Search for resonances decaying to three W bosons with CMS

Xudong Lyu (Peking University)

On behalf of the CMS Collaboration

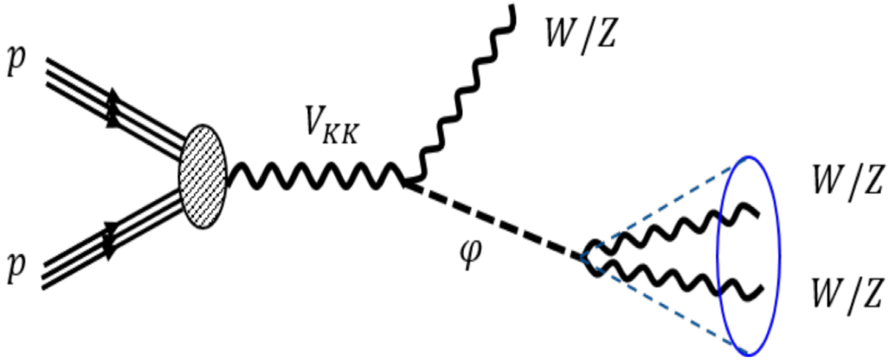
November 25-28, 2021

The 7th China LHC Physics Workshop

Outline

1. Motivation
2. Signal Region selection
3. Deep-taggers calibration
4. Prediction method
5. Systematic uncertainty (backup)
6. Results

CMS-PAS-B2G-20-001

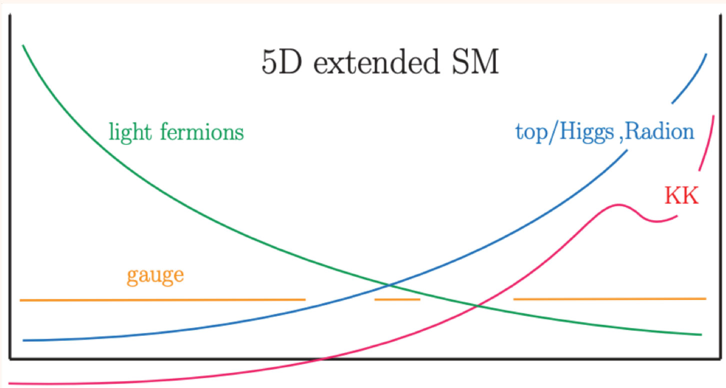


Motivation for “tri-object” search

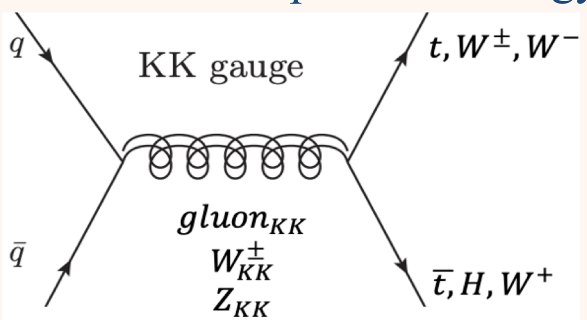
- M_{Pl}-EW scale gap motivates BSM physics (hierarchy problem)
- No BSM physics yet → time to look at non-standard final states/scenarios

Standard (Minimal) Warped ED model

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

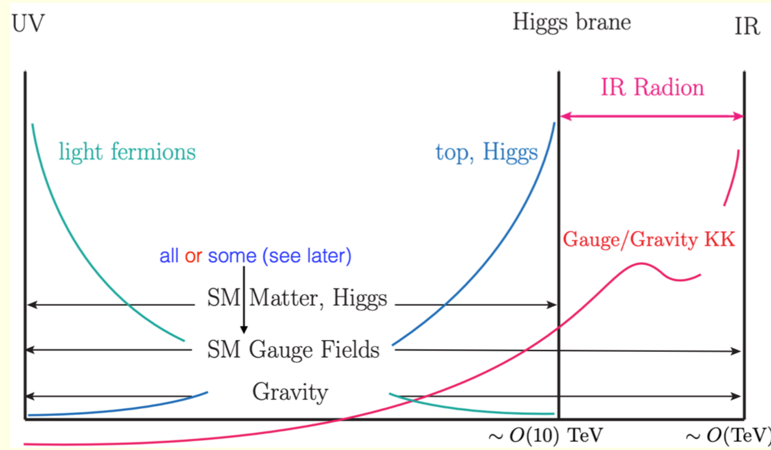


- “di-SM” dominant phenomenology

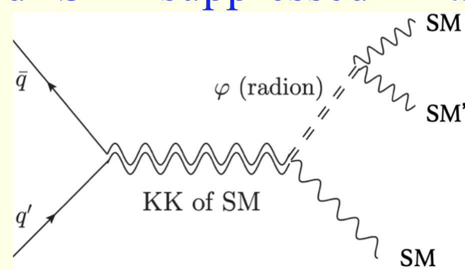


Extended Warped ED model:

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



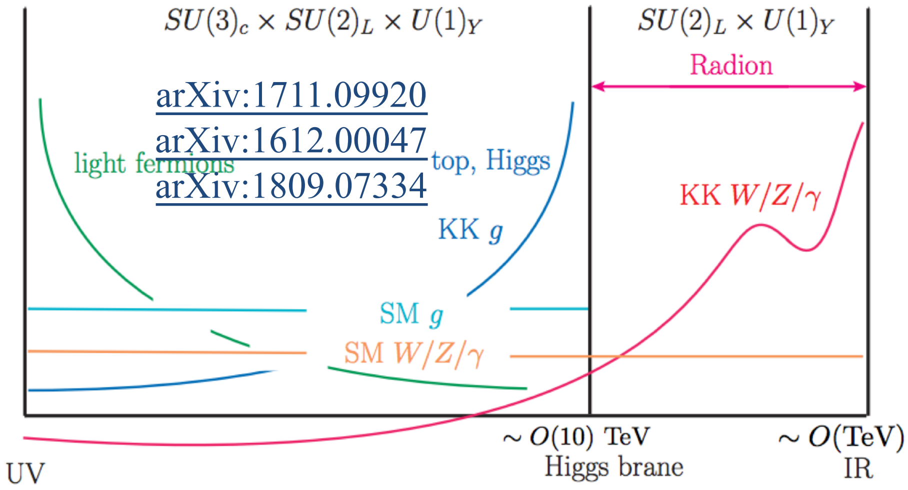
- A wealth of new signatures emerges
- “di-SM” suppressed in favor of “tri-SM”

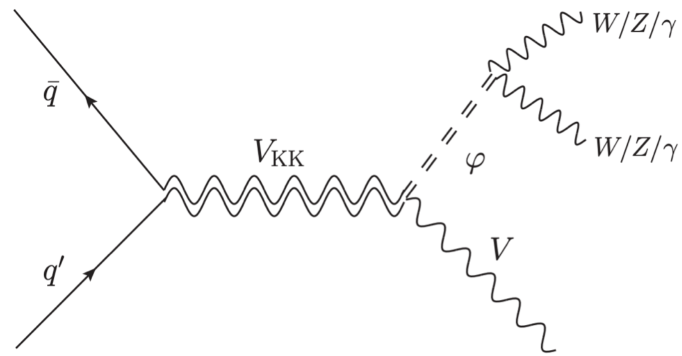


arXiv:1711.09920
arXiv:1612.00047
arXiv:1809.07334

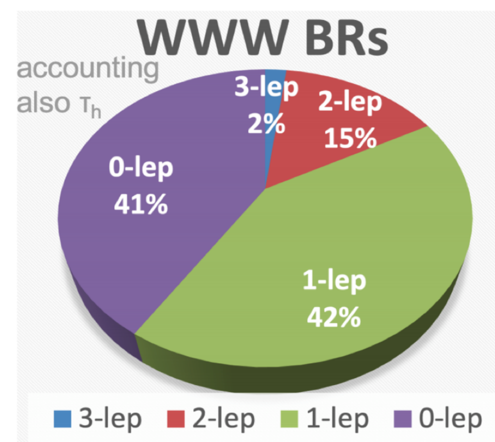
Motivation for "tri-object" search

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

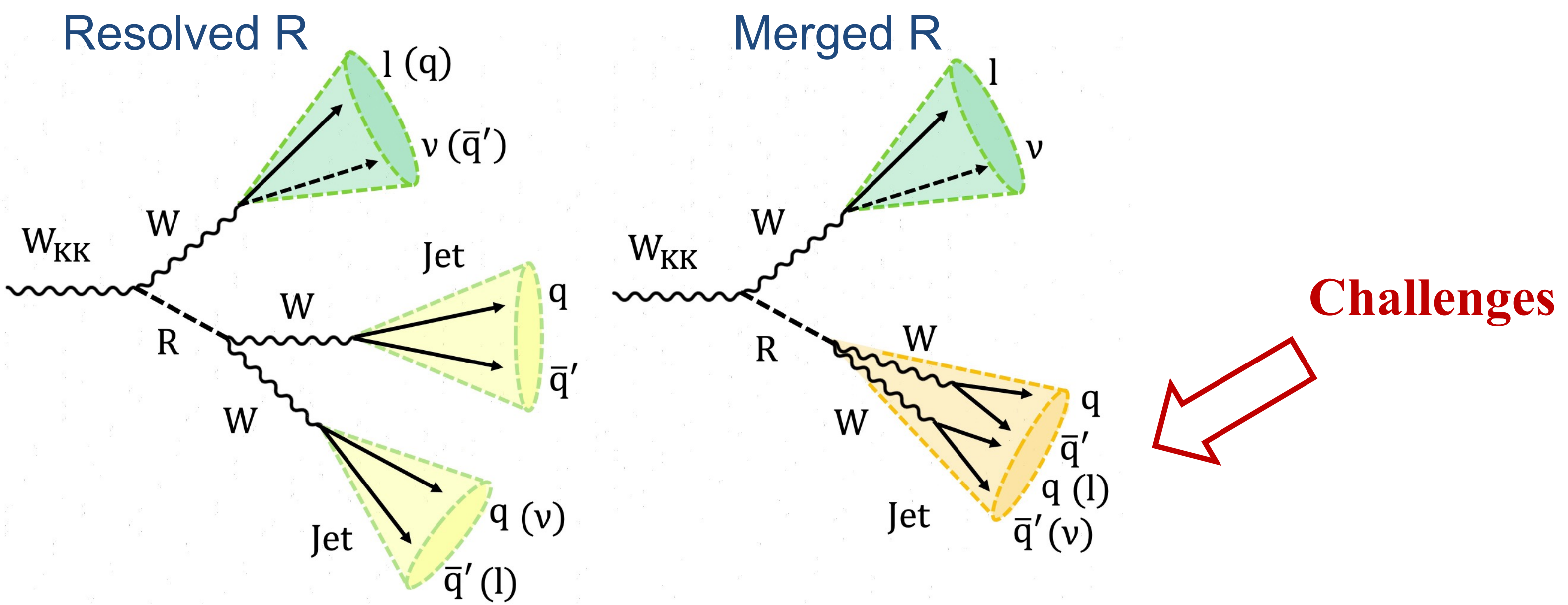




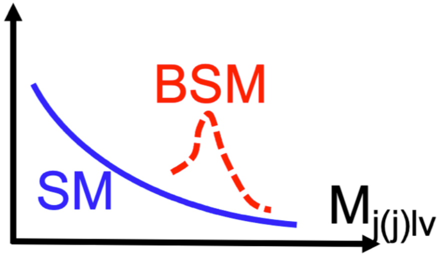
- Hierarchy of Radion BR_R: WW > ZZ > Zγ > γγ
- $W_{KK} \rightarrow R\ W \rightarrow WWW$
- Doubly resonant signal: spin-1 $V_{KK,}$ spin-0 radion R
- 1- and 0-lep. largest BRs ~40%
- 1-lep channel is investigated for the first time.



Signal Profile (1-lep)

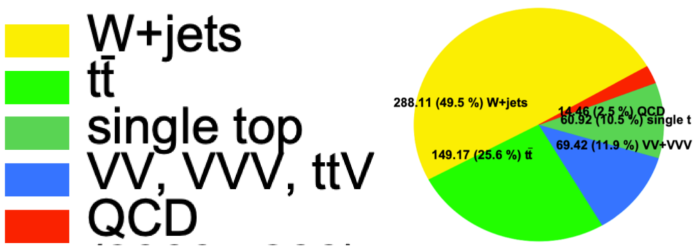


- Physics objects reconstruction
  - ➢ hadronic W bosons: jets (Probe **Resolved** in N_j=2, and **Merged** N_j=1 selections)
  - ➢ leptonic W boson: use info. of lep and MET, assume M_W=80 GeV
- Define selections to improve significance
- Background estimation
- Search of a peak over the reconstructed: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



Samples, Datasets, Triggers & Objects

SM BKG MC processes:



Signal Samples dataset: **MG LO**

- $W_{KK} \rightarrow WWW \rightarrow l\nu + jets$

DATA: Full Run2, Lumi: 138 fb^{-1}

HL-Triggers:

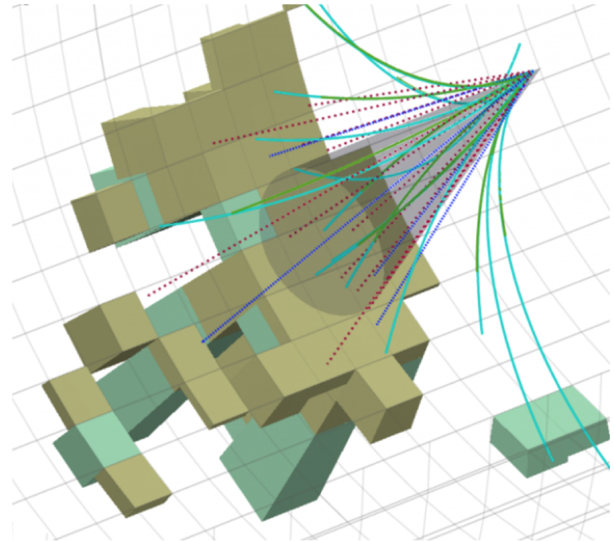
- μ: Single_Muon OR MET
- e: Single_Electron OR Photon

1 Isolated (tight) **lepton** (μ or e)

- Veto additional loose leptons

Jets (Tight ID), anti-k_T clustering

- R_0=0.8 → AK8 "fat" jets → W, R tagging
- R_0=0.4 → AK4 "narrow" jets → b tagging



- Pileup mitigation with PUPPI
- Use the groomed jet mass soft-drop m_j

- Jet cleaning: if an AK4 jet is within ΔR<0.4 of any selected lep, or ΔR<1 for AK8 jets, the jet is not used in the analysis

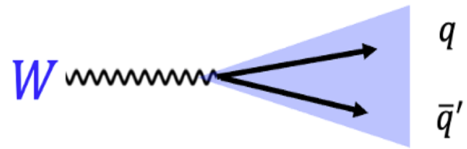
Jet tagging with deepAK8 framework

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



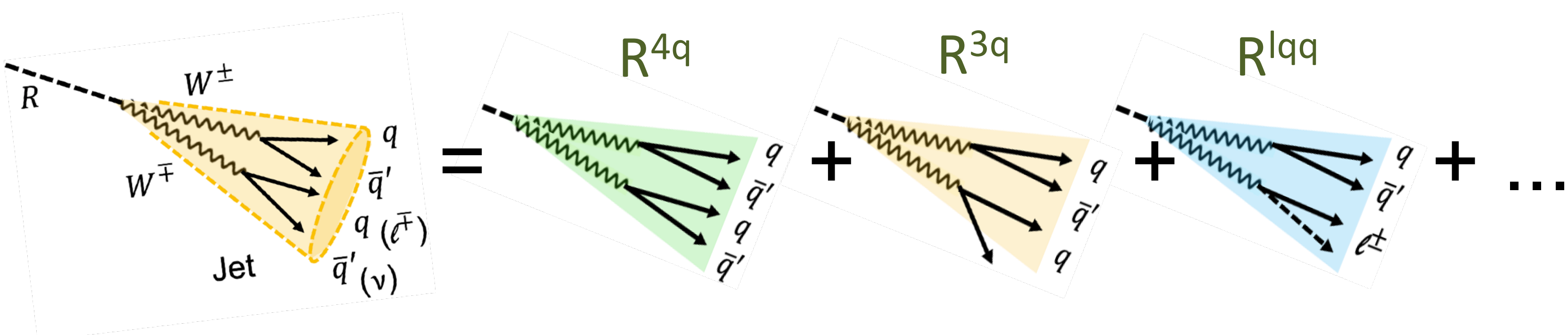
Radion tagging with hybrid:

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

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)

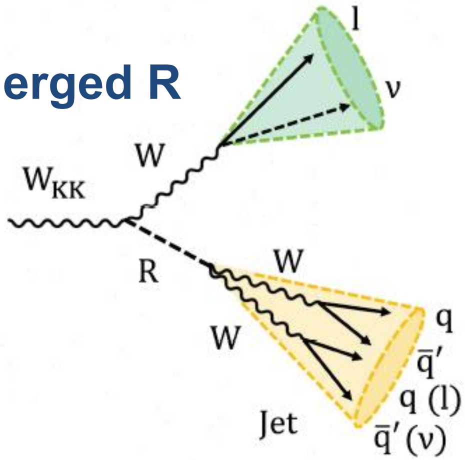


Selection (1-lep)

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

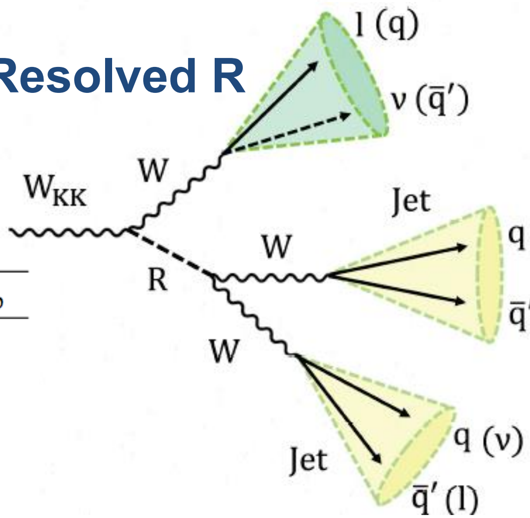
- Split to 6 signal regions based on:
- ➢ Merged: (SR1-3)
  - ○ single massive large-radius jet
  - ○ Bin over M_R: 60-100, 100-200, >200 GeV
  - ○ For $60 < M_j < 100$ GeV, use deep-W
  - ○ For Mj > 100 GeV, use deep-WH to tag radion

Merged R



- ➢ 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

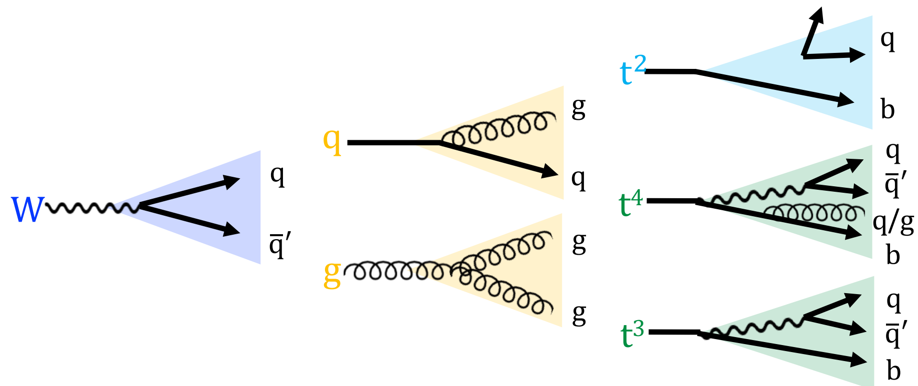
Resolved R

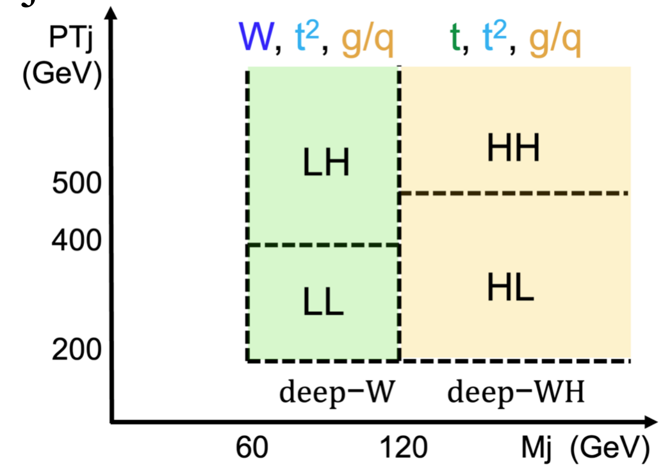


Region	m_j^{max} [GeV]	taggers	m_j^{min} [GeV]	tagger	N_j^{AK8}	N_j^{AK4}	N_b
SR1	60–100	deep-W > 0.7	—	—	1	≤ 2	0
SR2	100–200	deep-WH > 0.7	—	—	1	≤ 2	0
SR3	≥ 200	deep-WH > 0.7	—	—	1	≤ 2	0
SR4	60–100	deep-W > 0.5	60–100	deep-W > 0.5	2	≤ 2	0
SR5	60–100	deep-W >(<) 0.5	60–100	deep-W <(>) 0.5	2	≤ 2	0
SR6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

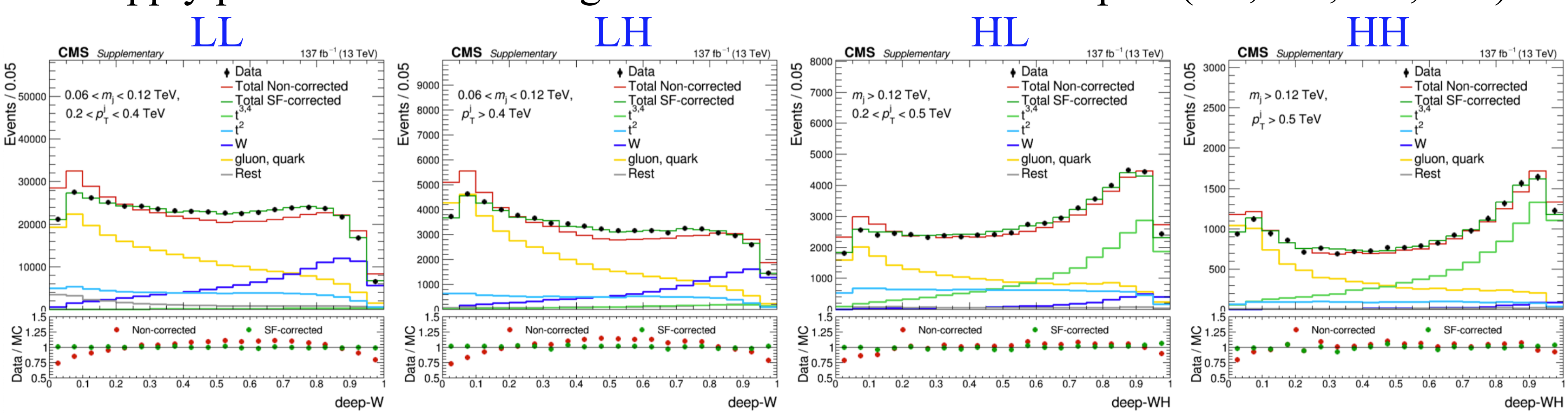
DeepAK8 tagger calibration

- Calibrate deep tagger discriminant shape using SM objects:





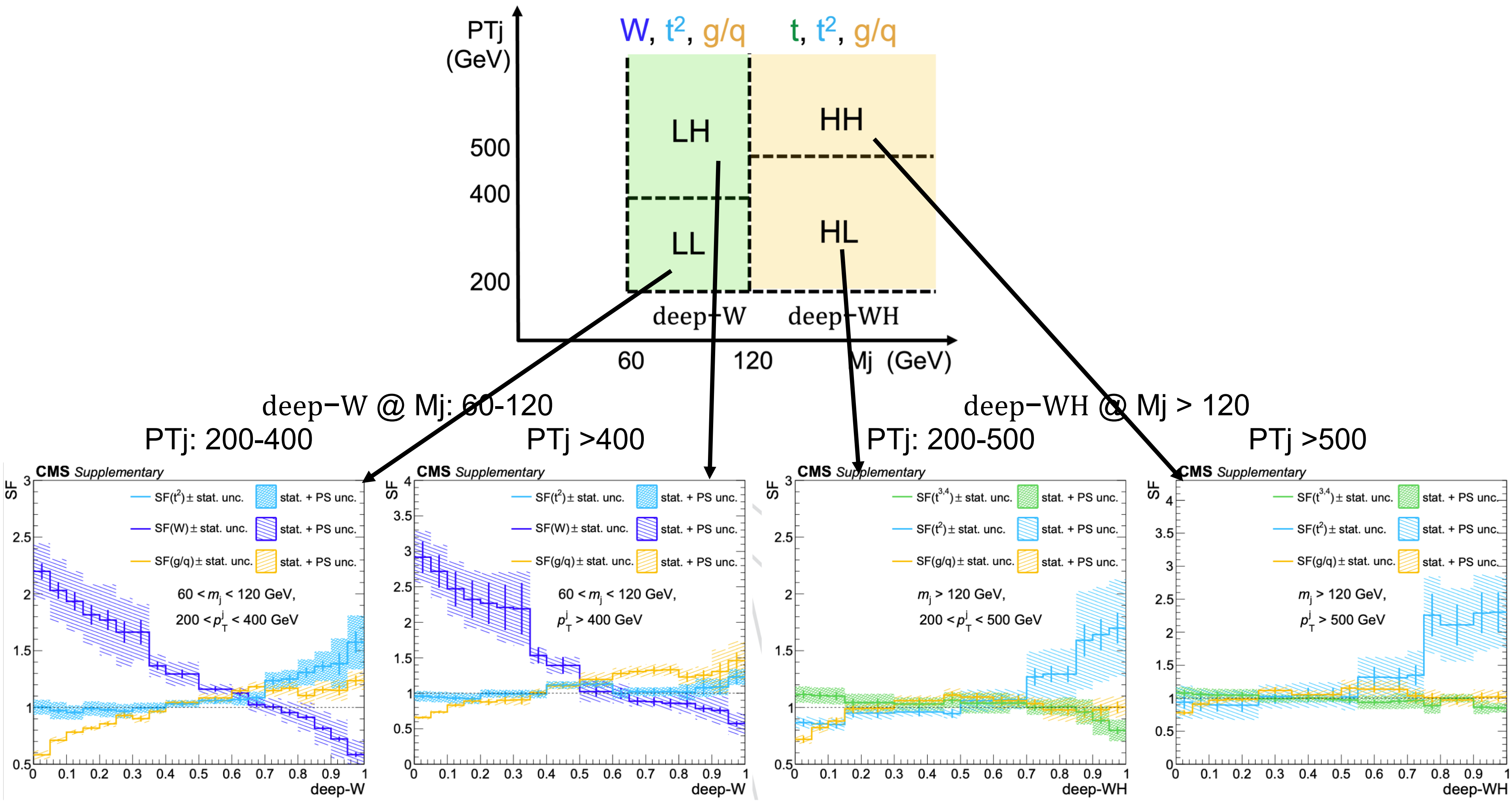
- Apply parton-level matching and break down into 4 samples (LL, LH, HL, HH)



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

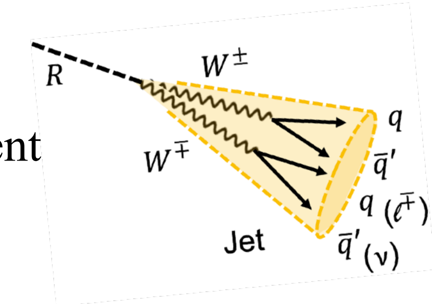


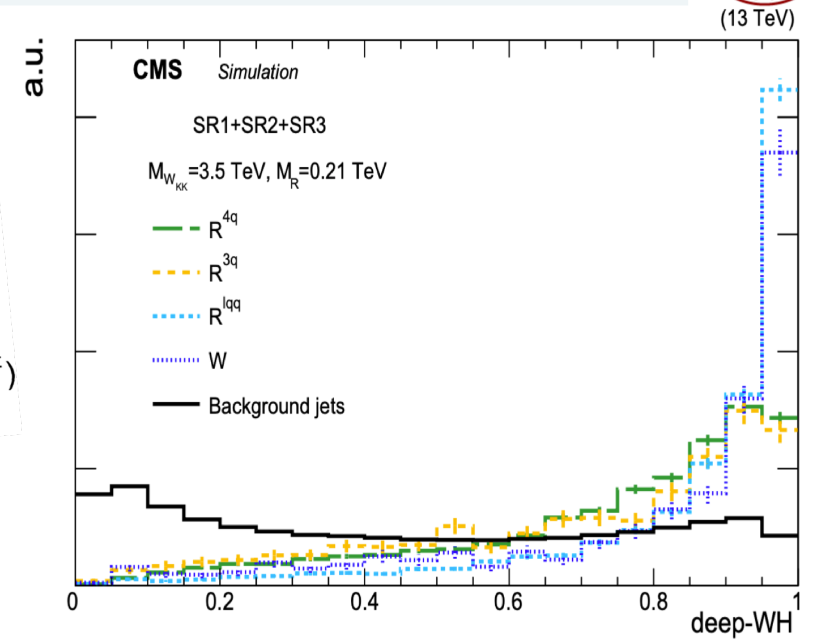
A large set of validation tests showed **good post SFs-correction performance**

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

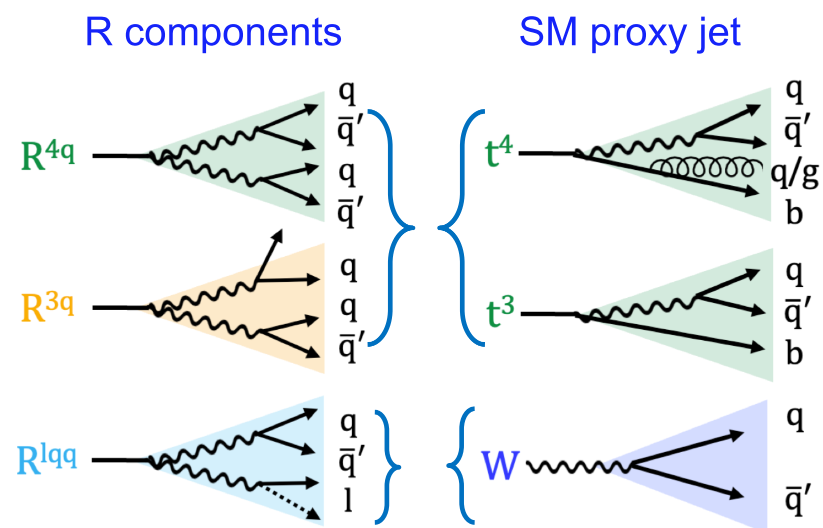




1. Observe similarity between R^{4q}↔R^{3q} jets with merged top: $t^{3,4}$
   → we apply SF($t^{3,4}$) on R^{4q}, R^{3q}

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

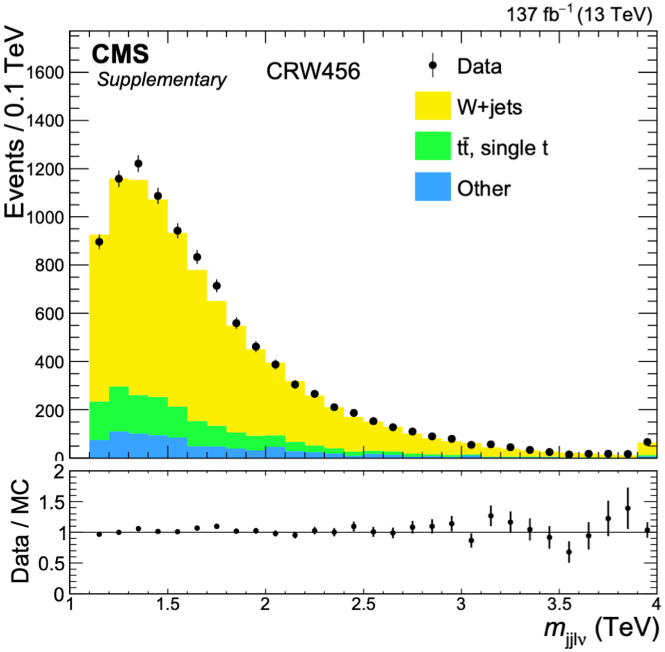
3. The difference between the performances of the SM candle and signal is taken into account as the systematic uncertainty.



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 ($N_{CR_i}^W$) and shape (TF_i^W) correction to SR as:

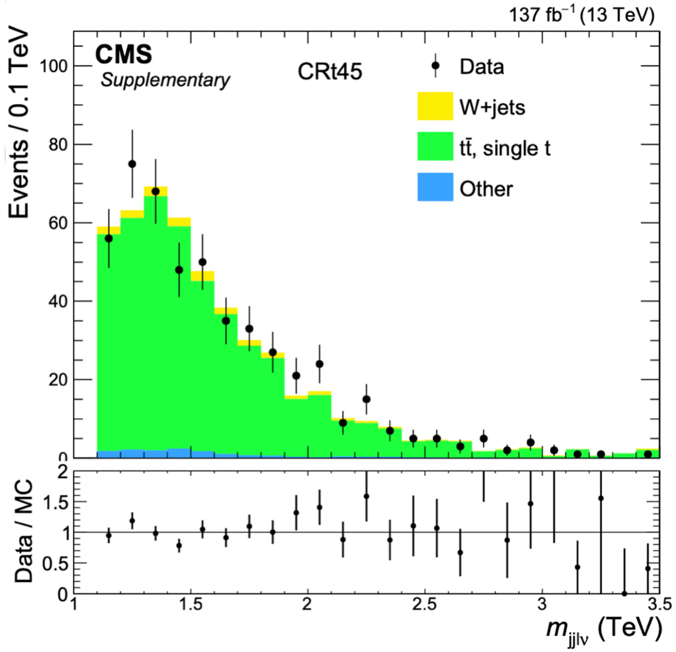
$$PRED_{SR_i}^W = N_{CR_i}^W\, MC_{SR_i}^W \frac{[DATA-rest]_{CRW_i}}{N_{CR_i}^W\, MC_{CRt_i}^W} = N_{CR_i}^W MC_{SR_i}^W TF_i^W$$

0.96 to 1.03

CR for top

- 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:

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

$N^t_{CR_i}$: 0.71 to 1.03

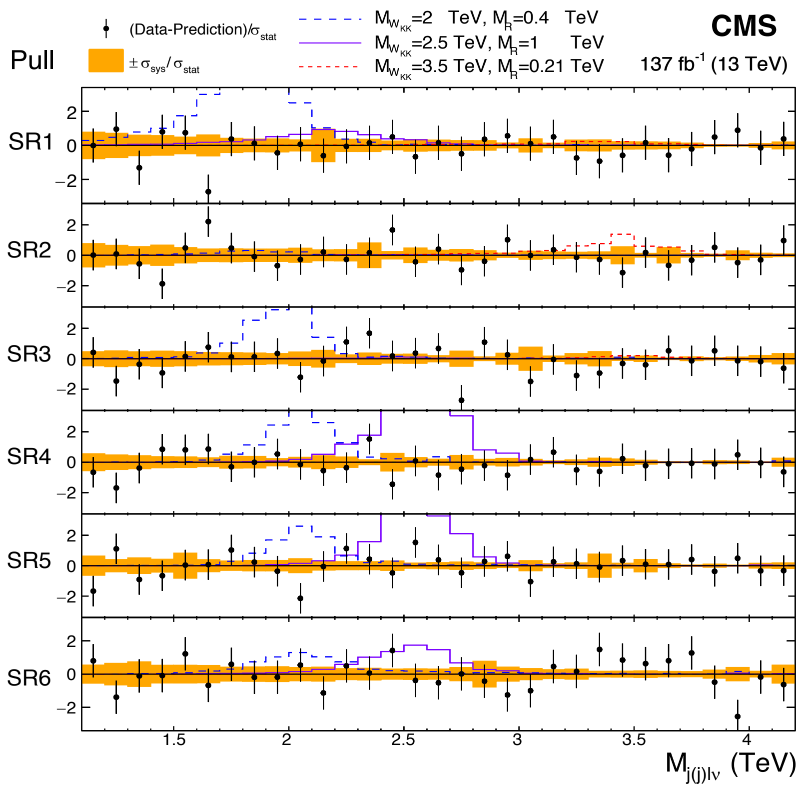
(Where MC is SF-corrected)

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

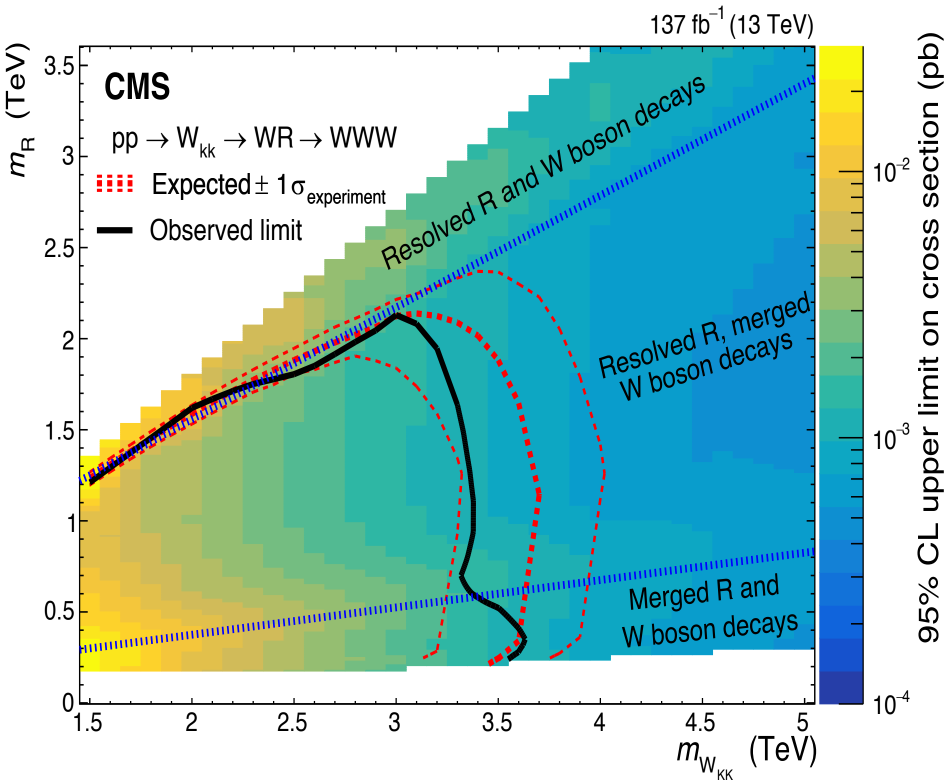
Results and limit

- Combined fit of six signal regions.

(No excess over the background estimation is observed.)



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

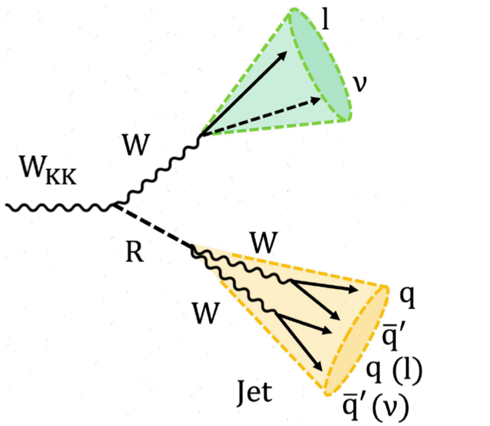


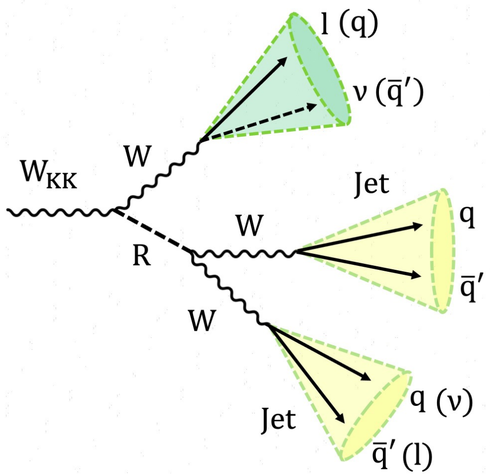
The triboson resonances are excluded up to m_{WKK} = 3.4 (3.6) TeV for m_R = 1 (0.35) TeV.

Summary

CMS-PAS-B2G-20-001

- **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 ~3.6 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

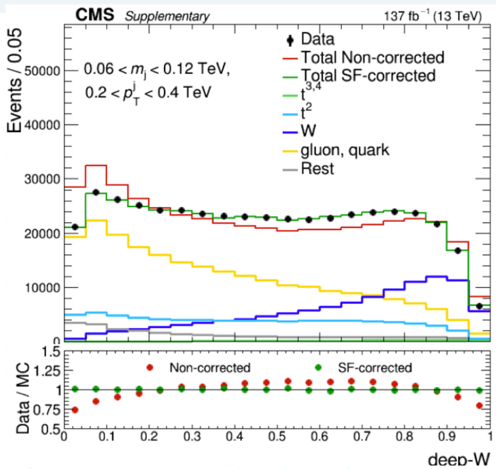
3. Demand: **Data = scaled sum of yields**

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

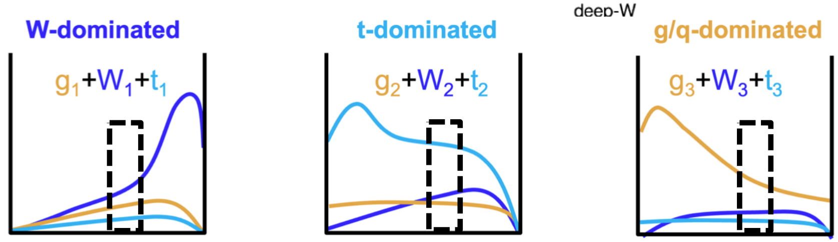
Define system of 3 equations, 1 per each subset "i", and per tagger score bin "k"

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)



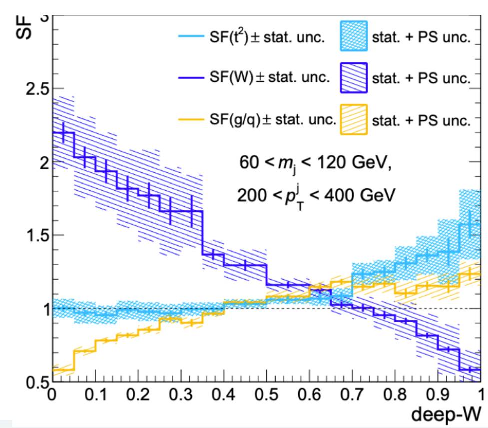
(2)



(3)

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

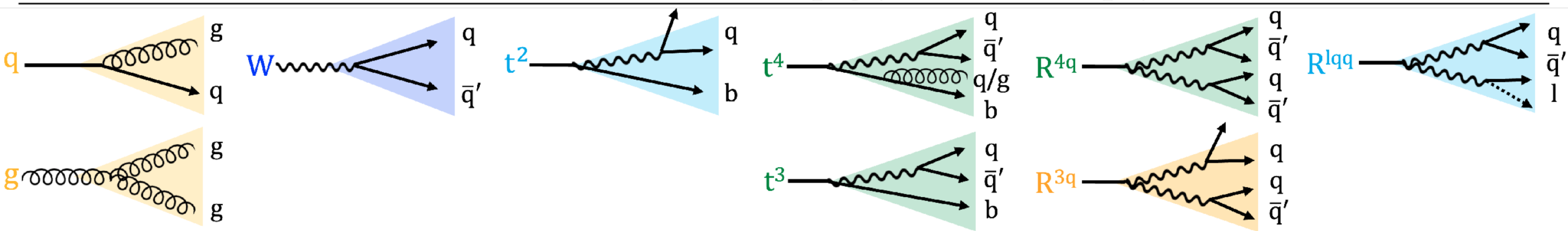
(4)



Matching criteria

CMS-PAS-B2G-20-001

q/g	W → 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}: $(q_4,j) < 0.8$	—



Systematic uncertainty for BKGs

- Attribute **nuisances** to each unc. source, in principle **uncorrelated** between SRs
- **Data-driven pred.** corrects for: Pu, JES/R, Lumi, Trigger, PDFs, $\mu_{R,F}$, lep. eff, reco, ID

Rate unc. from CRs

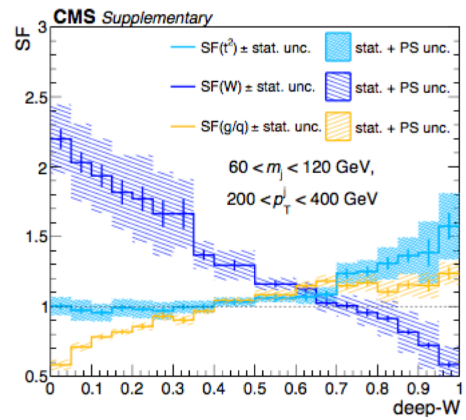
	SR1	SR2	SR3	SR4	SR5	SR6
Wjets	21%	18%	31%	5%		
top	10%	16%	29%	5%		14%
rest	50%					

Shape unc.

$\pm 1\sigma$ $M_{j(j)l\nu}$ templates from CRs fit bands.

Unc. on SFs

1. **Parton Shower (PS)** ~10-20%
   Extract SFs with 3 alternative tt samples (powheg+pythia8, powheg+herwig7, MG+pythia8) maximum difference is used as unc.



2. **Bias** due to Matrix method cuts 10%
   - Different per M_j, pT_j bin, jet-type
   - Translate SFs' unc.→ to SR yields:
   - Typical magnitude ~15-20%

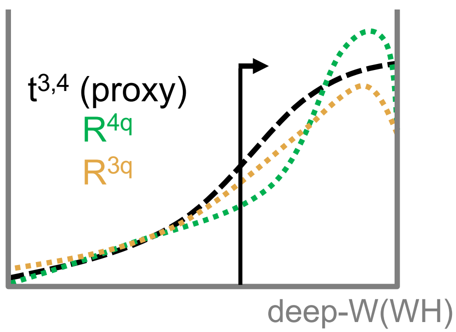
REGION	component proportion	Event yields: SF-corrected	SF_{eff} ± bias ± PS [% Total]
SR4	W 18%	20.3 [23.4]	0.87 ± 0.09 ± 0.11 [16%]
	t^2 6%	8.8 [8.0]	1.10 ± 1.10 ± 0.05 [100%]
	t^3, t^4 1%	1.8 [1.9]	0.97 ± 0.10 ± 0.09 [14%]
	g/q 71%	114.6 [94.9]	1.21 ± 0.12 ± 0.08 [12%]
	Rest 4%	5.4 [5.4]	1.00 - - -
	Inclusive	**150.8 [133.5]**	**1.13 ± 0.17 ± 0.08 [16%]**

Systematic uncertainty for signal

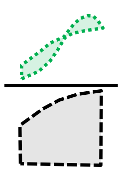
Apart from Pu, JES/R, Lumi, Trigger, PDFs, $\mu_{R,F}$, lep. eff, reco, ID

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:



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

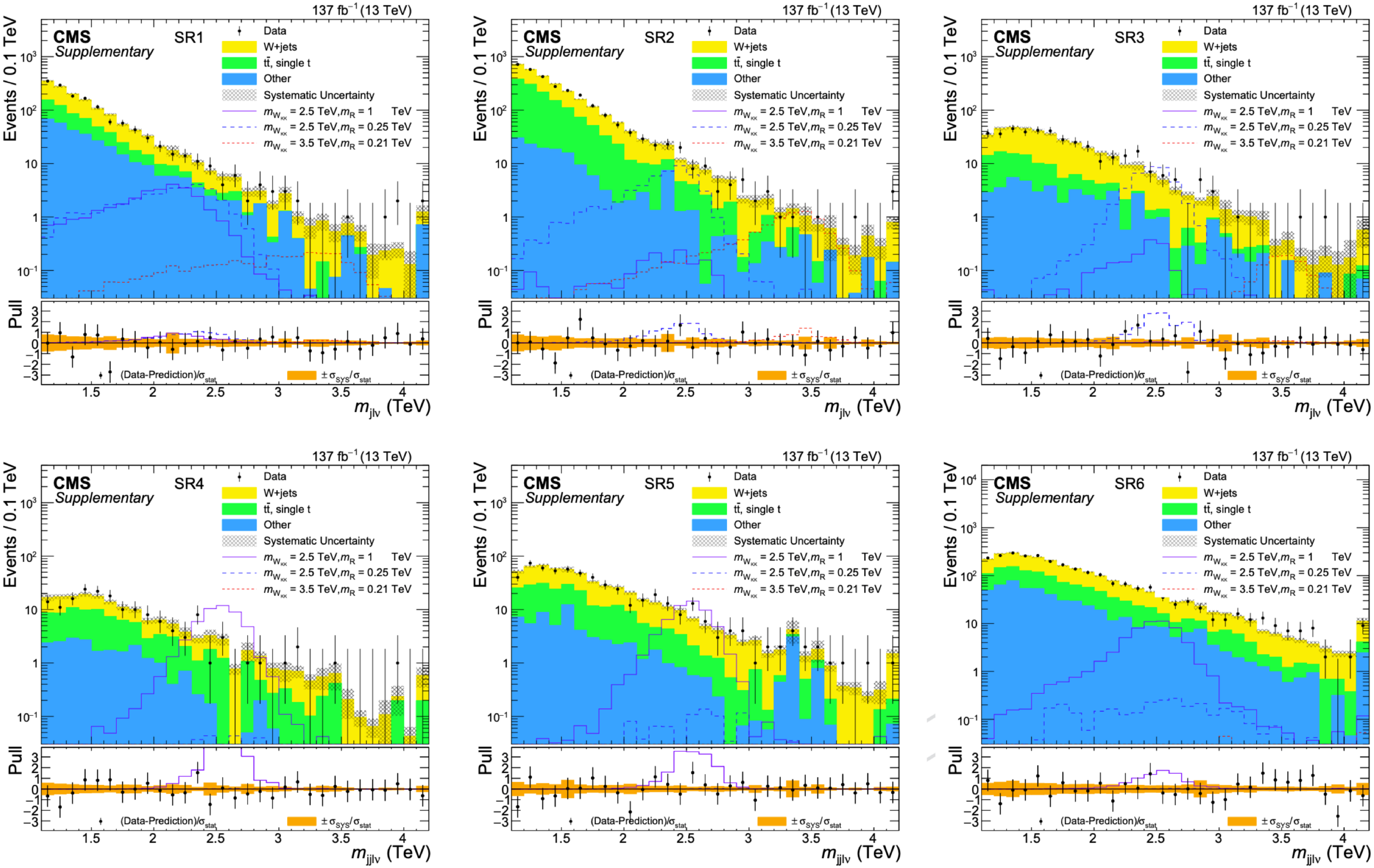


4. **High-pT extrapolation**
   Signal jets much more boosted wrt SM. Generate herwig++ signal, use % diff. wrt pythia8 as unc.

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

CMS-PAS-B2G-20-001

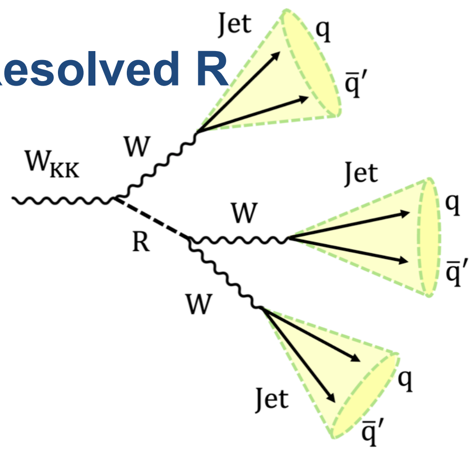
SR1-6 Postfit Results

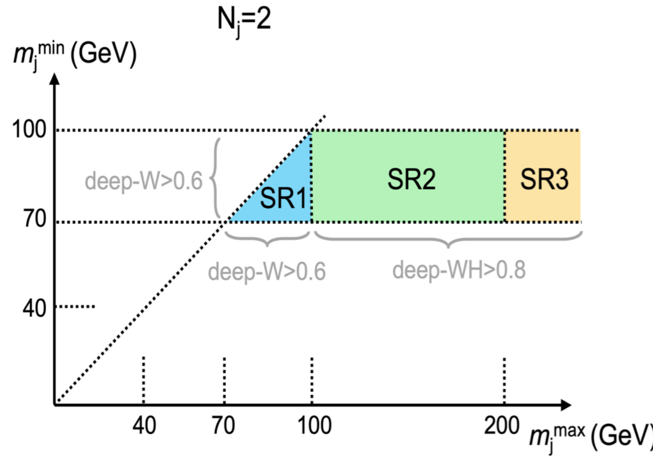


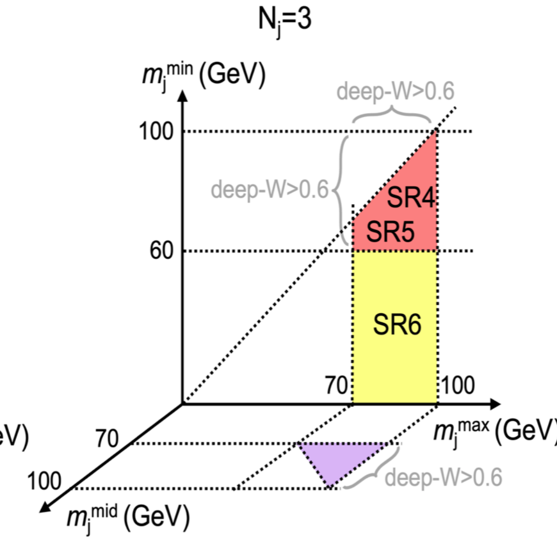
$W_{KK} \to WR \to WWW \to jets$

CMS-PAS-B2G-21-002

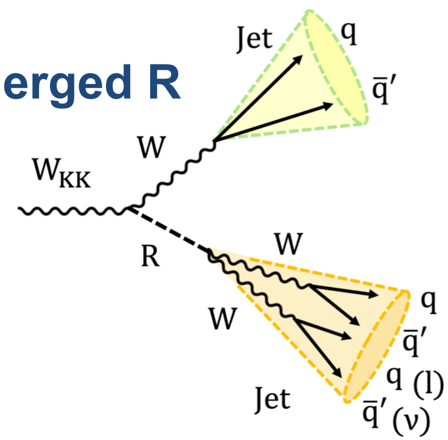
Resolved R



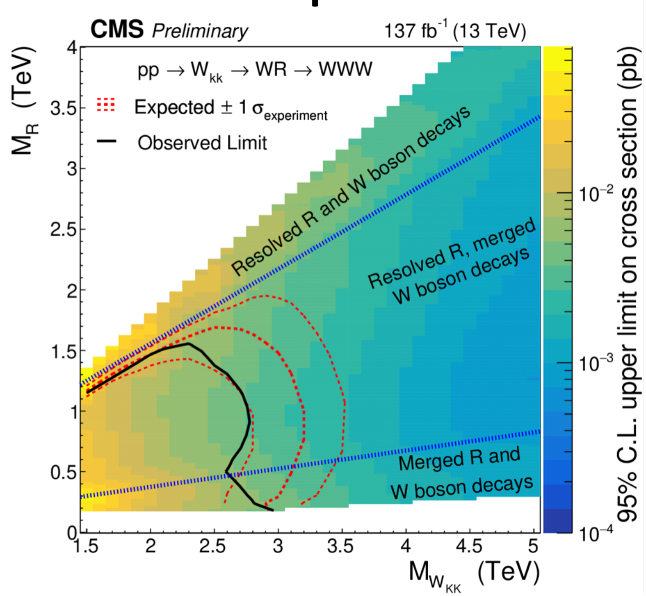




Merged R



0-lep limit



combination