Searches for heavy resonances decaying into Z, W, and Higgs bosons at CMS

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On behalf of the CMS Collaboration

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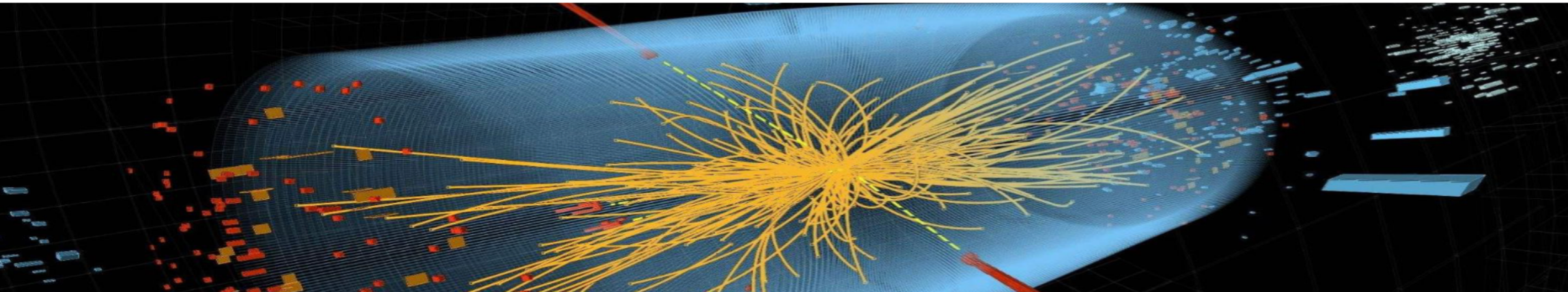


Introduction

- New CMS results related with searches for heavy resonances decaying into Z, W, and Higgs bosons using full Run-2 data:

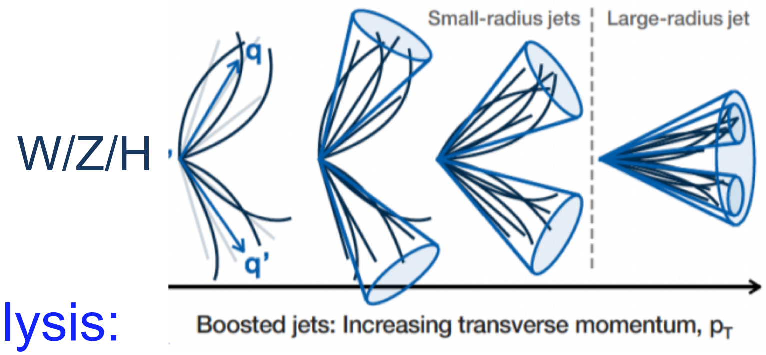
Search for resonant pair production of new particles decaying to pairs of b quarks in the boosted regime	**CMS-PAS-B2G-20-003**
Search for resonant production of HH to 4b in boosted and semi-boosted topologies	**CMS-PAS-B2G-20-004**
Search for resonant production of HH decaying to bb and leptons	**CMS-PAS-B2G-20-007**
Search for diboson resonances in ZV/H to llqq/bb final states including axion-like particles	**CMS-PAS-B2G-20-013**
Search for resonances decaying into WVV in the single lepton final state	**CMS-PAS-B2G-20-001**
Search for resonance decays to triple W-boson in full hadronic final states using 13TeV full Run-2 pp collision data	**CMS-PAS-B2G-21-002**

Jet tagging

Boosted objects → small angular separation → merged jets

(W/Z → qq; H → bb/qqqq/qqlv)

- large-radius jets
- Jet grooming



Techniques for a successful boosted analysis:

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

- ratios: $\tau_{21} = \tau_2/\tau_1$ to tag 2-prong objects
- Designing decorrelated taggers (DDT)

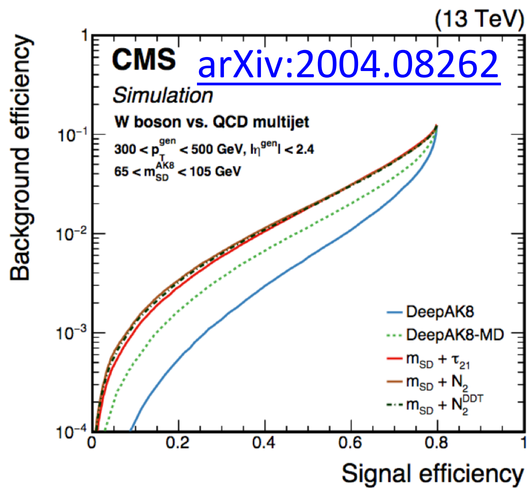
➢ DeepAK8 tagger

- multi-class tagger for t/W/Z/H tagging
- use PF candidates and secondary vertices

➢ Double-b tagger

- discriminate H → bb decays
- combine information from displaced tracks, secondary vertices as inputs to a BDT

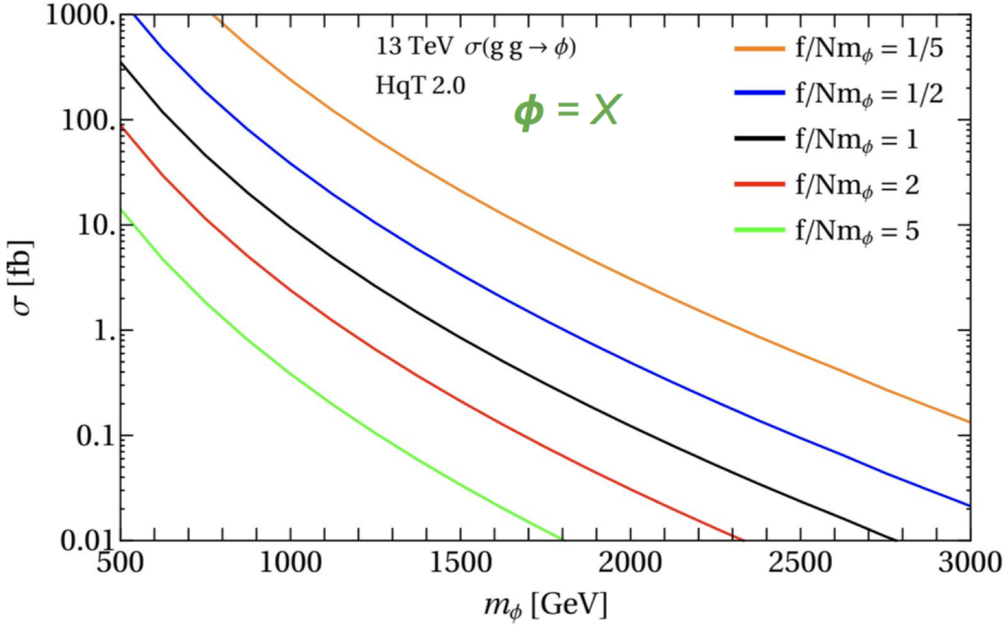
Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)



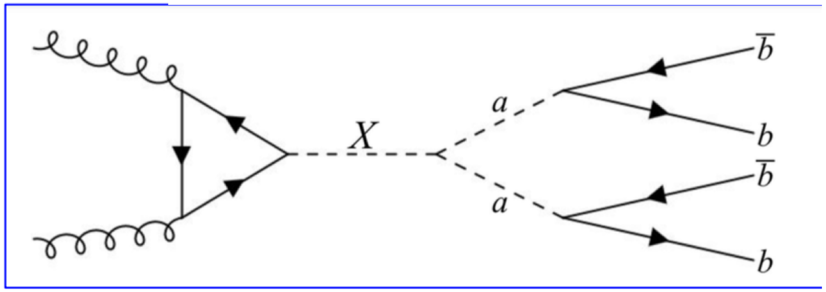
Physics Models

- Signature is a heavy scalar **X** decaying to two light scalars **a**.
  - **a** assumed to decay with 100% BR to pairs of **b**-quarks
  - Analysis considers **a** ∈ [25, 100] GeV and **X** ∈ [1, 3] TeV
  - No previous searches from CMS or ATLAS for this signature, though boosted **X** → **hh** has similar final states.

- Reference models:
  - Covers NMSSM, Higgs Doublet, 2HDM

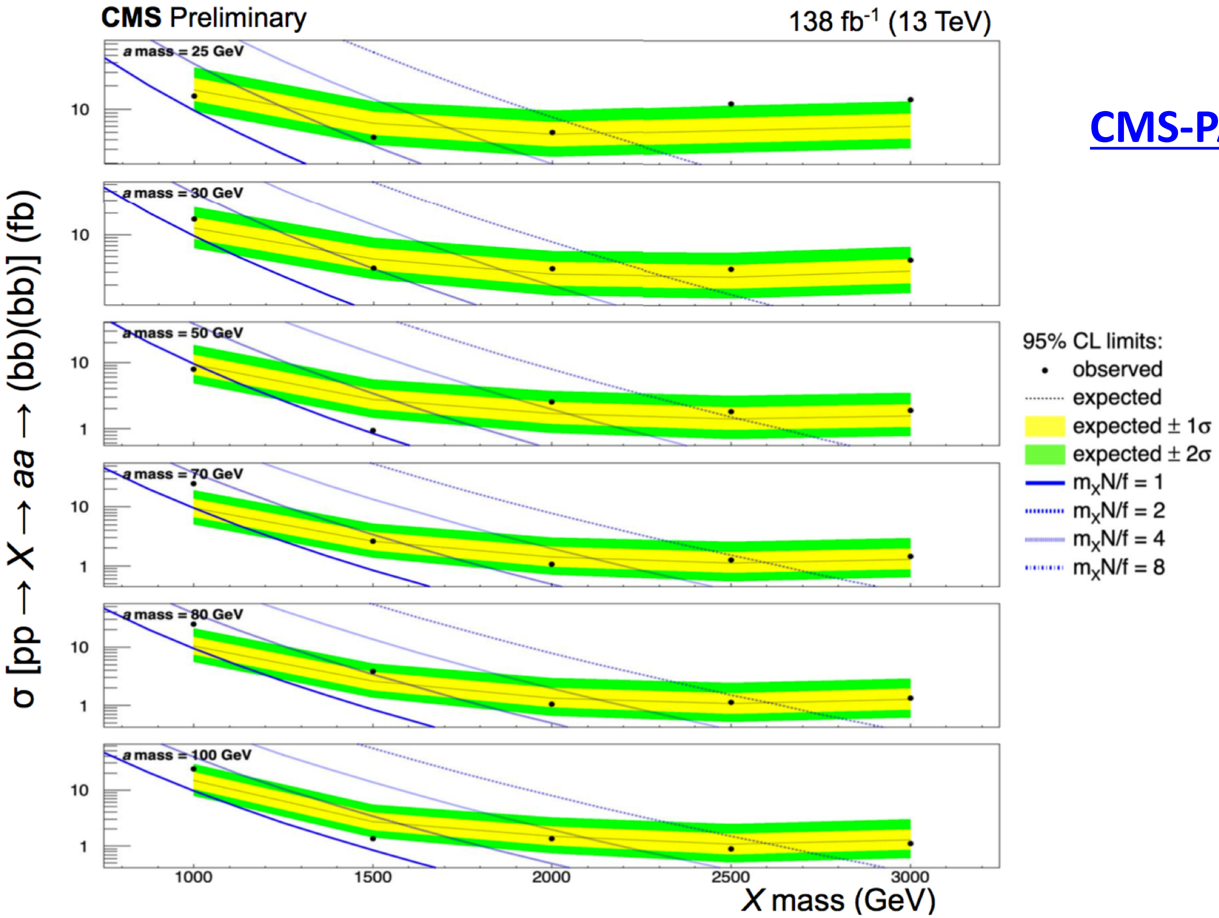


[CMS-PAS-B2G-20-003]



95% CL Exclusion Limits

- V, VV and top backgrounds considered (even with huge normalization uncertainty), but had no effect on slight excess. Many points correlated.
- 95% CL exclusion limits shown on the same plane:
  - Useful for talking about excluded phase space.

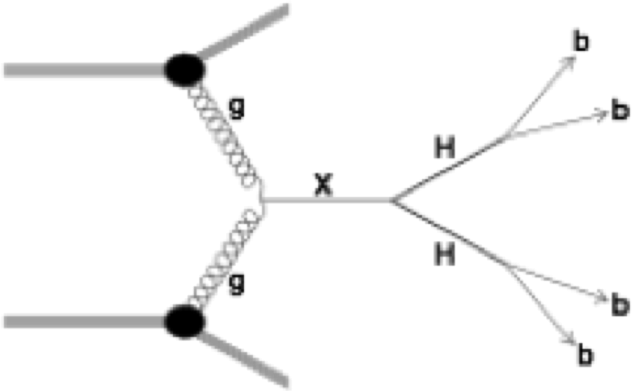


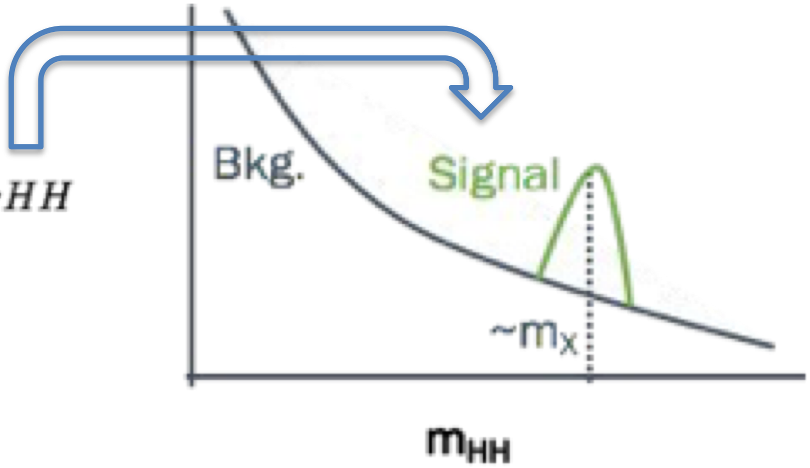
CMS-PAS-B2G-20-003

Boosted Higgs boson pairs

- Many models predict resonance ”X” decaying to HH
  - Warped ED, RS models, extra singlets
- Massive X => Lorentz-boosted Higgs bosons
- Efficient to reconstruct using large-area jets and substructure variables
- Boosted b tagging to reject multijet backgrounds
- Resonant X signal: a bump on falling m_{HH} background

[CMS-PAS-B2G-20-004]

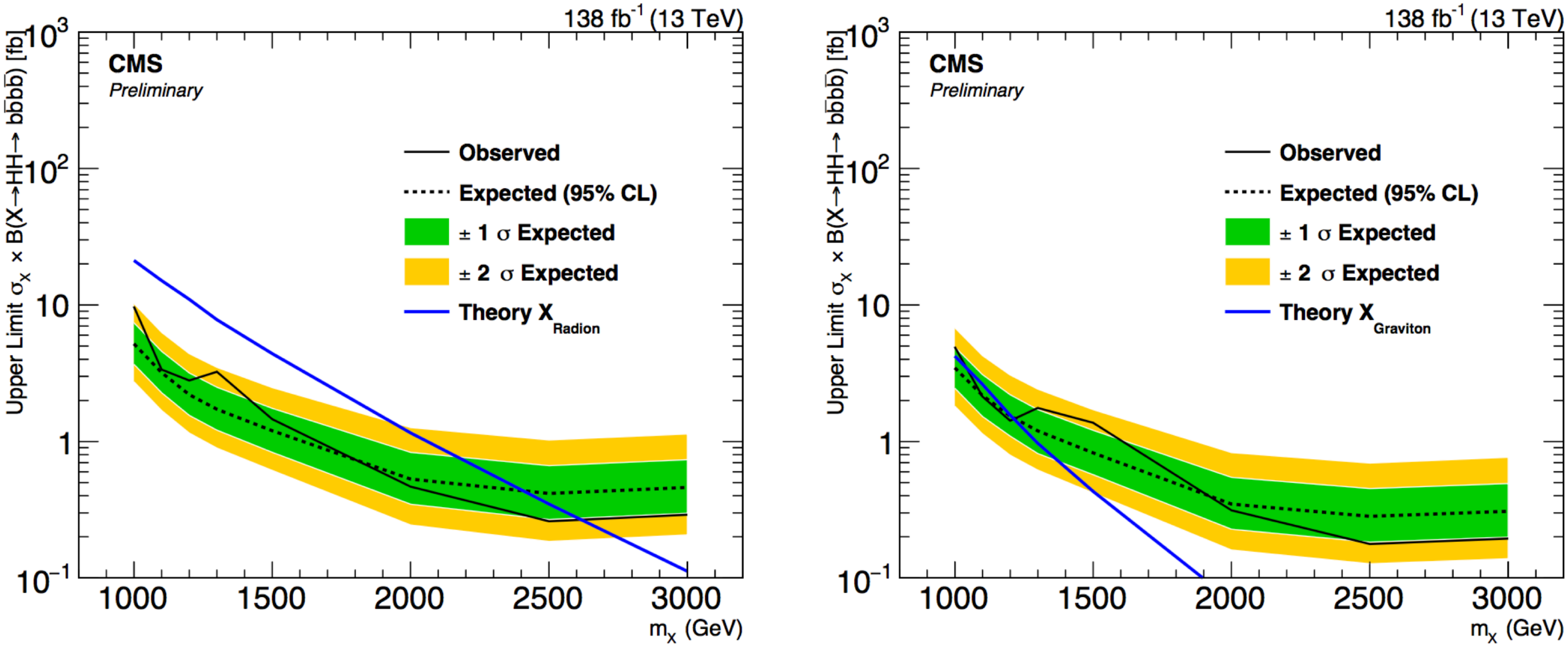


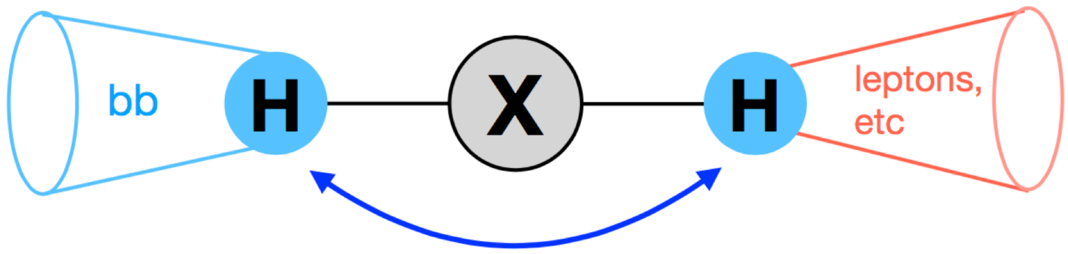


Unblinding limit with 2x2 fit function

CMS-PAS-B2G-20-004

- No significant excess over background only hypothesis.
- Most Significant local excess: 1.9 sigma at 1.5 TeV





CMS-PAS-B2G-20-007

Model-independent search for spin-0 or spin-2 X boson from 800 GeV to 4.5 TeV

Decays to two boosted Higgs bosons in opposite directions

One Higgs decays via H→bb

Boosted → reconstruct as large radius (AK8) jet with substructure

Soft-drop mass m_{bb} of the jet is one of two search variables

Other Higgs decays into a final state with leptons

H→WW* (one off-shell W) and H→ττ considered

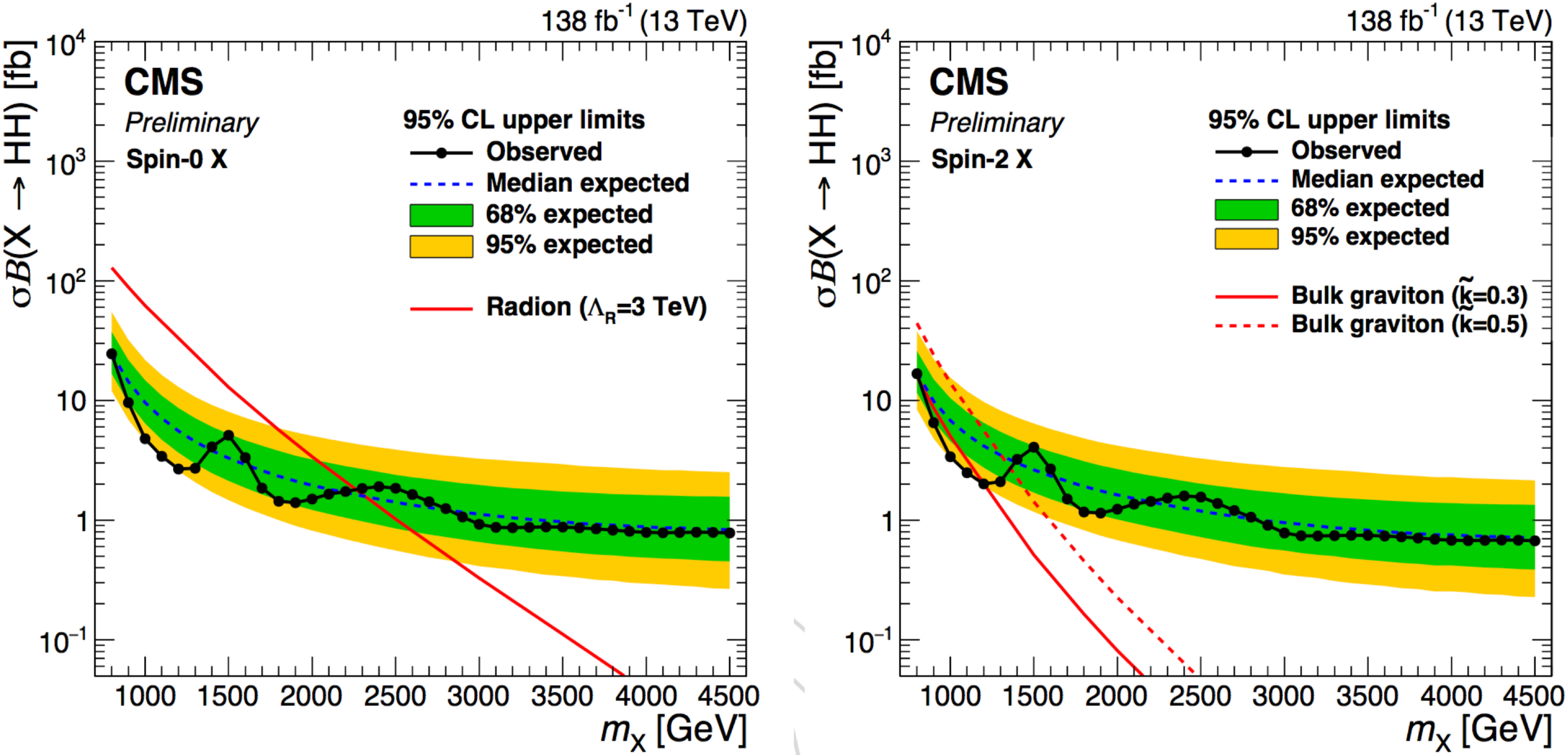
Different strategies for reconstructing momentum of leptonic H boson

Invariant mass of H→bb and leptonic H boson, m_{HH}, is second search variable

Simultaneous fit in 2D m_{bb}-m_{HH} plane to extract background and look for signal

Limits

[CMS-PAS-B2G-20-007](CMS-PAS-B2G-20-007)

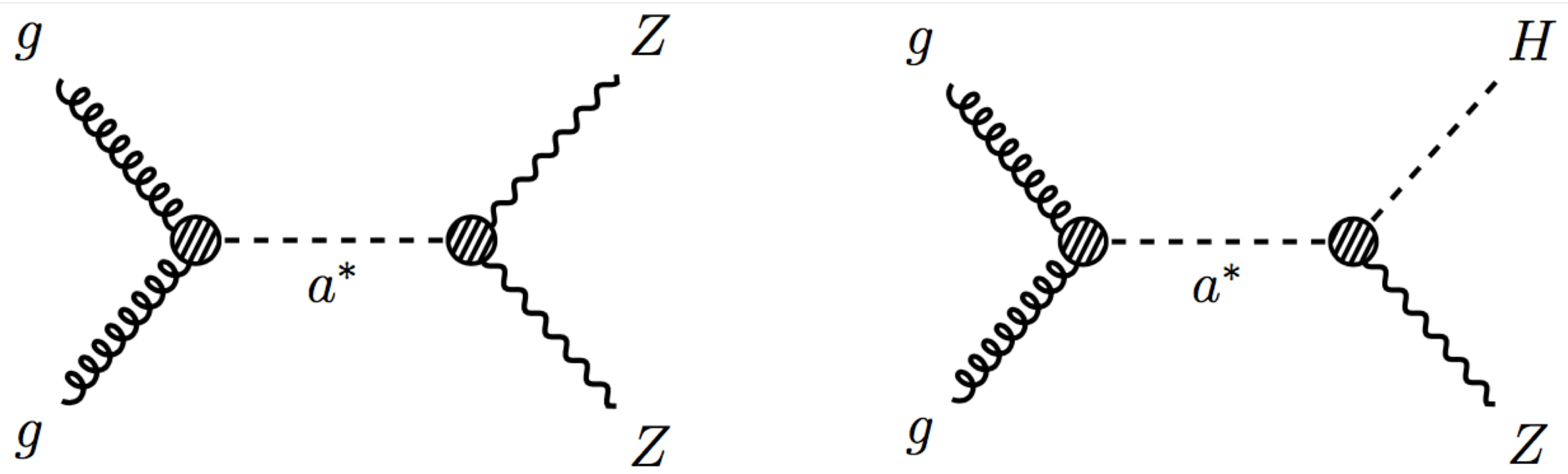


Spin-2 limits ~ 20% stronger than spin-0 due to larger signal acceptance

More central angular distribution of HH decays

GGF ALP-Mediated Processes

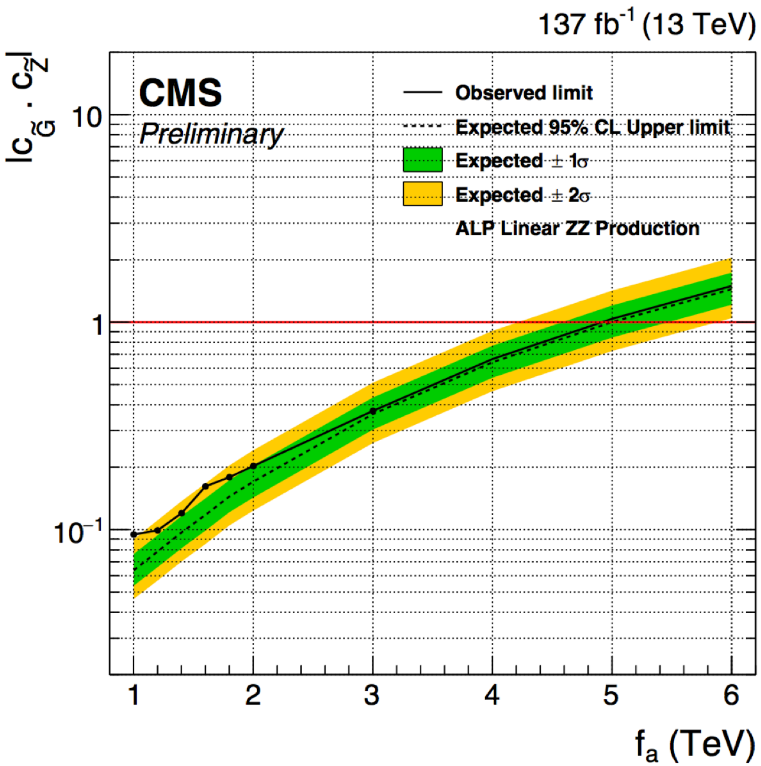
- Gluon-initiated ALP-mediated processes provide new possibilities to test the ALP universe beyond classical searches. CMS-PAS-B2G-20-013
- These channels are sensitive to the product of the ALP coupling to gluons times the coupling to EWK dibosons.

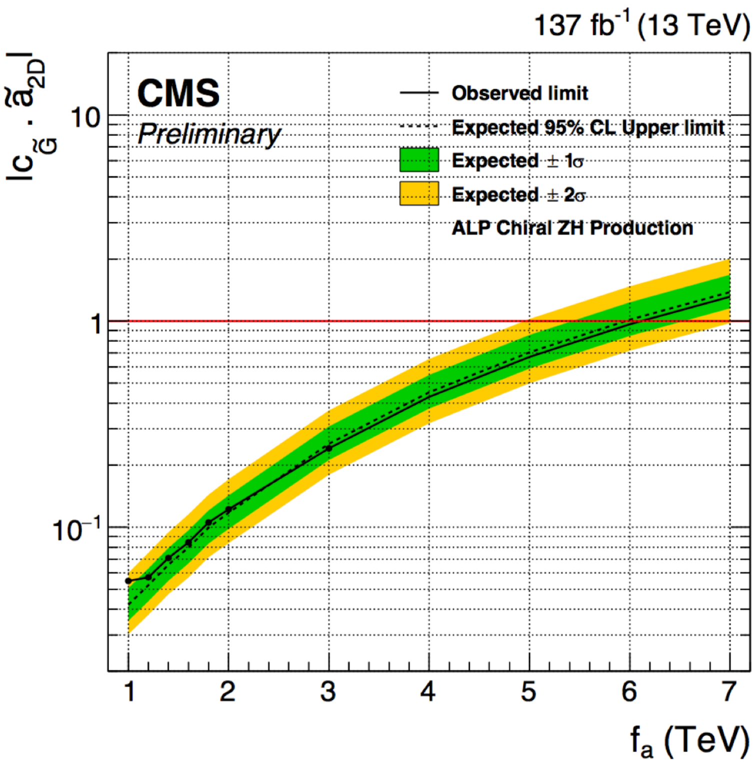


Gavela, No, Sanz, Trocóniz; PRL 124 (2020) 051802

Observed and Expected ALP Limits: ALP chiral ZH

CMS-PAS-B2G-20-013





- **Expected and observed 95% CLs upper limits on $\sigma(gg \rightarrow a^* \rightarrow ZZ/ZH)$ (fb) for f_a = 3 TeV.**

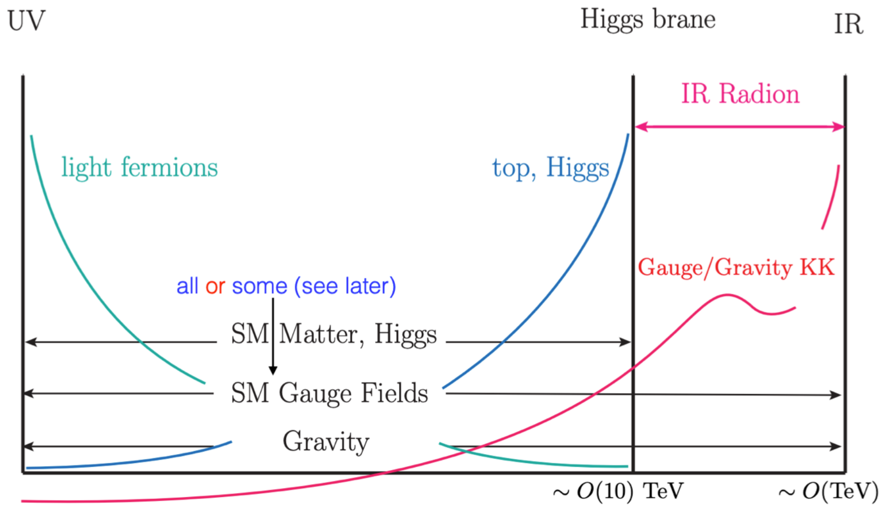
Model	2.5%	16%	50%	84%	97.5%	Observed
ALP linear ZZ	79	107	151	218	304	162
ALP chiral ZH	32	39	64	94	134	57

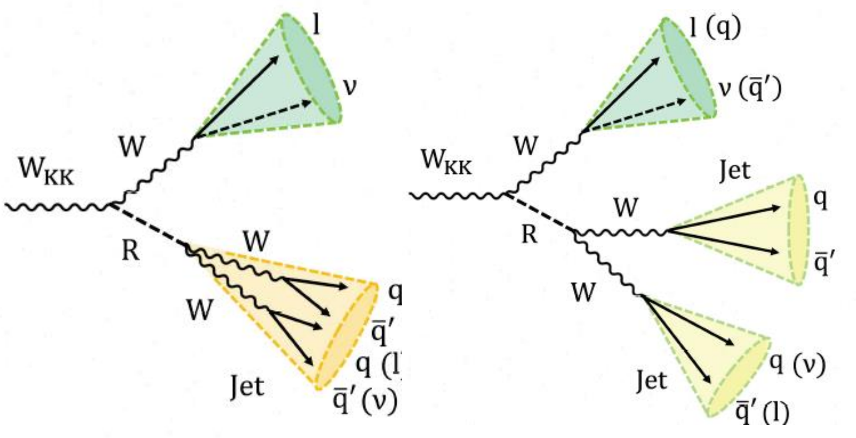
Tri-boson resonance

- First search for resonances decaying in cascade to final state with 3 W bosons

[CMS-PAS-B2G-20-001]

- Extended Warped ED model :
  - ➢ Extra brane by splitting the Bulk ([arXiv:1711.09920] , [arXiv:1612.00047]);
  - ➢ Only EW bosons in the extended bulk → dominant: $\mathrm{V_{KK}} \rightarrow \mathrm{R\ V} \rightarrow \mathrm{VVV}$
    - – WWW having the largest contribution





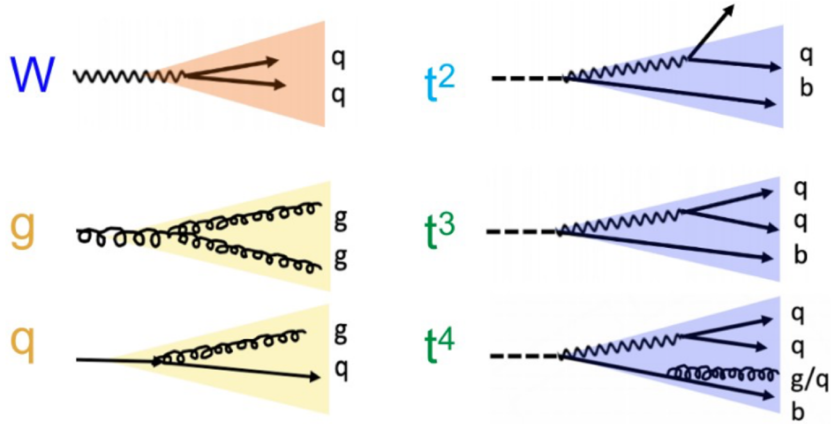
Merged R   Resolved R

- Various fields propagate in different regions
- "di-SM" suppressed in favor of "tri-SM"

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

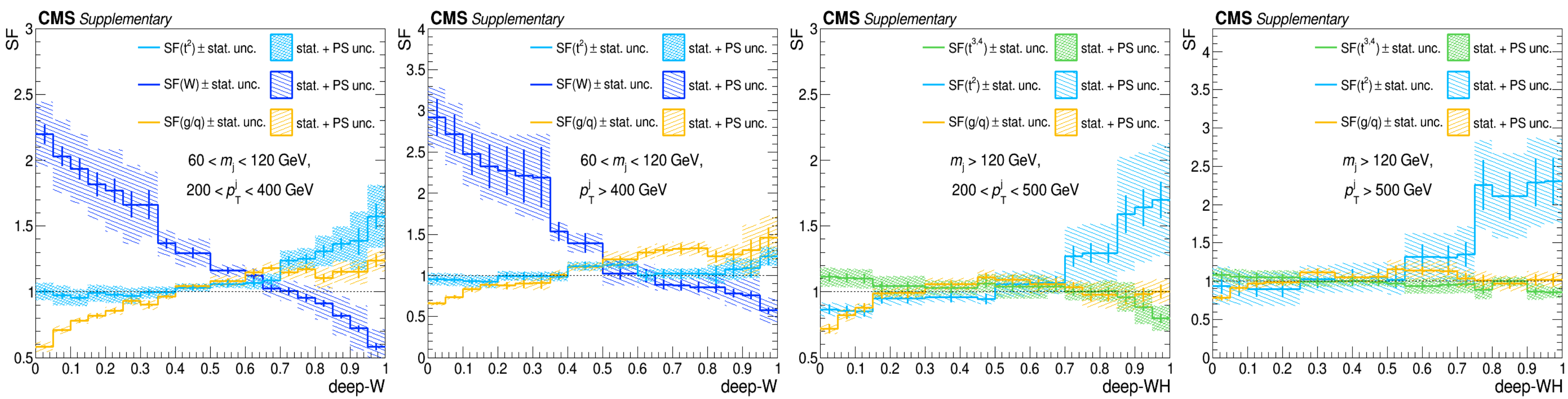
DeepAK8 tagger calibration

- Calibrate deep tagger discriminant shape using SM proxies:



[CMS-PAS-B2G-20-001](CMS-PAS-B2G-20-001)

- Apply parton-level matching and correct MC shapes bin by bin

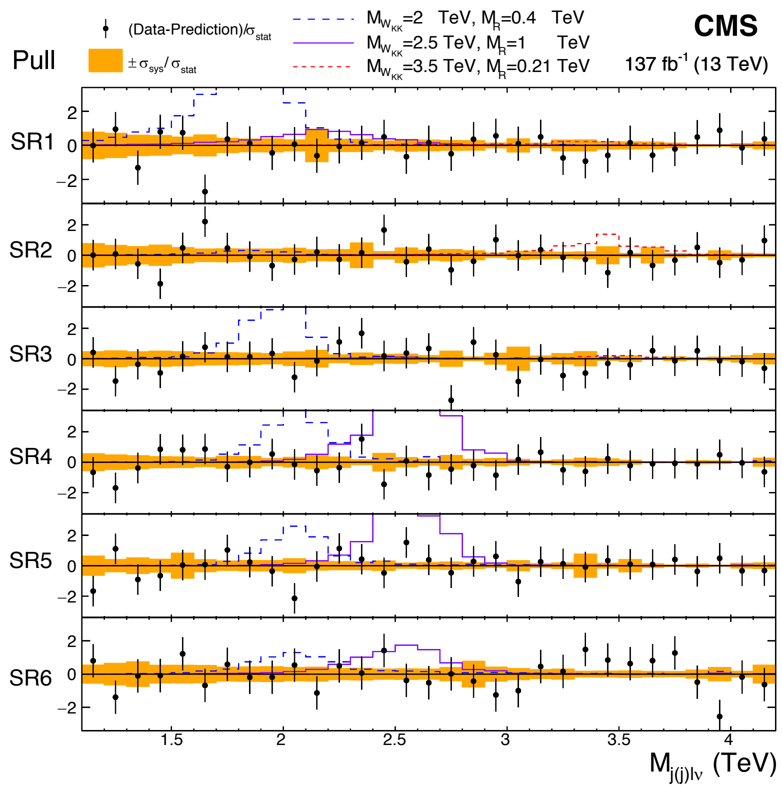


- Use these SFs to correct all jets for both BKG and signal

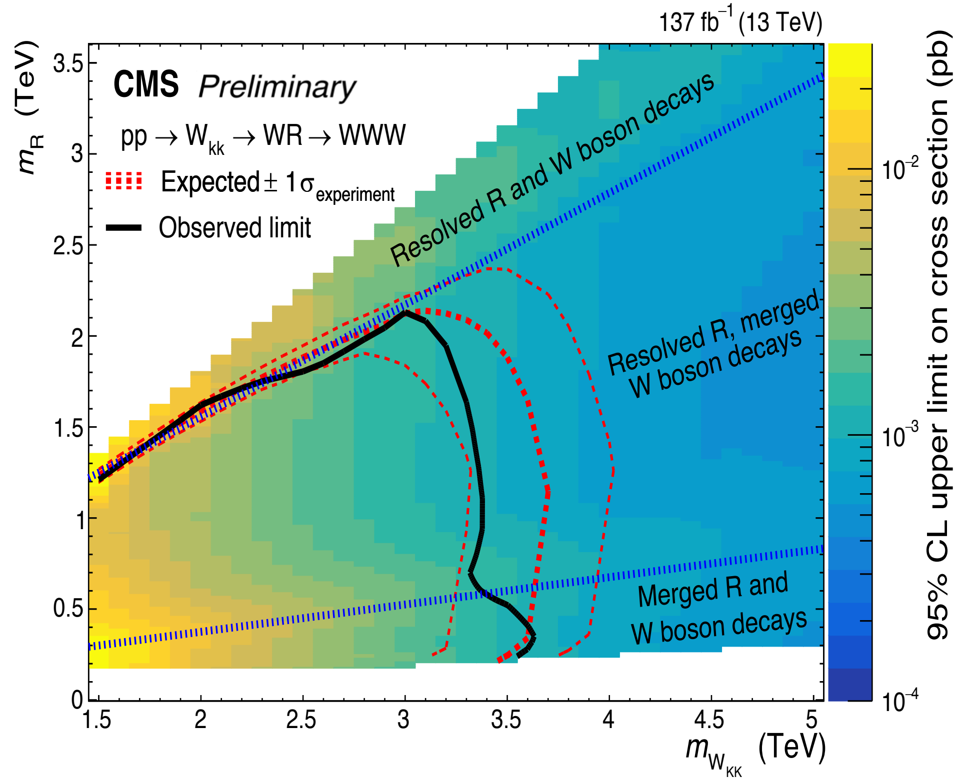
Results and limit

CMS-PAS-B2G-20-001

- Combined fit of six signal regions. (No excess over the background estimation is observed.)



- Limits in 2D W_{KK} vs. R mass plane. The first of their kind!

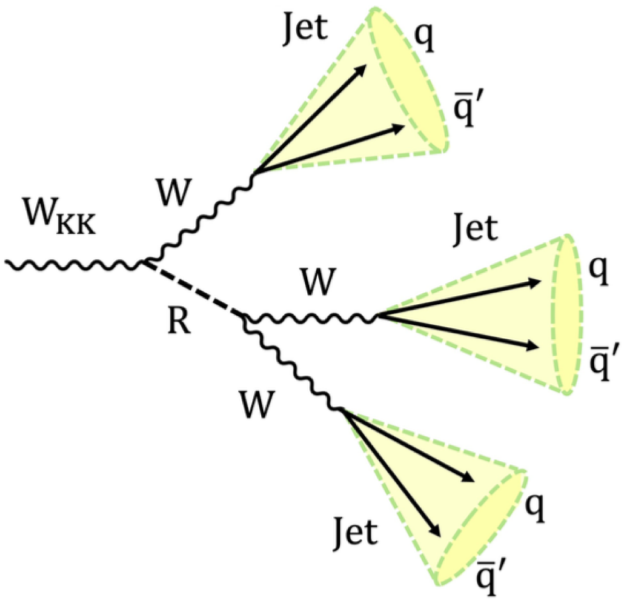


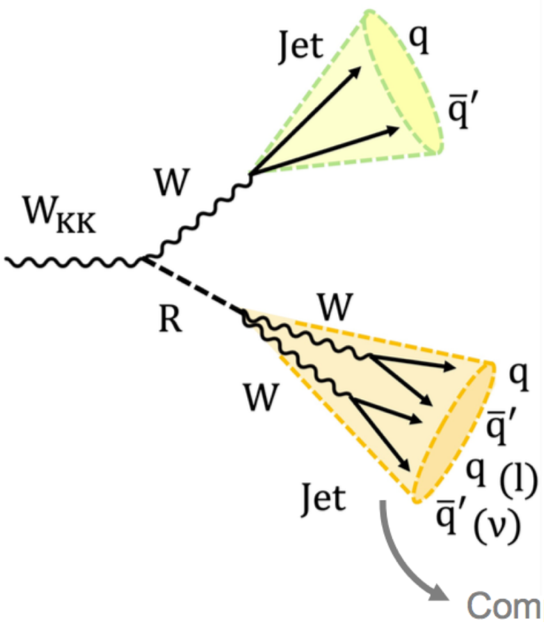
- The triboson resonances are excluded up to m_{WKK} = 3.4 (3.6) TeV for m_R = 1 (0.35) TeV.
- WKK masses below 3 TeV are excluded for $0.06 < m_R/m_{WKK} < 0.7$.

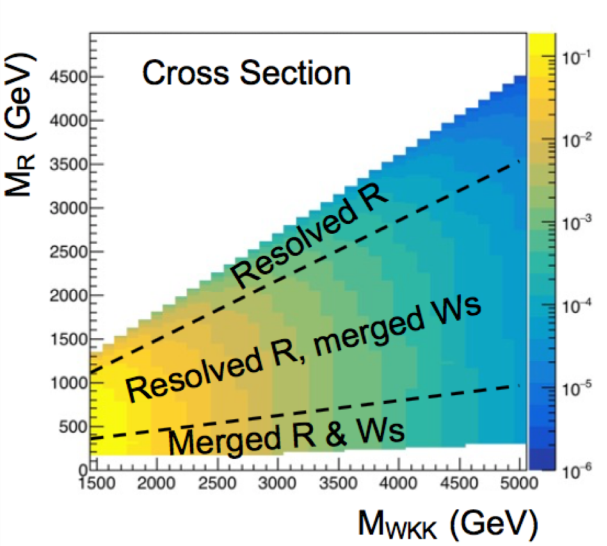
Signal profile for tri-boson 0-lep final state

CMS-PAS-B2G-21-002

Resolved Radion (R) **Merged** Radion (with potential leptonic decay inside R)



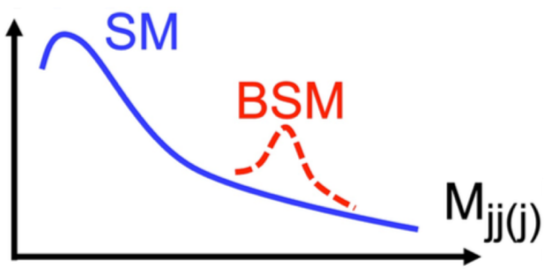




Clear objective:

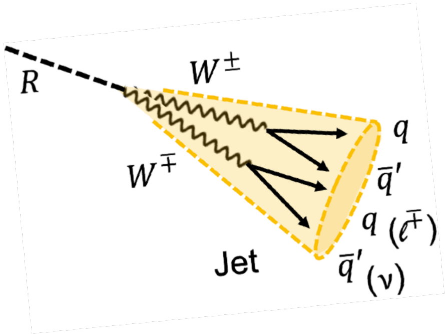
- Hunt a Reso formed by 3 or 2 massive jets

- **Resolved → 3 AK8 jets** → search for reso at M_{jjj}
- **Merged → 2 AK8 jets** → search for reso at M_{jj} (Binning over merged radion mass, i.e. m_{jmax})



Calibration for signal

CMS-PAS-B2G-21-002

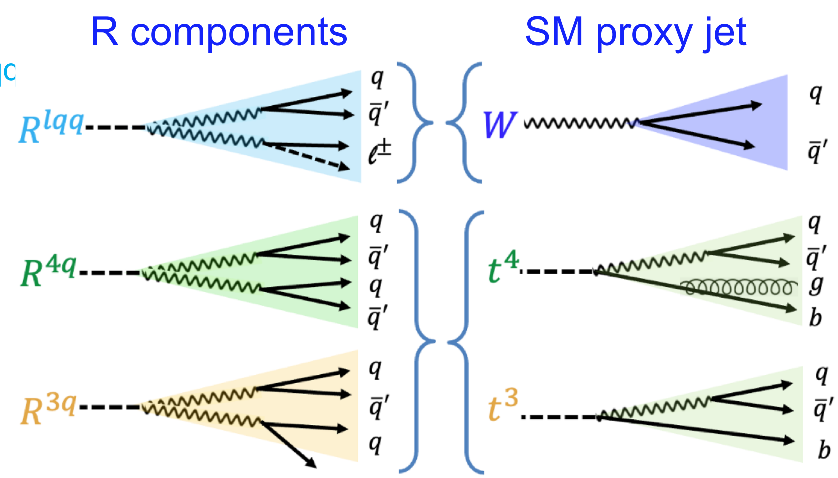


Merged Radion jet≈ R^{4q} + R^{3q} + R^{lqq}

Need special calibration

– no standard candle

1. Observe similarity between W↔R^{lqq} jets
   → we apply scale factors for W, SF(W), on R^{lqq}
2. 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}
3. The difference between the performances of the SM candle and signal is taken into account as the systematic uncertainty.

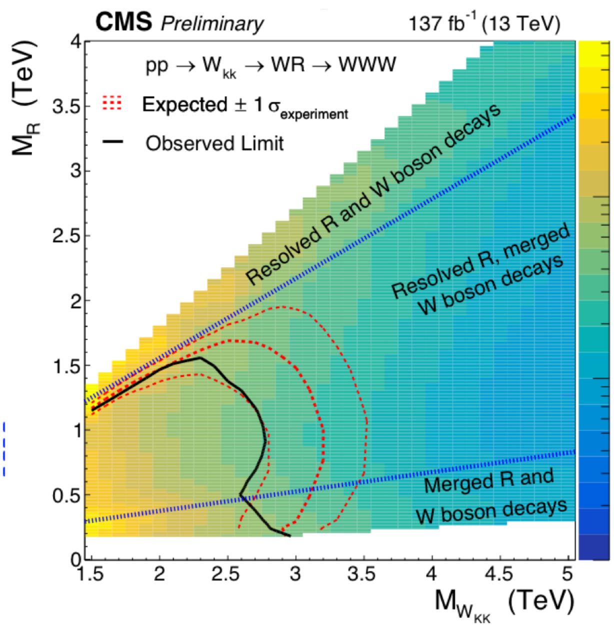


Results and limit

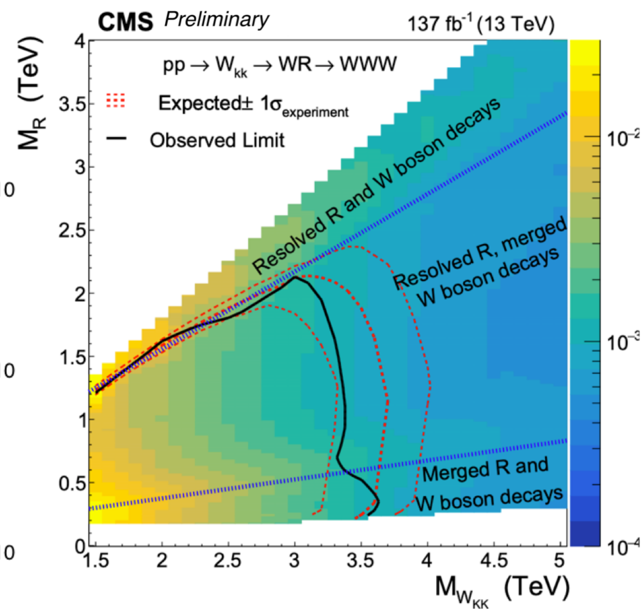
- We set upper limits on X → RW → WWW cross section, lower limits on $M_{W_{KK}}$, M_R masses (Asymptotic approximation)

CMS-PAS-B2G-21-002

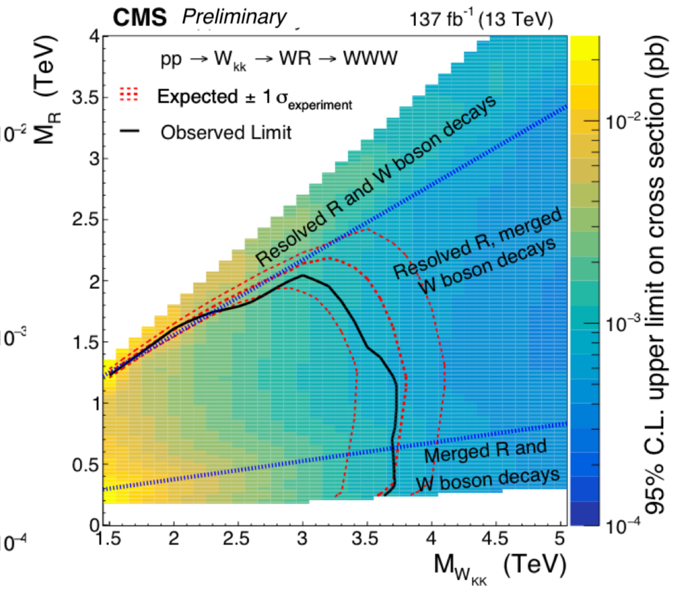
0-lep (B2G-21-002)



1-lep (B2G-20-001)



1- & 0-lep (Combination)



- Observed limit is ~1σ weaker wrt to the expected for resolved signal. This is due to the excess at SR4, at 3.0 TeV (not compatible with signal)

- Combination of B2G-21-002 with B2G-20-001 (1+0 lep.): Systematics on SFs correlated (apart from $SF_{q/g}$), as well as PU, PDFs, μ_R, μ_F All the rest uncorrelated.

Summary

- Rich phenomenology & final states ZH, WV, WH, WWW, clear experimental signatures
- The use of jet substructure enables the search for heavy bosons resonances
- No evidence for new physics observed yet, 95% CL limits are set.
- More results to come out, and follow also here to keep track!
  - CMS publications

Analysis Selection

- **Preselection:**
  - Event HT > 900 GeV (reconstructed from ak4 jets with |η| < 2.4 & p_T > 30 GeV)
  - Two Jets with |η| < 2.4 & p_T > 300 GeV
  - Tight jet ID (not muon-veto) applied to both jets
  - Using "Double-b tagger" for tagging. **ARC:** *ML taggers sculpted low mass!*
- Now use three quantities to divide remaining events into six region:
  - Mass asymmetry = (m1 - m2)/(m1 + m2)
  - Double-b tagging score of the leading jet: D^{bb}_{j1}
    - *Previously part of preselection*
  - Δη between the two jets
- These selections optimized using QCD and Signal MC to maximize s/√b (or punzi significance), with preference given to low **a** mass signals

CMS-PAS-B2G-20-003

	m_{asym}	$\Delta\eta$	D^{bb}_{j1}
tight search region	< 0.1	< 1.5	> 0.8
loose search region	$\in [0.1, 0.25]$	< 1.5	> 0.8
tight $\Delta\eta$ sideband	< 0.1	> 1.5	> 0.8
loose $\Delta\eta$ sideband	$\in [0.1, 0.25]$	> 1.5	> 0.8
tight double-b sideband	< 0.1	< 1.5	$[-0.8, 0.3]$
loose double-b sideband	$\in [0.1, 0.25]$	< 1.5	$[-0.8, 0.3]$

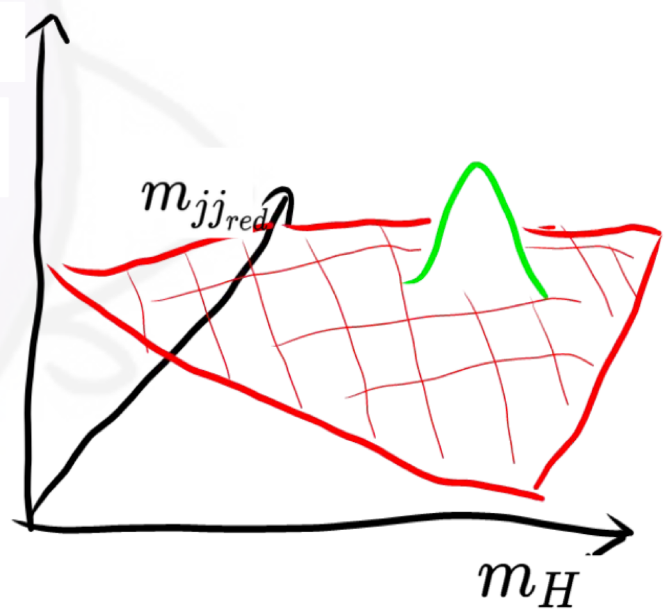
CMS-PAS-B2G-20-004

Analysis strategy:

- 2D likelihood fit over the m_H vs $m_{jj_{red}}$ space
  - Can blind an m_H signal region
- Simultaneous fit for signal and all backgrounds

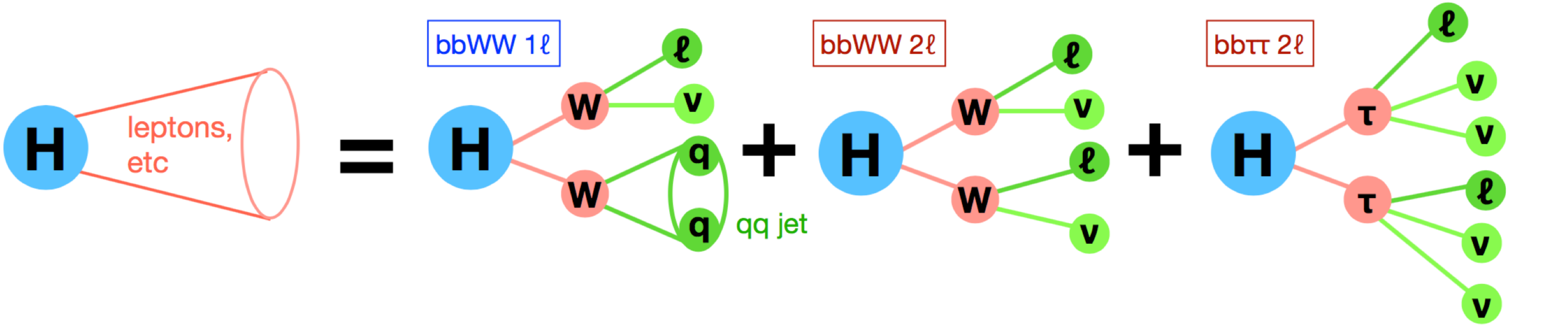
- Non-resonant bkg from data
- Resonant backgrounds from MC
  - Allowed to morph during fit via shape and normalization uncertainties

- Signal parameterized via templates as well



Leptonic Higgs boson

[CMS-PAS-B2G-20-007](CMS-PAS-B2G-20-007)



Only collect final state muons and electrons

- We are sensitive to W → τν → (e/μ) νν

Single-lepton (1ℓ) channel

Reconstruct W→qq as large radius (AK8) jet with substructure

- No mass constraint since W can be on- or off-shell

Lepton is often very close to the qq jet, sometimes overlapping

- Loose IDs and isolation, tailored for leptons in jets

Dilepton (2ℓ) channel

No jet → cleaner event than in 1ℓ

- IDs and isolation different than in 1ℓ

Looser impact parameter constraints to remain sensitive to leptons from ττ

GGF ALP-Mediated Non-Resonant Diboson Production

CMS-PAS-B2G-20-013

- Off-shell ALP production. This is very promising because the cross-sections are large enough to constraint significantly the theoretical models using Run 2 data.
- ALPs are s-channel mediators in $gg \rightarrow$ VV production with s-hat >> M_a^2. The size of s-hat is enhanced by the mass threshold of the on-shell diboson system in the final state; but most importantly by the hard pT-spectrum provided by the derivative couplings.
- The analysis uses the ZV, WW, ZH searches looking for high-pT / high-mass deviations in the tails of the transverse momentum / mass spectra with respect to SM expectations.
- For ALPs light enough the cross-sections, kinematical distributions, and expected limits are found independent of M_a, from the very-light limit up to masses of the order of 100 GeV.

Signal region

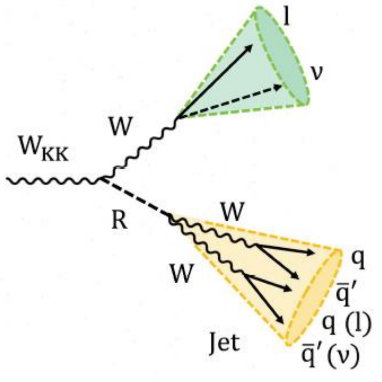
[CMS-PAS-B2G-20-001]

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

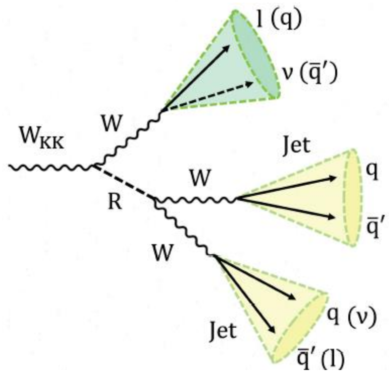
- Split to 6 signal regions based on:

➢ Merged: (SR1-3)
  - single massive large-radius jet
  - Bin over M_R: 60-100-200-... 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



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