VBF H → Invisible
Approval

R. Aggleton[3], C. Asawatangtrakuldee[1], **J. Brooke[3]**, O. Buchmueller[4], D. Colling[4], P. Dunne[4], S. Kumar[2], Q. Li[1], A-M. Magnan[4], K. Mazumdar[2], A. Nikitenko[4], J. Pela[4], P. Srimanobhas[5]

[1] Peking University, China
[2] Tata Institute of Fundamental Research, India
[3] University of Bristol, UK
[4] Imperial College of Science, Technology and Medicine, UK
[5] Chulalongkorn University, Thailand

Motivation

- H→invisible only possible in SM via H→ZZ*→νννν (~0.1%)
  - Visible decays of SM Higgs 125 GeV constrain invisible **BF < 64%**

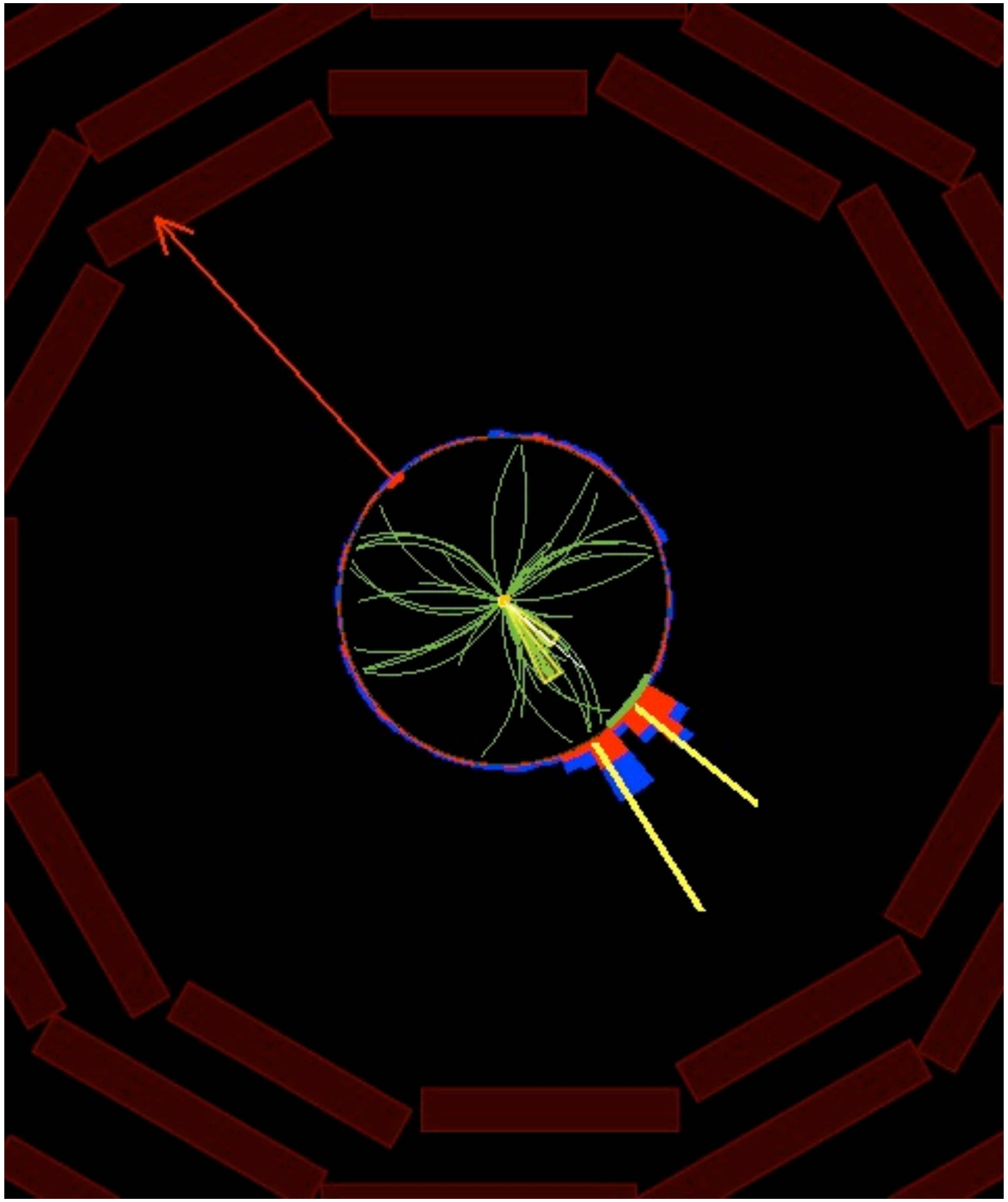
- Significant BF(H→invisible) would be a **strong sign of physics beyond the SM**
  - H→2LSPs in SUSY
  - H→graviscalars in the ADD model
  - etc.

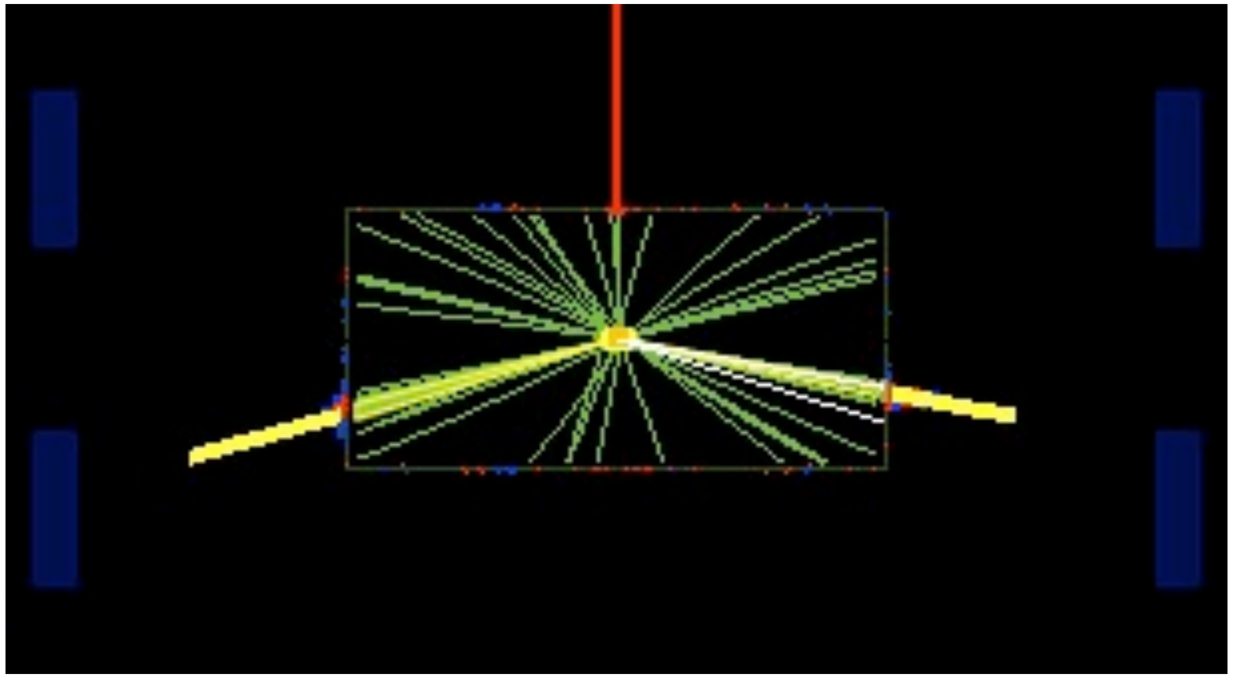
- Vector Boson Fusion production has higher cross section than VH and ttH
  - CMS ZH : **BF(H→inv) < 75% (observed) 91% (expected)** -- HIG-13-018
  - ATLAS ZH : **BF(H→inv) < 65% (observed) 84% (expected)** -- ATLAS-CONF-2013-011
  - Expect significantly improved sensitivity from VBF

- Events are tagged with 2 jets and large missing transverse energy in final state
  - Perform a simple counting experiment

- Estimate backgrounds using data-driven methods
  - Z(→νν)+jets, W+jets and QCD multijet

Event Display





Event 191202:51:82701983

Documentation

- **PAS-HIG-13-013**

- **AN 2012/403** - "Analysis A"
  - Documents the main analysis
  - All numbers used in PAS are taken from this AN

- **AN 2013/205** - "Analysis B"
  - Cross-check analysis
  - Replicates all W background estimates, as well as data yield in signal region
  - Same selection & methodology, some differences in object ID
  - Agreement at O(1%) level
    - Other than a discrepancy in $W \rightarrow \tau\nu$ - *which is understood, see later*

Trigger

- Two dedicated triggers implemented for VBF H→invisible
  - *HLT_DiPFJet40_PFMETnoMu65_MJJ600VBF_LeadingJets_v**
  - *HLT_DiPFJet40_PFMETnoMu65_MJJ800VBF_AllJets_v**
- Difference is the number of jets considered for tag jet pair, and Mjj threshold
  - “Leading” uses first 3 jets, “AllJets” searches the full jet list
  - We use “AllJets” for better efficiency in the V+jets control regions
- Trigger requirements
  - L1 MET > 40 GeV
  - Two jets, $p_T > 40$ GeV
  - $\eta 1 \cdot \eta 2 < 0$
  - $\Delta\eta_{jj} > 3.5$
  - $M_{jj} > 800$ GeV
  - CaloMET > 65 GeV
  - PFMET (muons subtracted) > 65 GeV
- Trigger turn-on measured with single-muon PD
  - Used to derive **trigger correction factors for MC**

Data

- **Prompt** MET PD using golden JSON (19.6 fb^{-1})
  - Using prompt data for the preliminary result
  - *Re-processed data will be used in future for publication*

Table 2: Datasets used in this analysis, with a total integrated luminosity of 19.6 fb^{-1}.

Dataset	Int. Lumi. [pb^{-1}]
/MET/Run2012A-recover-06Aug2012-v1/AOD	82
/MET/Run2012A-13Jul2012-v1/AOD	809
/MET/Run2012B-13Jul2012-v1/AOD	4404
/MET/Run2012C-24Aug2012-v1/AOD	495
/MET/Run2012C-PromptReco-v2/AOD	6378
/MET/Run2012C-EcalRecover_11Dec2012-v1/AOD	134
/MET/Run2012D-PromptReco-v1/AOD	7274

Monte-Carlo Samples

Signal

VBF H→Invisible	POWHEG
GluGlu H→Invisible	POWHEG

Background

Z(vv)+jets	MadGraph
W(lv)+jets	MadGraph
EWK V+2jets	MadGraph
QCD multijet	PYTHIA
DY+jets	MadGraph
WW,WZ,ZZ	PYTHIA
TTJets	MadGraph
Single top	POWHEG

Full details in backup

Reconstruction

- Jets
  - **AK5 PFJETs**
  - L1FastJet+L2+L3 [+L2L3Residual] JEC
  - "Loose" PFJet ID
  - Cleaned with veto leptons
  - "Loose" PU jet ID
  - JER is smeared in MC to match data
- **PFMET**
  - Type 0+1 corrections
  - Smeared PFMET for MC
- Veto Leptons
  - **Loose + PFiso muons**
    - p_T>10 GeV, $|\eta|$<2.1
  - **Veto + PFiso electrons**
    - p_T>10 GeV, $|\eta|$<2.5
    - Exclude gap region
- Control region Leptons
  - **Tight + PFiso muons**
    - p_T>20 GeV, $|\eta|$<2.1
  - **Tight + PFiso electrons**
    - p_T>20 GeV, $|\eta|$<2.5
    - Exclude gap region
- Control region **Hadronic Taus**
  - Tight ID, discriminant : "byTightCombinedIsolationDeltaBetaCorr3Hits"
  - p_T> 20 GeV, $|\eta|$ < 2.3, dZ< 0.2 cm

Selection

- Trigger + standard MET and cleaning filters

- Electron/muon veto
  - **p_T > 10 GeV, η < 2.1**

Reject W/Z backgrounds

- VBF dijet requirement, *applied to two leading jets passing PU jet ID*
  - **2 jets, E_T > 50 GeV, η < 4.7**
  - **$\eta 1 \cdot \eta 2 < 0$**
  - **$\Delta\eta_{jj} > 4.2$**
  - **M_{jj} > 1100 GeV**

Signal-like topology

- **E_T^{miss} > 130 GeV**

- Central jet veto
  - **PU jet ID, E_T > 30 GeV, $\eta_{jet1} < \eta < \eta_{jet2}$**

- **$\Delta\phi_{jj} < 1.0$**

Reject QCD

Signal Efficiency

m_H [GeV]	yield POWHEG qqH	eff [%] POWHEG qqH	eff [%] PYTHIA qqH	eff [%] POWHEG ggH
110	215.1 ± 9.2	0.607 ± 0.026	-	0.0047 ± 0.0017
120	-	-	0.562 ± 0.025	-
125	207.6 ± 8.6	0.673 ± 0.028	-	0.0037 ± 0.0014
150	199.0 ± 7.5	0.794 ± 0.030	0.703 ± 0.028	0.0045 ± 0.0015
200	147.1 ± 7.6	0.865 ± 0.044	0.893 ± 0.032	0.0076 ± 0.0021
300	95.6 ± 4.3	1.108 ± 0.050	1.278 ± 0.038	0.0200 ± 0.0034
400	69.8 ± 2.8	1.402 ± 0.056	1.457 ± 0.040	0.0300 ± 0.0042

- Use estimated signal yields from POWHEG
  - PYTHIA does not model colour flow, and hence central jet properties, well
- Note that **contamination from gluon fusion is negligible**
  - For m_H=125 GeV, ggH yield is ~14 events

Background Estimation

- Main backgrounds arise from V+jets with similar topology to VBF H production
  - Both EWK and QCD mediated processes
  - Backgrounds due to Z($\rightarrow\nu\nu$)+jets
  - And W($\rightarrow l\nu$)+jets when charged lepton is outside acceptance or not identified
- Minor backgrounds due to : QCD multijets, di-boson, single top, DY, ttbar
- *Should not expect MC to model backgrounds well in our corner of phase space*
- Estimate V+jets and QCD background using data-driven methods
  - Identify background rich control regions and extrapolate to signal region using factors derived from MC
  - Estimate QCD using ABCD methods
- Estimate remaining minor backgrounds from MC

Z→νν Background

- Estimate the Z(→**νν**) background from Z(→**μμ**) control sample

$$N(Z \to \nu\nu) = \frac{(N^c_{obs} - N^c_{bkg})}{\varepsilon_{\mu\mu}\varepsilon^C_{VBF}} \varepsilon^S_{VBF} \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^* \to \mu\mu)}$$

total # Z→μμ

ratio of BF

- Z(→**μμ**) control region is defined as for signal region, with changes :
  - 2 tight muons, with 60 < $M_{\mu\mu}$ < 120 GeV
  - Veto any *additional* leptons (ie. not from Z)
  - Redefine MET to exclude Z and require > 130 GeV
- Background in the control region (N^C_{bkg}) is estimated using MC
- Calculate transfer factor using MC
  - Z→**νν** selection efficiency in signal region : $\boldsymbol{\varepsilon}^S_{VBF}$
  - Z→**μμ** selection efficiency in control region : $\boldsymbol{\varepsilon}^C_{VBF}$
  - Dimuon selection efficiency : $\boldsymbol{\varepsilon}_{\mu\mu}$

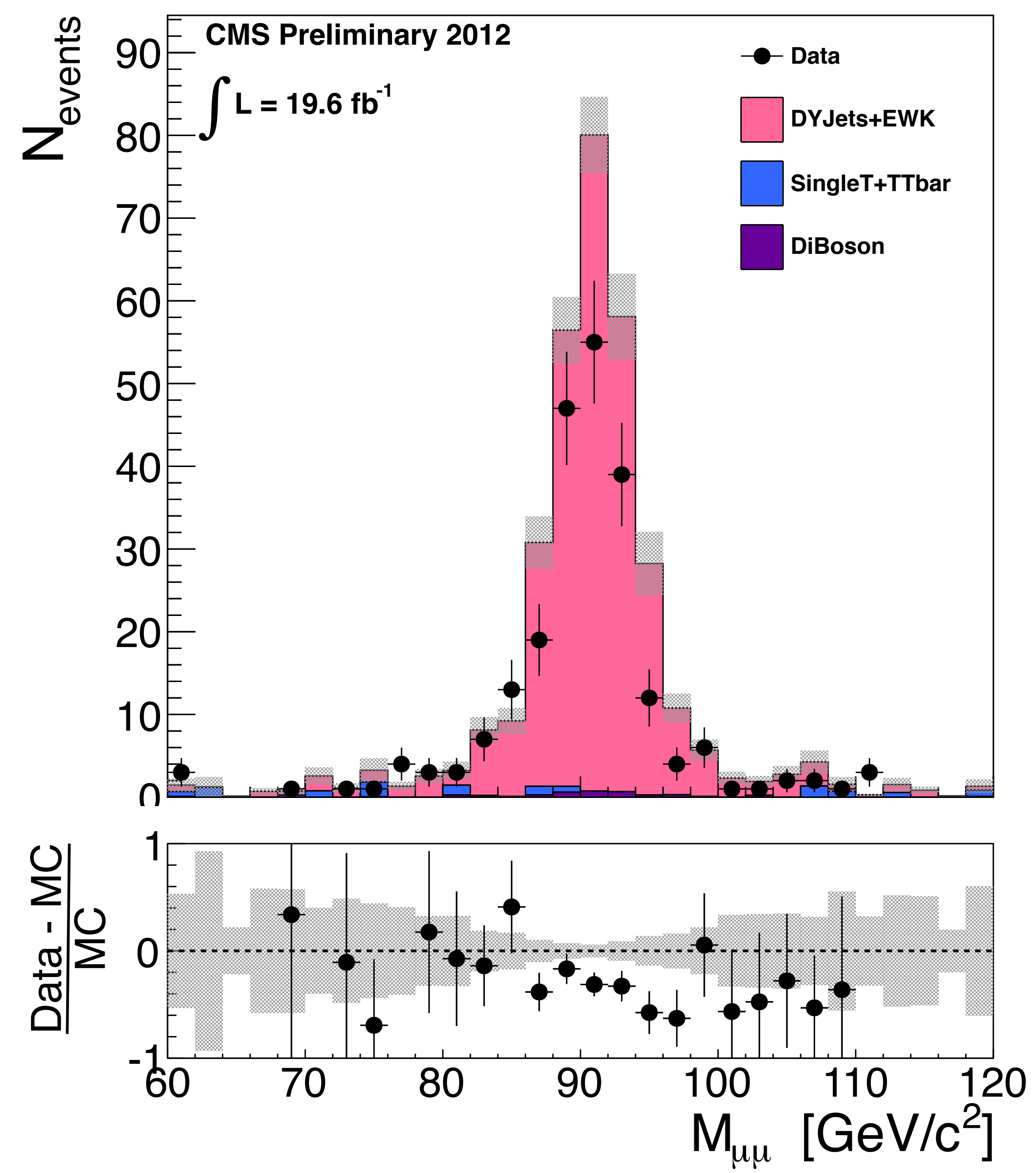
Z→νν Background

- Estimate the Z(→**νν**) background from Z(→**μμ**) control sample

$$N(Z \to \nu\nu) = \frac{(N^c_{obs} - N^c_{bkg})}{\varepsilon_{\mu\mu}\varepsilon^C_{VBF}} \varepsilon^S_{VBF} \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^* \to \mu\mu)}$$

MC normalisation discussed later !

- MC factors
  - Ratio of BF = 5.626 (MCFM)
  - $\varepsilon^C_{VBF} = 3.85 \pm 0.42$ (stat) $\times 10^{-6}$
  - $\varepsilon^S_{VBF} = 1.66 \pm 0.15$ (stat) $\times 10^{-6}$
  - $\varepsilon_{\mu\mu} = 0.280 \pm 0.007$ (stat)
- Results
  - $N^C_{obs} = 12$
  - $N^C_{bkg} = 0.22 \pm 0.11$
  - **$N^S = 102 \pm 30$ (stat)**
- Plot shows loose control region
  - **$M_{jj} > 1000$ GeV, no cuts on $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, CJV**



W→e/μ Background

- Estimate the W(→lν) background from a W(→eν) and W(→μν) control samples

$$N^s_\ell = (N^c_{obs} - N^c_{bkg}) \cdot (\epsilon^S_{VBF}/\epsilon^C_{VBF}) \frac{1 - \epsilon_{\ell-veto}}{\epsilon_\ell}$$

$$N^s_\ell = (N^c_{obs} - N^c_{bkg}) \cdot \frac{N^s_{WMC}}{N^c_{WMC}}$$

- Background in the control region is subtracted using MC

- Calculate transfer factor using MC
  - N^S_{VBF} - W+jets MC yield in signal region
  - N^C_{VBF} - W+jets MC yield in control region

- W(→lν) control region is defined as for signal region, with following changes :
  - 1 tight muon/electron
  - Veto any *additional* leptons (ie. not from W)
  - For muon channel only, redefine MET to exclude W muon and require > 130 GeV

W→e/μ Background

- Estimate the W(→lν) background from W(→eν) and W(→μν) control samples

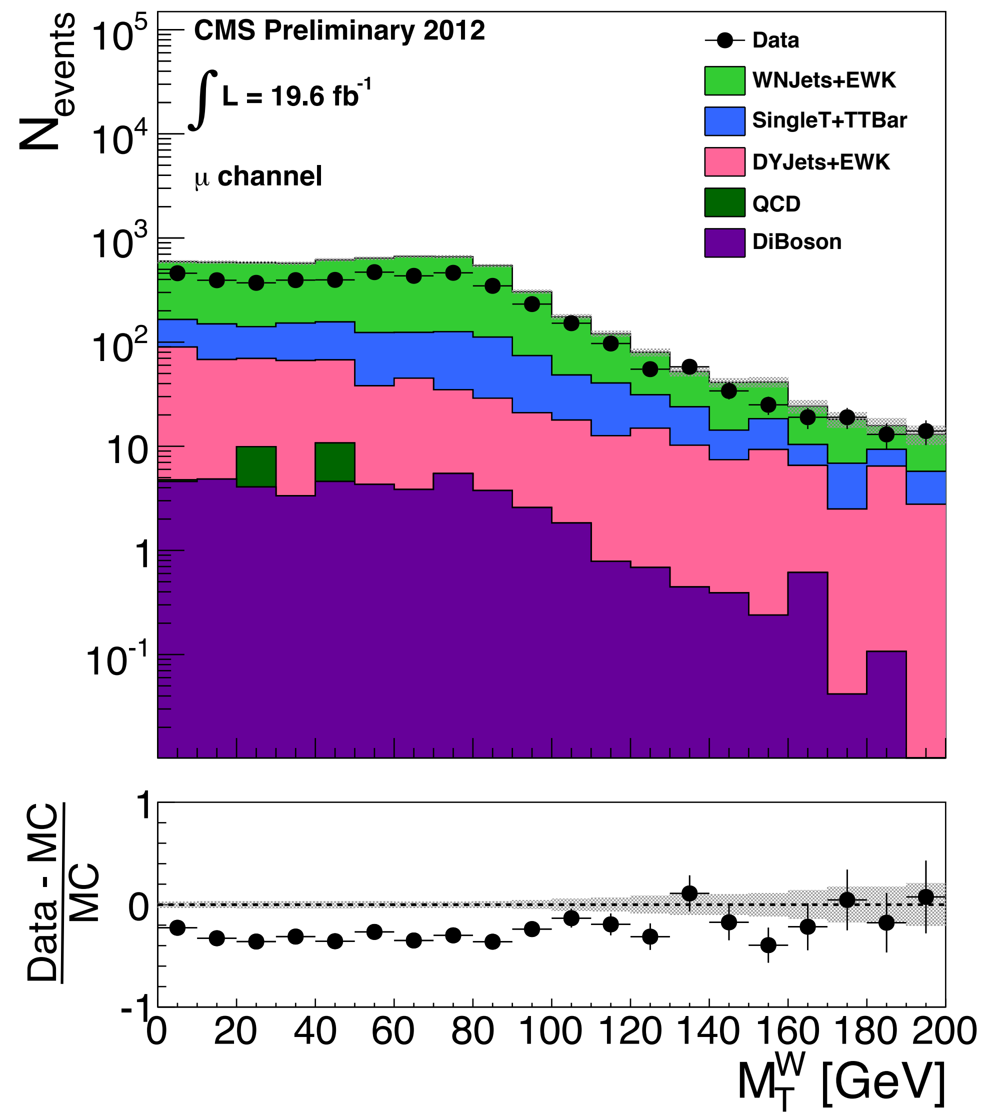
$$N_\ell^s = (N_{obs}^c - N_{bkg}^c) \cdot (\epsilon_{VBF}^S / \epsilon_{VBF}^C) \frac{1 - \epsilon_{\ell-veto}}{\epsilon_\ell}$$

$$N_\ell^s = (N_{obs}^c - N_{bkg}^c) \cdot \frac{N_{WMC}^s}{N_{WMC}^c}$$

MC normalisation discussed later !

- W→eν results
  - N^C_{obs} = 65
  - N^C_{bkg} = 5.4 ± 1.4
  - N^S_{WMC} / N^C_{WMC} = 1.14 ± 0.15
  - **N^S = 68.2 ± 9.2 (stat)**

- W→μν results
  - N^C_{obs} = 223
  - N^C_{bkg} = 23.9 ± 3.0
  - N^S_{WMC} / N^C_{WMC} = 0.338 ± 0.035
  - **N^S = 67.2 +/- 5.0 (stat)**



$W \rightarrow \tau_{had}$ Background

- Subtle difference, since do not apply an explicit veto on hadronic tau

- Define $W \rightarrow \tau_{had}$ control region as for signal region, with :
  - Require tight tau with $p_T > 20$ GeV, eta < 2.3, dz < 0.2 cm
  - No central jet veto requirement

- Background is then estimated using :

CJV efficiency on W(τ_{had}) events (MC)

$$\boxed{N^{S}_{W \rightarrow \tau_{had}} = \frac{(N^{C}_{obs} - N^{C}_{bkg})}{\varepsilon_{\tau}} \cdot \varepsilon^{W \rightarrow \tau_{had}}_{CJV}}$$

Total number of W(τ_{had}) events before CJV

- Where ε_τ and ε_τ^{CJV} are estimated from $W \rightarrow \tau_{had}$ MC

$W \rightarrow \tau_{hadronic}$ Background

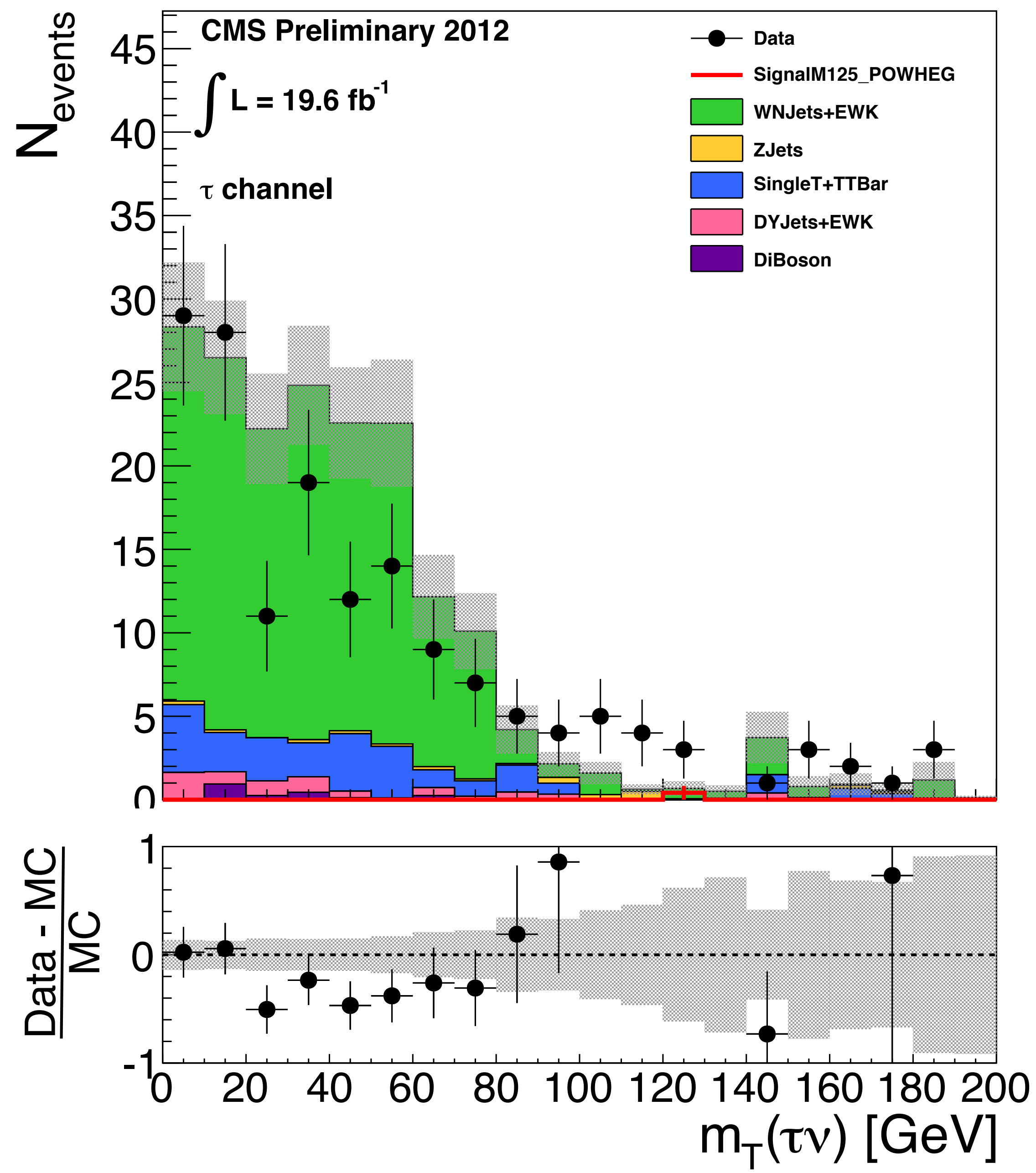
CJV efficiency on W(τ_{had}) events (MC)

$$N^{S}_{W\rightarrow\tau_{had}} = \frac{(N^{C}_{obs} - N^{C}_{bkg})}{\varepsilon_{\tau}} \cdot \varepsilon^{W\rightarrow\tau_{had}}_{CJV}$$

Total number of W(τ_{had}) events before CJV

- MC factors
  - Tau selection efficiency, ε_{τ} = 0.16 ± 0.03 (stat)
  - CJV efficiency, $\varepsilon^{\tau}{}_{CJV}$ = 0.423 ± 0.043 (stat)

- N^{C}_{obs} = 32
- N^{C}_{bkg} = 12.9
- **N^{S}_{τ} = 54 ± 16 (stat)**



V+Jets Uncertainty

- All V+jets estimates rely on factors estimated from MadGraph MC, relating control region yields to signal region yields

$$N(Z \to \nu\nu) = \frac{(N^c_{obs} - N^c_{bkg})}{\varepsilon_{\mu\mu}\varepsilon^C_{VBF}} \varepsilon^S_{VBF} \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^* \to \mu\mu)}$$

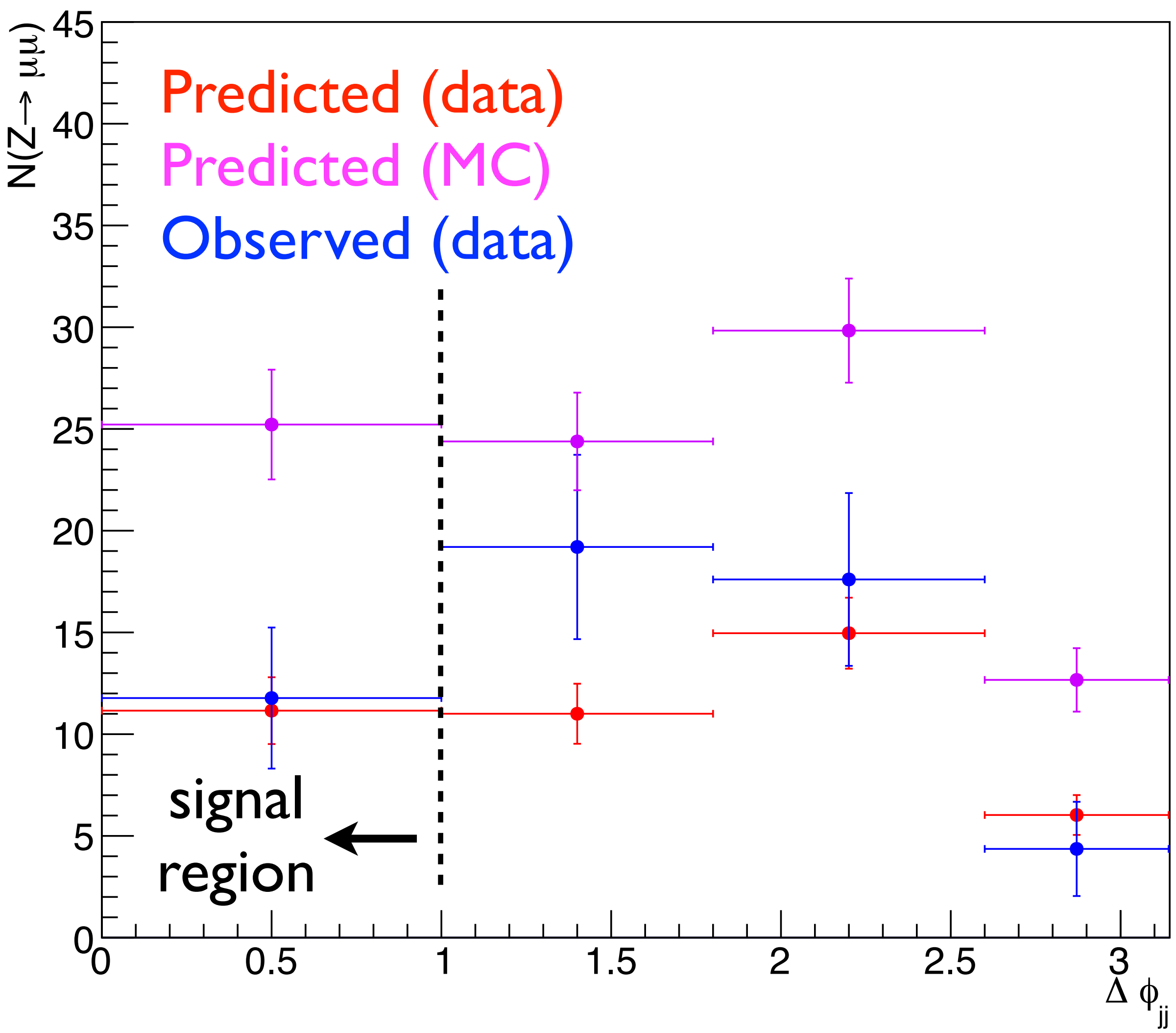
- Compare MadGraph factors with MCFM
  - Parton (and parton jet) level selection
  - Calculate VBF selection efficiency for **Z(→νν)jj** and **Z(→μμ)jj**
  - Compare ratio $\boldsymbol{\varepsilon}^S_{VBF}$ / $\boldsymbol{\varepsilon}^C_{VBF}$ between Madgraph and MCFM

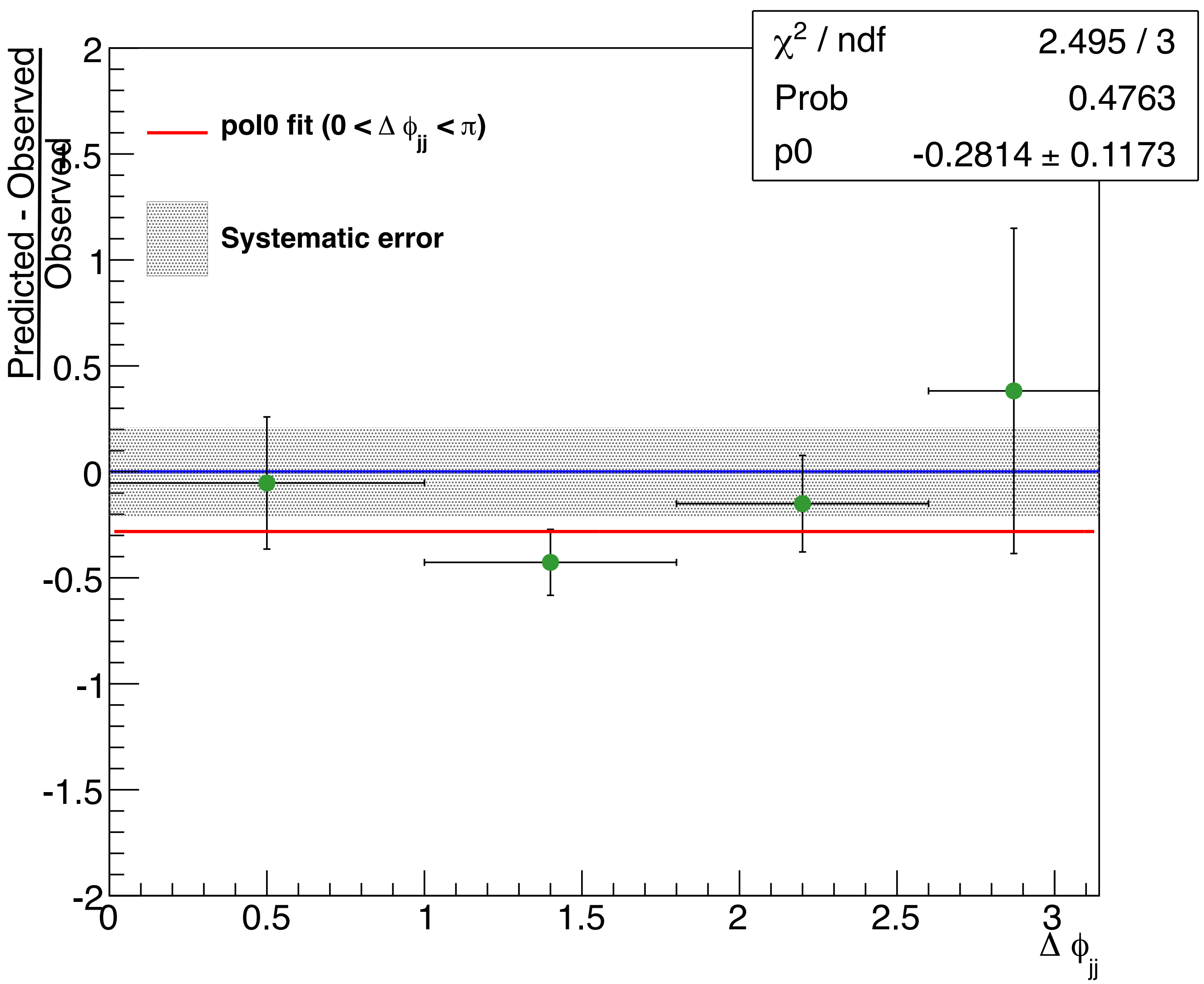
cuts	σ MCFM NLO(LO), fb	ε_{VBF} MCFM	ε_{VBF} MadGraph
$Z_{\nu\nu jj}$	**9300+/-100 (7940)**	**LO: 5.4e-3** **NLO: (4.8+/-0.5) e-3**	**(4.6+/-0.3)e-3**
$Z_{\nu\nu jj}$+VBF	**45+/-3 (43)**		
$Z_{\mu\mu jj}$	**5700+/-100 (4770)**	**LO : 4.2 e-3** **NLO: (4.2+/-0.8)e-3**	**(3.8+/-0.3)e-3**
$Z_{\mu\mu jj}$+VBF	**24+/-2 (20)**		
Ratio of VBF efficiencies $Z_{\nu\nu jj}/Z_{\mu\mu jj}$:		**LO: 1.28; NLO:1.14**	**1.20+/- 0.2**

- Based on these results, we assign a **20% theoretical uncertainty** to all V+jets estimate

V+Jets Consistency : Z→μμ from W→μ

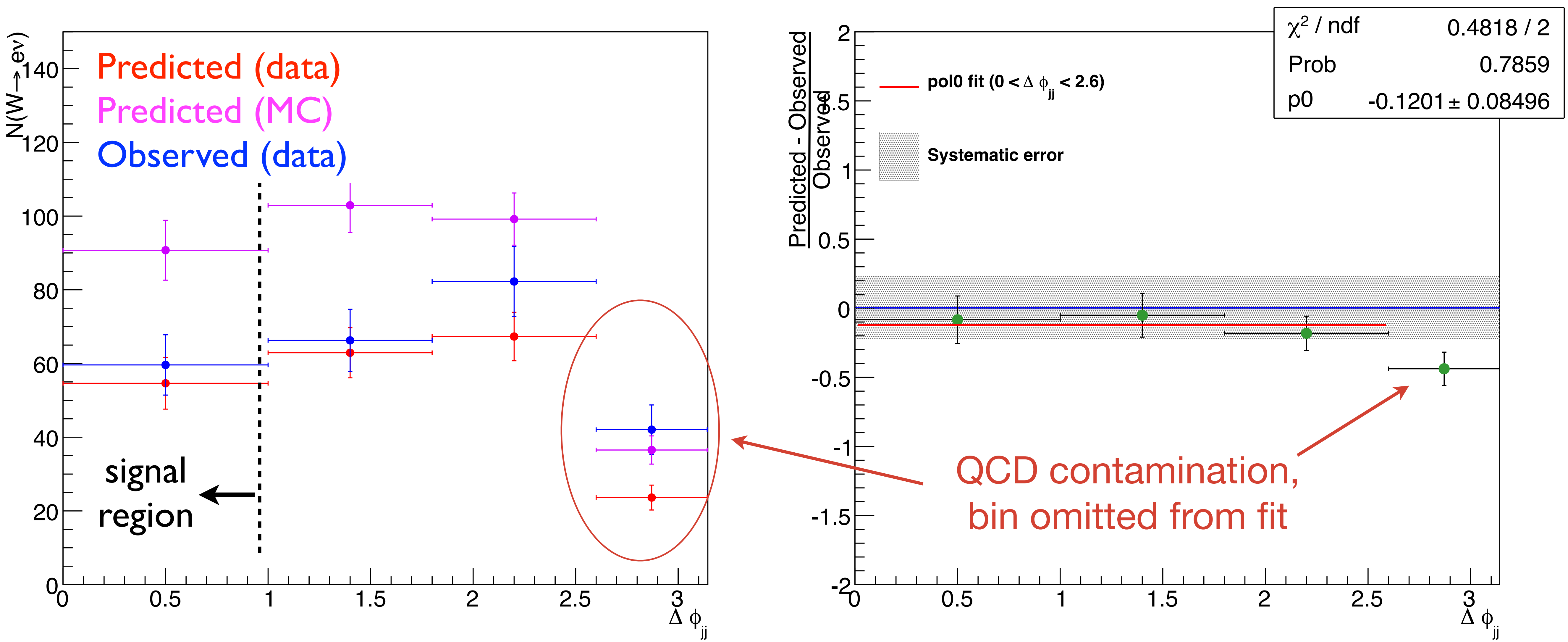
- Use W→**μ** control sample to predict yields in other control regions
  - Z→**μμ**, W→e, W→**τ**
- In all cases, scale W→**μ** yield by the ratio between regions in MC
- Do this in bins of **Δϕ** to give several additional independent samples
  - Fit constant to fractional difference to measure closure within uncertainties





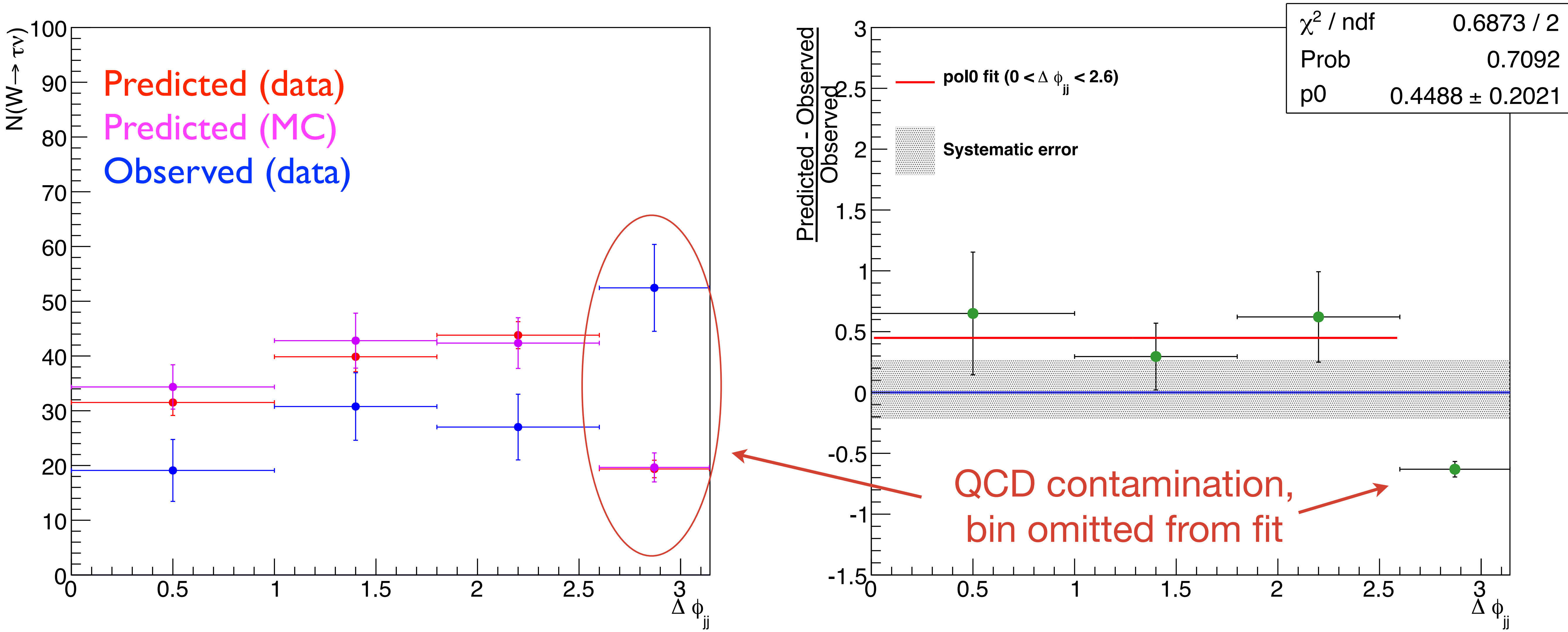
V+Jets Consistency : W→e from W→μ

- Good agreement for signal region (low **Δφ**)
- Discrepancy at high **Δφ**
  - Compatible with QCD contamination in the W→e control sample at high **Δφ**
  - We subtract backgrounds from control regions using MC
  - But QCD MC statistics are insufficient, so we cannot account for this



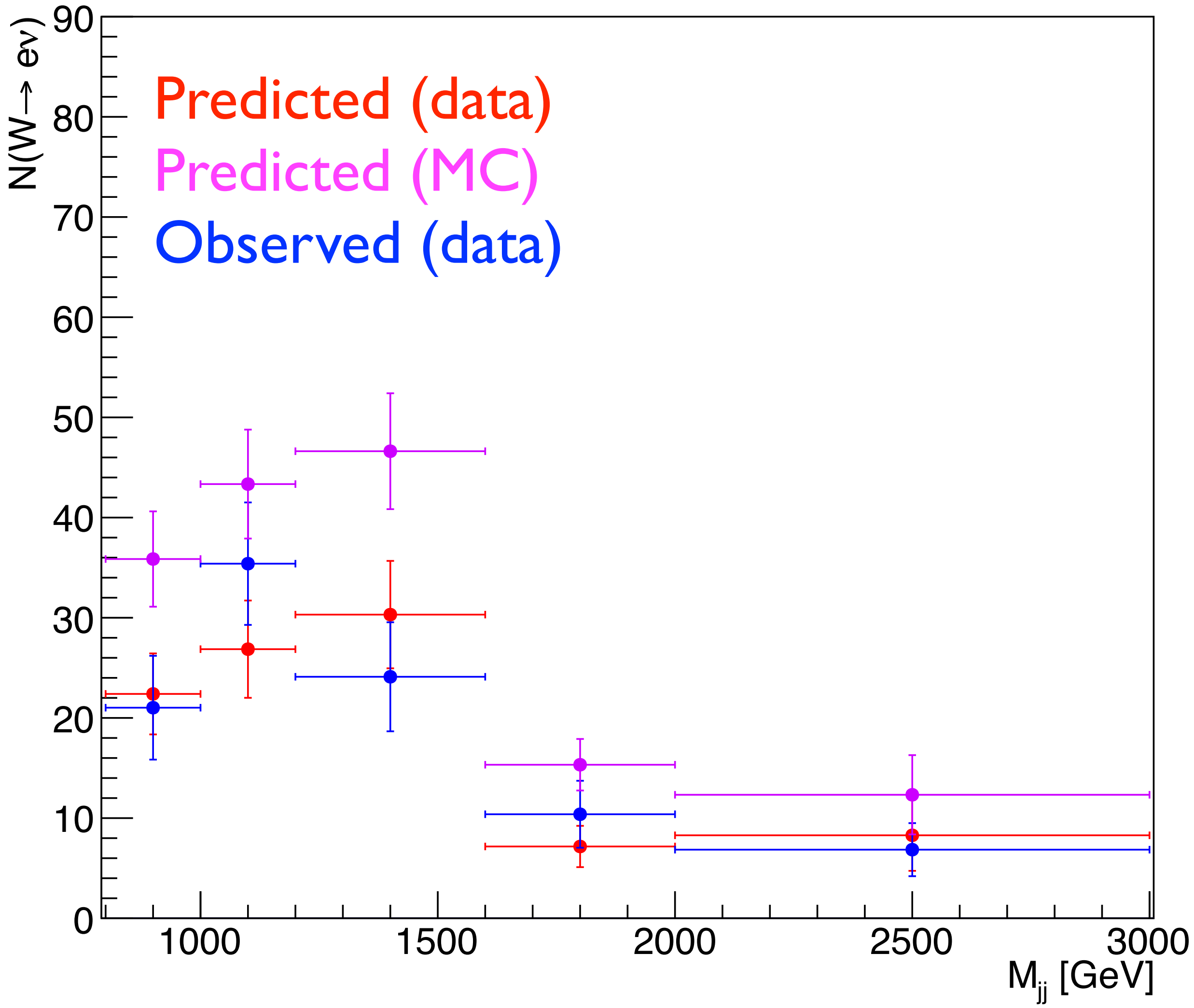
V+Jets Consistency : W→τ from W→μ

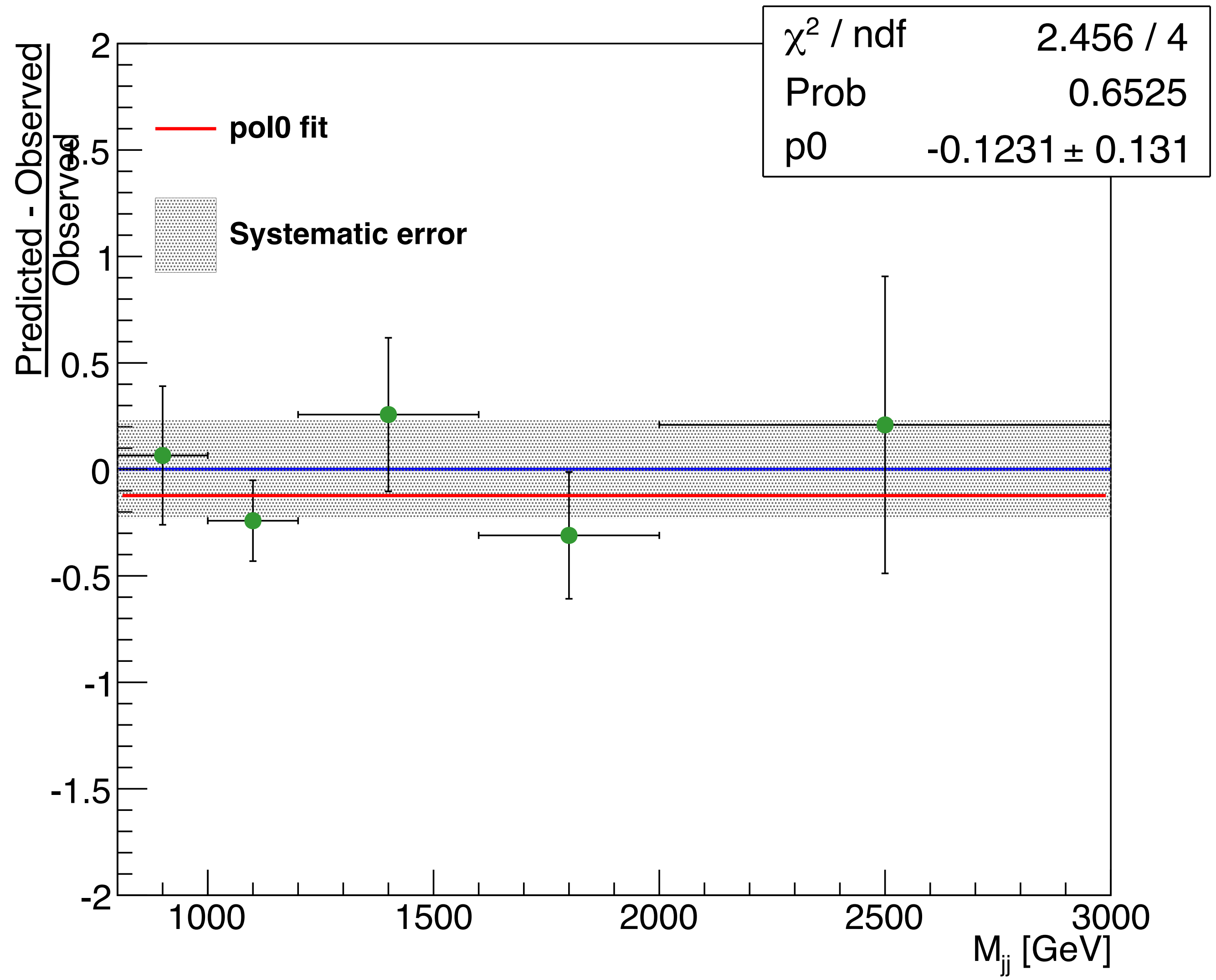
- Reasonable agreement for signal region (low **Δφ**)
- Discrepancy at high **Δφ**
  - Again compatible with QCD contamination in the W→**τ** control sample at high **Δφ**
  - Larger discrepancy than observed for W→e, but we expect greater QCD contamination in **τ** sample than electron sample



V+Jets Consistency : Mjj

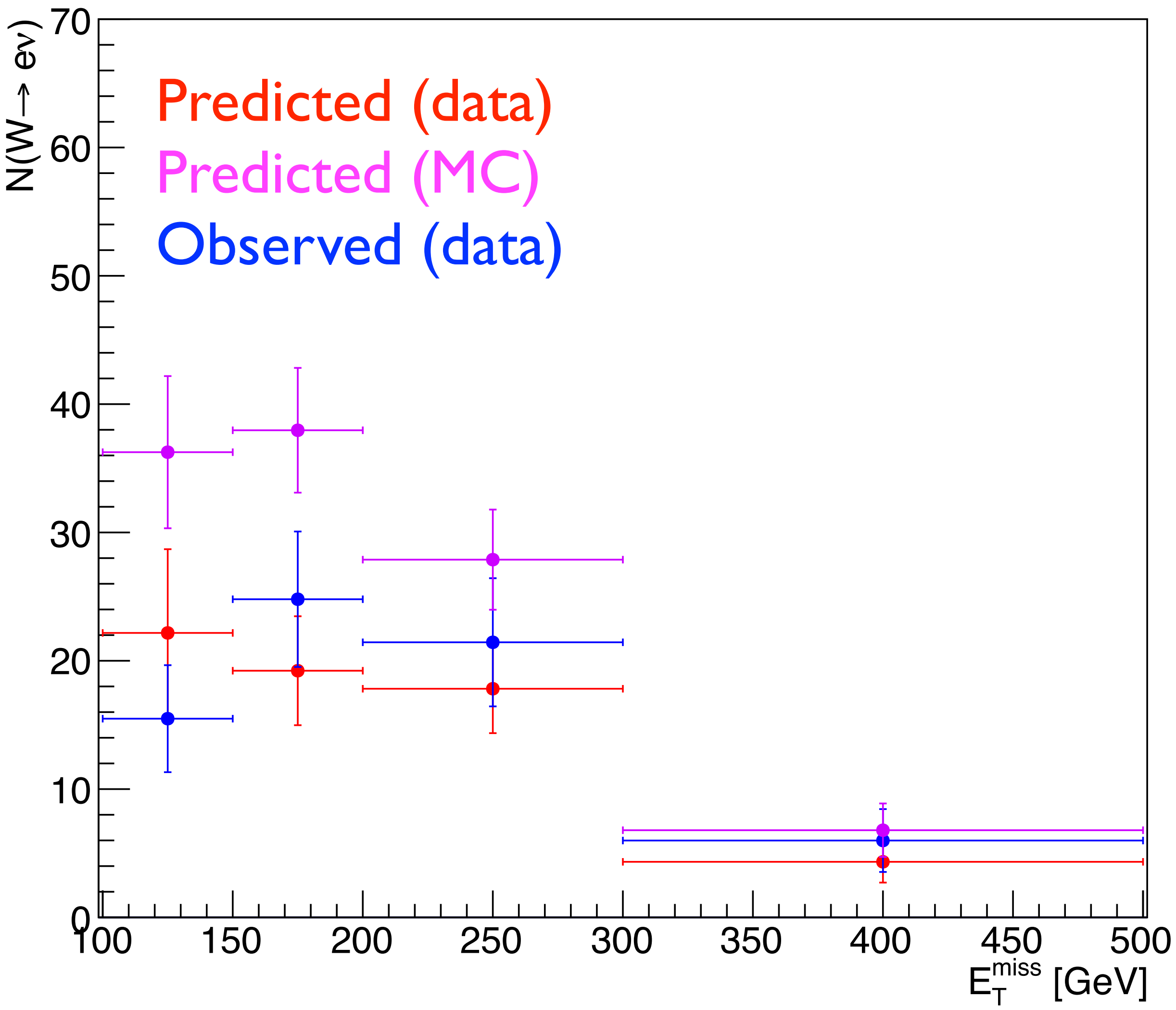
For W→e from W→μ, we have sufficient statistics to look at other variables

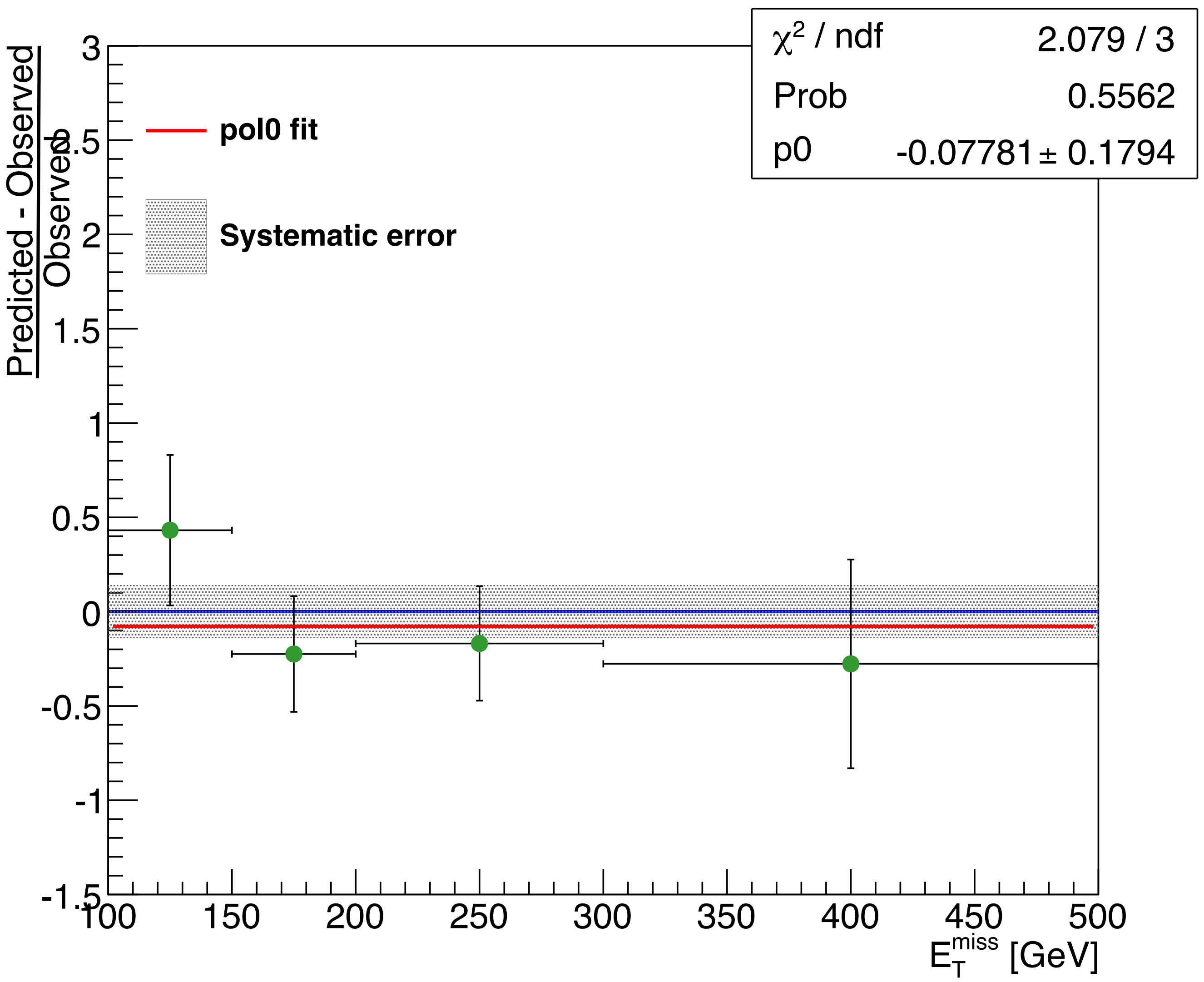




Excellent agreement !

V+Jets Consistency : MET

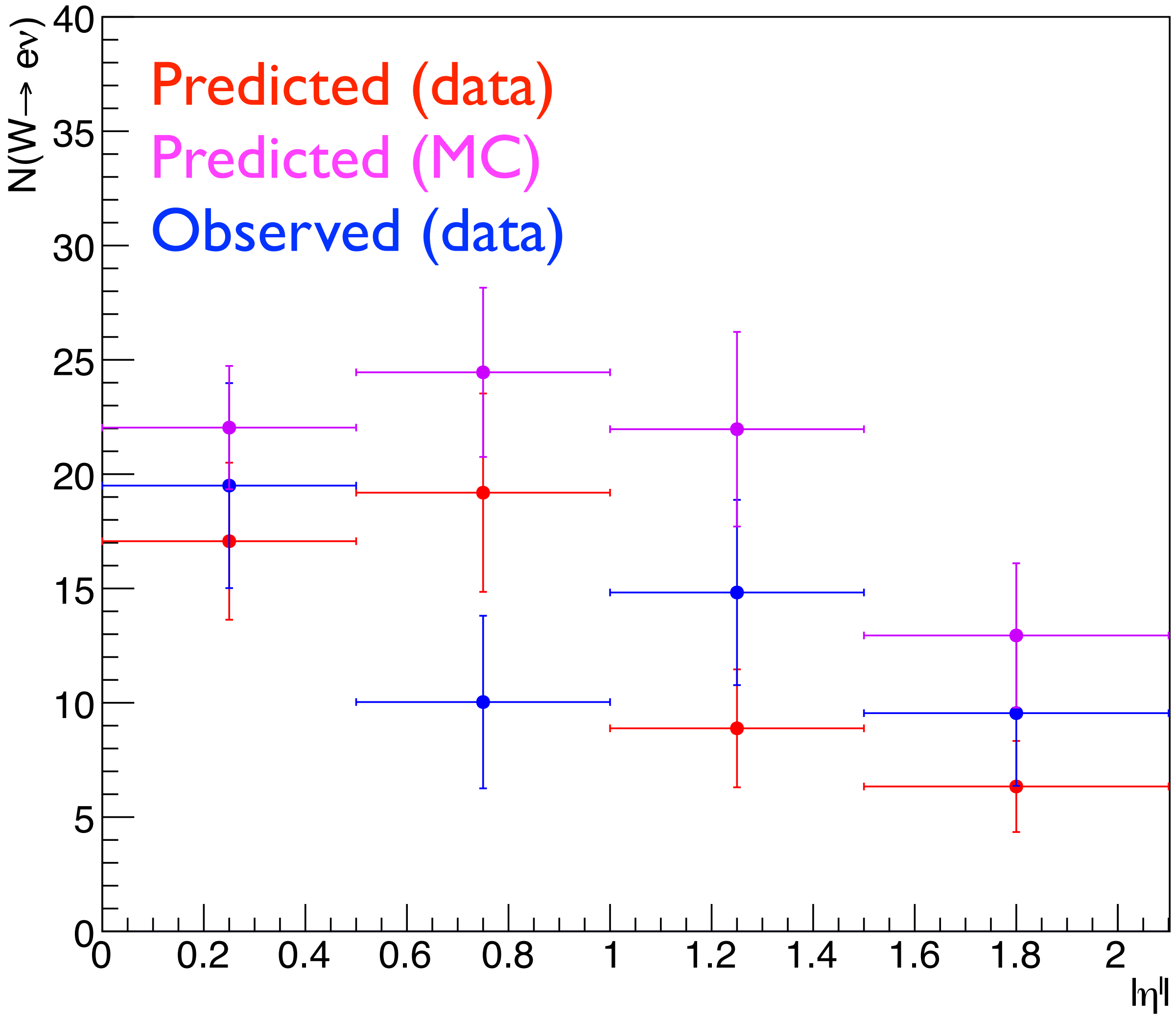


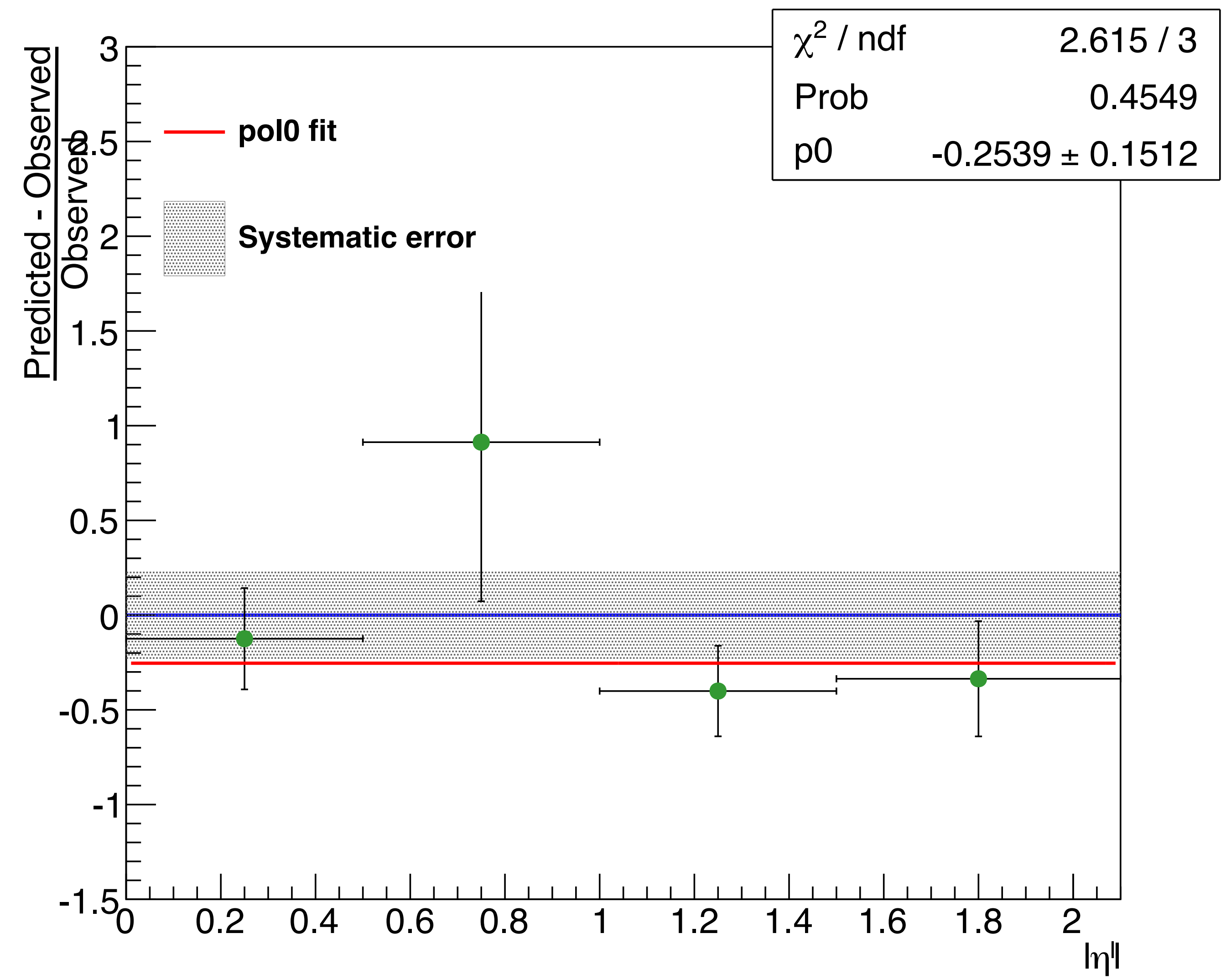


Excellent agreement !

V+Jets Consistency : Lepton η

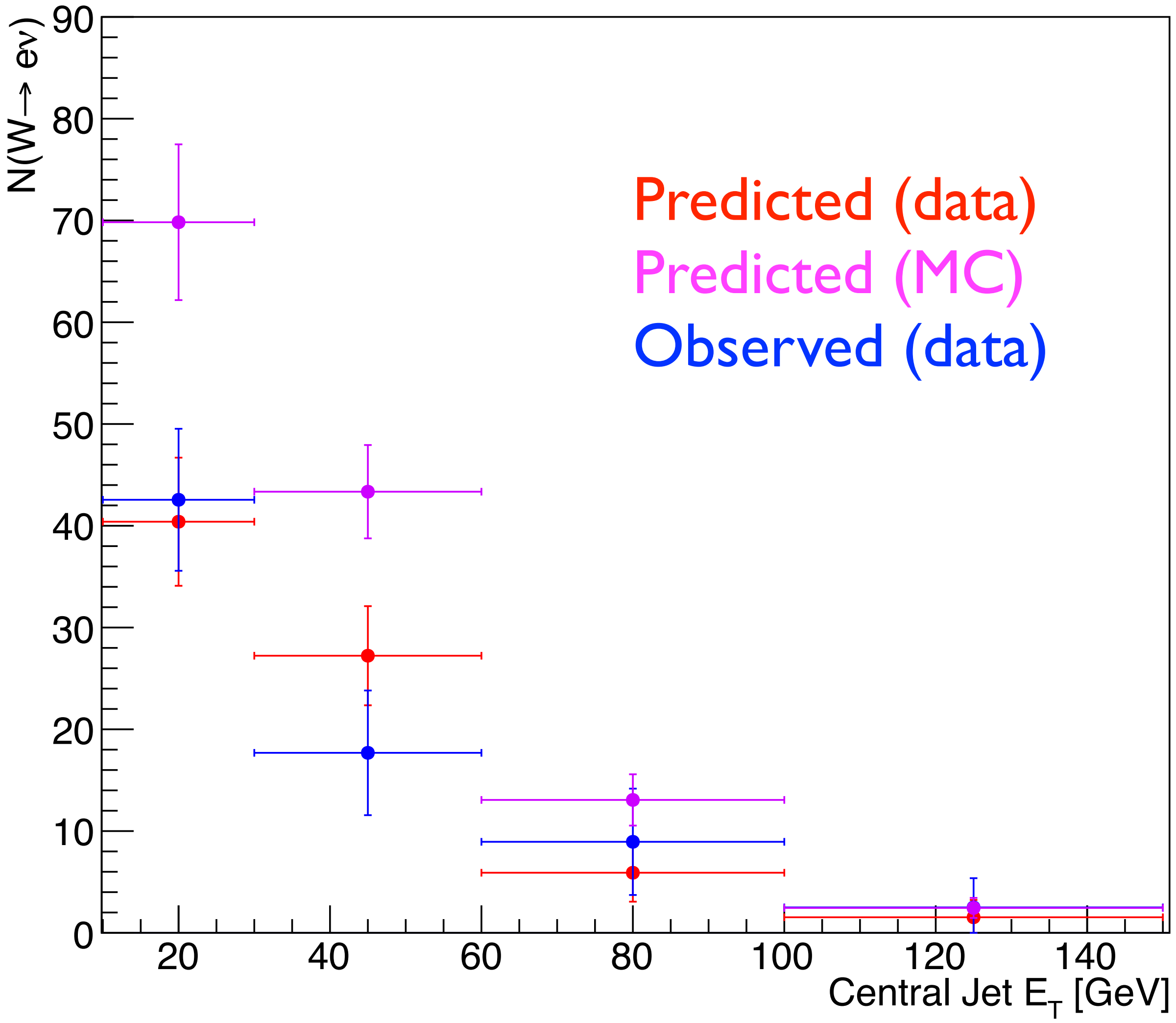
Lepton η is of interest since we extrapolate from within lepton acceptance to outside it

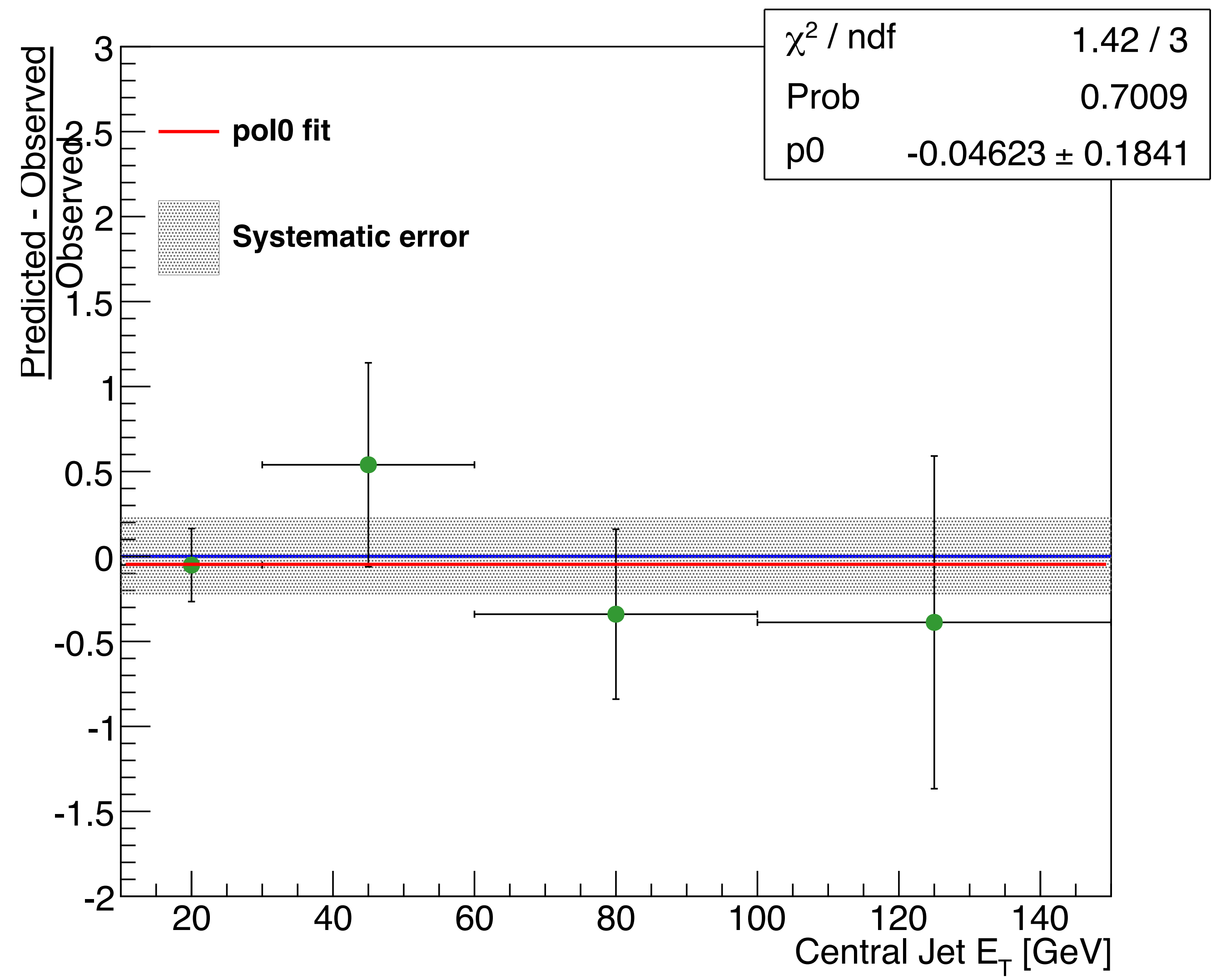




Excellent agreement !

V+Jets Consistency : central jet E_T

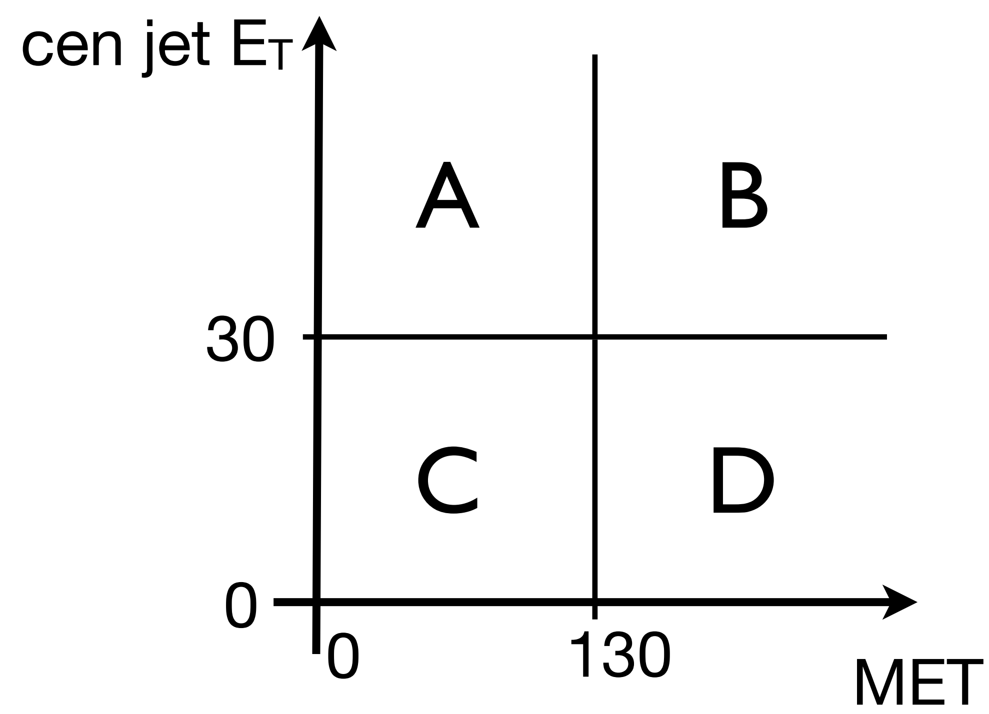




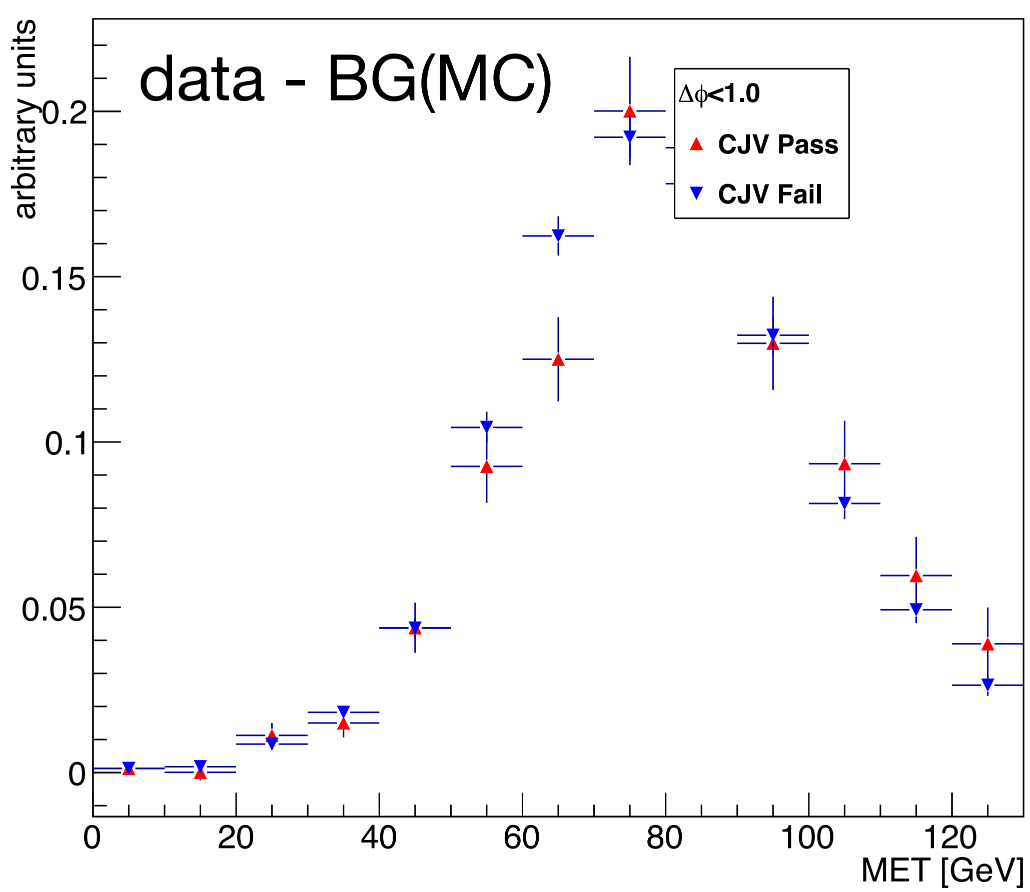
Excellent agreement !

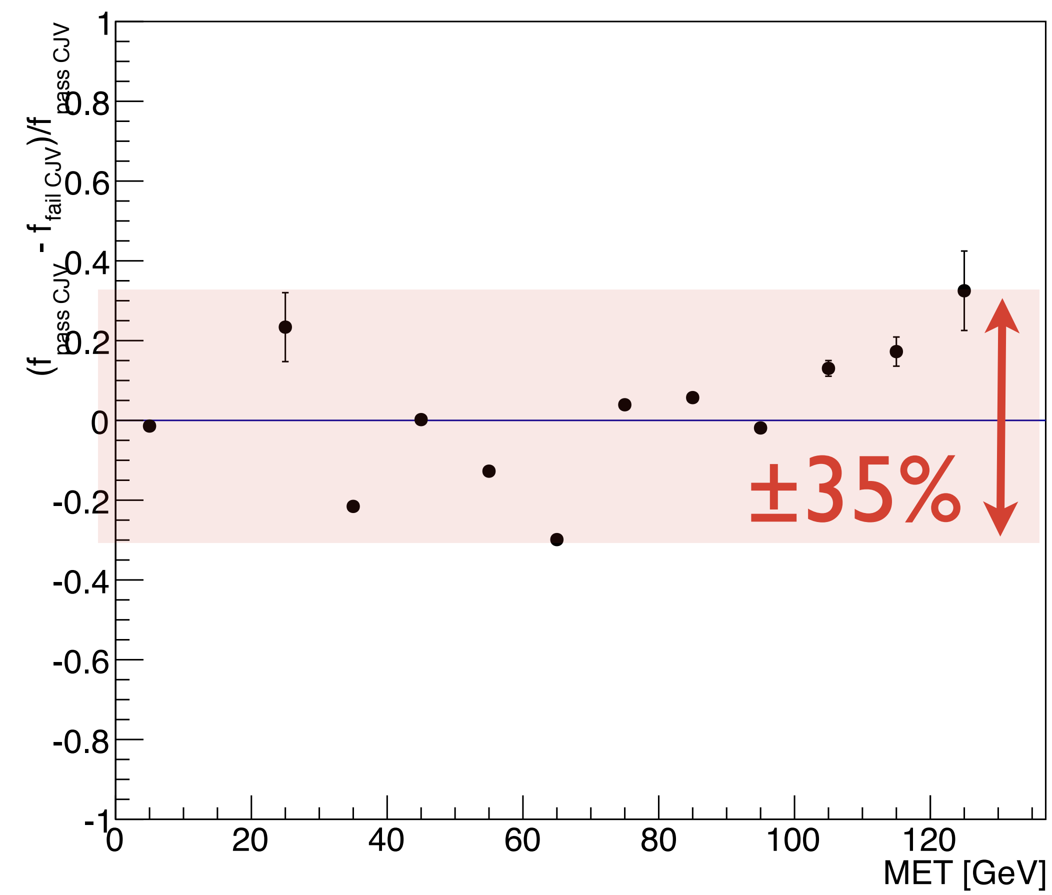
QCD Background

- ABCD method based on CJV and MET cuts
  - A - fail MET, fail CJV
  - B - pass MET, fail CJV
  - C - fail MET, pass CJV
  - D - pass MET, pass CJV *(signal region)*



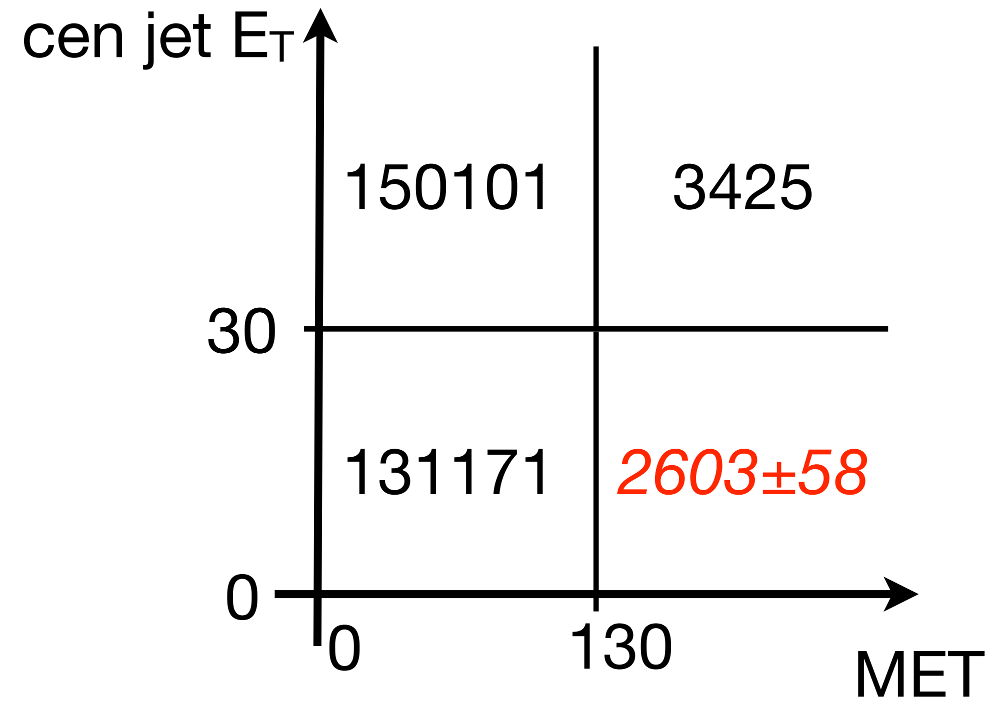
- Below - MET distribution for CJV pass/fail samples
  - Assign 35% uncertainty based on fractional difference



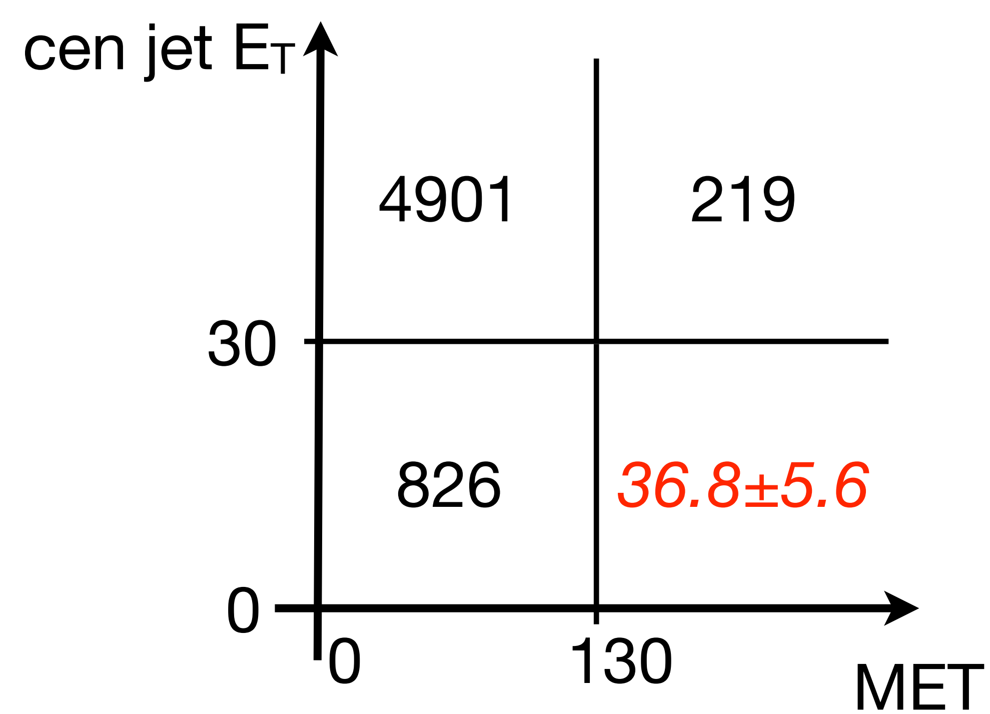


QCD Background

- Closure test using $\Delta\phi$>2.6 control region
  - Counts are data minus BG (from MC)
  - Prediction in region D : *2603 ± 58 (stat)*
  - Observation in region D : *2993*
  - ~10% difference

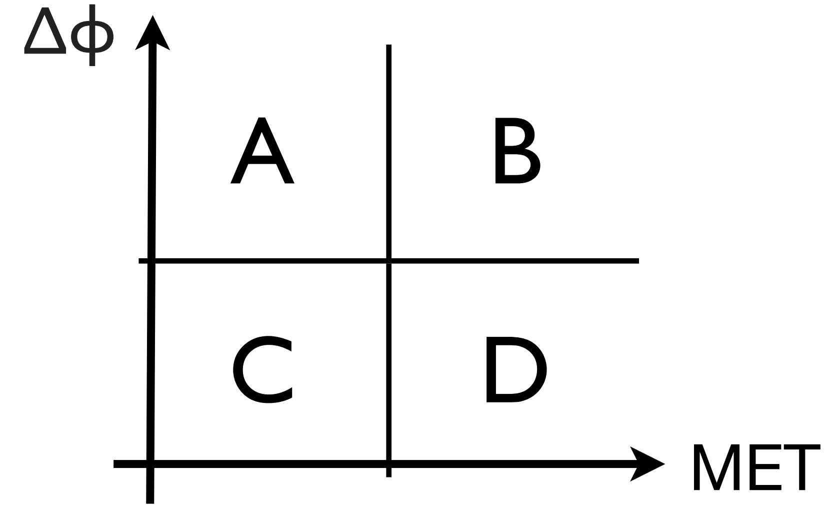


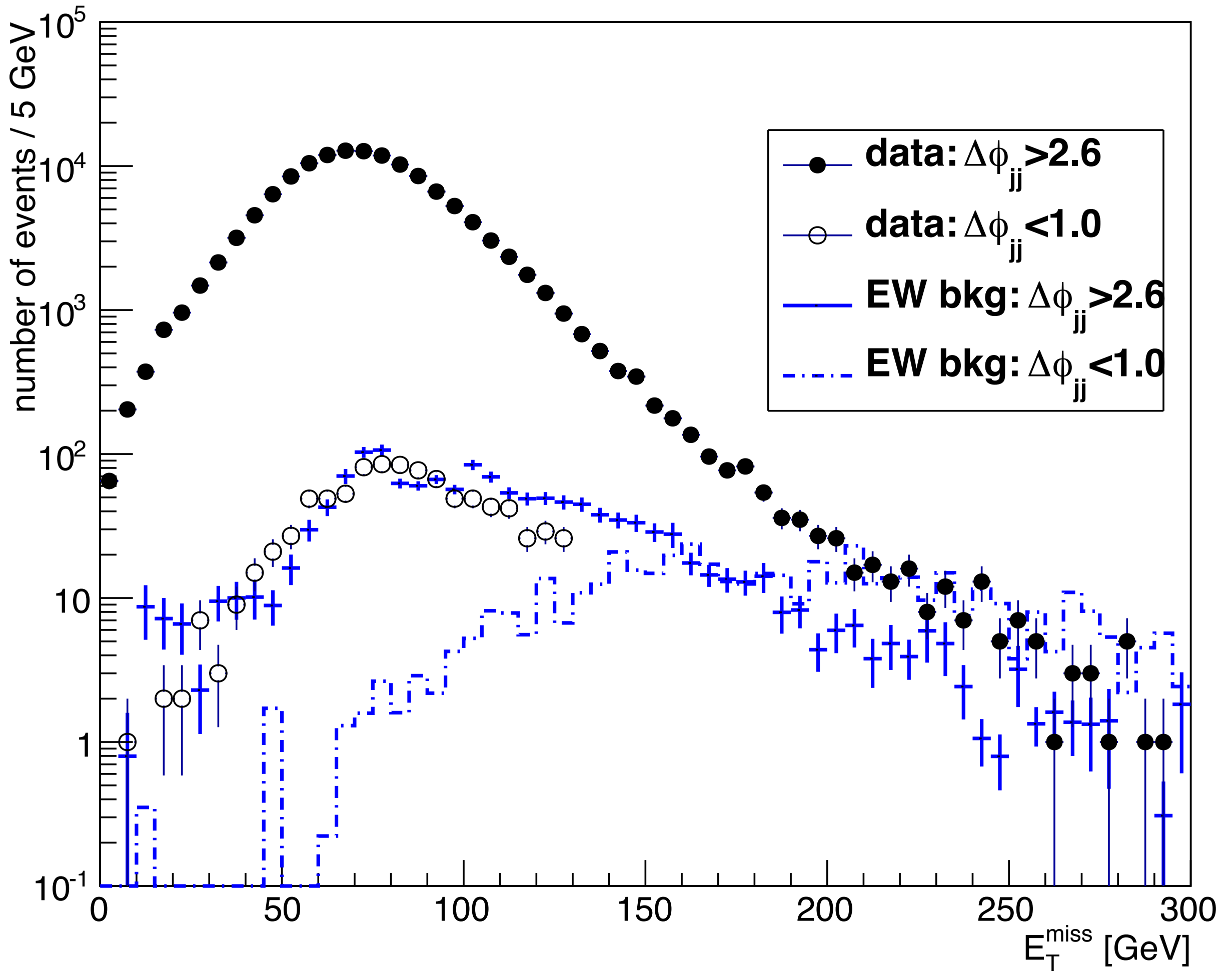
- Results for $\Delta\phi$<1.0 signal region
  - Counts are data minus BG (from MC)
  - Prediction in region D = *36.8 ± 5.6 (stat)*

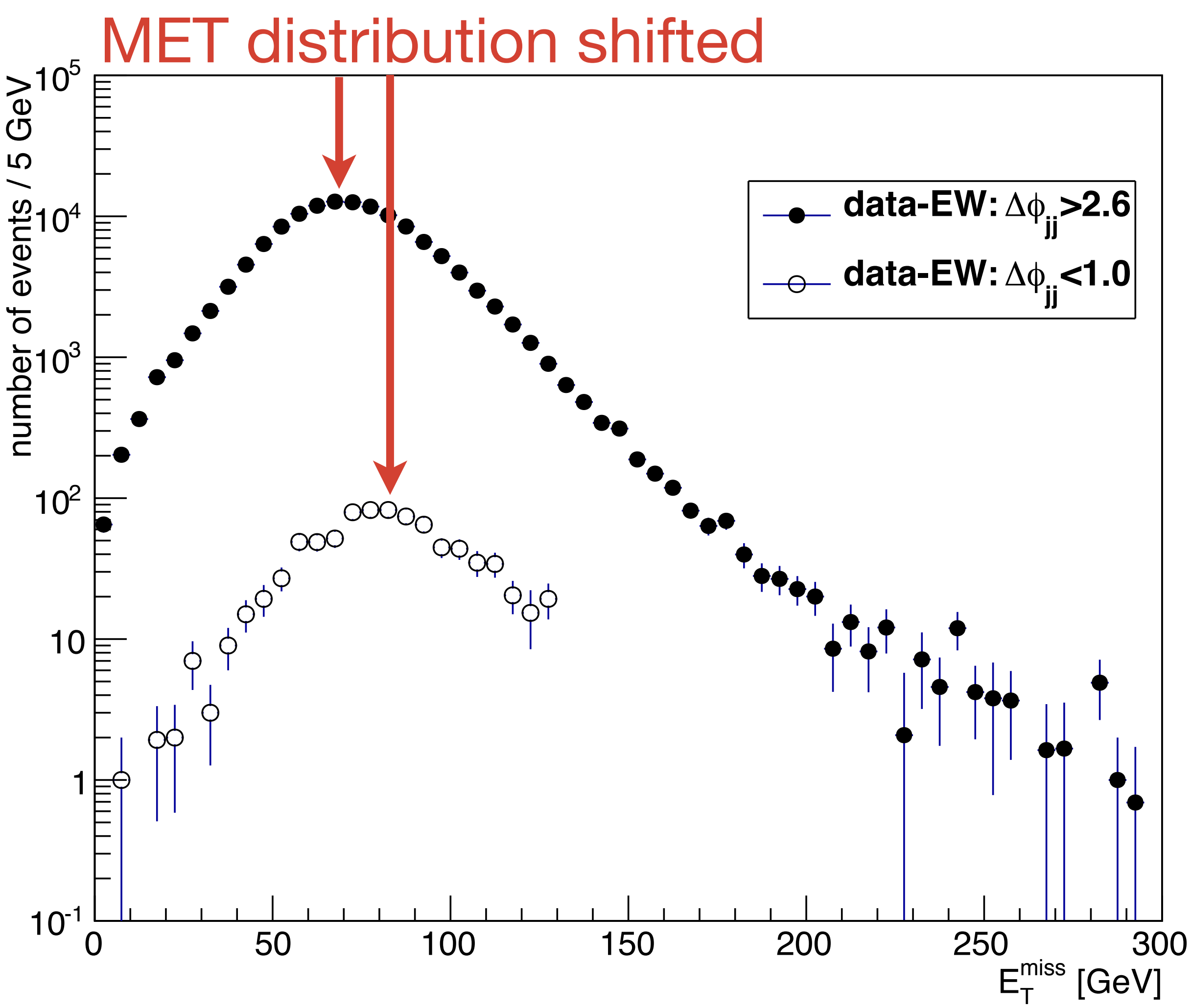


QCD Cross-check

- We cross-check the QCD method using a modified ABCD method based on MET/$\Delta\phi$
  - A - MET < 120, $\Delta\phi$ > 2.6
  - B - MET > 120, $\Delta\phi$ > 2.6
  - C - MET < 130, $\Delta\phi$ > 1.0
  - D - MET > 130, $\Delta\phi$ < 1.0 *(signal region)*

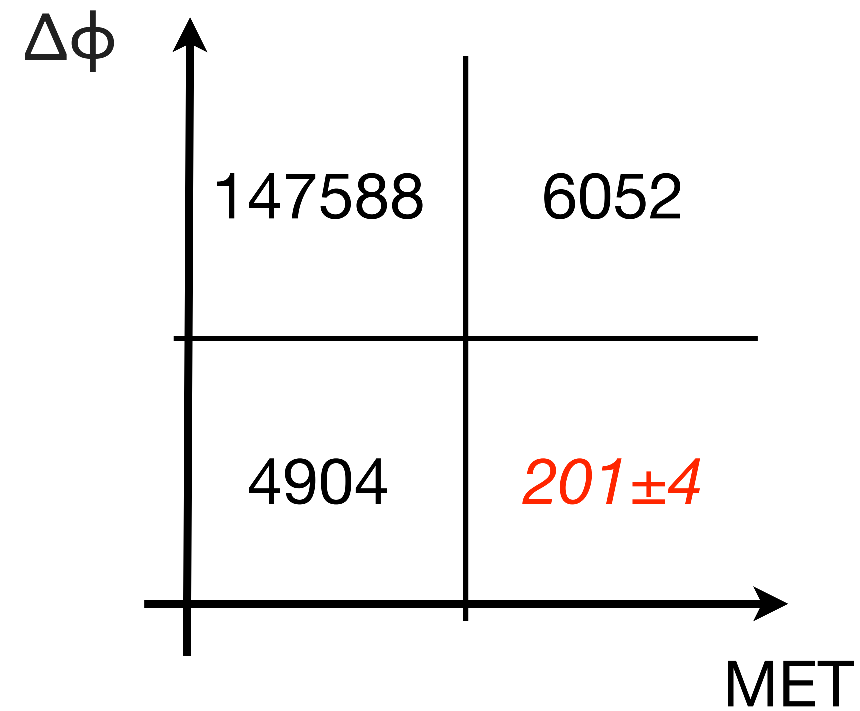






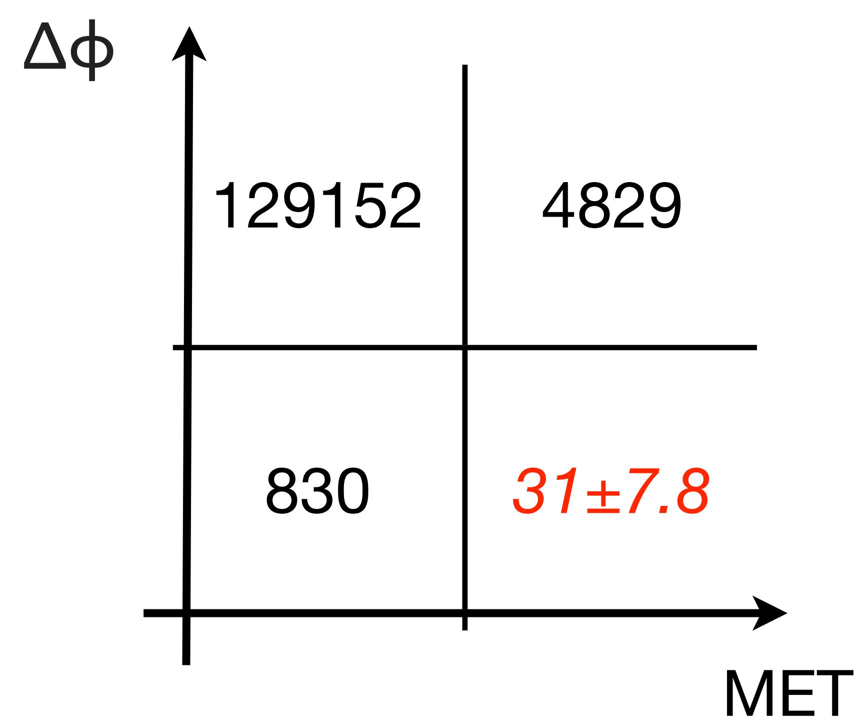
QCD Cross-check

- Closure test using events that fail CJV
  - Counts are data minus BG (from MC)
  - Prediction in region D : *201 ± 4 (stat)*
  - Observation in region D : *252*
  - Assign *25% systematic* based on this difference



- Prediction in signal region (pass CJV)
  - Prediction in region D : *31 ± 7.8 (stat) ± 7.8 (syst)*
  - Good agreement with main method :
    - *36.8 ± 5.6 (stat) ± 12.9 (syst)*

- This is a ***cross-check*** - does not enter final result



Minor Backgrounds

Process	N_{est}(MC)
VV	3.9 ± 1.4
single t	3.1 ± 1.7
DY	2.1 ± 1.8
ttbar	1.4 ± 1.2
Total	**10.4 ± 3.1**

- Minor backgrounds are estimated directly from MC
- Uncertainties include MC statistics and JES/JER

Summary of Uncertainties

Background	Source	Uncertainty
$Z \to \nu\nu$		
	Statistics in control region	29%
	MC statistics	14%
	Theory uncertainty	20%
	Jet/MET scale/resolution	5%
$W \to \mu\nu$		
	Statistics in control region	5%
	MC statistics	10%
	Theory uncertainty	20%
	Jet/MET scale/resolution	4%
$W \to e\nu$		
	Statistics in control region	10%
	MC statistics	10%
	Theory uncertainty	20%
	Jet/MET scale/resolution	$^{+5}_{-11}$%
$W \to \tau\nu$		
	Statistics in control region	30%
	MC statistics	20%
	Theory uncertainty	20%
	Jet/MET scale/resolution	$^{+16}_{-2}$%
	Tau ID efficiency	8%
	Electron contamination	5%

QCD		
	Statistics in control region	2%
	MC stats (background)	2%
	Jet/MET scale/resolution	$^{+45}_{-75}$%
	$\not{E}_T$ shape	35%
Other backgrounds		
	Luminosity	4%
	MC statistics	10%
	Jet/MET scale/resolution	28-81%
	Cross-section uncertainty	8-20%
Signal		
	MC statistics	10%
	Jet/MET scale/resolution	11%
	PDF uncertainty	5%
	QCD Scale uncertainty	4%

Results

PAS Table 1

Background	N_{est}
$Z \rightarrow \nu\nu$	$102 \pm 30\,(\text{stat.}) \pm 26\,(\text{syst.})$
$W \rightarrow \mu\nu$	$67.2 \pm 5.0\,(\text{stat.}) \pm 15.1\,(\text{syst.})$
$W \rightarrow e\nu$	$68.2 \pm 9.2\,(\text{stat.}) \pm 18.1\,(\text{syst.})$
$W \rightarrow \tau\nu$	$54 \pm 16\,(\text{stat.}) \pm 18\,(\text{syst.})$
QCD multijet	$36.8 \pm 5.6\,(\text{stat.}) \pm 30.6\,(\text{syst.})$
Other SM	$10.4 \pm 3.1\,(\text{syst.})$
Total	$339 \pm 36\,(\text{stat.}) \pm 50\,(\text{syst.})$
Observed	390

Observed yield in very good agreement with prediction
~0.5 sigma difference

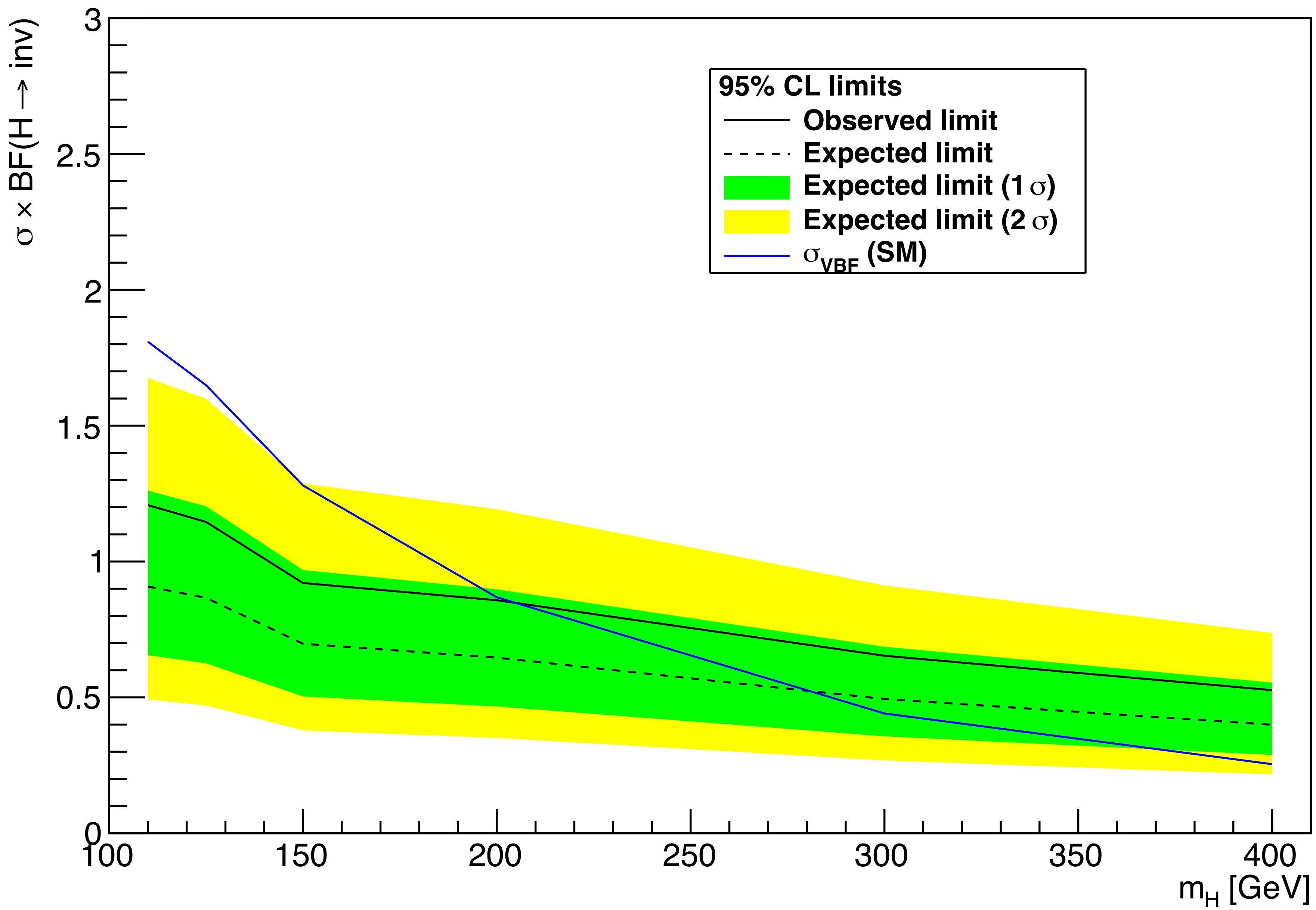
Limit Setting

- Use standard Higgs combination tool to perform a single bin counting experiment
  - Asymptotic CLs
  - Use --*noFitAsimov* option (ensure expected limit is independent of N_{obs})

- 6 backgrounds
  - Z, $W \rightarrow e$, $W \rightarrow \mu$, $W \rightarrow \tau_{had}$, QCD, other SM

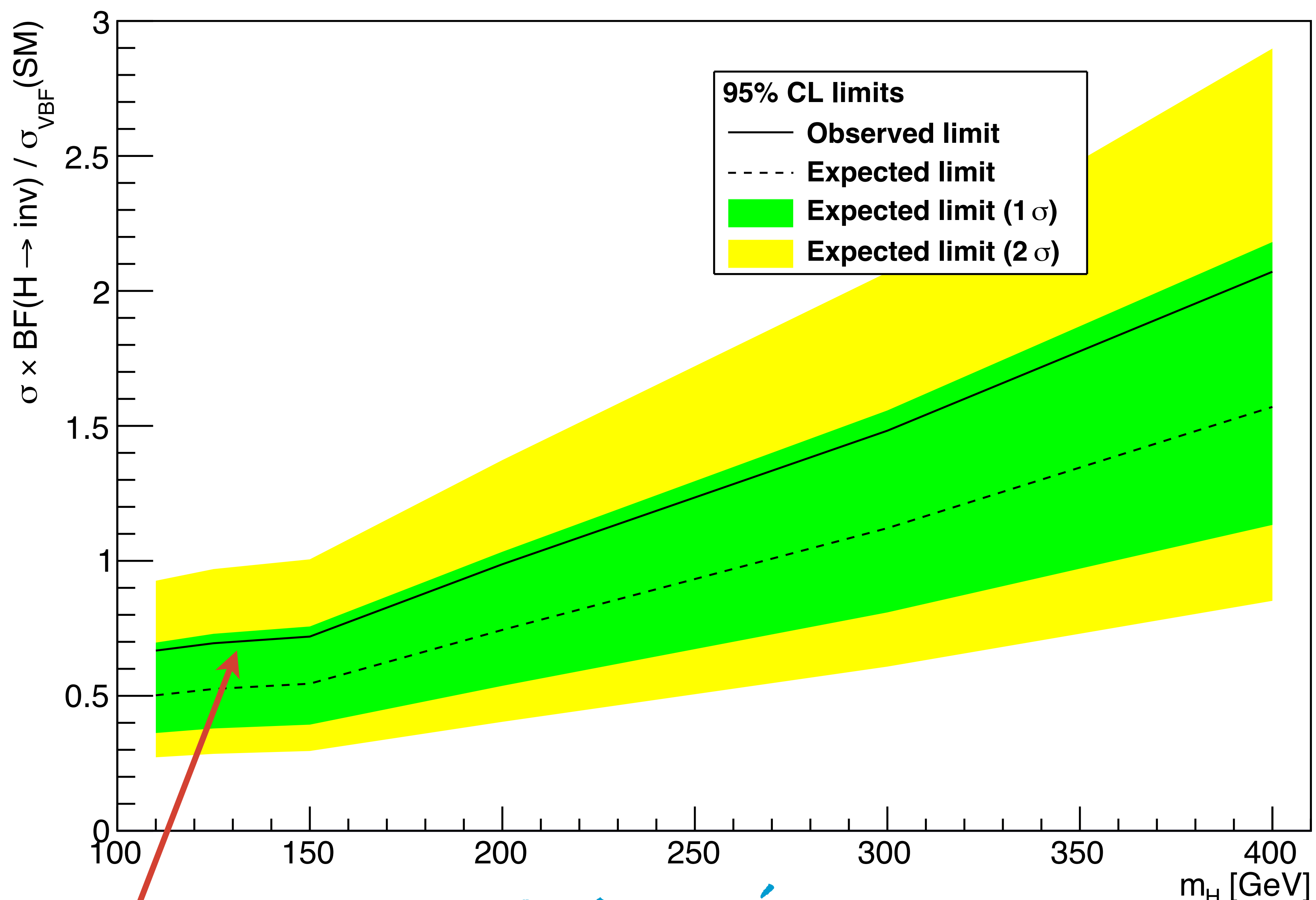
- 8 nuisance parameters
  - Lumi uncertainty (log-normal)
  - Z control region statistics (Gamma-normal)
  - 6 x BG uncertainties (log-normal)
  - Signal uncertainty (log-normal)

Limit Plots



PAS Fig 1

Limit Plots



PAS Fig 2

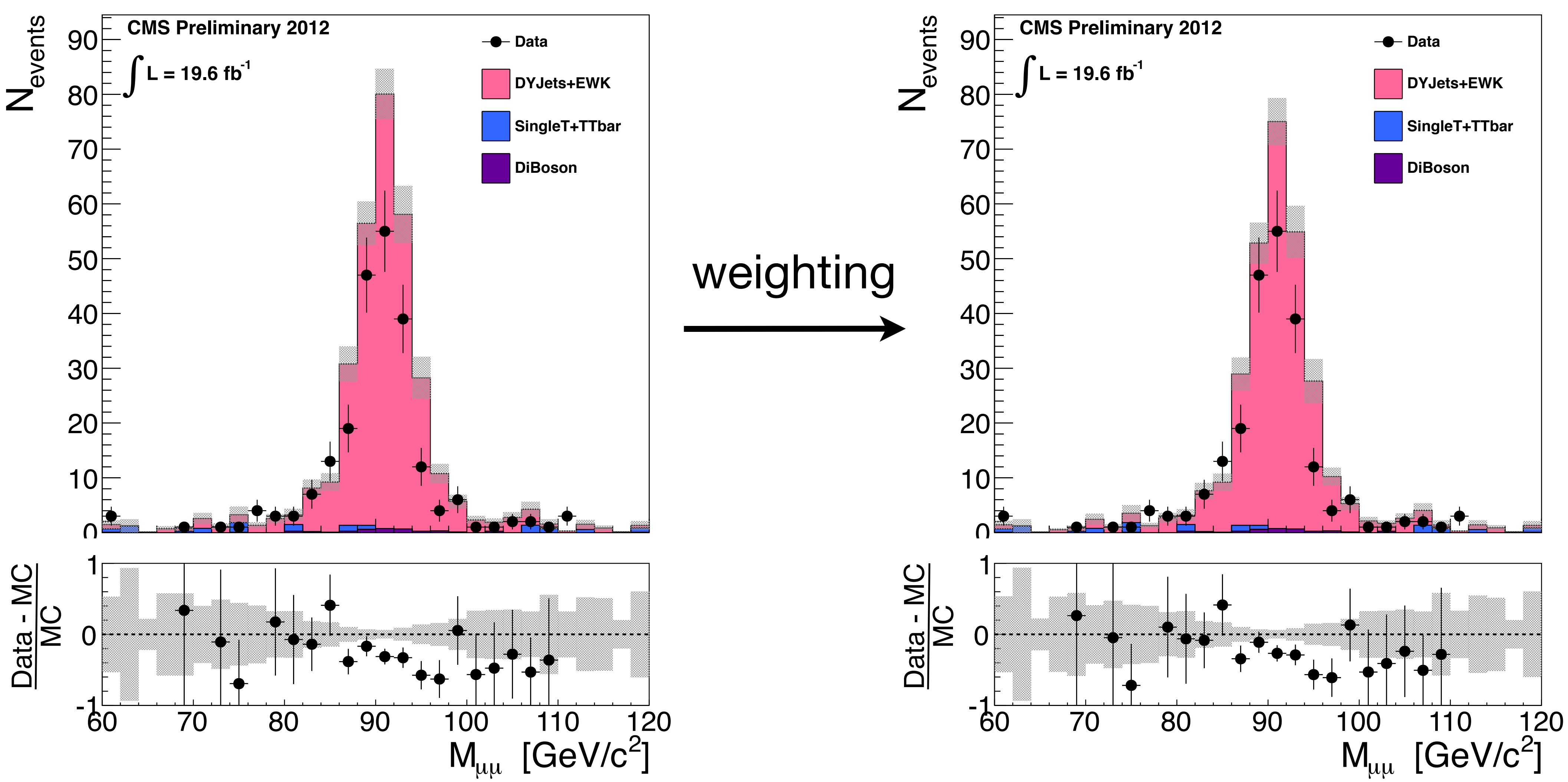
69% at m_H=125 GeV
(53% expected)

Issues during ARC Review

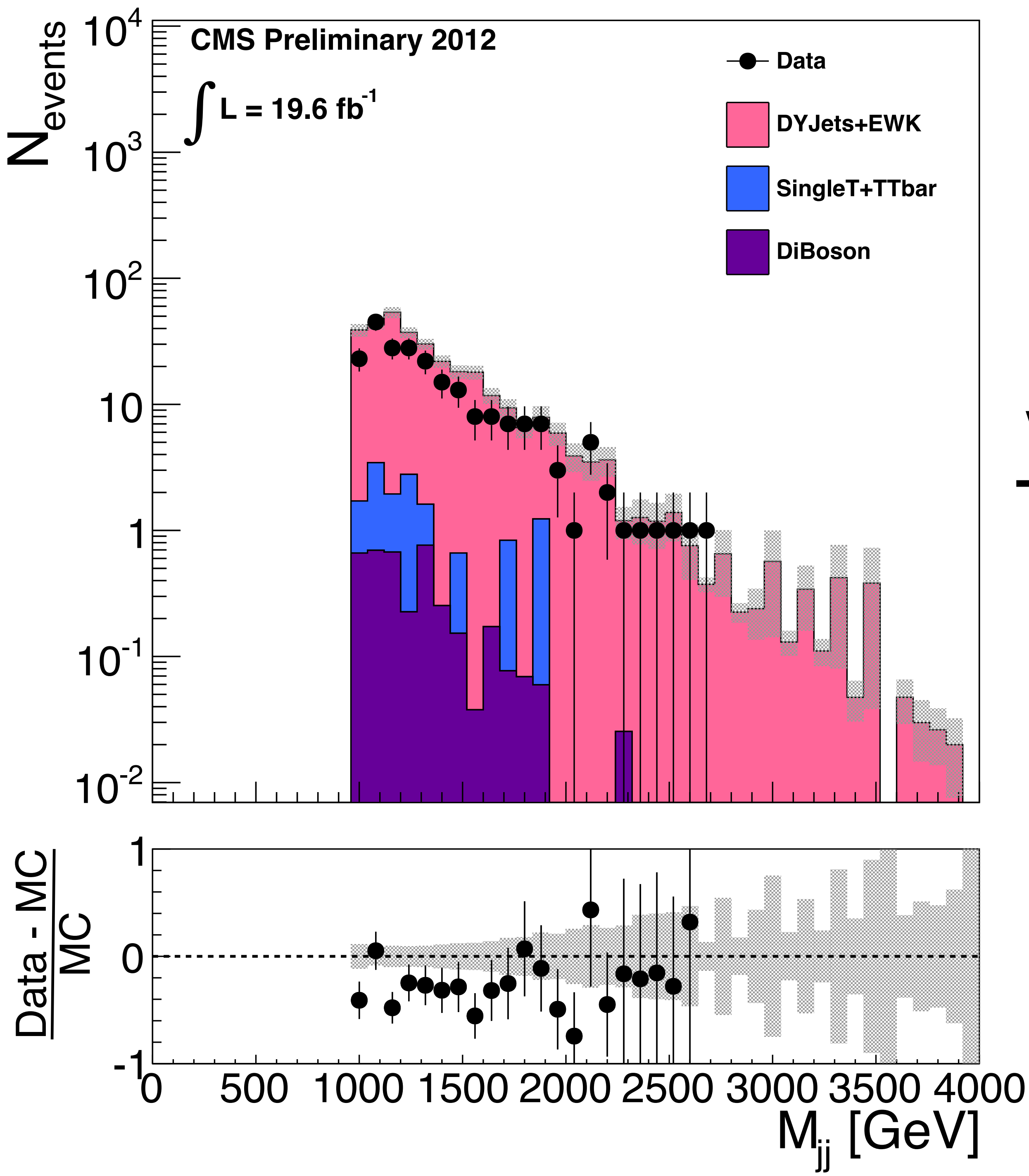
- Add V+jets closure tests - done
- Add closure test and systematic for QCD cross-check method - done
- $W \rightarrow \tau_{had}$ synchronisation - resolved
  - We observed a ~15% discrepancy between two analyses in $W \rightarrow \tau_{had}$ estimate
  - **Analysis A = 54.4 events, Analysis B = 64.6 events**
  - This was traced to a difference in QCD W+jets MC yields
  - Resulting from different handling of JER smearing for jets with no match at gen level
  - **Analysis A applies Gaussian smearing, analysis B does not smear**
  - Chose to **use analysis A (for consistency)** prior to unblinding, no reason to change
- Investigate MC normalisation - presented here
  - Re-weight MadGraph to MCFM using weights derived for FSQ-12-036
  - Derive MC scale factors from data in sidebands to control regions

QCD V+jets Re-weighting

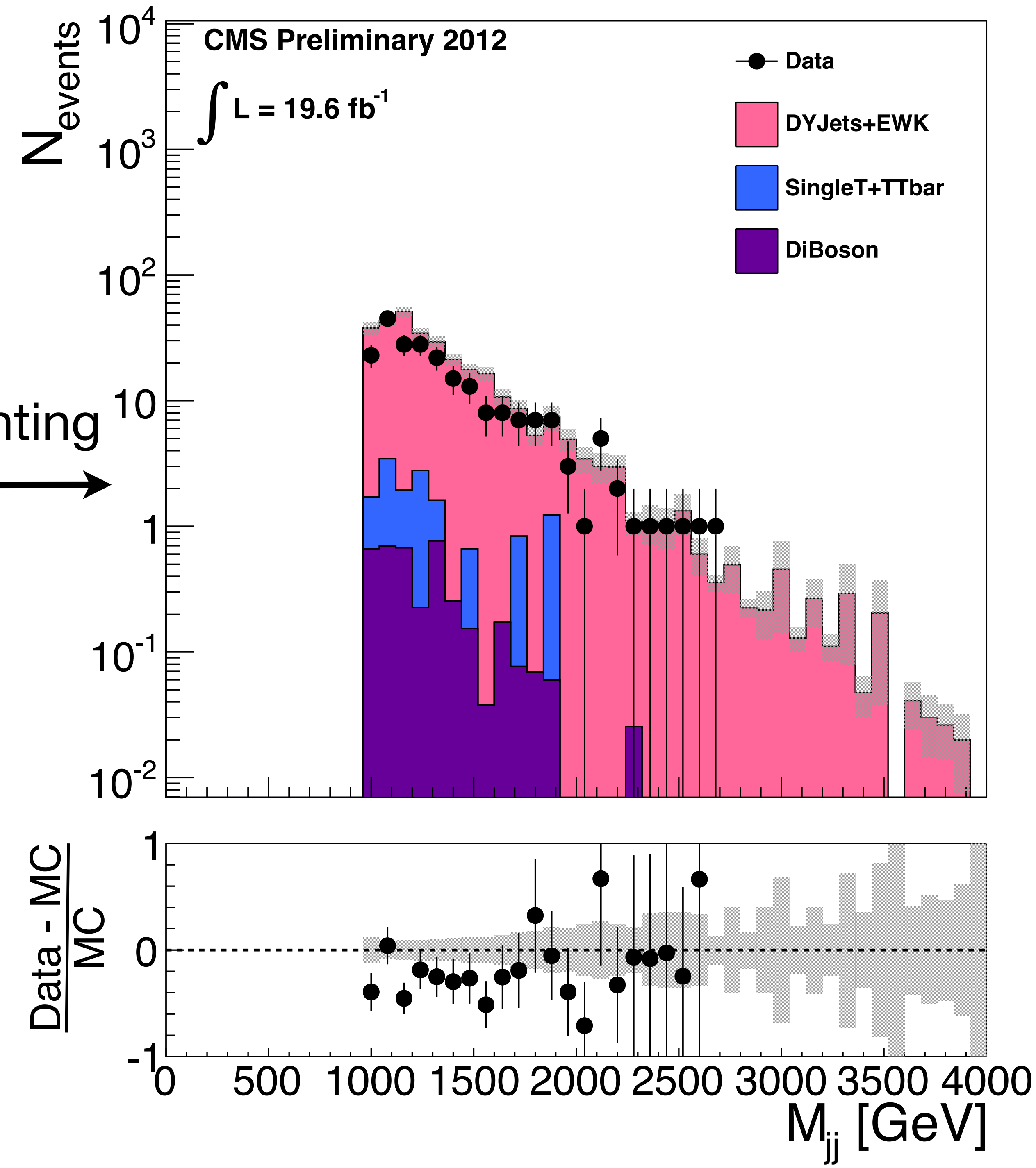
- Re-weight DY+Jets using procedure developed for VBF Z+jets analysis
  - **FSQ-12-036, AN 2013/170**
  - The authors derive event weights to correct MadGraph to MCFM
  - Weights calculated in bins of 2 variables : $\mathbf{y^* = y_Z - 0.5(y_{jet1} + y_{jet2})}$ and $\mathbf{M_{jj}}$
- We have applied these weights to our MC
  - < 1% change to V+jets BG estimates, but also minimal change to control plots



QCD V+jets Re-weighting



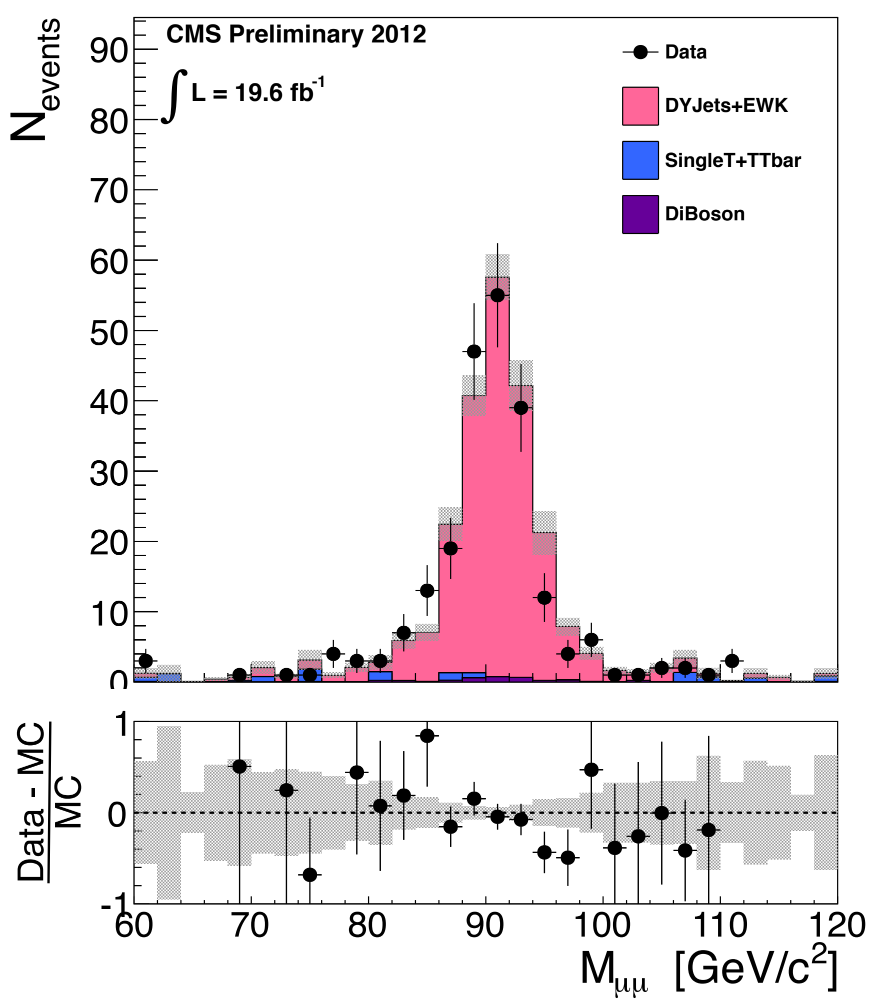
weighting

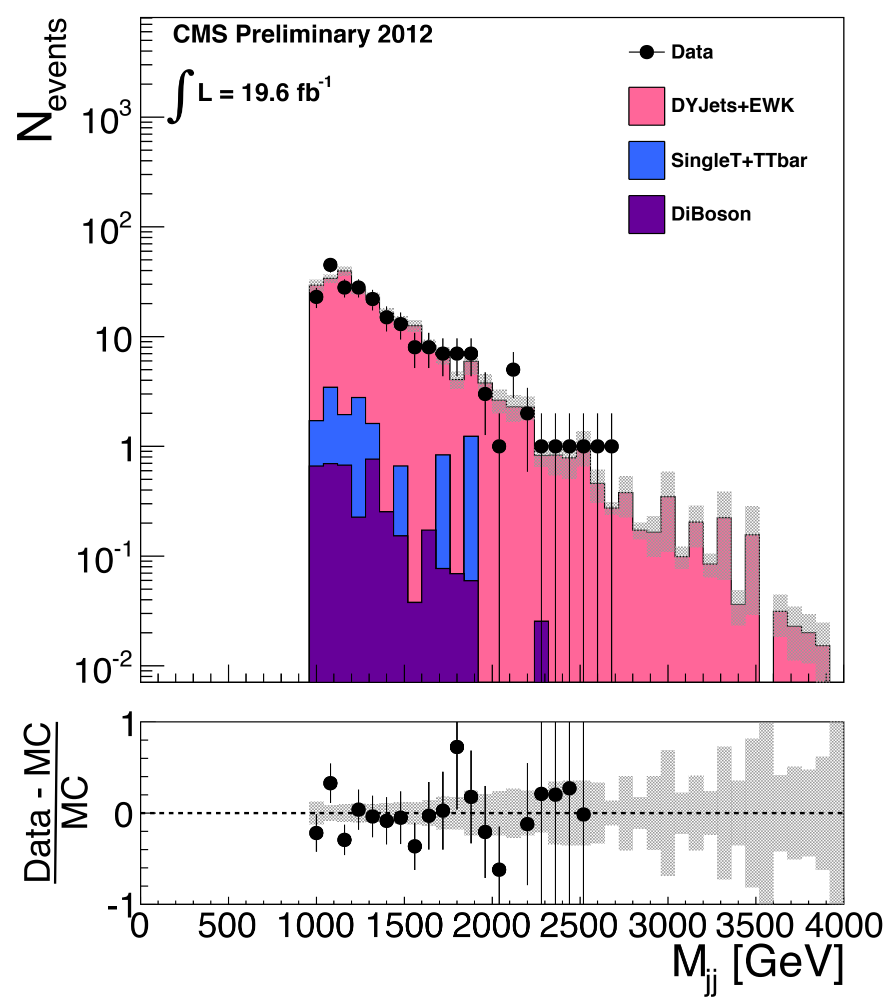


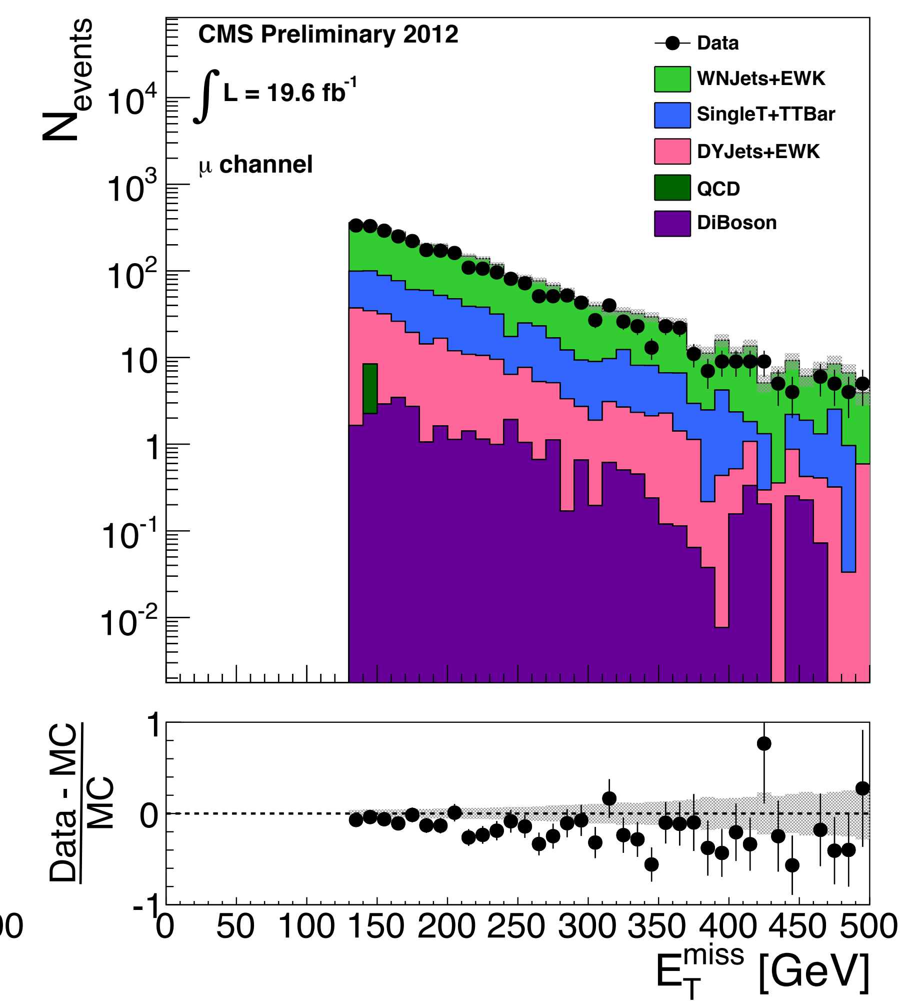
V+Jets MC Normalisation

- Derive normalisation using sidebands to the W (e/μ) control regions
  - **900 < M_{jj} < 1100, M_T>40 GeV**
  - Also possible with Z, but very low statistics - 9 data events in sideband region
- Calculate data/MC for these sidebands and apply as overall normalisation to all V+jets MC
  - W→e data/MC = 25.7476/32.987 = **0.781**
  - W→μ data/MC = 110.296/147.364 = **0.748**
  - Mean (used for scaling) = **0.765**

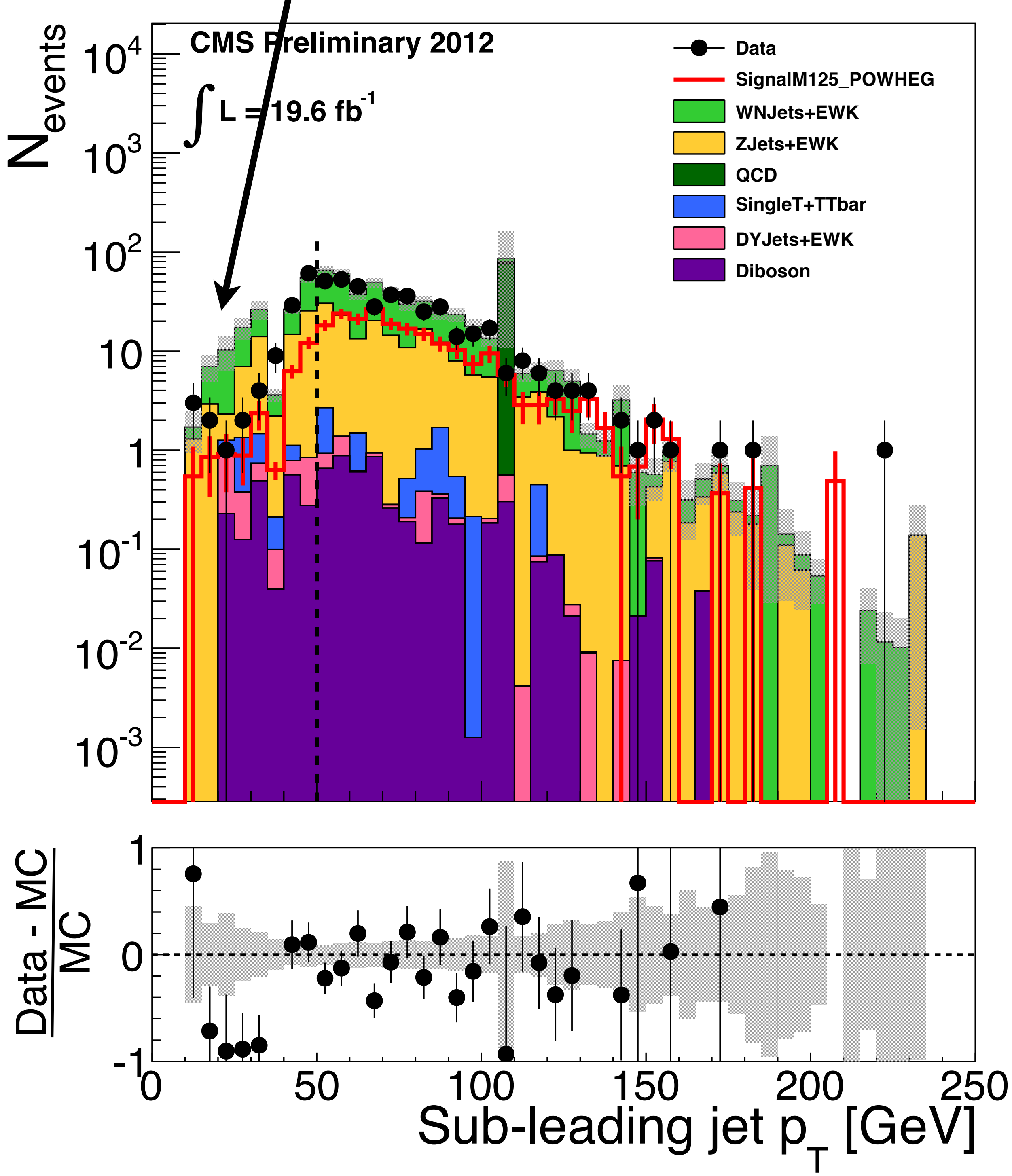
more in backup!

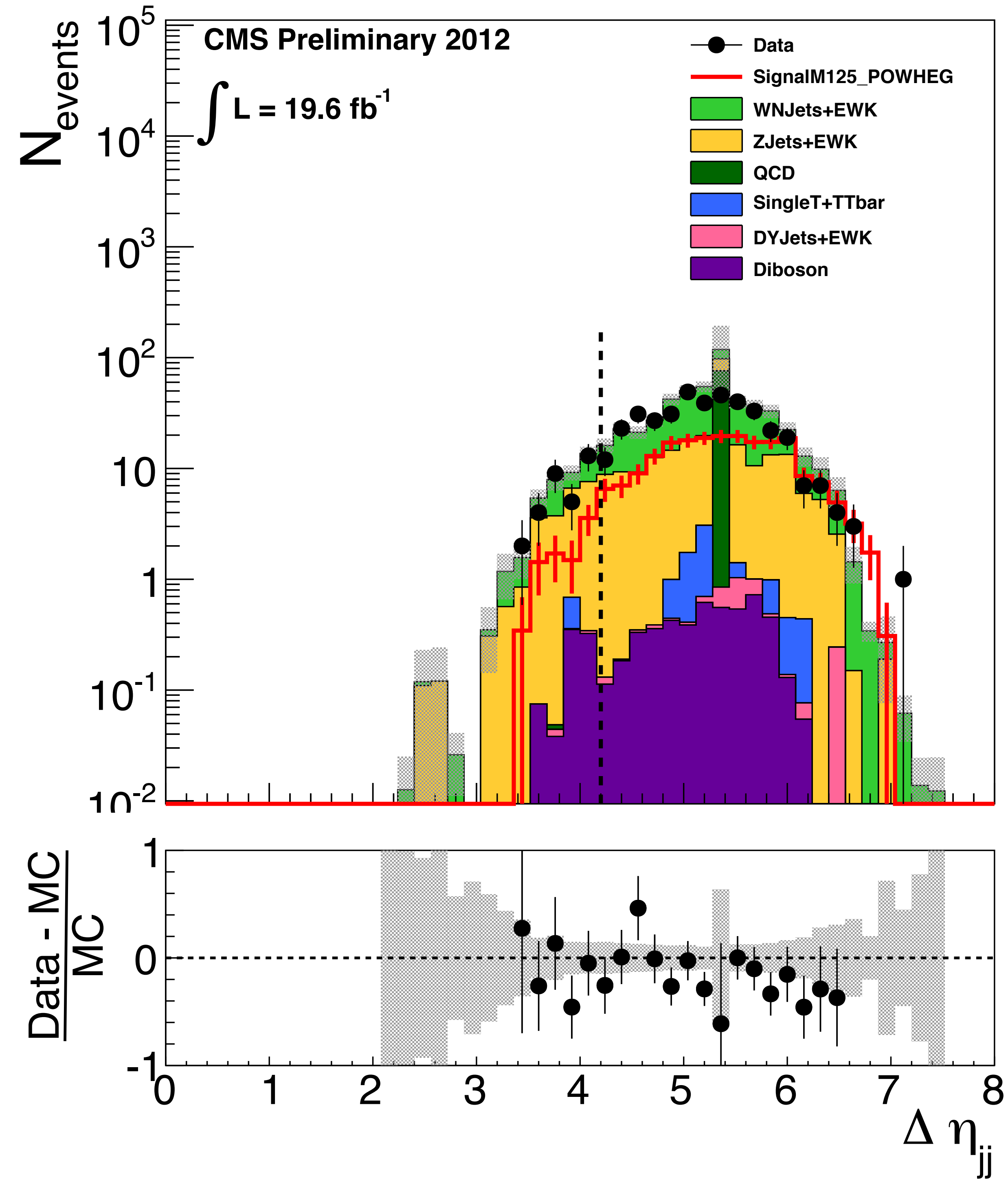




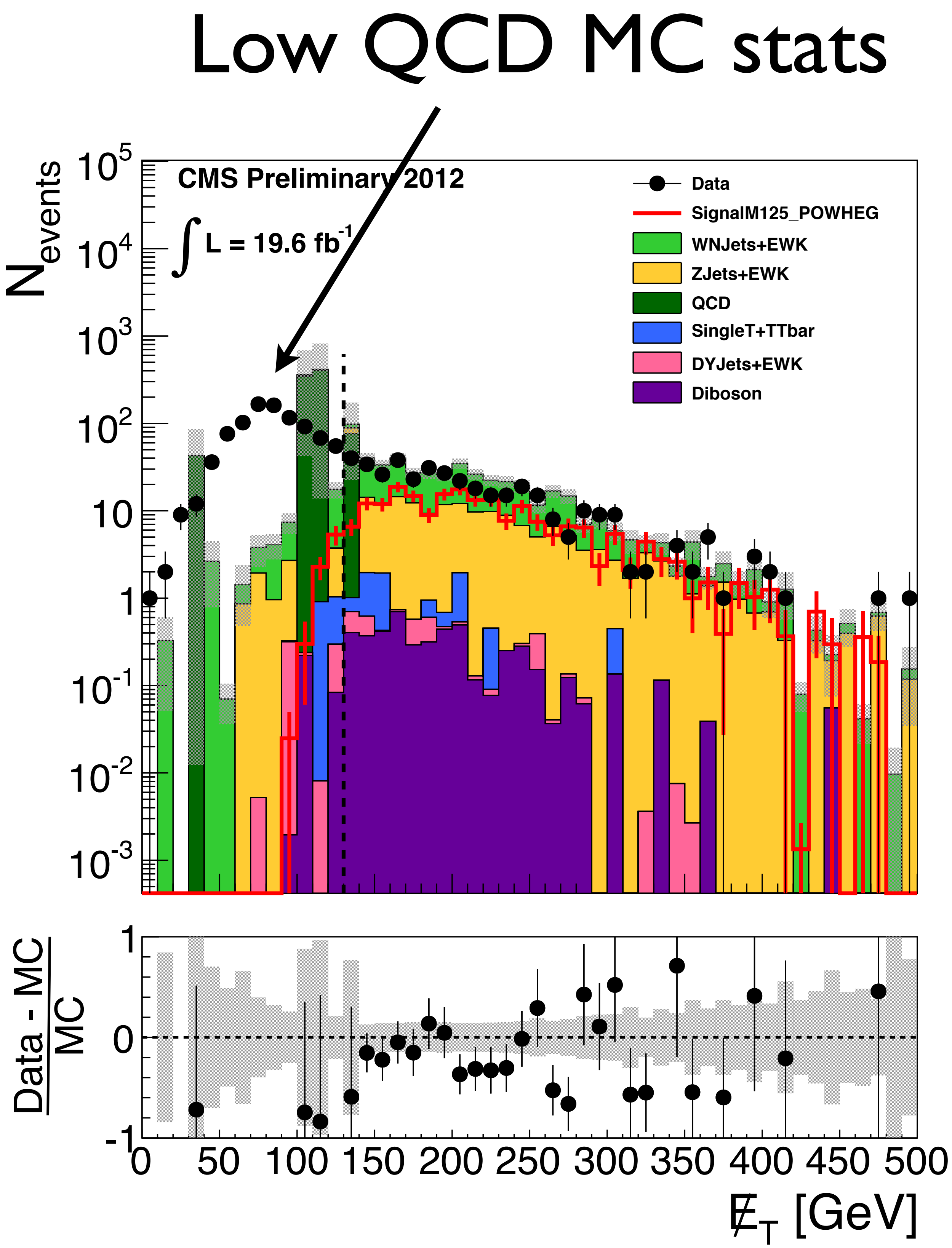


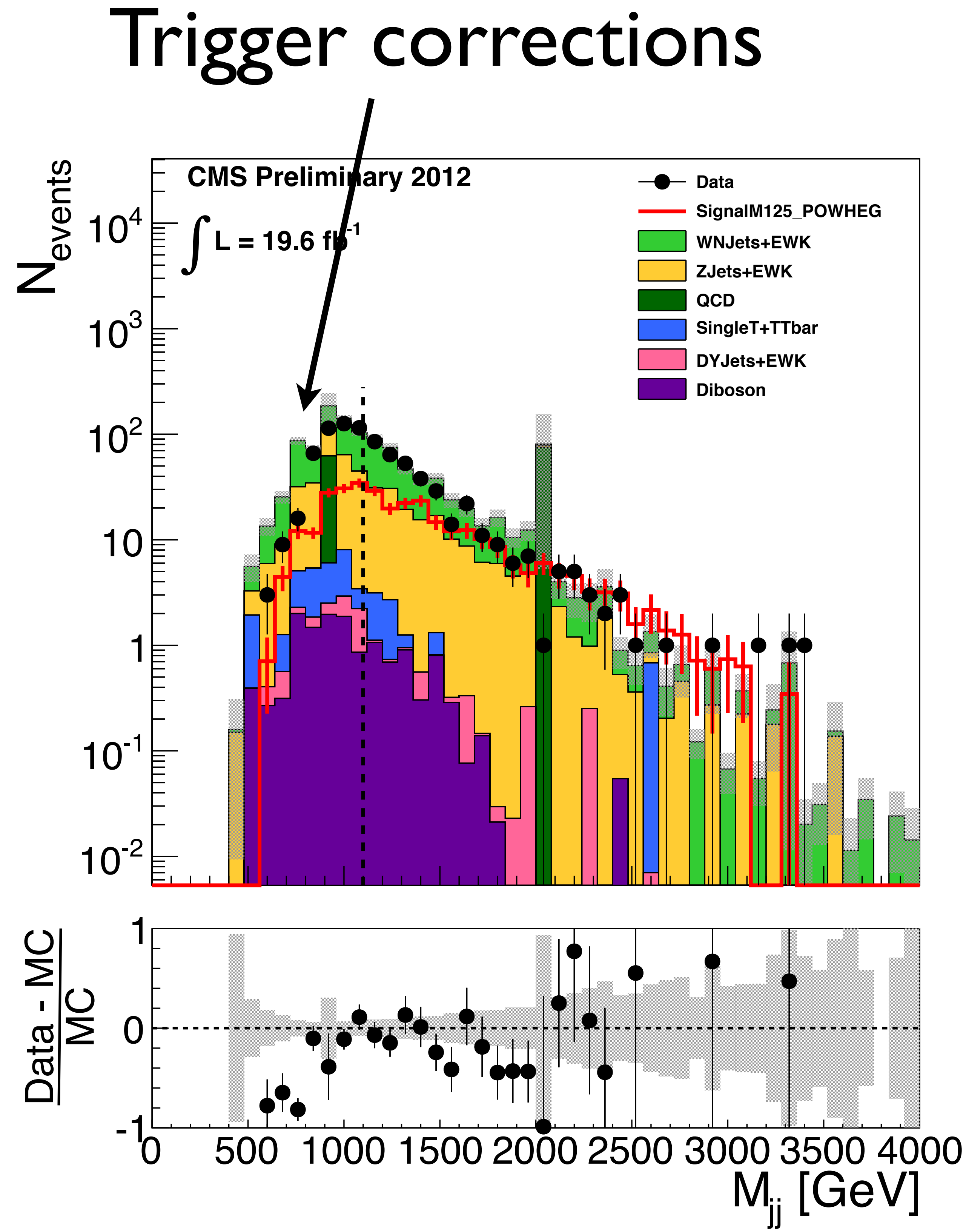
Trigger corrections





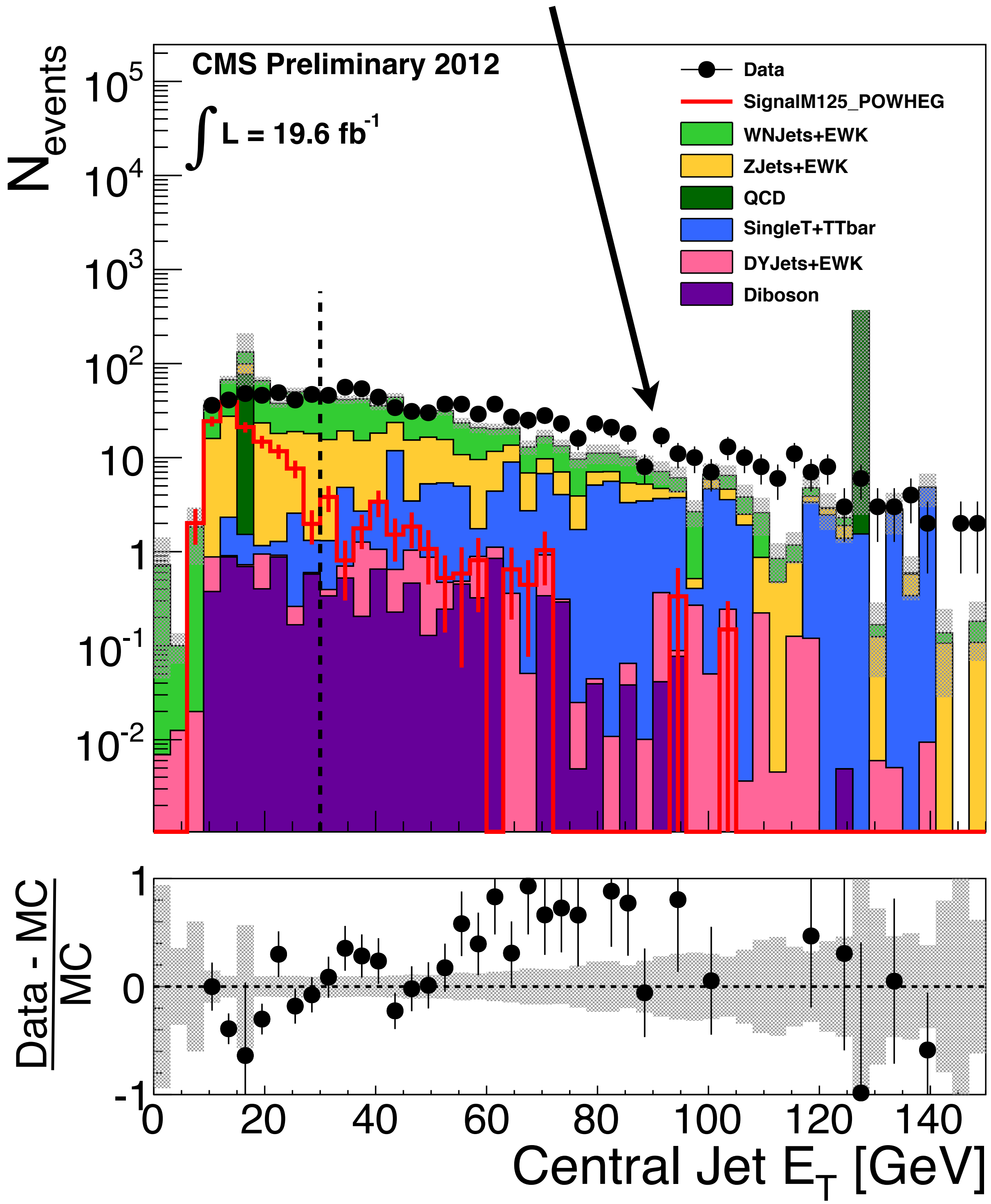
V+Jets MC Normalisation

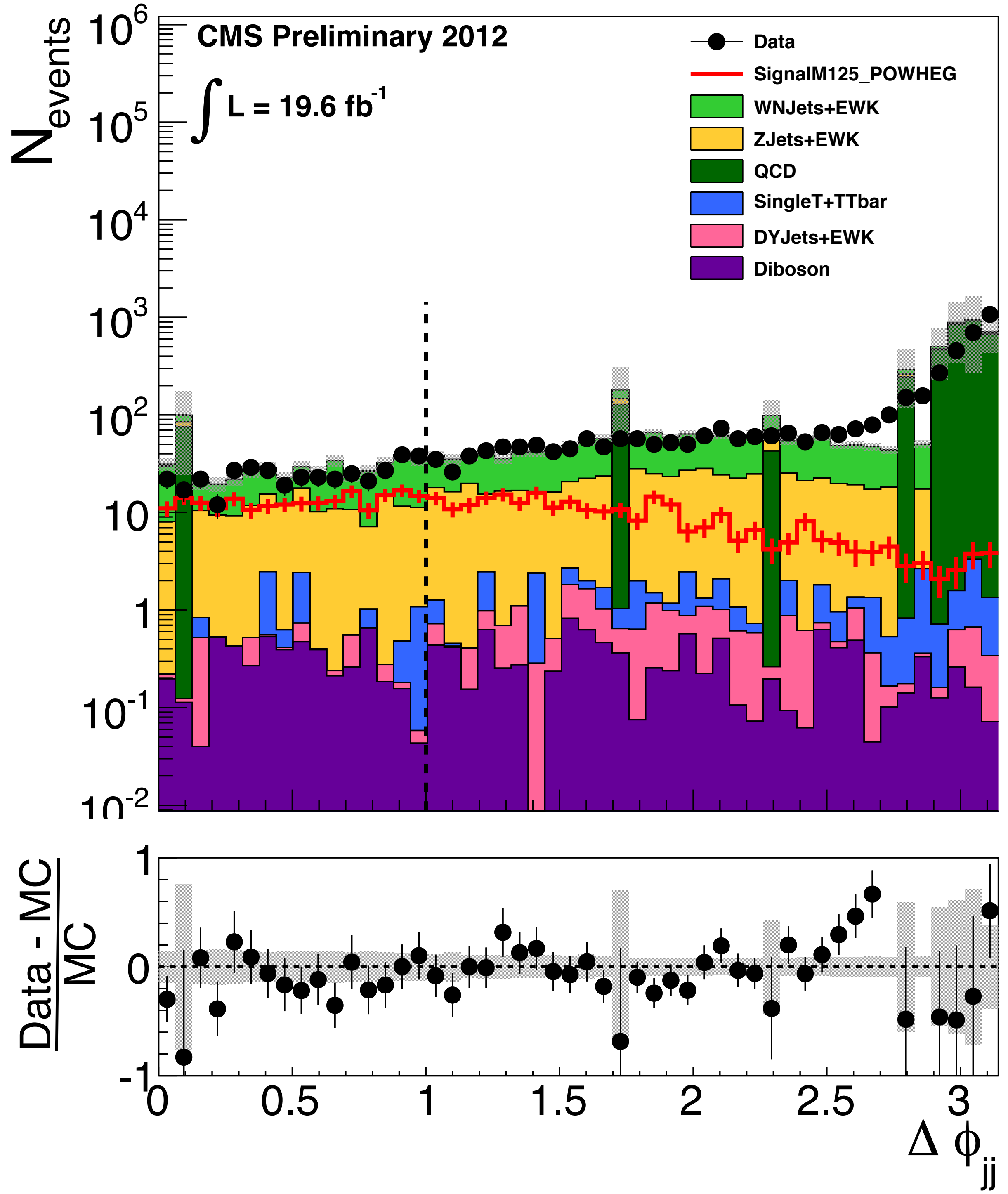




V+Jets MC Normalisation

Low QCD MC stats





Summary

- Searched for **invisible decays of a Higgs boson** in the vector boson fusion channel
- Dominant backgrounds predicted using **data-driven methods**
- Background **closure tests show excellent agreement with data**
- Predict a **background of 339 ± 36 ± 50 events** in the signal region
- **Observe 390 events**
- No evidence for a signal
- **Place limits on the invisible BF of the 125 GeV Higgs at 69% (53% expected)**

Backup

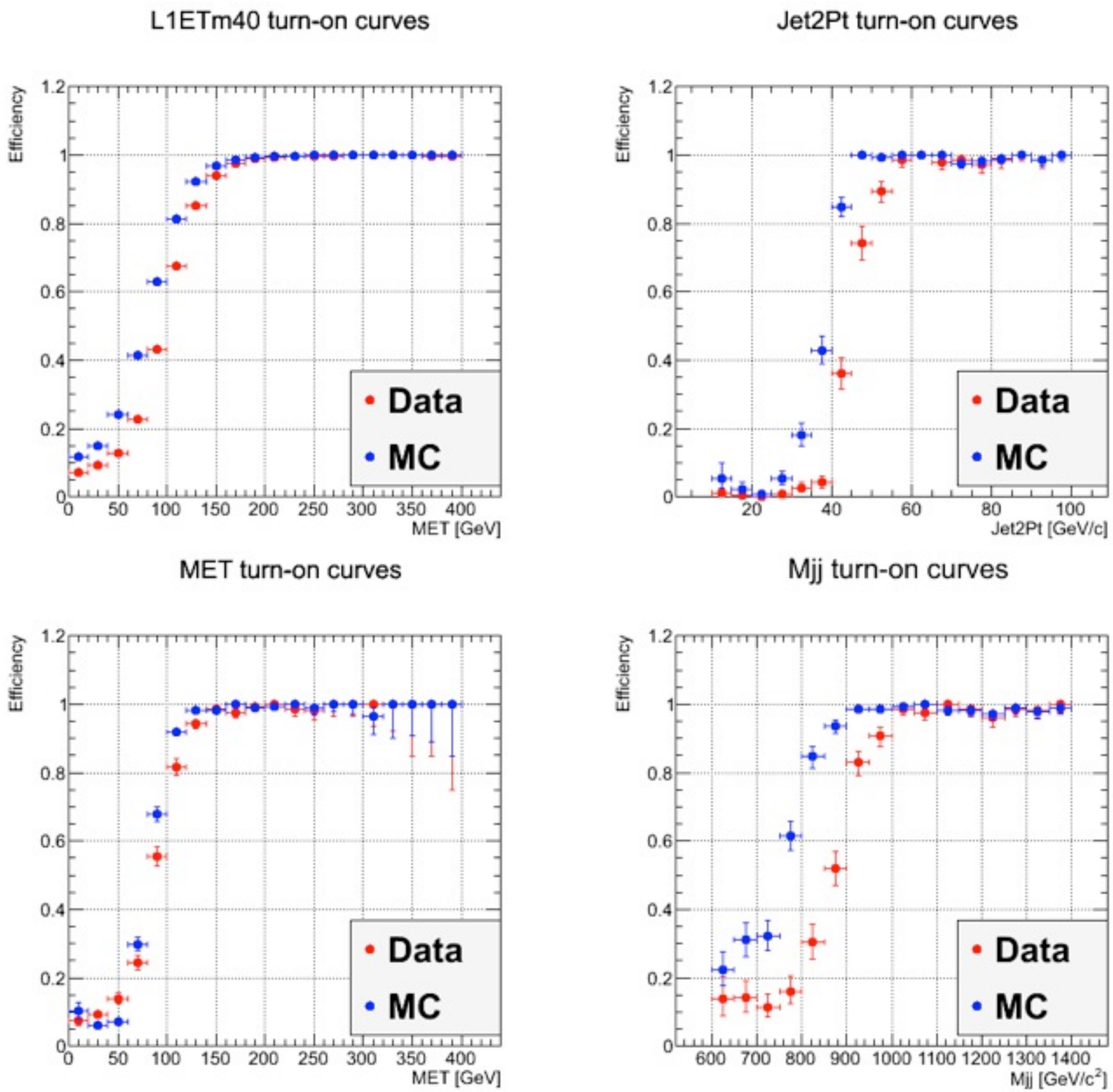
Trigger Turn-on Curves

Samples

- Single mu PD
- W+jets MC
- HLT_IsoMu24_eta2p1

“AllJets” turn on shown as function of jet, MET and Mjj

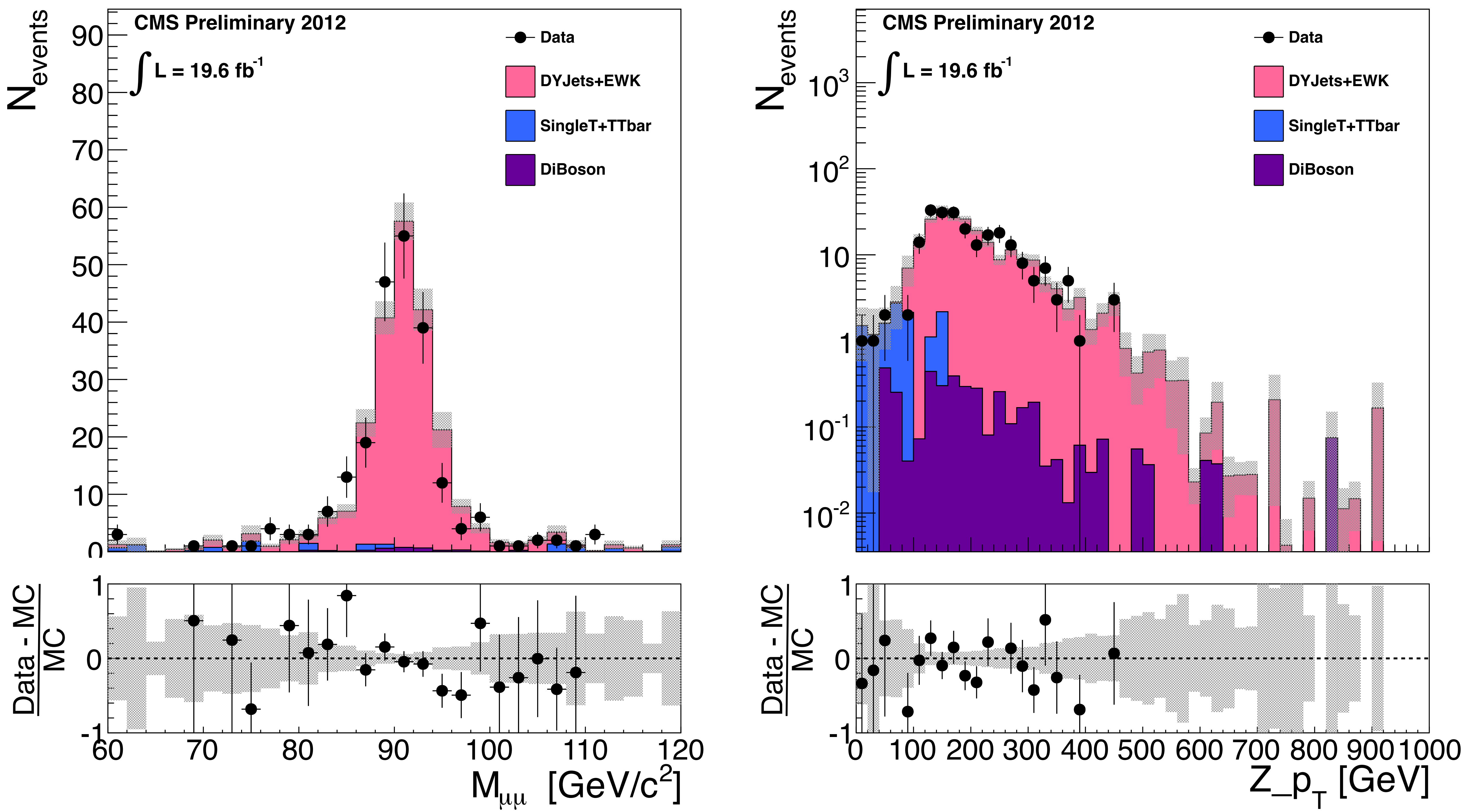
Ratio used to derive MC correction factors



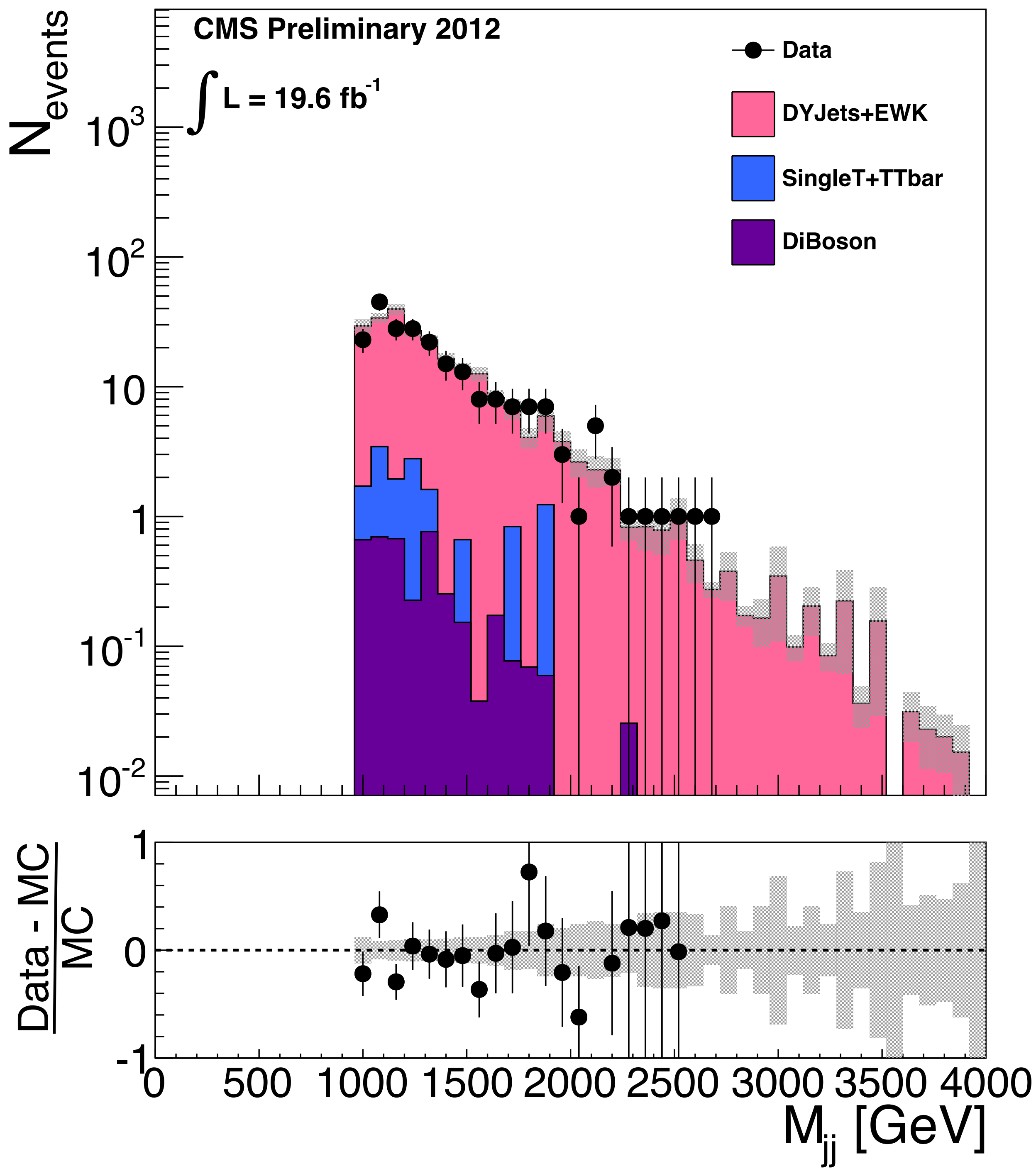
Scaled MC

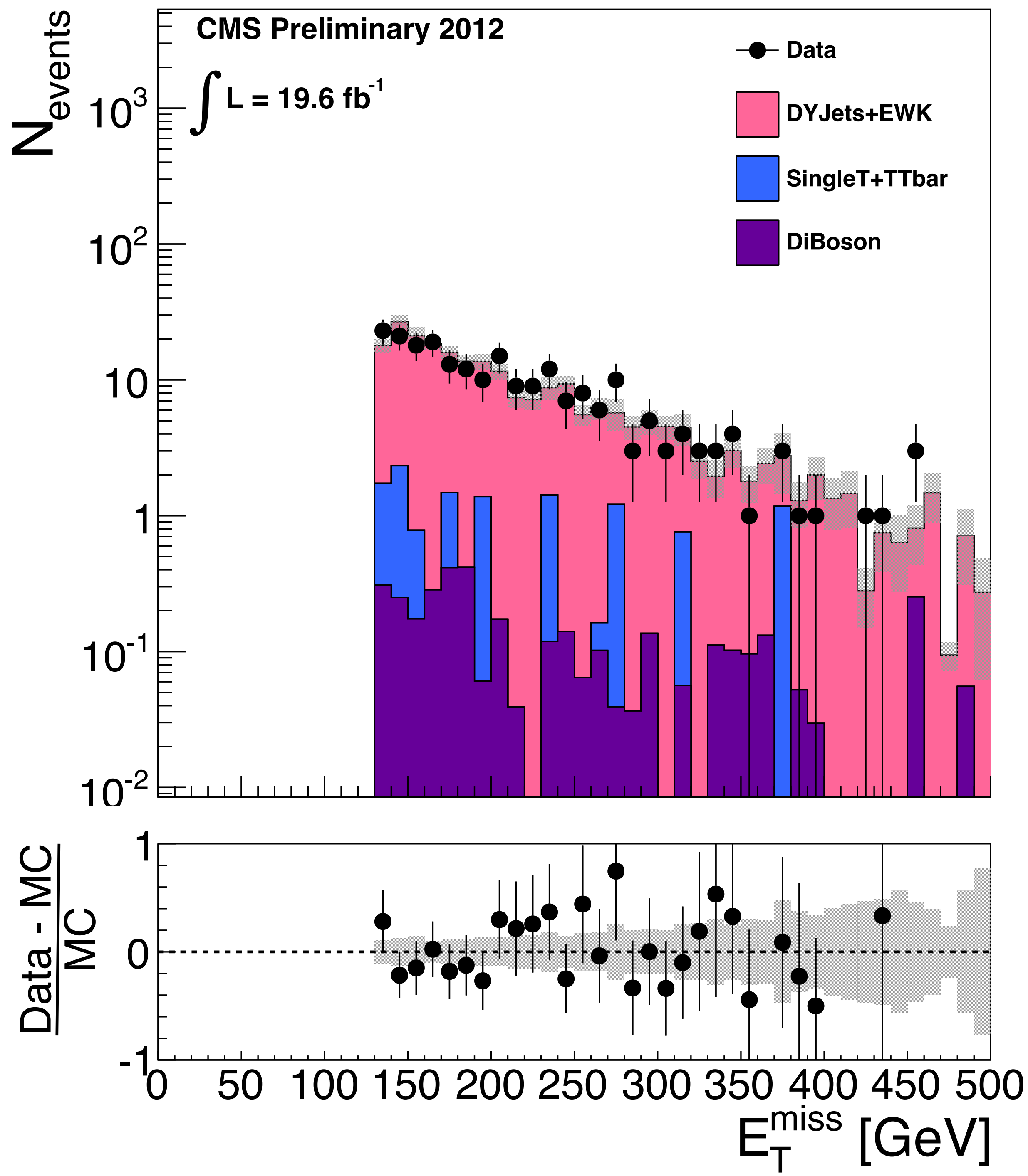
Scaled V+Jets MC

Z control plots - $M_{\mu\mu}$, p_T^Z



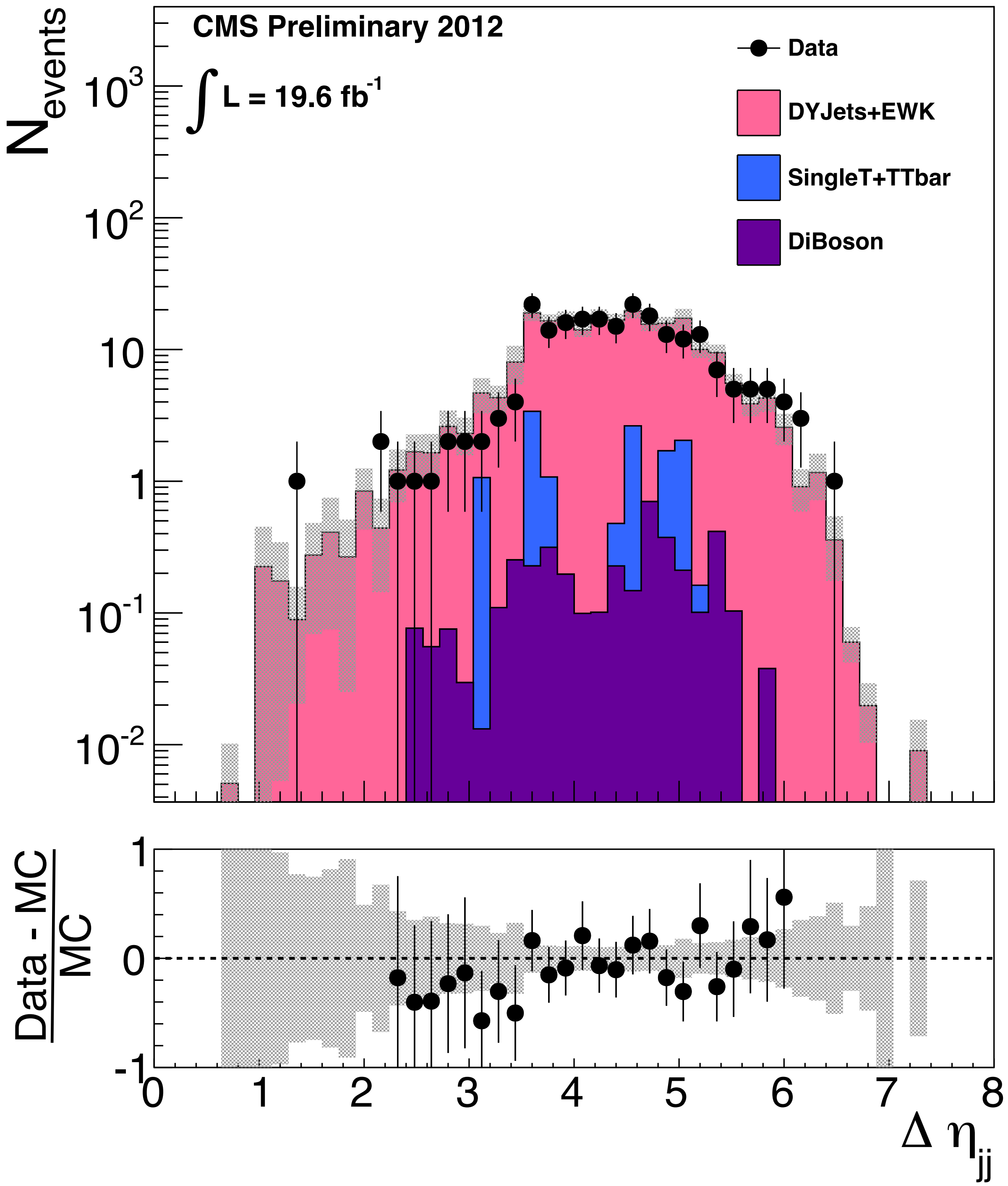
Z control plots - M_{jj}, MET

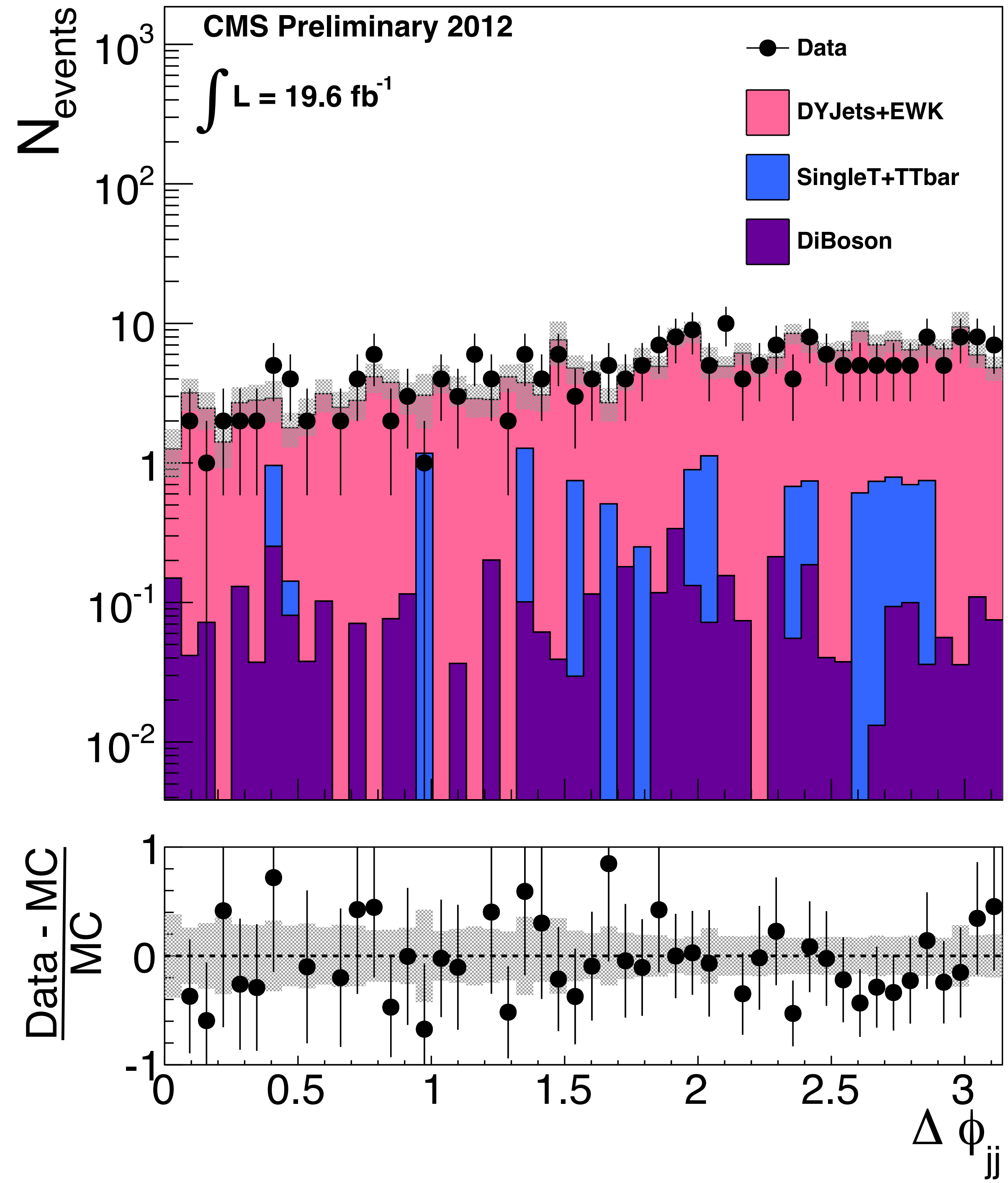




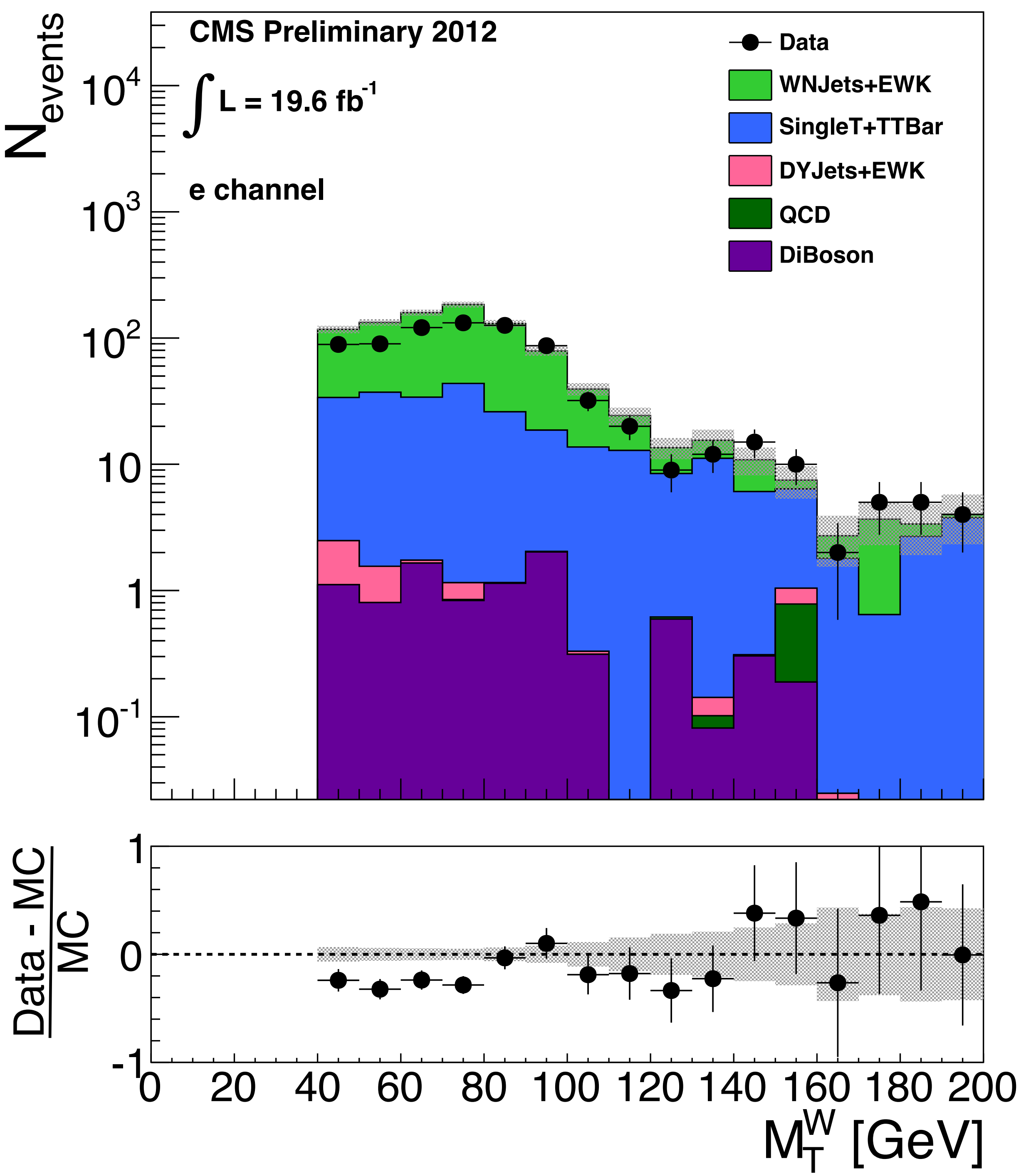
Scaled V+Jets MC

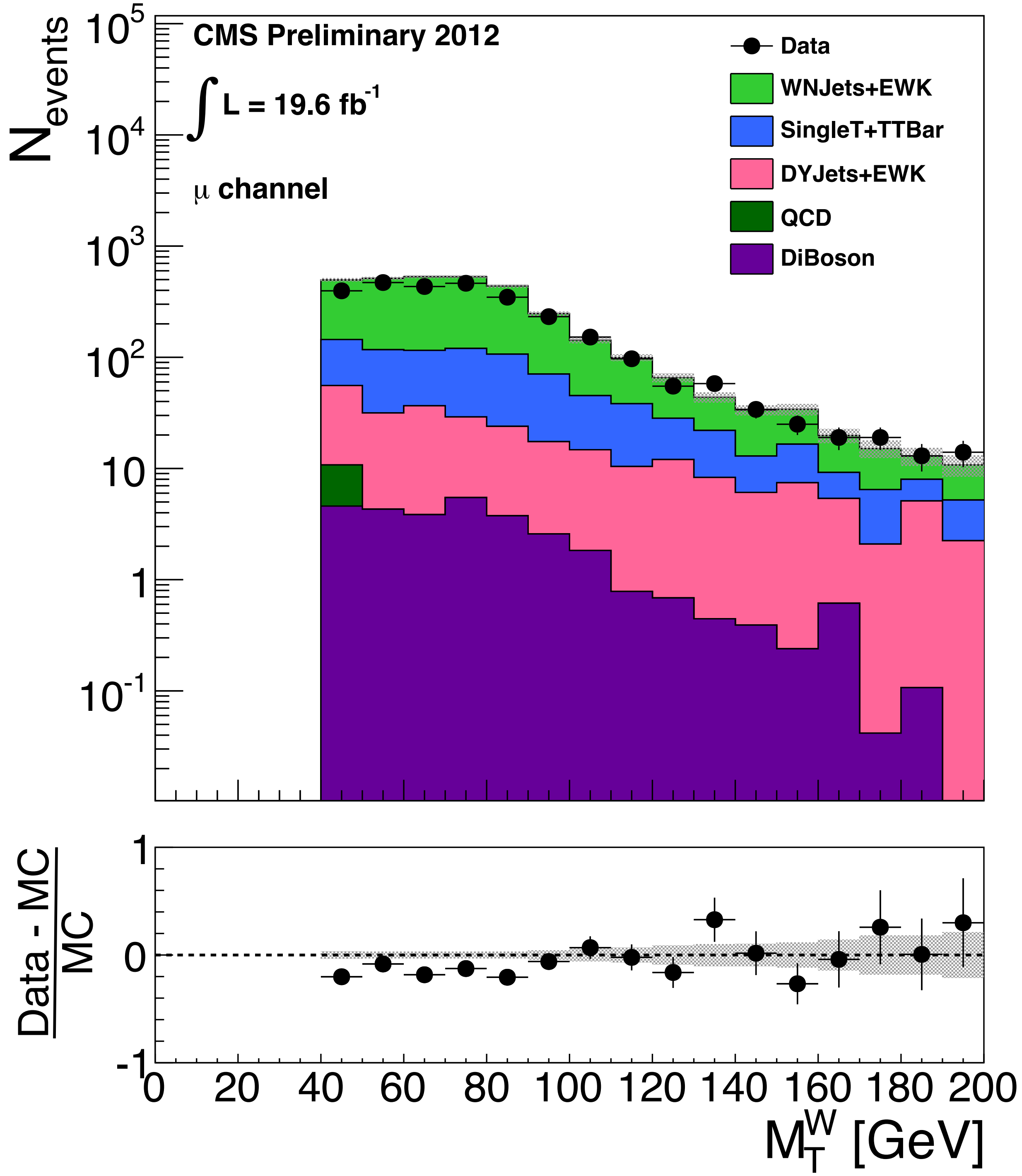
Z control plots - Δη, Δϕ



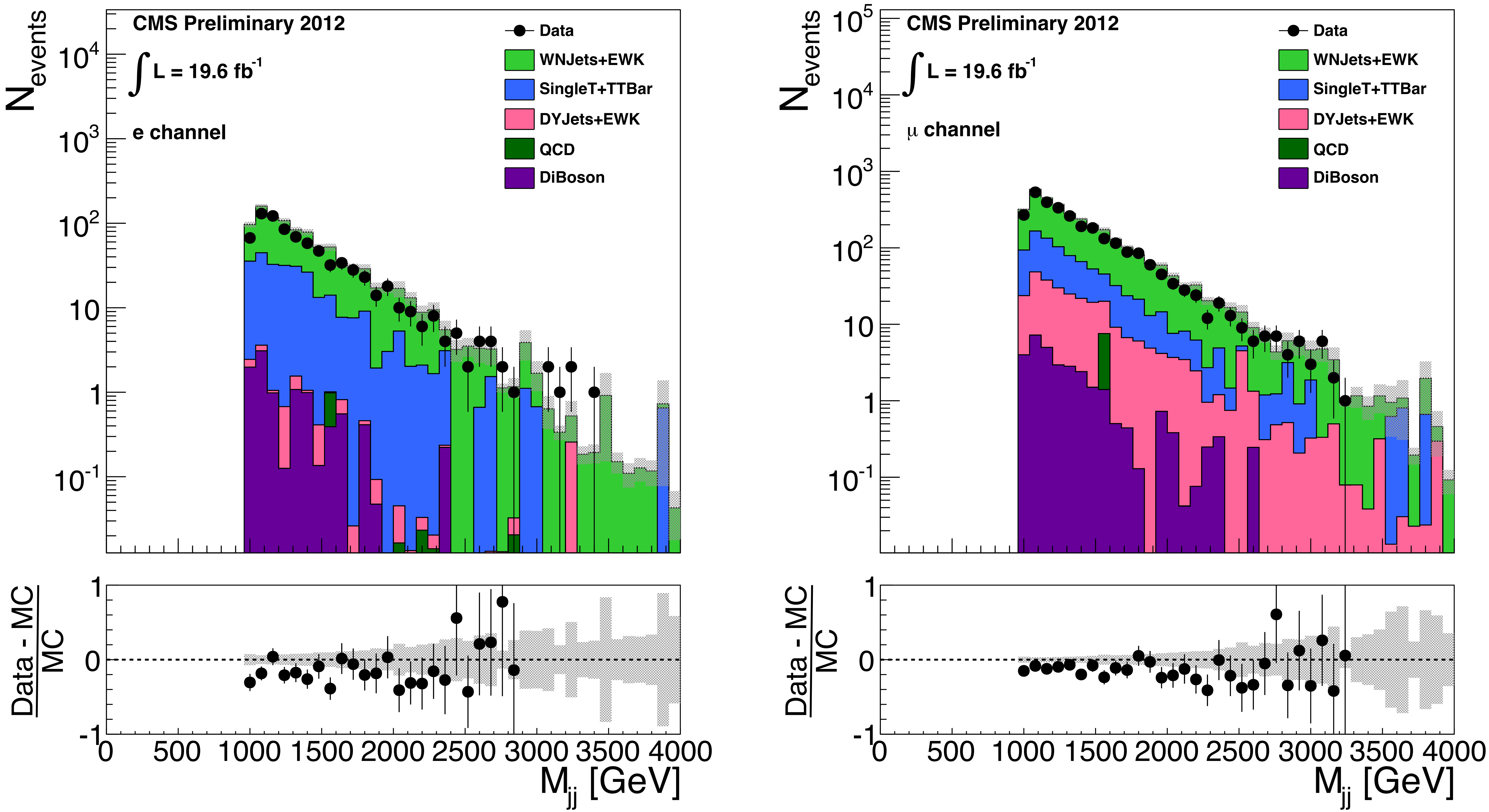


W control plots - M_T



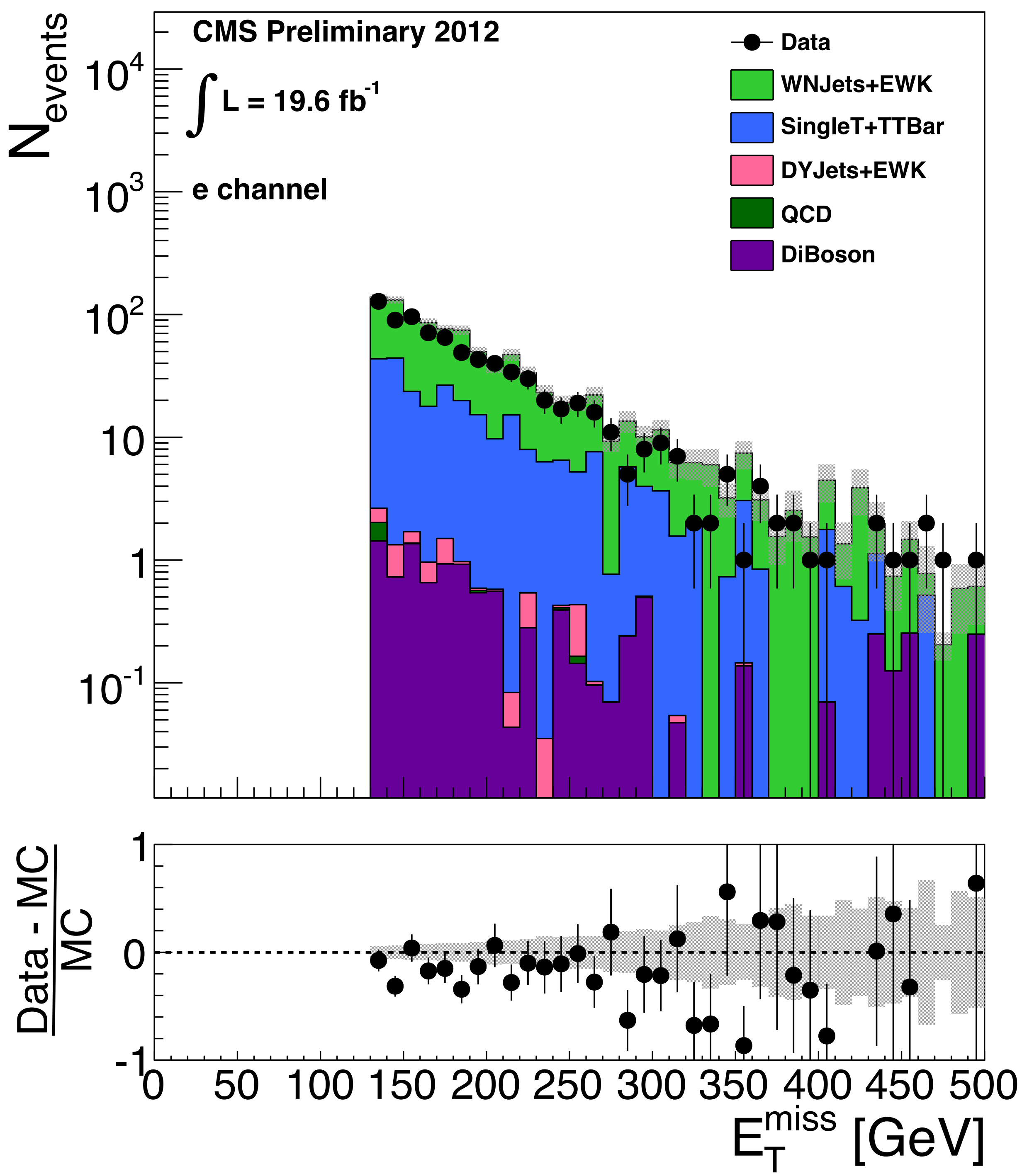


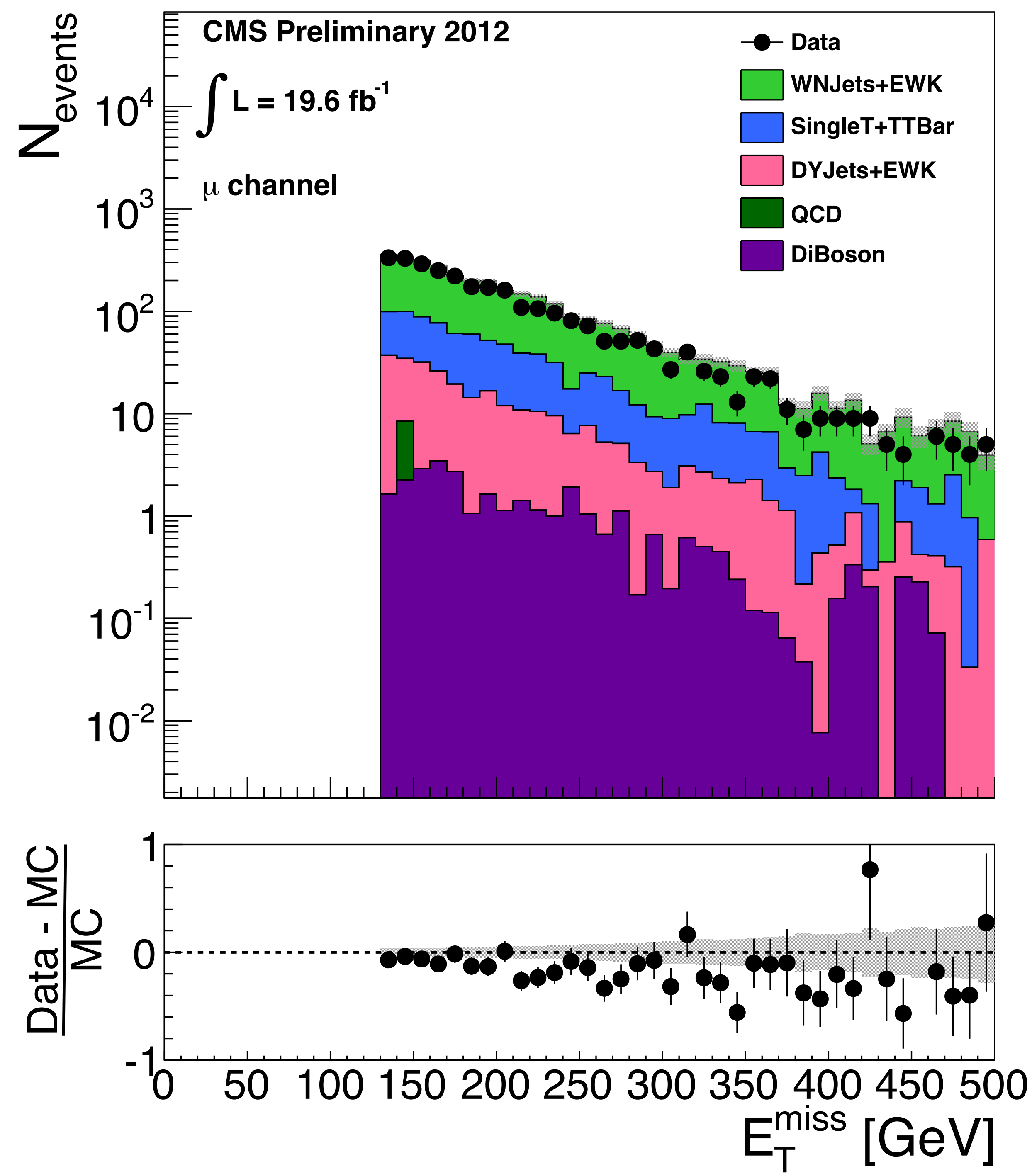
W control plots - M_{jj}



Scaled V+Jets MC

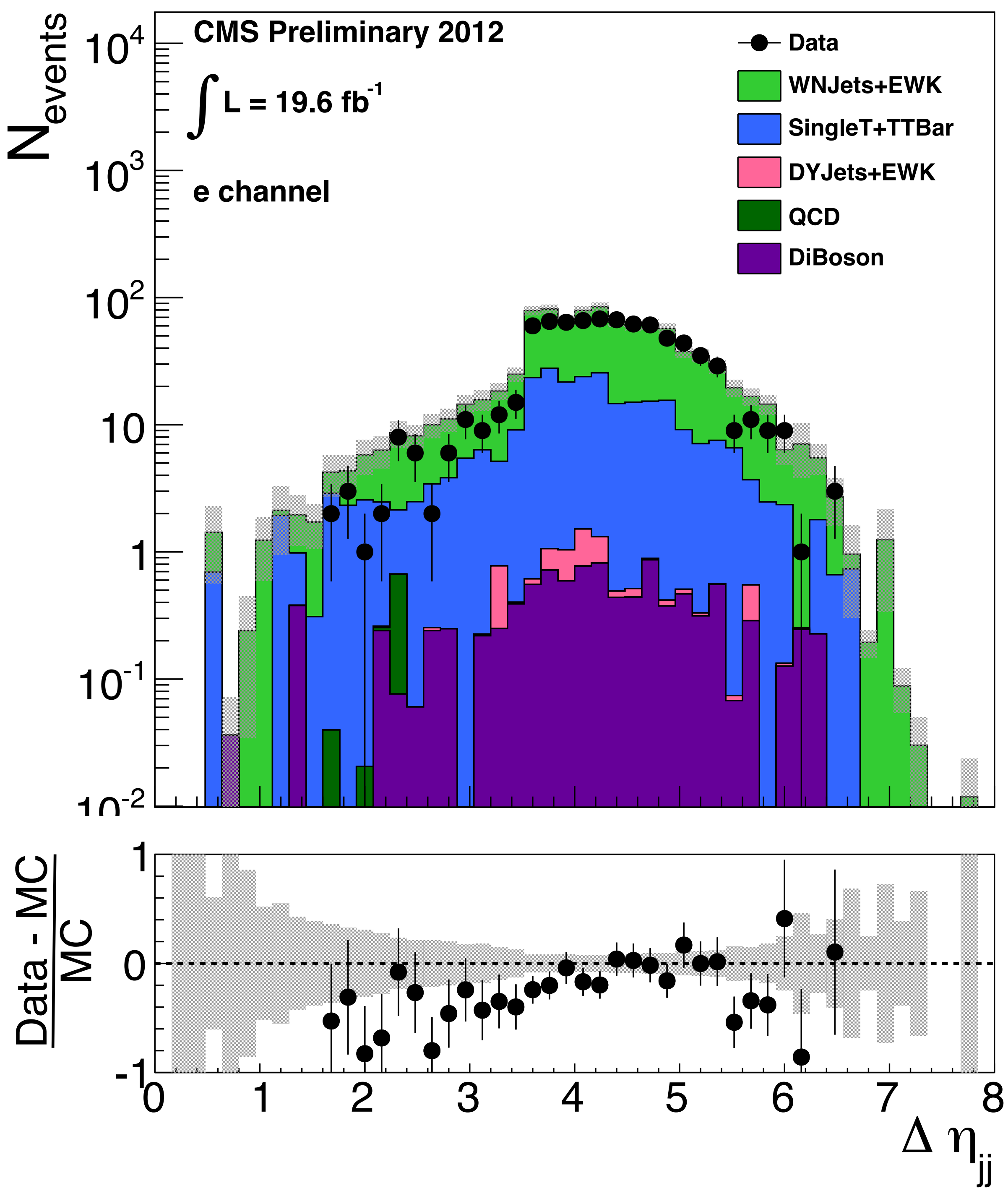
W control plots - MET

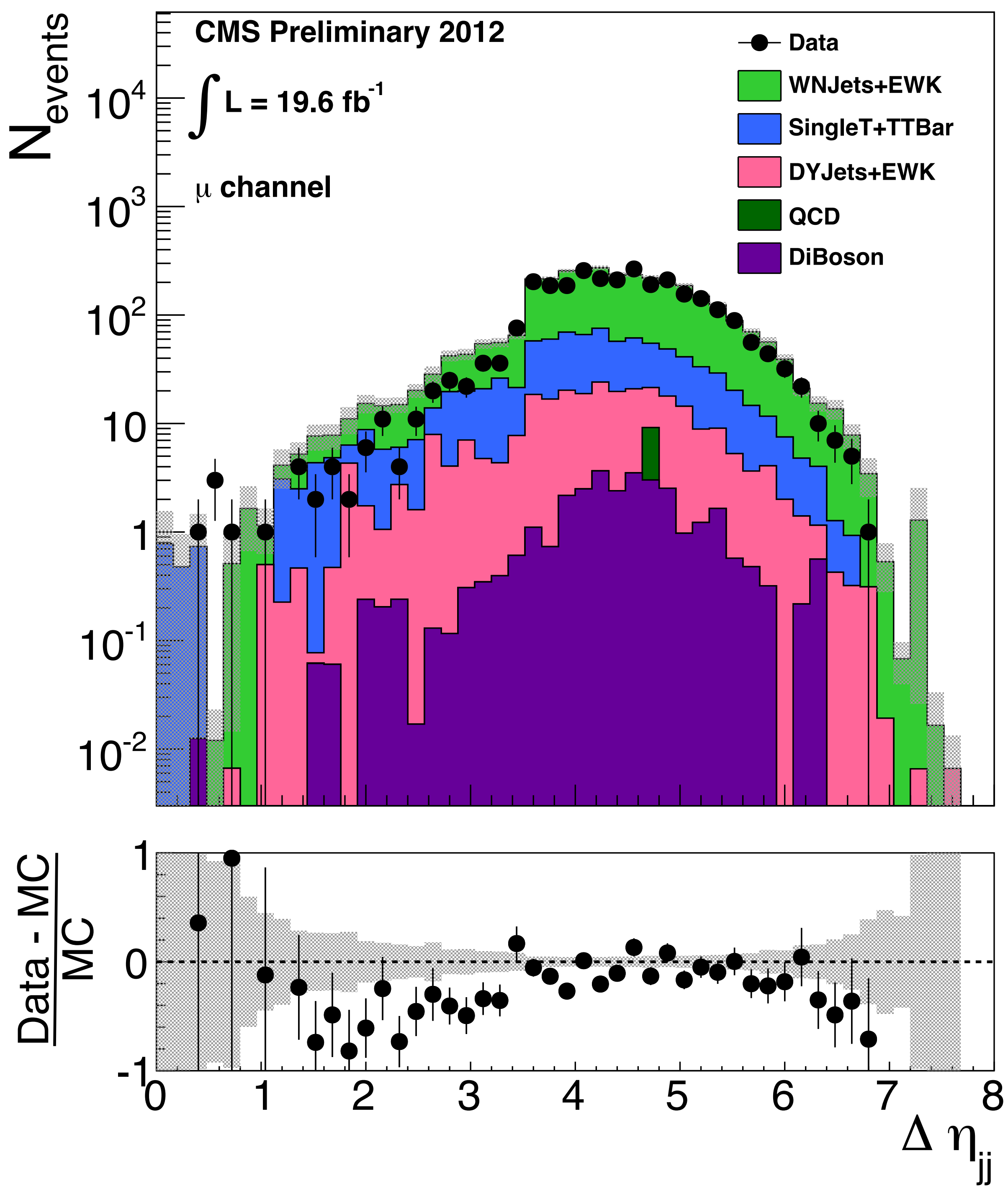




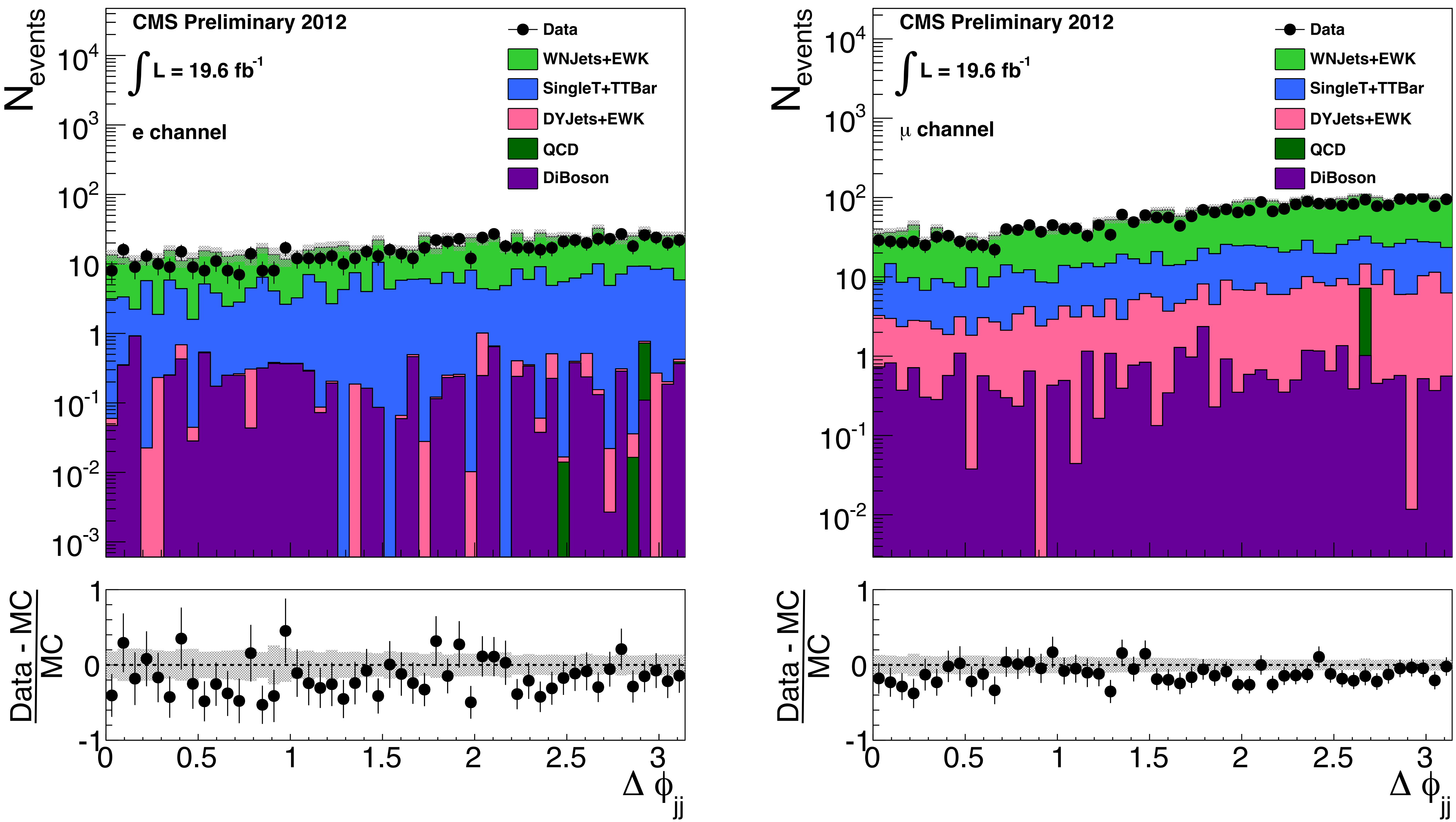
Scaled V+Jets MC

W control plots - Δη



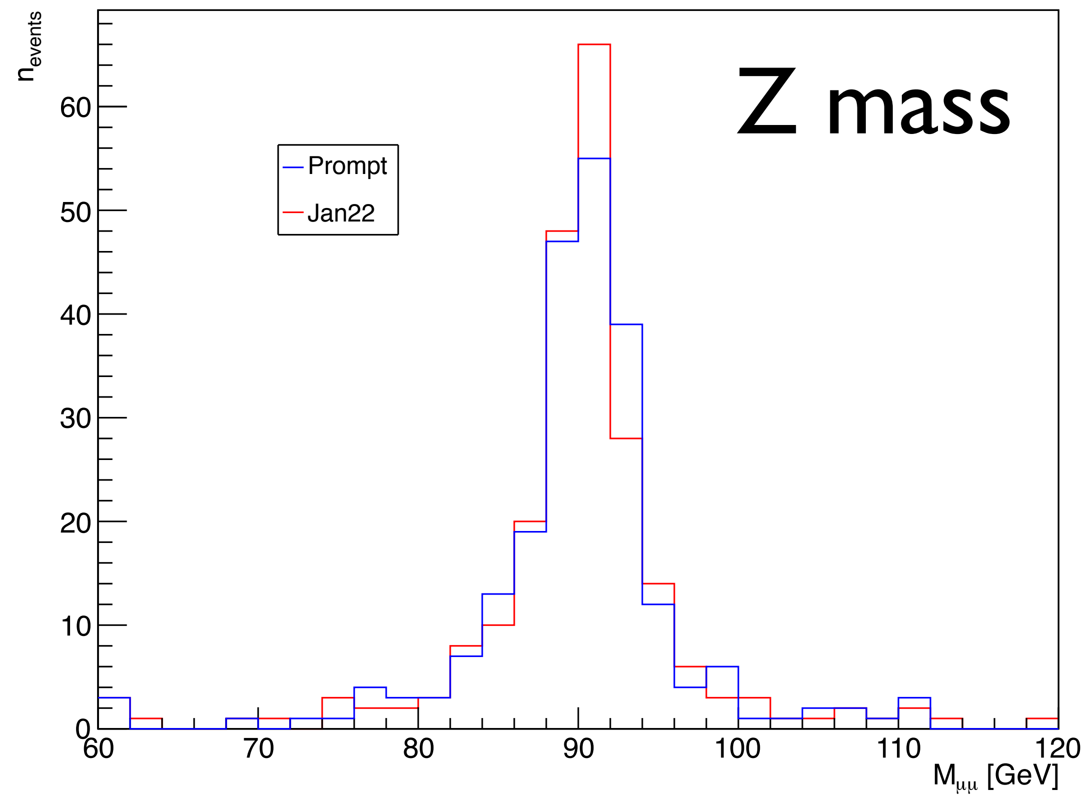


W control plots - Δϕ

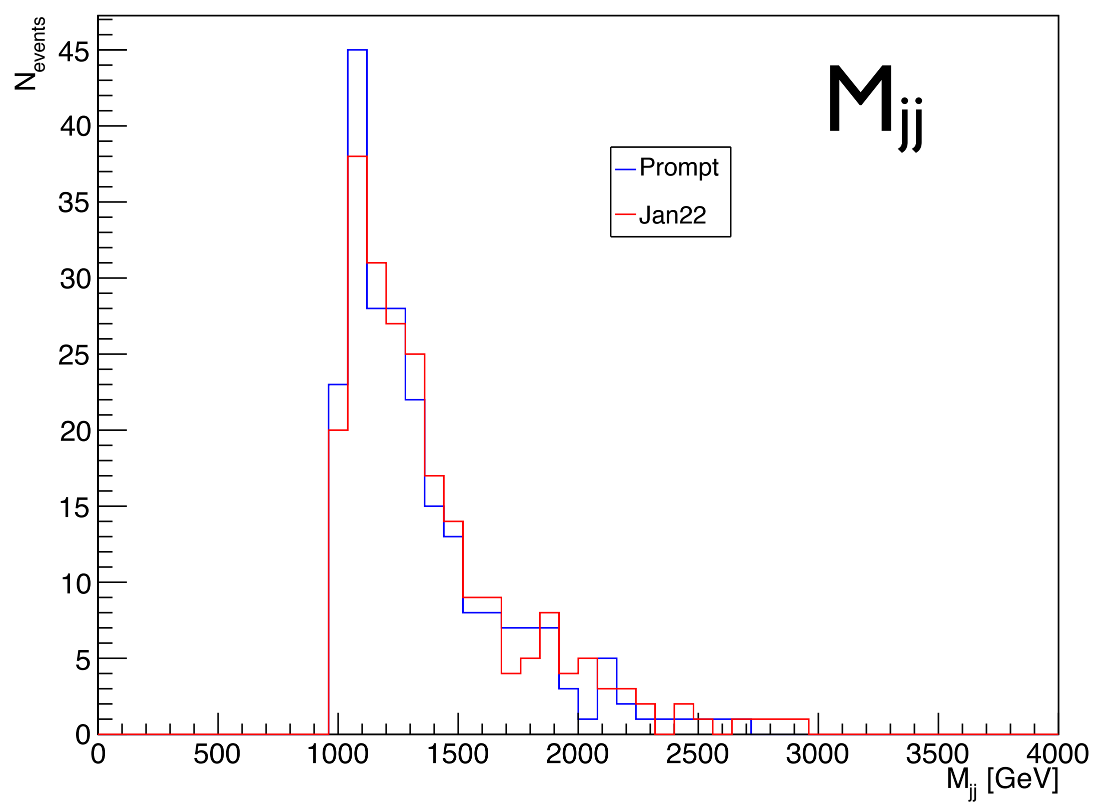


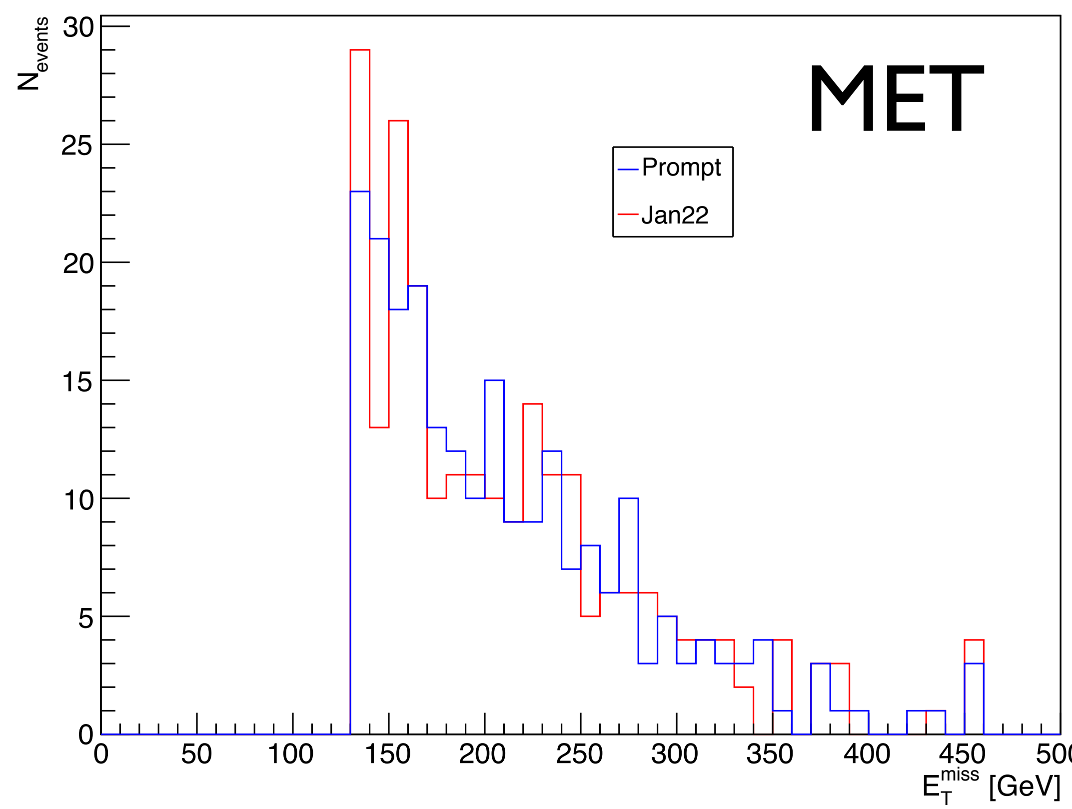
Prompt vs Jan22 Re-Reco

Prompt vs Jan22 Re-reco



Comparison of variables in Z control region between prompt and re-reco





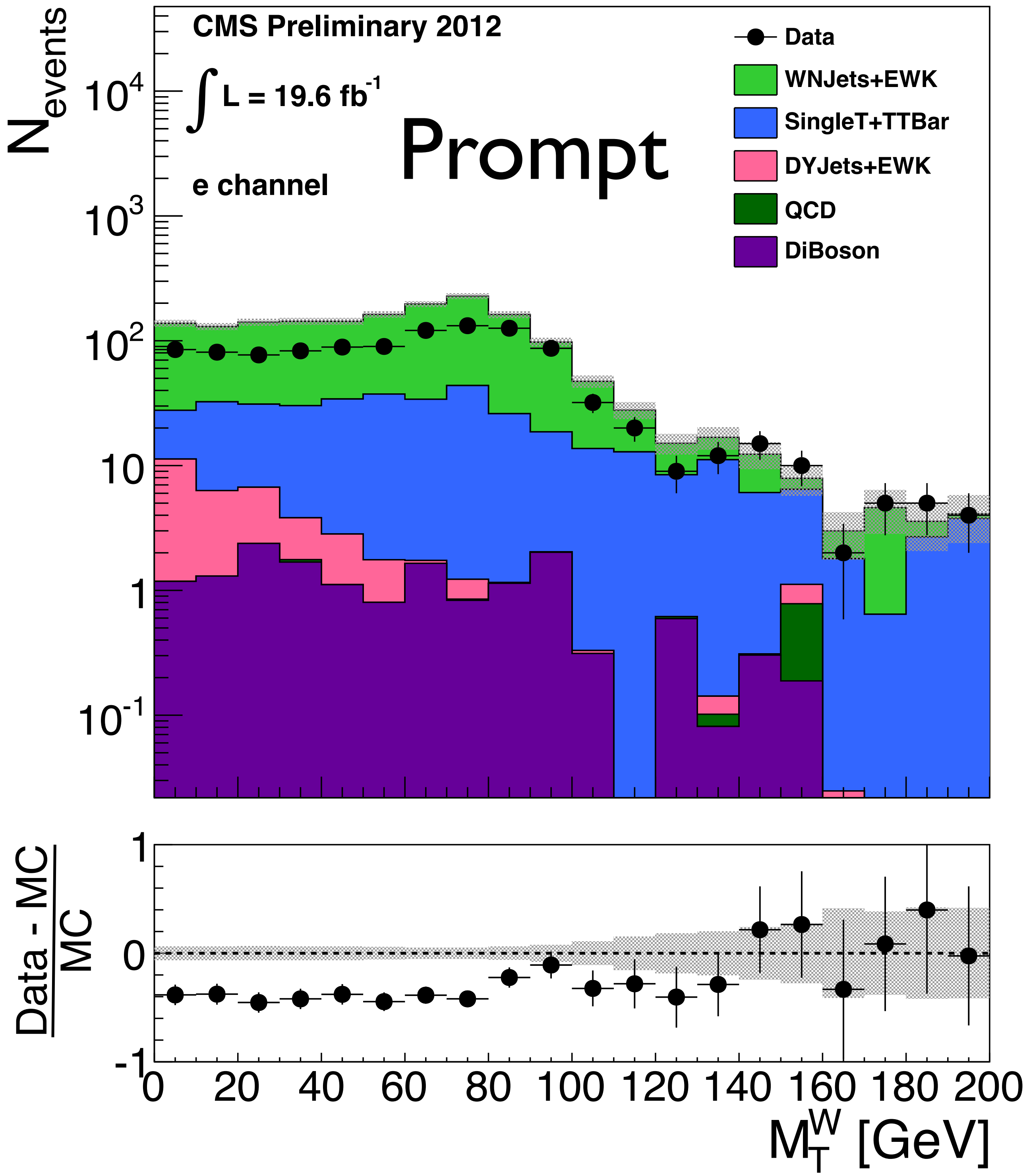
Prompt vs Jan22 Re-reco

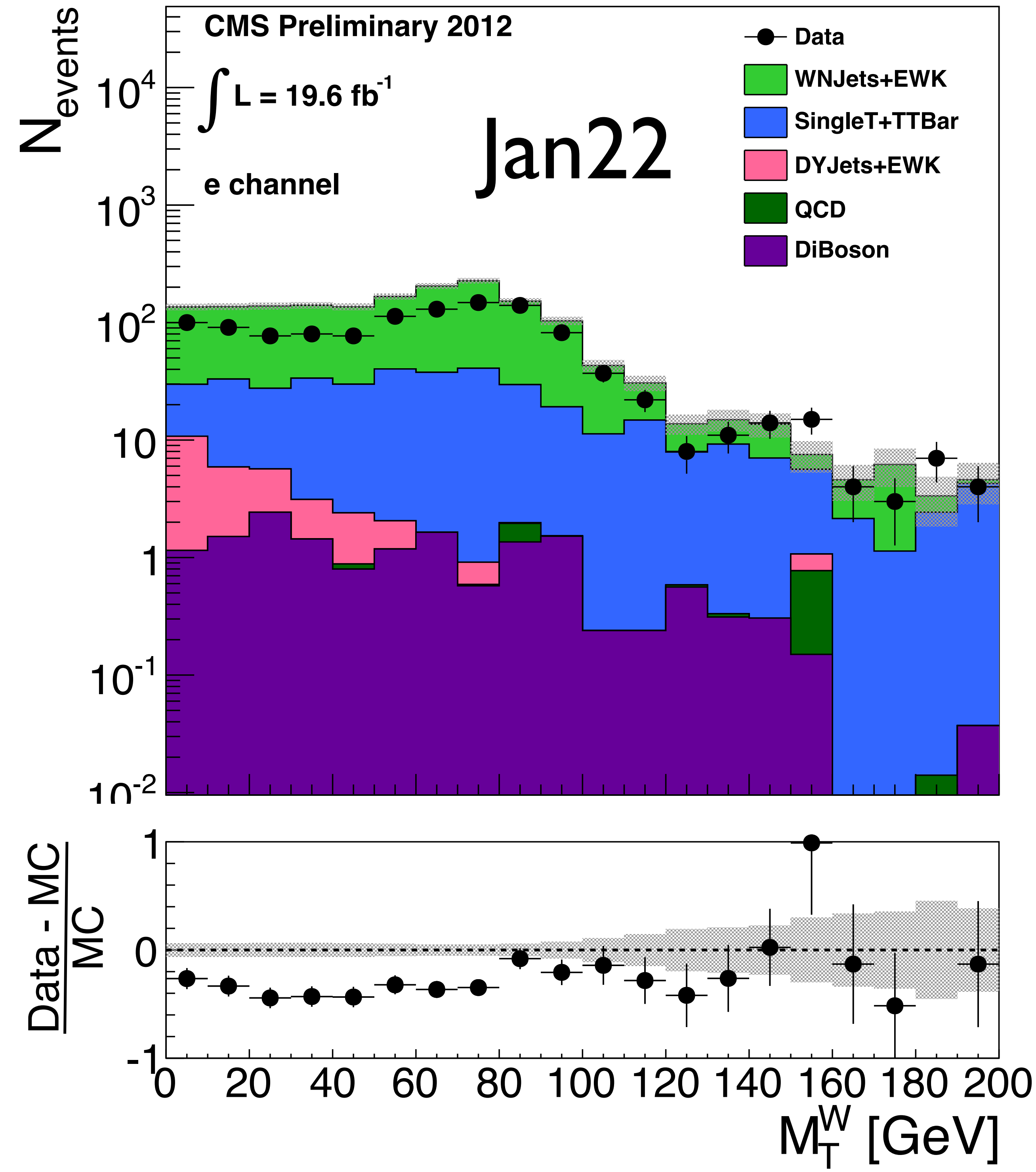
	Prompt	Jan22
Z	102 ± 30 ± 26	111 ± 31 ± 30
W→e	67.2 ± 5.0 ± 15.1	71.9 ± 9.4 ± 19.2
W→μ	68.2 ± 9.2 ± 18.1	78.4 ± 5.5 ± 17.7
W→τ	54 ± 16 ± 18	n/a
QCD	36.8 ± 5.6 ± 30.6	49.2 ± 5.3 ± 40.9
VV	3.9 ± 1.4	3.8 ± 1.4
single t	3.1 ± 1.7	2.7 ± 1.6
DY	2.1 ± 1.8	1.7 ± 1.6
tt	1.4 ± 1.2	1.4 ± 1.3
Total	349 ± 36 ± 50	374 ± 39 ± 63

Using prompt estimate for W→τ

Prompt vs Jan22 Re-reco

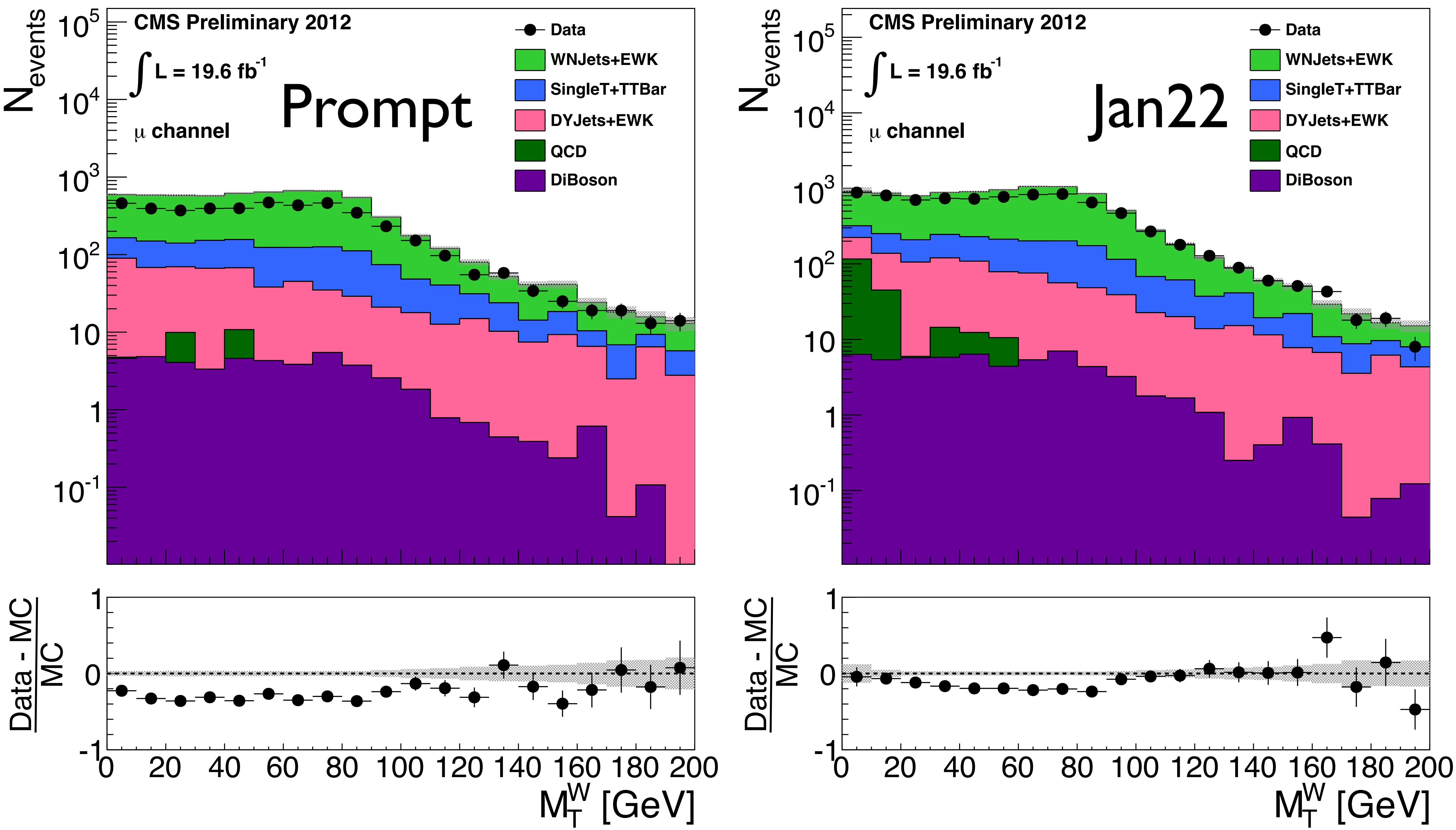
W→e control plots - M_T





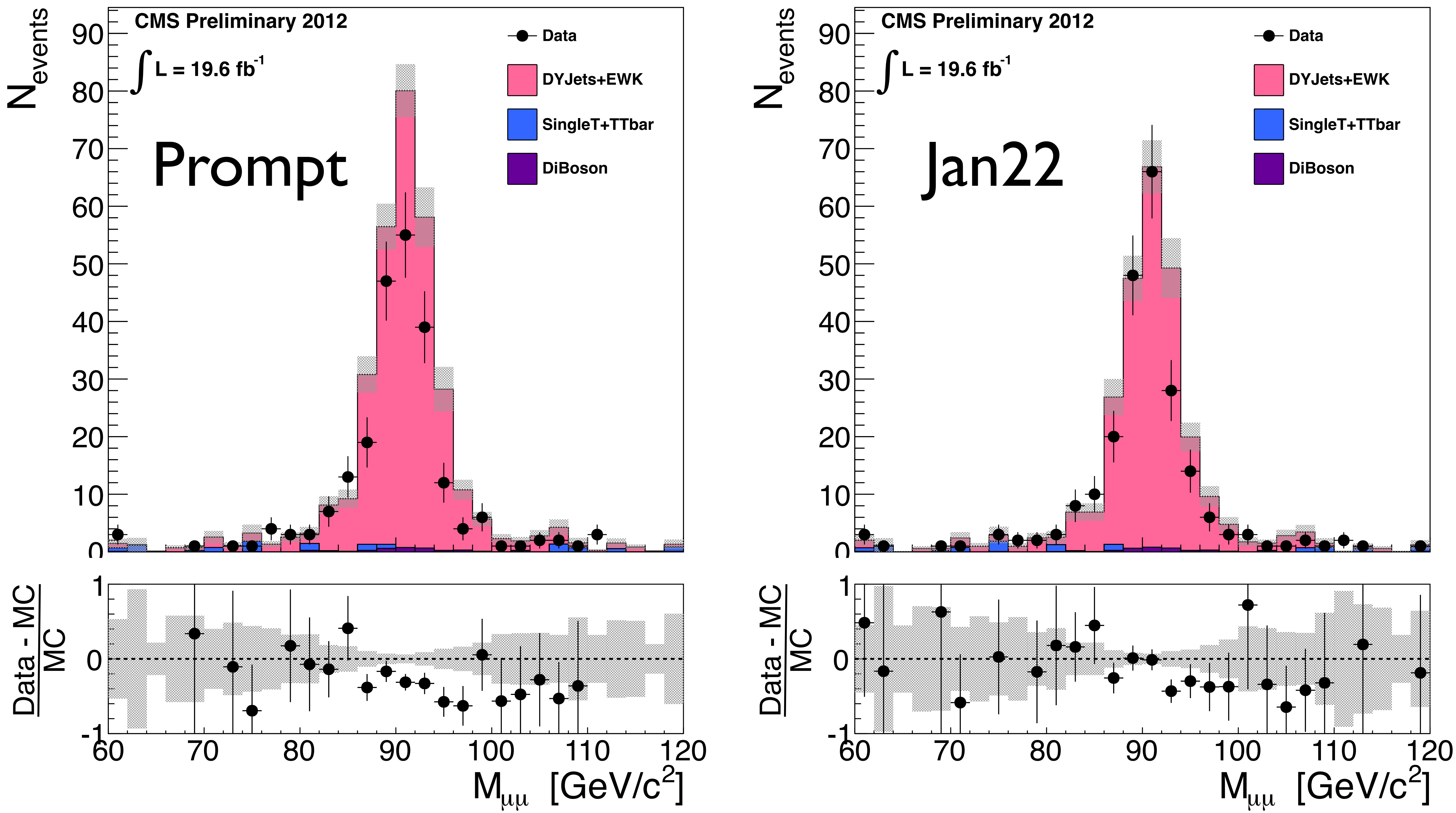
Prompt vs Jan22 Re-reco

W→μ control plots - M_T



Prompt vs Jan22 Re-reco

Z control plots - central jet E_T



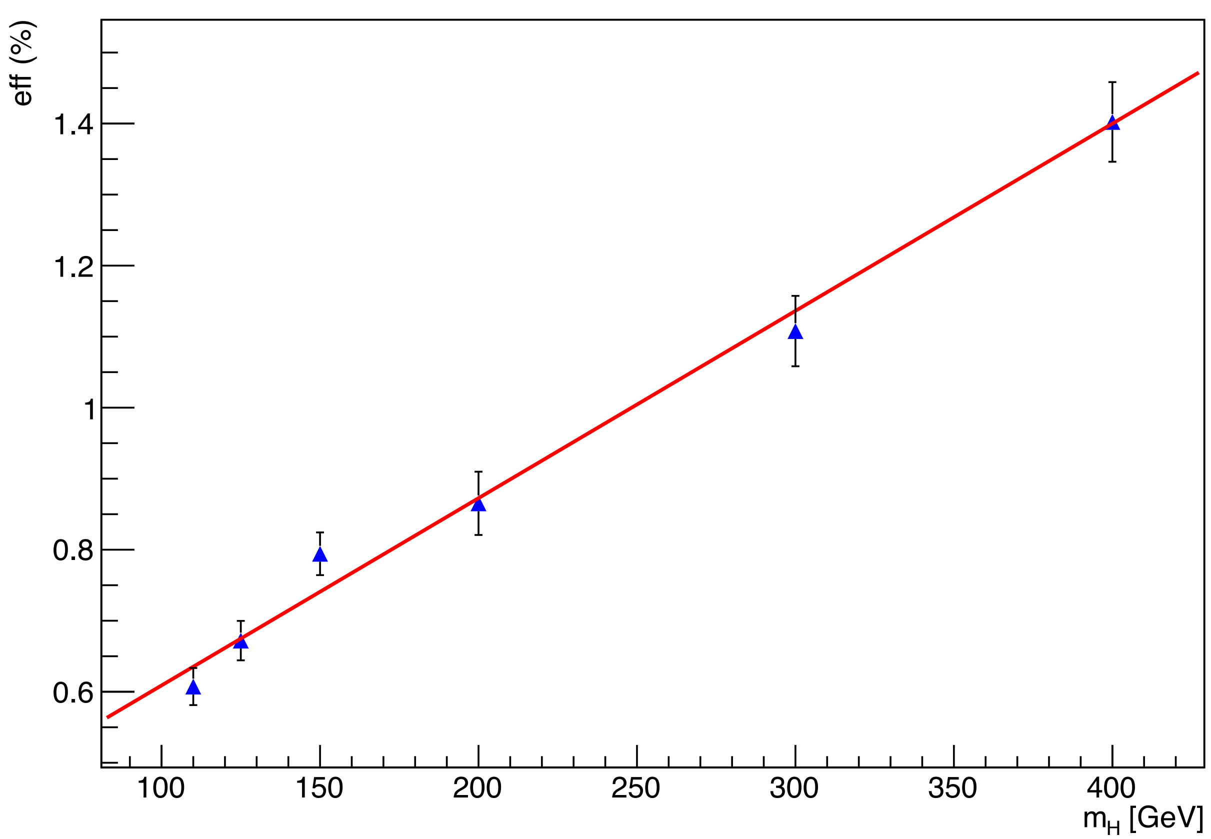
N-1 Plots

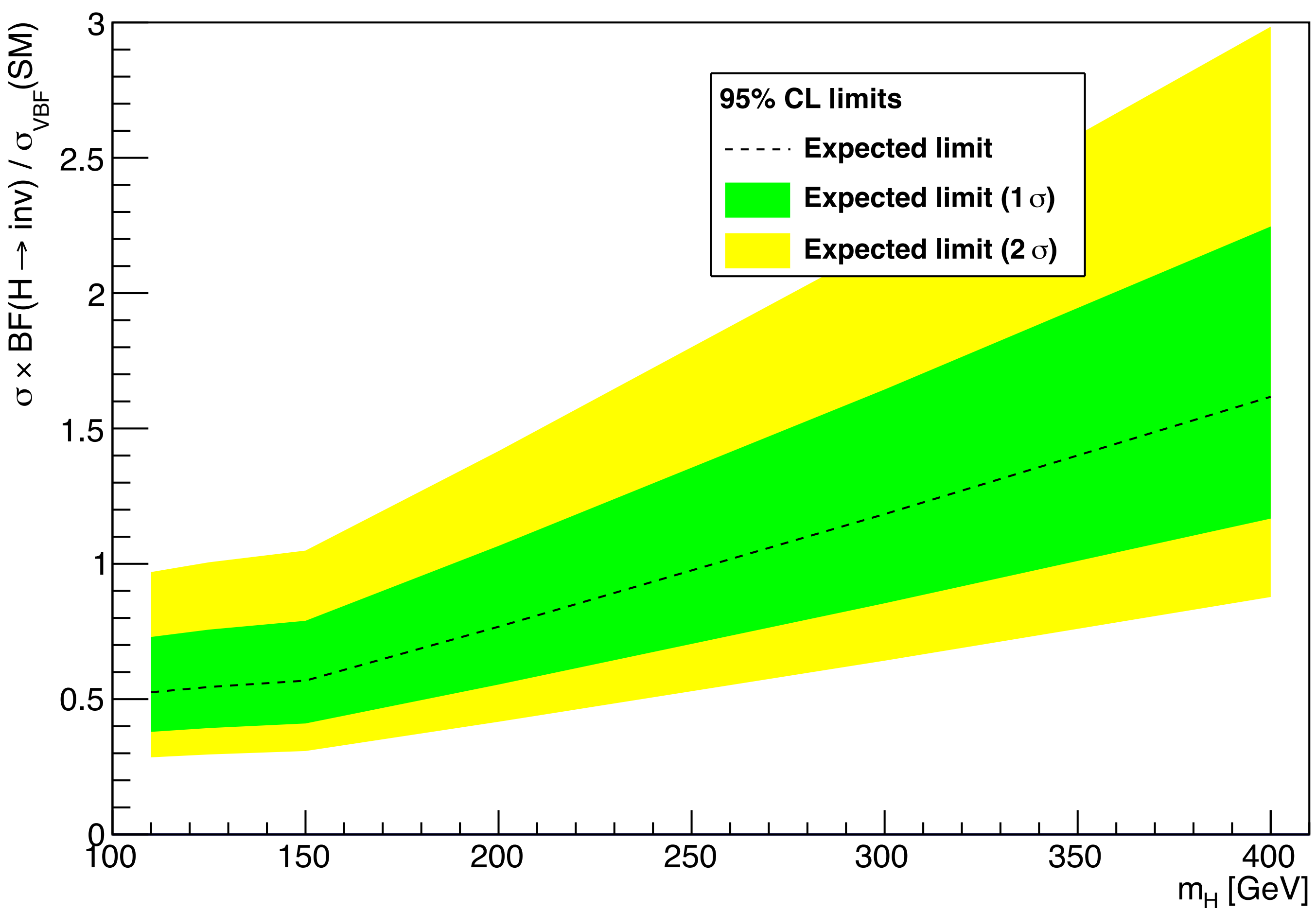
With V+Jets Scaling

ARC Slides

Limit Uncertainty Bands

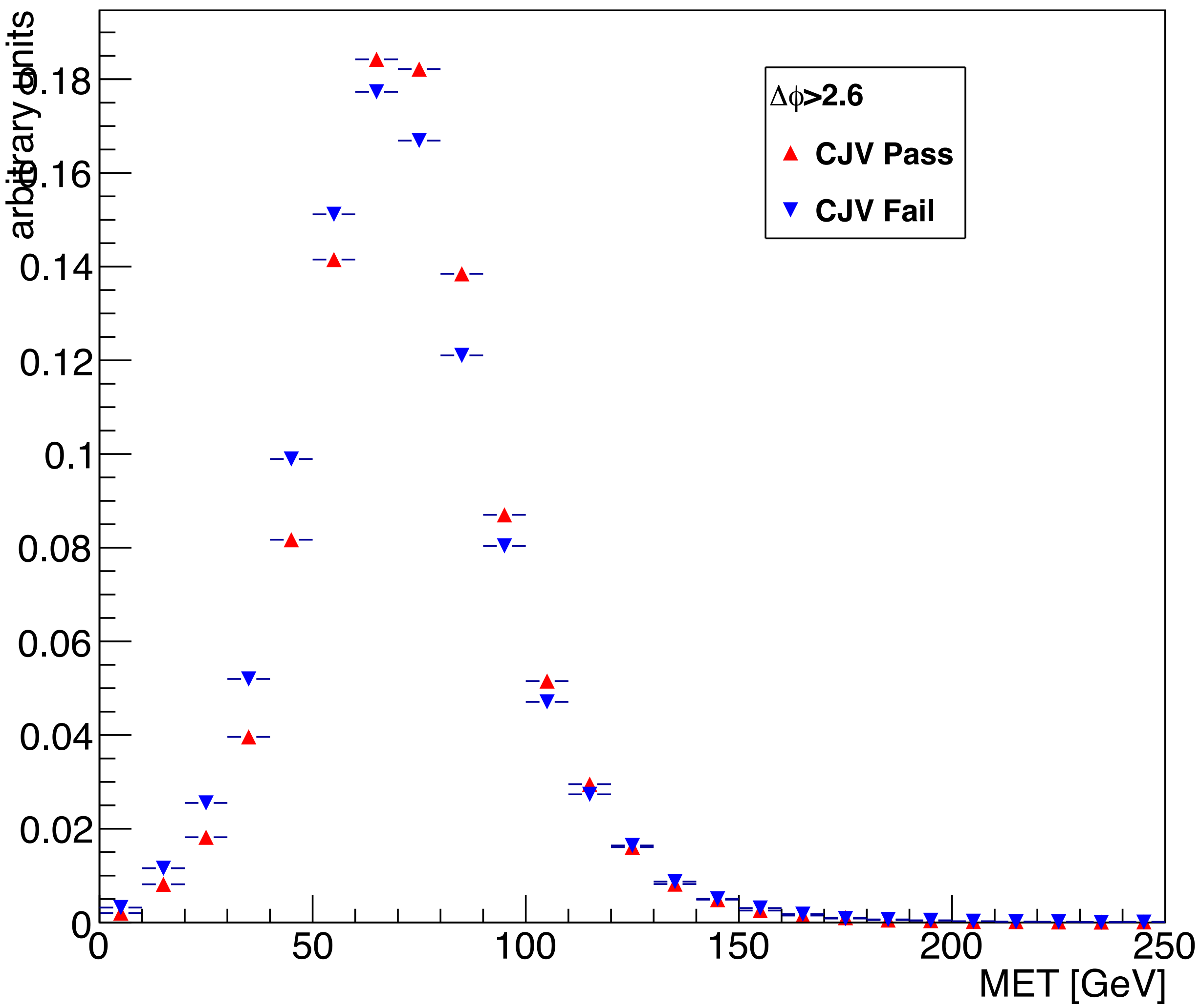
- Large error bands due to bug in plot making code...
  - Fixed plot below (includes 35% uncertainty on QCD
- Kink in limit plot appears to be due to statistical fluctuation in signal efficiency (below)
  - Use linear fit to signal efficiency to smooth this - in progress
  - May need to interpolate between MC points

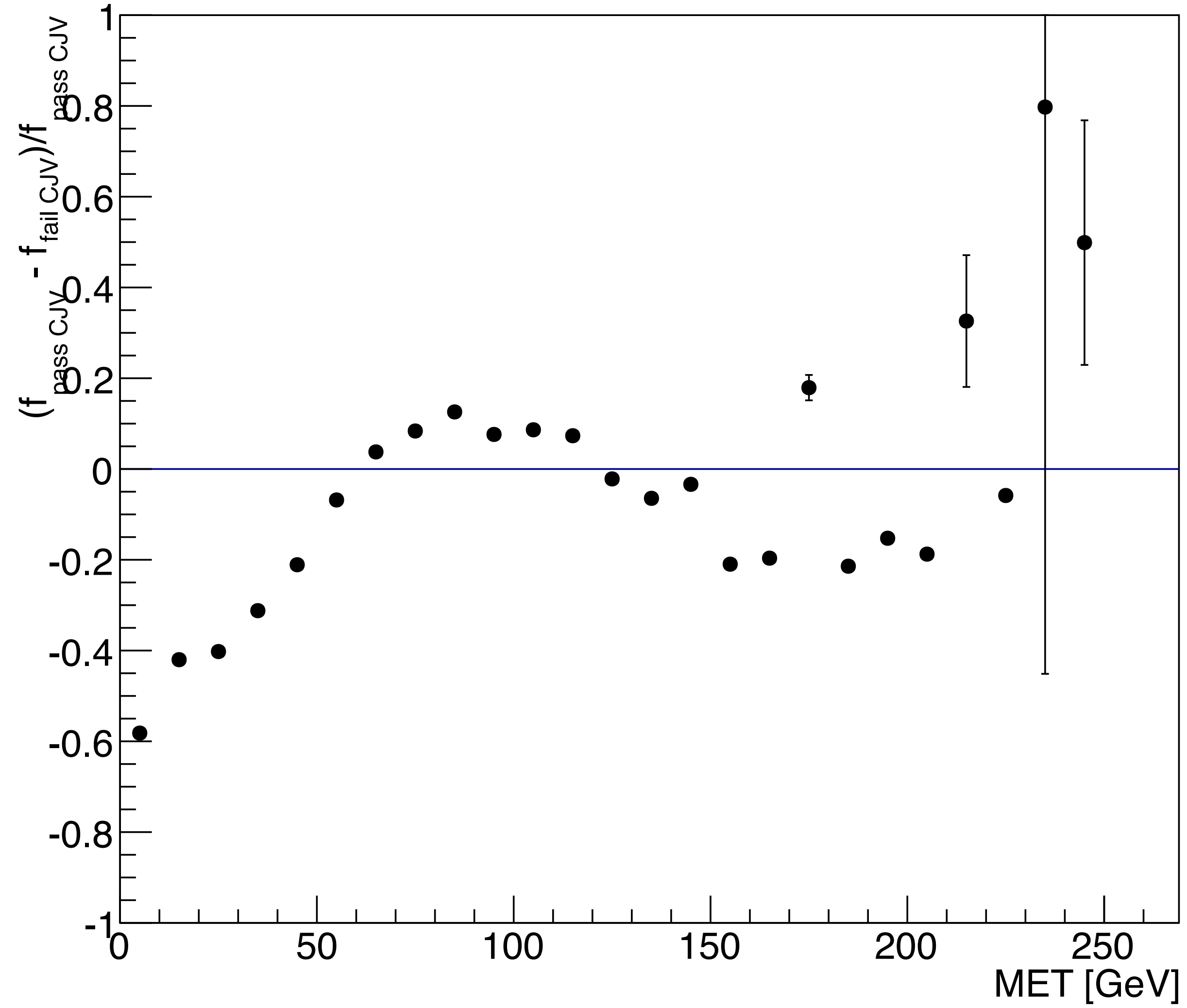




QCD Background - Closure Test

- MET distribution for CJV pass/fail in closure test region, **Δϕ**>2.6





QCD "MET/DPhi" Closure Test

- Cross-check of QCD background
- ABCD method based on MET and dphi
  - A : MET<120, $\Delta\phi$>2.6
  - B : MET>120, $\Delta\phi$>2.6
  - C : MET<130, $\Delta\phi$<1.0
  - D : MET>130, $\Delta\phi$<1.0 - *signal region*

Different MET cuts account for observed shift in MET distribution between $\Delta\phi$>2.6 and $\Delta\phi$<1.0

- Construct a closure test using the "CJV fail" region
  - Prediction : **201 ± 4 (stat)**
  - Observation : **253 ± 32 (stat)**

	MET<120 (130)	MET>120 (130)
$\Delta\phi$>2.6	147588 ± 387	6052 ± 83
$\Delta\phi$<1.0	4904 ± 74	253 ± 32

- Propose we assign **25% systematic** to this method
  - Signal region : **31.0 ± 7.8 (stat) ± 7.8 (syst)**
  - cf Method 3 : **36.8 ± 5.6 (stat) ± 12.9 (syst)**

W→tau synchronisation

- We have two analysis codes (A and B) to cross-check the calculations
  - Generally very good agreement (<1%) between A and B
  - Except for W→tau, where **A = 54.4** and **B = 64.6**, discrepancy of ~20%

- See very good agreement between A & B in W→tau control region yields

- Differences arises from MC ratio between W→tau control region and signal region, calculated from W+jets MC
  - Comparing a few events, we saw that the differences arise in MET and low pT jets

- Known differences between A and B
  - Different versions of PU jet ID MVA training between A and B
  - Different handling of unmatched jets in JER smearing

- Smear MC jets such that JER matches data (and propagate this to MET)
  - Match each RECO jet to generator jet, and smear the RECO deterministically
  - For unmatched jets
    - **Analysis A applies a Gaussian smearing** (using runMetUncertainties tool in PAT)
    - **Analysis B does not apply any smearing**

W→tau synchronisation

- Ran both analyses with JER smearing and PU jet ID turned off
  - Example for one control region below - tau ID required, CJV not required

W MC		PU on JER on	PU on JER off	PU off JER off
QCD	A	24.7	18.9	19.1
	B	20.1	19.2	19.2
EWK	A	9.6	9.1	9.1
	B	9.3	9.2	9.2
QCD+EWK	A	34.3	28.0	28.2
	B	29.4	28.4	28.4

Discrepancy between A and B

Good agreement when JER off shows this is source of discrepancy

W→tau synchronisation

- One condition of GL to unblind was to fix which analysis to use for W→tau

- We chose analysis A for consistency with the other backgrounds
  - **No reason to change this**

- Added a systematic to cover the difference between A and B (18%)
  - Propose to remove this

Unblinding

- Predict **339 ± 36 (stat) ± 56 (syst)** background
- Observe **390** events in data
  - Less than 1 sigma above prediction
- Observed limit on **σ × BF(H→inv) = 70%** for m_H=125 GeV
  - Expected limit is 53%
- While unblinding we found and fixed two minor bugs in limit setting card files
  - Non-dominant systematics in Z and W→tau were not being included
  - Expected limit has risen slightly as a result
- Above numbers include the **additional 18% systematic** for W-tau discrepancy
  - **Reducing this to 12% results in observed limit of 69%**
  - No change in expected (52.7% to 52.5%)

Monte-Carlo Samples

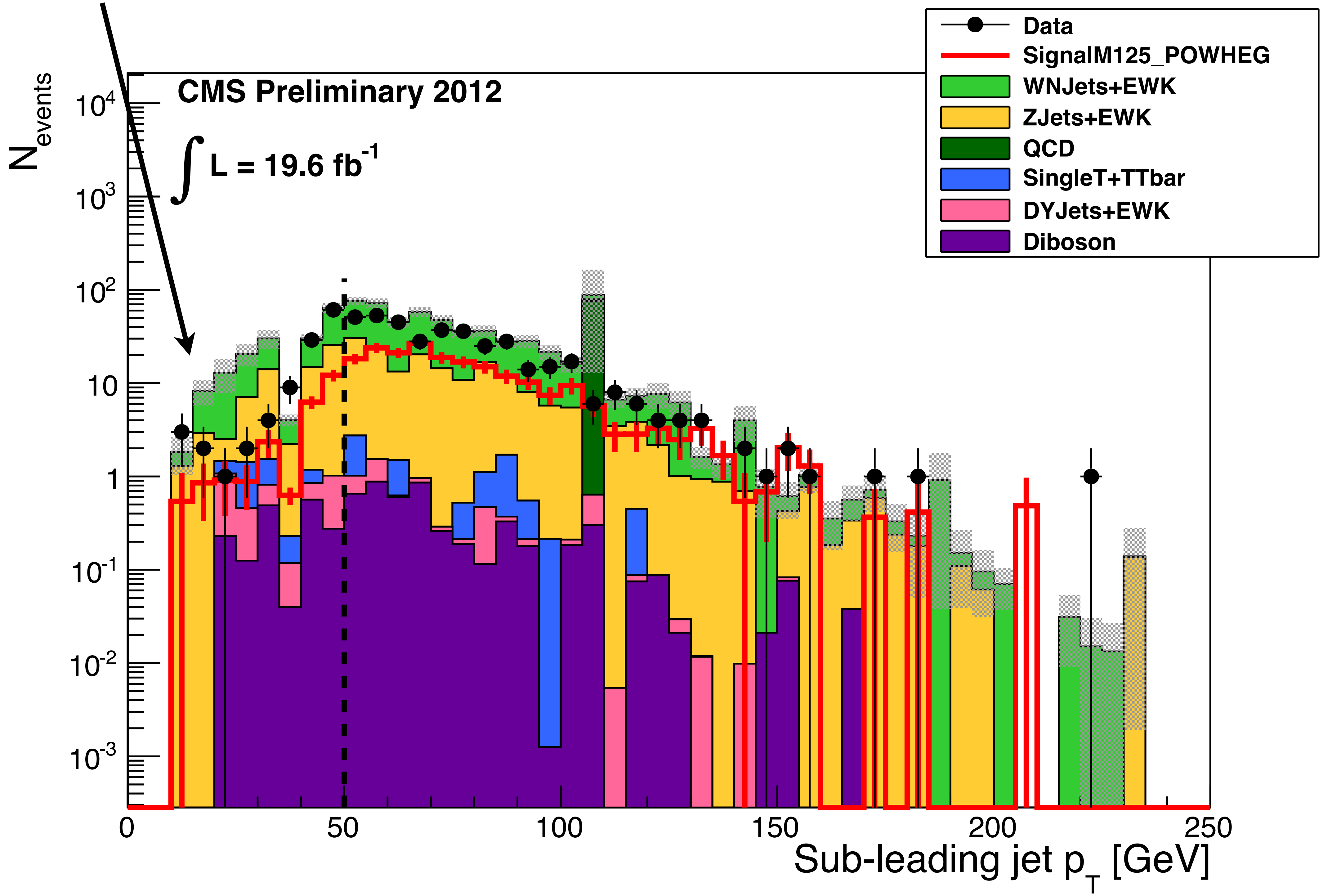
- Summer12 53X Monte Carlo

- Summer12_DR53X-PU_S10_START53_V7A
  - /ZJetsToNuNu_*_HT_*_TuneZ2Star_8TeV_madgraph/
  - /ZVBF_Mqq-120_8TeV-madgraph
  - /W*JetsToLNu_TuneZ2Star_8TeV-madgraph/
  - /L*Nu*VBF_Mqq-120_8TeV-madgraph/
  - /DYJetsToLL_M-50(PtZ-100)_TuneZ2Star_8TeV-madgraph-tarball/
  - /DYJJ01JetsToLL_M-50_MJJ-200_TuneZ2Star_8TeV-madgraph_tauola/
  - /VV_TuneZ2star_8TeV_pythia6_tauola/
  - /TTJets_MassiveBinDECAY_TuneZ2star_8TeV-madgraph-tauola/
  - /Tbar_*-channel-DR_TuneZ2star_8TeV-powheg-tauola/
  - /T_*-channel-DR_TuneZ2star_8TeV-powheg-tauola/
  - /QCD Pt-*to* TuneZ2star_8TeV_pythia6/
  - /VBF_HToInvisible_M-*_8TeV-powheg-pythia6
  - /GluGlu_HToInvisible_M-*_8TeV-powheg-pythia6

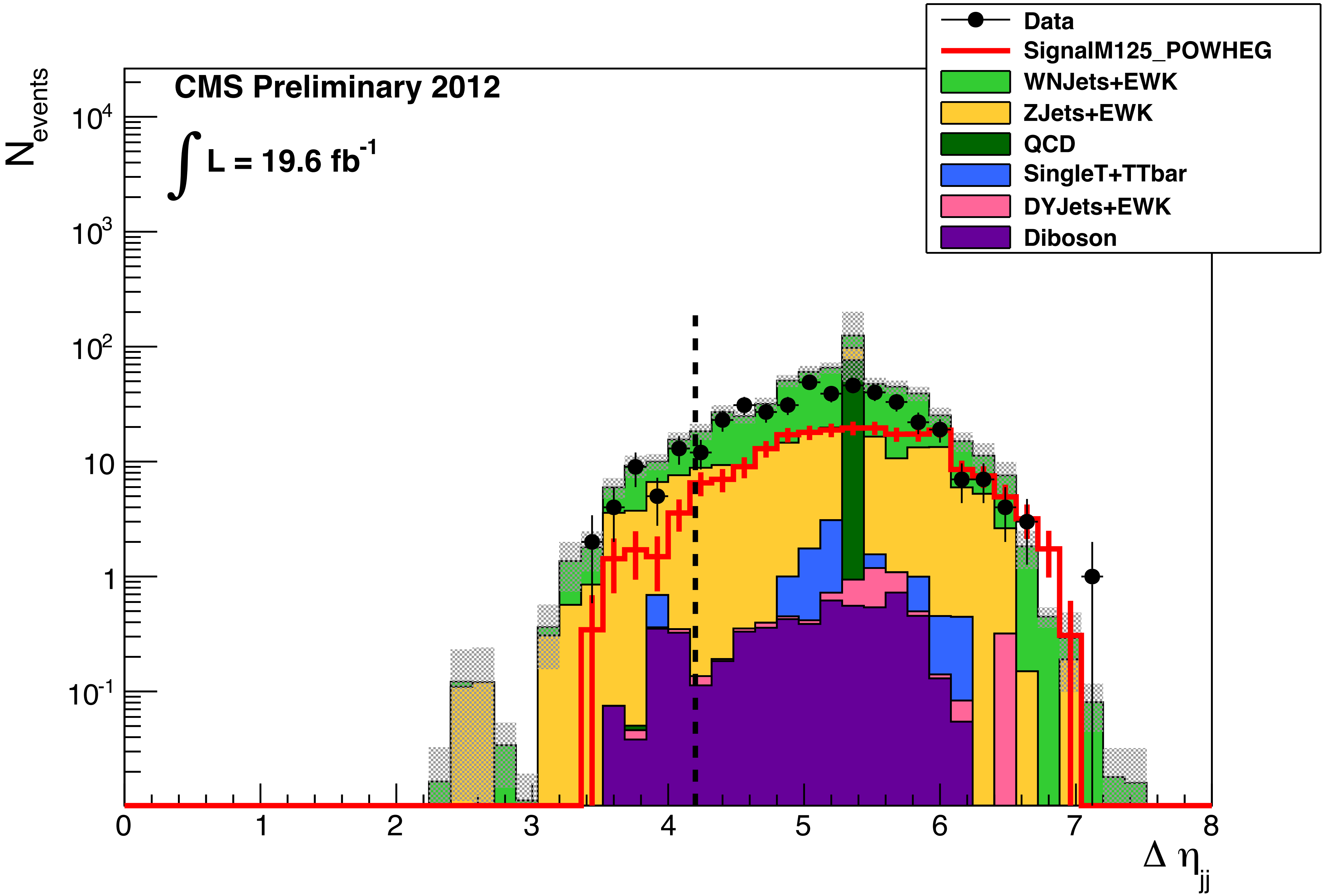
N-1 Plots

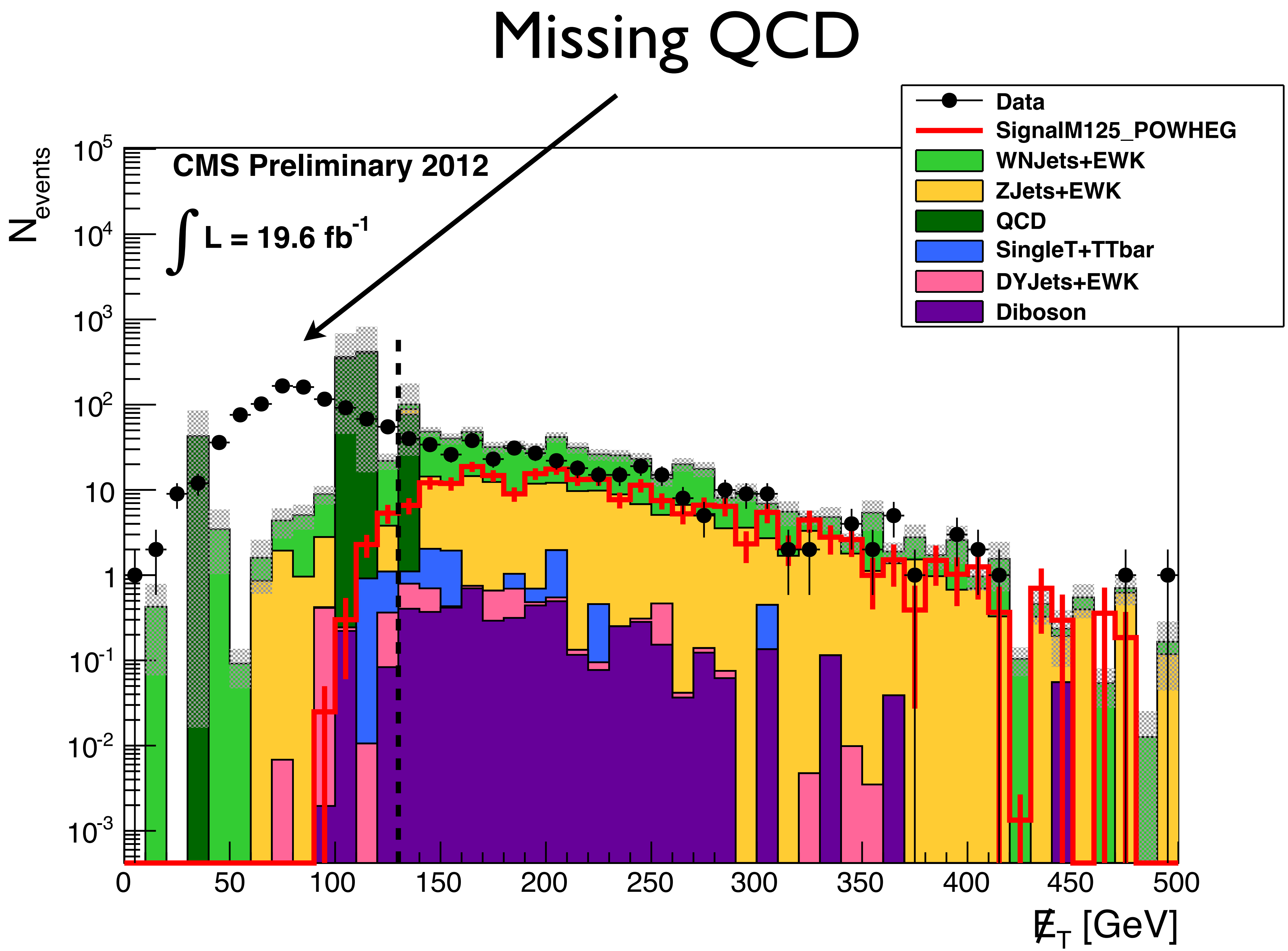
No V+Jets Scaling

Trigger corrections



Δη

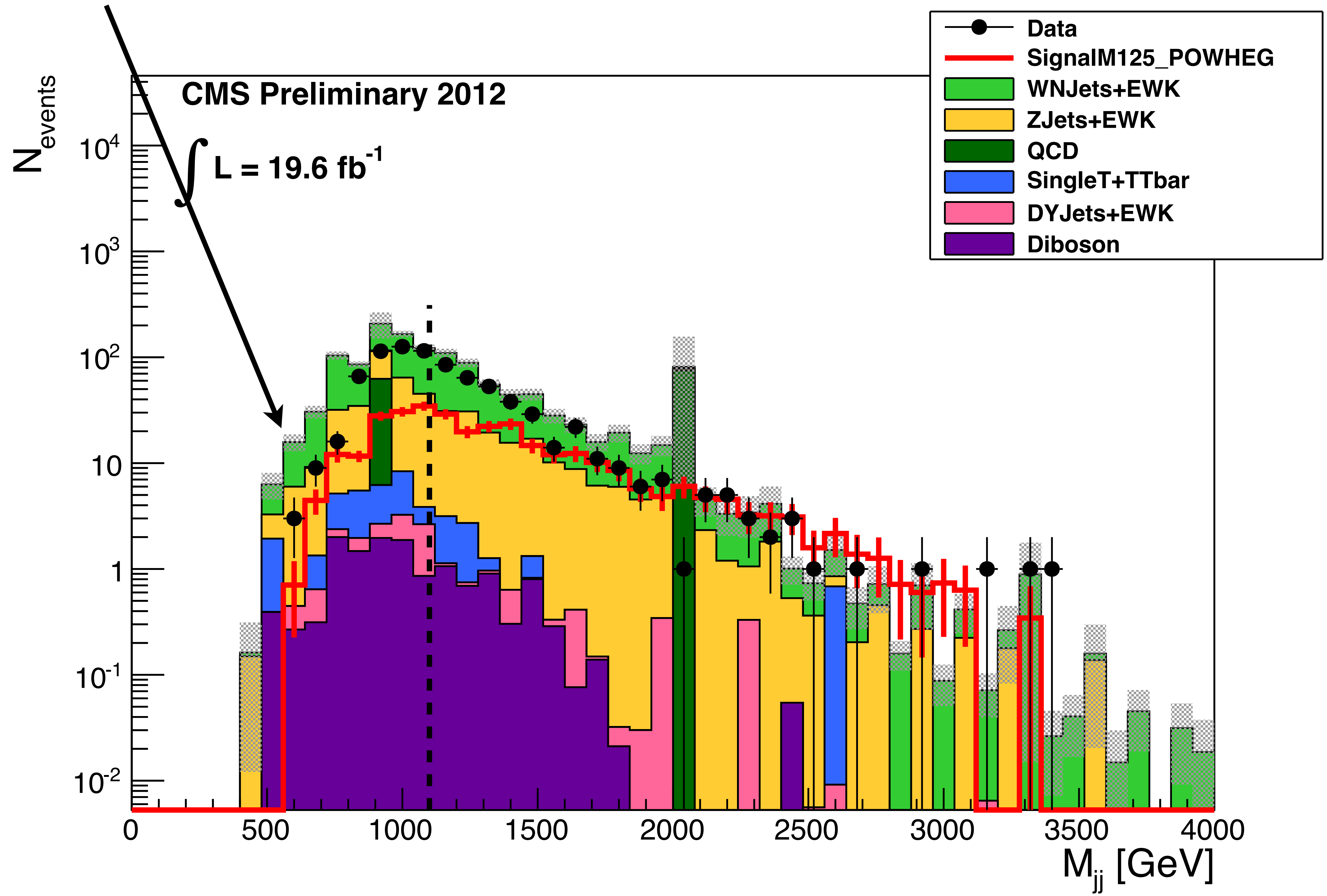

CMS Preliminary 2012
$\int L = 19.6\ fb^{-1}$
Data
SignalM125_POWHEG
WNJets+EWK
ZJets+EWK
QCD
SingleT+TTbar
DYJets+EWK
Diboson
N_{events}
10^4
10^3
10^2
10
1
10^{-1}
0
1
2
3
4
5
6
7
8
$\Delta\eta_{jj}$



Missing QCD
CMS Preliminary 2012
$\int L = 19.6\ fb^{-1}$
Data
SignalM125_POWHEG
WNJets+EWK
ZJets+EWK
QCD
SingleT+TTbar
DYJets+EWK
Diboson
N_{events}
$\not{E}_T$ [GeV]

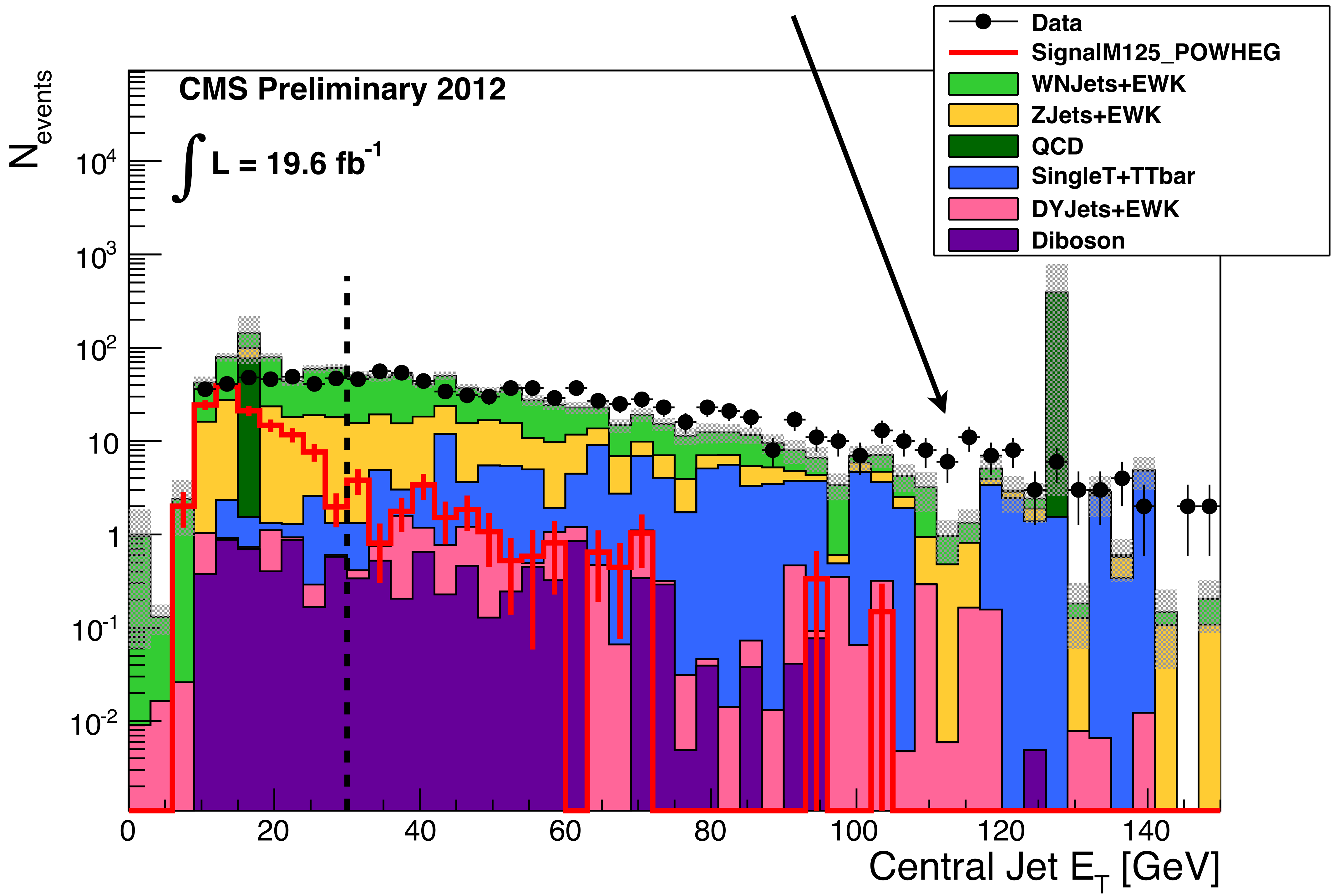
Mjj

Trigger corrections

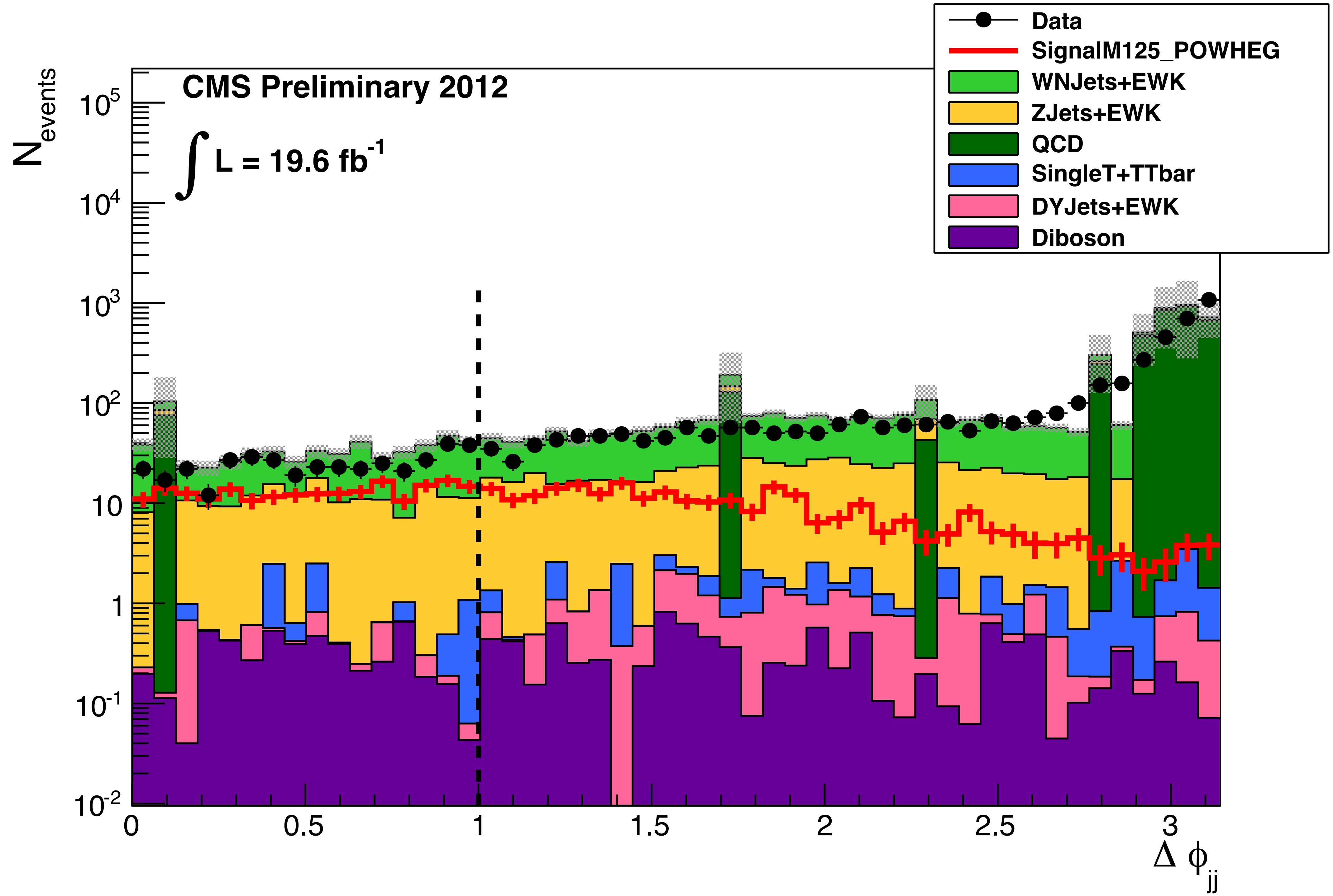


Central Jet E_T

Missing QCD



Δϕ


CMS Preliminary 2012
$\int L = 19.6\ fb^{-1}$
N_{events}
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
0
0.5
1
1.5
2
2.5
3
$\Delta\ \phi_{jj}$
Data
SignalM125_POWHEG
WNJets+EWK
ZJets+EWK
QCD
SingleT+TTbar
DYJets+EWK
Diboson