Higgs as a probe for exotic new physics

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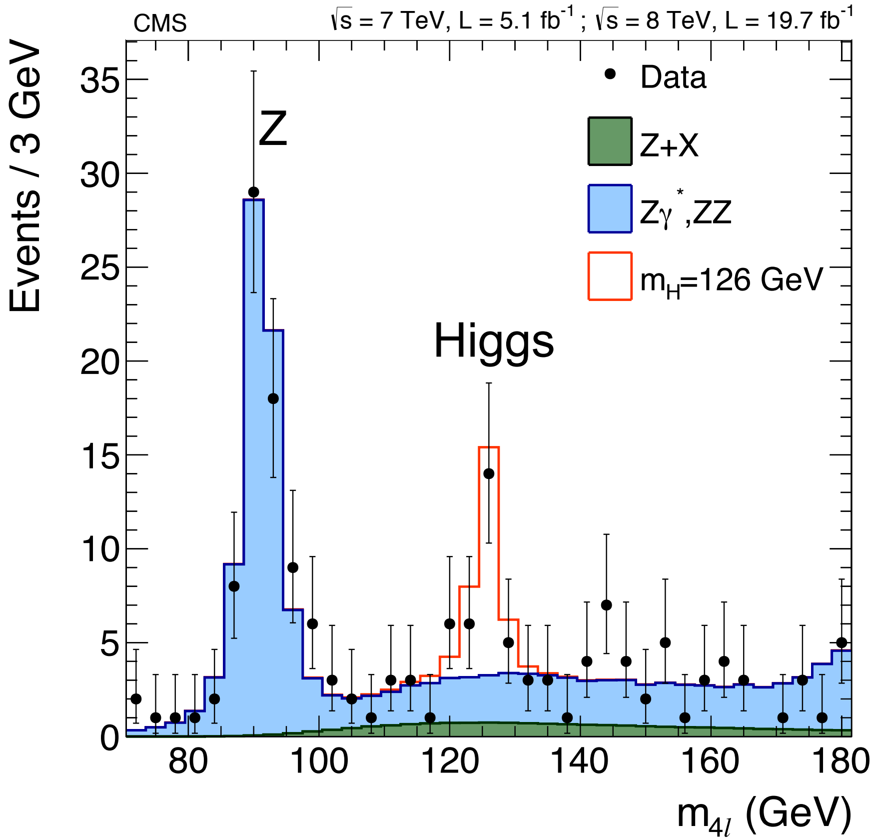
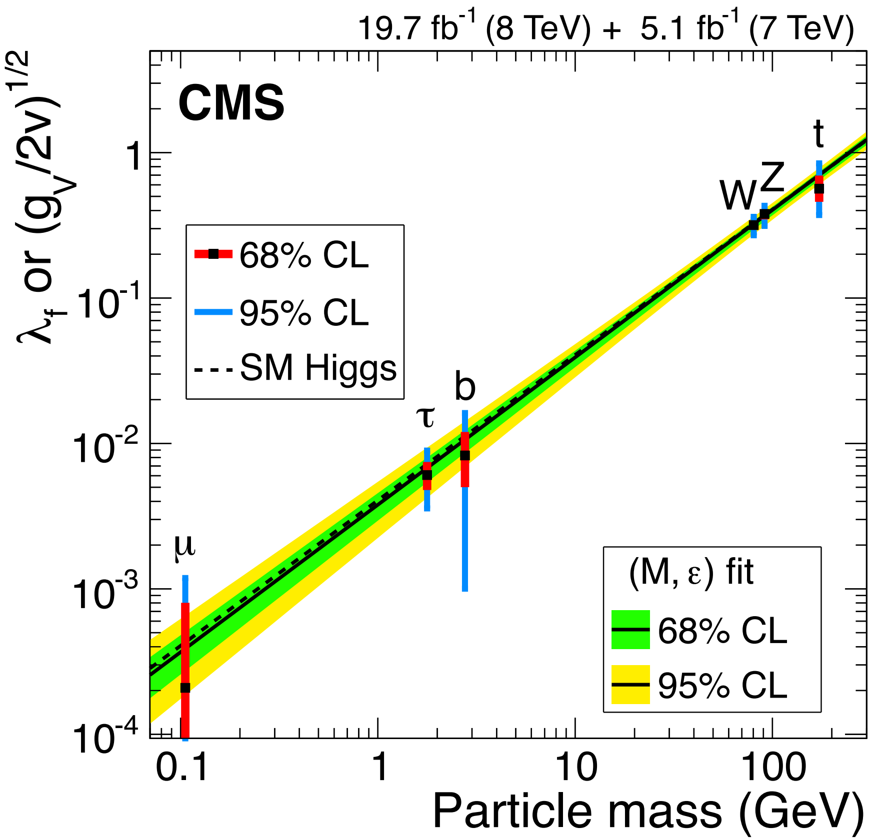
(UZH)

14.07.2015

The Higgs boson

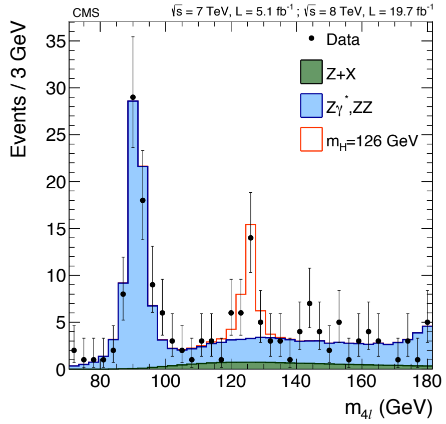




- Mass (ATLAS+CMS): 125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV/c^2

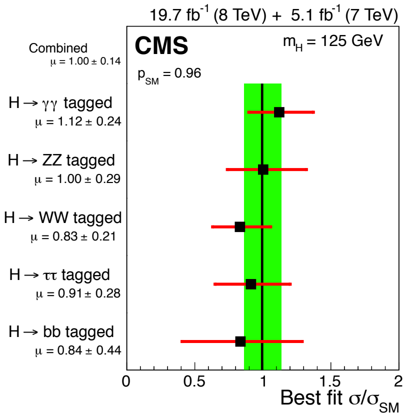
- BR(H→WW)=21% (5σ)
  BR(H→ZZ)=2.7% (7σ)
  BR(H→γγ)=0.2% (6σ)
  BR(H→bb)=57% (2σ)
  BR(H→ττ)=6.4% (4σ)

The Higgs as probe for new physics

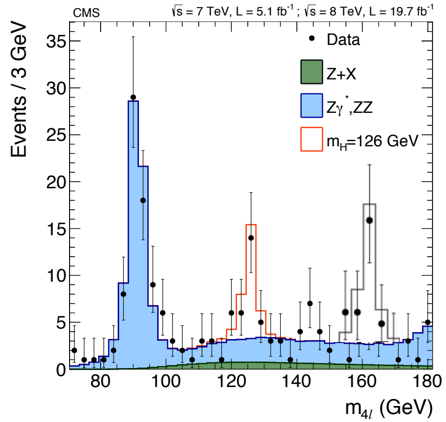


Found one!

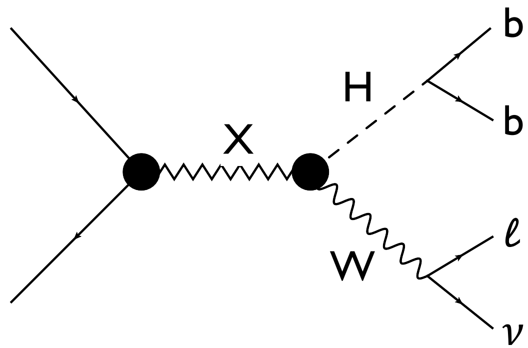
Does it look as expected?



Is there more than one?



Is new physics producing more of it than expected?



This talk

What new physics could we think of?

The hierarchy problem

- Why is the weak force 10^{32} times stronger than gravity? Or why is the Higgs boson so much lighter than the Planck mass?

- 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 electro weak scale

- Solutions
  - New supersymmetric (SUSY) particles cancel the radiative corrections
  - Extra dimensions reduce the effective Planck scale
  - Higgs is composite object and its mass generated by a new interaction

This talk

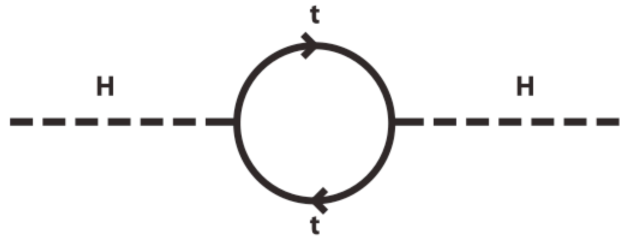
Planck mass

$m_{Pl} = 10^{19}$ GeV/c^2

$$m_{Pl} = \sqrt{\frac{\hbar \cdot c}{G}}$$

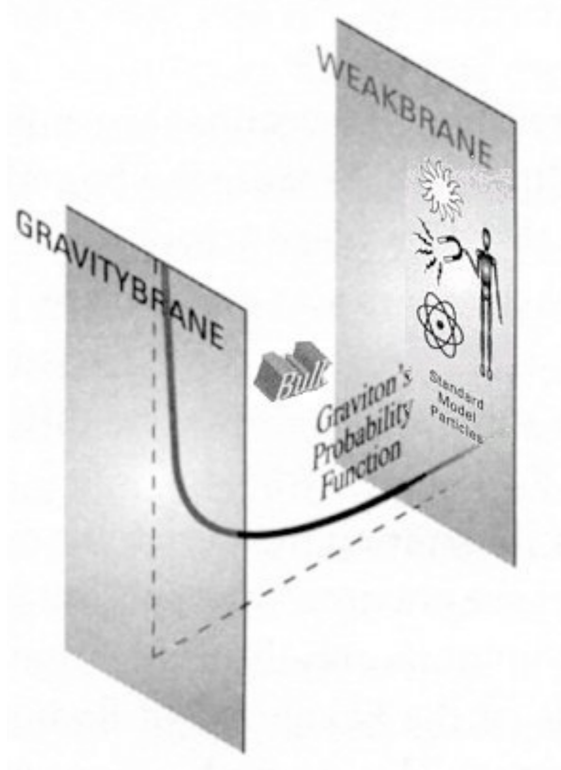
Higgs mass at EWK scale

m_H=125 GeV/c^2

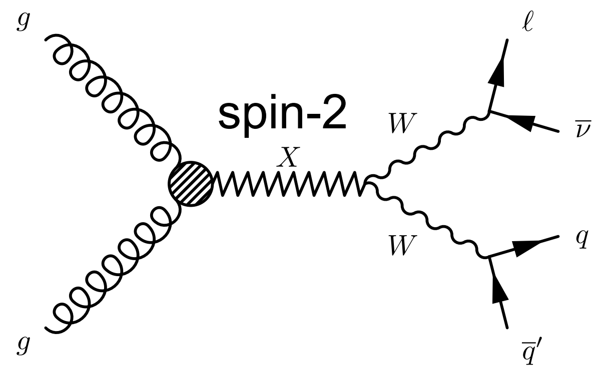


Extra dimension models

- Solve hierarchy problem: gravity can propagate in extra spatial dimensions making it appear weak
- Models
  - Arkani-Hamed Dimopoulus Dvali (ADD): N large extra dimensions of size x: $M_{Pl}{}^{2}{}_{3+1} = M_{Pl}{}^{2+N}{}_{3+1+N}\, x^{N}$
  - 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

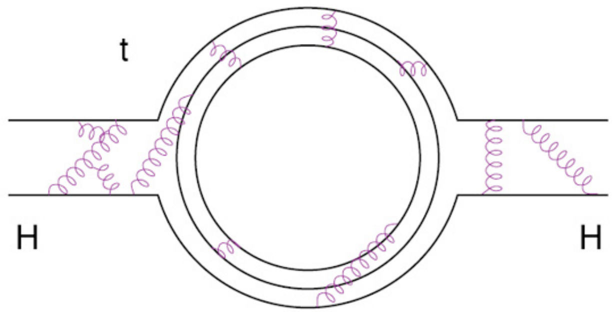


- Signature: Kaluza-Klein (KK) excitations of gravitons (G_{RS}) resonances
  - RS1 scenario: Narrow resonances decaying primarily to fermions
  - Bulk scenario: Narrow resonances decaying primarily to bosons (W_L, Z_L, H)
  - ADD model: Broad excess from many narrow-spaced resonances



Composite Higgs models

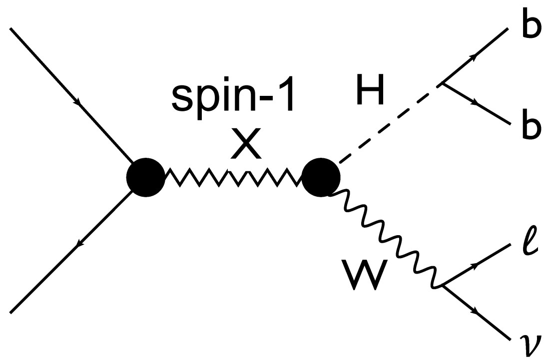
- Solve hierarchy problem: Higgs is composite object and its mass driven by new strong interaction (like the mass of the proton is predicted by QCD)



- Predict new heavy particles, Higgs is just one of the composite states formed by the new strong interaction, analogous to nuclear physics

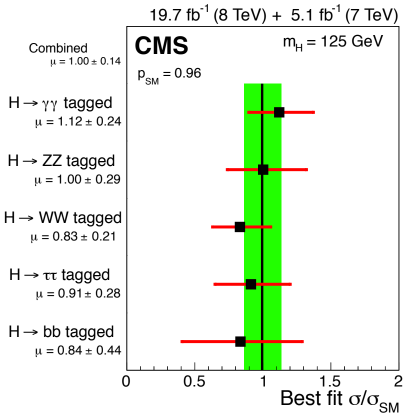
- Signature: Heavy (~TeV) copies of SM particles decaying primarily to bosons (and top quarks)

- Focus here 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)



What do we look for with the Higgs?

Does it look as expected?



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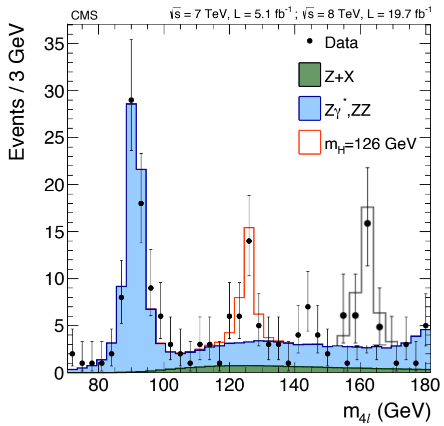

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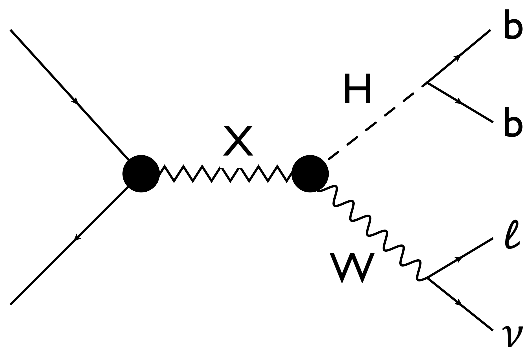


This talk

SUSY

Extra dimensions

Composite Higgs

SUSY, two-Higgs-doublet models (h,H,A,$H^{\pm}$)

SUSY

Extra dimensions

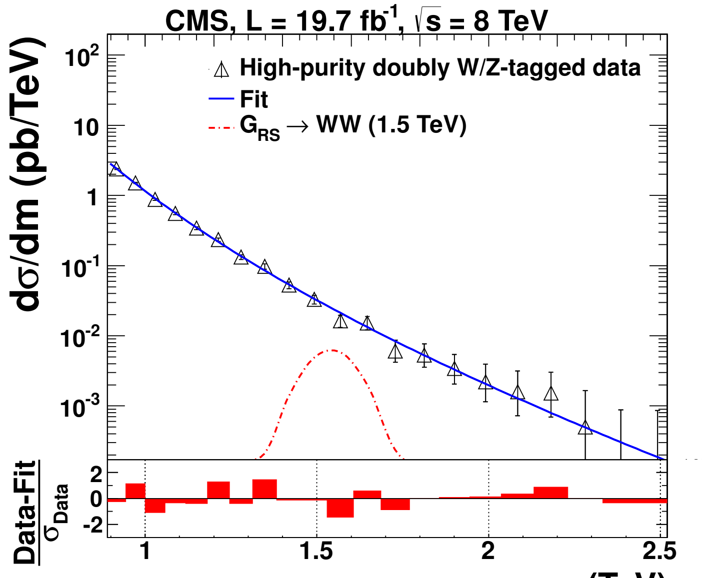
Composite Higgs

This talk

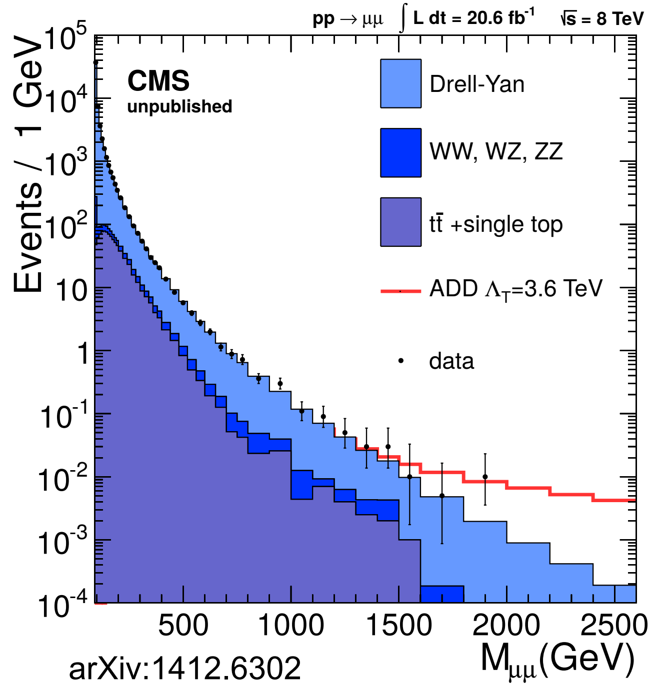
…and many other new physics scenarios

Overview on extra dimension searches

- Signatures explored in CMS
  - Narrow spin-2 graviton resonances: →
    - di-jet, di-lepton, di-photon
      (most sensitive to RS1 scenario)
    - WW, ZZ, HH
      (most sensitive to Bulk scenario)
    - di-top
      (most sensitive to Bulk scenario with top)
  - Broad excess in mass spectrum: →
    - di-jet, di-lepton, di-photon
      (most sensitive to ADD model)
  - Microscopic black holes:
    - multijets



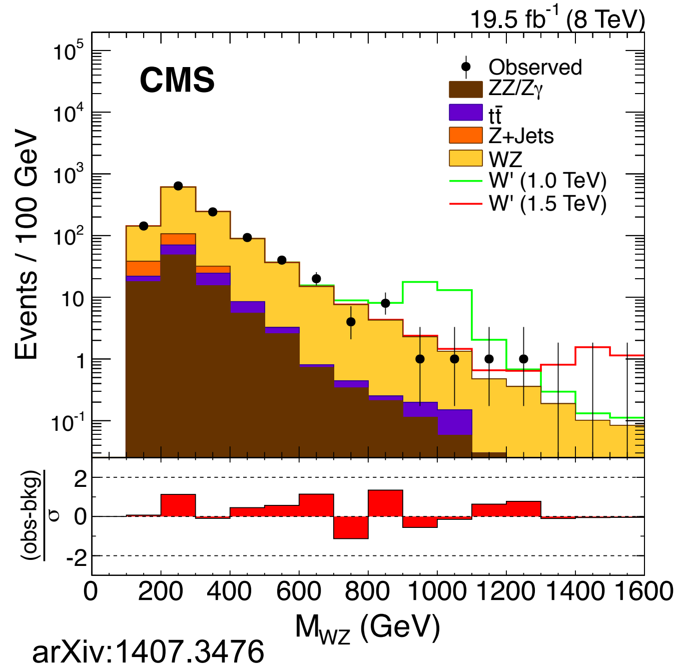
arXiv:1405.1994



arXiv:1412.6302

Overview on W'/Z' resonance searches

- Signatures explored in CMS
  - Narrow spin-1 resonances:
    - W'/Z'→dijets, W'→lν, Z'→ll (most sensitive to SSM/EGM)
    - W'→WZ, Z'→WW, W'→WH, Z'→ZH (most sensitive to composite Higgs models)
    - W'→tb, Z'→tt (most sensitive to topflavor W' / topcolor Z')



arXiv:1407.3476

Outline for the remainder of the talk

Topology

↓

Searches with W/Z

↓

Searches with Higgs

↓

Findings

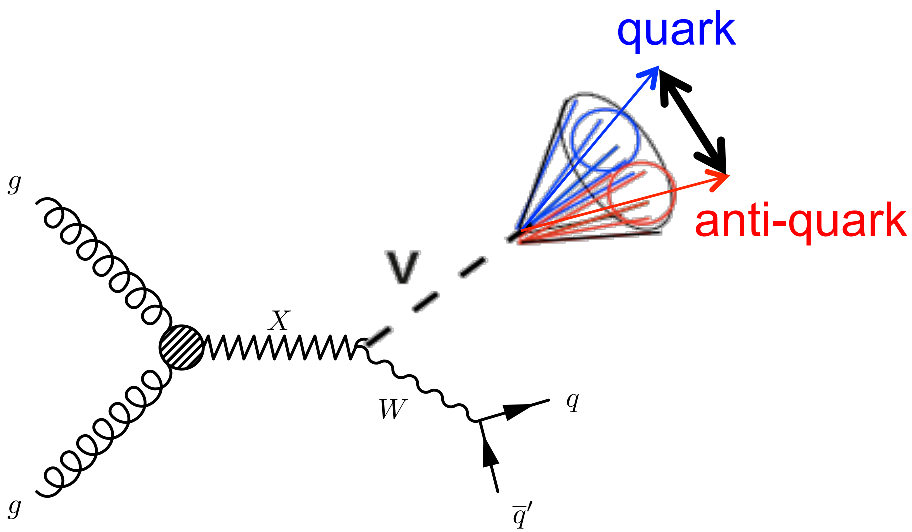
↓

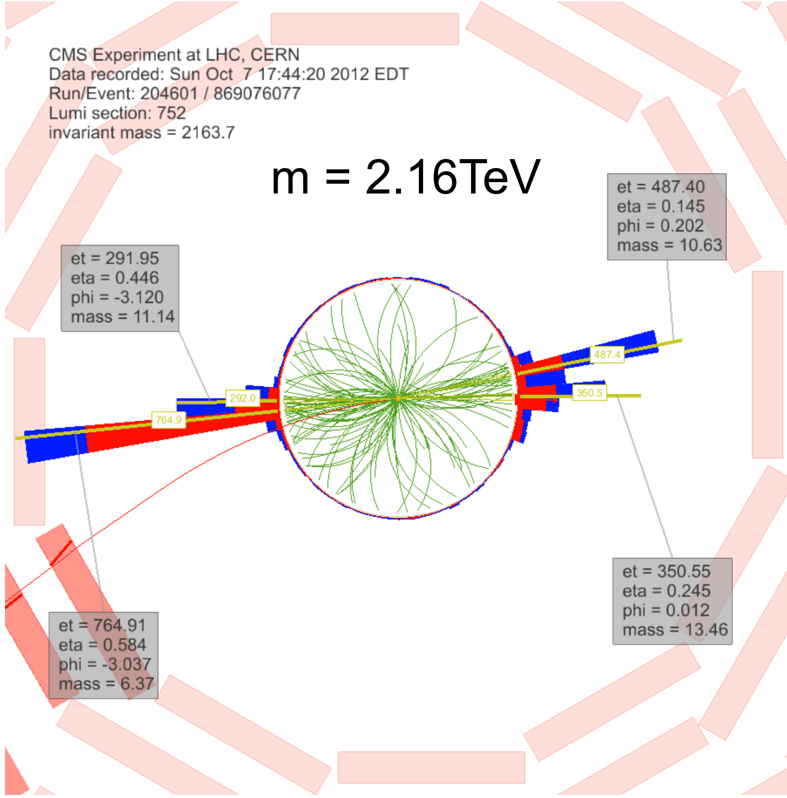
Future

- Boosted topologies
- Jet reconstruction in CMS
- W-jet identification
  - All-jets WW/ZZ/WZ search
  - Leptons+jets WW/ZZ searches
- H-jet identification
  - All-jets WH/ZH search
  - Leptons+jets WH/ZH searches
  - HH searches
- Findings on extra dimensions and composite Higgs models
- Outlook to Run II
  - Search sensitivity
  - Jet reconstruction

Boosted topologies

- Main challenge for searches for di-boson resonances above 1 TeV



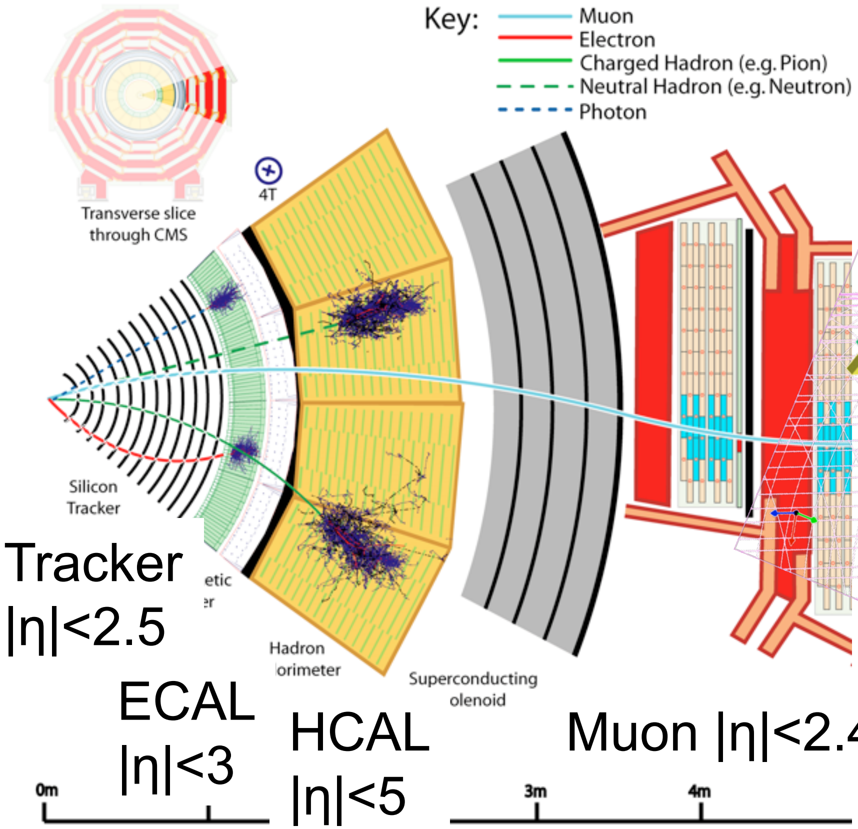


- Quarks from W→qq' and Z→qq and H→bb merge into single jet
  - Example: m=2 TeV G_{Bulk}→ZZ, $p_T^Z \sim$ 1TeV, $M_Z \sim$ 90GeV

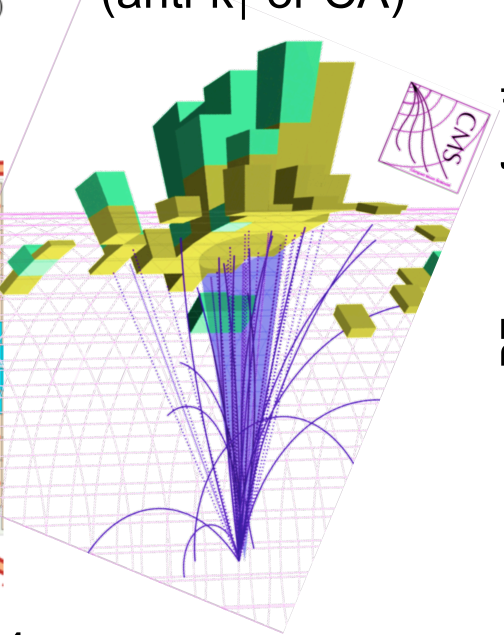
$$\Delta R_{qq}^{\min} \approx \Delta\theta_{qq}^{\min} \approx 2\frac{M_V}{p_{T,V}} \sim 0.2 < \text{jet cone of } 0.5$$

Jet reconstruction in CMS

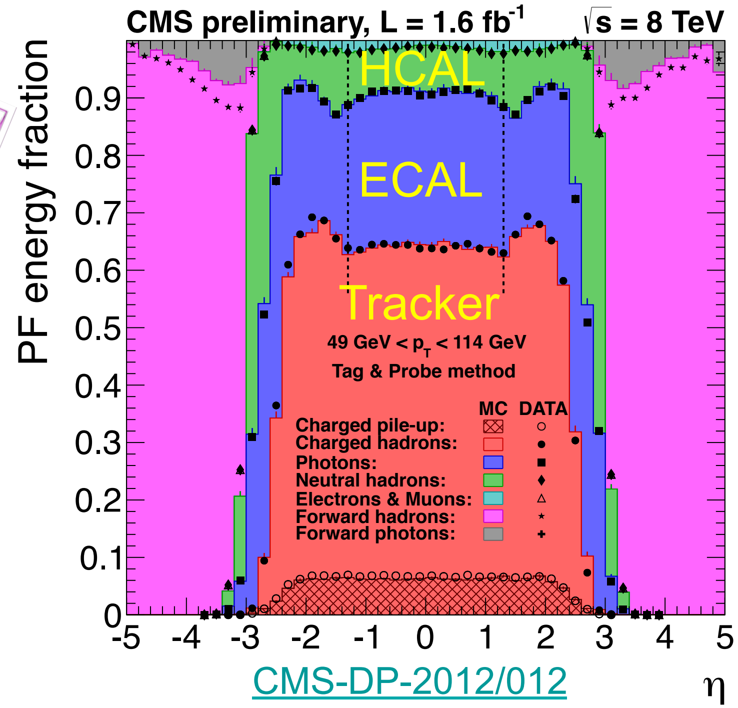
Particle flow reconstruction



Jet clustering
(anti-k_T or CA)



Jet energy fractions

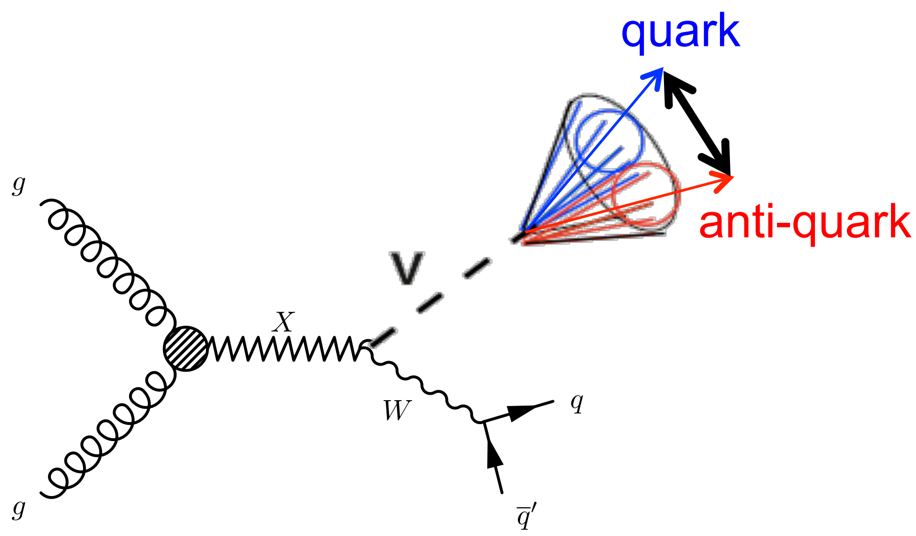


CMS-DP-2012/012

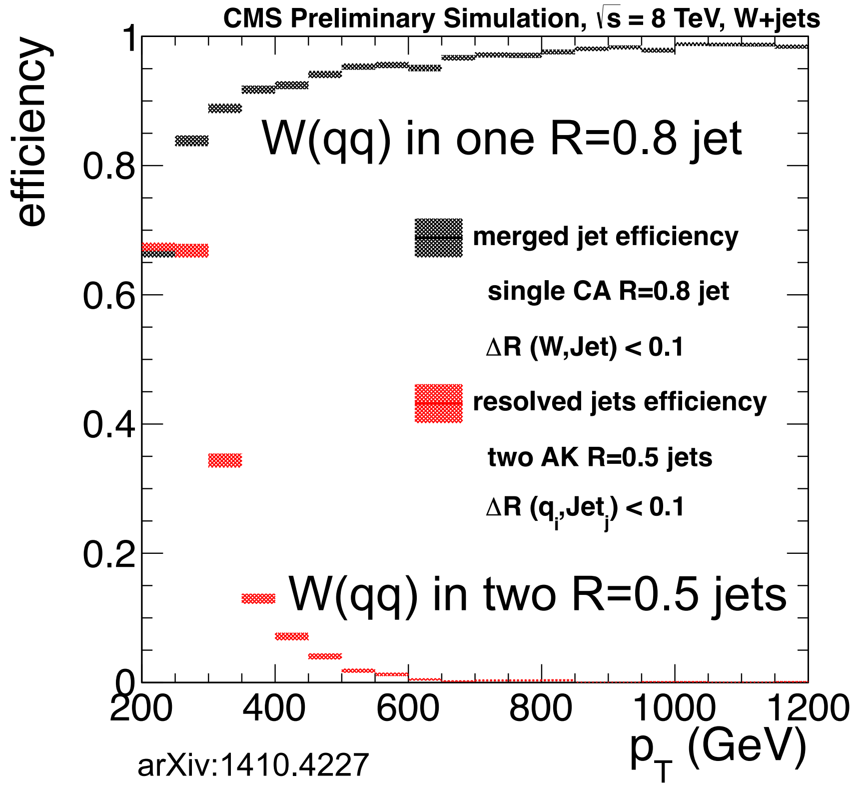
Particle Flow algorithm benefits from sub-detectors with best spatial+energy resolution

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)

W/Z-tagging



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

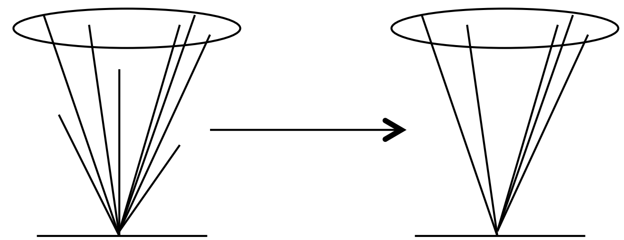


arXiv:1410.4227

- Above W/Z p_T>200 GeV quarks merge into R=0.8 jet
- Use discriminators based on jet substructure
  - Jet mass → expected at W/Z/H mass
  - N-subjettiness → Should look like composed of two smaller jets

Pruned jet mass

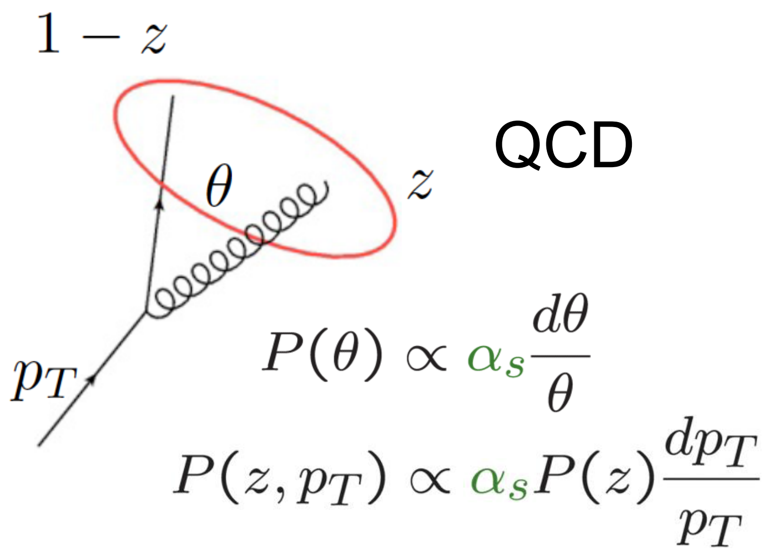
- Improve jet mass resolution by removing soft, large angle particles

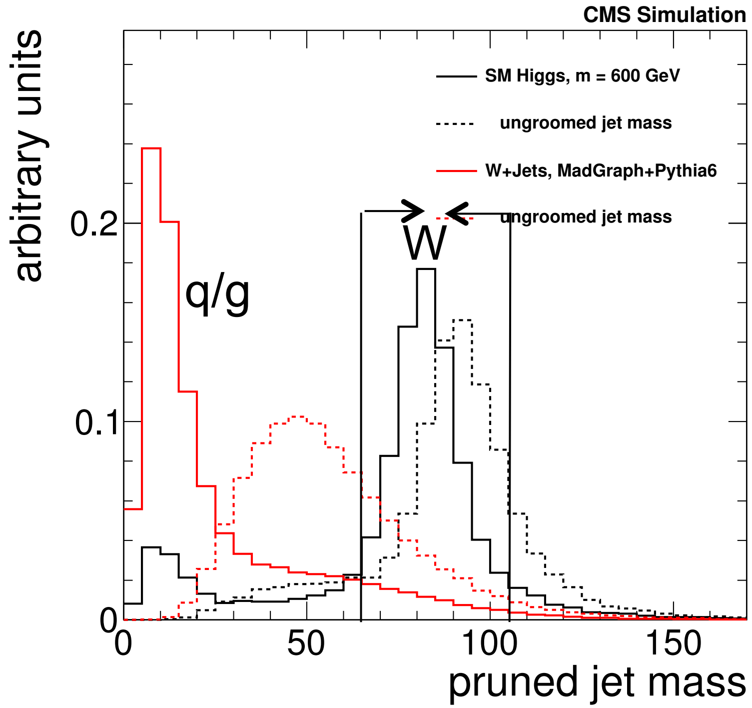


- Strongly reduce the mass of quark/gluon-jets
- Recluster each jet with Cambridge Aachen (CA) with R=0.8, requiring that each recombination satisfy the following:

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

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





N-subjettiness

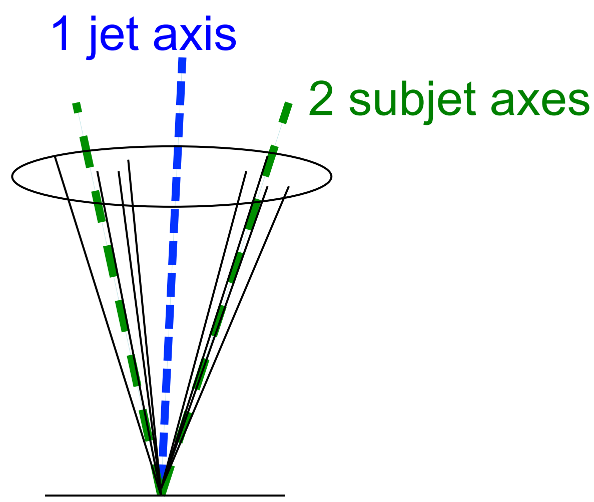
- N-subjettiness is a p_T-weighted sum over all jet constituents of their distance w.r.t. the closest of N axes in a jet

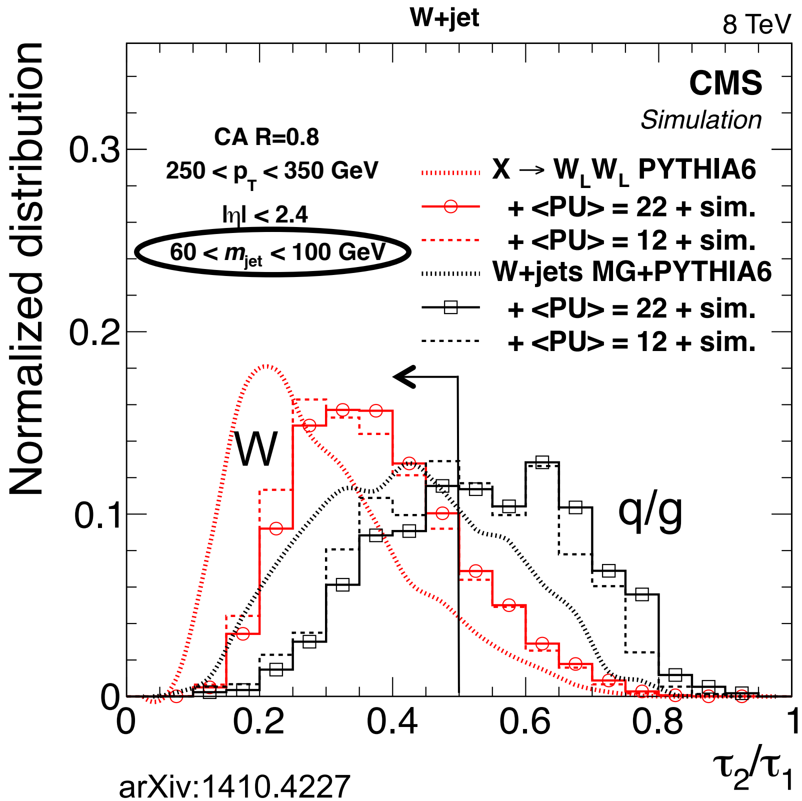
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left((\Delta R_{1,k}), (\Delta R_{2,k}) ... (\Delta R_{N,k})\right)$$

- 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



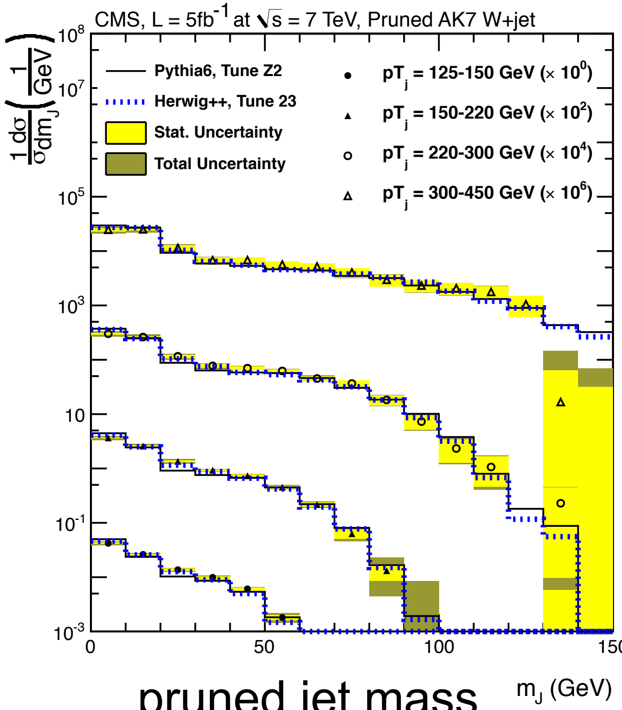


arXiv:1410.4227

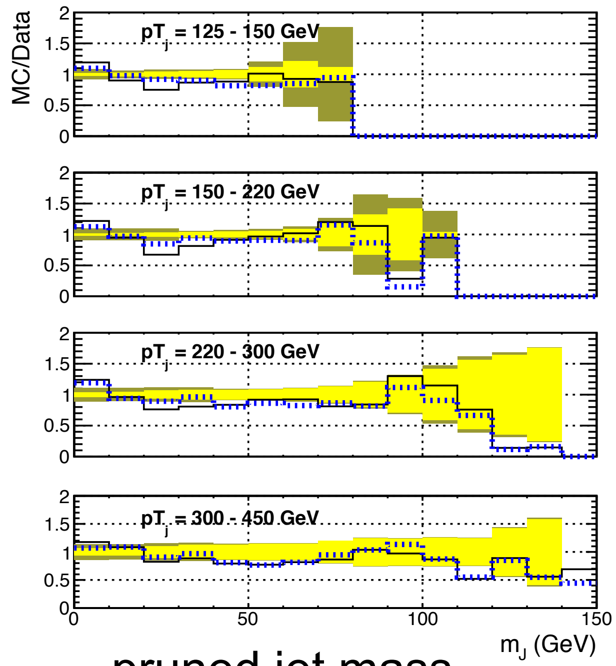
Pruning validation in q/g-jet data

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

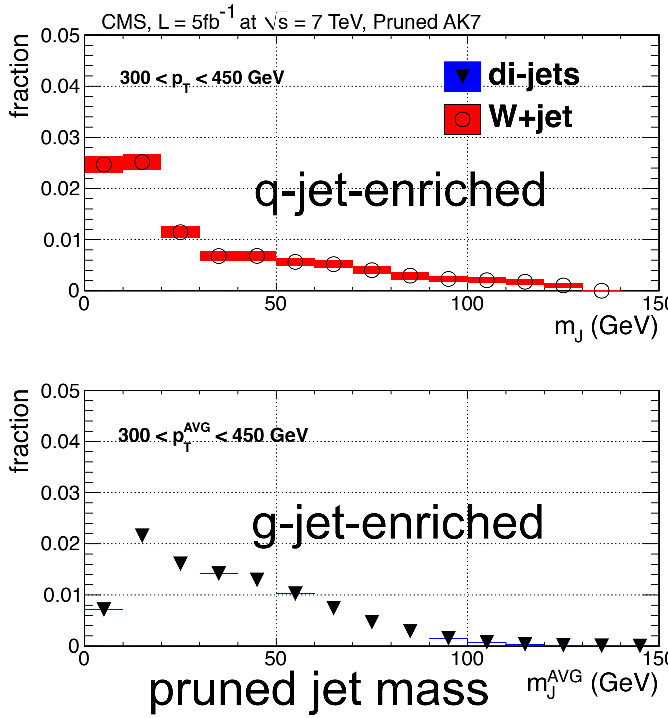
- Matrix-element plus parton-shower MC describes data at 10% level
- Generator differences particularly at low jet mass order 10%



pruned jet mass



pruned jet mass



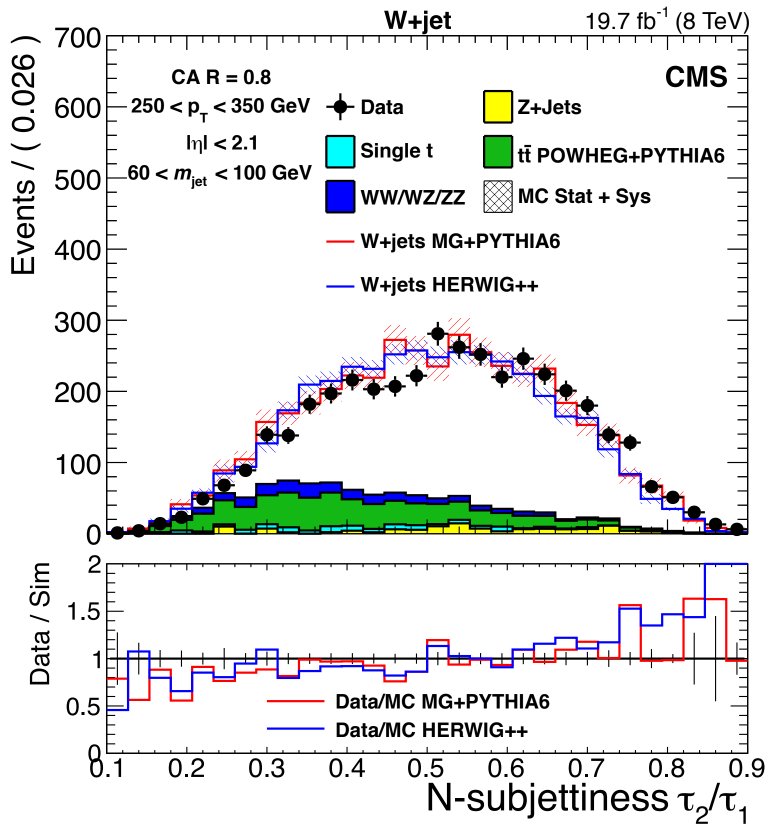
pruned jet mass

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%



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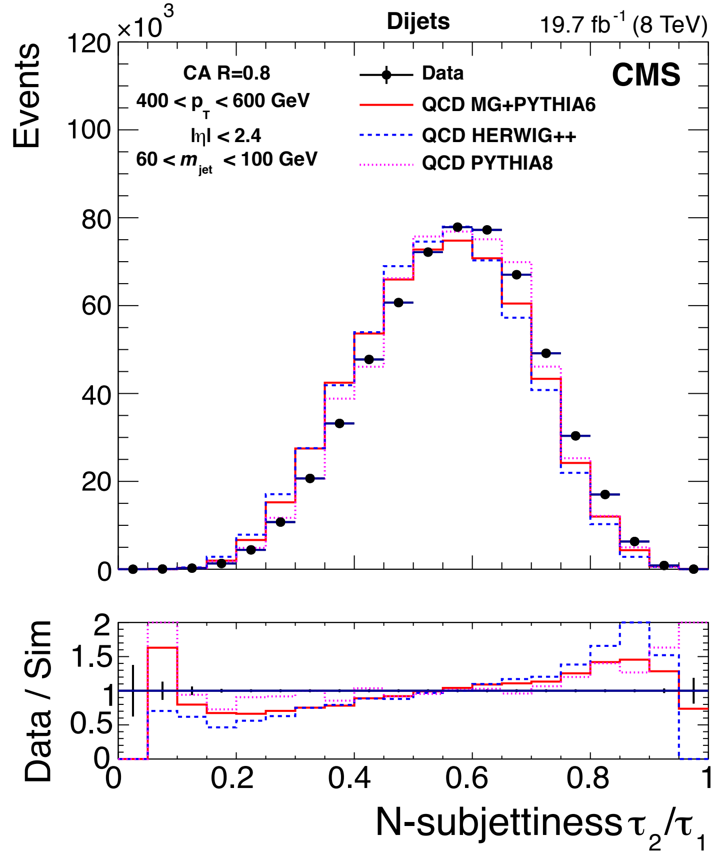
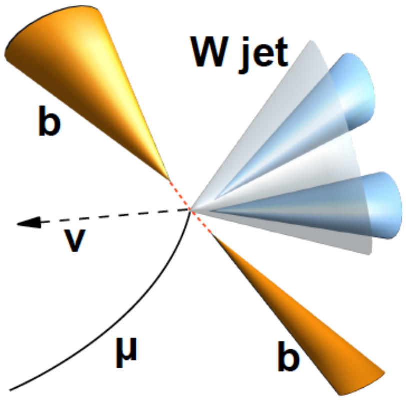


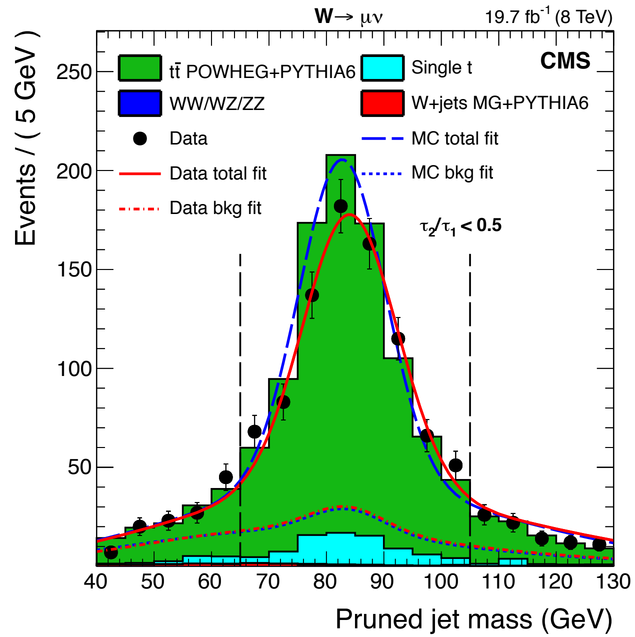
W-tagging validation in W-jet data

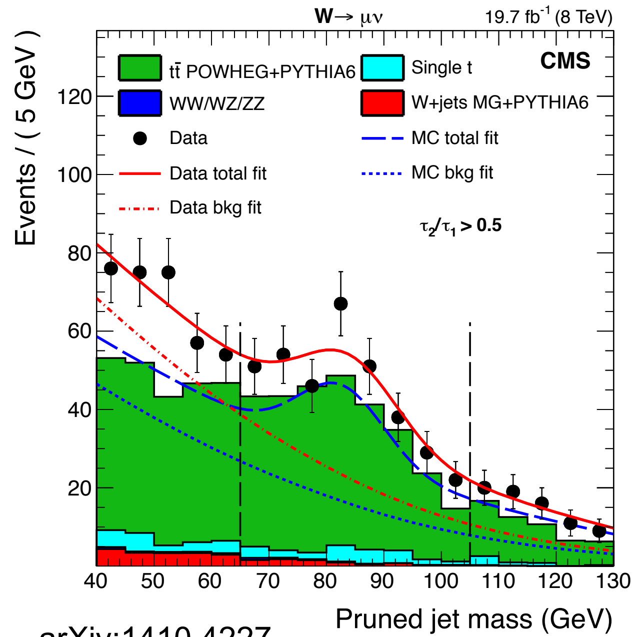
- Semileptonic ttbar sample contains real W-jets



- 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%

Analysis flow

Trigger event

↓

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

↓

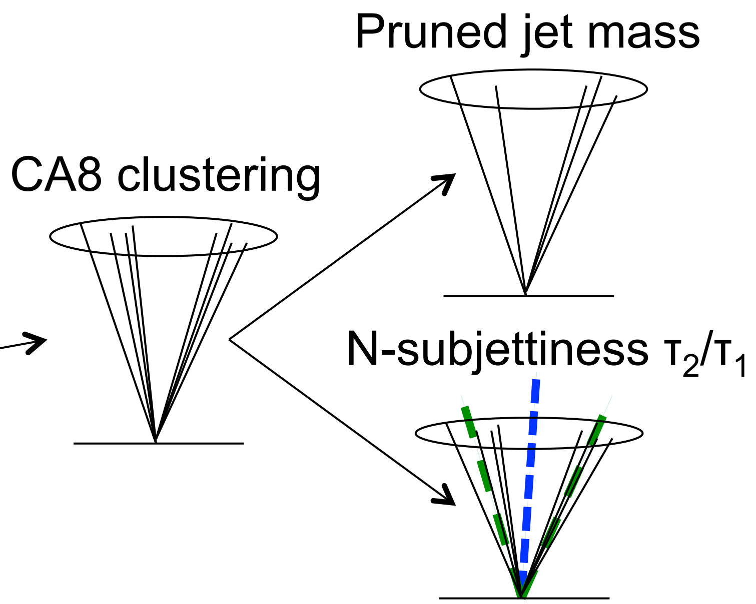
Reconstruct VV/VH invariant mass

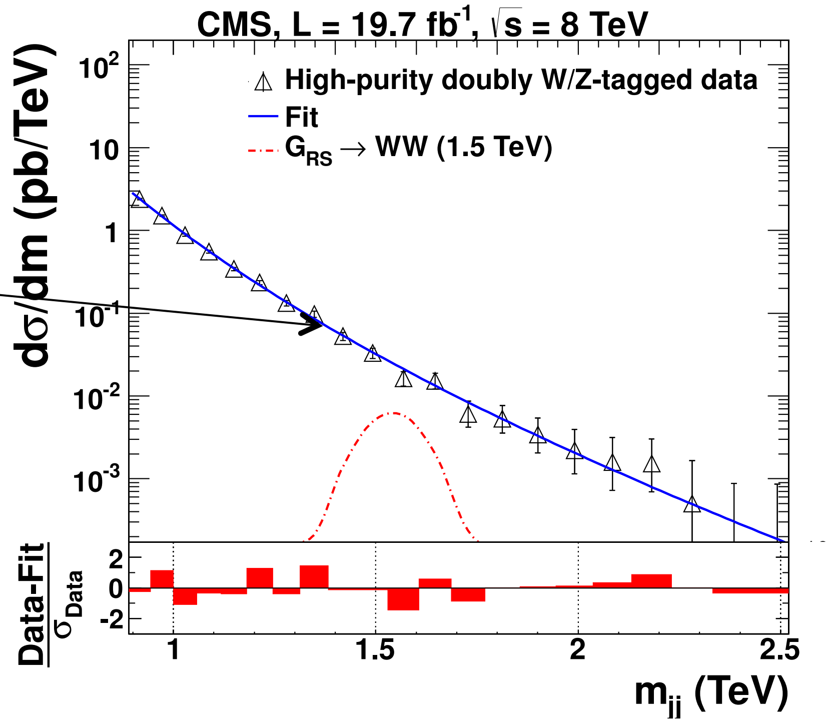
↓

Estimate background

↓

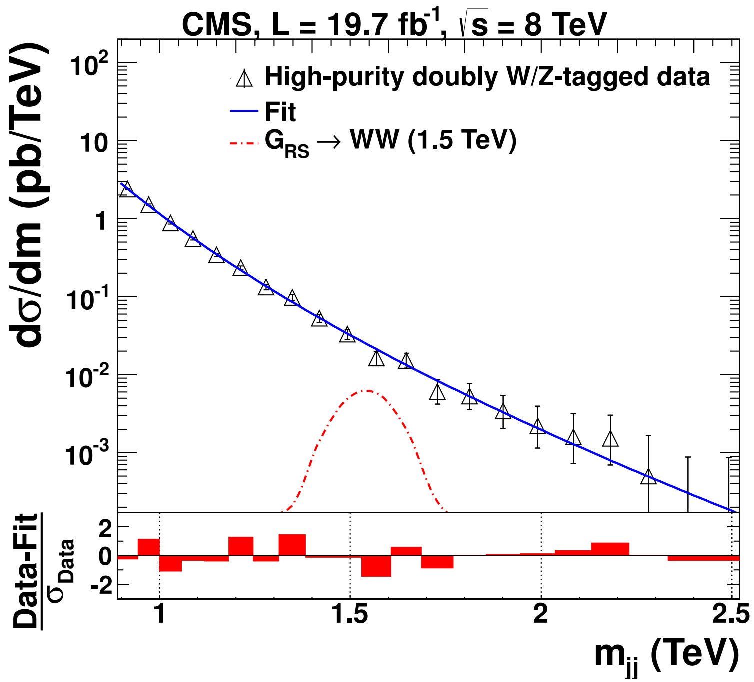
Scan over resonance mass
searching for an excess





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 function in statistical analysis

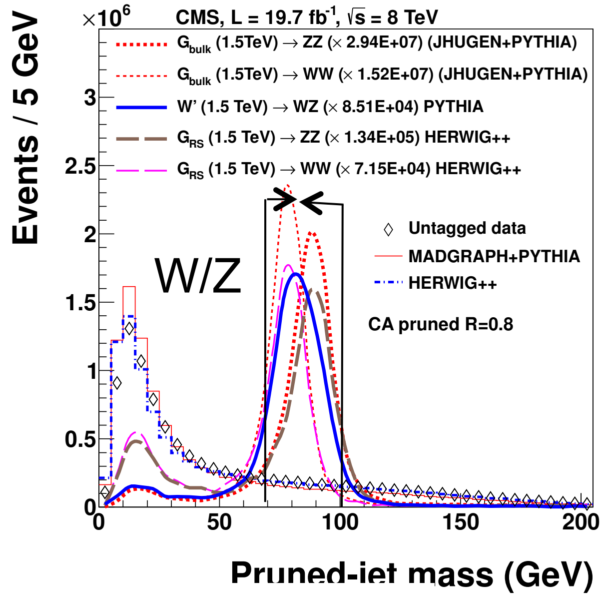


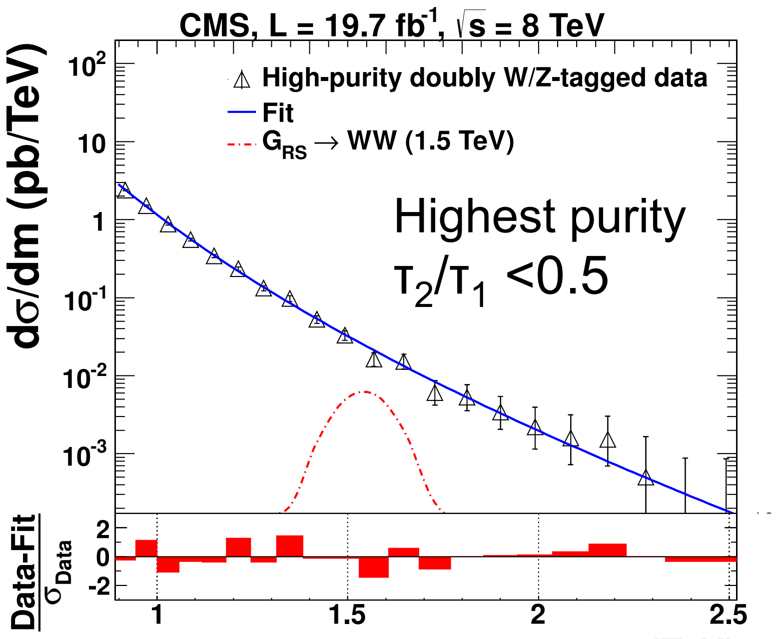
- Advantages:
  - No need for background simulation
- Disadvantages:
  - Arbitrary choice of background functional form and a systematic uncertainty assigned to it
  - Not possible in regions of discontinuity due to trigger turn-ons or kinematic selections
  - Only works for bumps, not for enhancements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

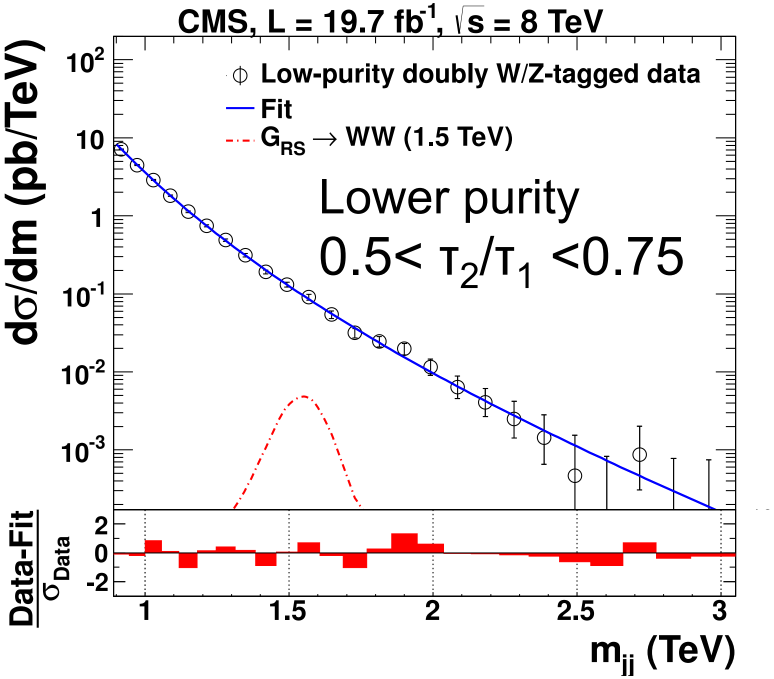
VV→qqqq resonances in dijets

- Trigger $\Sigma_{jets} p_T$>650 GeV
- Two R=0.8 jets with
  - 70<m_{pruned}<100 GeV to select both W and Z
  - τ_2/τ_1 <0.5 for highest purity
- Dijet $|\eta_1-\eta_2|$<1.3
- 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

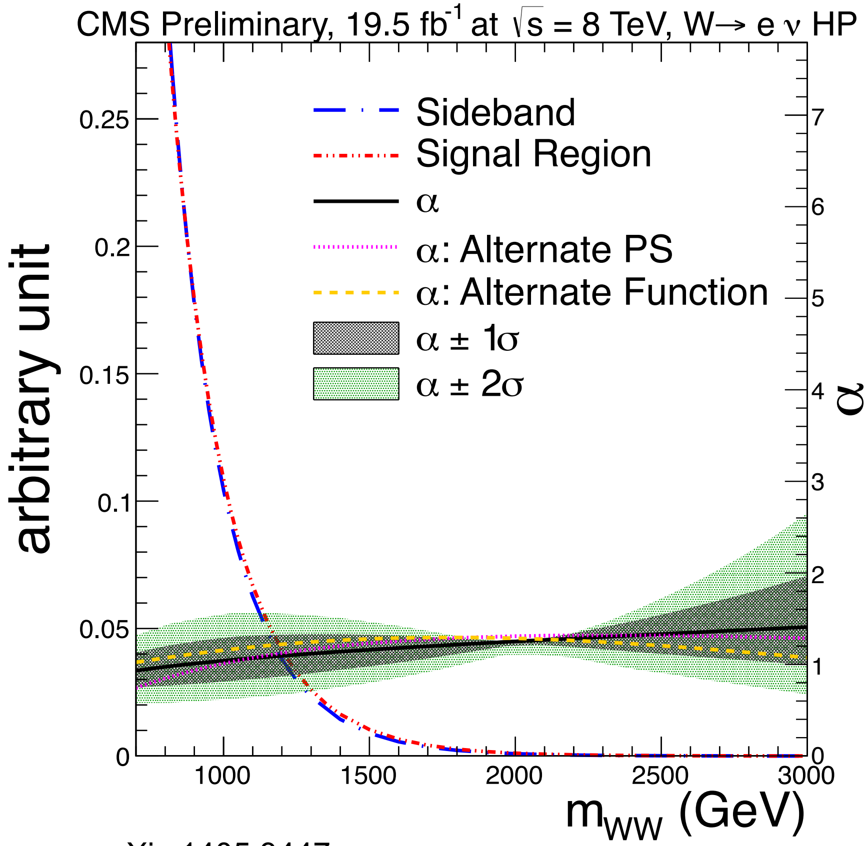


Background – leptons+jets final states

- 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 or other data sideband

- 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

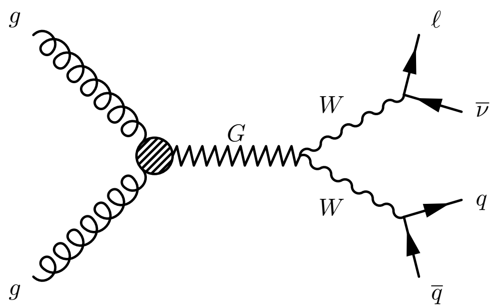
- Checks:
  - Closure test in simulation and/or other data sideband

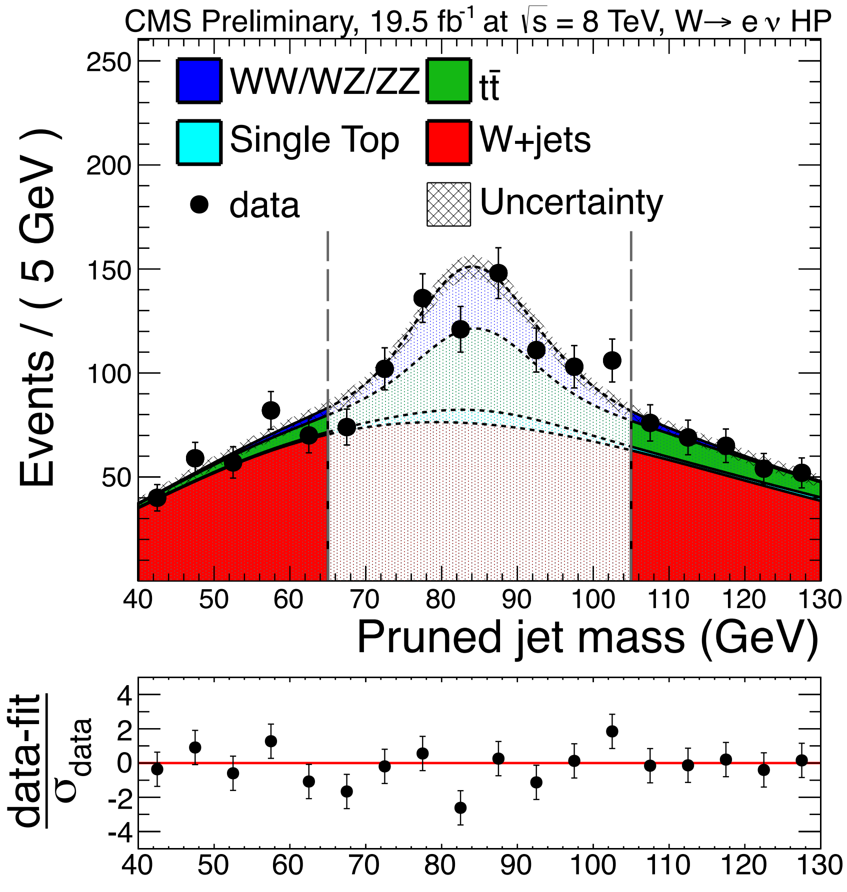


arXiv:1405.3447

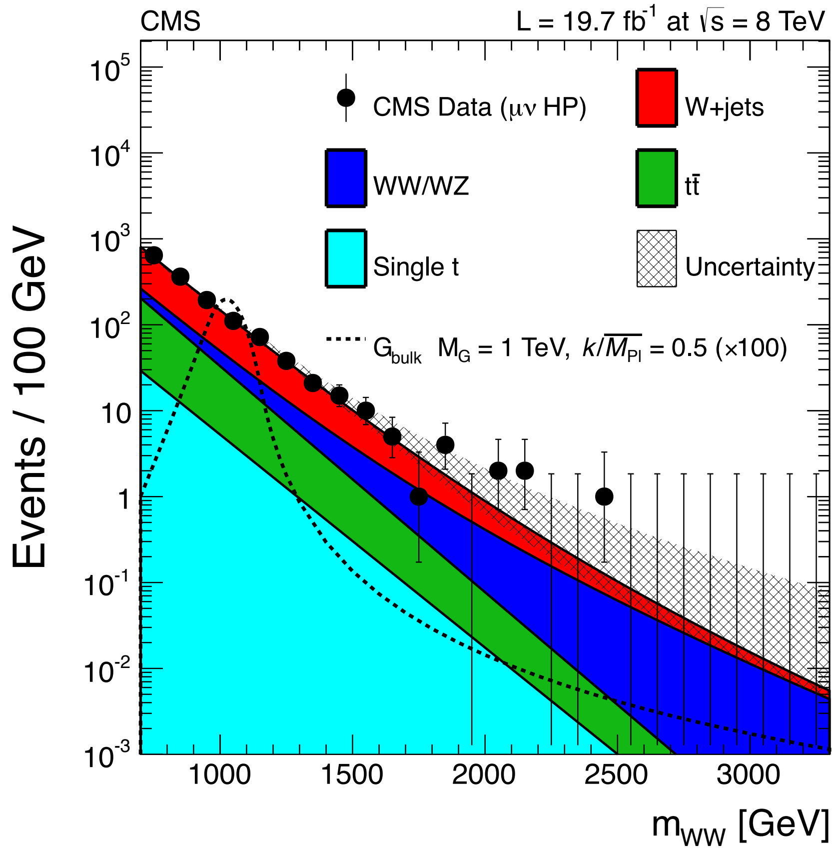
WV→lνqq resonances in l+MET+jet

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



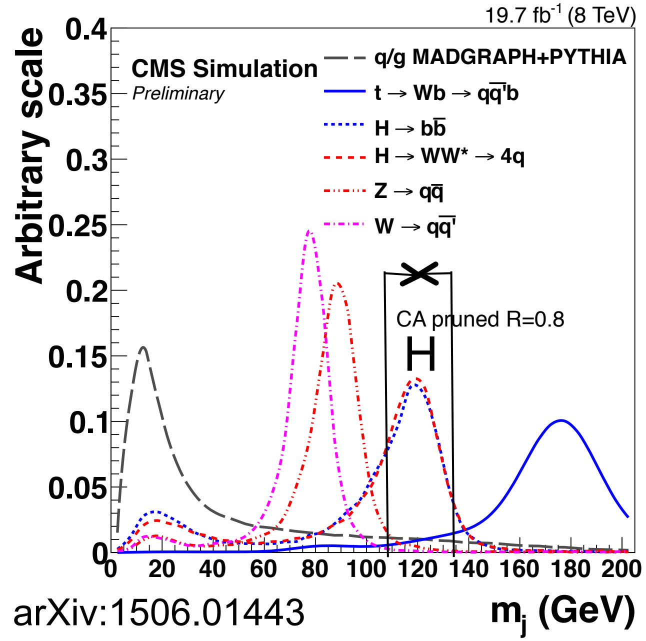


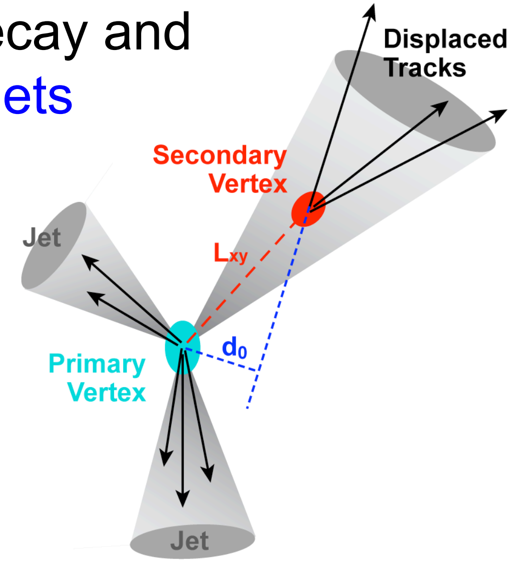
arXiv:1405.3447

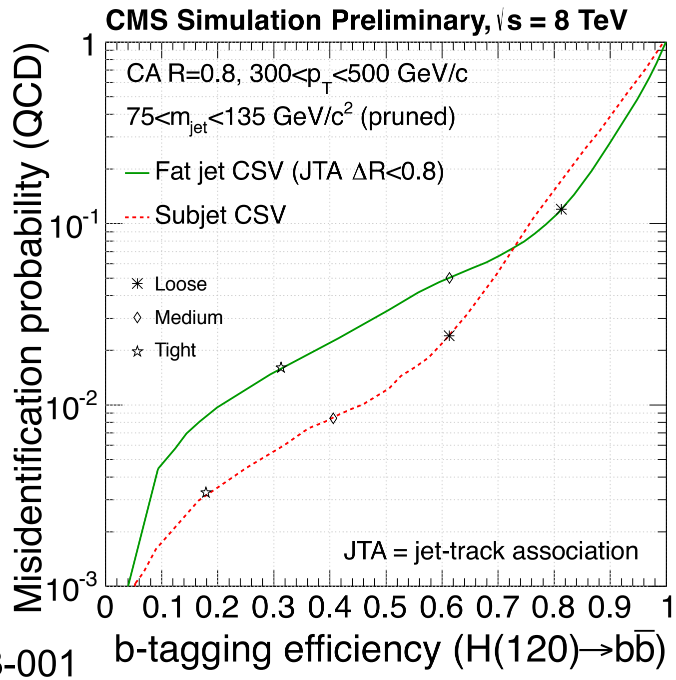


H→bb-tagging

- 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







CMS-PAS-BTV-13-001

W/Z/H tagging comparison

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

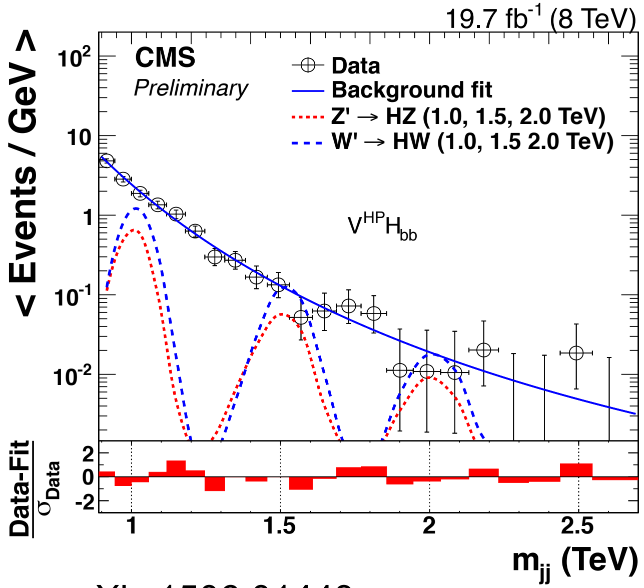
Tagger	BR(W/Z/H→xx)	Efficiency (W/Z/H)	Mistag rate (q/g-jets)
W/Z(qq)-tagger	70% / 68%	35%	1.2%
H(bb)-tagger	57%	35%	0.5%
H(WW→qqqq)-tagger	10%	35%	1.5%
H(ττ)-tagger	6%	35%	0.03%

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

VH(bb) resonances

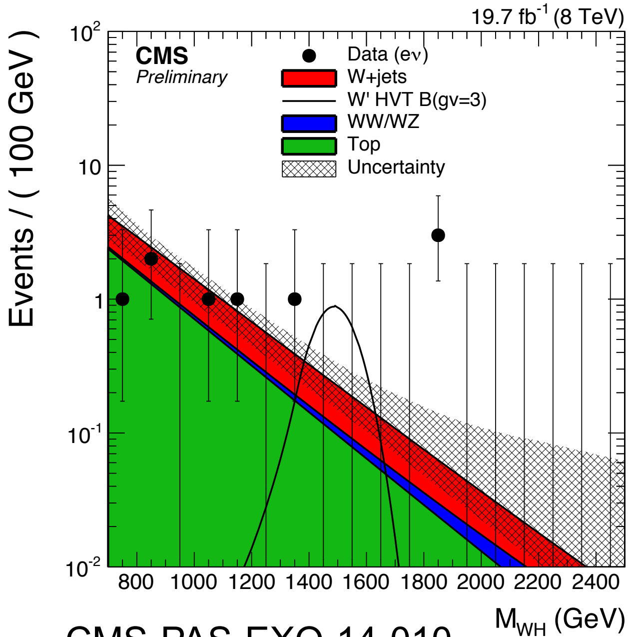
- Same search techniques as V(qq)V(qq) and W(lv)V(qq) searches
- Lower backgrounds due to better background rejection of H(bb)-tagger compared to W(qq)/Z(qq)-tagger

V(qq)H(bb)



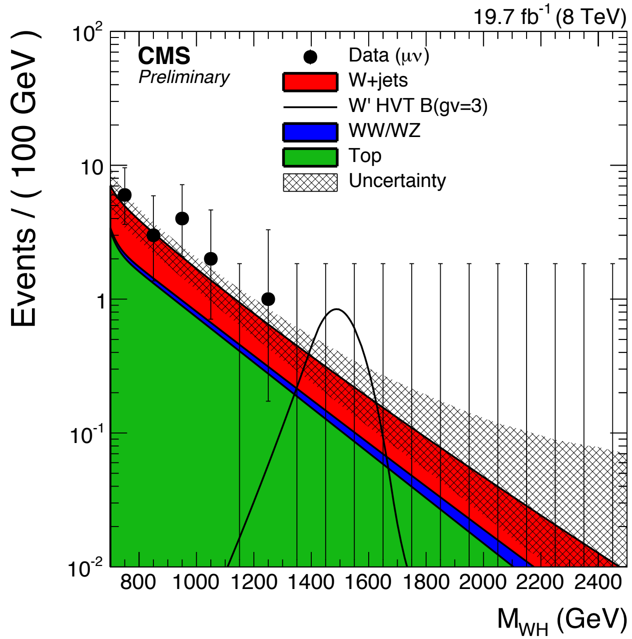
arXiv:1506.01443

W(ev)H(bb)



CMS-PAS-EXO-14-010

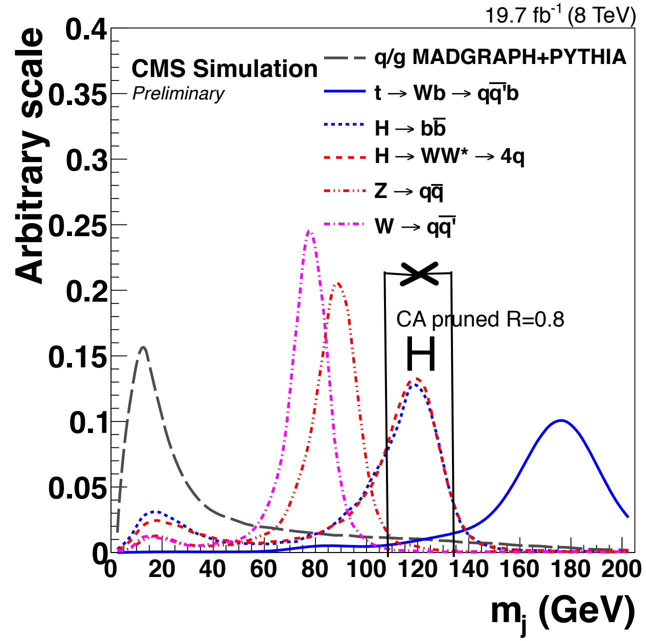
W(μv)H(bb)

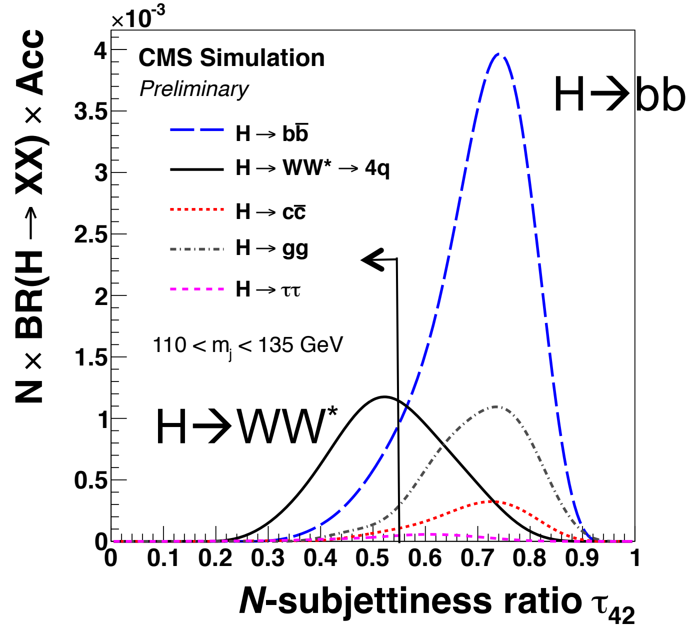


- Excess in W(lv)H(bb) at 1.8 TeV has a global significance of 2.2 s.d.
- Not seen in W(lv)V(qq) channel, but some small hints in other VV/VH channels

H→WW→qqqq-tagging

- H→WW* has second highest BR after H→bb
- Same pruned jet mass selection as for H→bb jets
- 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 in analysis



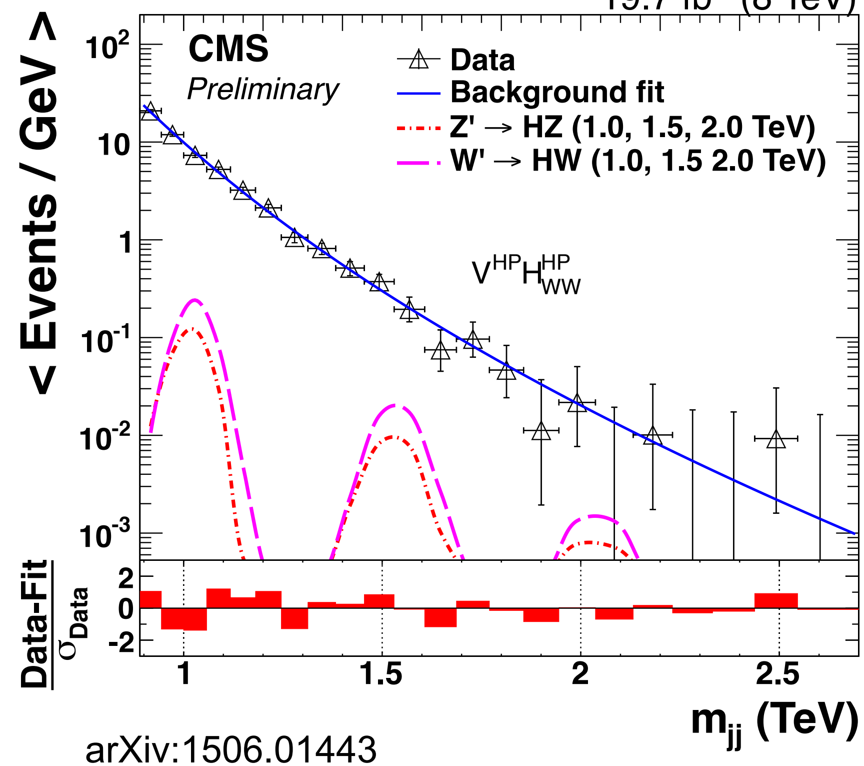


arXiv:1506.01443

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

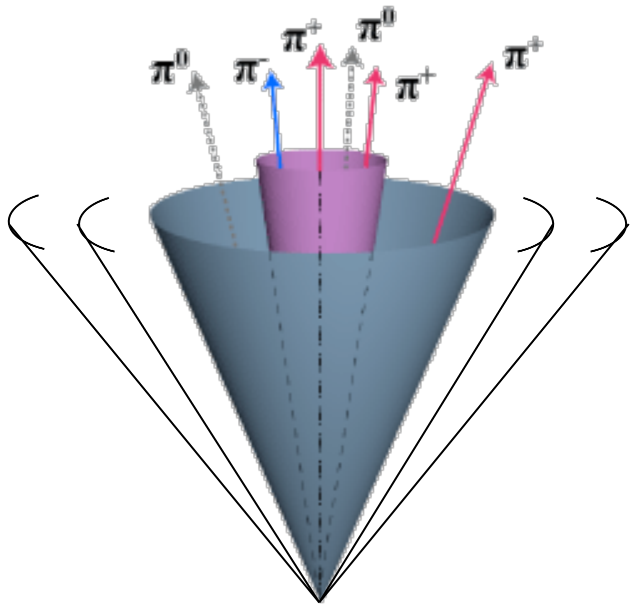
V(qq)H(WW→qqqq)



arXiv:1506.01443

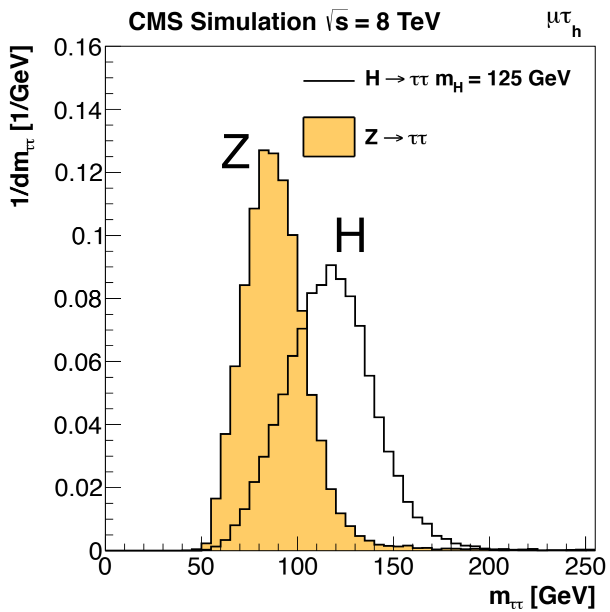
H→ττ-tagging

Decay Mode	Resonance	BR [%]
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$		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 MVA-based isolation summing reconstructed particle energies in various cones around tau decay products
  - Decay products of one excluded from isolation cone of other tau forming the H→ττ

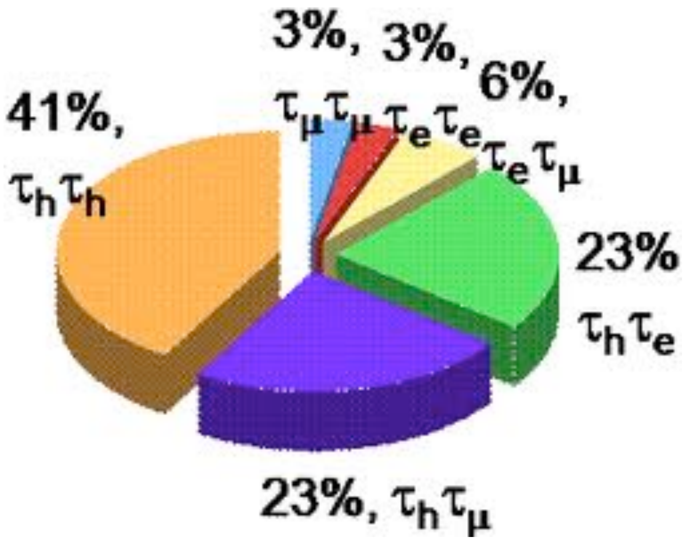
- Higgs mass reconstructed from visible tau decay products and missing transverse energy



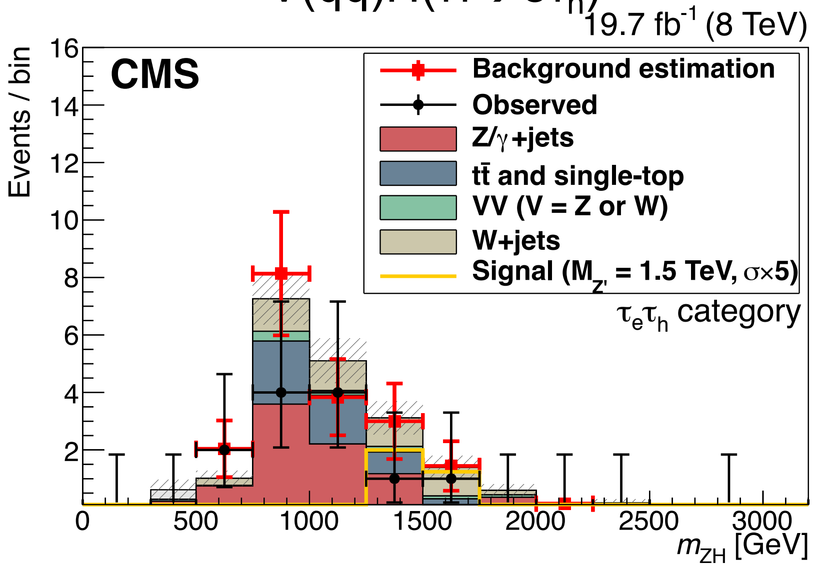
 14 July 2015 Andreas Hinzmann University of Zurich

V(qq)H(ττ) resonances

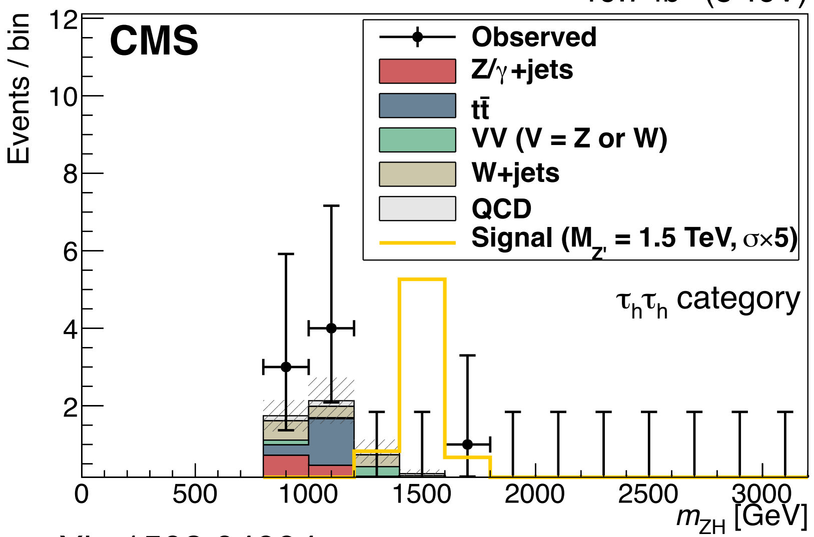
- All tau decay modes taken into account



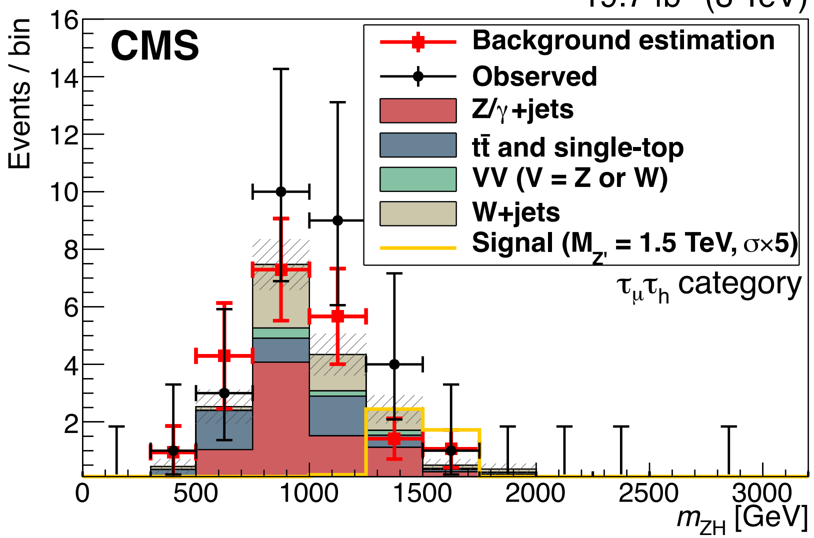
V(qq)H(ττ→eτ$_h$)



V(qq)H(ττ→τ$_h$τ$_h$)



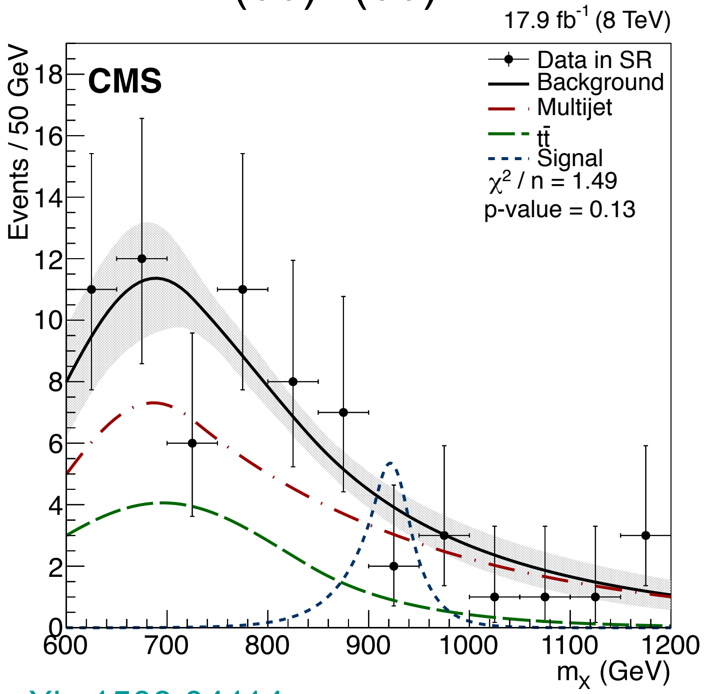
V(qq)H(ττ→μτ$_h$)



arXiv:1502.04994

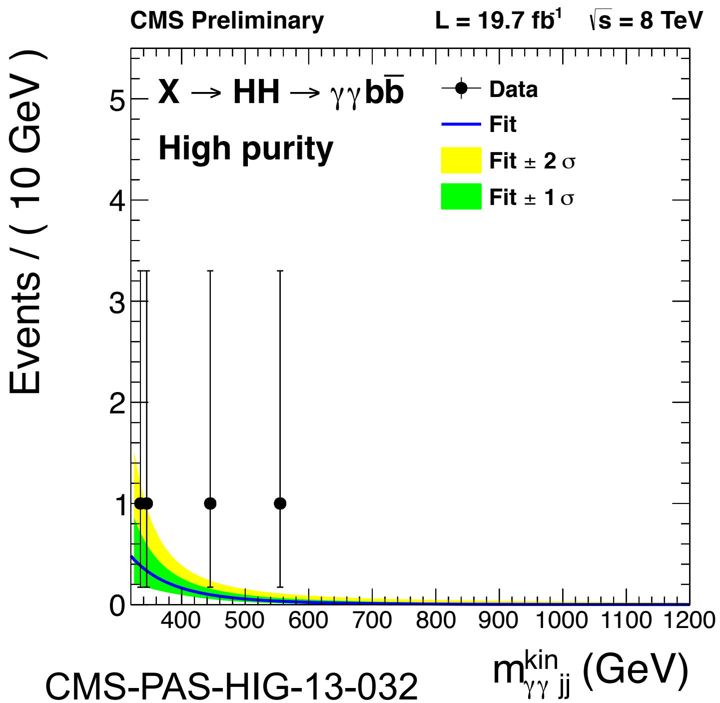
HH resonances

H(bb)H(bb)



arXiv:1503.04114

H(bb)H(γγ)



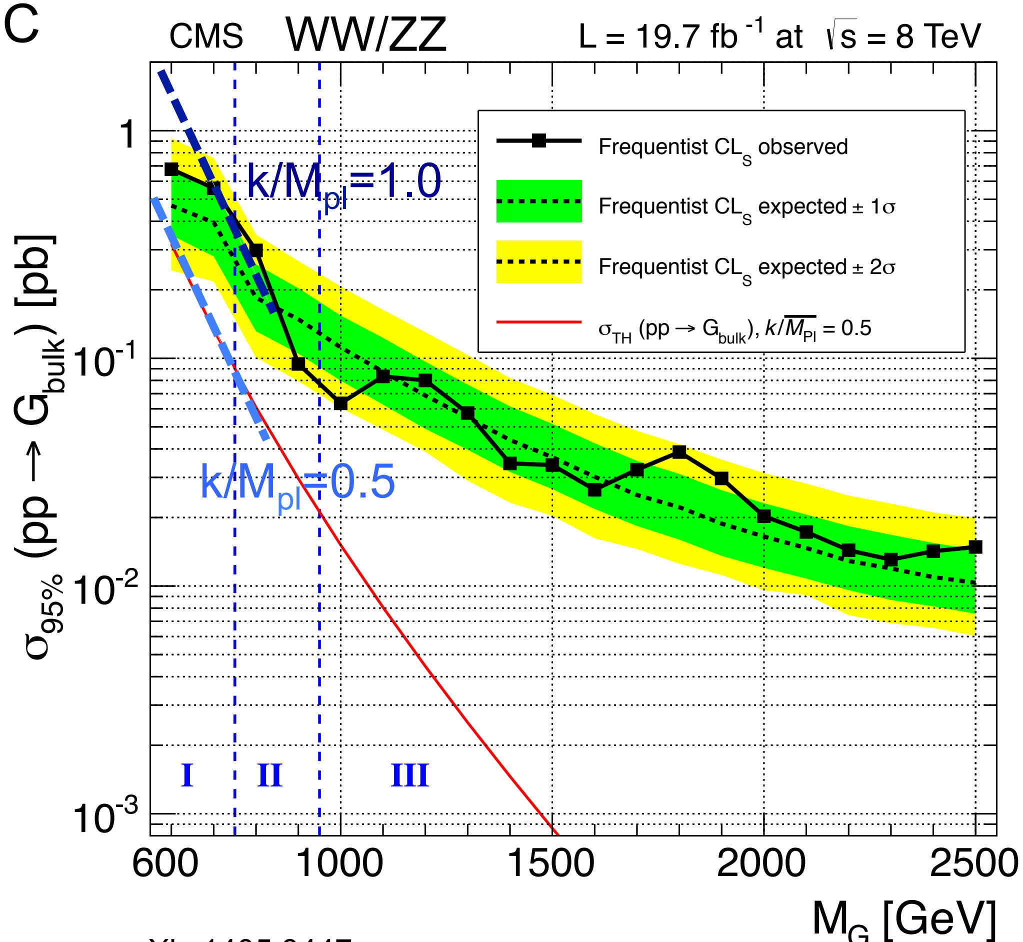
CMS-PAS-HIG-13-032

- Public results go up to 1 TeV, not yet exploiting the presented techniques
- Searches in H(bb)H(bb) and H(bb)H(ττ) beyond 1 TeV ongoing

Findings for extra dimensions – 1

- 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 $k/M_{pl} < 0.5$
  - Interesting search for Run II of LHC

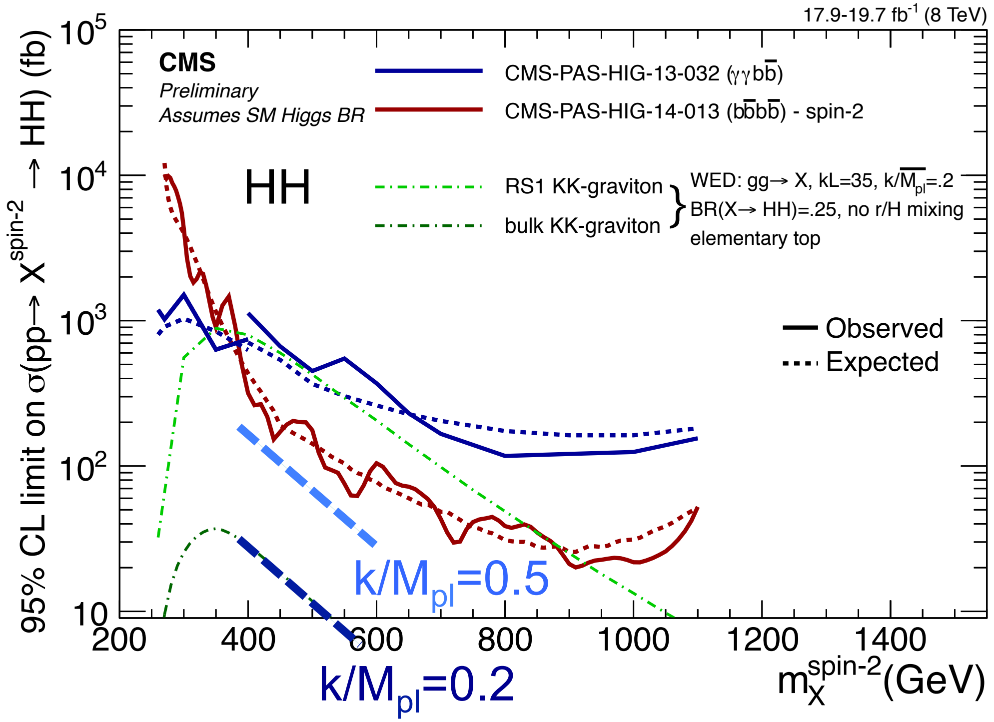
- Limit on RS1 ($k/M_{pl} = 0.1$) graviton mass:
  - 2 TeV (re-interpreted model independent limits)
  - Competitive with dilepton (2.4 TeV) and dijet (1.6 TeV)

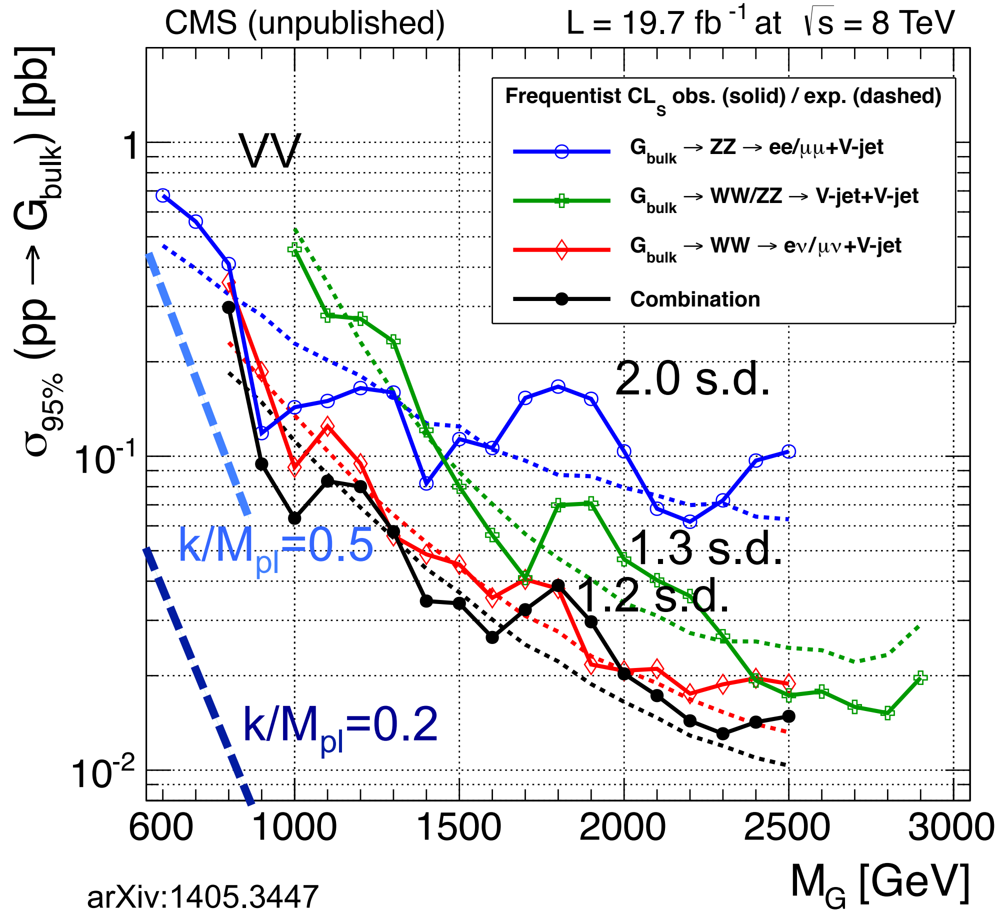


arXiv:1405.3447

Findings for extra dimensions – 2

- All WW, ZZ and HH searches add to combined sensitivity

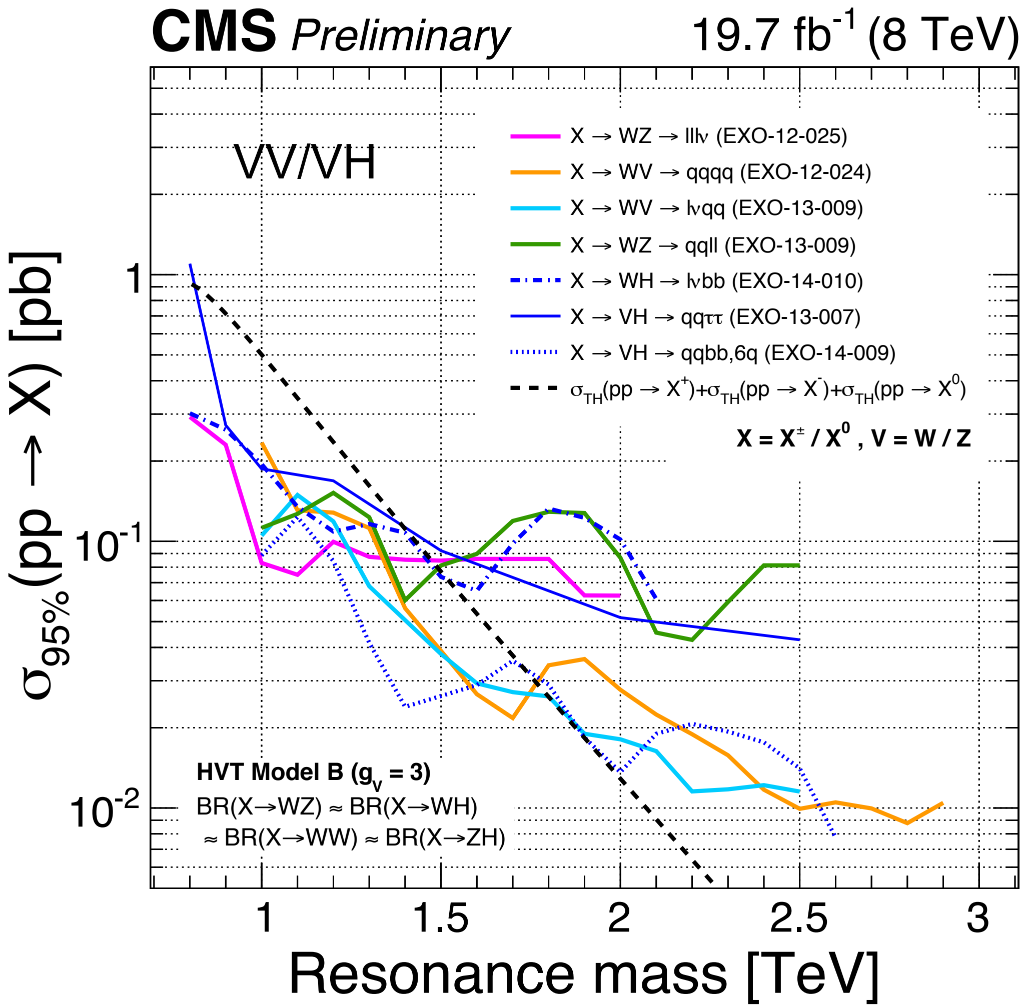




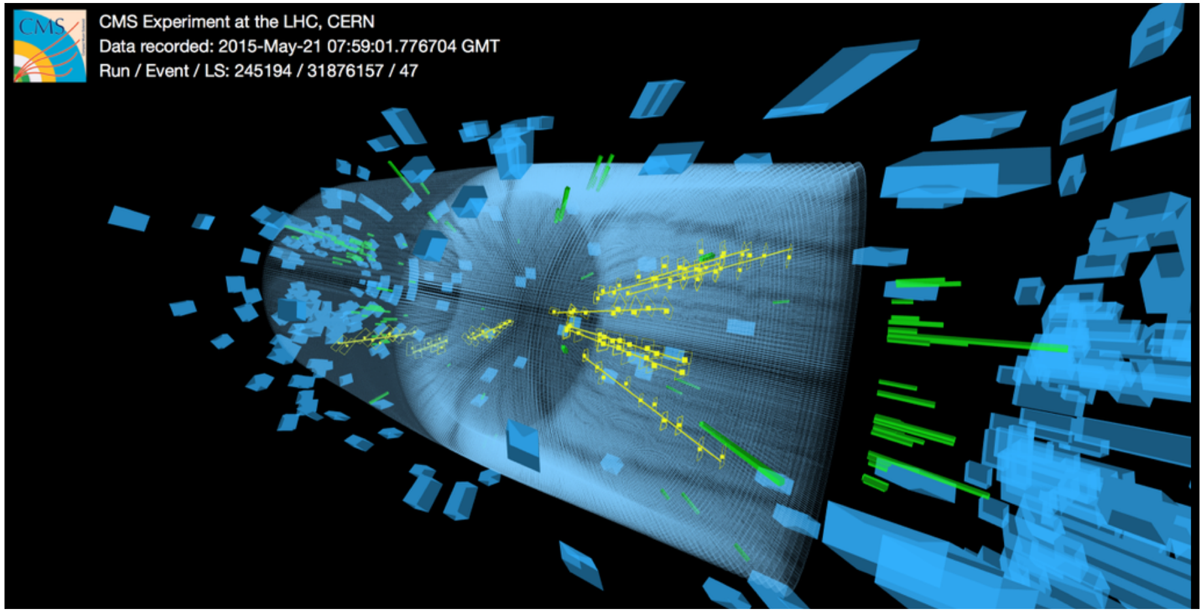
arXiv:1405.3447

Findings for W'/Z' models

- Composite Higgs models / Heavy Vector Triplet model B W' and Z' excluded up to 1.8 TeV
  - WV(lvqq), VV(qqqq) and VH(qqbb) have best sensitivity at high masses
- Not competitive in SequentialSM/EGM W' model, W'(lv) excludes 2.9 TeV



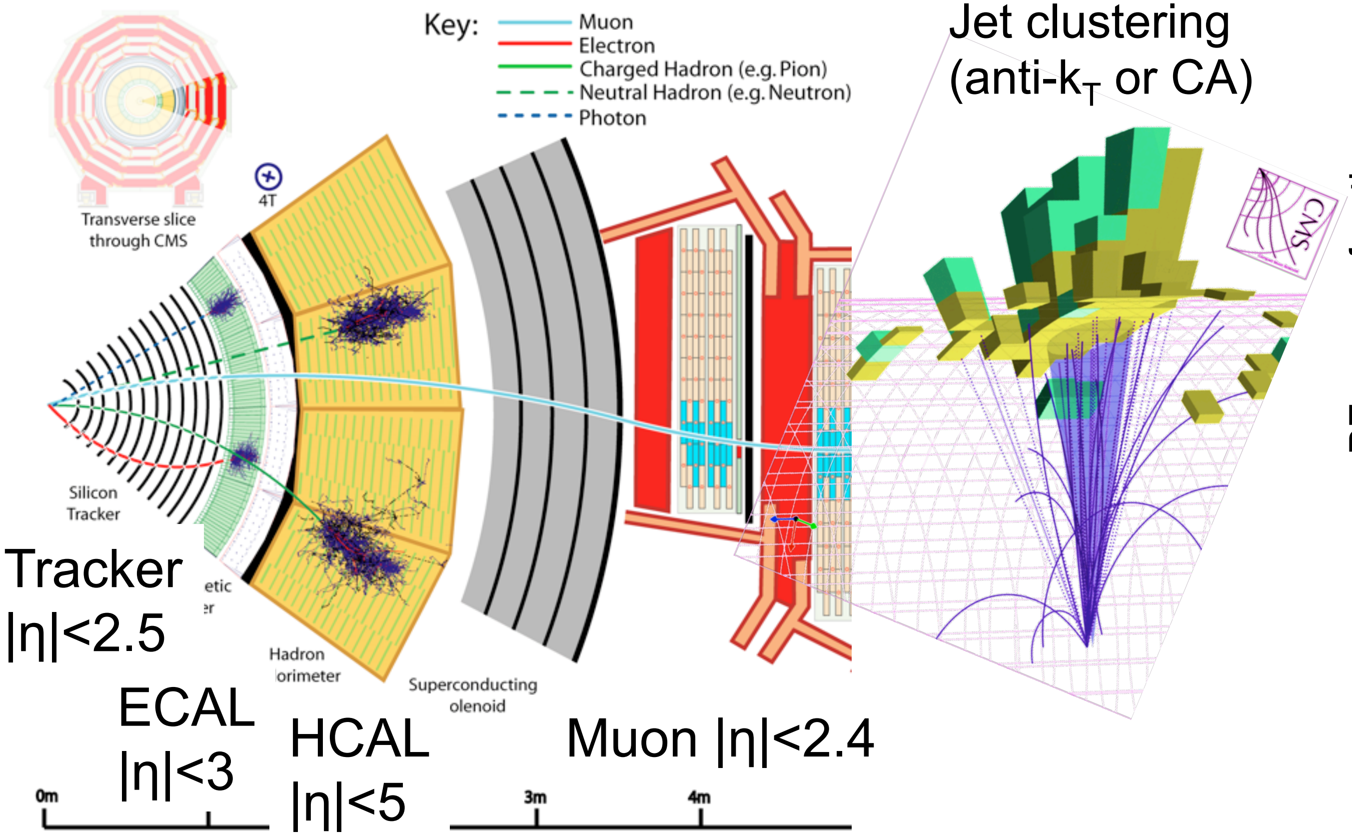
Outlook for Run II



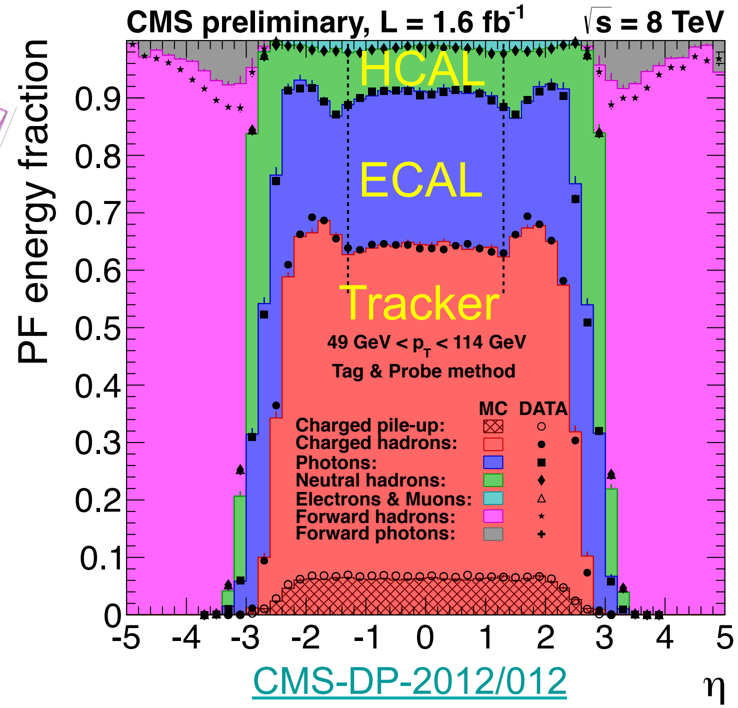
- First 13 TeV collisions recorded!
- Rule of the thumb for high mass resonances in Run II.
  Reach sensitivity of Run I for
  - 3 TeV resonance with 1/fb of Run II data
  - 2 TeV resonance with 3/fb of Run II data
  - 1 TeV resonance with 10/fb of Run II data
- Expect to explore new territory for > 1 TeV resonances already this year
- LHC runs in 2015 to find di-boson resonance at 2 TeV
- Main experimental challenges:
  - Higher jet momenta ever seen
  - Higher number of pileup interaction

Reminder – Jet reconstruction in CMS

Particle flow reconstruction



Jet energy fractions



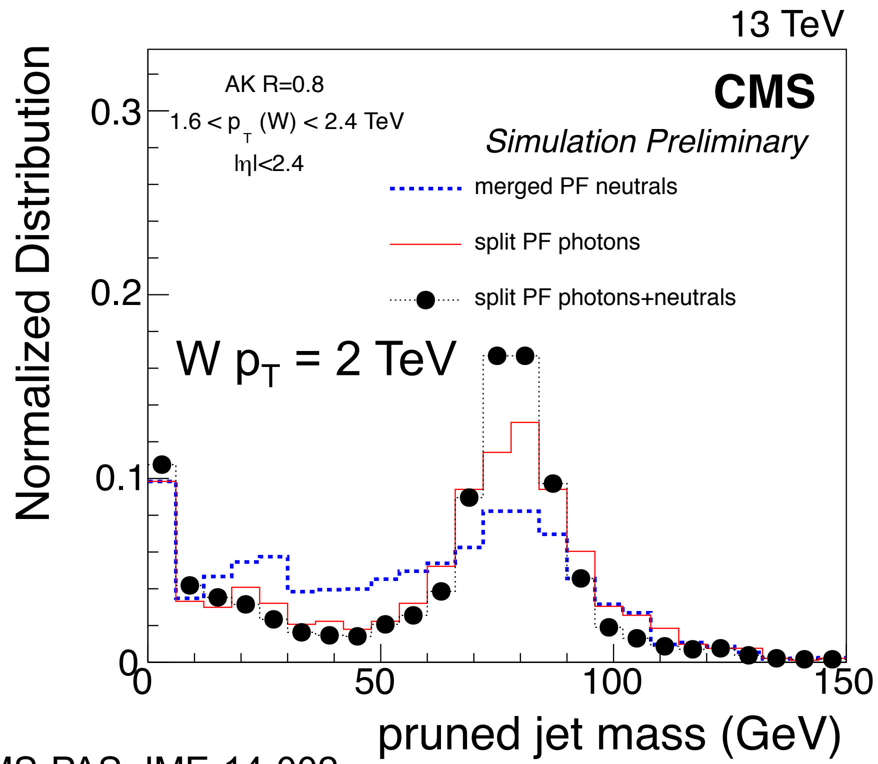
CMS-DP-2012/012

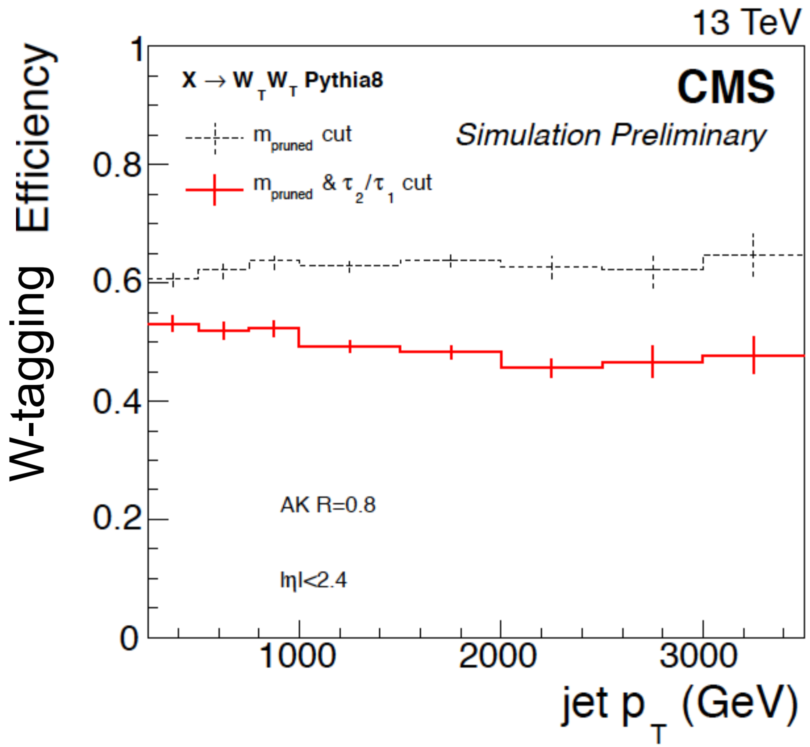
Particle Flow algorithm benefits from sub-detectors with best spatial+energy resolution

Detector	p_T-resolution (range)	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)

High momentum jet substructure in Run II

- For jet p_T>1.5 TeV, tracking resolution and efficiency degrade, such that ECAL and HCAL dominate jet substructure reconstruction
- Extend particle flow algorithm to use fine ECAL granularity to determine multiplicity of hadrons in a jet (rather than only energy as in Run I)
  - Split hadron excess energy in ECAL+HCAL according to direction and energy distribution of ECAL clusters ("split PF neutrals")

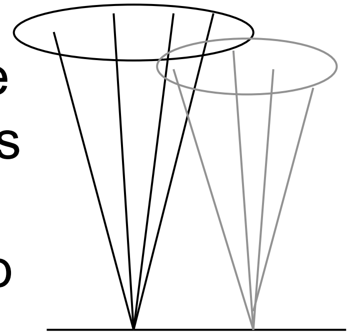




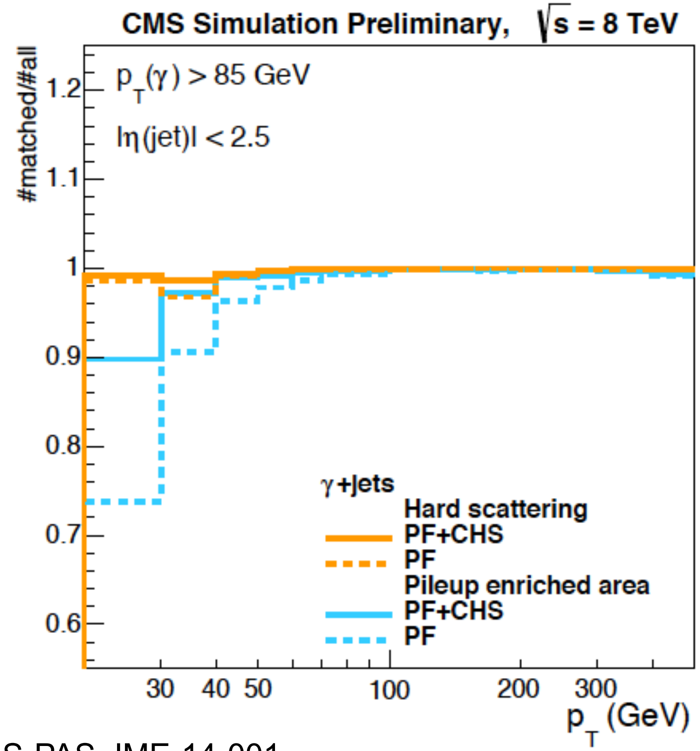
CMS-PAS-JME-14-002

Pileup mitigation in Run I

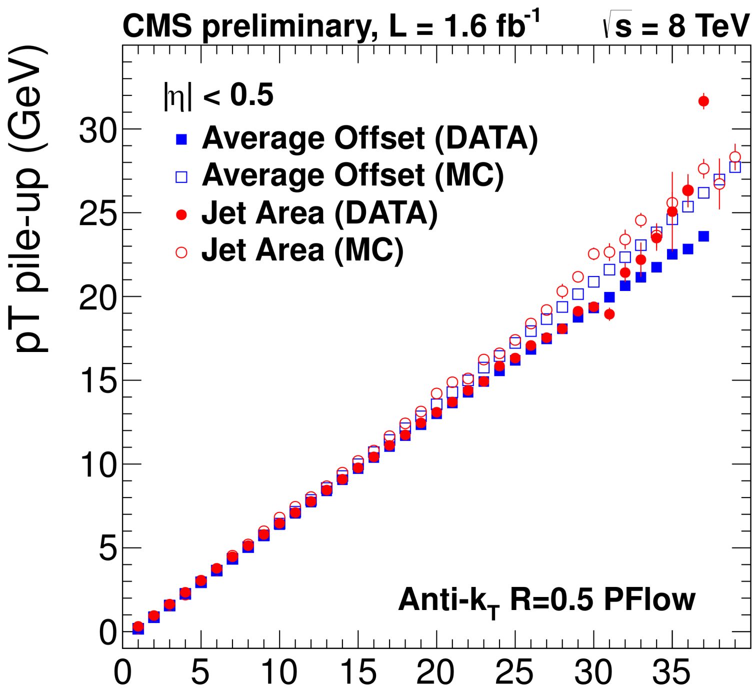
- CHS: Remove charged hadrons coming from pileup vertices
  - Correct charged component (60%) of jet including substructure
  - Rejects pileup jets from merging of jets from two pileup vertices



- Multiply jet 4-momentum by (1 – ρA), where A is area of jet and ρ is (eta-dependent) pileup energy density per unit area in event
  - Correct neutral component (40%) of jet momentum



CMS-PAS-JME-14-001



CMS-DP-2012/012

Pileup mitigation in Run II with PUPPI

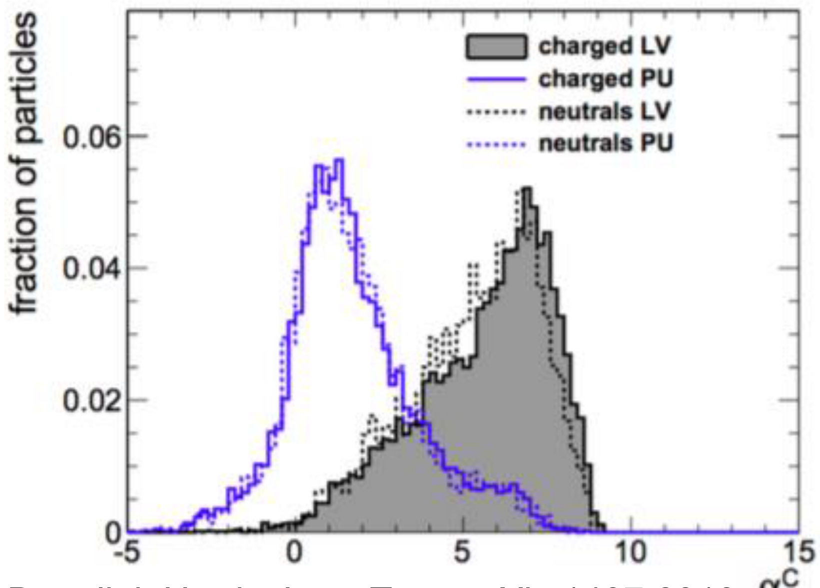
- Use knowledge about origin from pileup of charged particles, to estimate origin of neutral particles
- Distribution of α (eta-dependent) is computed for each event

$$\alpha_i = \log \sum_{j \in \text{event}} \frac{p_{Tj}}{\Delta R_{ij}} \times \Theta(R_{\min} \leq \Delta R_{ij} \leq R_0)$$

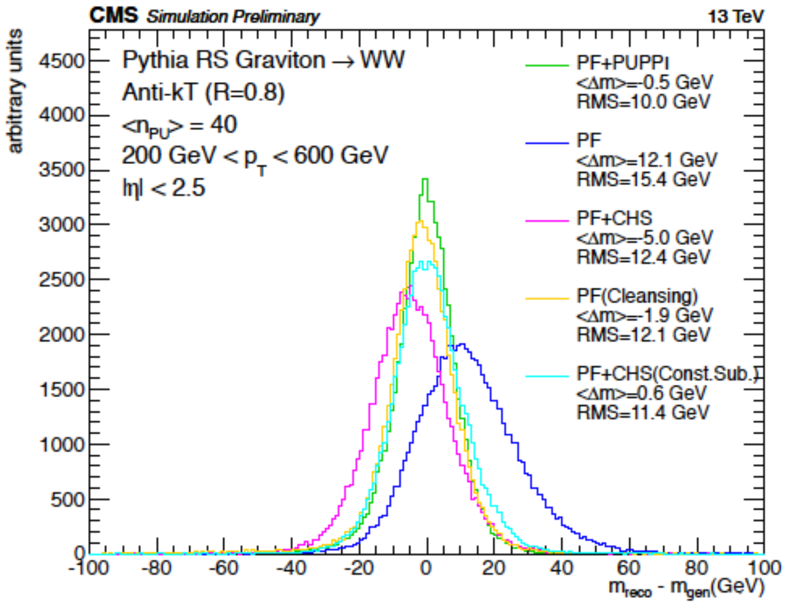
- Reweight 4-vectors of neutrals according to their probability to come from a PU vertex

$$\chi_i^2 = \frac{\left(\alpha_i - \bar{\alpha}_{PU}\right)^2}{RMS_{PU}^2}$$

- Reject neutrals if weighted p_T < threshold (0.2 GeV in barrel)
- All 4-vector operations on particles, like jet clustering, jet substructure variables are automatically corrected



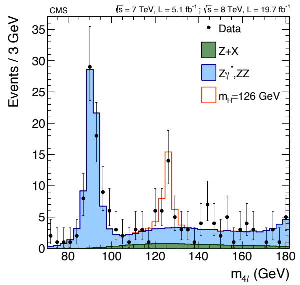
Bertolini, Harris, Low, Tran, arXiv:1407.6013



CMS-PAS-JME-14-001

Summary

LHC Run I



Probe for exotic new physics

What models?

What signatures?

What is its strength?

Composite Higgs
Extra dimensions

and others…

Resonances decaying to
W_L, Z_L, H
Boosted topologies

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

LHC Run II