Searches for RS Gravitons at the CMS Experiment

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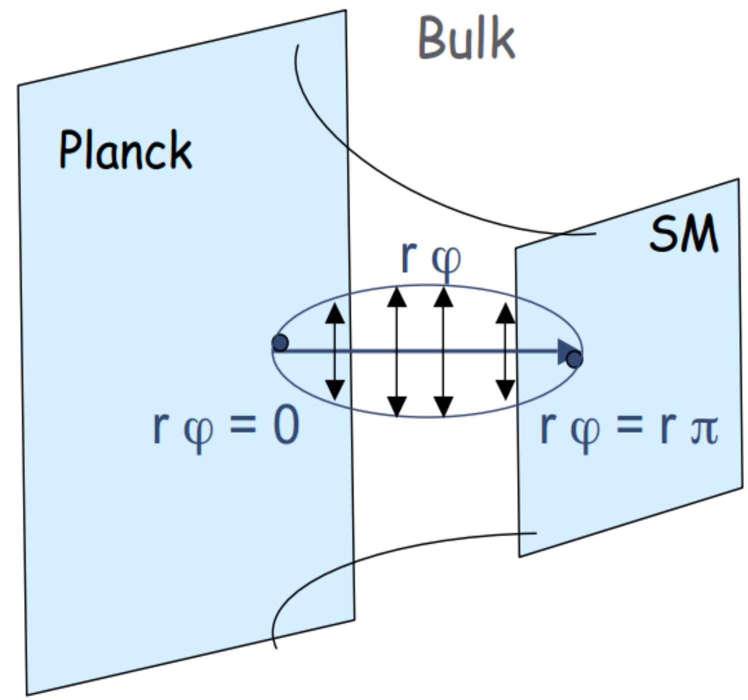
Outline

- The Randall-Sundrum model
- The CMS detector
- Overview of CMS results
- Summary

The Randall-Sundrum Model

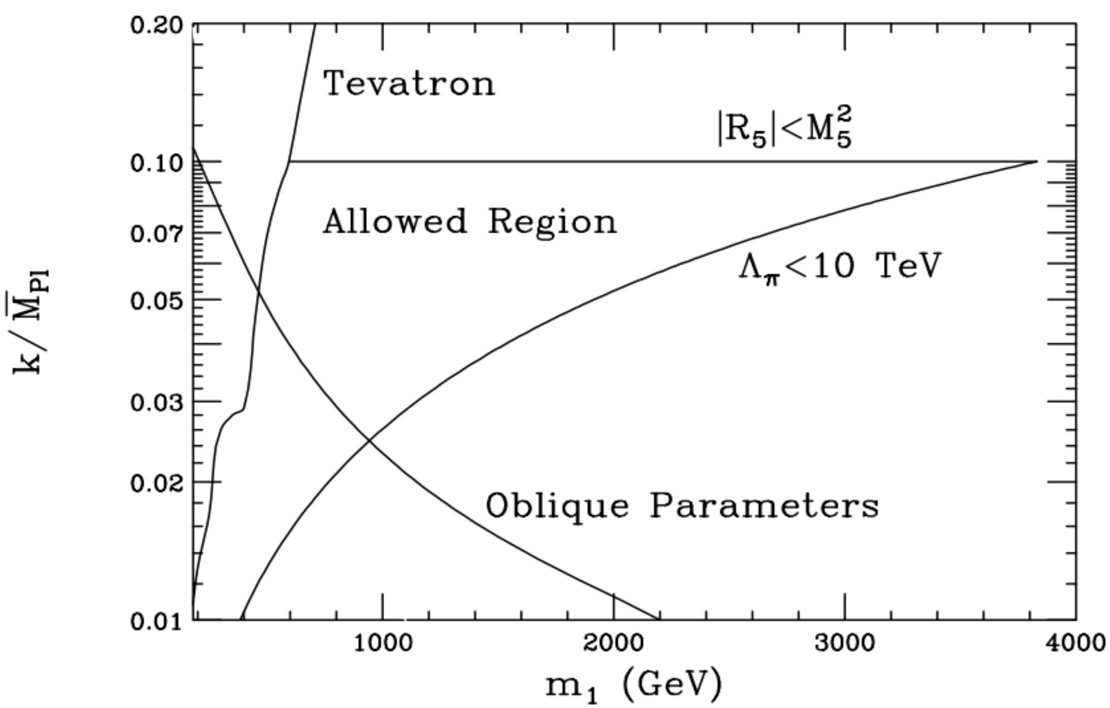
- Involves a finite five-dimensional bulk that is extremely warped and contains two branes: the Planckbrane and the Tevbrane (our home with the Standard Model particles)
- The Planckbrane has positive brane energy, and the Tevbrane has negative brane energy. These energies are the cause of the extremely warped spacetime.
- Answer to the hierarchy problem
- k/M_{Pl} mass scale parameter of the theory
- Compactification radius: r
- New coordinate: φ ($-\pi \le \varphi \le \pi$)



The Randall-Sundrum Model

Two free parameters for RS model:

1. The coupling parameter $c = k / M_{Pl}$,
   the ratio of the 5-dimensional curvature to the reduced Planck mass
2. M_G, mass of the graviton



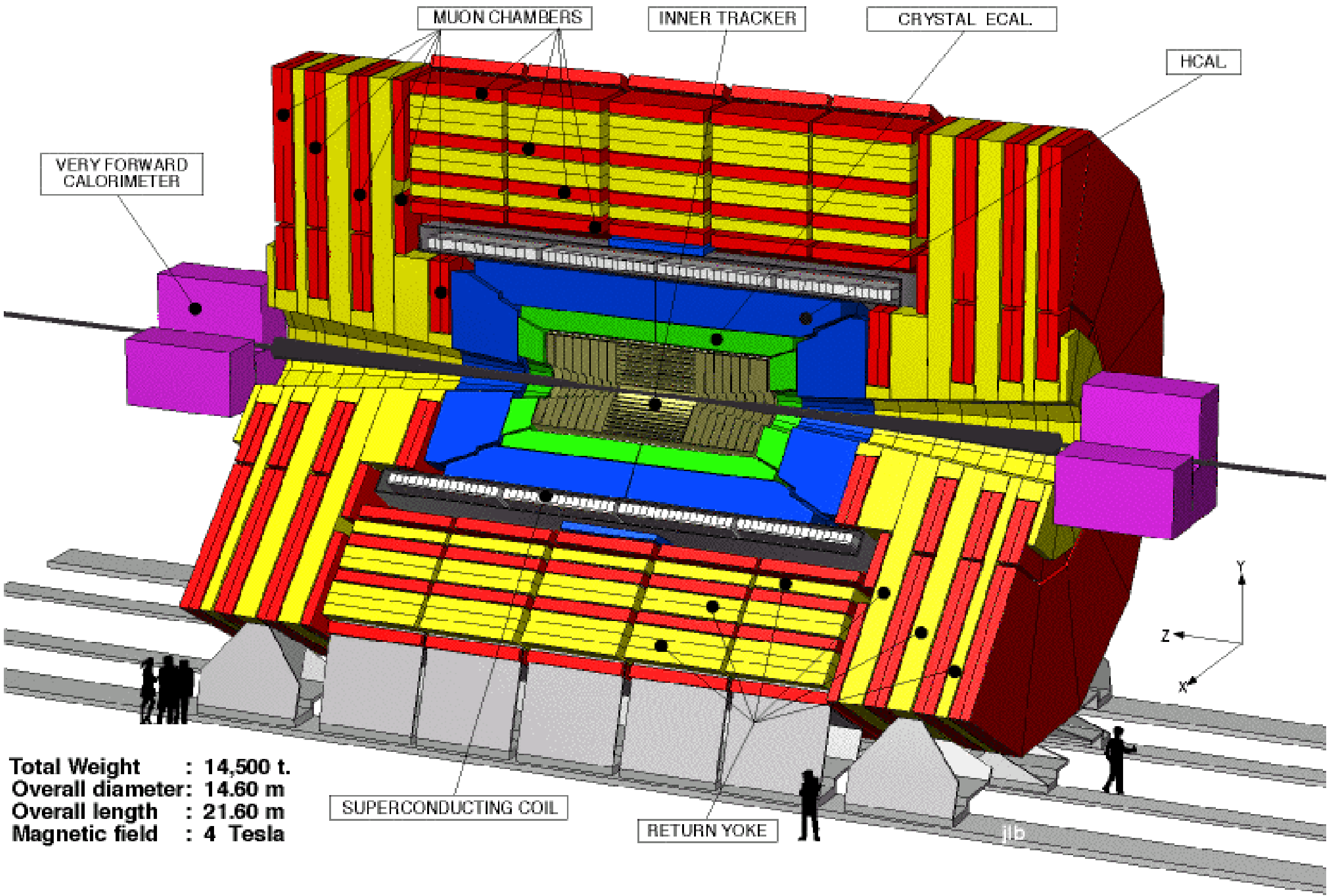
Piotr Traczyk, Grzegorz Wrochna
arXiv:hep-ex/0207061

Bulk graviton

- A Randall-Sundrum (RS) graviton allowed to propagate in the bulk.
- Evolution of RS warped extra-dimensions: spin-2 G* lives near TeVbrane, close to H, top and V_L
- Graviton couples preferentially due to overlap integrals to WL. Coupling WT suppressed by overlap integrals.
- Better agreement w with EWK precision tests that traditional RS1 model.
- Production process at LHC similar to SM higgs decays preferentially to t, then W, Z and H.
  - BR to diphotons is zero.

Ref: arXiv:hep-ph/0701186

The CMS detector



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

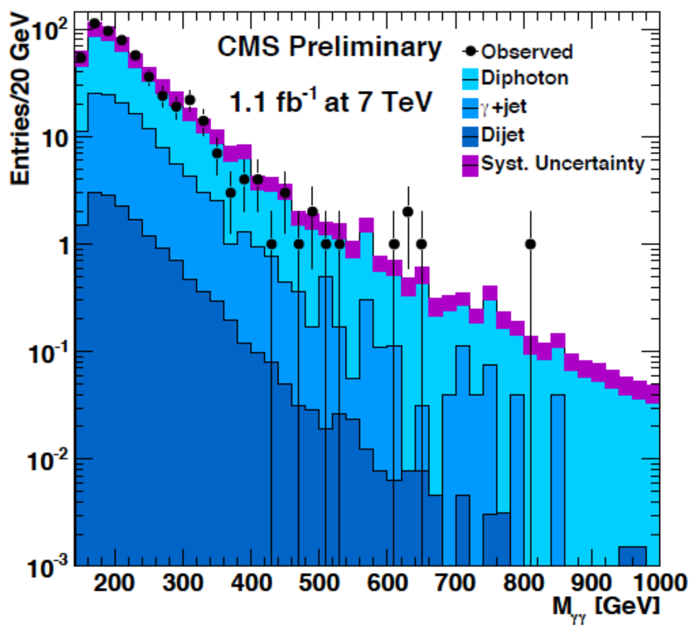
Overview of CMS results

Process	Luminosity (fb^{-1})		Search Range (GeV)
	7TeV	8TeV	
γγ	1.1		(800,2000)
ZZ->qνν	4.7		(1000,1500)
ZZ->qqll	4.9		(400,1000)
JJ		4.0	(1000,1400)
bb		19.6	(1000,4000)
ll		4.1	(300,3000)
tt		19.6	(1000,3000)
VV->JJ		19.8	(1000,4000)
ZZ->llJ		19.8	(600,2500)
WW->lνJ		19.5	(800,2500)

RSG->γγ

Events selections:

- Utilize various isolation variables to discriminate against jets misidentified as photons
- pT of the photons > 60GeV
- Mγγ > 120 GeV



Diphoton invariant mass distribution after selection

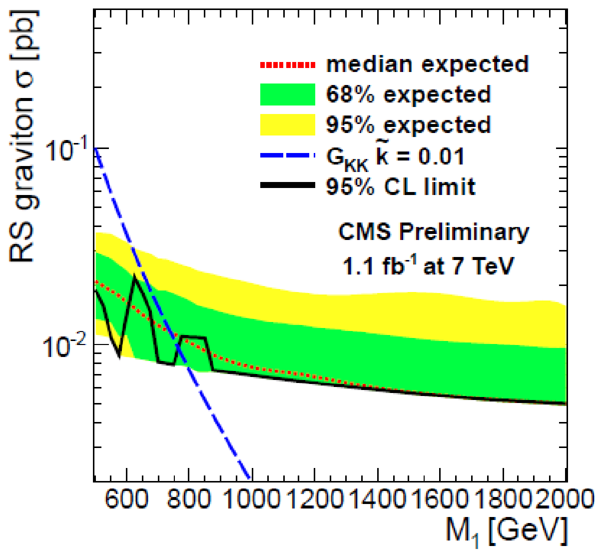
Main Backgrounds

- γγ
- γ+jets
- jets

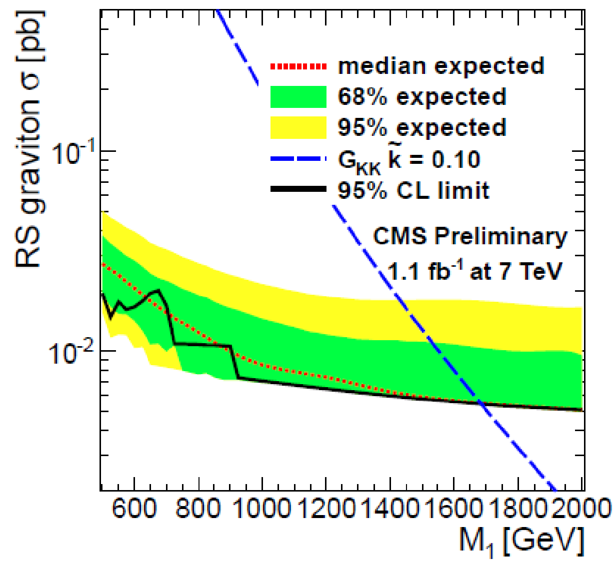
Technique

- use a data-derived photon fake rate
- Use the sum of three exponentials for the background parametrization

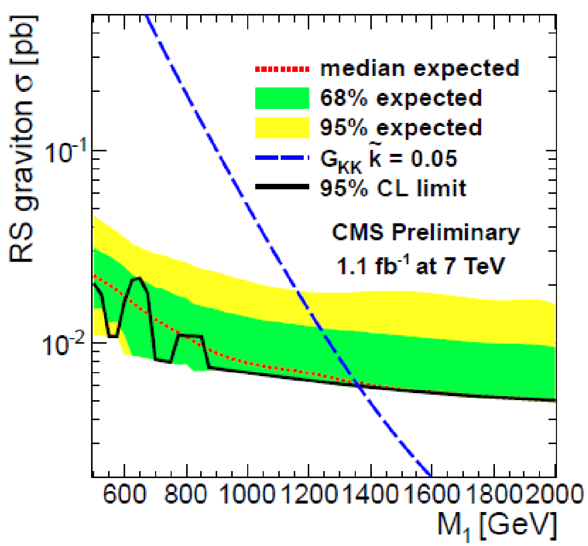
RSG->γγ (2)



k=0.01



k=0.1



k=0.05

The lower limits to date on the Randall–Sundrum graviton mass are set in the range of 0.76–1.73 TeV, for values of the coupling parameter between 0.01–0.10.

CMS PAS EXO-11-061

7TeV

RSG->ZZ->qqvv

Events selections:

- Leading Jet pt > 300 GeV
- MET>300 GeV
- Reject events with isolated leptons
- Mj>70GeV
- Jet-met transvers mass>900GeV

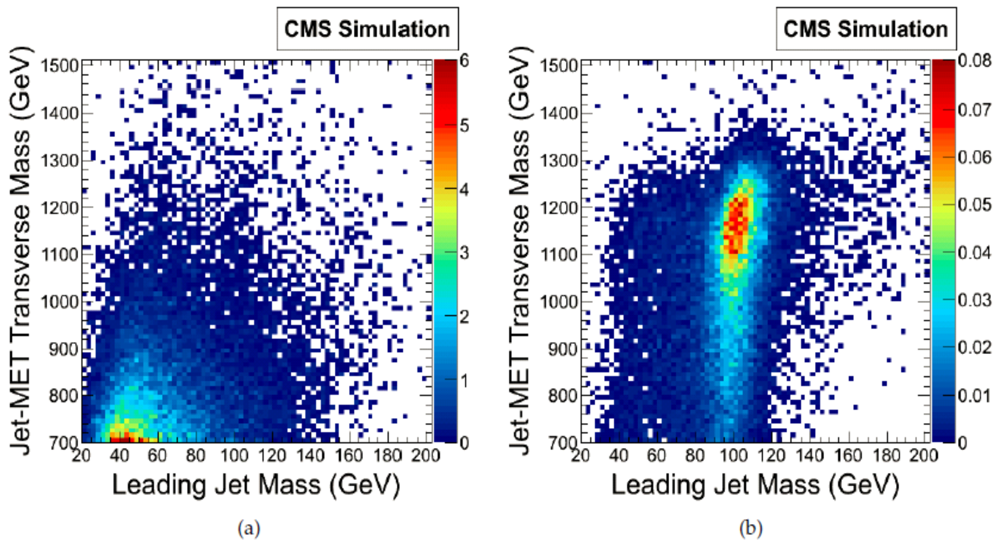


Figure 1: Joint distributions of leading jet mass jet-$\not{E}_T$ transverse mass, for (a) Standard Model simulated samples (b) RS sample with $M_G = 1250\,\text{GeV}$ and $k/M_{Pl} = 0.05$.

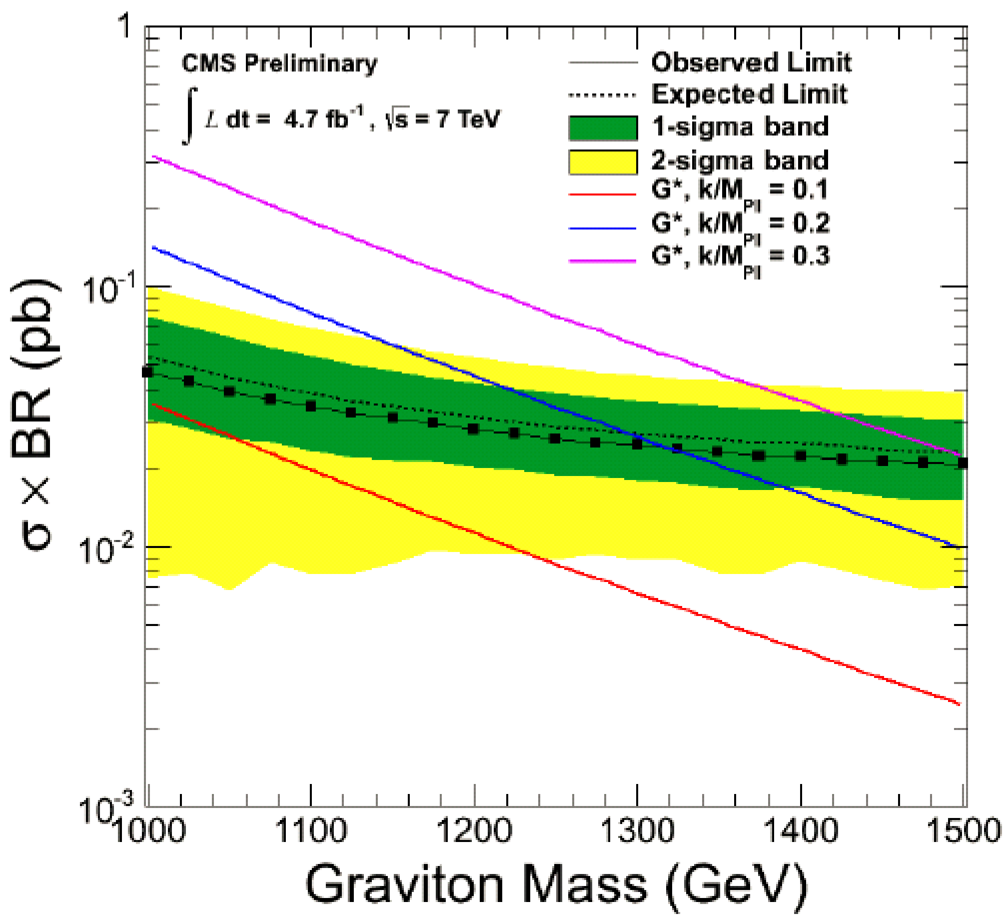
Main Backgrounds

- WW
- WZ
- ZZ

Technique

- Boosted Z->qq could be detected as one single jet
- AK7 jet used for Z jet
- Data-driven background estimation

RSG->ZZ->qqvv (2)



Exclude k=0.11 below 1000 GeV

CMS PAS EXO-11-102 Phys. Lett. B 718 (2013) 1208 7TeV

RSG->ZZ->qqll

Events selections:

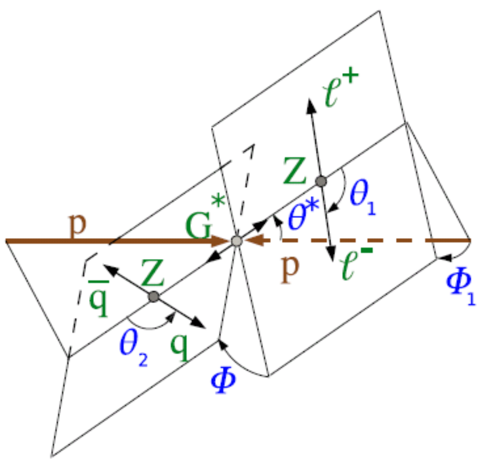
- Lepton pt>40,20 GeV
- Jet pt >30 GeV
- Mjj in (75,105) GeV
- Mll in (70,110) GeV
- angular LD 0.277, 0.353, 0.212 for 0,1,2 btag category

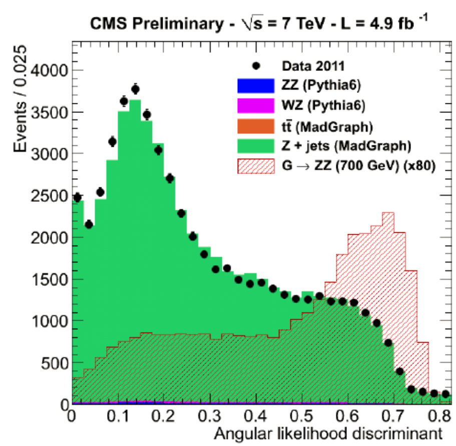
Main Backgrounds

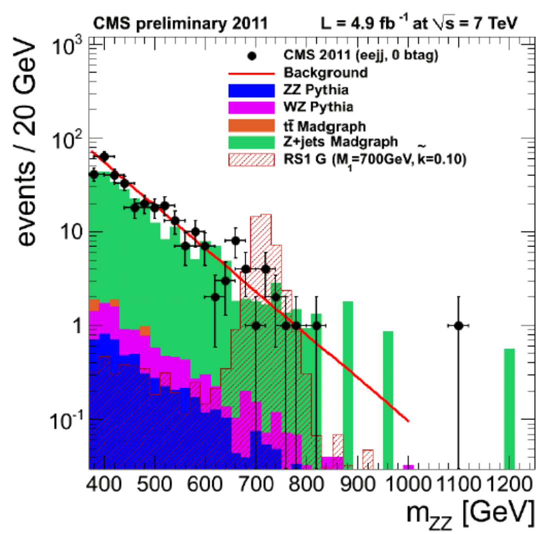
- Z+jets
- WZ/ZZ
- TTbar

Technique

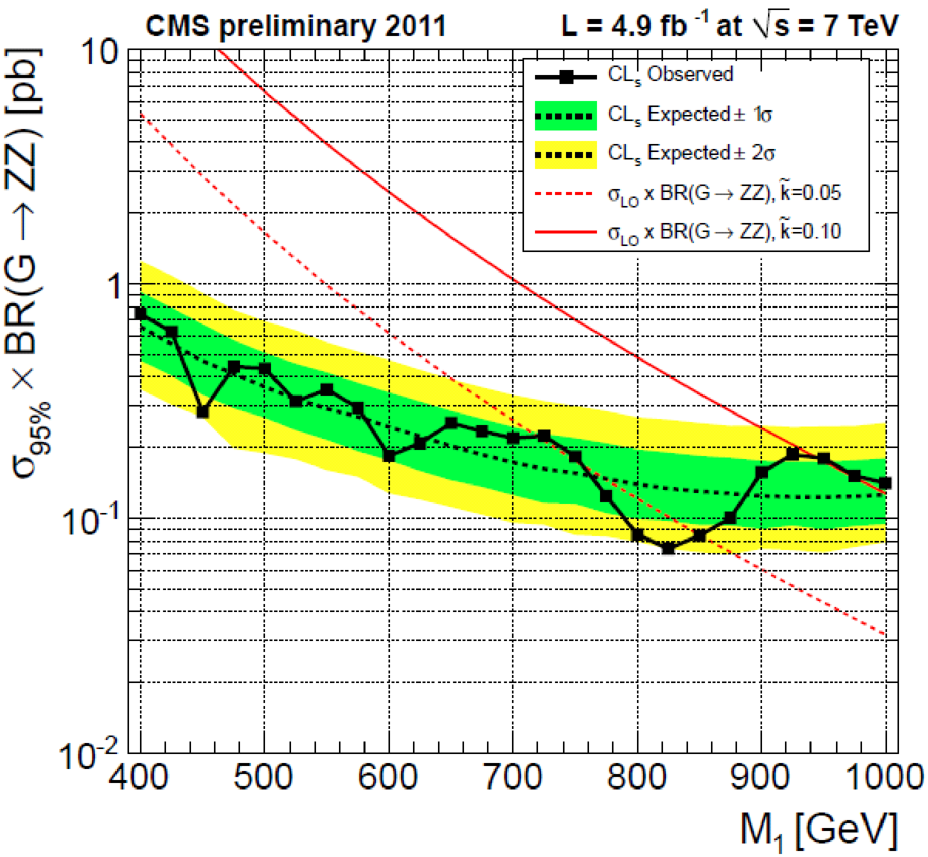
- Angular analysis
- Jet flavor analysis (0,1,2 btag category)
- estimate bkg from data







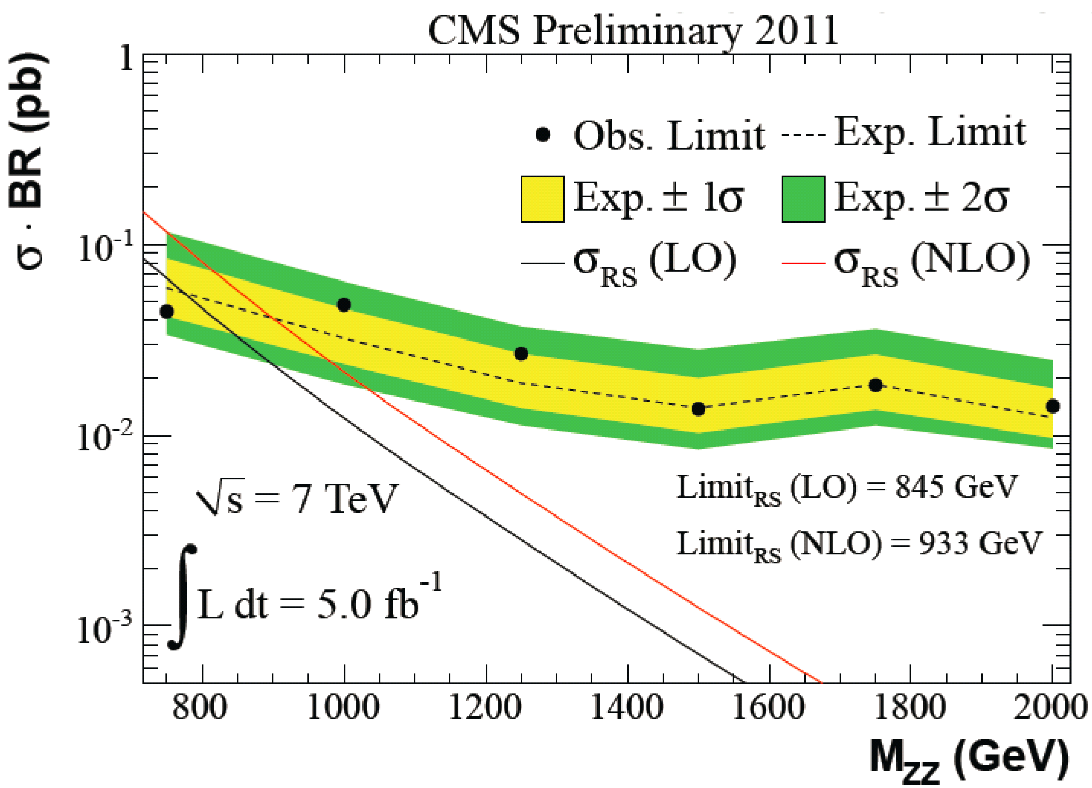
RSG->ZZ->qqll(2)



Exclude M<945GeV for k=0.1

Exclude M<720 and (760,850) for k=0.05

RSG->ZZ->qqll/qqvv combine



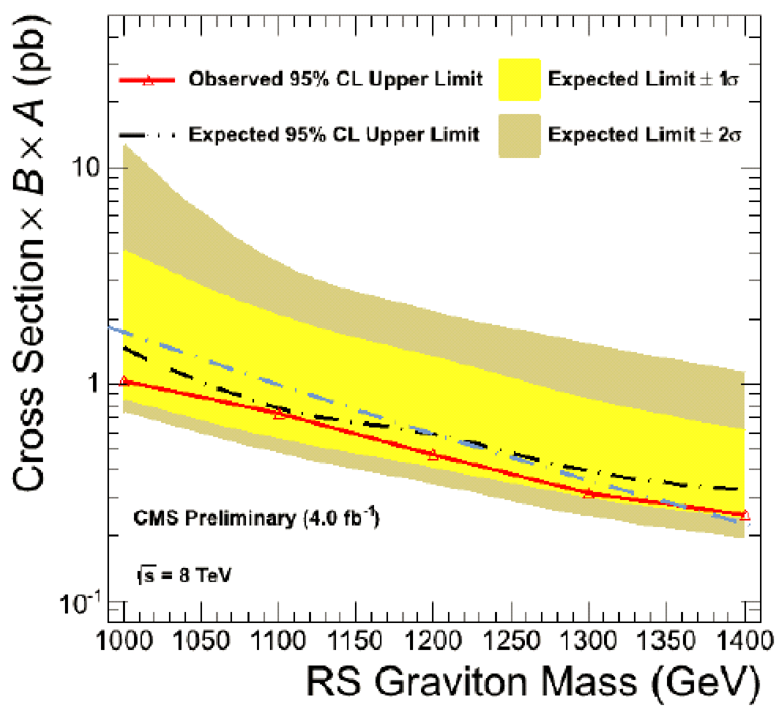
In the Randall-Sundrum model, we exclude graviton resonances with masses **between 700 and 933** GeV for k=0.05.

8TeV

RSG->JetJet

Events selections:

- Pt jet > 30 GeV
- Jet |η| < 2.5
- Δη separation of the two jets < 1.3



Main Backgrounds

- QCD

Technique

- **Using wide jets**: All other jets with pT > 30 GeV and |η| < 2.5 are added to the closest leading jet if they are within ΔR<1.1

The wide jet algorithm is inspired by studies using jet-grooming algorithms and is intended to reduce sensitivity to gluon radiation

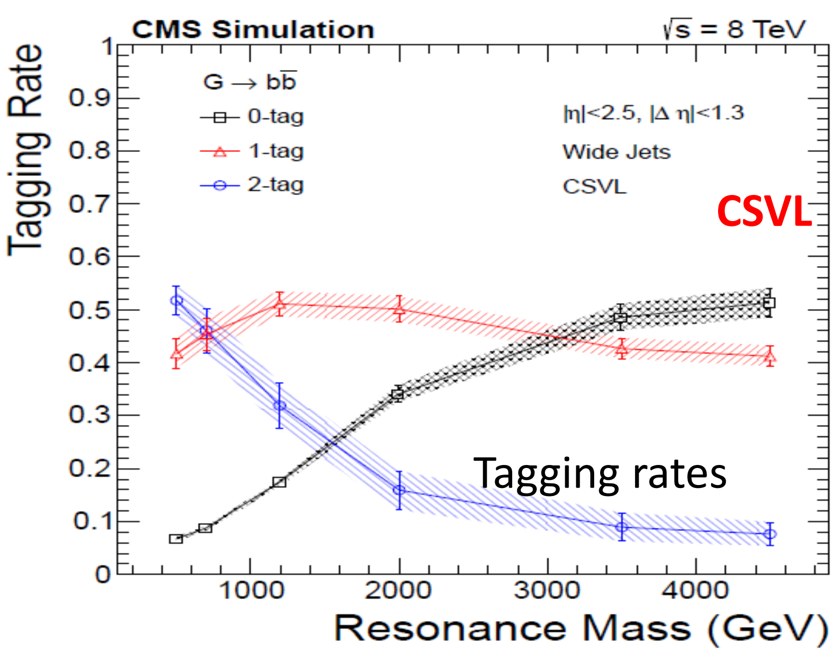
CMS PAS EXO-12-023

8TeV

RSG->bb

Events selections:

- Pt jet > 30 GeV
- Jet |η| < 2.5
- Δη separation of the two jets < 1.3
- Combined secondary-vertex (CSV) algorithm to tag b jets.

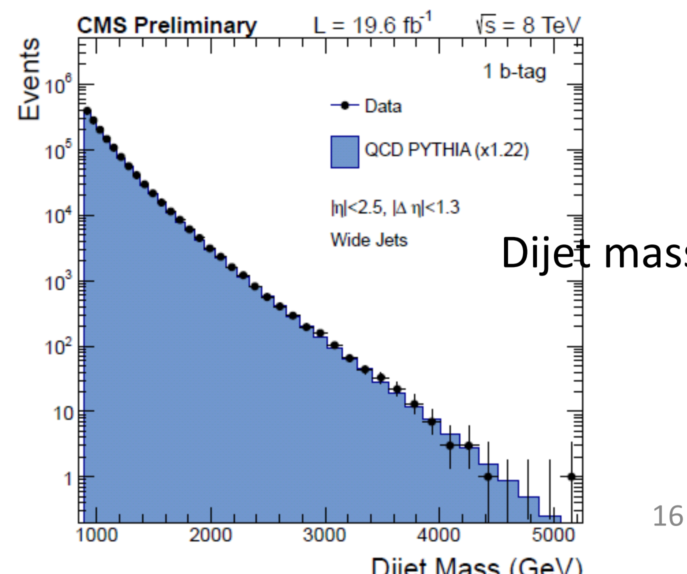


Main Backgrounds

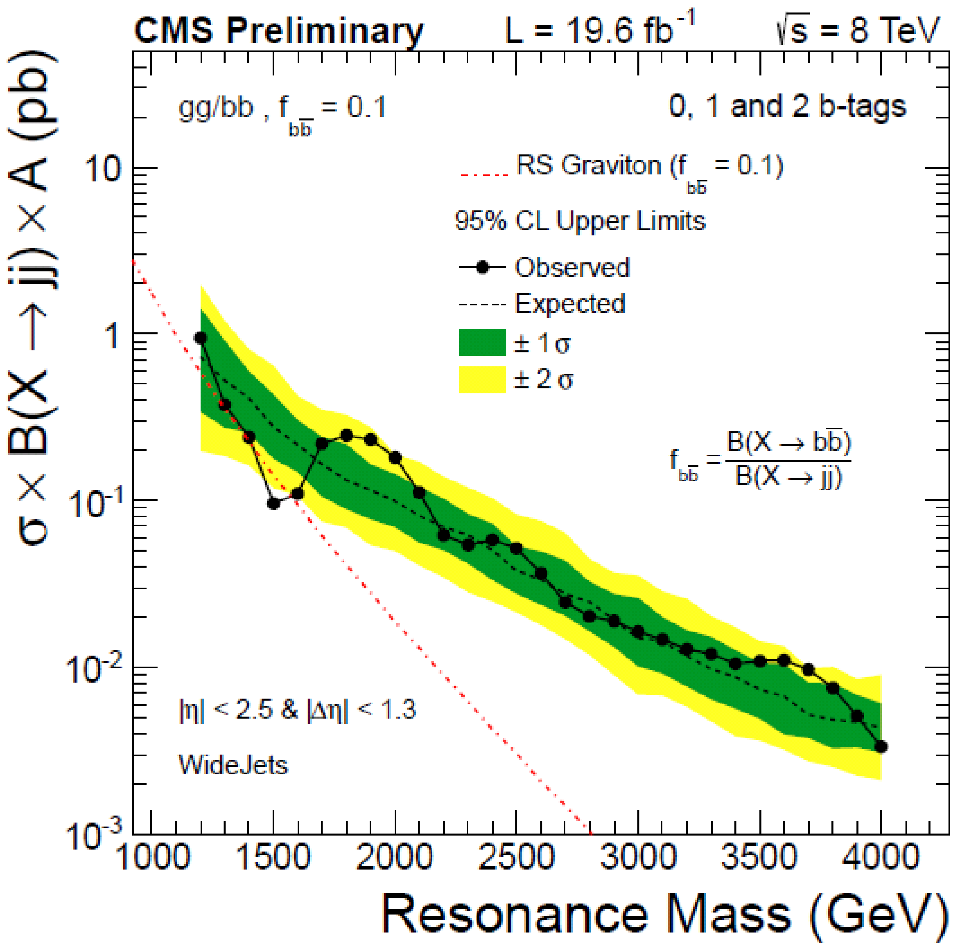
- QCD

Technique

- Three exclusive categories: 0, 1, and 2 b tags
- **Using wide jets**: All other jets with pT > 30 GeV and |η| < 2.5 are added to the closest leading jet if they are within ΔR<1.1



RSG->bb (2)



Exclude k=0.1 with mass between 1420 and 1570 GeV

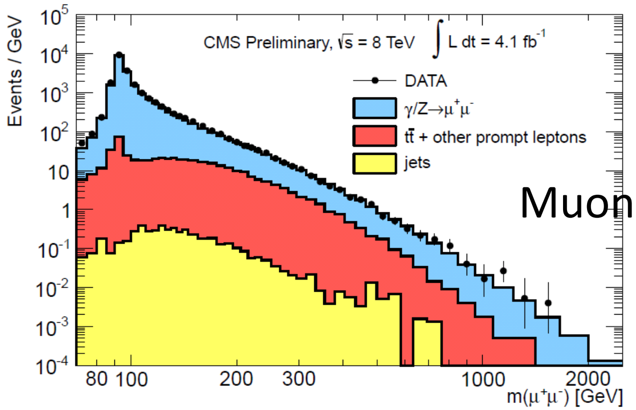
Dilepton

Events selections:

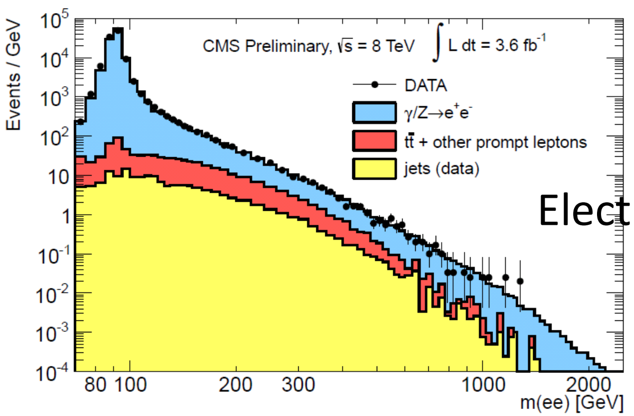
- Electron pt >35 GeV
- Muon pt > 45 GeV

Main Backgrounds

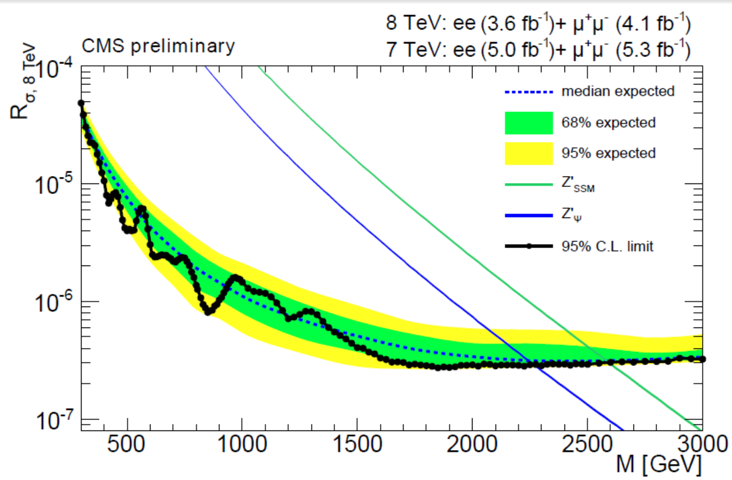
- Z/γ*
- tt, tW, VV
- jets



Muon channel



Electron channel



No evidence for non-standard model physics is observed

CMS PAS B2G-12-005

8TeV

Z’-> tt-> JJ

Events selections:

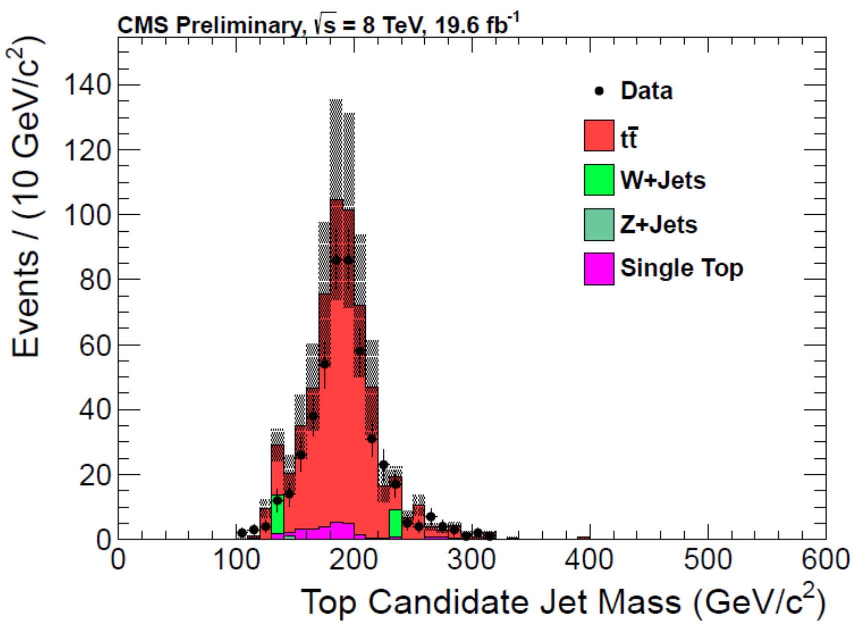
- The two leading jets are required to be back-to-back, with $\Delta\varphi > \pi/2$.
- Jet $\Delta\eta < 1.0$
- Jet mass in range (140,250)
- Top tagging described at http://arxiv.org/pdf/0806.0848v2.pdf

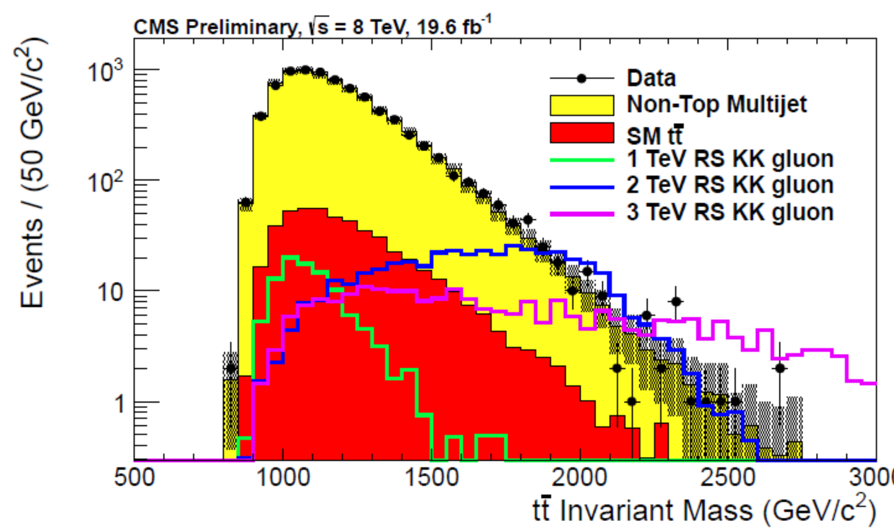
Main Backgrounds

- non-top multijet (NTMJ)

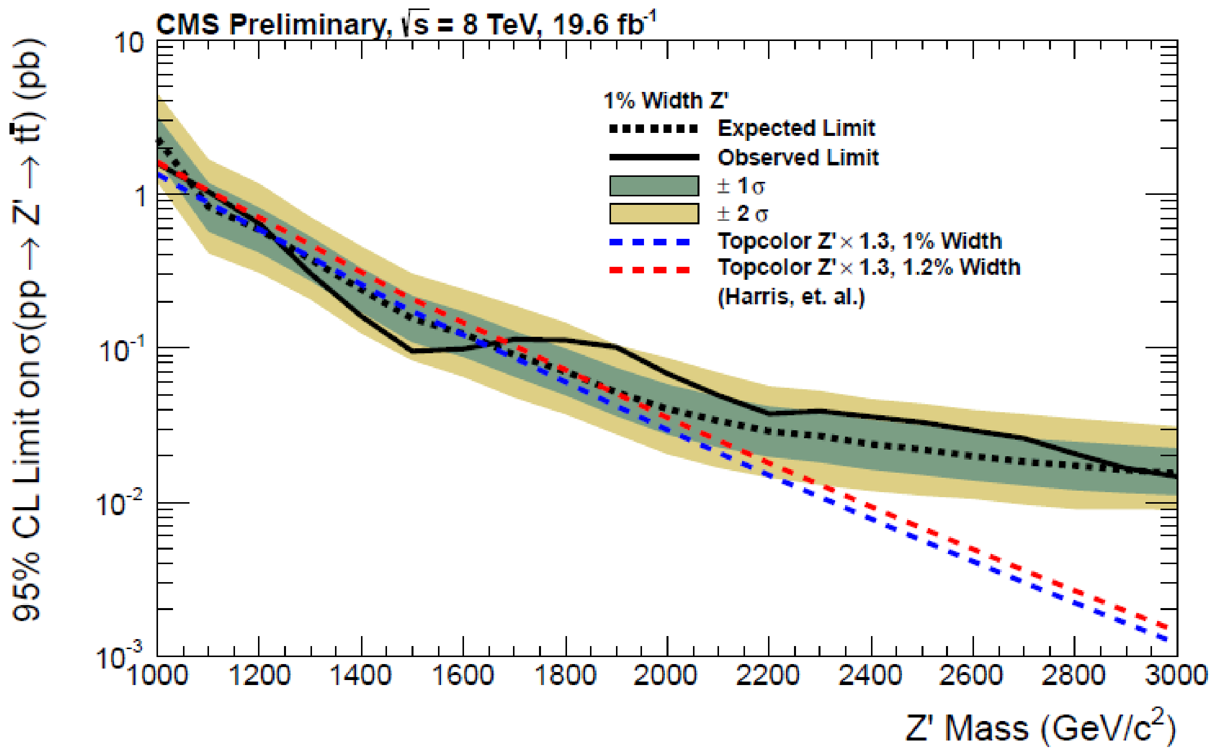
Technique

- Using jet substructure. Using CA8 jet as top jet.
- Data-driven background esitimation



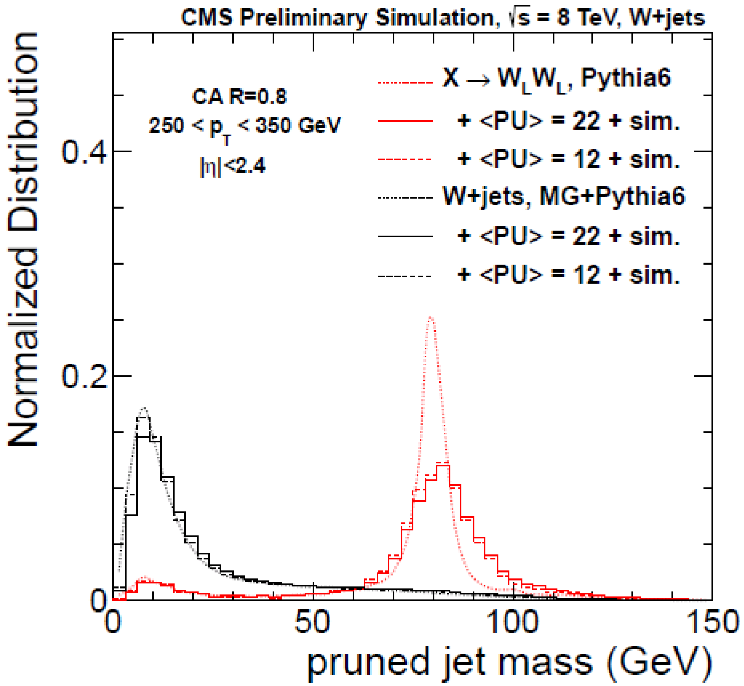


Z'-> tt-> JJ (2)

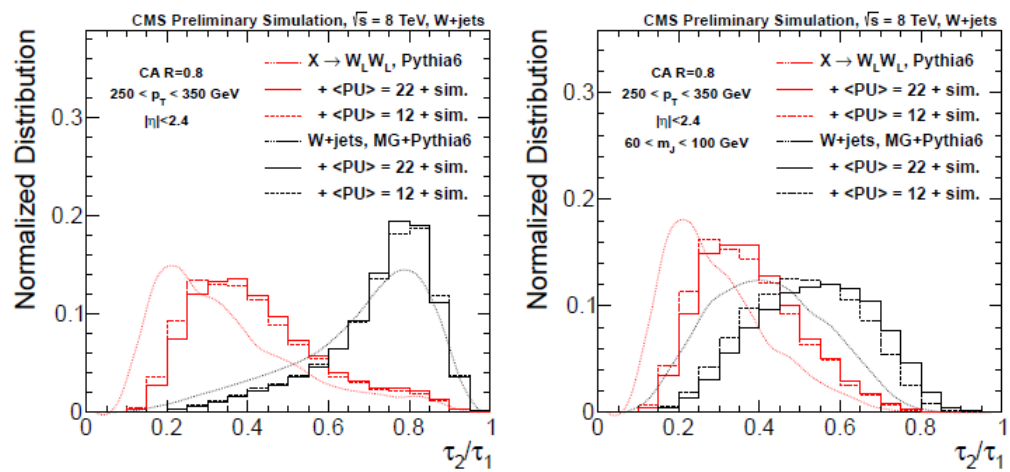


No significant excess in tt spectrum.

Identify merged W jet



Jet prunned mass



Nsubjettiness (τ_2/τ_1) distribution before (left) and after (right) the pruned mass cut

RSG->VV->JJ

Events selections:

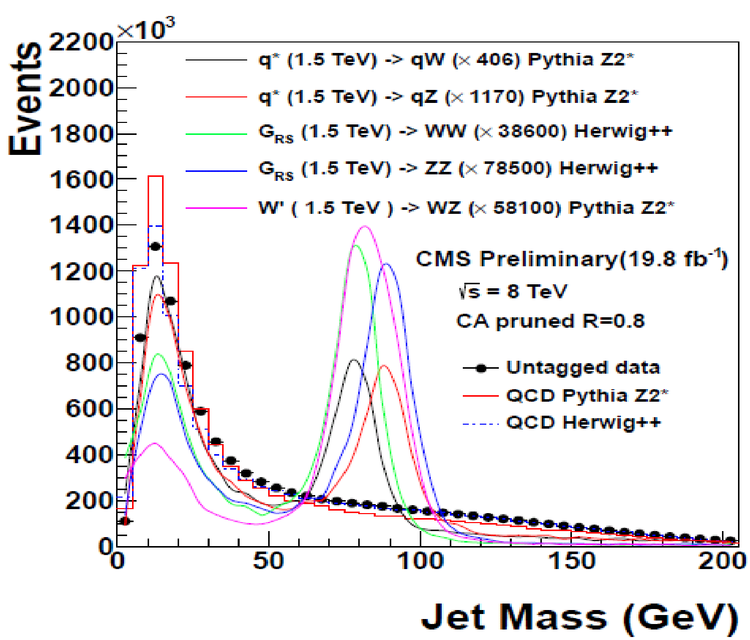
- At leaset two jet with pt > 30 GeV and |η| < 2.5
- Pseudorapidity separation $\Delta\eta < 1.3$
- Dijet invariant mass is required to be > 890 GeV
- Jet mass in range (70,100) GeV
- High purity: $\tau_2/\tau_1 < 0.5$

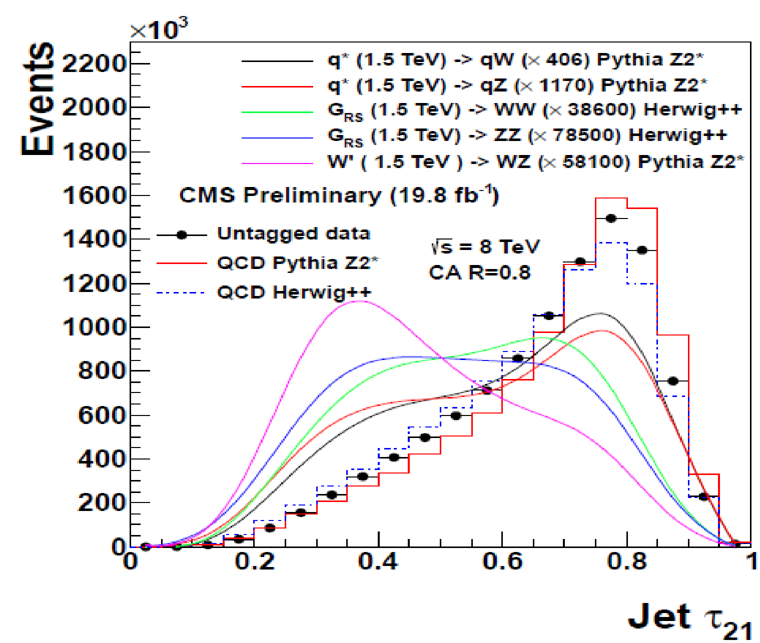
Main Backgrounds

- QCD

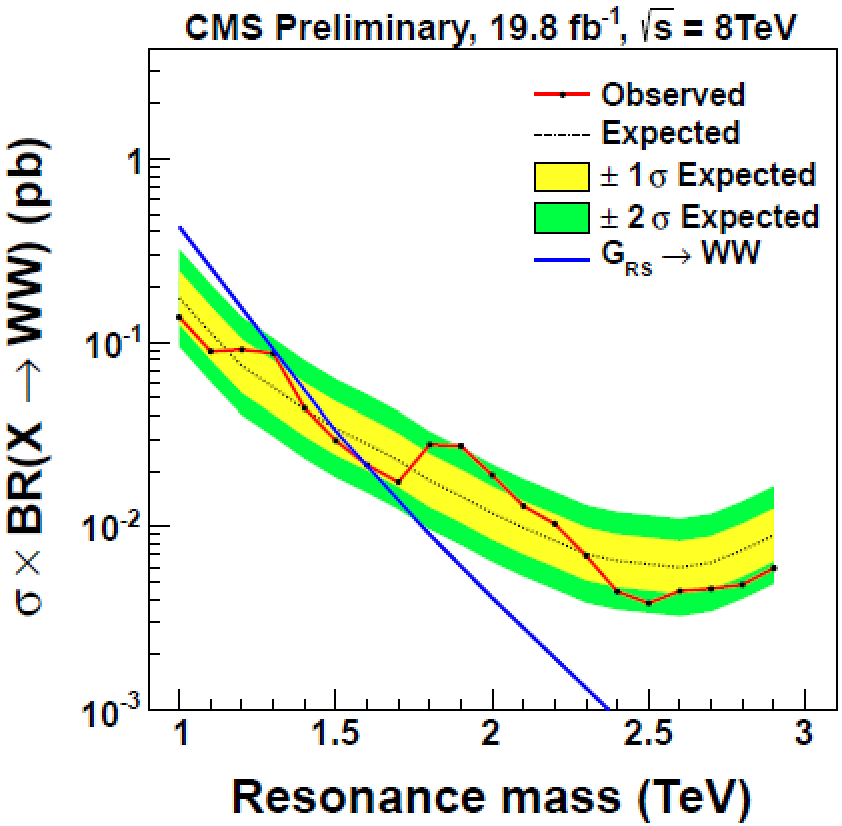
Technique

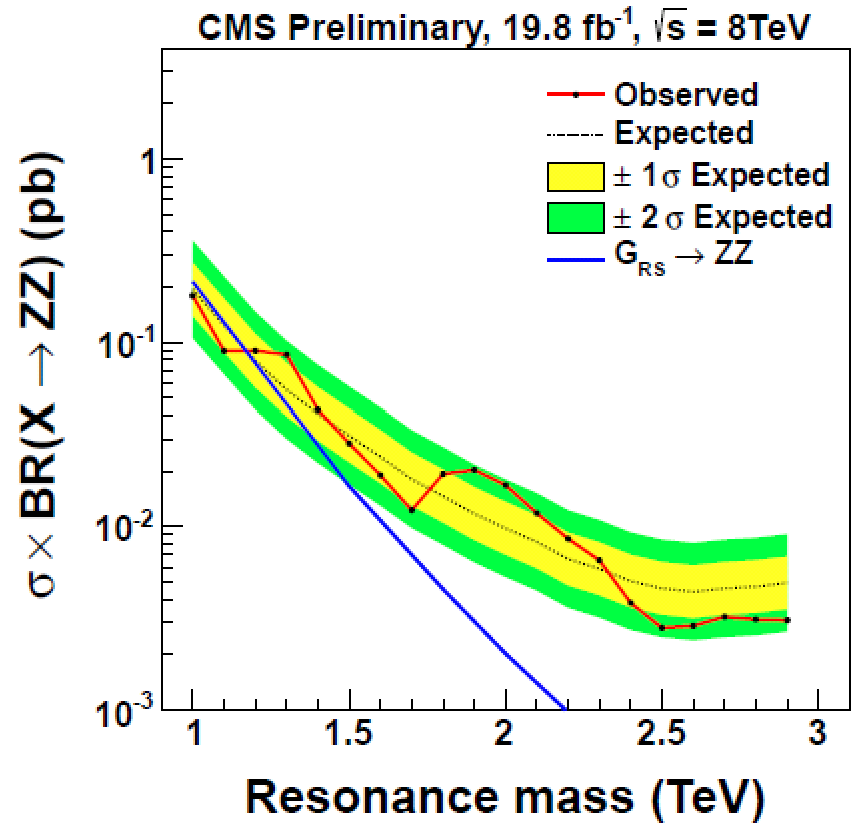
- Using jet substructure. Using CA8 jet as V jet.
- Nsubjettiness is used as V tagging discriminant





RSG->VV->JJ(2)





A Randall-Sundrum graviton is excluded between **1.00 TeV and 1.59 TeV** assuming decay into WW and between **1.00 TeV and 1.17 TeV** assuming decay into ZZ

CMS PAS EXO-12-022

8TeV

RSG->ZZ->llJ

Events selections:

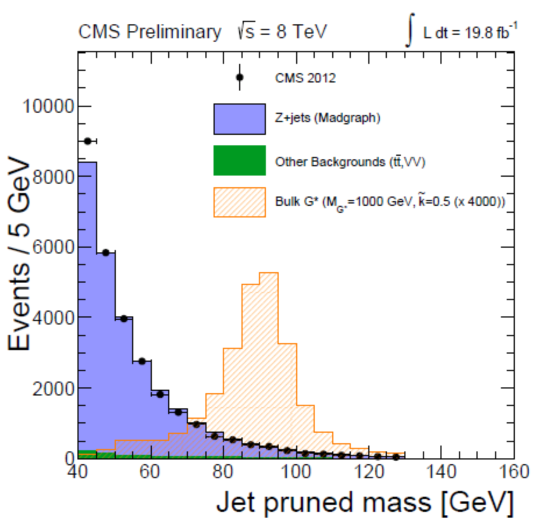
- Lepton pt > 40, 20 GeV
- Z_{ll} pt > 200 GeV
- Jet pt > 200 GeV
- Jet mass in range (70,110) GeV
- High purity: $\tau_2/\tau_1 < 0.5$

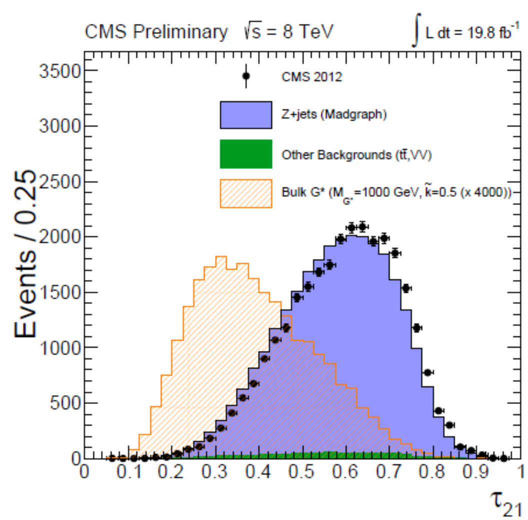
Main Backgrounds

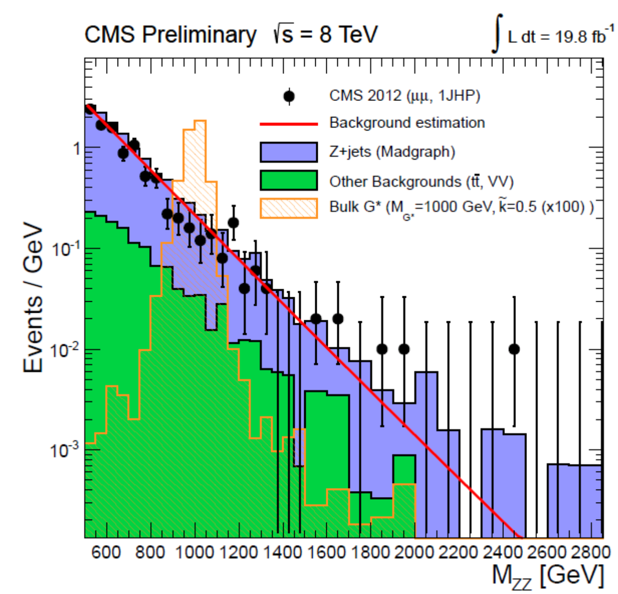
- Z+jets
- TT/VV

Technique

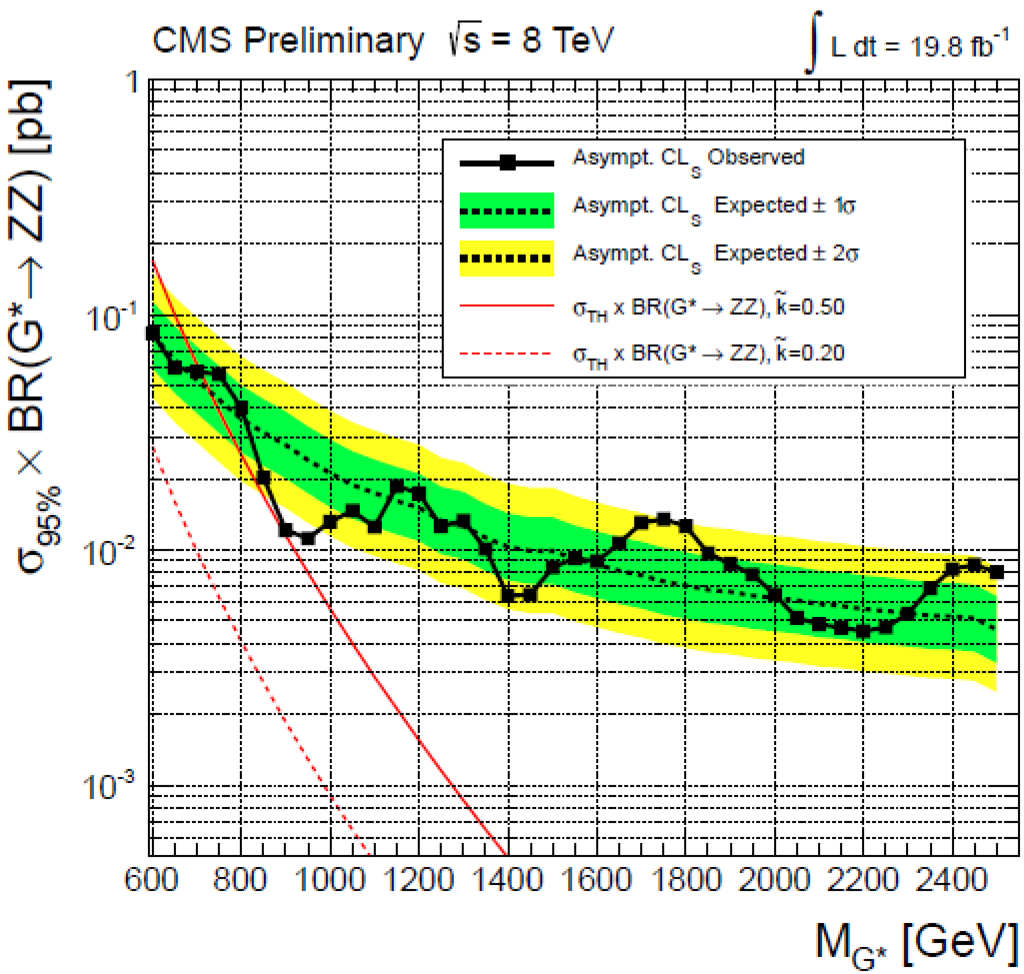
- Using jet substructure. Using CA8 jet as V jet.
- Nsubjettiness is used as V tagging discriminant
- Data-driven bkg estimation







RSG->ZZ->llJ (2)



Bulk gravitons with coupling constant k = 0.5 and mass **smaller than 710 TeV** are excluded.

CMS PAS EXO-12-021

8TeV

RSG->WW->lvJ

Events selections:

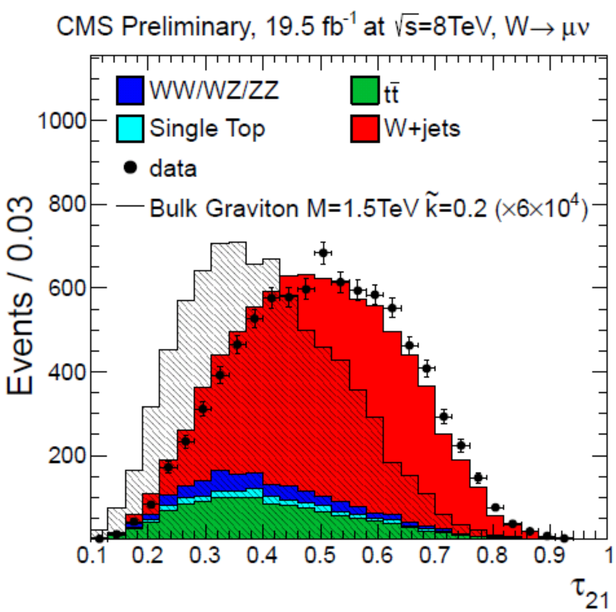
- Lepton pt > 40(80) GeV for moun(electron)
- W_{lv} pt > 200 GeV
- Jet pt > 200 GeV
- Jet mass in range (65,105) GeV
- High purity: $\tau_2/\tau_1 < 0.5$

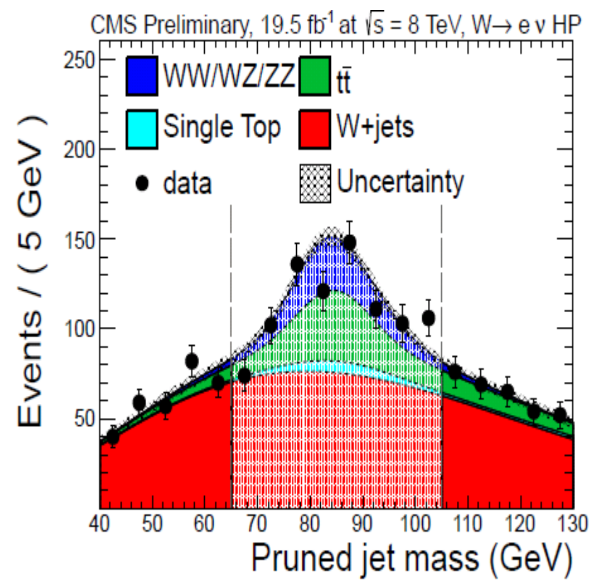
Main Backgrounds

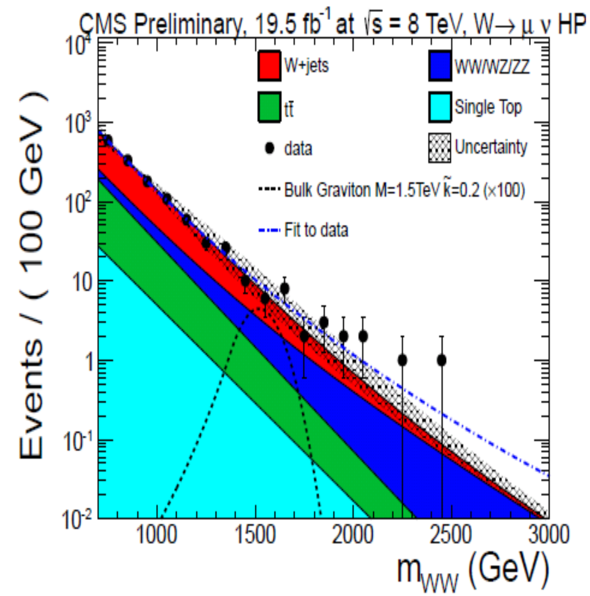
- Wjets , VV, TT

Technique

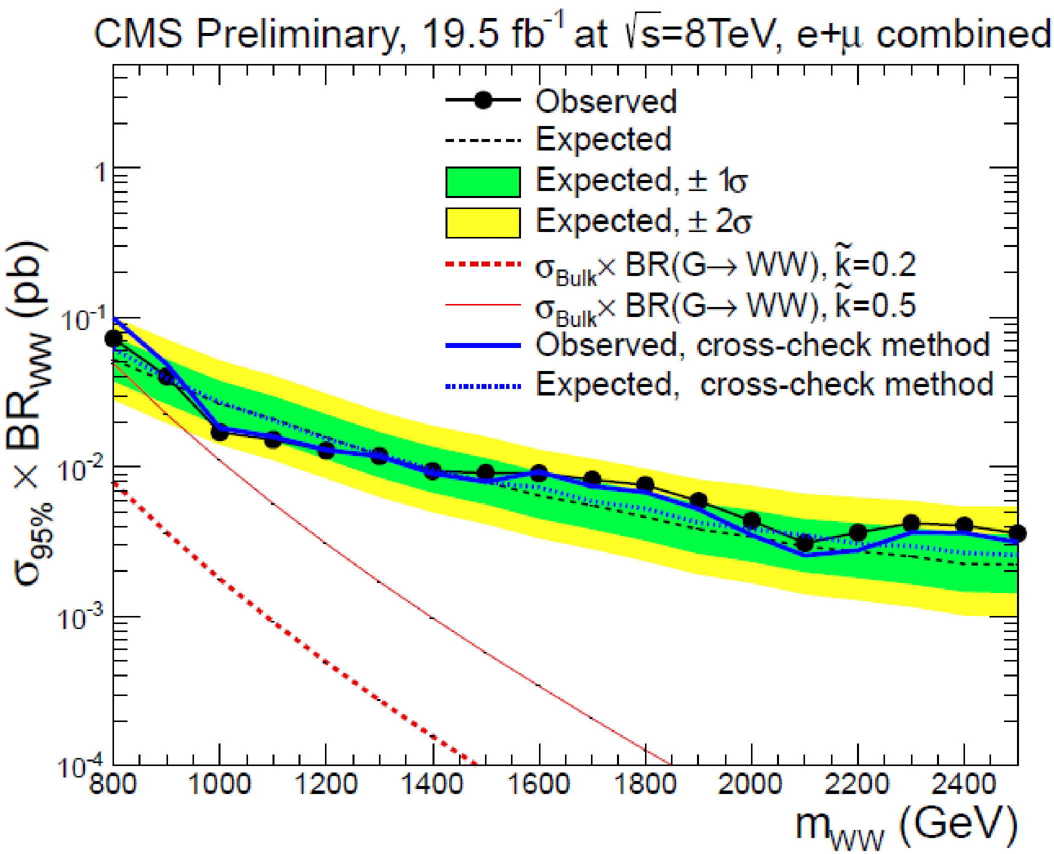
- Using jet substructure. Using CA8 jet as V jet.
- Nsubjettiness is used as V tagging discriminant
- Data-driven bkg estimation







RSG->WW->lvJ (2)



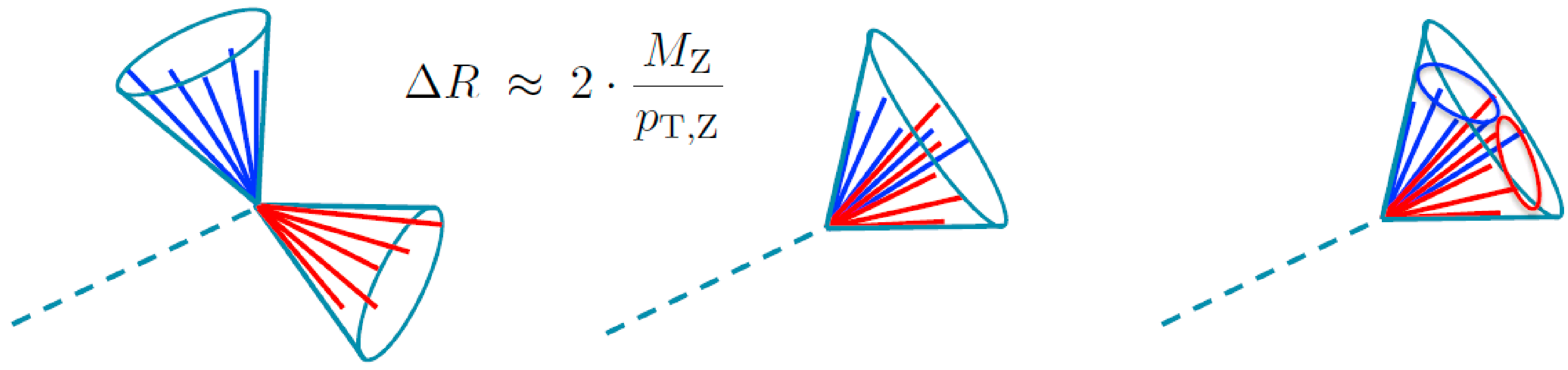
Upper limits are set on bulk graviton production cross section times branching ratio to WW in the range from 70 fb to 3 fb for resonance masses between 0.8 and 2.5 TeV, respectively.

Summary

- The CMS experiment has performed a number of analysis to search for Randall-Sundrum Graviton in various final states.
- No significant access observed in very large mass range (400-4000 GeV).
- The two free parameters of the RS model are further constrained by these analysis

Backup

Jet substructure



$$\Delta R \approx 2 \cdot \frac{M_Z}{p_{T,Z}}$$

Moderately boosted V
Resolved dijets

Boosted V
Jet merging

Boosted V, jet merging
Jet substructure analysis
recovers initial information

- **Jet :** **CA8 jet**
- **Pruning:** **Get pruned jet mass**
- **Vtagging:** **Using nsubjettiness**

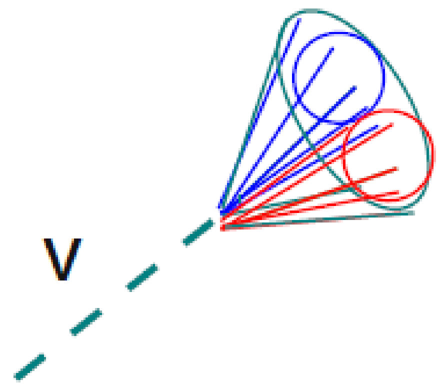
Cambridge-Aachen algorithm

CA8 jet : Jet clustered by Cambridge-Aachen algorithm with R=0.8

Jet clustering algorithm: identify the smallest of the distances and if it is a dij, recombine entities i and j

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$\text{where } \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$



Ref: http://arxiv.org/pdf/0802.1189v2.pdf

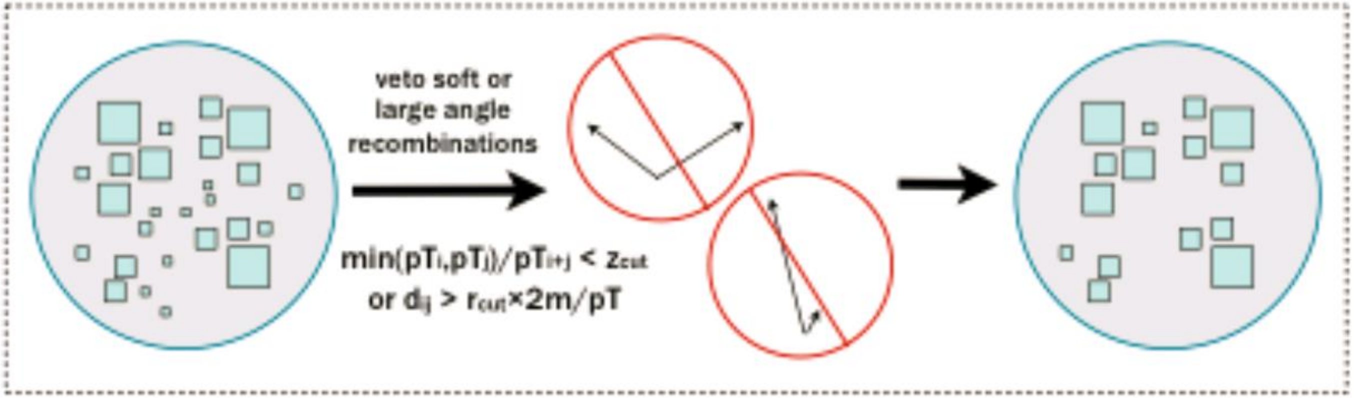
p=1 : KT algorithm, combining small entries first
p=-1 : anti-KT algorithm, combining big entries first
p=0 : Cambridge-Aachen algorithm, combining close entries first

Before the last step of clustering → two subjets

Jet pruning

Jet grooming techniques: pruning, trimming, filtering

"Pruning" → http://arxiv.org/abs/0903.5081
(S.Ellis, C.Vermilion, J.Walsh)
Re-clustering (CA algo) with while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents: Veto $d_{12} > R_{cut} \times 2m/p_T$; $z=\min(p_{T1},p_{T2})/p_T < z_{cut}$
→ default parameters: $z_{cut} = 0.3$, $R_{cut} = 0.5$
→ Doesn't recreate subjets but prunes at each point in jet reconstruction



Vtagging: N-subjettiness

Main Discriminants for V tagging: N-subjettiness
Here we want to use N-subjettiness as : τ_2/τ_1
Definition:

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

Where k loops over the constituents and N is the number of subjets. And

$$d_0 = \sum_k p_{T,k} R_0, \ \Delta R_{J,k} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Ref: http://arxiv.org/pdf/1011.2268v3.pdf

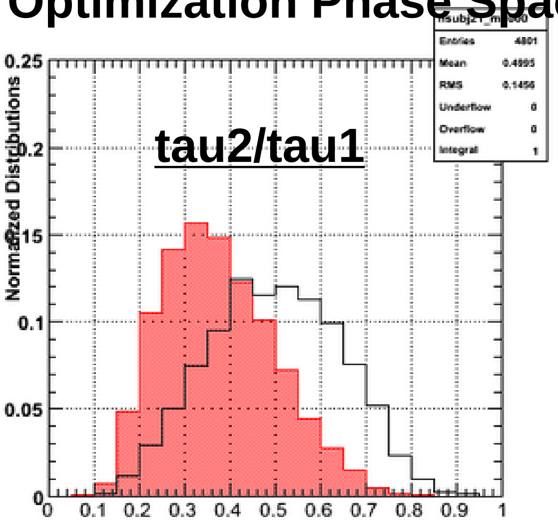
Other discriminants: Qjets, planner flow, mass drop, etc

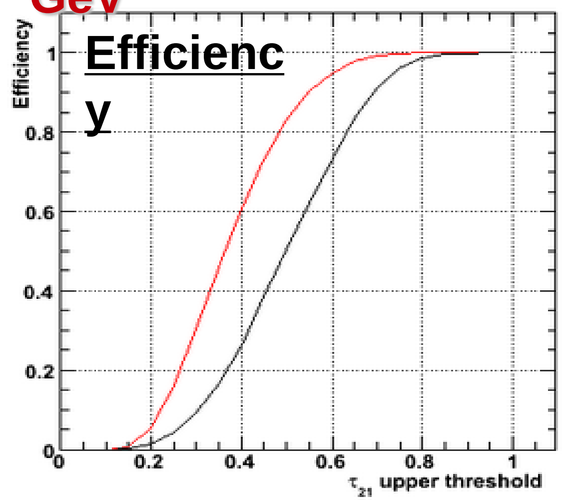
N-Subjettines Optimization

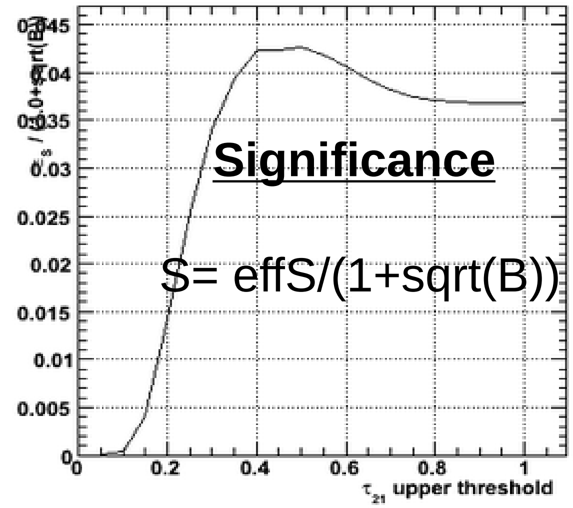
- Single Rectangular cut optimization → **Signal : Bulk Graviton, masses [0.6 , 2.5] TeV**

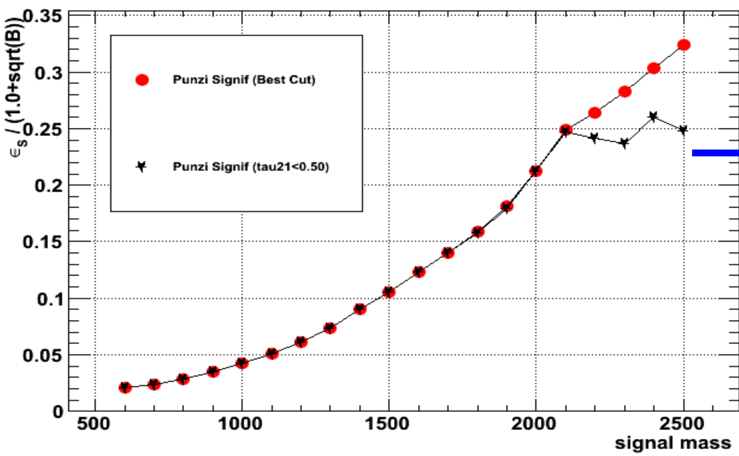
  Background : W+jets, ttbar, VV and Stop

- **Optimization Phase Space : Preselection Cuts + Signal Region [65,105] GeV**









Best Significance Cut

Cut fixed at 0.5

Event Categorization:

tau2/tau1 < 0.5 → High Purity

0.5<tau2/tau1<0.75 → Low Purity

Scale factors from TTbar control region

1) Normalization correction for TTbar and Single Top

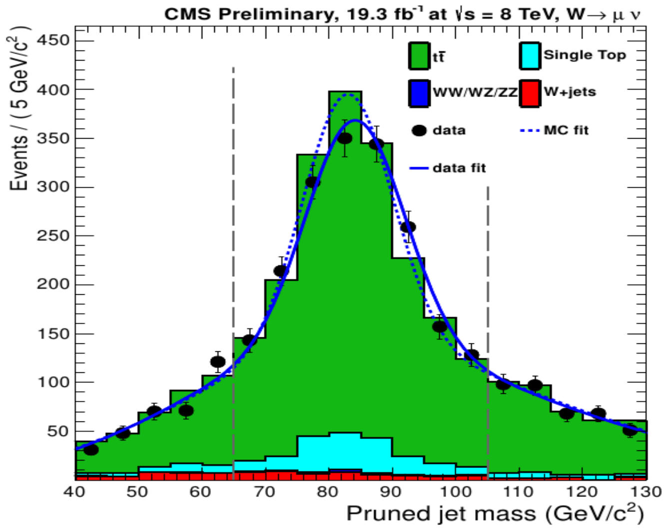
The top scale factors are just derived by DATA/MC in the signal region (not fit at all).
This includes peak and combinatorial.
These numbers are analysis dependent in principle.

Top	μ	el
SF HP	0.96 ± 0.02	0.97 ± 0.03
SF LP	1.23 ± 0.05	1.30 ± 0.07

2) Correction for W-jet mass peak for VV and TTbar

Simultaneous of el and mu mJ spectrum.
Used later when extracting the Wjets normalization.

Peak Shape	<m> [GeV]	σ [GeV]
Data	84.4 ± 0.4	7.9 ± 0.06
MC	82.9 ± 0.3	7.1 ± 0.04
Correction	Shift + 1.4 GeV	Times 11%



3) Normalization correction for VV and Signal

Simultaneous fit of pass and fail for each channel (see next slide)

W	Scale Factor
HP	0.93 ± 0.08
LP	1.10 ± 0.30

Shapes from TTbar MC

TTbar sample has two components:

→ Real merged W-peak

→ Combinatorial Bkg.

To isolate the two components:

→ Matching CA8 with hadronic W at generator level in a cone 0.3

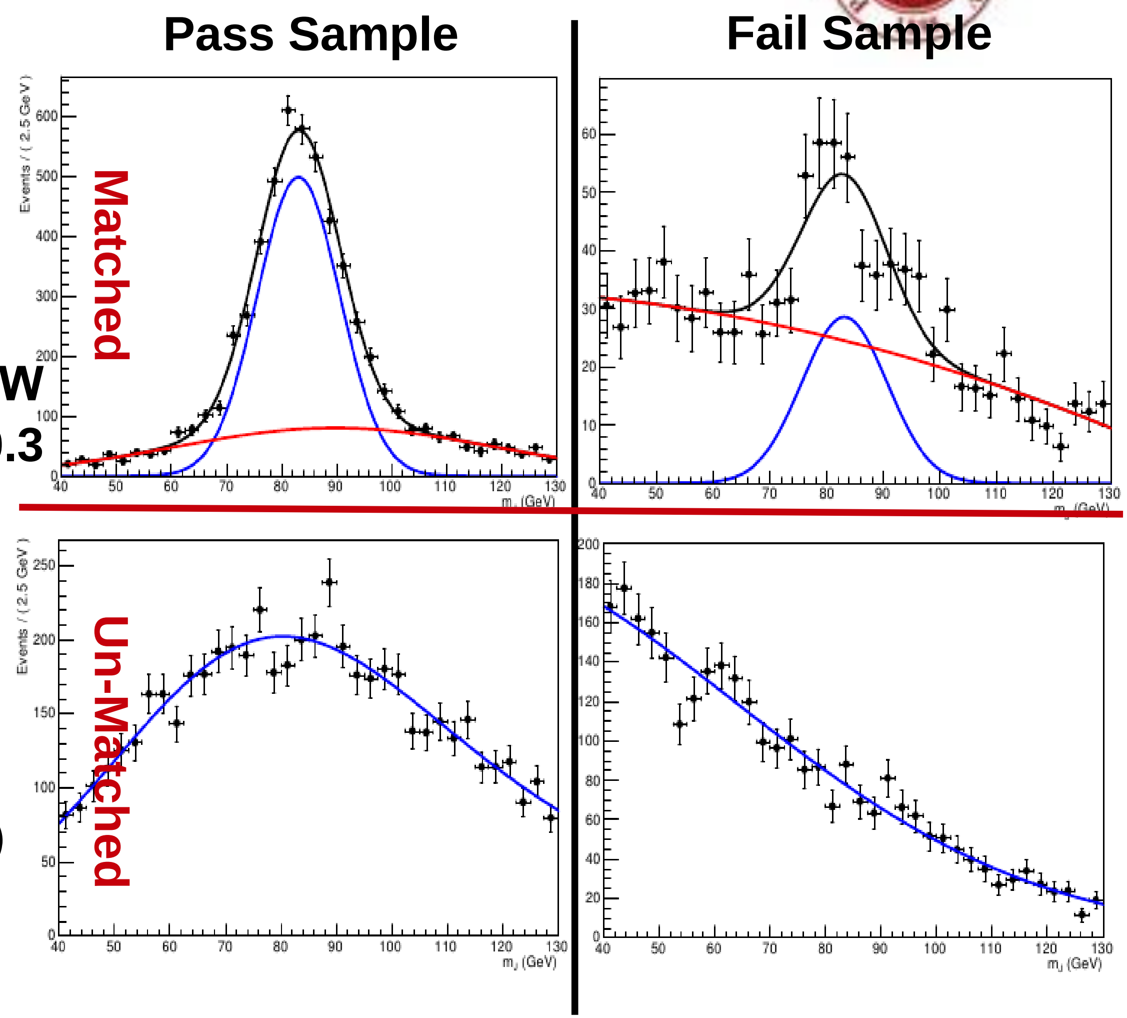
Real W-jet shape = matched

Comb. Bkg shape = un-matched

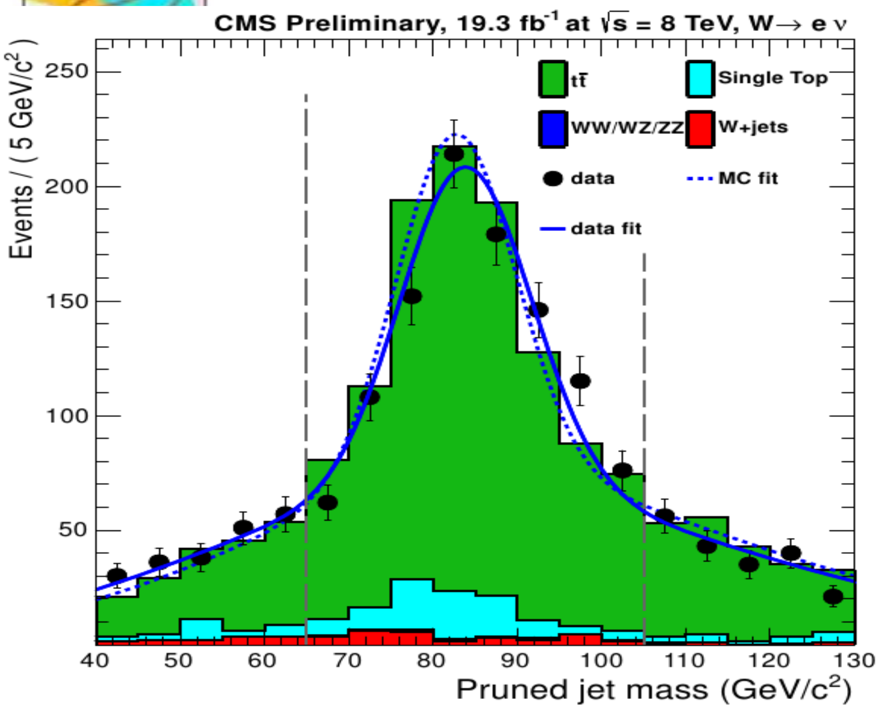
W-tagger Cut :

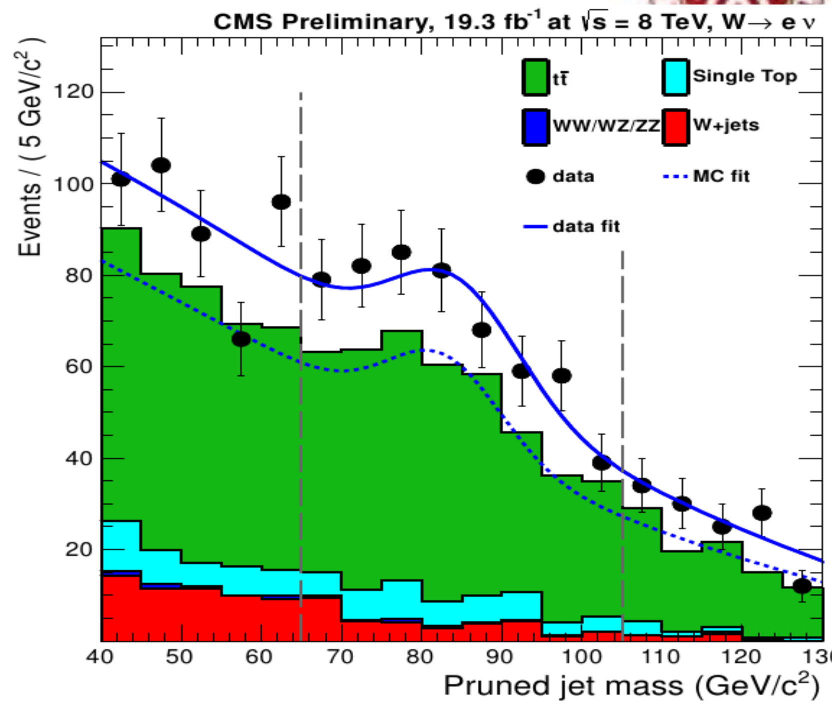
→ tau2/tau1 < 0.5 (pass sample)

→ tau2/tau1 >= 0.5 (fail sample)



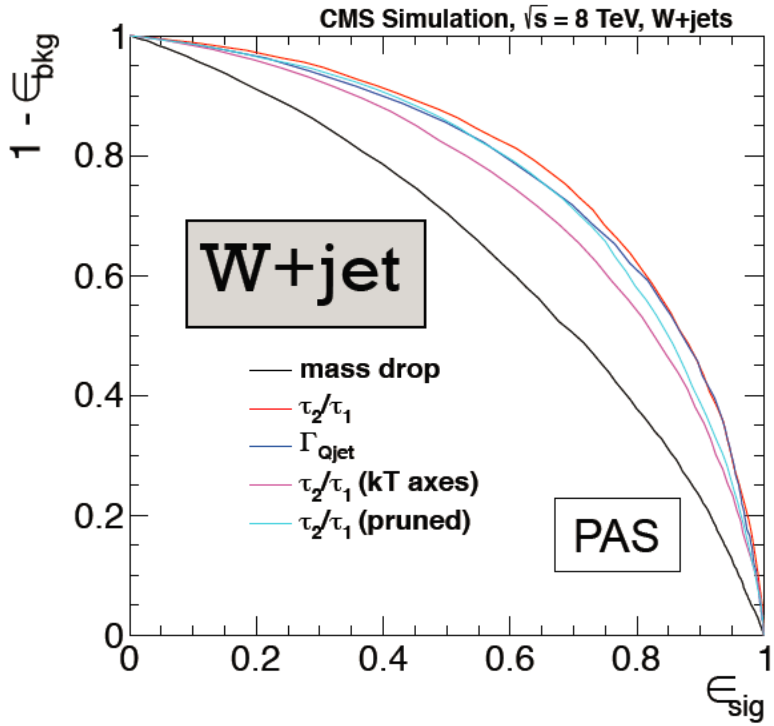
Normalization correction for VV and Signal





- **Bkg (WW / Stop / W+jets) are taken from MC→Shapes and Normalization Fixed**
- **Pass PDF :** $f_{pass} = f_{pass}^{W-match} \times \epsilon \times N_W + f_{pass}^{W-nomatch} \times N_2 + F_{pass}^{STop} + F_{pass}^{VV} + F_{pass}^{Wjet}$
- **Fail PDF :** $f_{fail} = f_{fail}^{W-match} \times (1-\epsilon) \times N_W + f_{fail}^{W-nomatch} \times N_3 + F_{fail}^{STop} + F_{fail}^{VV} + F_{fail}^{Wjet}$
- **Pass and Fail are fitted simultaneously → extract efficiency and number of Real W**
- **Shape parameters like mean and sigma of Gaussian + exp index are floating**

Different tau21



Plot from wtagging PAS

Comparison of different N-subjettiness variants

τ_2/τ_1 **(kT axes)**: subjet axes taken from kT clustering

τ_2/τ_1: subjet axes initialized from kT clustering then one additional optimization pass

τ_2/τ_1 **(pruned)**: one-pass kT axis optimization, but only including constituents from a pruned jet

Neutrino Pz calculation

Neutrino Pt: Using MET as neutrino pt

Neutrino Pz: solve the second order equaton of leptonic W mass = 80.4

$$p_z^{\nu_{1,2}} = \frac{p_z^\ell \left(\mathbf{p_T}^\ell \cdot \mathbf{E}_\mathrm{T}^\mathrm{miss} + m_\mathrm{W}^2/2\right) \pm \sqrt{\Delta}}{\left(p_\mathrm{T}^\ell\right)^2}, \text{ where}$$

$$\Delta = \left(\mathbf{p_T}^\ell \cdot \mathbf{E}_\mathrm{T}^\mathrm{miss} + m_\mathrm{W}^2/2\right)^2 - \left(p_\mathrm{T}^\ell\right)^2 \left(E_\mathrm{T}^\mathrm{miss}\right)^2.$$

If real root, choose the smaller absolute value one.

If complex root, use the real part of the root.

WHY we get complex root?

Imagine a real W with mass > 80.4, and Delta will positive. Then if you use 80.4 to solve the function, Delta decreases and you may get complex root.