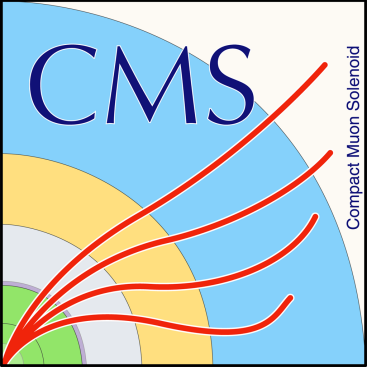


The Search for an Excited Bottom Quark (b*)

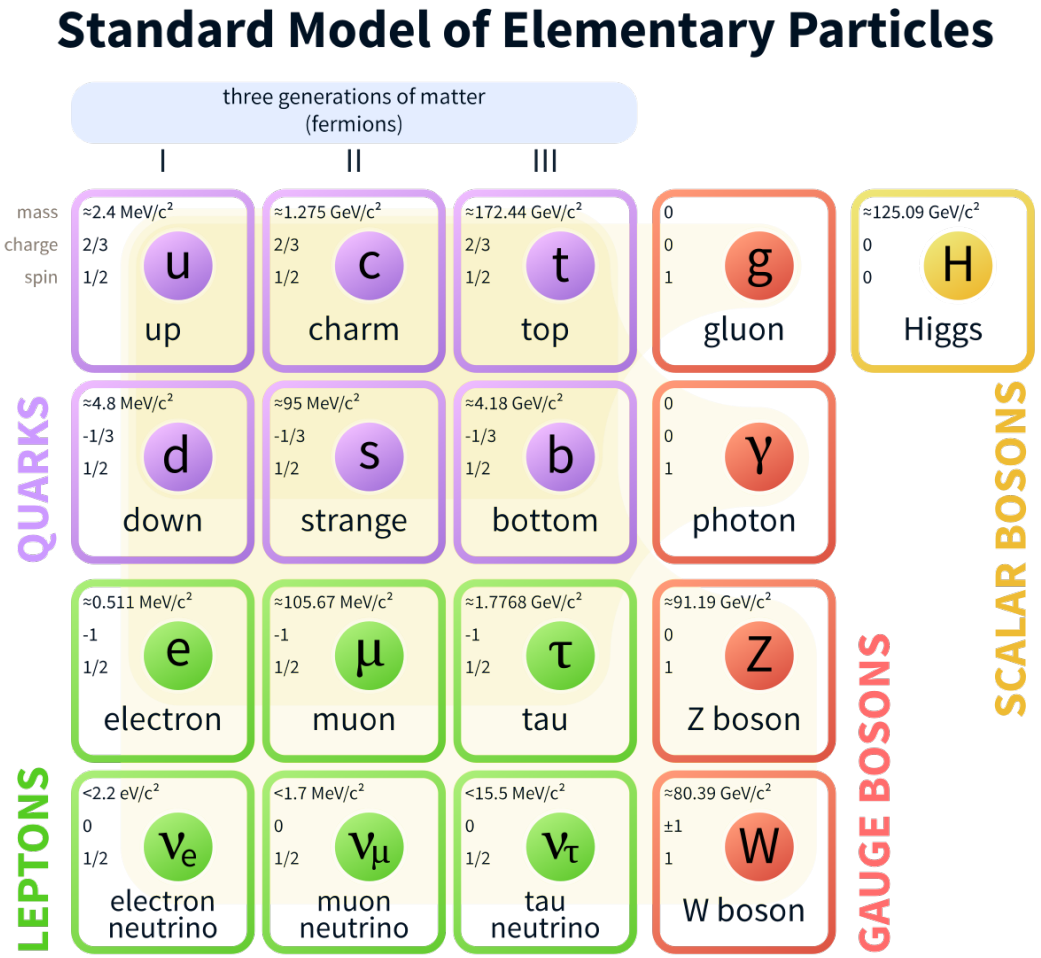
Lucas Corcodilos
Advisor: Petar Maksimovic
Research Exam
9/12/17

The Standard Model of Particle Physics

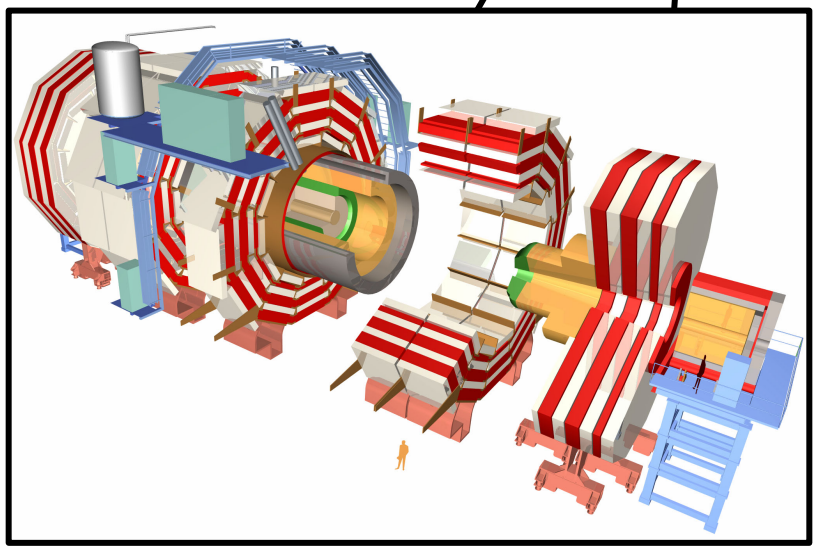
- The Standard Model
  - Experimentally accurate
  - Does not explain everything

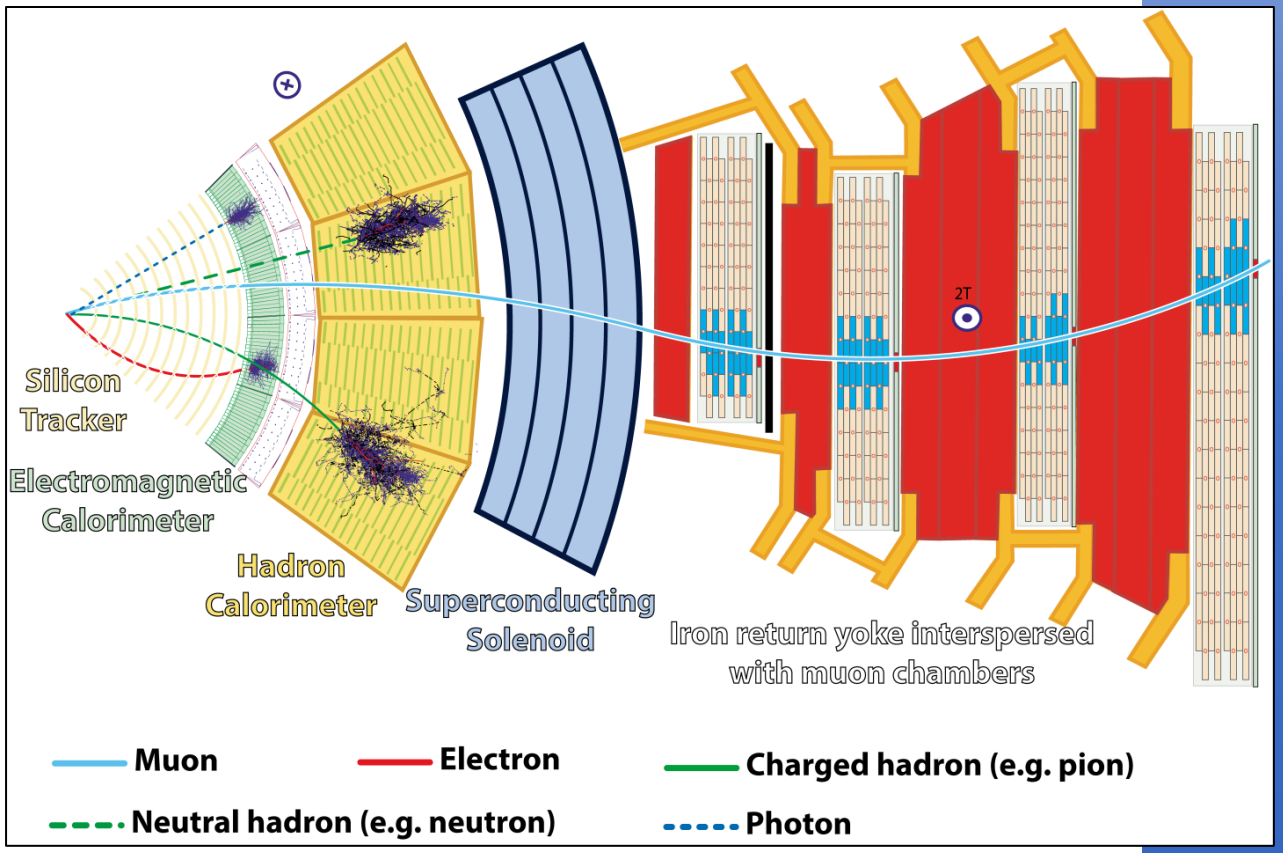
- Missing explanations for
  - Dark Matter/Energy
  - The Hierarchy problem
  - Matter/anti-matter asymmetry

- Smashing particles at increasing energies has got us this far so why not keep going?



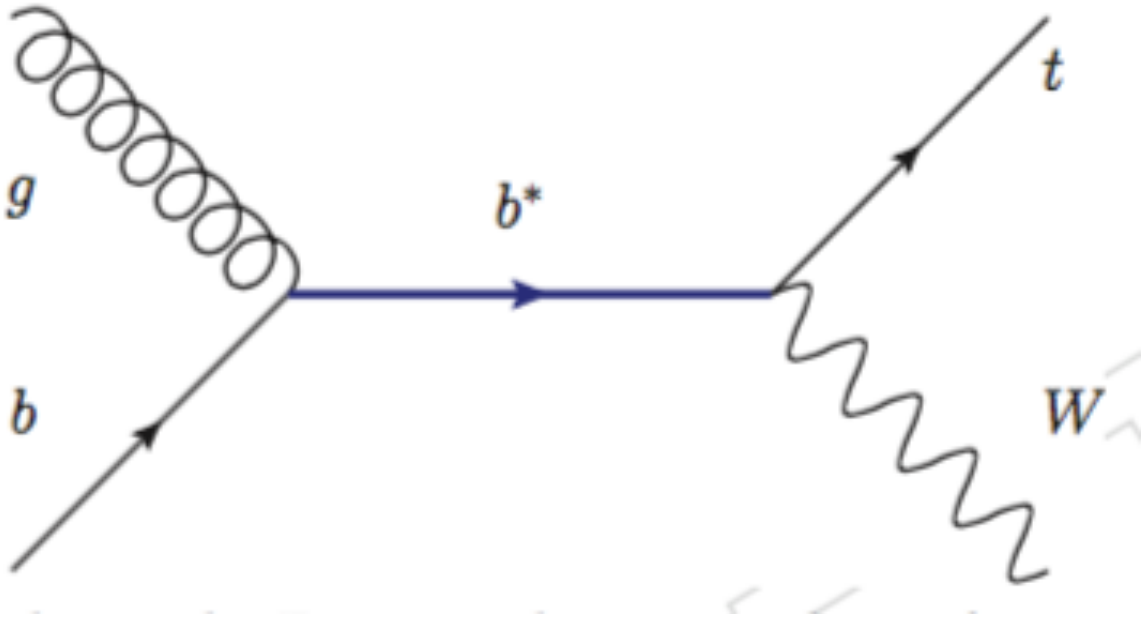
The LHC and CMS





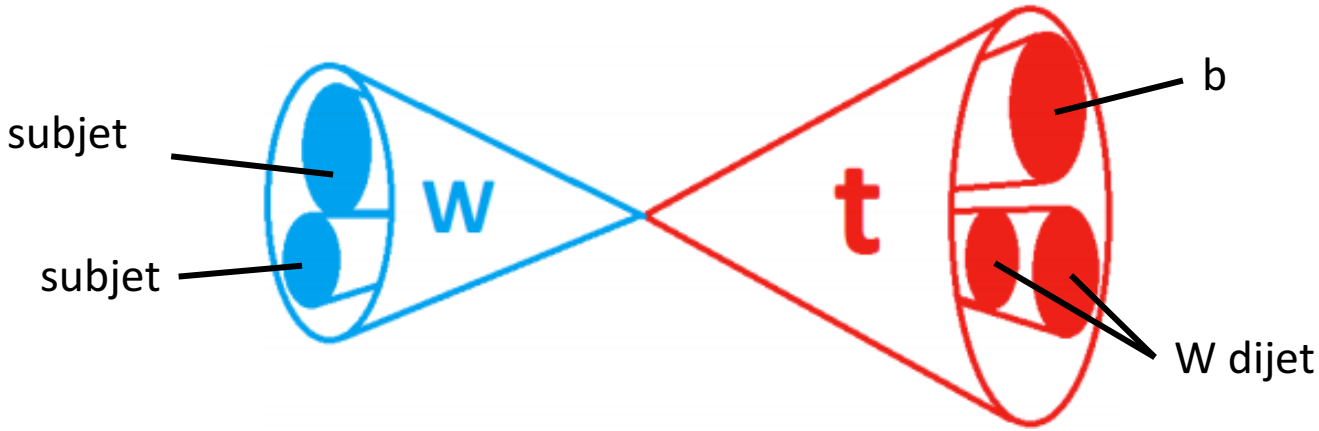
What is a b*?

- A bottom quark is excited by a gluon to produce a b*
- Existence of a b* would imply that quarks are not fundamental



What would a b* look like?

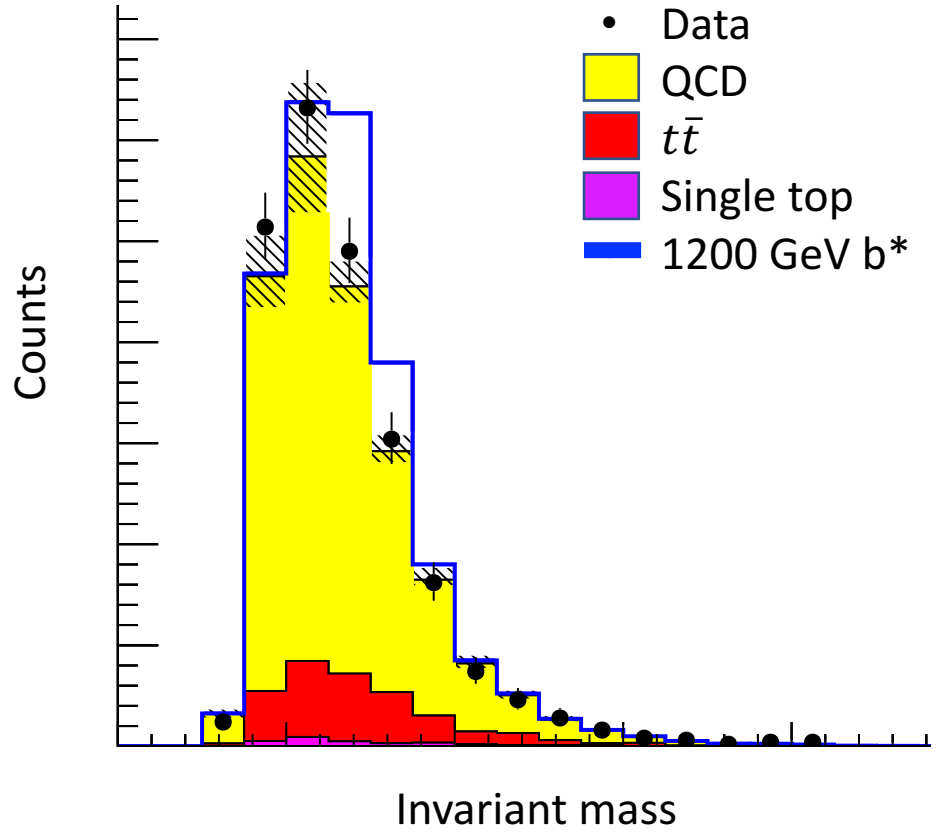
- Very heavy (> 1 TeV)
  - Slowly moving along beamline
  - Decay products have high momentum
    - “boosted"
- All hadronic decay
  - Hadronic showers – “jets”
  - b* → tW
  - W → two jets
  - t → W + b → two jets + b

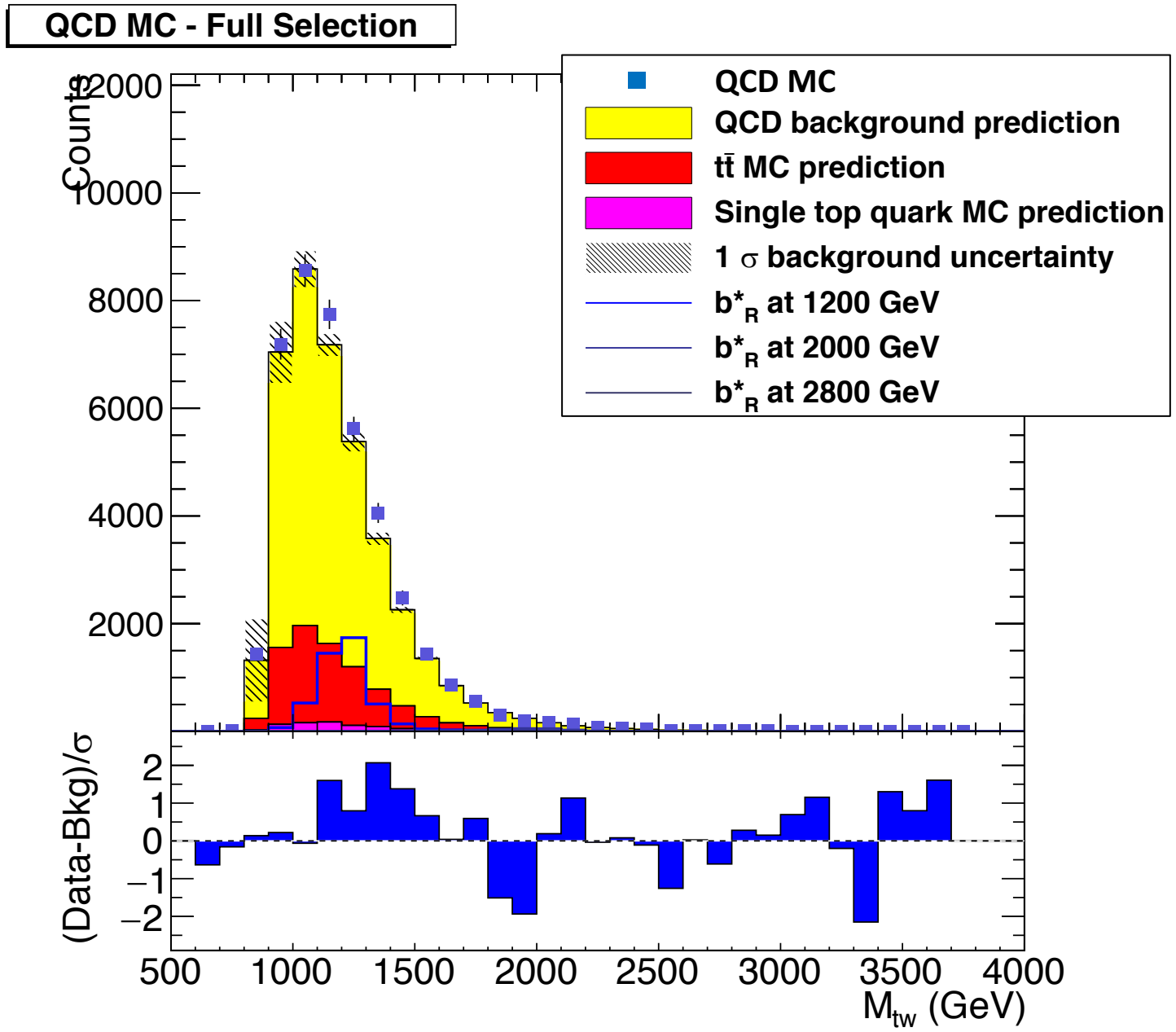


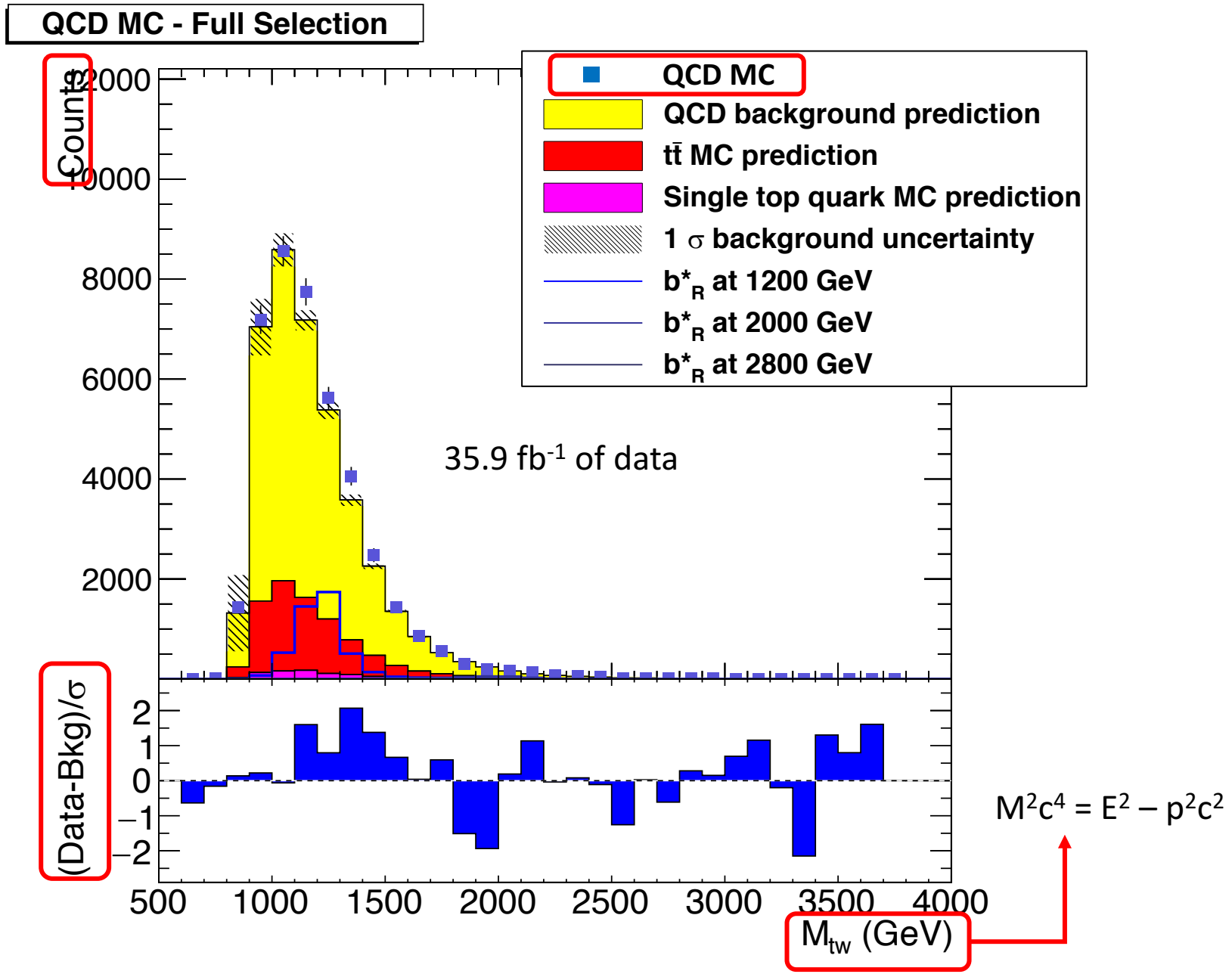
Top and W jets in opposite hemispheres

Bump Hunt

- Search for heavy top-W resonance
  - Invariant mass as smooth background
  - Any signal will be a peak

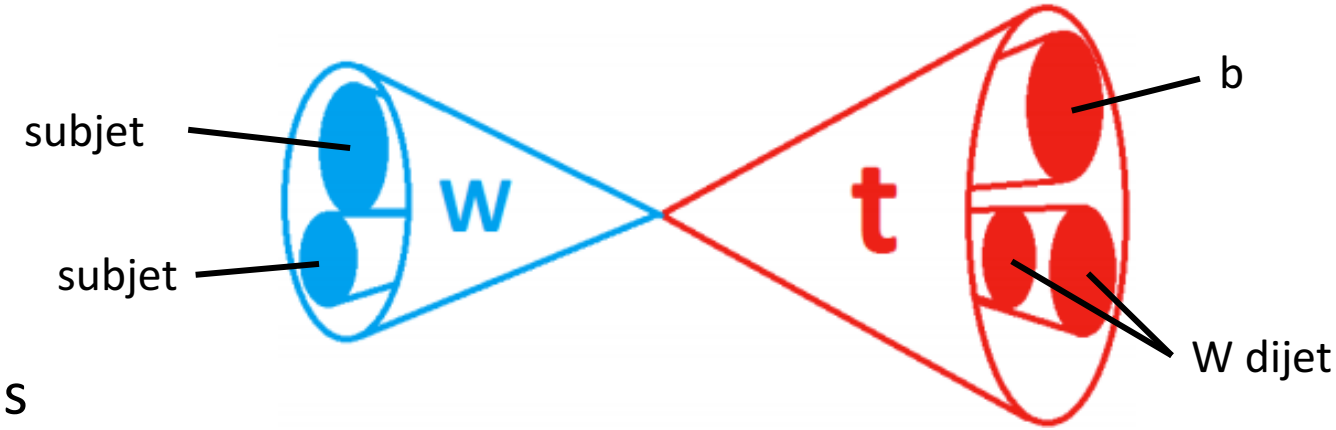



QCD MC - Full Selection
QCD MC
QCD background prediction
tt̄ MC prediction
Single top quark MC prediction
1 σ background uncertainty
b*R at 1200 GeV
b*R at 2000 GeV
b*R at 2800 GeV
Counts
(Data-Bkg)/σ
Mtw (GeV)


QCD MC - Full Selection
Counts
12000
10000
8000
6000
4000
2000
QCD MC
QCD background prediction
tt̄ MC prediction
Single top quark MC prediction
1 σ background uncertainty
b*R at 1200 GeV
b*R at 2000 GeV
b*R at 2800 GeV
35.9 fb-1 of data
(Data-Bkg)/σ
2
1
0
−1
−2
500
1000
1500
2000
2500
3000
3500
4000
Mtw (GeV)
M²c⁴ = E² – p²c²

Data Selection - Isolating Signal

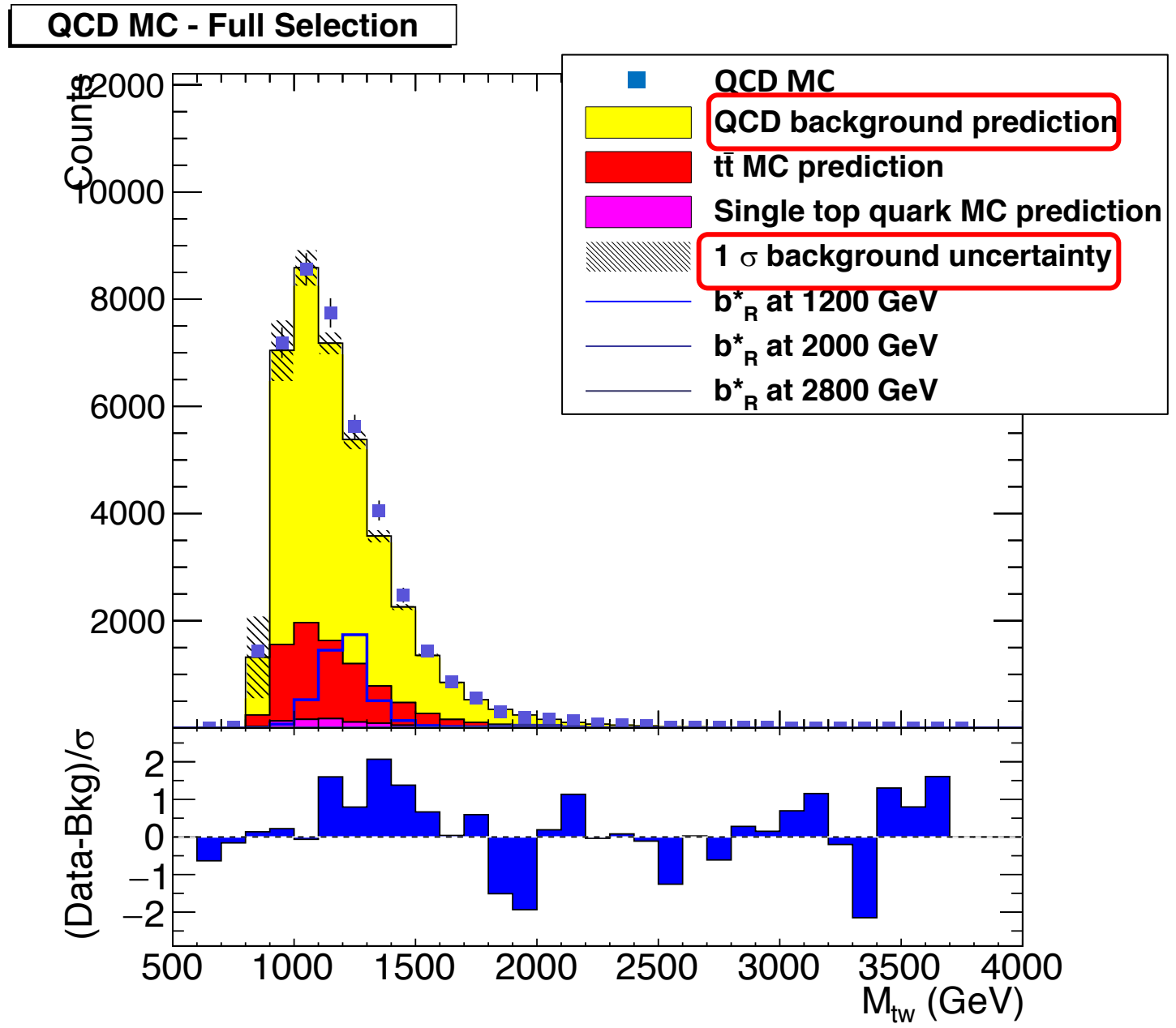
- Kinematics
  - p_T(top) > 400 GeV
  - p_T(W) > 400 GeV
  - $|\Delta Y| < 1.8$
    - Top and W back-to-back
- Standard CMS tagging algorithms to 'tag' candidate jets
  - Mass
  - Jet Substructure
  - b-tag



Top and W jets in opposite hemispheres

Data Selection - Cutflow

Selection	QCD MC	$t\bar{t}$ MC	Single top MC	M_{b^*} = 1200 GeV	M_{b^*} = 2800 GeV
2 jets, p_T	61,272,226	330,094	59,349	51,190	307
$\|\Delta y\|$	48,673,108	287,211	51,155	49,860	251
M_{top}	9,771,616	152,108	17,112	17,609	71
M_W	1,139,835	27,959	3,920	12,004	41
τ_2/τ_1	231,390	14,352	2,223	9,013	27
Subjet b-tag	71,099	11,175	1,771	7,196	21
τ_3/τ_2	19,071	6,722	887	5,041	14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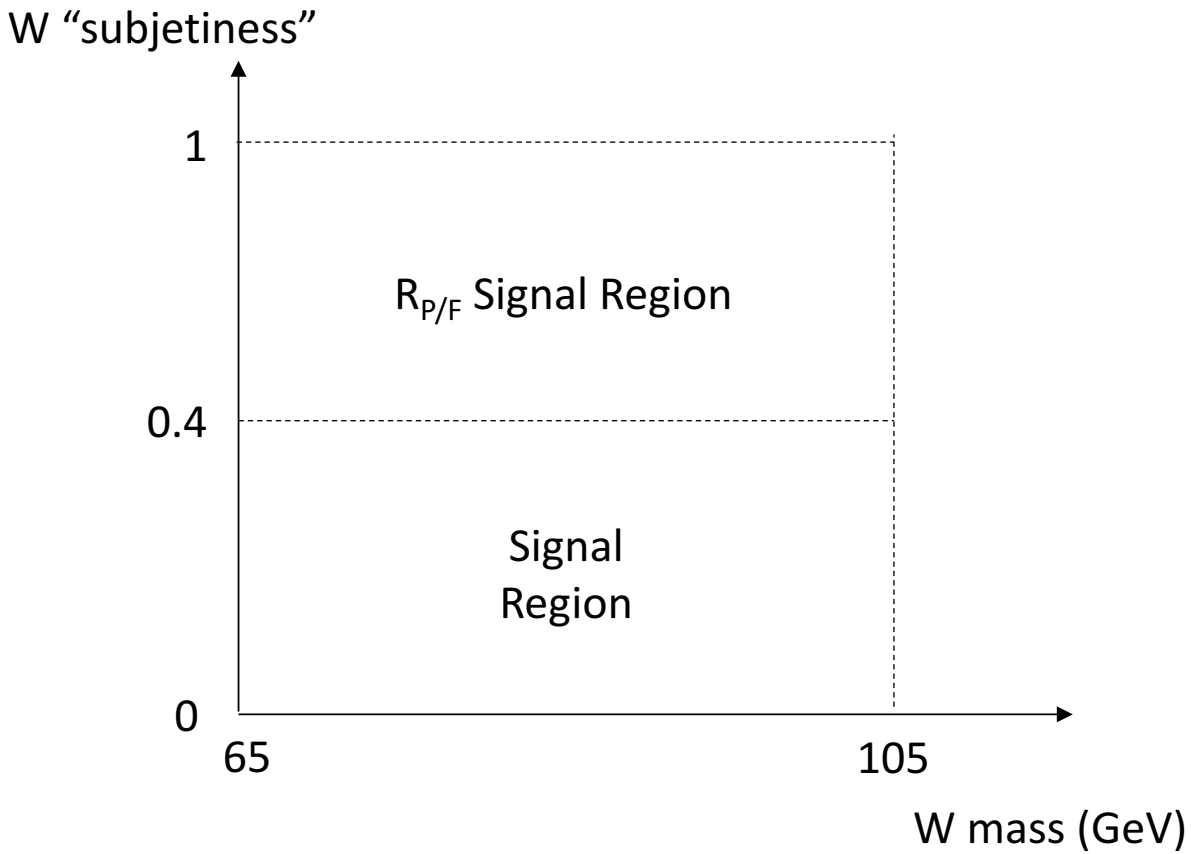
b*R at 1200 GeV
b*R at 2000 GeV
b*R at 2800 GeV
Counts
(Data-Bkg)/σ
Mtw (GeV)

QCD Background Estimate Extracted from Data

- Look to another region to estimate QCD background
  - Invert part of W-tag selection
- Derive top tagging pass/fail ratio as a function of top p_T ($R_{P/F}$) in two eta regions

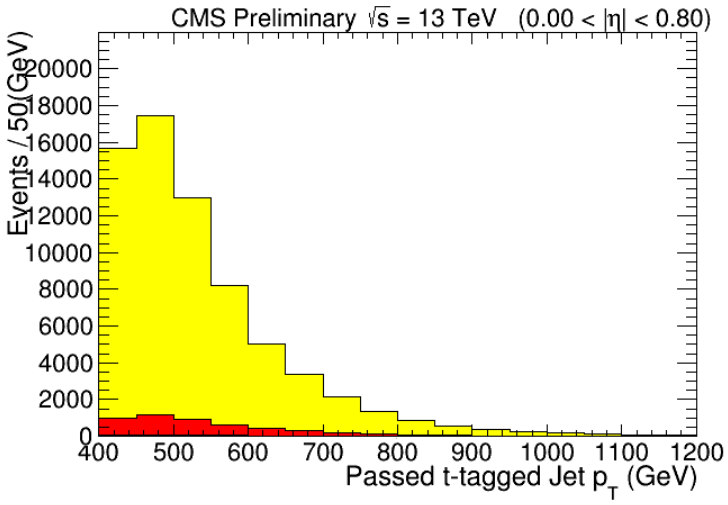


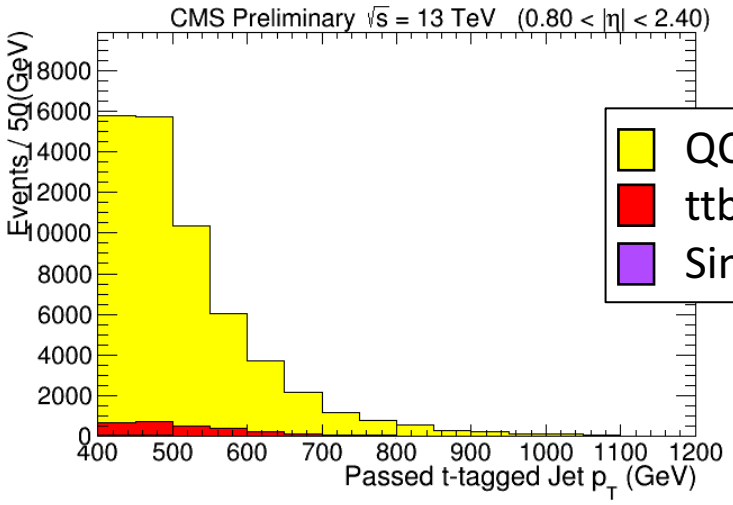
Background Estimate

$0 < \eta < 0.8$

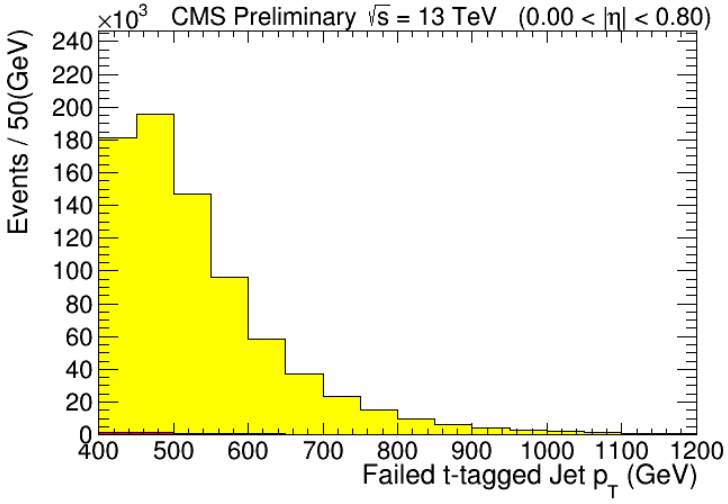
$0.8 < \eta < 2.4$

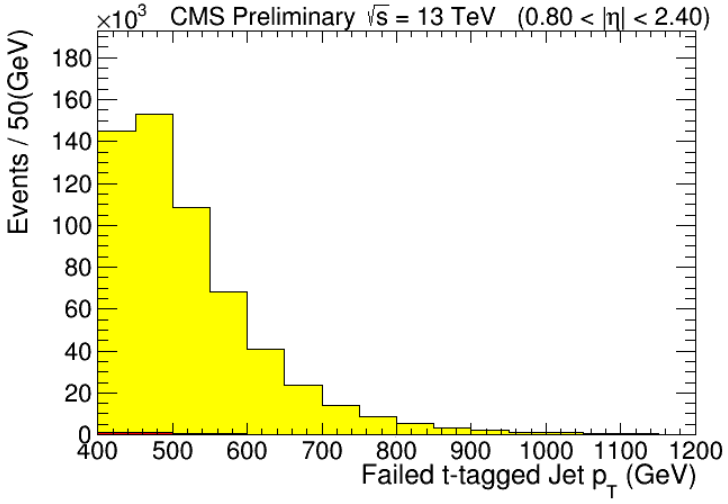
Pass





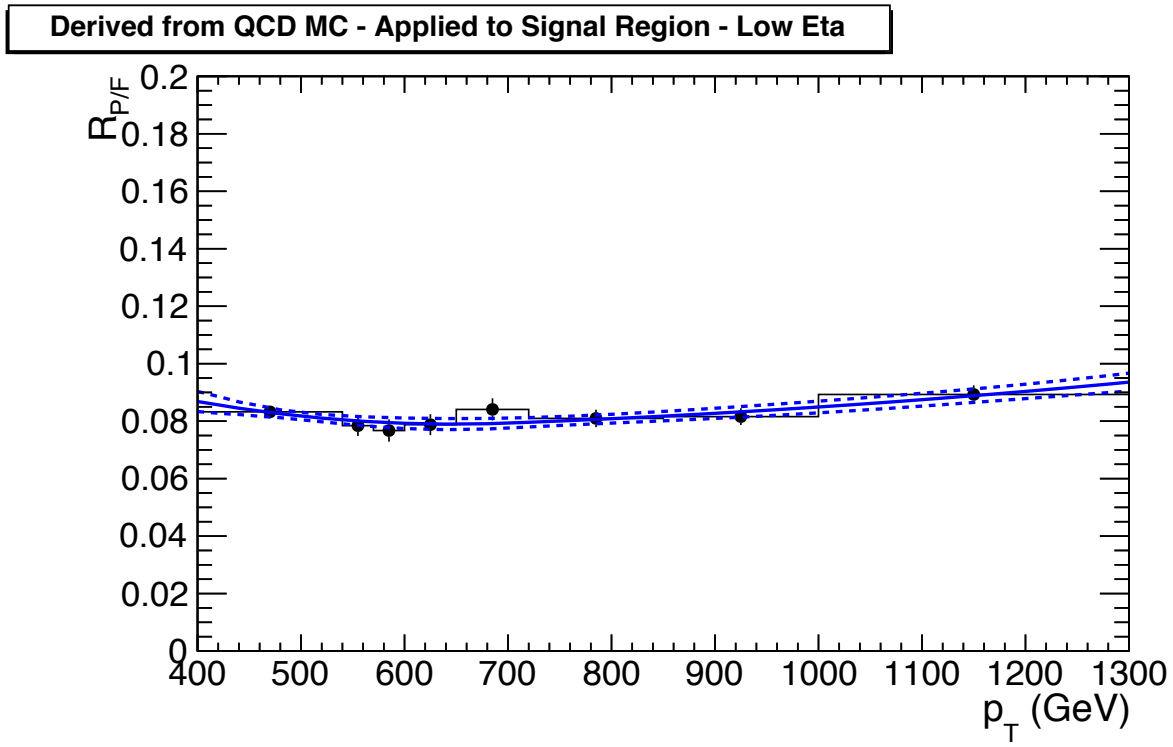
Fail

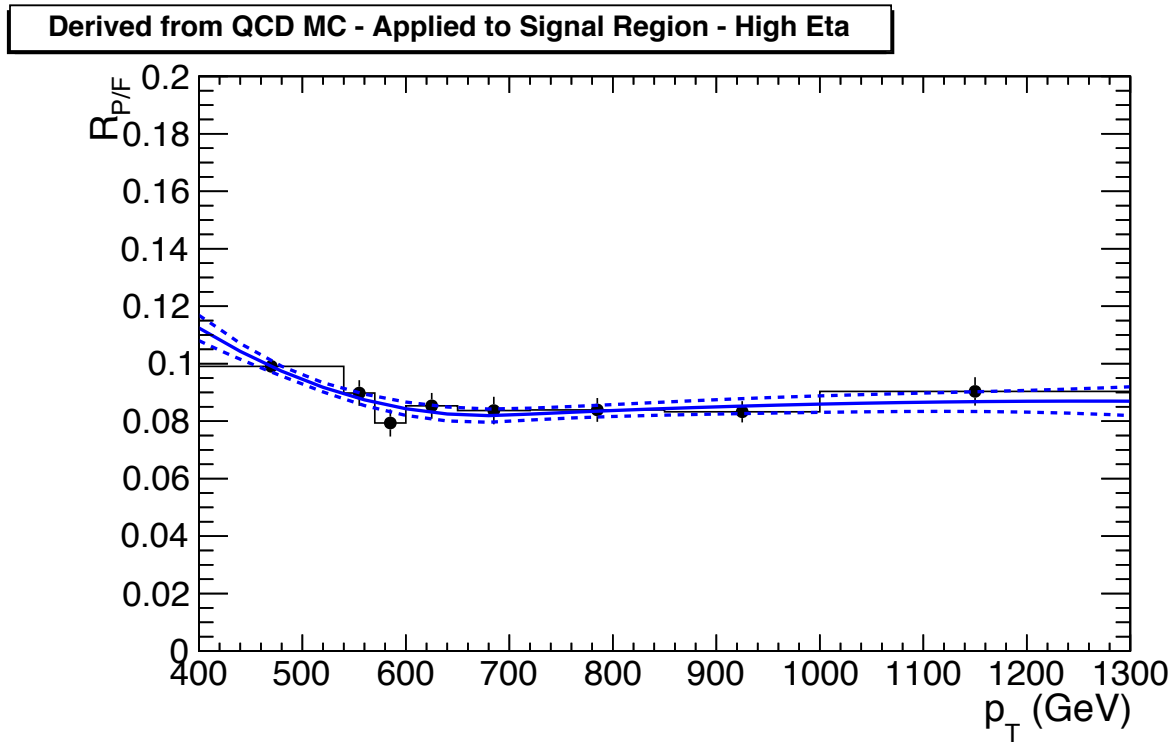




Background Estimate

Fit $R_{P/F}$ with bifurcated polynomial



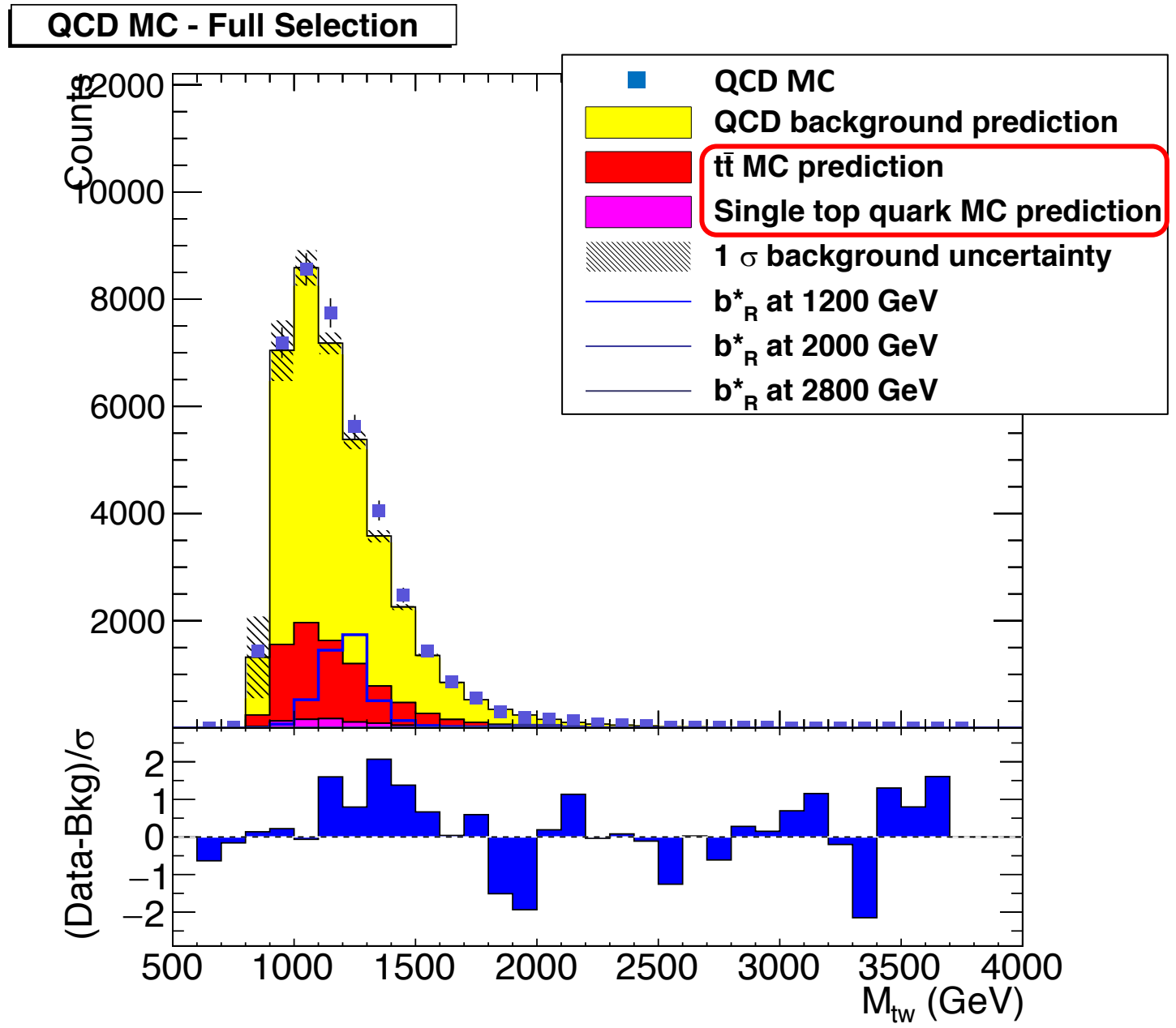


Background Estimate

Apply to failed top-tag events in signal region to estimate QCD background

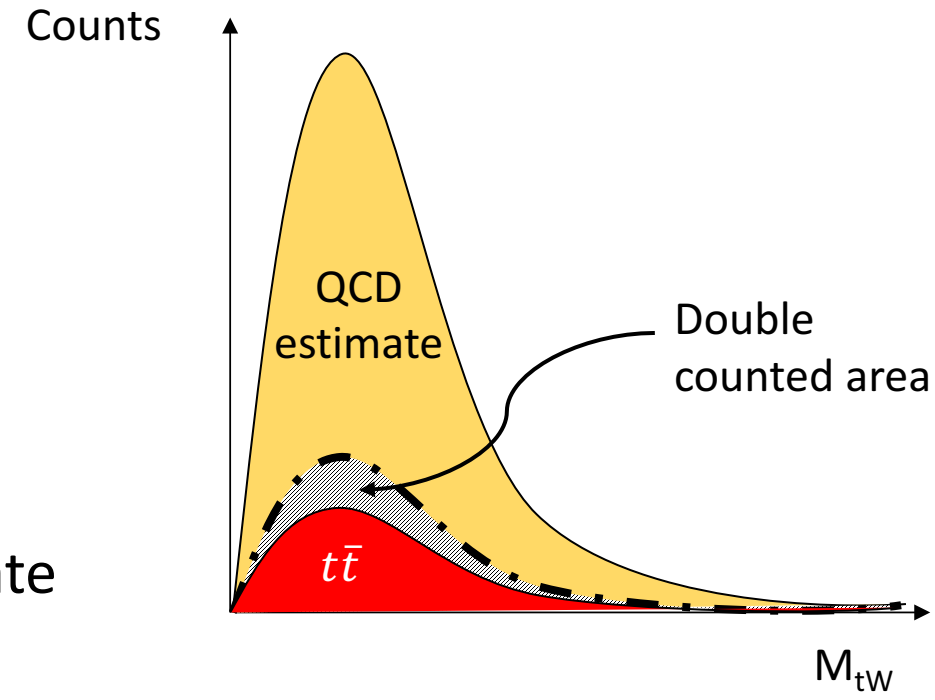
$$signal\ selection = Passed_{Signal\ Region}$$

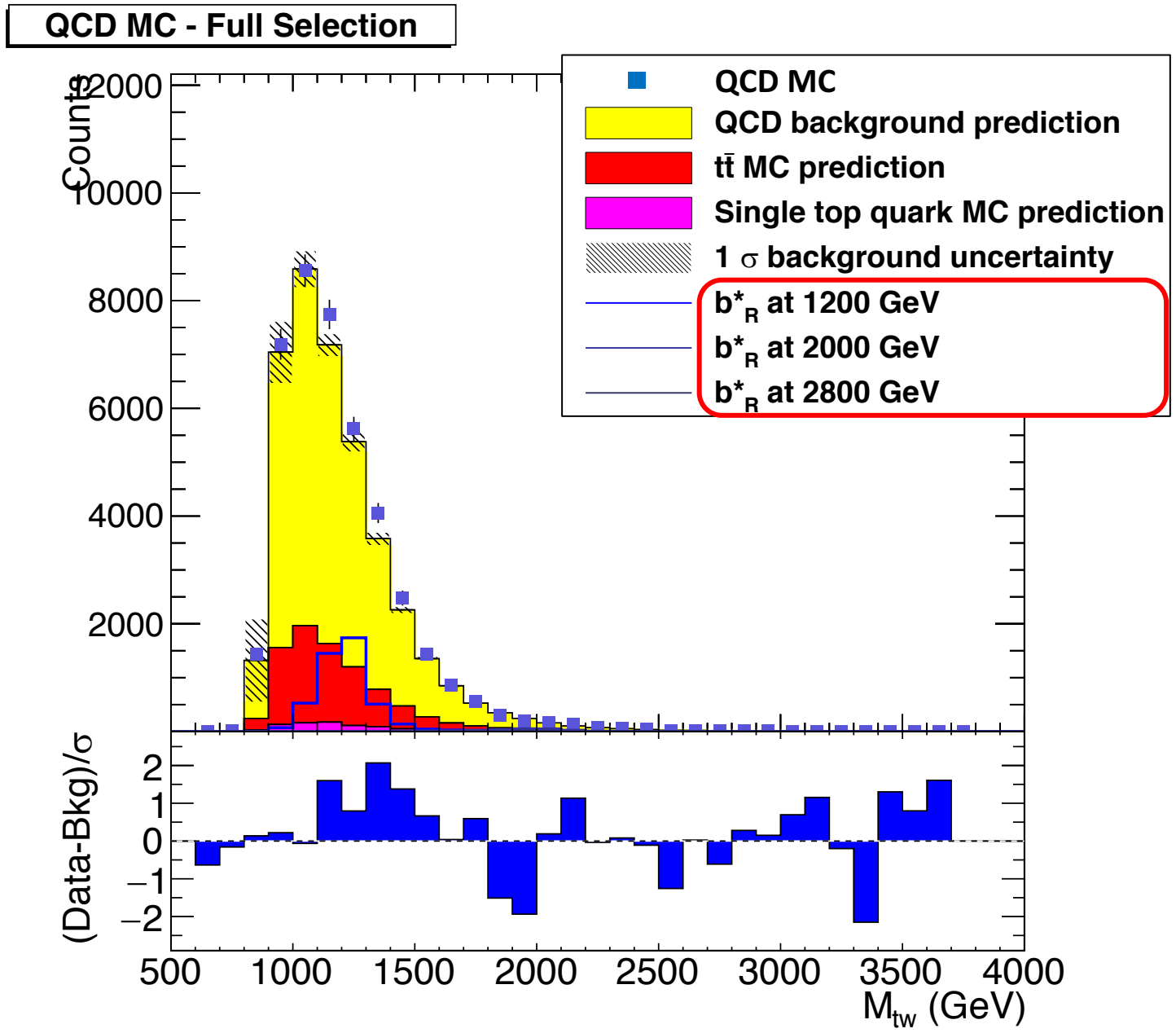
$$background\ estimate = Failed_{Signal\ Region} * \frac{Passed_{Ratio\ Region}}{Failed_{Ratio\ Region}}$$


QCD MC - Full Selection
QCD MC
QCD background prediction
tt̄ MC prediction
Single top quark MC prediction
1 σ background uncertainty
b*R at 1200 GeV
b*R at 2000 GeV
b*R at 2800 GeV
Counts
(Data-Bkg)/σ
Mtw (GeV)

Single top and $t\bar{t}$

- Well simulated but need some corrections
  - Pileup, top p_T reweighting, …
- Double counting
  - QCD estimate <u>from data</u> and simulations count same bit
  - Extract QCD background estimate from single top and $t\bar{t}$ MC
  - Subtract from estimate

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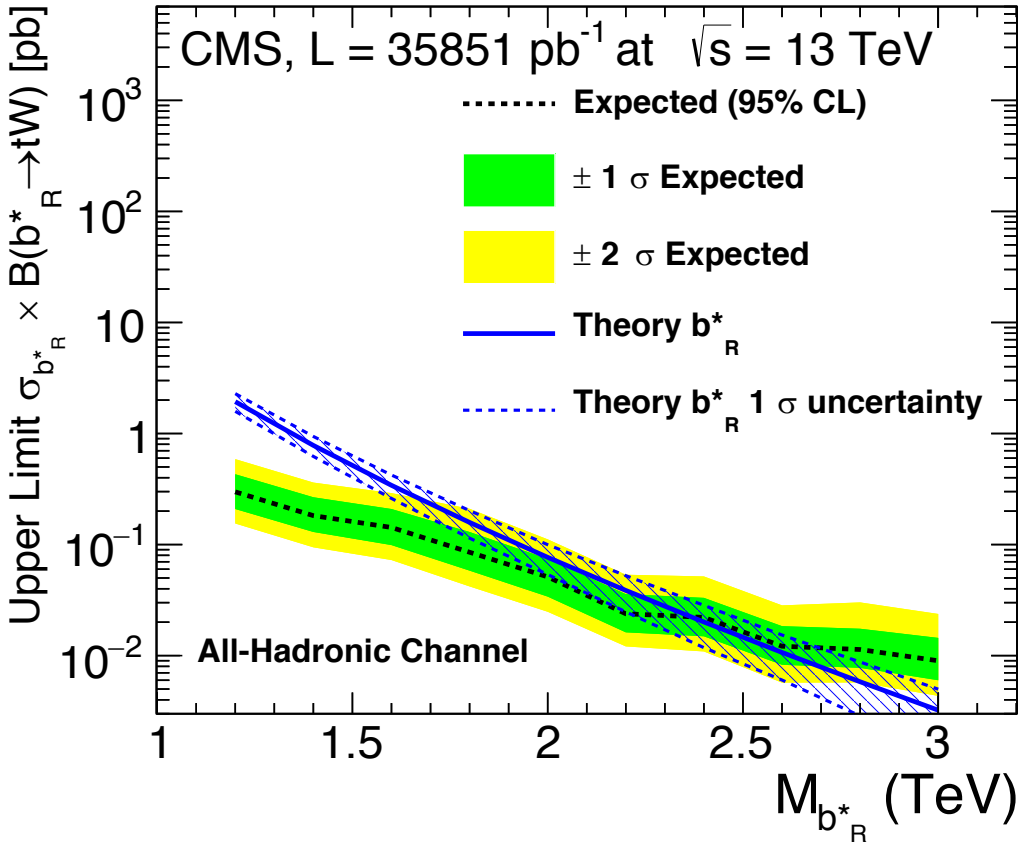
b*R at 1200 GeV
b*R at 2000 GeV
b*R at 2800 GeV
Counts
(Data-Bkg)/σ
Mtw (GeV)

b* Simulated Signals

- Signals simulating a b* with signature we're looking for
  - 1200 GeV to 3000 GeV in increments of 200 GeV
- Used to set limits on b*
- Run 1 (at 8 TeV) excluded at 1.43 TeV



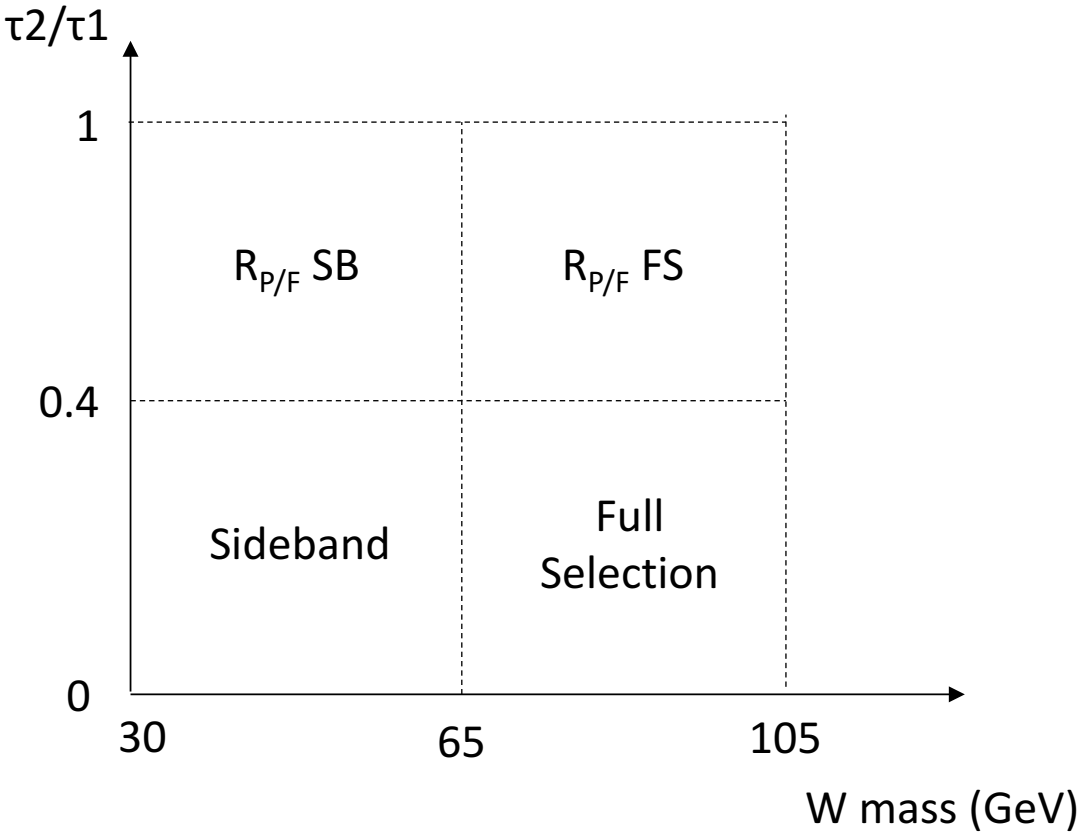
Summary

- The Standard Model of particle physics has been a great start
  - Need to look for more to study current mysteries
- The LHC is producing enormous amounts of data
  - A great time to be doing experimental particle physics
- The search for an excited bottom quark in an all-hadronic channel at 13 TeV nearing completion
- Submitting analysis note for review by end of the month

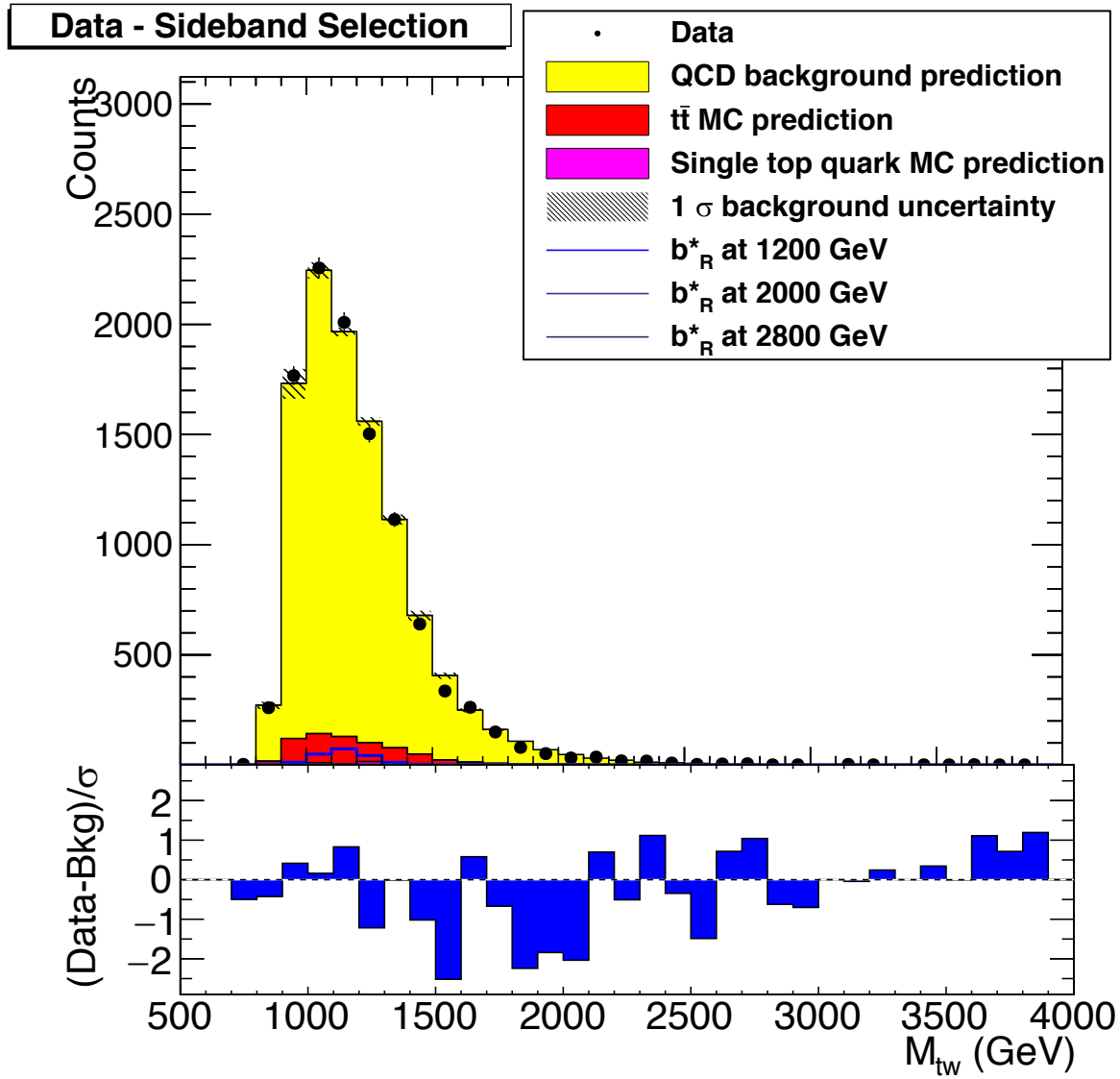
Backup

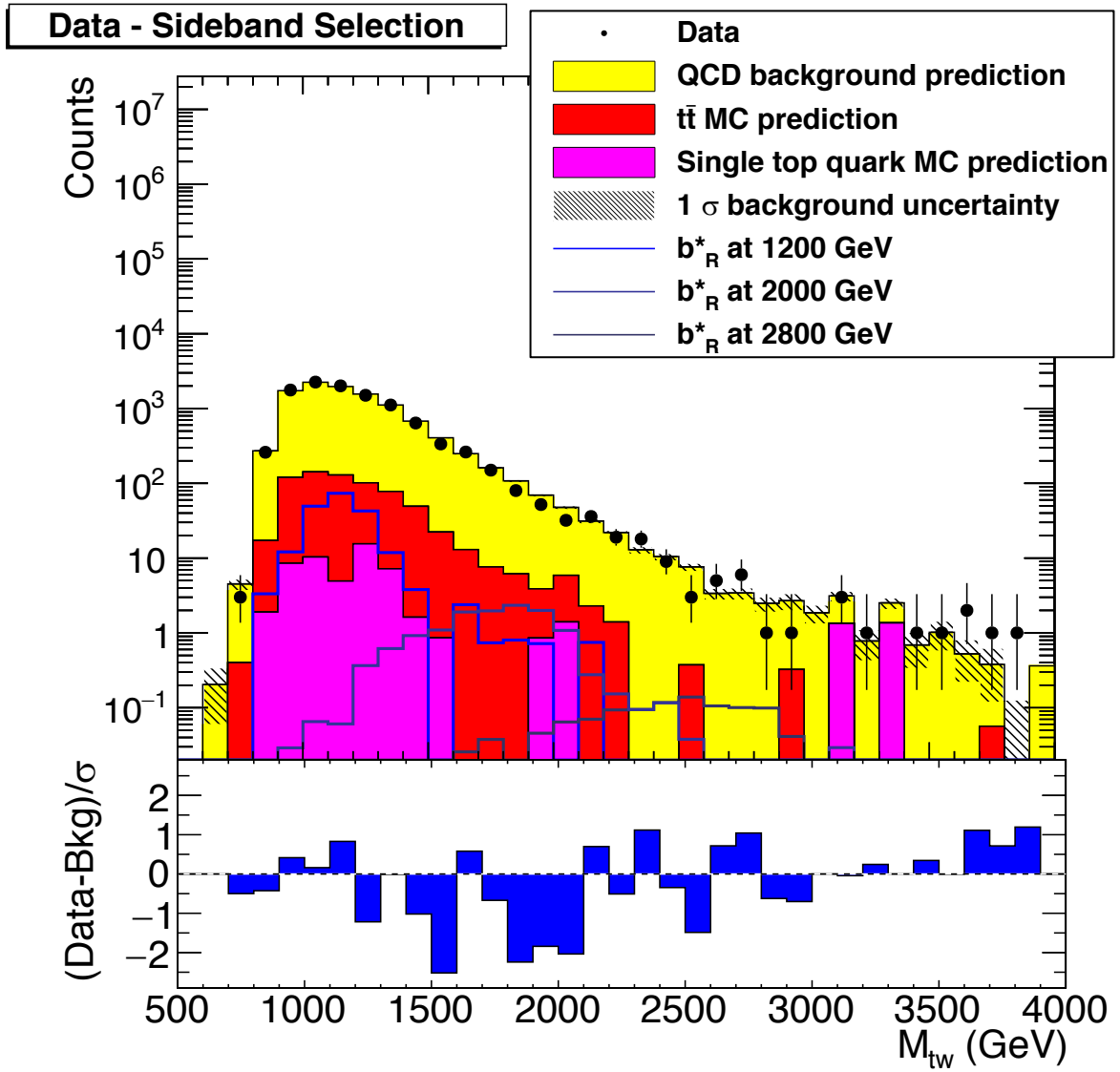
Closure Tests

- Sideband
  - Investigate QCD estimate in control region
  - Low W mass
    - 30 GeV < M_W < 65 GeV
  - $R_{P/F}$ found by inverting τ2/τ1 selection
- QCD MC closure
  - Investigate QCD MC behavior in full selection region



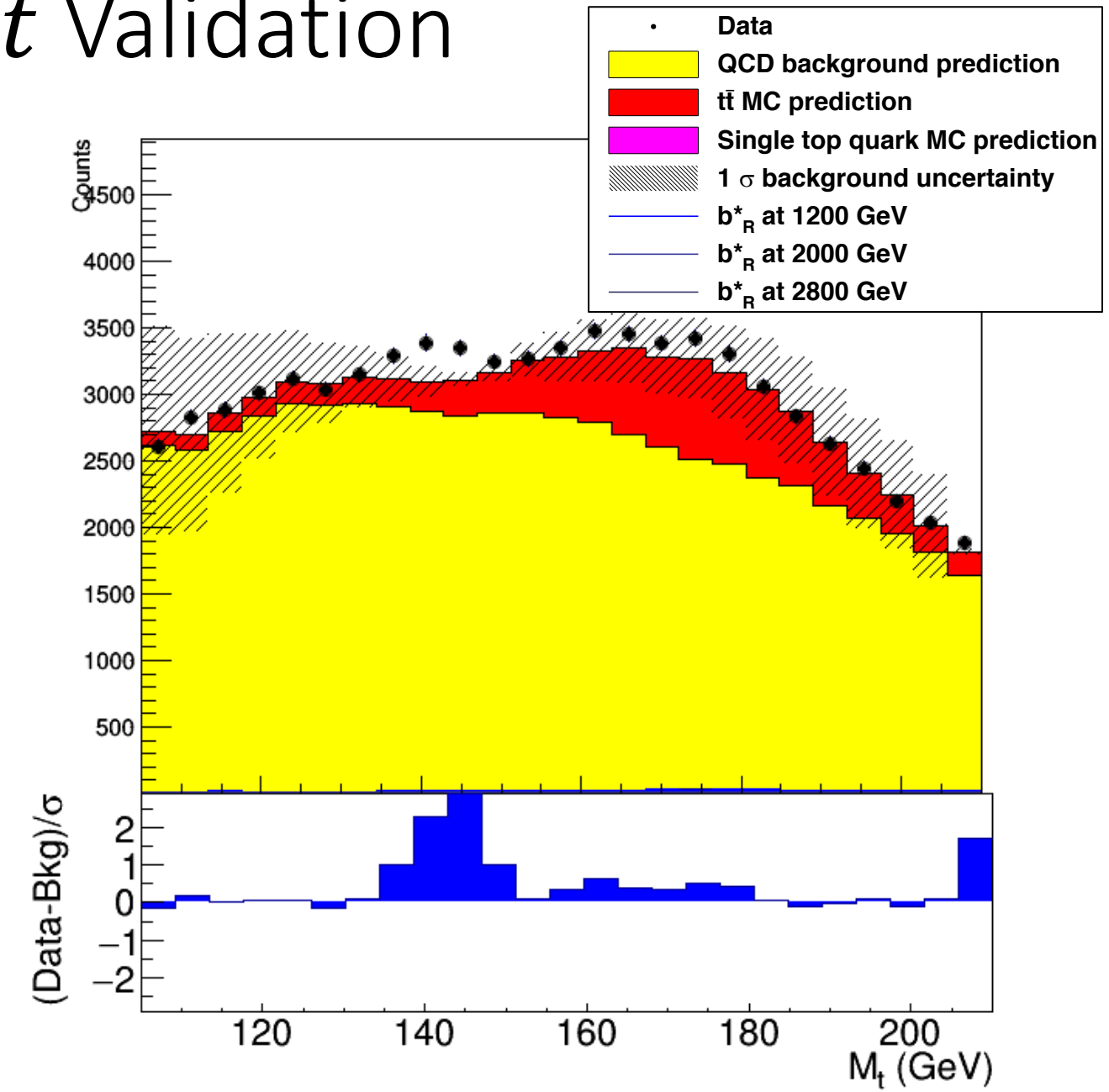
Sideband Closure - Data





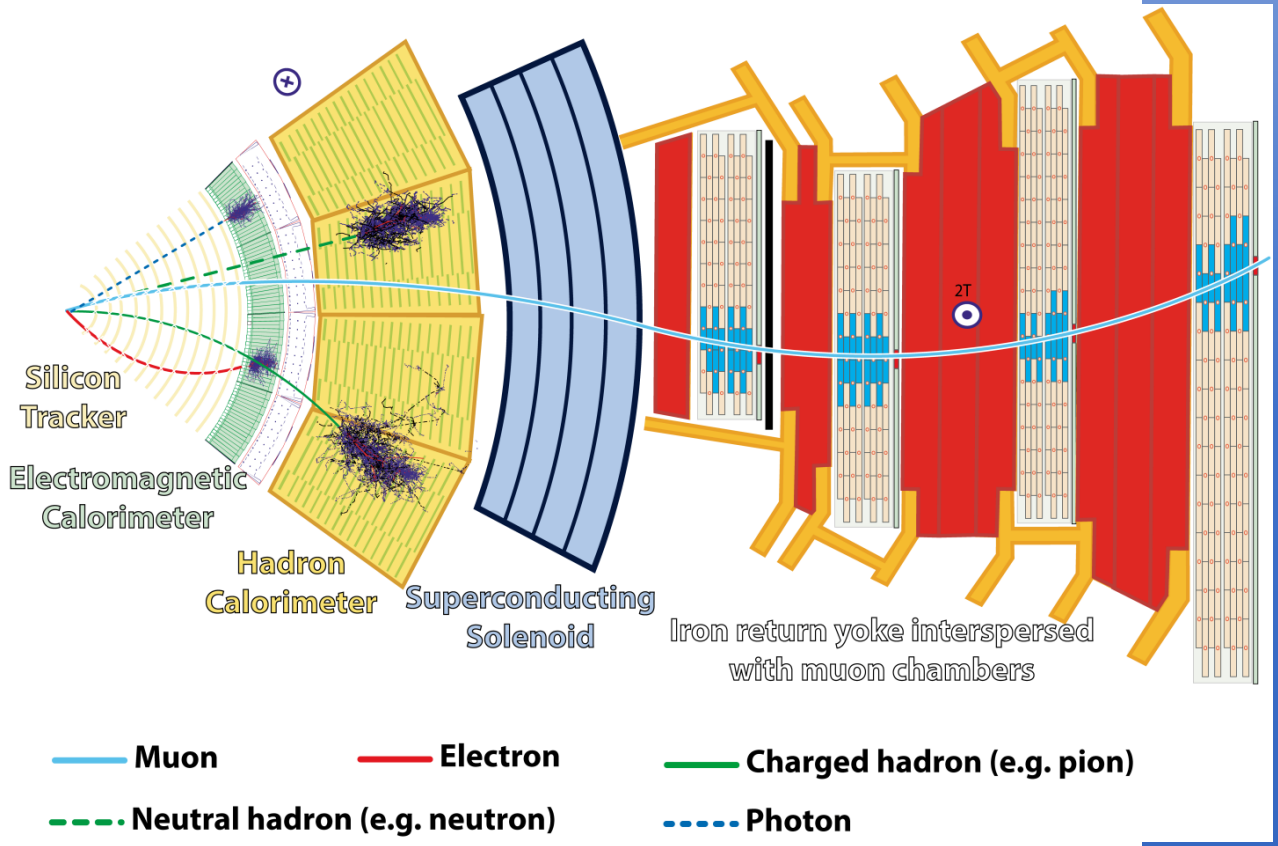
$t\bar{t}$ Validation

- Use $t\bar{t}$ rich high W mass sideband
  - $M_W > 130$ GeV
- Mass shape correction and top p_T reweighting applied

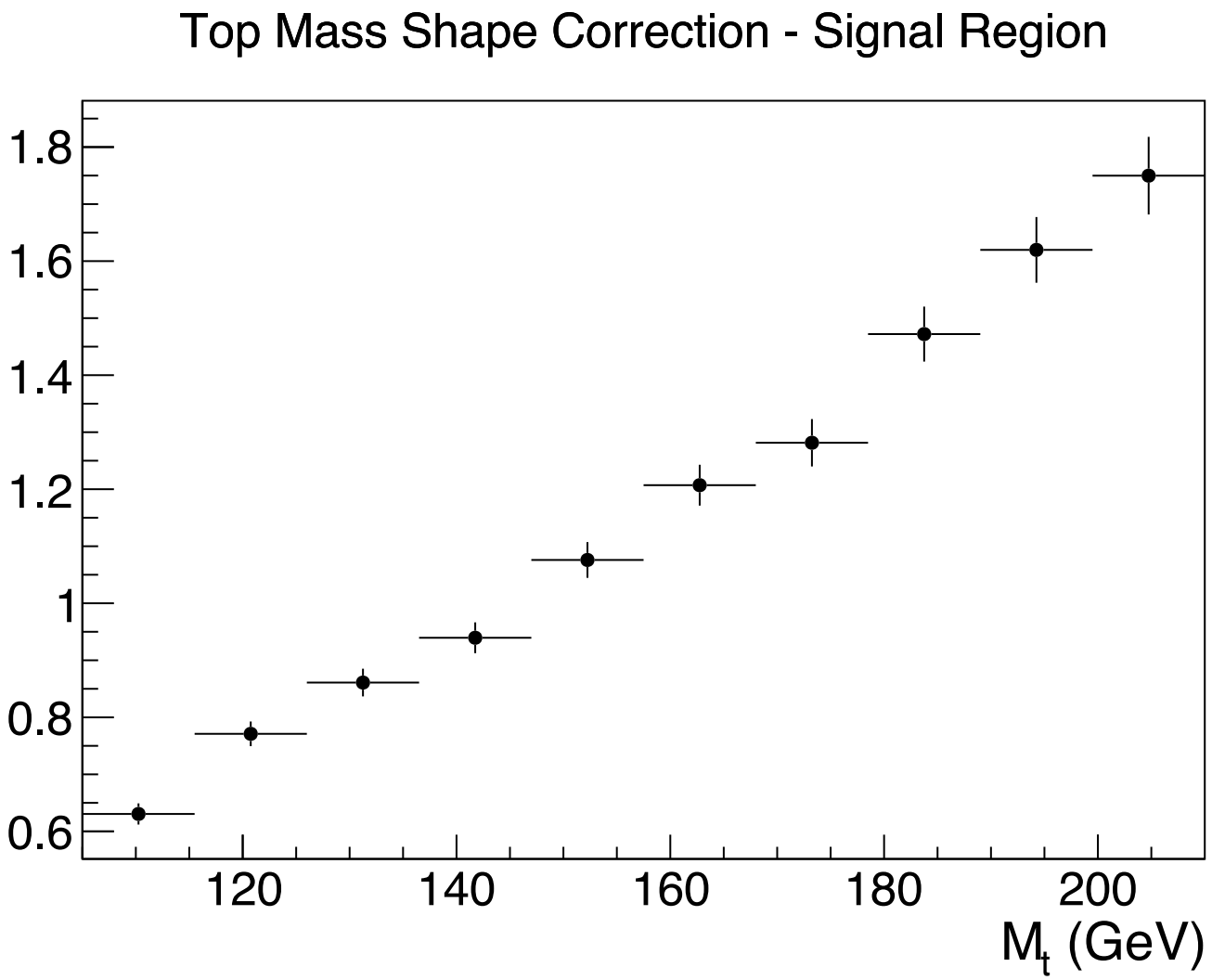


The CMS Detector

- Compact Muon Solenoid
- 5 Main Layers
  1. Tracker – charged particle position and momentum
  2. Electromagnetic Calorimeter (ECAL) – charge particle energies
  3. Hadronic Calorimeter (HCAL) – measures energy of hadrons
  4. Magnet – 3.8 Tesla, bends charged particle paths
  5. Muon detectors/Return yoke – Directs magnetic field, detects isolated muons

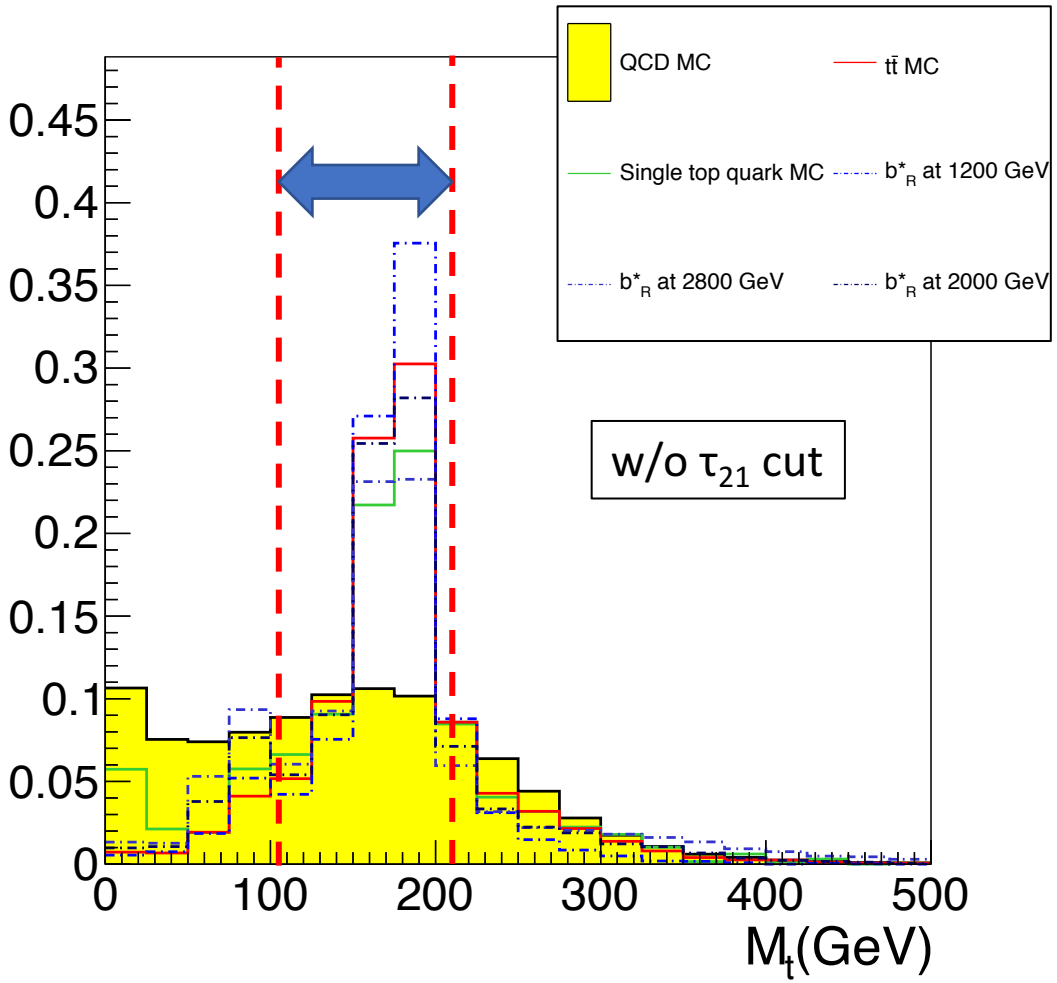


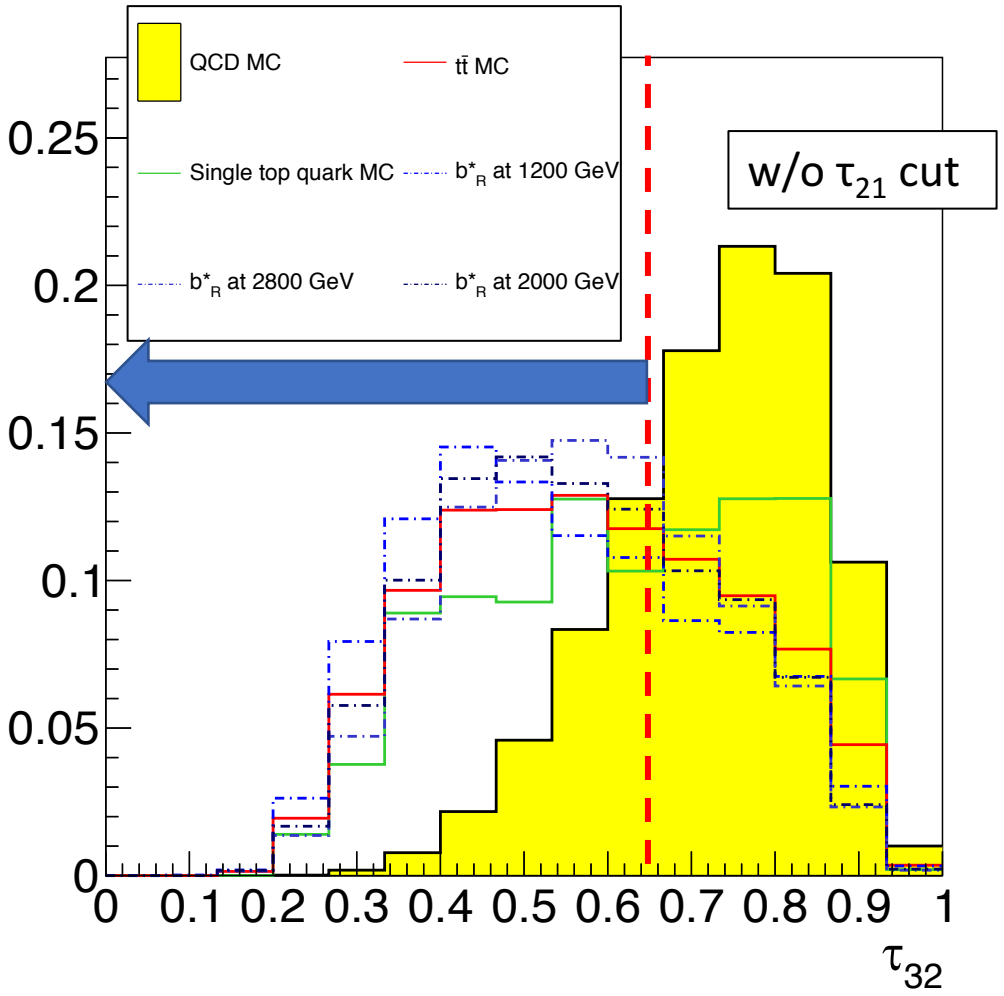
Correction to Shape of M_{top} Distribution



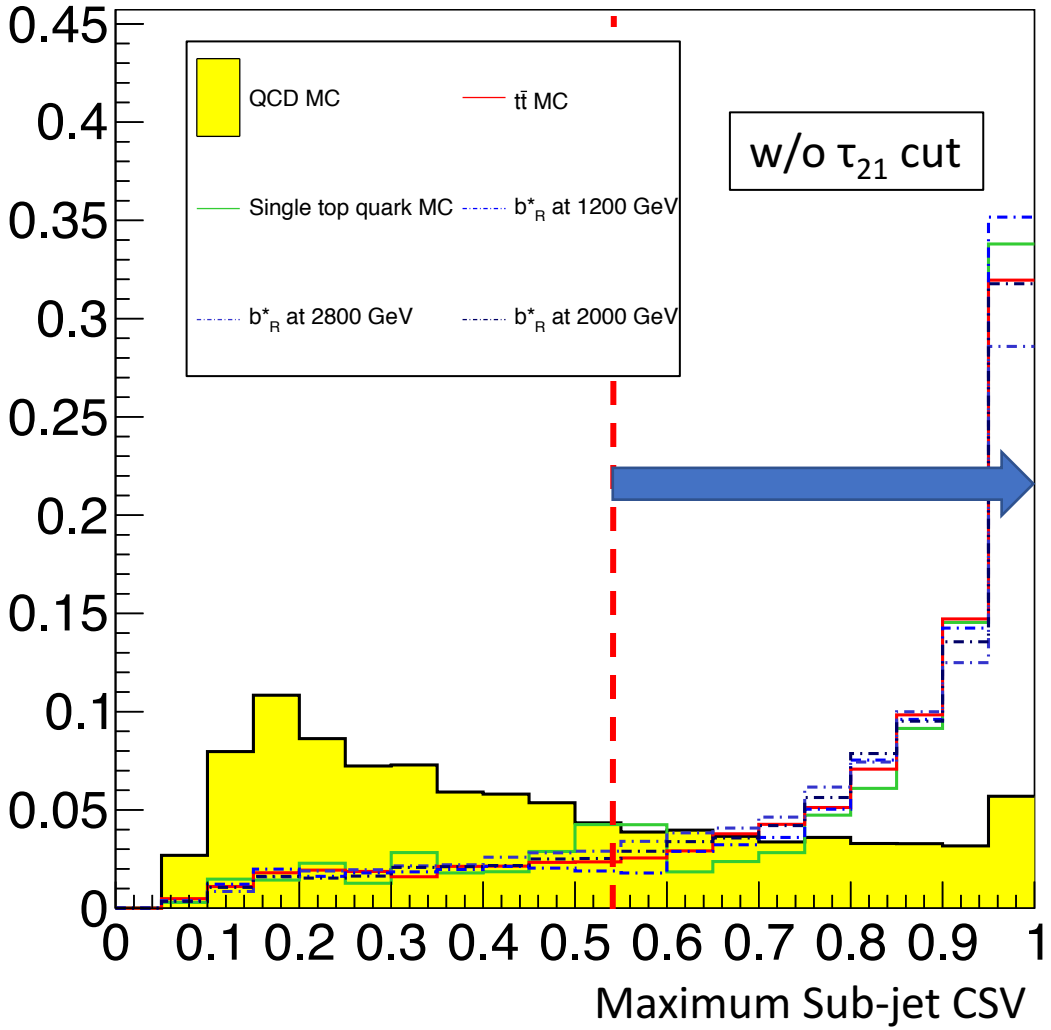
1. Normalize top tag pass and fail distributions as functions of M_{top} for QCD MC
2. Find $R_{P/F}(M_{top})$

Cut Variables in Signal Region

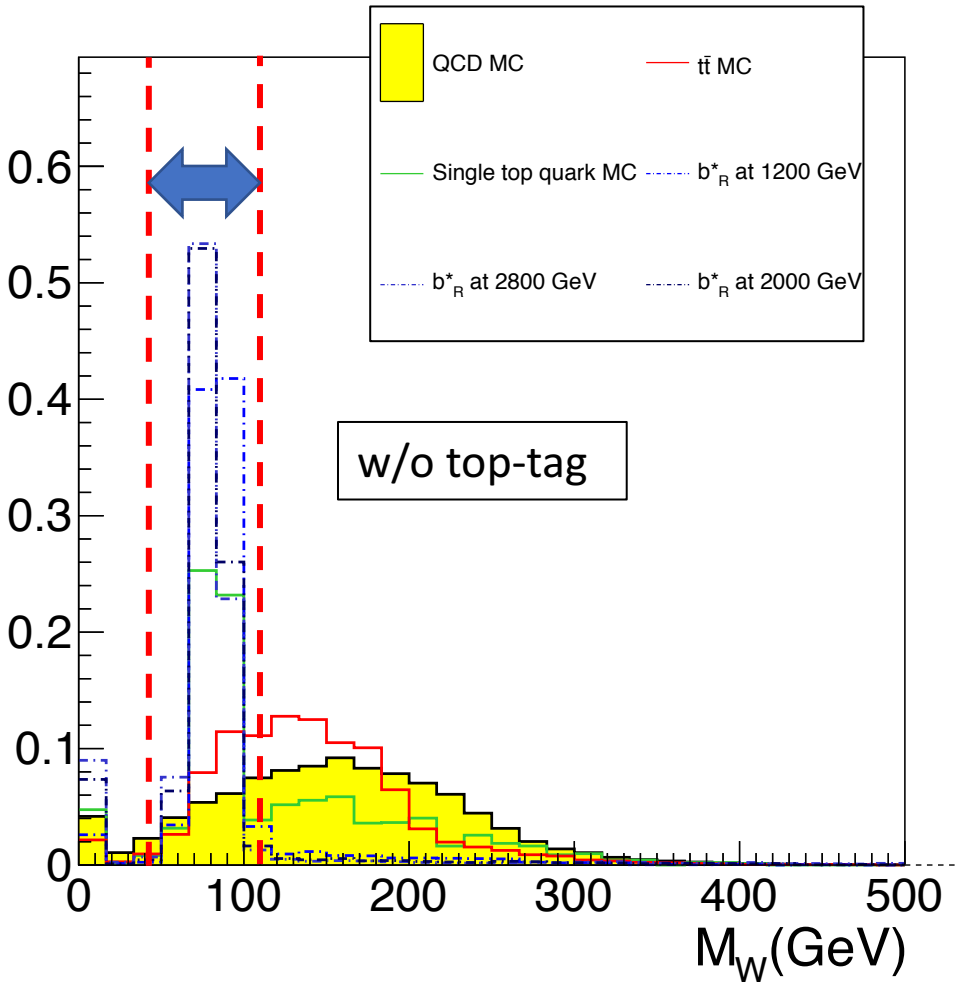


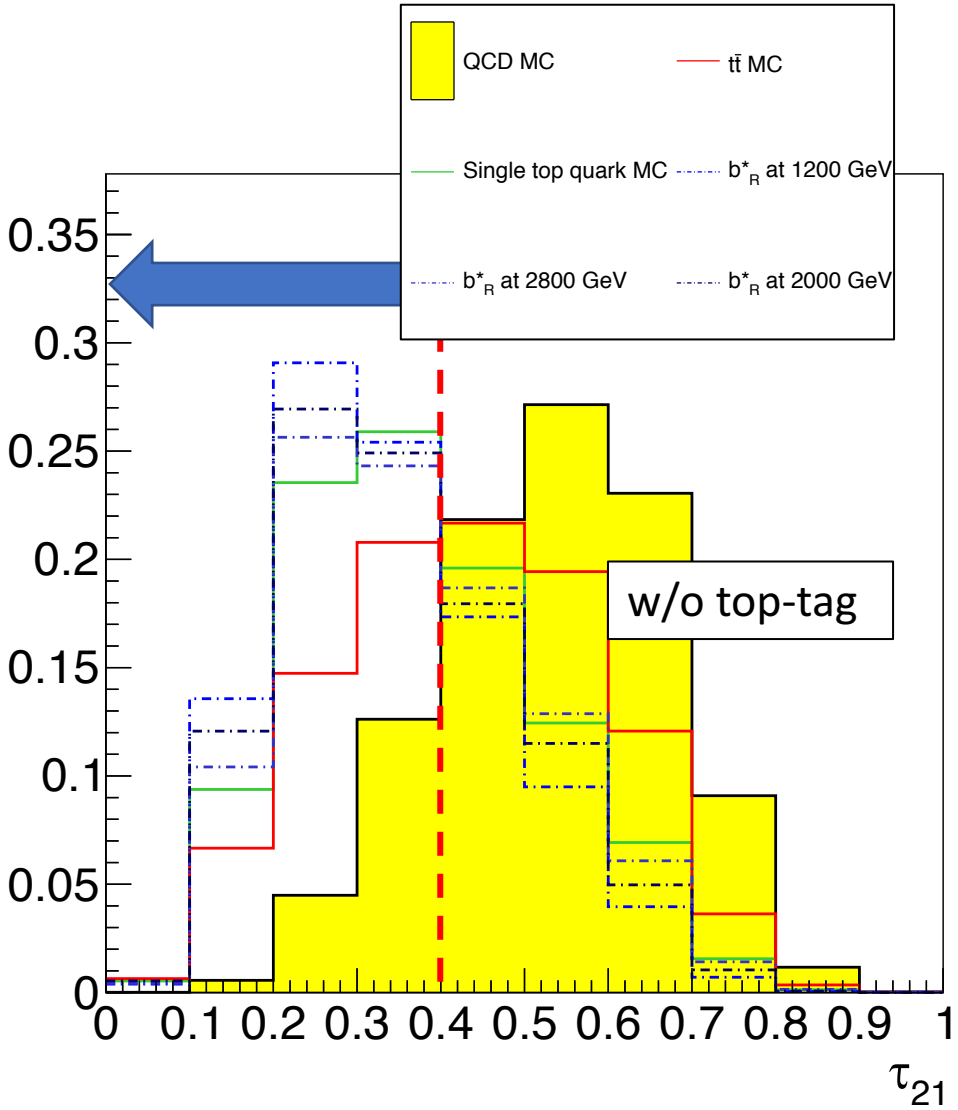


Cut Variables in Signal Region



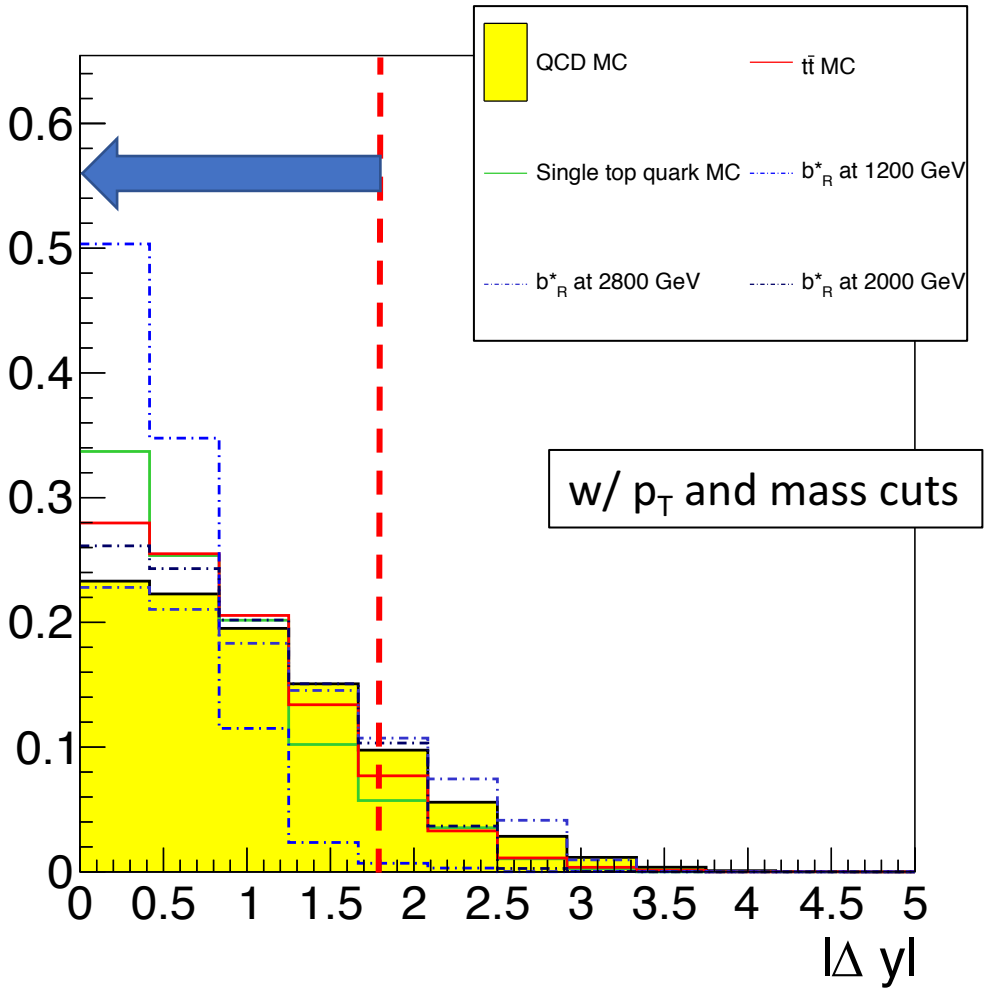
Cut Variables in Signal Region



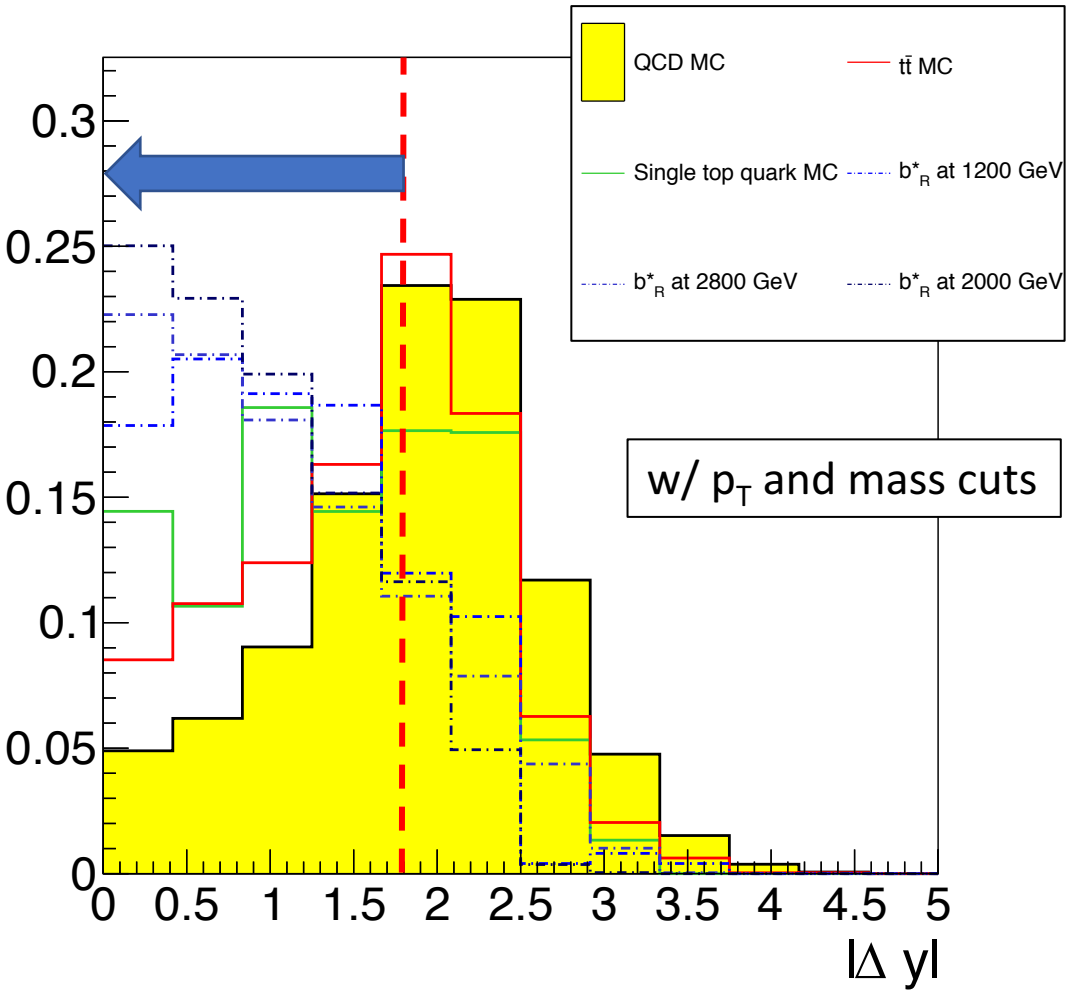


Cut Variables in Signal Region

No M_{tW} cut



M_{tW} > 1800 GeV

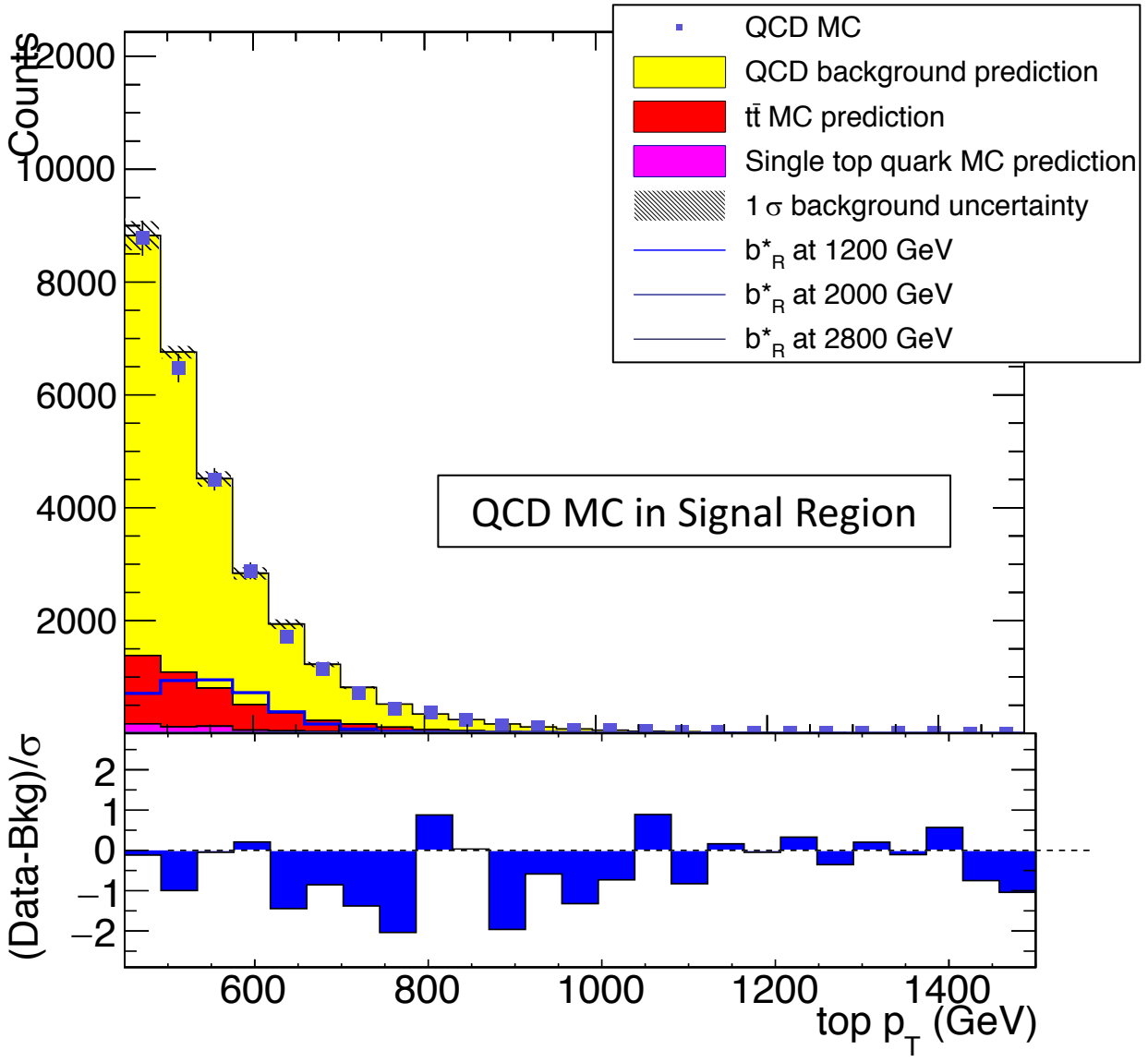


Top p_T Reweighting

Using TOP groups recommendation for $p_T < 400$ GeV as first-order reweight

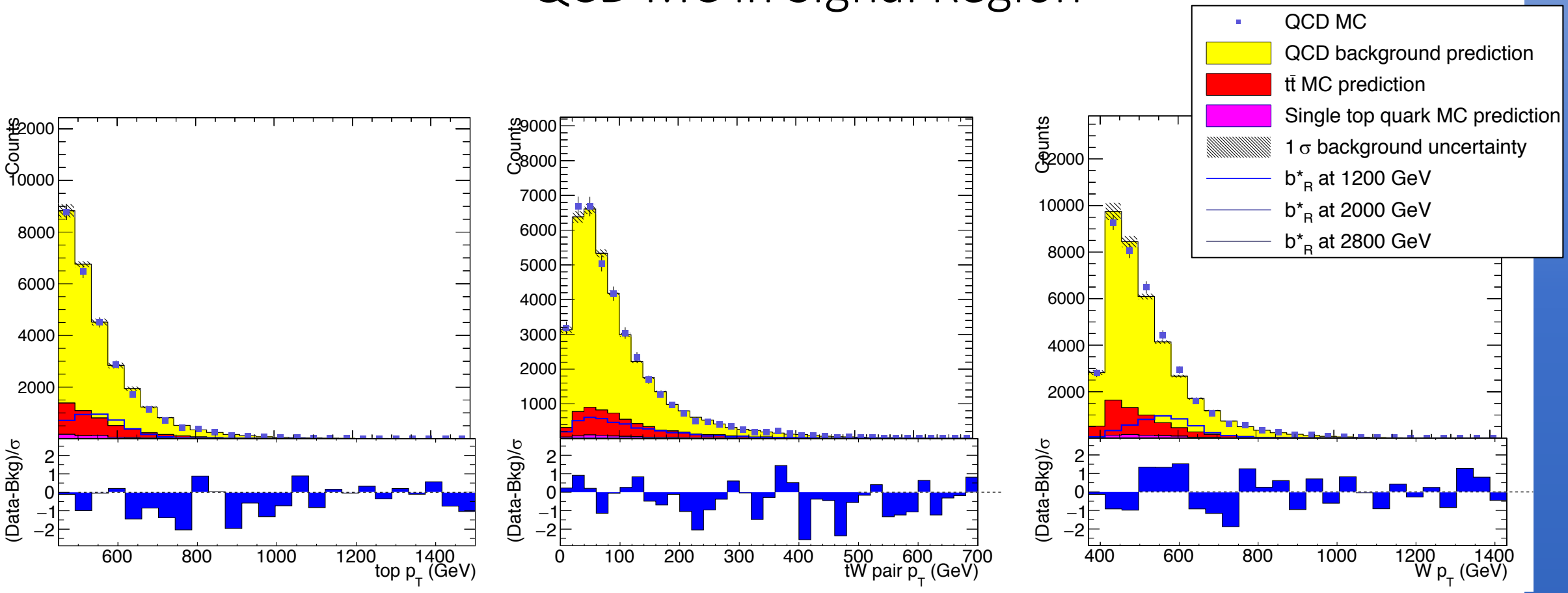
- $SF(p_T) = e^{0.0615 - 0.0005 \cdot p_T}$
- $w = \sqrt{SF(t)SF(\bar{t})}$

Uncertainty taken as +/- half the difference between weighting and not weighting



Kinematic Distributions – p_T

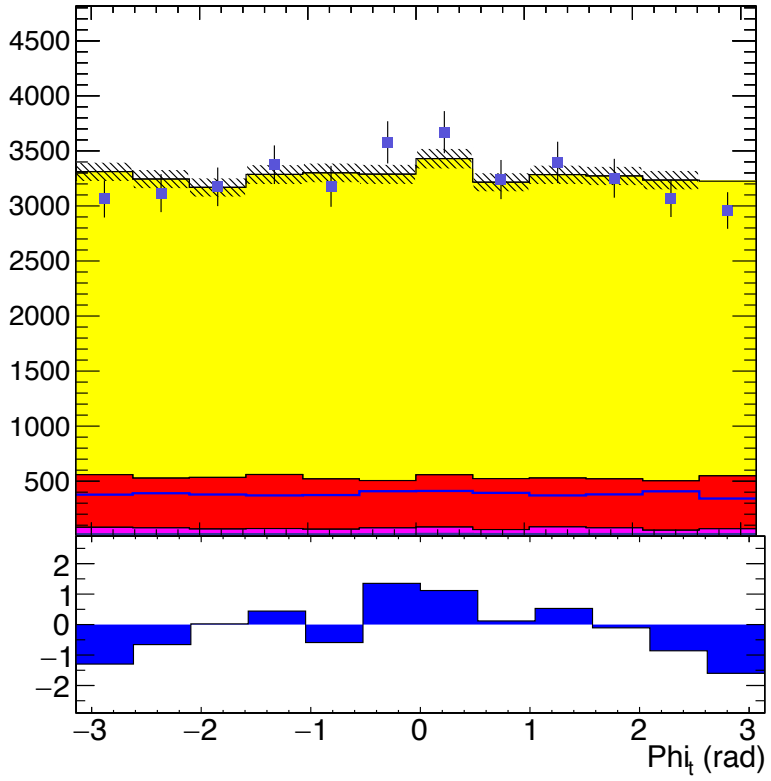
QCD MC in Signal Region



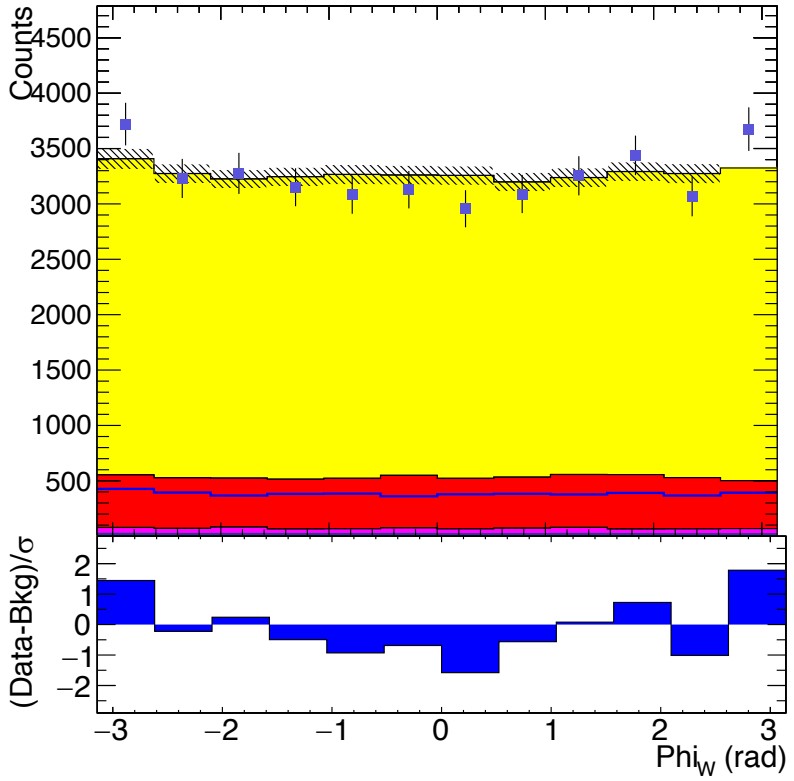
Top p_T W p_T tW p_T

Kinematic Distributions – phi

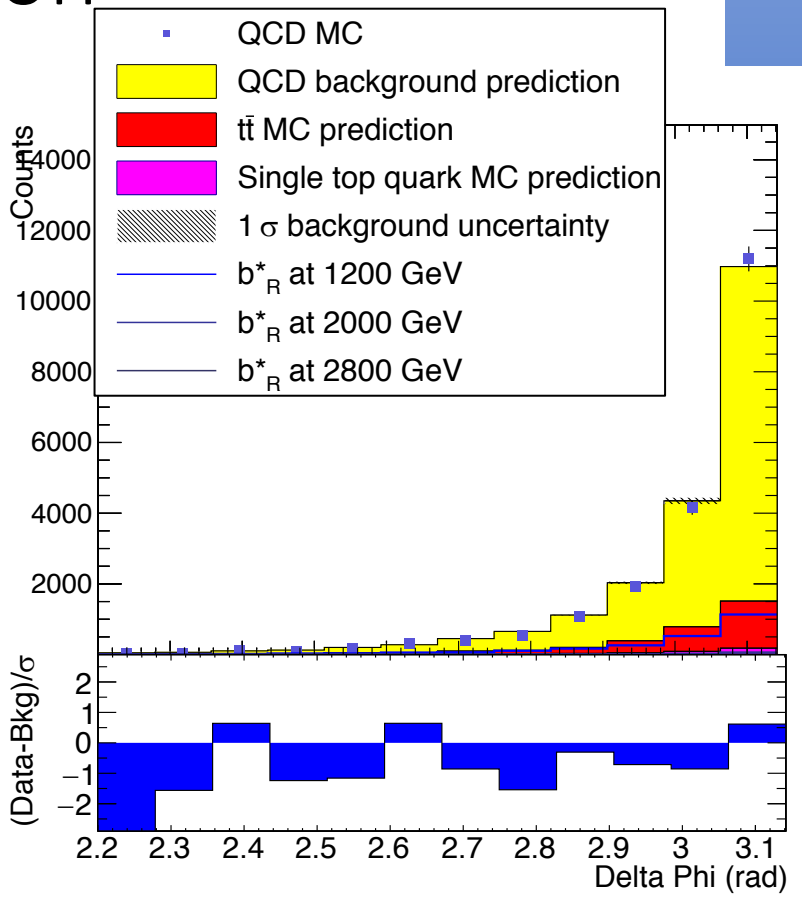
QCD MC in Signal Region



Top Phi



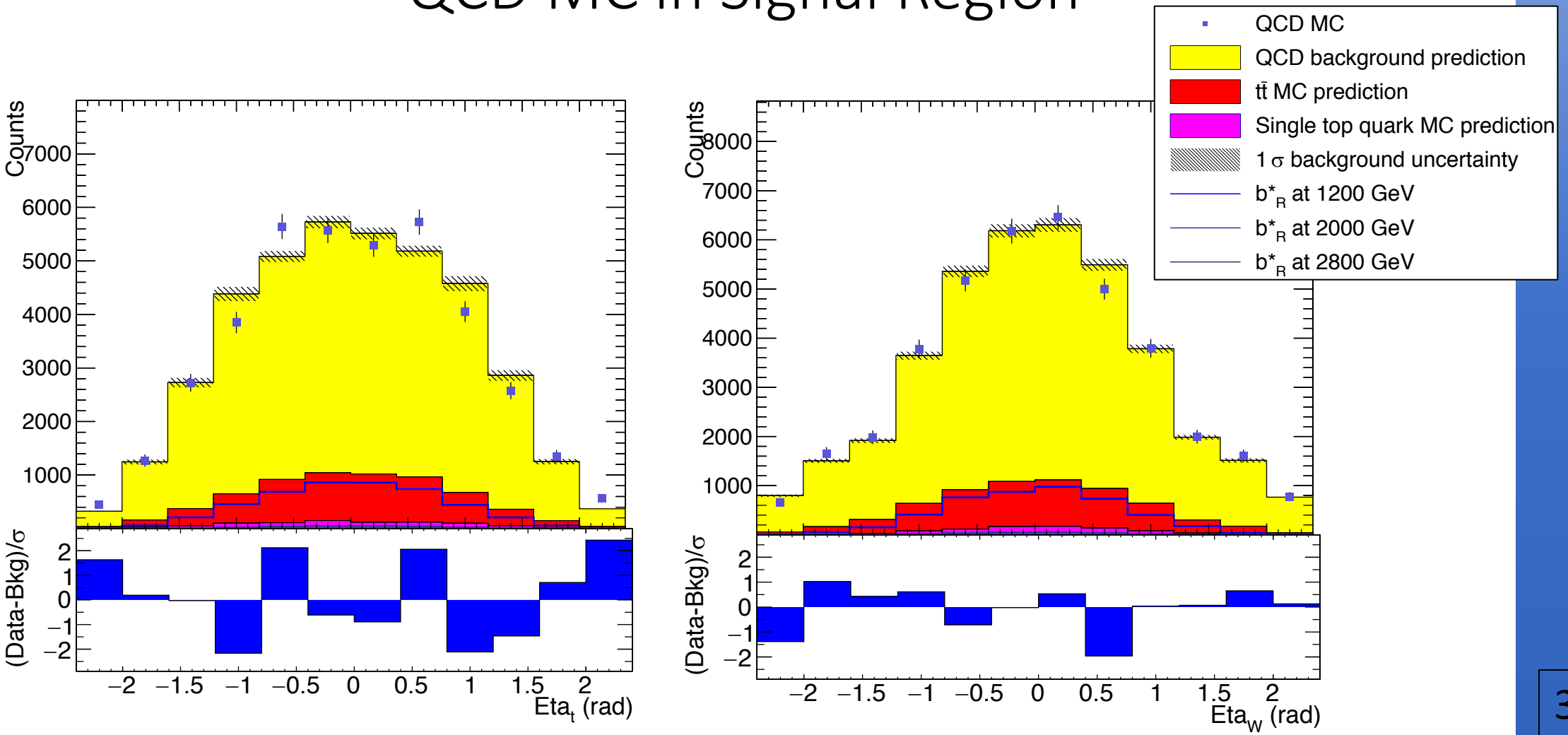
W Phi



Δφ

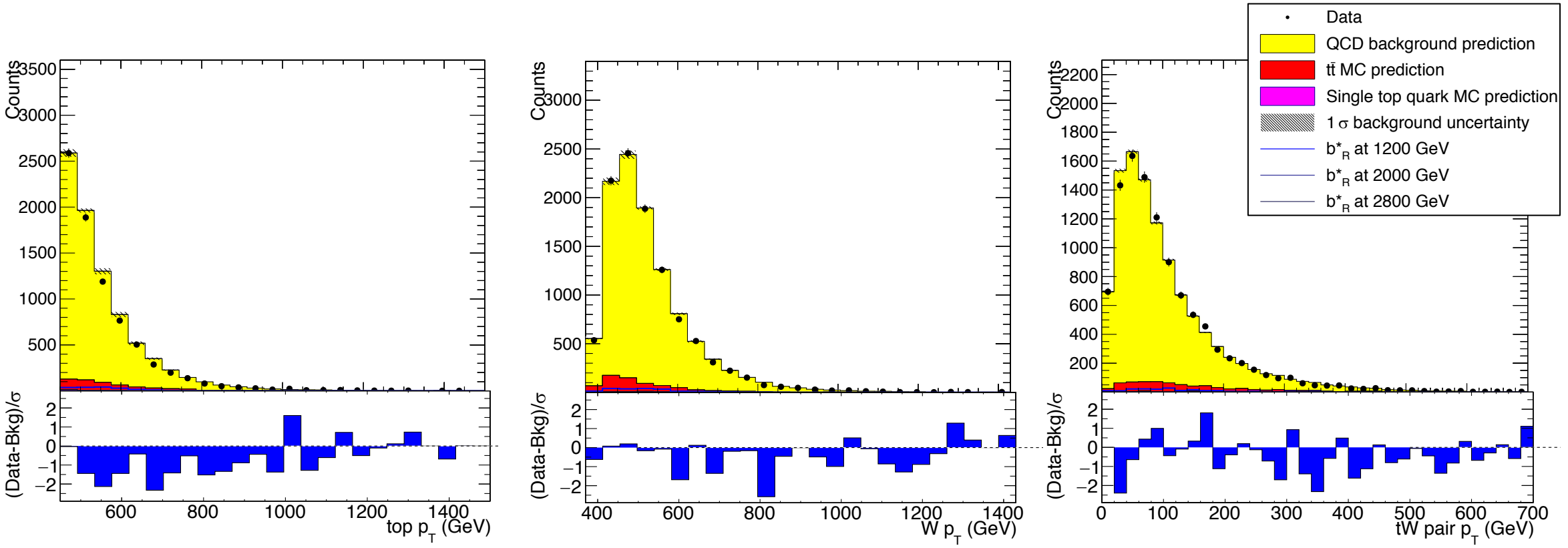
Kinematic Distributions – Eta

QCD MC in Signal Region



Kinematic Distributions – p_T

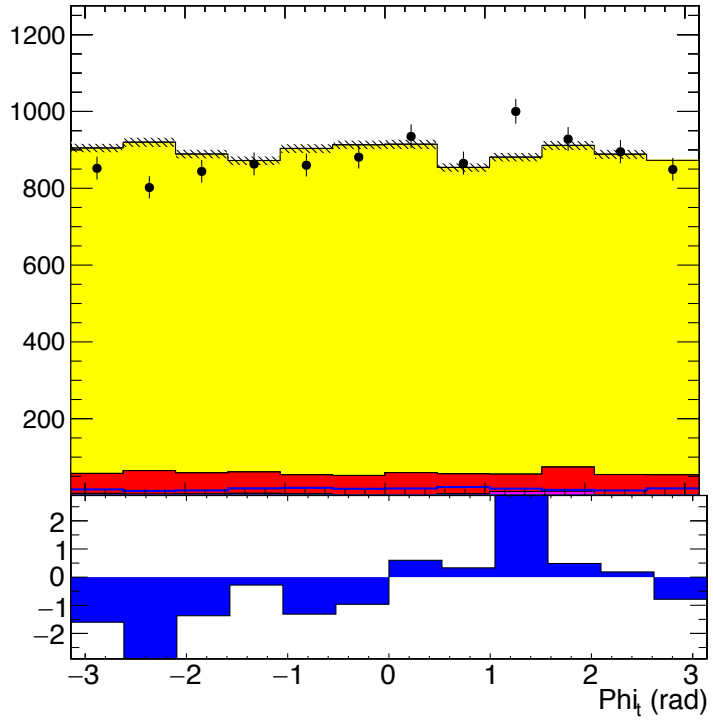
Data in Sideband Region



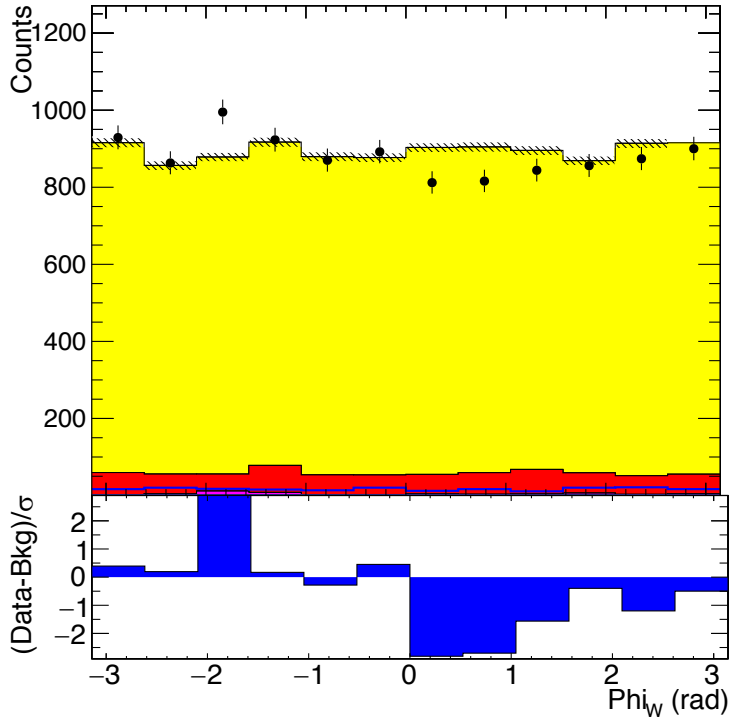
Top p_T W p_T tW p_T

Kinematic Distributions – phi

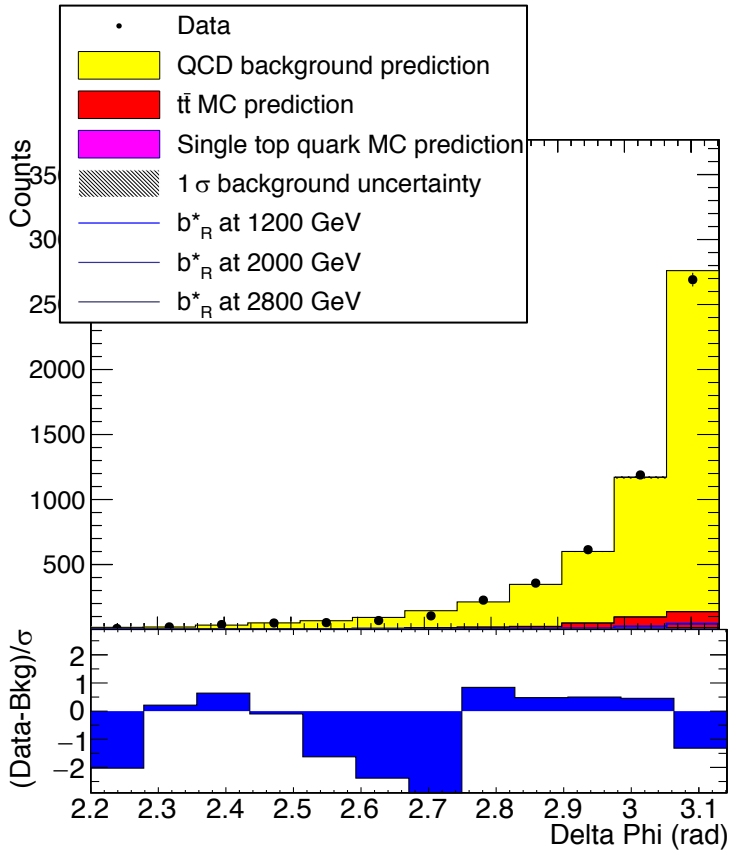
Data in Sideband Region



Top Phi



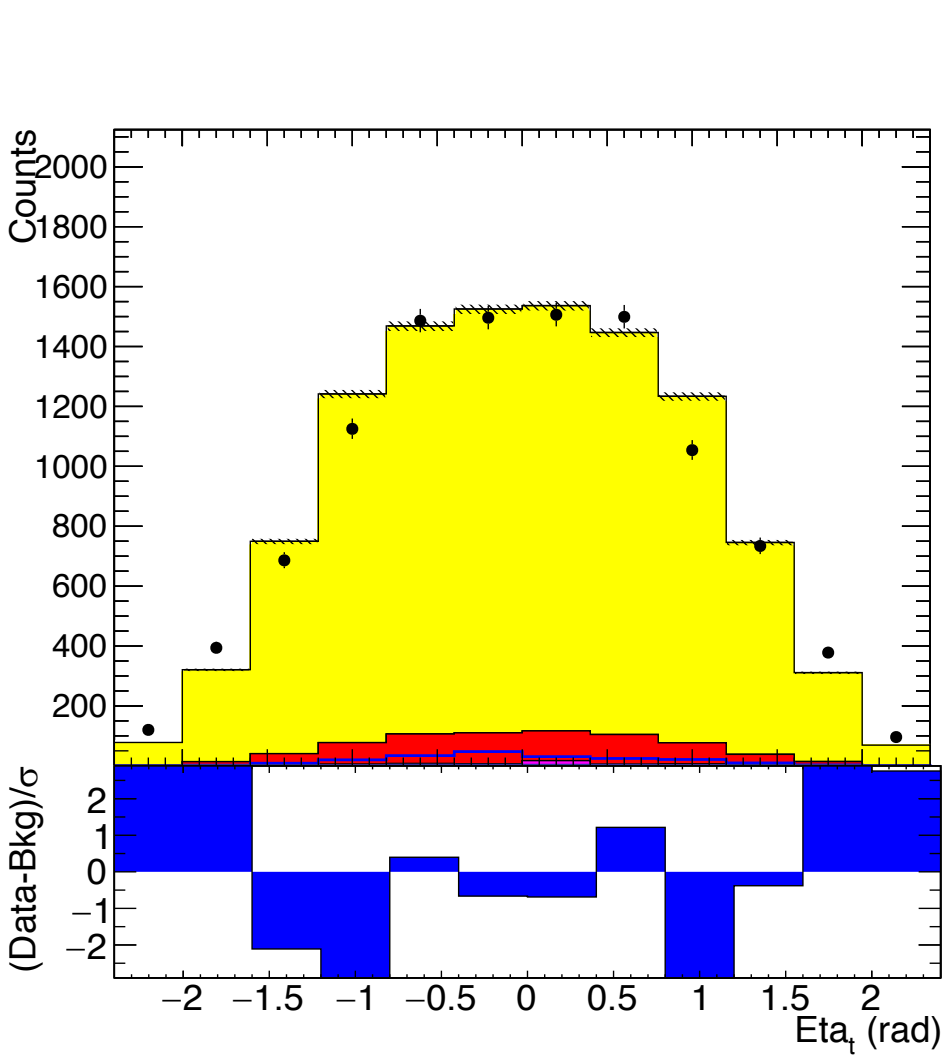
W Phi

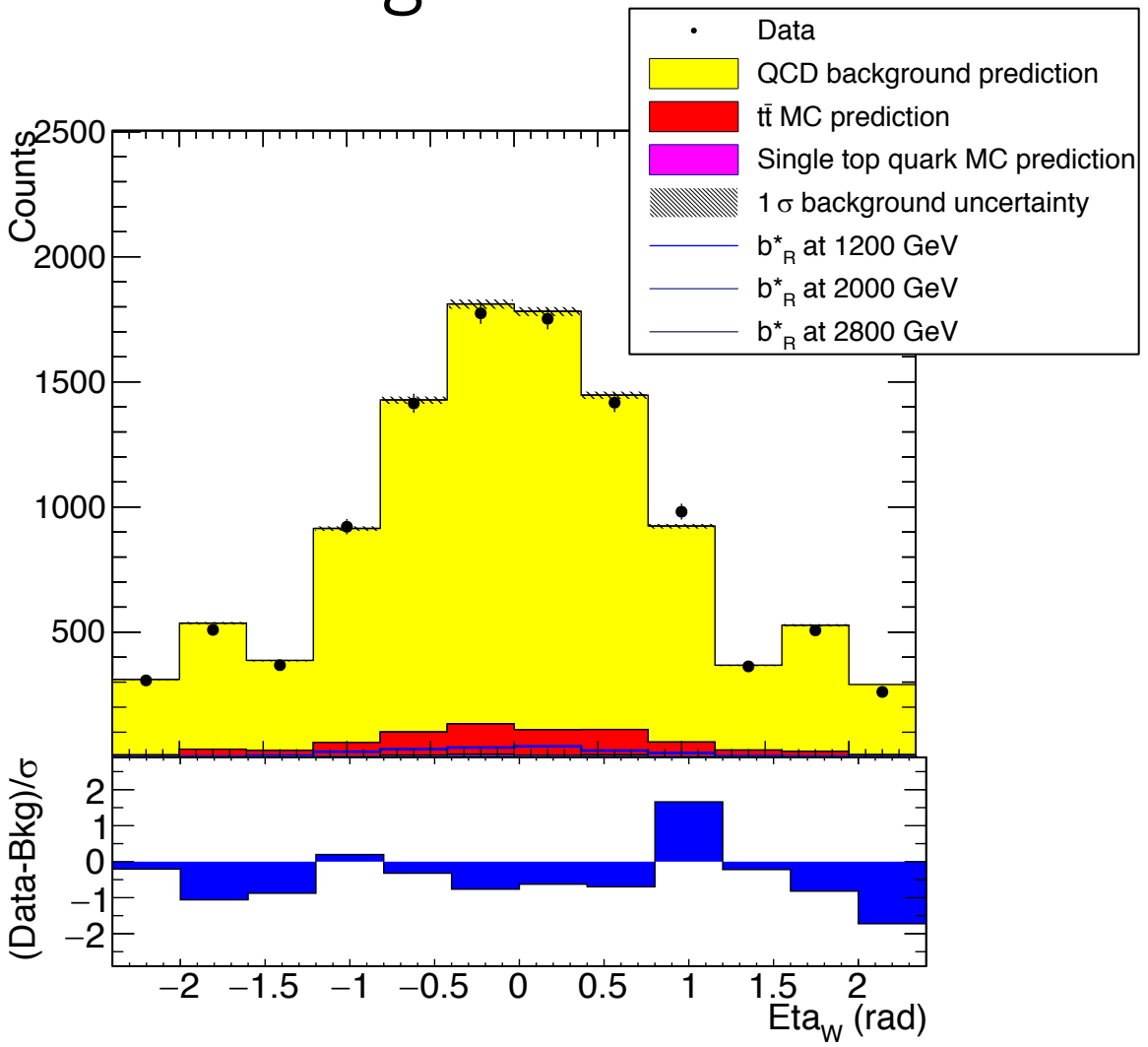


Δφ

Kinematic Distributions – Eta

Data in Sideband Region

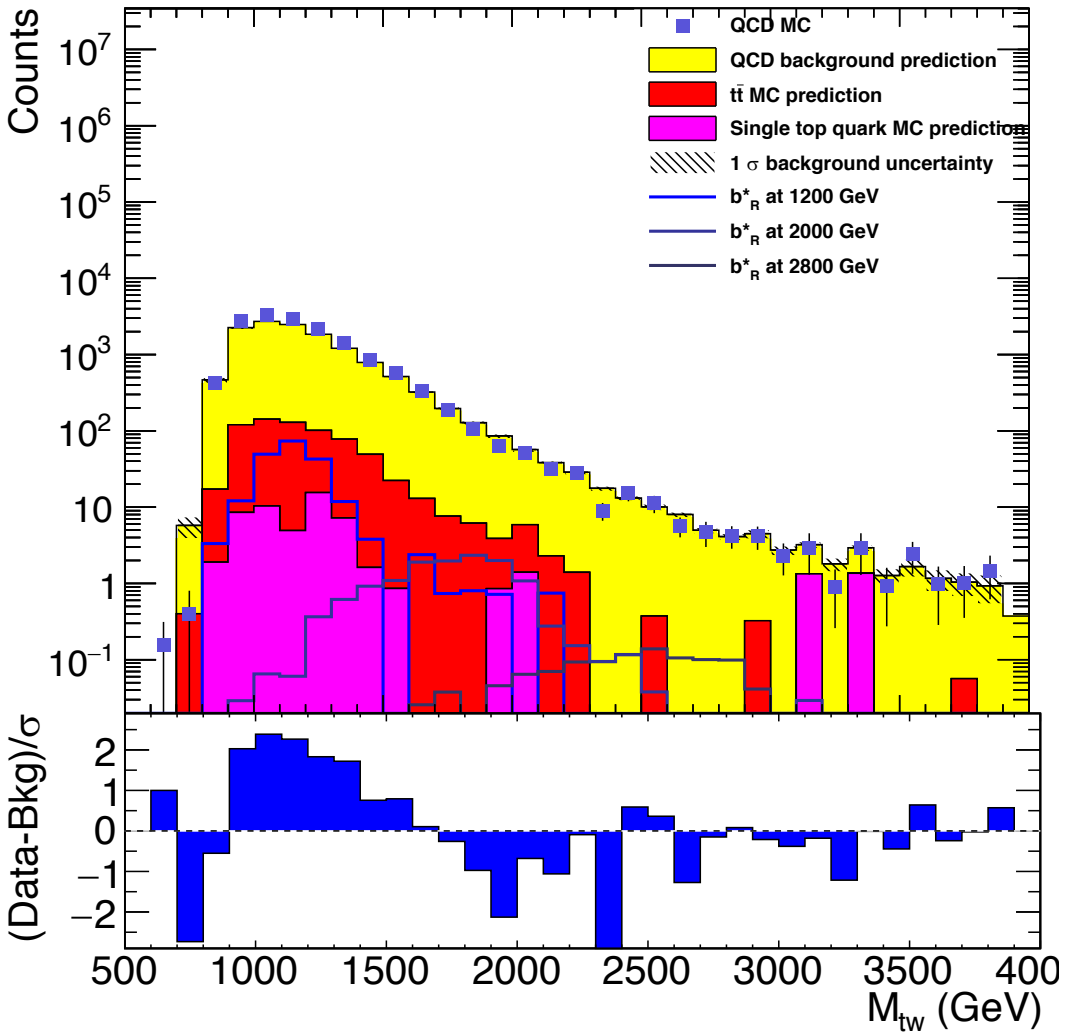


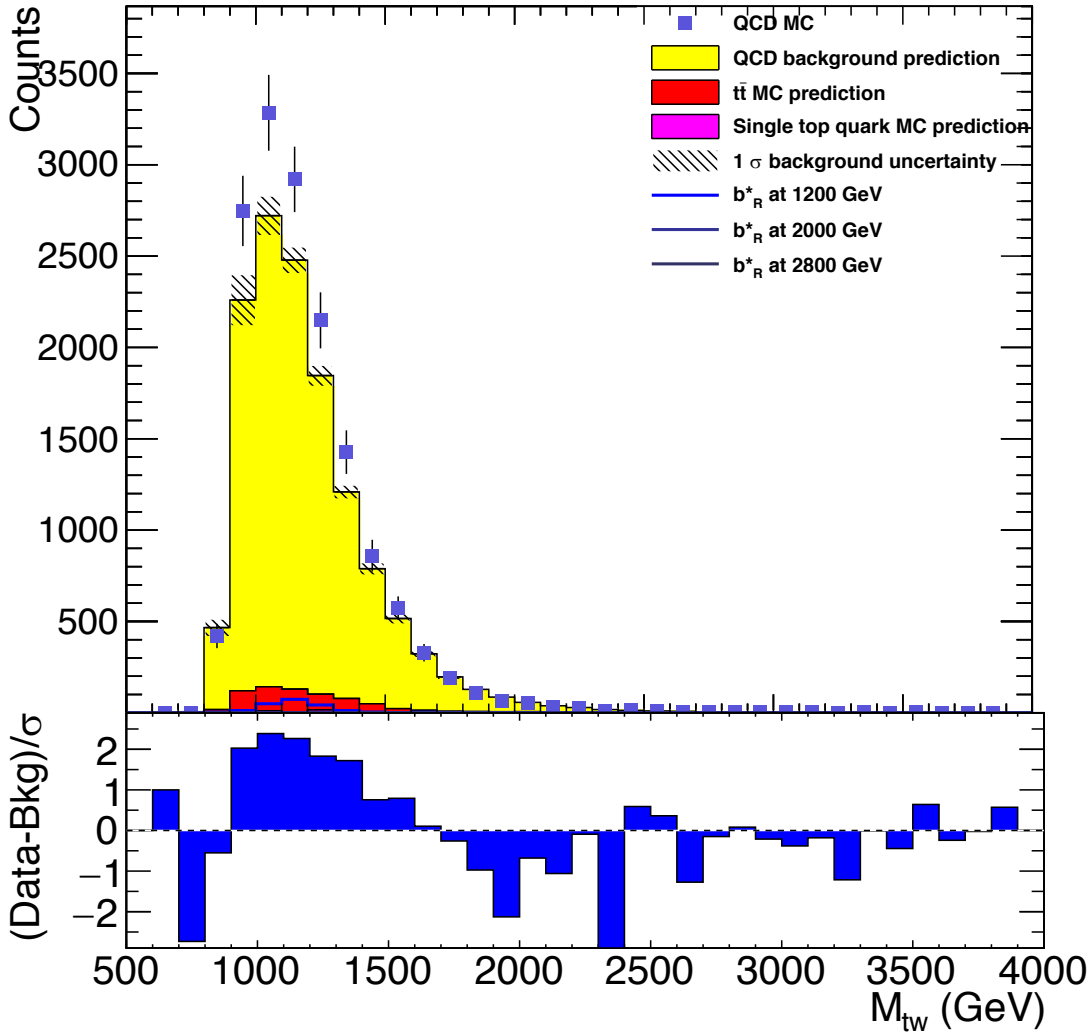


Systematic Uncertainties - MC

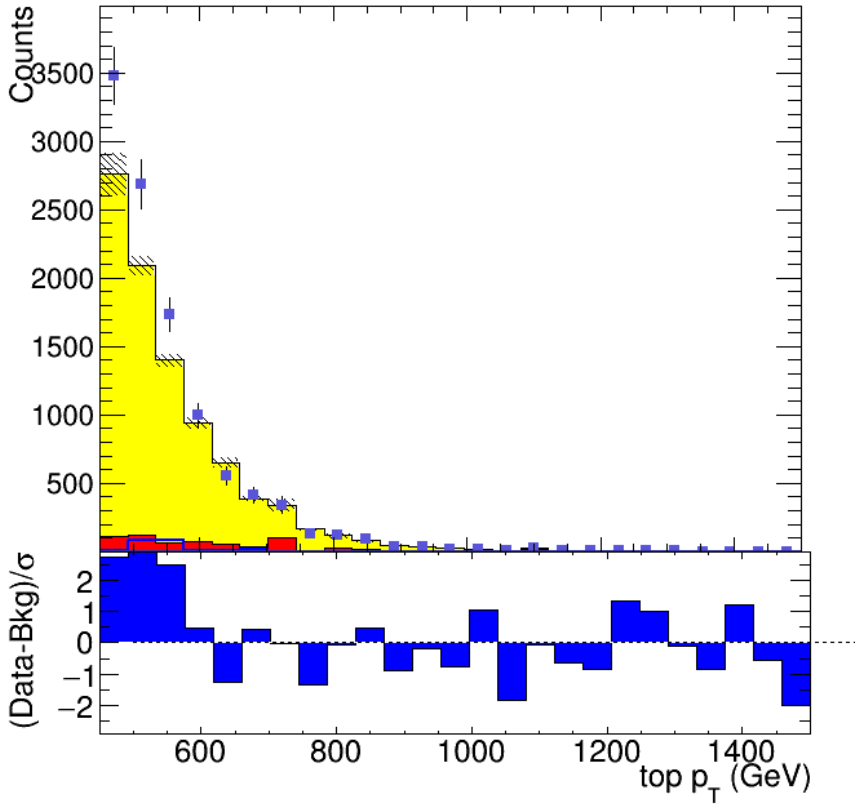
Source	Variation	Samples
$t\bar{t}$ cross section	+ 4.8%, - 5.5%	$t\bar{t}$
Single top (tW) cross section	± 3.9%	Single top (tW-channel)
Single top (t-channel, top) cross section	+ 3.4%, - 4.0%	Single top (t-channel, top)
Single top (t-channel, anti-top) cross section	+ 4.5%, - 5.0%	Single top (t-channel, anti-top)
Luminosity	± 2.6%	$t\bar{t}$, single top, signal
Pileup	± 1σ (σ_{mb})	$t\bar{t}$, single top, signal
PDF	± 1σ (x, Q^2)	$t\bar{t}$, signal
Jet Energy Scale	± 1σ (p_T)	$t\bar{t}$, single top, signal
Jet Energy Resolution	± 1σ (p_T, η)	$t\bar{t}$, single top, signal
Q^2 Scale	± 1σ (Q^2)	$t\bar{t}$
W tagging	± 6%	single top, signal
Top tagging	+ 14%, - 5.6%	$t\bar{t}$, single top, signal
Trigger	± 1σ (H_T)	$t\bar{t}$, single top, signal
Alternate functional forms, Pass-fail ratio fit, Top mass shape correction	± 1σ (p_T, η)	QCD (from data)

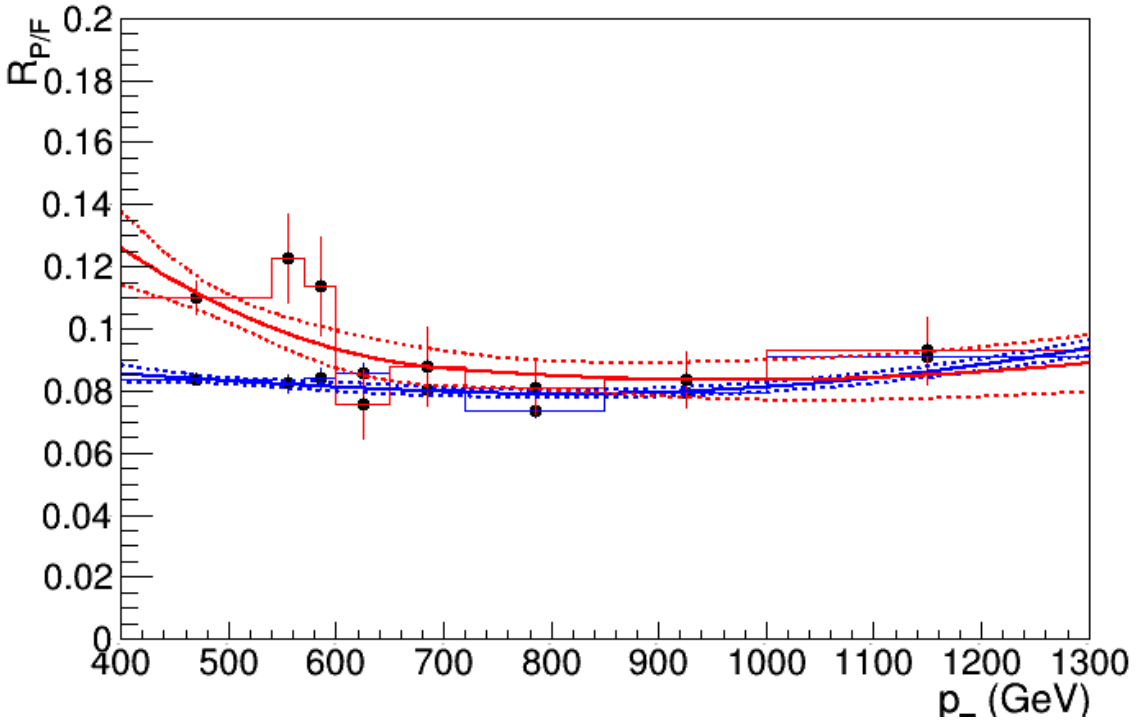
Sideband Closure – QCD MC





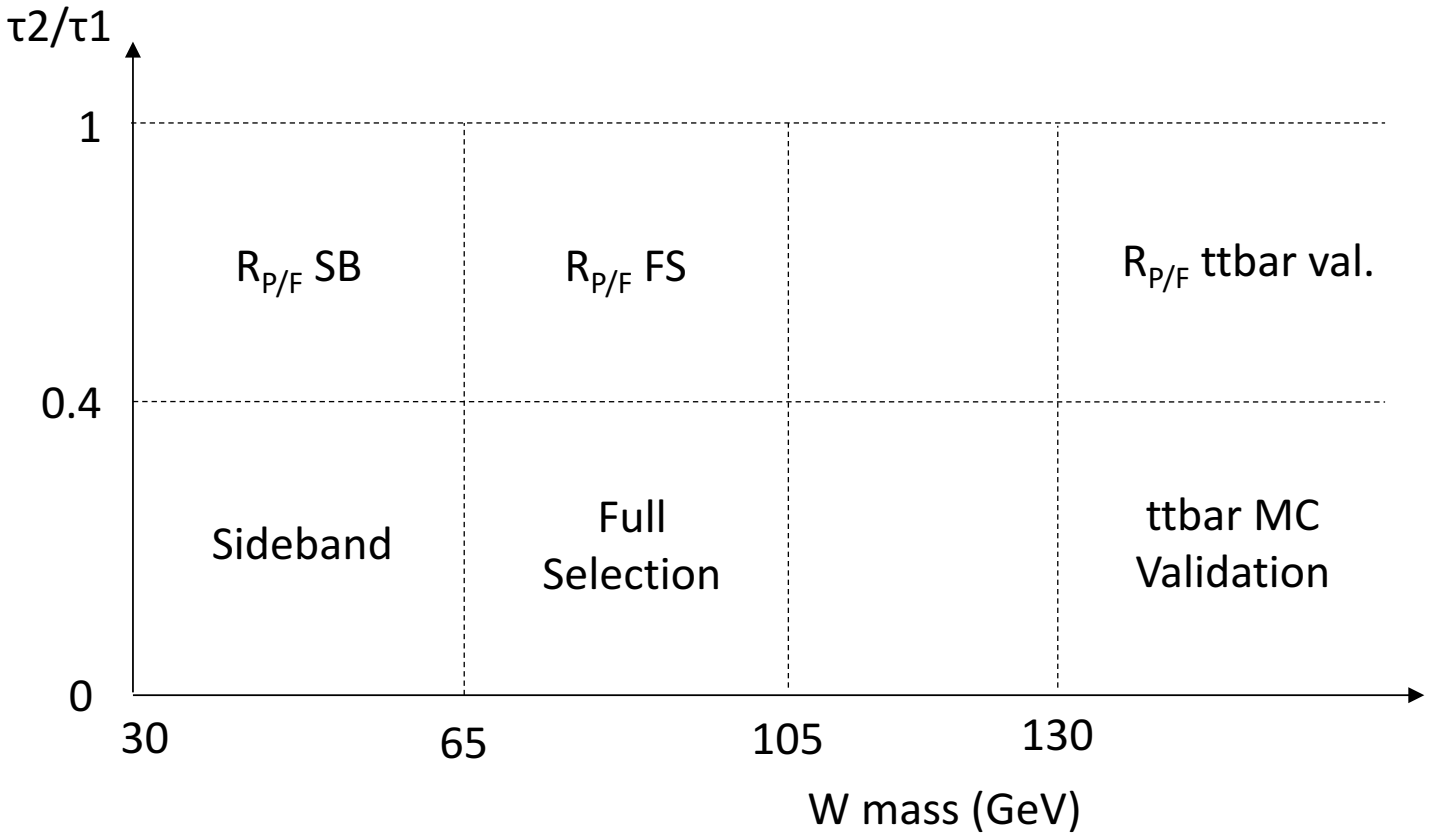
Sideband Closure – QCD MC





Background Estimate Studies

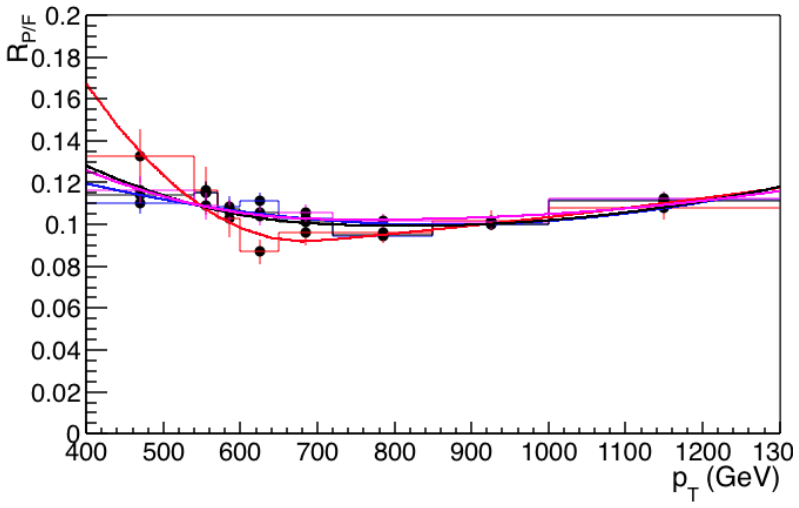
- Looked at QCD MC in various ”W space” to study pass-fail ratios
  - Also tried parameterizing in M_{tW}

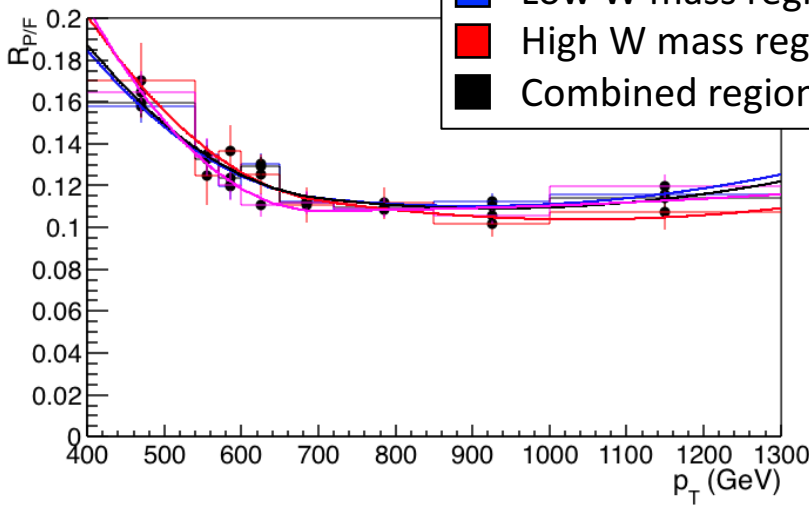


Background Studies

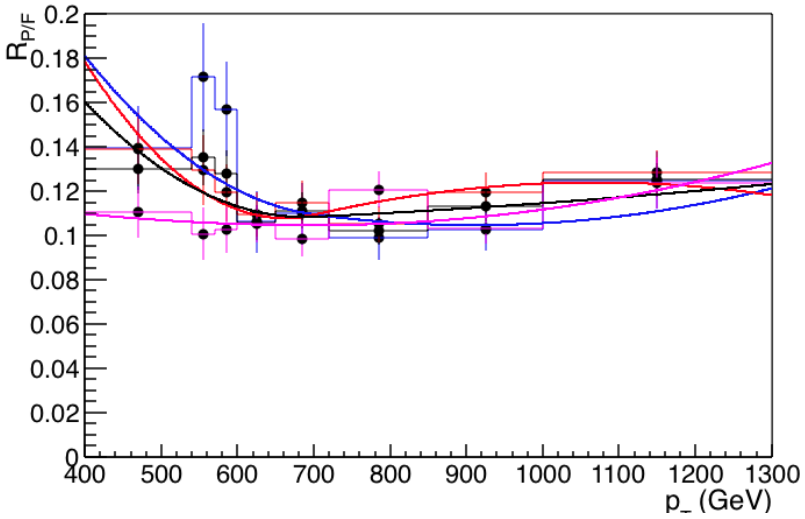
Cheat region (what we want to model)
Low W mass region
High W mass region
Combined region (default)

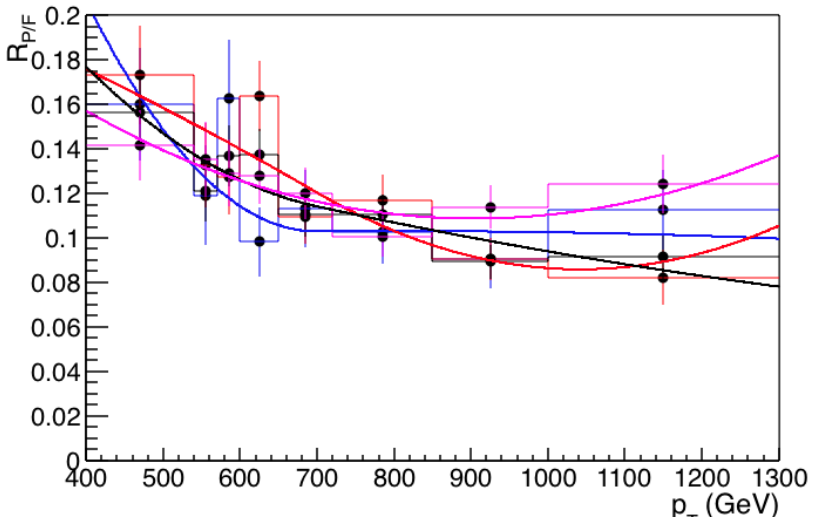
Tau21 > 0.4



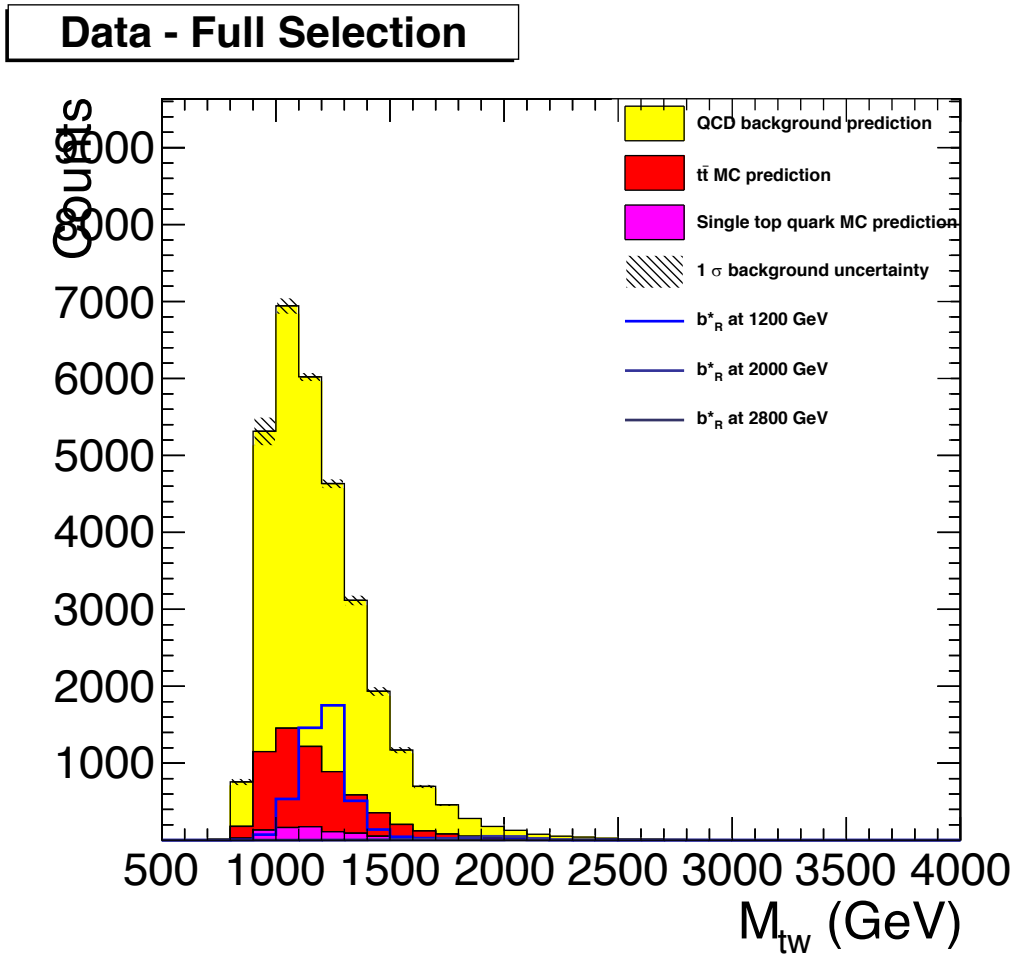


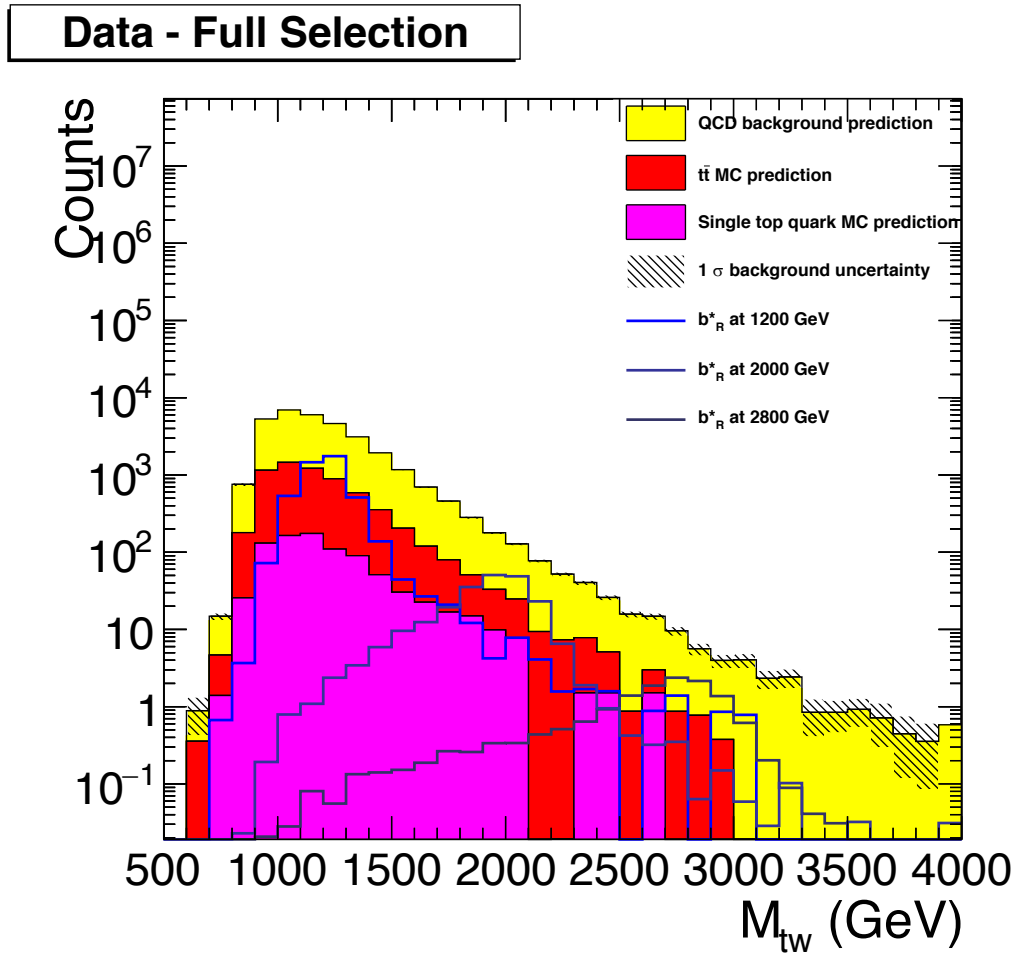
Tau21 < 0.4





Blinded Data - Signal Region





Data/MC Sets

Set	Name	Cross Section (pb)
Data	JetHT/Run2016BCD(E)(F)(G)(H)(HV2)-PromptReco-v2	N/A
QCDHT500	QCD_HT500to700_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	31630
QCDHT700	QCD_HT700to1000_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	6802
QCDHT1000	QCD_HT1000to1500_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	1206
QCDHT1500	QCD_HT1500to2000_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	120.4
QCDHT2000	QCD_HT2000toInf_TuneCUETP8M1_13TeV-madgraphMLM-pythia8	25.25
ttbar MC	TT_TuneCUETP8M2T4_13TeV-powheg-pythia8	831.76
Single-t_top	ST_t-channel_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M2T4	136.02
Single-t_antitop	ST_t-channel_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M2T4	80.95
Single-tW	ST_tW-channel_(anti)top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M2T4	80.95

Signal Sets

Signal Left (GeV)	Name	Cross Section (pb)
1200	BstarToTW_M-1200_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	1.944
1400	BstarToTW_M-1400_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.7848
1600	BstarToTW_M-1600_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.3431
1800	BstarToTW_M-1800_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.1588
2000	BstarToTW_M-2000_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0771
2200	BstarToTW_M-2200_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0388
2400	BstarToTW_M-2400_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0202
2600	BstarToTW_M-2600_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0107
2800	BstarToTW_M-2800_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0058
3000	BstarToTW_M-3000_LH_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0032