Search for new resonances with boosted signatures at CMS

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ULB Physique Théorique Seminar, Brussels

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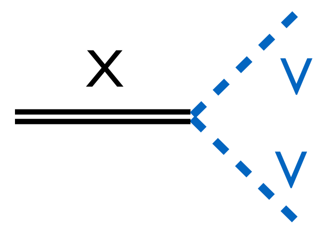
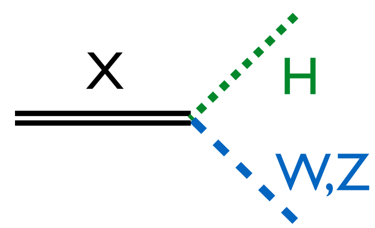
Overview

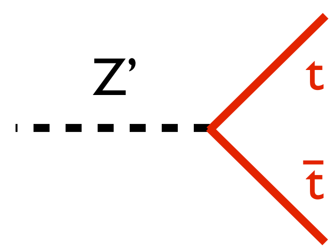
- Introduction
- Reconstruction Methods
- Searches at Run 1
  - WW, WZ, ZZ Resonances

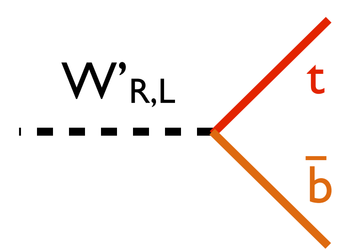


  - WH, ZH Resonances

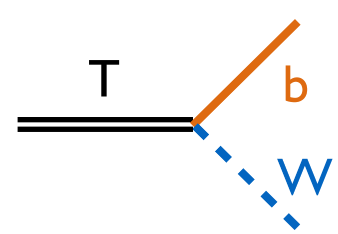


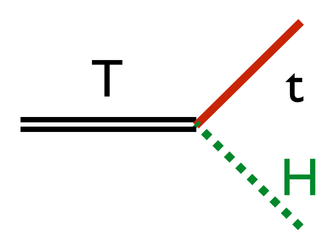
  - $t\bar{t}$ and $t\bar{b}$ Resonances

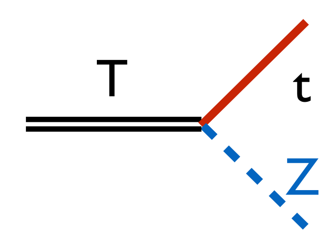




  - Vector-like quarks



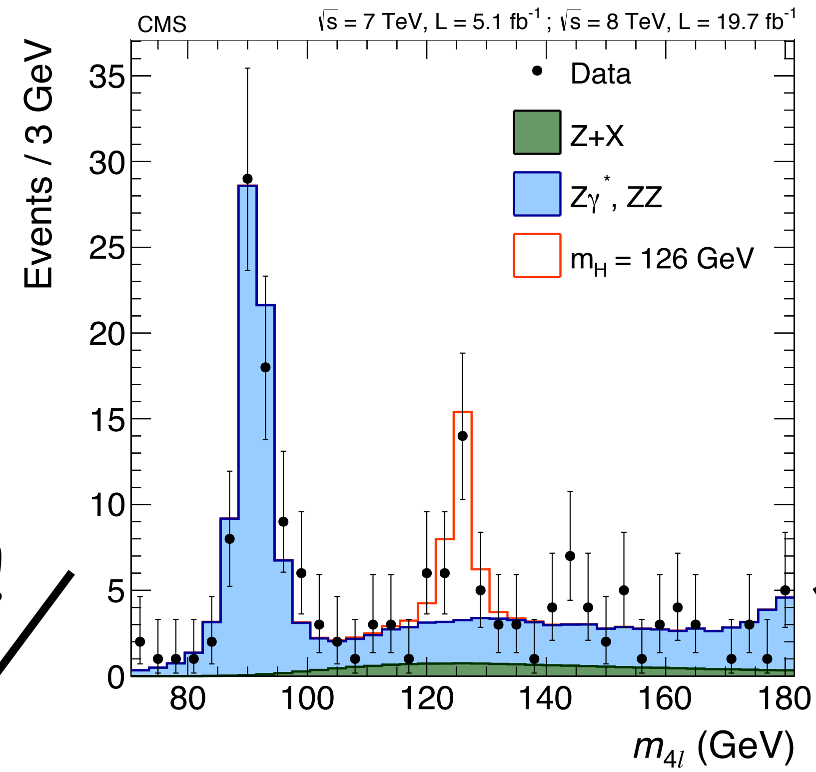




- Outlook for Run 2

[HIG-13-002, PRD 89, 092007 (2014)]

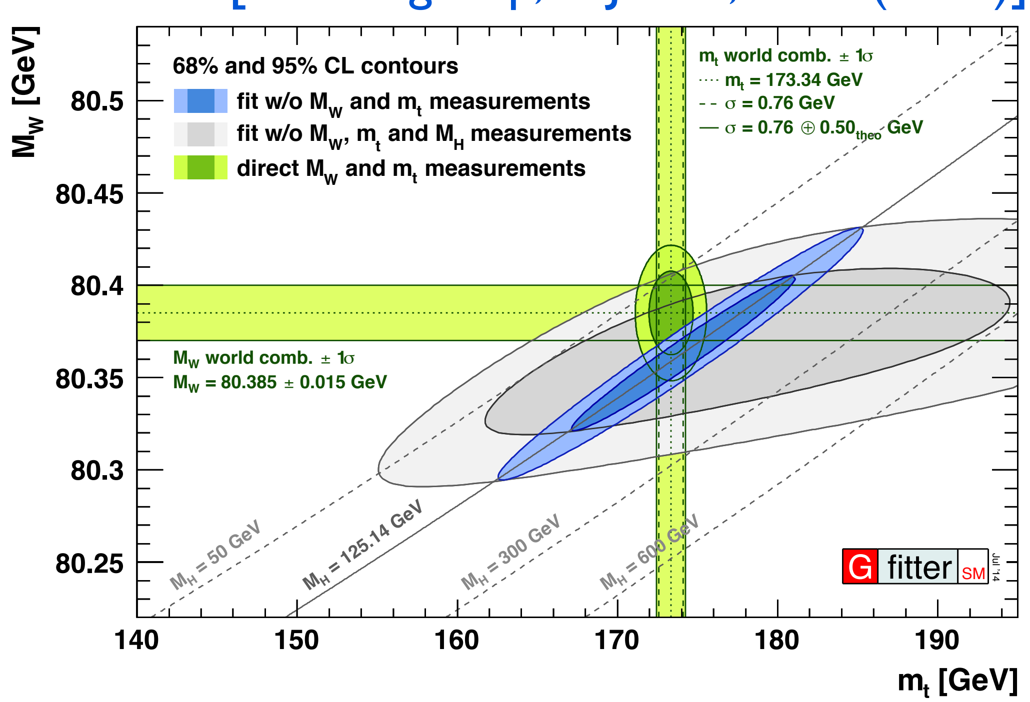
Discovery!

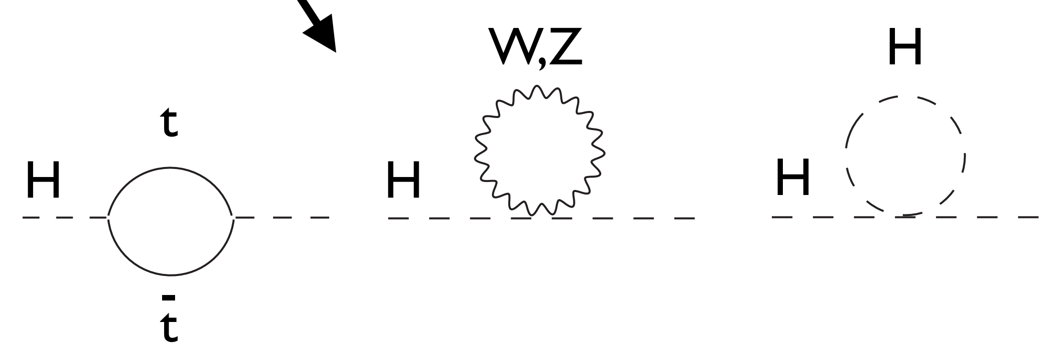


Huge success of the SM!
Internally consistent

Many open questions!
Point to new physics?

[Gfitter group, EPJC 74, 3046 (2014)]





$$m_H^2 = m_0^2 + \Delta m_t^2 + \Delta m_{WZ}^2 + \Delta m_H^2$$

$$m_H^2 \approx m_0^2 - (2\,\text{TeV})^2 + (0.7\,\text{TeV})^2 + (0.5\,\text{TeV})^2$$

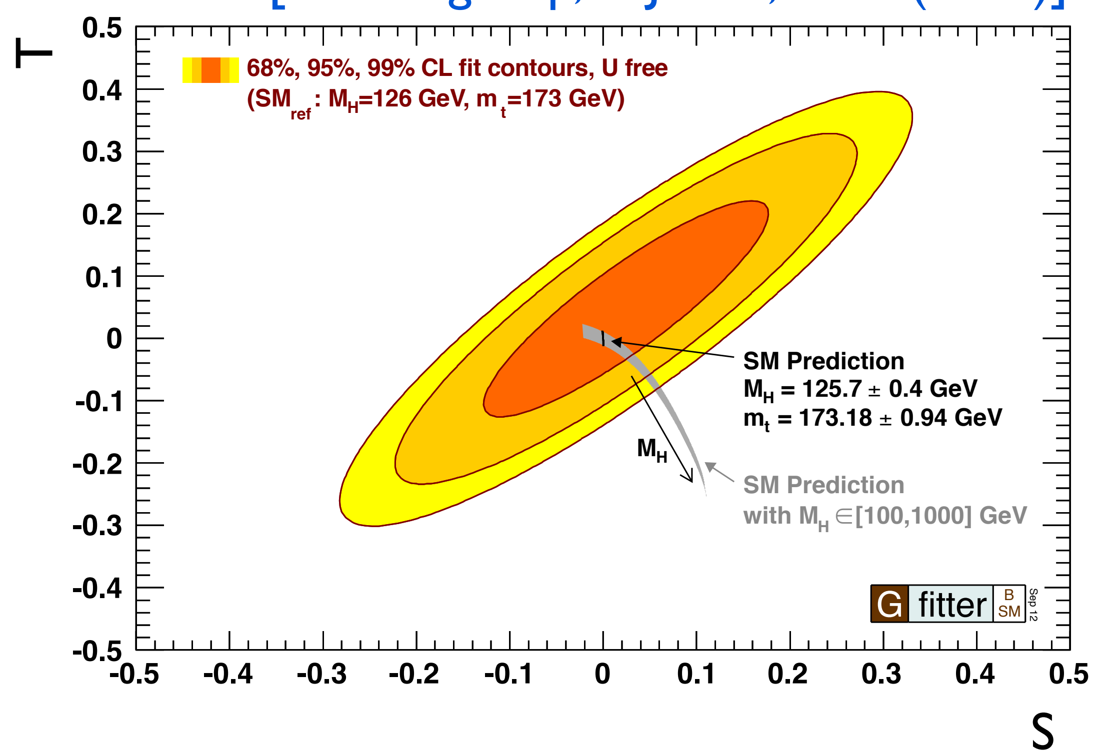
$m_0^2/\Delta m^2 \approx 1.002 \rightarrow$ *fine tuning* of 0.2% at Λ=10 TeV

BSM Theories

- Why is the weak force so much stronger than gravity?
  - Fine tuning of the SM parameters if SM is valid up to the Planck mass
- Possible solutions
  - SUSY (not covered in this talk)
  - Extra Dimensions
    - Warped extra dimension models where fermions propagate in the bulk
  - Composite Higgs
    - Heavy Vector Triplet model with new $W'^{\pm}$, Z' states
- Contributions to S and T parameters should not be too large:
  - extra dimensions, $M_{Z'}$ > 2-3 TeV
  - Composite Higgs, $M_{W'}$ > 1-2 TeV

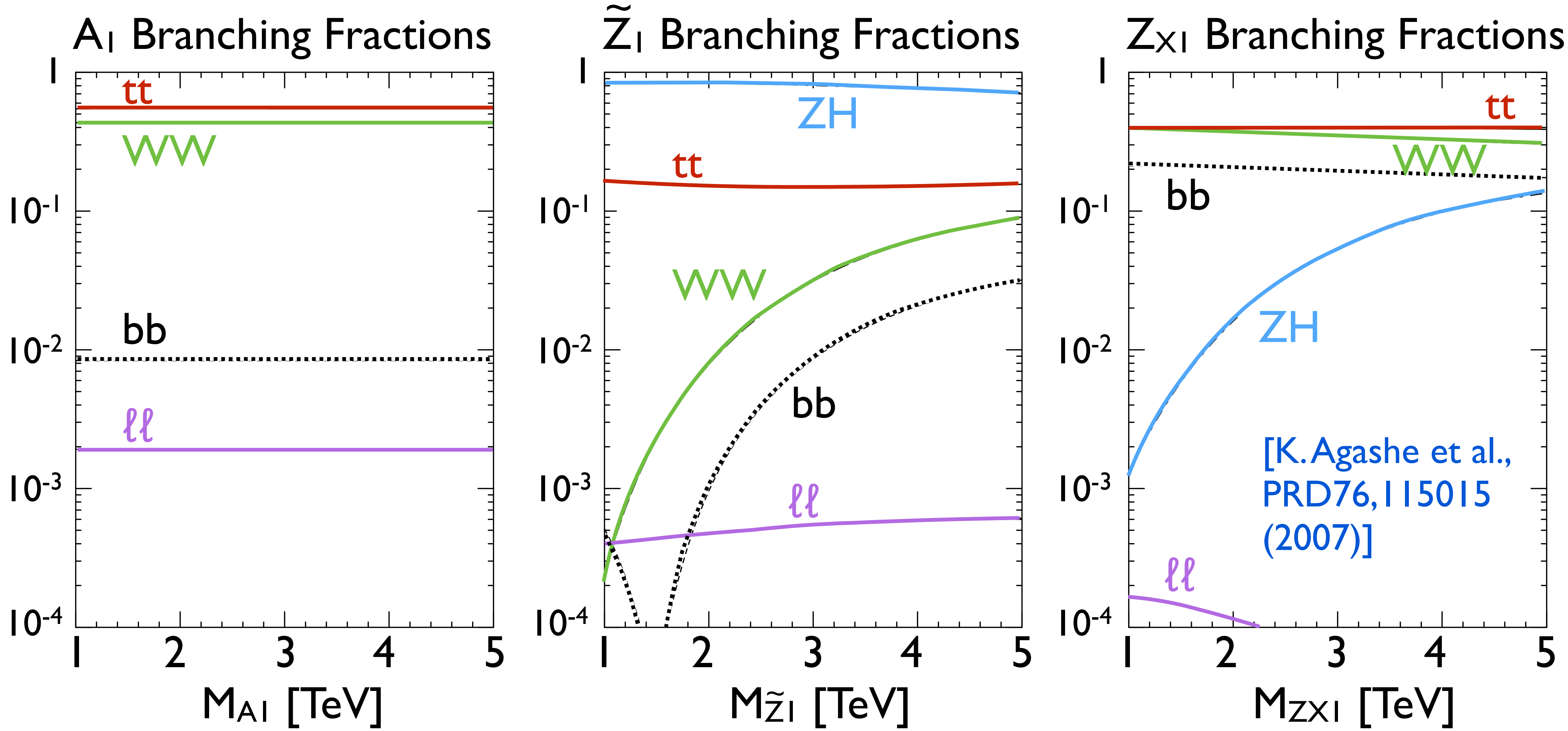
⇒ Look for heavy resonances!

[Gfitter group, EPJC 72, 2205 (2012)]



Phenomenology Example

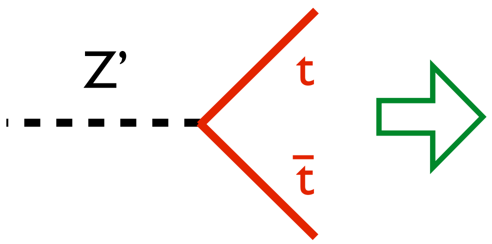
- Warped extra dimensions on the bulk, EWK KK modes
  - increased BR to W_LW_L, Z_LH, tt
  - suppressed decays to light quarks and lepton pairs
- Also: composite Higgs models with Z'→tt and W'→WZ, WH, tb and heavy quark partners B→tW, bH, bZ and T→bW, tH, tZ

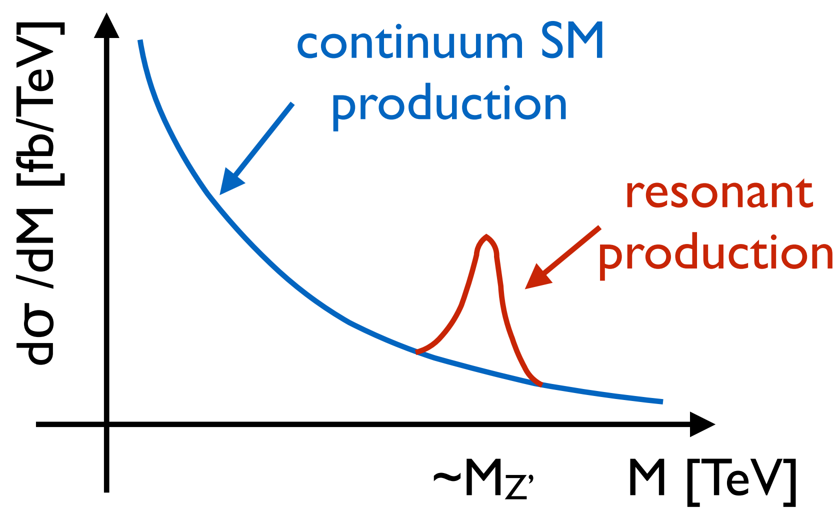


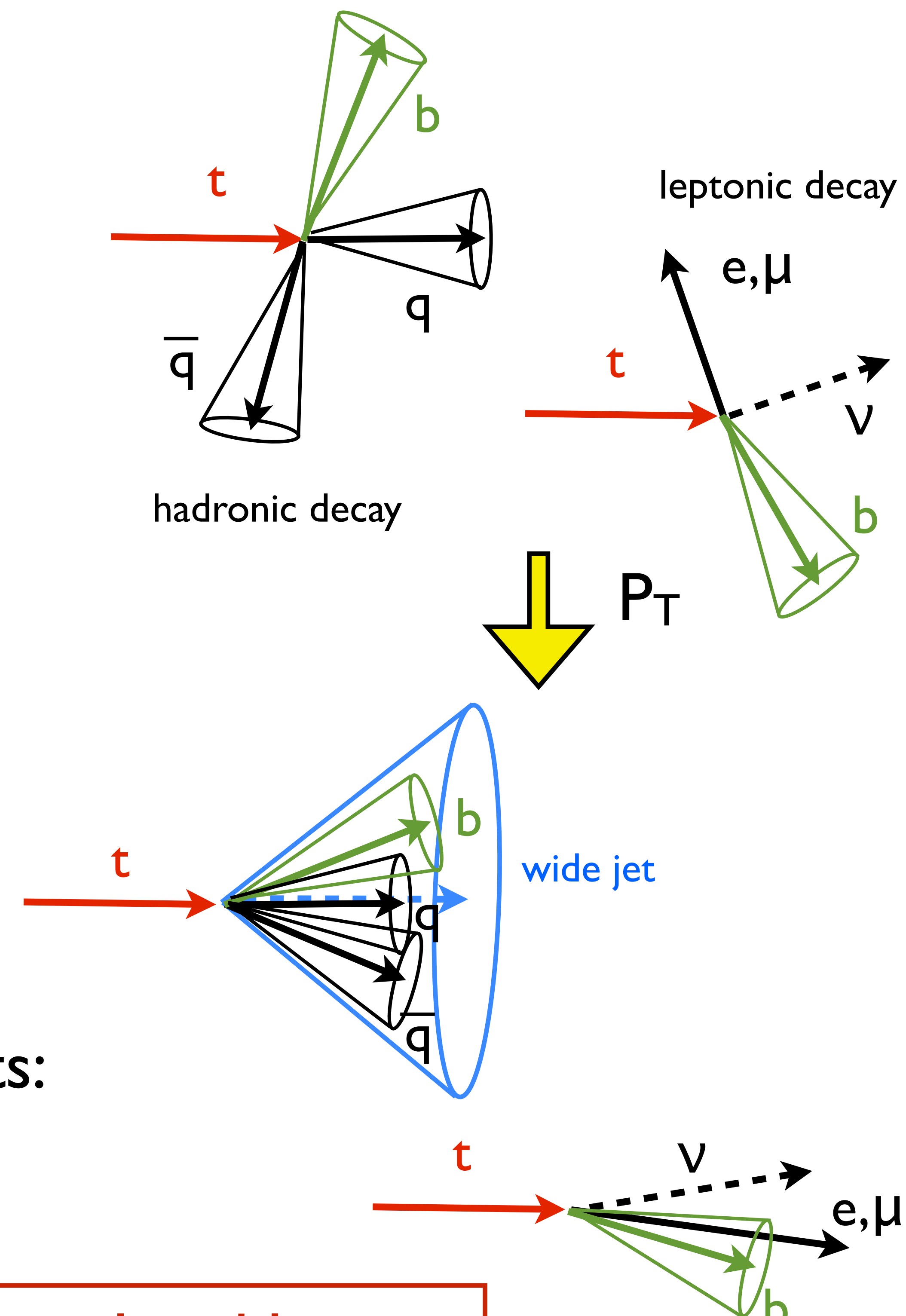
[K. Agashe et al., PRD76, 115015 (2007)]

Boosted Physics Searches

- Principle of resonance searches







- Heavy resonances (M ~ 2 TeV):
  - decay products with p_T ~ 1 TeV
  - large γ factor (>3)
  - boosted (collimated) final state topology
  - min. distance between final state products:

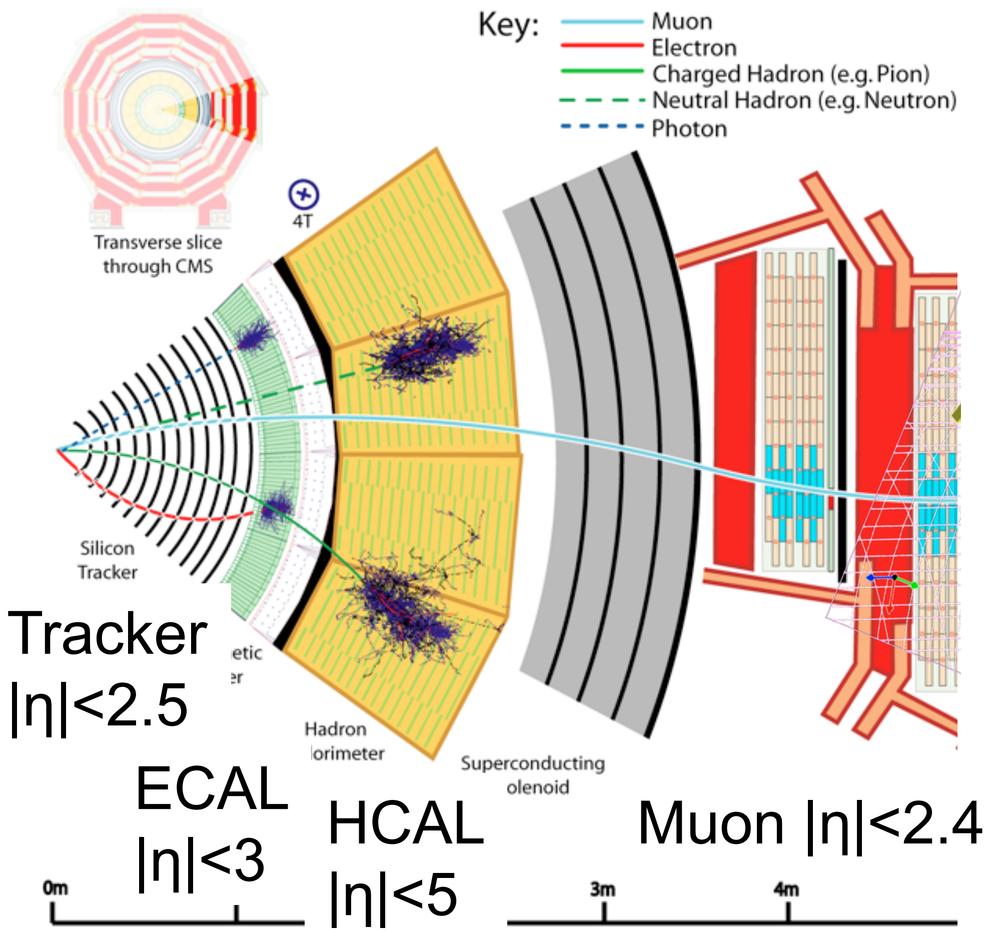
$$\Delta R_{\min} \approx \frac{2m}{p_T} \approx 0.2\text{-}0.4$$

⇒ Jets with substructure and non-isolated leptons

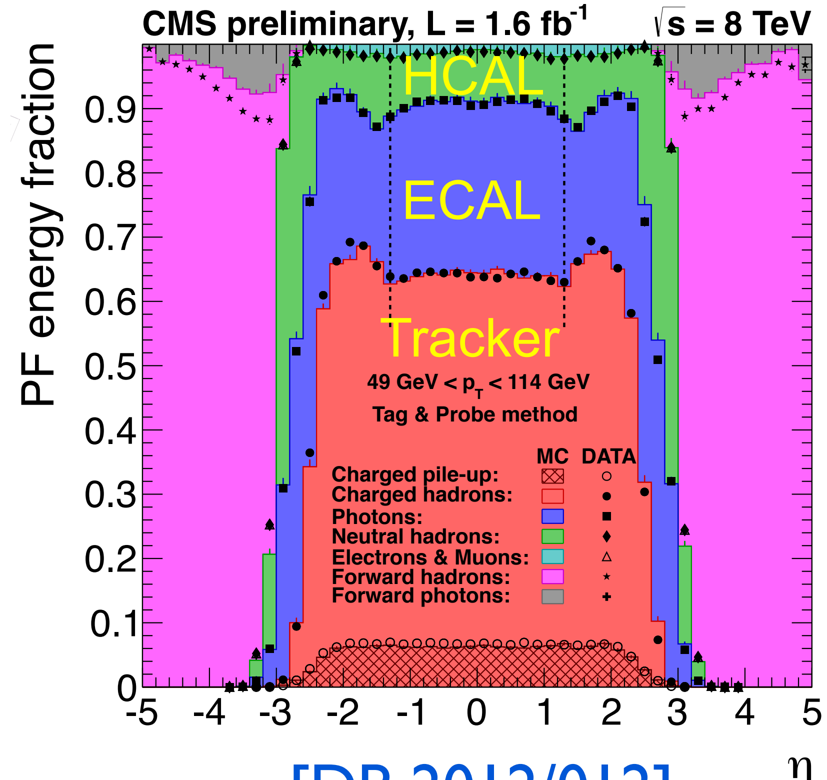
Reconstruction Techniques

PF and PU

Particle flow reconstruction

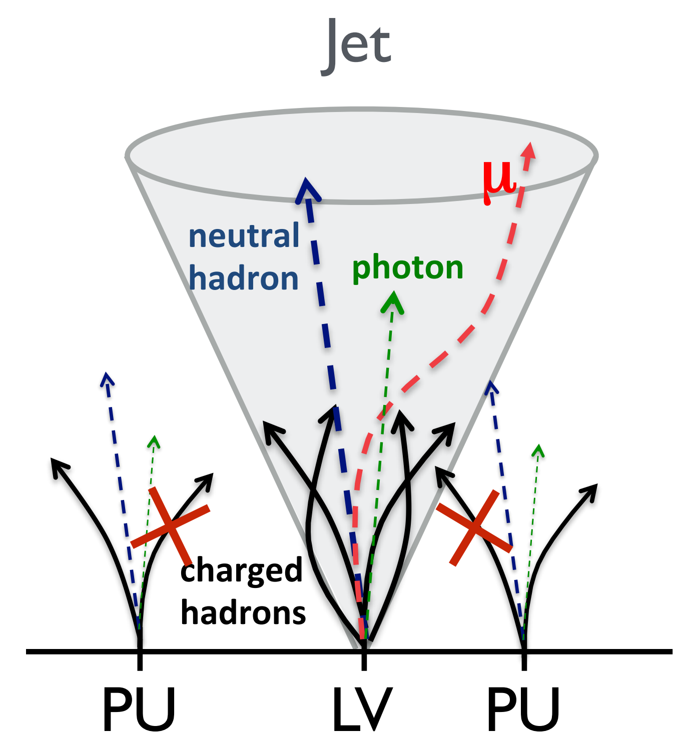


Jet energy fractions



[DP-2012/012]

Charged Hadron Subtraction



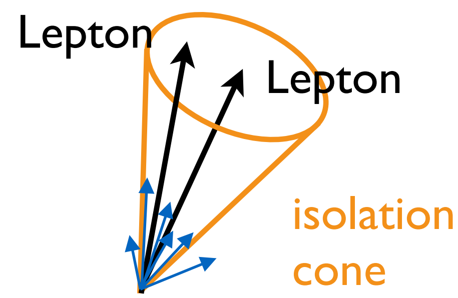
- PF benefits from all sub-detectors, use the one with best resolution

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)

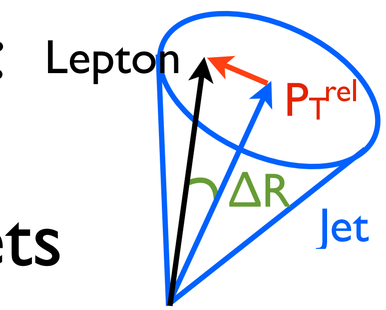
Non-isolated Leptons

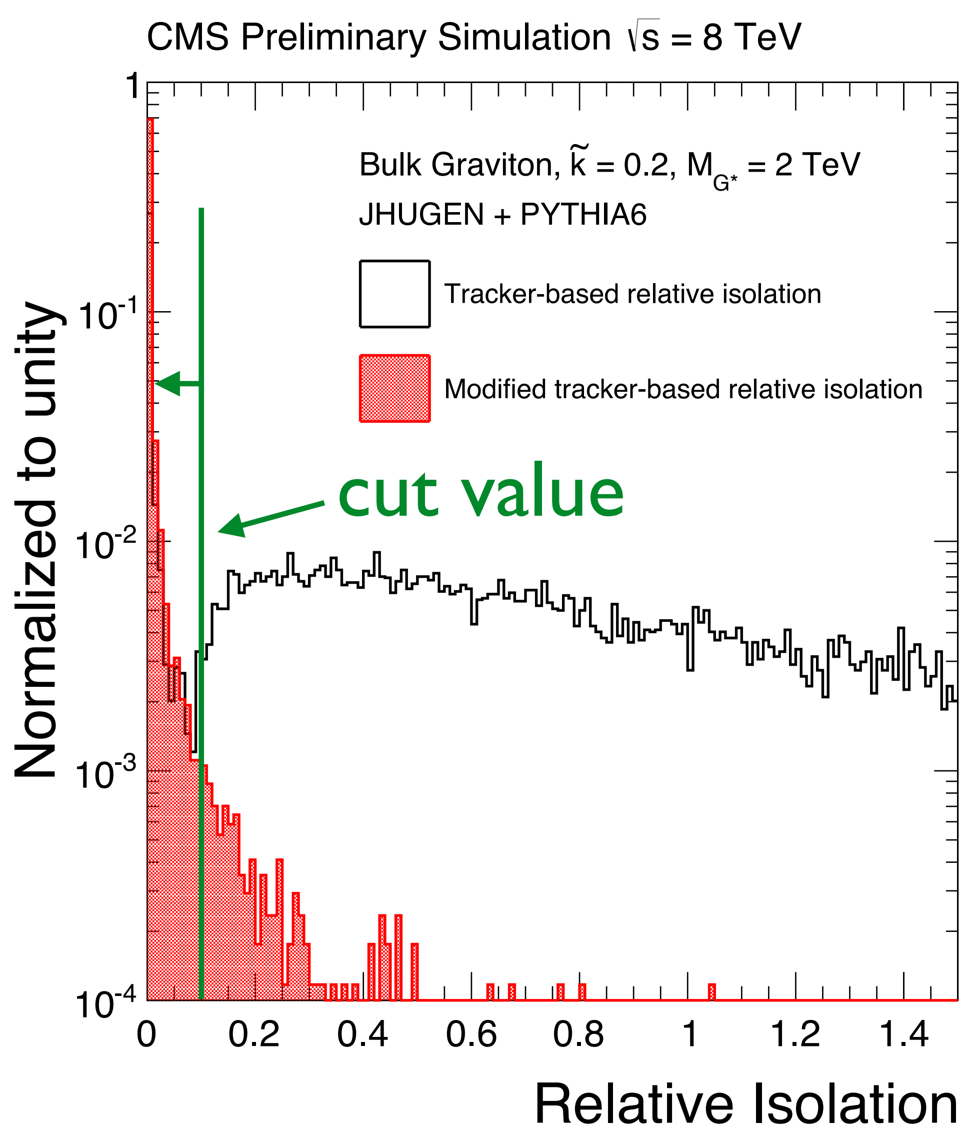
Boosted W,Z decays

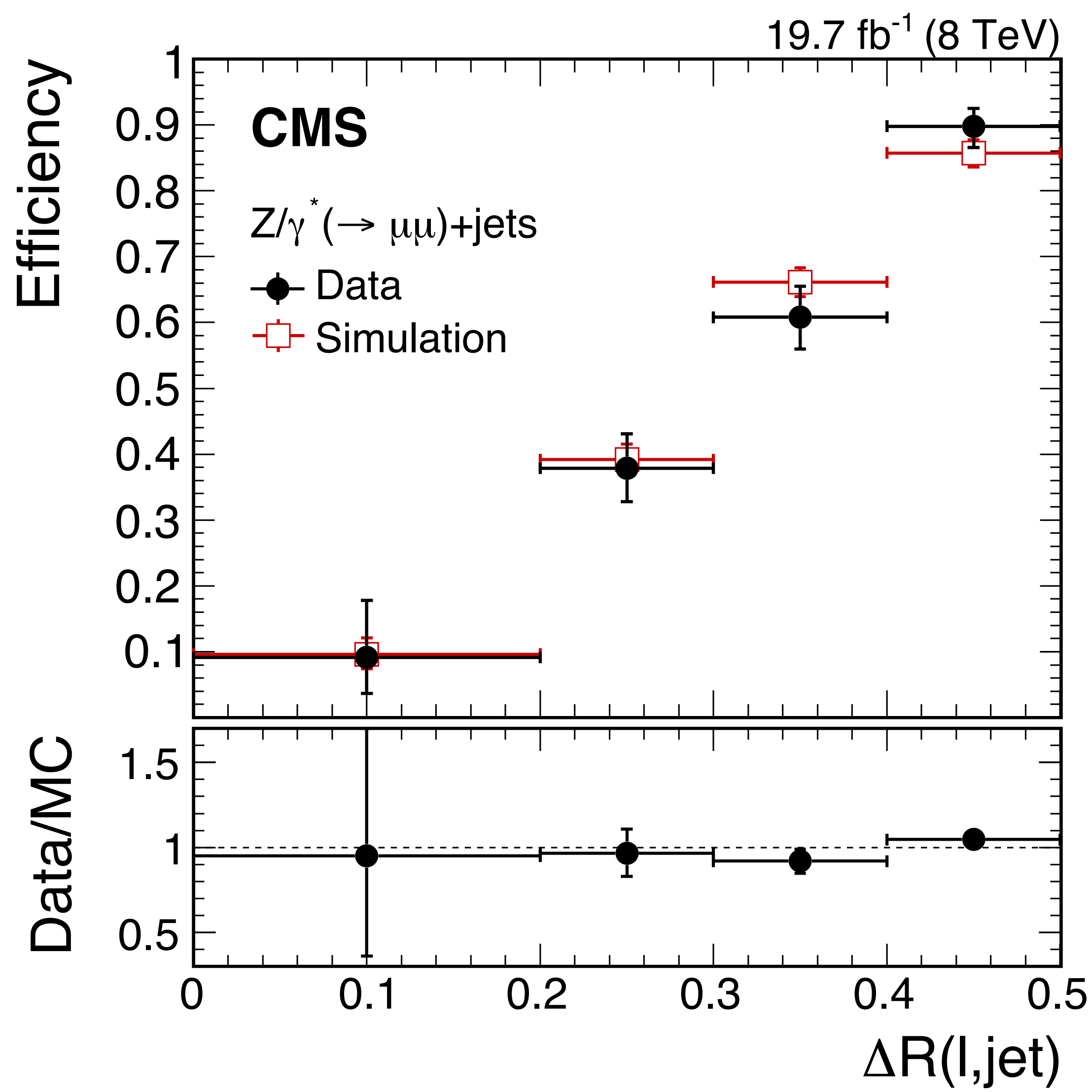
- $Z \to \ell\ell$ case: remove other lepton from isolation cone



- ℓ+jet case (boosted top): use p_T^{rel} for separation of b,c meson decays in jets

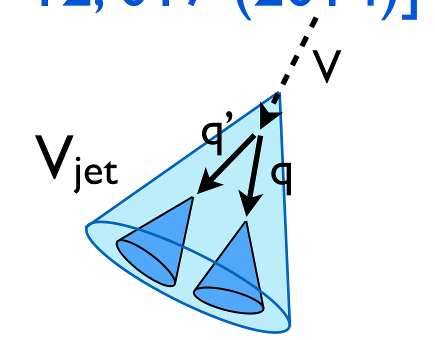




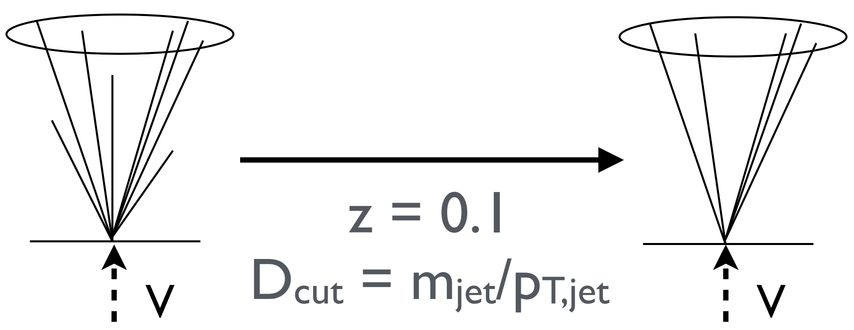


[CMS JME-13-007, JHEP 12, 017 (2014)]

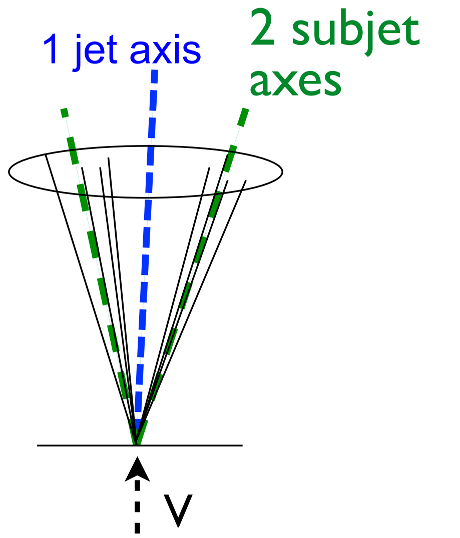
V Tagging

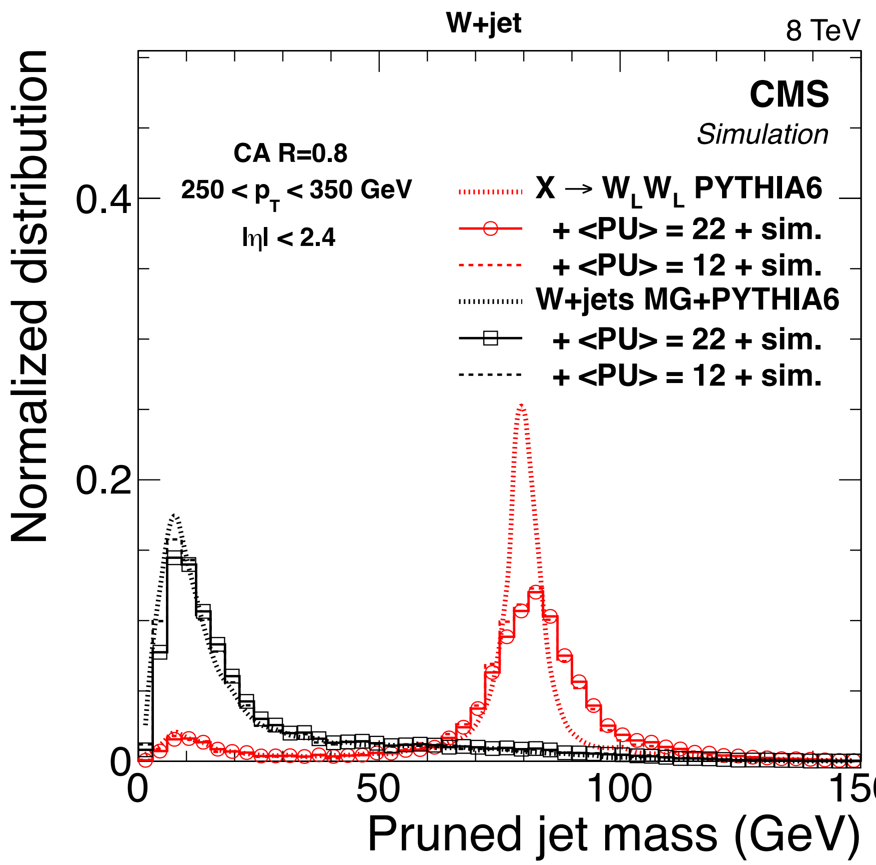


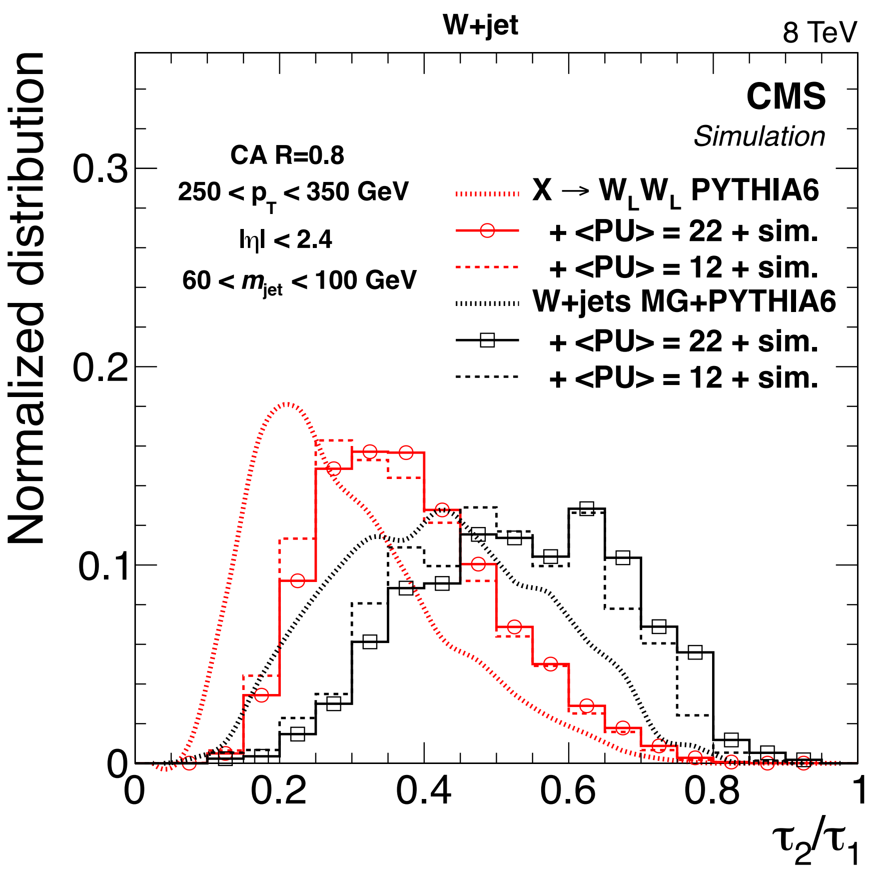
- Discriminate V jets based on substructure variables from q/g
  - Pruned jet mass [Ellis et al. PRD81, 094023(2010)]
    - remove soft/wide angle radiation
    - strongly reduce q/g jet mass



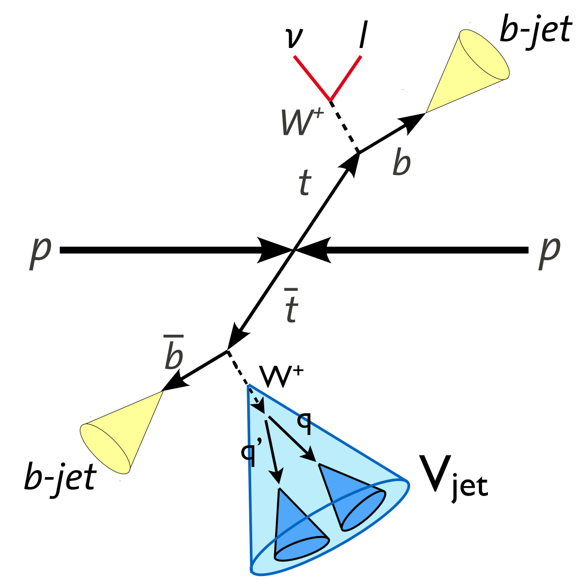
  - N-subjetiness ratio $\tau_{21} = \tau_2/\tau_1$ [Thaler et al., JHEP 1103,015(2011)]
    - one-step minimisation to obtain best subjet axes
    - small N indicates compatibility with N-prong decay



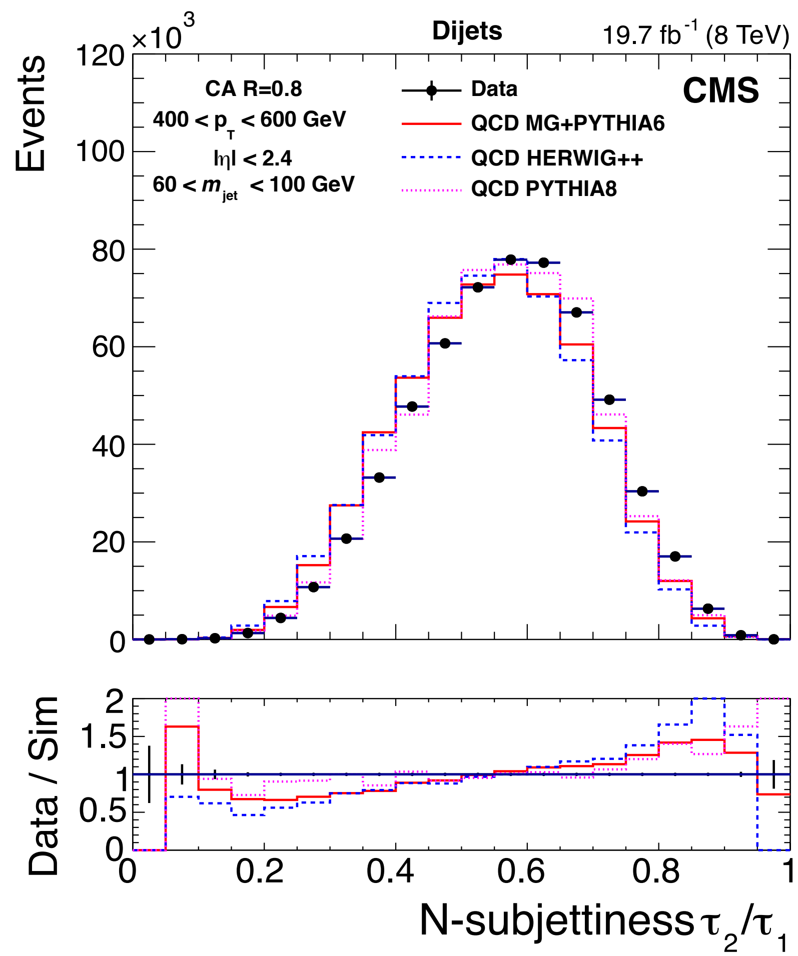


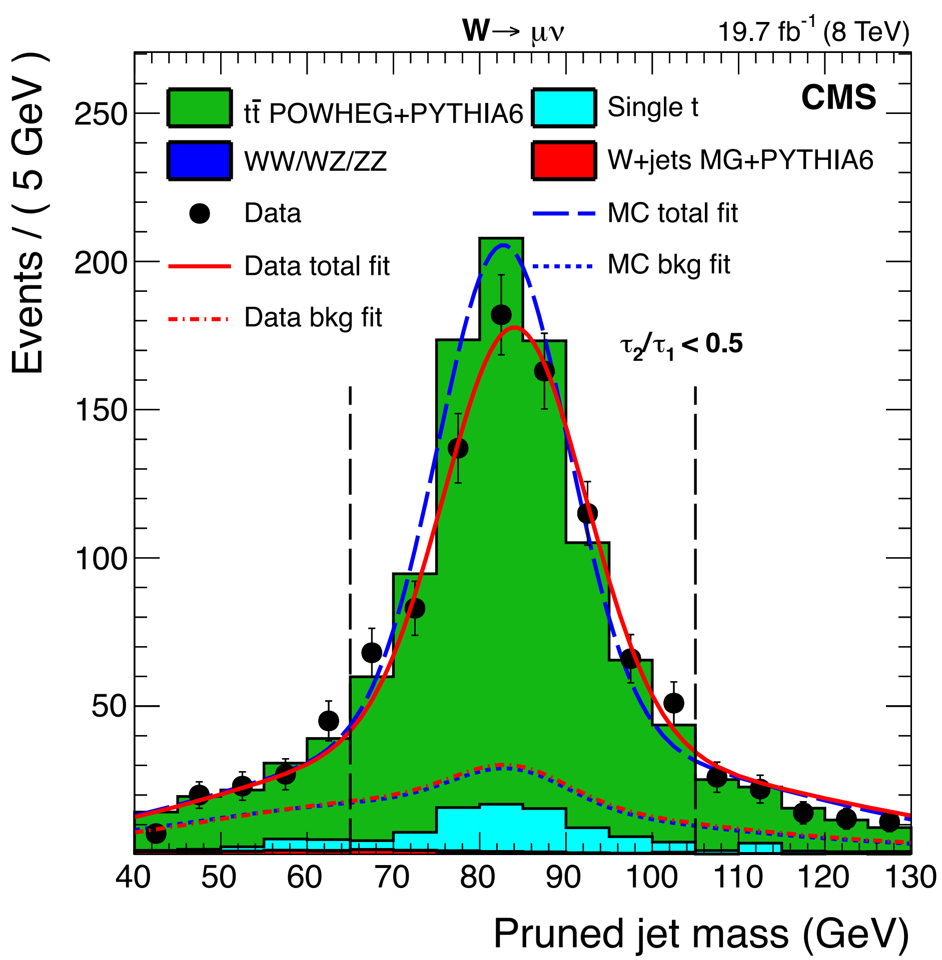


V Tagging in Data



- Validation of substructure observables in W+jet, QCD multijet and $t\bar{t}$ production
- ME+PS simulations describe τ_{21} within 10%
  - depends on shower and hadronisation model
- Efficiency described within 10% (absolute value depends on τ_{21} cut)





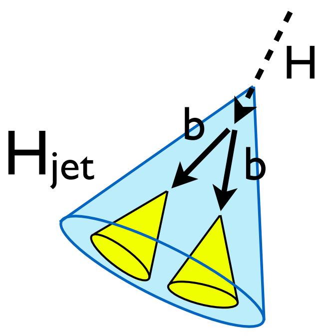
M_{peak}
Data - MC = 1.1 ± 0.4 GeV

Width
Data - MC = 1.2 ± 0.7 GeV

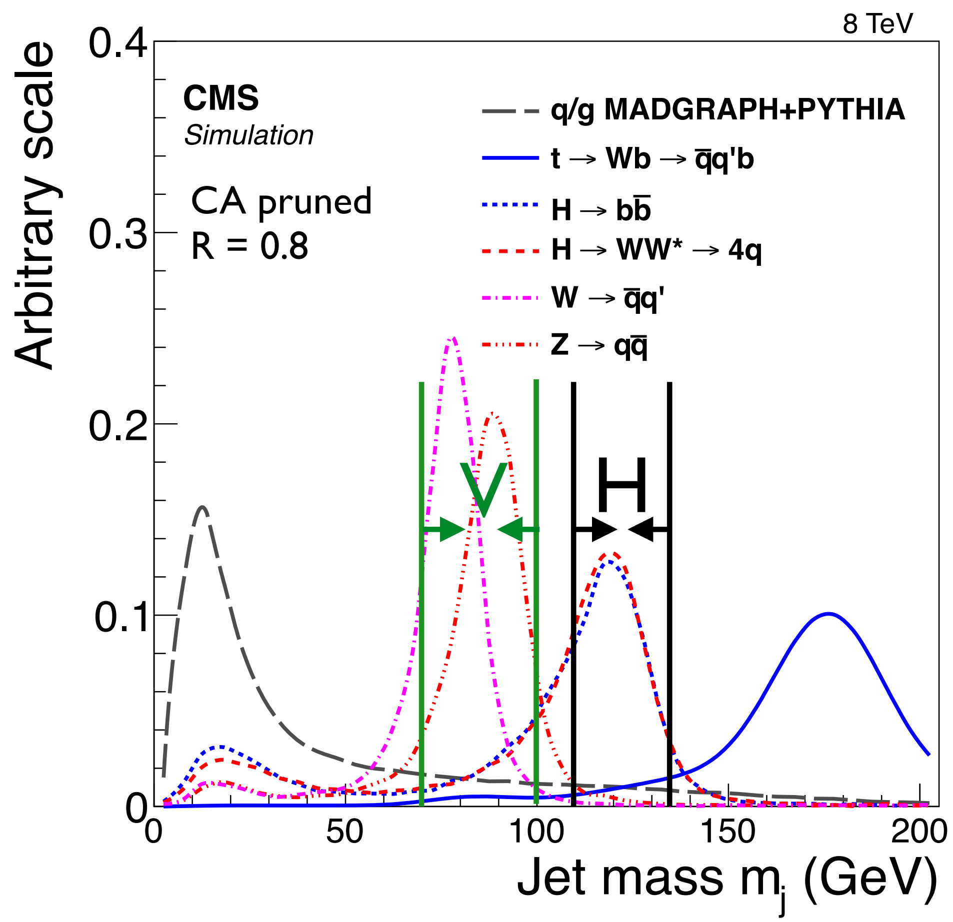
Eff (200 < p_T < 265 GeV)
Data / MC = 0.96 ± 0.08

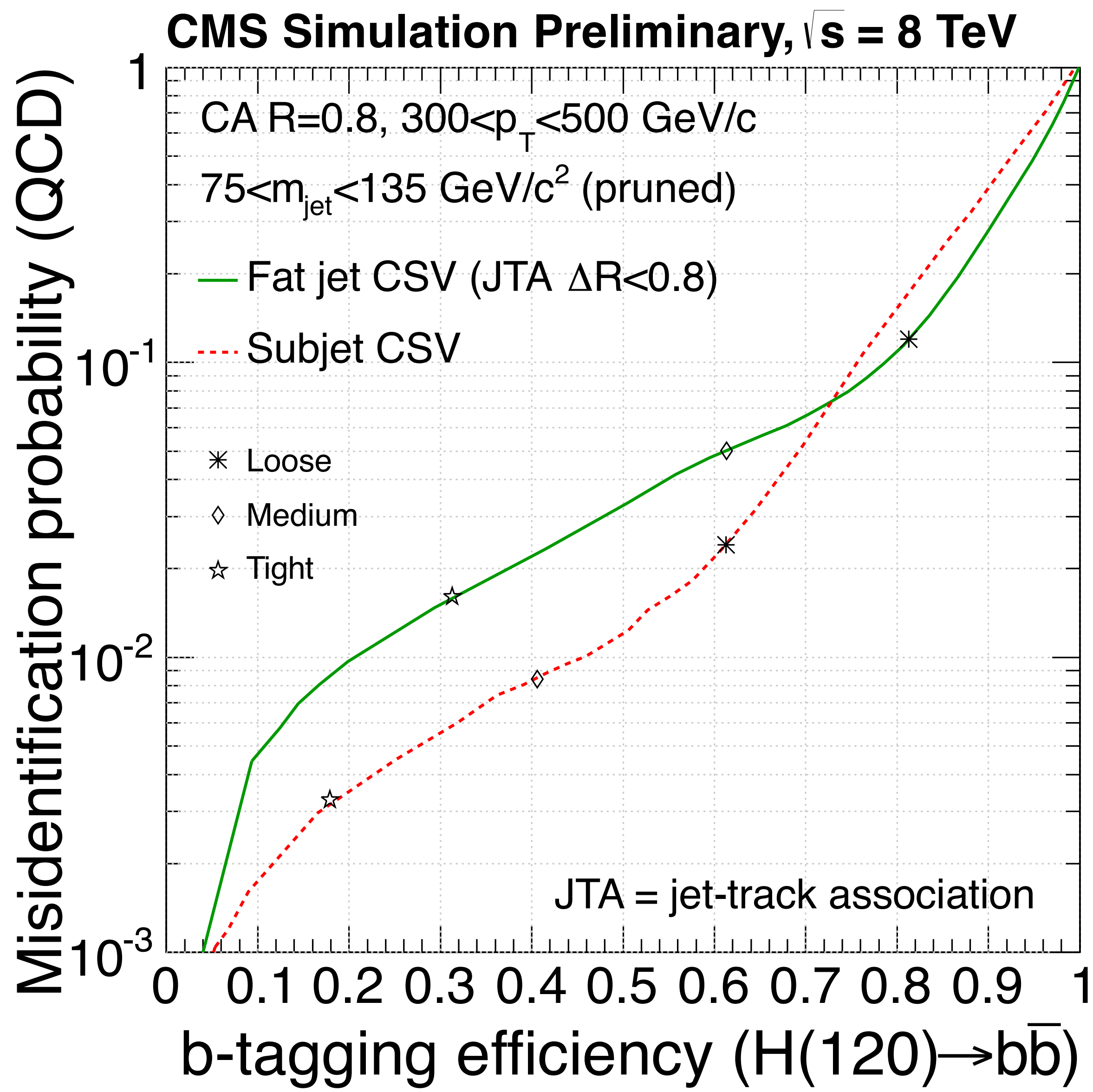
Eff (265 < p_T < 600 GeV)
Data / MC = 0.89 ± 0.10

H Tagging in $H \rightarrow b\bar{b}$

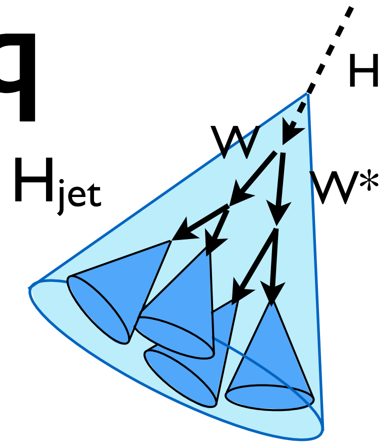


- Pruned jet mass main discriminator
  - mass window [110,135] GeV exclusive to V taggers
- (Sub)jet b-tagging powerful tool for discrimination, use:
  - subjets if well separated ($\Delta R>0.3$)
  - else, R=0.8 jet (at very high p_T)

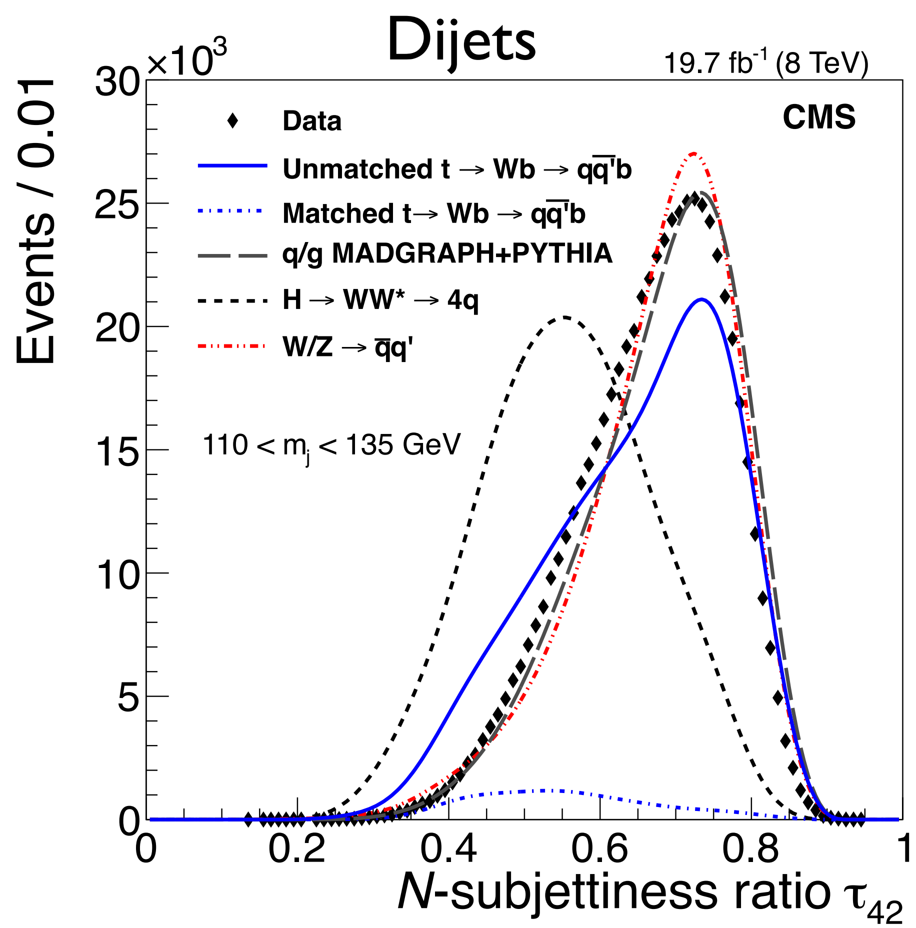




H Tagging in H→WW*→qqqq



- H→WW*→4q has second highest BR after H→$b\bar{b}$
- Various combinations of τ_i possible
  - τ_{42} best discrimination against q/g/W/Z/H(bb) jets (1 or 2 prong)
- distribution of τ_{42} agrees in shape with simulation, but is shifted towards smaller values (similar, but opposite to τ_{21})

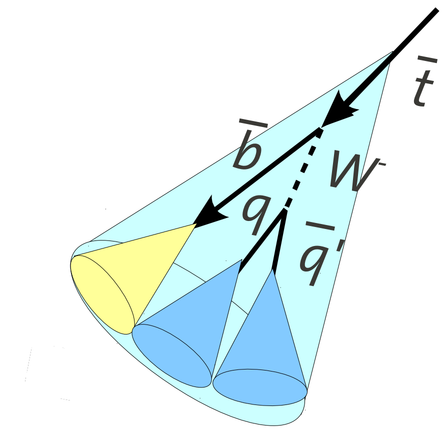


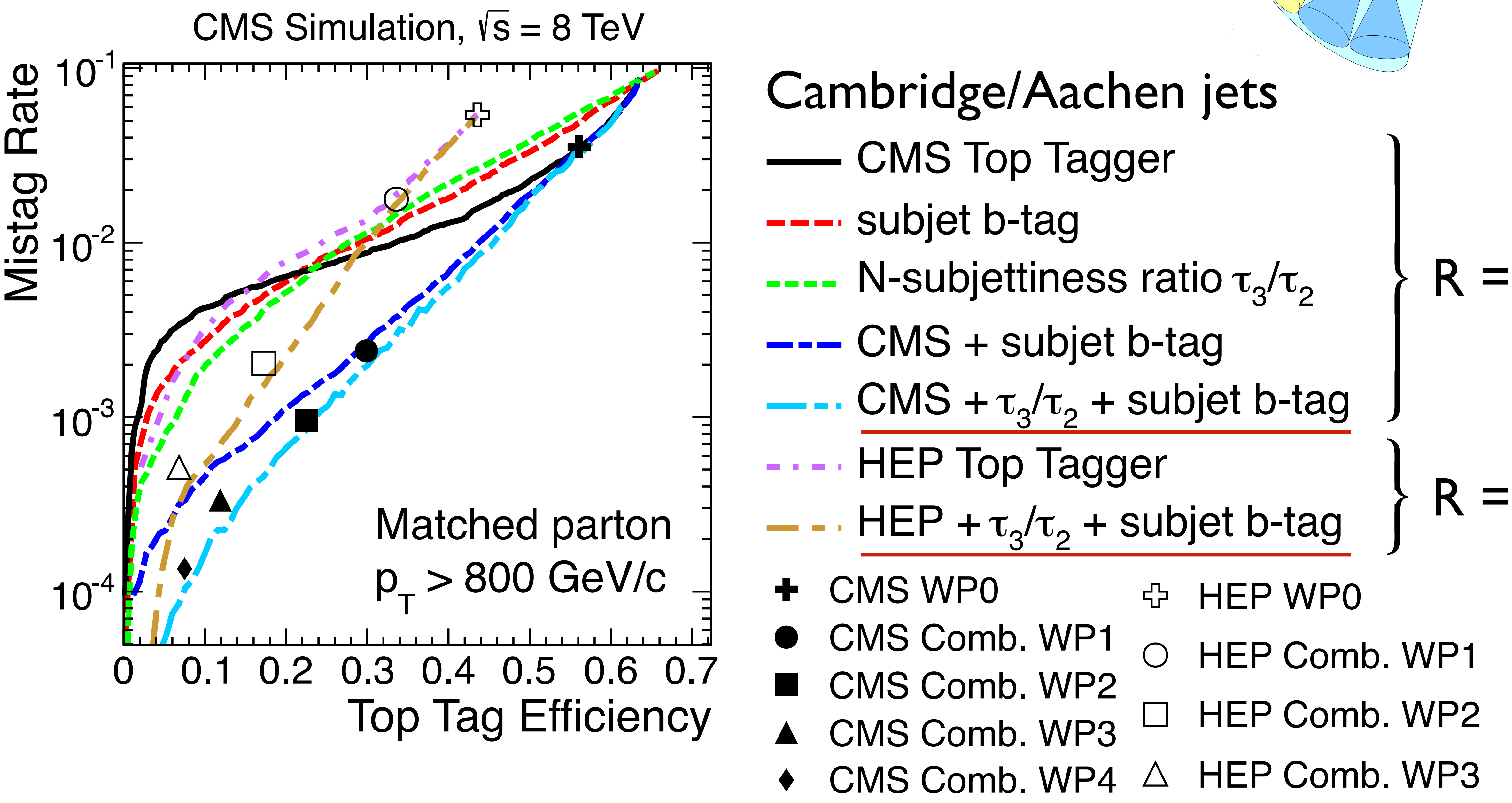
Comparison of V/H taggers at 35% efficiency

	BR(W/Z/H→XX)	Mistag
V(qq) tagger	70%/68%	**1.2%**
H(bb) tagger	57%	**0.5%**
H(WW→4q) tagger	10%	**1.5%**
H(ττ) tagger	6%	**0.03%**

Background rejection of H(bb) better by factor of 2 w.r.t V(qq) and H(4q) taggers

t Tagging

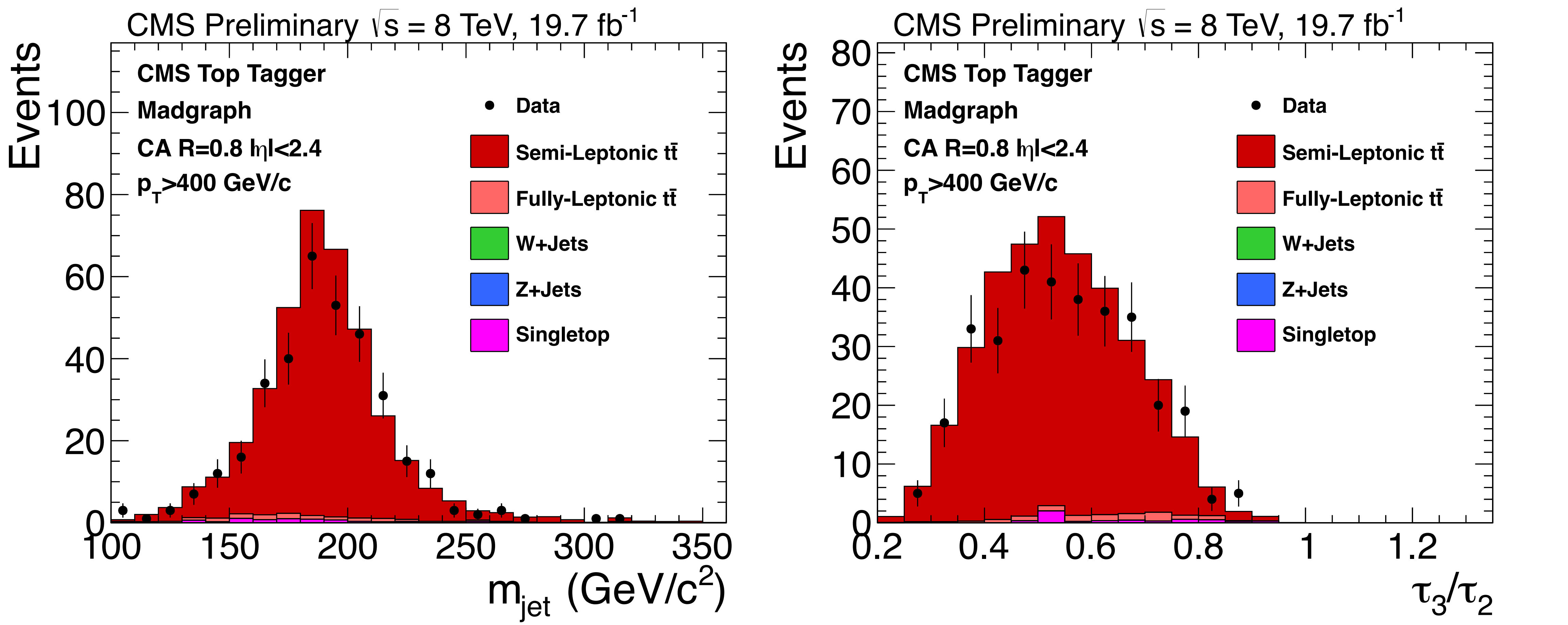

t̄
b̄
W⁻
q
q̄'


CMS Simulation, √s = 8 TeV
Mistag Rate
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Top Tag Efficiency
Matched parton
p_T > 800 GeV/c
Cambridge/Aachen jets
CMS Top Tagger
subjet b-tag
N-subjettiness ratio τ3/τ2
CMS + subjet b-tag
CMS + τ3/τ2 + subjet b-tag
R = 0.8
HEP Top Tagger
HEP + τ3/τ2 + subjet b-tag
R = 1.5
CMS WP0
CMS Comb. WP1
CMS Comb. WP2
CMS Comb. WP3
CMS Comb. WP4
HEP WP0
HEP Comb. WP1
HEP Comb. WP2
HEP Comb. WP3

[CMS PAS JME-13-007]

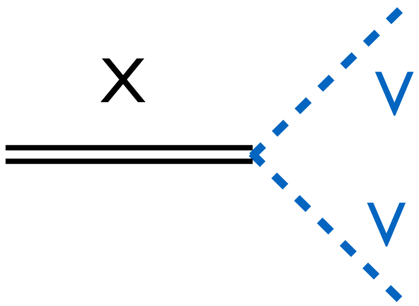
t Tagging: Performance in Data

- Performance study in $t\bar{t}$ events
  - reconstruct leptonic hemisphere using mass constraints and b-tagging
  - validate top-tagging on single jet on hadronic hemisphere

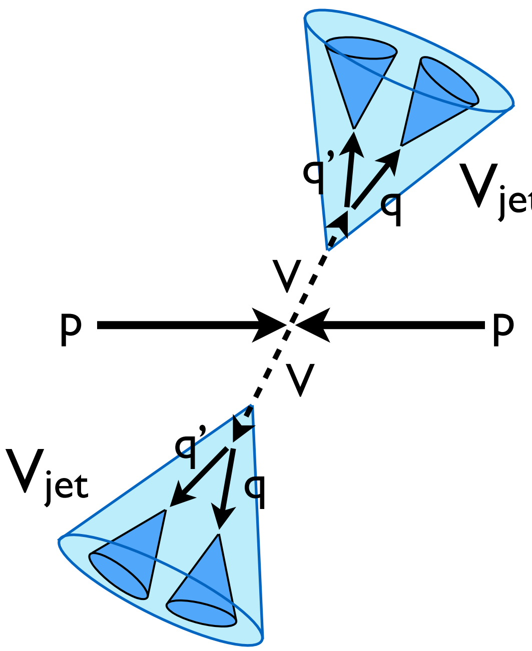


- good general agreement, efficiencies described within 10-20% (depends on definition of tagger, p_T and $|\eta|$)

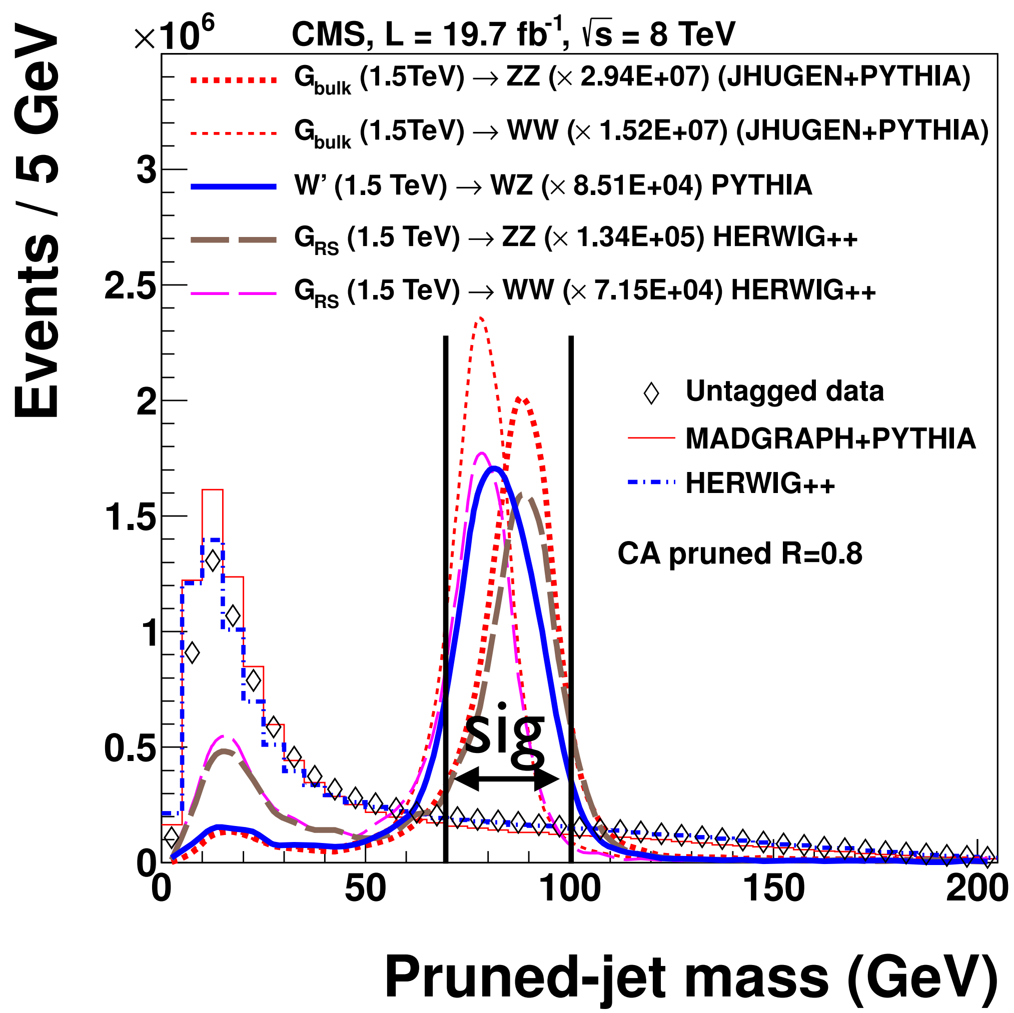
VV Resonances

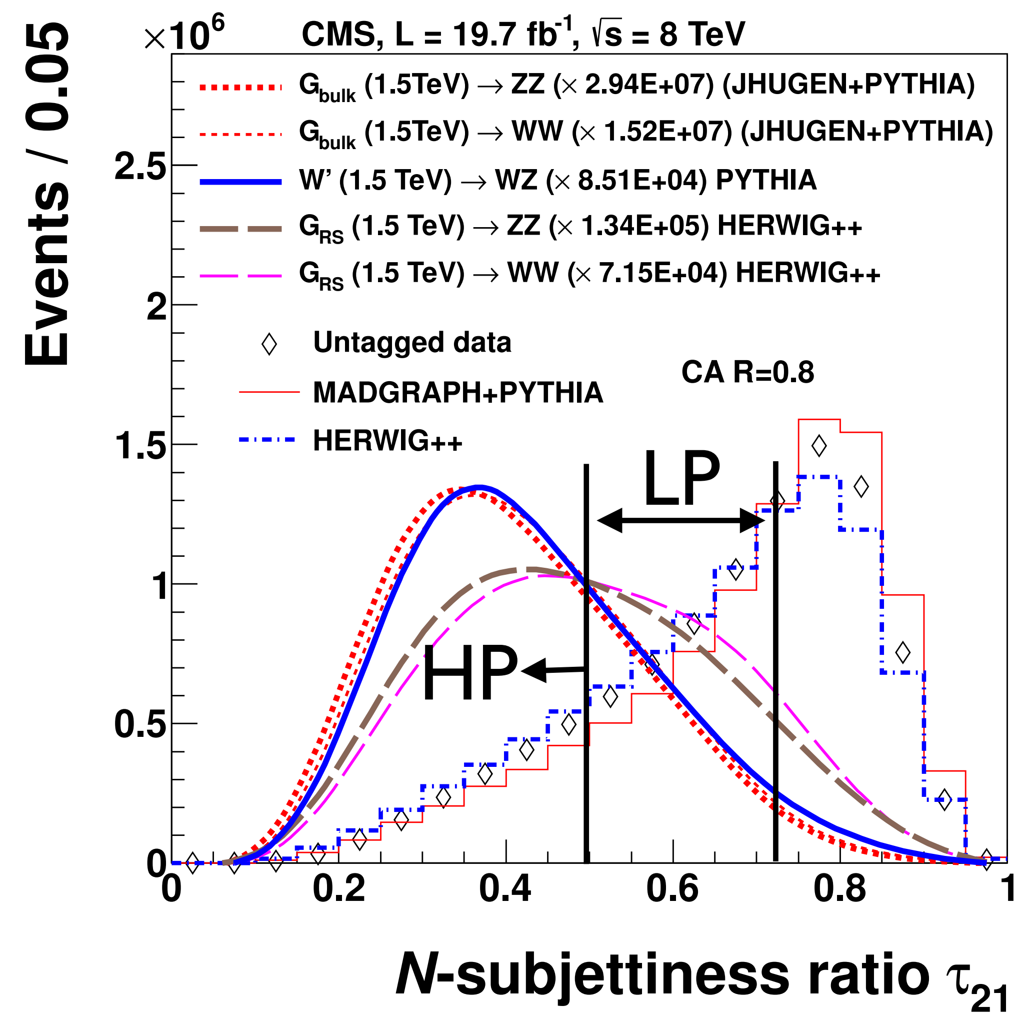


VV → (q$\bar{q}$) (q$\bar{q}$)

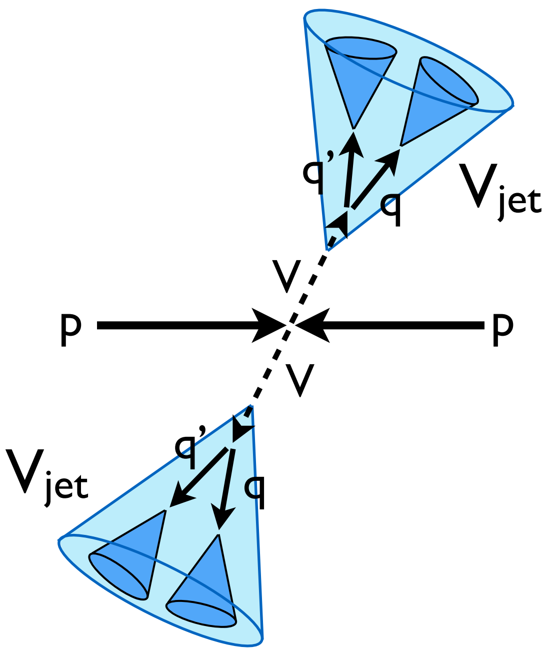


- Highest BR, highest background
- Trigger using H_T and M_{jj}, fully efficient for M_{jj} > 900 GeV
- V_{jet} selection
  - pruned mass: 70 < m_{pruned} < 100 GeV
  - high purity (HP): τ_{21} < 0.5, low purity: 0.5 < τ_{21} < 0.75

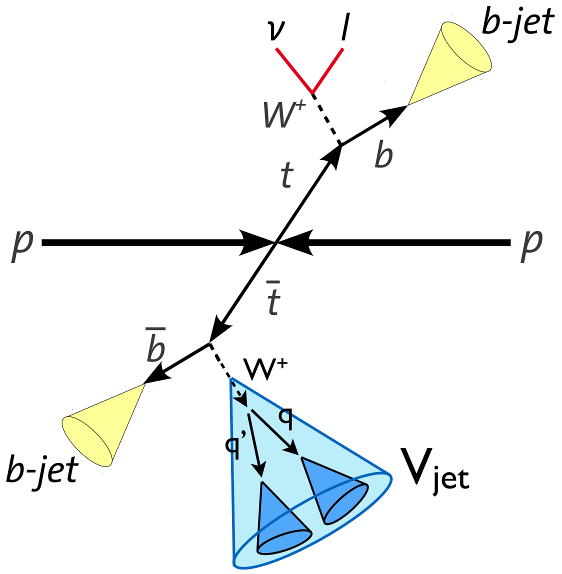


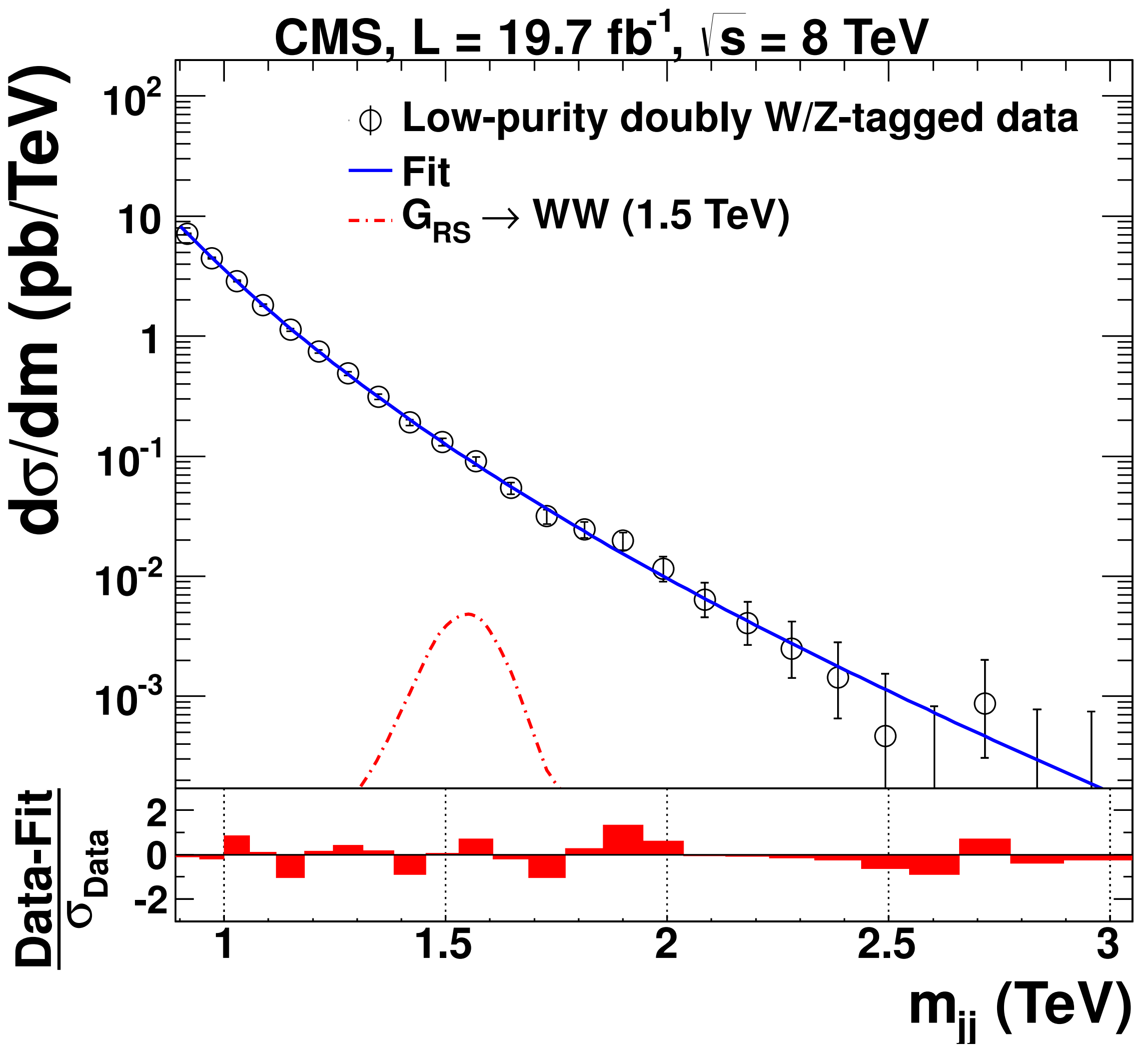


VV → ($q\bar{q}$) ($q\bar{q}$)

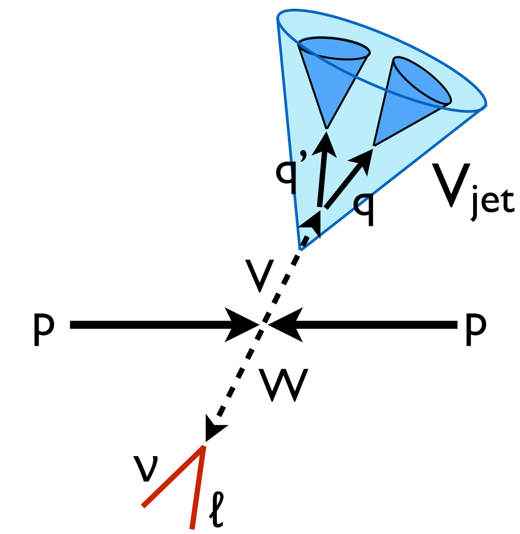


- four categories (HP, LP)
  - single V_{jet}, sensitive to $q^* \rightarrow qV$
  - double V_{jet}, sensitive to $X \rightarrow VV$
- parametrise background with smoothly falling function
  - rely on data only, not affected by mismodelling in simulation
  - sensitivity to bumps
  - no sensitivity to enhancements
- corrections for signal efficiency obtained in $t\bar{t}$ control region



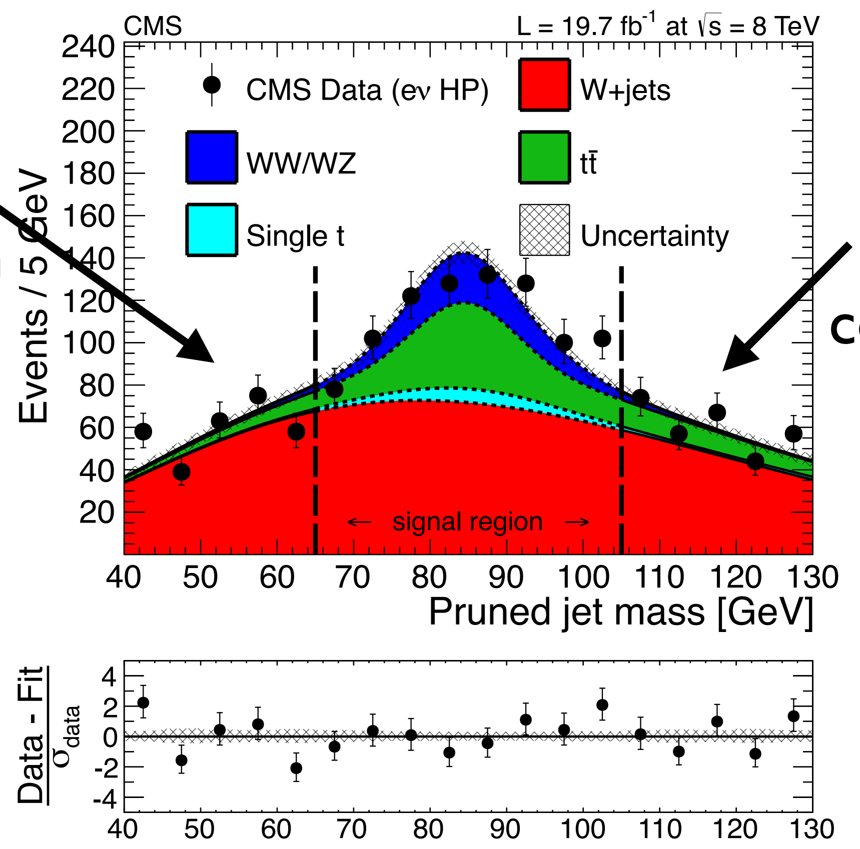


WV → ℓν (q$\bar{q}$)

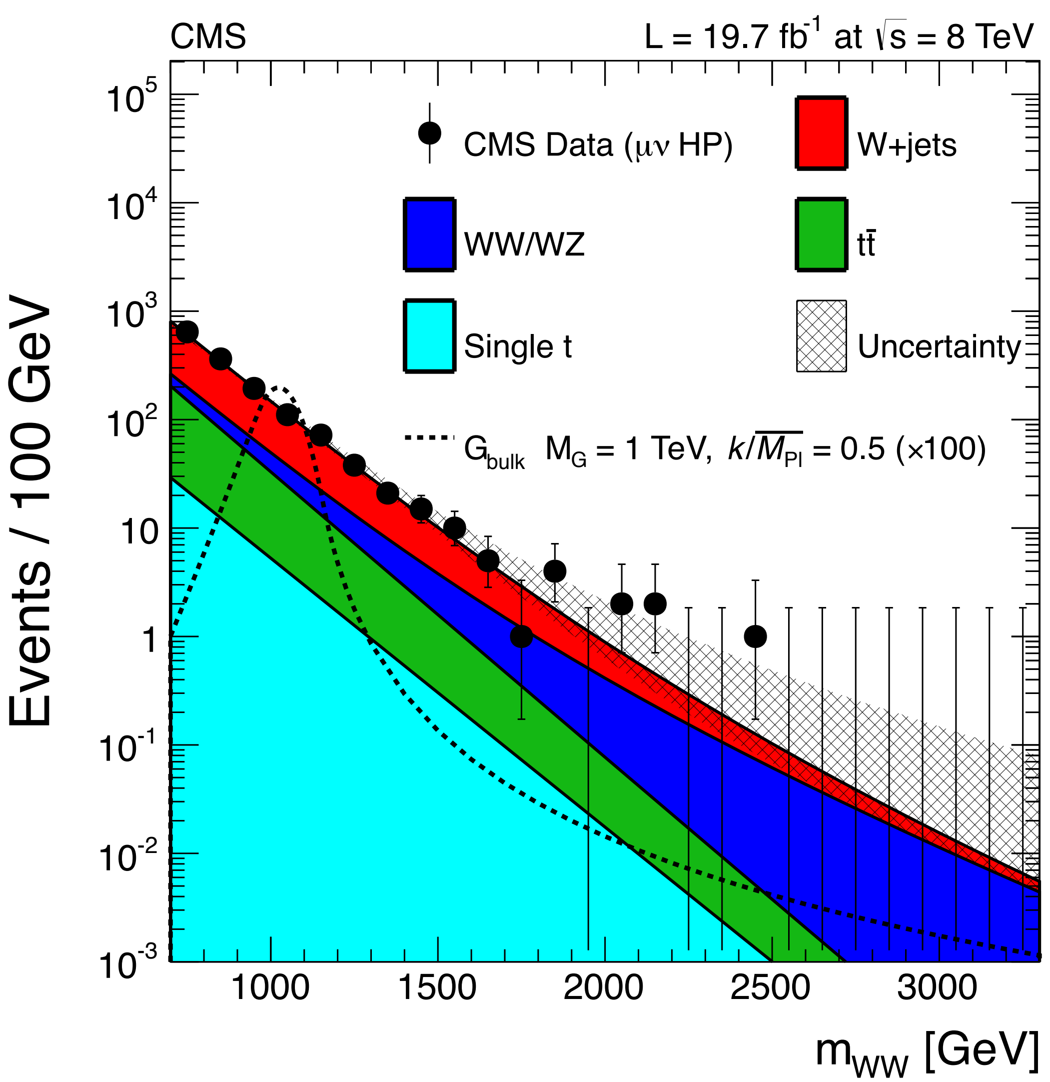


- Trigger high p_T lepton: p_T > 80 (40) GeV for e (μ)
- Reconstruct one W from lepton and E_T^{miss}
- Second W reconstructed from V-tagged jet
- W+jets background estimated from lower jet mass side-band (α method)

extract shape of M_{VV} distribution

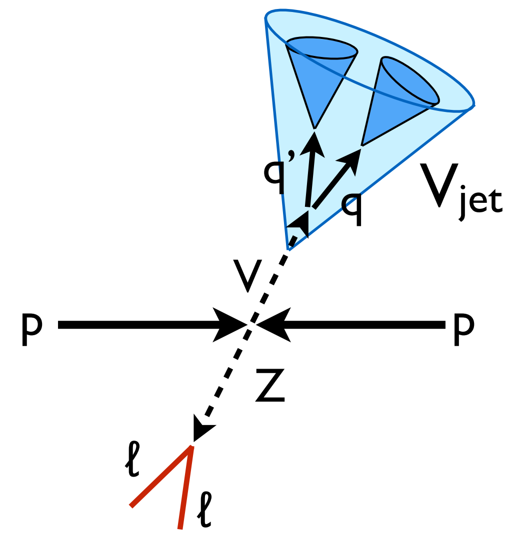


use for validation (possible contamination from VH signals)

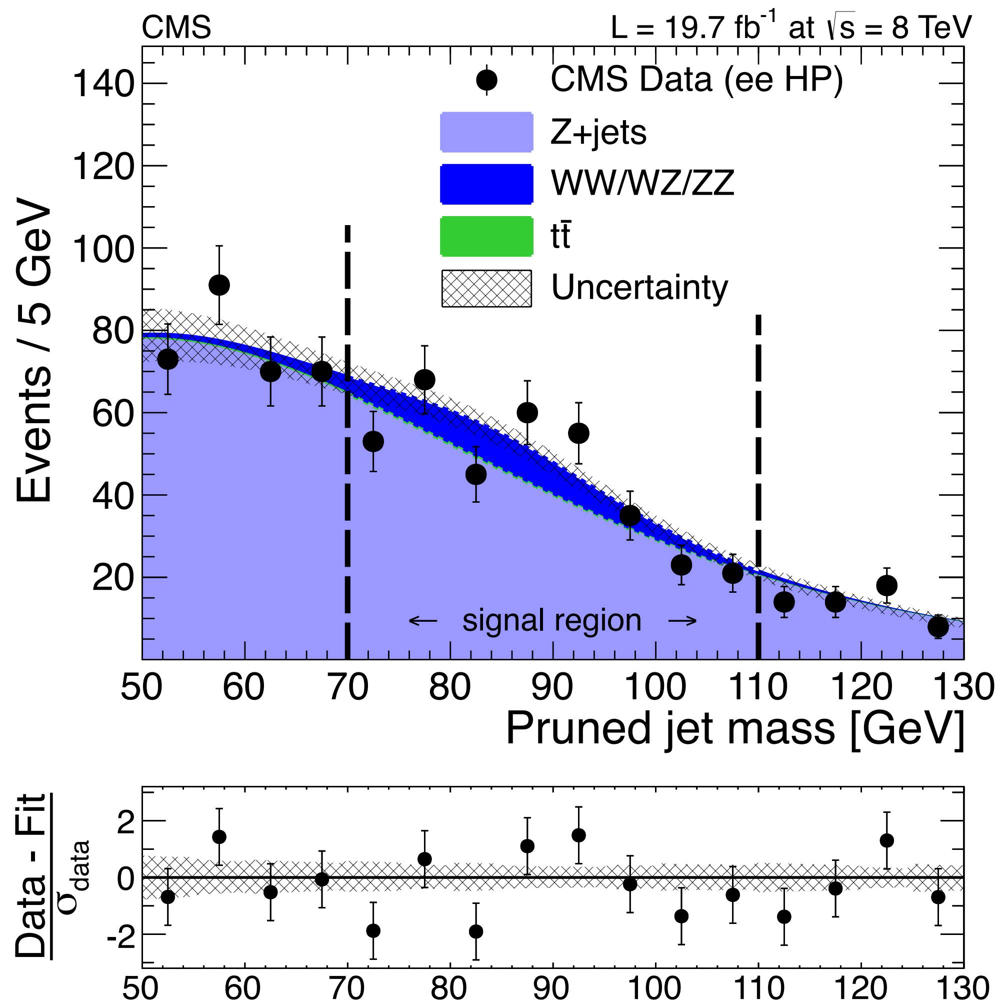


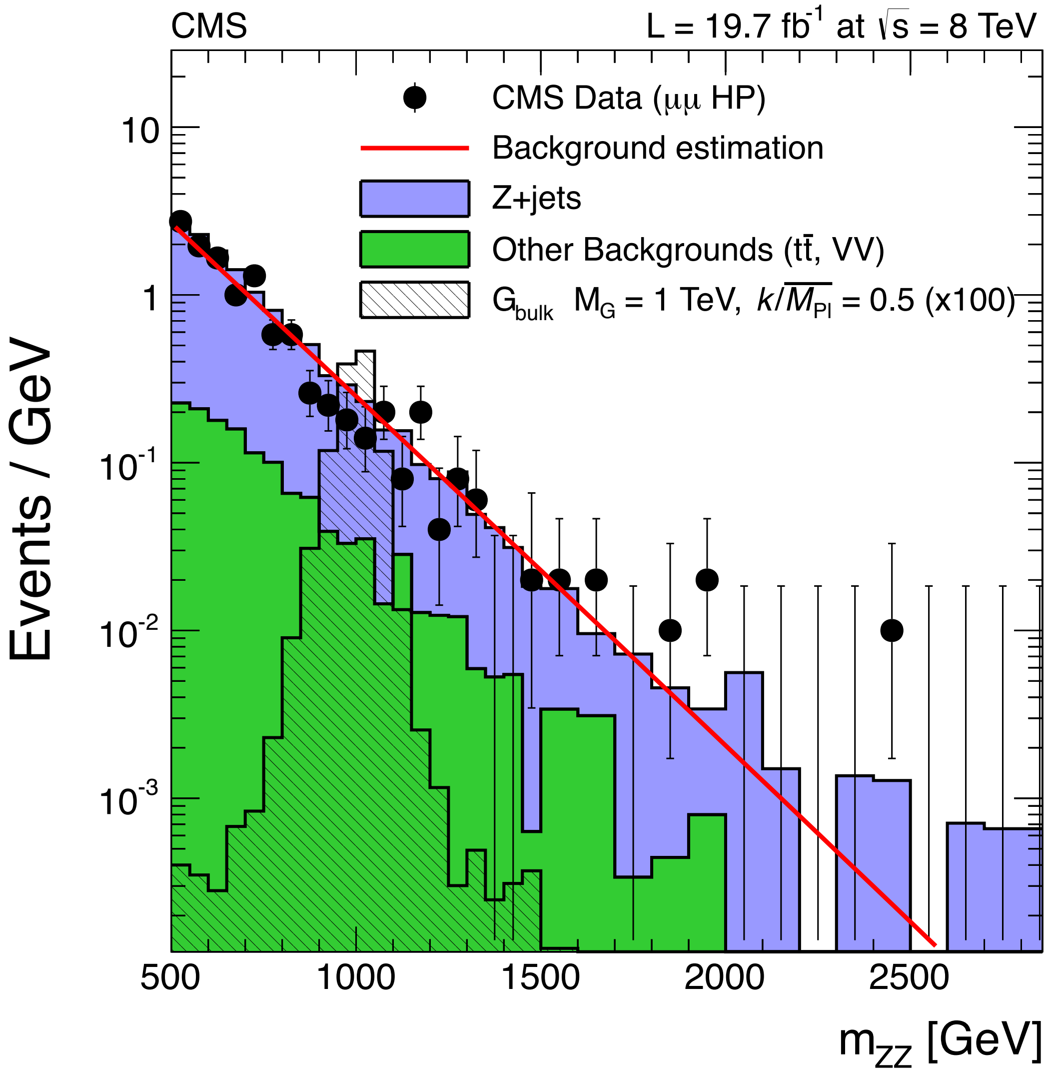
[EXO-13-009, JHEP08, 174 (2014)]

ZV → ℓℓ (q$\bar{q}$)

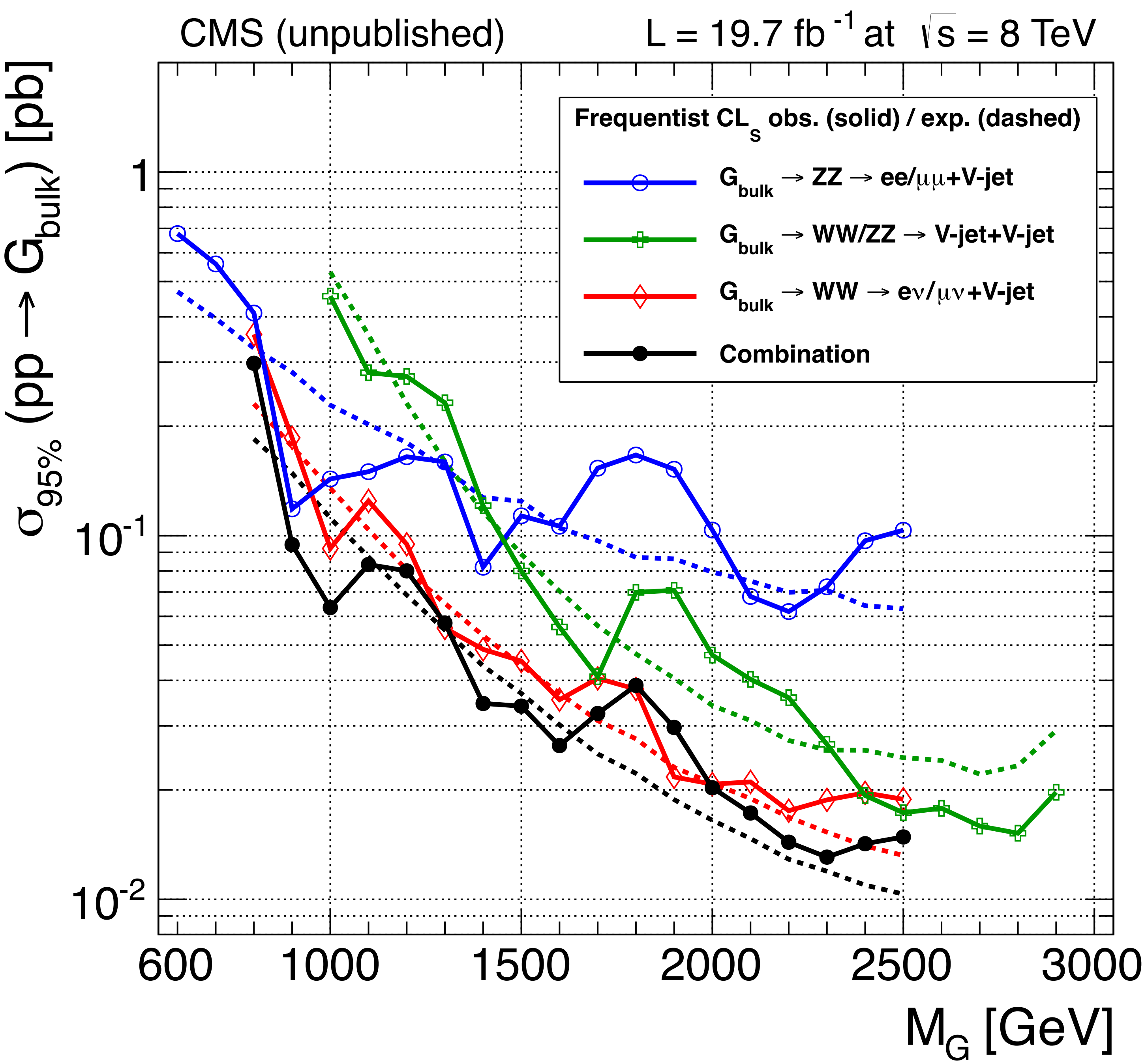


- Follow similar strategy as in ℓν channel
- Dilepton triggers (reach lower M_{VV})
- Remove other lepton from isolation cone
- Higher purity but less sensitivity due to smaller BR





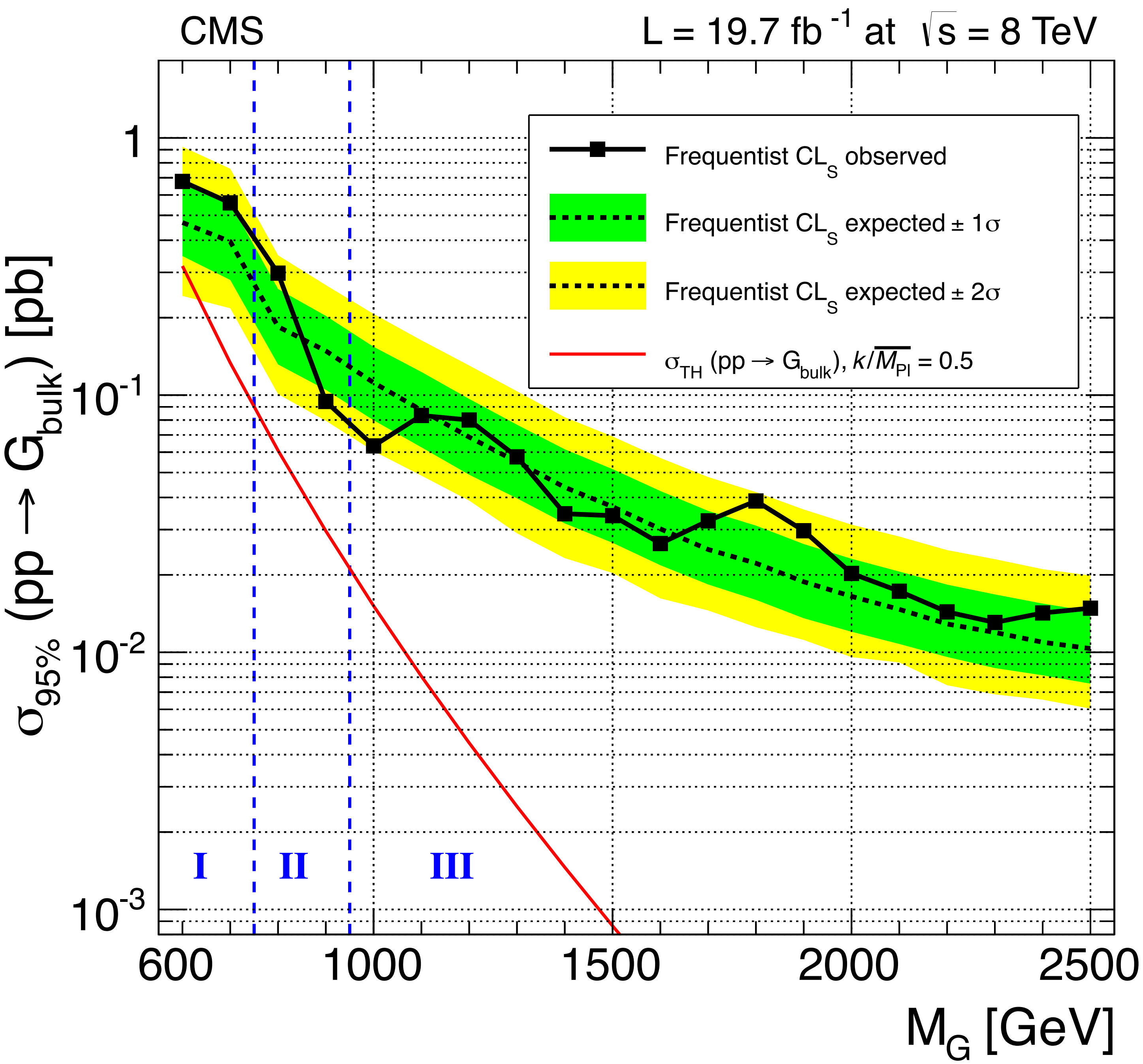
Combination of VV Searches



Combination in bulk graviton model

- Highest sensitivity from ℓν+jet channel
- Sensitivity of Jet+Jet channel comparable at high mass
- ℓℓ+jet channel reaches lower mass
- Combination improves sensitivity by 15-20%

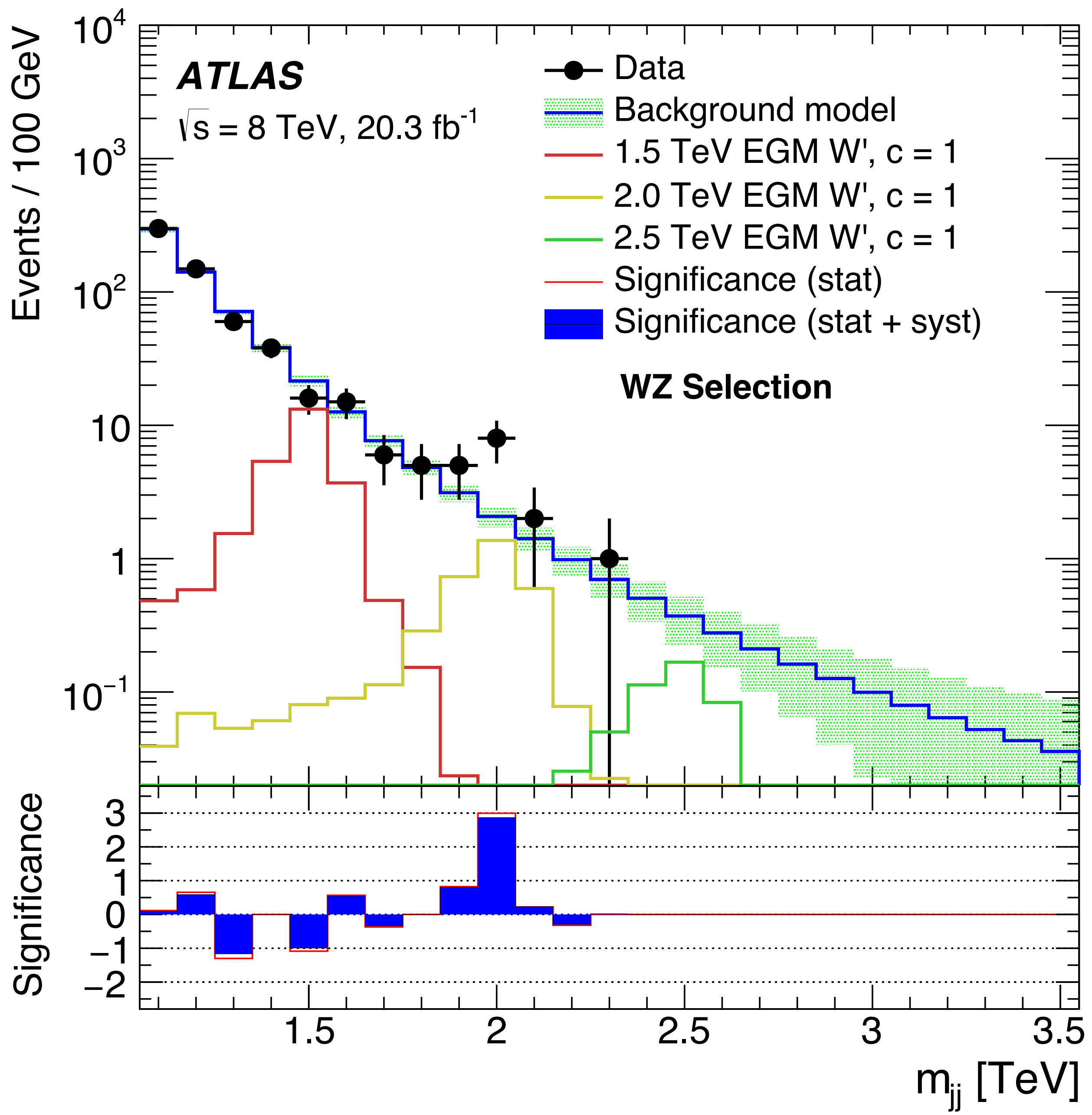
Combination of VV Searches



Combination in bulk graviton model

- No significant deviations from expected
- Sensitivity not high enough to exclude graviton in this model (with $k/\bar{M}_{Pl} = 0.5$)

ATLAS VV → $(q\bar{q})\,(q\bar{q})$



ATLAS dijet search, similar to CMS one

- 3.4σ (local) at M = 2 TeV (2.5σ global)
- also analysed WW and ZZ channels, but highly correlated
- 84 citations since June (~15 per month)
  - rather exceptional for an experimental publication (except the H discovery)
  - many interpretations (left-right models, VLQs, SUSY, extra dimensions, 2HDM,…)

[J. Brehmer et al., arXiv:1507.00013]

Comparison CMS / ATLAS

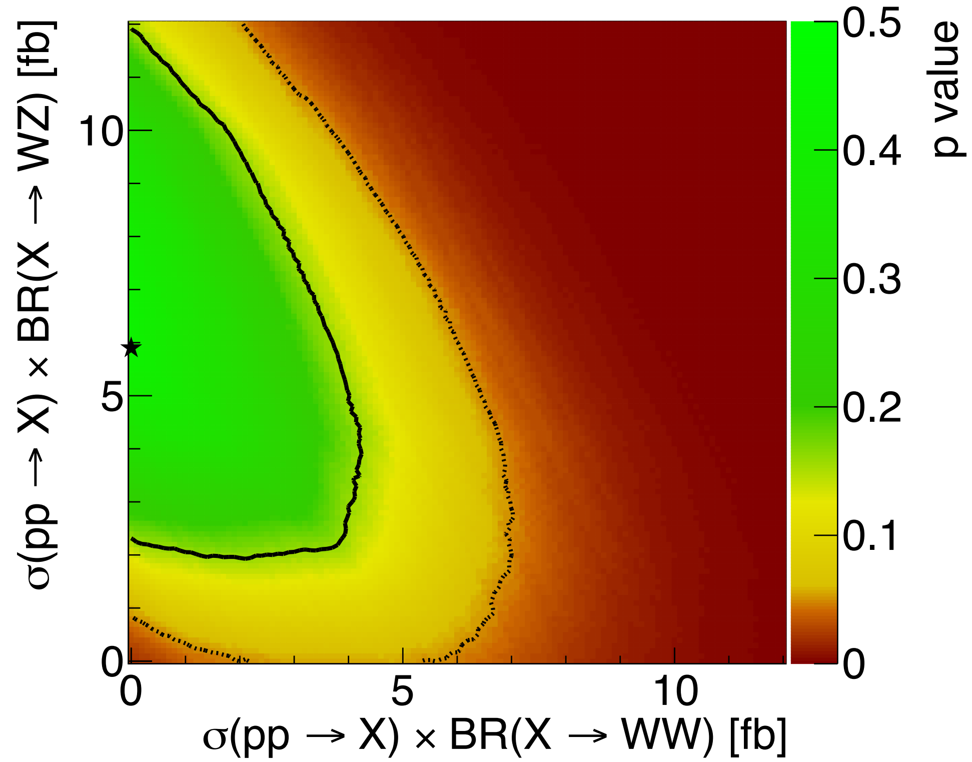
Simple fit of observed events vs. expected

- use data around M = 1.8 TeV (no correlations)

WZ **resonance analyses**

comparable sensitivity

Analysis	Expected 95% CLs [fb]	Observed 95% CLs [fb]	Excess significance [σ]	Fitted cross section [fb]
ATLAS hadronic [1]	14.2	25.8	2.4	6.9
CMS hadronic [9]	11.9	17.5	1.0	5.8
ATLAS single lepton [6]	27.6	25.7	0.0	0.0
CMS single lepton [5]	14.9	16.8	0.3	2.4
ATLAS double lepton [7]	19.5	28.9	0.3	4.1
CMS double lepton [5]	14.4	27.4	1.5	10.0



Combination of all channels

- $\sigma \times BR(X \rightarrow WZ) \approx 6\ fb^{-1}$
- while $\sigma \times BR(X \rightarrow WW) \approx 0\ fb^{-1}$
- within about 2σ of SM
- what about HV and $t\bar{b}$ final states?

[J. Brehmer et al., arXiv:1507.00013]

Comparison CMS / ATLAS

1) Should we be excited about this?

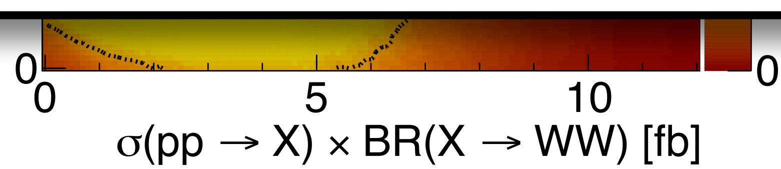
Intriguing, since upward fluctuations in several channels, BUT:
- the fluctuations are small
- the "signal" is not visible in all channels
- nothing in most sensitive channel ($\ell\nu$+jet)

2) Should I try to explain this with a new BSM theory?

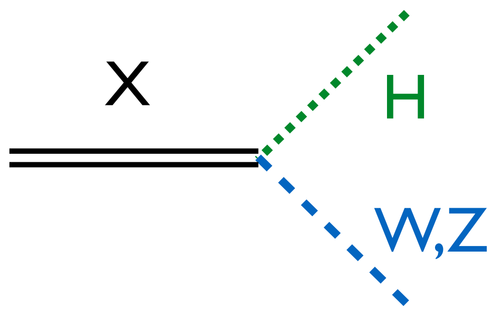
If you like…

3) Will you follow up in Run 2?

Definitely! We will know more with 3-5 fb^{-1} at 13 TeV!

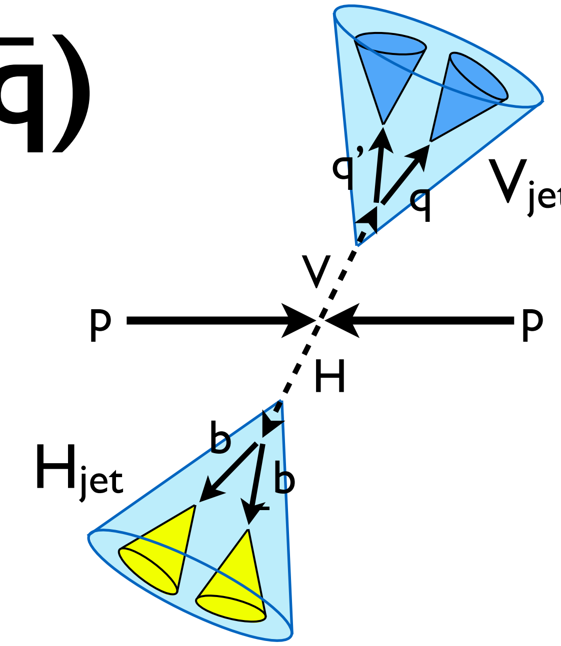


VH Resonances

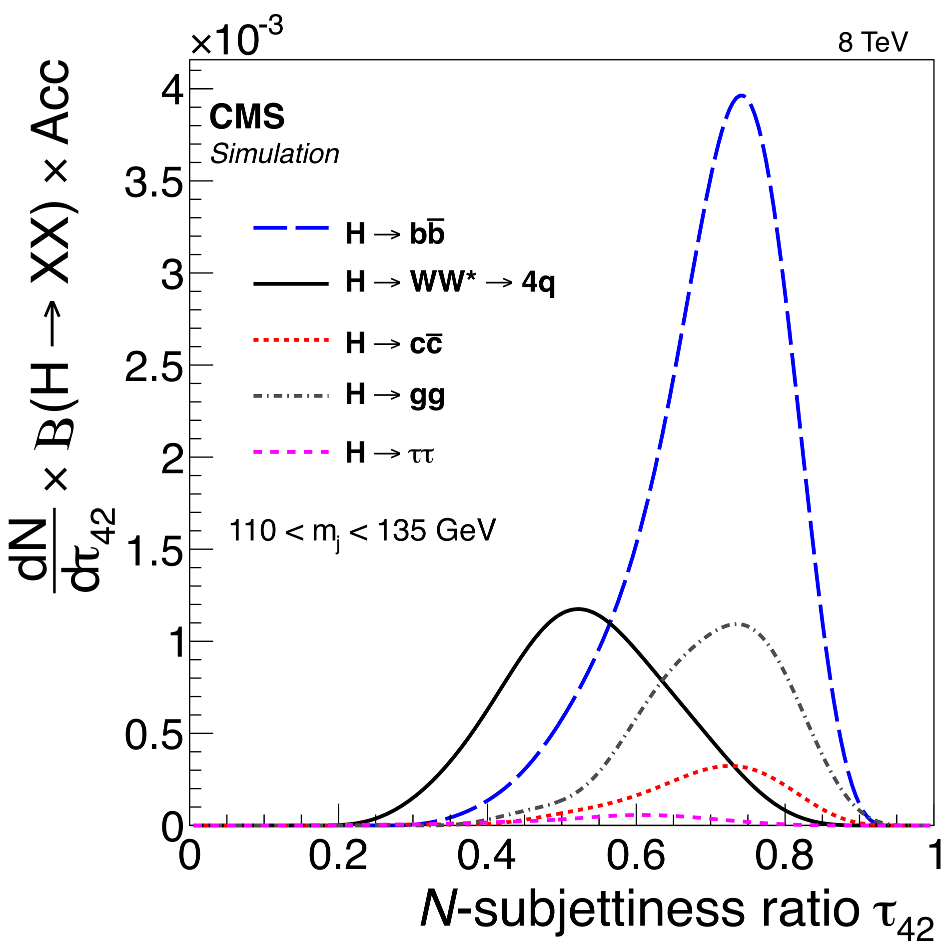


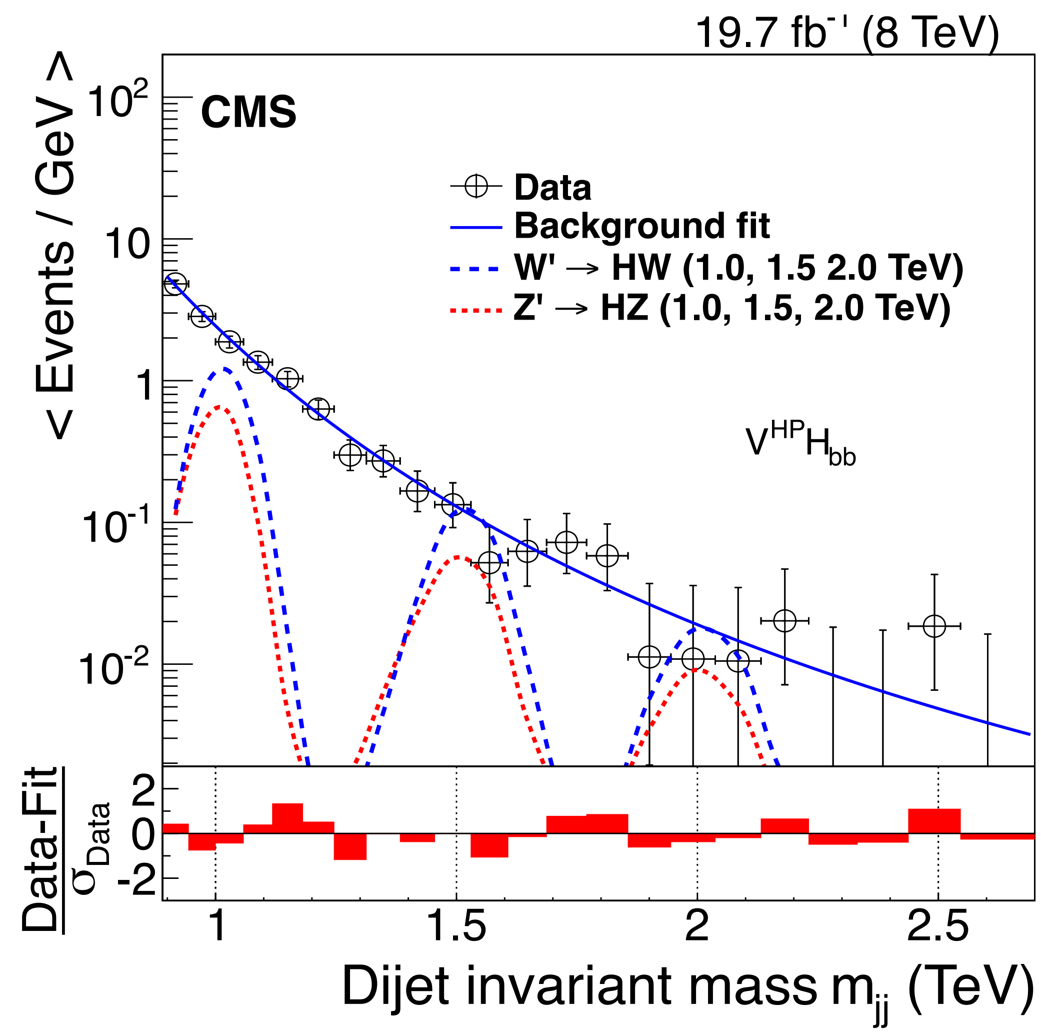
[EXO-14-009, arXiv:1506.01443]

$VH \rightarrow (q\bar{q})(b\bar{b})$ or $(q\bar{q})(q\bar{q}q\bar{q})$



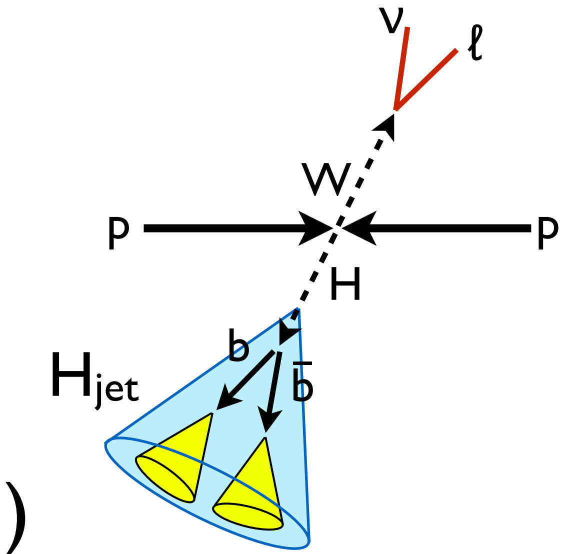
- Fraction of $H \rightarrow b\bar{b}$ events failing b-tagging, but passing τ_{42} selection non-negligible since $BR(H \rightarrow b\bar{b}) > BR(H \rightarrow WW \rightarrow qqqq)$
  - Need to consider all possible Higgs decays in analysis
  - Check for $H \rightarrow b\bar{b}$ tag before $H \rightarrow WW \rightarrow qqqq$ tag
- analysis similar to $VV \rightarrow$ jet+jet case



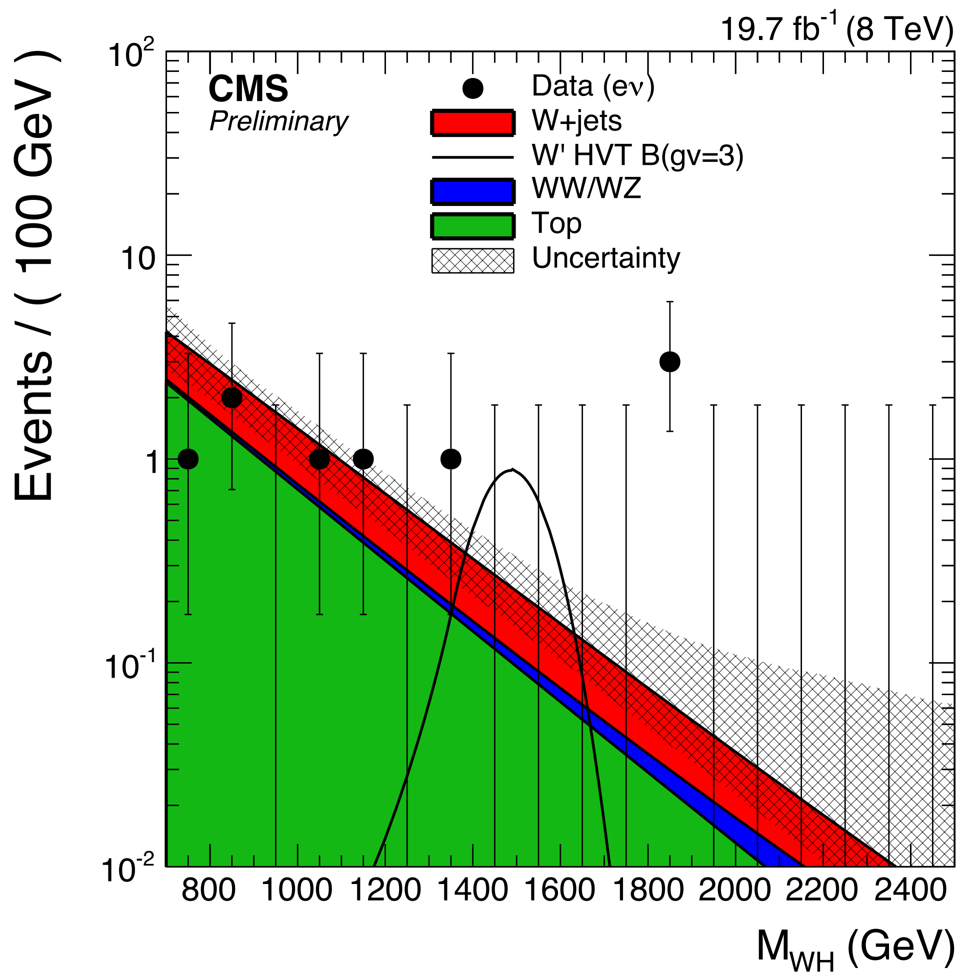


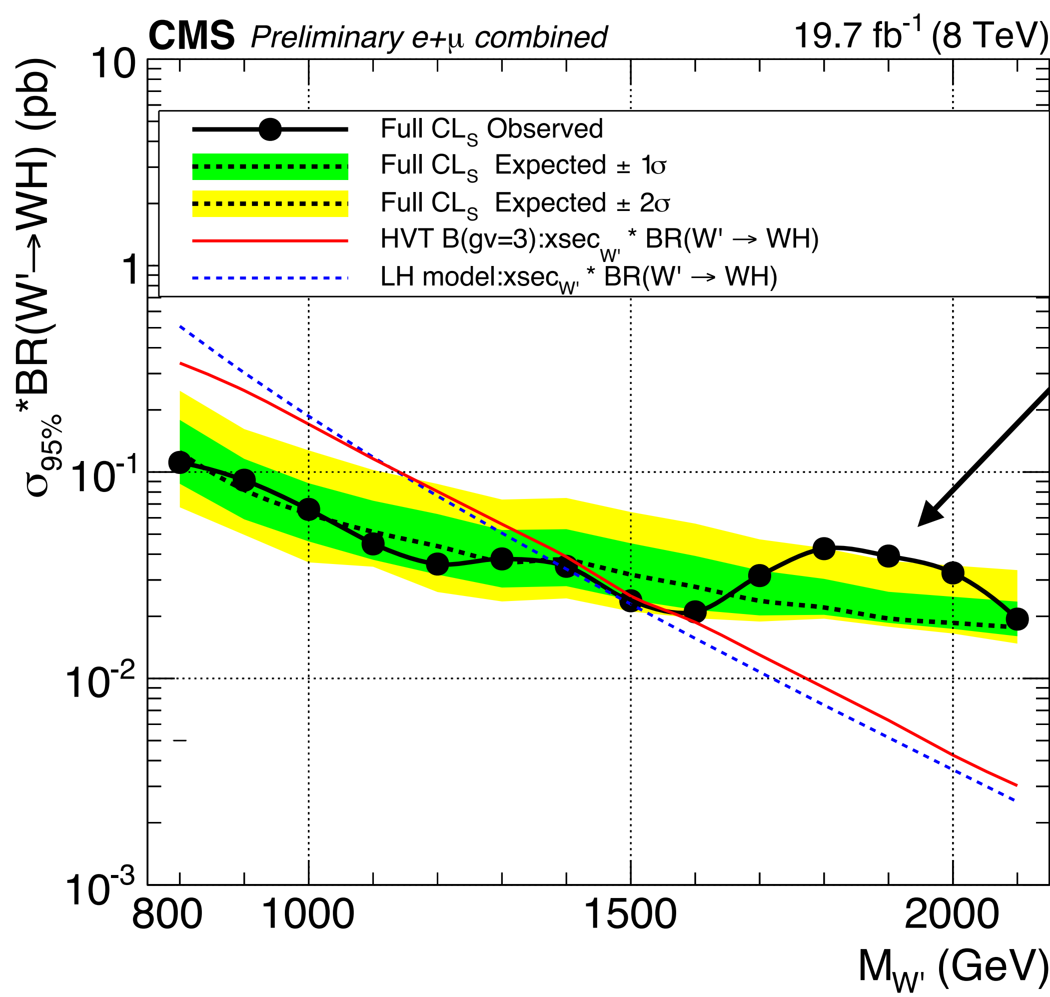
[PAS EXO-14-010]

WH→ (ℓν) ($b\bar{b}$)



- Analysis similar to WV→ℓν V_{jet}
  - Background estimate from lower M_{jet} sideband region
  - Extrapolation of M_{WH} shape to signal region (α method)
- See 3 events at M_{WH} ~ 1.8 TeV (< 0.3 expected)
  - nothing in μ channel

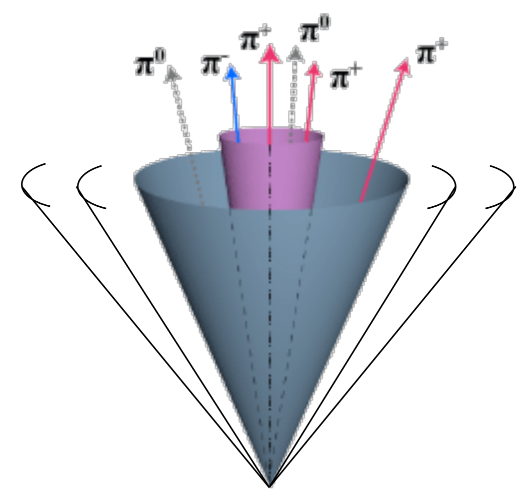


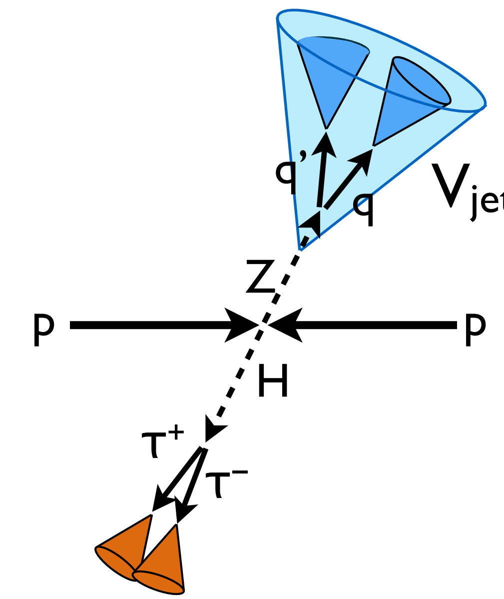


combined significance (e+μ) of 2.2σ (1.9σ global)

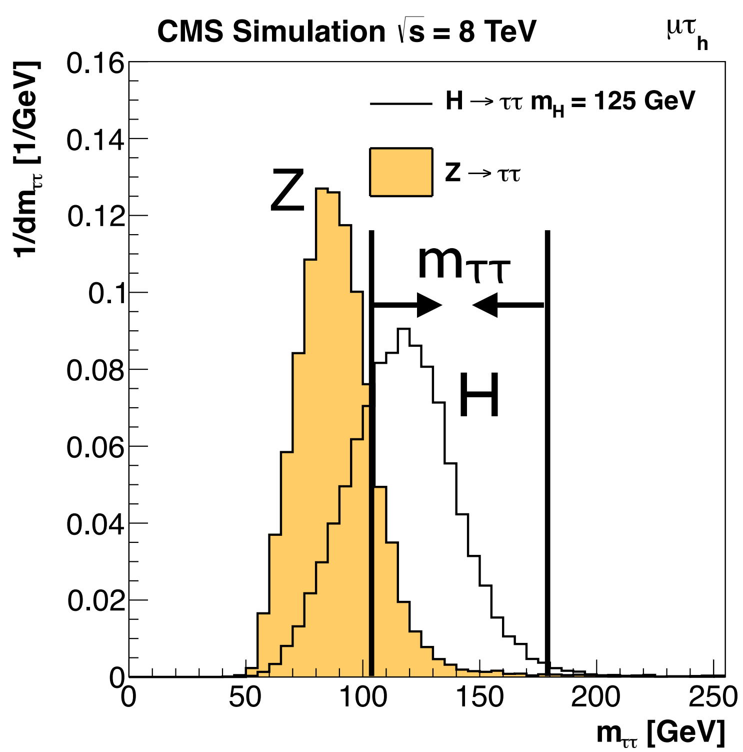
$ZH \rightarrow (q\bar{q})\ (\tau^+\tau^-)$

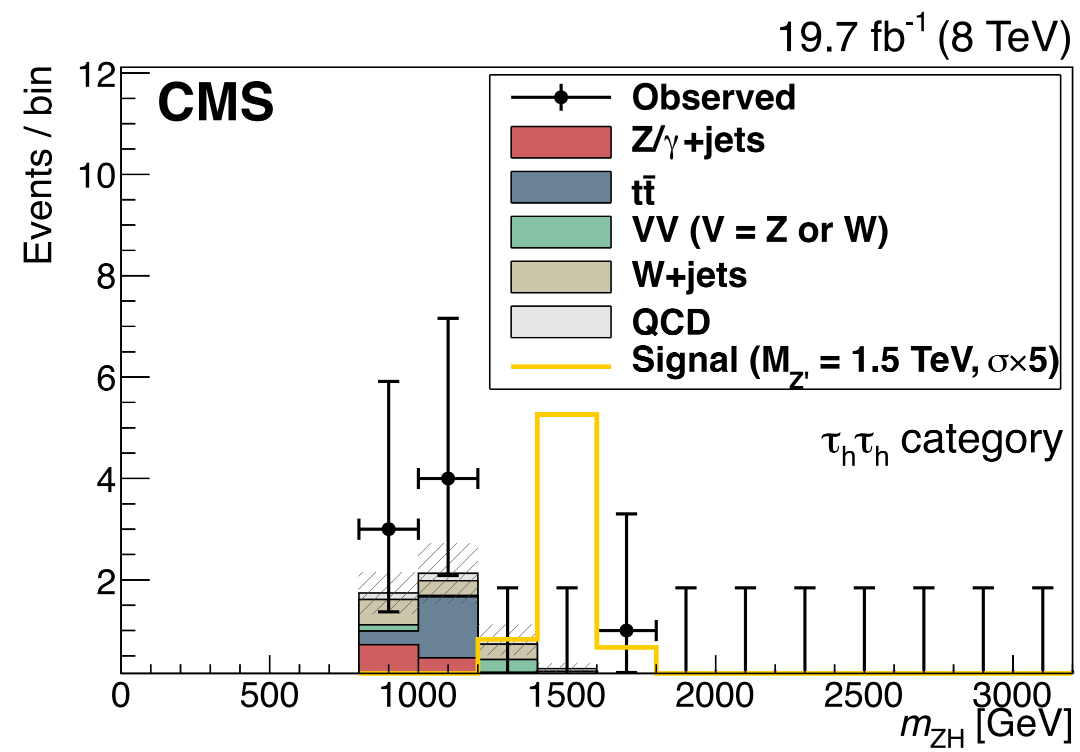
decay mode	BR[%]
$\tau \rightarrow e\nu\nu$	17.8
$\tau \rightarrow \mu\nu\nu$	17.4
$\tau \rightarrow$ had+ν	64.8





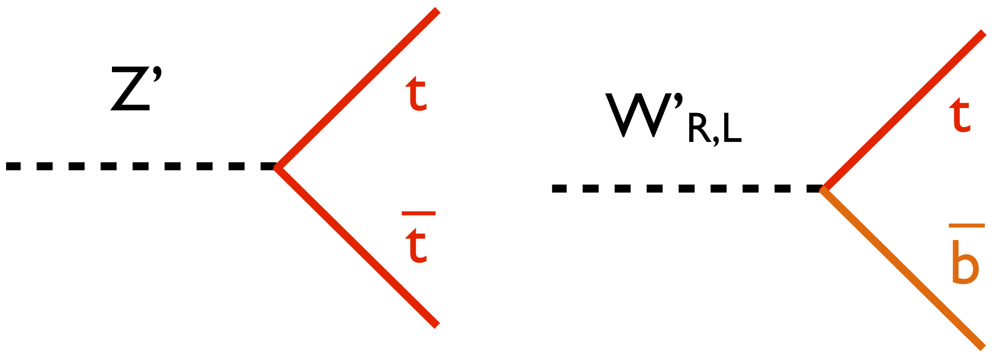
- take all decay modes into account
  - main discriminator of τ_{had} vs q/g is MVA based isolation, summing energies of particles around cones of τ decay products
  - remove decay products of other τ from isolation cone



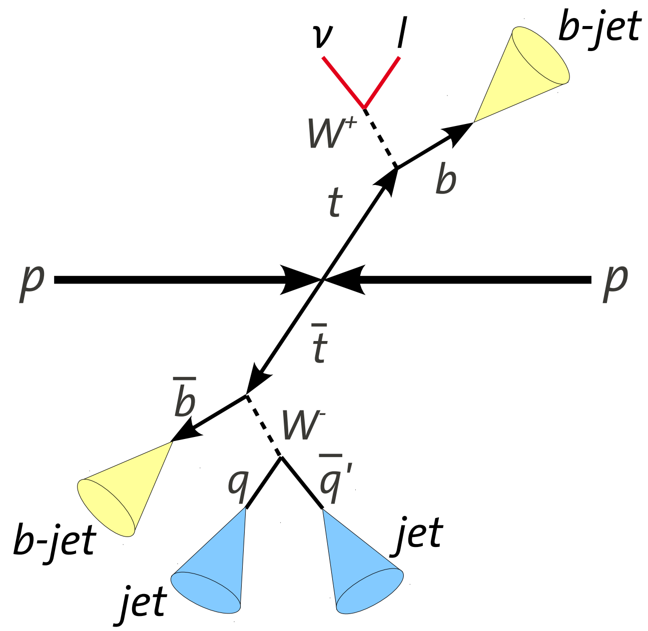


also measured: $\tau_e\tau_e$, $\tau_e\tau_\mu$, $\tau_e\tau_{had}$, $\tau_\mu\tau_\mu$, $\tau_\mu\tau_{had}$

$t\bar{t}$ and $\bar{t}b$ Resonances



Z'→$t\bar{t}$ ℓ+Jets Resolved



Conventional analysis

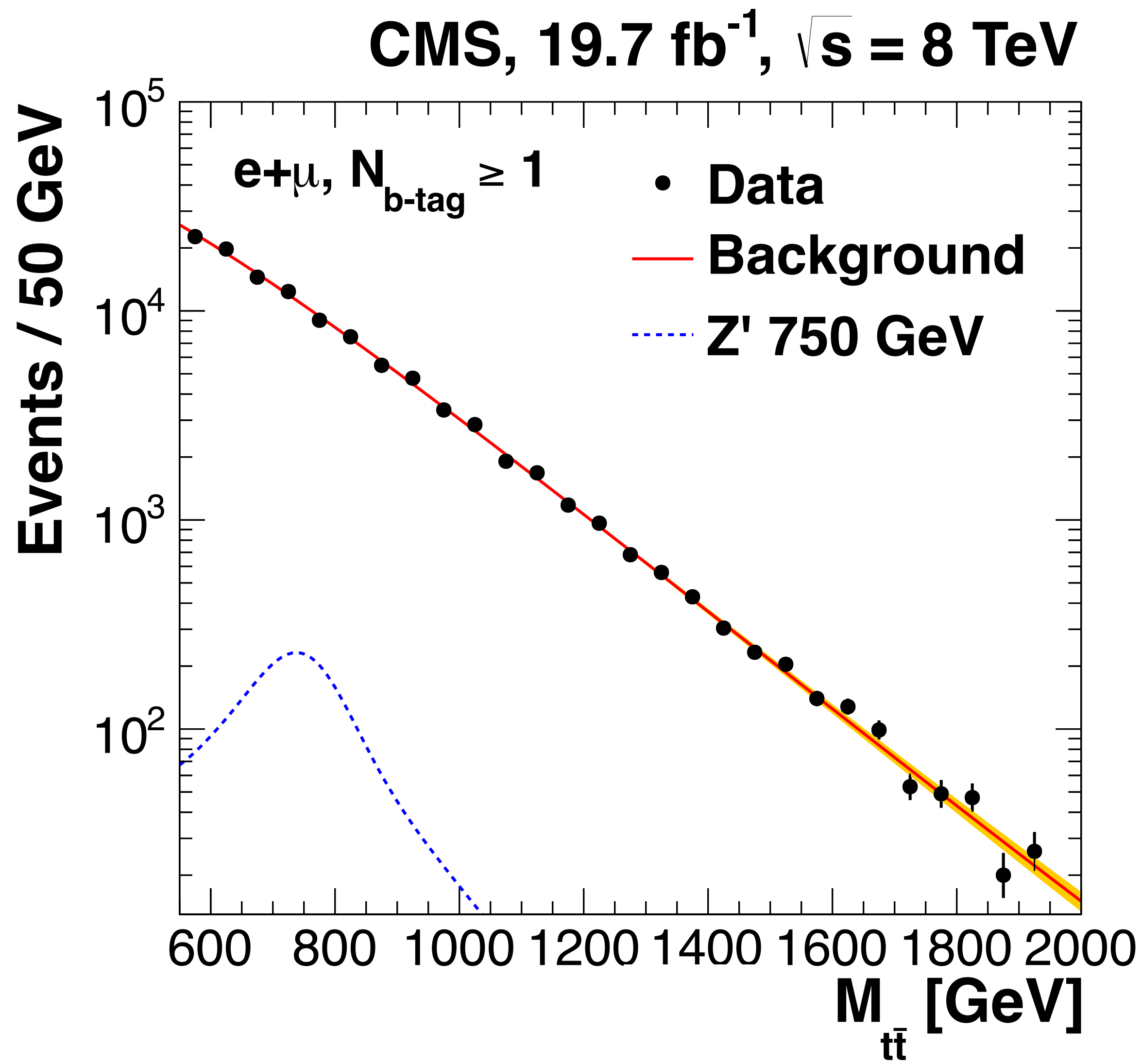
- 1 isolated lepton
- 4 jets, at least on b-tag

Reconstruction of $t\bar{t}$ system

$$\chi^2 = \chi^2_{m(tlep)} + \chi^2_{m(thad)} + \chi^2_{m(whad)} + \chi^2_{p_T(t\bar{t})}$$

with

$$\chi^2_x = (x_{meas} - x_{MC})^2/\sigma^2_{MC}$$



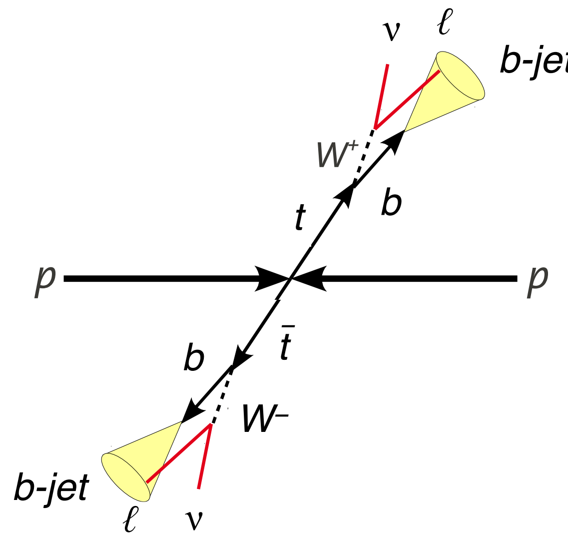
Background

- continuously falling function

Signal

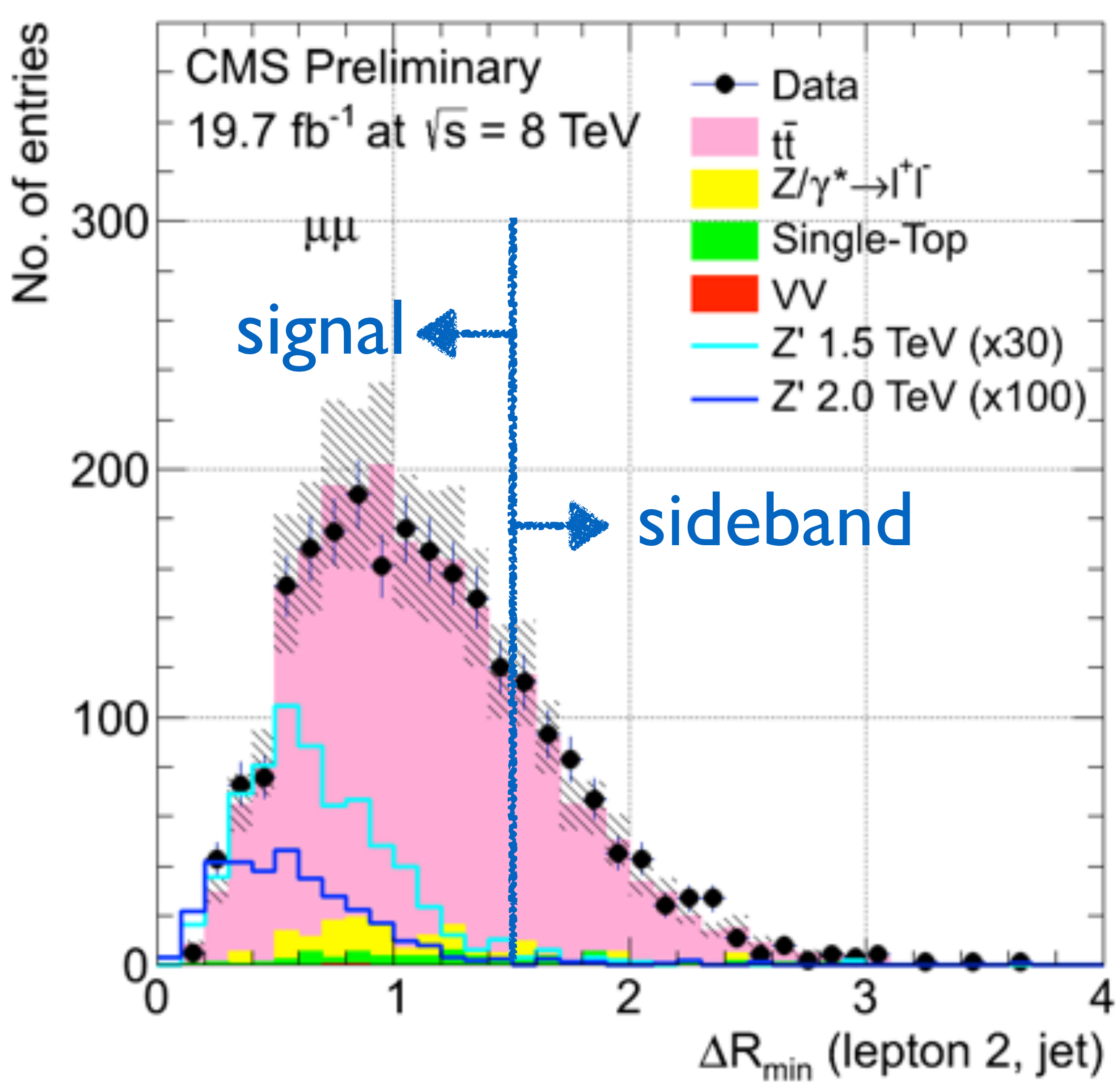
- fit to MC templates

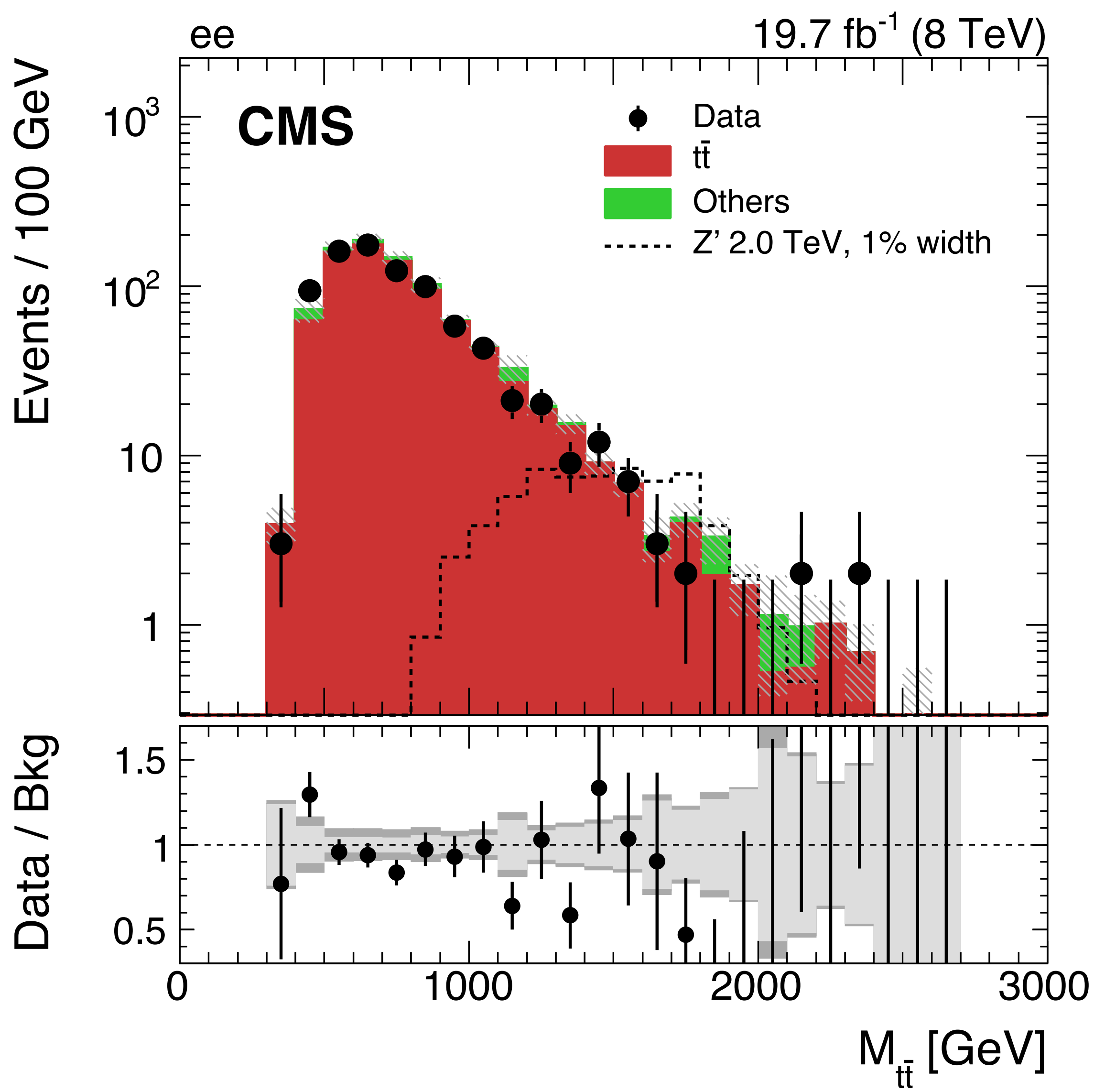
Z’→$t\bar{t}$ Dilepton



Selection of two non-isolated leptons (ee, eμ, μμ)

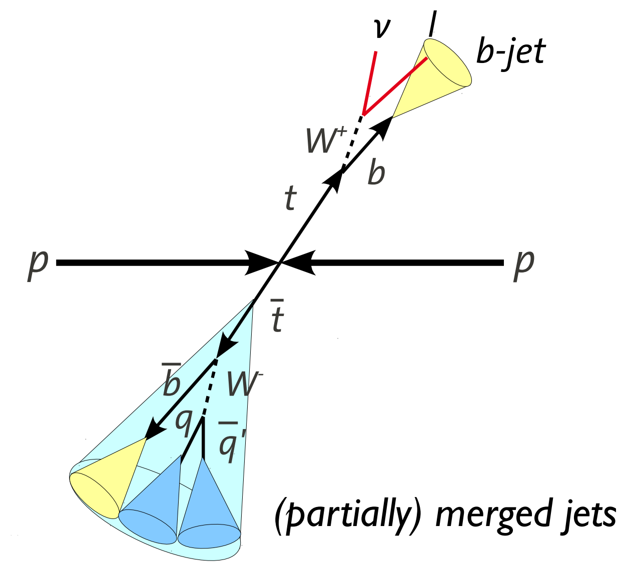
- 1 tight or 2 loose b-tagged jets
- control $t\bar{t}$ background in sideband region, defined by $\Delta R_{min}(\ell_2,\text{jet}) > 1.5$

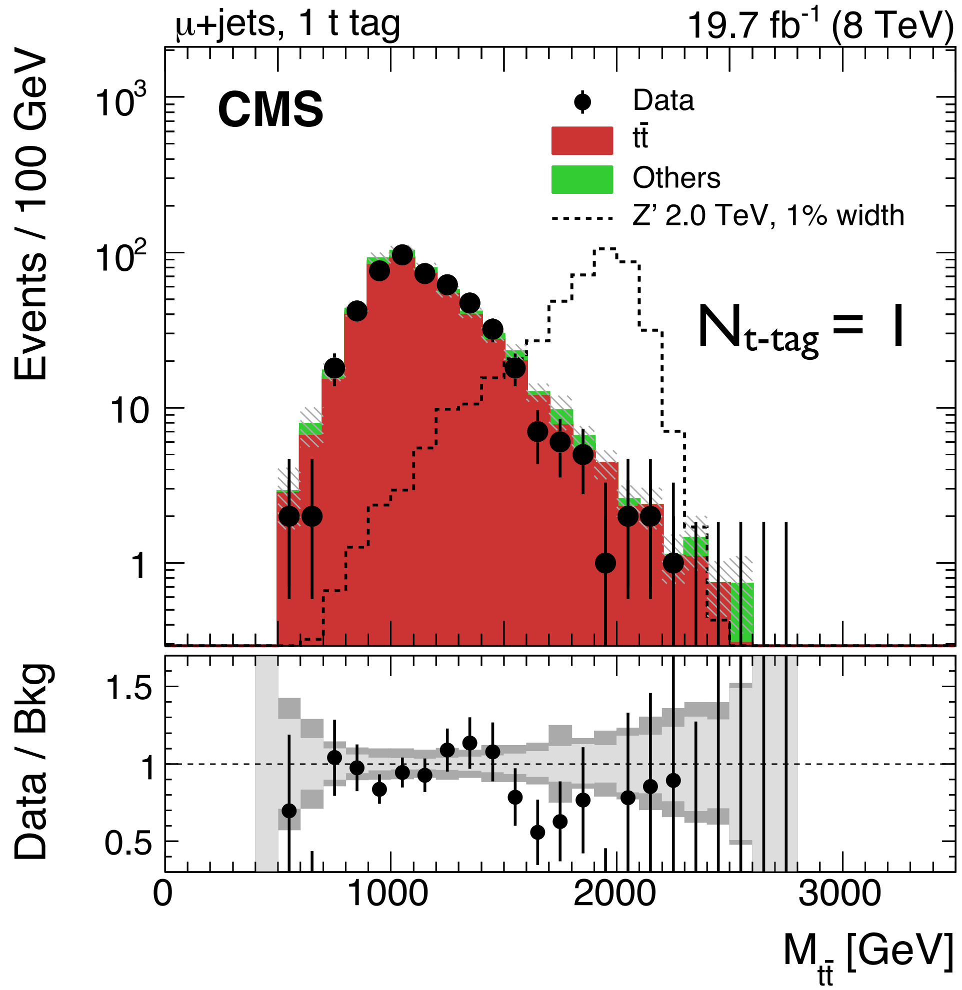


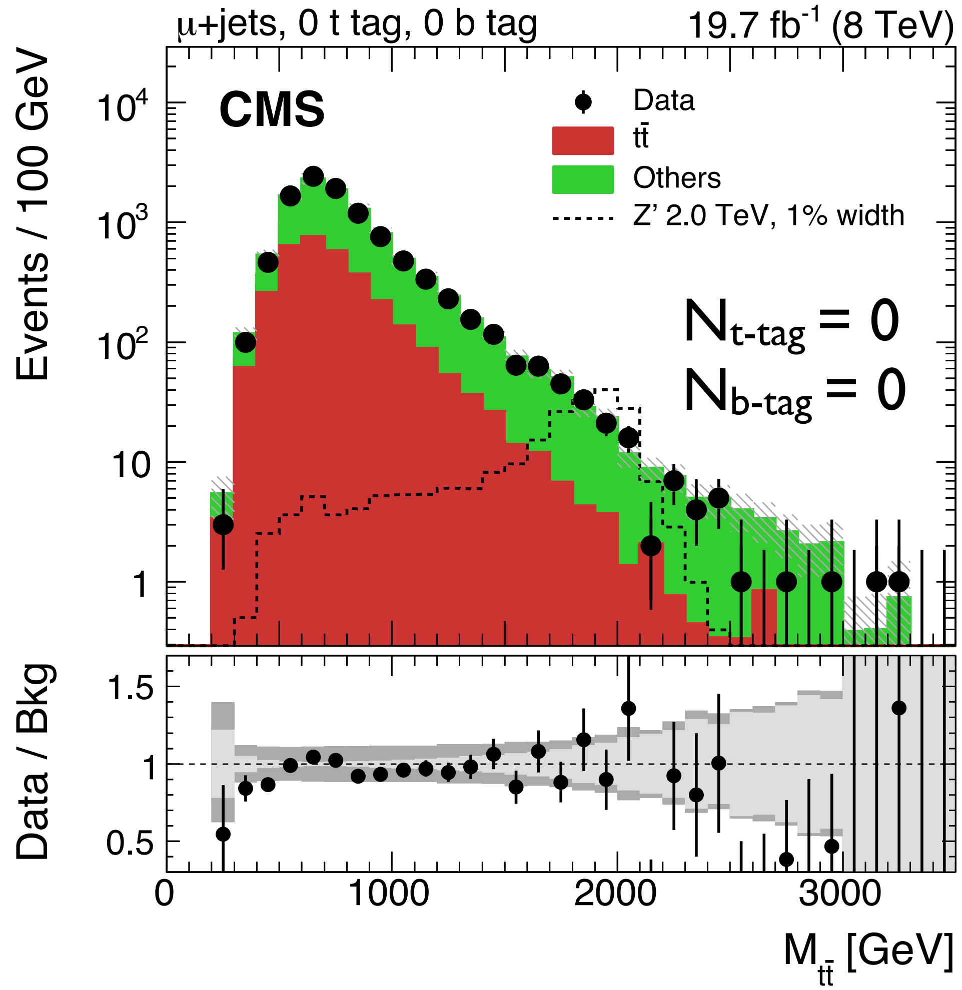


Z'→$t\bar{t}$ ℓ+Jets

- Cascading selection with non-isolated lepton
  - highly boosted events with 1 CMS t-tagged jet
  - χ^2 discriminator: select partially resolved and merged hadronic decays
- Mistag rate of t-tagged jets from W+jets sideband

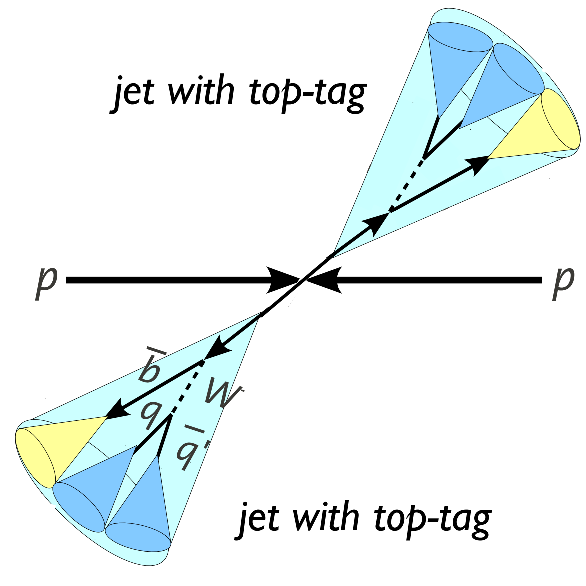




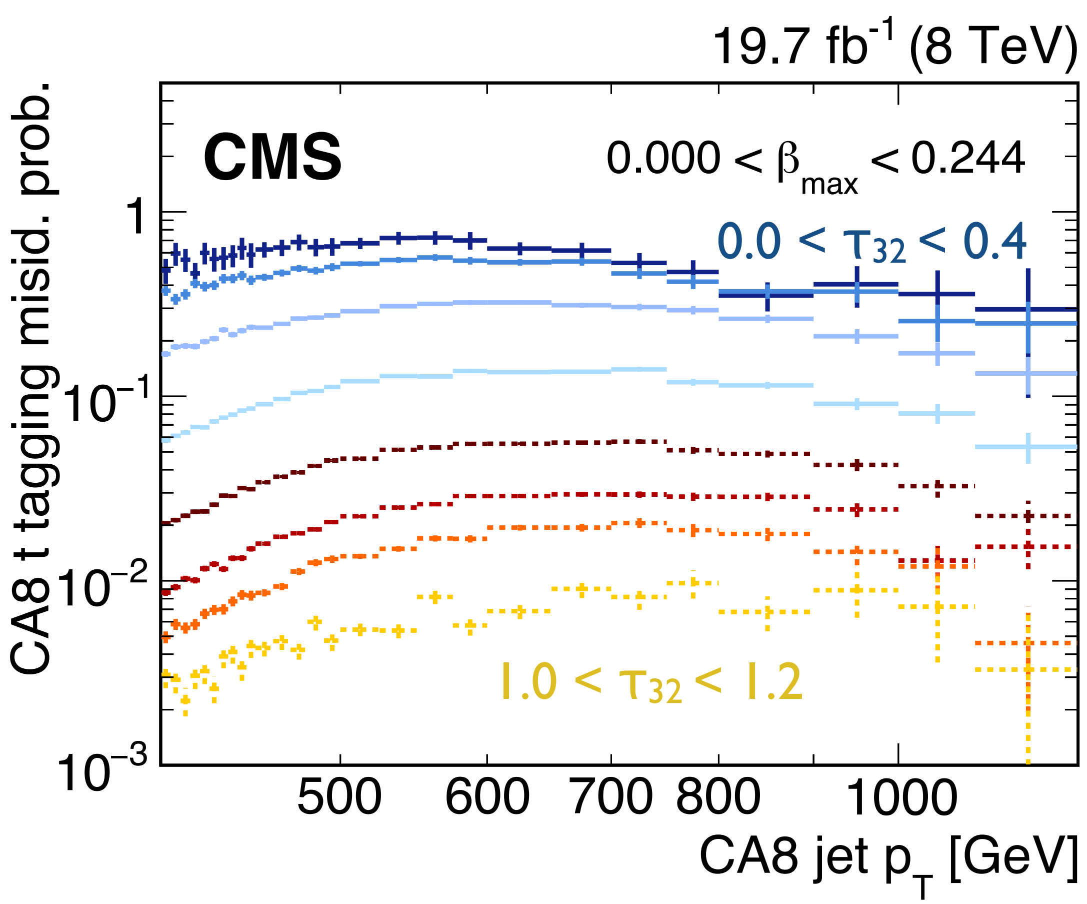


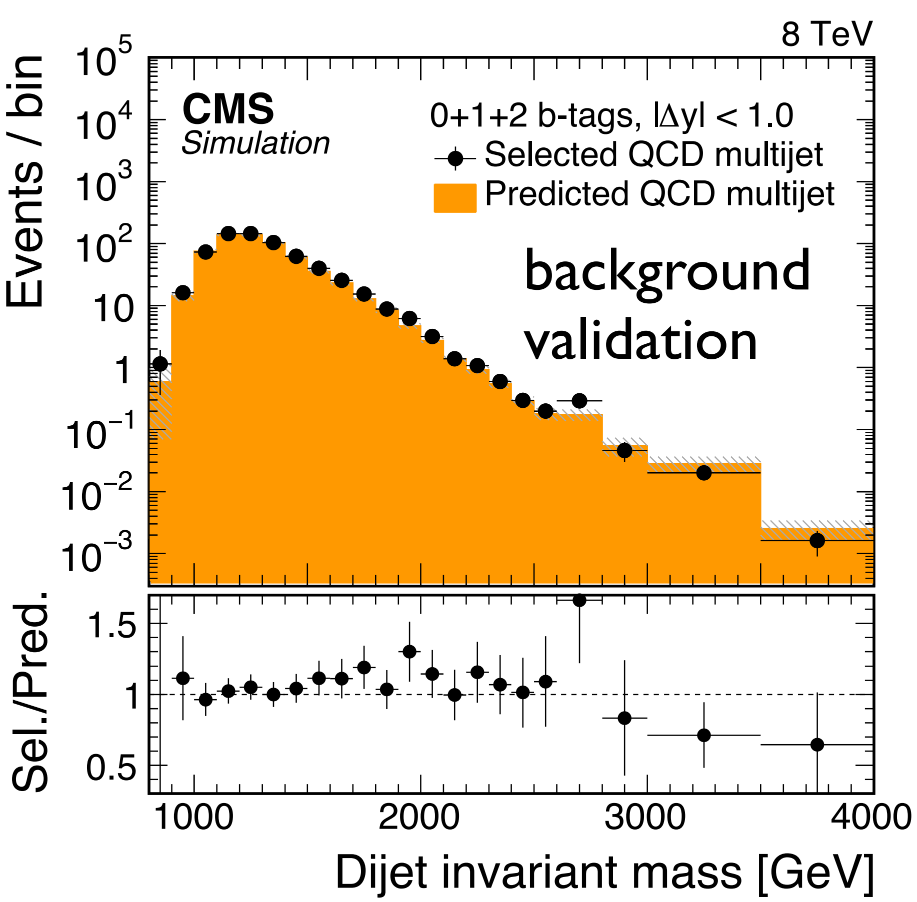
[B2G-13-008, arXiv:1506.03062]

Z'→$t\bar{t}$ Fully Hadronic

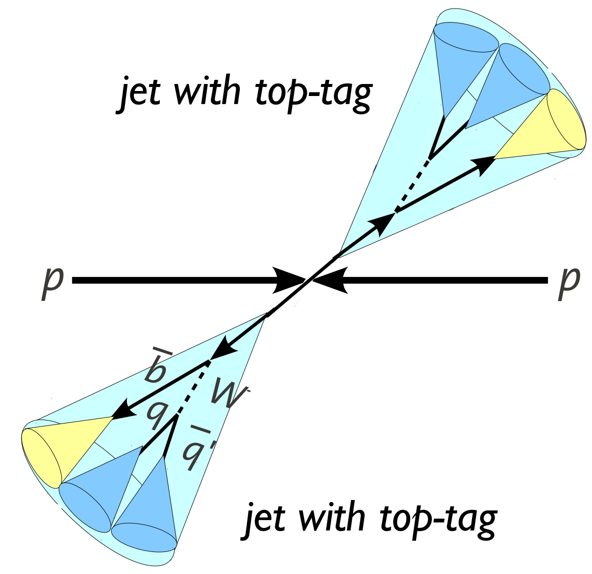


- 2 CA jets, back-to-back
  - R=0.8, p_T > 400 GeV: CMS t tagger
  - R=1.5, p_T > 200 GeV: HEPTopTagger
- QCD multijet background estimation from mistag rate in sideband region (inverted mass criteria)
  - mistag rate depends on p_T, τ_{32} and b-tag discriminator

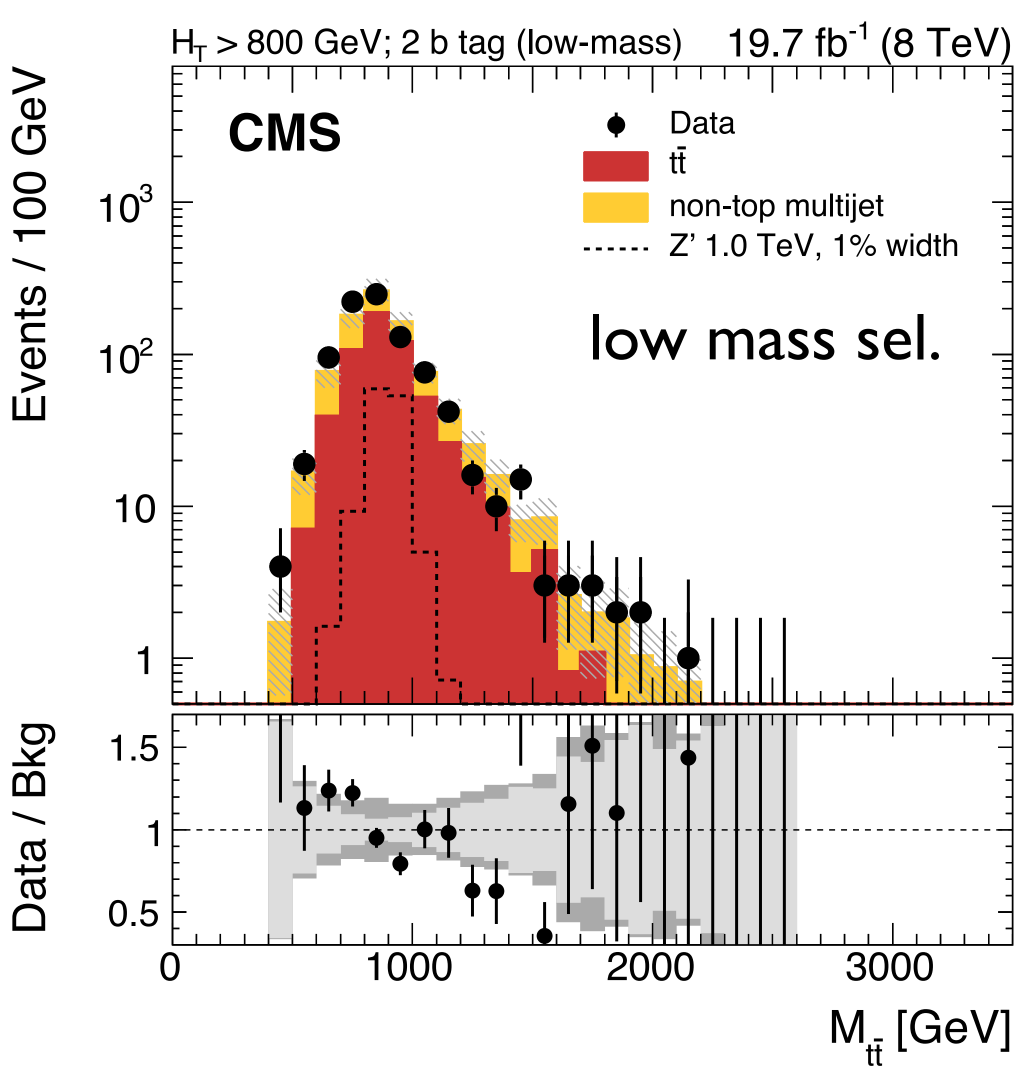


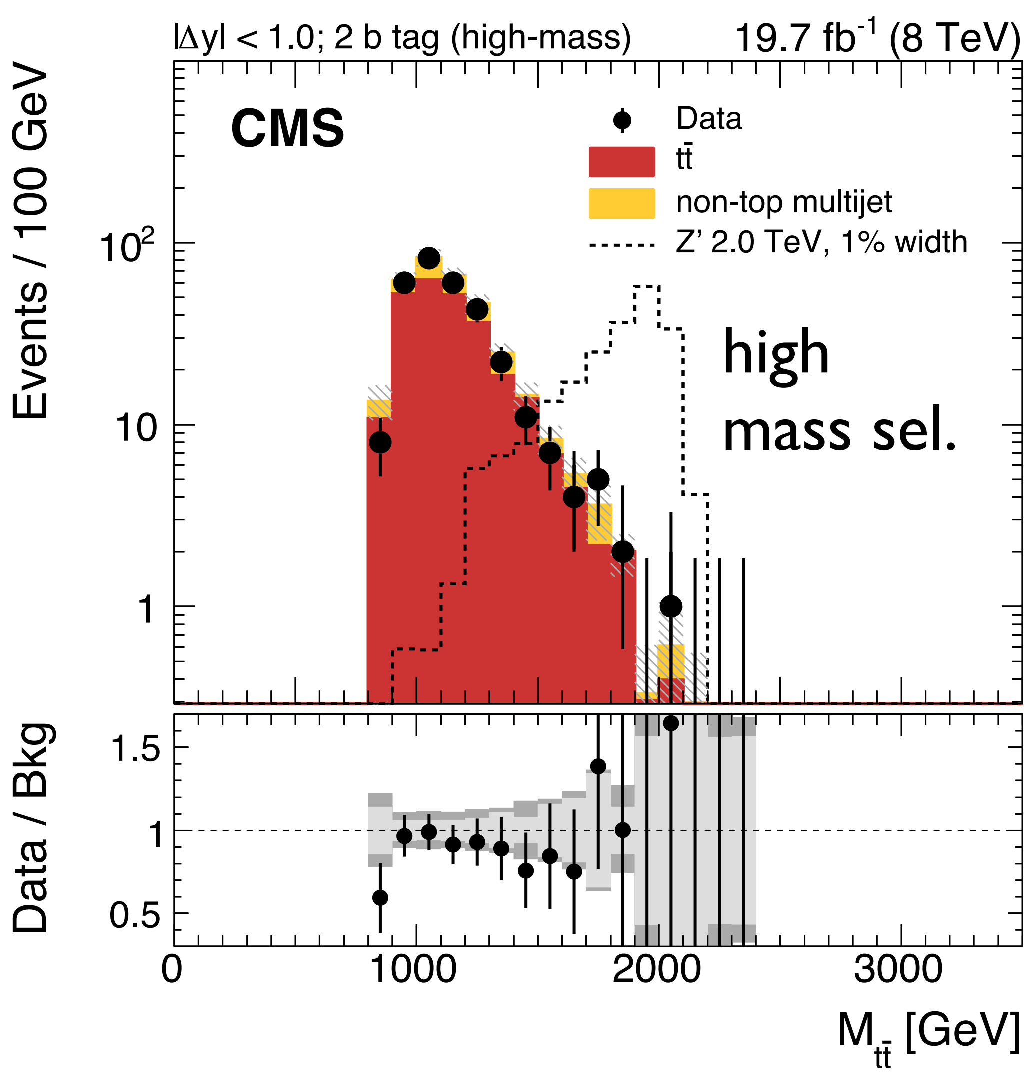


Z'→$t\bar{t}$ Fully Hadronic



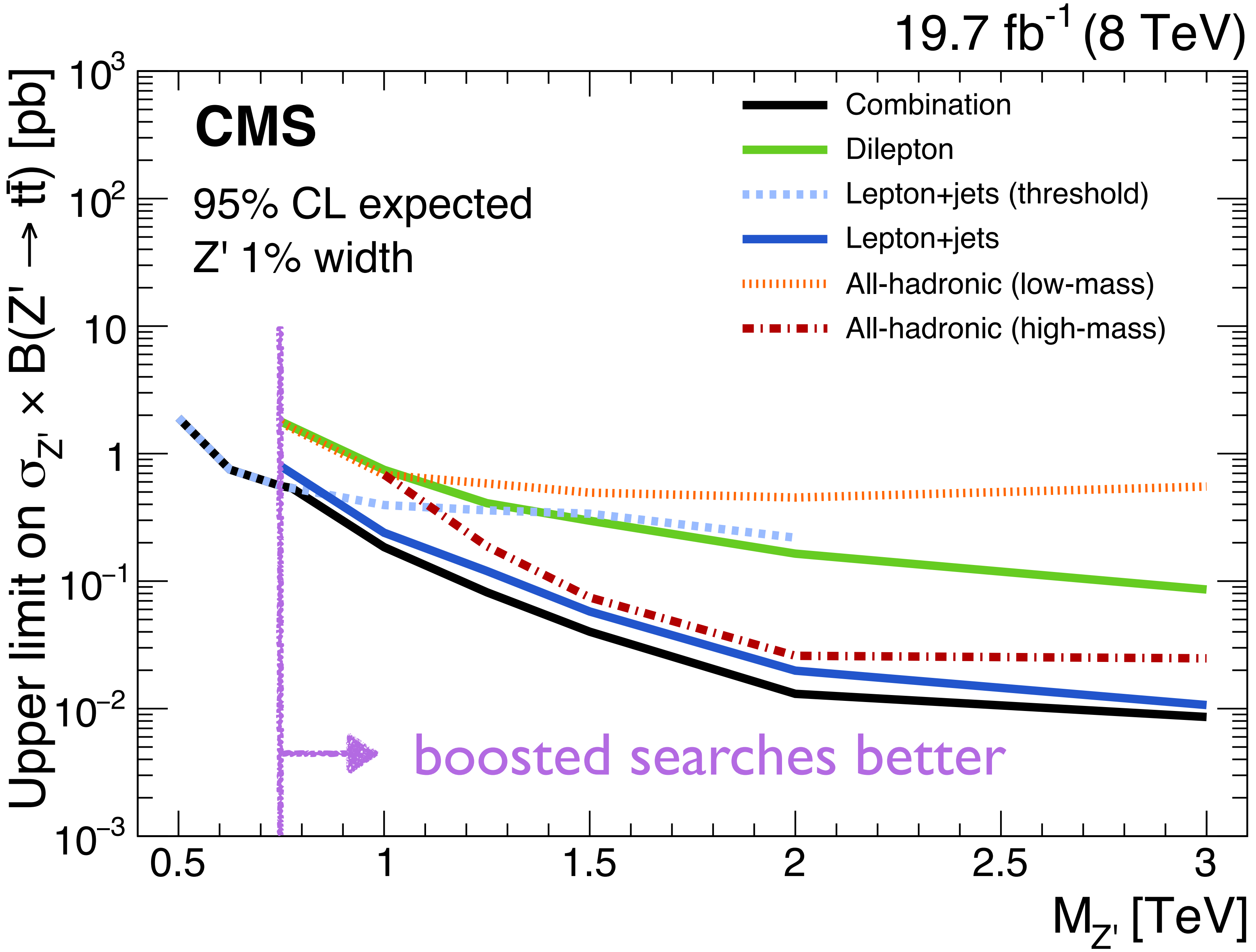
- Categorization of events
  - low and high mass, H_T, $|\Delta y|$ and N_{btag}
- Estimation of t-tagging efficiency correction
  - combined maximum-likelihood with lepton+jets channel





Z'→$t\bar{t}$ Combination

Channels contribute to sensitivity in different mass regions



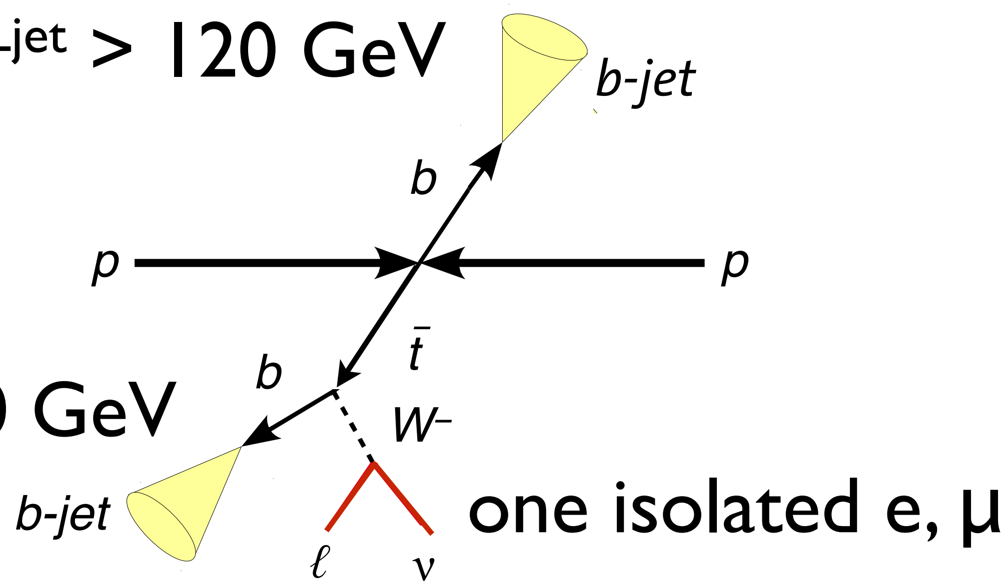
Observed limits: no significant deviations from expected

Exclude $g_{KK} \rightarrow t\bar{t}$ for M_{gKK} < 2.8 TeV (2.7 expected)

W'→$\bar{t}$b ℓ+Jets Resolved

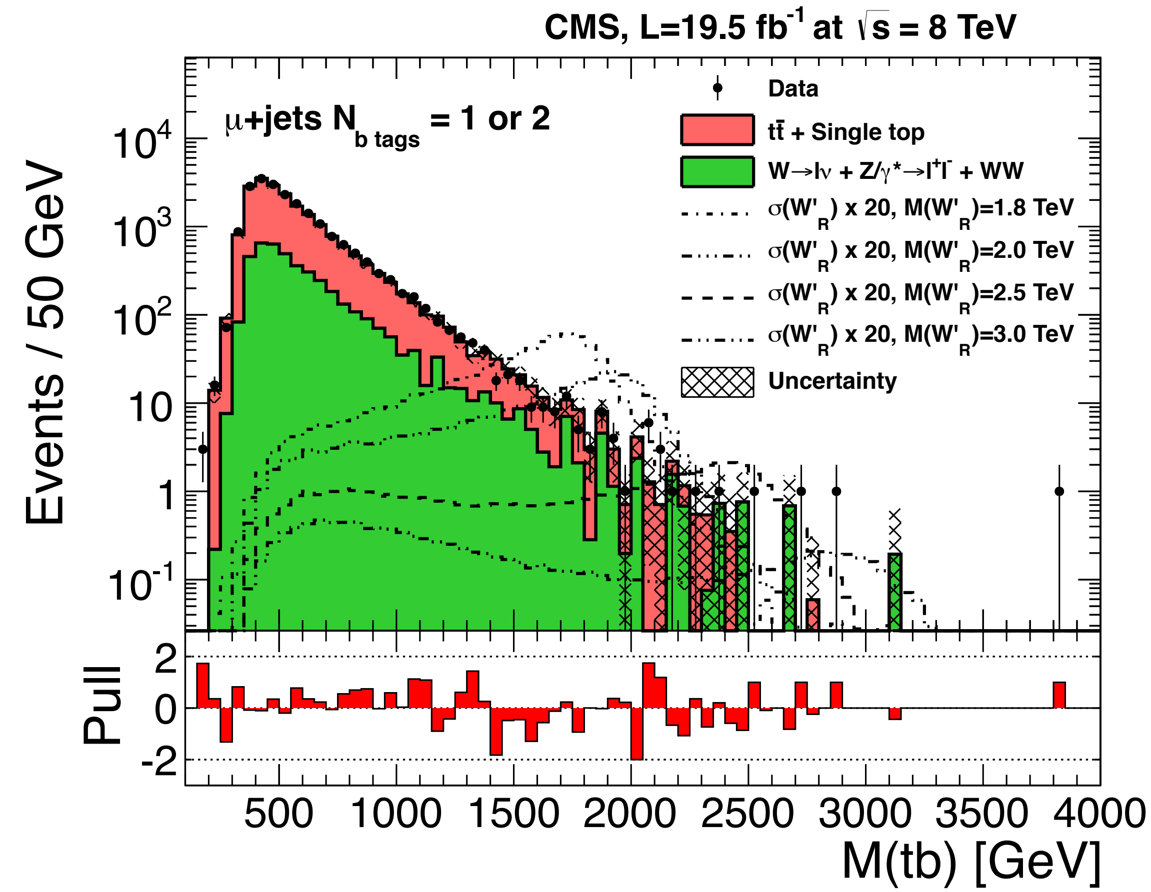
$P_T^{jet} > 120$ GeV

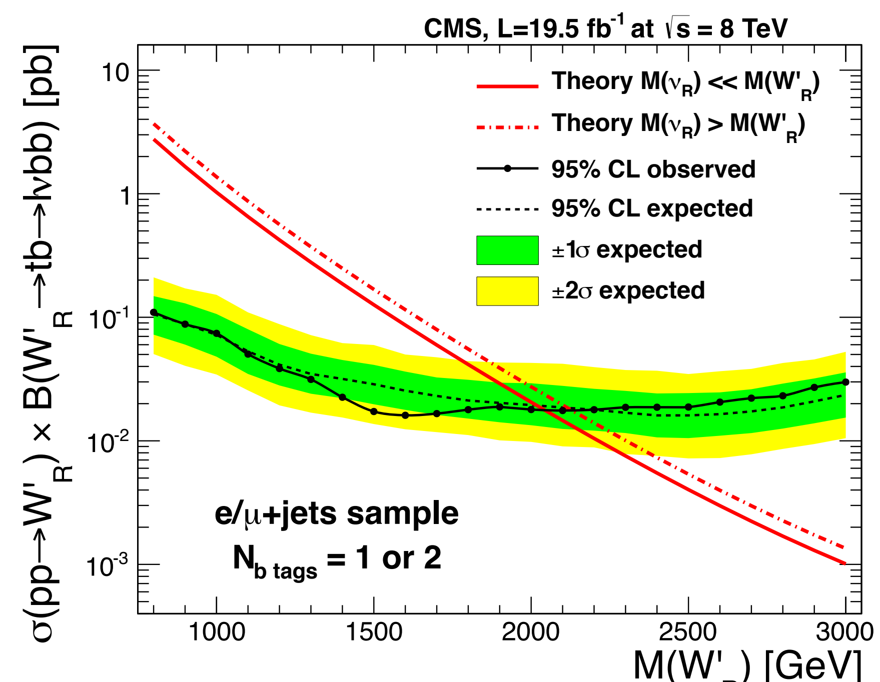
$P_T^{jet} > 40$ GeV



$P_T^{top} > 85$ GeV

$130 < m_{top} < 210$ GeV





Background prediction

- Verified in sideband regions for W+jets and $t\bar{t}$

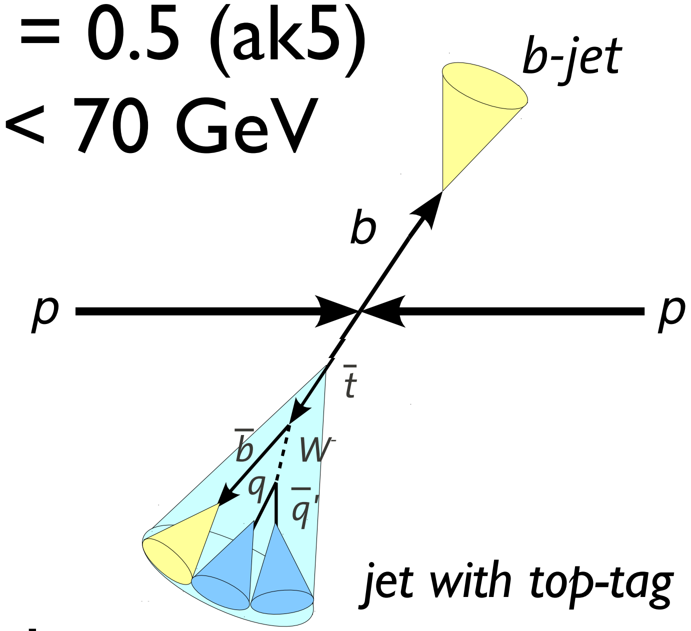
Exclusion limits

- M(W'$_R$) > 2.03 TeV (2.09 TeV expected)
- Limits for left- and right-handed couplings

[B2G-12-009, arXiv:1509.06051]

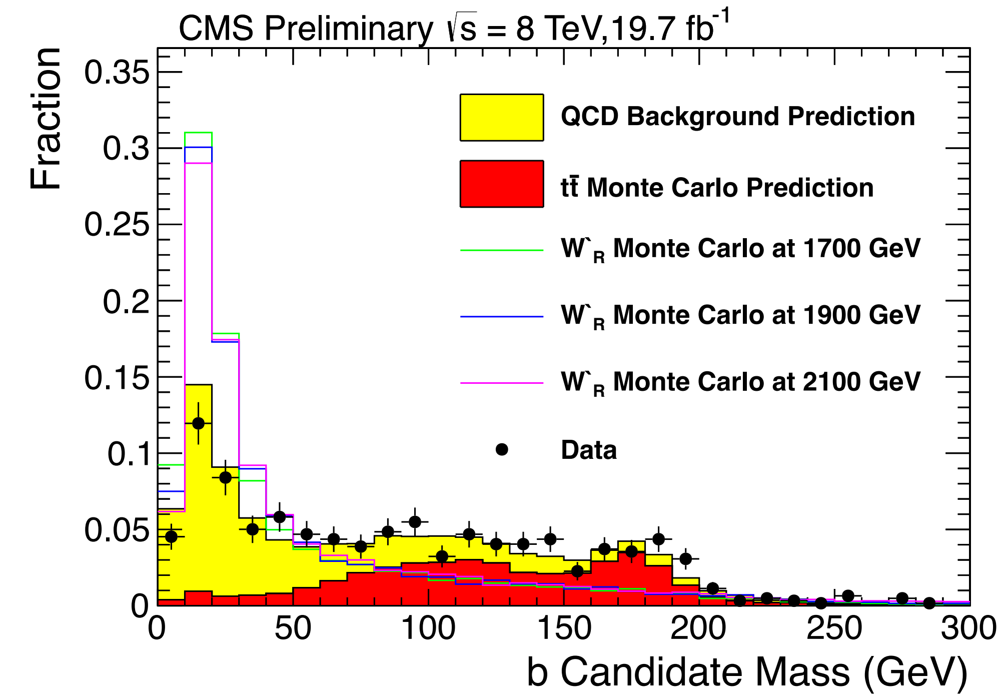
W'→t̄b Fully Hadronic

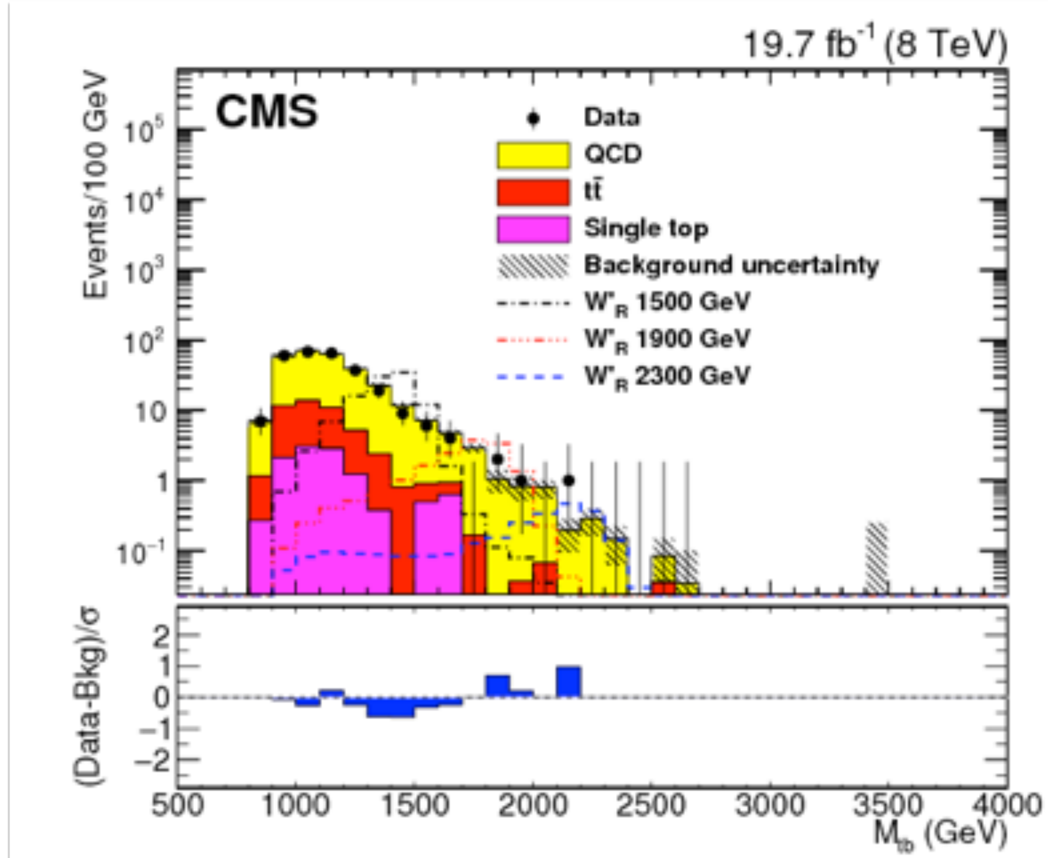
1 anti-k_T jet R = 0.5 (ak5)
b-tag and m_{jet} < 70 GeV



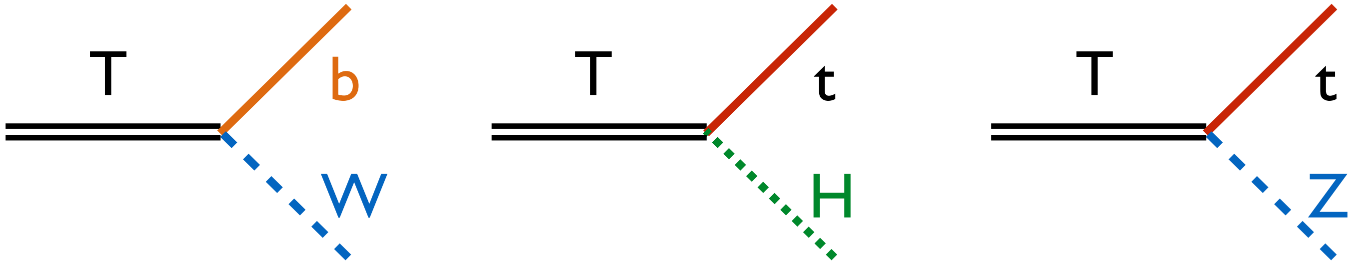
1 CMS t-tagged jet:
p_T > 450 GeV, τ_{32} < 0.55, subjet b-tag

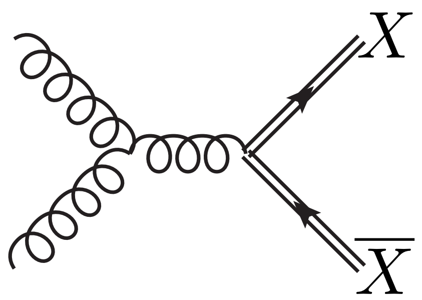
- QCD multijet background from sideband
  - $N_{subjets}$ < 3, no b-tag on ak5 jet
  - other kinematics unchanged
- Similar sensitivity as l+jets channel
- Combination with lepton+jets channel





Vector-like Quarks

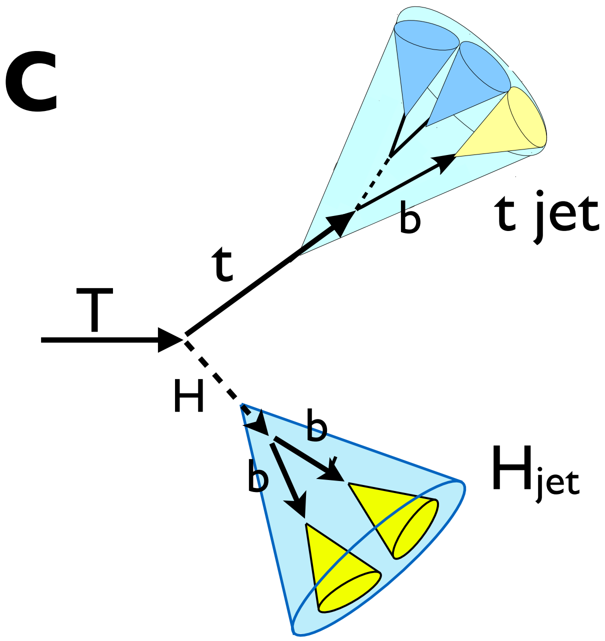




QCD pair-production
dominant at $M_X \lesssim 1$ TeV

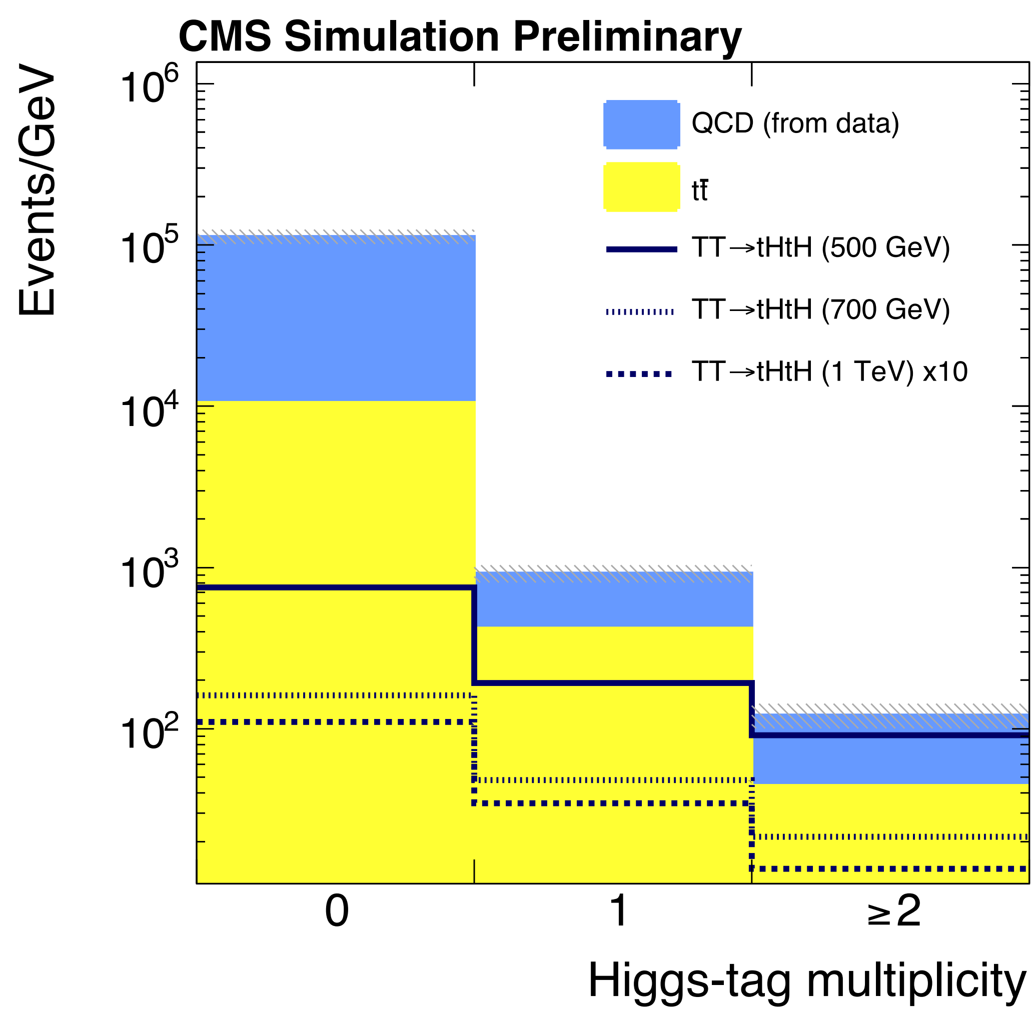
[B2G-14-002, arXiv:1503.01952]

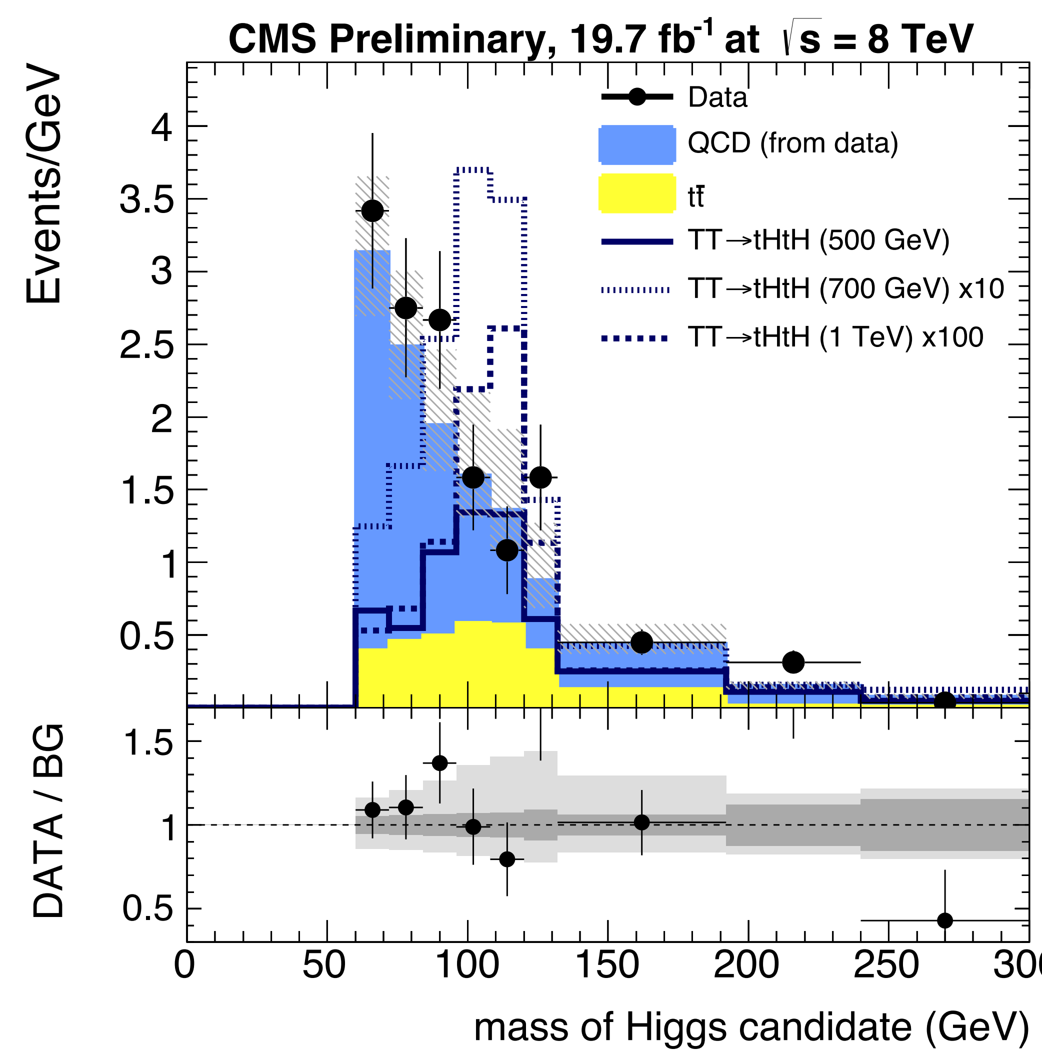
T → tH Fully Hadronic



All-hadronic analysis in t+H channel

- Special substructure analysis
  - 1 HEP top-tagger jet and 1 or 2 H→b$\bar{b}$ jets
  - Analysis possible because of subjet b-tagging

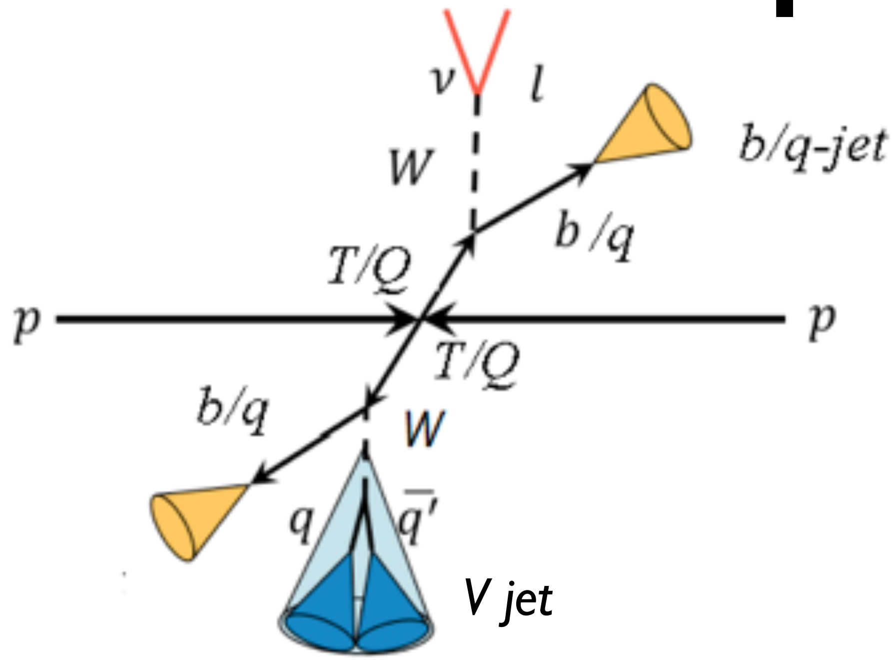


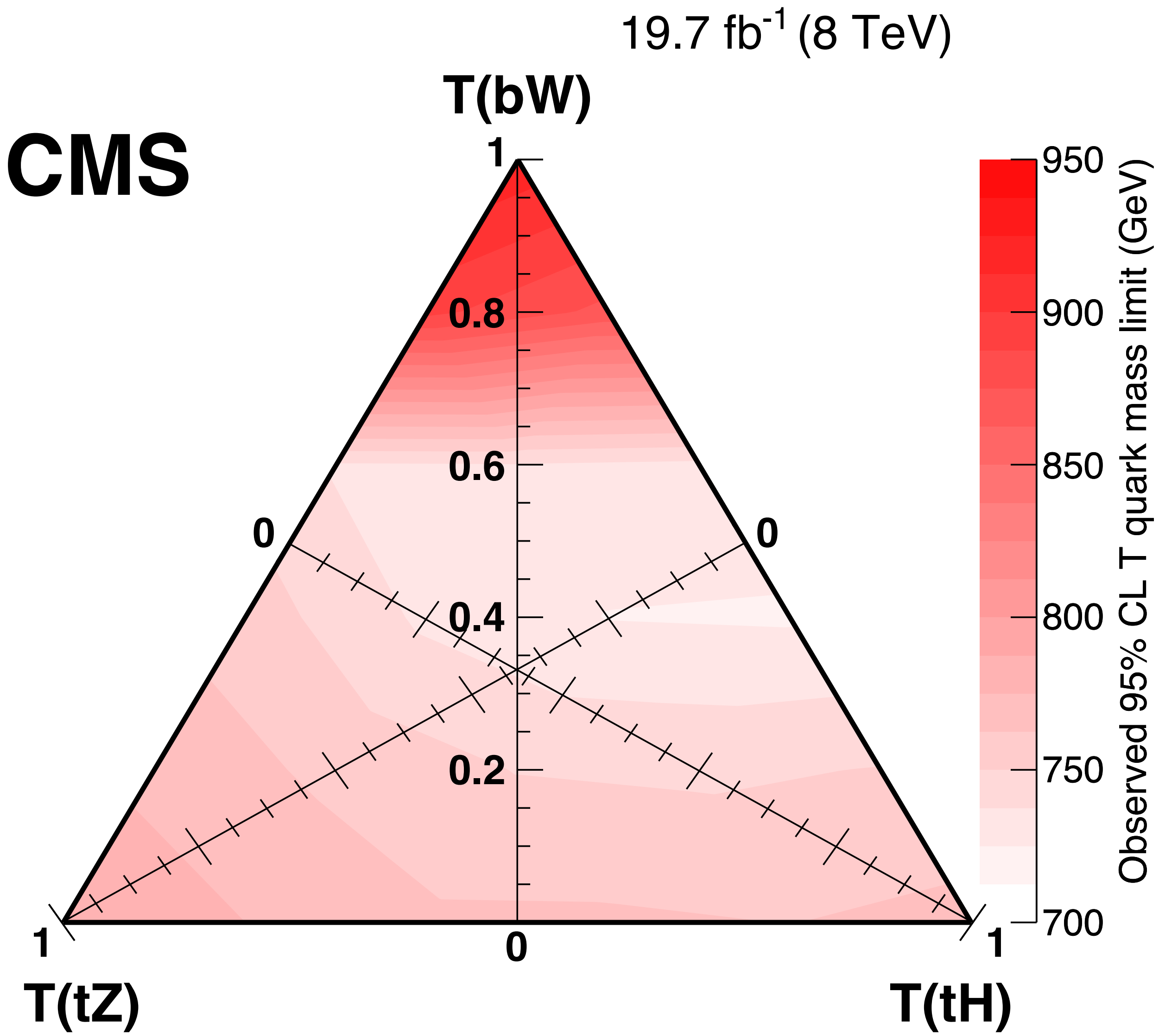


- Exclusion limits: M_T < 747 (701) GeV for 100% BR T→t+H

[PAS B2G-12-013, PAS B2G-12-017, B2G-12-015 PLB 279, 149 (2014), B2G-13-005, arXiv:1509.04177]

T → bW, tZ, tH





Inclusive lepton analyses

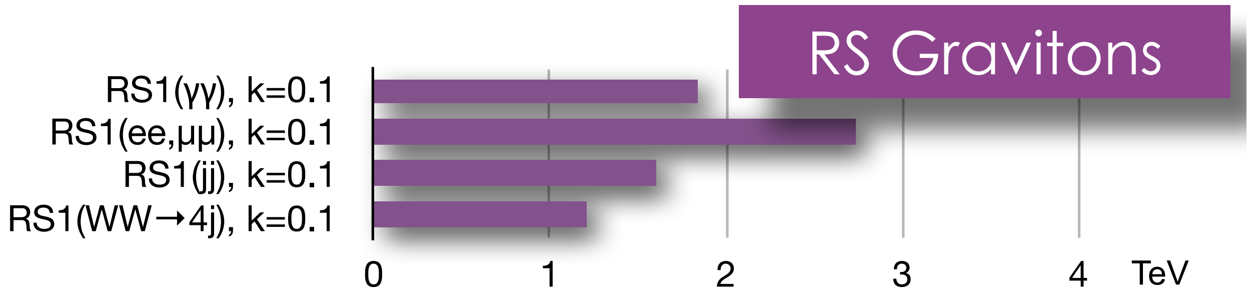
- Single-lepton channel
  - Hadronic W-tag and top-tagging
  - Kinematic fit for reconstruction
  - BDT for best overall sensitivity
- Multi-lepton channel
  - Counting experiment in high S_T region

All-hadronic analysis

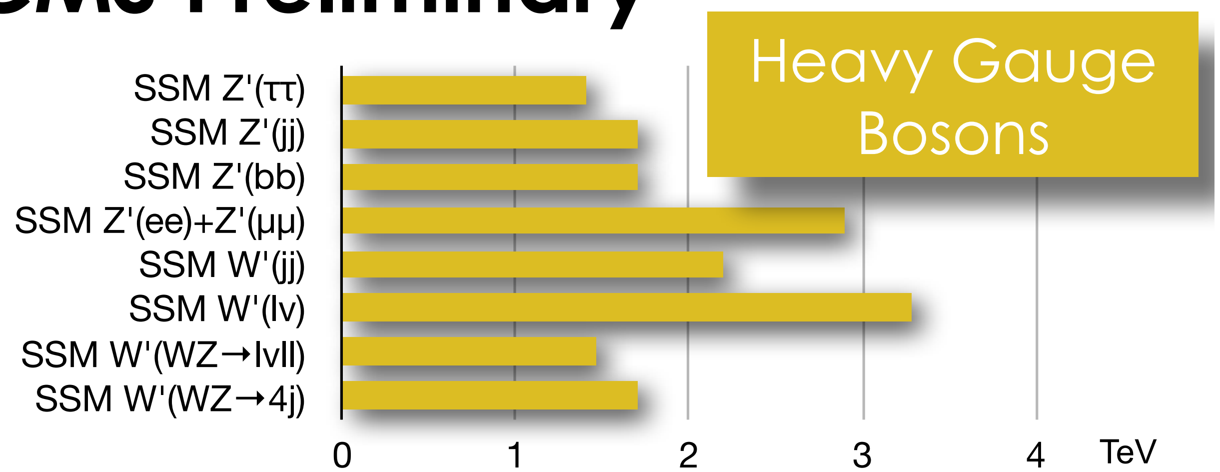
- 2 V-tagged jets, 1 or 2 b-tagged jets

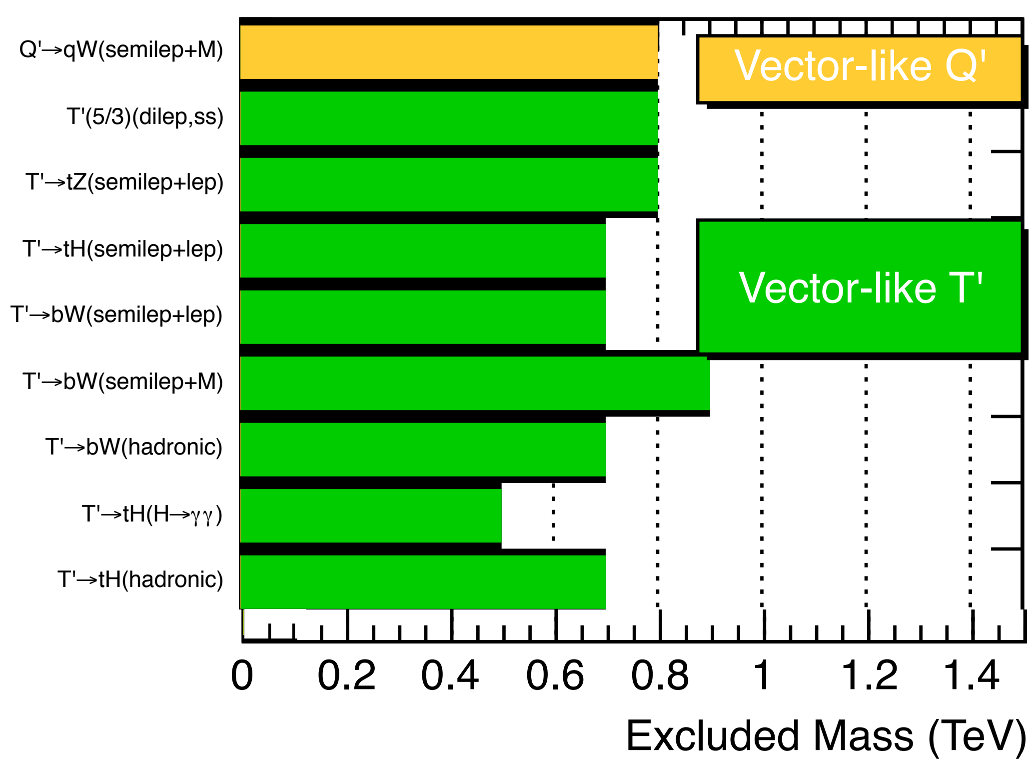
- Combination: sensitivity for bW, tZ and tH final states
- Exclusion limits: between 790 and 890 GeV

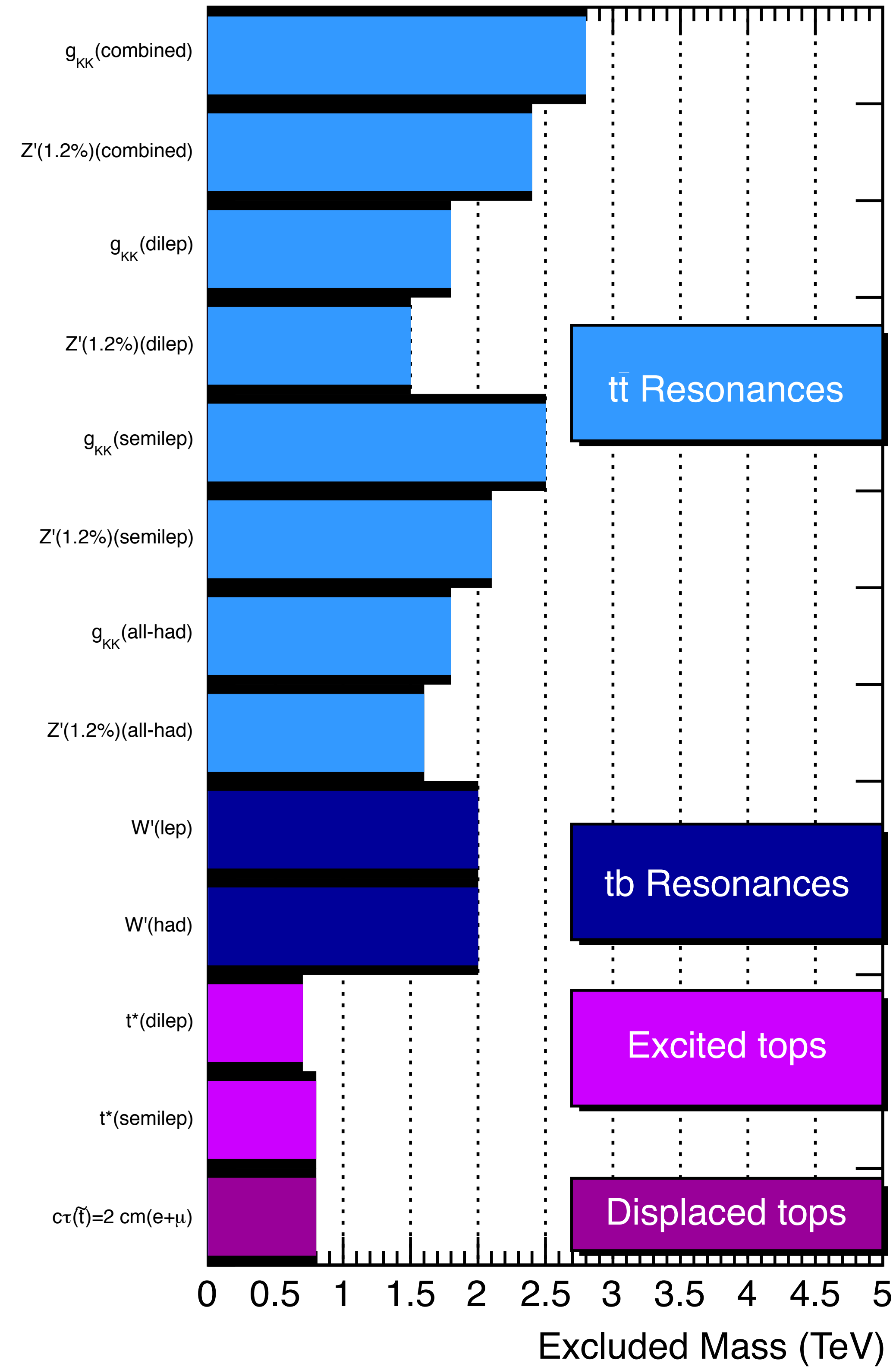
Harvest of Run 1



CMS Preliminary





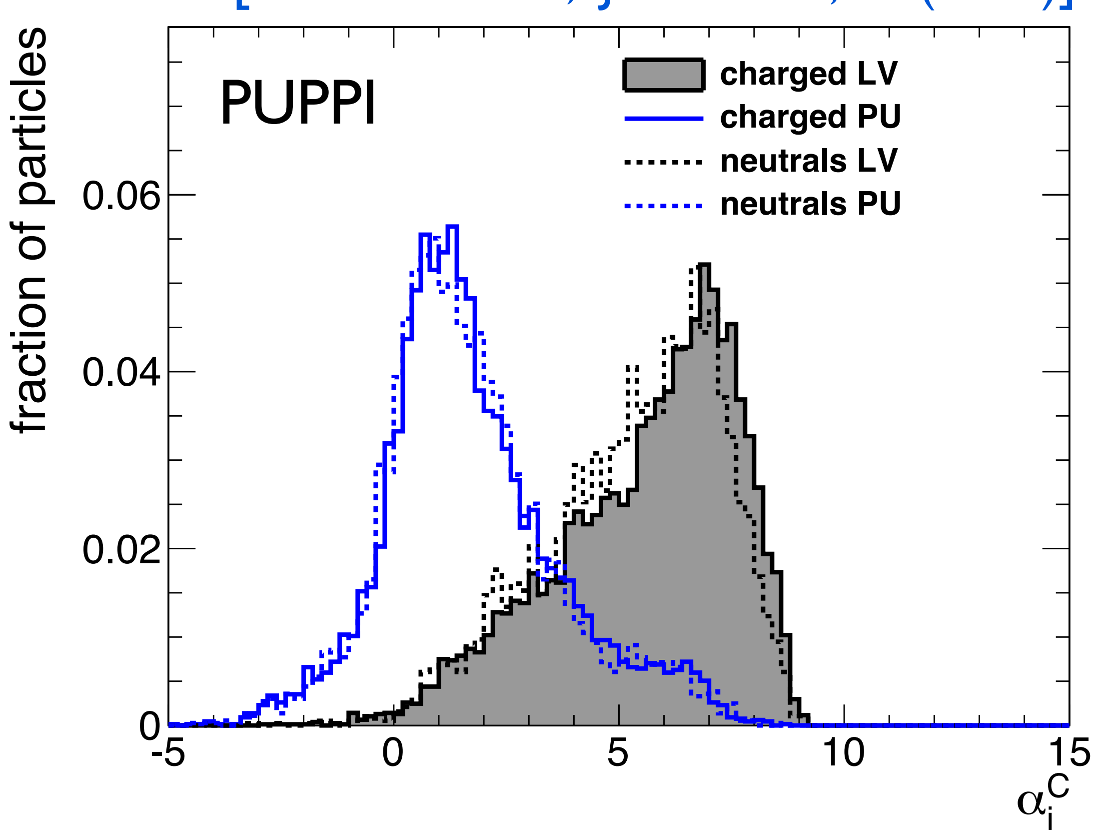


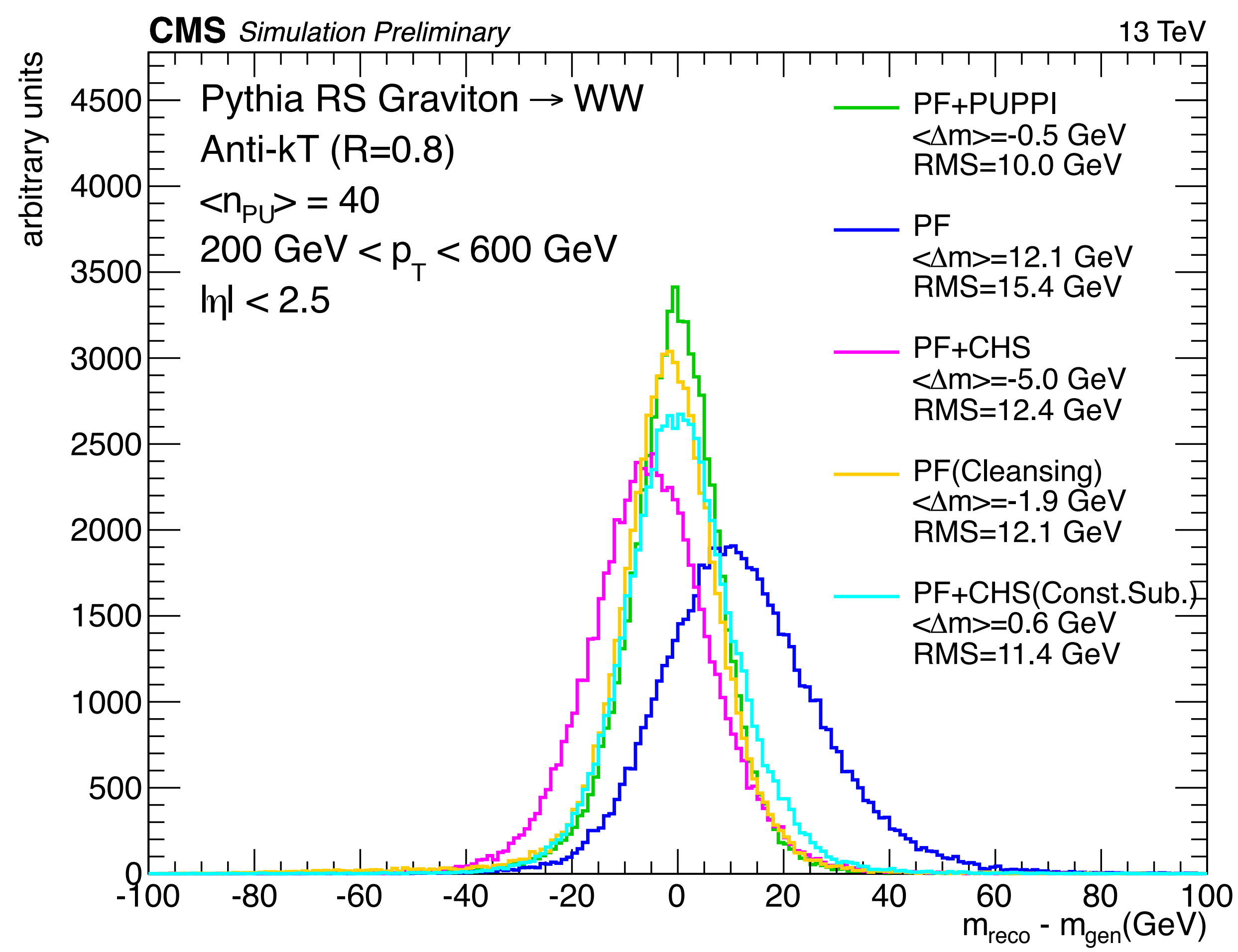
Outlook for Run 2

PU in Run 2

- Various methods are studied for pileup mitigation in Run 2
- Example: PUPPI (PileUp Per Particle Identification)
  - Use knowledge of origin of PU charged particles to deduce information on neutral PU component
  - Reweight neutrals according to their probability to originate from PU
- Intuitive correction for jet substructure observables

[Bertolini et al., JHEP 1410, 59 (2014)]

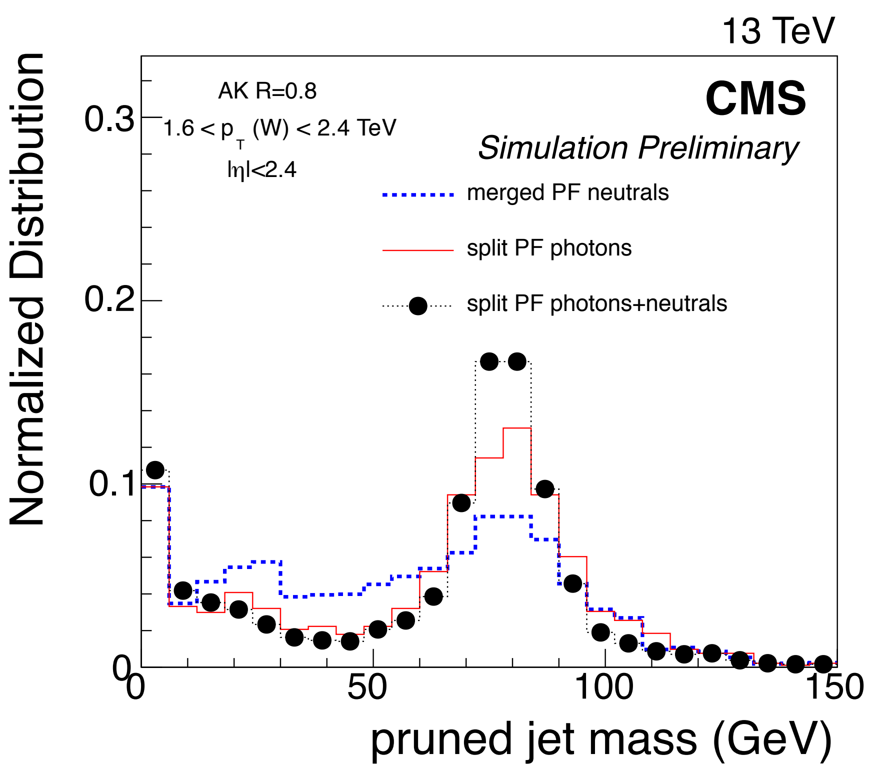


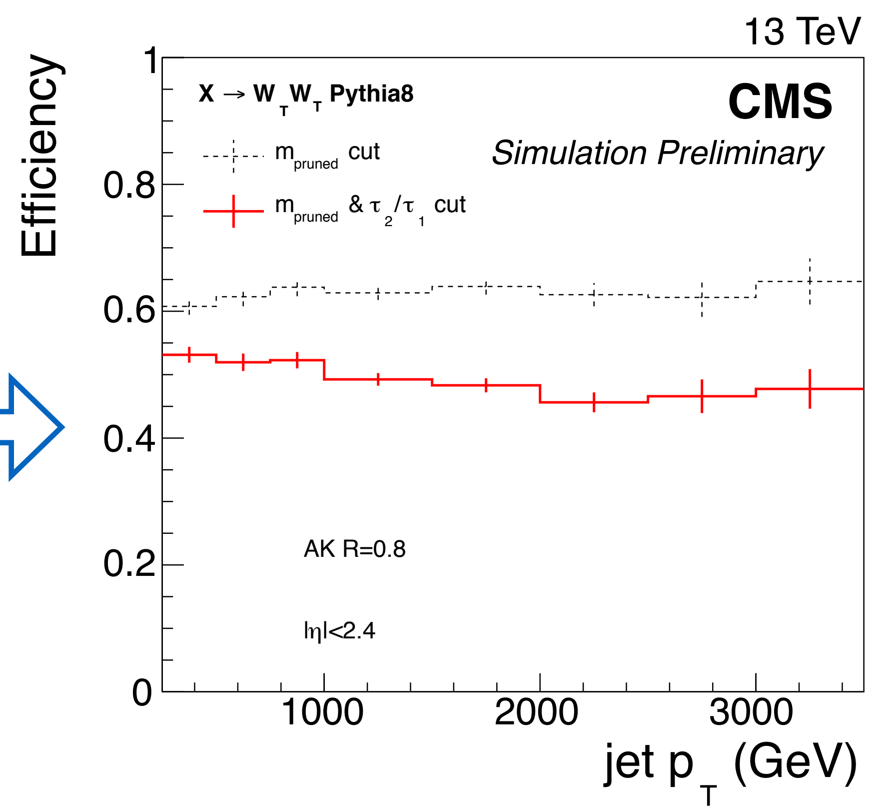


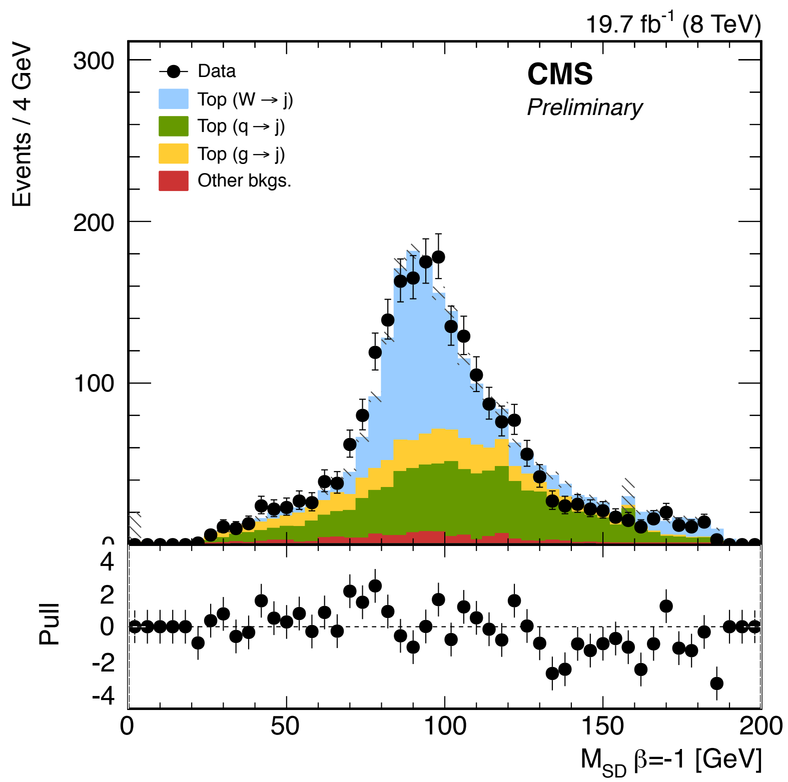
[PAS PAS JME-14-002]

V Tagging in Run 2

- Jet p_T > 1.5 TeV: tracking resolution and efficiency degrade, such that ECAL and HCAL dominate jet substructure reconstruction
- Extend particle flow algorithm
  - use fine ECAL granularity to determine multiplicity of hadrons in jet
  - Split hadron excess energy in ECAL+HCAL according to direction and energy distribution of ECAL clusters ("split PF neutrals")
- New tool: Softdrop for mass reconstruction and subjet finding







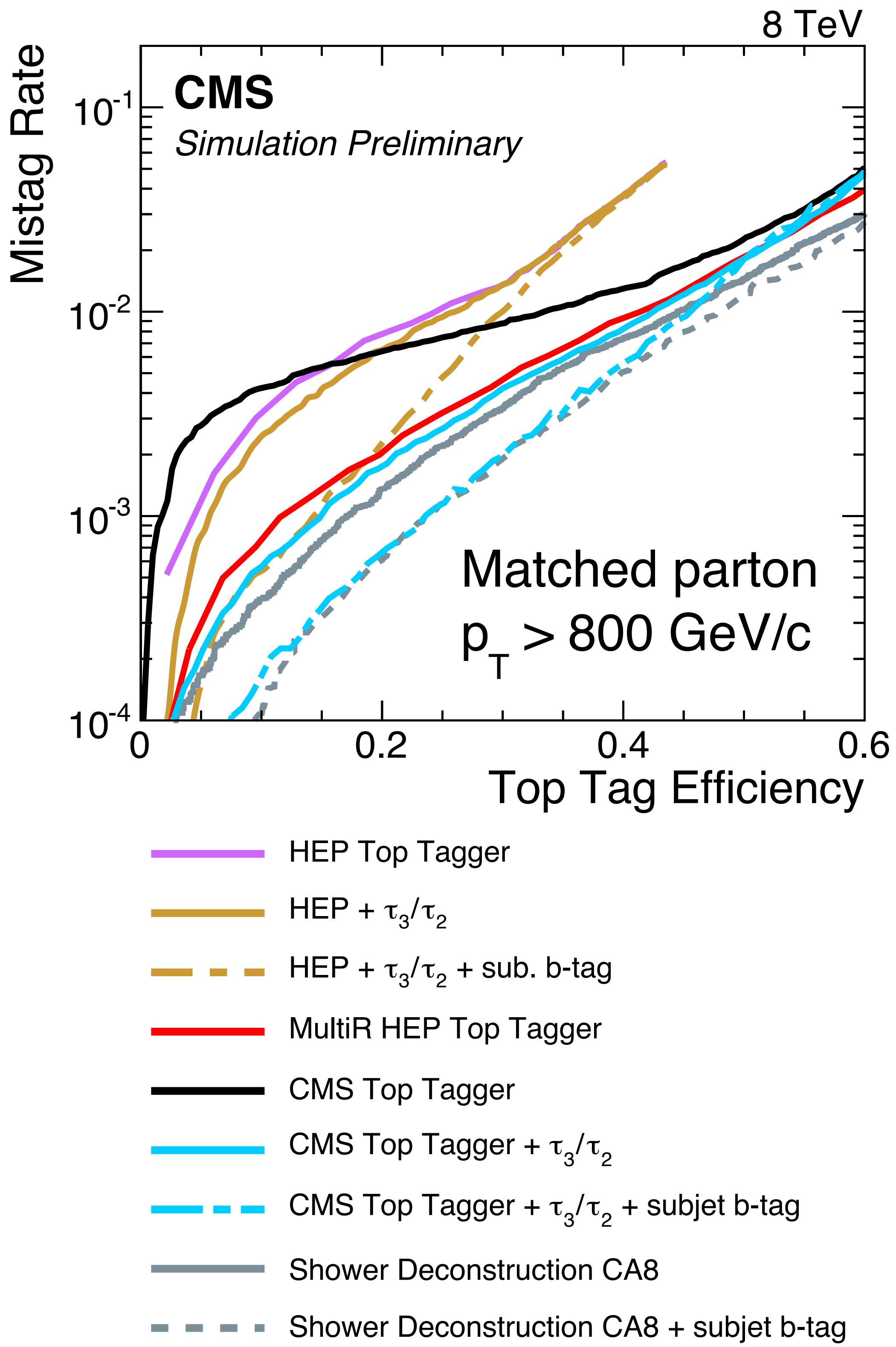
[CMS DP-14-036]

t Tagging in Run 2

New methods and algorithms available

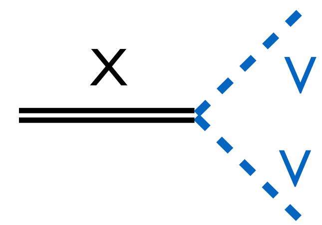
A few examples

- Soft drop for mass and subjet reconstruction
- Shower deconstruction
  - calculate probability for a jet to originate from a top quark decay
    - using QCD splitting functions
    - similarity to matrix-element method
- MultiR HEP Top Tagger
  - shrink effective cone size of jet, adds additional separation power
- Improvements in subjet b tagging
  - Secondary vertex finding independent of jets [CMS DP-14-031]

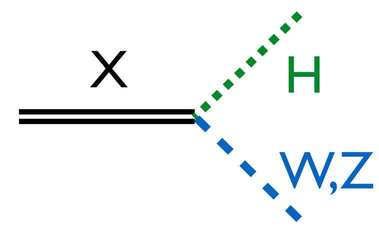


Summary

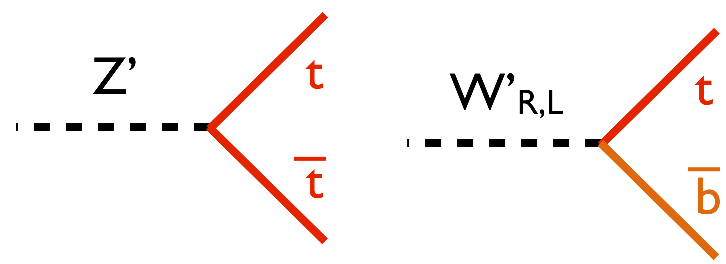
- **Substructure methods crucial for new physics searches**
  - WW, WZ, ZZ Resonances



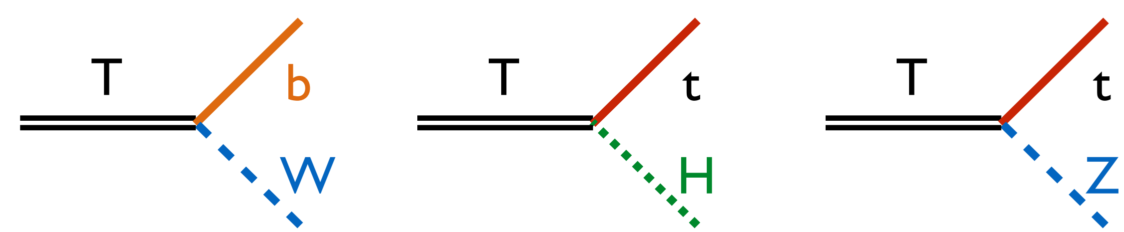
  - WH, ZH Resonances



  - tt and tb Resonances



  - Vector-like quarks



- **Even more important at Run 2**

Conclusion

- Celebrated a huge success not long ago

- Depressing that we did not find anything else?
- We have just started!
- Run 1: only a glimpse into the parameter space that's explorable
- Consider it a 'training run' (for BSM searches)
  - Incredible how much we learned about the tools and techniques
- No one said it would be easy…

Conclusion

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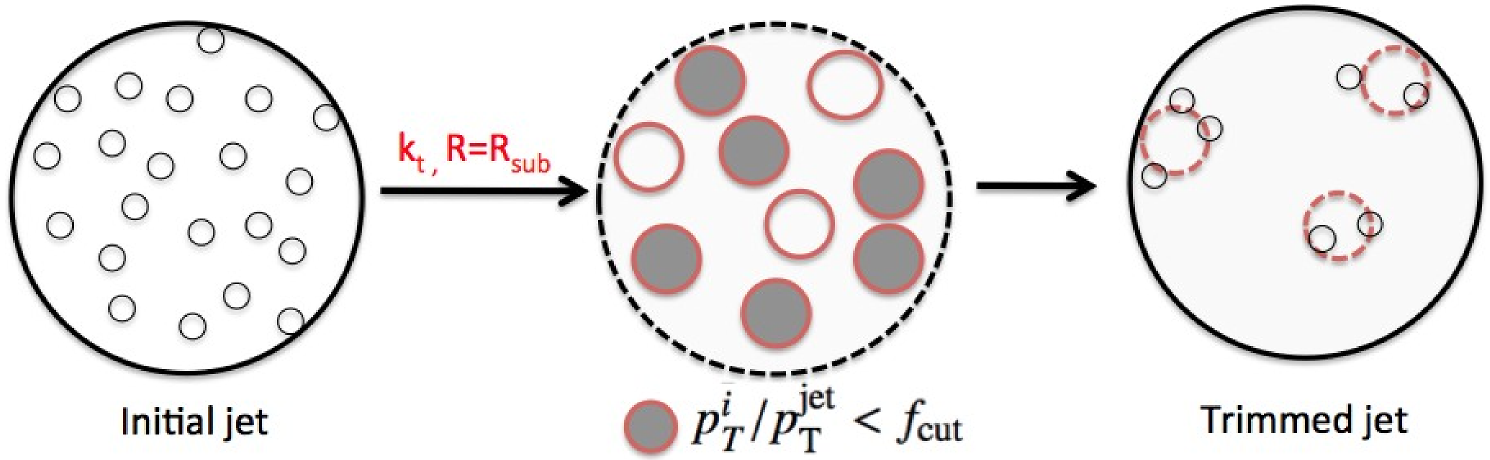
But no one said it'd be this hard
No one said it would be easy
No one thought we'd come this far
[Sheryl Crow, 1993]

Additional Material

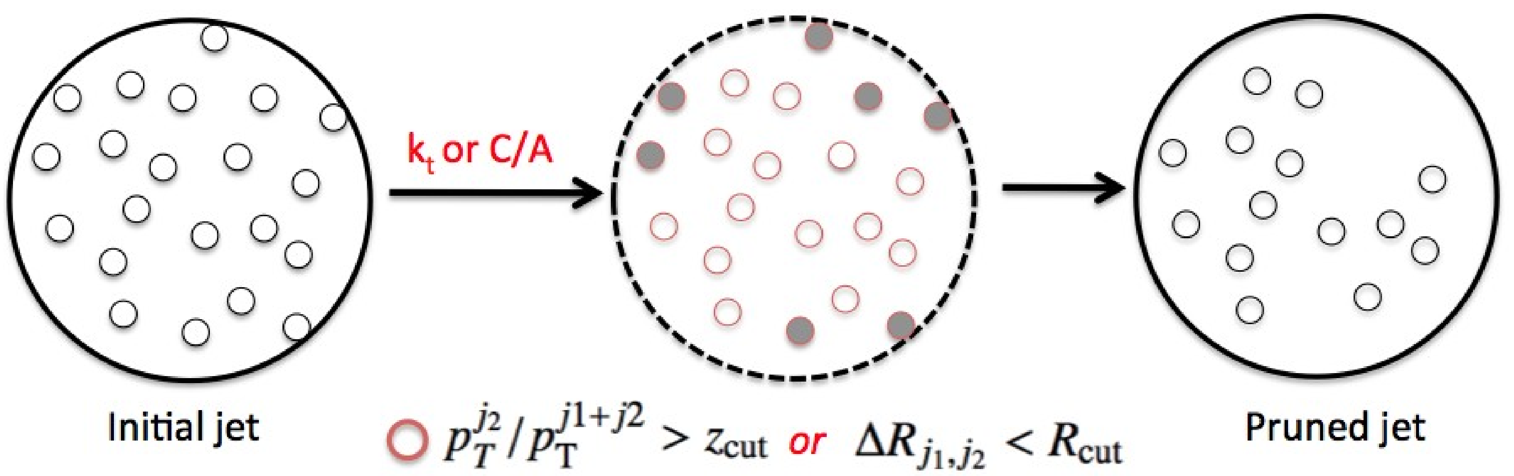
Jet Grooming

- **"Trimming"** http://arxiv.org/abs/0912.1342
  (D. Krohn, J. Thaler, L. Wang)
  - uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_T i$ / $p_T < f_{cut}$ are removed



free parameters:
f_{cut} and R_{sub}

- **"Pruning"** http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)
  - Recombine jet constituents with C/A or kt while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents. Does not recreate subjets but prunes at each point in jet reconstruction

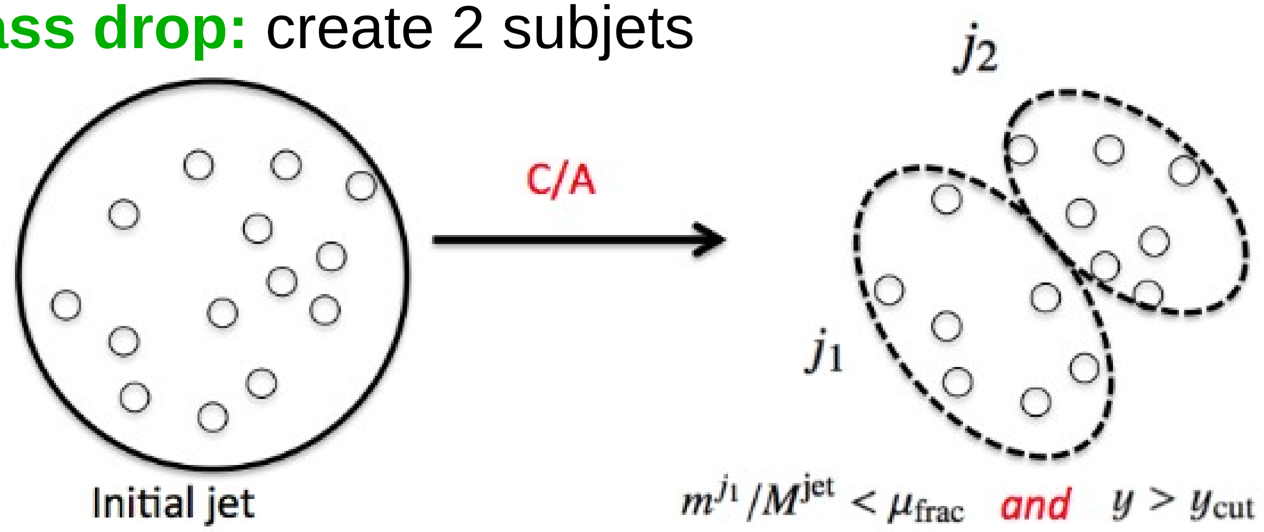


free parameters:
z_{cut} and R_{cut}

Jet Grooming

- **“Mass drop/filtering”** http://arxiv.org/abs/0802.2470
  (J. Butterworth, A. Davidson, M. Rubin, G. Salam)
    - Identify relatively symmetric subjets, each with significantly smaller mass than their sum

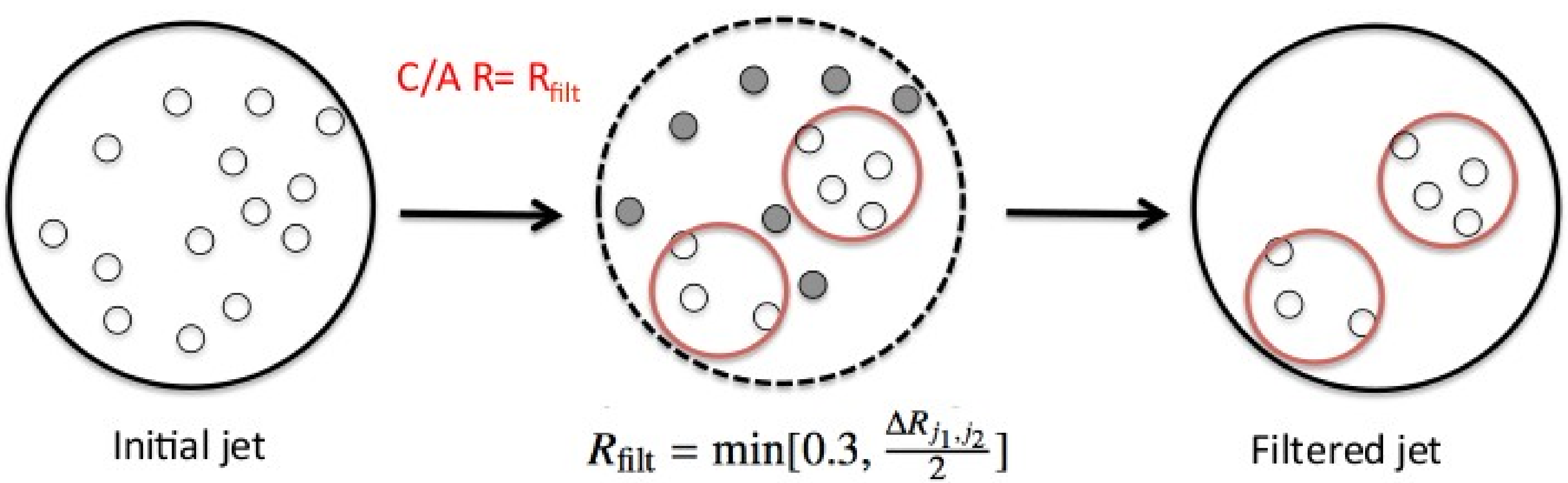
Mass drop: create 2 subjets



$$\frac{\min[(p_T^{j_1})^2, (p_T^{j_2})^2]}{(M^{\text{jet}})^2} \times \Delta R^2_{j_1,j_2} > y_{\text{cut}}$$

free parameters:
μ_{frac} and y_{cut}

Filtering: constituents of j1, j2 are reclustered using C/A



free parameter:
R_{filt}

V+Jets Background in ℓν+Jet and ℓℓ+Jet

- Obtain V+jets background from low mass sideband in M_{jet}
- Shape of M_{VV} extrapolated to signal region using transfer function

$$\alpha_{\mathrm{MC}}(m_{\mathrm{VV}}) = \frac{F^{\mathrm{V+jets}}_{\mathrm{MC,SR}}(m_{\mathrm{VV}})}{F^{\mathrm{V+jets}}_{\mathrm{MC,SB}}(m_{\mathrm{VV}})}$$

advantage: retain sensitivity in tails

- Correct sideband for non-V+jets backgrounds
- Validate in simulation and high M_{jet} sideband