Search for resonances decaying to three W bosons with CMS

Xudong Lyu (Peking University)

On behalf of the CMS Collaboration

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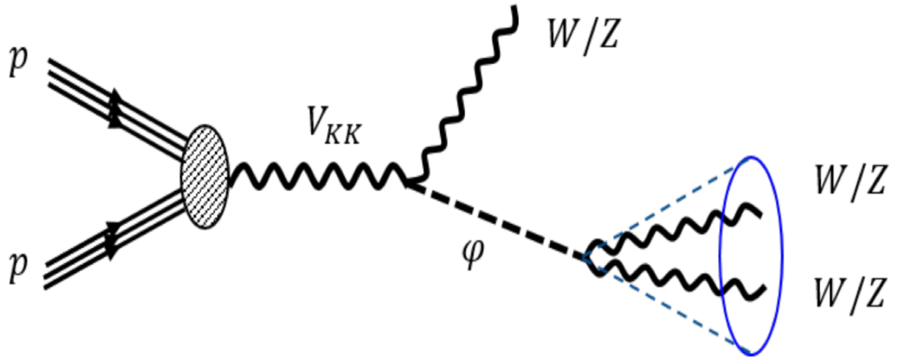
Outline

1. Motivation

2. Single lepton final state (1-lep) **CMS-PAS-B2G-20-001**
   - Signal Region selection
   - Deep-taggers calibration
   - Prediction method

3. Full hadronic final states (0-lep) **CMS-PAS-B2G-21-002**
   - Signal Region selection
   - Prediction method

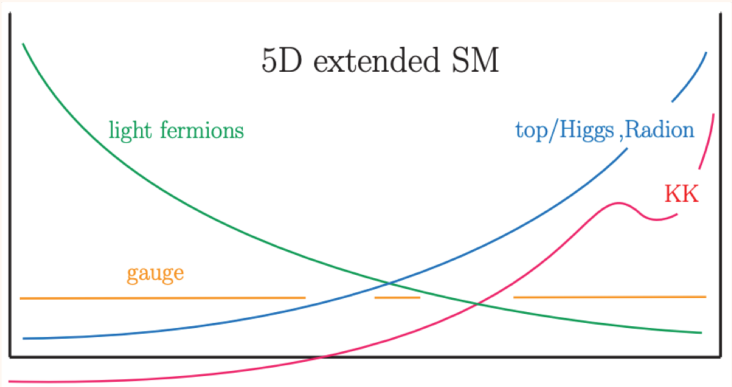
4. Results



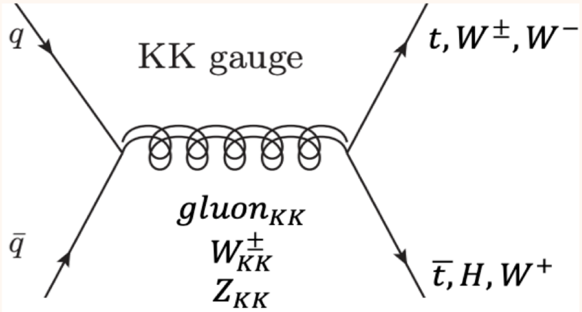
Motivation for "tri-object" search

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

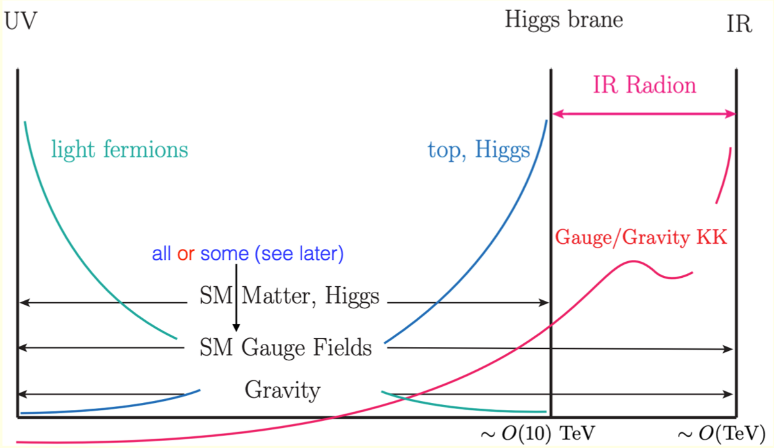
Standard (Minimal) Warped ED model
- 2 Branes in Bulk (in the RS framework)
- Everything propagates to the same bulk
- Constrained by LHC searches



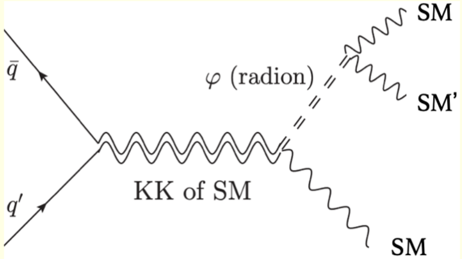
- "di-SM" dominant phenomenology



Extended Warped ED model:
- Extra brane by splitting→ Extended Bulk 3 branes
- Various fields propagate in diff. regions



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



arXiv:1711.09920
arXiv:1612.00047
arXiv:1809.07334

Motivation for “tri-object” search

- Only EW in extended bulk → dominant: $V_{KK} \rightarrow R\,V \rightarrow VVV$

arXiv:1711.09920
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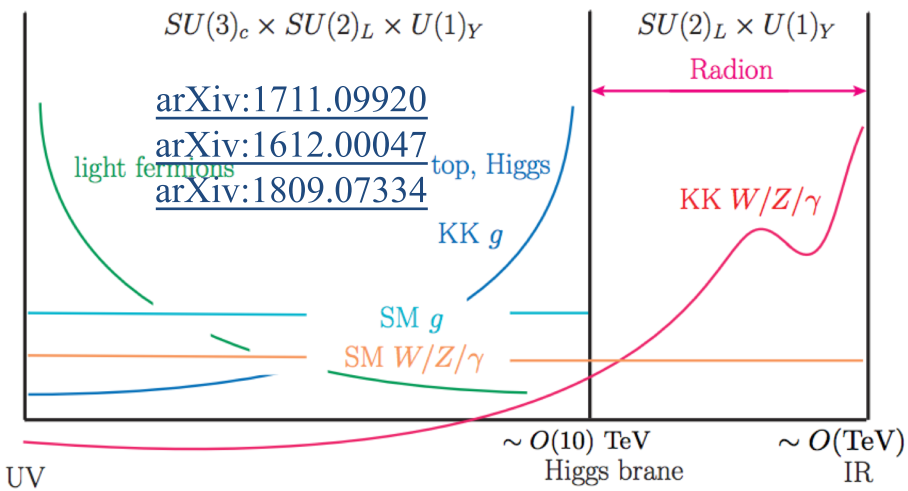
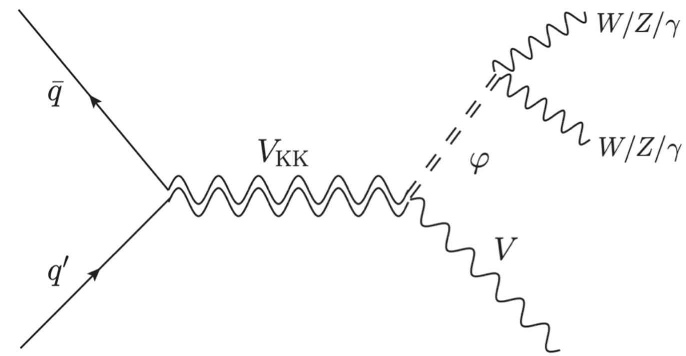
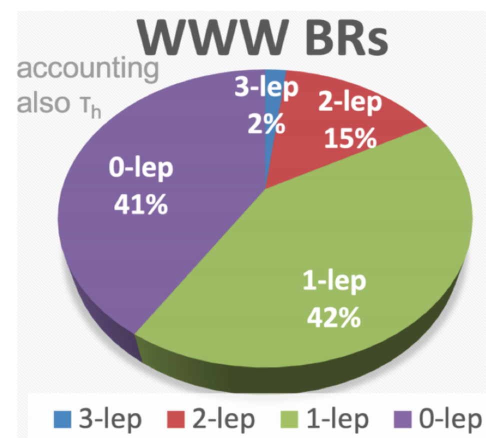


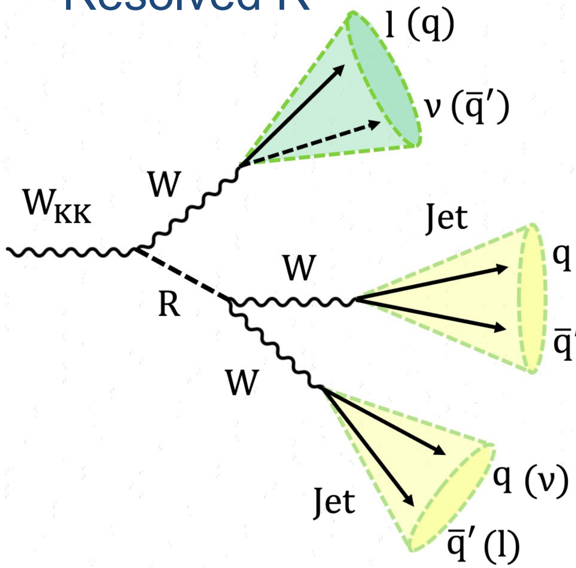


- Hierarchy of Radion BR_R: WW > ZZ > Zγ > γγ
- $W_{KK} \rightarrow R\,W \rightarrow WWW$
- Doubly resonant signal: spin-1 $V_{KK,}$ spin-0 radion R
- 1- and 0-lep. largest BRs ~40%
- Both1-lep and 0-lep channel are investigated for the first time.

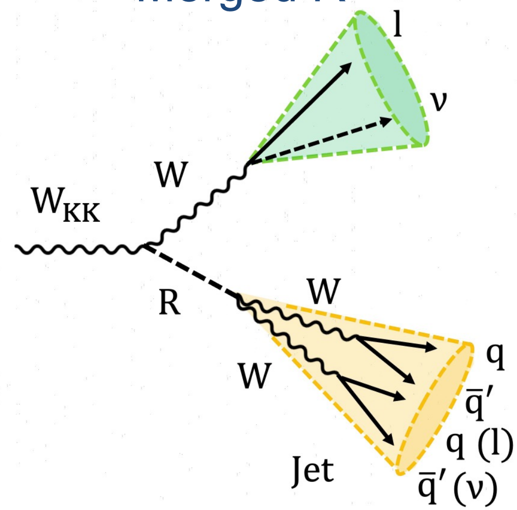


Signal Profile (1-lep)

Resolved R

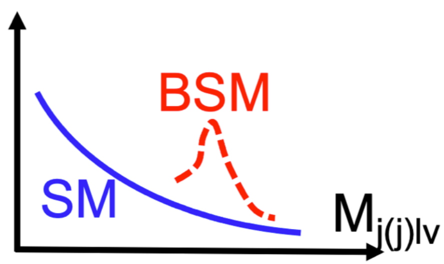


Merged R



Challenges

- Physics objects reconstruction
  - ➢ hadronic W bosons: jets (Probe **Resolved** in N_j=2, and **Merged** N_j=1 selections)
  - ➢ leptonic W boson: use info. of lep and MET, assume M_W=80 GeV
- Define selections to improve significance
- Background estimation
- Search of a peak over the reconstructed: $M_{jl\nu}$, $M_{jjl\nu}$



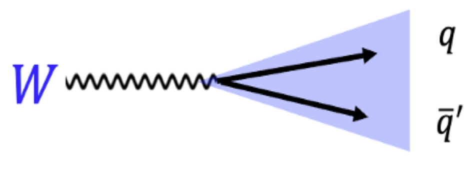
Jet tagging with deepAK8 framework

According to the signal topology, we use two taggers:

W tagging with "binary" scores

$$\text{deep-W} = \frac{W_{qq,qc}}{QCD_{g,q,b,..} + W_{qq,qc}}$$

M_j: 60-100 GeV



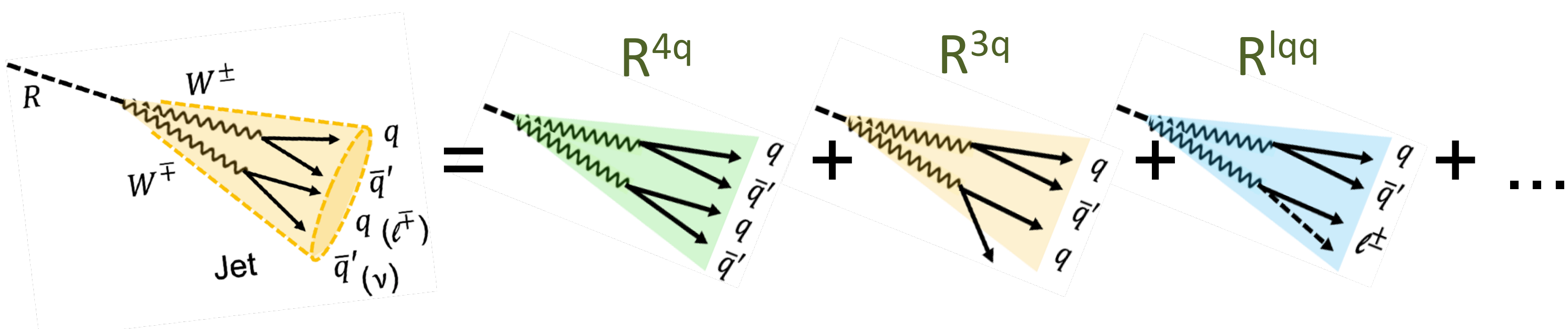
Radion tagging with hybrid:

$$\text{deep-WH} = \frac{W_{qq,qc} + H_{4q}}{QCD_{g,q,b,..} + W_{qq,qc} + H_{4q}}$$

M_j: > 100 GeV

Output

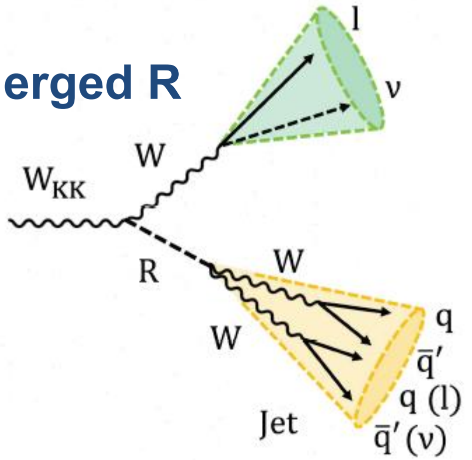
Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

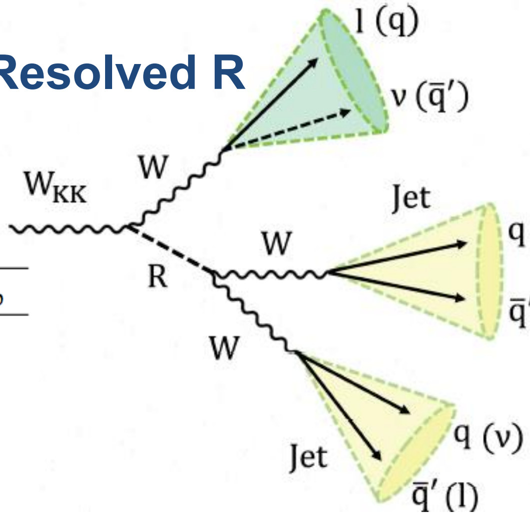


Selection (1-lep)

- 1-lepton channel with BR of 42%: $W_{KK} \rightarrow WWW \rightarrow l + \nu + jets$

- Split to 6 signal regions based on:
  - Merged: (SR1-3)
    - single massive large-radius jet
    - Bin over M_R: 60-100, 100-200, >200 GeV
    - For $60 < M_j < 100$ GeV, use deep-W
    - For Mj > 100 GeV, use deep-WH to tag radion
  - Resolved: (SR4-6)
    - 2 jets, ordered due to mass
      M_j^{max}: 60-100 GeV
      M_j^{min}:0-60-100 GeV binning
    - For $60 < M_j < 100$ GeV, use deep-W

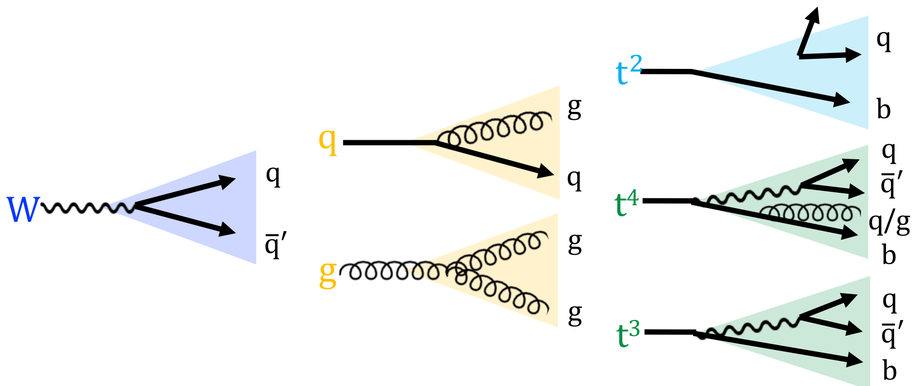


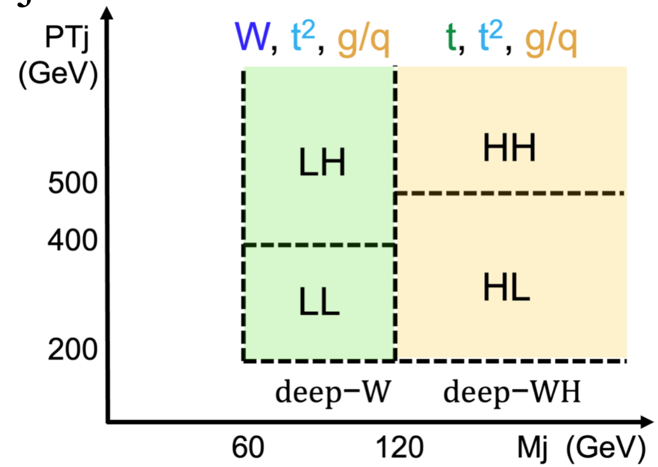


Region	m_j^{max} [GeV]	taggers	m_j^{min} [GeV]	tagger	N_j^{AK8}	N_j^{AK4}	N_b
SR1	60–100	deep-W > 0.7	—	—	1	≤ 2	0
SR2	100–200	deep-WH > 0.7	—	—	1	≤ 2	0
SR3	≥ 200	deep-WH > 0.7	—	—	1	≤ 2	0
SR4	60–100	deep-W > 0.5	60–100	deep-W > 0.5	2	≤ 2	0
SR5	60–100	deep-W >(<) 0.5	60–100	deep-W <(>) 0.5	2	≤ 2	0
SR6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

DeepAK8 tagger calibration

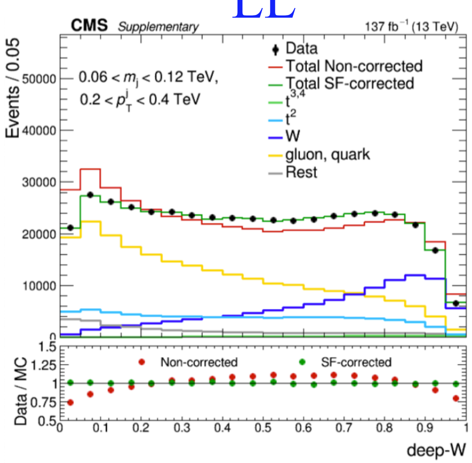
- Calibrate deep tagger discriminant shape using SM objects:



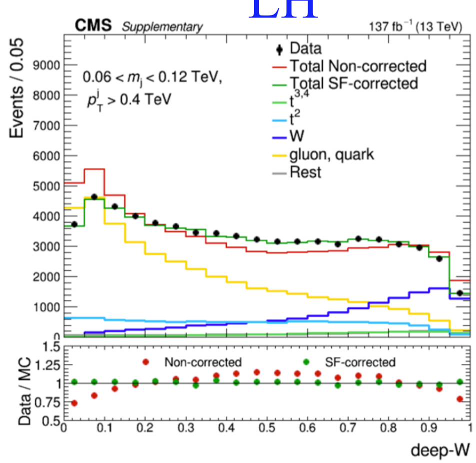


- Apply parton-level matching and break down into 4 samples (LL, LH, HL, HH)

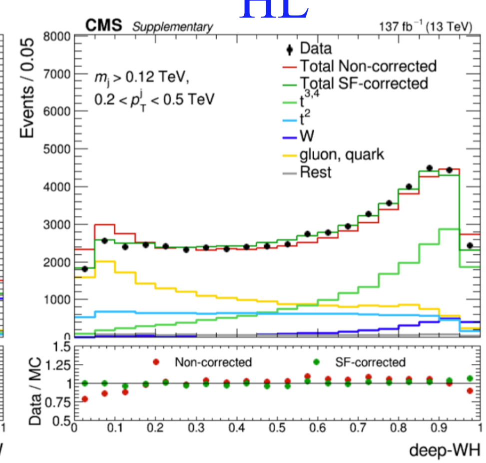
LL



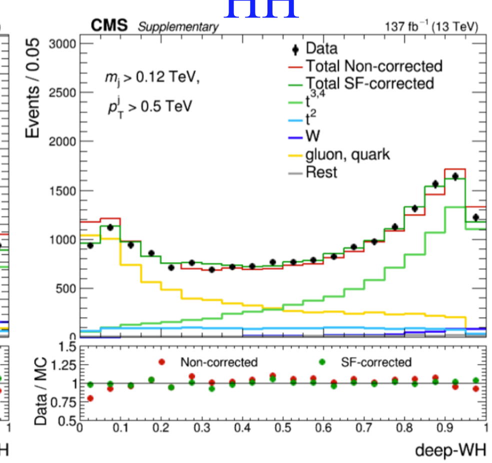
LH



HL



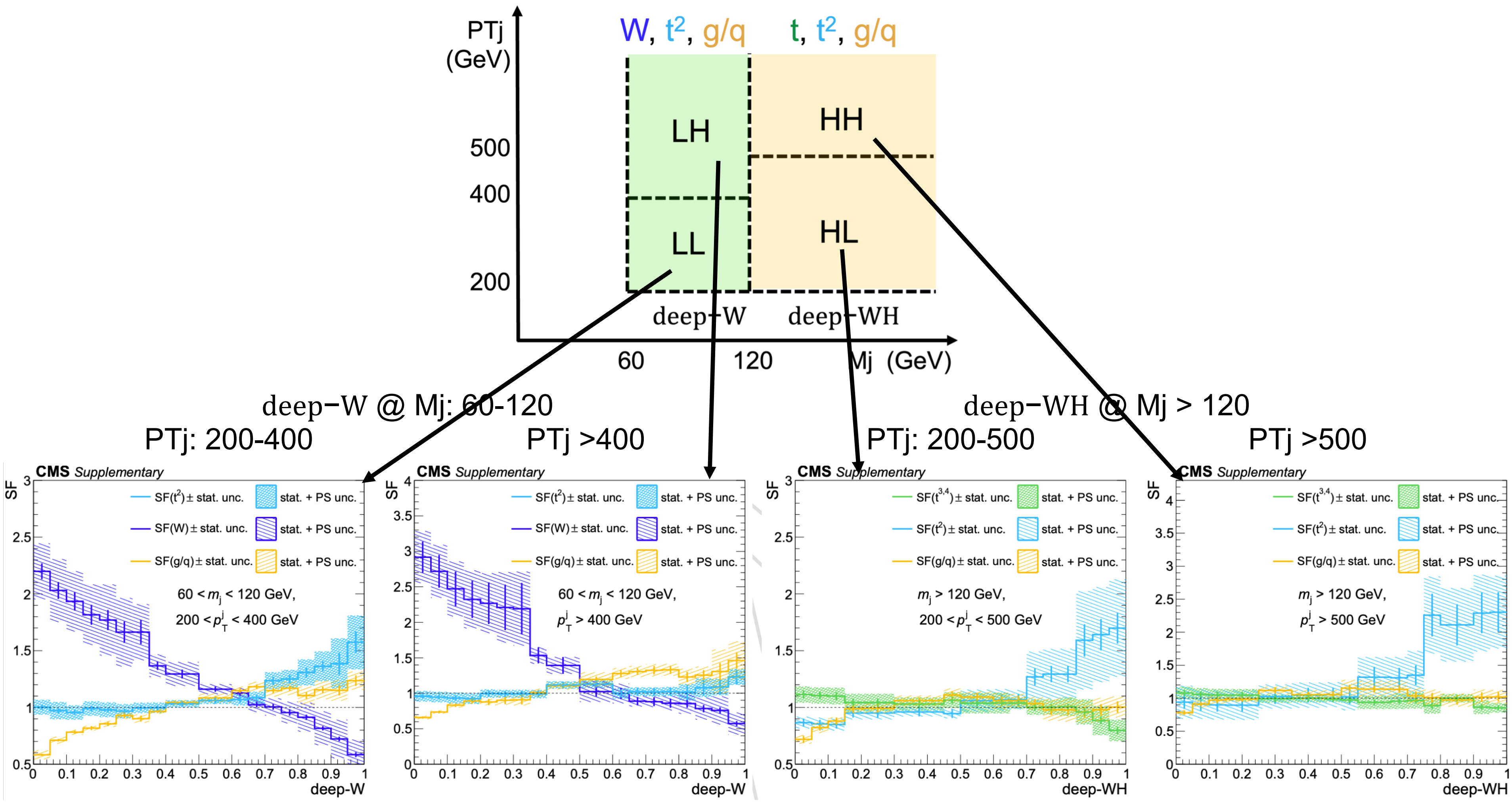
HH



- Split each sample into 3 pure subsets and correct MC shapes bin by bin to derive scale factors for each SM object (details in backup)

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

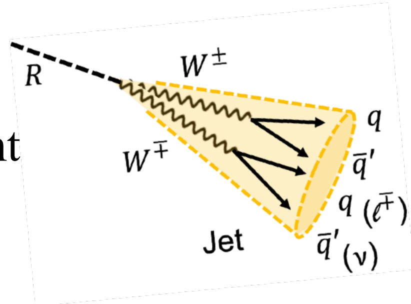


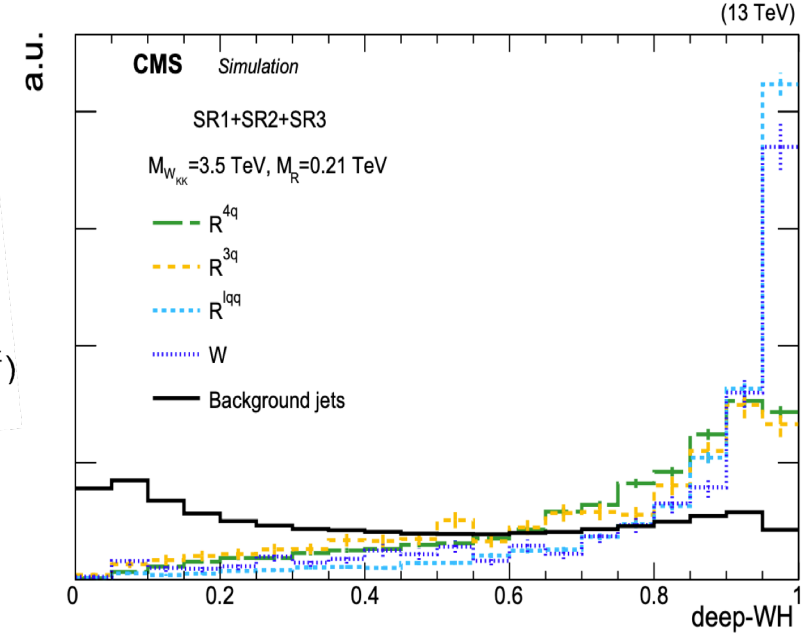
A large set of validation tests showed **good post SFs-correction performance**

We **use these SFs to correct all jets** for both signal and BKG

Calibration for signal

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

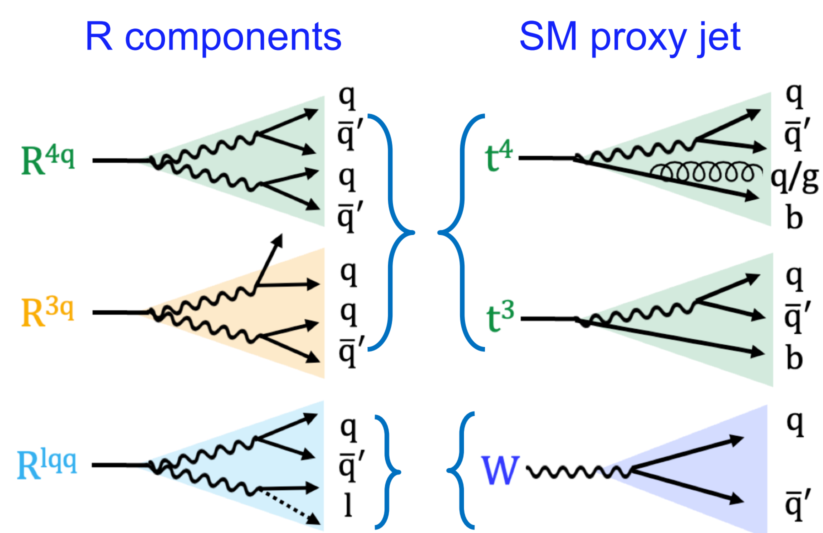




1. Observe similarity between R^{4q}↔R^{3q} jets with merged top: $t^{3,4}$
   → we apply SF($t^{3,4}$) on R^{4q}, R^{3q}

2. Observe similarity between W↔R^{lqq} jets
   → we apply scale factors for W, SF(W), on R^{lqq}

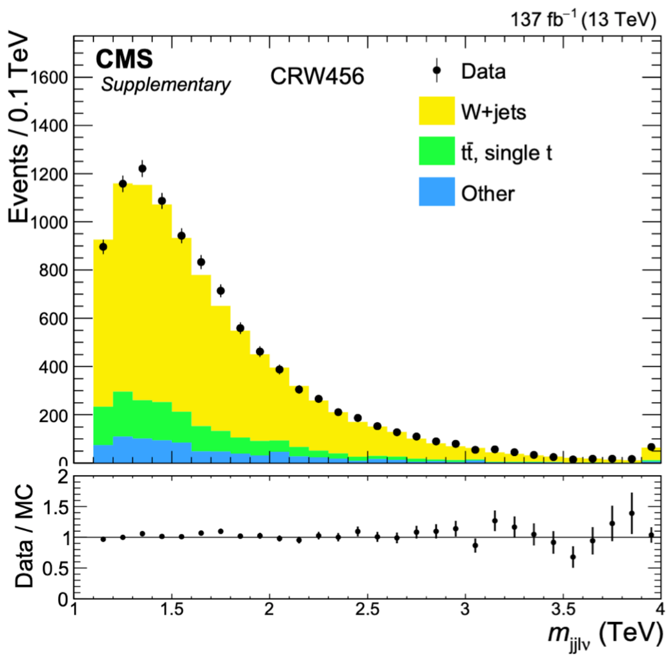
3. The difference between the performances of the SM candle and signal is taken into account as the systematic uncertainty.



Control region 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:

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

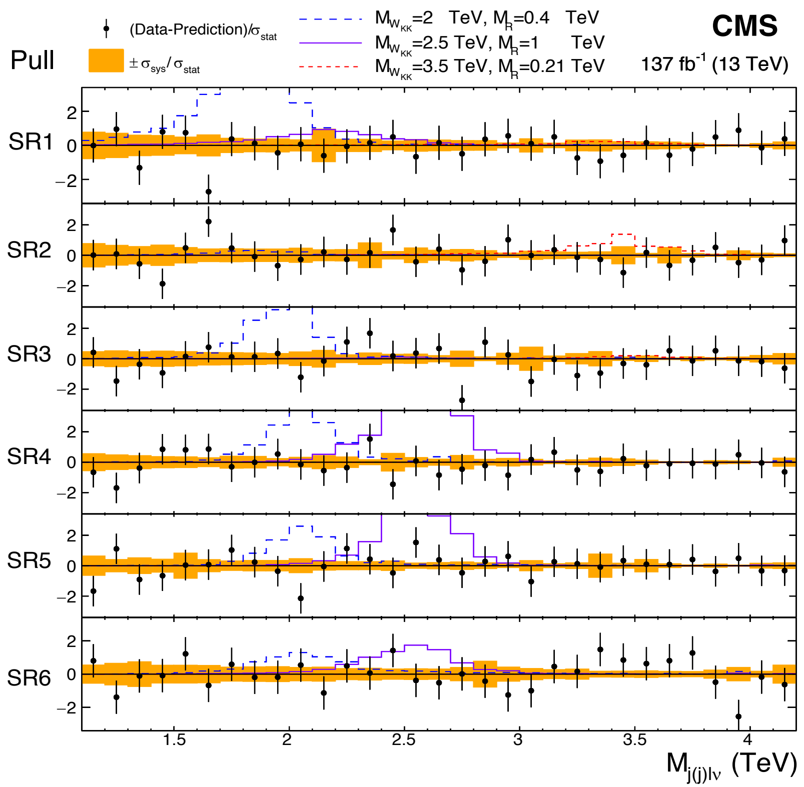
0.96 to 1.03

Prediction for top is similar, we invert b-veto selection as top control region.

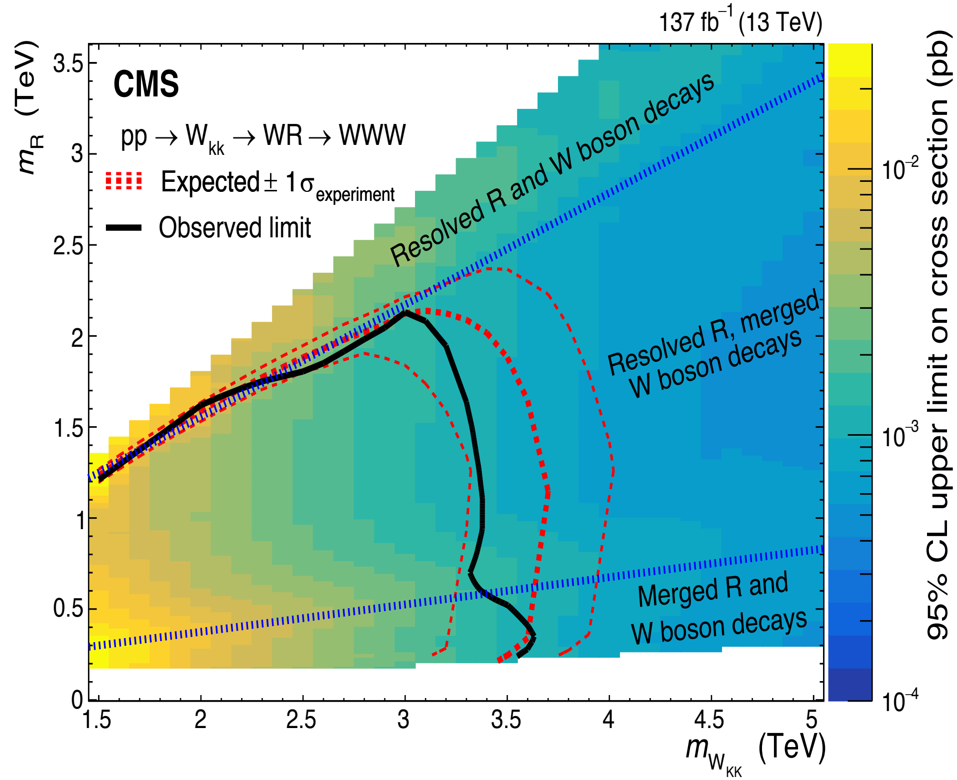
Results and limit (1-lep)

- Combined fit of six signal regions.

(No excess over the background estimation is observed.)



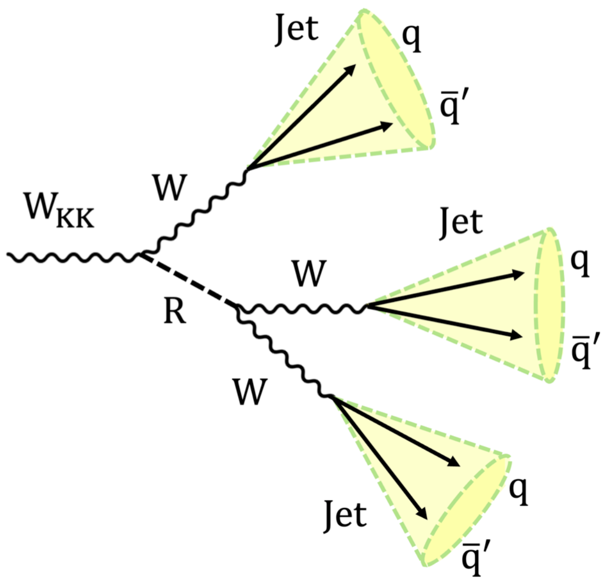
- Limits in 2D W_{KK} vs. R mass plane.



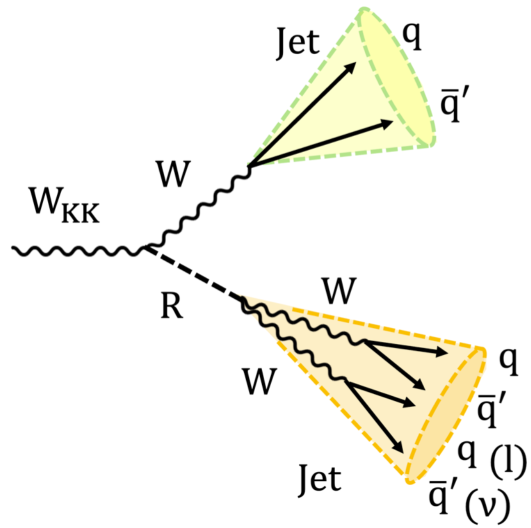
The triboson resonances are excluded up to m_{WKK} = 3.4 (3.6) TeV for m_R = 1 (0.35) TeV.

Signal Profile (0-lep)

Resolved R

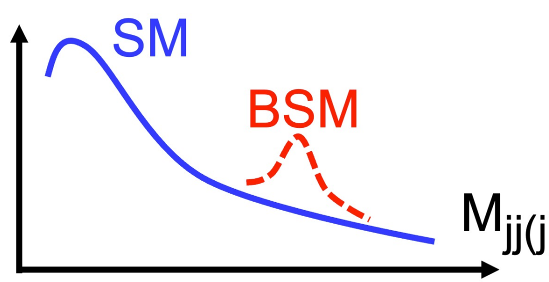


Merged R



- Clear objective:
  Hunt a resonance formed by 3 or 2 massive jets

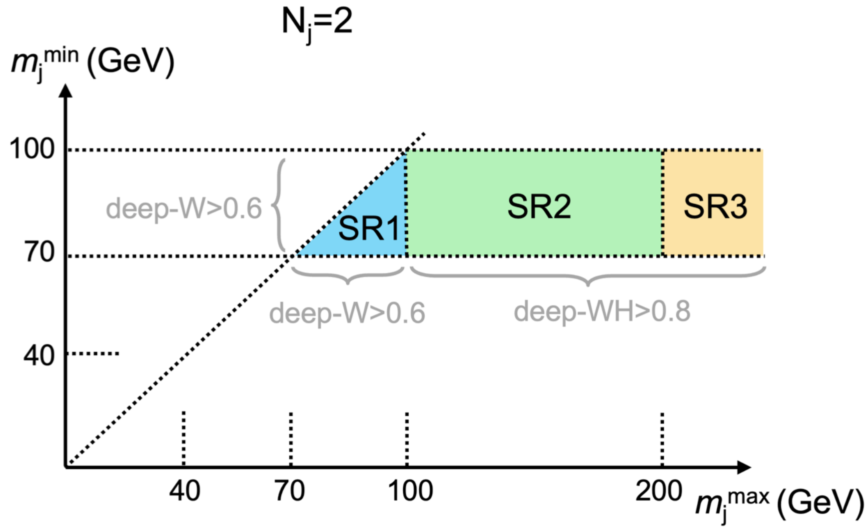
Resolved → 3 AK8 jets → search for resonance at M_{jjj}
Merged → 2 AK8 jets → search for resonance at M_{jj}

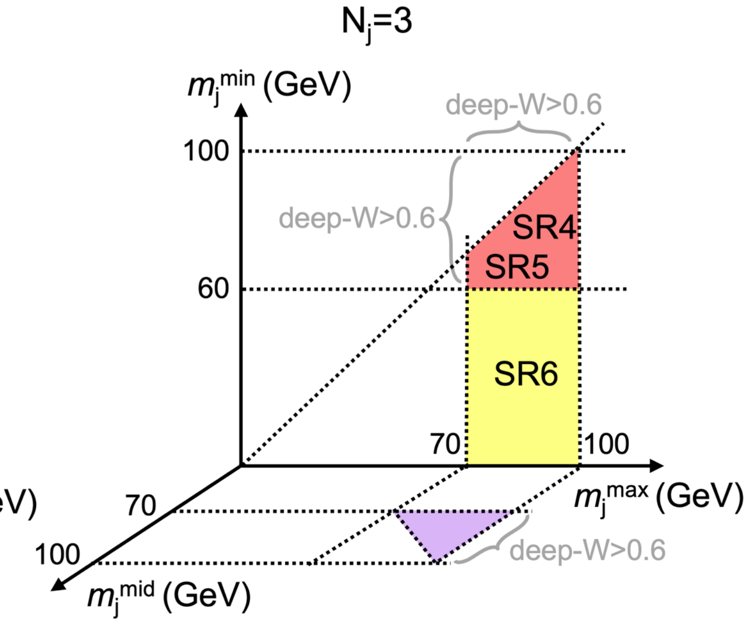


SR definition

Jets ordered due to mass

SR4 and SR5 differ in demanding exactly 3 and 2 W-tagged jets respectively



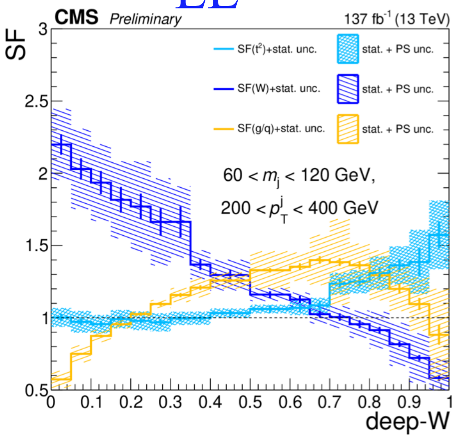


Region	N_j	m_j^{max} (GeV)	m_j^{mid} (GeV)	m_j^{min} (GeV)	Jet tagging conditions
SR1	2	70–100	—	70–100	Both with deep-W > 0.8
SR2	2	100–200	—	70–100	Higher with deep-WH > 0.8, lower with deep-W > 0.8
SR3	2	>200	—	70–100	Higher with deep-WH > 0.8, lower with deep-W > 0.8
SR4	3	70–100	70–100	60–100	All 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

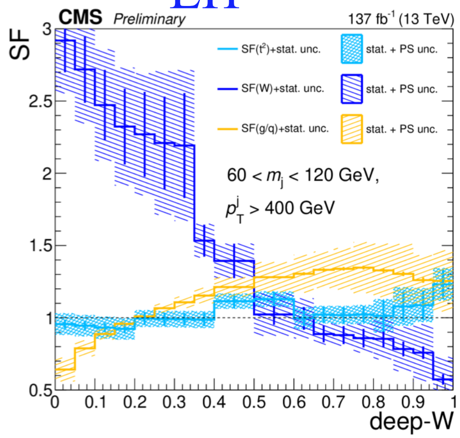
BKG prediction

- ➢ 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 $\frac{\text{Data} - \text{non q/g}}{\text{MC}} = \text{SF}^{q/g}$

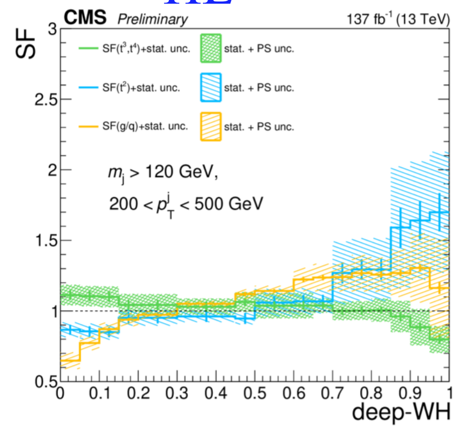
LL



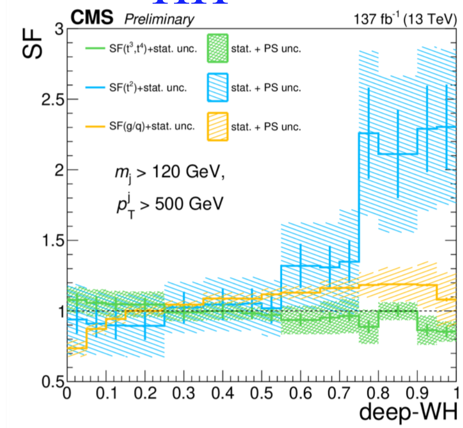
LH

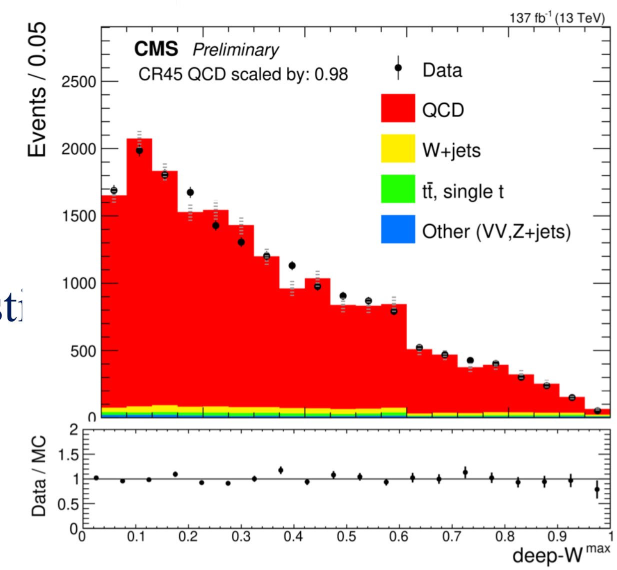


HL



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 statisti

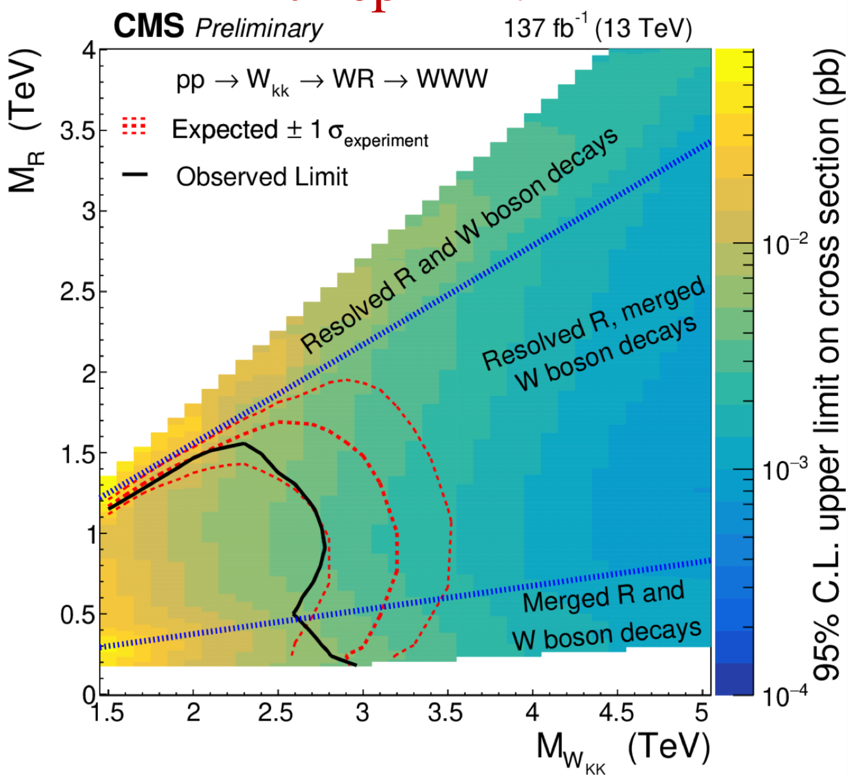
→ QCD has consistent shapes in SRs and CRs

- ➢ Replace QCD MC in SRs by “Data-rest” in CRs

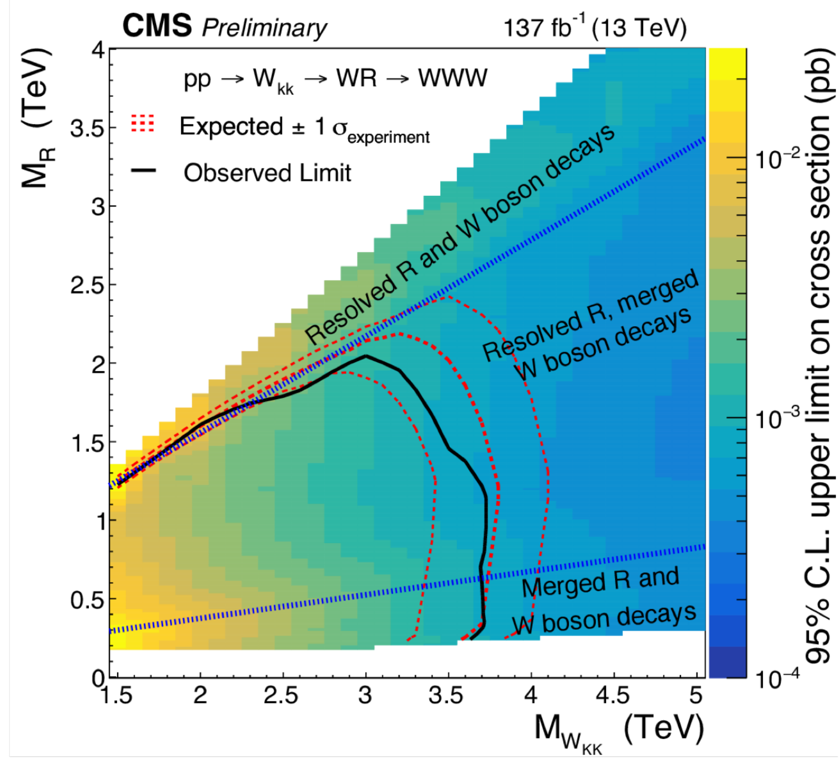
Combined results

We set upper limits on $X \to RW \to WWW$ cross section,
lower limits on M_{WKK}, M_R masses (Asymptotic approximation)

0-lep limit



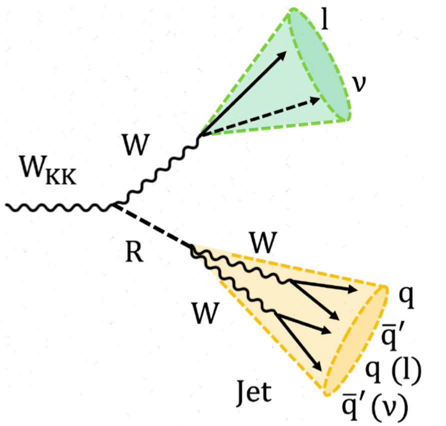
Combination

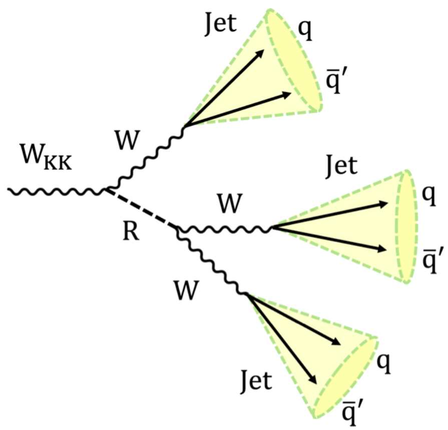


- Combination of 1+0 lep.
  Systematics on SFs correlated (apart from SFq/g), as well as PU, PDFs, μR, μF are correlated
  All the rest uncorrelated.

Summary

- **First search for 3 massive W boson resonances**
- Probe very **recent** (2017-2019) theoretical scenario
- Search features:
  - Simultaneous probe of both **merged and resolved**
  - Featuring **discovery potential**
  - Extensive **use of deep-AK8** taggers
  - **Novel tagger calibration** with "matrix method"
  - Exclusion **limits up to ~3.7 TeV**





Backup

Matrix method

CMS-PAS-B2G-20-001

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

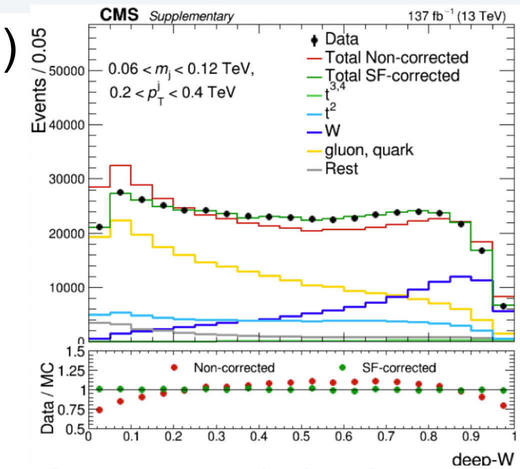
3. Demand: **Data = scaled sum of yields**

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

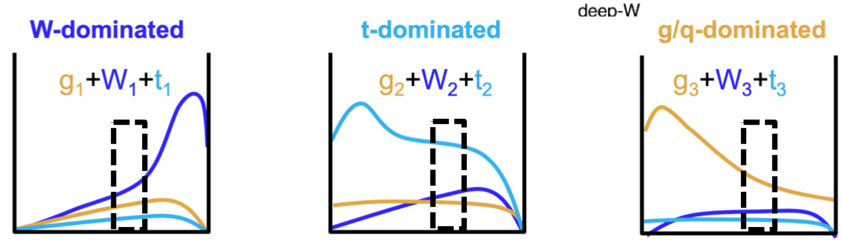
   Define system of 3 equations, 1 per each subset "i", and per tagger score bin "k"

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

(1)



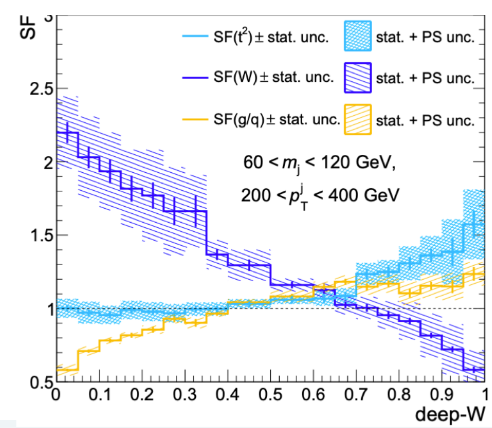
(2)



(3)

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

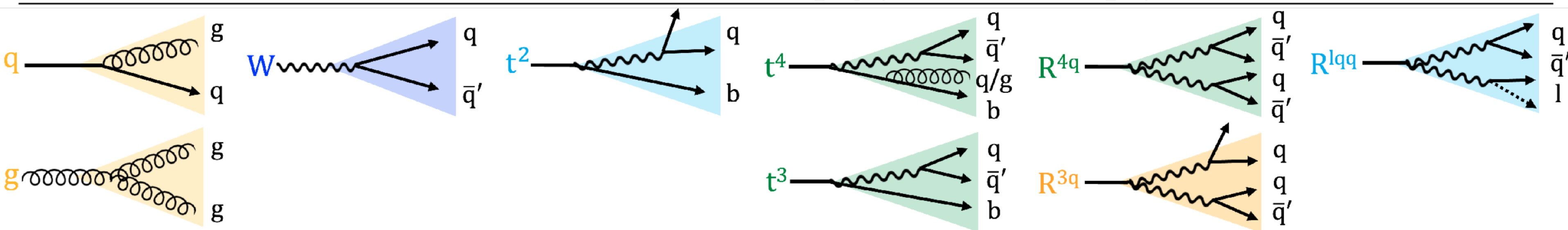
(4)



Matching criteria

CMS-PAS-B2G-20-001

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}: $(q_4,j) < 0.8$	—

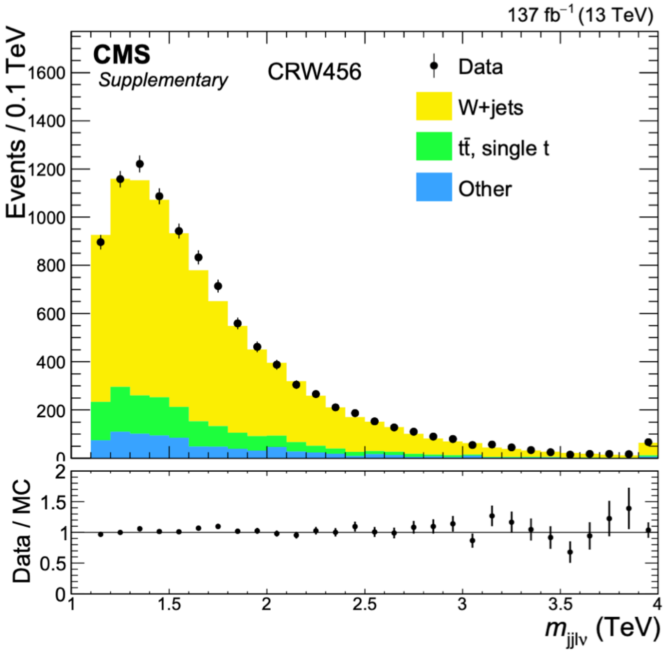


CR for W+jets

CMS-PAS-B2G-20-001

- 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 $M_{j(j)lv}$ 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)

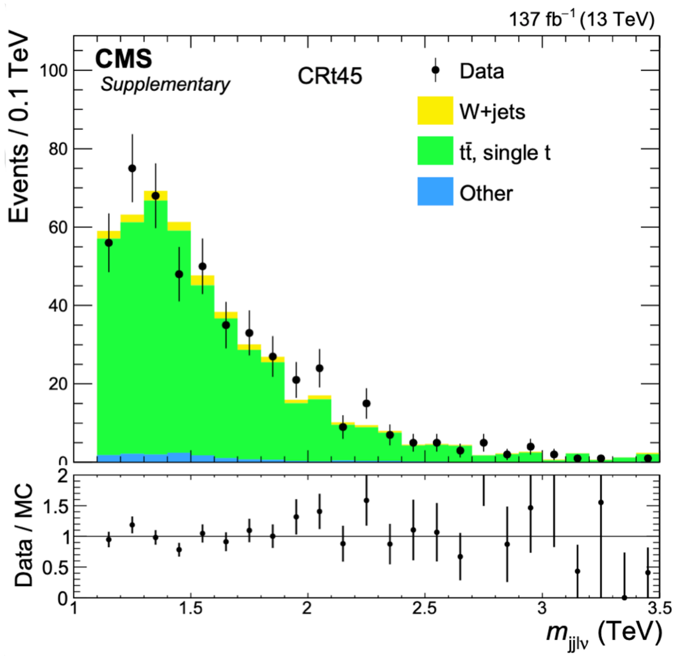
We **validate** prediction in low-ST samples

CR for top

CMS-PAS-B2G-20-001

- Use SR-selection → Maintain kinematics as in SR
- Invert b-veto to $N_b \geq 1$ → 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 $M_{j(j)lv}$ 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

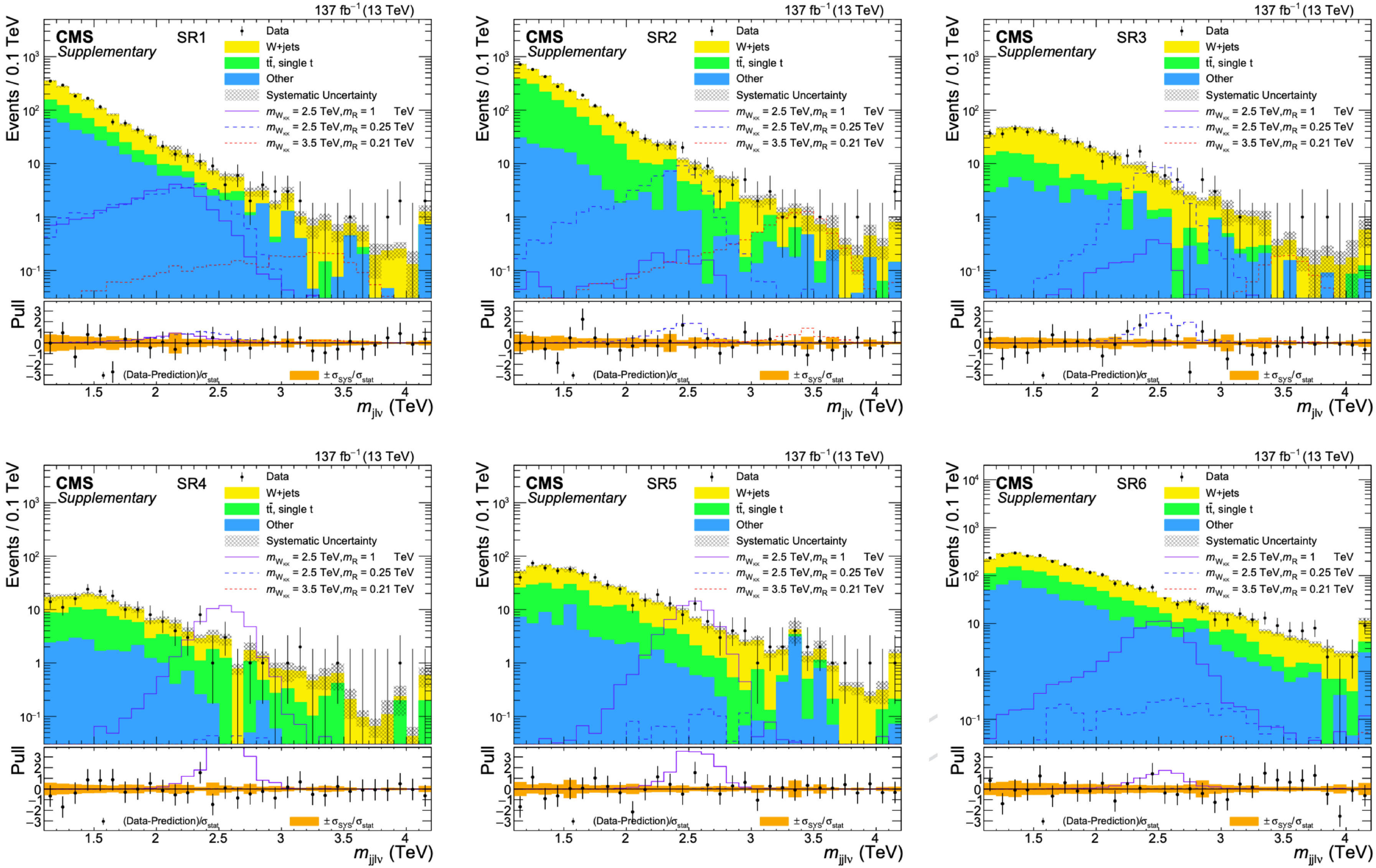
(Where MC is SF-corrected)

We **validate** prediction in low-ST samples

$W_{KK} \to WR \to WWW \to l\nu$+jets

CMS-PAS-B2G-20-001

SR1-6 Postfit Results

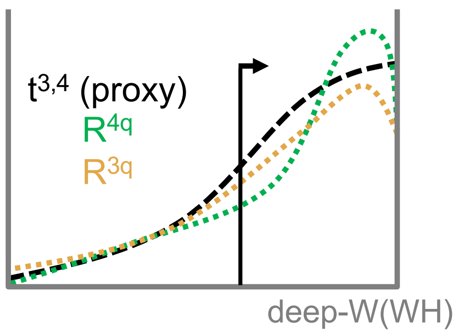


Systematic uncertainty

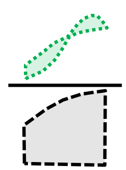
CMS-PAS-B2G-20-001

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:



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



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

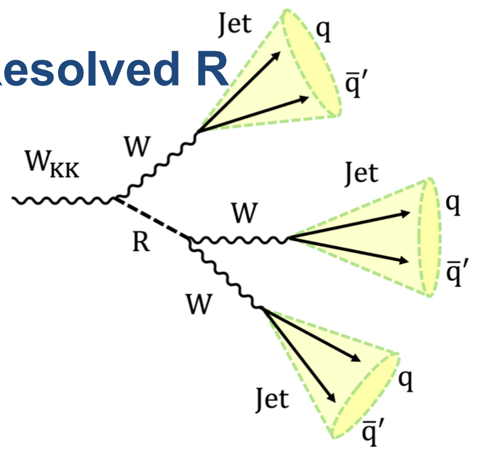
Systematic uncertainty (0-lep)

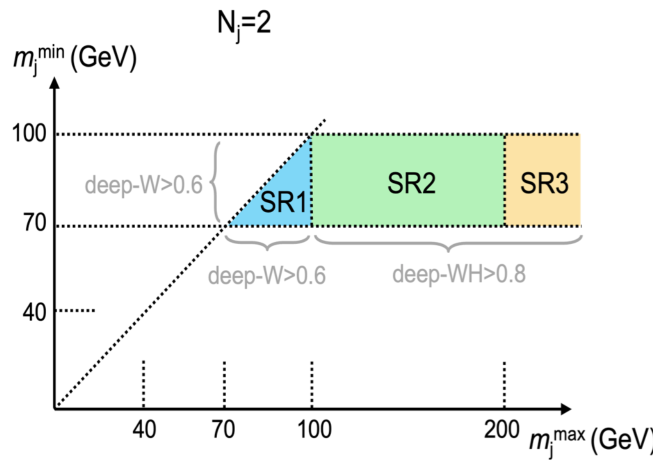
Sources	B or S	Effect on	Magnitude	Nuisance parameters
Parton shower + selection bias for W, $R^{\ell qq}$	B+S	Shape+rate		4, for LL, LH, HL, HH
Parton shower + selection bias for t^2	B	Shape+rate		8, for LL, LH, HL, HH
Parton shower + selection bias for $t^{3,4}$, $R^{3q,4q}$	B+S	Shape+rate		4, for 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

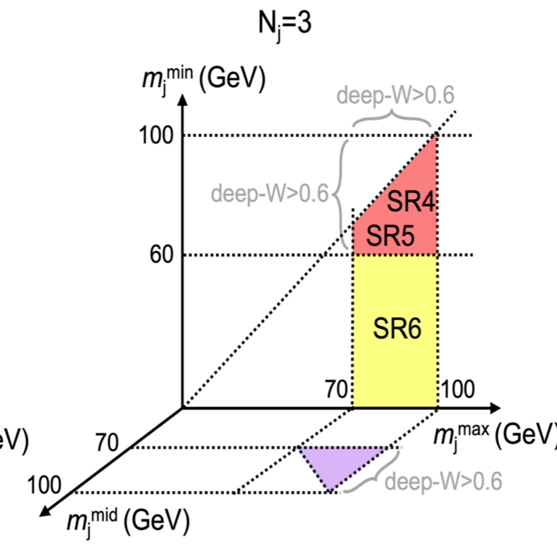
$W_{KK} \to WR \to WWW \to$ jets

CMS-PAS-B2G-21-002

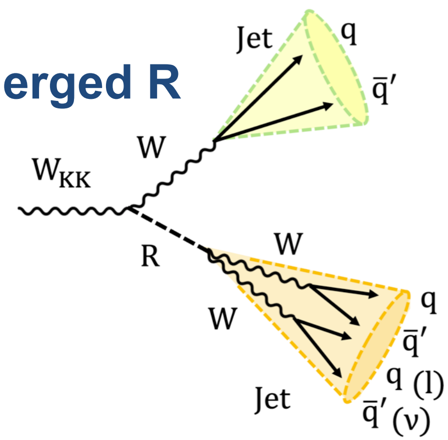
Resolved R



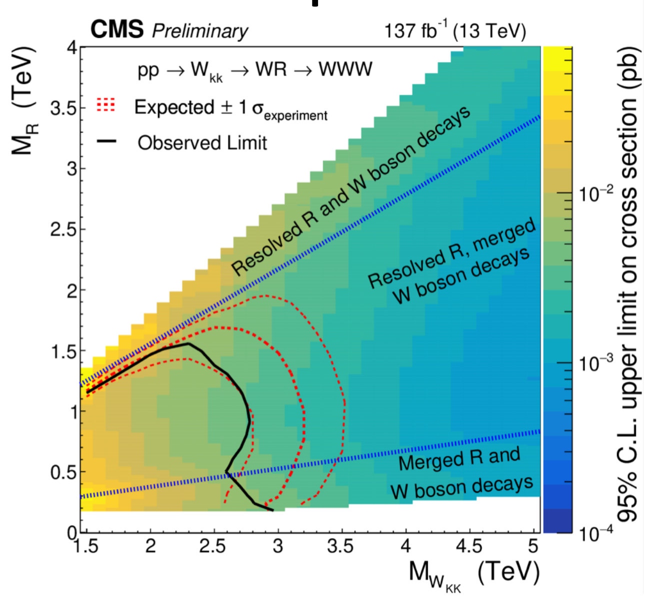




Merged R



0-lep limit



combination