Searches for resonances decaying to SM bosons at CMS

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on behalf of the CMS collaboration

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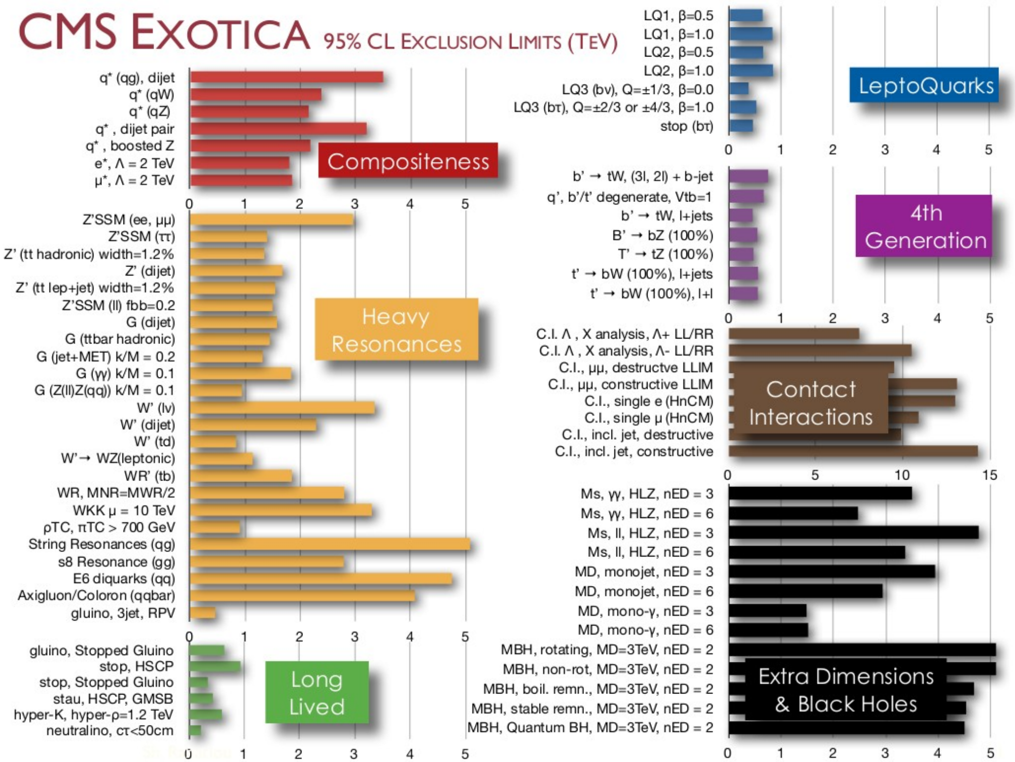
New Physics
in the diboson final state

- Where to look for signatures of NP, in particular if one targets the hierarchy problem?
  Only reasonable guesses for now:
  - large mass, O(1 TeV)
  - couplings to heavy SM particles: top and heavy gauge bosons V (V=W,Z)
  - if NP connected with EWSB, interesting to investigate V_L scattering at high masses

X → VV



Experimental advantages in having V (V=W / Z) in the final state

- well-known mass, used also for detector calibration
- selection on V mass suppresses non-resonant SM backgrounds
- mass resolution of the final X → VV

Recent VV searches at CMS

Very broad spectrum of published results at $\sqrt{s}$ = 7 TeV.
New set of preliminary results at 8 TeV, pushing sensitivity and energy reach:

CMS-PAS-EXO-12-021: Search for resonances decaying to **WV** $\rightarrow \ell + \nu + 2q$

CMS-PAS-EXO-12-022: Search for resonances decaying to **ZV** $\rightarrow 2\ell + 2q$

CMS-PAS-EXO-12-024: Search for resonances decaying to **VV** $\rightarrow 4q$

CMS-PAS-EXO-12-025: Search for resonances decaying to **WZ** $\rightarrow 3\ell + \nu$

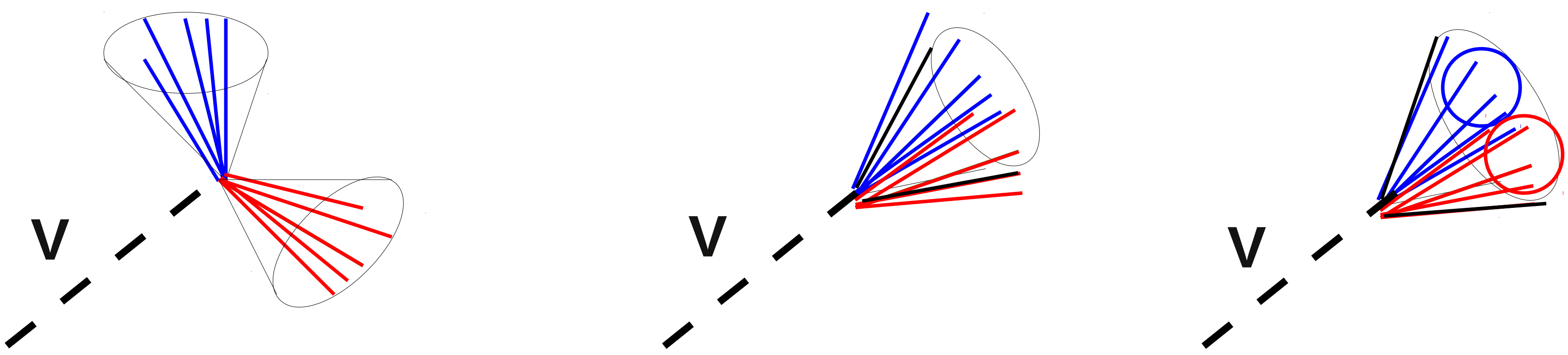
- All results based on full 8 TeV dataset (~20 fb^{-1})
- Several models predict NP decaying to V or H in sizable fraction
  - Just few benchmarks considered, but try not to be too specific in the selections → allow re-interpretation in different models.
  - Narrow-width approximation: benchmark signals always with natural width << detector resolution and neglected

Boosted jets and V-tagging

- About 70% of W and Z decay hadronically: we must use hadronic decays for being sensitive to small signals of NP !!!
- Boosted topology affects dramatically hadronic side: **jets start to merge !**
  - cannot ask anymore for two jets (QCD 1J >> QCD 2J)
  - look inside merged jet and try to find two subjets → **jet substructure !**

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

→ if ΔR_{qq} ~ jet radius → jet merging !



Moderately boosted V
Resolved dijets

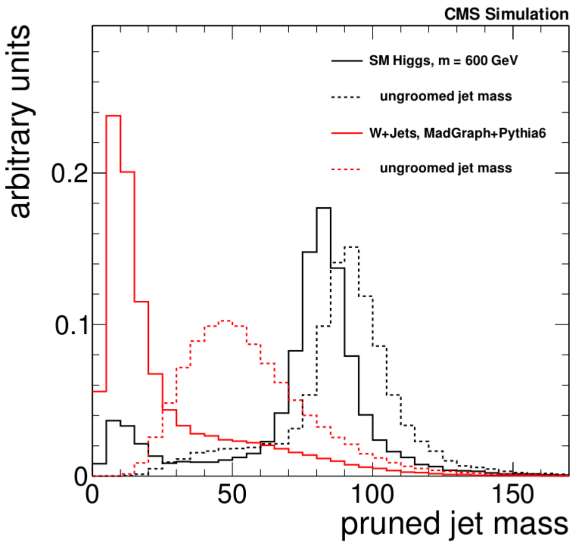
Boosted V,
jet merging

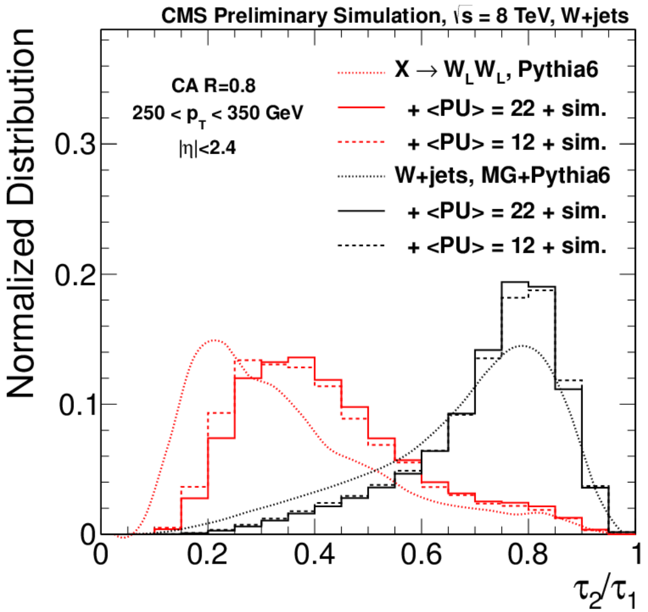
Boosted V, jet merging,
Jet substructure analysis
recovers initial information

Boosted jets and substructure

How can we tell if a jet comes from a V decay or plain QCD ?

- **$M_{Jet} \sim M_V$**
  - Jet grooming: remove color radiation from PU and QCD, stay left with only hard kinematics
  - Several techniques proposed and studied: filtering, trimming, pruning





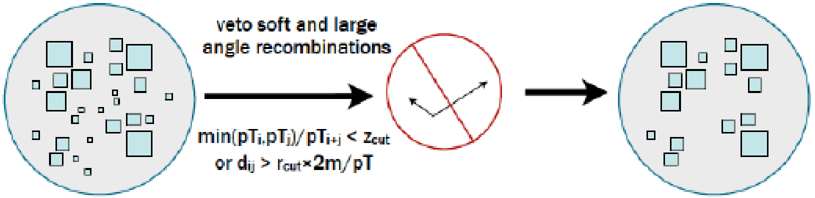
- **V-jets originated from two quarks**
  - Jets are "de-clustered", study properties of subjets and topology of the jet constituents
  - Many options considered: N-subjettiness ratios, mass drop, Qjet volatility, energy correlations
  - Look for dipole-like, symmetric configurations inside jets
  - Correlations between vars (often) and jet mass (always)

Jet substructure techniques

Jet Pruning (arXiv:0903.5081, arXiv:0912.0033)

- recluster jet constituents applying additional requirements at each recombination

$$z = \frac{min(p_{T,i}, p_{T,j})}{p_{T,JET}} > 0.1 \qquad \Delta R < 0.5 \frac{M_{JET}}{p_{T,JET}}$$



- filter out soft and large angle QCD emissions

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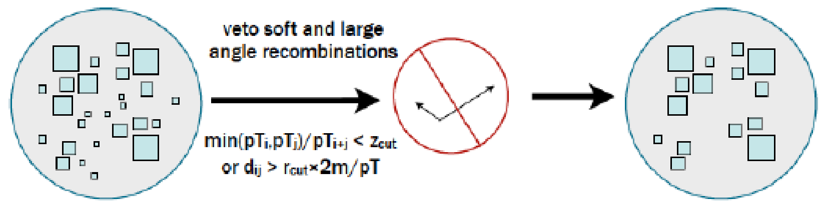
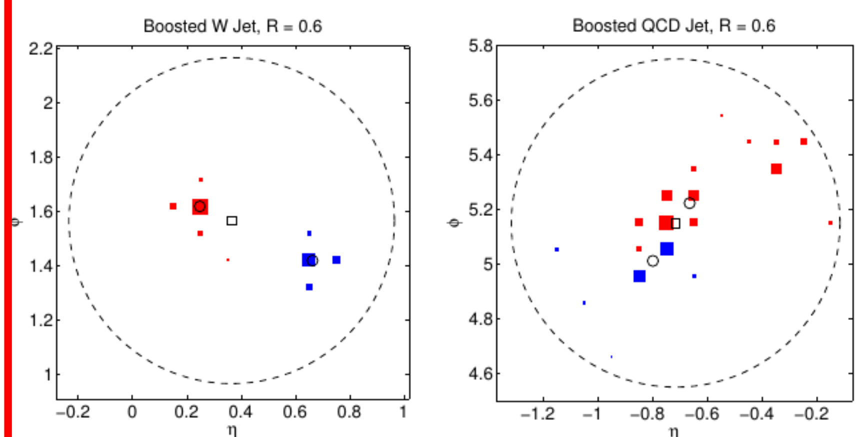


- filter out soft and large angle QCD emissions

N-subjettiness (arXiv:1011.2268)

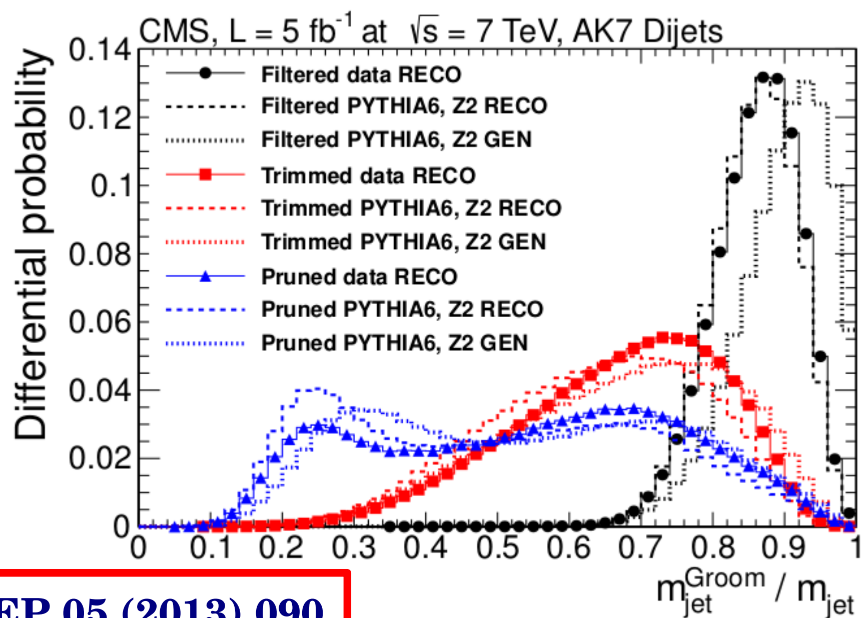


- topological compatibility with hyp of N subjets
- recluster jet, halting once reached N subjets
- τ_N : p_T-weighted sum over jet constituents of distances from closest subjet axis

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \, min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$$

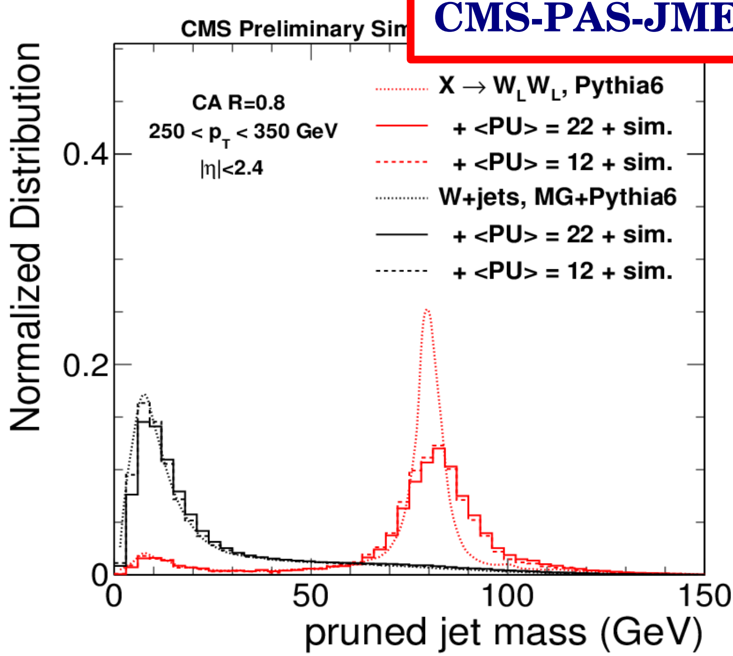
These are NOT THE ONLY POSSIBILITIES ! Plenty of alternatives available and studied at CMS. See backup and references for a broader overview.

- At CMS, two main references on jet grooming and V-tagging
  - JHEP 05 (2013) 090 → performances of jet grooming in SM dijets and V+jets
  - CMS-PAS-JME-13-006 → performances of jet pruning and V-tagging
- Good understanding of these tools:
  - Test of our understanding of hadronization and parton shower.
    MC in use at CMS describes well most of the features (but not everything...)
  - Jet grooming resilient against pileup
  - Data-driven techniques for estimating V-tagging efficiency



JHEP 05 (2013) 090

CMS-PAS-JME-13-006

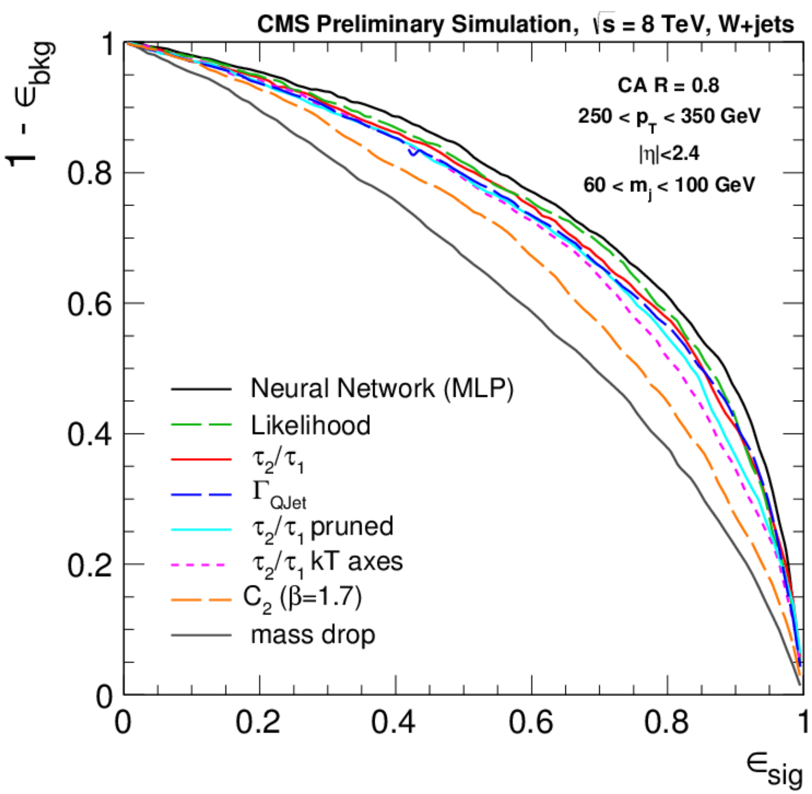


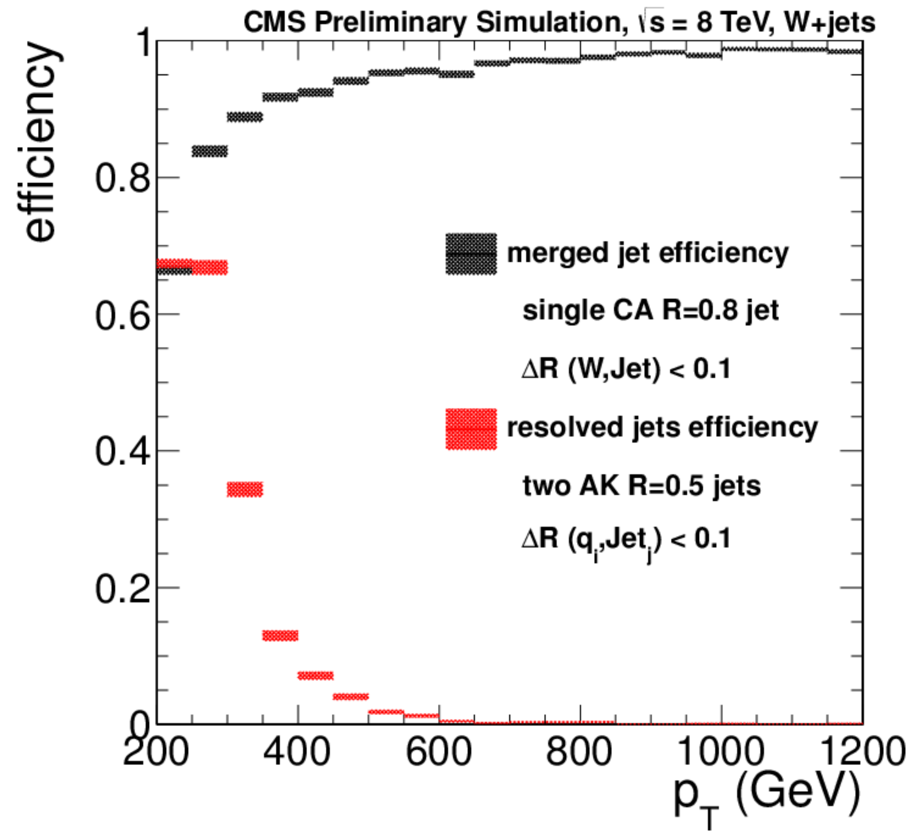
Boosted jets and V-tagging

Several aspects of V-tagging investigated in detail

- pileup, signal eff vs bkgd rejection, correlations, sensitivity to polarization of V, angular resolution of subjets, jet charge

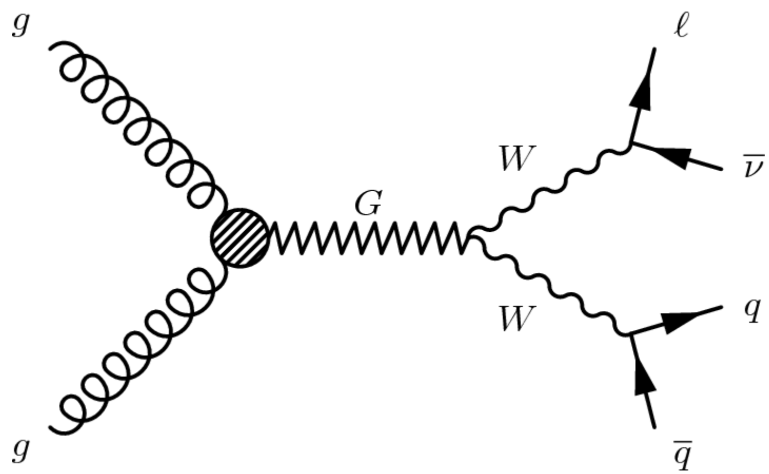
CMS-PAS-JME-13-006

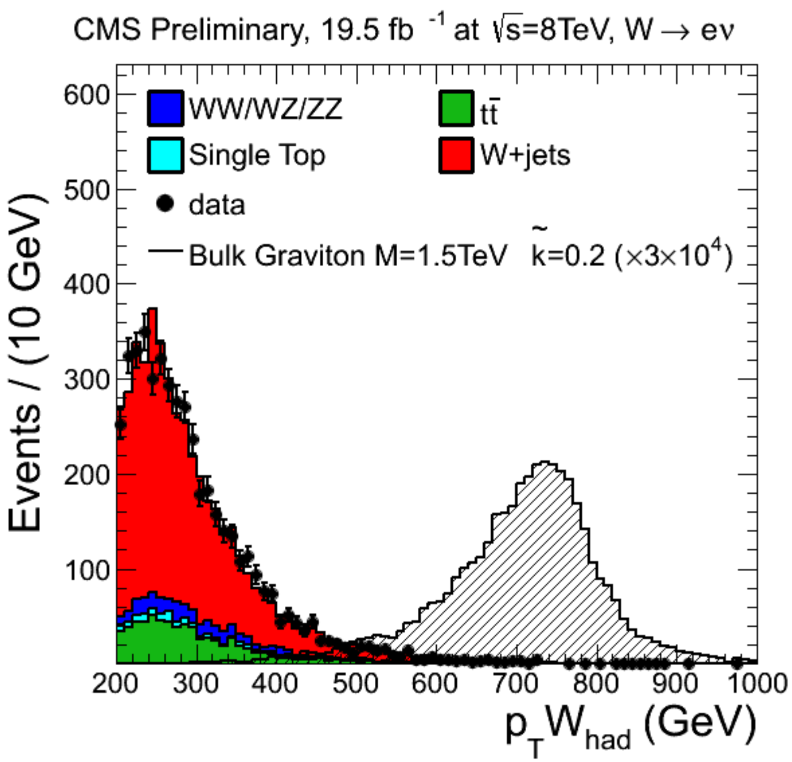




$X \to W V \to \ell + \nu + 1$ jet

CMS-PAS-EXO-12-021





- WW semi-leptonic (ℓ=e, μ) : large BR, good bkgd rej thanks to isolated lepton
- Main SM bkgd are W+jets and $t\bar{t}$
- Isolated, high-p_T ℓ: p_T> 50 (90) GeV for μ (e)
- MET > 40 (80) GeV for μ (e)
- Neutrino kinematics fully determined from kinematic fit constraining $M_{\ell\nu} = M_W$
- C-A jets (R=0.8) from Particle Flow objects
- $p_{T,W}$ > 200 GeV
- Veto on b-jets and additional isolated leptons

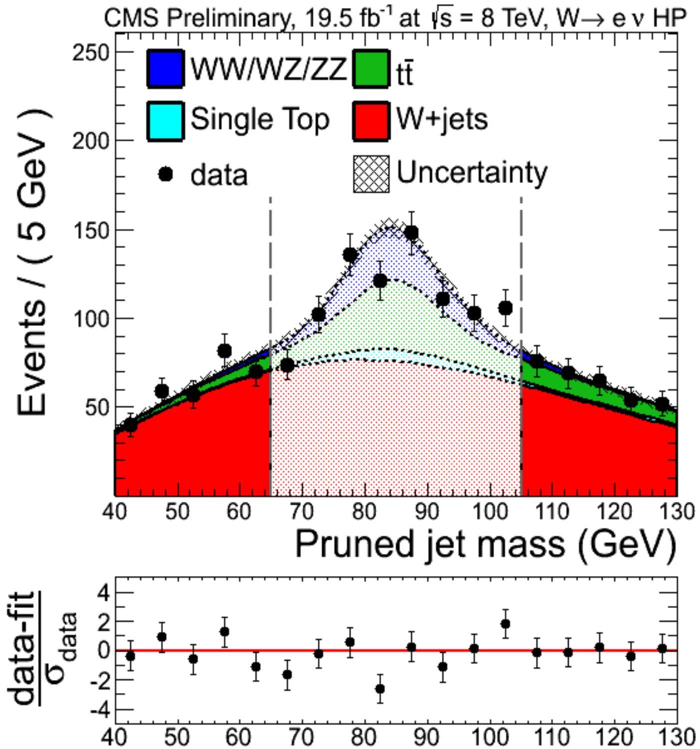
Analysis uses bulk graviton as signal benchmark, <u>cuts are the loosest possible, compatibly with triggers and reconstruction ID</u>
→ not very dependent on specific model tested.

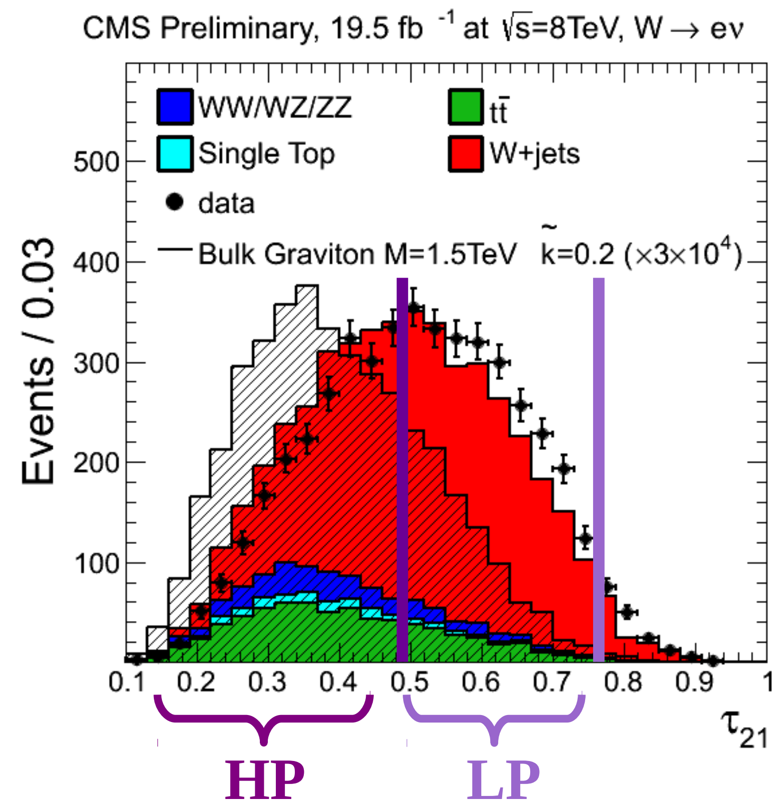
V-tagging

N-subjettiness ratio

$$\tau_{21} = \tau_2 / \tau_1$$

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



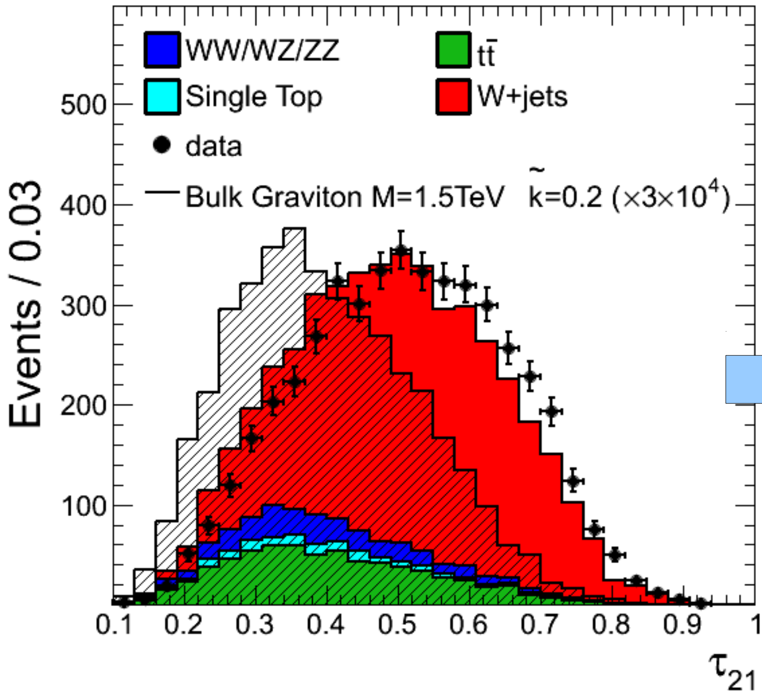


V-tagging selection:

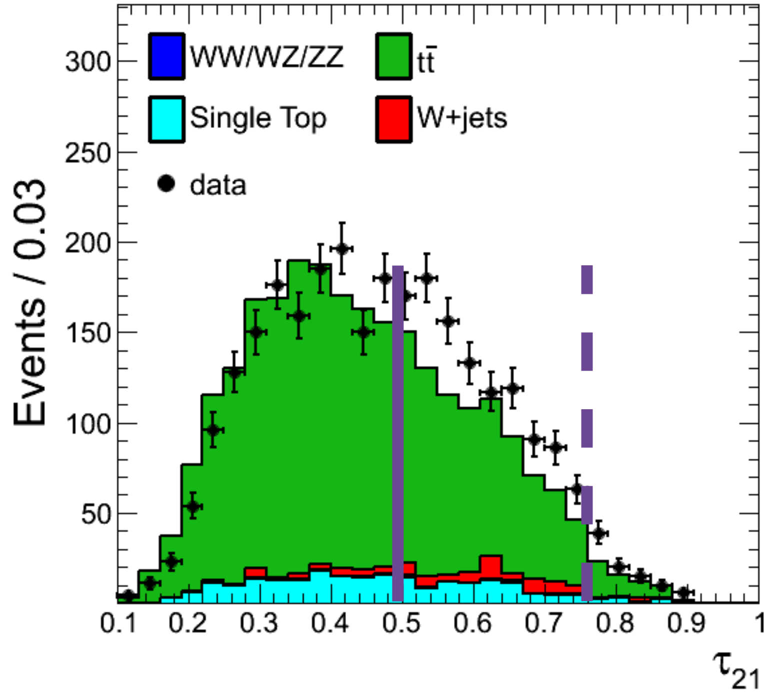
- Pruned jet mass in [65, 105] GeV
- τ_{21} : High-Purity (τ_{21}<0.5) and Low-Purity (0.5 < τ_{21}<0.75)

V-tagging efficiency

$X \to WW \to \ell + \nu + 1$ W-jet



$t\bar{t} \to \ell + \nu + 1$ W-jet + ≥ 1 b-jet



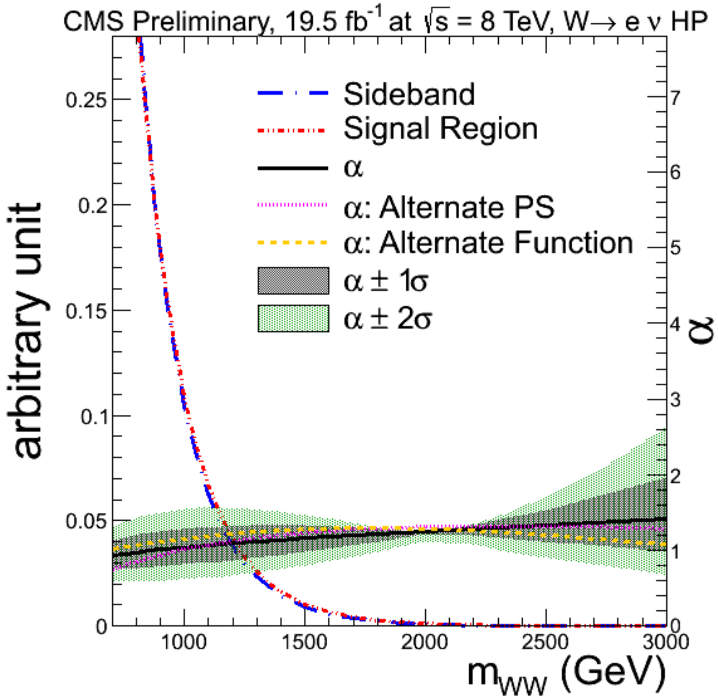
- Disagreements between data and background MC in the key variables used for V-tagging
  → hints for a mismodeling of V-tagging eff in the signal MC as well
- We can correct the efficiencies by comparing data and simulation in a control sample with high-purity of V→qq: semi-leptonic $t\bar{t}$ sample
- Extract data/MC scale factors (SF): correct MC eff because of imprecise modeling of τ_{21}
- Error on SF: ~8% in HP, 30% in LP (driven by statistics in $t\bar{t}$ sample) → **main systematic**

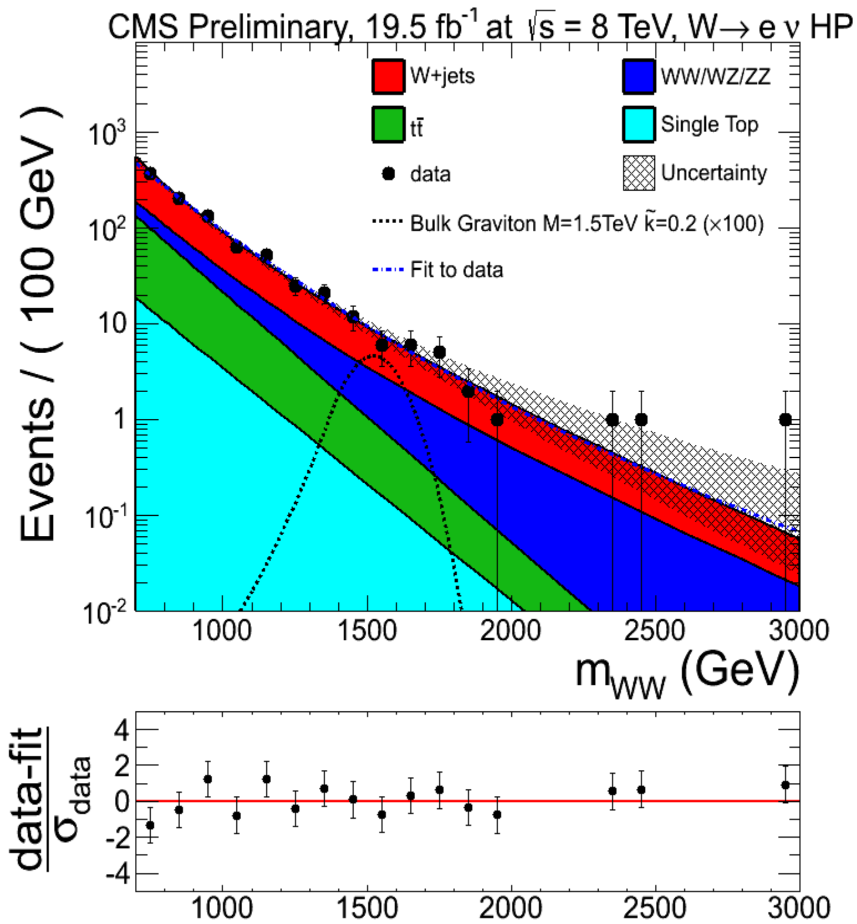
Background estimation

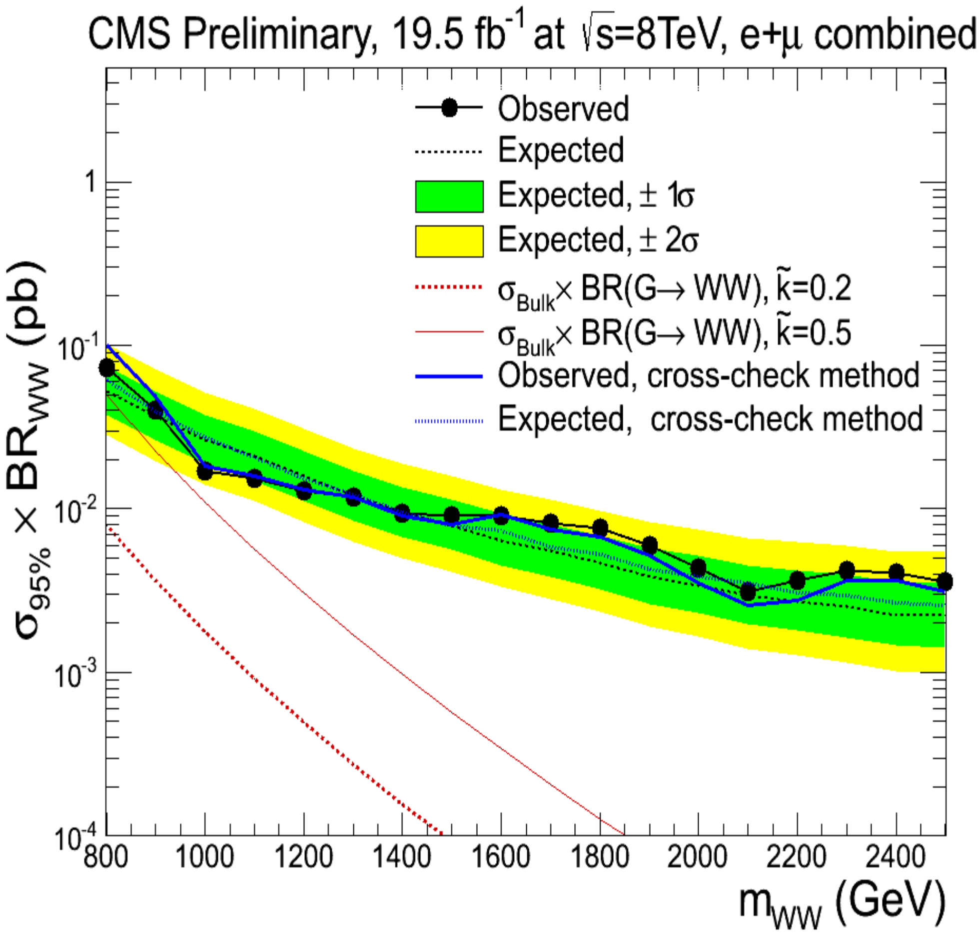
Data-driven background estimation from signal-free control region

- Define control region from M_{Jet} sideband [40, 65] GeV
- M_{WW} distribution in sideband extrapolated to signal region via α factor from MC
- Use analytical fits rather than raw distributions

$$\alpha = \frac{N^{MC-Bkg}_{Sig-Reg}}{N^{MC}_{SB-Reg}} \qquad N^{DATA-Bkg}_{Sig-Reg} = \alpha \cdot N^{DATA}_{SB-Reg}$$







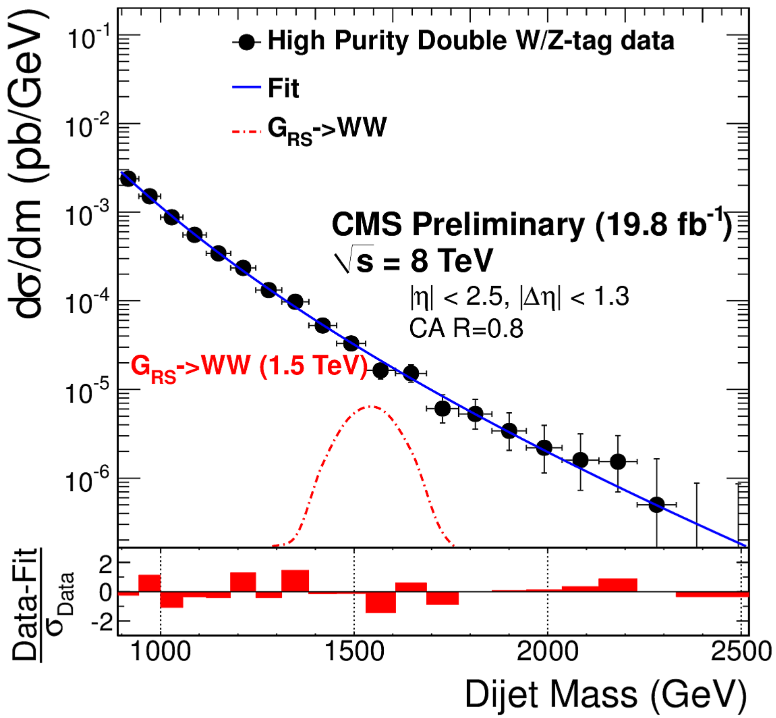
- Set limits on narrow bulk graviton mass
- 95% CL exclusion on σ x BR(G* → WW) between 70 and 3 fb over the search range $M_{G*} \in [800, 2500]$ GeV
- Cross-check from different background estimation and statistical analysis (smoothness test of M_{WW} spectrum)

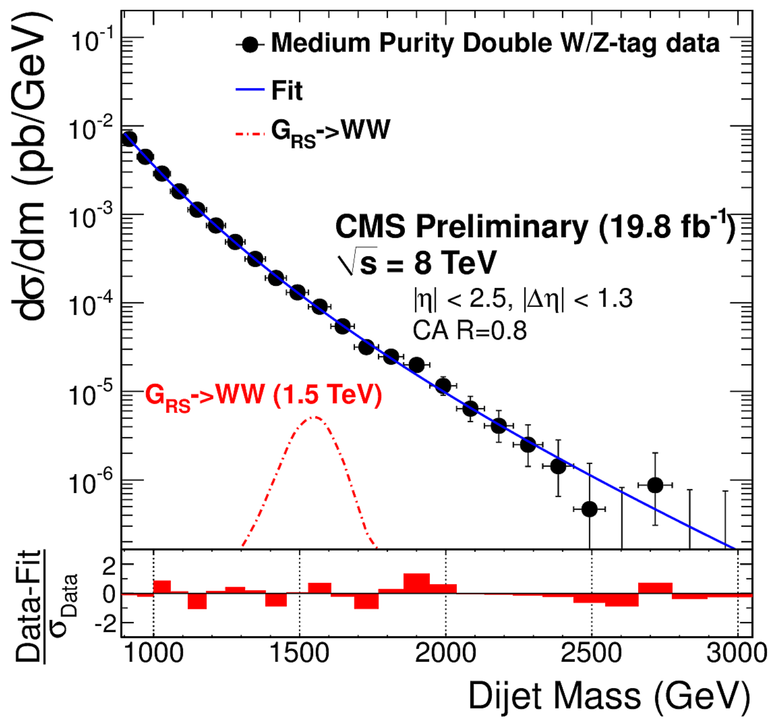
CMS-PAS-EXO-12-021

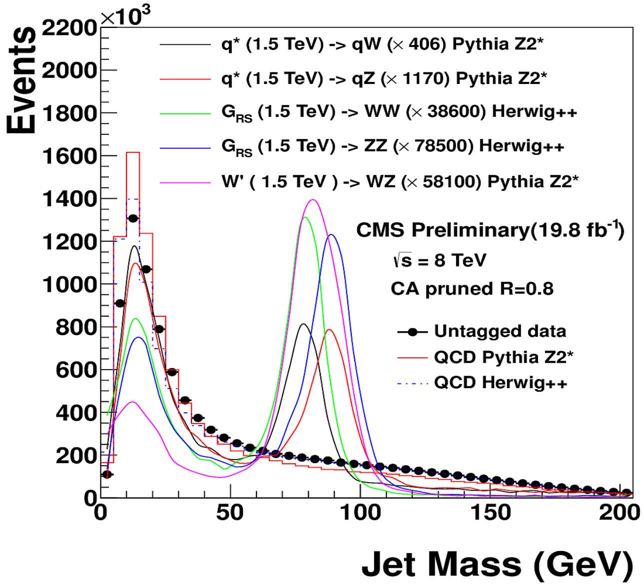
X → V V → 2 jets (V-tagged)

- Dijet Bump hunt with V-tagging on both hemispheres
- X → VV → 4q (→ 2 jets): large BR but also large QCD background
- Double V-tagging suppresses heavily the background (~ x200), retaining ~10% of signal efficiency
- Background prediction from smoothness test of dijet mass spectrum (completely data-driven, no MC involved at any stage)

CMS-PAS-EXO-12-024

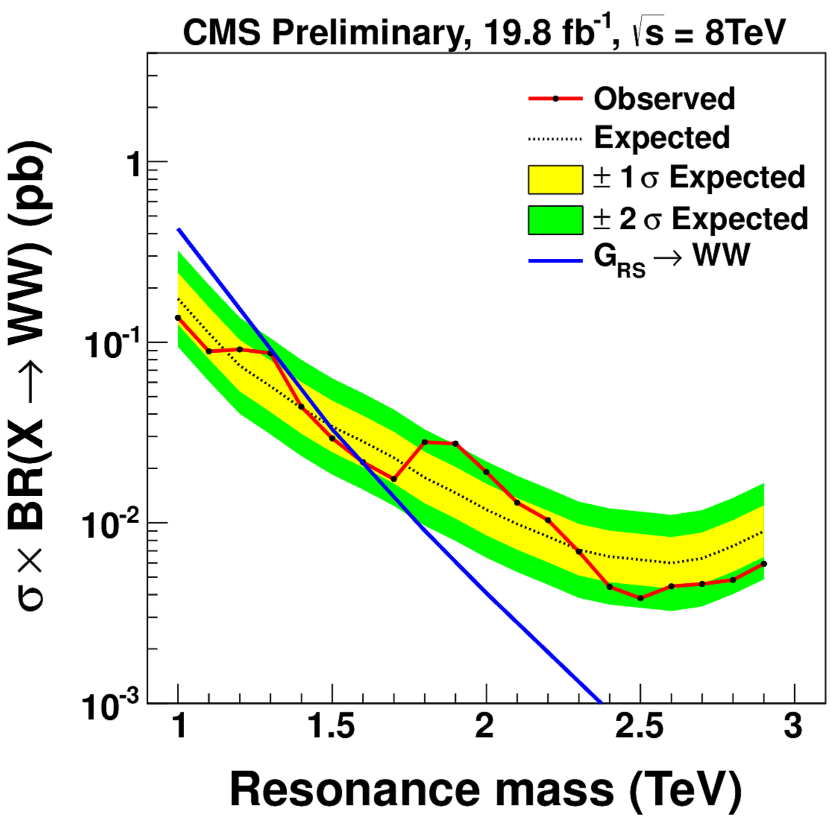


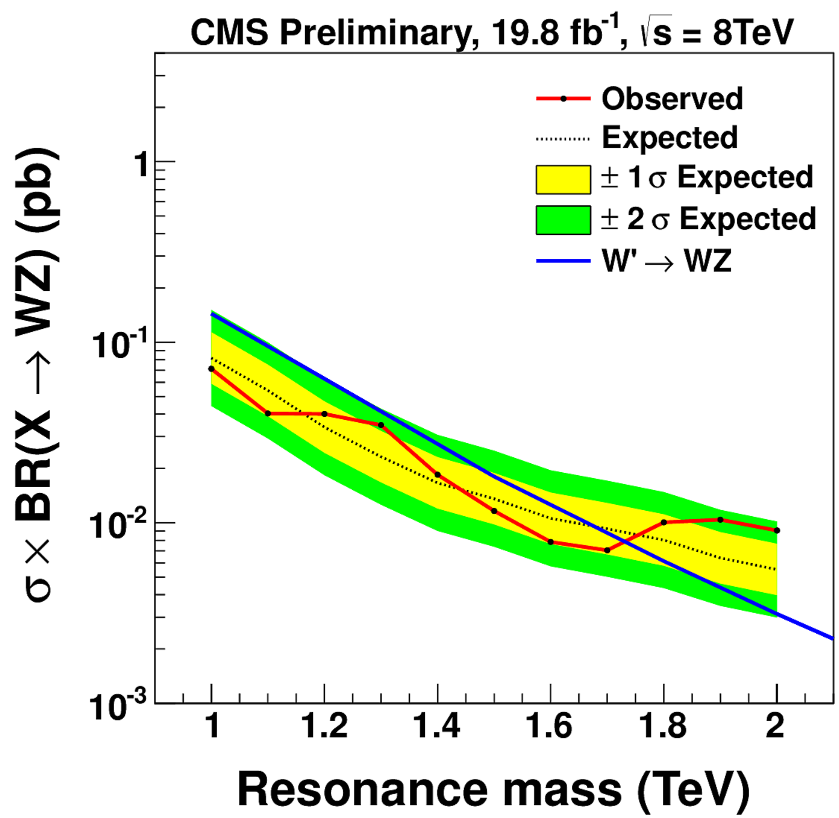




- Different efficiencies and resolutions depending whether jet comes from W or Z
- Interpret result for different signal hypotheses: RS1 $G \rightarrow WW$, RS1 $G \rightarrow ZZ$, $W' \rightarrow WZ$, $q^* \rightarrow qV$
- No significant excess, exclude RS1 $\rightarrow$ WW ($k = 0.1$) for $M < 1.7$ TeV and $W' \rightarrow WZ$ for $M_{W'} < 1.72$ TeV

CMS-PAS-EXO-12-024

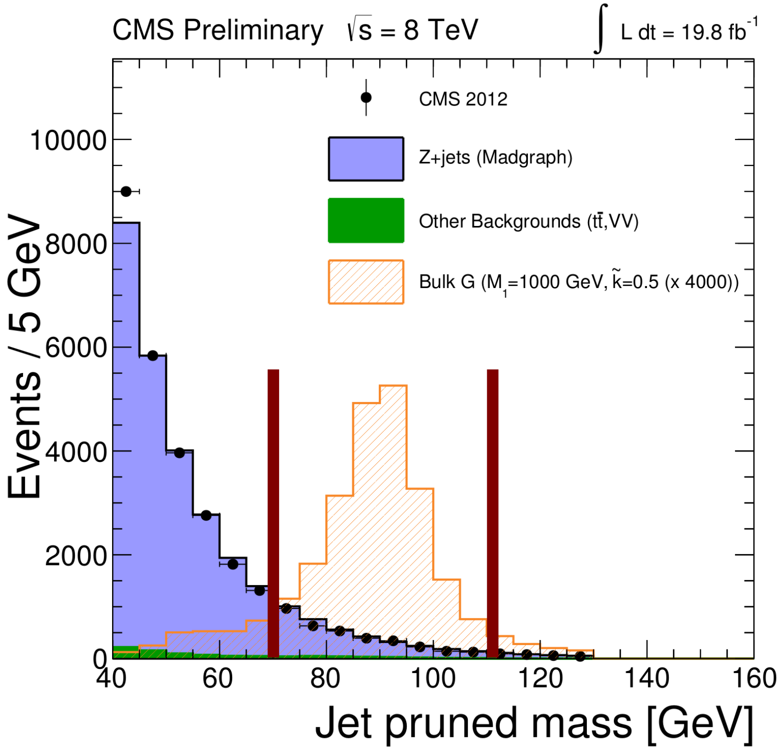


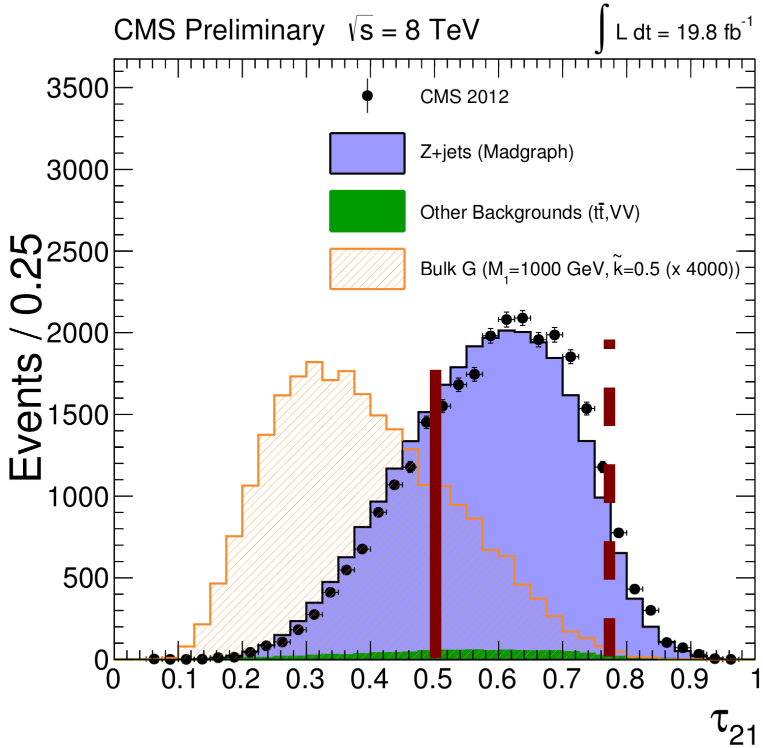


$X \to Z\,V \to 2\ell + 1$ jet

- Presence of a $Z \to \ell\ell$ ($M_{\ell\ell}$ in [70, 100] GeV) helps to further suppress SM bkgd
- Two isolated ℓ (ℓ=e or μ). Hadronic hemisphere selection ~ WV semileptonic
  - pruned jet mass in [70, 110] GeV
  - τ_{21} categories re-optimized, found to be the same as WV (HP: $\tau_{21} < 0.5$)
    → W-jets and Z-jets are not that much different
  - $p_{T,Z} > 80$ GeV (less background than WW semileptonic)

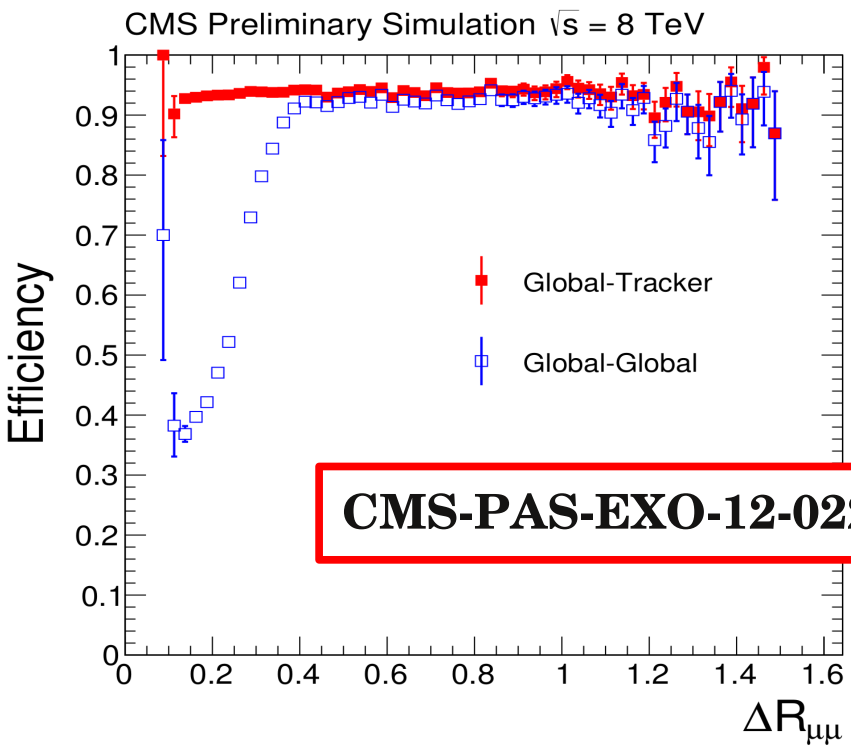
CMS-PAS-EXO-12-022



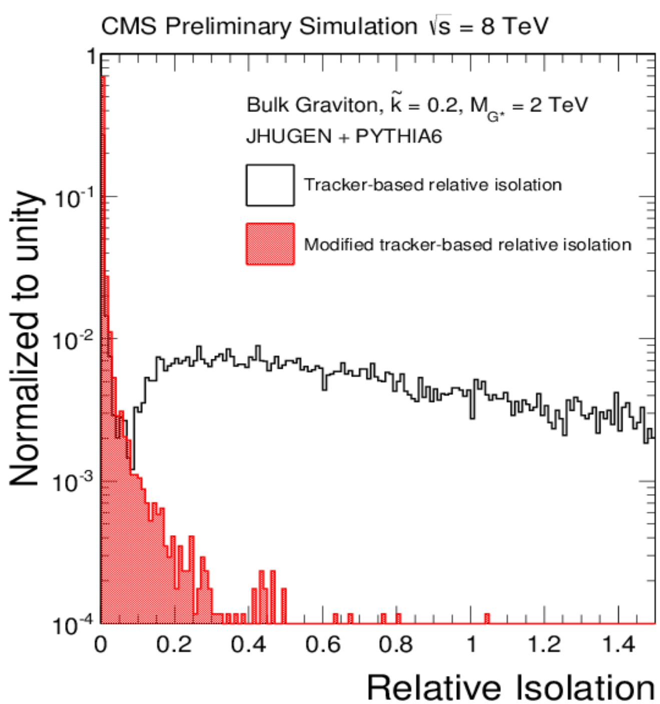


Collimated leptons

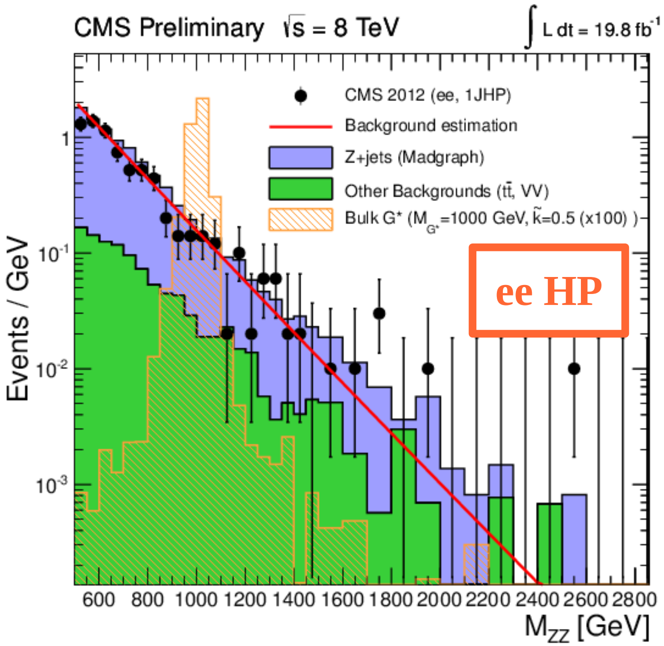
- Standard reco and ID techniques lose efficiency with near-by leptons ($\Delta R < \sim 0.5$)
- If muons very close, joint fit using inner tracker and μ-chambers ("global") associates wrong μ-chamber hits to tracks.
- Recover eff by requesting only one global μ, use only inner tracker for reconstructing the kinematics of the other.

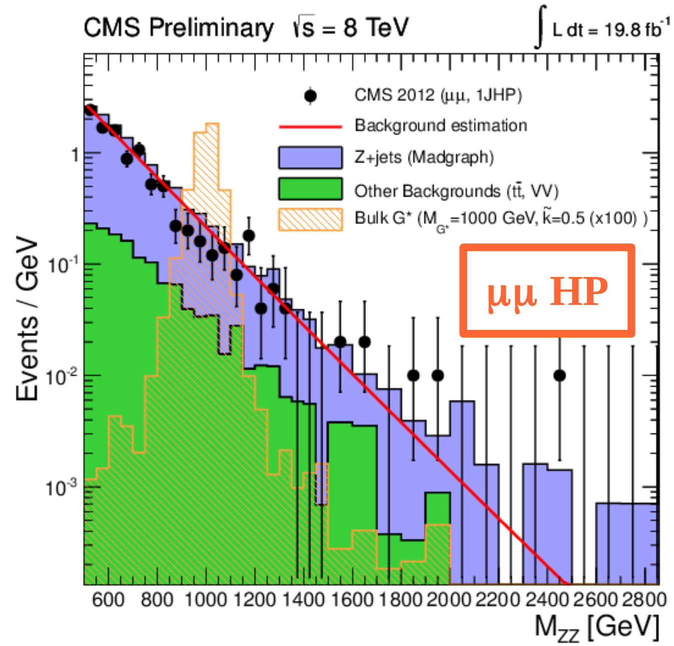


CMS-PAS-EXO-12-022



- Require no track activity in a cone around the muon in order to suppress muons from QCD background ("isolated" muons).
- When very collimated ($\Delta R < \sim 0.3$), one muon falls in isolation cone of the other, vetoing.
- Isolation recalculated after removal of other muon and recover completely the inefficiency





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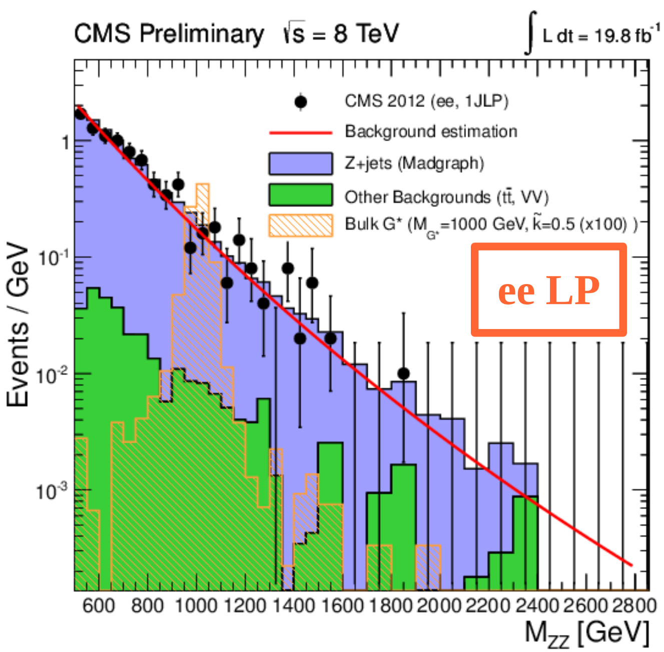
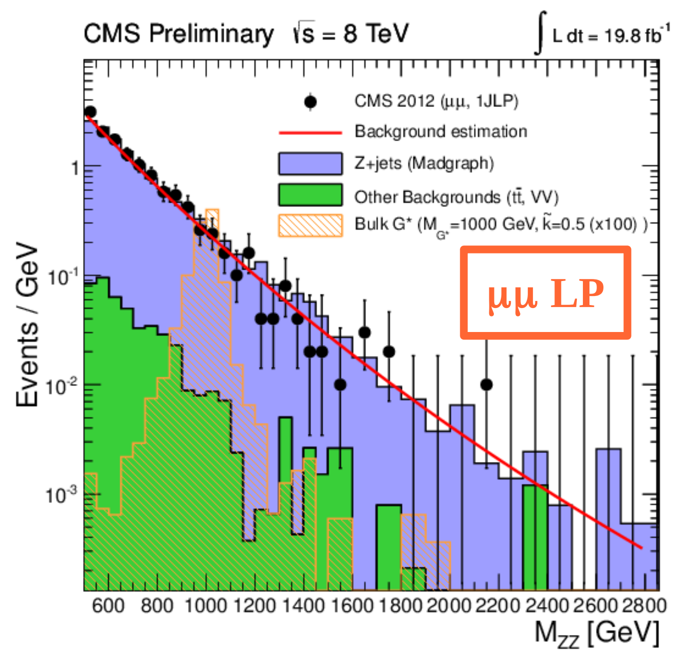
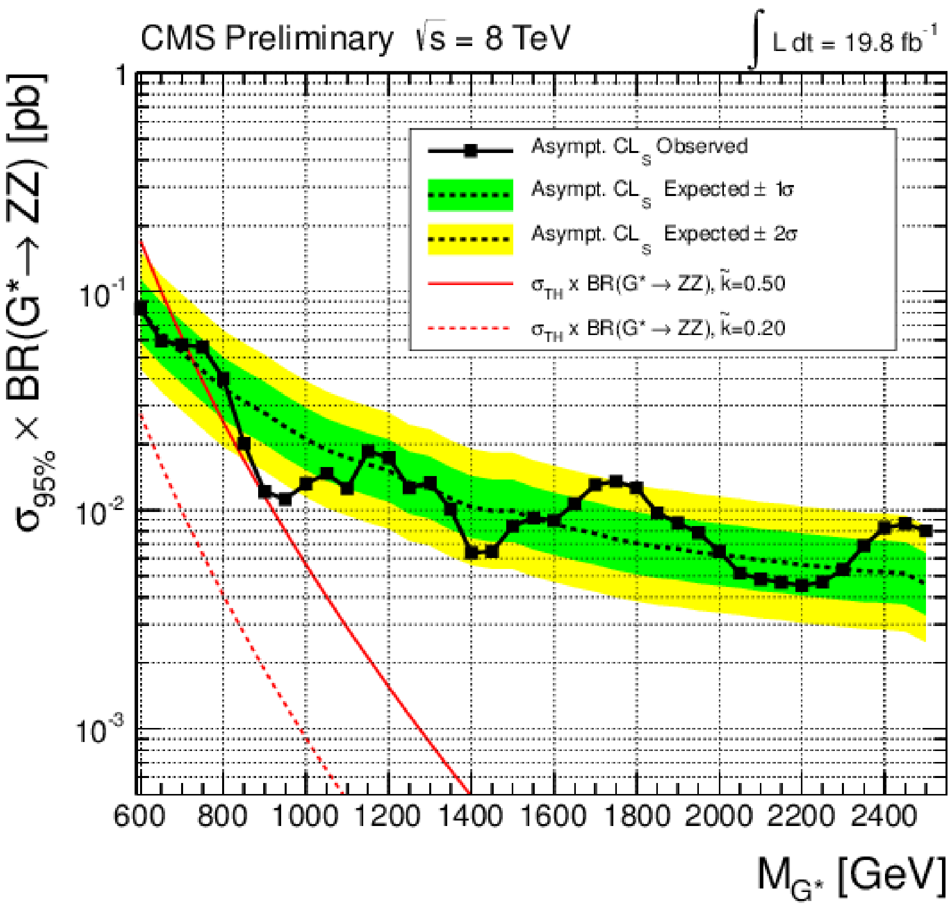




Background estimation strategy like the WW semi-leptonic analysis (control region from M_J sidebands, extrapolate to signal region with MC-based α-ratio)

Good description of both shape and normalization of the MZZ mass spectrum



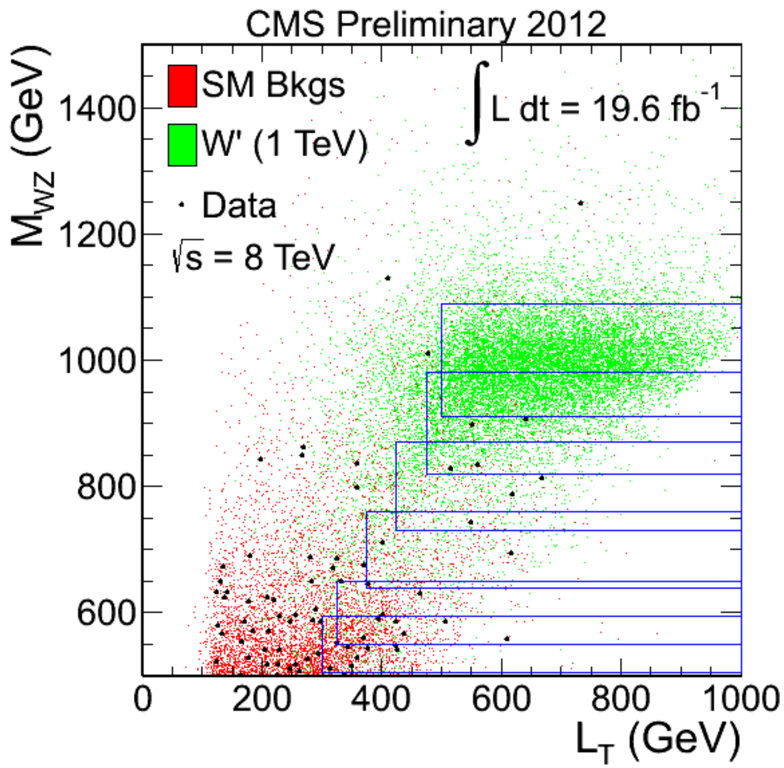
Set limits on narrow bulk graviton mass
95% CL exclusion on σ x BR($G^* \rightarrow ZZ$)
between 83 and 4 fb over the search range
$M_{G^*} \in [600, 2500]$ GeV
Bulk graviton excluded for M_{G^*} <710 GeV
(k/M_{Pl} = 0.5)

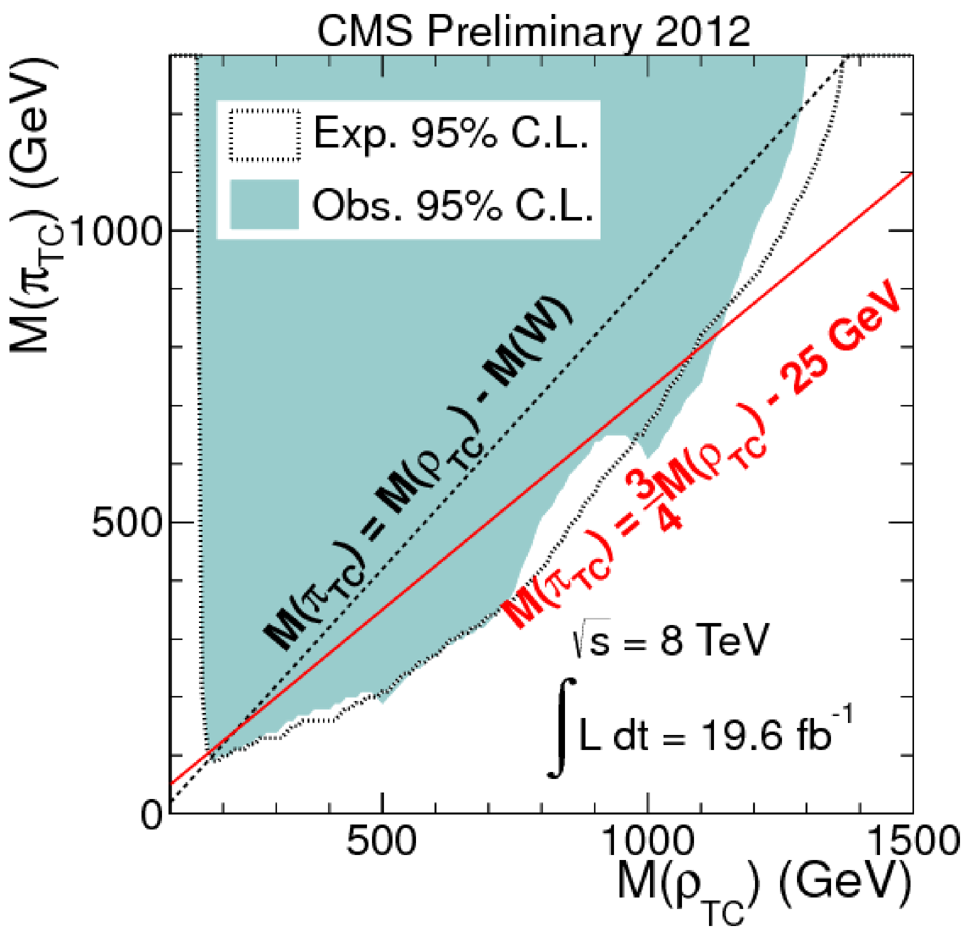
CMS-PAS-EXO-12-022

W' → WZ → 3ℓ+ν

- Final state: 3ℓ + MET (ℓ=e or μ)
- Same treatment of collimated leptons as ZZ
- Main bkgd from SM WZ (from MC + large syst.)
- Count event inside signal box in M_{WZ} vs L_T plane
  (L_T → scalar sum of p_T of three leptons)

CMS-PAS-EXO-12-025



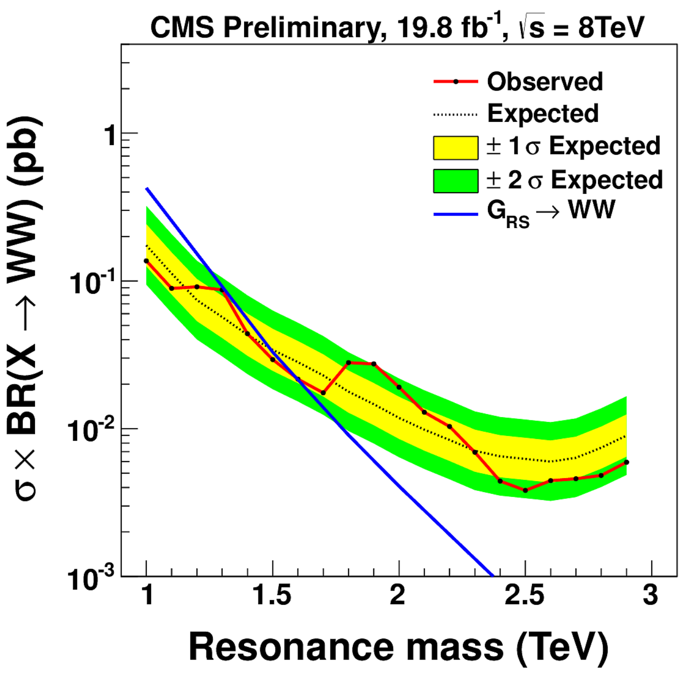


- Exclude SSM W' : $0.17 < M_{W'} < 1.45$ TeV
- Set limits on ρ_{TC} techni-hadron masses
  – Low-scale Techni-Color: masses of ρ_{TC} and π_{TC} affect BR($\rho_{TC} \to WZ$)

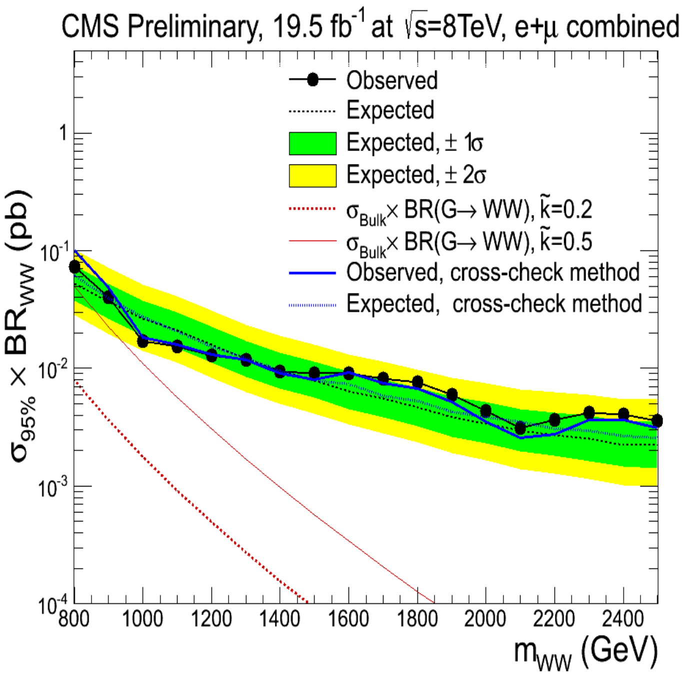
Still a lot to explore !

- Statistical combination of the VV searches
  - requires a specific model to fix BR of BSM resonance to WW and ZZ

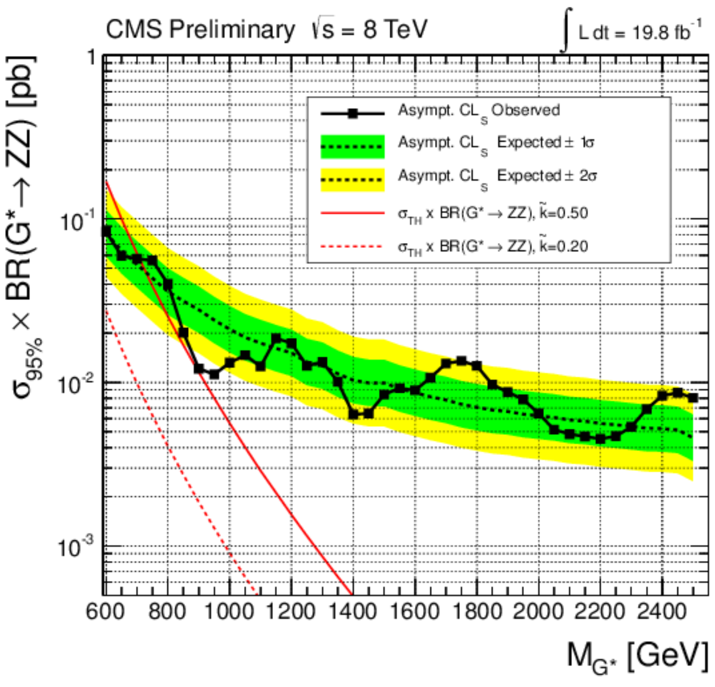
VV → fully hadronic



WV → semileptonic

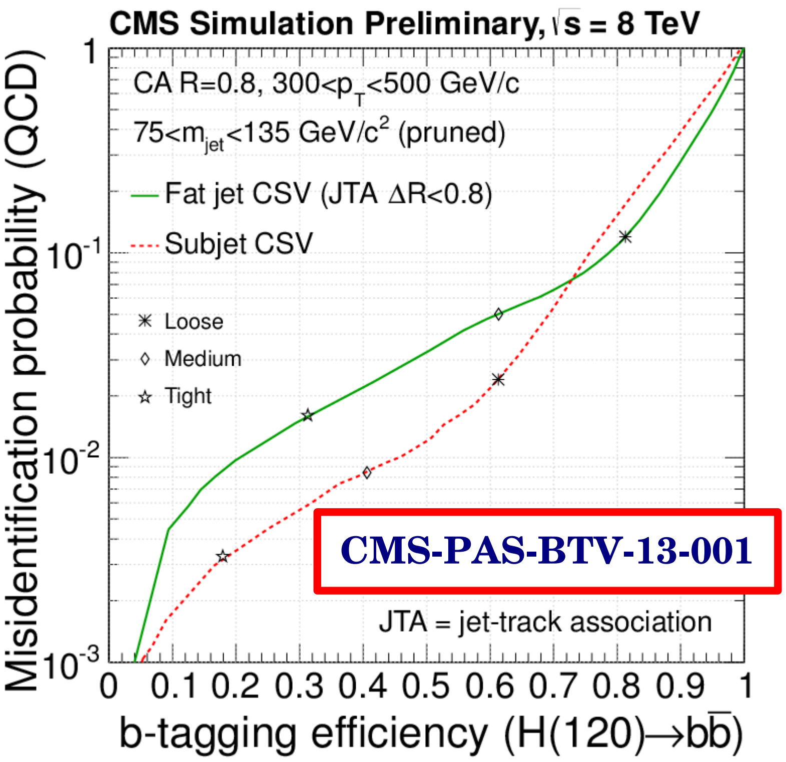


ZV → semileptonic



Still a lot to explore !

- Statistical combination of the VV searches
  - requires a specific model to fix BR of BSM resonance to WW and ZZ
- Extend to more final states
  - VH and HH
  - add channels with boosted tau pairs
- Include b-tagging of the subjets
  - particularly useful for channels with H
  - huge reduction of the QCD background

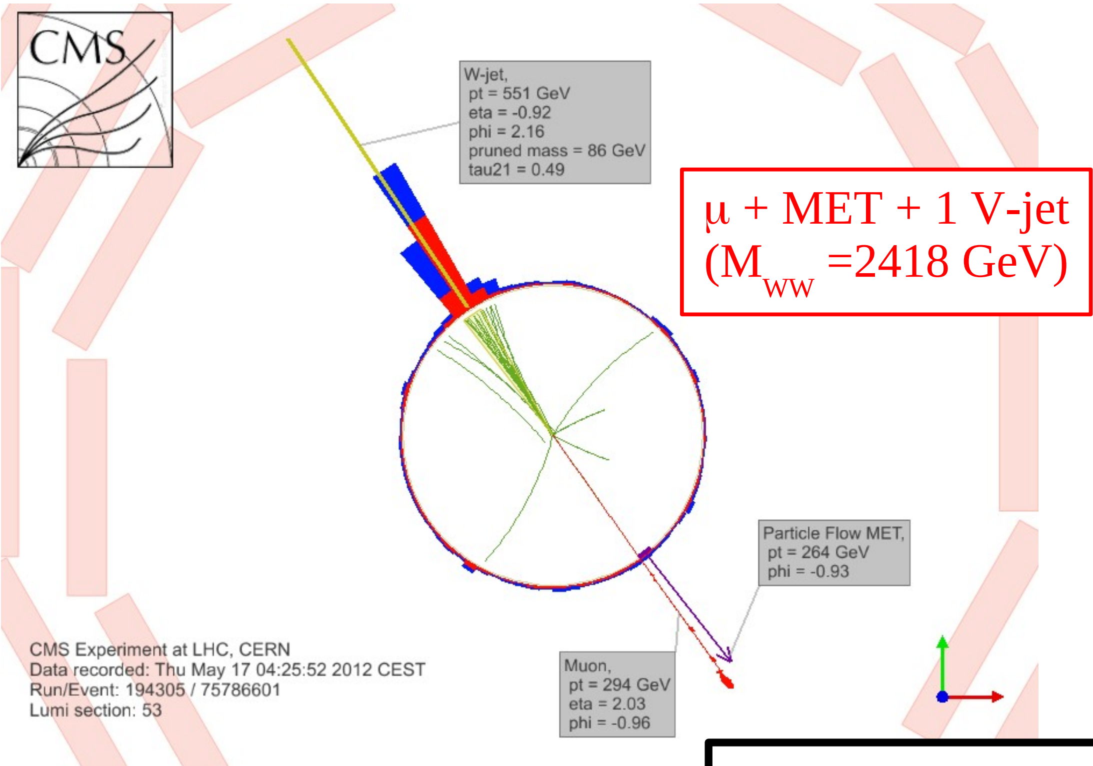


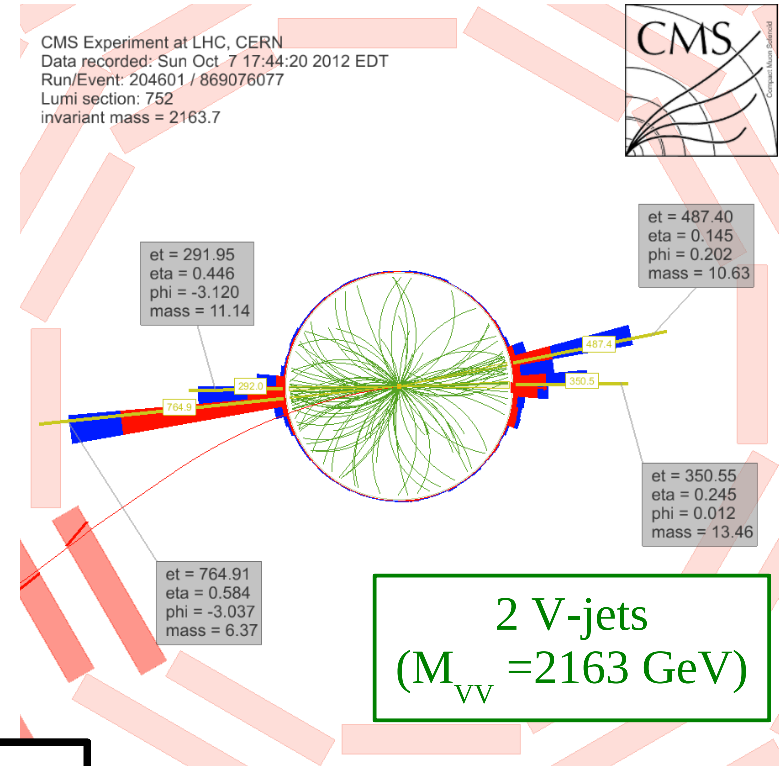
- Close 8TeV analyses, get ready for 13 TeV
  - Pileup rejection techniques (CMS-PAS-JME-13-005), VBF tag with q/g tagging (CMS-PAS-JME-13-002) and many more techniques to be included

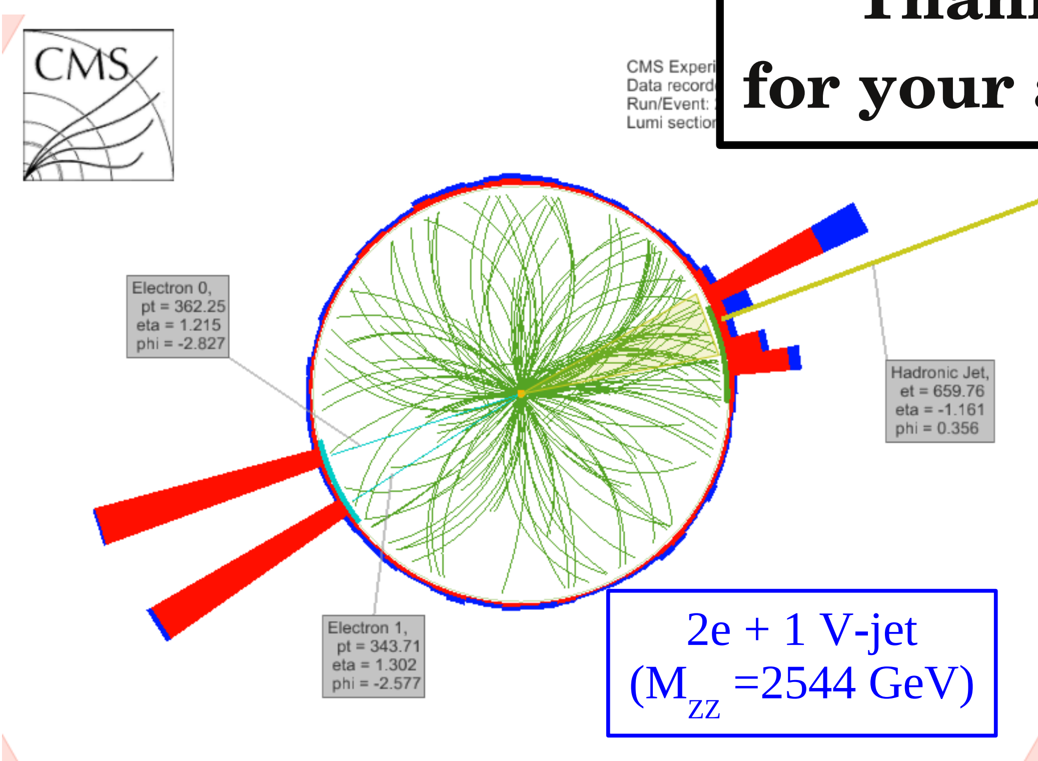
Summary

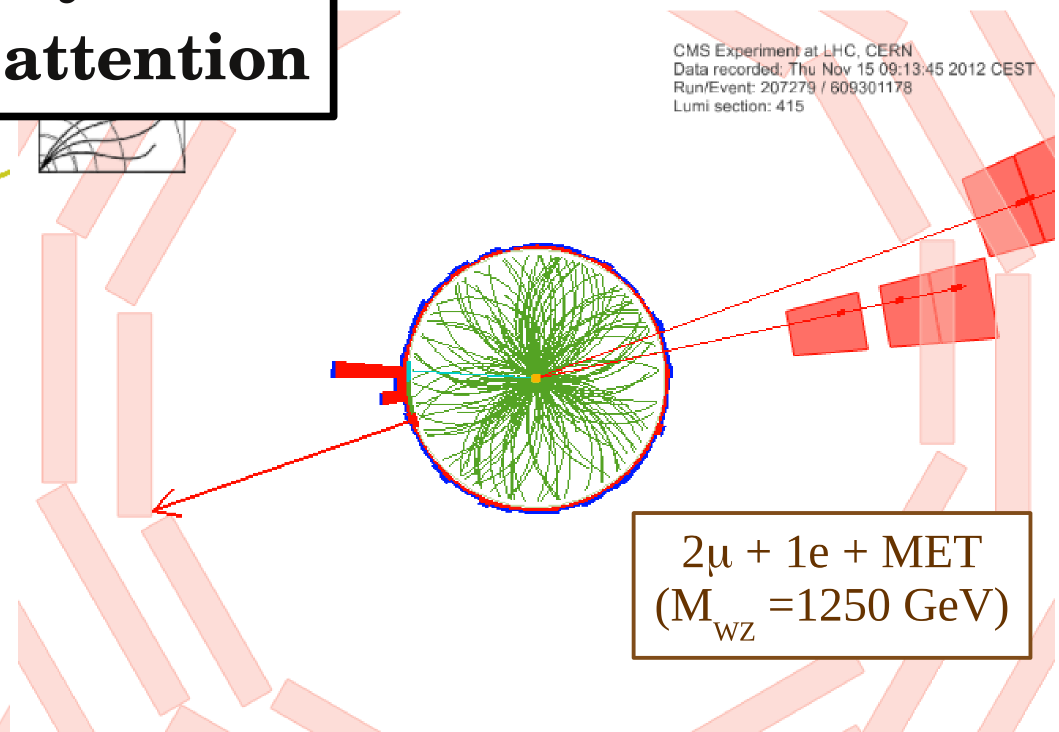
- Searches for BSM keep pushing higher and higher the energy frontier
  - Dealing with the high boosts of the final decay products requires new experimental techniques.
- Extensive set of studies of boosted physics objects at CMS.
- Brand new set of searches in the diboson final state exploit these tools
  - sensitivity at high masses significantly improved. Most stringent limits for several models (bulk G, ρ_{TC}, q*)
- As the energy frontier raises, boosted techniques will not be an option anymore, rather a must !
  - These searches are paving the way for future standards.
  - More to come in the future: stay tuned, as usual ;-)

Thank you for your attention



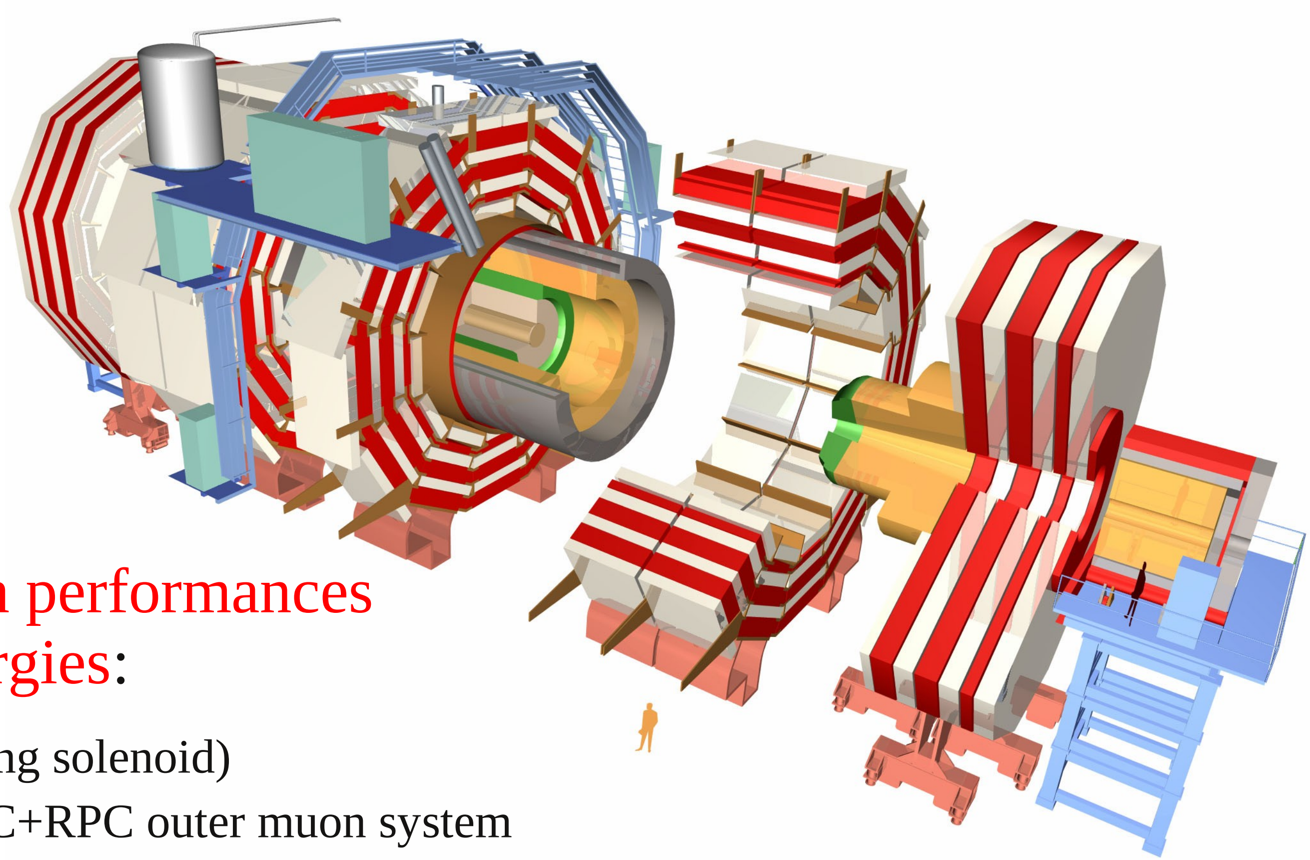






Backup slides

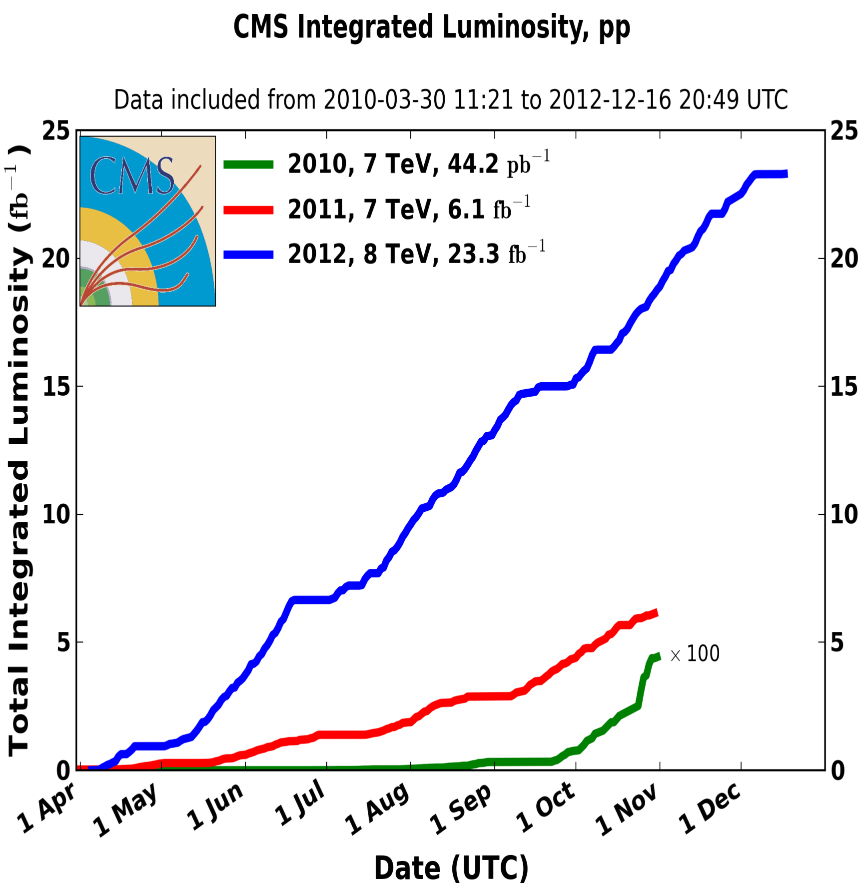
The CMS detector

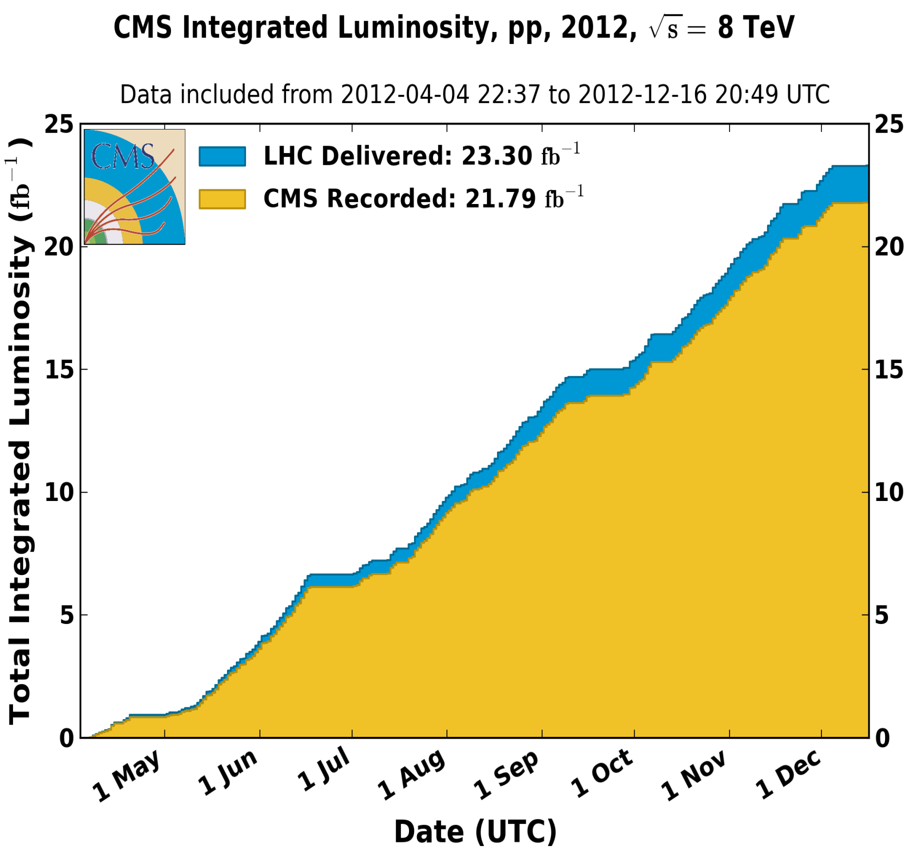


CMS is designed for high performances over a large range of energies:

- **3.8T B-field** (super-conducting solenoid)
- All-Si inner tracker; DT+CSC+RPC outer muon system
- Muon resolution <10% at p_T=1 TeV
- Well calibrated and aligned: bias on $Z \rightarrow \mu\mu$ mass <0.1%
- $PbW0_4$ crystal ECAL; $\sigma(E)/E$ const term: ~0.5% (barrel), <2% (endcaps)
- $Z \rightarrow ee$ resolution btw 1% and 4%, depending on η and ele quality
- Brass-scintillator sampling HCAL
- Flexible trigger system, output at 10^5 (300) Hz at L1 (HLT)

Luminosity collected





Excellent performances of LHC, thanks to all the accelerator crew !
High data-taking efficiency of CMS

Typical models considered

RS Extra-Dimensions: RS1 and Bulk G

- RS1: traditional benchmark, small BR to VV
- bulk G: localize light SM fields in 5th dim (bulk)
- bulk G: large BR to $t\bar{t}$, $W_L W_L$, $Z_L Z_L$ and HH
- radions decaying to HH

New strong sector

- Techni-hadrons , W' ->WZ
- Little Higgs
- Partial compositness, spin-1 → WW and VH

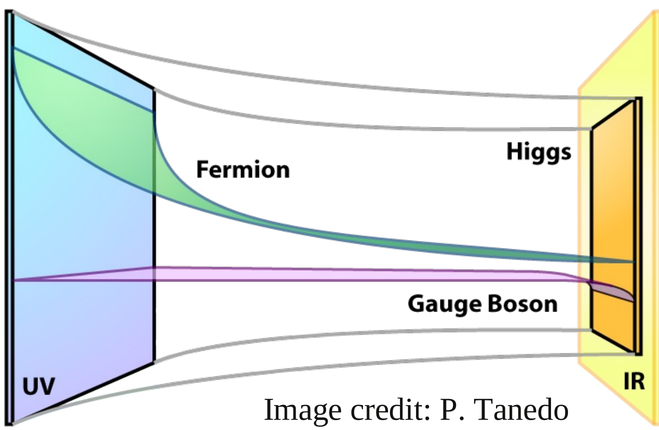


Image credit: P. Tanedo

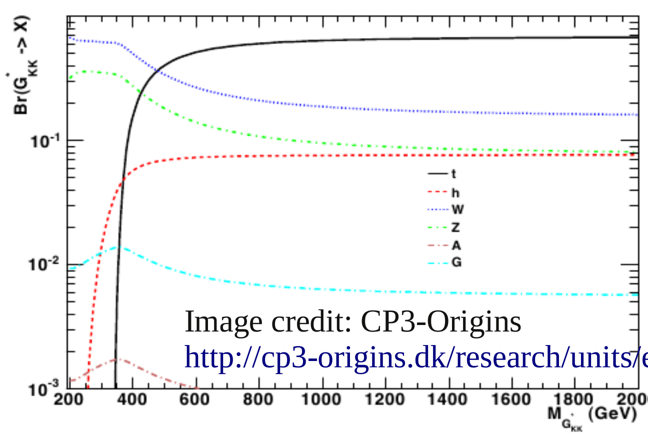
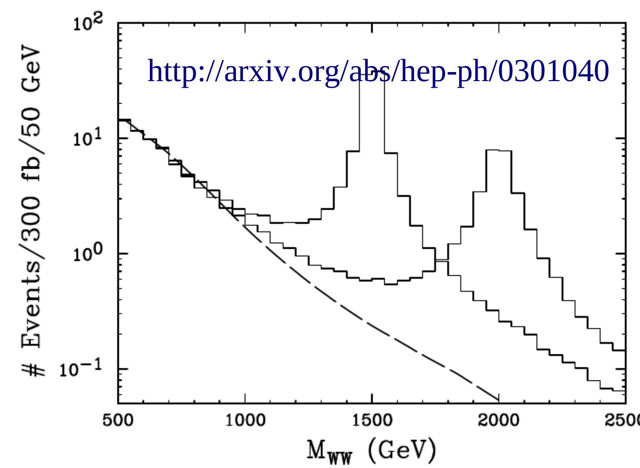


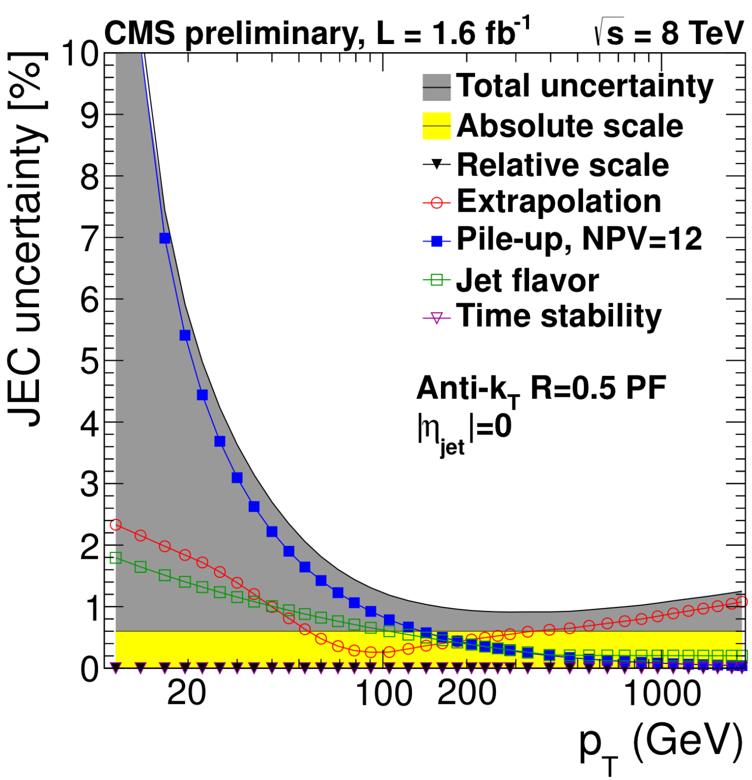
Image credit: CP3-Origins
http://cp3-origins.dk/research/units/ed-tools

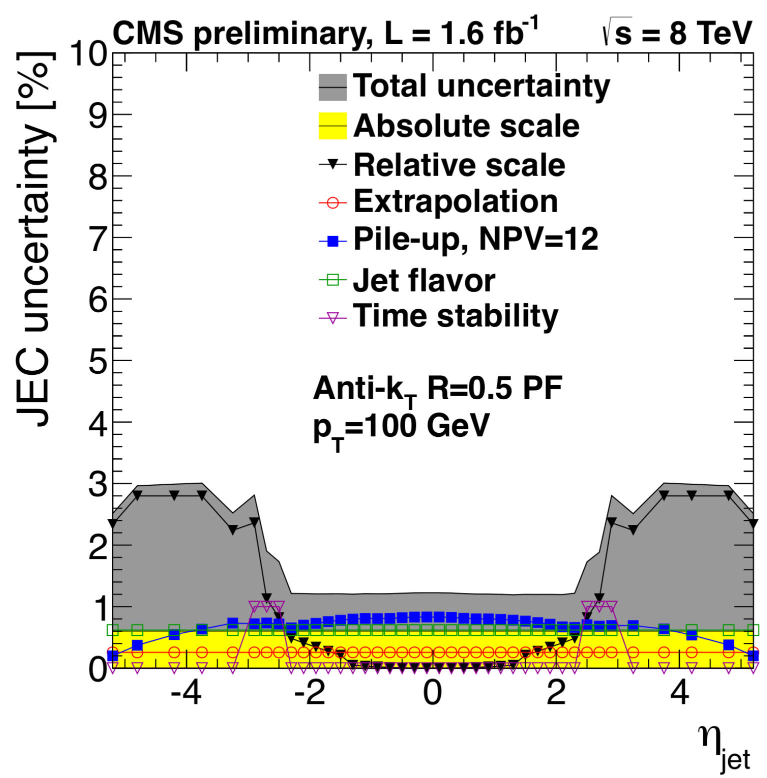


New ideas and suggestions very welcome,
please contact us proposing more alternatives !

PF jets

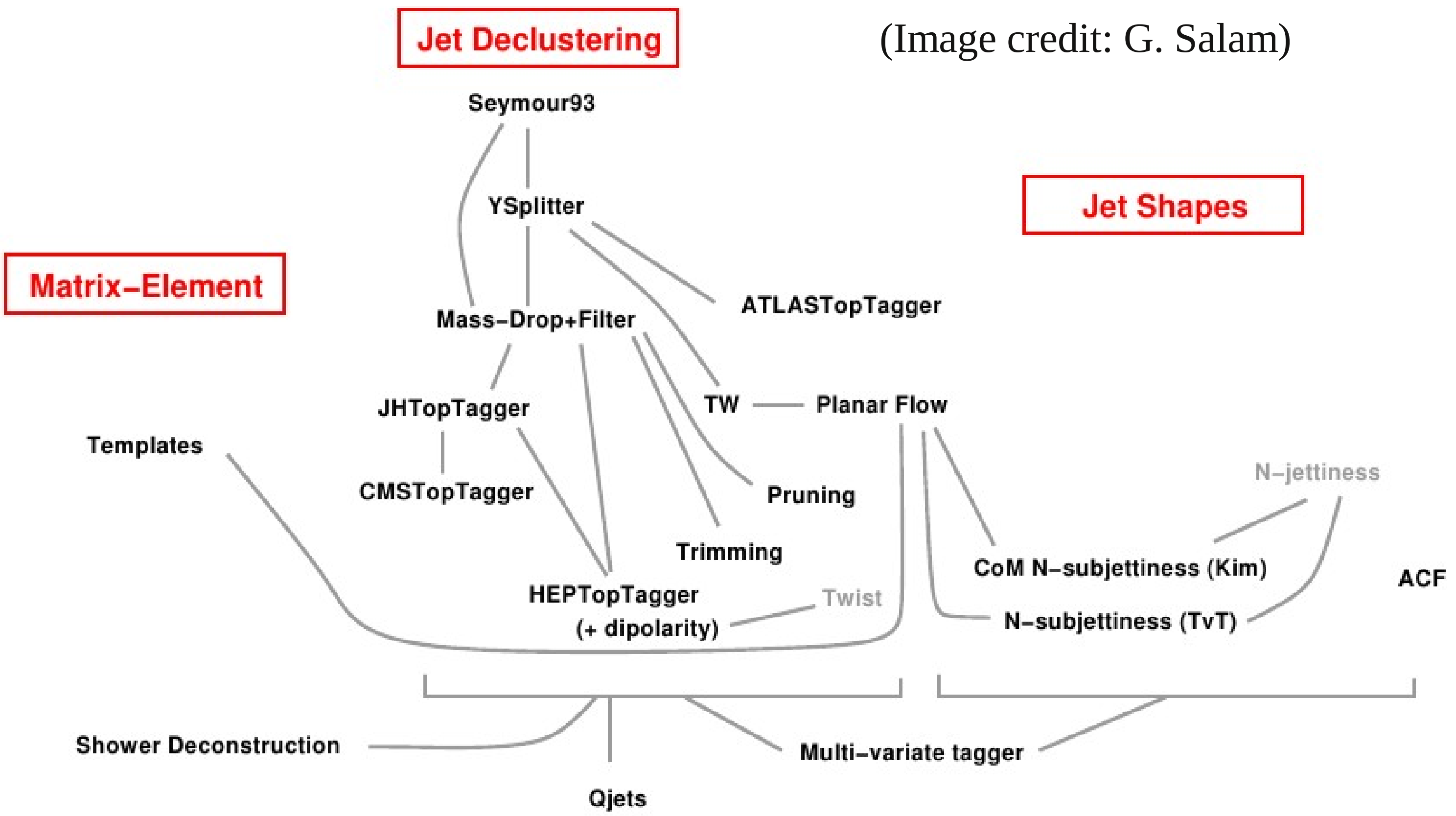
- Plenty of BSM models with high-p_T jets in final state. Lot of focus on this type of searches
- Need extremely well calibrated calorimeters and jets
- Particle-Flow algorithm merges information from tracks and calo, boost of performances.
- Pile-up energy subtraction techniques
- Final result: **calibration at percent level** for jets with p_T>100 GeV and central rapidities
- Missing transverse energy (MET) performances strictly related to jets, profits from these calibs.





V-tagging discriminators

(Image credit: G. Salam)



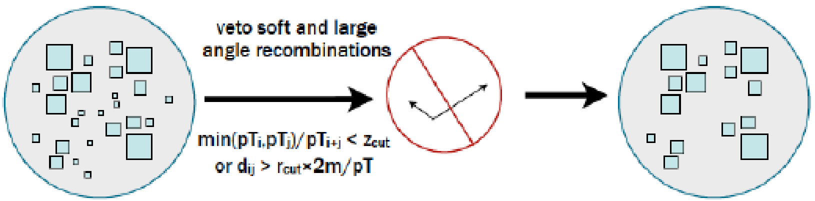
Field continuously growing, vast amount of phenomenological work in the last years.
State-of-the-art of the field given at the Boost'13 conference (link to website)

Jet substructure techniques

Jet Pruning (arXiv:0903.5081, arXiv:0912.0033)

- recluster jet constituents applying additional requirements at each recombination

$$z = \frac{min\left(p_{T,i}, p_{T,j}\right)}{p_{T,JET}} > 0.1 \qquad \Delta R < 0.5 \frac{M_{JET}}{p_{T,JET}}$$



- filter out soft and large angle QCD emissions

Mass drop (arXiv:0802.2470)

- de-cluster jet by stopping jet algo before last iteration → two subjets
- a jet is V-tagged if its mass drop μ_D < (analysis dependent) cut value

$$\mu_D = M_1 / M_{JET}$$

N-subjettiness (arXiv:1011.2268)

- topological compatibility with hyp of N subjets
- recluster jet, halting once reached N subjets
- τ_N : p_T-weighted sum over jet constituents of distances from closest subjet axis

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \, min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$$

These are NOT THE ONLY POSSIBILITIES ! Plenty of alternatives available and studied at CMS. See backup and references for a broader overview.

More on jet grooming

Jet Filtering

- recluster jet constituents applying additional requirements at each recombination
- filter out recombinations that are asymmetric or do not contribute a lot to jet mass
- Decluster original jet and for each backward step of the declustering check that
  - ✓ mass drop < 0.67
  - ✓ asymmetry of recombination $v < 0.09$ → $v = \frac{min(p_{T_i}^2, p_{T_j}^2)}{m_k^2} \Delta R^2$
  - ✓ if any of the two above fails: reject the subjet with smallest mass
- Finally, take all surviving jet constituents and re-cluster them with small radius
  → define kinematics of subjets

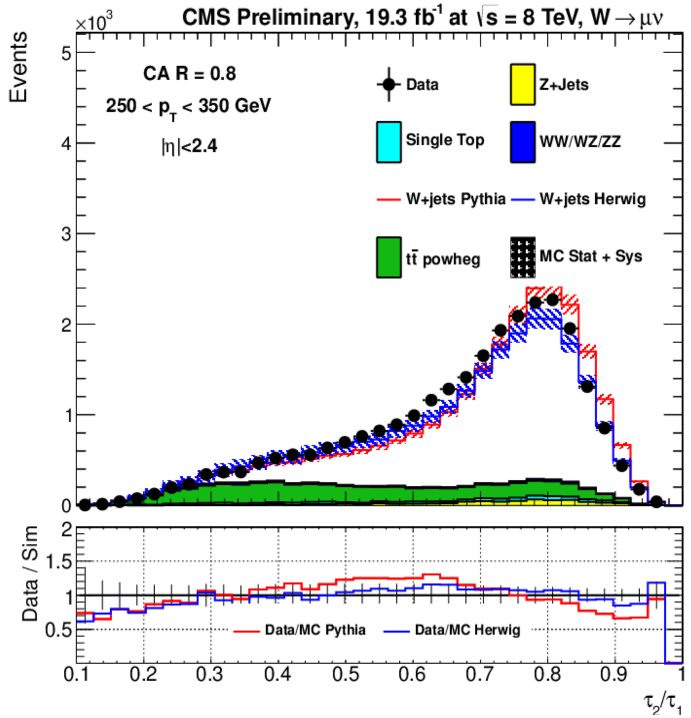
Jet Trimming

- recluster jet constituents applying dynamical p_T threshold
- recluster jet constituents with k_T jet algorithm, R=0.2
- use only constituents with $p_{T,sub} > 0.03\ p_{T,JET}$

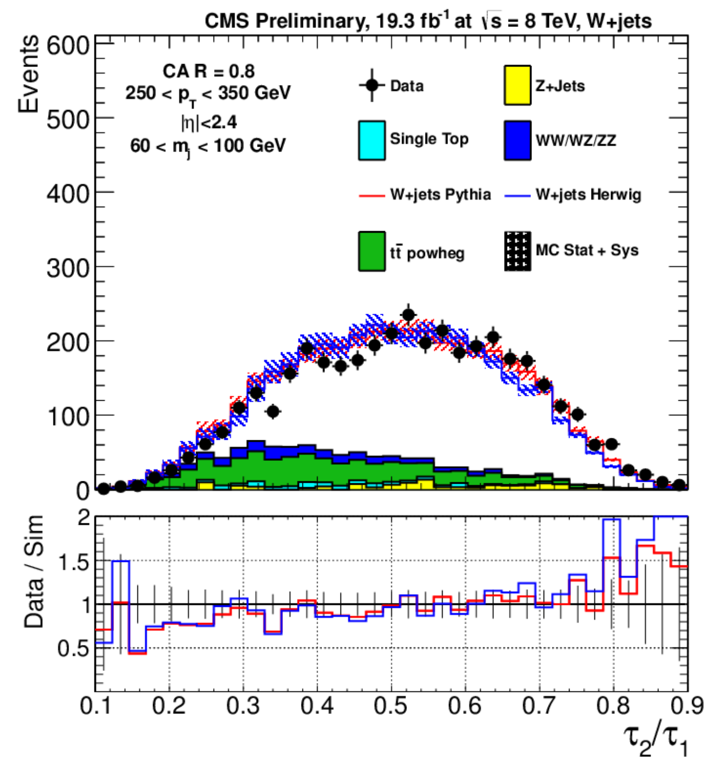
N-subjettiness

CMS-PAS-JME-13-006

(arXiv:1011.2268)



No pruned M_{JET} cut

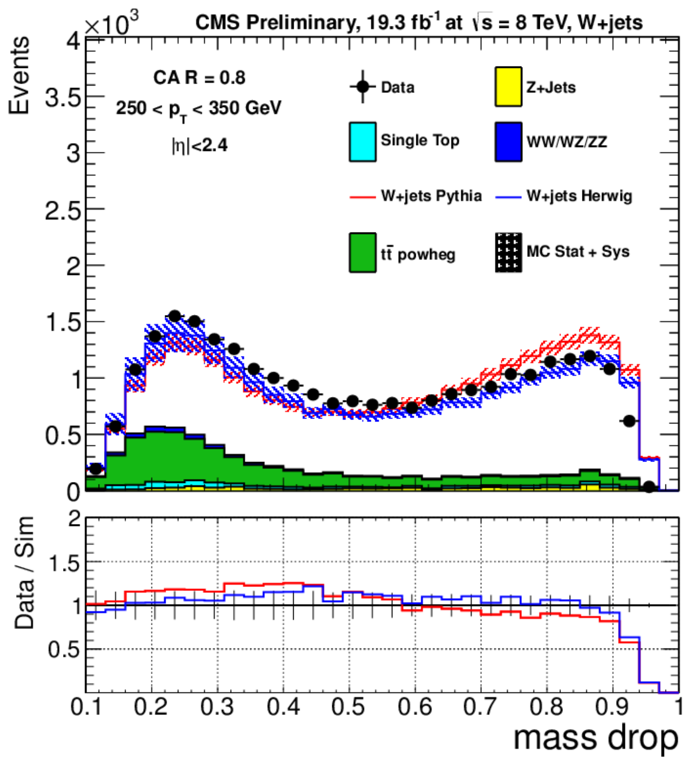


60 < M_{JET} < 100 GeV

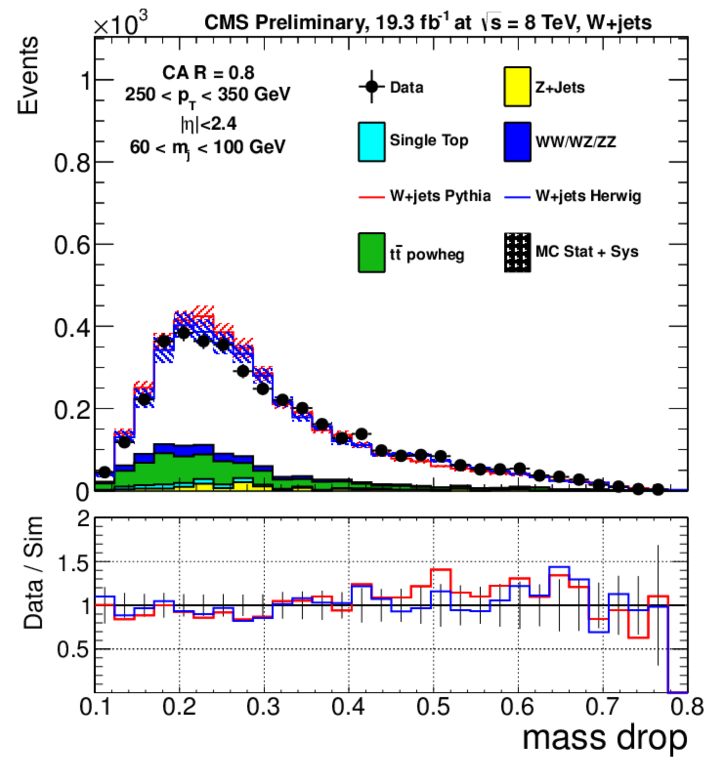
Mass drop

(arXiv:0802.2470)

CMS-PAS-JME-13-006



No pruned M_{JET} cut

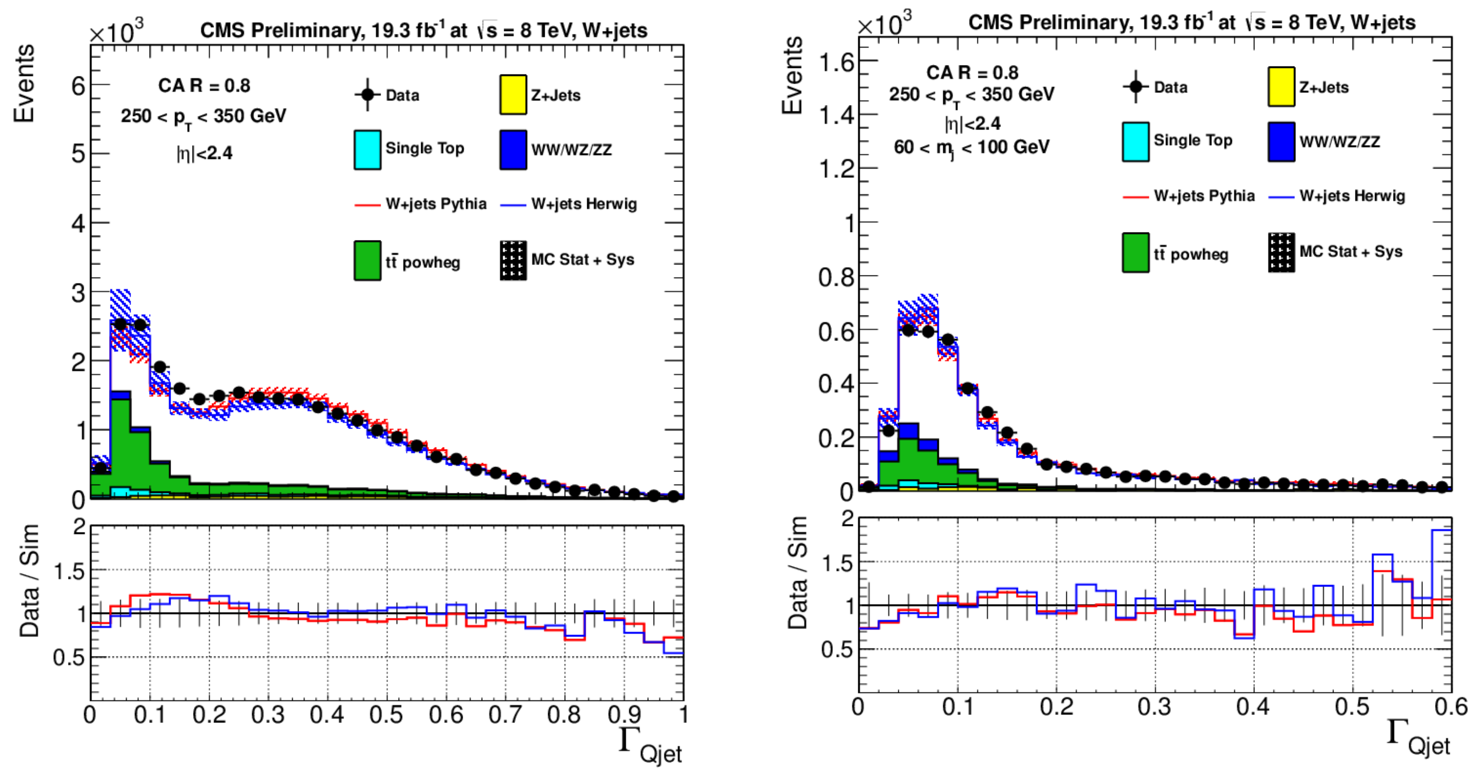


$60 < M_{JET} < 100$ GeV

Qjets volatility

CMS-PAS-JME-13-006

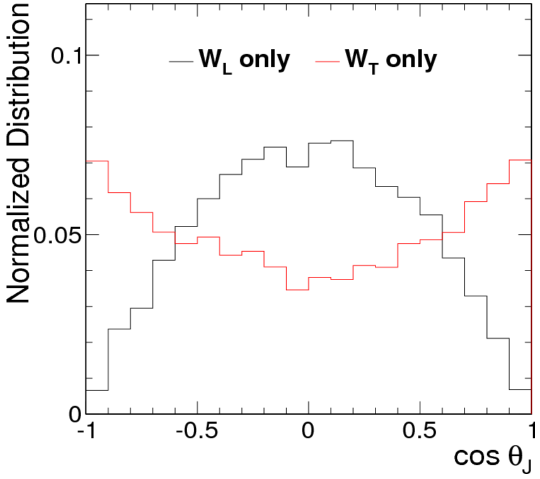
(arXiv:1201.1914)



No pruned M_{JET} cut

$60 < M_{JET} < 100$ GeV

Sensitivity to polarization

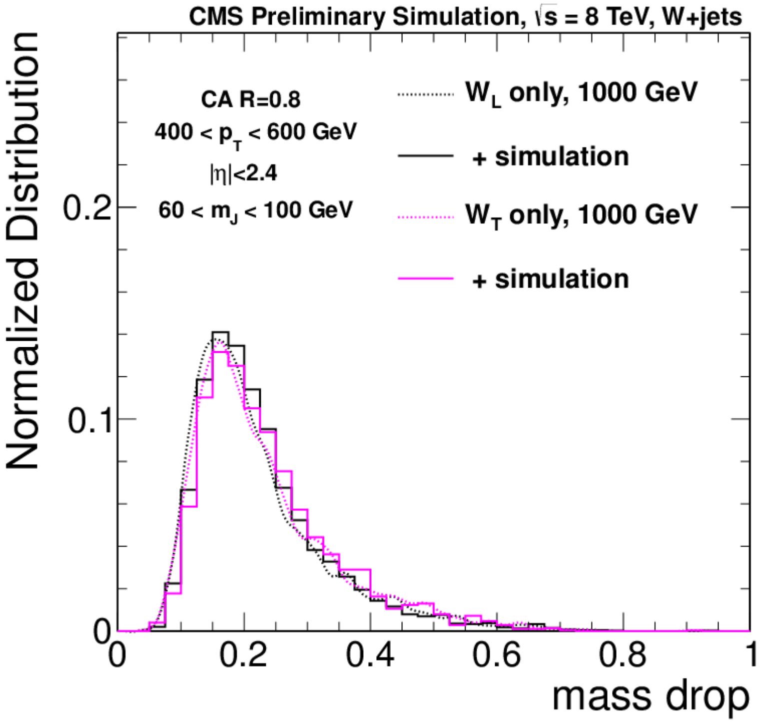


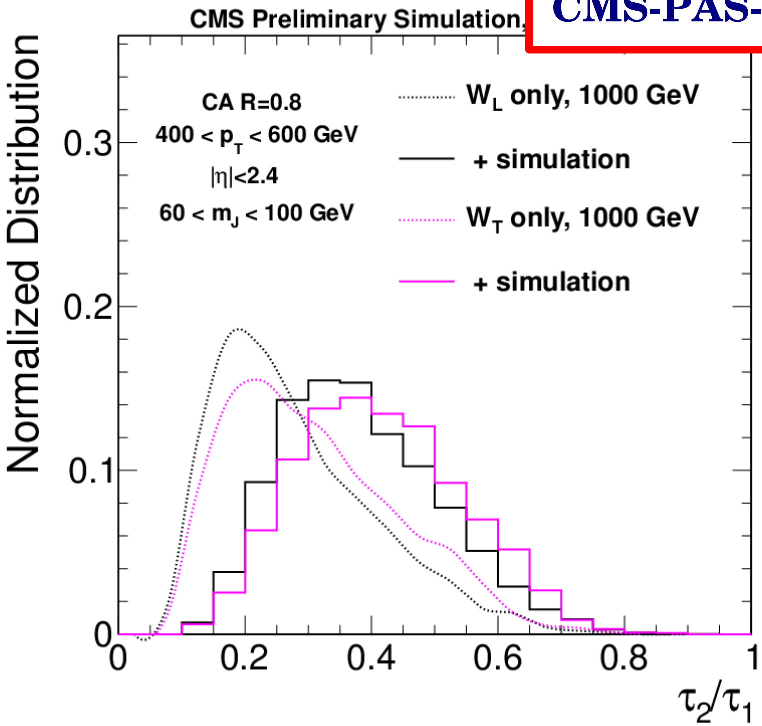
Polarization of W determines angular distributions of quarks
→ substructure of final merged jet

Mass drop insensitive to polarization of W
τ_{21} shows mild difference in performances between W_L and W_T

Angular resolution of subjets in W rest frame ~65 mrad

CMS-PAS-JME-13-006

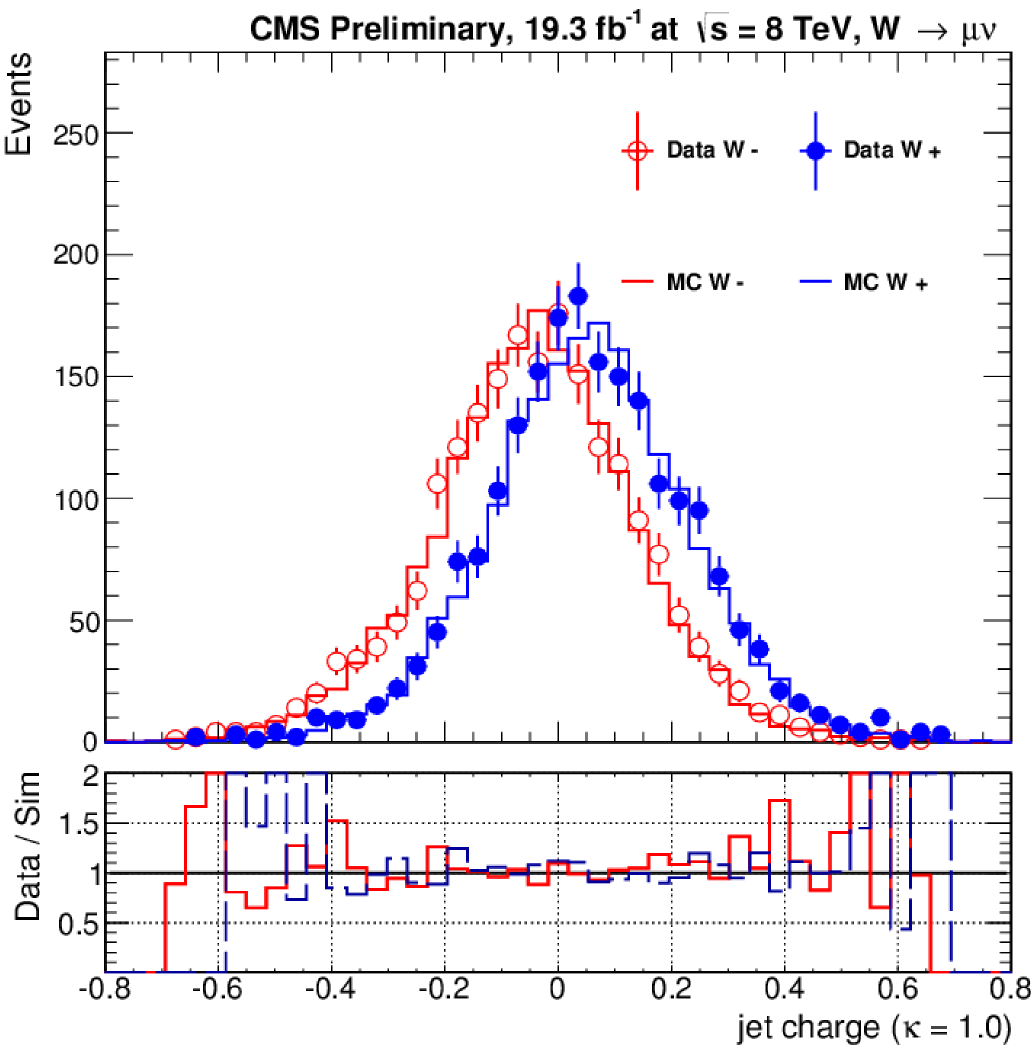




Jet charge

(arXiv:1209.2421)

CMS-PAS-JME-13-006



Jet charge: pT-weighted sum of charges in a jet

$$Q^k = \frac{\sum_i q_i (p_{T,i})^k}{\left(\sum_i p_{T,i}\right)^k}$$

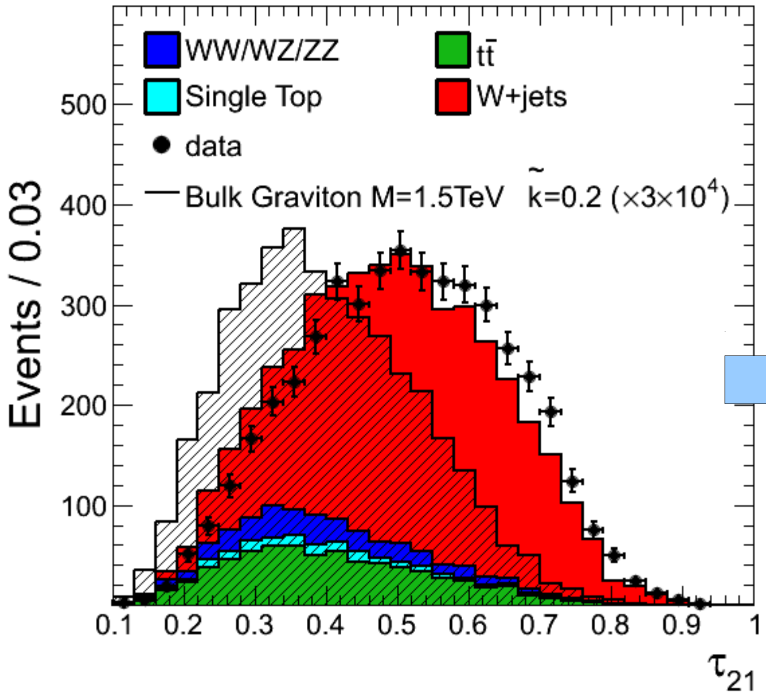
It works !!!

Clear distinction between W^+ and W^-

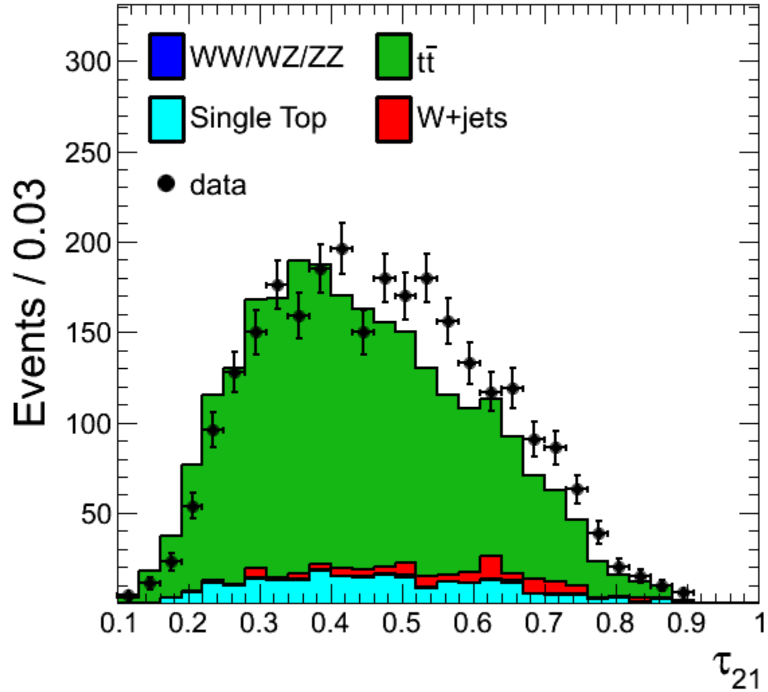
MC able to describe data

V-tagging efficiency

$X \rightarrow WW \rightarrow \ell + \nu + 1$ W-jet



$t\bar{t} \rightarrow \ell + \nu + 1$ W-jet + 2 b-jets

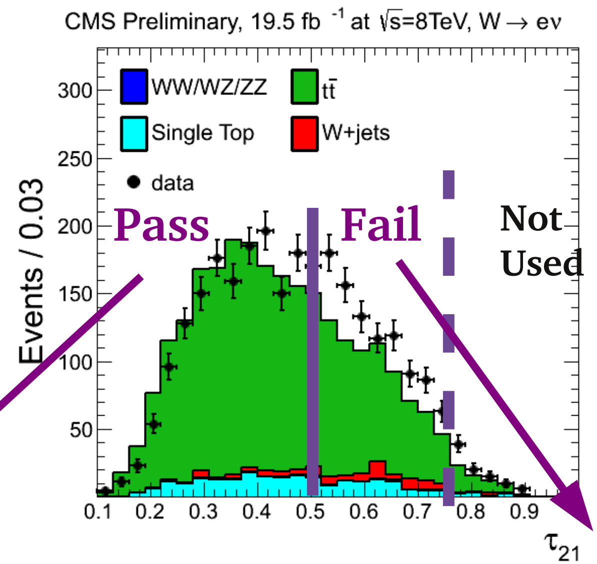


- Disagreements between data and MC in the key variables used for V-tagging → mismodel of V-tagging eff by the MC
- We can correct the efficiencies in MC comparing data and MC in a control sample with high-purity of $V \rightarrow qq$: semi-leptonic $t\bar{t}$

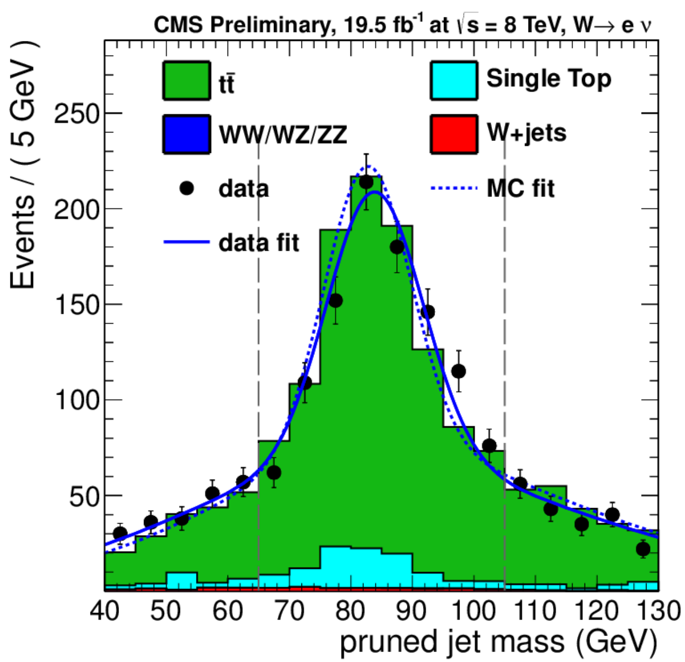
V-tagging efficiency

V-tag efficiency:

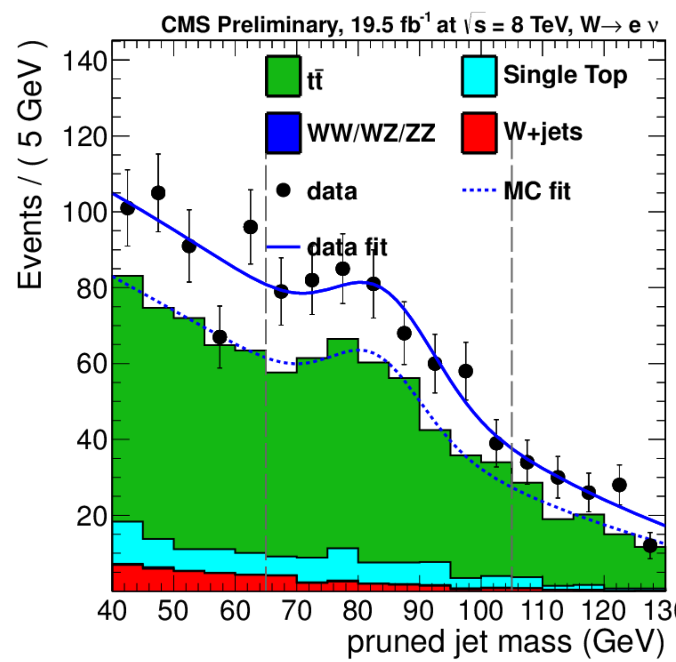
- simultaneous fit to pruned jet mass in "pass" and "fail" categories
- fit function describes resonant W-jet and combinatorial from not fully merged $t\bar{t}$



$$\varepsilon = \frac{N_{Pass}}{N_{Pass} + N_{Fail}}$$



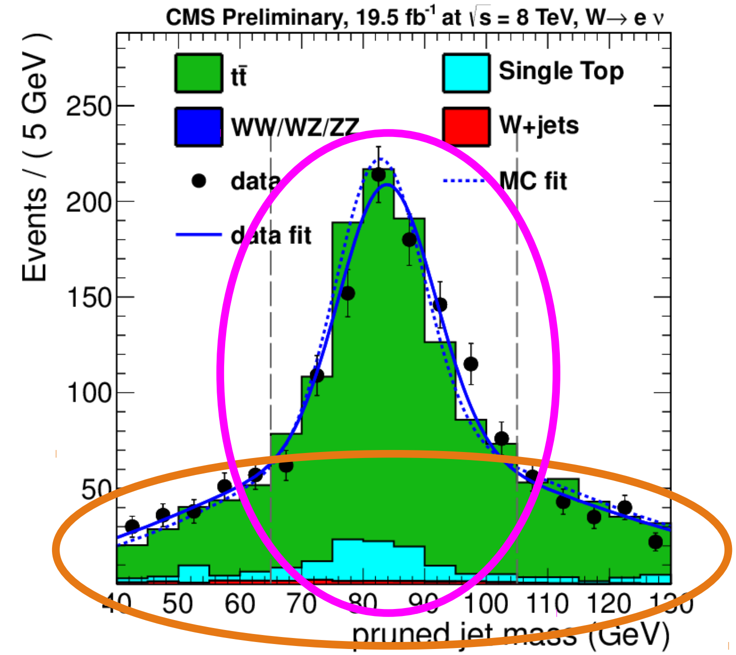
Pass



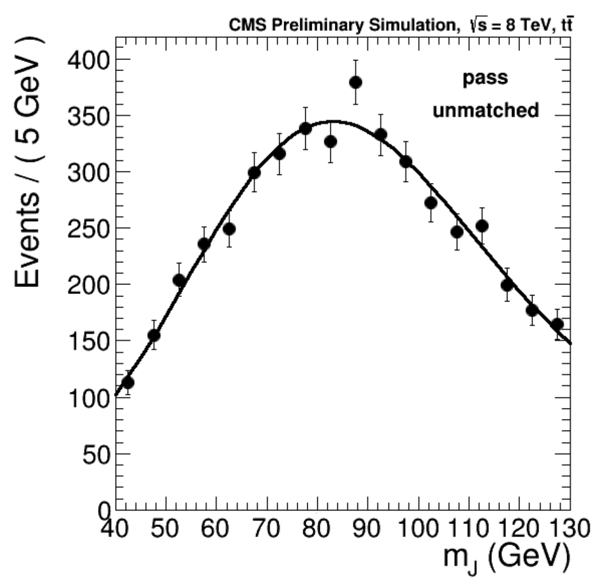
Fail

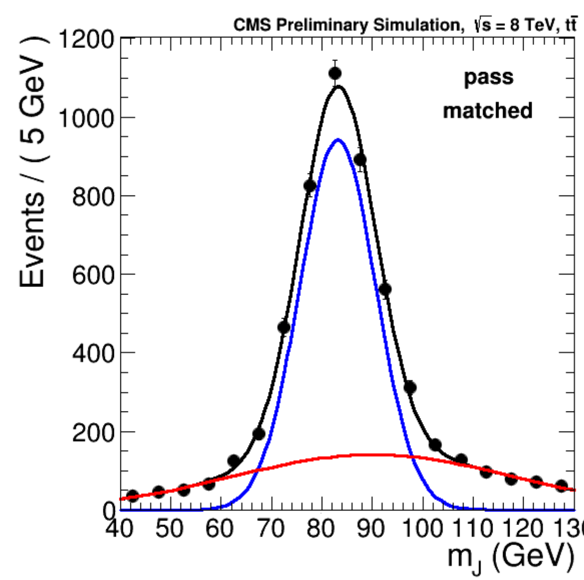
Pruned jet mass in tt control sample receives contribution from **genuine W-jets** and **combinatorial background** from QCD radiation. Combinatorial needs to be subtracted out from N_{Pass} and N_{Fail} for proper efficiency calculation.

→ **done via simultaneous fit**



Gen-matched MC jets
tell how to parametrize W-jet and combinatorial component





V-tagging efficiency

$$\varepsilon = \frac{N_{Pass}}{N_{Pass} + N_{Fail}}$$

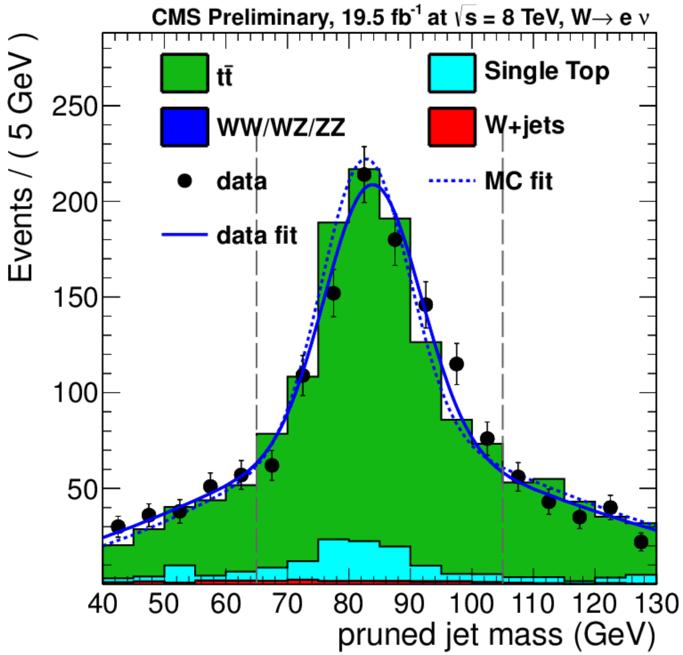
$SF = \varepsilon_{DATA} / \varepsilon_{MC}$

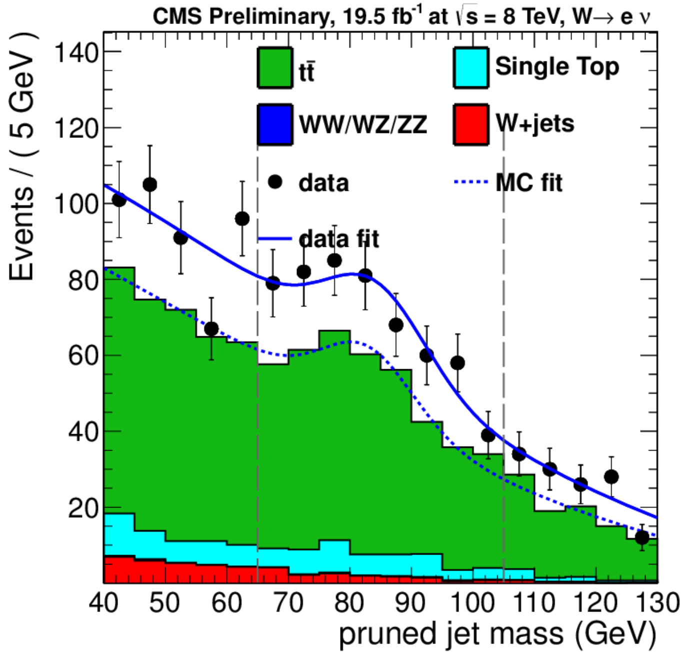
Scale factor tells us how much we must correct the V-tag efficiency of MC for compensating observed discrepancy with data.

$SF_{HP} = 0.93 \pm 0.08$

$SF_{LP} = 1.10 \pm 0.30$

Errors on SF are our syst unc on V-tagging: ~ 8%, by far dominant systematic of analysis; statistical in nature (limited statistics in $t\bar{t}$ control sample).





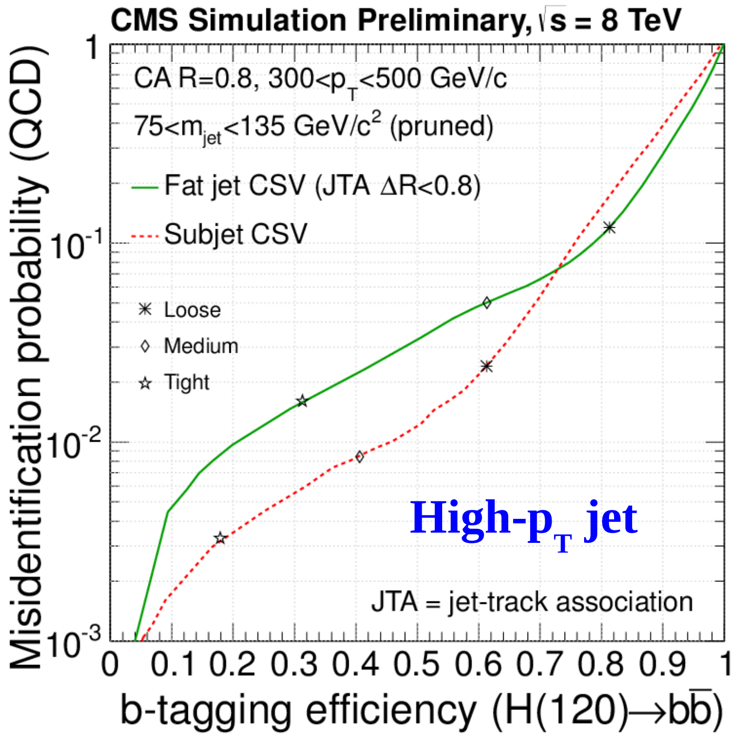
Subjet b-tagging

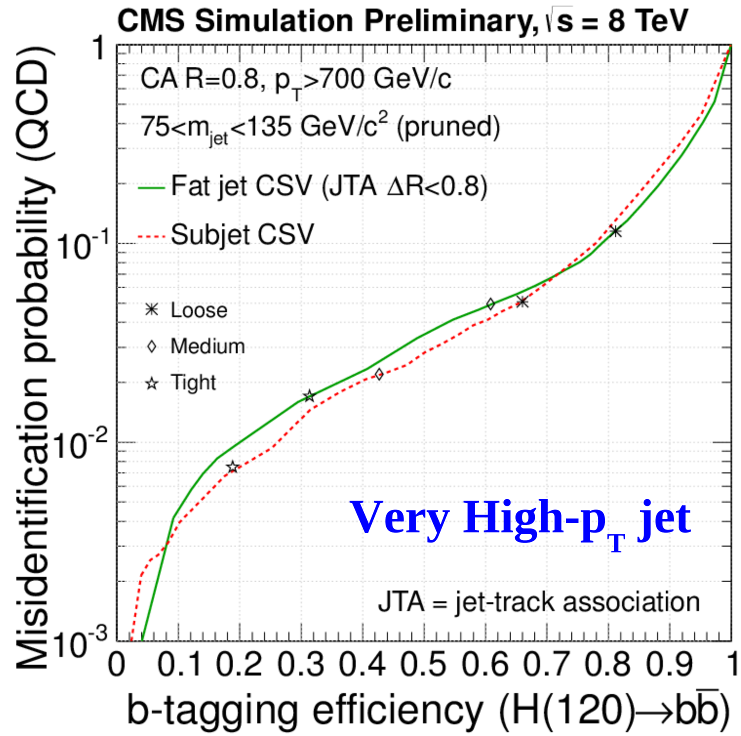
Use standard b-tagging tools at CMS (CSV discriminator). Inputs to b-tag discriminator: tracks inside a jet and subjet axes.

Very good description by simulation, data/MC b-tag scale factors same as in normal non-V jets.

Plot with data/MC validation (IP ?)

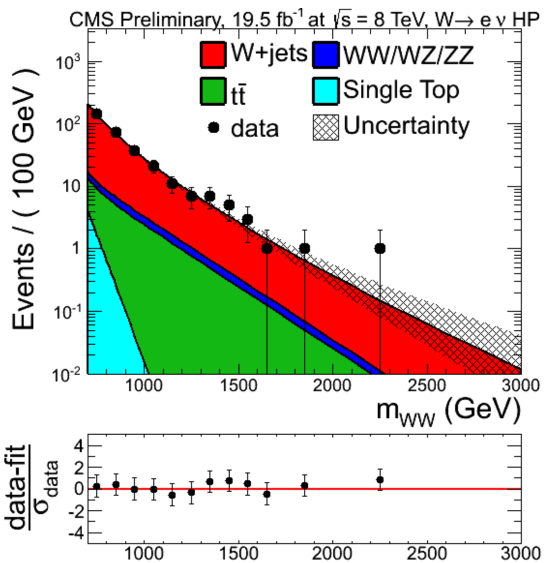
CMS-PAS-BTV-13-001



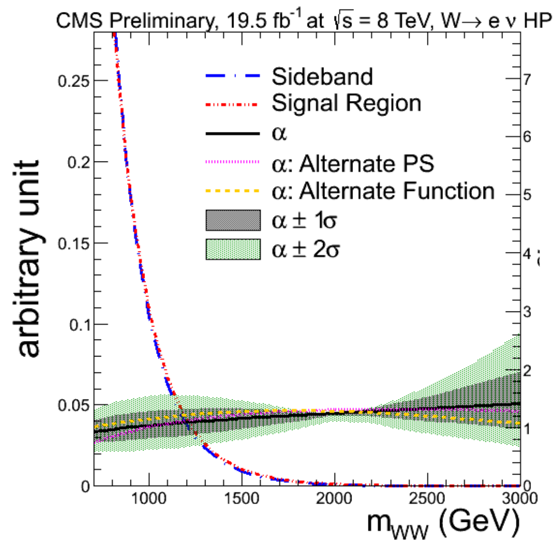


Background estimation in WZ semileptonic

CMS-PAS-EXO-12-021



x



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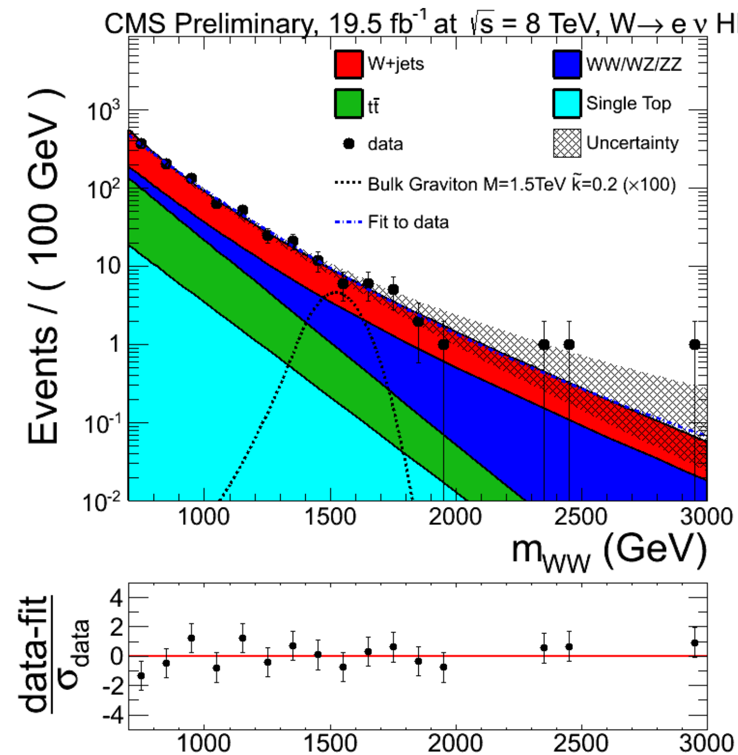


Ele HP
Sideband region

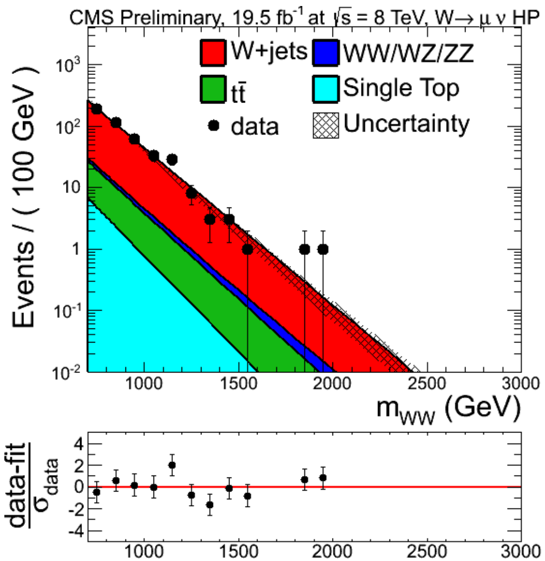
Ele HP
α-ratio from MC

Ele HP
Signal region

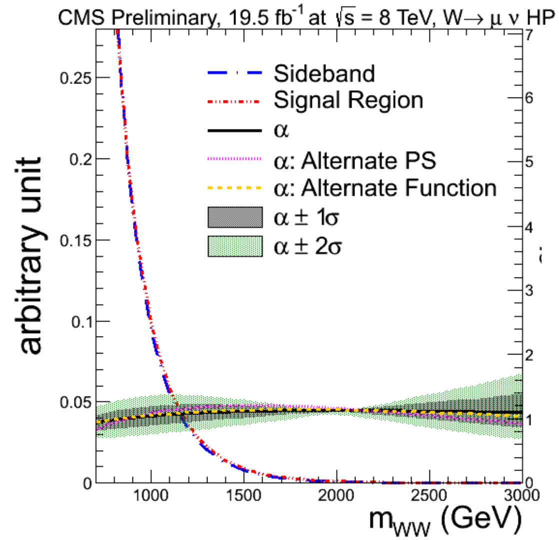
NOTE: minor backgrounds (SM VV, tt) taken directly from MC

Background estimation in WZ semileptonic

CMS-PAS-EXO-12-021



x



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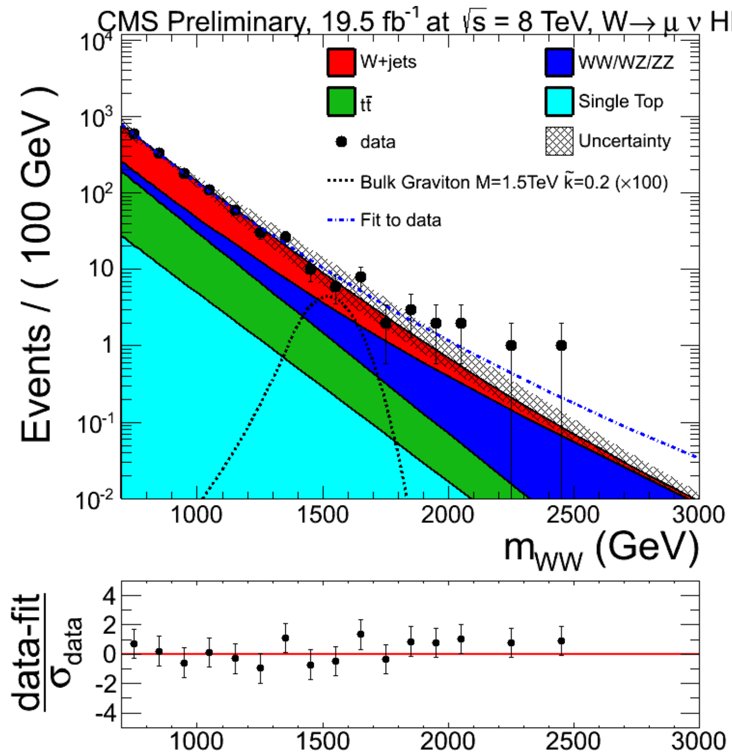


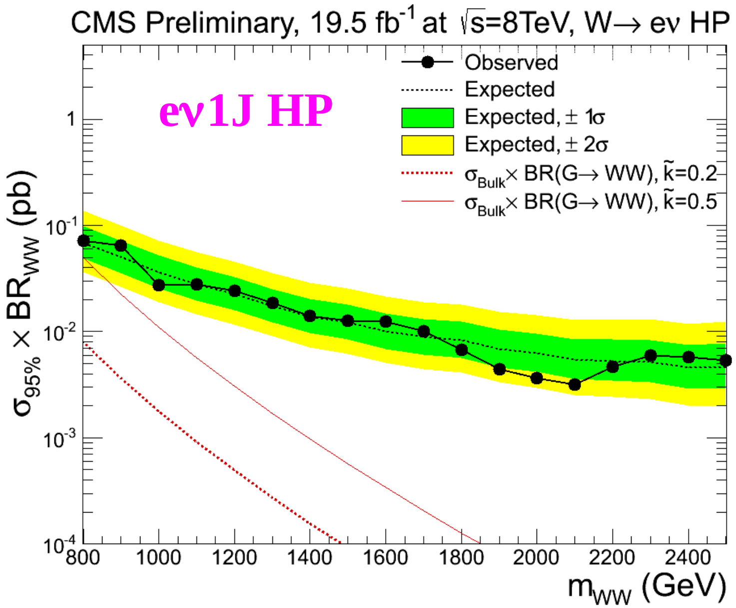
Mu HP
Sideband region

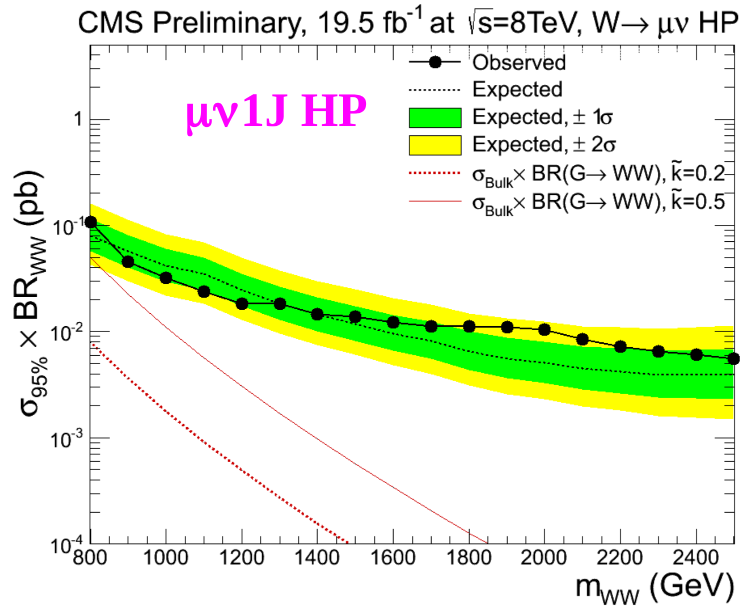
Mu HP
α-ratio from MC

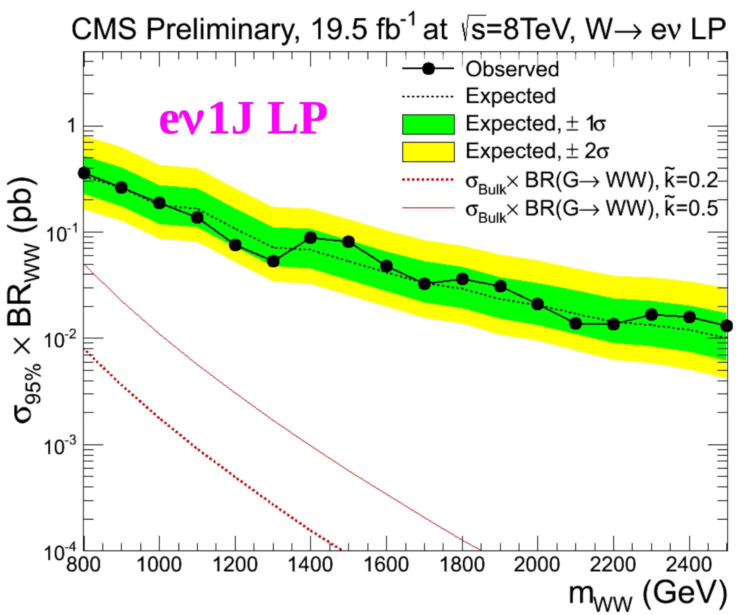
Mu HP
Signal region

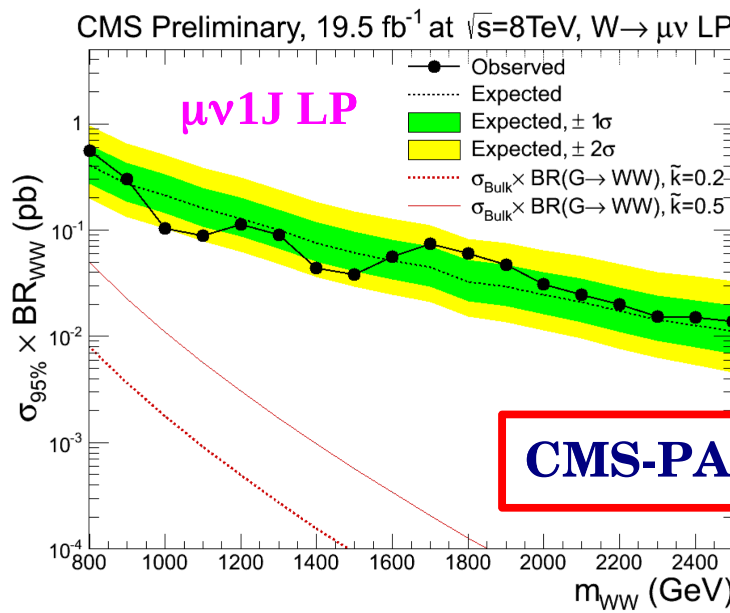
NOTE: minor backgrounds (SM VV, tt) taken directly from MC

WV semileptonic: upper limits









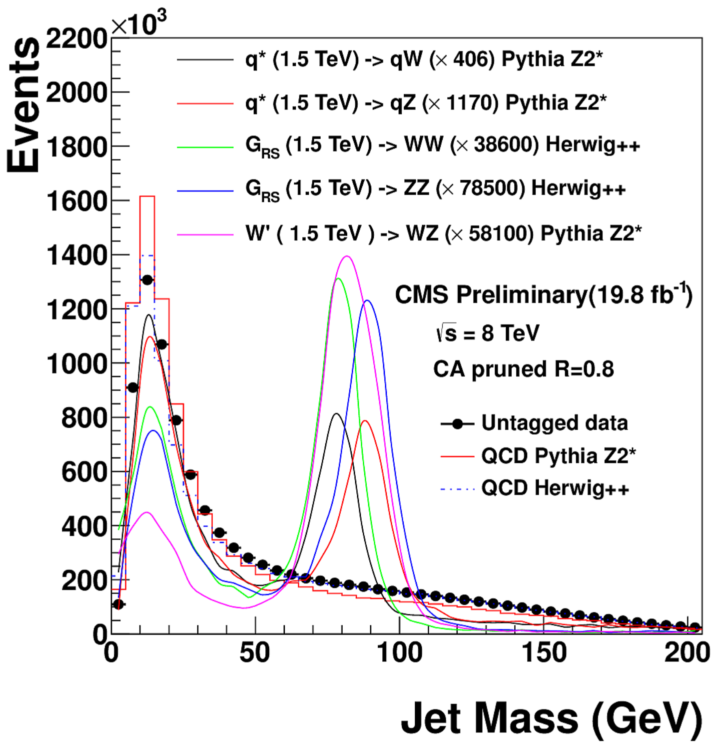
CMS-PAS-EXO-12-021

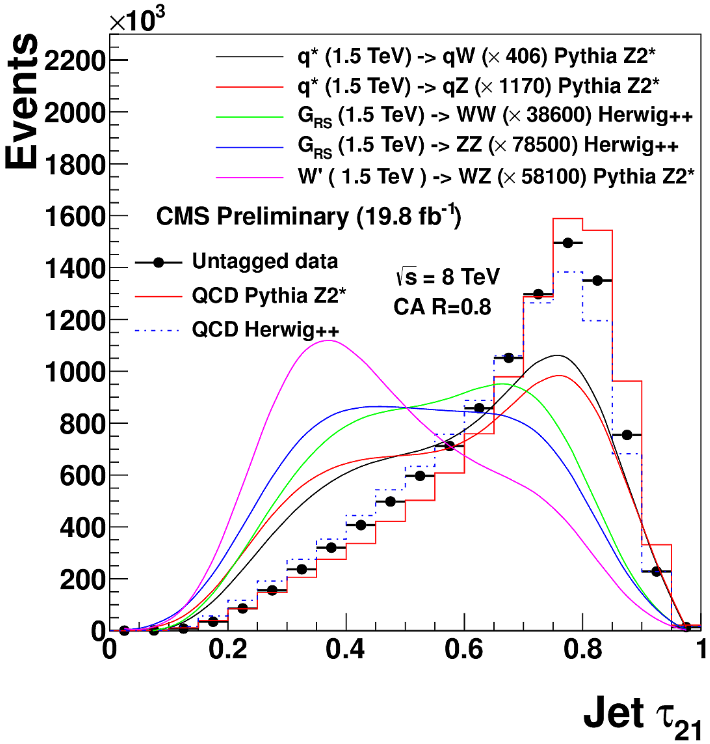
VV fully hadronic: signal models

Several BSM scenarios considered, differing by spin, V in final state.
Comparison between different hadronization models.

→ V-tagging has different performances

CMS-PAS-EXO-12-024

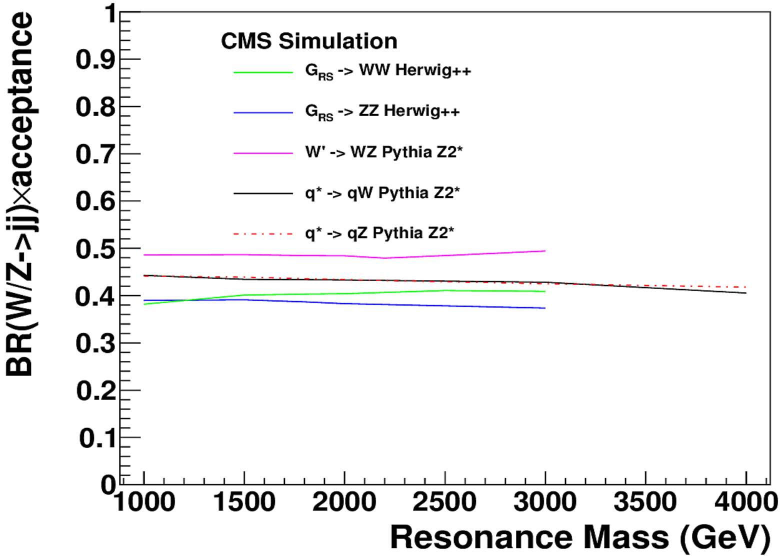


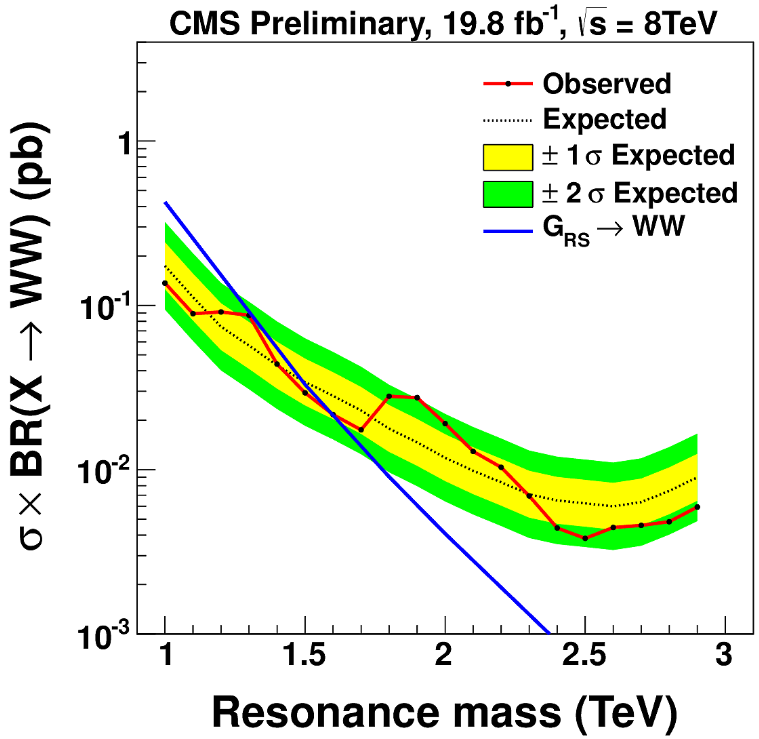


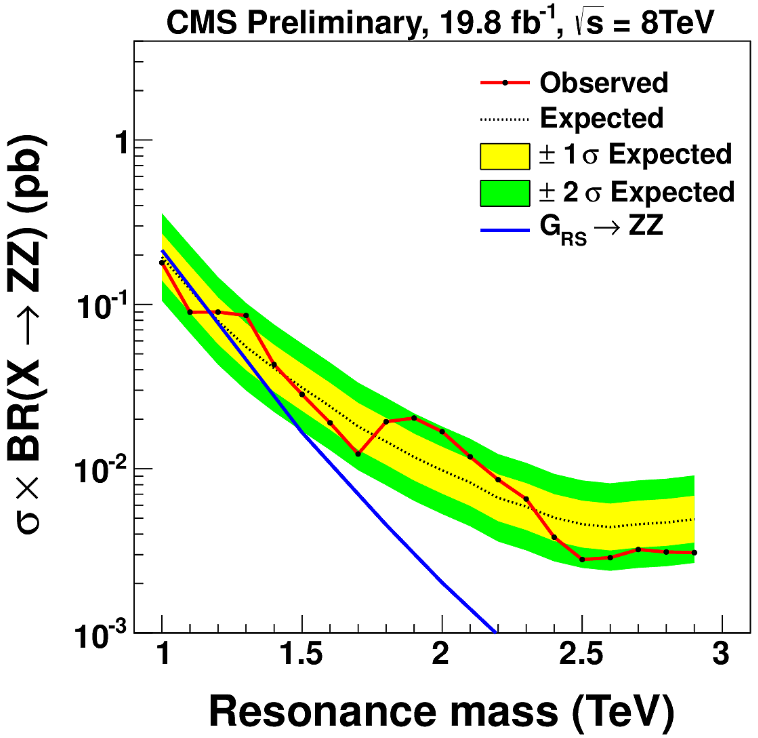
VV fully hadronic: WW vs ZZ

Choice of signal model has impact on signal efficiencies and limits.Compare RS1 limits (k/Mpl=0.1) assuming BR(RSG → WW) =100% and BR(RSG → ZZ) = 100%).

CMS-PAS-EXO-12-024



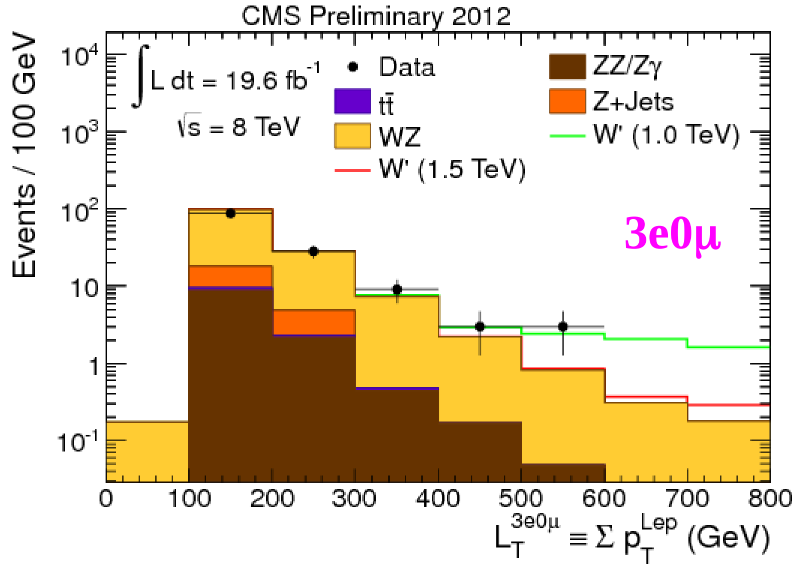


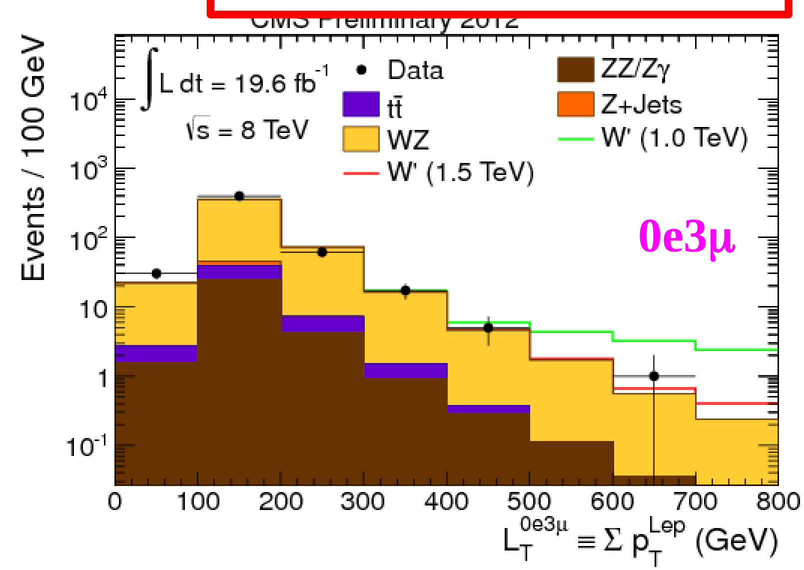


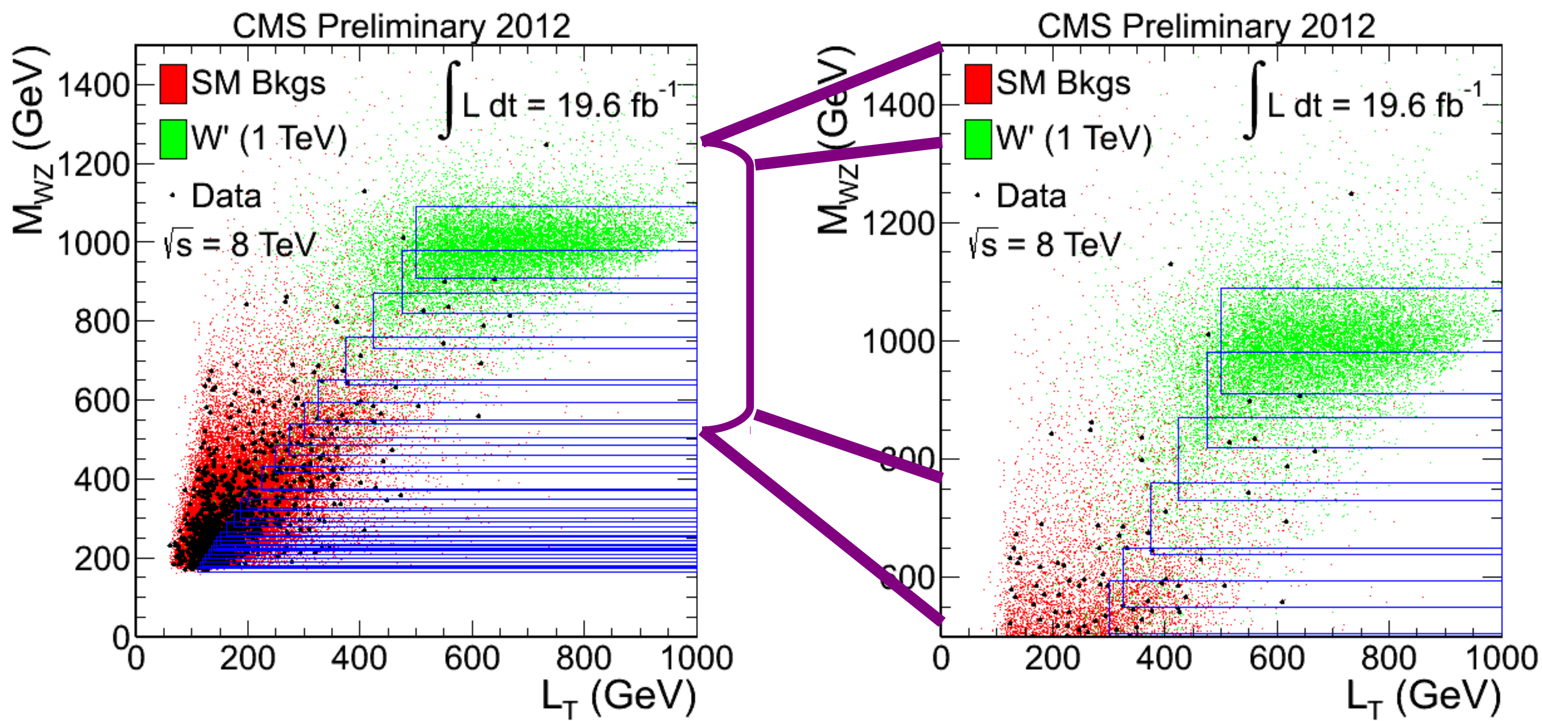
WZ $\rightarrow 3\ell+\nu$: distributions

CMS-PAS-EXO-12-025

$$L_T \equiv \sum_{lep} p_{T,lep}$$

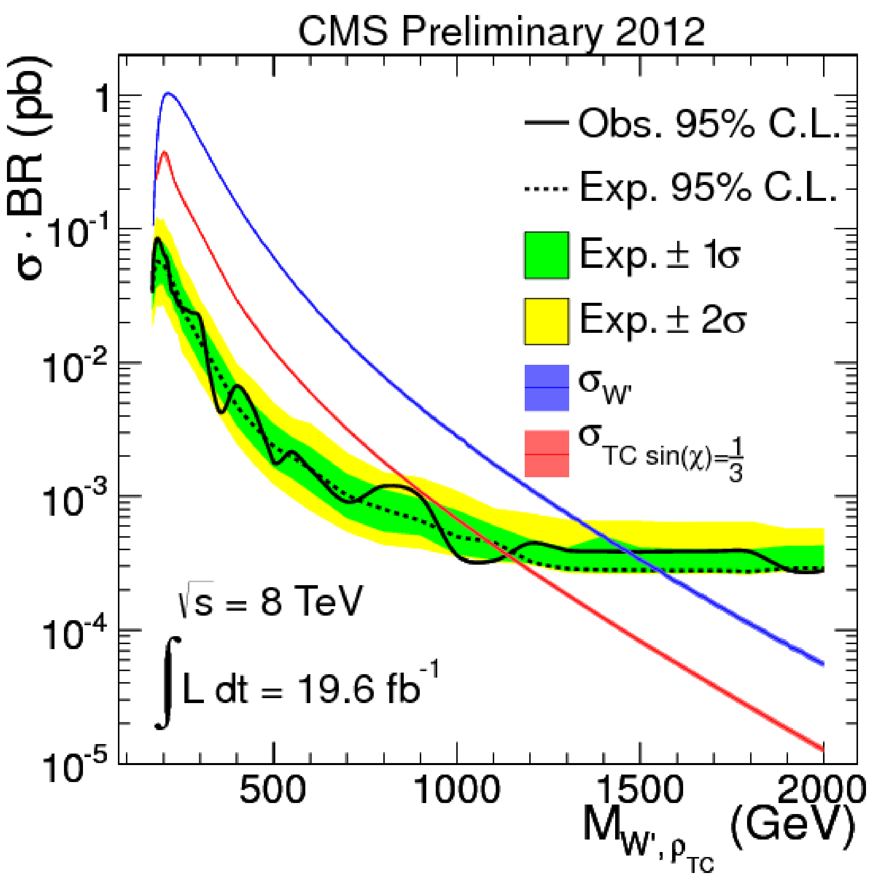




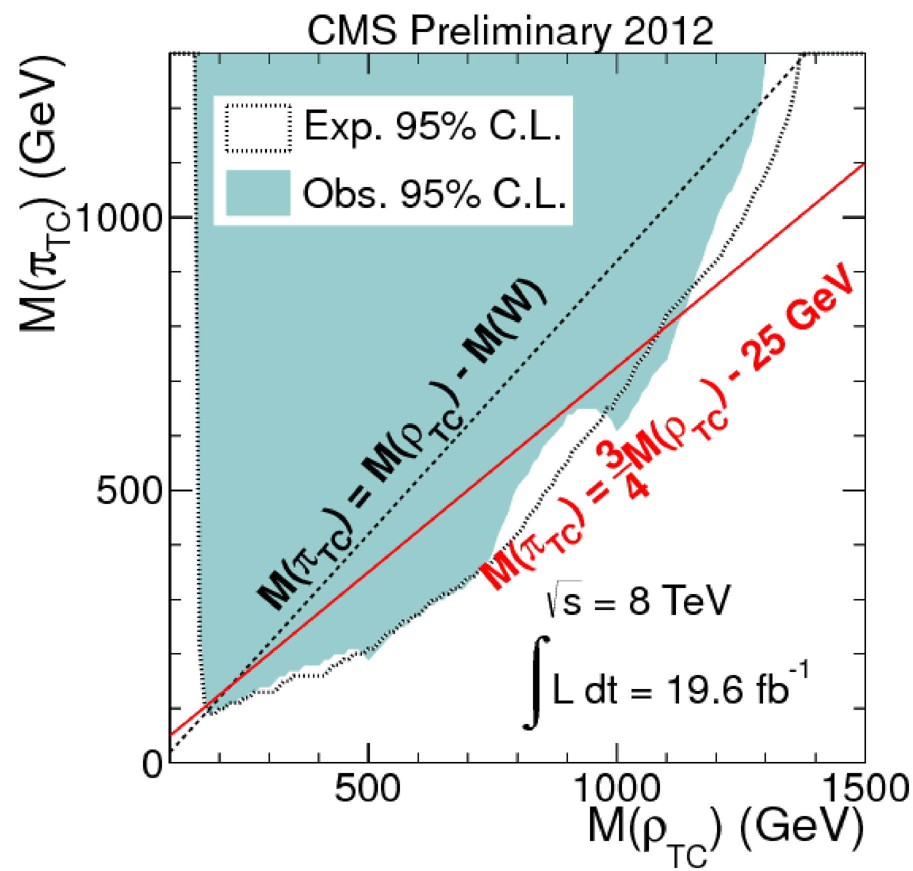


WZ $\rightarrow 3\ell+\nu$: Exclusion Limits

CMS-PAS-EXO-12-025



Limit on SSM W'
+
Limit on M(ρ_{TC}) fixing
LSTC parameter sin(χ)=1/3



Limit in M(ρ_{TC}) vs M(π_{TC}) plane
(Low-Scale TC)