Search for anomalous couplings in semileptonic WW and WZ decays in the CMS experiment

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Introduction

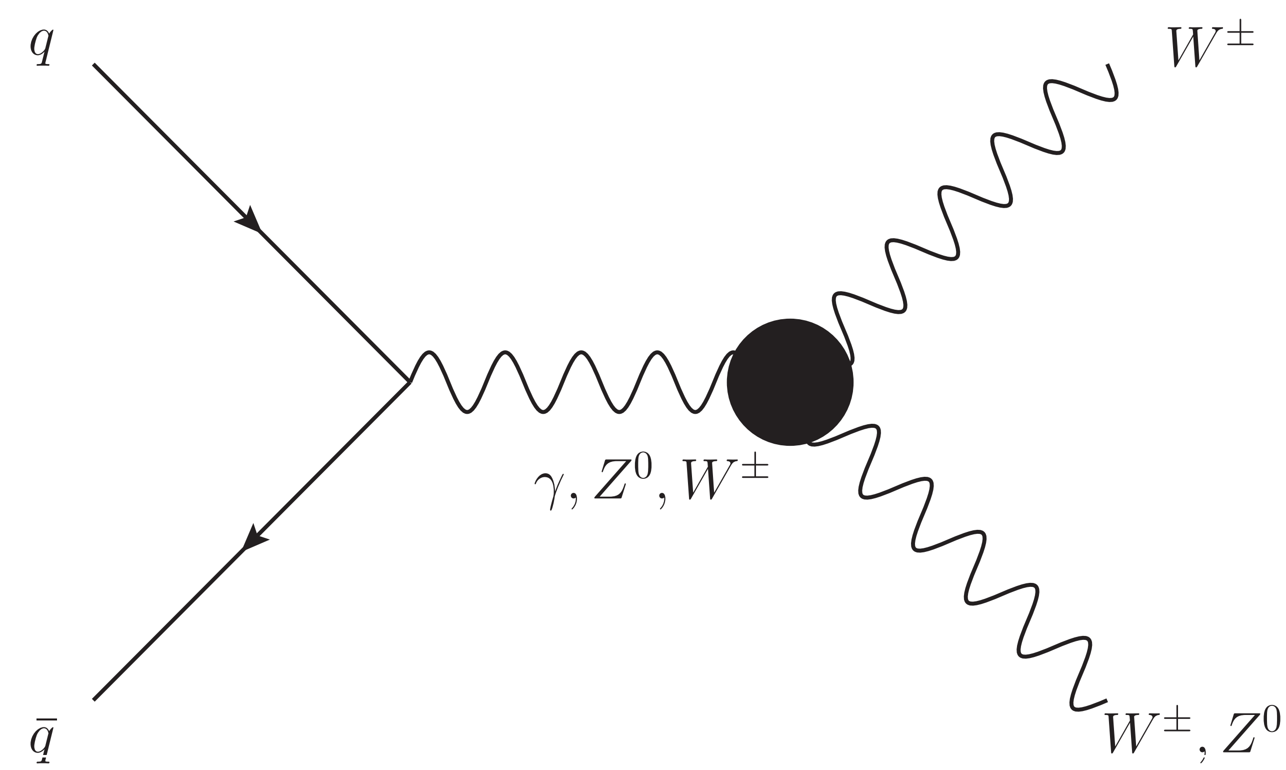
- Search for anomalous triple gauge couplings at $\sqrt{s}$= 13 TeV is presented using full 2015 dataset (L= 2.3 fb^{-1}).
- Search is based on the effective field theory approach (EFT)
- Semileptonic channel.
- Events with boosted topology (boosted AK8 jet) are used → jet-substructure techniques used for V-tagging.
- Limits are extracted from diboson mass distribution modelled by analytical functions.

Effective field theory approach

- Standard Model Lagrangian is extended with 3 CP-conserving dimension 6 operators:

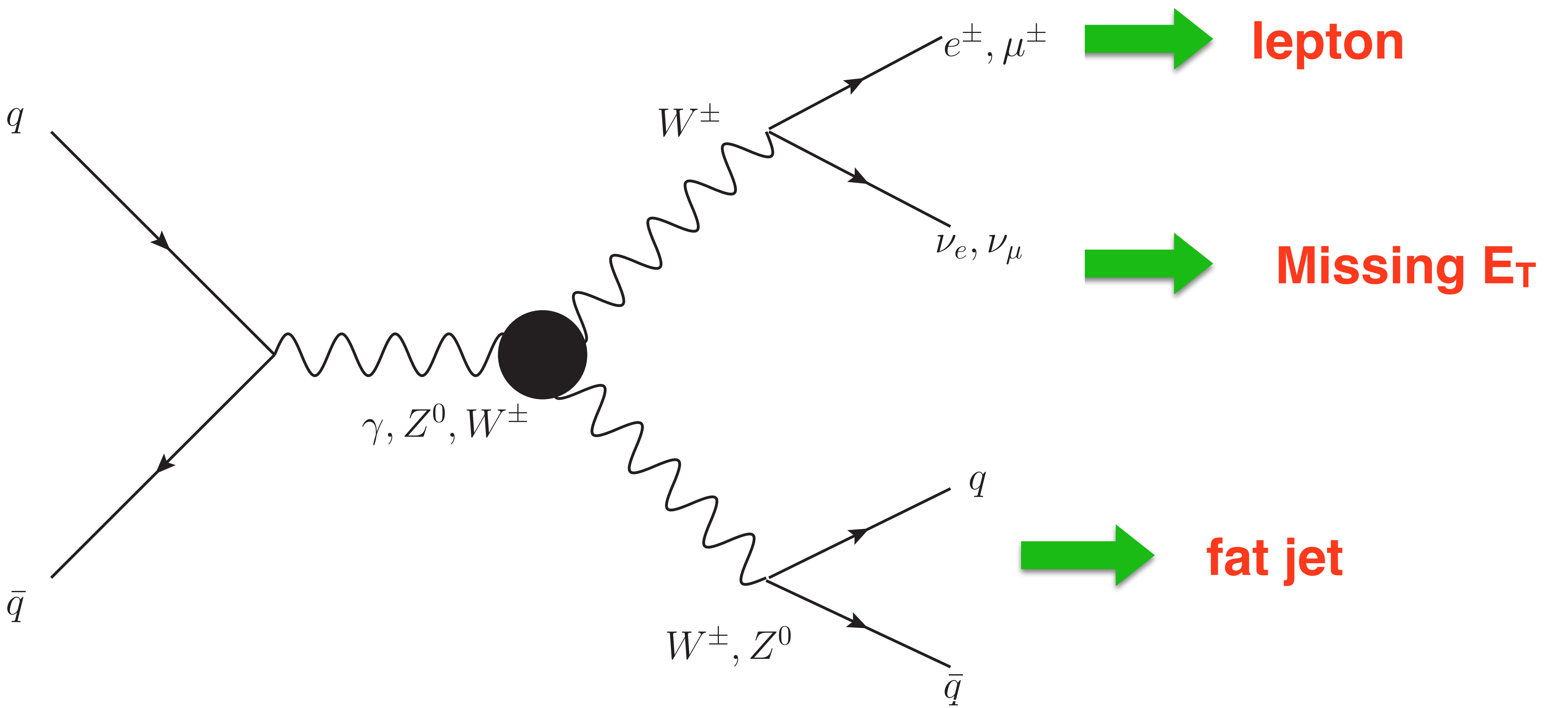
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{c_W}{\Lambda^2}\mathcal{O}_W + \frac{c_B}{\Lambda^2}\mathcal{O}_B$$

- Assumption: $E/\Lambda \ll 1$



Event signature

- Semileptonic channel



Event selection

cut	electron channel	muon channel
lepton $p_T >$	50 GeV	53 GeV
lepton $\|\eta\| <$	2.5	2.4
$E_T^{miss} >$	80 GeV	40 GeV
$\tau_{21} <$	0.6	0.6
$M_{WV} >$	900 GeV	900 GeV
$W_{lep}\ p_T >$	200 GeV	200 GeV
fat jet $p_T >$	200 GeV	200 GeV
fat jet $\|\eta\| <$	2.4	2.4
$\Delta R(lepton, jet) >$	$\frac{\pi}{2}$	$\frac{\pi}{2}$
$\Delta\Phi(jet, E_T^{miss}) >$	2.0	2.0
$\Delta\Phi(jet, Wlep) >$	2.0	2.0
m_{pruned} window	$[40., 150.]$ GeV	$[40., 150.]$ GeV

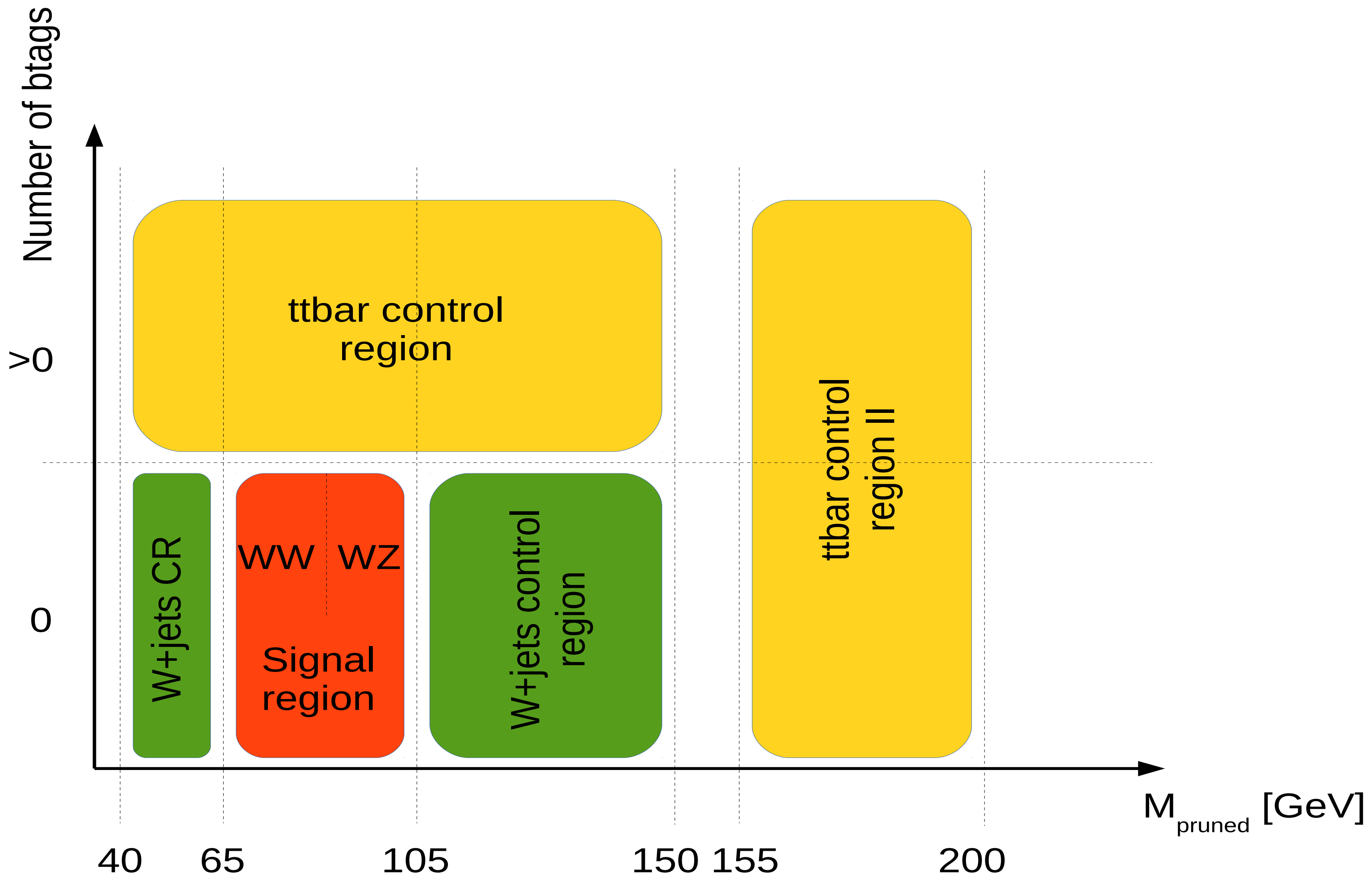
- **Exactly 1 electron or muon** passing quality criteria
- **No additional loose leptons**
- **at least 1 AK8** jet passing quality requirements
- AK4 jets are used for b-tag veto, cleaned from AK8 ΔR=0.8)

Backgrounds

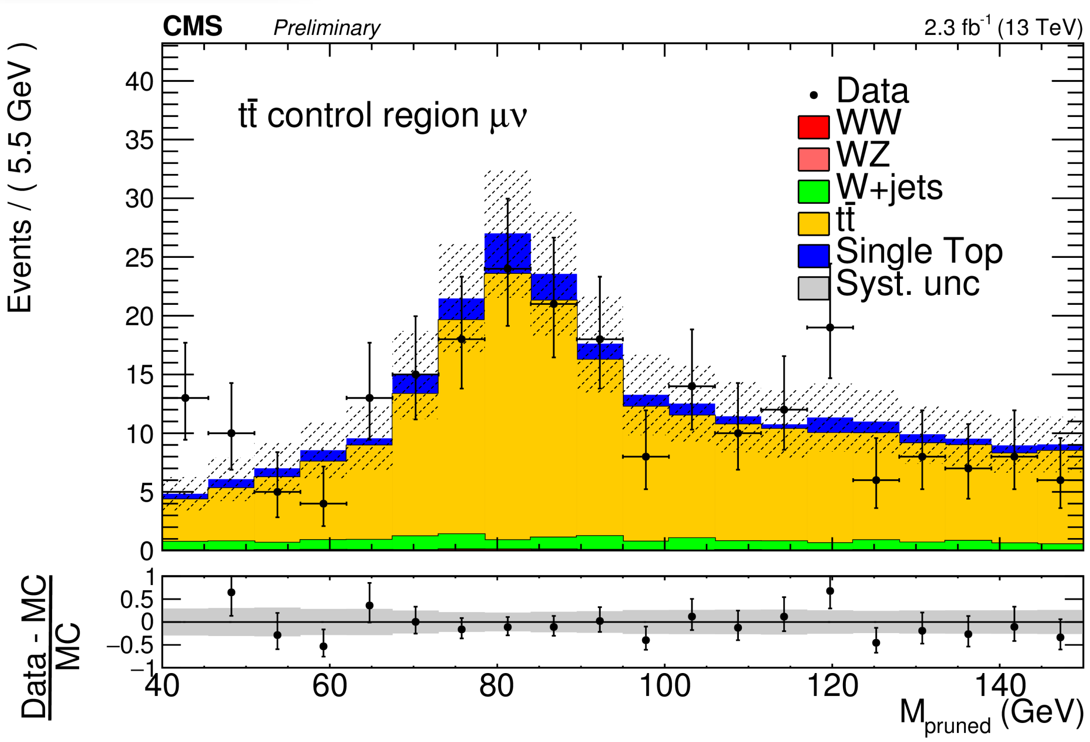
- top pair production (ttbar)
- W+jets
- Diboson production (WW, WZ)
- Single top

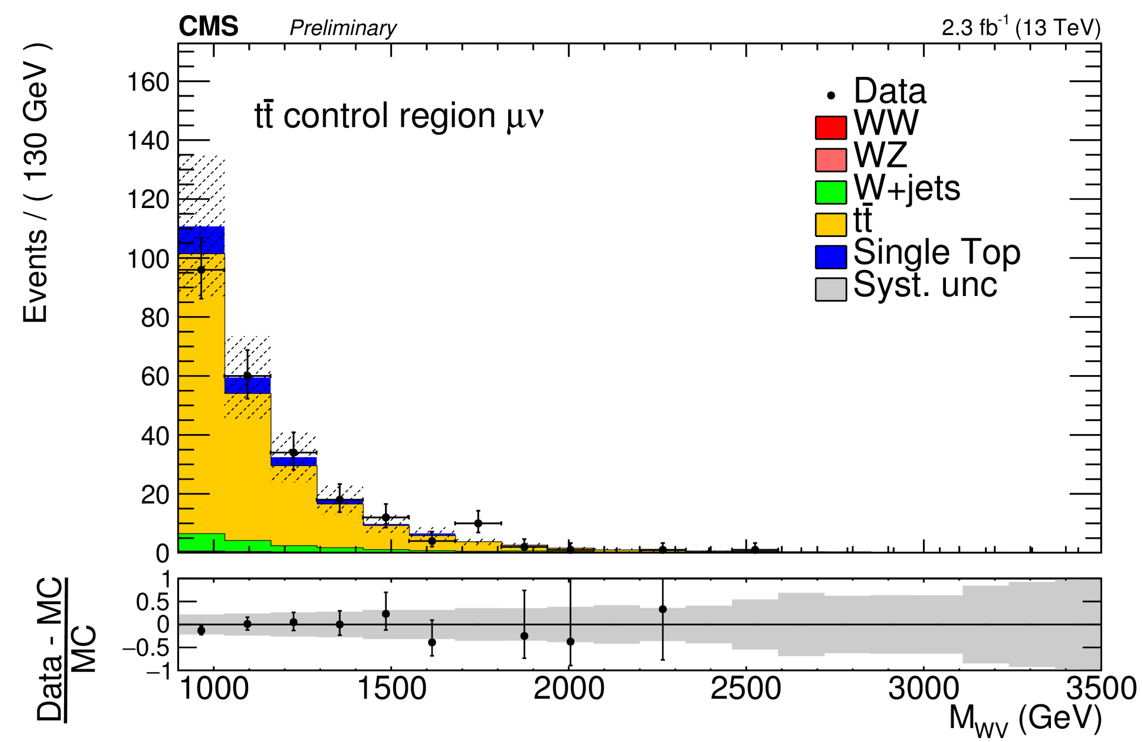
Control regions

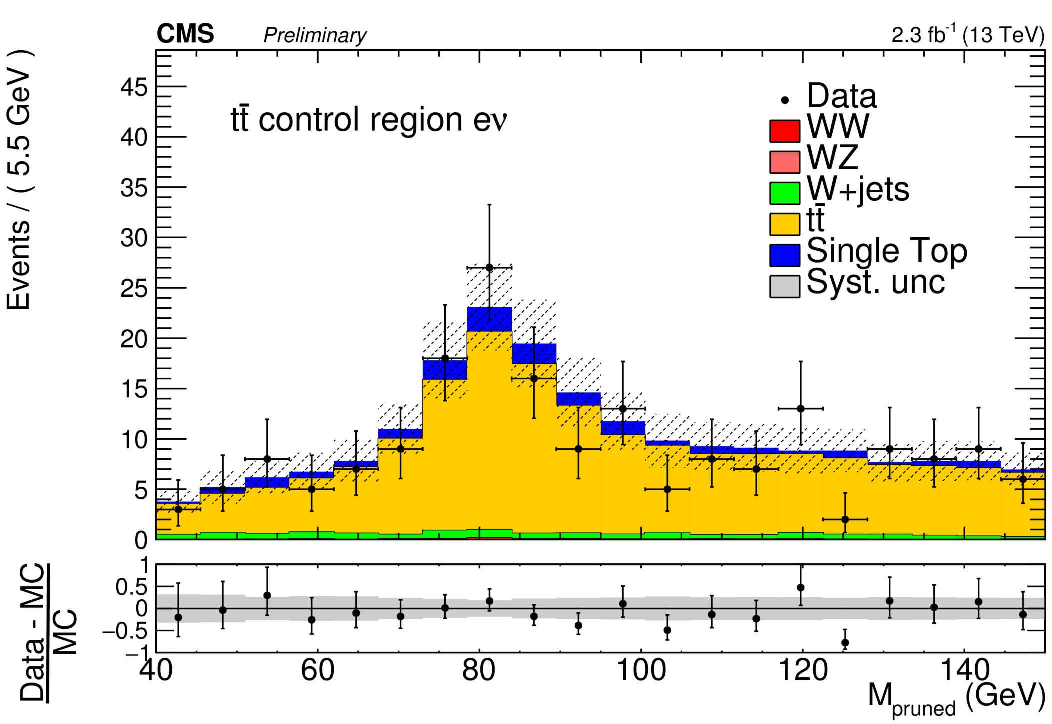
- 3 control regions are defined to validate modelling of main backgrounds

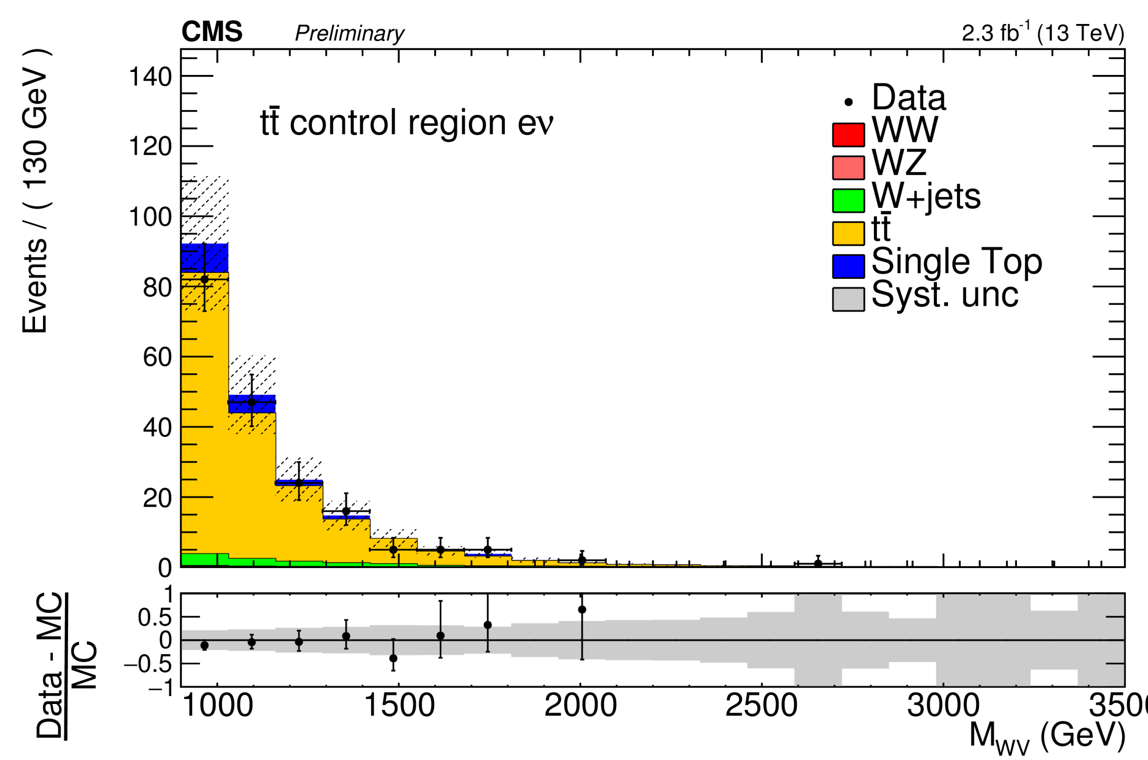


ttbar control region









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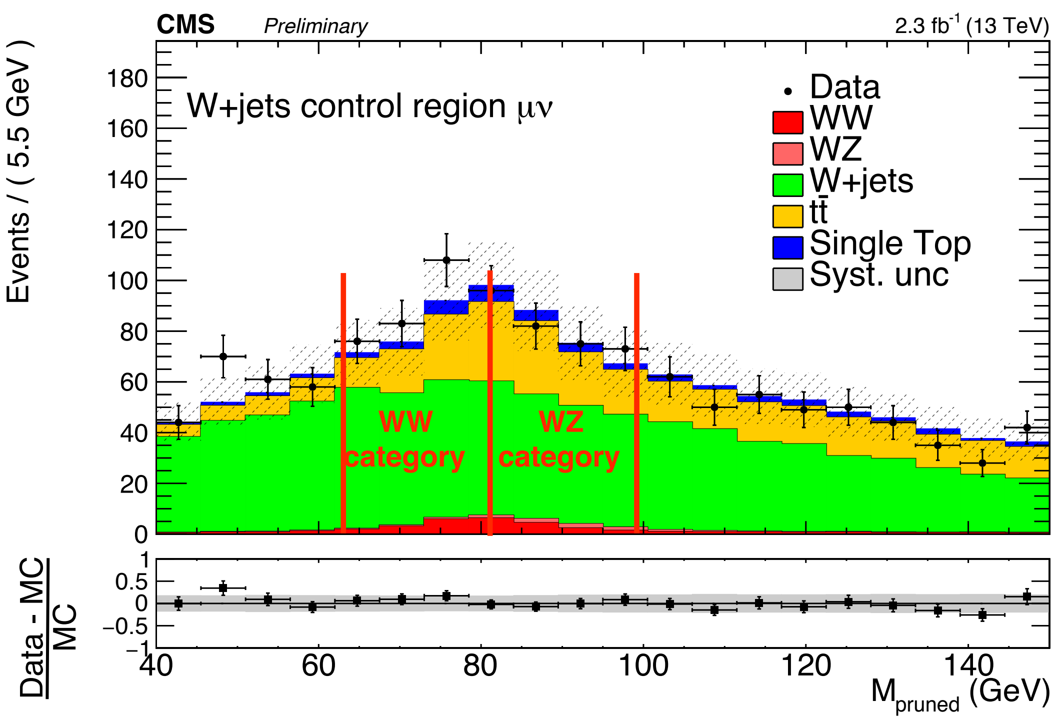
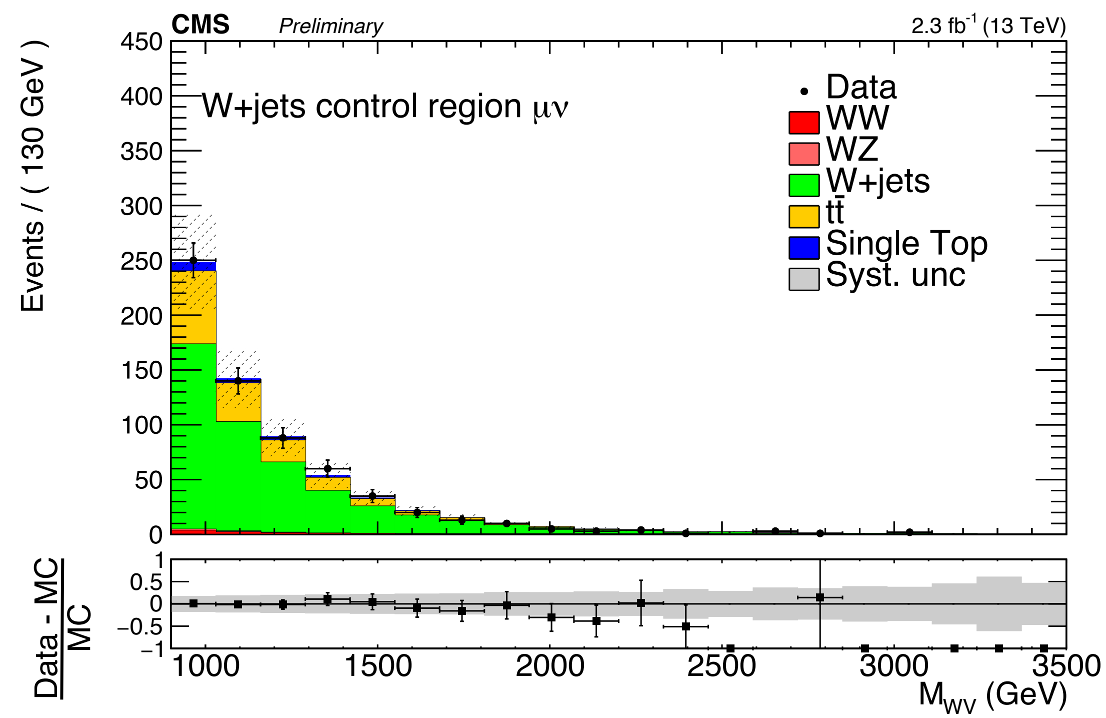
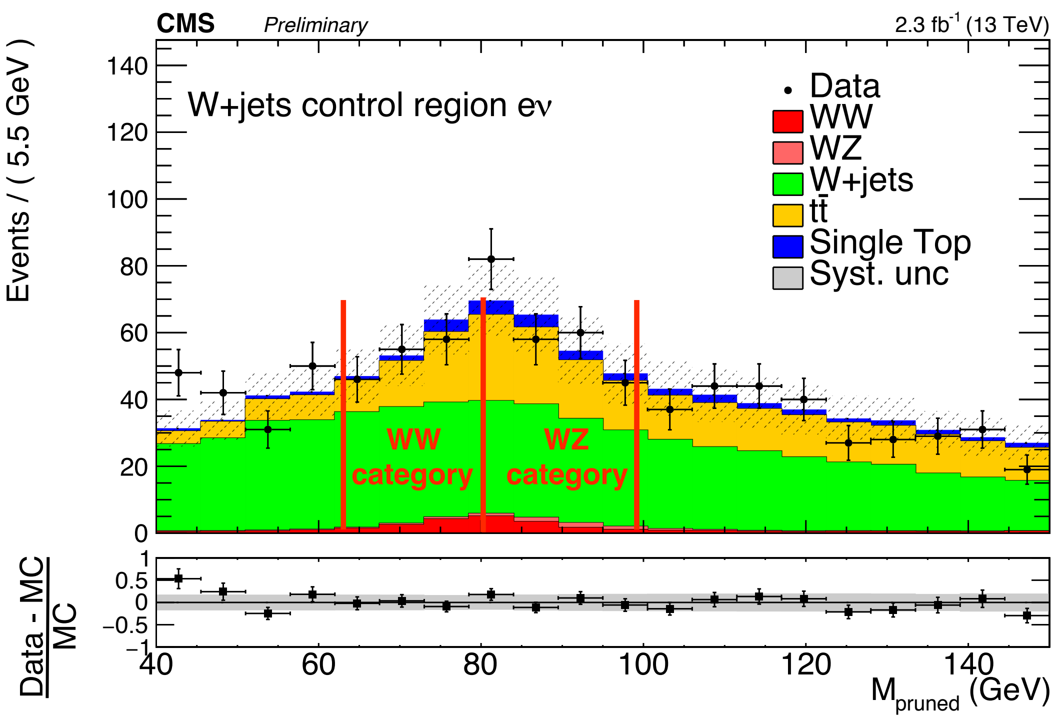
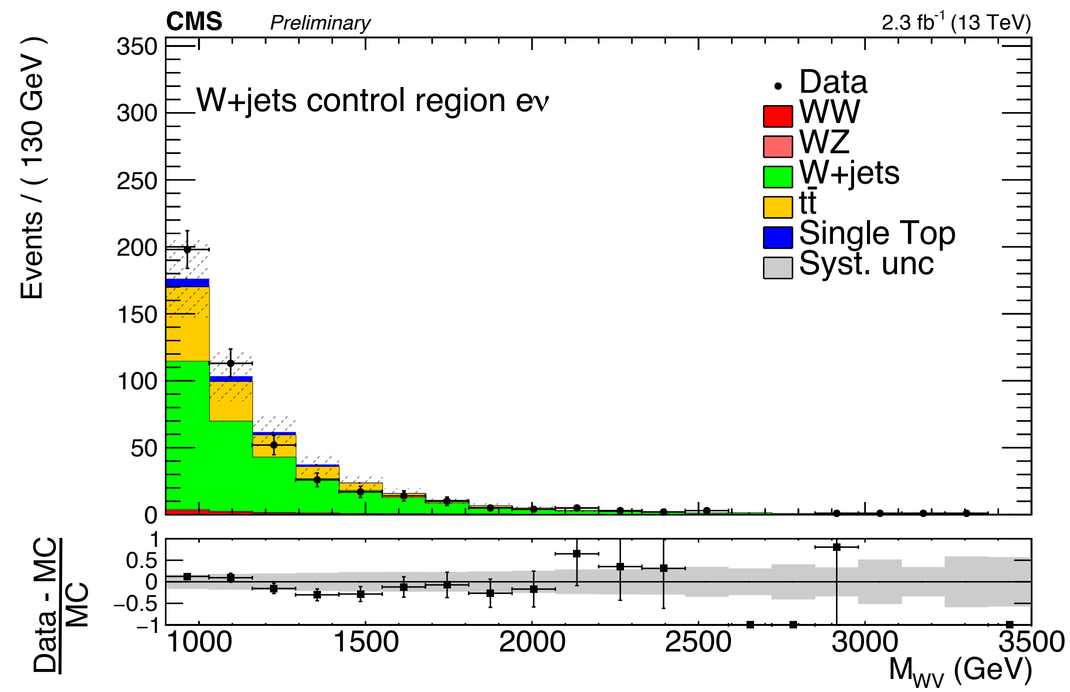
W+jets control region

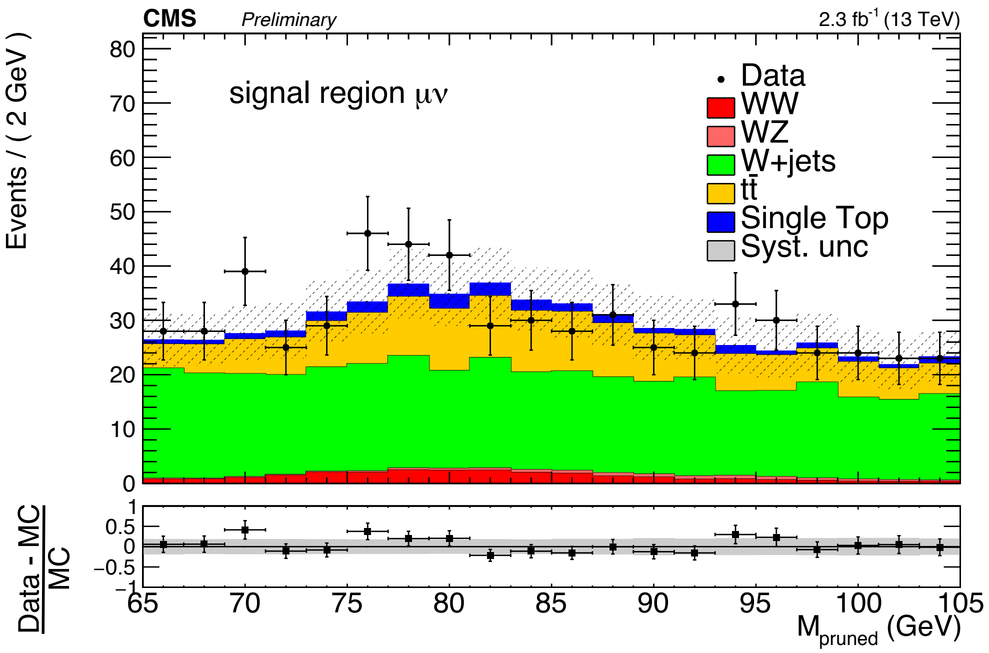


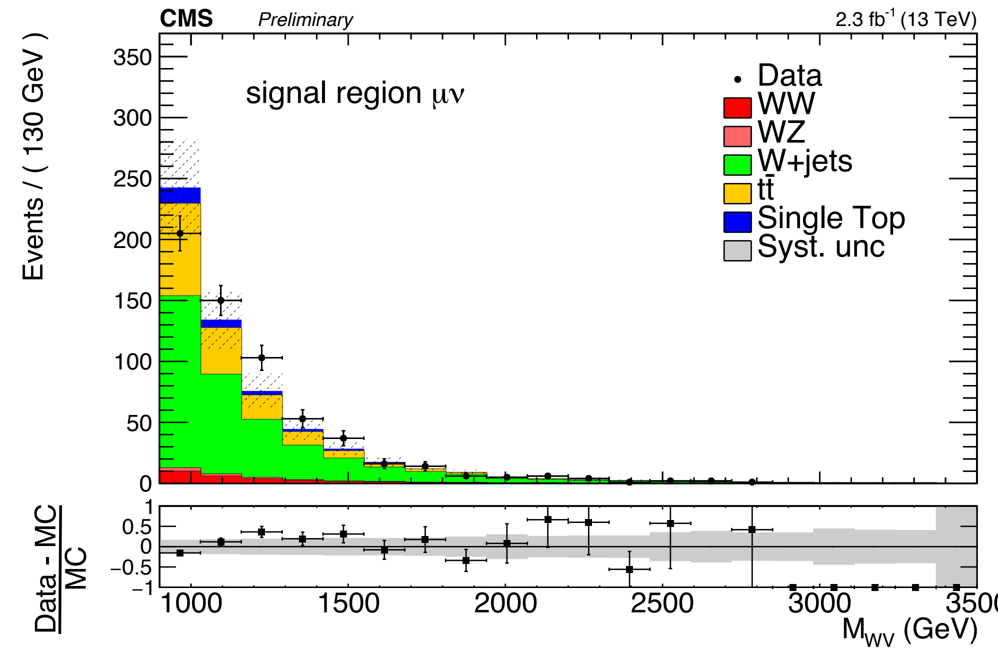


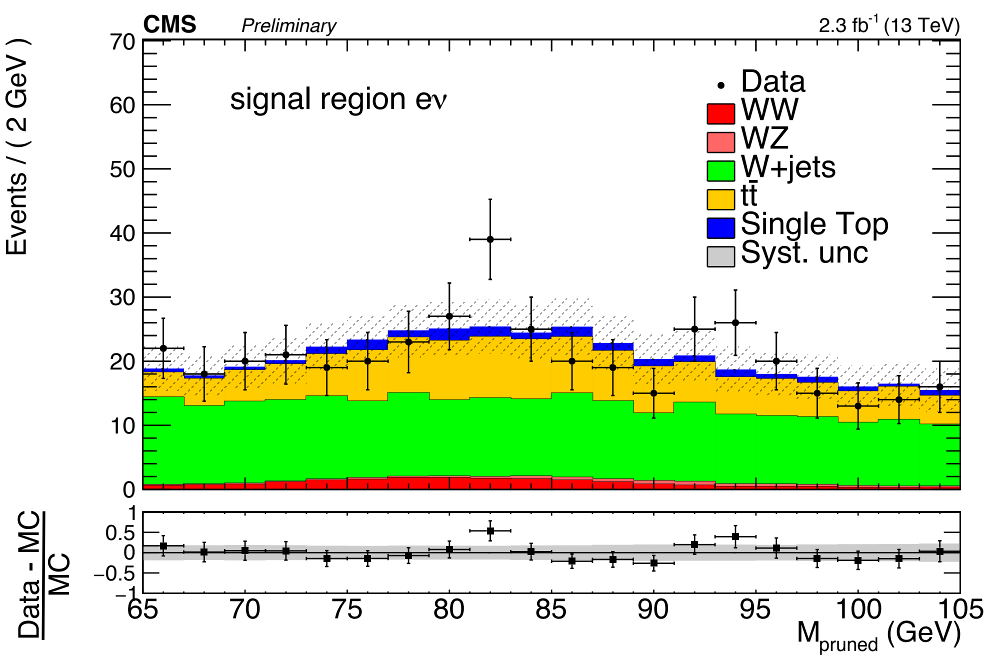


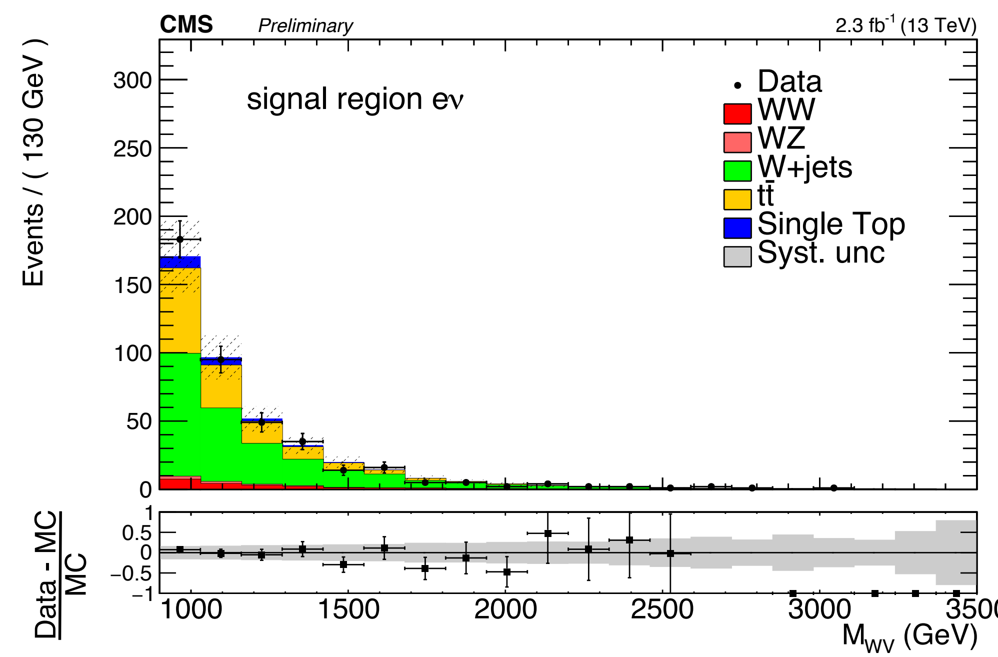


Signal region









Analysis strategy

M_{Pruned} fit in range (40, 150) GeV:
normalization of ttbar,W+jets,
W+jets uncertainty

↓

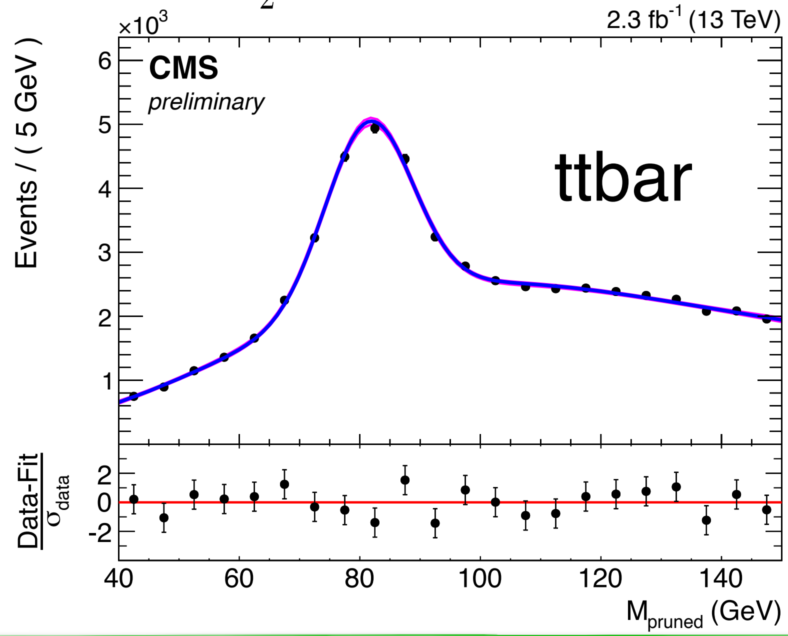
M_{WV} fit (sideband: (40.,65) $\cup$(105, 150) GeV):
shape of W+jets

↓

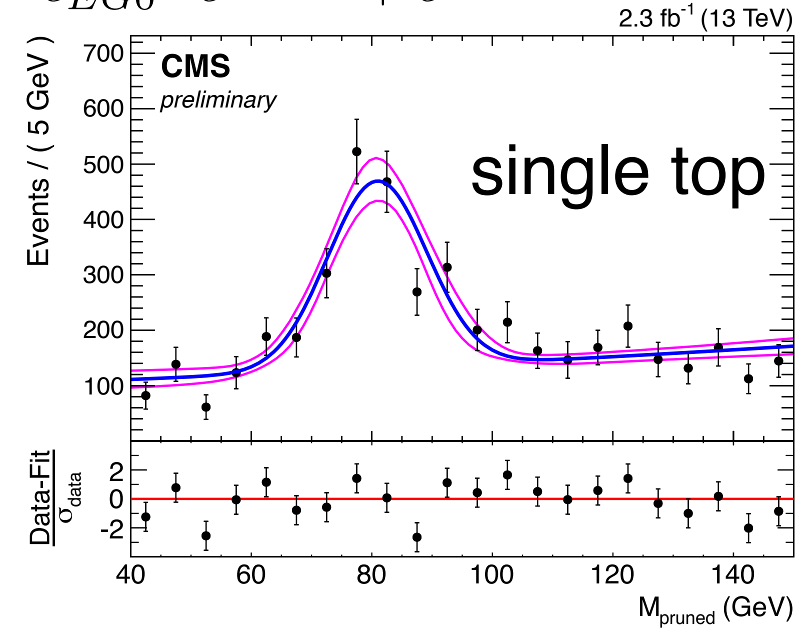
extract limits in the signal region

M_{pruned} fit: parametric shapes from Monte-Carlo

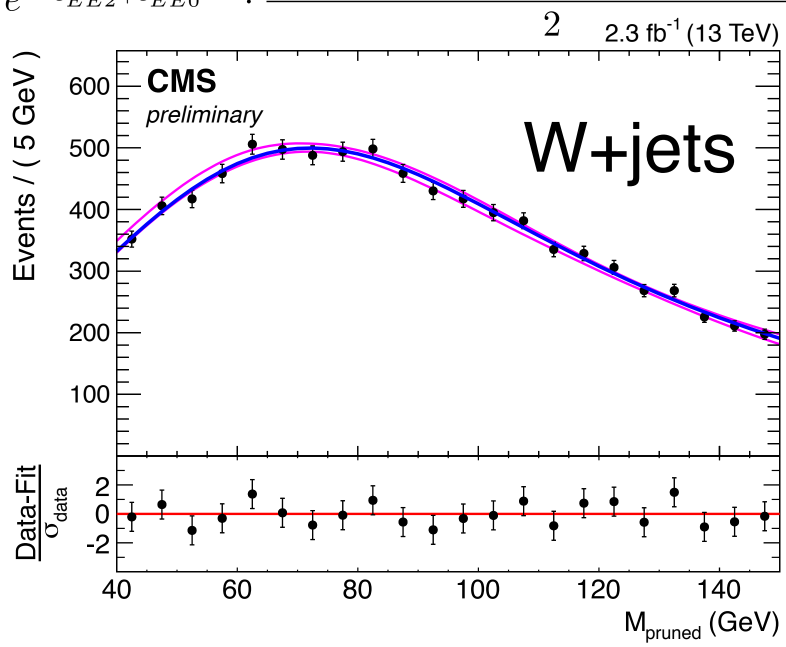
$$e^{c_{EEG0}x} \cdot \frac{1+\mathrm{Erf}((x-c_{EEG1})/c_{EEG2})}{2} + c_{EEG3} \cdot G(x, c_{EEG4}, c_{EEG5})$$



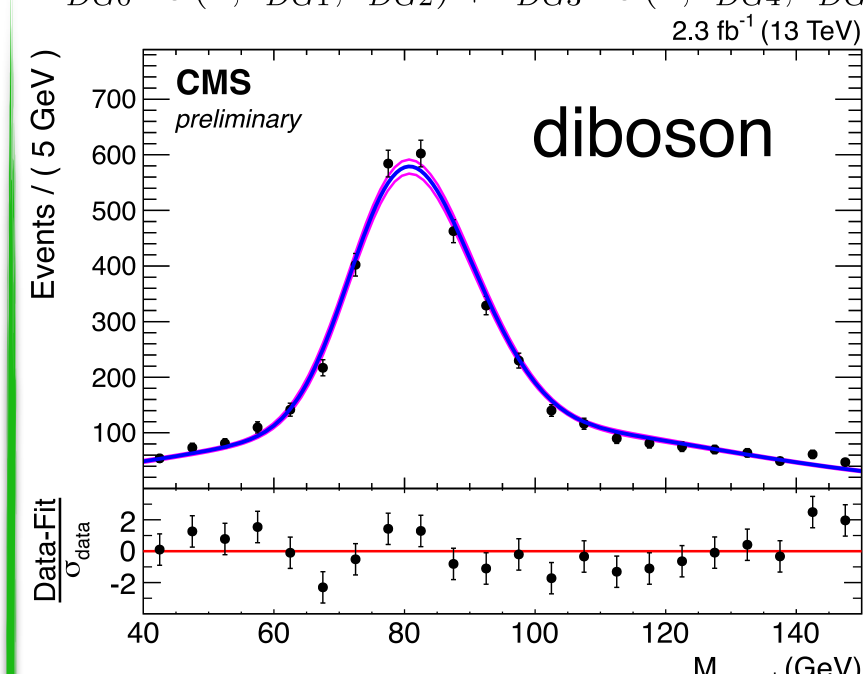
$$c_{EG0} \cdot e^{c_{EG1}x} + e^{-(x-c_{EG2})^2/2c_{EG3}^2}$$



$$e^{\frac{-c_{EE0}(x-c_{EE1})}{c_{EE2}+c_{EE0}}} \cdot \frac{1+\mathrm{Erf}\left((x-c_{EE1})/(c_{EE2}-c_{EE0})\right)}{2}$$



$$c_{DG0} \cdot G(x, c_{DG1}, c_{DG2}) + c_{DG3} \cdot G(x, c_{DG4}, c_{DG5})$$



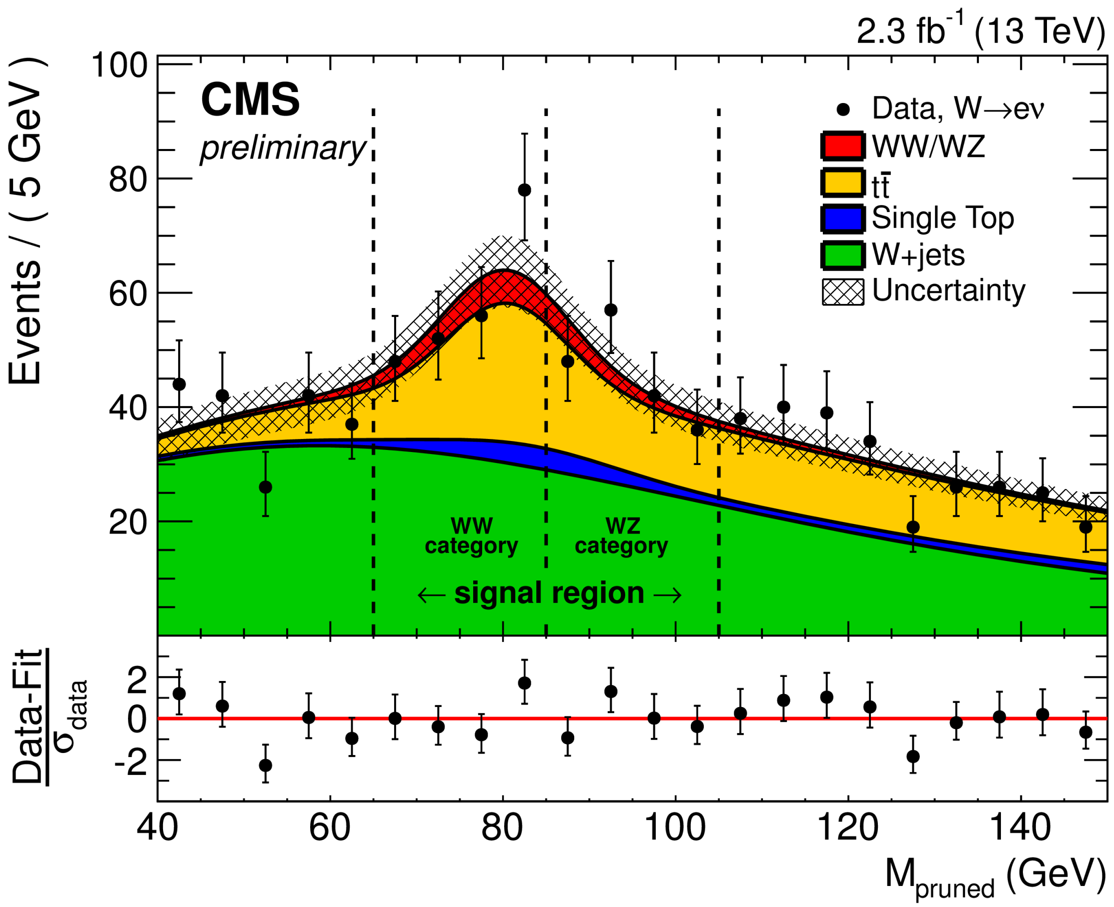
muon channel

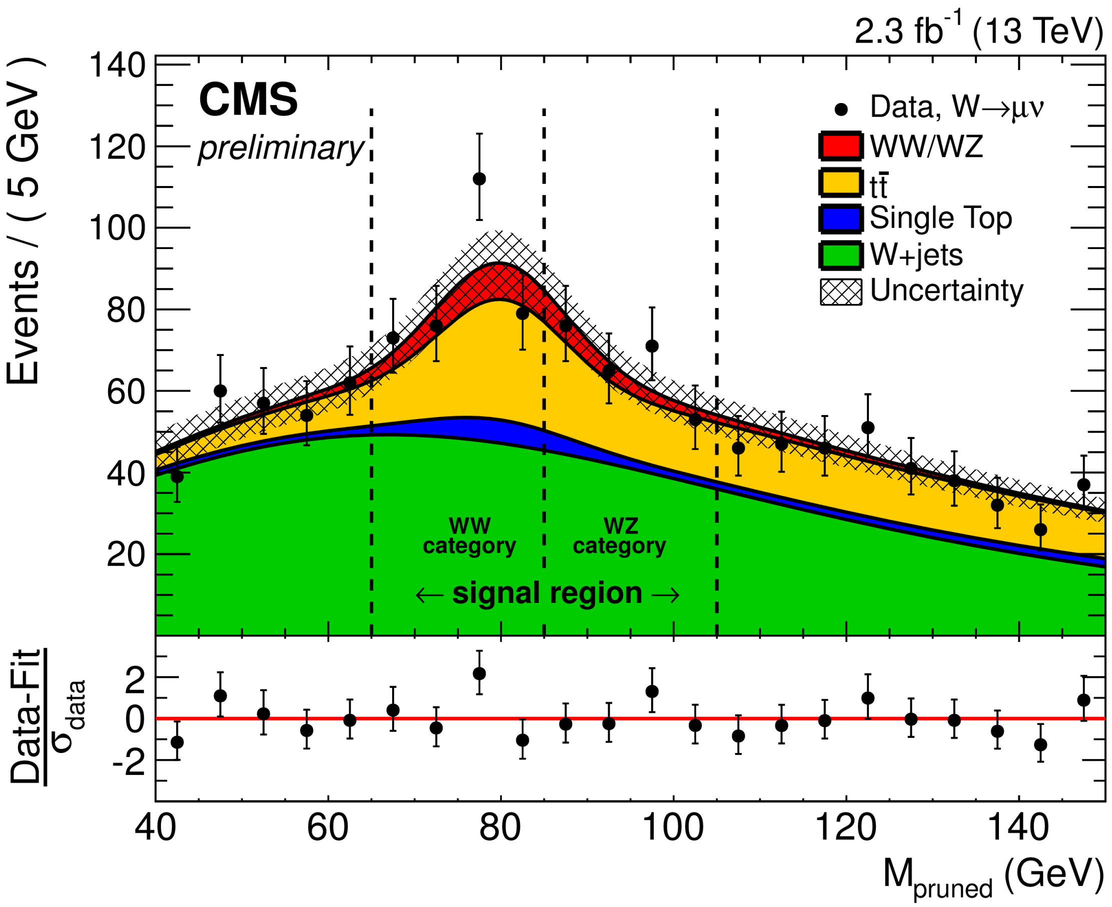
M_{pruned} fit

- Range [40., 150] GeV is used.
- ttbar normalization is constrained with Gaussian with uncertainty 20%
- W+jets normalization is floated freely + c_{EE0} in shape
- Diboson (SM) is constrained with 100% (possible enhancements from aTGC): **number is not used later**.
- single top is fixed to Monte-Carlo prediction.
- **ttbar and W+jets normalizations are extracted from the fit.**

M_{pruned} fit

- Data vs Monte-Carlo after the fit:





M_{WV} shapes

sideband region	
ttbar	$F_{\mathrm{ExpN}}(x) = e^{ax+b/x}$
single-top	$F_{\mathrm{Exp}}(x) = e^{ax}$
diboson	$F_{\mathrm{ExpN}}(x) = e^{ax}$
W+jets	$F_{\mathrm{ExpN}}(x) = e^{ax+b/x}$

signal region	
ttbar	$F_{\mathrm{ExpN}}(x) = e^{ax+b/x}$
single-top	$F_{\mathrm{Exp}}(x) = e^{ax}$
diboson	$F_{\mathrm{ExpN}}(x) = e^{ax+b/x}$
W+jets	$F_{\mathrm{ExpN}}(x) = e^{ax+b/x}$

- Fit to sideband data
- Shapes fixed to one extracted from MC except W+jets
- Shape parameter for W+jets are freely floating
- Normalization is taken from M_{pruned} fit.

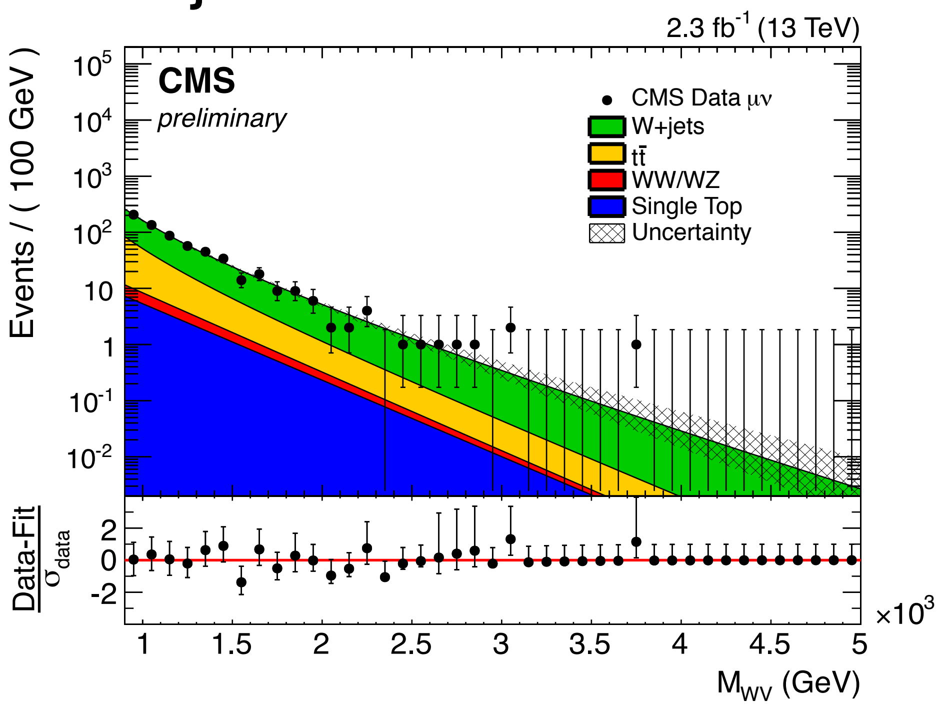
Estimate W+Jets from data:

$$F^{SB,data}_{Wjets} \quad \frac{F^{SR,MC}_{Wjets}}{F^{SB,MC}_{Wjets}}$$

$$\alpha^{MC}(M_{\ell\nu j})$$

M_{WV} shapes

W+jets fitted in sideband



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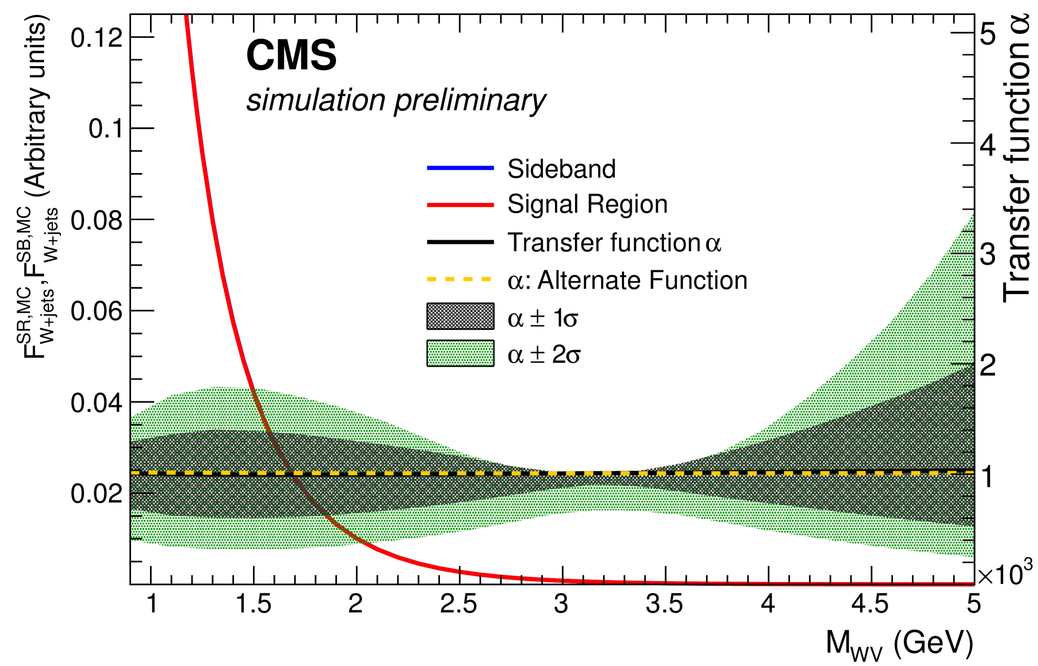

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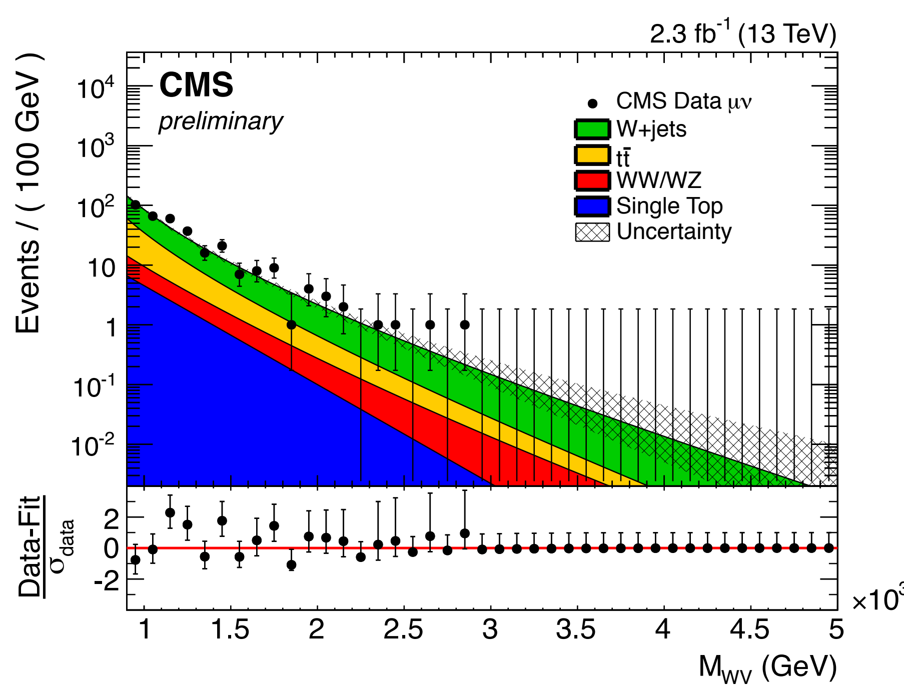
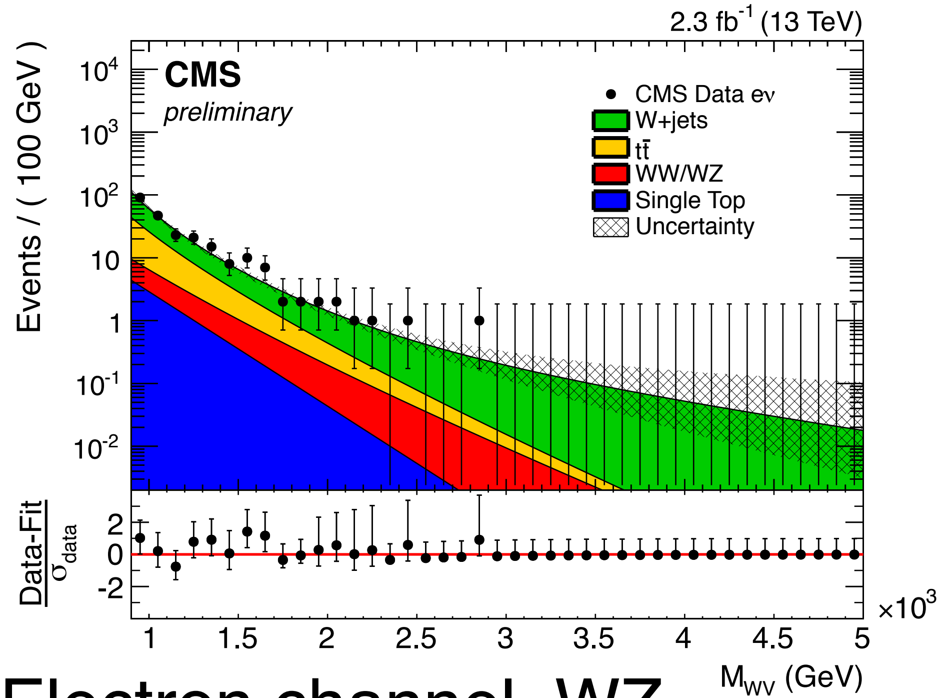


result in the signal region

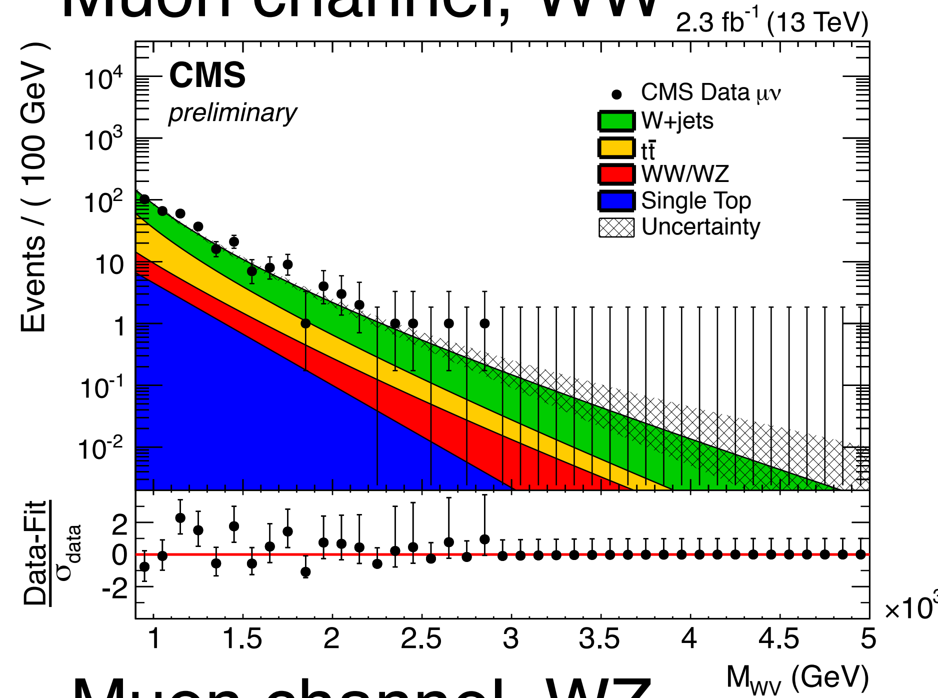
Final background shapes for M_{WV}

cut on $M_{WV} < 3.5$ TeV

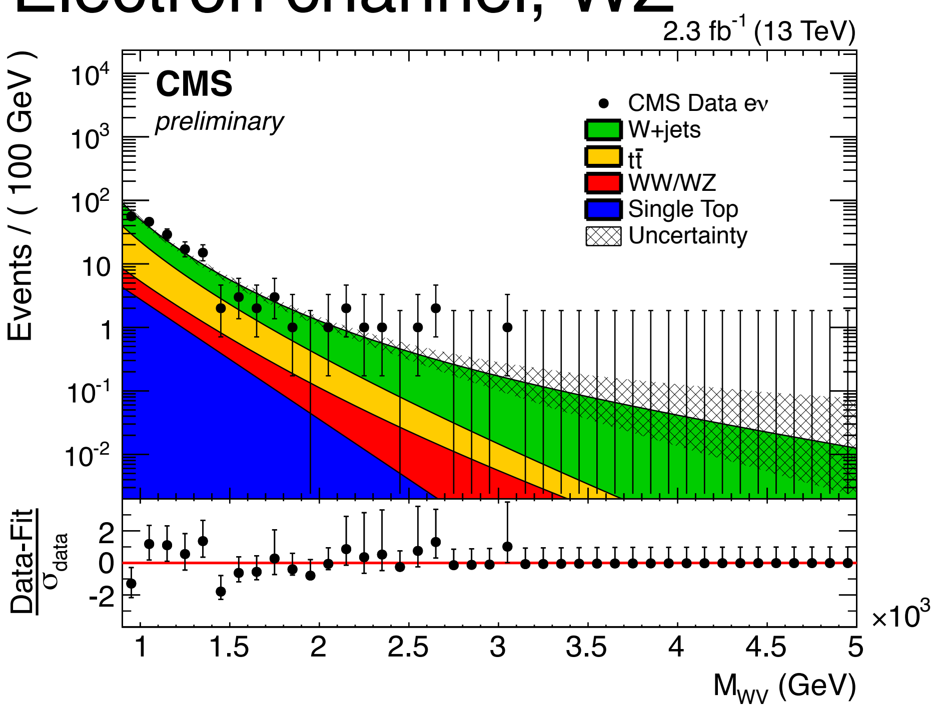
Electron channel, WW



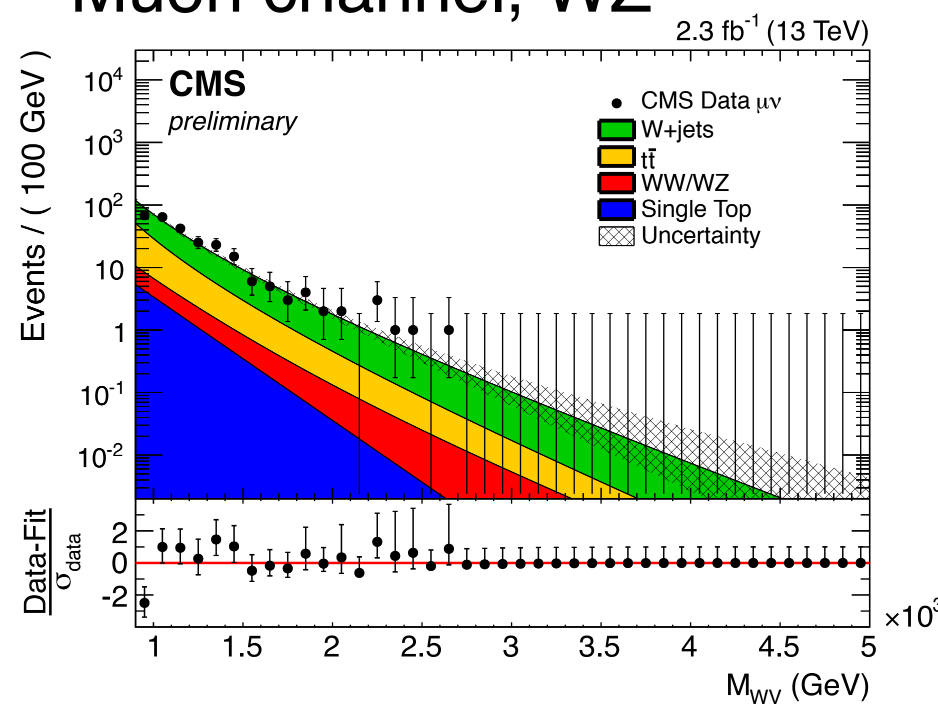
Muon channel, WW



Electron channel, WZ



Muon channel, WZ

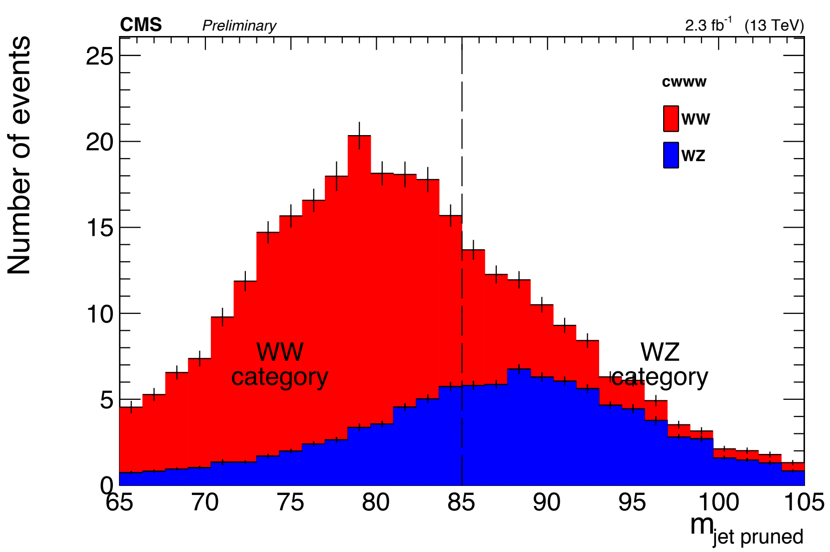


Signal regions

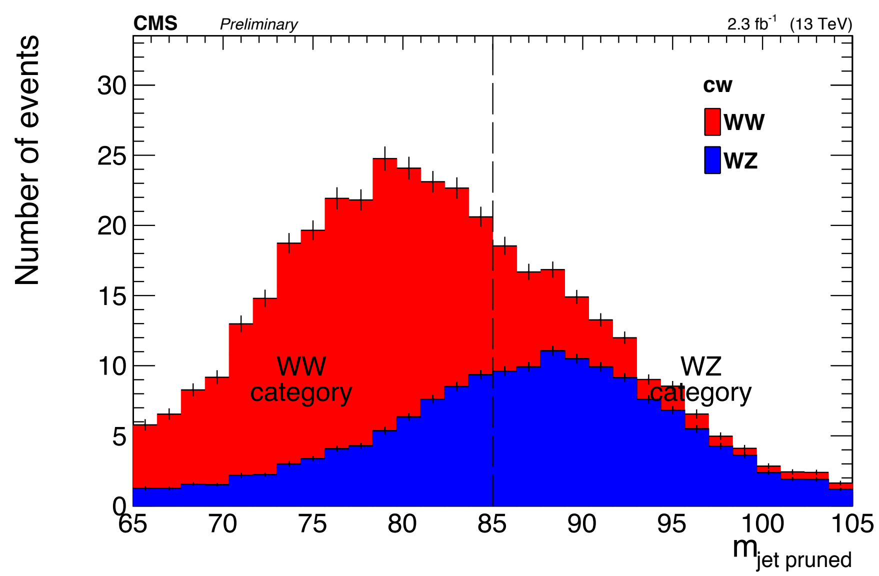
- Signal is divided into 2 categories: WW and WZ
- This provides discrimination c_B vs. c_W and c_{WWW}

Muon channel

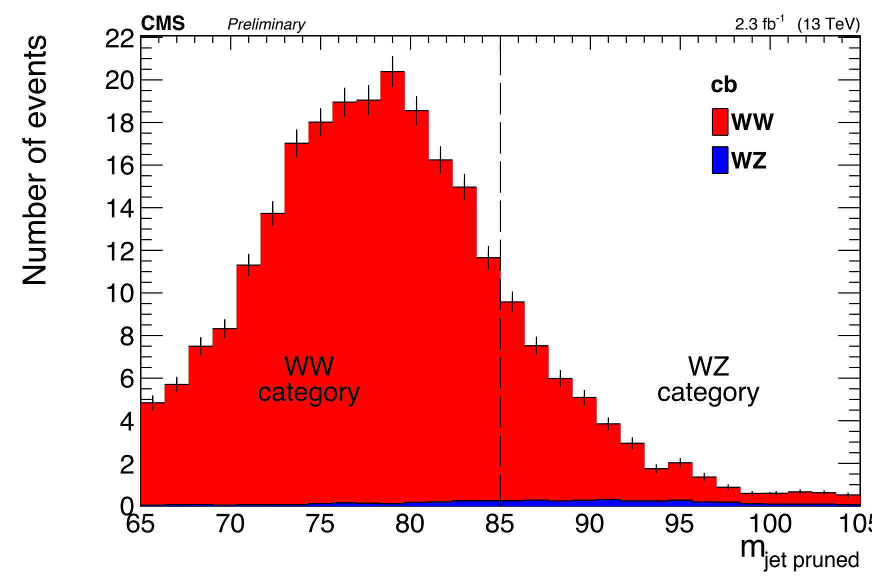
c_{WWW}



c_W



c_b



Signal modelling

- Diboson contribution (SM + aTGC):

$$F_{WV} = N_{SM} \cdot e^{a_0 x} + \sum_i \left(N_{c_i,1} \cdot c_i^2 \cdot e^{a_{i,1} x} \cdot \frac{1 + \mathrm{Erf}((x - a_{o,i})/a_{w,i})}{2} + N_{c_i,2} \cdot c_i \cdot e^{a_{i,2} x} \right)$$

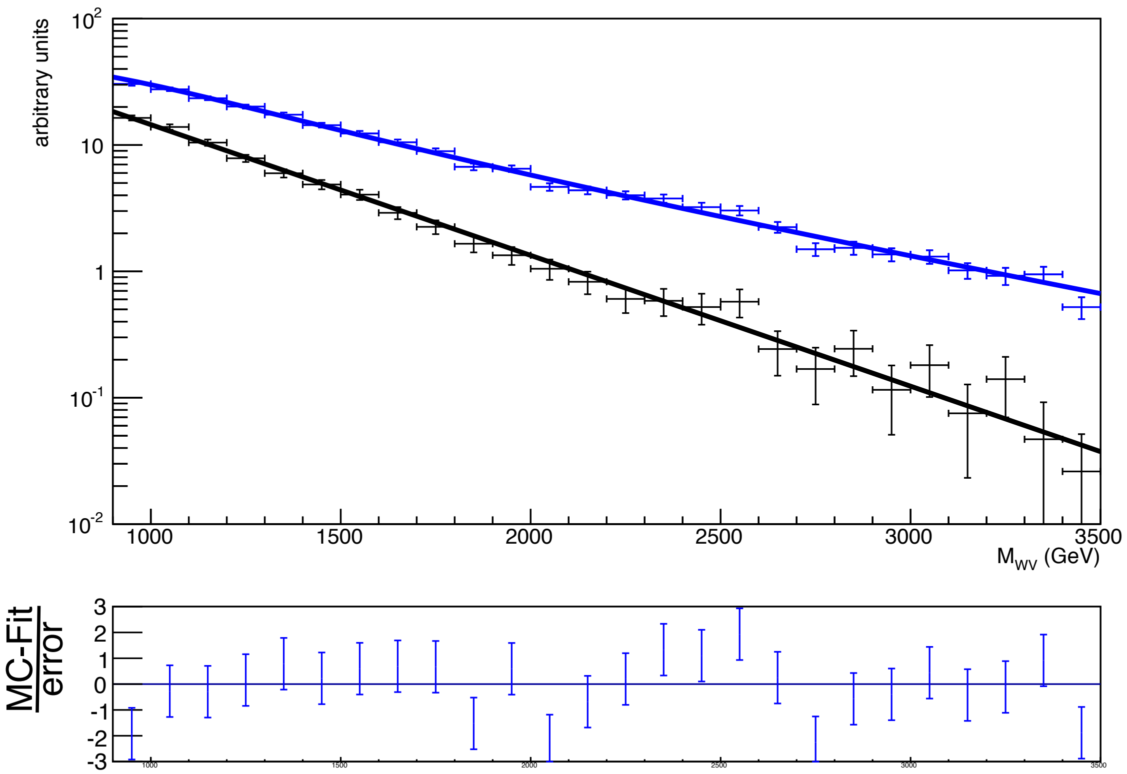
$$+ \sum_{i \neq j}^{i<j} \left(N_{c_i,c_j} \cdot c_i \cdot c_j \cdot e^{a_{ij} x} \right)$$

SM contribution ($N_{SM} \cdot e^{a_0 x}$); pure aTGC term (c_i^2 term); SM-aTGC interference (c_i term); aTGC-aTGC interference ($c_i \cdot c_j$ term)

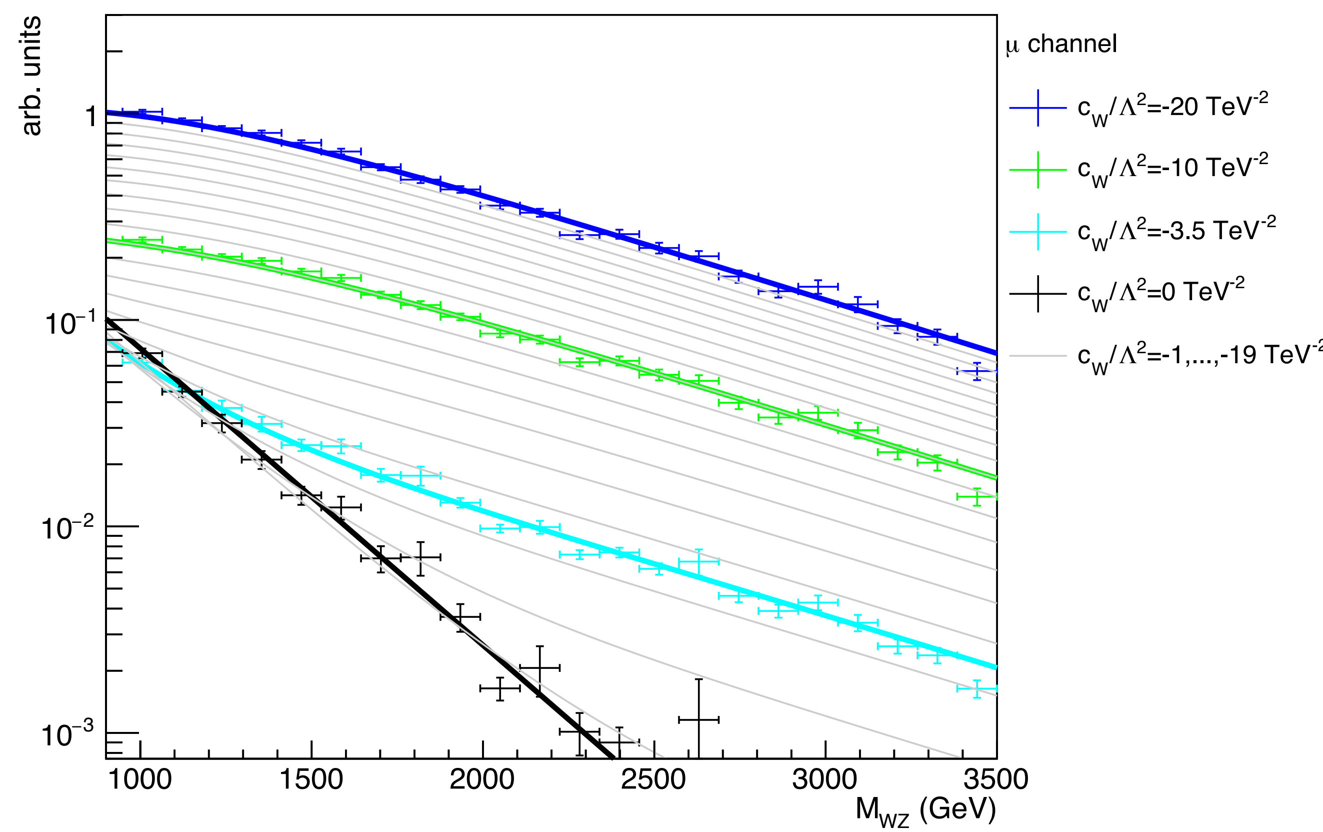
- a_0 - fit to MC sample, c_i set to 0.
- $a_{i,1}$, $a_{o,i}$, $a_{w,i}$ - fit to MC sample, c_i set to non-zero.
- a_{ij} - fit to generator level, c_i and c_j set to non-zero.

Signal modelling

c_b positive WW muon channel



c_W negative WZ muon channel

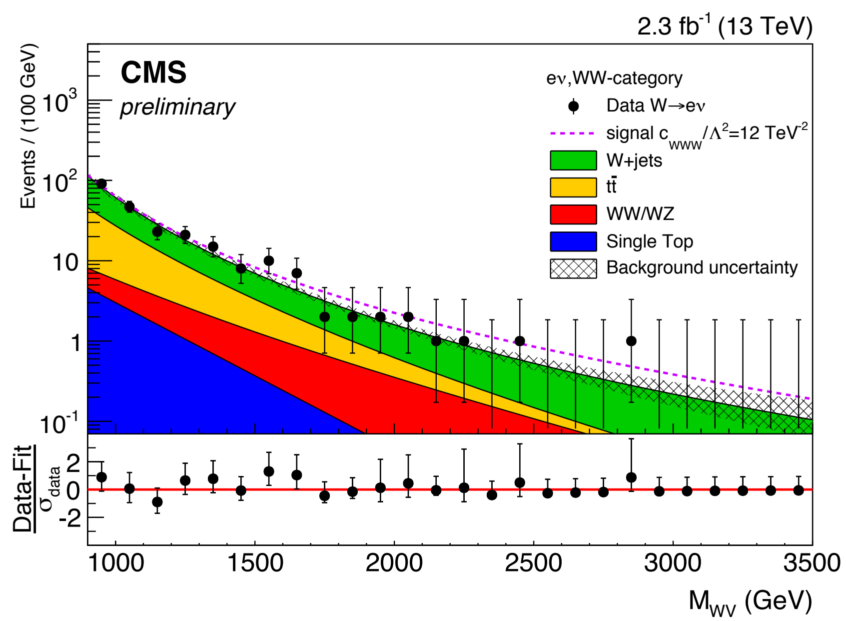


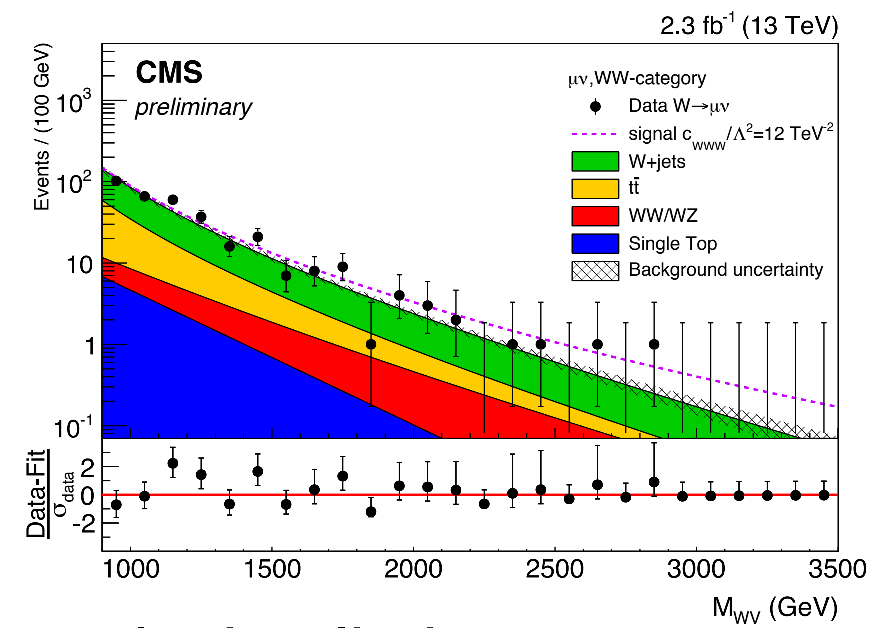
generator level

lines represent signal function→working at lower aTGC

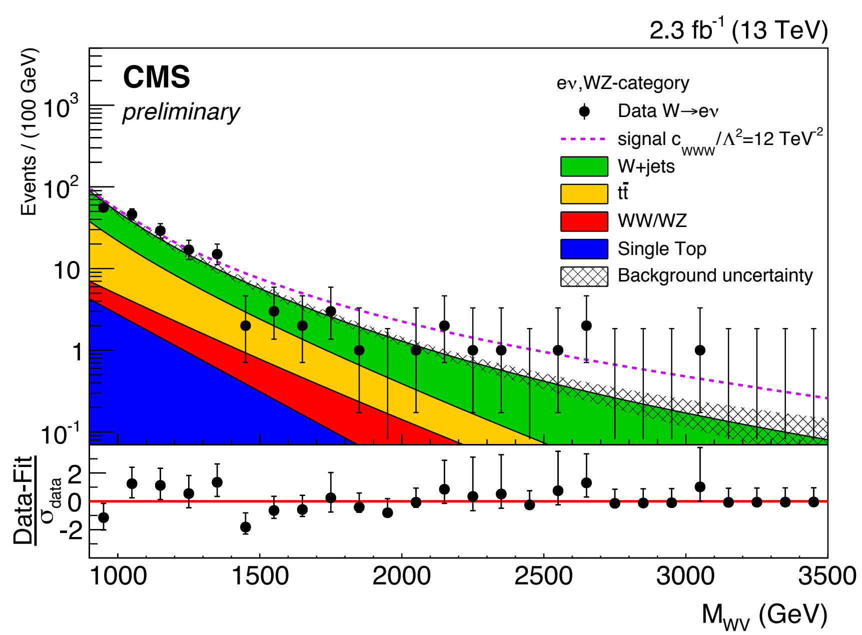
Limits on aTGCs

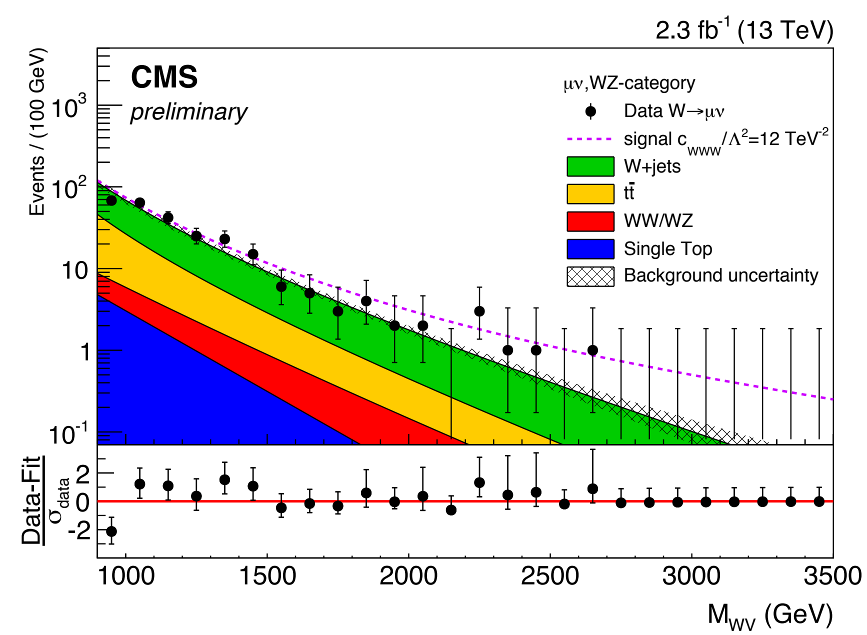
- Limits are extracted in a simultaneous **unbinned maximum likelihood fit** in WW and WZ category, muon and electron channel.





- ΔNLL contours are used for exclusion limits.

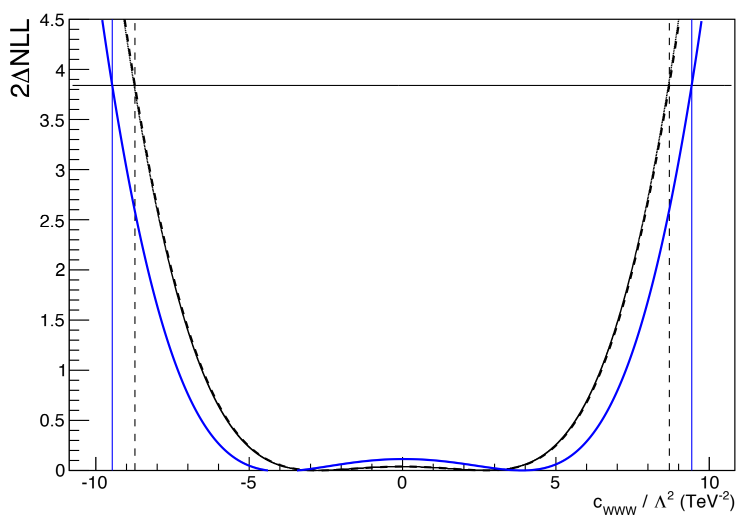


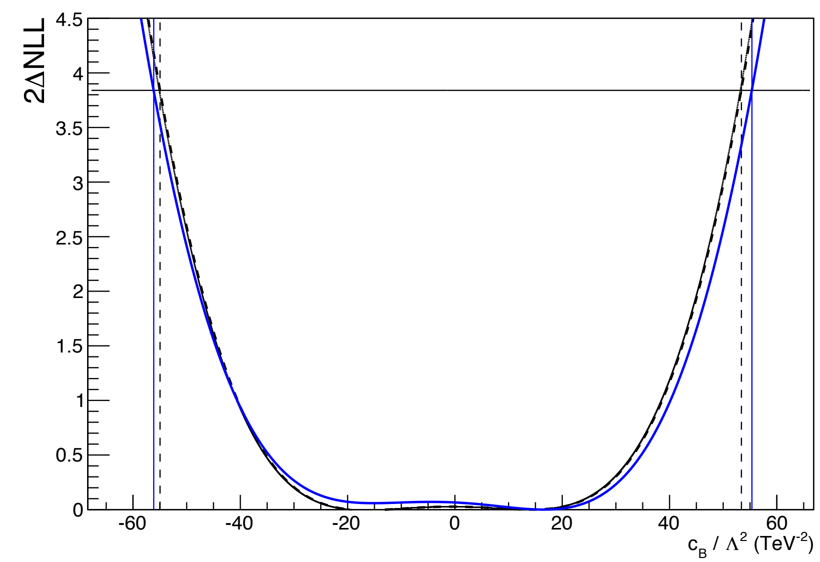


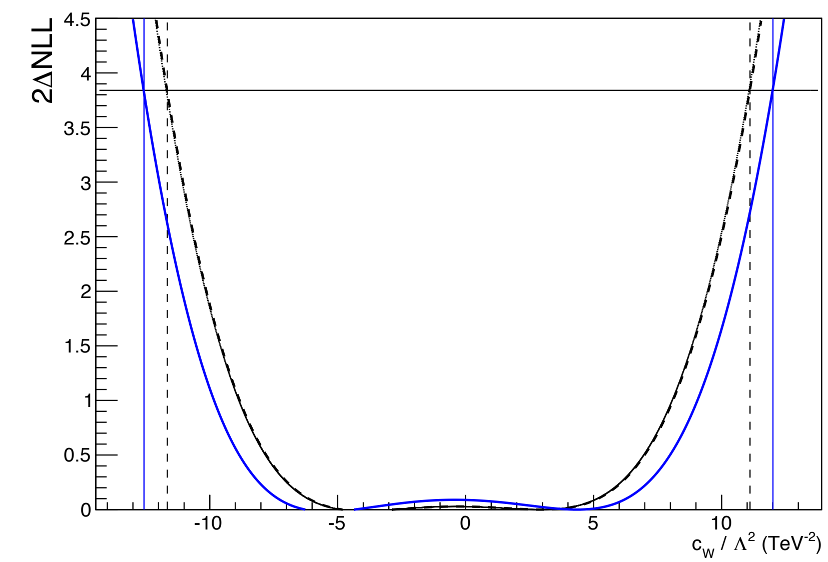
Limits on aTGCs

expected
observed

- 1 dimension limits:





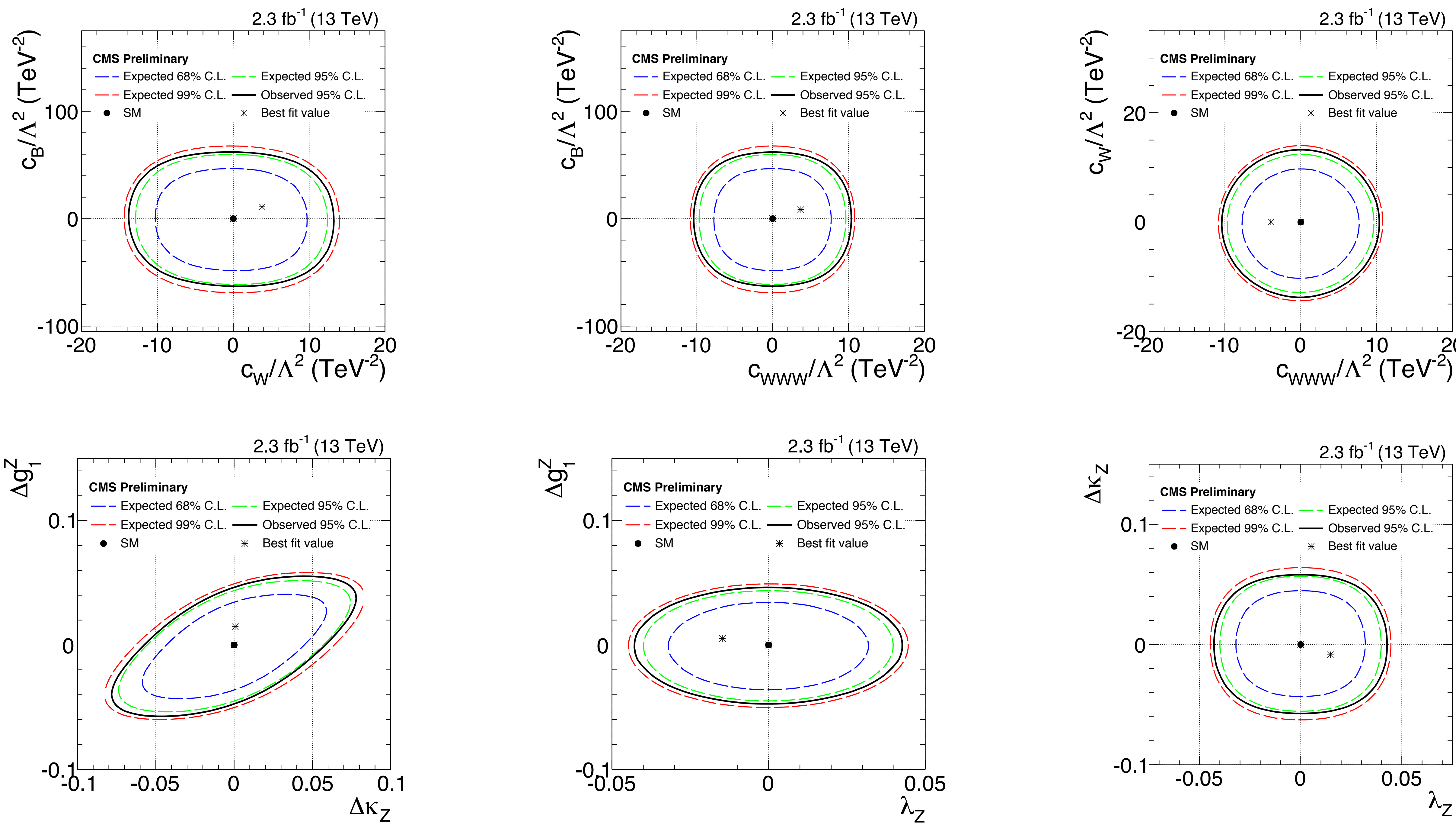


- Results presented in terms of EFT and LEP parametrization:

	aTGC	expected limit	observed limit
EFT param.	$\frac{c_{WWW}}{\Lambda^2}$ (TeV^{-2})	[-8.73 , 8.70]	[-9.46 , 9.42]
	$\frac{c_W}{\Lambda^2}$ (TeV^{-2})	[-11.7 , 11.1]	[-12.6 , 12.0]
	$\frac{c_B}{\Lambda^2}$ (TeV^{-2})	[-54.9 , 53.3]	[-56.1 , 55.4]
Vertex param.	λ	[-0.036 , 0.036]	[-0.039 , 0.039]
	Δg_1^Z	[-0.066 , 0.064]	[-0.067 , 0.066]
	$\Delta\kappa_Z$	[-0.038 , 0.040]	[-0.040 , 0.041]

Limits on aTGCs

- 2 dimensional limits:



Conclusions and outlook

- Search for anomalous triple gauge couplings using semileptonic WV decays was presented.
- Full 2015 dataset with integrated luminosity 2.3 fb^{-1} is used.
- Results were approved by the CMS experiment in August and shown at QCD@LHC conference in Zürich: SMP-16-012.
- First aTGC result from CMS at 13 TeV.
- We plan to update results with 2016 dataset.

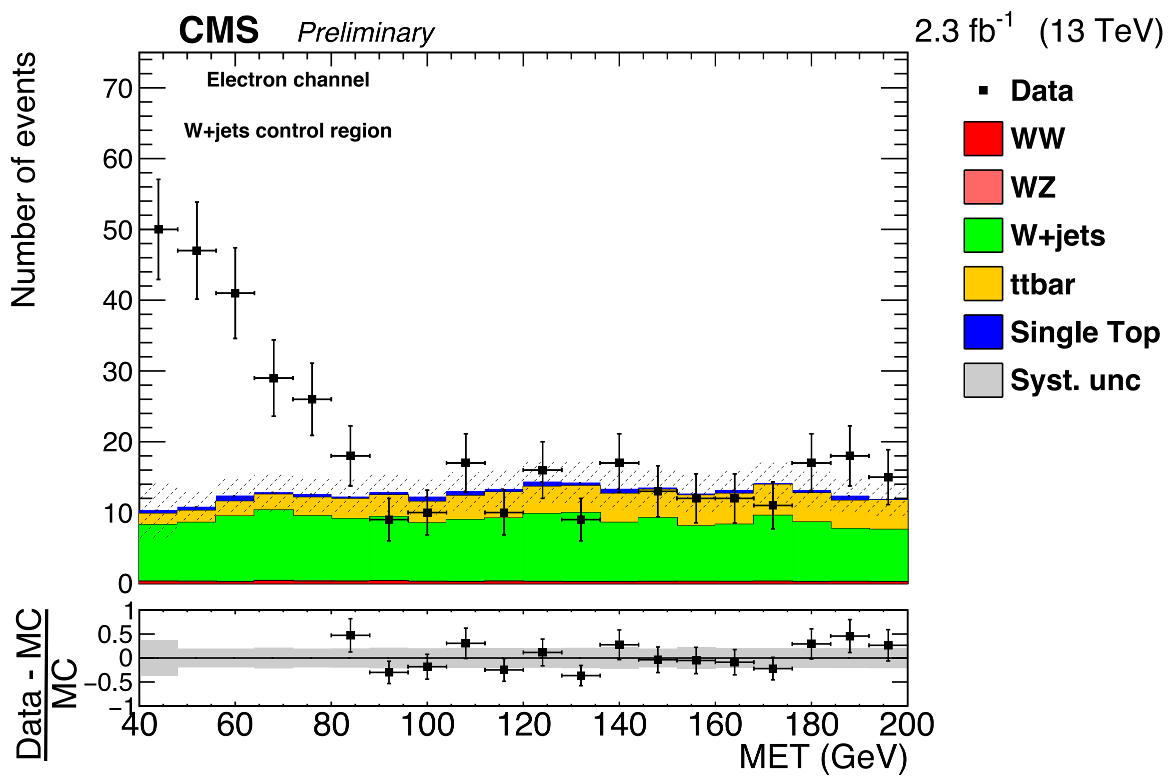
Backup

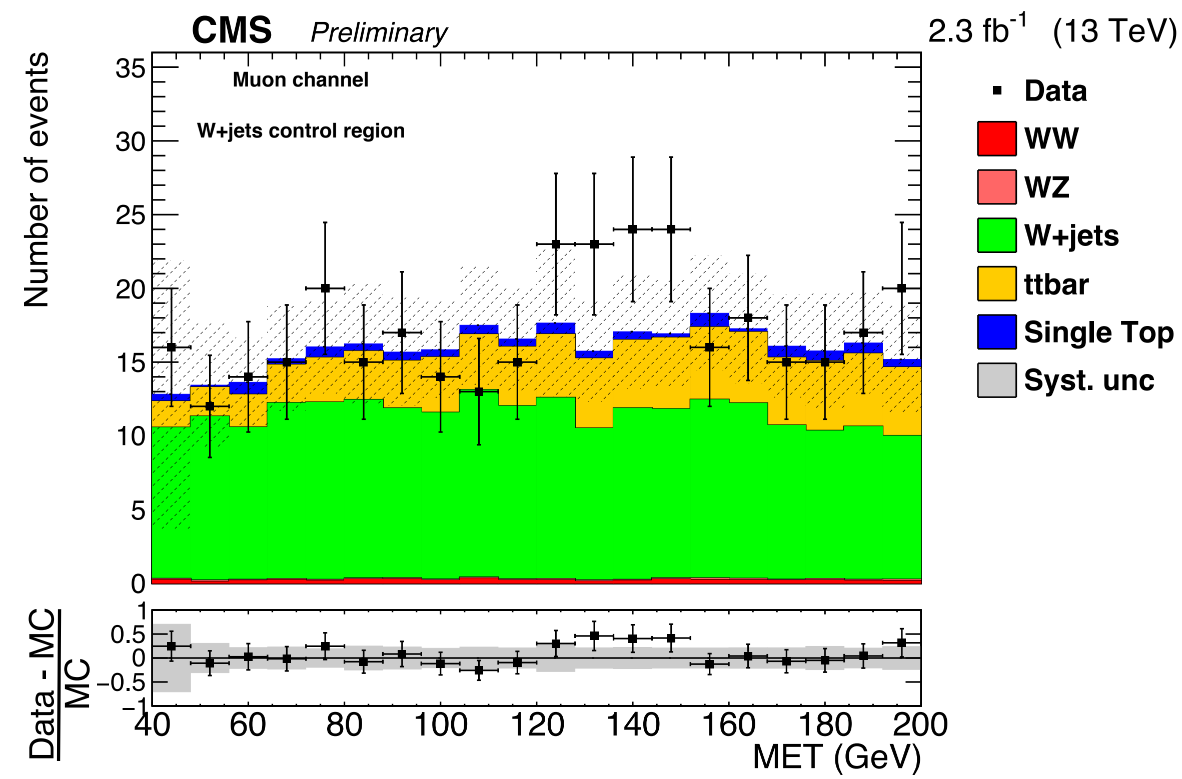
Signal sample

- Signal generated with madgraph using EWdim6 model, Madgraph 2.2.3 →**LO sample**
- 9 points are generated (roughly correspond to sensitivity):

$c_{WWW}/\Lambda^2[TeV^{-2}]$	$c_W/\Lambda^2[TeV^{-2}]$	$c_B/\Lambda^2[TeV^{-2}]$
± 12.0	± 20.0	± 60.0
± 12.0	0.0	0.0
0.0	± 20.0	0.0
0.0	0.0	± 60.0
0.0	0.0	0.0

MET cut


CMS Preliminary
2.3 fb-1 (13 TeV)
Electron channel
W+jets control region
Number of events
Data
WW
WZ
W+jets
ttbar
Single Top
Syst. unc
Data - MC / MC
MET (GeV)


CMS Preliminary
2.3 fb-1 (13 TeV)
Muon channel
W+jets control region
Number of events
Data
WW
WZ
W+jets
ttbar
Single Top
Syst. unc
Data - MC / MC
MET (GeV)

dim 6 operators

$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\ \mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

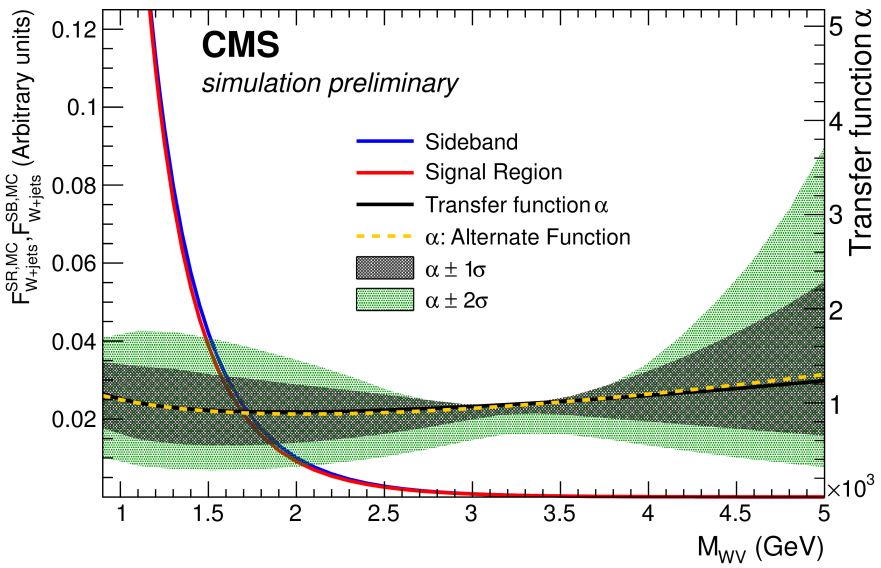
M_{pruned} fit

- Results of the fit:

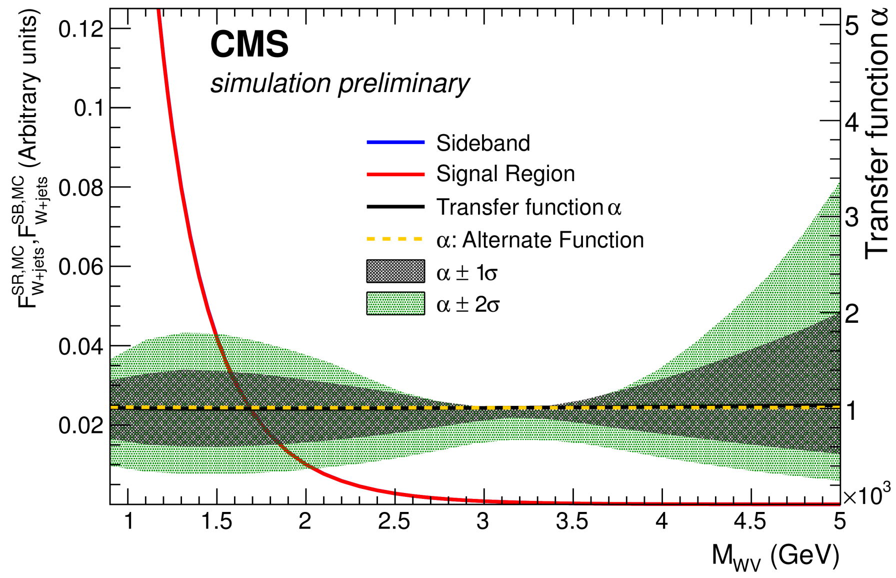
PAS	electron			muon		
	pre-fit	post-fit	scale factor	pre-fit	post-fit	scale-factor
W+jets	584	538 ± 56	0.92 ± 0.10	767	814 ± 72	1.06 ± 0.09
$t\bar{t}$	243 ± 49	256 ± 46	1.1 ± 0.2	318 ± 64	313 ± 60	1.0 ± 0.2
single top	37	37	1	52	52	1
diboson	34 ± 34	41 ± 27	1.2 ± 0.8	45 ± 45	61 ± 35	1.4 ± 0.8
Total expected	898	872 ± 30	0.97 ± 0.03	1182	1240 ± 35	1.05 ± 0.03
Data		874			1241	

α-function

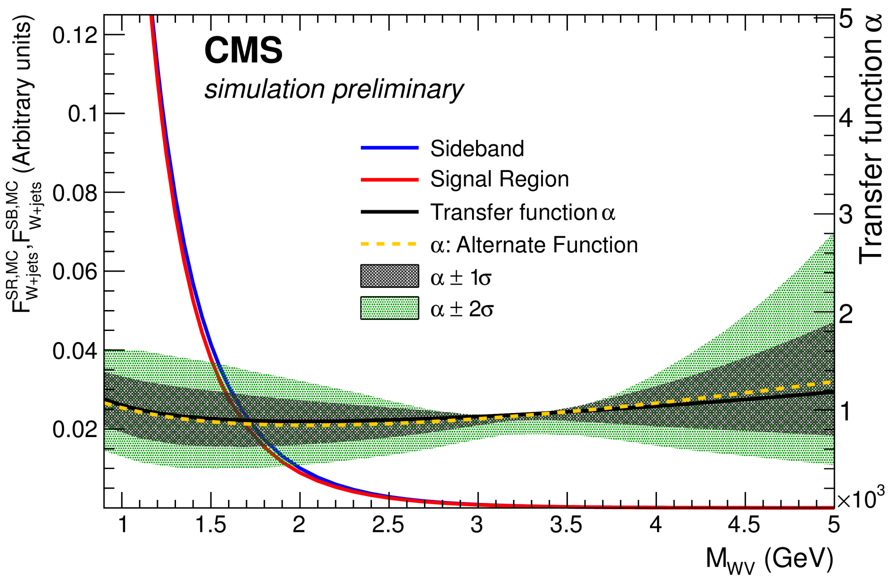
WW, electron channel



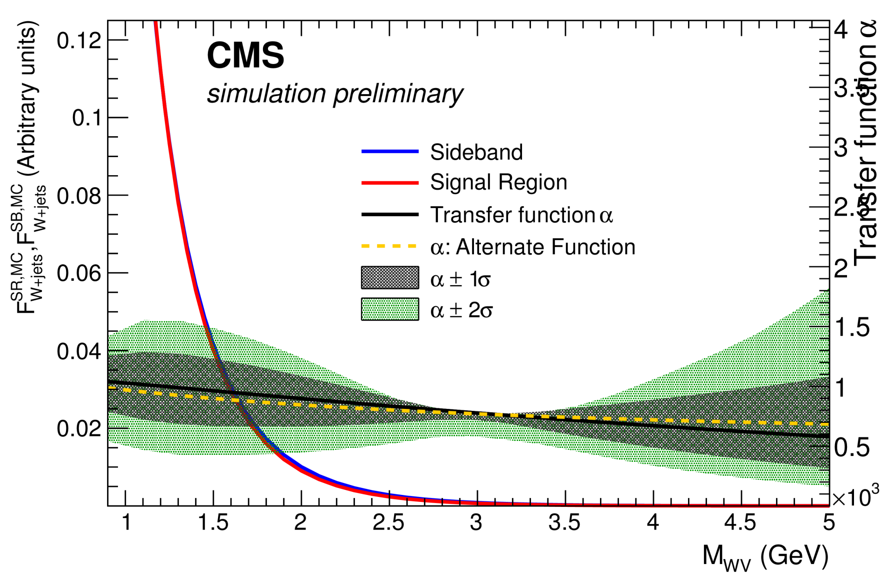
WW, muon channel



WZ, electron channel



WZ, muon channel



Summary of background extraction

- Normalisation of ttbar and W+jets are extracted from M_{pruned} fit, other backgrounds → from theory prediction.
- W+jets shape is extracted from sideband data and corrected with alpha-function.
- Fit was verified with closure test.

Signal and background yields

- Yields in the signal region
- W+jets uncertainty: statistical uncertainty from M_{pruned} fit and alternative function.

	electron		muon	
	WW	WZ	WW	WZ
W+jets	124 ± 17	103 ± 16	192 ± 20	164 ± 20
$t\bar{t}$	73 ± 17	58 ± 13	90 ± 21	71 ± 17
single top	10.9 ± 1.4	9.8 ± 1.2	17.8 ± 2.3	10.6 ± 1.4
diboson (SM)	15.8 ± 2.2	9.3 ± 1.3	20.6 ± 3.0	12.2 ± 1.8
Total expected (SM)	224 ± 24	180 ± 21	320 ± 29	258 ± 26
diboson $\frac{c_{WWW}}{\Lambda^2} = 12\,\text{TeV}^{-2}$	36.2 ± 5.1	39.9 ± 5.7	50.8 ± 7.3	55.4 ± 8.0
diboson $\frac{c_W}{\Lambda^2} = 20\,\text{TeV}^{-2}$	51.6 ± 7.4	69 ± 10	72 ± 10	91 ± 13
diboson $\frac{c_B}{\Lambda^2} = 60\,\text{TeV}^{-2}$	41.5 ± 5.9	20.1 ± 2.9	57.0 ± 8.2	26.8 ± 3.9
Data	234	183	340	265

Systematics uncertainties: normalization

- b-tagging/mis-tagging (ttbar and WZ)
- Jet energy scale and resolution
- Lepton energy scale and resolution
- Missing E_T uncertainty
- PDF uncertainty → PDF4LHC recommendations
- Q_2 uncertainty (Scale) → envelope

process	b-tag	jet en.	lept. en.	lept. id	PDF	scale	$\not{E}_T$	lumi	V-tag
	electron channel								
$t\bar{t}$	0.8	2.8	<0.05	1.0	2.5	19	0.5	2.7	12
WZ	0.1	1.7	<0.05	1.0	2.5	3.6	0.5	2.7	12
WW	<0.05	2.4	0.6	1.0	1.9	6.0	0.6	2.7	12
Single Top	<0.05	1.6	0.5	1.0	0.3	2.0	1.2	2.7	12
	muon channel								
$t\bar{t}$	0.8	2.6	1.6	3.2	2.6	19	0.1	2.7	12
WZ	<0.05	1.6	1.4	3.8	2.3	3.5	0.3	2.7	12
WW	<0.05	2.3	1.7	3.9	1.8	6.0	0.2	2.7	12
Single Top	<0.05	0.6	1.9	3.6	0.4	1.9	0.5	2.7	12

Systematics uncertainties: shapes

- Fit done varying MC up/down
- Uncertainties on slopes of the signal function (without interference):

category	a_{cw}	a_{cb}	a_{cwww}
WW, muon	4.54	5.37	5.28
WW, electron	4.98	6.04	5.90
WZ, muon	4.53	15.50	4.72
WZ, electron	4.87	15.88	5.06

- Slope involving c_b is assigned to have 15 % uncertainty (WZ-category).
- Other slopes: 5 %

HEEP ID

https://twiki.cern.ch/twiki/bin/view/CMS/HEEPElectronIdentificationRun2#Selection_Cuts_HEEP_V6_1_Optiona

Selection Cuts: HEEP V6.1 (Optional for 76X)

Variable	Barrel	Endcap
E_T	> 35 GeV	> 35 GeV
η range	$\|\eta_{sc}\| < 1.4442$	$1.566 < \|\eta_{sc}\| < 2.5$
isEcalDriven	=1	=1
$\|\Delta\eta_{in}^{seed}\|$	< 0.004	< 0.006
$\|\Delta\varphi_{in}\|$	< 0.06	< 0.06
H/E	<1/E + 0.05	< 5/E + 0.05
full 5x5 $\sigma_{i\eta i\eta}$	n/a	<0.03
full 5x5 E_{2x5}/E_{5x5}	>0.94 OR E_{1x5}/E_{5x5} > 0.83	n/a
EM + Had Depth 1 Isolation	<2+0.03*Et +0.28*rho	<2.5 +0.28*rho for Et<50 else
		<2.5+0.03*(Et-50) +0.28*rho
Track Isol: Trk Pt	<5 for Et<95 else	<5 for Et<100 else
	<5 + 1.5*rho	<5 + 0.5*rho
Inner Layer Lost Hits	<=1	<=1
|dxy|	<0.02	<0.05

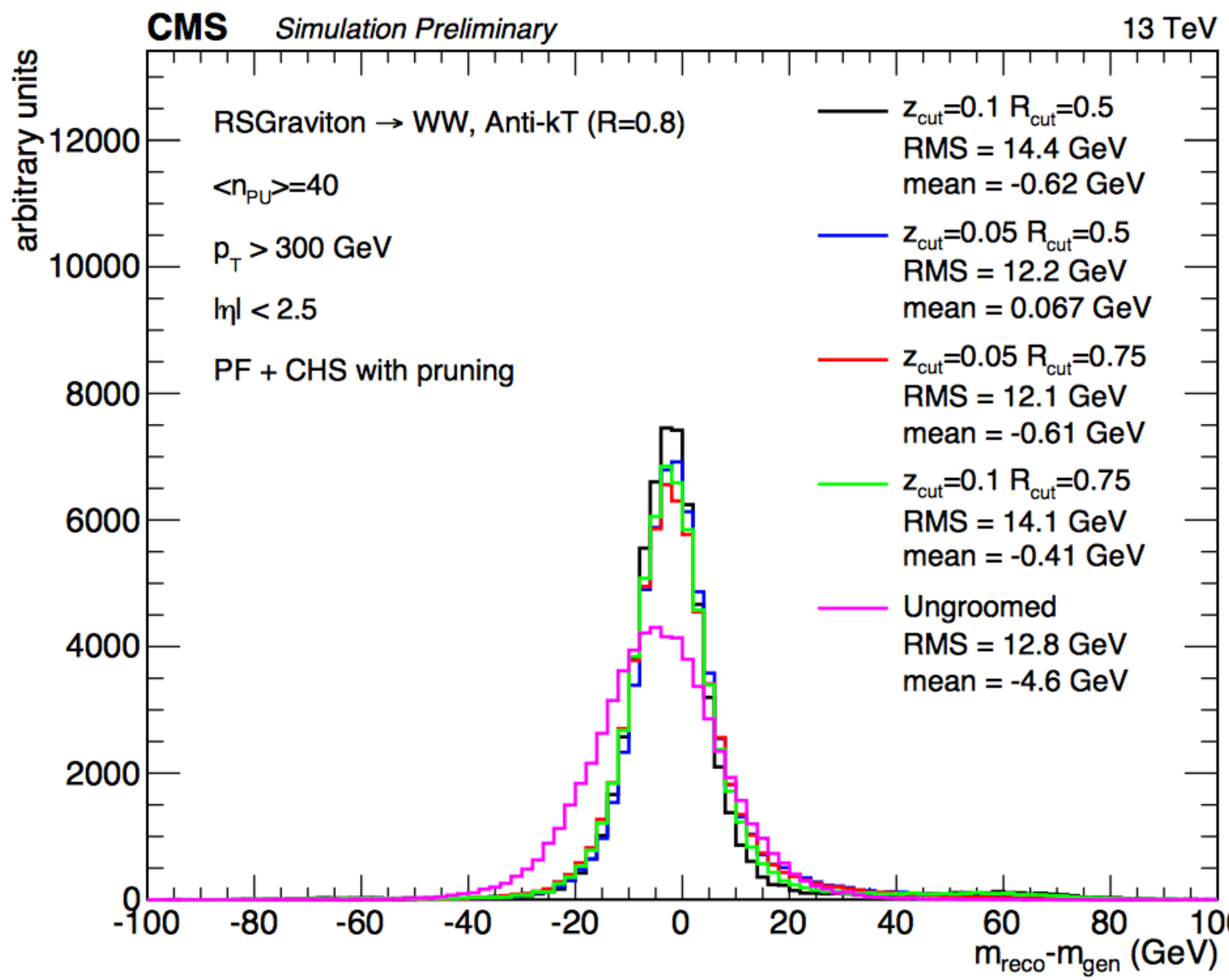
HighPt muon ID

Karlsruhe Institute of Technology

https://twiki.cern.ch/twiki/bin/viewauth/CMS/SWGuideMuonIdRun2#HighPt_Muon

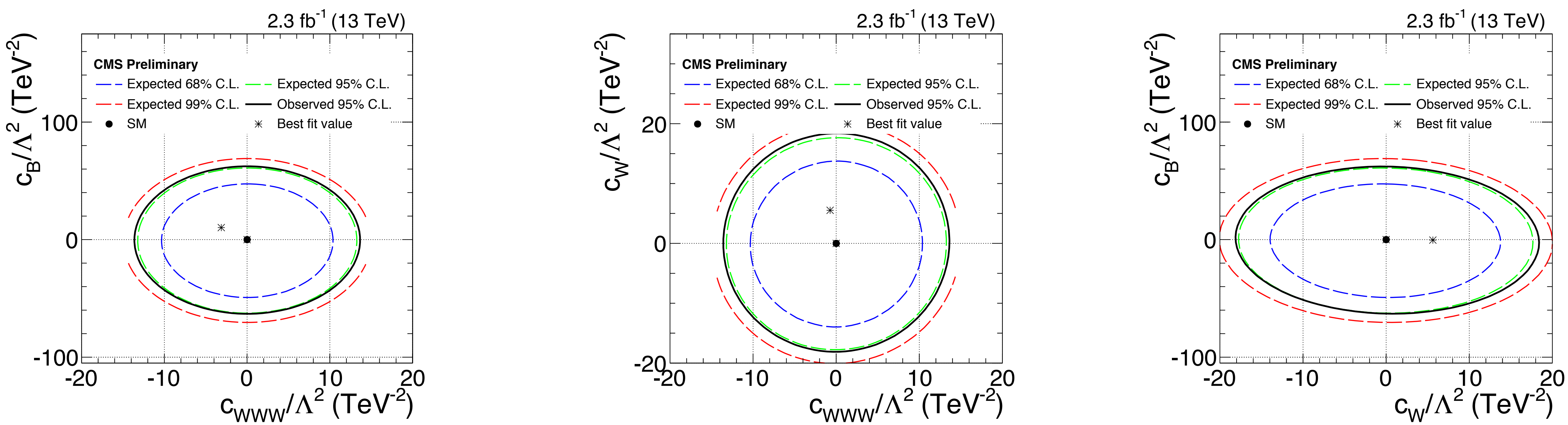
Plain-text description	Technical description	Comments
The candidate is reconstructed as a Global Muon	`recoMu.isGlobalMuon()`	
At least one muon-chamber hit included in the global-muon track fit	`recoMu.globalTrack()->hitPattern().numberOfValidMuonHits() > 0`	To suppress hadronic punch-through and muons from decays in flight.
Muon segments in at least two muon stations This implies that the muon is also an arbitrated tracker muon, see SWGuideTrackerMuons	`recoMu.numberOfMatchedStations() > 1`	To suppress punch-through and accidental track-to-segment matches. Also makes selection consistent with the logic of the muon trigger, which requires segments in at least two muon stations to obtain a meaningful estimate of the muon p_T.
The p_T relative error of the muon best track is less than 30%	`recoMu.muonBestTrack()->ptError()/recoMu.muonBestTrack()->pt() < 0.3`	
Its tracker track has transverse impact parameter d_{xy} < 2 mm w.r.t. the primary vertex	`fabs(recoMu.muonBestTrack()->dxy(vertex->position())) < 0.2` Or `dB() < 0.2` on `pat::Muon` [1]	To suppress cosmic muons and further suppress muons from decays in flight (see CMS AN 2008/098). The 2 mm cut preserves efficiency for muons from decays of b and c hadrons. It is a loose cut and can be tightened further with minimal loss of efficiency for prompt muons if background from cosmic muons is an issue. Another way to obtain a better cosmic-ray suppression is to complement the d_{xy} cut with a cut on the opening angle α or use a dedicated cosmic-id algorithm (see Section 7.1 of MUO-10-004). innerTrack() is also supported for dxy cut, as the performance of the two is very close.
The longitudinal distance of the tracker track wrt. the primary vertex is d_z < 5 mm	`fabs(recoMu.muonBestTrack()->dz(vertex->position())) < 0.5`	Loose cut to further suppress cosmic muons, muons from decays in flight and tracks from PU. innerTrack() is also supported for dz cut, as the performance of the two is very close.
Number of pixel hits > 0	`recoMu.innerTrack()->hitPattern().numberOfValidPixelHits() > 0`	To further suppress muons from decays in flight.
Cut on number of tracker layers with hits >5	`recoMu.innerTrack()->hitPattern().trackerLayersWithMeasurement() > 5`	To guarantee a good p_T measurement, for which some minimal number of measurement points in the tracker is needed. Also suppresses muons from decays in flight.

Pruning

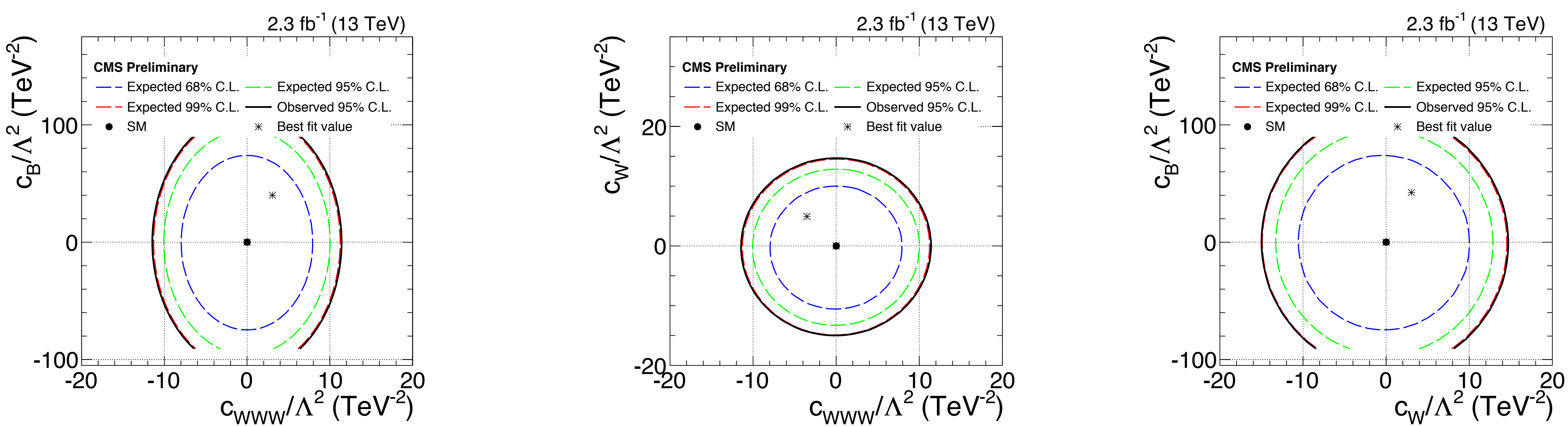

CMS Simulation Preliminary
13 TeV
RSGraviton → WW, Anti-kT (R=0.8)
<n_PU>=40
p_T > 300 GeV
|η| < 2.5
PF + CHS with pruning
z_cut=0.1 R_cut=0.5
RMS = 14.4 GeV
mean = -0.62 GeV
z_cut=0.05 R_cut=0.5
RMS = 12.2 GeV
mean = 0.067 GeV
z_cut=0.05 R_cut=0.75
RMS = 12.1 GeV
mean = -0.61 GeV
z_cut=0.1 R_cut=0.75
RMS = 14.1 GeV
mean = -0.41 GeV
Ungroomed
RMS = 12.8 GeV
mean = -4.6 GeV
arbitrary units
0
2000
4000
6000
8000
10000
12000
-100
-80
-60
-40
-20
0
20
40
60
80
100
m_reco-m_gen (GeV)

limits for WW and WZ categories

WW

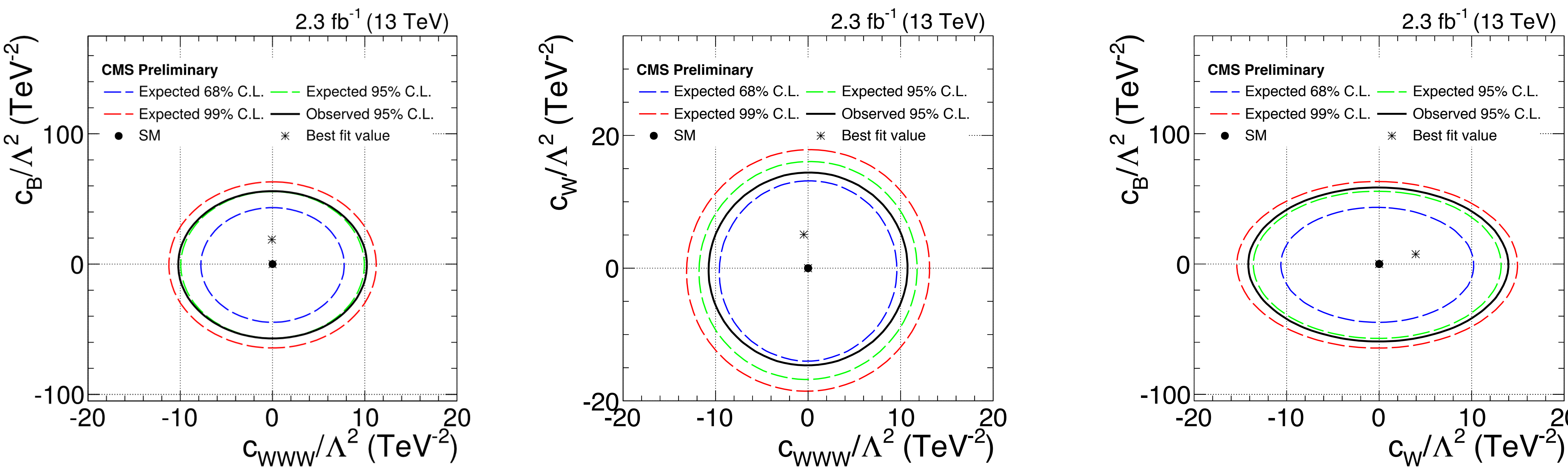


WZ



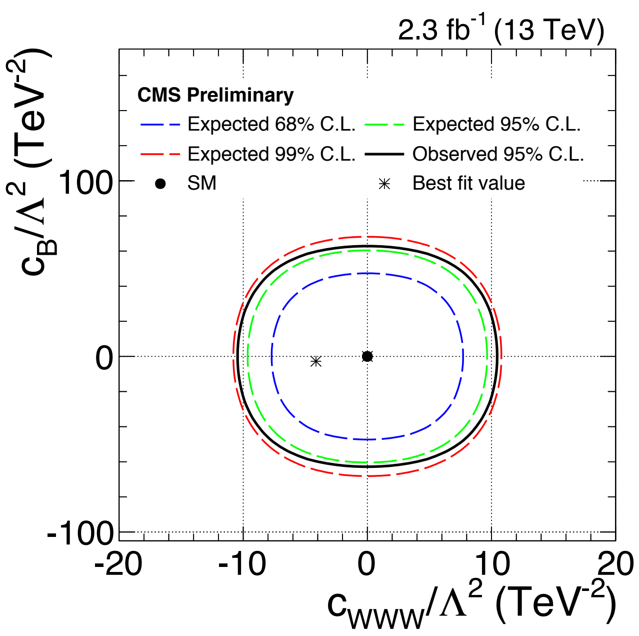
WW+WZ

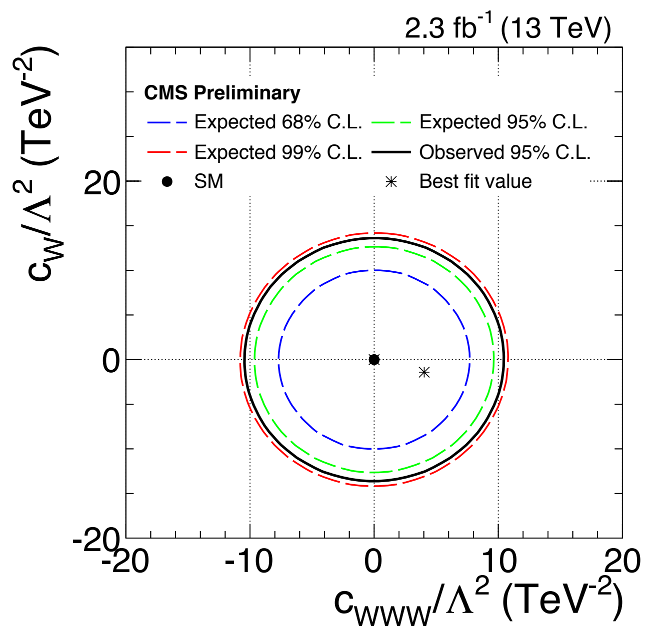
merged WW+WZ, no interference

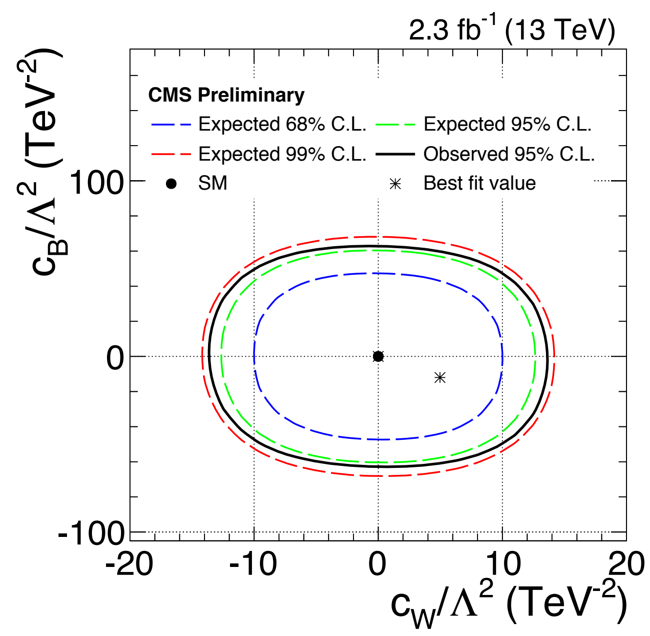


Effects of the SM-interference

- No SM interference: $N_{obs} = N_{SM} + c_1 \cdot aTGC_1^2 + c_2 \cdot aTGC_2^2$



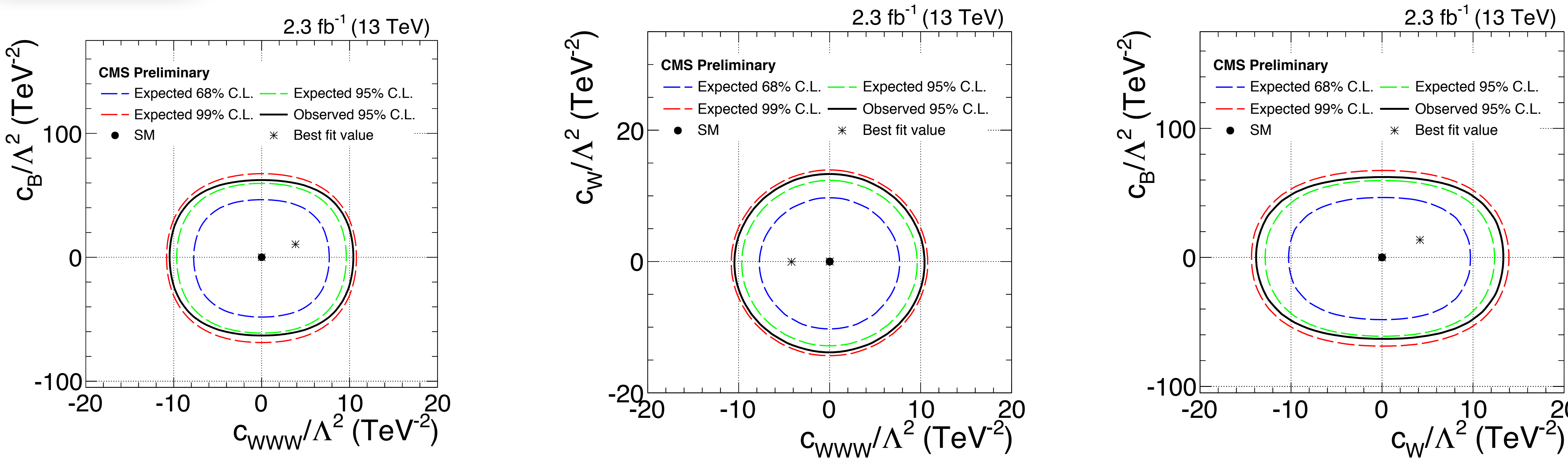




- SM interference: $N_{obs} = N_{SM} + c_i \cdot aTGC_1 + c_1 \cdot aTGC_1^2 + c_2 \cdot aTGC_2^2$

- → shift in the ellipse

Effects of the aTGC-aTGC interference



- aTGC-aTGC interference:

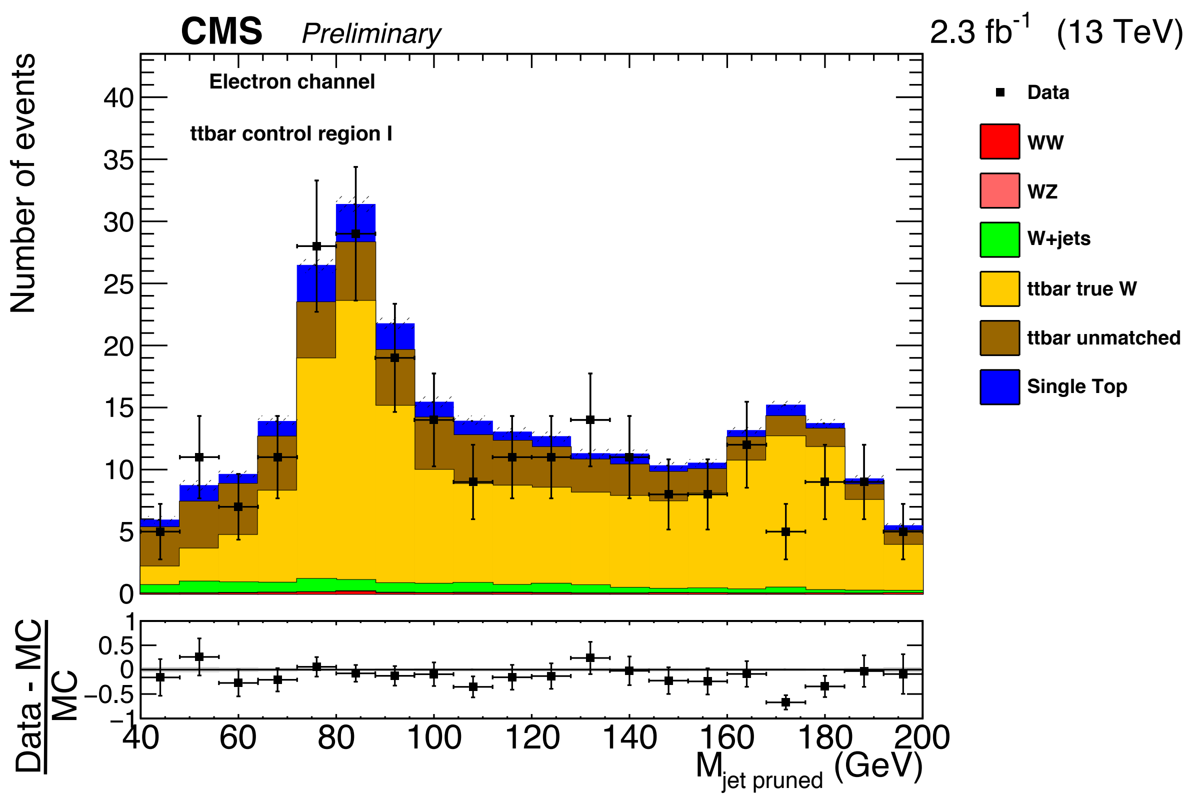
$$N_{obs} = N_{SM} + c_i \cdot aTGC_1 \cdot aTGC_2 + c_1 \cdot aTGC_1^2 + c_2 \cdot aTGC_2^2$$

- → rotation of the ellipse:

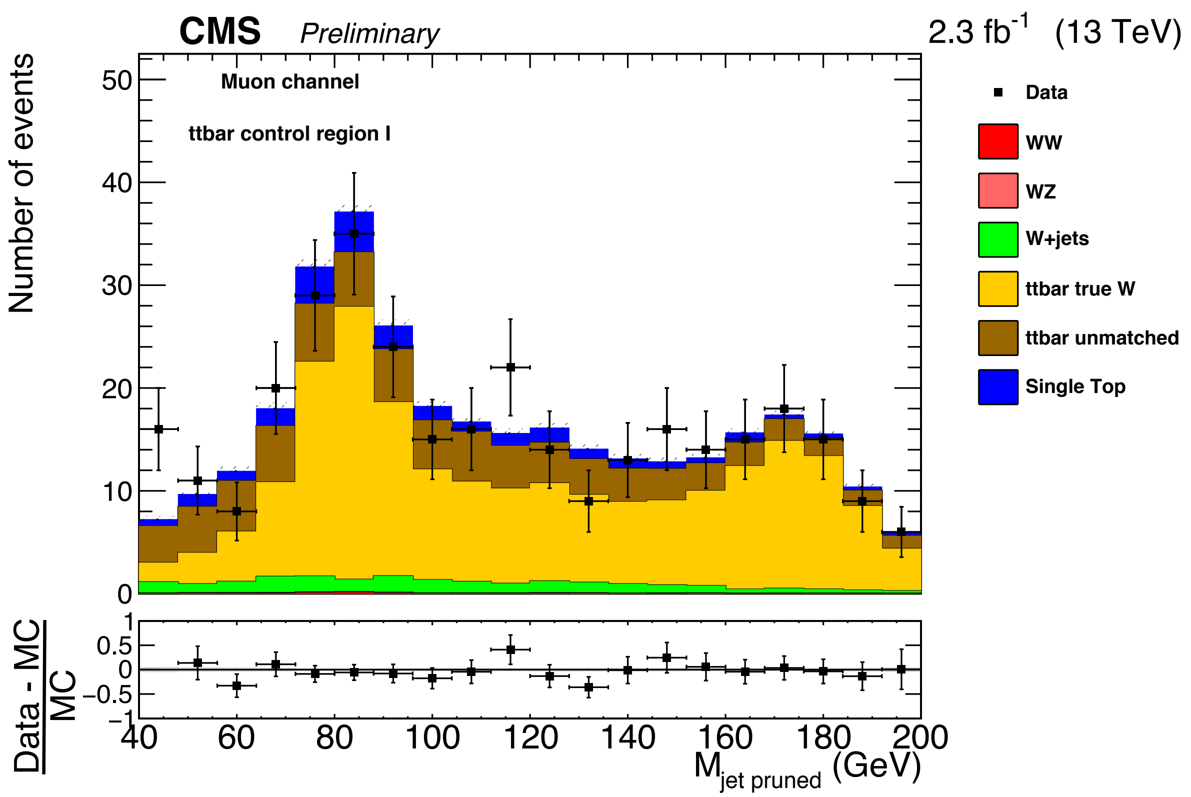
$$aTGC_1' = cos\alpha \cdot aTGC_1 + sin\alpha \cdot aTGC_2$$
$$aTGC_2' = -sin\alpha \cdot aTGC_1 + cos\alpha \cdot aTGC_2$$

Cross-checks for ttbar control region

Electron channel

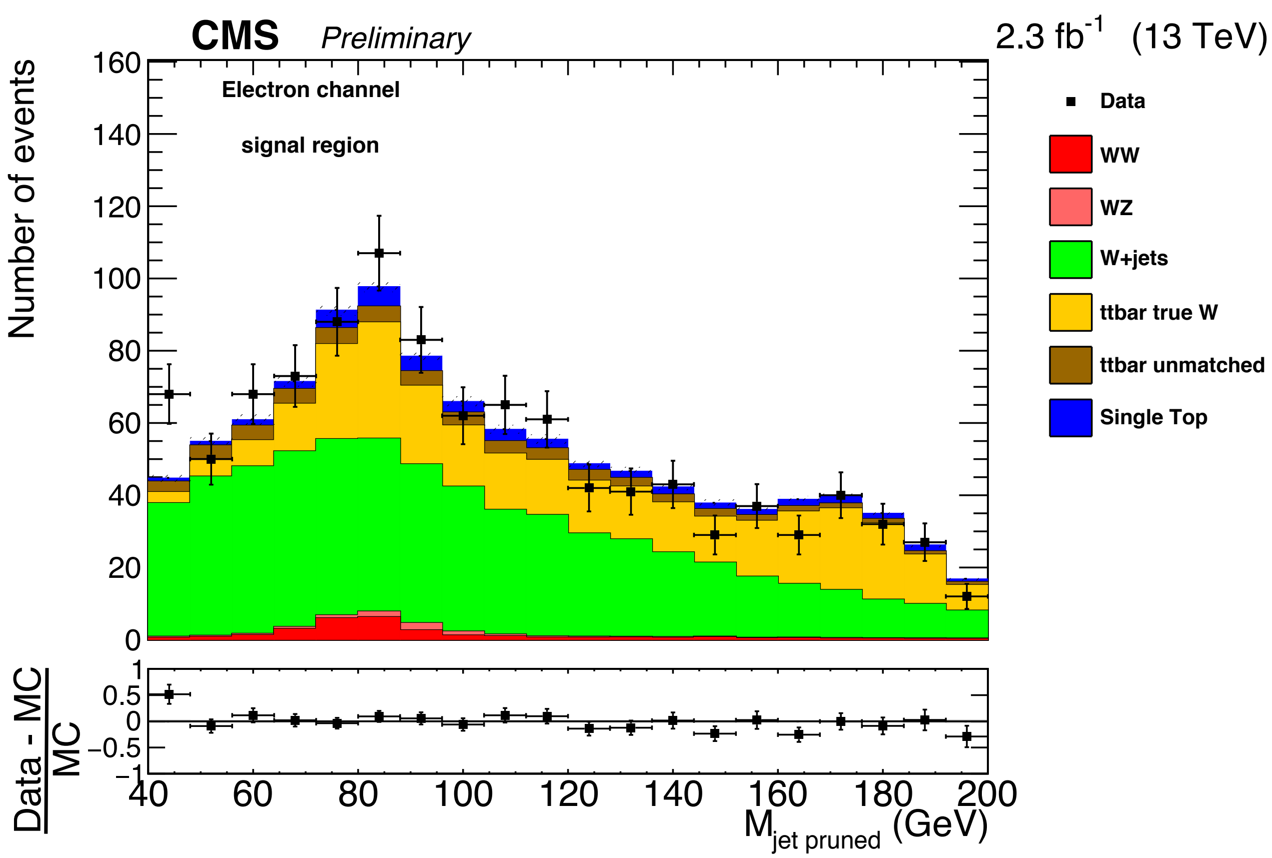


Muon channel

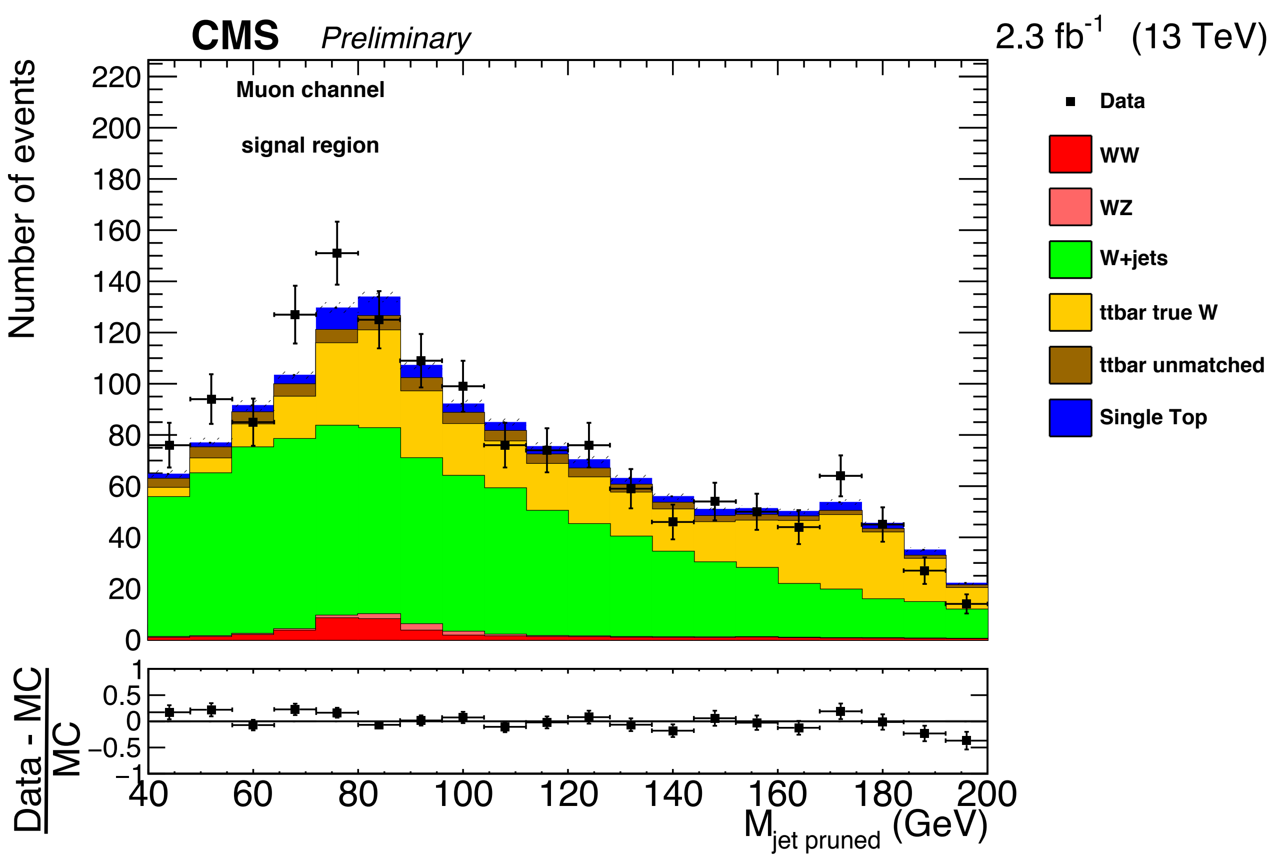


Signal region

Electron channel

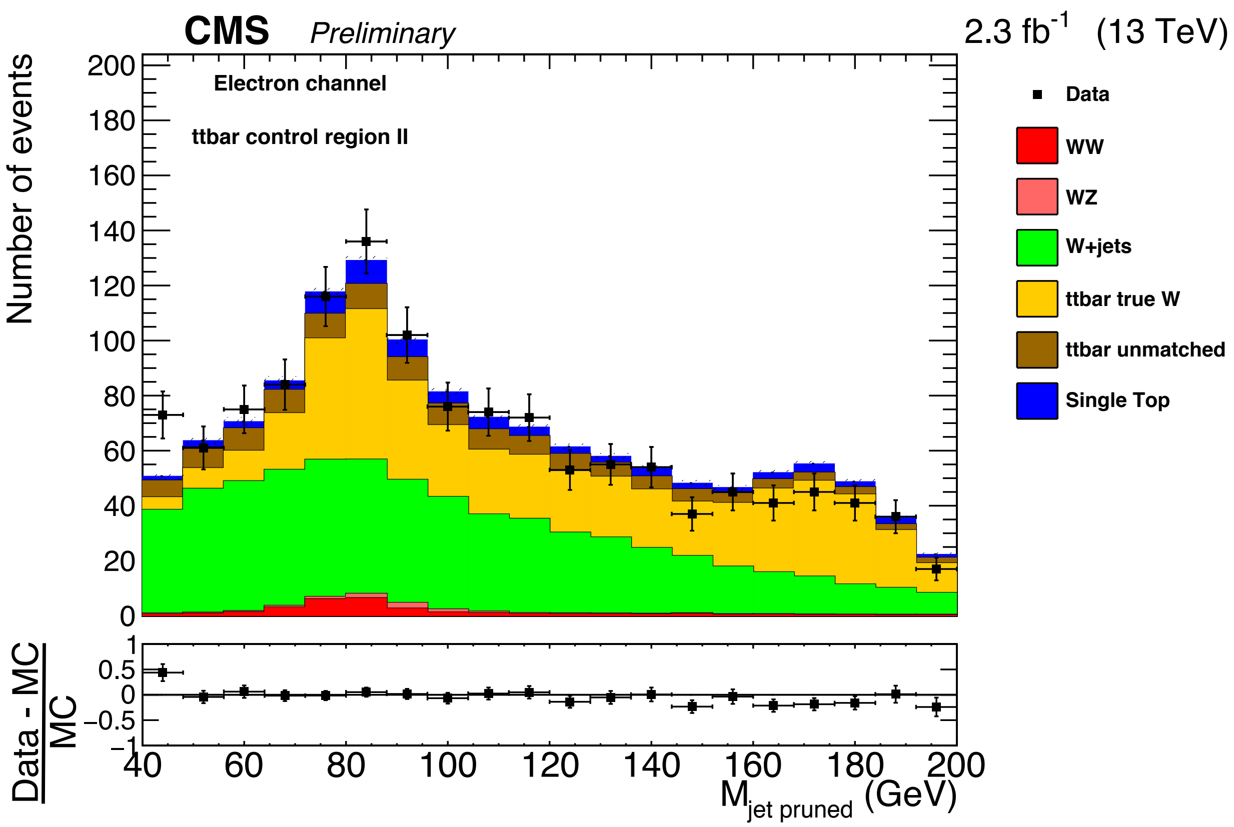


Muon channel

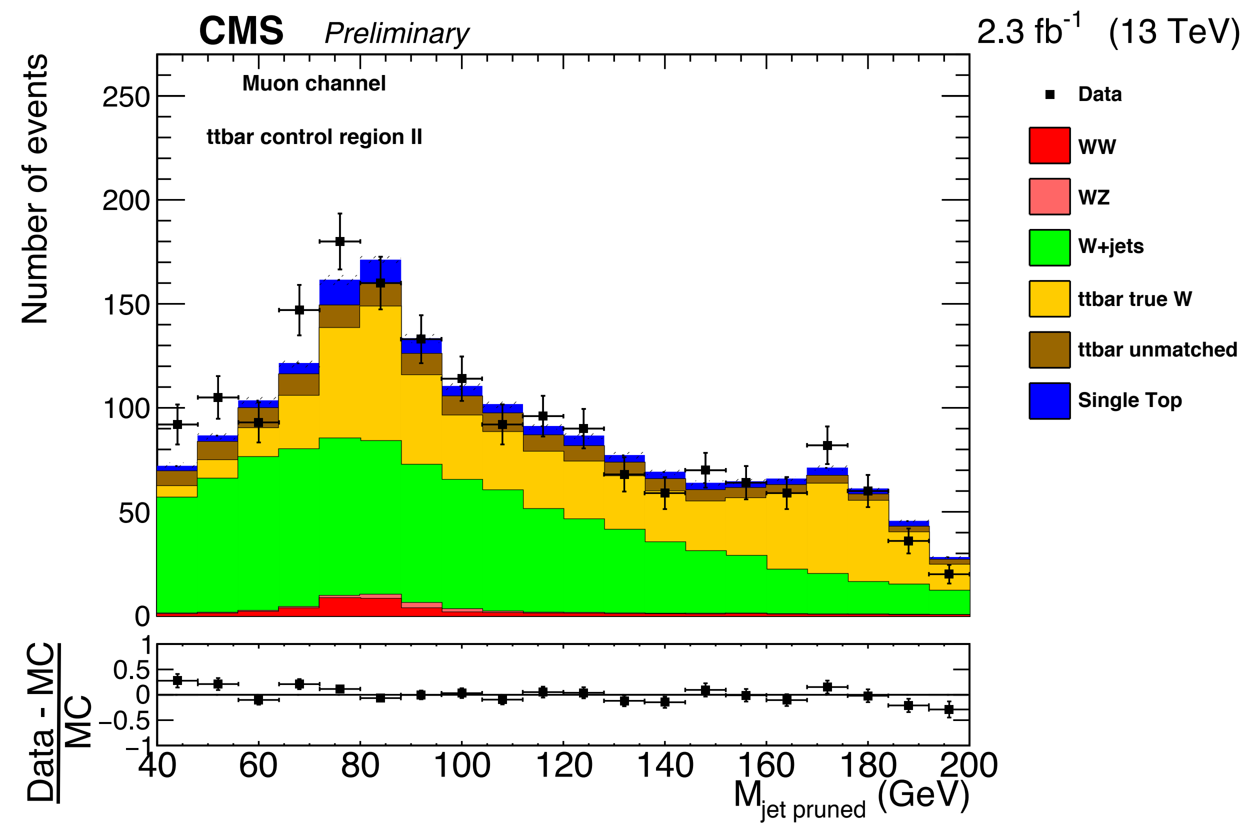


no requirement on b-tagging

Electron channel



Muon channel



Details about signal function

$$F_{atgc} \cdot A_N = N_{SM} \cdot e^{a_0 x} + \sum_i \left(N_{c_i,1} \cdot c_i^2 \cdot e^{a_{i,1} x} \cdot \frac{1 + \mathrm{Erf}((x - a_{o,i})/a_{w,i})}{2} + N_{c_i,2} \cdot c_i \cdot e^{a_{i,2} x} \right) + \sum_{i \neq j}^{i<j} \left(N_{c_i,c_j} \cdot c_i \cdot c_j \cdot e^{a_{ij} x} \right) ,$$

$$S_{aTGC} = 1 + \sum_i S_{c_i}$$

$$F_{atgc} \rightarrow S_{aTGC} \cdot F_{atgc}$$

$$S_{c_i} = b_0 + b_1 \cdot c_i + b_2 \cdot c_i^2 - 1$$

$$A_N = N_{SM} + \sum_i (N_{c_i,1} \cdot c_i^2 + N_{c_i,2} \cdot c_i) + \sum_{i \neq j}^{i<j} (N_{c_i,c_j} \cdot c_i \cdot c_j)$$

$$N_{c_i,1} = \frac{N_{c_i}^{MC^+} + N_{c_i}^{MC^-}}{2} - N_{SM}$$

$$N_{c_i,2} = \frac{N_{c_i}^{MC^+} - N_{c_i}^{MC^-}}{2}$$

$$\begin{aligned} N_{c_i,c_j} =& N_{c_i,c_j}^{gen} - (N_{SM} + N_{c_i,1} + N_{c_i,2} + N_{c_j,1} + N_{c_j,2}) \\ =& N_{c_i+,c_j+}^{gen} - \left(N_{SM} + \frac{N_{c_i}^{MC^+} + N_{c_i}^{MC^-}}{2} - N_{SM} + \frac{N_{c_i}^{MC^+} - N_{c_i}^{MC^-}}{2} \right. \\ & \left. + \frac{N_{c_j}^{MC^+} + N_{c_j}^{MC^-}}{2} - N_{SM} + \frac{N_{c_j}^{MC^+} - N_{c_j}^{MC^-}}{2} \right) \\ =& (N_{c_i+,c_j+}^{gen} + N_{SM}) - (N_{c_i}^{MC^+} + N_{c_j}^{MC+}) . \end{aligned}$$

W reconstruction

$$p_{z,\nu}^{1,2} = \frac{\mu \cdot p_{z,lepton}}{p_{T,lepton}^2} \pm \sqrt{\frac{\mu^2 \cdot p_{z,lepton}^2}{p_{T,lepton}^4} - \frac{E_{lepton}^2 \cdot |\vec{E}_T^{miss}|^2 - \mu}{p_{T,lepton}^2}}$$

$$\mu = \frac{m_W^2}{2} + \vec{p}_{T,lepton} \cdot \vec{E}_T^{miss}$$

- take real part if complex solution
- take the one with the smallest absolute value if 2 real solutions

Other results