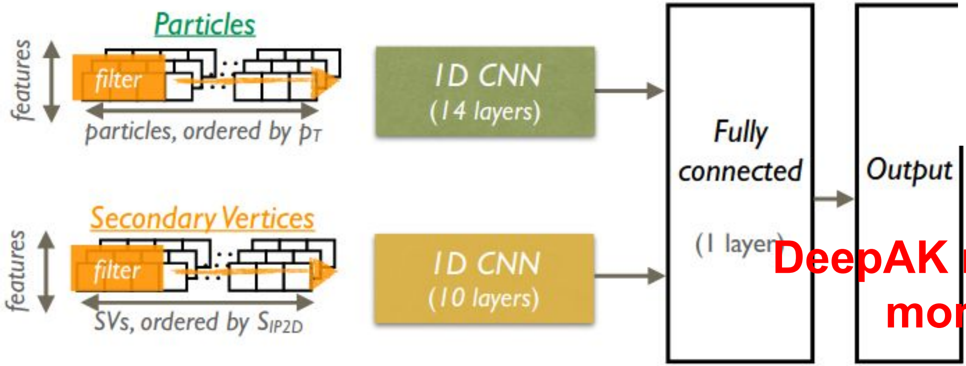
Similar ML approach using low-level features now applied to large-radius jets

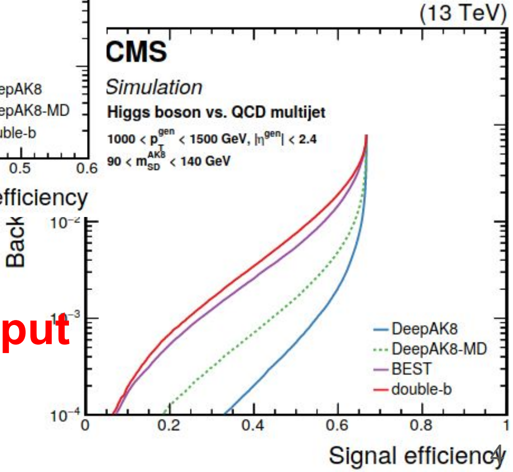


50-70% H(bb) eff for 1% mis-id (depending on mSD, PT range)



Mass decorrelation via penalty term in loss

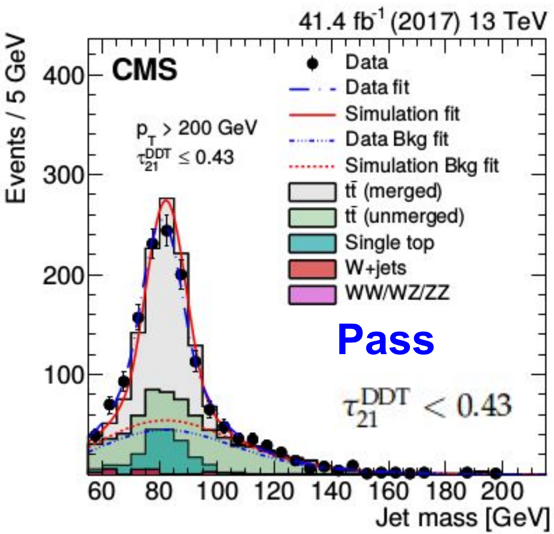


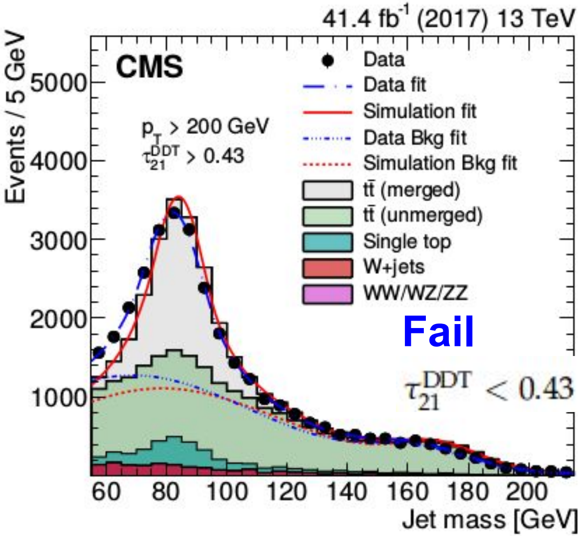


DeepAK multi-category output more in Huilin's talk

Calibration

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

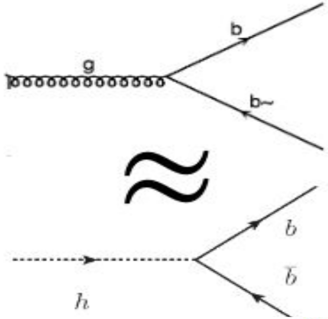


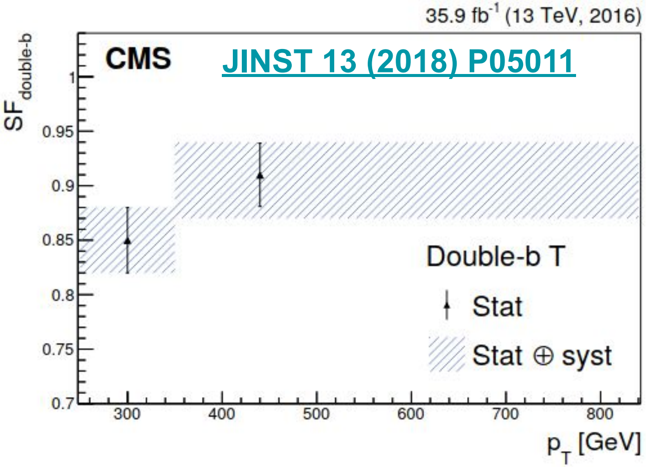


	m [GeV]	σ [GeV]	W-tagging efficiency
	2017		
$\tau_{21}^{DDT} < 0.43$			
Data	80.8 ± 0.4 (stat)	7.7 ± 0.4 (stat)	0.060 ± 0.006 (stat)
Simulation	82.2 ± 0.3 (stat)	7.1 ± 0.3 (stat)	0.070 ± 0.005 (stat)
Data/simulation	0.983 ± 0.007 (stat+syst)	1.08 ± 0.08 (stat+syst)	0.96 ± 0.12 (stat+syst)

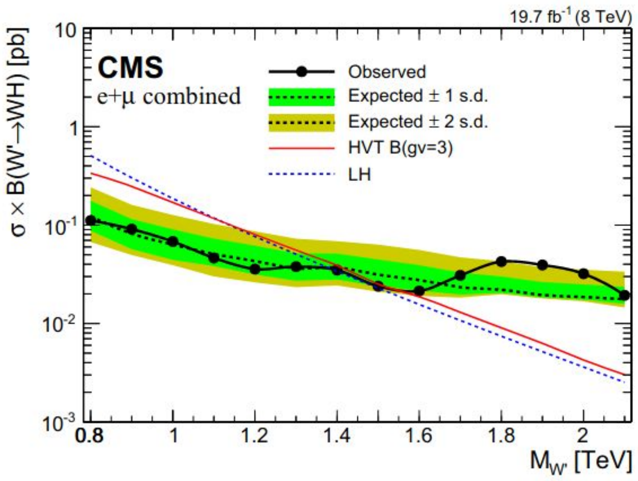
Or using proxy e.g. gluon splitting

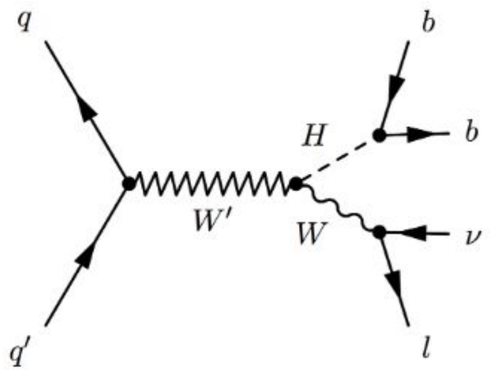
Tag via two muons aligned with subjets;
Perform template fit to SV mass:

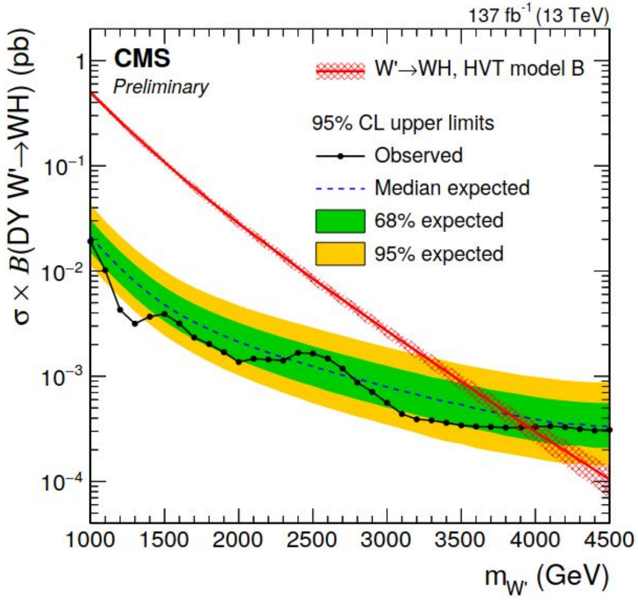




WH(bb) Resonance Searches







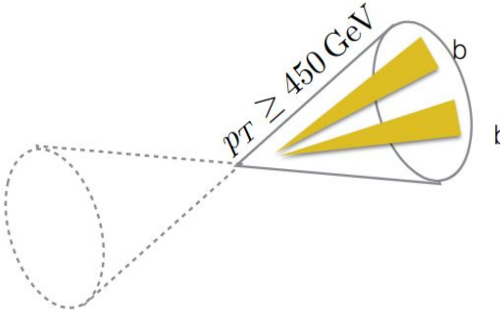
EPJC 76 (2016) 237
CMS 2012 data
Higgs tagging based on (sub-)jets

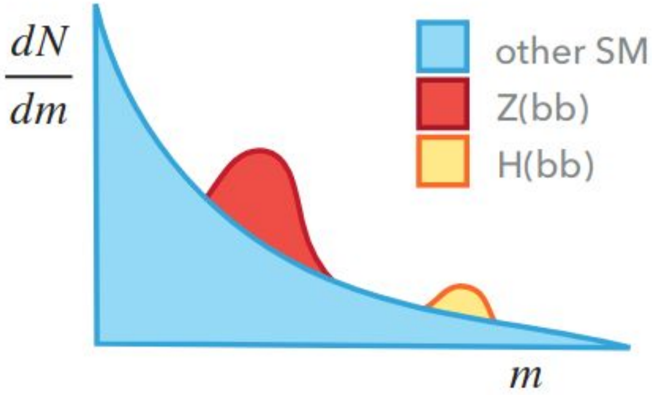
CMS-PAS-B2G-19-002
Full Run2, Double b-tagger
a multivariate discriminant that combines information from displaced tracks, secondary vertices, and the two-SV system within the Higgs boson jet candidate

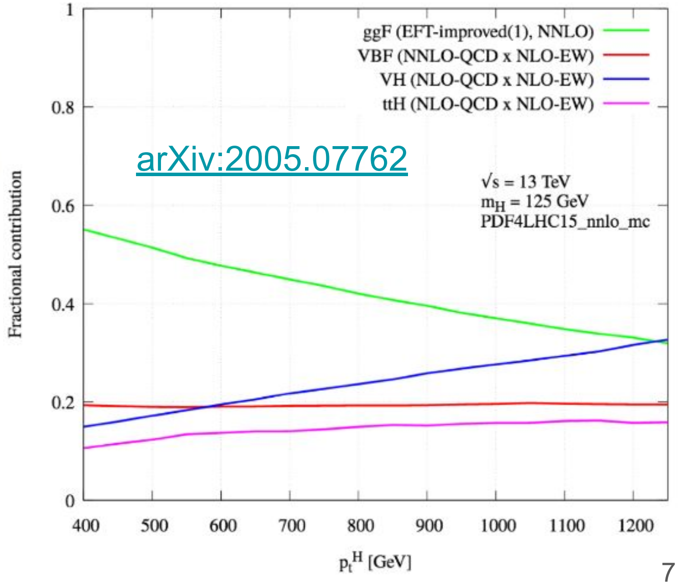
Boosted H→bb

Reconstruction of boosted Higgs as a tool to access very high-pT regime, sensitive to BSM physics, with full Run2 dataset

- Preselect boosted large-radius jet with two-prong substructure
- Use **DeepDoubleB** tagger to select bb-enriched events
- Constrain QCD background via jet mass sideband + control region
- **Search for peak in jet mass distribution**







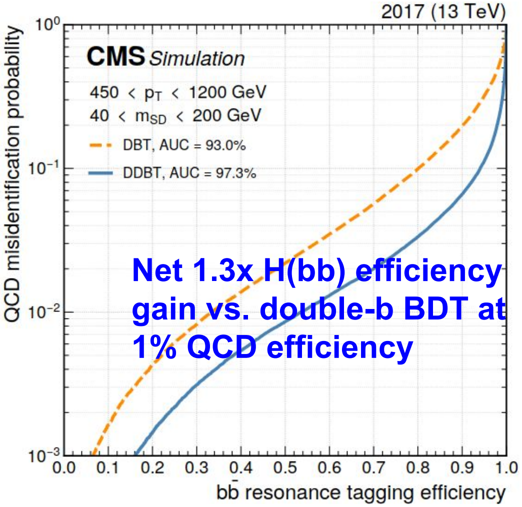
Boosted H→bb

- Trigger on high-p_T large-radius (AK8) jet and/or HT
- Select p_T-leading AK8 jet within kinematic region ➜
- Softdrop mass algorithm
  Removes soft & wide-angle QCD radiation to improve mass resolution
- Require 2-prong substructure with N2 energy correlation variable
- Apply lepton vetoes and top rejection selections

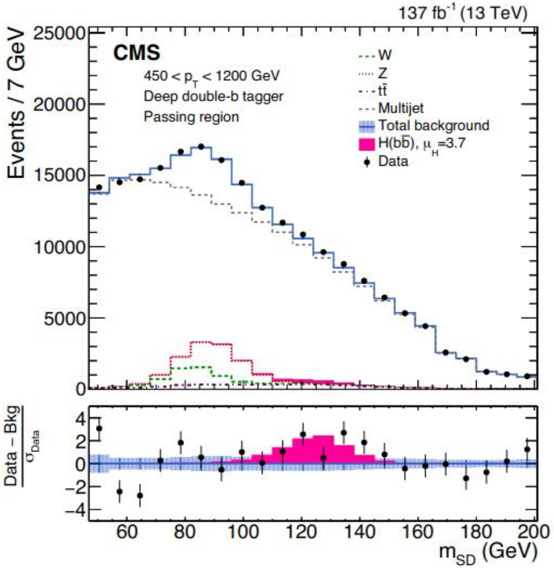
$$p_T \geq 450\,\mathrm{GeV}$$
$$|\eta| \leq 2.5$$
$$m_{\mathrm{softdrop}} \geq 47\,\mathrm{GeV}$$

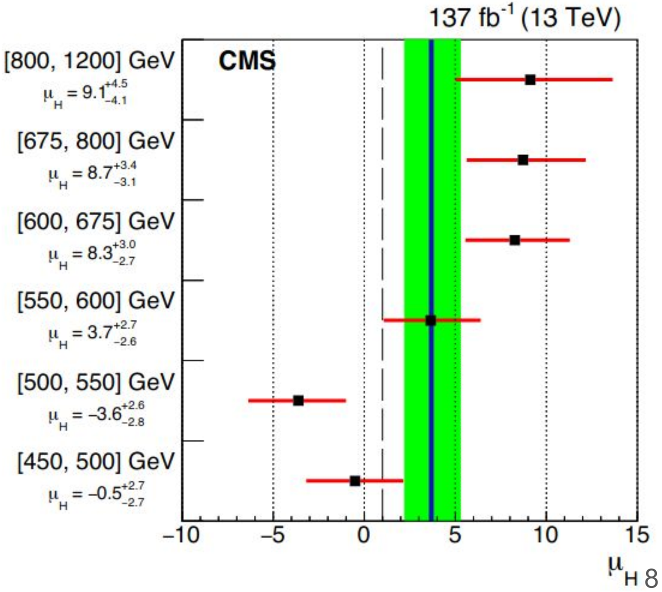
Observed $\mu_H = 3.7 \pm 1.2\ (\mathrm{stat})\ ^{+0.6}_{-0.7}\ (\mathrm{syst})\ ^{+0.8}_{-0.5}\ (\mathrm{theo})$

Observed significance: 2.5σ



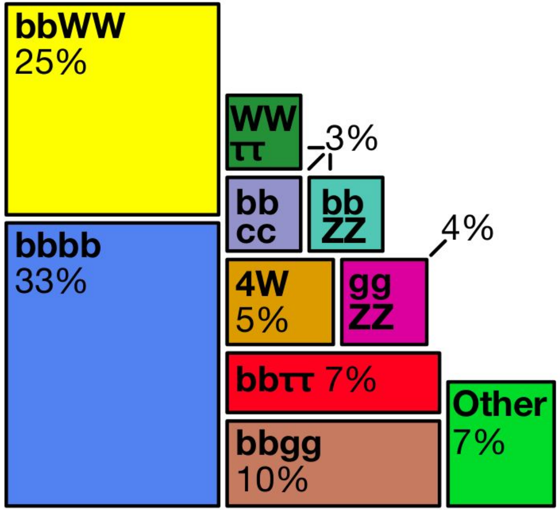
Net 1.3x H(bb) efficiency gain vs. double-b BDT at 1% QCD efficiency

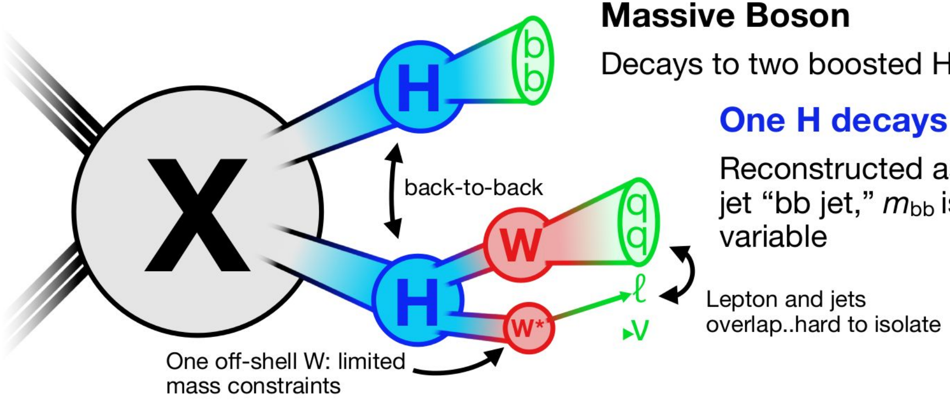




X→HH→bbWW

CMS-PAS-B2G-20-007 JHEP 10 (2019) 125





Massive Boson

Decays to two boosted H's

One H decays to b's

Reconstructed as an AK8 jet "bb jet," m_{bb} is a search variable

2ℓ final states also included: bbWW and bbττ → bbℓℓ + ν's

Event categorization:

- W→qq: n-subjettiness
- H→bb: DeepAK8 /sub-jet b-tagging(2016)

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

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

- lepton subtraction from the AK8 jet

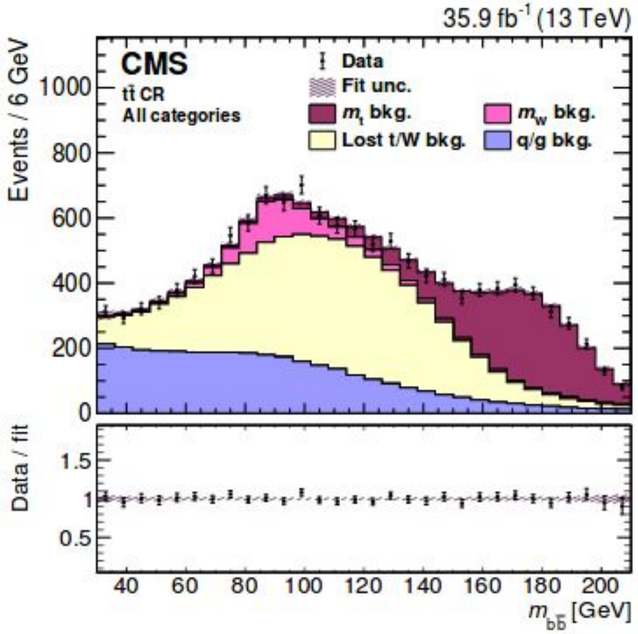
X→HH→bbWW (2016)

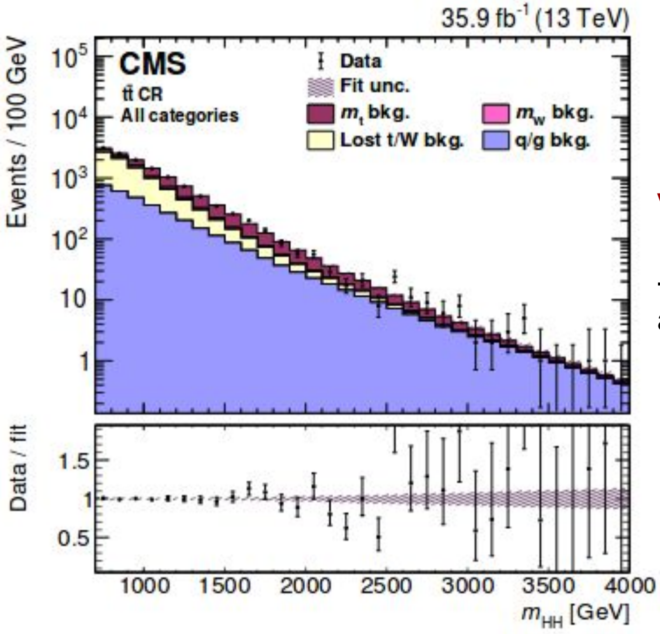
Background divided into 4 categories with gen-information:

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



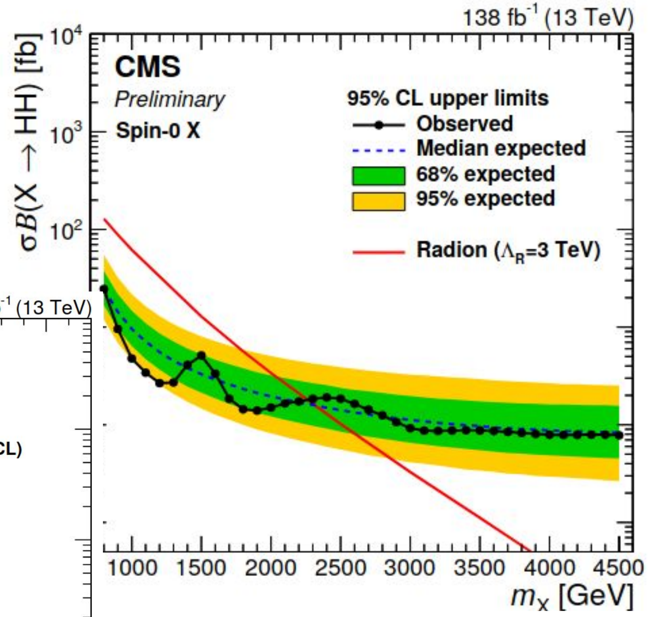


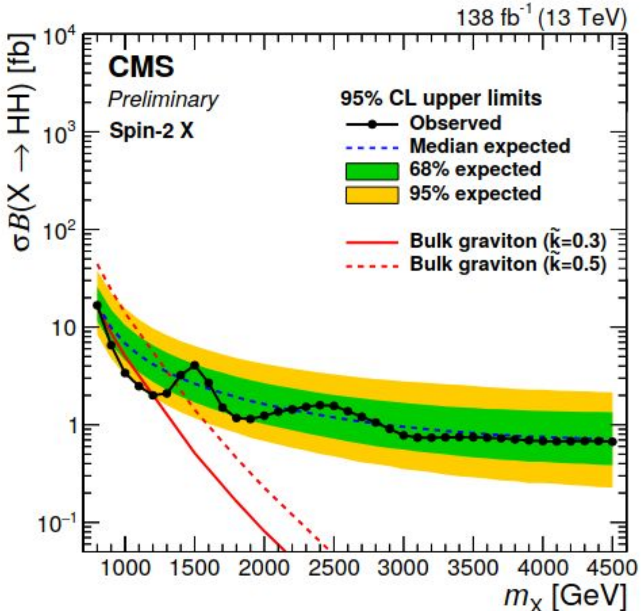
Validated in TTbar and q/g CR

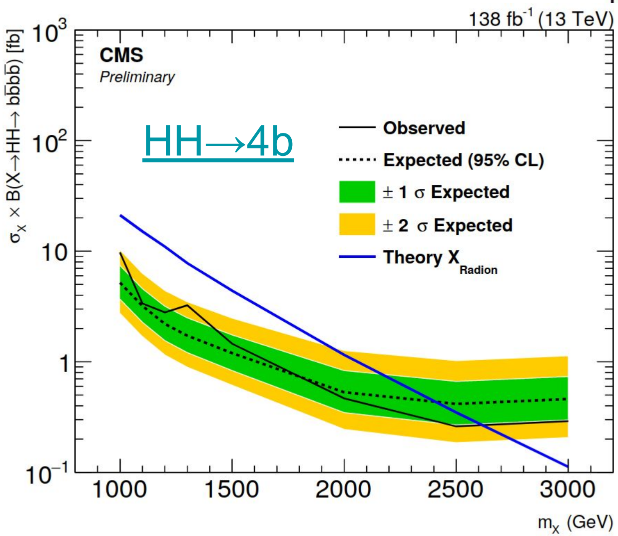
- Data vs MC differences encoded as shape systematics

X→HH→bbWW

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





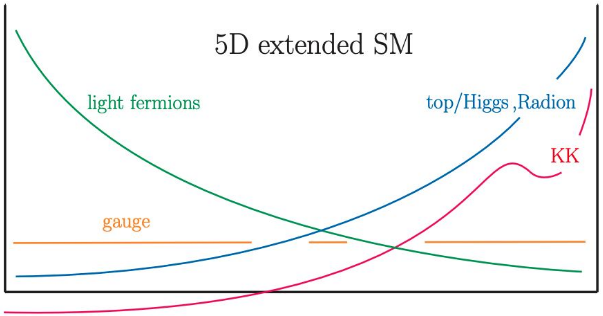


Tri-W resonance Searches

- **MPI-EW scale gap motivates BSM physics (hierarchy problem)**
- **No BSM physics yet → time to look at non-standard final states/scenarios**

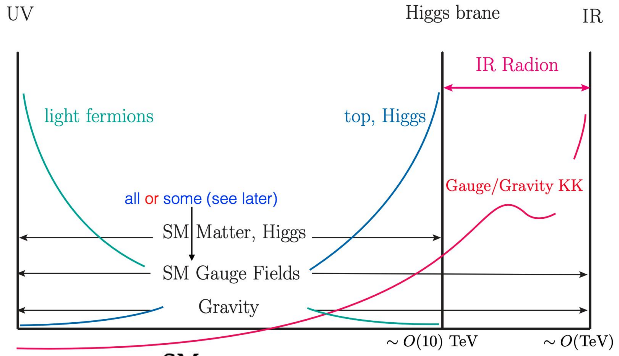
Standard (Minimal) Warped ED model

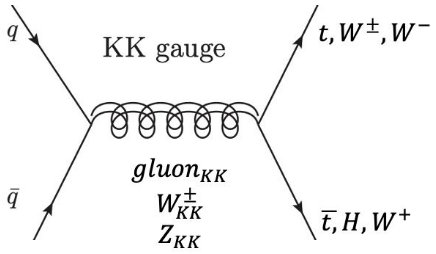
- 2 Branes in Bulk (in the RS framework)
- Everything propagates to the same bulk
- Constrained by LHC searches

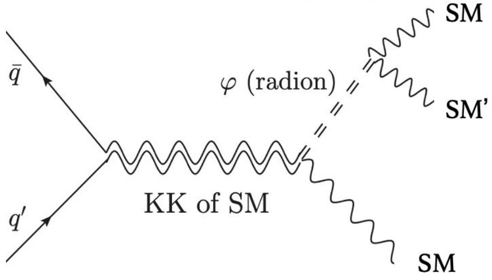


Extended Warped ED model:

- Extra brane by splitting→Extended Bulk
- Various fields propagate in diff. regions





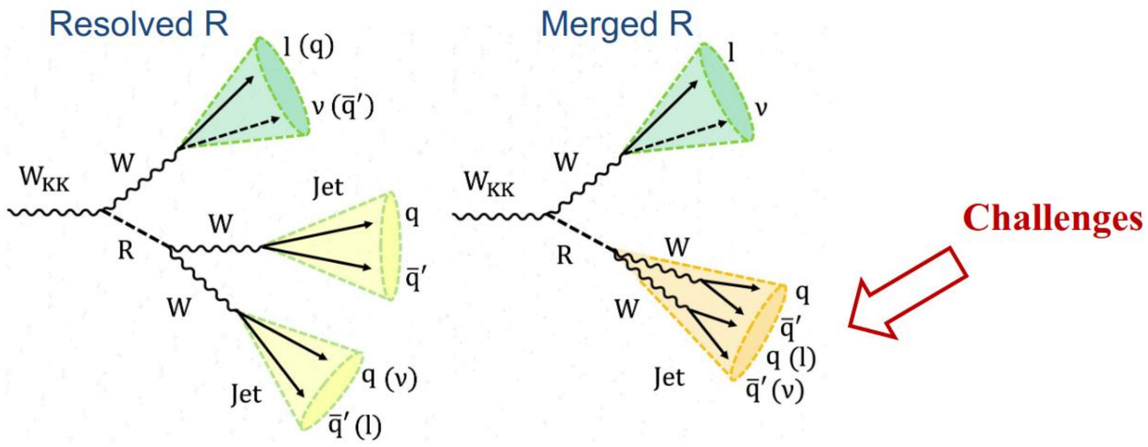


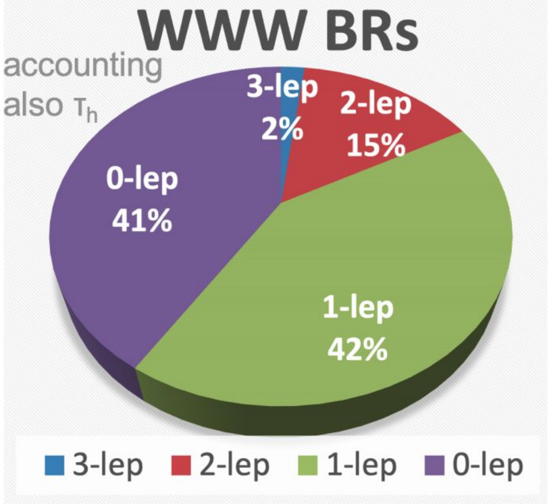
A wealth of new signatures emerges; "di-SM" suppressed in favor of "tri-SM"

arXiv:1711.09920,1612.00047,1809.07334

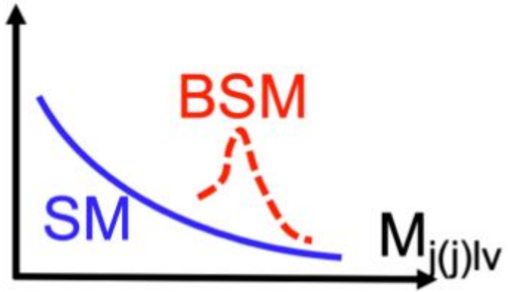
Tri-W resonance Searches

- **Only EW in extended bulk → dominant: VKK→RV→VVW**
- **1- and 0-lep. largest BRs ~40%**
- **Both 1/0-lep channels are investigated for the first time**





- ➢ **hadronic W bosons:** jets (Probe Resolved in Nj=2, and Merged Nj=1 selections)
- ➢ **leptonic W boson:** use info. of lep and MET, assume MW=80 GeV

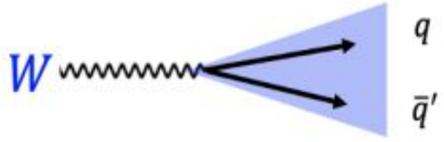


Tri-W : Jet tagging

According to the signal topology, we use two taggers:

W tagging with "binary" scores

Mj: 60-100 GeV



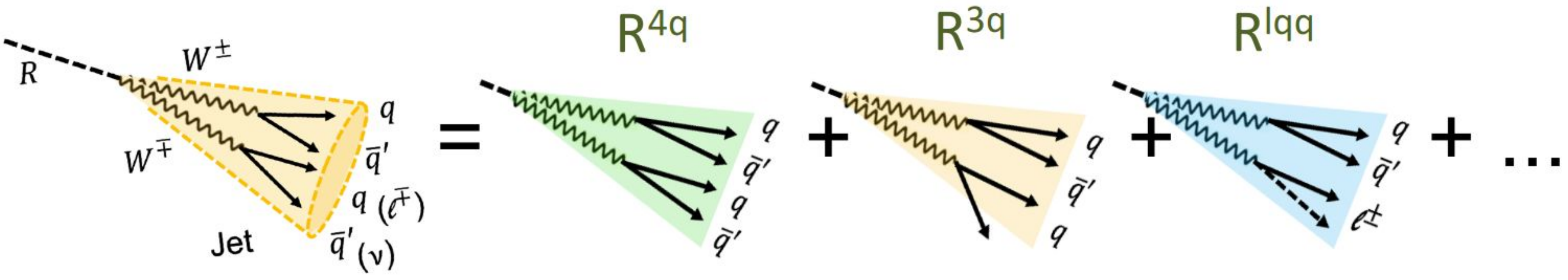
Radion tagging with hybrid:

Mj: > 100 GeV

DeepAK8 Taggers

Output

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)



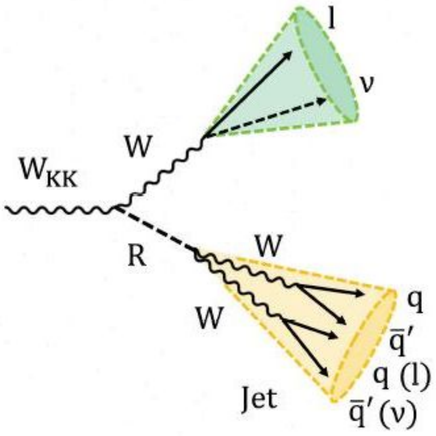
Tri-W: Selections

1-lepton channel with BR of 42%:, Split to 6 signal regions:

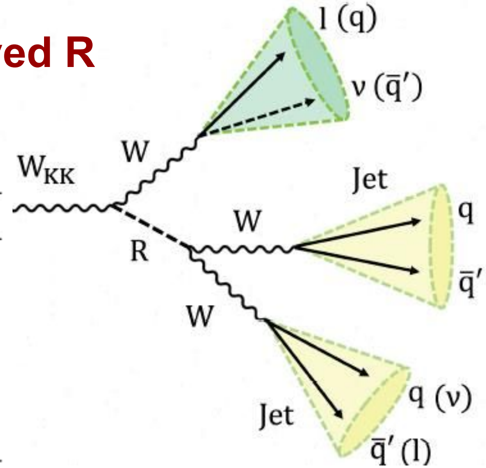
Merged: (SR1-3)
Single massive large-radius jet
Bin over MR: 60-100, 100-200, >200 GeV
For 60 < Mj < 100 GeV, use deep-W
For Mj > 100 GeV, use deep-WH to tag radion

Resolved: (SR4-6)
2 jets, ordered due to mass
Mjmax: 60-100 GeV
Mjmin:0-60-100 GeV binning
For 60 < Mj < 100 GeV, use deep-W

Merged R



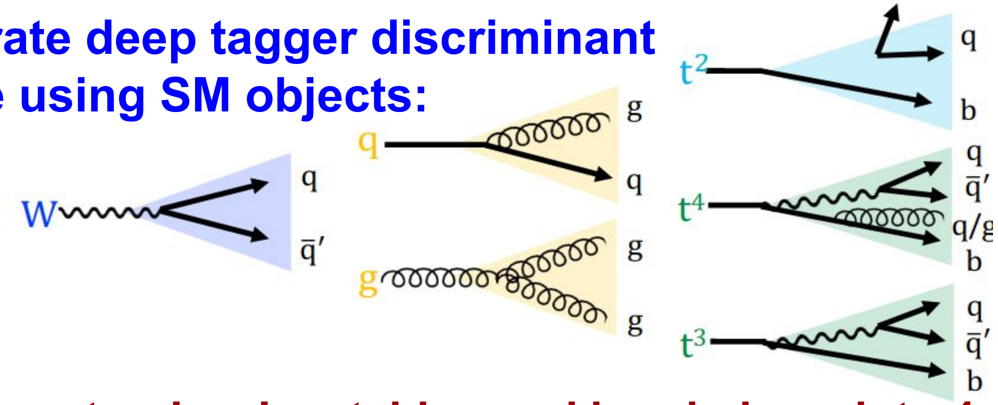
Resolved R

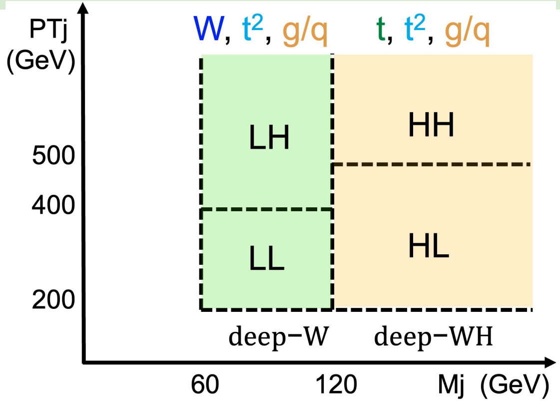


Region	m_j^{max} [GeV]	taggers	m_j^{min} [GeV]	tagger	N_j^{AK8}	N_j^{AK4}	N_b
SR1	60–100	deep-W > 0.7	—	—	1	≤ 2	0
SR2	100–200	deep-WH > 0.7	—	—	1	≤ 2	0
SR3	≥ 200	deep-WH > 0.7	—	—	1	≤ 2	0
SR4	60–100	deep-W > 0.5	60–100	deep-W > 0.5	2	≤ 2	0
SR5	60–100	deep-W >(<) 0.5	60–100	deep-W <(>) 0.5	2	≤ 2	0
SR6	60–100	deep-W > 0.7	0–60	—	2	≤ 2	0

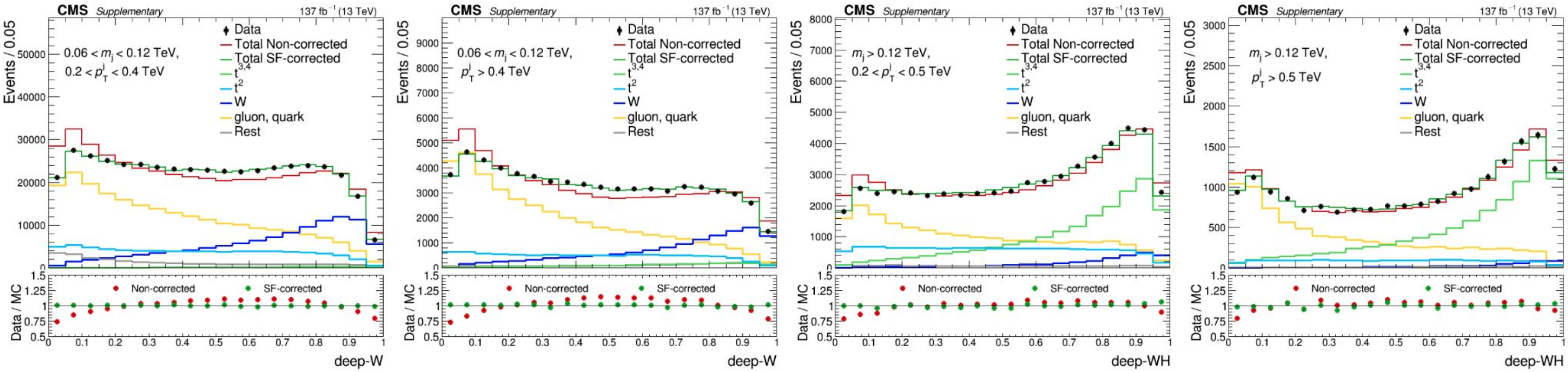
Tri-W: DeepAK8 tagger calibration

Calibrate deep tagger discriminant shape using SM objects:





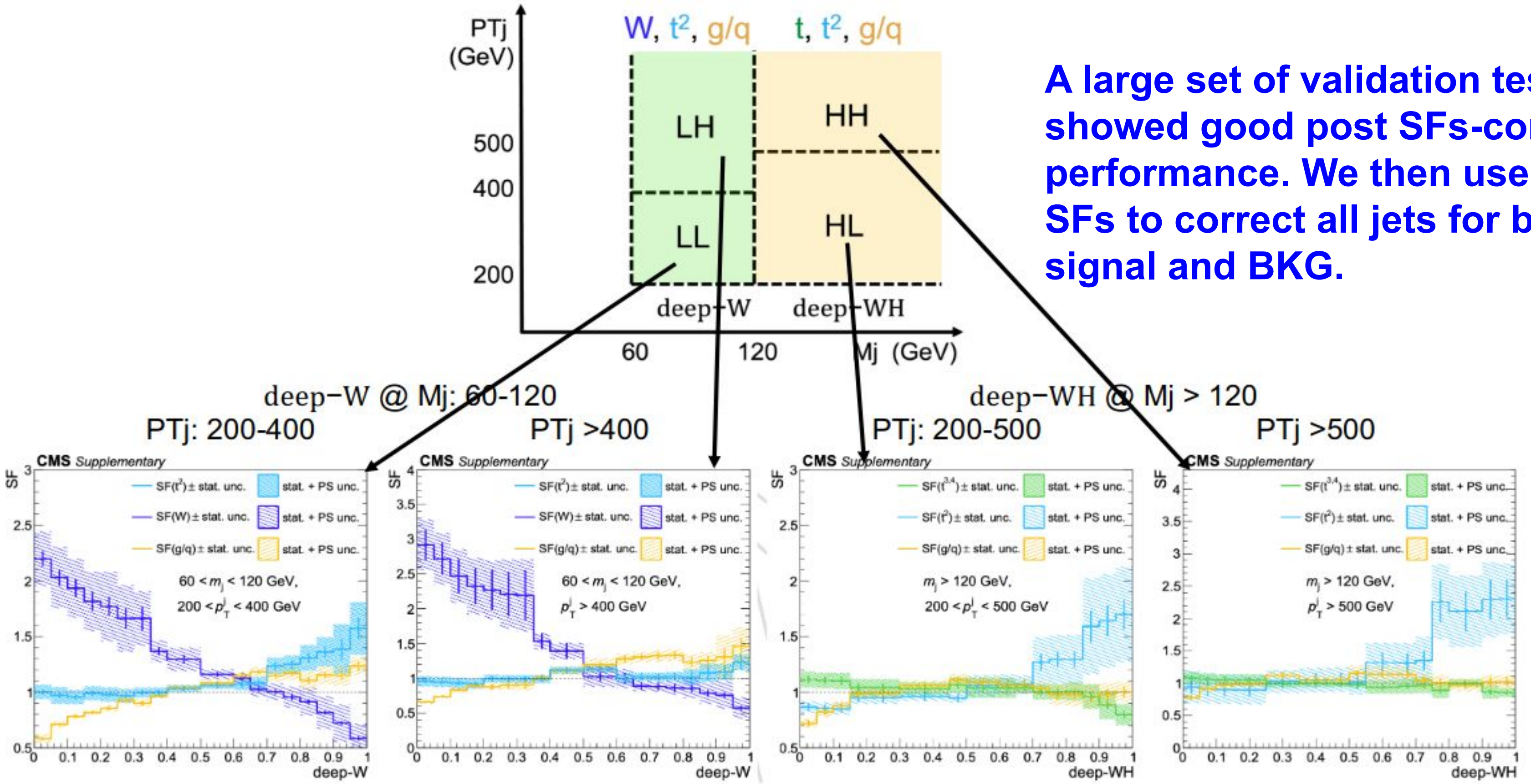
Apply parton-level matching and break down into 4 samples (LL, LH, HL, HH)



Split each sample into 3 pure subsets and correct MC shapes bin by bin to derive scale factors

Tri-W: DeepAK8 tagger calibration

All SFs derived for all 4 bins (2 Mj , 2 pTj bins) and for all types of jets W, t^2, $t^{3,4}$, g/q

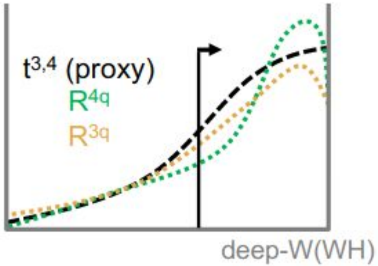


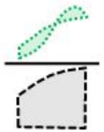
A large set of validation tests showed good post SFs-correction performance. We then use these SFs to correct all jets for both signal and BKG.

Tri-W: SFs uncertainties

Unc. on SFs

1. **Parton Shower** ~10-20%
   Extract SFs with 3 alternative tt samples (powheg+p8, powheg+herwig7, MG+p8), maximum difference is used as unc.
2. **Bias** 10%
   (due to Matrix method selection cuts)
3. **Proxy-unc.**
   Accounts for differences between $R^{4q/3q}$, R^{lqq} and SM proxy jets: $t^{3,4}$, W.
   Compare normalized deep-W(WH) spectra to **evaluate % diff.** above the cut with metric:

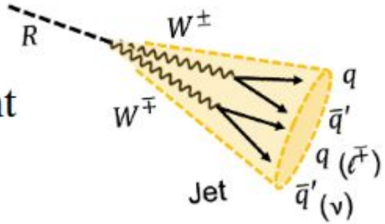


Proxy unc.= $\sqrt{\left(\frac{\sum_i |t_i^3 - t_i^4|}{\sum_i t_i^4}\right)^2 + \left(\frac{\sum_i |R_i^{3q|4q} - t_i^{3,4}|}{\sum_i t_i^{3,4}}\right)^2} \propto$ 

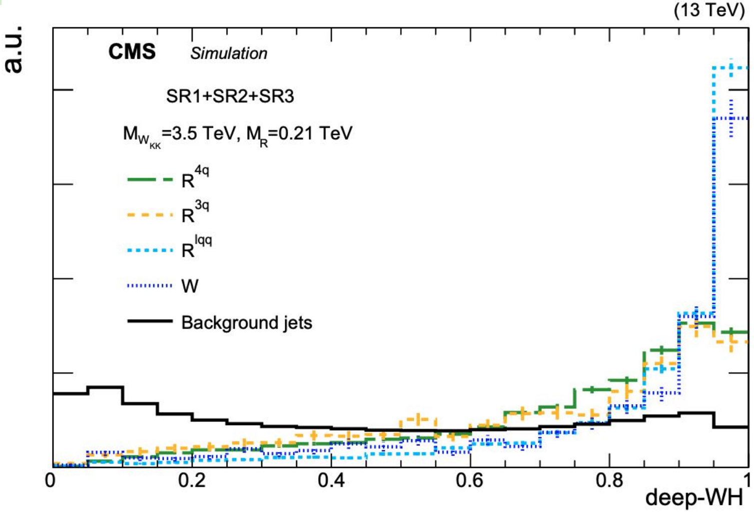
4. **High-pT extrapolation**
   Signal jets much more boosted wrt SM. Generate herwig++ signal, use % diff. wrt pythia8 as unc.

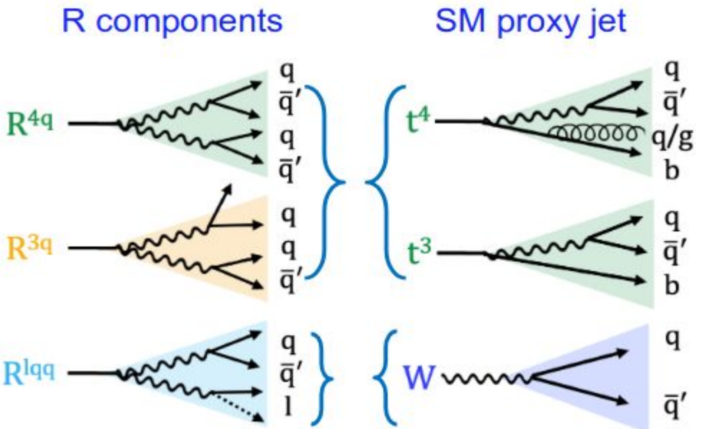
Tri-W: signal corrections

- Merged Radion jet ≈ $R^{4q} + R^{3q} + R^{lqq}$
- no standard candle in SM
  - special calibration treatment



1. Observe similarity between $R^{4q} \leftrightarrow R^{3q}$ jets with merged top: $t^{3,4}$
   → we apply SF($t^{3,4}$) on R^{4q}, R^{3q}
2. Observe similarity between $W \leftrightarrow R^{lqq}$ jets
   → we apply scale factors for W, SF(W), on R^{lqq}
3. The difference between the performances of the SM candle and signal is taken into account as the systematic uncertainty.

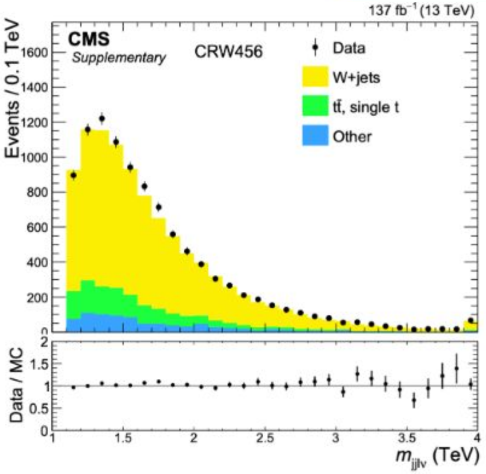




Tri-W: CR for W+jets

- Use SR-selection → Maintain kinematics as in SR
- **Invert deep-W(WH)** tagger cuts → Signal free samples with large statistics
- Reject tops: **deep-t<0.4** → Enhance W+jets purity (rejecting top)

Region	m_j^{max} [GeV]	taggers	m_j^{min} [GeV]	tagger	N_j^{AK8}	N_j^{AK4}	N_b
CRW1	60–100	deep-W(t) < 0.7(0.4)	—	—	1	≤ 2	0
CRW2	100–200	deep-WH(t)< 0.7(0.4)	—	—	1	≤ 2	0
CRW3	≥ 200	deep-WH(t)< 0.7(0.4)	—	—	1	≤ 2	0
CRW456	60–100	deep-W(t) < 0.5/0.7(0.4)	60–100/0–60	deep-W < 0.5/—	2	≤ 2	0



We have 4 such CRWs (in accordance with SR1-6); we illustrate only the CRW456 here.

- SR^{MC}, CR^{MC}, $CR^{DATA\text{-}Rest}$ have consistent $M_{j(j)l\nu}$ shapes
- Use the CR to deliver rate ($N^W_{CR_i}$) and shape (TF^W_i) correction to SR as:

$$PRED^W_{SR_i} = N^W_{CR_i}\, MC^W_{SR_i} \frac{[DATA-rest]_{CRW_i}}{N^W_{CR_i}\, MC^W_{CRt_i}} = N^W_{CR_i} MC^W_{SR_i} TF^W_i$$

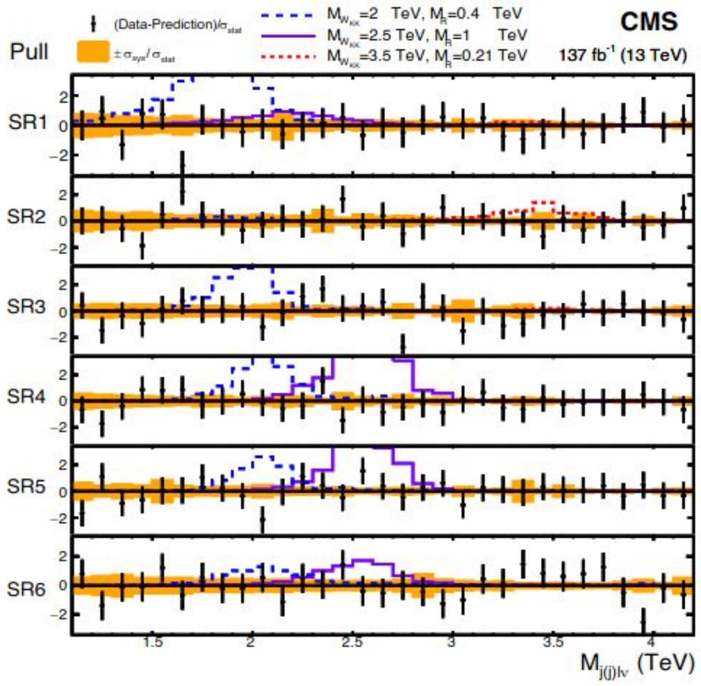
0.96 to 1.03

(Where MC is SF-corrected)
We **validate** prediction in low-ST samples

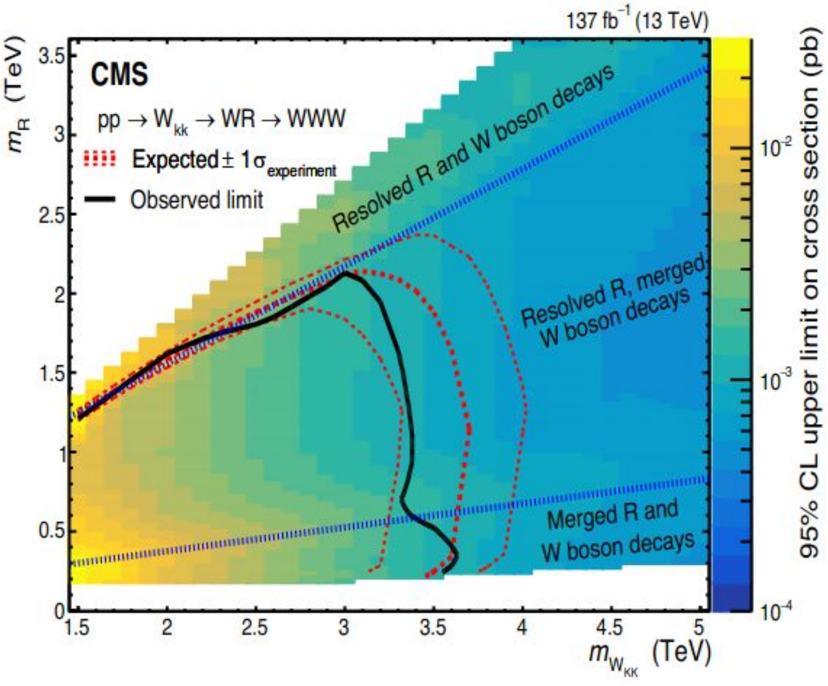
Tri-W: Results and limit (1-lep)

- Combined fit of six signal regions.

(No excess over the background estimation is observed.)

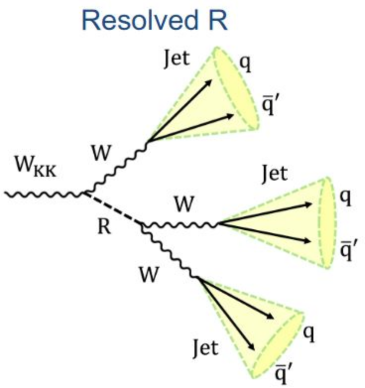


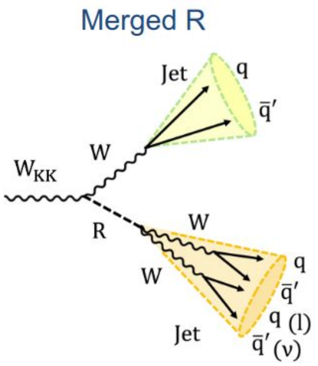
- Limits in 2D W_{KK} vs. R mass plane.

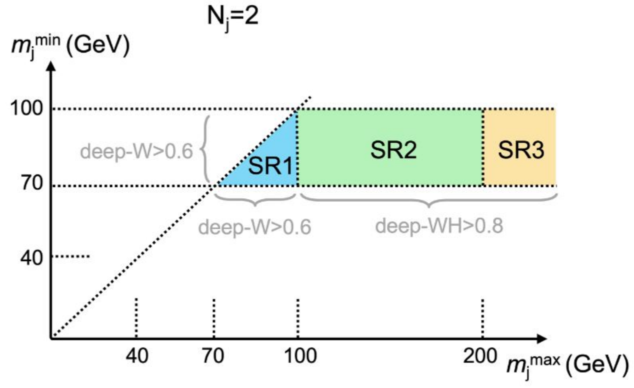


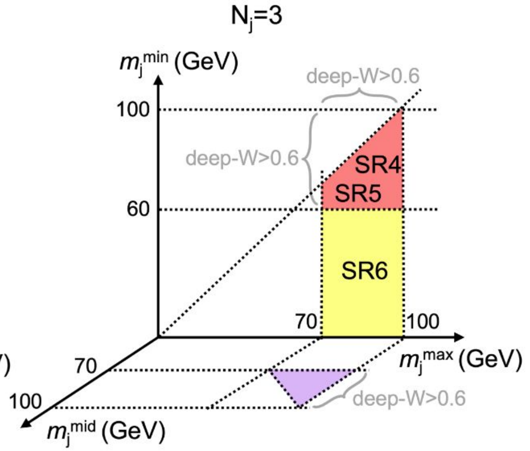
The triboson resonances are excluded up to m_{WKK} = 3.4 (3.6) TeV for m_R = 1 (0.35) TeV.

Tri-W: 0-lep









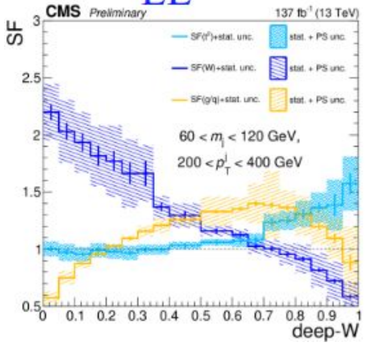
Resolved →3 AK8 jets → search for resonance at M_{jjj}
Merged →2 AK8 jets → search for resonance at M_{jj}

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

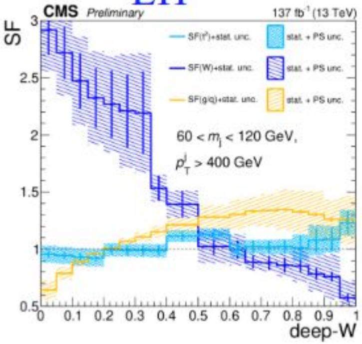
Tri-W: 0-lep

- ➢ We apply the same SFs as 1-lep apart from q/g to correct both bkg and signal
- ➢ Attribute residual mismodeling to q/g → interpreting $\frac{\text{Data}-\text{non q/g}}{\text{MC}} = \text{SF}^{q/g}$

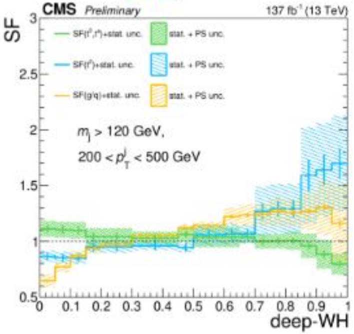
LL



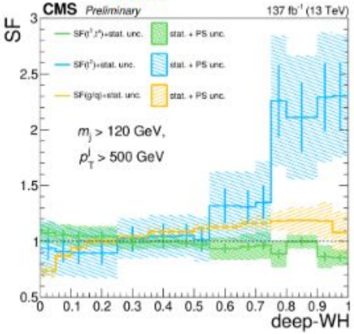
LH



HL



HH

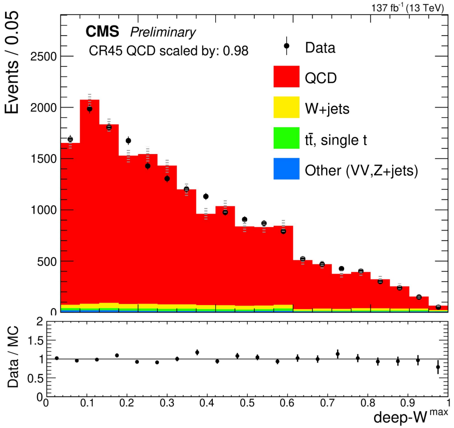


The dominant bkg is QCD.

Use the CRs defined by SRs **inverting deep taggers** (at least one)

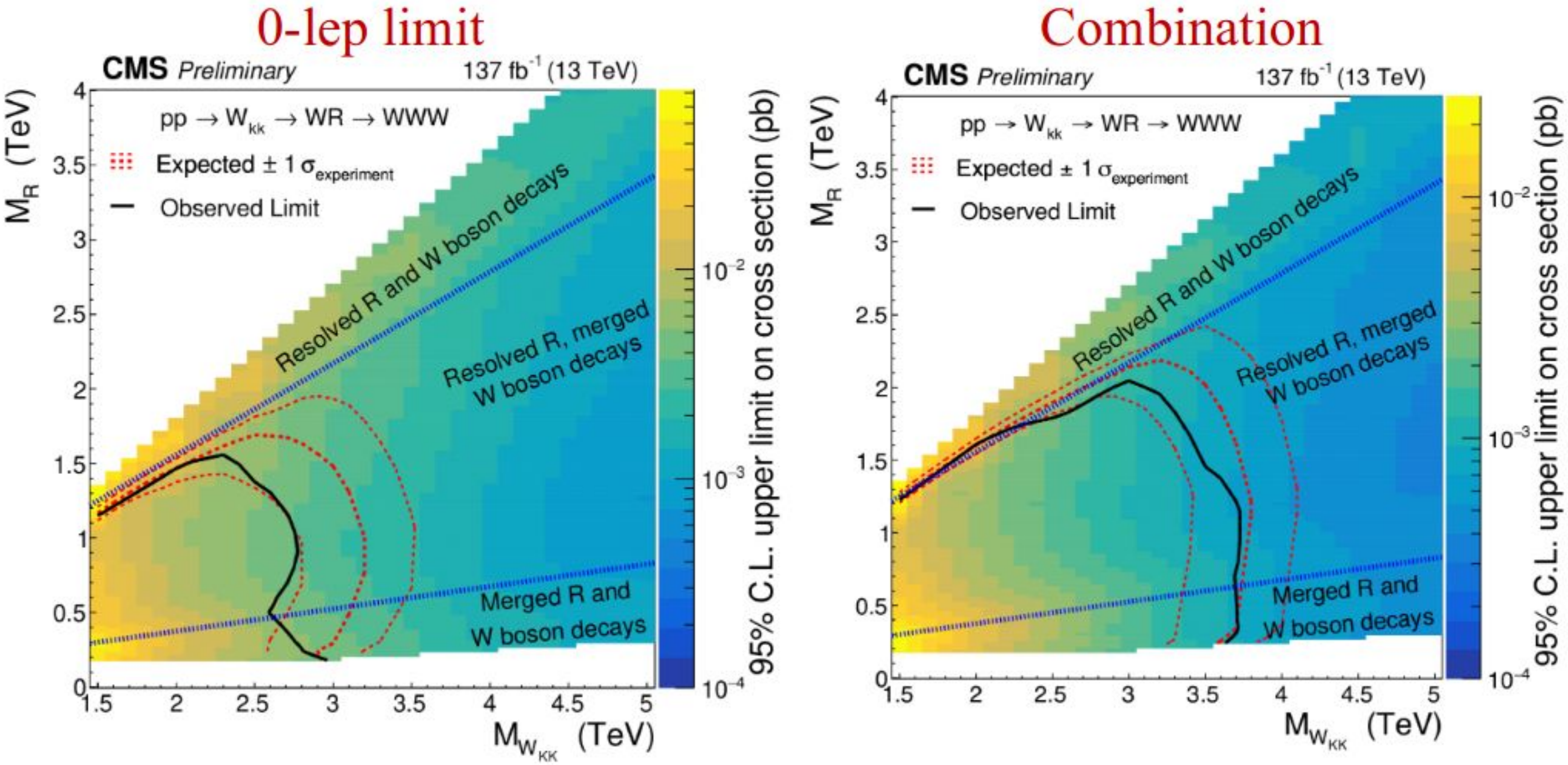
→ Maintain SR kinematics, signal-free, QCD-pure, high sta

→ QCD has consistent shapes in SRs and CRs



- ➢ Replace QCD MC in SRs by "Data-rest" in CRs̀

Tri-W: Combined results



Systematics on SFs correlated (apart from SFq/g), as well as PU, PDFs, μR, μF are correlated. All the rest uncorrelated.

Summary

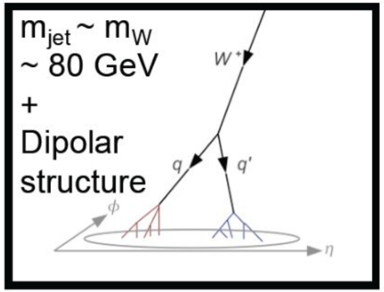
Rich results from CMS on searches with boosted Higgs/Scalars, although no obvious anomaly.
For more results not covered in this talk see CMS EXO and B2G pages
Long road ahead with fun and possible surprise!

- Advanced taggers
- Calibrations methods
- Boosted H->bb, WW, ZZ….
- For SM measurements and Searches

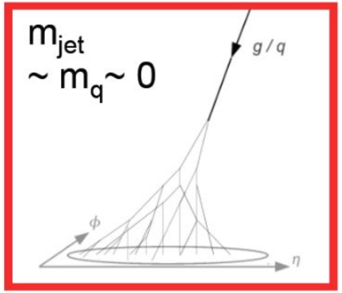
Backup

Substructure tagging: mass decorrelation

SIGNAL



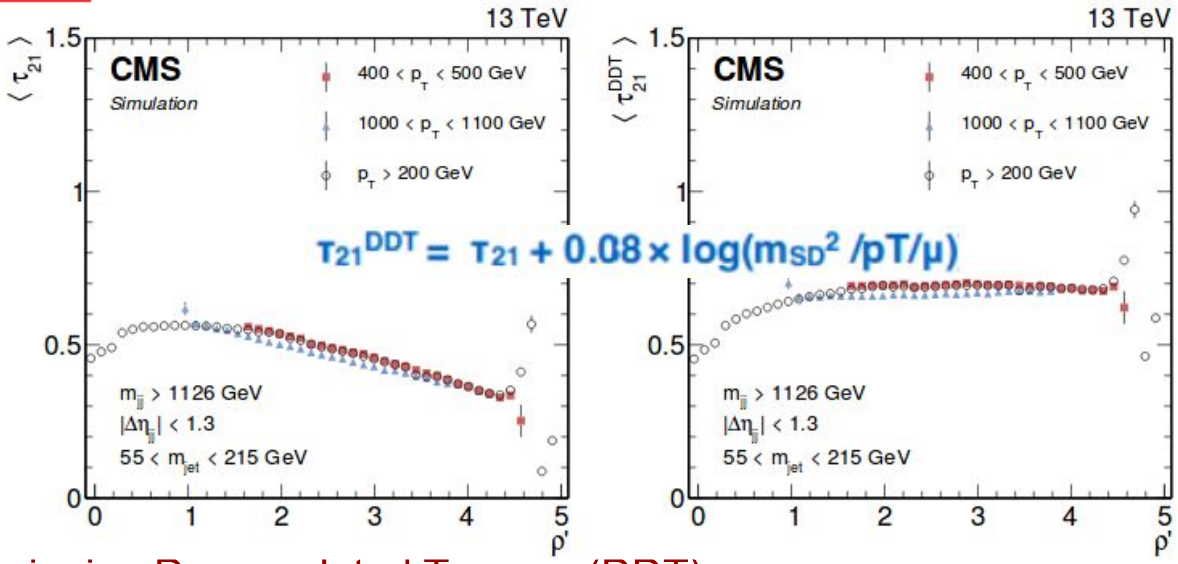
BACKGROUND



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

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

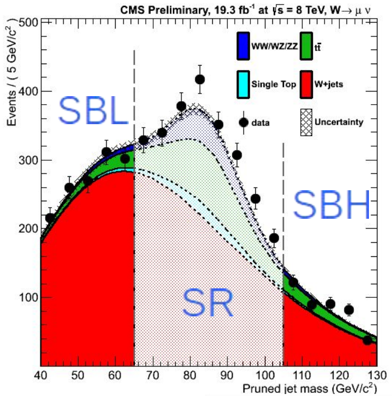
T21 variable shows a dependence on the jet pT-scale as well as the jet mass. This particularly affects the monotonically falling behaviour of the nonresonant background distributions.

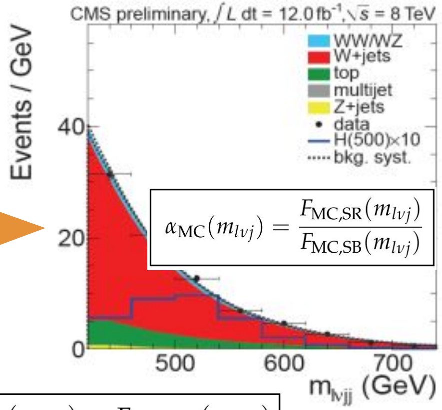


$\tau_{21}^{DDT} = \tau_{21} + 0.08 \times \log(m_{SD}^2/pT/\mu)$

Designing De-correlated Taggers (DDT)

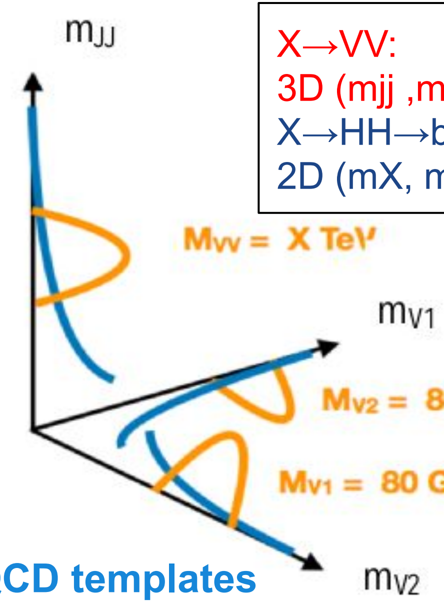
Background Estimations: alpha and 2/3D





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

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



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)

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

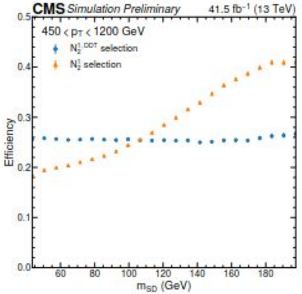
- Each event contributing to a 1D/2D gaussian kernel defined by detector scale and resolution.

Boosted Hbb

Event selection

- Trigger on high-p_T large-radius (AK8) jet and/or HT
- Select p_T-leading AK8 jet within kinematic region ➜
- Softdrop mass algorithm
  - Removes soft & wide-angle QCD radiation to improve mass resolution
- Require 2-prong substructure with N2 energy correlation variable
  - N2 is IRC-safe, relatively independent of jet mass, p_T
  - Residual dependence removed by DDT* procedure ➜
  - 26% QCD efficiency, 60% signal efficiency
- Apply lepton vetos and top rejection selections

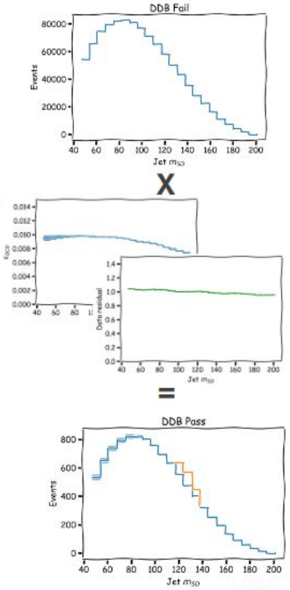
$$p_T \geq 450\,\mathrm{GeV}$$
$$|\eta| \leq 2.5$$
$$m_{\mathrm{softdrop}} \geq 47\,\mathrm{GeV}$$
$$\rho = 2\ln\frac{m_{\mathrm{softdrop}}}{p_T} \in (-6, -2.1)$$



* Designed Decorrelated Tagger, arXiv:1603.00027

QCD background estimation

- Differential ABCD method
- Leave DDBT fail region QCD unconstrained
- Fix DDBT pass QCD by transfer factor
  - Classic ABCD: flat TF, mass sideband ➜ yield under peak
  - Here: correlation regulated by polynomial order
- TF factorized into:
  - Polynomial with constrained parameters defined by separate fit to QCD simulation
    - Captures residual tagger-kinematics correlation
  - Data residual polynomial with free parameters
    - Captures data-simulation discrepancies
- Polynomial order determined by F-test

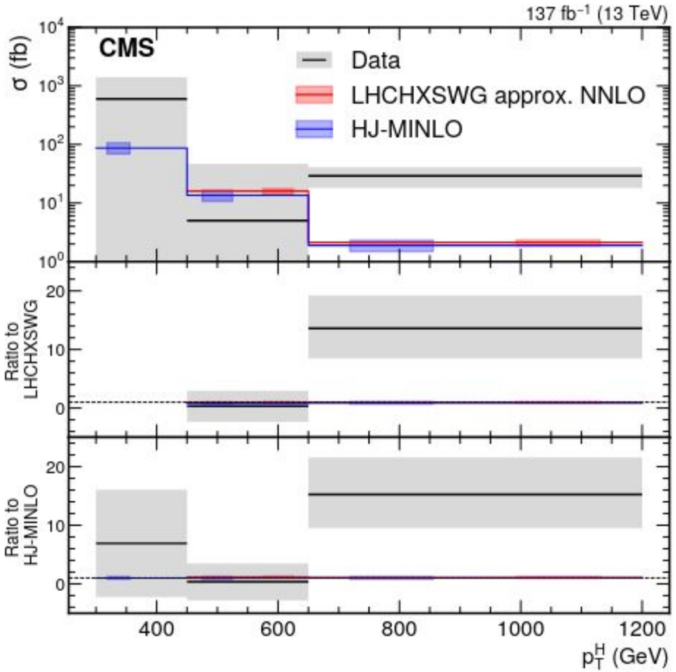


Boosted Hbb

Table 3: Fitted signal strength, and expected and observed significance of the Higgs and Z boson signals. The Higgs boson results are presented with two ggH signal models, one using the nominal HJ-MINLO sample and the other simulated with the same procedure described in Ref. [23]. The 95% confidence level upper limit (UL) on the Higgs boson signal strength is also listed. In the results for the Higgs boson, the Z boson yield is fixed to the SM prediction value with the corresponding theoretical uncertainties to better constrain the data-to-simulation scale factor for the DDBT. For the expected and observed signal strengths of the Z boson, the Higgs boson signal strength is freely floating.

	2016	2017	2018	Combined
Expected μ_Z	$1.00^{+0.38}_{-0.28}$	$1.00^{+0.42}_{-0.29}$	$1.00^{+0.43}_{-0.29}$	$1.00^{+0.23}_{-0.19}$
Observed μ_Z	$0.86^{+0.32}_{-0.24}$	$1.11^{+0.48}_{-0.33}$	$0.91^{+0.37}_{-0.26}$	$1.01^{+0.24}_{-0.20}$
HJ-MINLO [32, 33]				
Expected μ_H	$1.0^{+3.3}_{-3.5}$	1.0 ± 2.5	$1.0^{+2.3}_{-2.4}$	1.0 ± 1.4
Observed μ_H	$7.9^{+3.4}_{-3.2}$	$4.8^{+2.6}_{-2.5}$	1.7 ± 2.3	$3.7^{+1.6}_{-1.5}$
Expected H significance ($\mu_H = 1$)	$0.3\,\sigma$	$0.4\,\sigma$	$0.4\,\sigma$	$0.7\,\sigma$
Observed H significance	$2.4\,\sigma$	$1.9\,\sigma$	$0.7\,\sigma$	$2.5\,\sigma$
Expected UL μ_H ($\mu_H = 0$)	<6.8	<5.0	<4.7	<2.9
Observed UL μ_H	<13.9	<9.3	<5.9	<6.4
Ref. [23] H p_T spectrum				
Expected μ_H	1.0 ± 1.5	$1.0^{+1.1}_{-1.0}$	$1.0^{+1.1}_{-1.0}$	$1.0^{+0.7}_{-0.6}$
Observed μ_H	$4.0^{+1.9}_{-1.6}$	$2.2^{+1.4}_{-1.2}$	1.1 ± 1.1	$1.9^{+0.9}_{-0.7}$
Expected H significance ($\mu_H = 1$)	$0.7\,\sigma$	$0.9\,\sigma$	$1.0\,\sigma$	$1.7\,\sigma$
Observed H significance	$2.6\,\sigma$	$1.8\,\sigma$	$1.1\,\sigma$	$2.9\,\sigma$
Expected UL μ_H ($\mu_H = 0$)	<3.4	<2.4	<2.3	<1.4
Observed UL μ_H	<7.4	<4.6	<3.2	<3.4

The prediction used for the ggH pT spectrum in Ref. [23] is different from that of HJ-MINLO in both shape and total cross section, which is primarily due to the different accuracy of finite top quark mass correction included in the simulation.



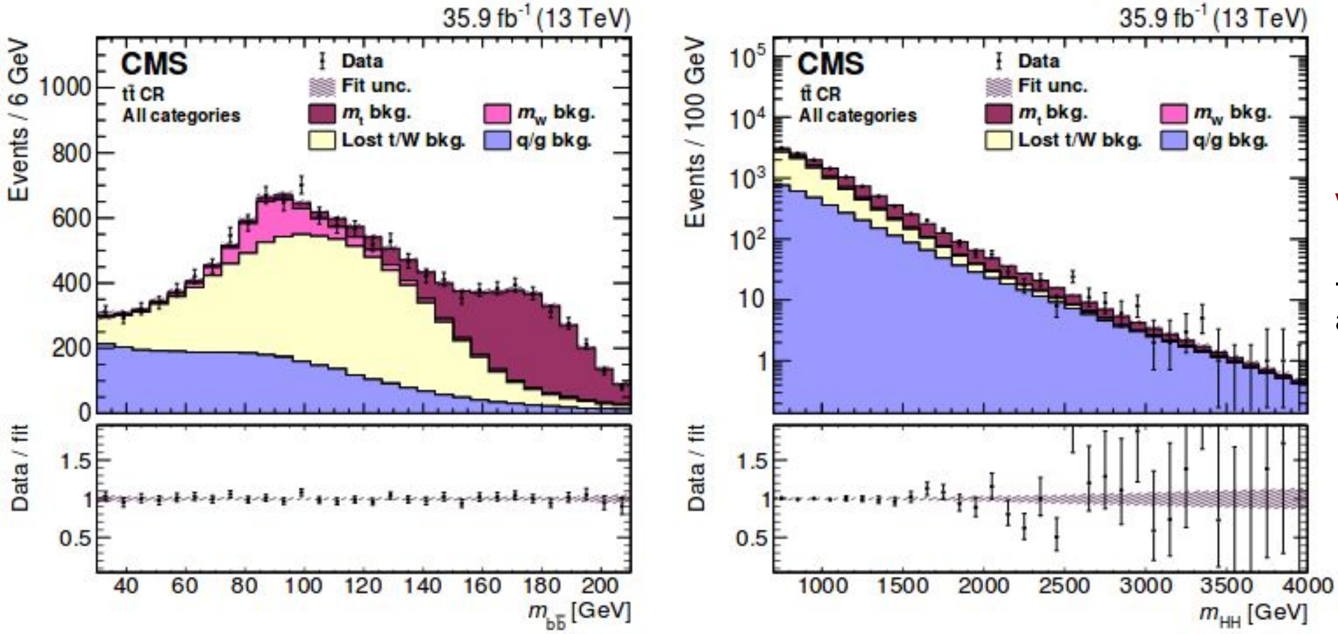
X→HH→bbWW 2016

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



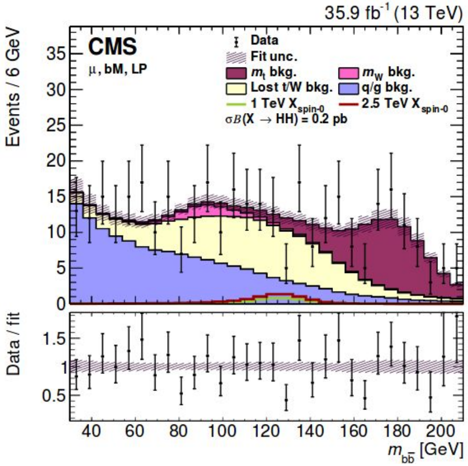
Validated in TTbar and q/g CR

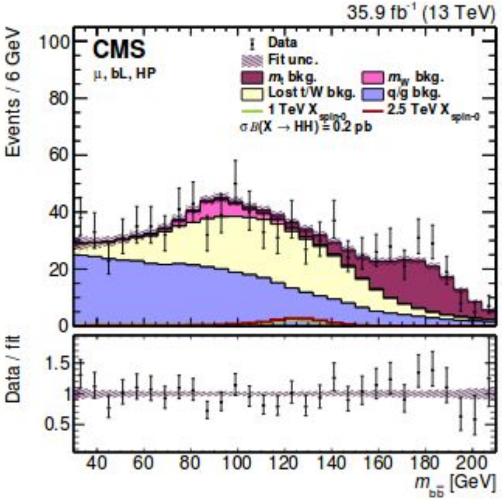
- Data vs MC differences encoded as shape systematics

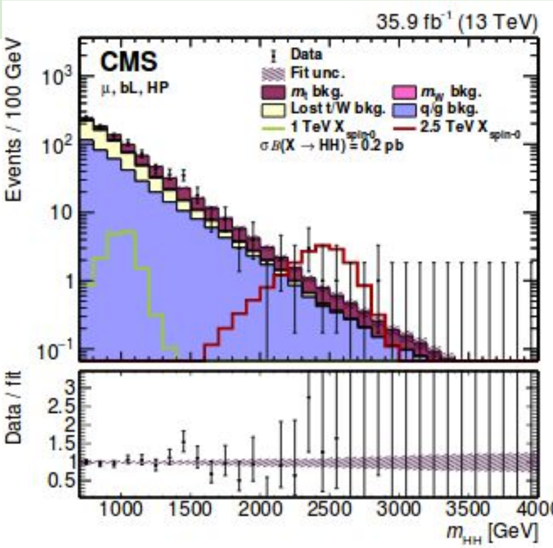
X→HH→bbWW 2016

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

Alternative background template included as shape uncertainties







Signal modelled with conditional probabilities

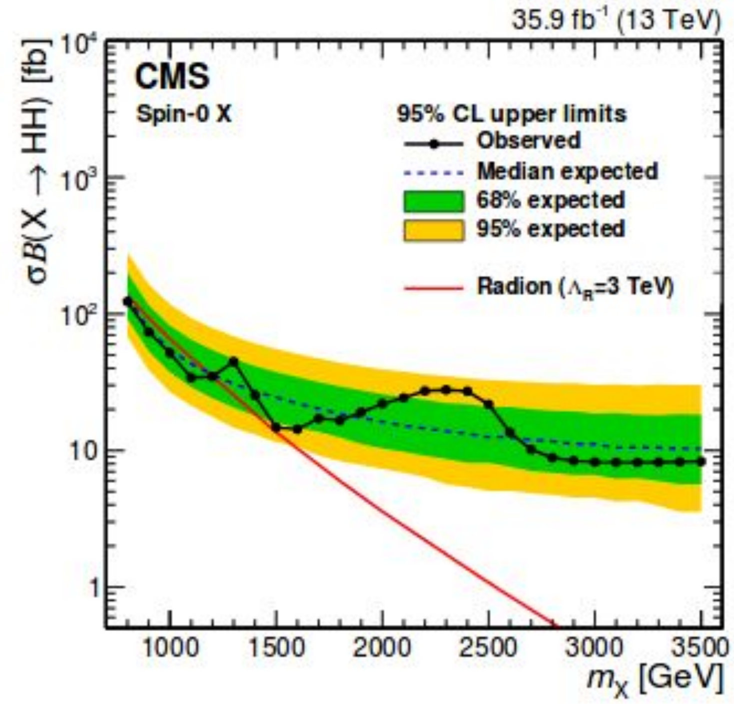
(double CB + exp)

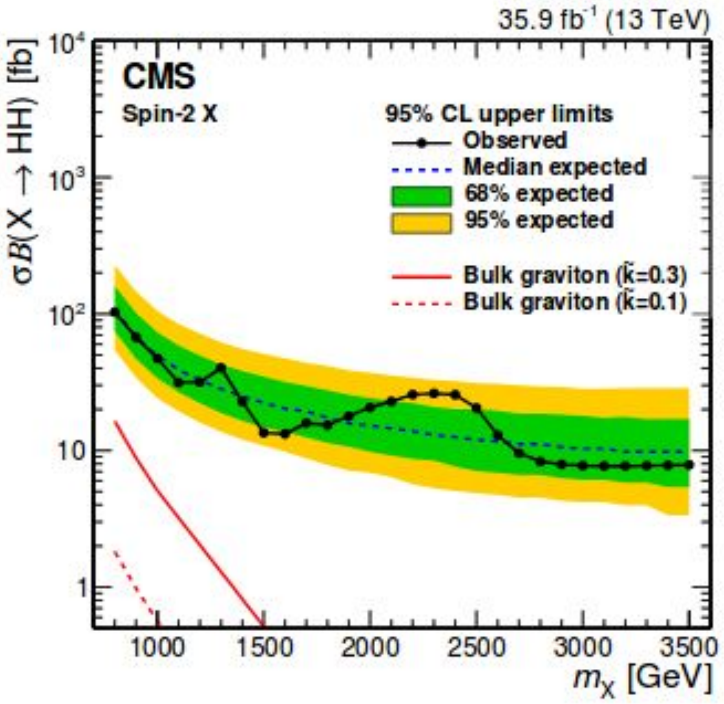
$$P_{\mathrm{signal}}(m_{\mathrm{b\bar{b}}}, m_{\mathrm{HH}}|m_{\mathrm{X}}) = P_{\mathrm{HH}}(m_{\mathrm{HH}}|m_{\mathrm{b\bar{b}}}, m_{\mathrm{X}}, \theta_1) P_{\mathrm{b\bar{b}}}(m_{\mathrm{b\bar{b}}}|m_{\mathrm{X}}, \theta_2).$$

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
$\mathrm{b\bar{b}}$ jet b tagging	Y	Signal
AK4 jet b tagging veto	Y	Signal
$\mathrm{q\bar{q}'}$ τ_2/τ_1 HP:14% LP:33%	Y	Signal
$\mathrm{q\bar{q}'}$ τ_2/τ_1 extrapolation	Y	Signal

X→HH→bbWW 2016

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





Matrix method

1. Focus at LL sample with W, t^2, g/q (left plot of last slides)

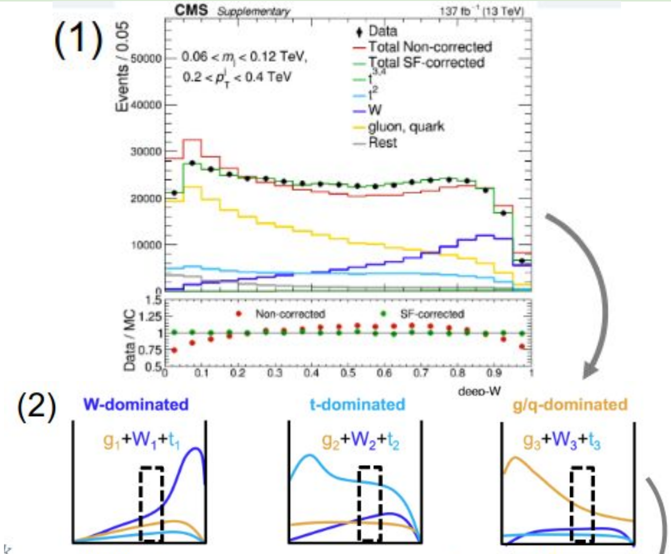
2. **Split the samples into 3 pure subsets** (applying cuts on τ_{ij}, deep-x/y, N_b, m_j) **in a way where each subset is dominated by a single type of jets**
   → mismodeling revealed

3. Demand: **Data = scaled sum of yields**

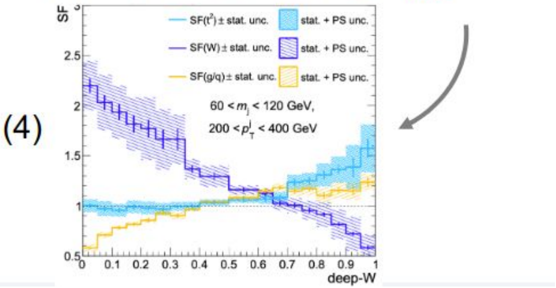
   $$D_{i,k} = (g_{i,k})SF_k^g + (w_{i,k})SF_k^W + (t_{i,k})SF_k^t + d_{i,k}$$

   Define system of 3 equations, 1 per each subset "i", and per tagger score bin "k"

4. **Solve a 3x3 system** for SFs per each tagger score bin and **get SFs**→
   - **Known** yields: D, W, t, g/q, d
   - **Unknown** SFs



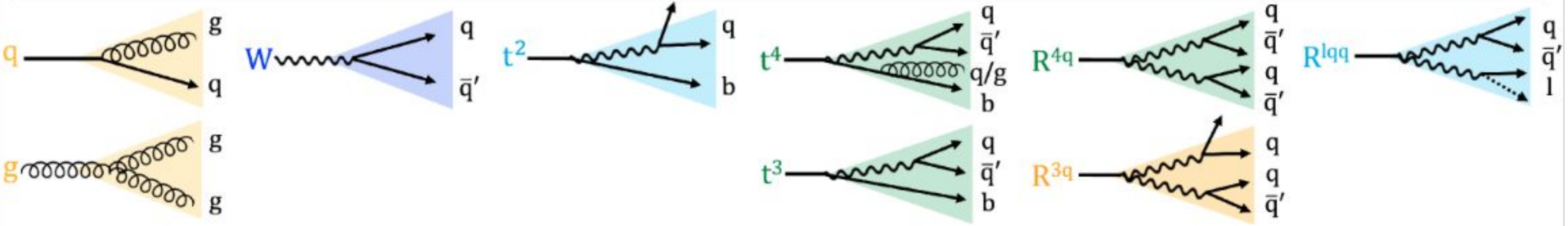
$$\begin{pmatrix} D_{1,k} - d_{1,k} \\ D_{2,k} - d_{2,k} \\ D_{3,k} - d_{3,k} \end{pmatrix} = \begin{bmatrix} g_{1,k} & w_{1,k} & t_{1,k} \\ g_{2,k} & w_{2,k} & t_{2,k} \\ g_{3,k} & w_{3,k} & t_{3,k} \end{bmatrix} \begin{pmatrix} SF_k^g \\ SF_k^W \\ SF_k^t \end{pmatrix}$$



1-lep channel
0-lep channel

Matching criteria

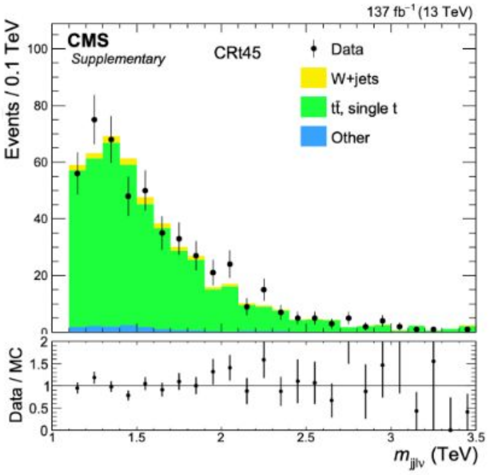
q/g	$W \to qq$	t^2	$t^{3,4}$	$R^{3,4q}$	$R^{\ell qq}$
$(W,j) < 0.6$	$(W,j) < 0.6$	$(t,j) < 0.6$	$(t,j) < 0.6$	$(R,j) < 0.6$	$(R,j) < 0.6$
—	$(q_{1W},j) < 0.8$	$(b_t,j) < 0.8$	$(b_t,j) < 0.8$	$(q_1,j) < 0.8$	$(q_1,j) < 0.8$
—	$(q_{2W},j) < 0.8$	$(q_{1W},j) < 0.8$	$(q_{1W},j) < 0.8$	$(q_2,j) < 0.8$	$(q_2,j) < 0.8$
—	$(b_t,j) > 0.8$	$(q_{2W},j) > 0.8$	$(q_{2W},j) < 0.8$	$(q_3,j) < 0.8$	$(\ell,j) < 0.8$
—	—	—	For t^4 vs. t^3: $(q/g,j) < 0.8$	For R^{4q} vs. R^{3q}: $(q_4,j) < 0.8$	—



CR for top

- Use SR-selection → Maintain kinematics as in SR
- Invert b-veto to $\mathbf{N_b \geq 1}$ → Get signal-free, top-pure sample
- Remove tagger cuts: **deep-W(WH)>0** → Enhance statistics

Region	m_j^{max} [GeV]	taggers	m_j^{min} [GeV]	tagger	N_j^{AK8}	N_j^{AK4}	N_b
CRt1	60–100	deep-W > 0	—	—	1	≤ 4	≥ 1
CRt2	100–200	deep-WH > 0	—	—	1	≤ 4	≥ 1
CRt3	≥ 200	deep-WH > 0	—	—	1	≤ 4	≥ 1
CRt45	60–100	deep-W > 0	60–100	deep-W > 0	2	≤ 4	≥ 1
CRt6	60–100	deep-W > 0	0-60	—	2	≤ 4	≥ 1



We have 5 such CRts (in accordance with SR1-6); we illustrate only the CR45 here.

- SR^{MC}, CR^{MC}, $CR^{DATA\text{-}Rest}$ have consistent $M_{j(j)l\nu}$ shapes
- Use the CR to deliver rate ($N^t_{CR_i}$) and shape (TF^t_i) correction to SR as:

$$PRED^{top}_{SR_i} = N^t_{CR_i}\, MC^{top}_{SR_i} \frac{[DATA-rest]_{CRt_i}}{N^t_{CR_i}\, MC^t_{CRt_i}} = N^t_{CR_i}\, MC^t_{SR_i} TF^t_i$$

0.71 to 1.03

(Where MC is SF-corrected)
We **validate** prediction in low-ST samples

Systematic uncertainty (0-lep)

Sources	B or S	Effect on	Magnitude	Nuisance parameters
Parton shower + selection bias for W, $R^{\ell qq}$	B+S	Shape+rate		4, for LL, LH, HL, HH
Parton shower + selection bias for t^2	B	Shape+rate		8, for LL, LH, HL, HH
Parton shower + selection bias for $t^{3,4}$, $R^{3q,4q}$	B+S	Shape+rate		4, for LL, LH, HL, HH
Parton shower + selection bias for q/g	B	Shape+rate		8, for LL, LH, HL, HH
Proxy uncertainty for $R^{\ell qq}$	S	Rate	10–35%	2, for deep-W/WH
Proxy uncertainty for $R^{3q,4q}$	S	Rate	12–43%	2, for deep-W/WH
Proxy uncertainty for unmatched	S	Rate	100%	2, for deep-W/WH
High-p_T extrapolation for W	S	Rate	100%	2, for deep-W/WH
High-p_T extrapolation for $R^{\ell qq}$	S	Rate	23–30%	2, for deep-W/WH
High-p_T extrapolation for R^{3q}	S	Rate	16–34%	2, for deep-W/WH
High-p_T extrapolation for R^{4q}	S	Rate	24–33%	2, for deep-W/WH
QCD multijet normalization	B	Rate	5–40%	5, common for SR4,5
$t\bar{t}$ normalization	B	Rate	15–30%	5, common for SR4,5
Other background normalization	B	Rate	30%	5, common for SR4,5
m_{jj}, m_{jjj} tail shape	B	Shape		6, one for each SR
$t\bar{t}$ shape	B	Shape		6, one for each SR
Pileup and luminosity	S	Rate	1.7%	1, common for all SRs
PDFs, QCD renormalization and factorization scales	S	Rate	1.4%	1, common for all SRs
Jet energy scale and resolution	S	Shape		2, common for all SRs
Jet mass scale	S	Shape		1, common for all SRs