New results from CMS on the search for VV/VH/HH resonances in Run 1

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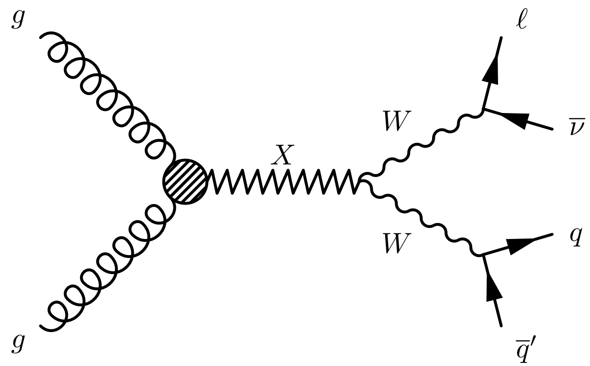
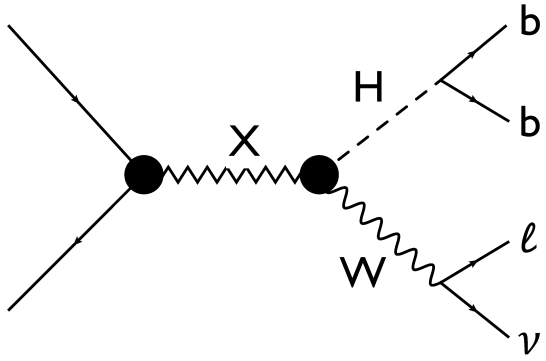
Outline of the talk

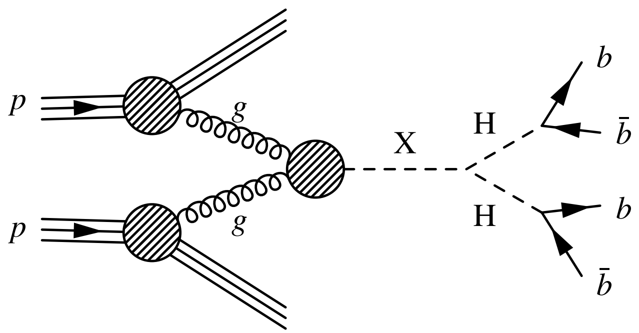
- Di-boson resonance models
- Final state overview
- WW/WZ/ZZ resonance searches



- WH/ZH resonance searches



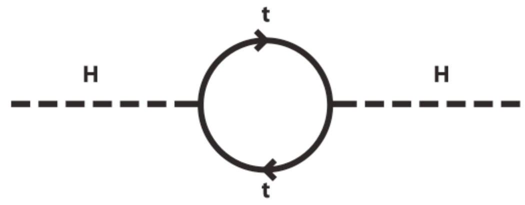
- HH resonance searches



Di-boson resonance models

- Big question: Hierarchy problem
  - If new physics happens at the Planck scale radiative corrections to the Higgs mass need to be fine-tuned in new physics theory to cancel at electroweak scale

Higgs mass at EWK scale
m_H=125 GeV/c^2



- New supersymmetric (SUSY) particles cancel the radiative corrections
  - Two Higgs double models, SUSY MSSM
    - h,H,A,$H^\pm$ → di-boson searches, mass ≤ 1 TeV

- Extra dimensions reduce the effective Planck scale
  - Bulk scenario of RS model → di-boson searches, mass ≥ 0.5 TeV
  - spin-2 gravitons, spin-0 radions decaying mainly to W_L,Z_L,H

- Higgs is composite object and its mass generated by a new interaction
  - Heavy Vector Triplet (scenario B) → di-boson searches, mass ≥ 0.5 TeV
  - spin-1 $W'^\pm$ and Z' (like $\rho^\pm$, ρ^0 in nuclear physics) decaying mainly to W_L,Z_L,H

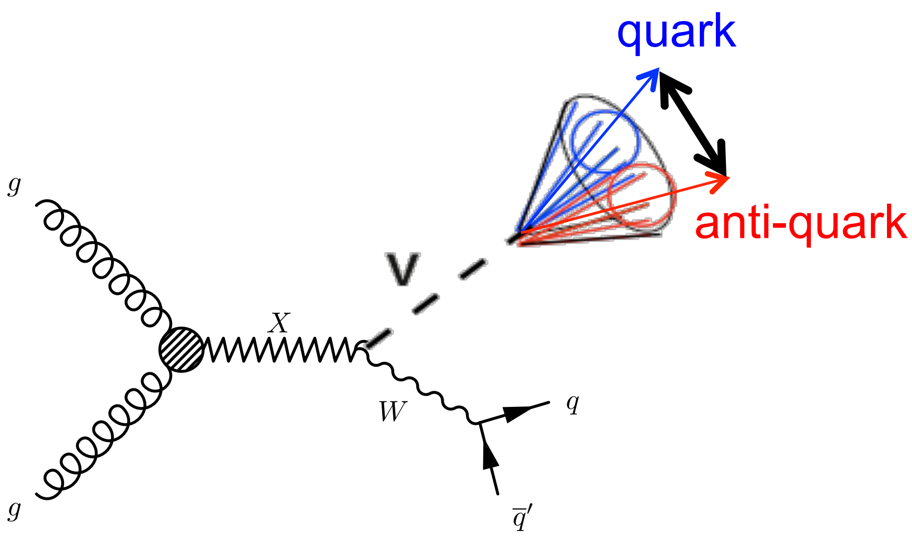
Di-boson final states

- Searches for WW, WZ, ZZ, WH, ZH, HH resonances with mass ≥ 1 TeV
  - Only listing searches where boosted W/Z/H bosons are considered

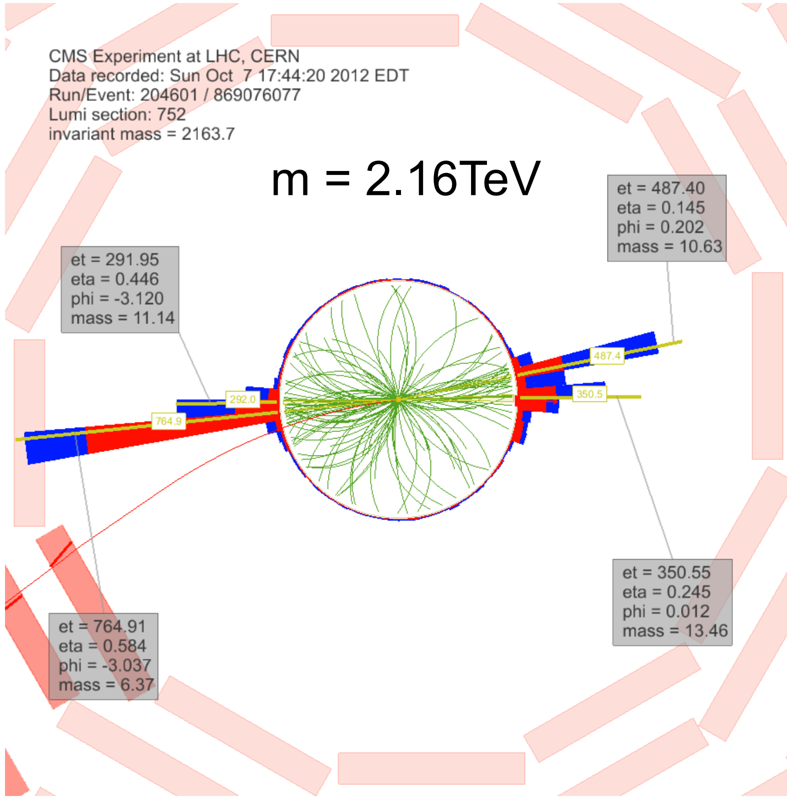
	W	Z	H
W	qqqq (EXO-12-024) lvqq (EXO-13-009, HIG-13-031)	qqqq (EXO-12-024) lvqq (EXO-13-009) llqq (EXO-13-009) lvll (EXO-12-025)	qqbb (EXO-14-009) lvbb (EXO-14-010) qqττ (EXO-13-007)
Z		qqqq (EXO-12-024) llqq (EXO-13-009, HIG-13-031)	qqbb (EXO-14-009) qqττ (EXO-13-007)
H			bbbb (EXO-12-053)

BOOST 2014 and before
New in 2014+2015
New at BOOST 2015

Final states with boosted W/Z/H



$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}}$$



- Above W,Z(H) p_T>200(300) GeV quarks merge into R=0.8 jet
- Discrimination based on jet substructure in Run 1 di-boson analyses
  - Reconstruct W/Z/H with CA R=0.8 jet
  - Pruned jet mass → expected at W/Z/H mass
  - N-subjettiness τ_2/τ_1 → Should look like composed of two smaller jets
  - Calibrated in semileptonic ttbar sample containing real boosted Ws

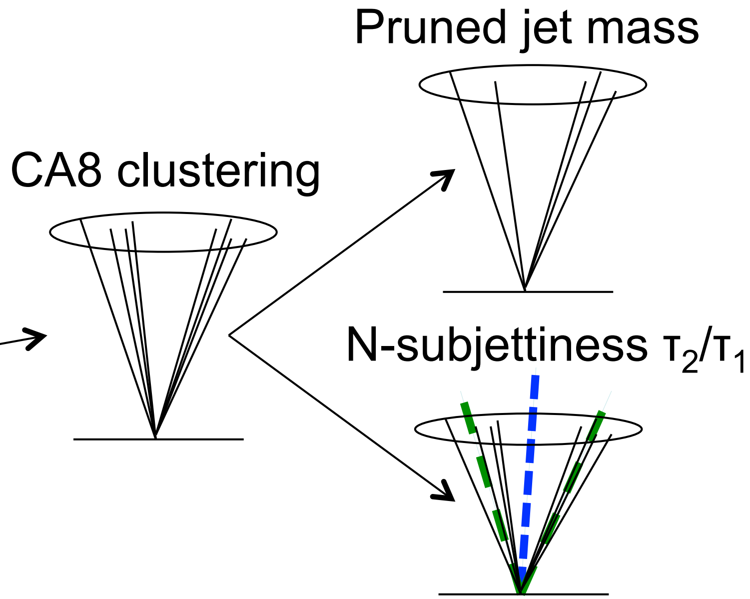
Details in backup

Analysis flow

Trigger event

↓

Reconstruct two bosons
W(lν), Z(ll), H(ττ)
W(qq), Z(qq), H(bb), H(WW→qqqq)



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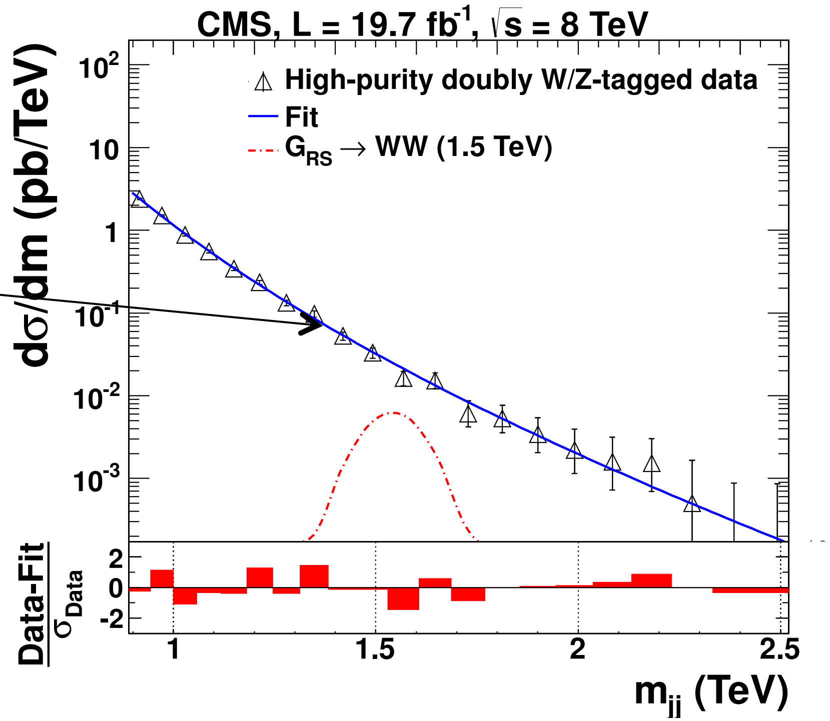
Reconstruct VV/VH/HH invariant mass

↓

Estimate background



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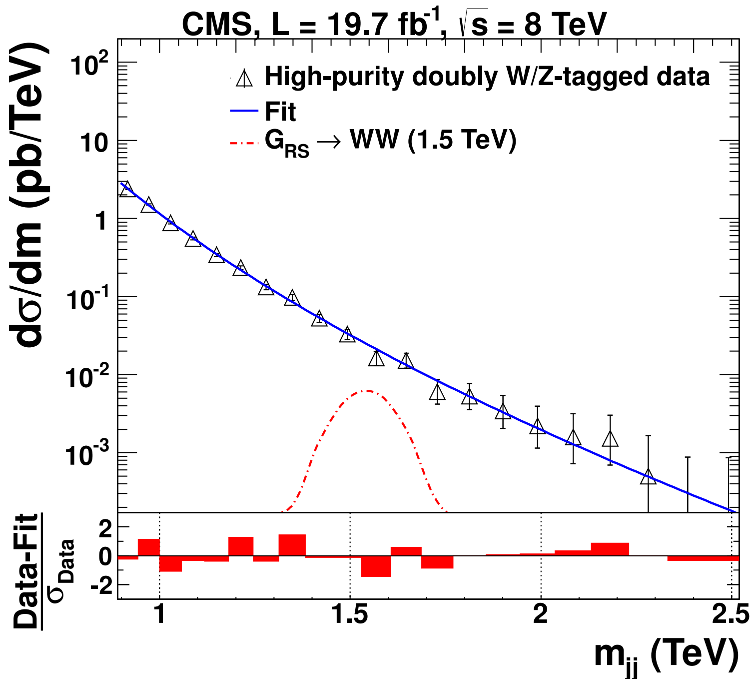
Scan over resonance mass
searching for an excess

Background estimation – all-jets final states

- Assumption: Background has a smooth distribution and can be described by a fit function
- Simultaneously fit signal yield and background parameters

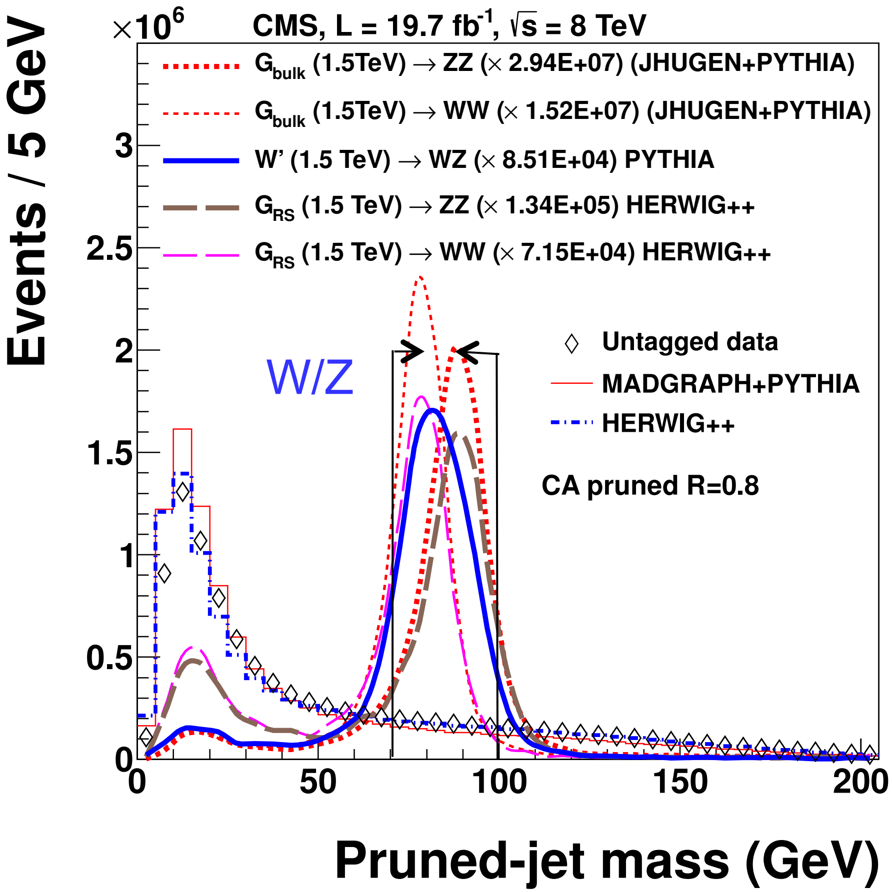


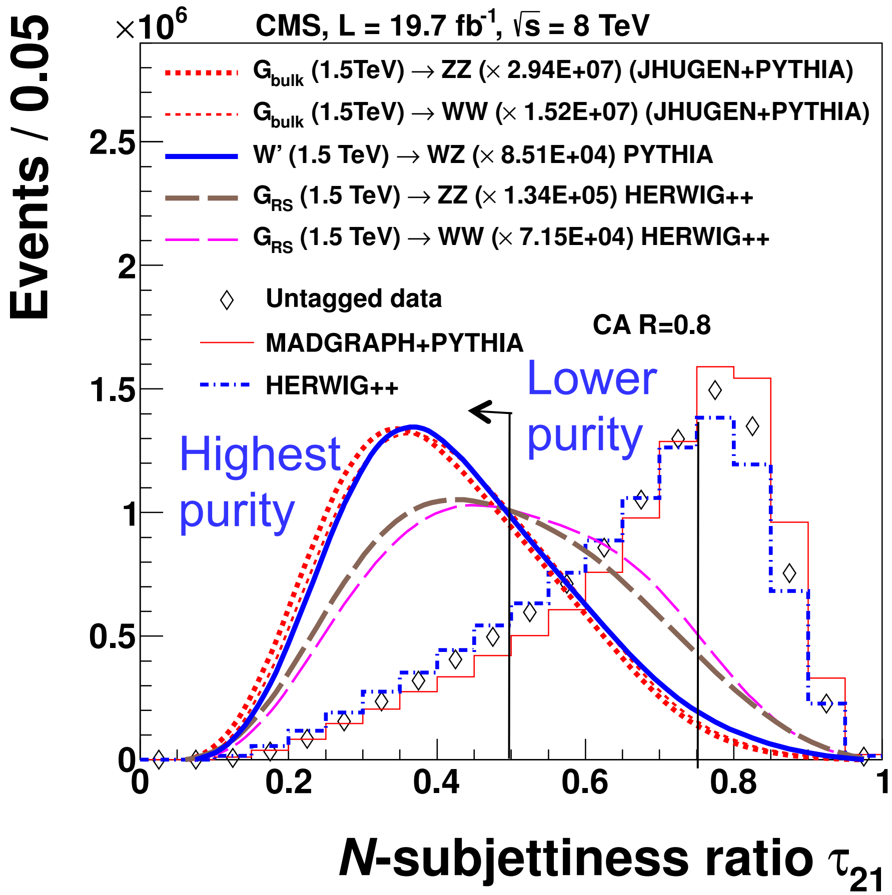
- Advantages:
  - No need for background simulation
- Disadvantages:
  - Arbitrary choice of background functional form and a systematic uncertainty assigned to it
  - Not possible in regions of discontinuity due to trigger turn-ons or kinematic selections
  - Only works for bumps, not for enhancements in tails

- Checks:
  - Bias-test: How much is signal yield mis-fitted when fitting toy spectra of default fit function with alternative functional form
  - F-test: Increase number of parameters until fit shows no significant improvement

V(qq)V(qq) resonances in dijets – 1

- Trigger $\Sigma_{jets} p_T$>650 GeV OR dijet mass>750 GeV
- Event selection: two R=0.8 jets with
  - $|\eta_1-\eta_2|$<1.3 (supress t-channel like QCD multijet background)
  - 70<m_{pruned}<100 GeV to select both W and Z
  - τ_2/τ_1 <0.5 for highest purity, 0.5< τ_2/τ_1 <0.75 for lower purity

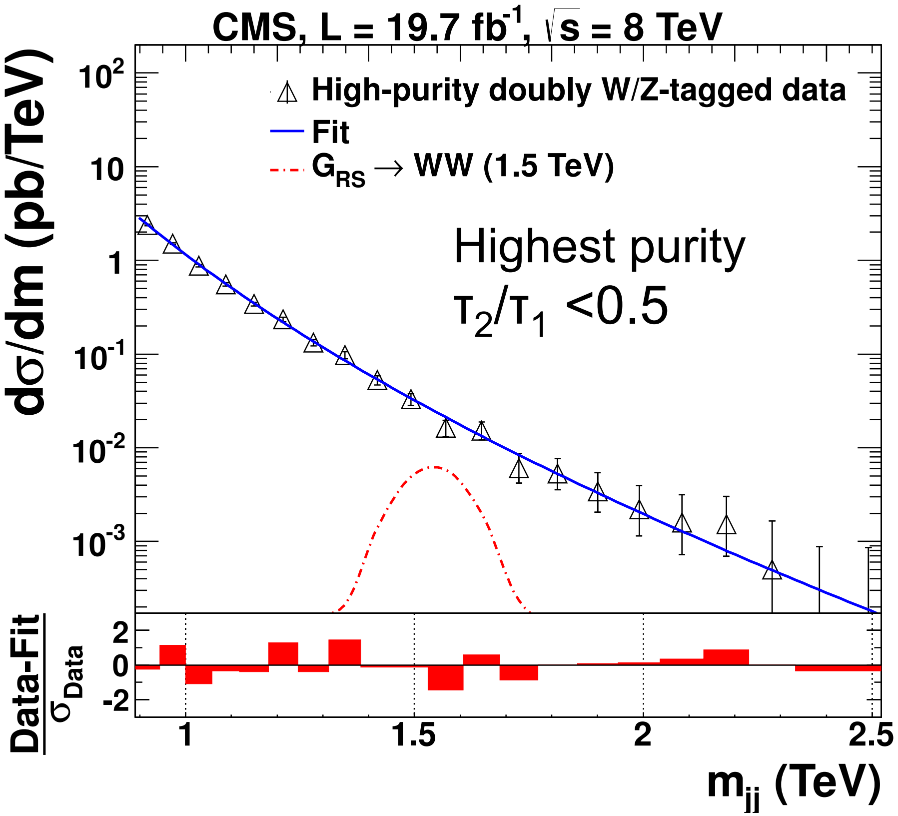


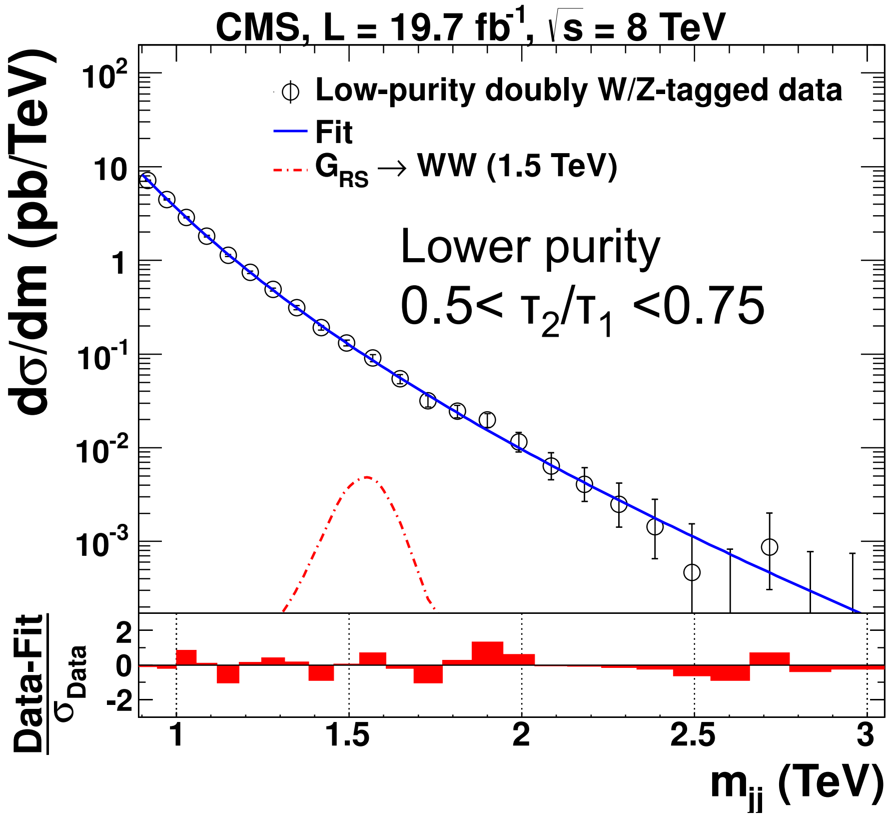


arXiv:1405.1994

V(qq)V(qq) resonances in dijets – 2

- ATLAS sees excess at 2 TeV with 2.5 s.d. global signficance (arXiv:1506.00962)
- CMS higher+lower purity combined signficance at 1.8 TeV is 1.3 s.d.





arXiv:1405.1994

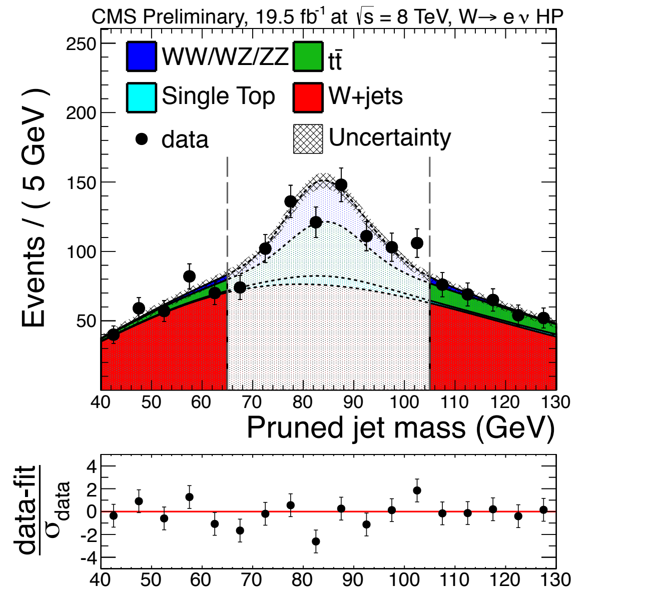
Background – leptons+jets final states

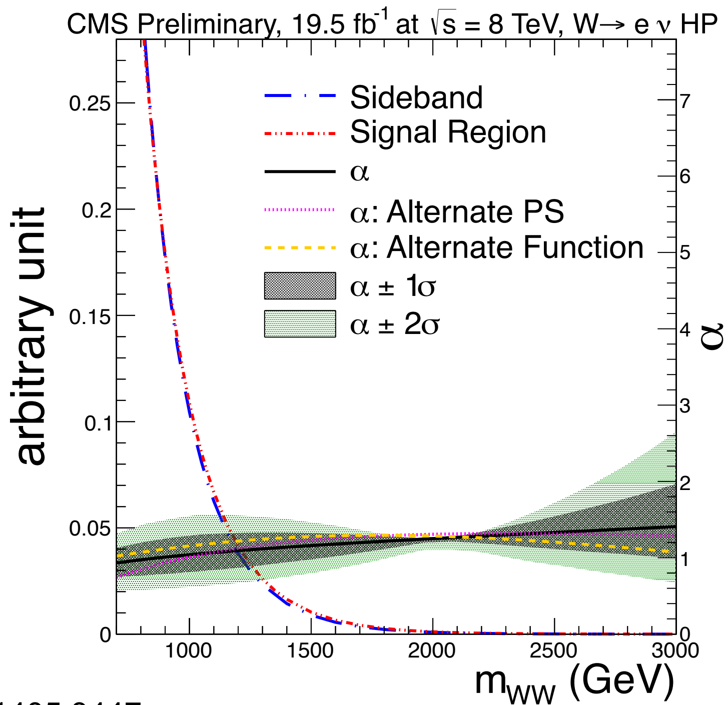
- Assumption: Observable in signal-depleted sideband closely related to signal region
- Background rate+shape estimated from data in sideband extrapolated to signal region using simulation

- Advantages:
  - Limited use of background simulation
  - Can search for enhancements in tails, not only bumps

- Disadvantages:
  - Uncertainties associated to extrapolation to signal region sometimes arbitrary

- Checks:
  - Closure test in simulation and/or other data sideband

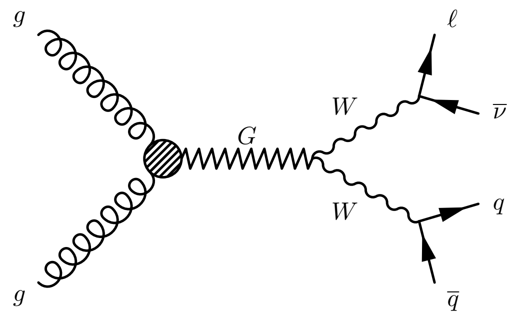




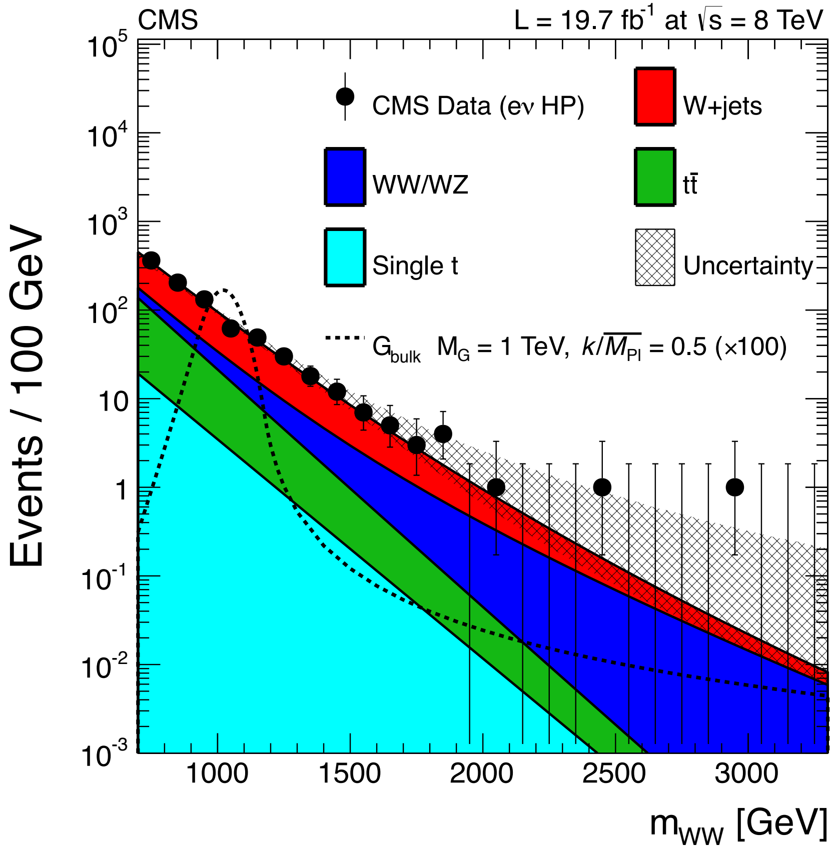
arXiv:1405.3447

W(lν)V(qq) resonances in l+MET+jet

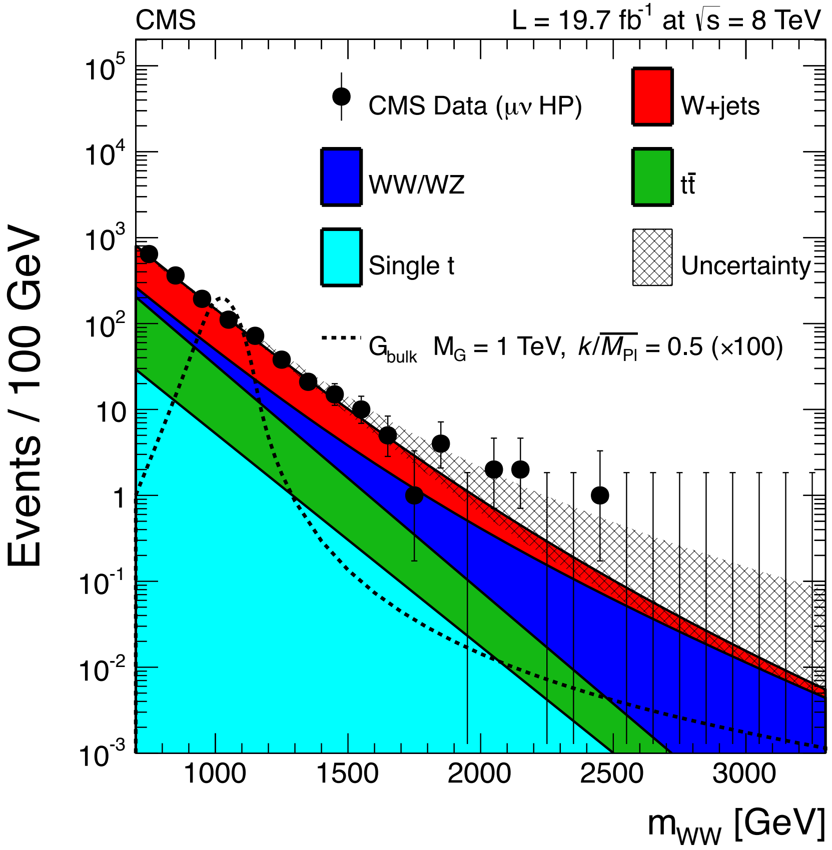
- Trigger high p_T lepton: p_T>80(40) GeV for e(μ)
- Reconstructed one W from 1 lepton and E_T^{miss}
- Second V reconstructed from V-tagged CA8 jet
  - Categorize in purity based on τ_2/τ_1
- W+jets background estimated from jet mass side-band



electron high purity



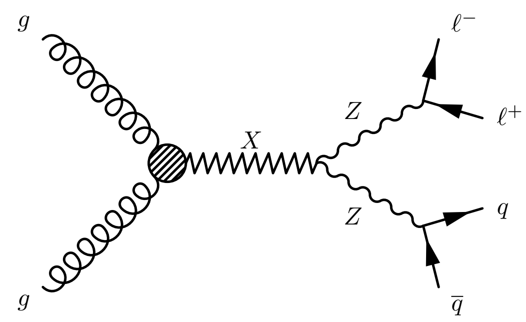
muon high purity



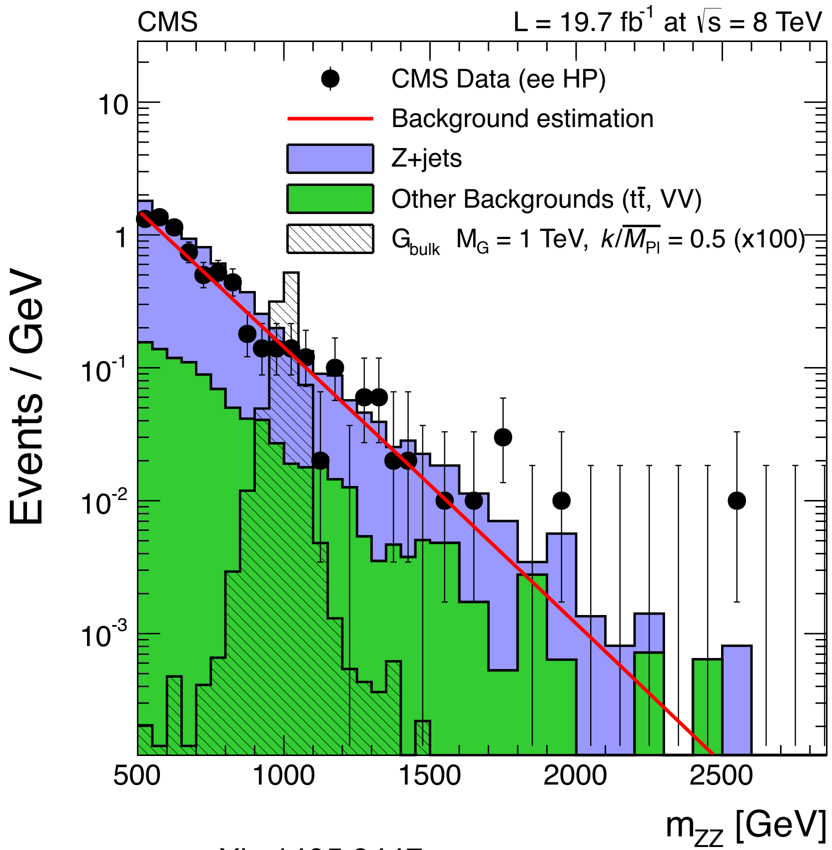
arXiv:1405.3447

Z(ll)V(qq) resonances in ll+jet

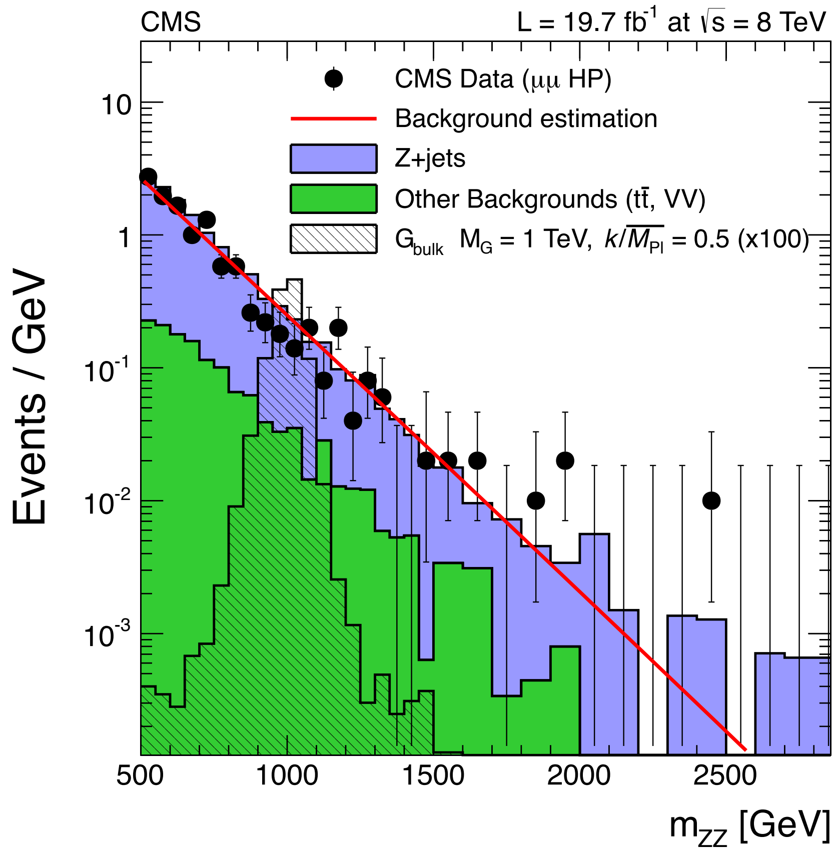
- Trigger two leptons: p_T>33/33 (22/8) GeV for e(μ)
- Reconstructed one Z from 2 leptons
- Second V reconstructed from V-tagged CA8 jet
  - Categorize in purity based on τ_2/τ_1
- Z+jets background estimated from jet mass side-band



electron high purity



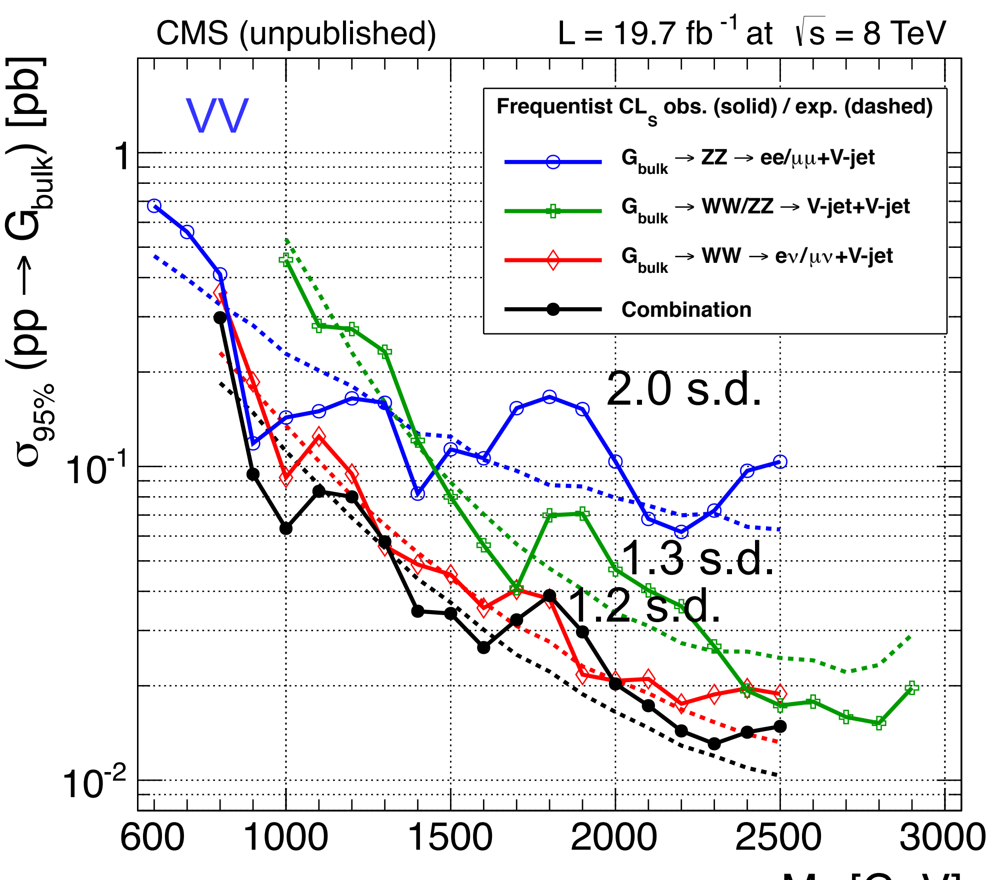
muon high purity



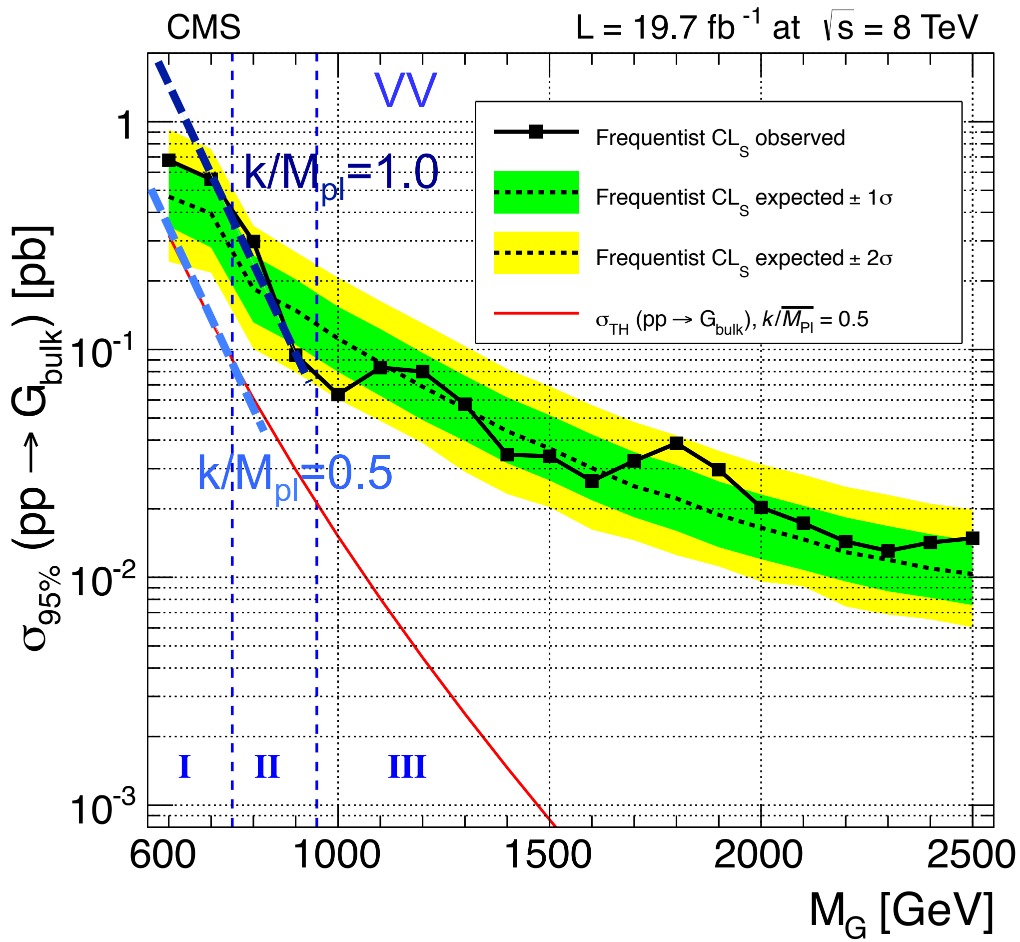
arXiv:1405.3447

Limits on spin-2 WW/ZZ resonances

- Run I searches start to be sensitive to gravitons in Bulk model
  - Cross section and width related to coupling parameter k/M_{pl}
    - Narrow width for $k/M_{pl} \leq 0.5$
- Model independent limits provided allowing reinterpretation for wide width resonance and as spin-1 WZ resonance (see later)

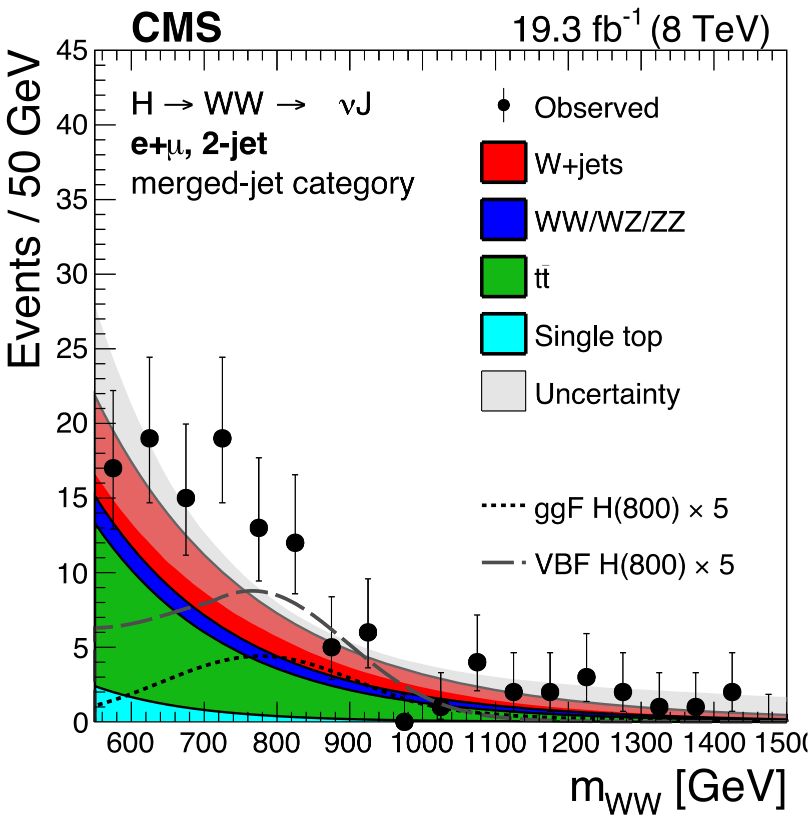


arXiv:1405.3447

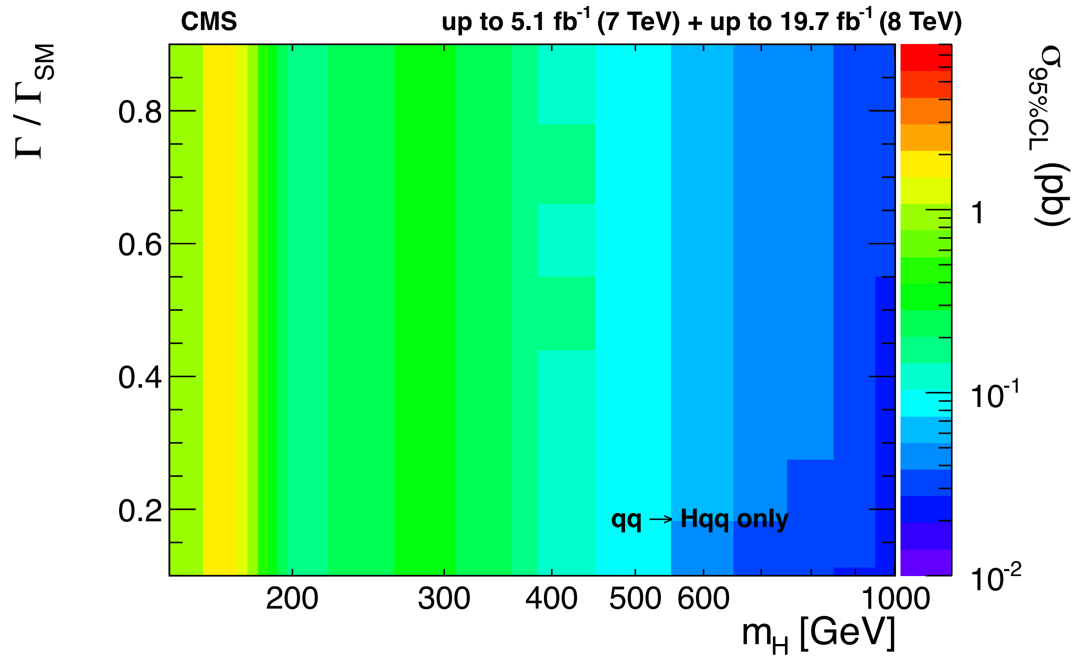


VBF W(lν)W(qq) resonances in l+MET+jet

- Search optimized for spin-0 resonances
- Consider also VBF category $|\Delta\eta_{jj}| > 2.5$, m_{jj}>250 GeV
- Interpreted with SM-like Higgs couplings → large width at high masses
- Interpreted with EW singlet extension of SM



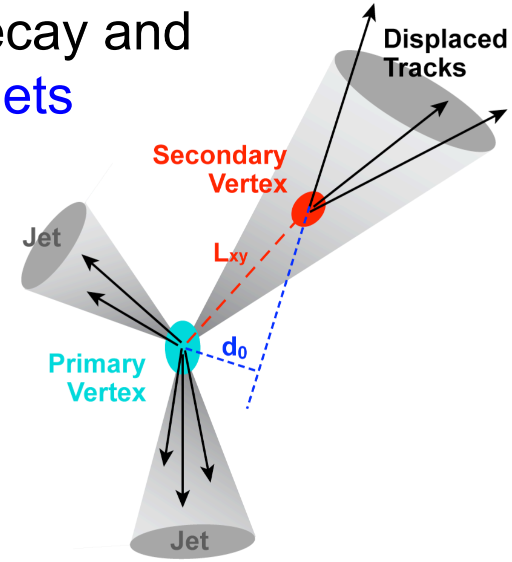
Limit on VBF production
(assuming a SM-like ratio between
VBF and gluon-fusion)

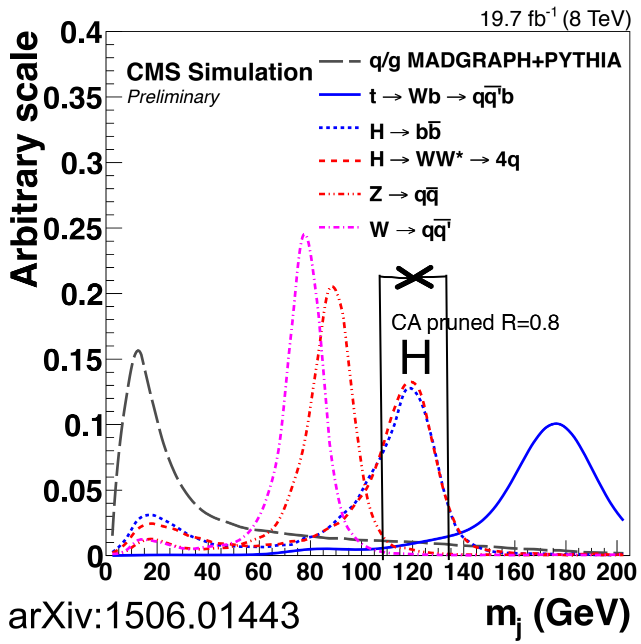


arXiv:1504.00936

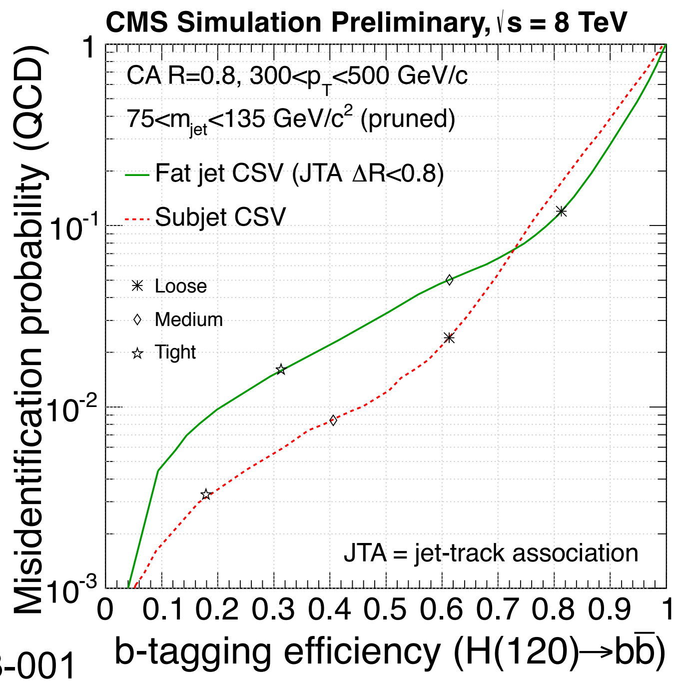
H→bb-tagging

- Pruned jet mass used as main discriminator
- Identify b-quark initiated jets with multivariate discriminant based on secondary vertices from B-hadron decay and associated tracks
- Two variants of b-tagging
  - Fat-jet: apply b-tagging on R=0.8 jet
  - Sub-jet: Undo last iteration of jet clustering to obtain two subjets corresponding to the b-quarks from Higgs decay and apply b-tagging on subjets





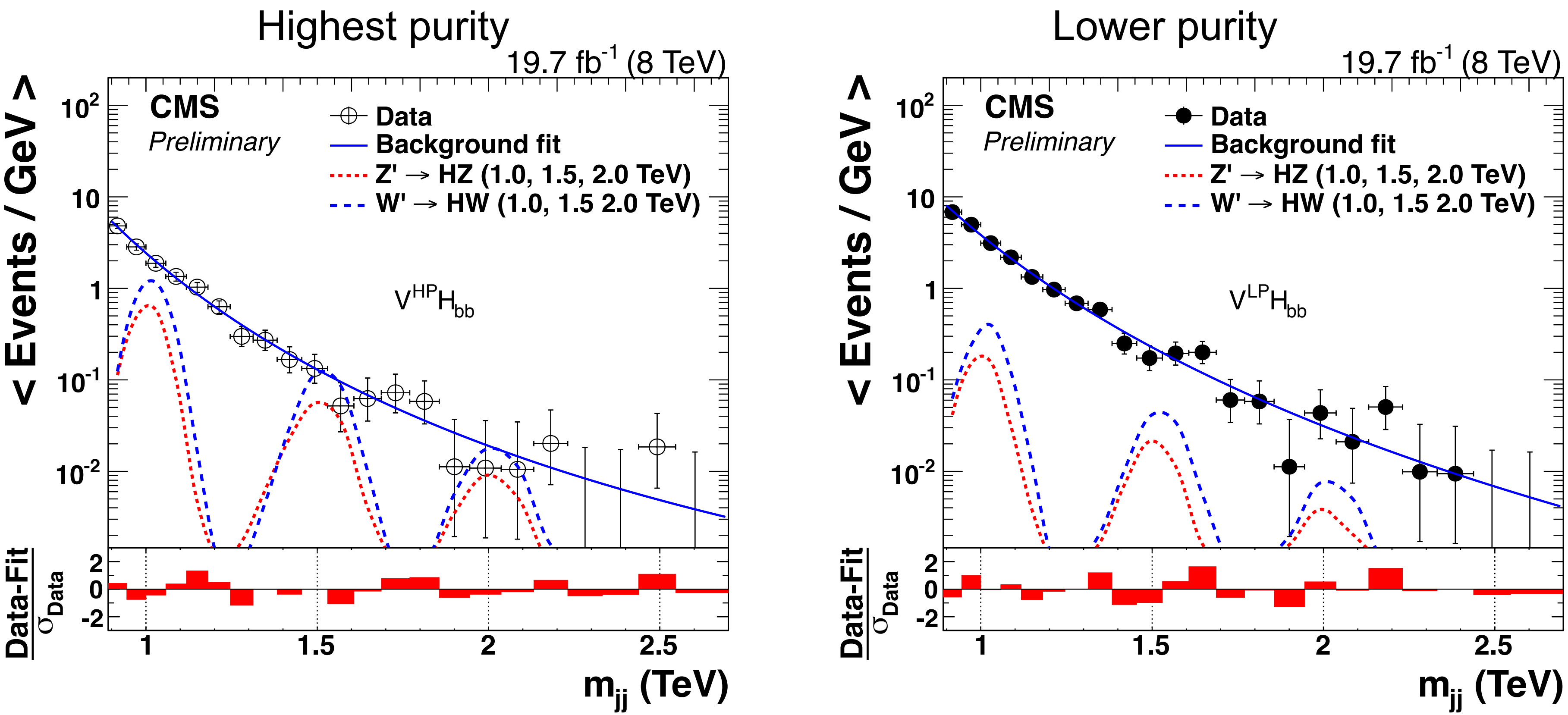
arXiv:1506.01443



CMS-PAS-BTV-13-001

V(qq)H(bb) resonances

- Same search techniques as V(qq)V(qq) search
- Lower backgrounds due to better background rejection of H(bb)-tagger compared to W(qq)/Z(qq)-tagger

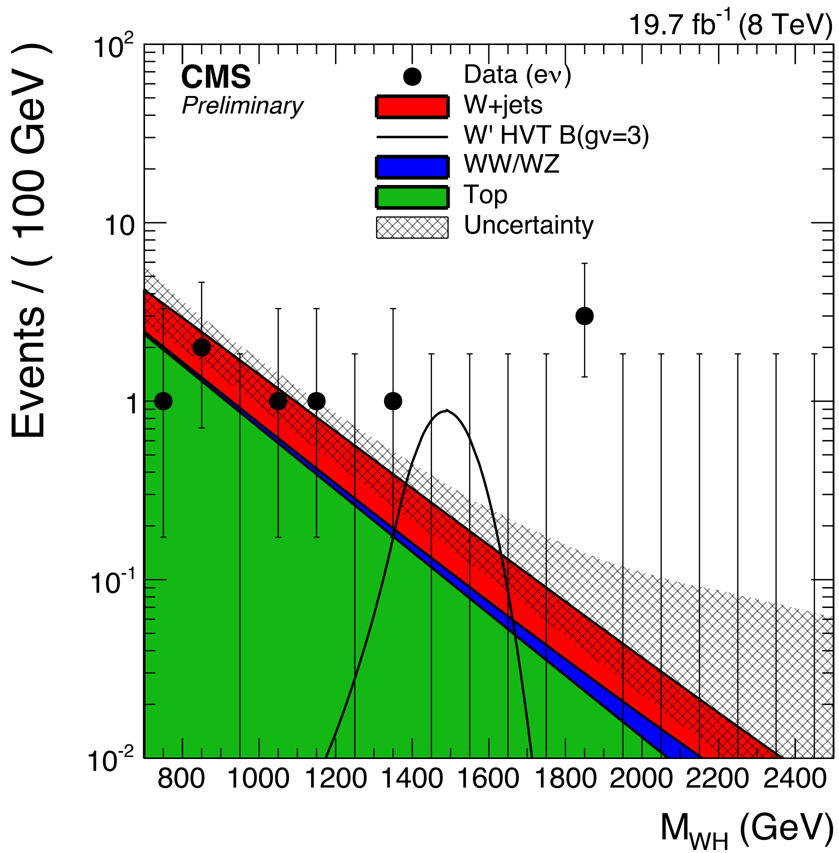


arXiv:1506.01443

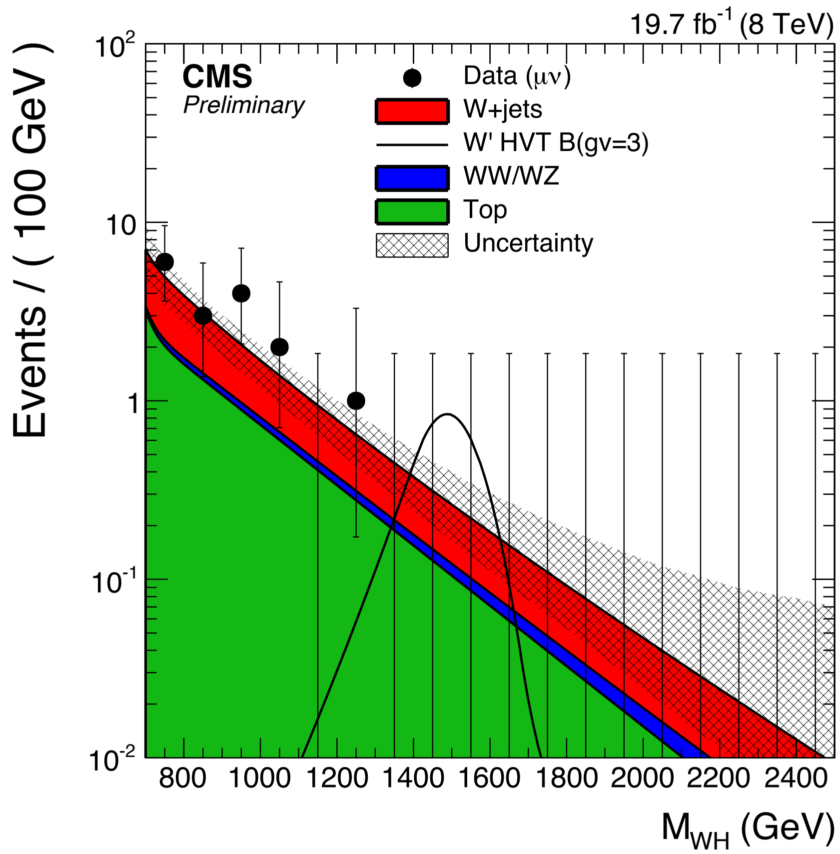
W(lv)H(bb) resonances

- Same search techniques as W(lv)V(qq) search
- Lower backgrounds due to better background rejection of H(bb)-tagger compared to W(qq)/Z(qq)-tagger
- Excess in W(lv)H(bb) at 1.8 TeV has a global significance of 2.2 s.d.

electron channel



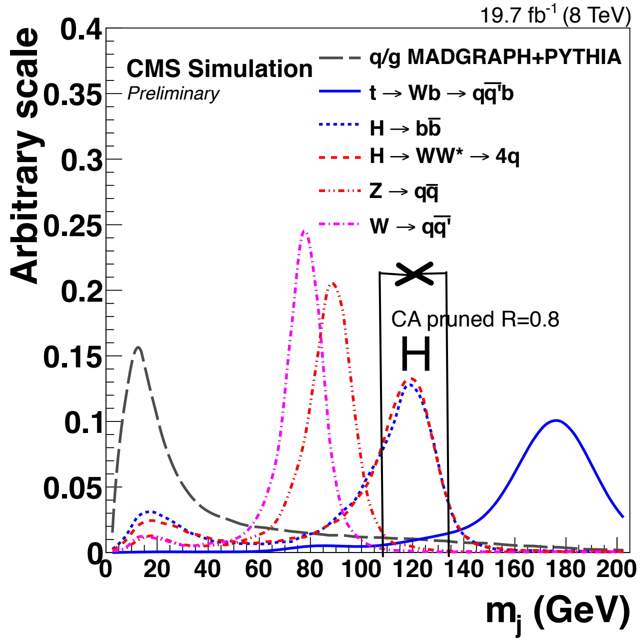
muon channel

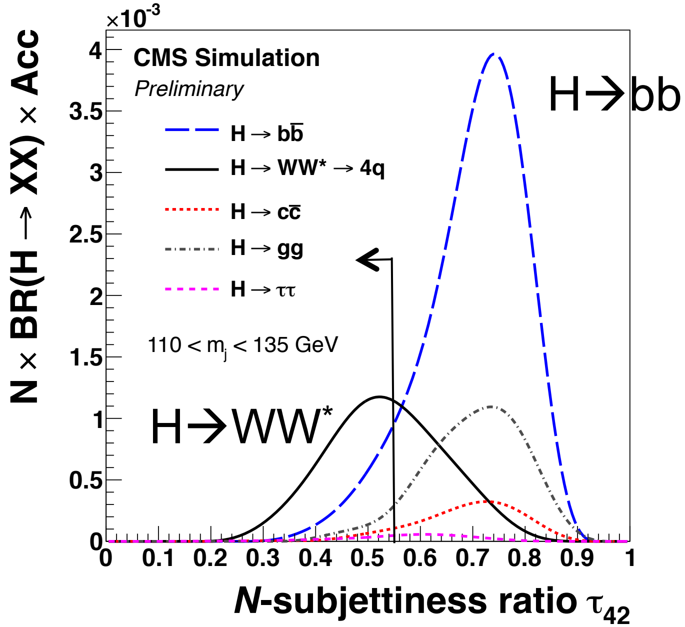


CMS-PAS-EXO-14-010

H→WW→qqqq-tagging

- H→WW* has second highest BR after H→bb
- Same pruned jet mass selection as for H→bb jets
- Best discriminating variable between H→WW*→qqqq jet (initiated from 4 partons) and quark/gluon/W/Z/H(bb) jets (initiated from 1 or 2 partons): τ_4/τ_2
- Since BR(H→bb)>>BR(H→WW→qqqq), fraction of H→bb event failing b-tagging, but passing τ_4/τ_2 selection non-negligible
  - Need to consider all possible Higgs decays simultaneously in analysis

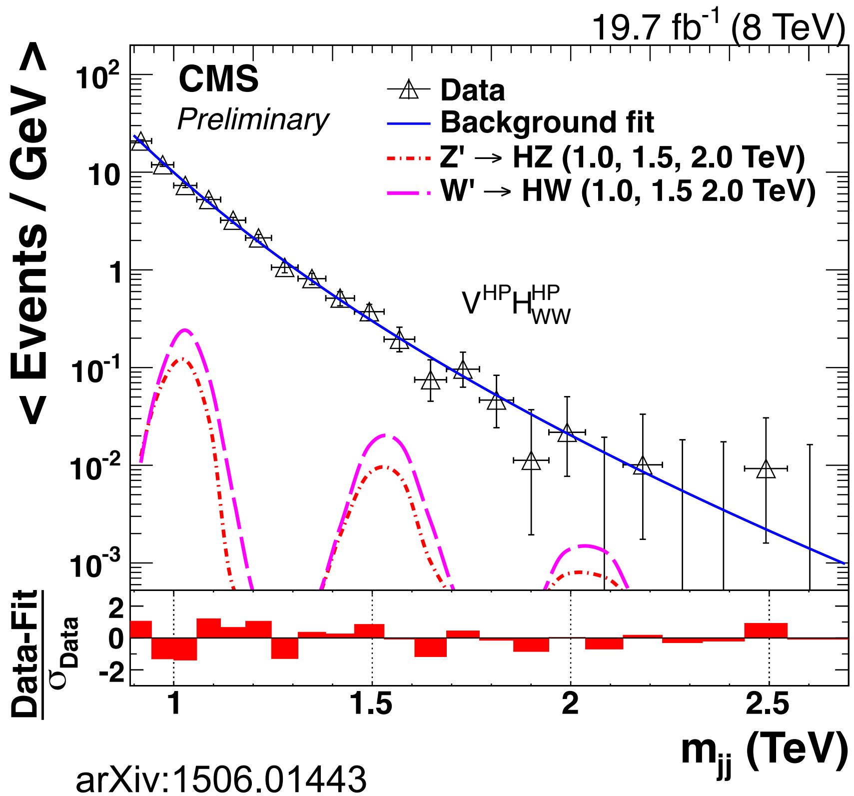




arXiv:1506.01443

V(qq)H(WW→qqqq) resonances

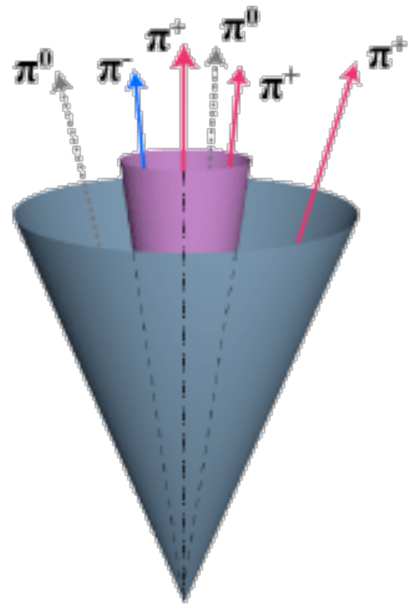
- Exclusive search channel: Only events that fail H(bb) tagger
- Factor 4 less stringent limits on cross section than H(bb) channel
  - Still adds 10% to combination with H(bb)
- For Run II also consider H(WW→lνqq) jets



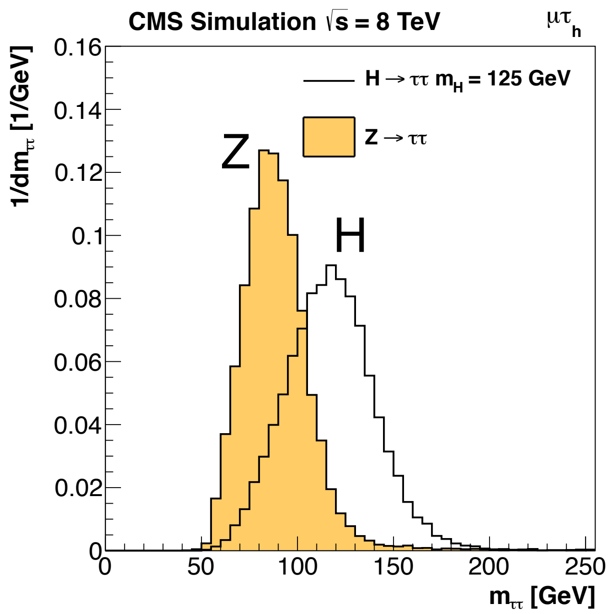
arXiv:1506.01443

H→ττ-tagging

Decay Mode	Resonance	BR [%]
$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
$\tau^- \rightarrow \pi^- \nu_\tau$	$\pi(140)$	11.6
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.7
All hadronic modes		64.8

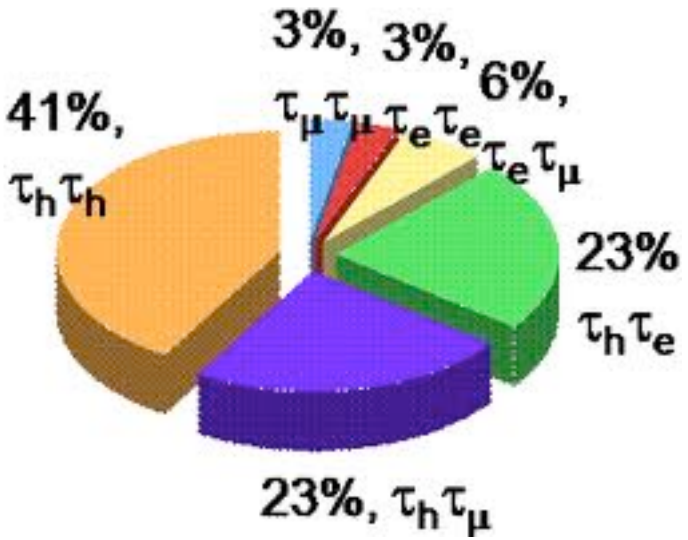


- Main discriminator of taus against q/g-jets is isolation summing reconstructed particle energies in cone around tau decay products
  - Decay products of one excluded from isolation cone of other tau forming the H→ττ
- Higgs mass reconstructed from visible tau decay products and missing transverse energy

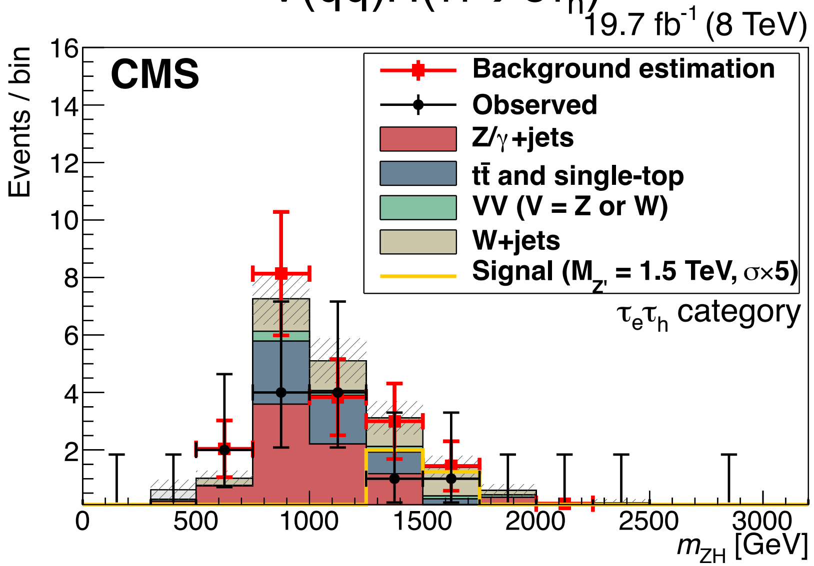


V(qq)H(ττ) resonances

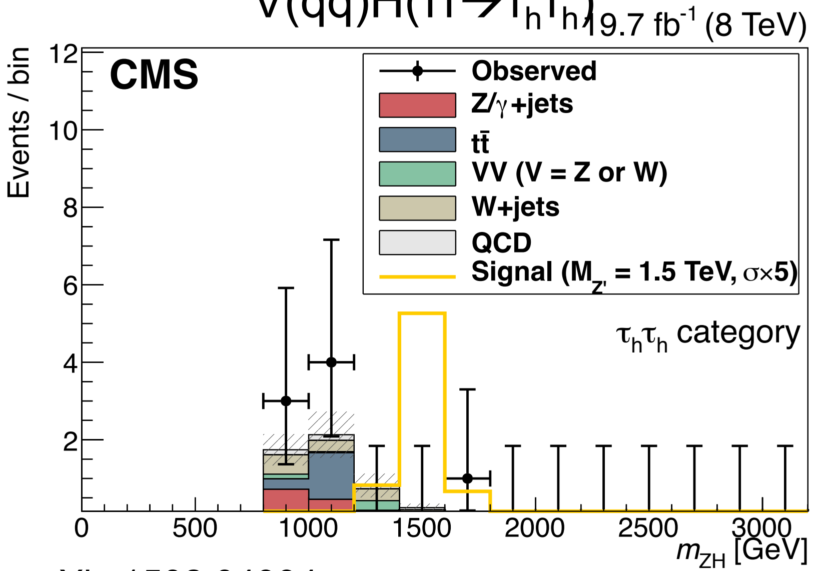
- All tau decay modes taken into account



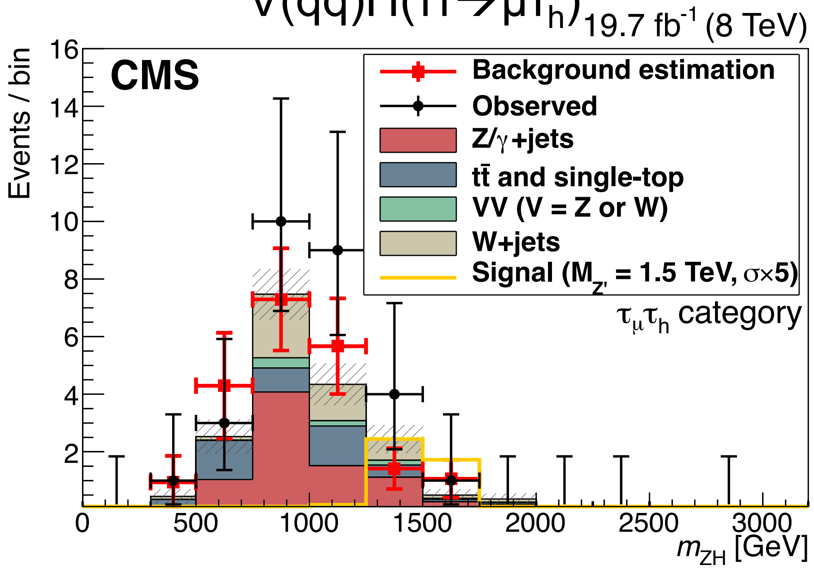
V(qq)H(ττ→eτ$_h$)



V(qq)H(ττ→τ$_h$τ$_h$)



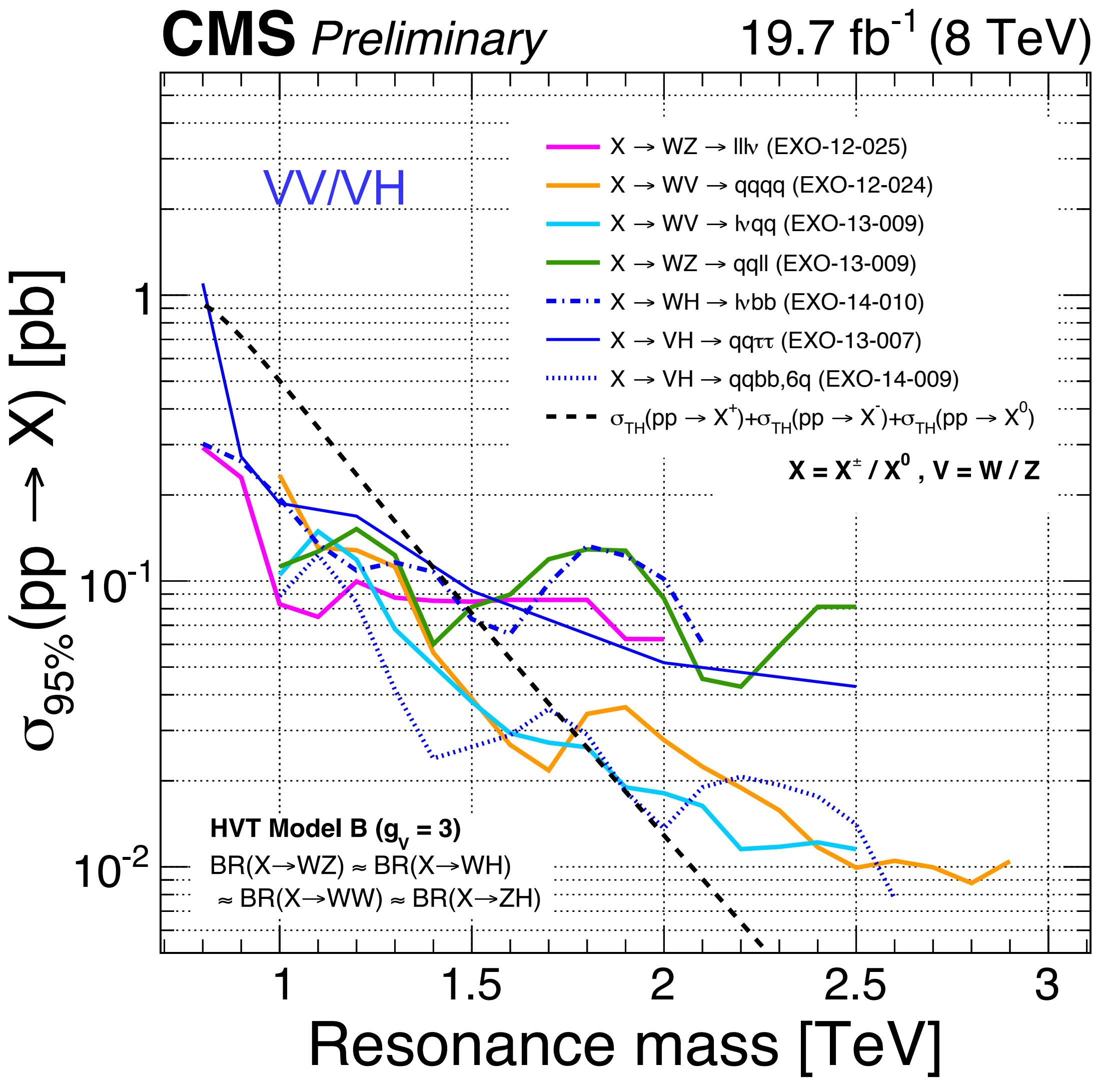
V(qq)H(ττ→μτ$_h$)



arXiv:1502.04994

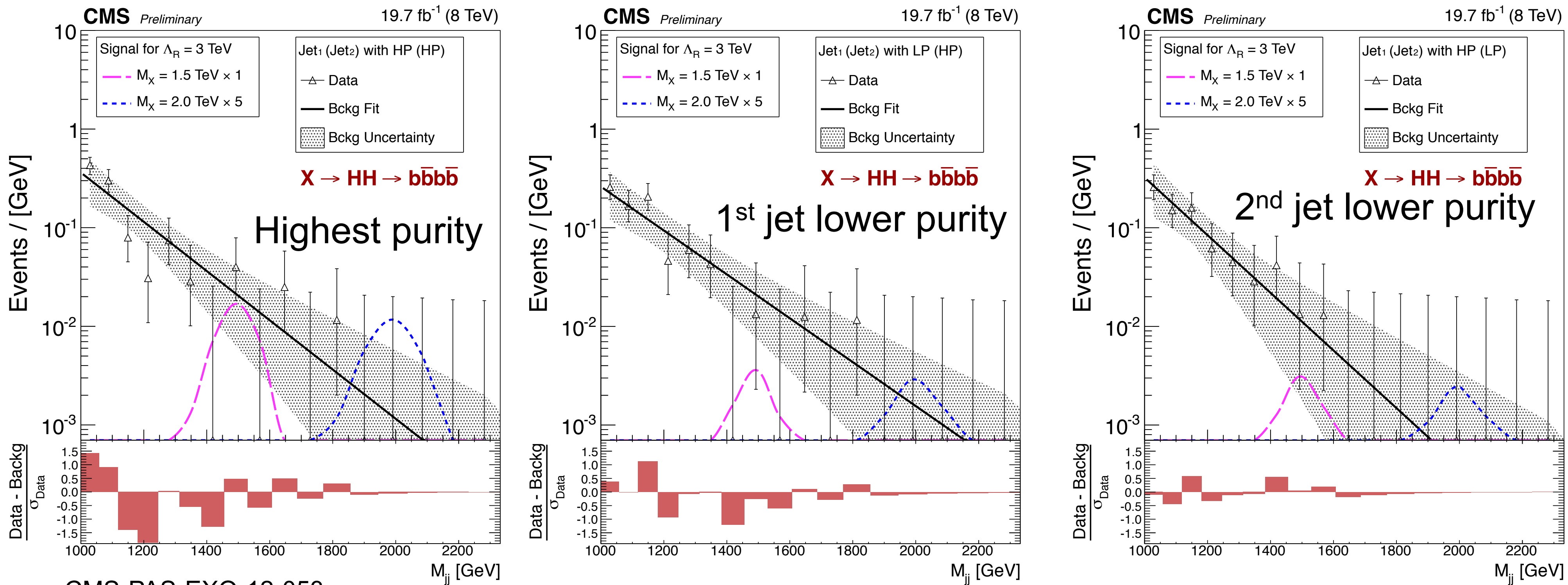
Limits on spin-1 WW/WZ/ZH/WH resonances

- Heavy Vector Triplet model B (composite Higgs-like model) m(W')=m(Z') excluded up to 1.8 TeV
  - WV(lvqq), VV(qqqq) and VH(qqbb) have best sensitivity at high masses



H(bb)H(bb) resonances – 2

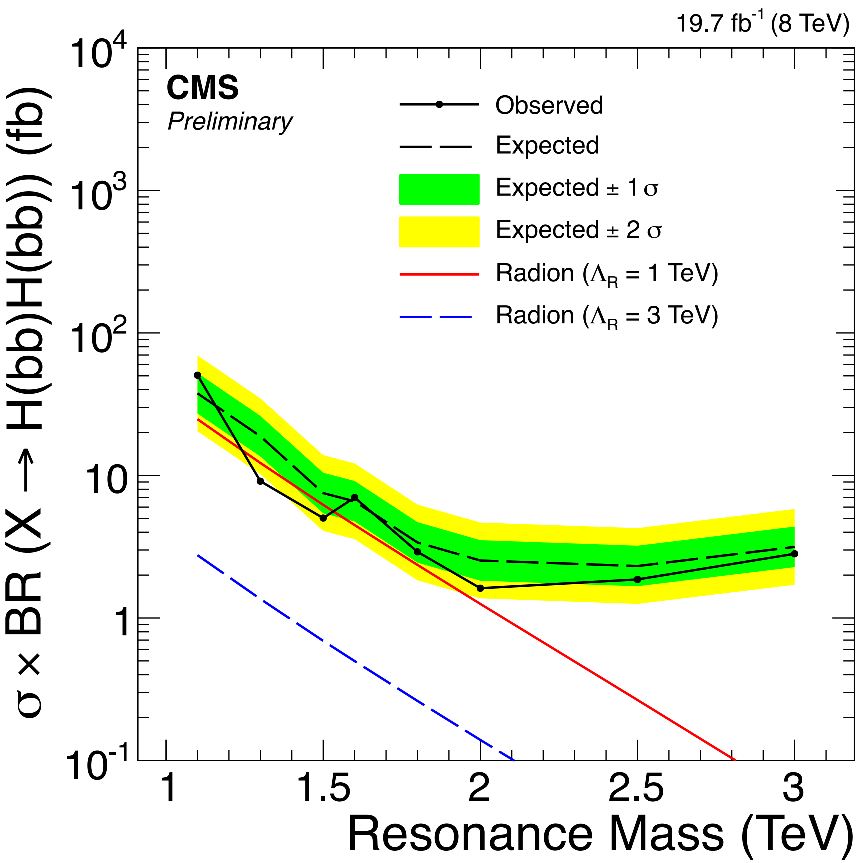
- Require ≥3 b-tagged subjets in event
  - If subjets closer than $\Delta R<0.3$: Require b-tagged fatjet instead of 2 subjets
- Categorize in purity via τ_2/τ_1
- Background estimate is intermediate approach between fitting background shape in signal region (limited by statistics) and estimation from sideband (limited by understanding of b-tagging fake rate)
  - Background shape from pruned jet mass sideband $70<m_J<100$ GeV
  - Background yield fit together in signal region excluding resonance window

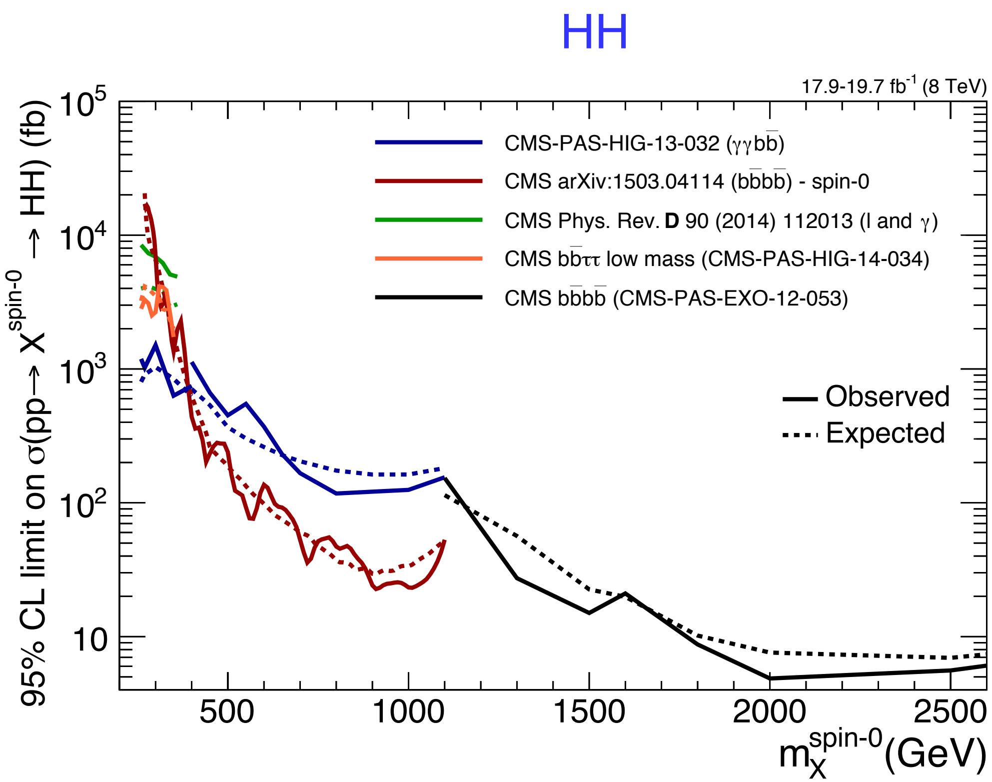


CMS-PAS-EXO-12-053

Findings for spin-0 HH resonances

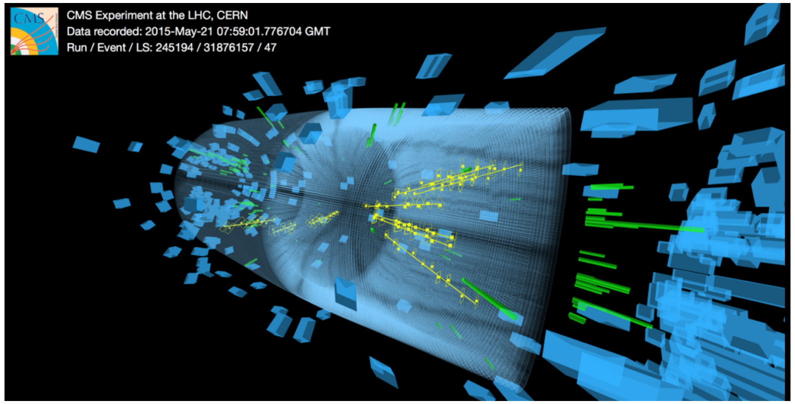
- Extra dimension spin-0 radion (Λ_R=1 TeV) excluded around 1.2-1.5 TeV (note: model at edge of validity of narrow width approximation)





CMS-PAS-EXO-12-053

Outlook for Run II

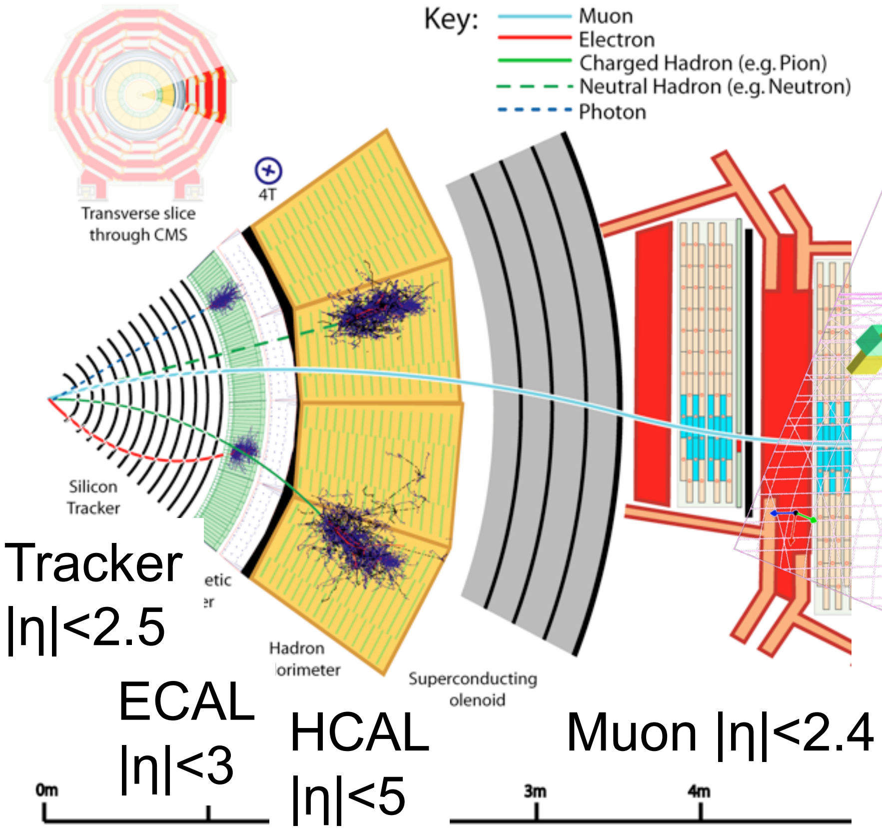


- First 13 TeV collisions recorded!
- Rule of the thumb for high mass resonances in Run II.
  Reach sensitivity of Run I for
  - 3 TeV resonance with 1/fb of Run II data
  - 2 TeV resonance with 3/fb of Run II data
  - 1 TeV resonance with 10/fb of Run II data
- Expect to explore new territory for > 1 TeV resonances already this year
- LHC runs in 2015 to find di-boson resonance at 2 TeV

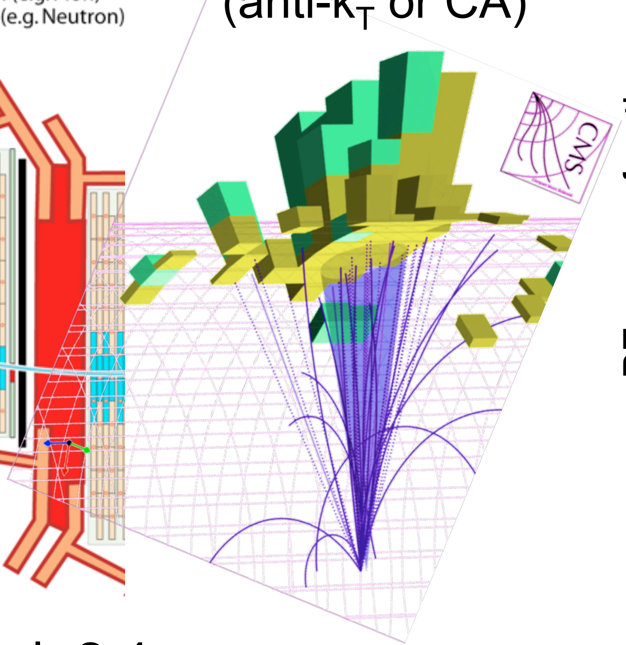
Backup

Jet reconstruction in CMS

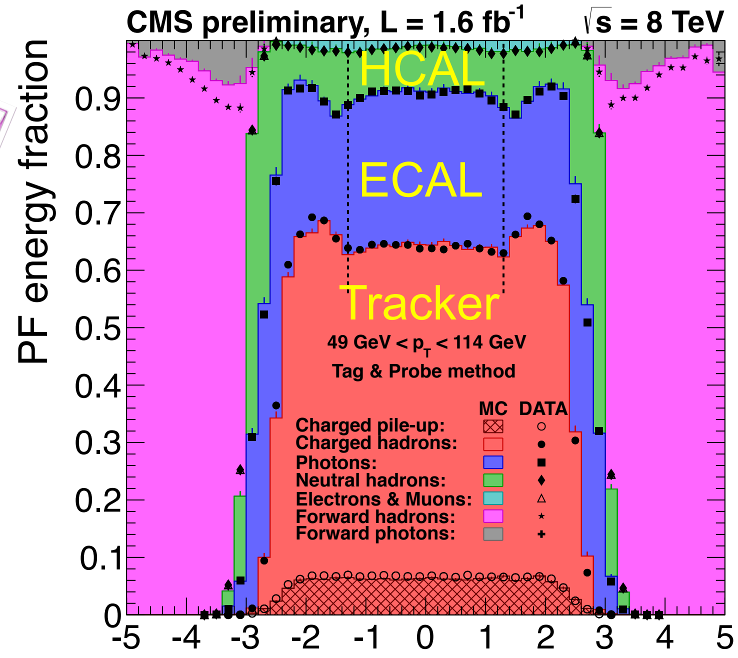
Particle flow reconstruction



Jet clustering (anti-k_T or CA)



Jet energy fractions



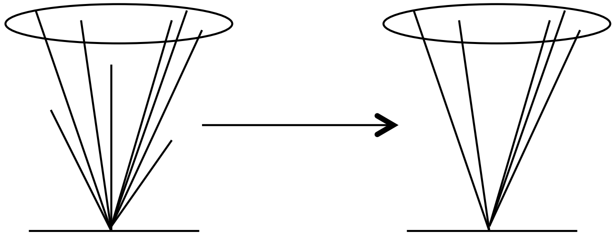
CMS-DP-2012/012

Particle Flow algorithm benefits from sub-detectors with best spatial+energy resolution

Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

Pruned jet mass

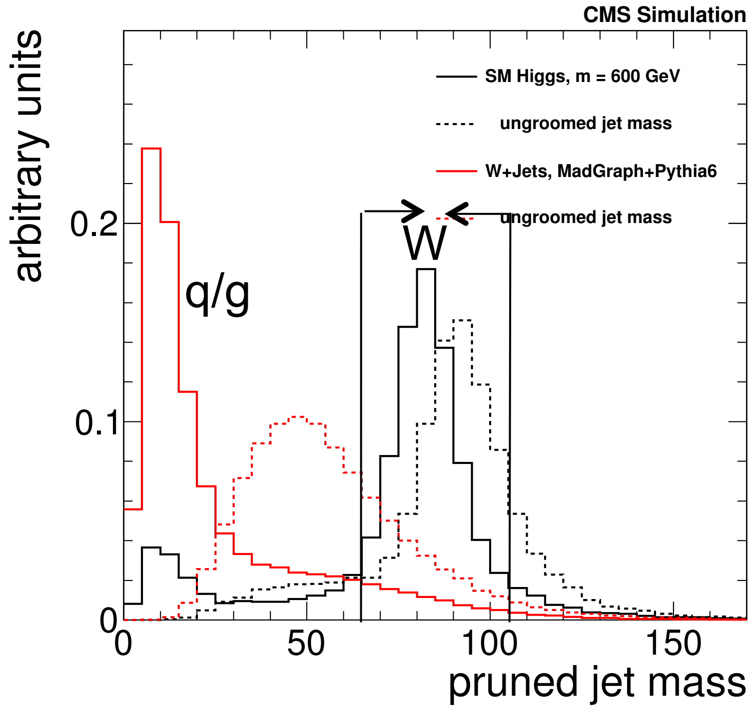
- Improve jet mass resolution by removing soft, large angle particles



- Strongly reduce the mass of quark/gluon-jets
- Recluster each jet with Cambridge Aachen (CA) with R=0.8, requiring that each recombination satisfy the following:

$$\frac{\min(p_{T1}, p_{T2})}{p_{Tp}} > 0.1 \text{ or } \Delta R_{12} < 0.5 \times \frac{m_{jet}}{p_T}$$

- Ellis, Vermilion, Walsh: arXiv:0912.0033
- Other "grooming" algorithms studied in CMS-PAS-SMP-12-019 and CMS-PAS-JME-14-002



N-subjettiness

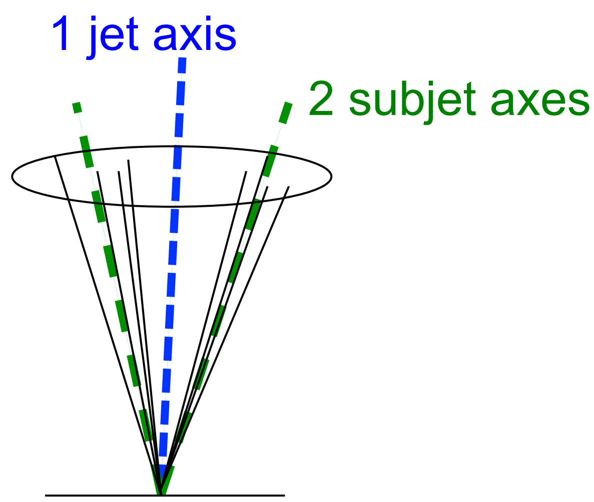
- N-subjettiness is a p_T-weighted sum over all jet constituents of their distance w.r.t. the closest of N axes in a jet

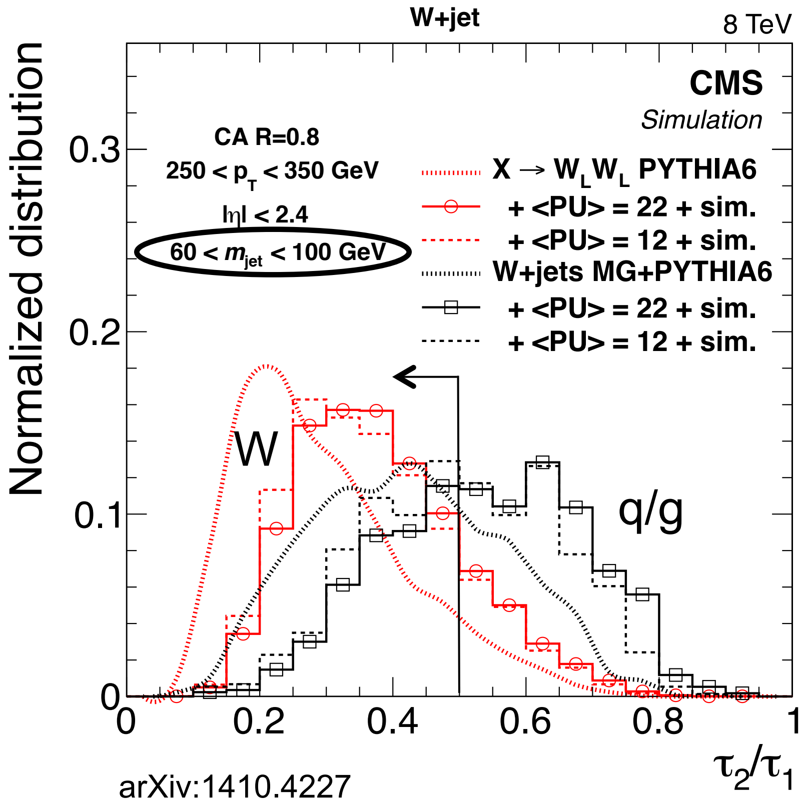
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left((\Delta R_{1,k}),(\Delta R_{2,k})...(\Delta R_{N,k})\right)$$

- Axes obtained by undoing last (N-1) step(s) of k_T algorithm
  - Then optimize the axis directions once to minimize τ_N
- Small τ_N indicates compatibility with the hypothesis of N axes

- Discriminating variable between W-jet (initiated from 2 partons) and quark/gluon jets (initiated from 1 parton): τ_2/τ_1

- Thaler, Tilburg: arXiv:1011.2268



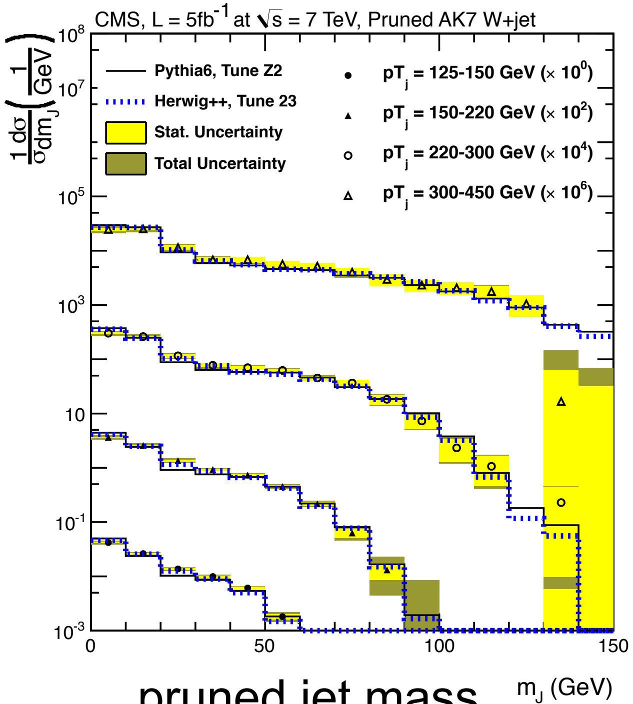


arXiv:1410.4227

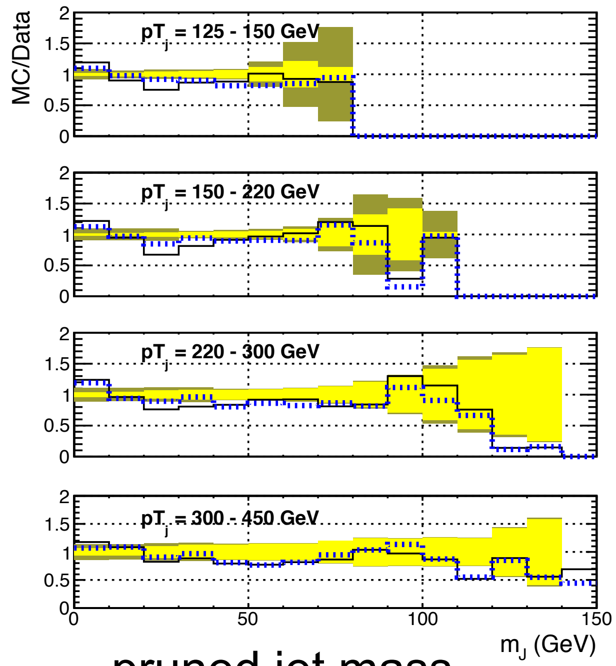
Pruning validation in q/g-jet data

- Pruned jet mass measured in dijet and W+jets data samples, allowing comparison of q-jet-enriched and g-jet enriched masses

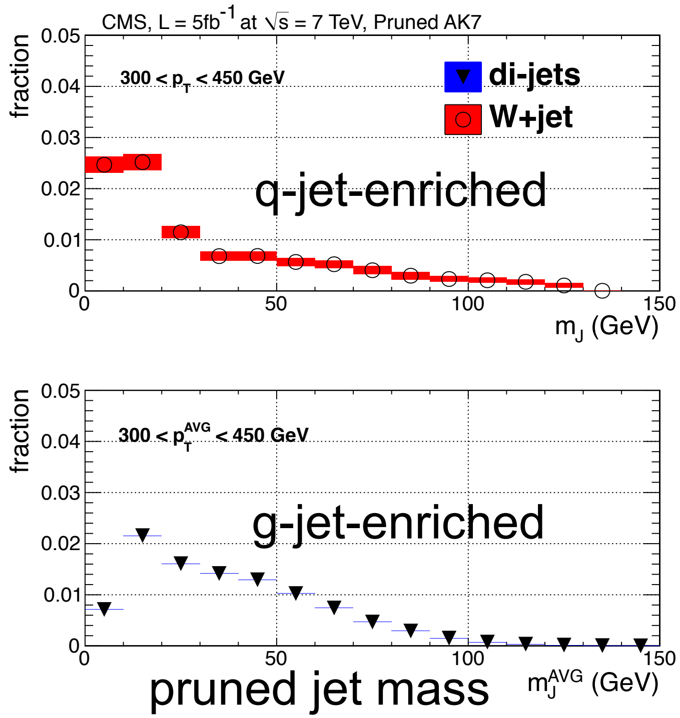
- Matrix-element plus parton-shower MC describes data at 10% level
- Generator differences particularly at low jet mass order 10%



pruned jet mass



pruned jet mass



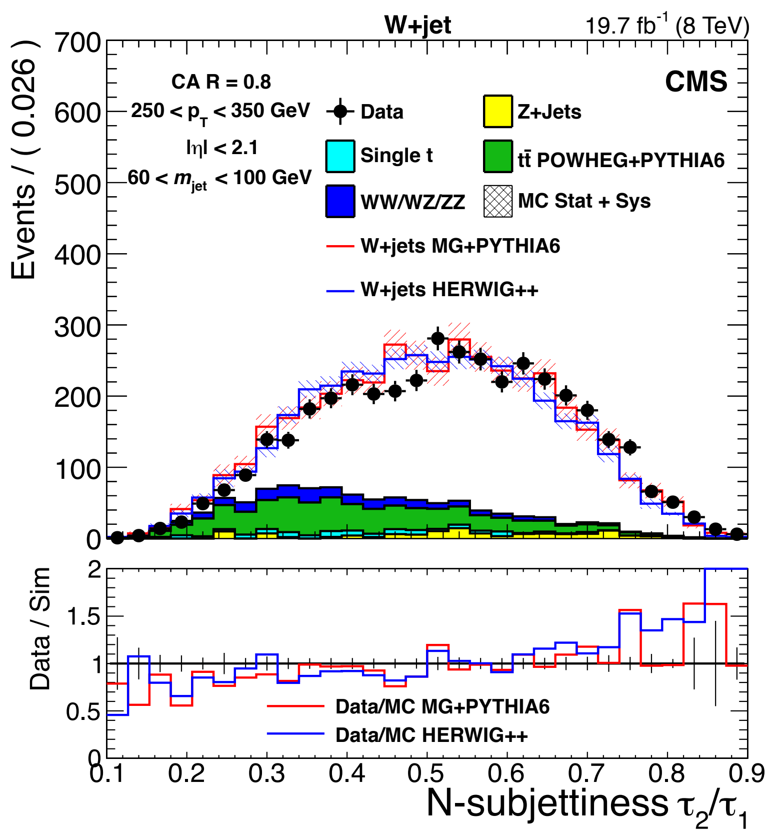
pruned jet mass

arXiv:1303.4811

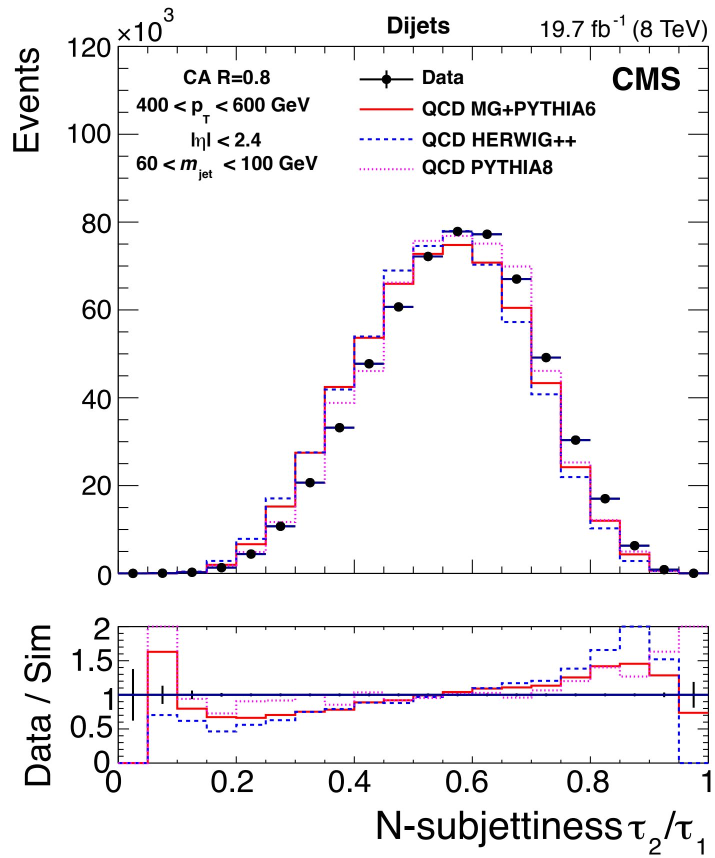
τ_2/τ_1 validation in q/g-jet data

- N-subjettiness compared in dijet and W+jets data samples

- Matrix-element plus parton-shower MC describes data at 10% level
- Generator differences particularly at low jet mass order 10%

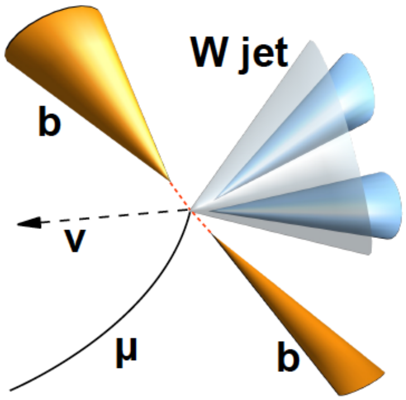


arXiv:1410.4227

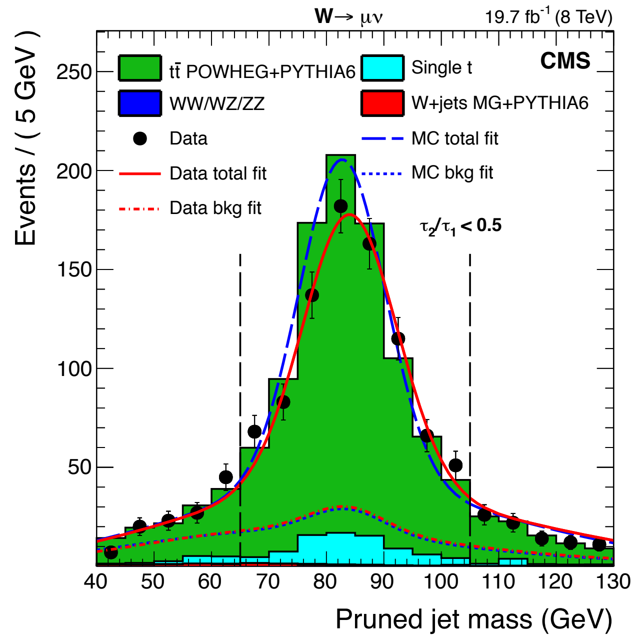


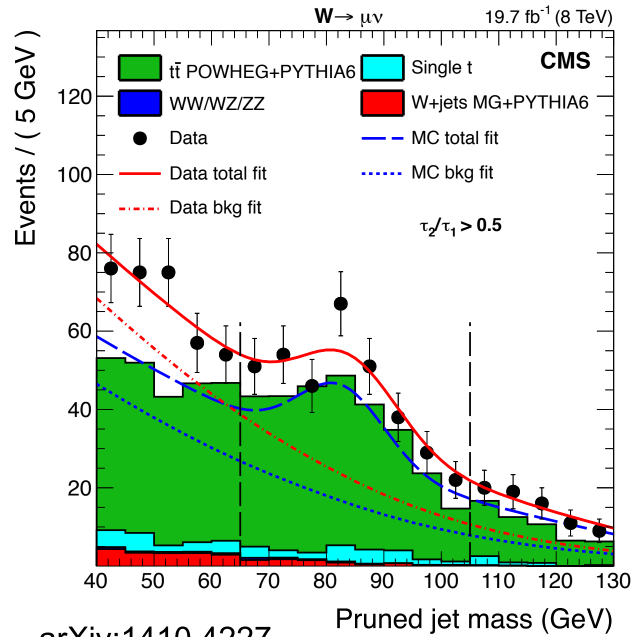
W-tagging validation in W-jet data

- Semileptonic ttbar sample contains real W-jets



- Derive shapes for generator-matched W-jets and combinatorial background from ttbar MC
- Simultaneously fit events that pass and fail the $\tau_2/\tau_1<0.5$ cut



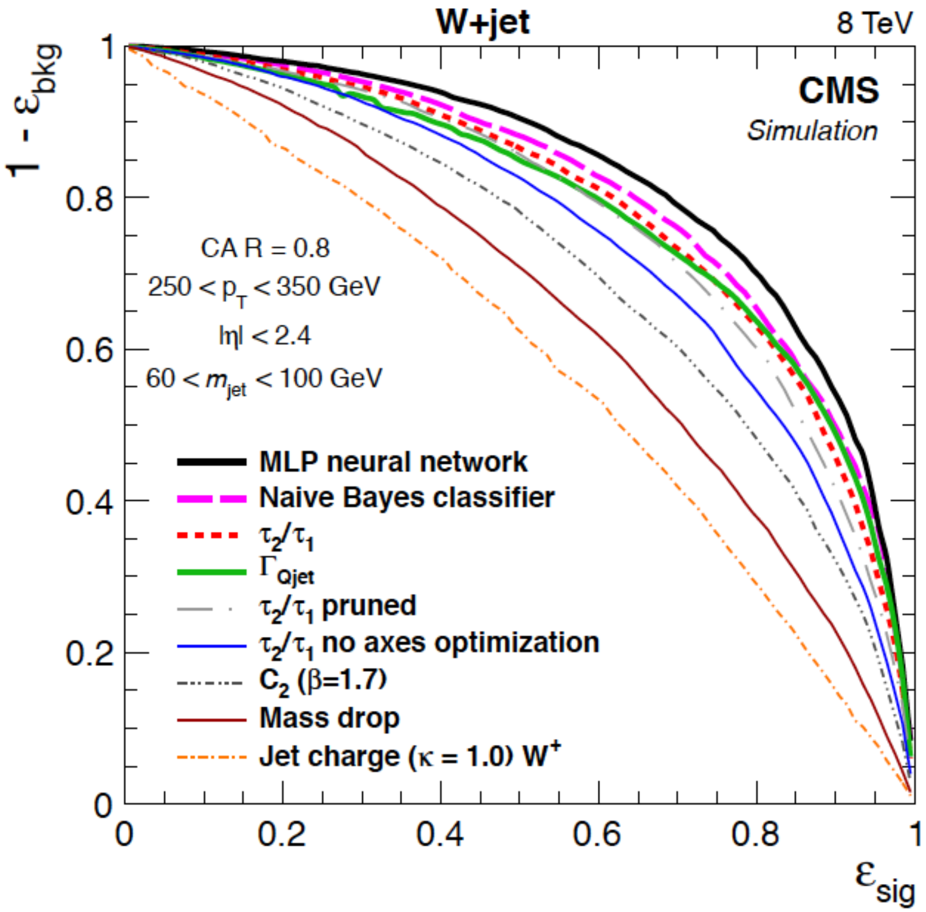


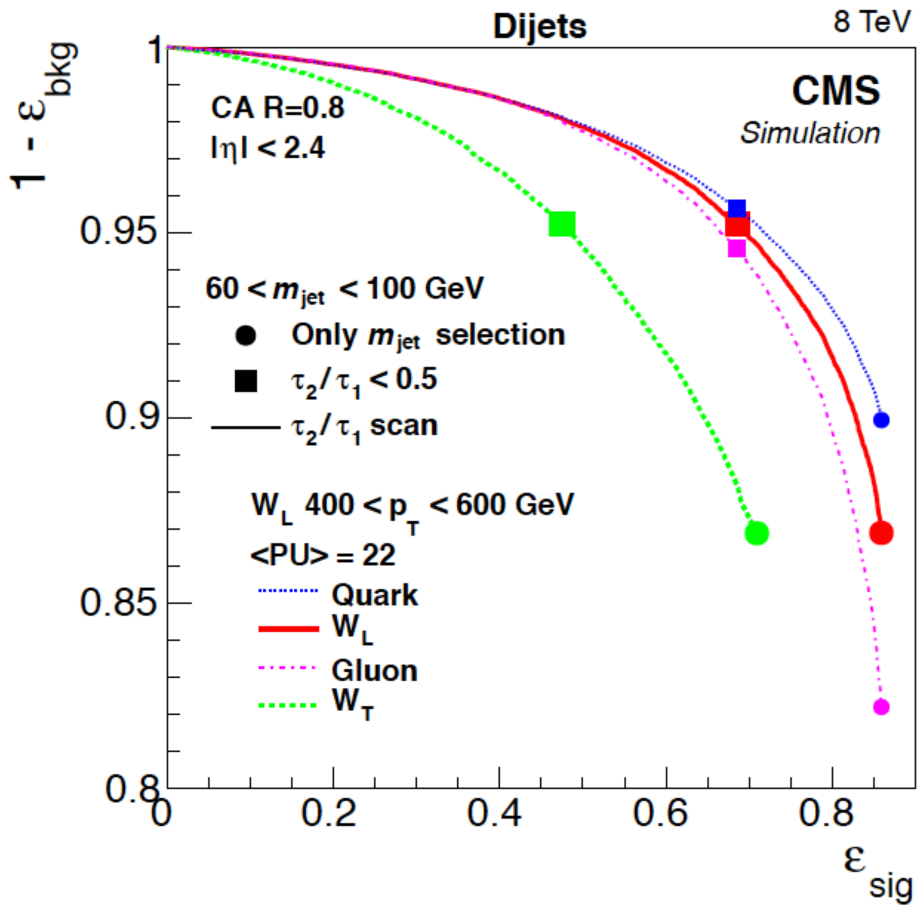
arXiv:1410.4227

Data/MC scale factors

	data	MC	scale factor / shift
efficiency $200<p_T<265$ GeV	τ_2/τ_1cut		* 0.96 +- 0.08
efficiency $265<p_T<600$ GeV			* 0.89 +- 0.10
mass peak position	84.5 +- 0.4 GeV	83.4 +- 0.4 GeV	+1.1 +- 0.4 GeV
mass peak width	8.7 +- 0.6 GeV	7.5 +- 0.4 GeV	+16% +- 9%

W-tagger optimization





arXiv:1410.4227

W/Z/H tagging comparison

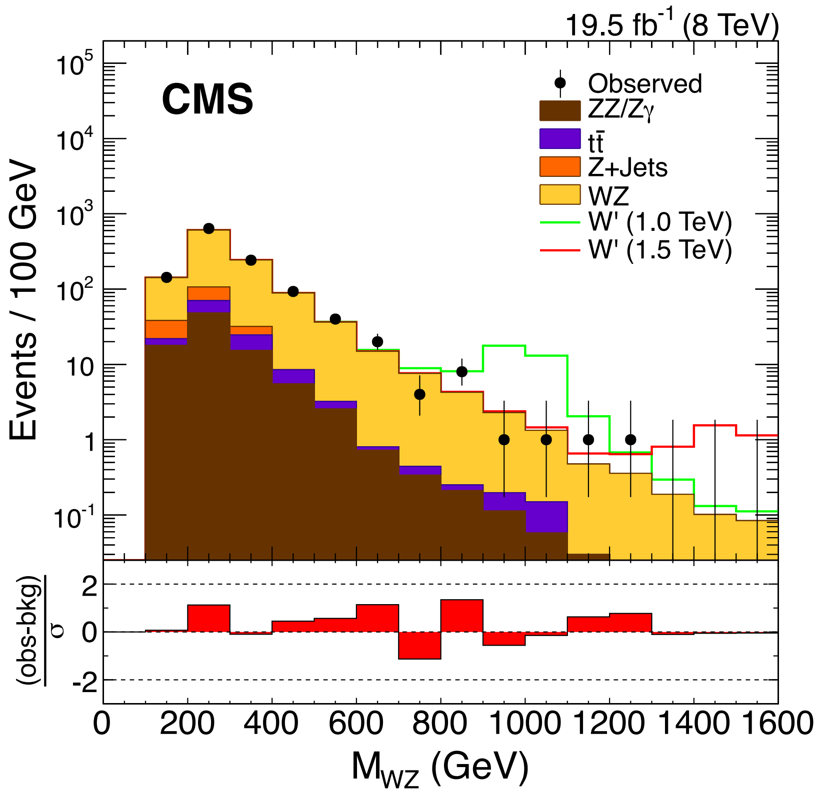
- Compare Run I W/Z/H taggers at 35% efficiency working point

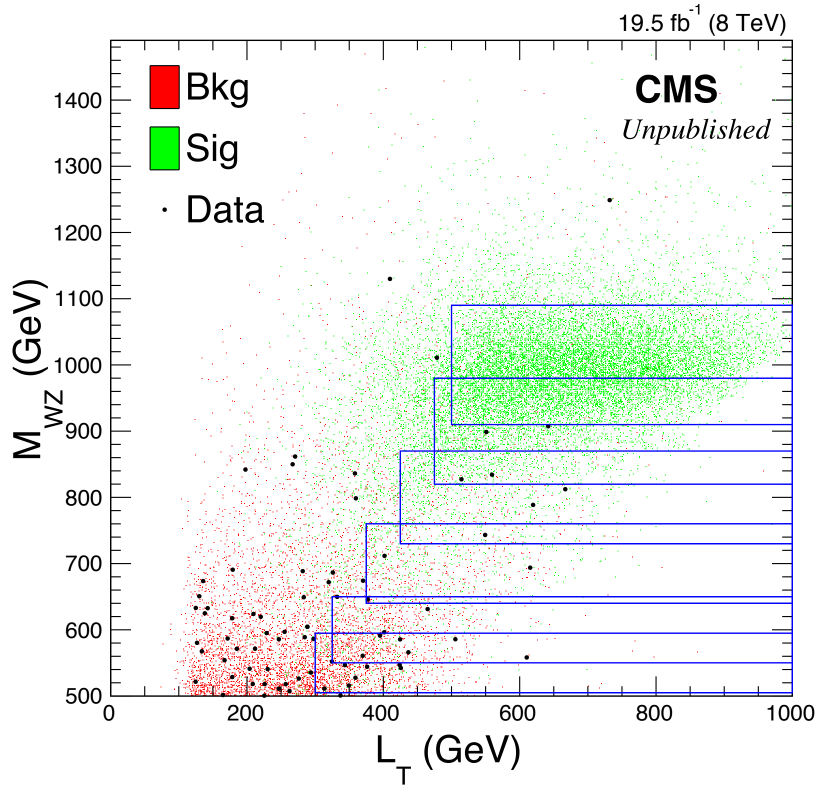
Tagger	BR(W/Z/H→xx)	Efficiency (W/Z/H)	Mistag rate (q/g-jets)
W/Z(qq)-tagger	70% / 68%	35%	1.2%
H(bb)-tagger	57%	35%	0.5%
H(WW→qqqq)-tagger	10%	35%	1.5%
H(ττ)-tagger	6%	35%	0.03%

- H(bb) can be discriminated from background by a factor >2 better than W(qq)/Z(qq)

$W'/\rho_{TC} \rightarrow WZ\ 3l+E_T^{miss}$

- 2 opposite-sign same-flavor leptons from Z falling in Z mass window
- 1 lepton and E_T^{miss} from W
- Special identification+isolation for leptons from (boosted) Z boson
  - one muon with relaxed muon system requirements (tracker muons)
  - other lepton excluded from particle based lepton isolation
- M_{WZ} and $L_T \equiv \Sigma\, p_T^{Lep}$ cuts optimized for each signal mass



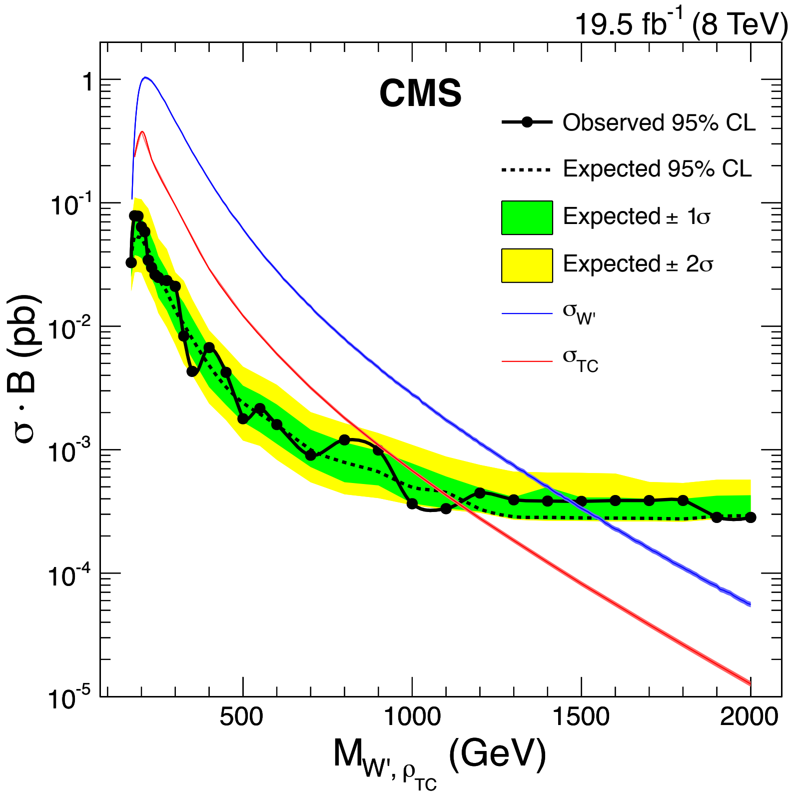


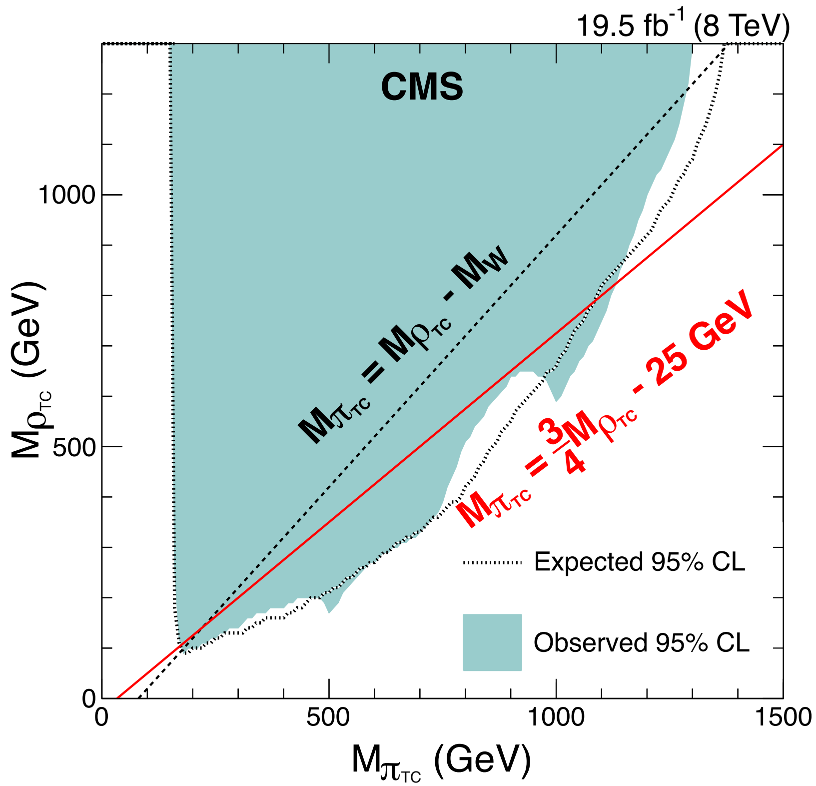
CMS-PAS-EXO-12-025

W'/ρ_{TC} → WZ 3l+E_T^{miss}

- No significant excess observed
- Cut-and-count method for limit setting
- W'→WZ excluded in mass range 0.17 to 1.45 TeV
- Most stringent limits on ρ_{TC} to date

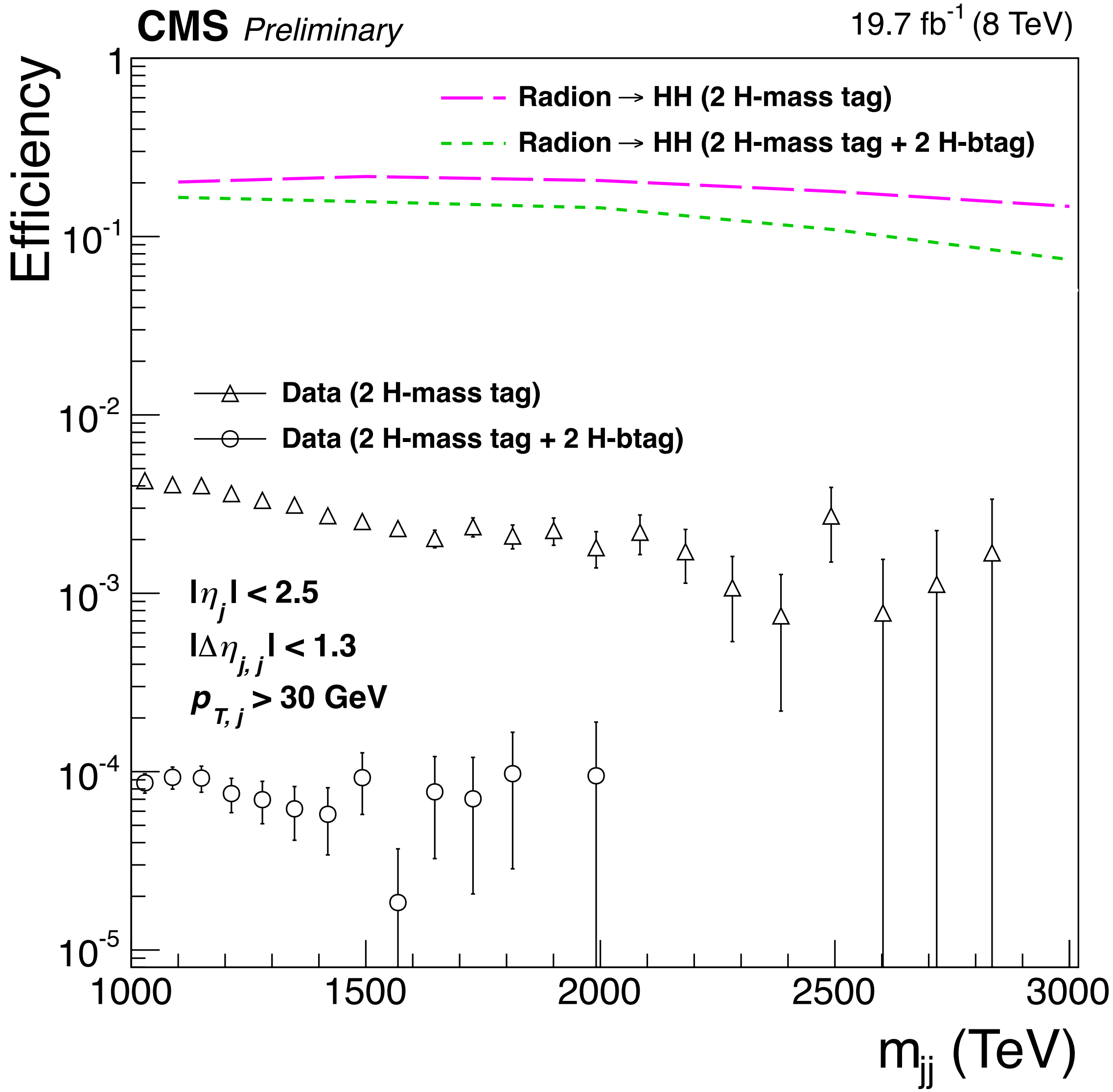
ρ_{TC} → WZ
ρ_{TC} → Wπ_{TC}





CMS-PAS-EXO-12-025

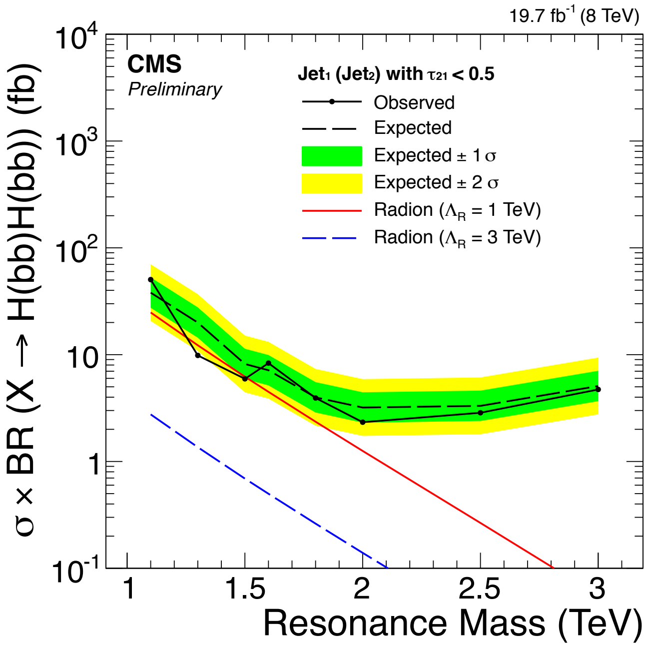
H(bb)H(bb) resonances – efficiencies



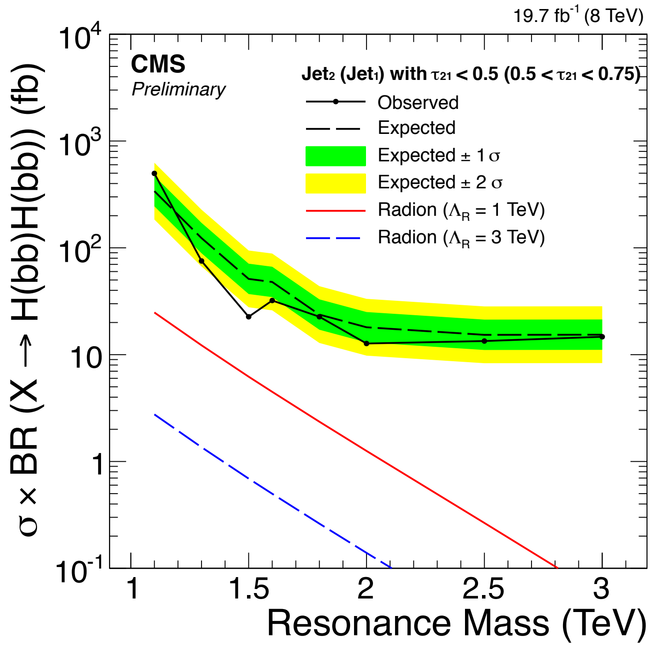
CMS-PAS-EXO-12-053

H(bb)H(bb) resonances – limits

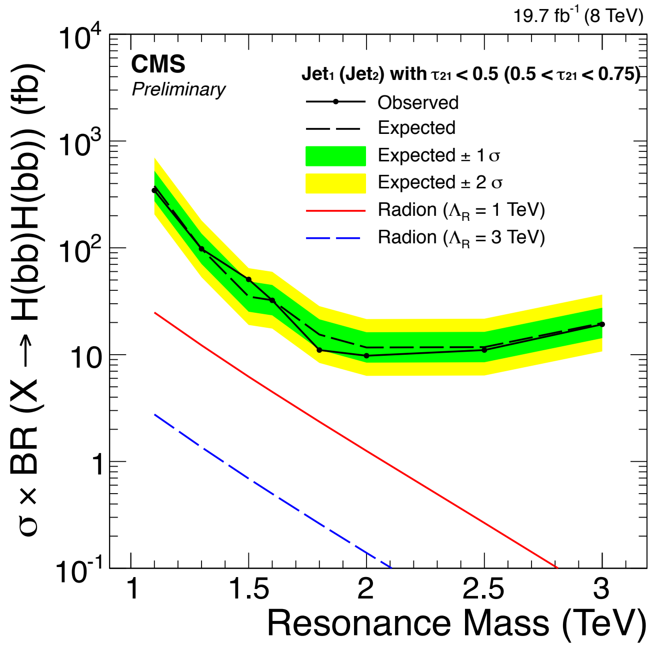
Highest purity



1st jet lower purity



2nd jet lower purity

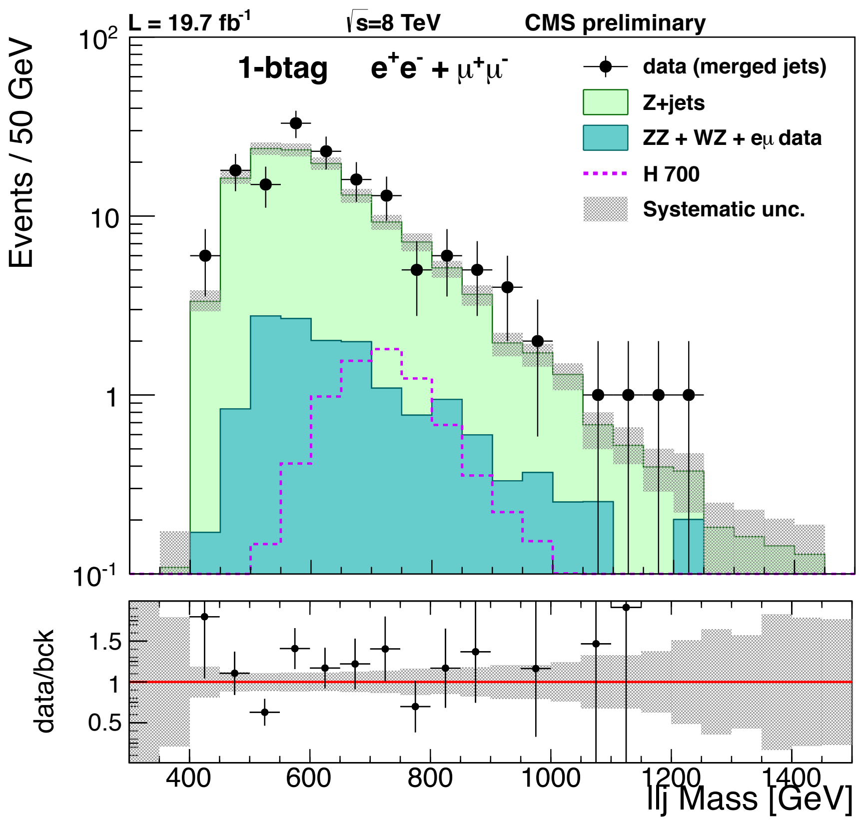


CMS-PAS-EXO-12-053

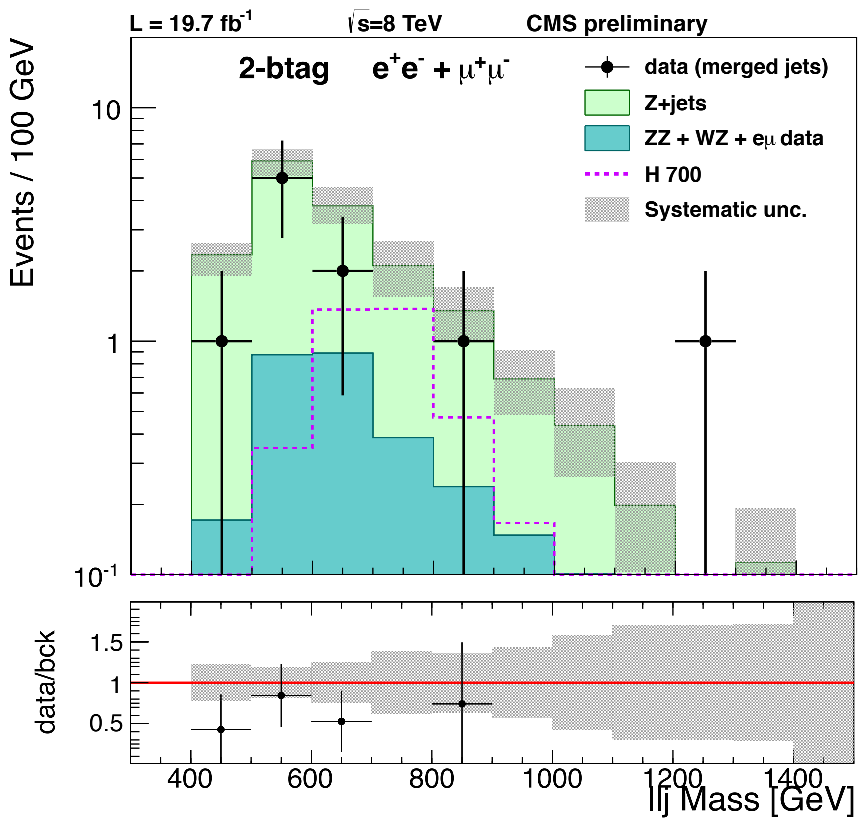
Spin-0 Z(ll)V(qq) resonances in ll+jet

- Search optimized for spin-0 resonances
- Consider also VBF category and subjet b-tag categories to supress Z+jets background

1 b-tag



2 b-tag



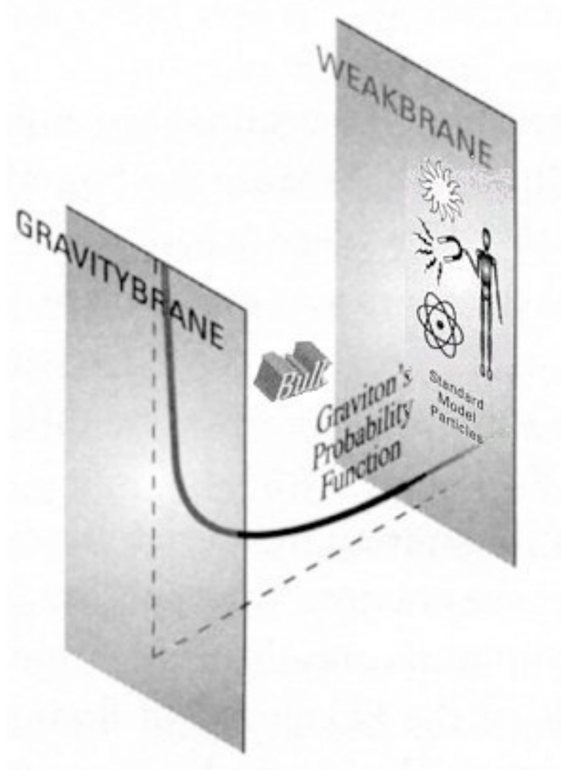
arXiv:1504.00936

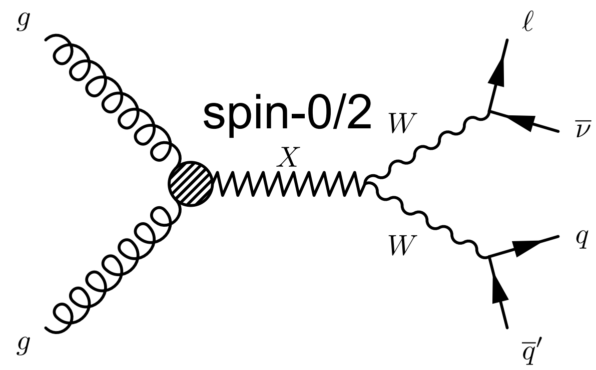
Extra dimension models

- Solve hierarchy problem: gravity can propagate in extra spatial dimensions making it appear weak

- Models
  - Randall-Sundrum (RS): One warped extra dimension of radius R: $M_{Pl}^{RS} = M_{Pl}e^{-k\pi R}$
  - Bulk scenario of RS model: fermions allowed to propagate in bulk of extra dimension explaining their unpredicted Higgs Yukawa couplings

- Signature: Kaluza-Klein (KK) excitations of spin-2 gravitons resonances and spin-0 radion resonances
  - RS1 scenario: Narrow resonances decaying primarily to fermions
  - Bulk scenario: Narrow resonances decaying primarily to bosons (W_L, Z_L, H)





Composite Higgs models

- Solve hierarchy problem: Higgs is composite object and its mass driven by new strong interaction (like the mass of the proton is predicted by QCD)
- Predict new heavy particles, Higgs is just one of the composite states formed by the new strong interaction, analogous to nuclear physics
- Signature: Heavy (~TeV) copies of SM particles decaying primarily to bosons (and top quarks)
- Focus for di-boson searches on generalized Heavy Vector Triplet model (scenario B) predicting W'$^{\pm}$ and Z' (analogues to $\rho^{\pm}$, ρ^{0} in nuclear physics) decaying primarily to bosons (W_L, Z_L, H)