Search for $H^+ \rightarrow cbbar$

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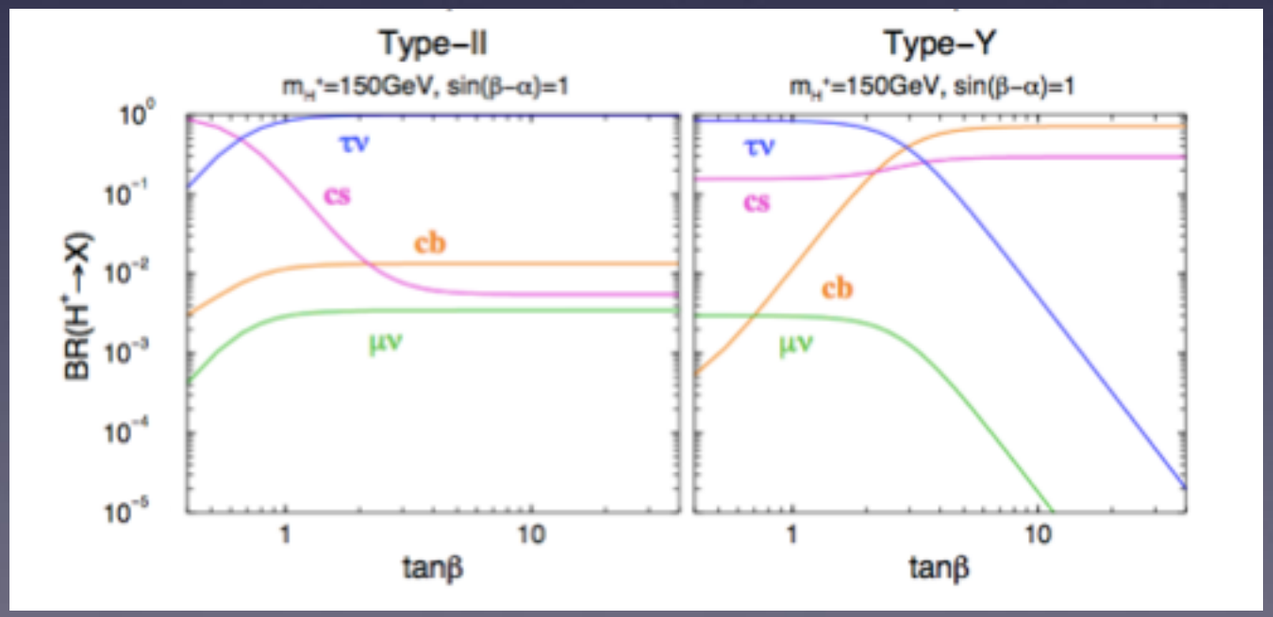
ARC review meeting, 12/12/17

Basics

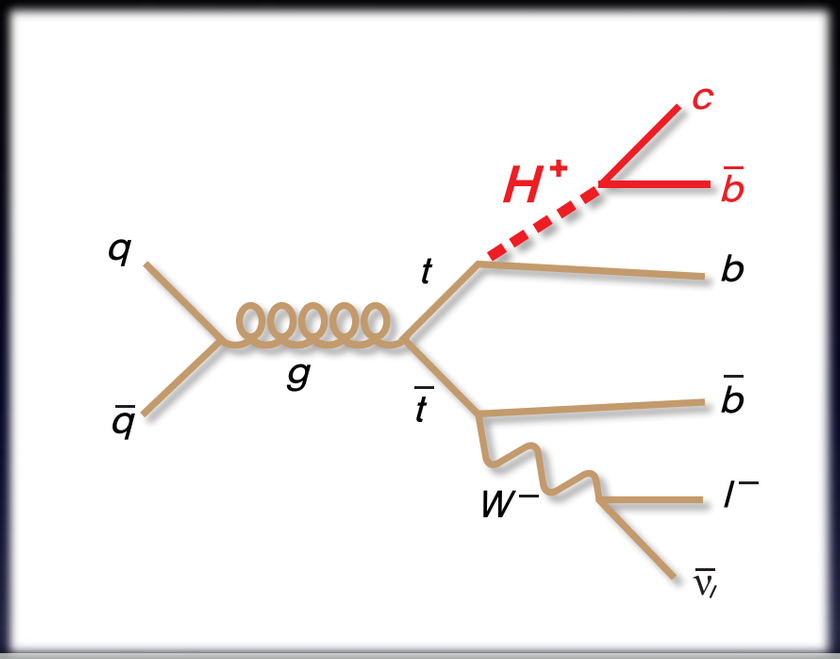
- $H^+ \rightarrow c\bar{b}$ study was started on demand after $H^+ \rightarrow c\bar{s}$ study was published
- Consider light H^+ search from top quark decays : $M(H^+)<M(t)$
- Famous 2HDM four different types : type-Y expects sizable branching ratio of $H^+ \rightarrow c\bar{b}$
- The search is performed assuming $B(H^+ \rightarrow c\bar{b})=100\%$ and aims to measure $B(t \rightarrow H^+b)$ in lepton+jets top quark pair events



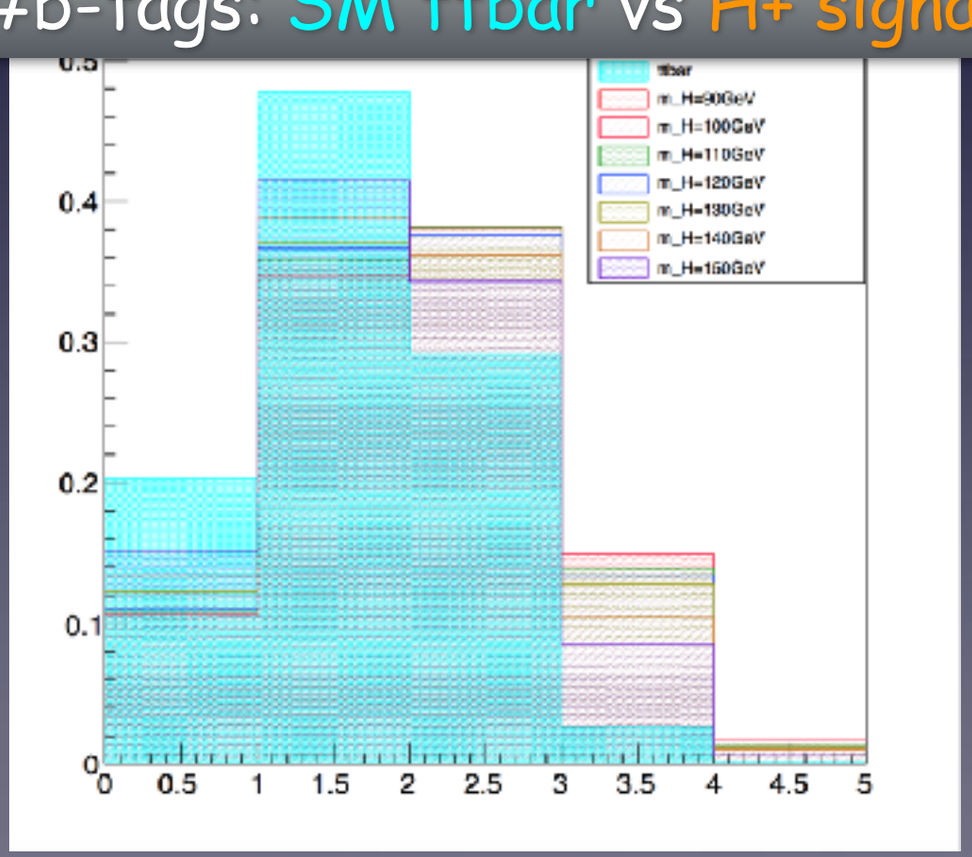
Modified from Kei Yagyu et al., arXiv:0902.4665v3

Search Strategy

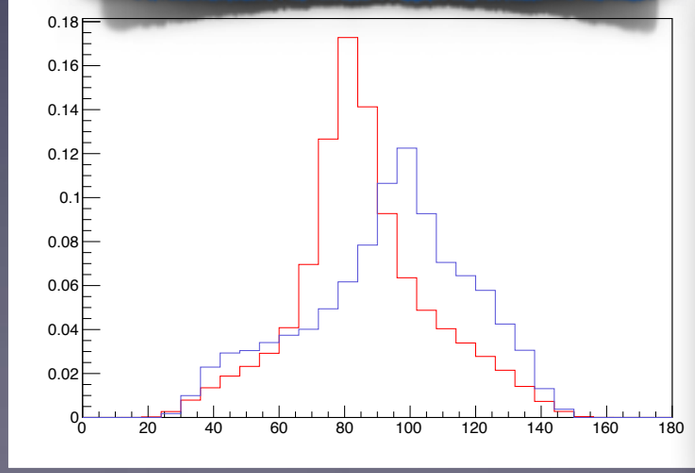
- Simultaneous fit both 2 b-tag and 3 b-tag events
  - In 2 b-tag region: extract SM ttbar normalization
  - In 3 b-tag region: extract the signal with a constrained SMttbar background from 2 b-tag events
- Look for a second peak over W from SM ttbar in the di-jet mass distribution
  - Template fit on the di-jet mass distribution
- When no excess is observed, the limit on B(t→H⁺b) will be estimated using Asymptotic CLs method (Combine)



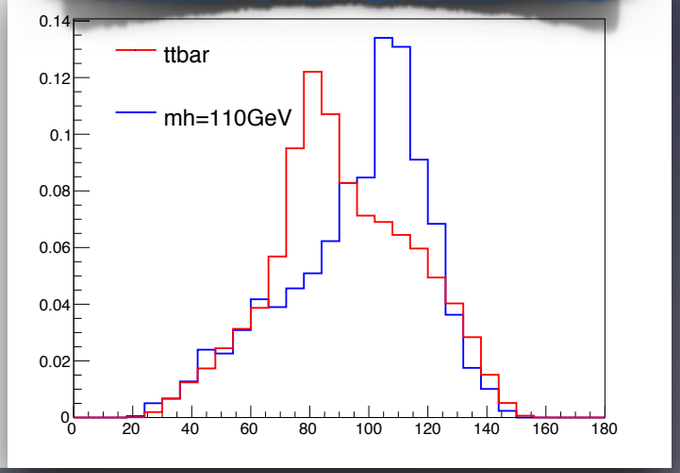
#b-tags: SM ttbar vs H+ signal



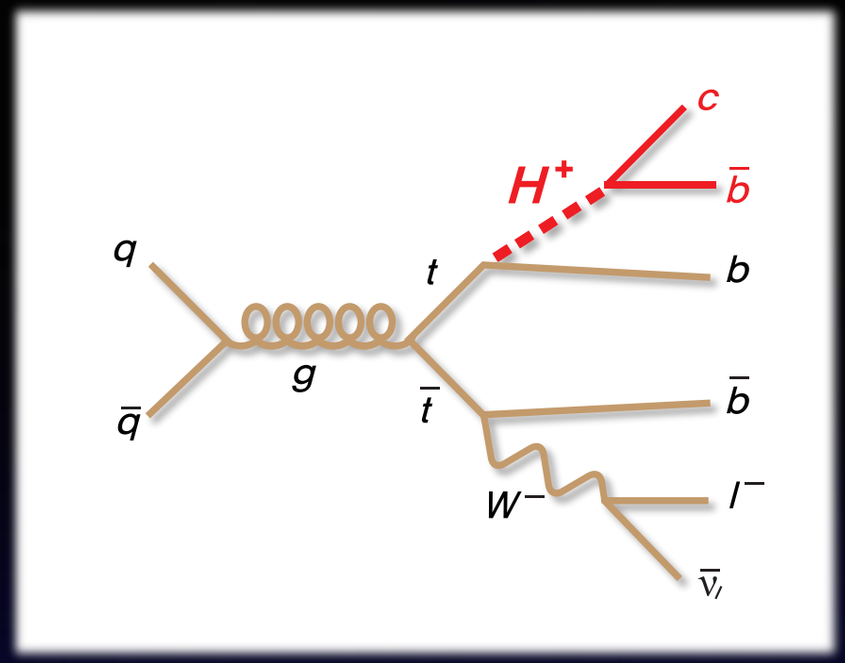
W vs H+(110GeV), 2b



W vs H+(110GeV), 3b

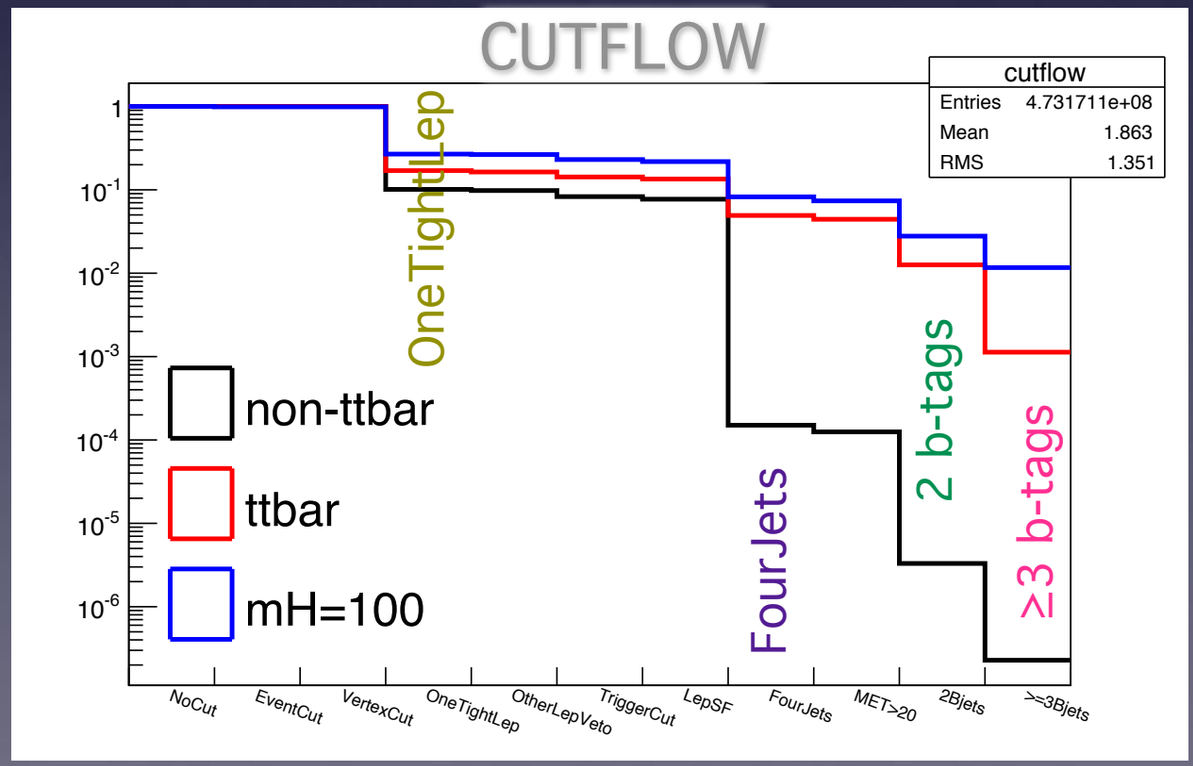


Event Selection



- Single lepton trigger (8TeV)
  - IsoMu24_eta2p1
  - Ele27_WP80
- Final state object (based on run-I TRS):
  - one well-identified, isolated lepton (Veto events with additional veto lepton)
  - electron (p_T>30GeV, $|\eta|$<2.5) or muon (p_T>26GeV, $|\eta|$<2.1)
  - ≥ 4 jets with p_T>30 GeV, $|\eta|$<2.4
  - ≥ 2 jets identified as having a secondary vertex (CSVM)
  - MET ≥ 20 GeV
- Jet energy corrected up to particle-level jets (L1,L23)

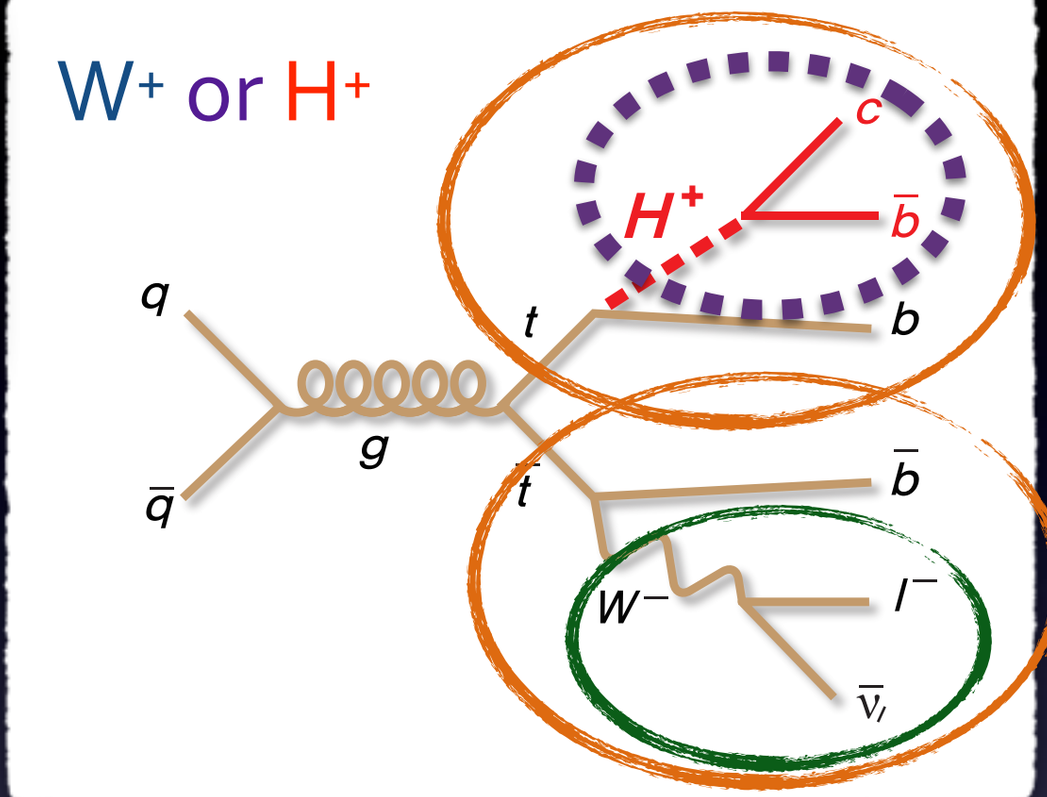
Full reconstruction of ttbar events by kinematic fitter



TTbar kinematic fitter

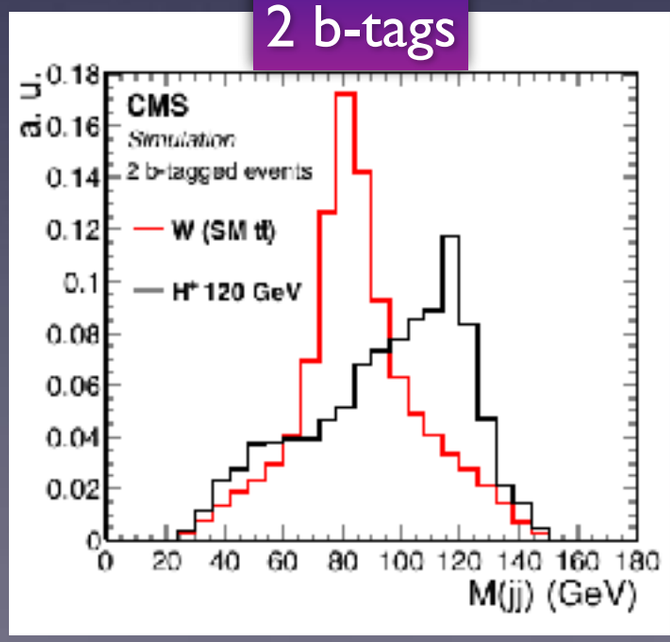
$$\chi^2 = \sum_{i=l,4\,\mathrm{jets}} \frac{(p_T^{i,\mathrm{fit}} - p_T^{i,\mathrm{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{\mathrm{UE,fit}} - p_j^{\mathrm{UE,meas}})^2}{\sigma_{\mathrm{UE}}^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bl\nu} - M_t)^2}{\Gamma_t^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2},$$

- Assign leading four jets to four partons of ttbar
- Constrain masses except the hadronic boson
- Combination satisfying a set of goodness cuts & minimum χ^2 selected for template
  - ~55%(ttbar),~65% (H^+) success rate

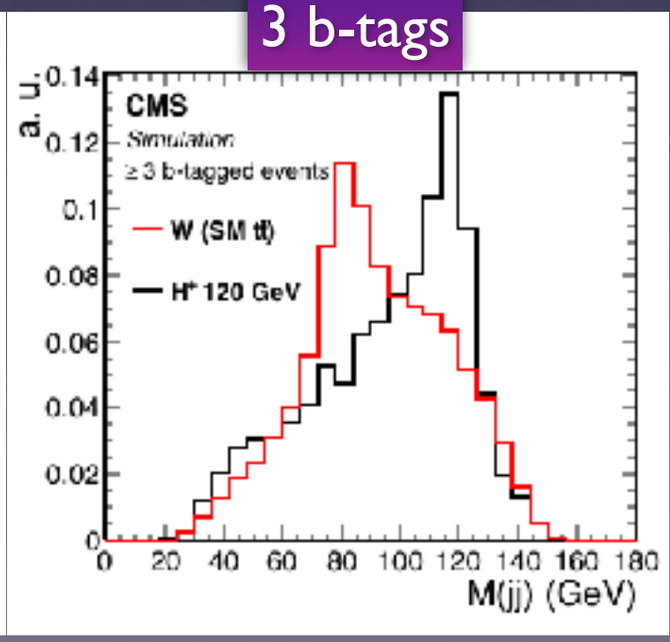


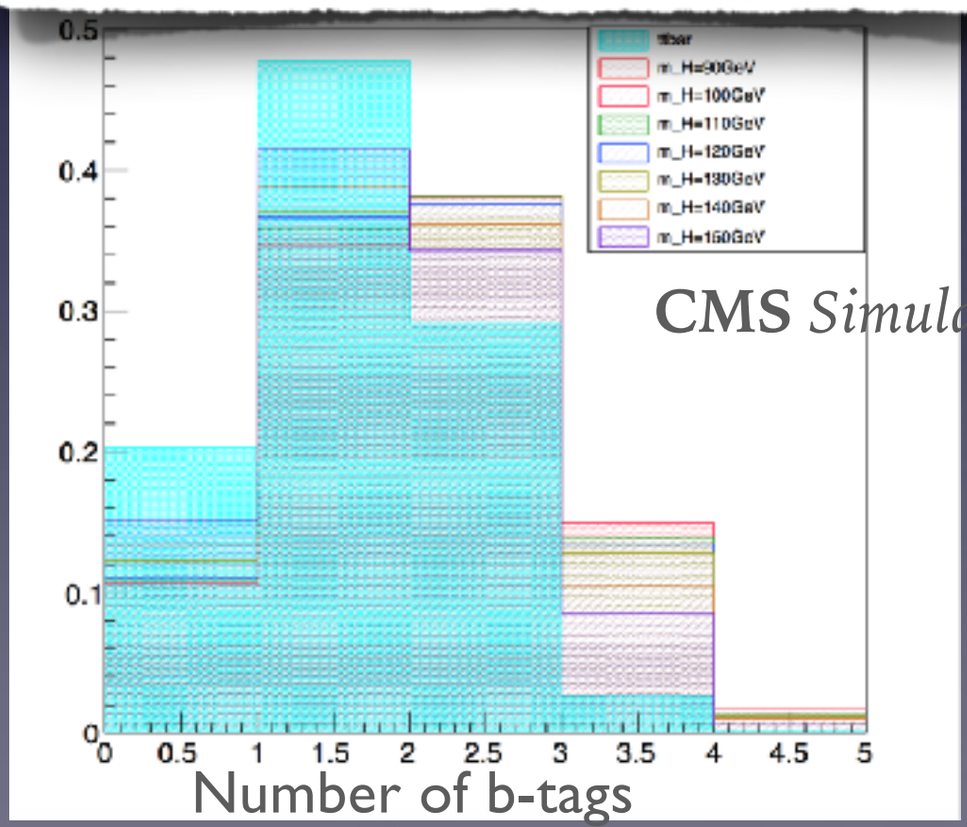
Di-jet mass in 2b/3b events prepared for template fit

2 b-tags

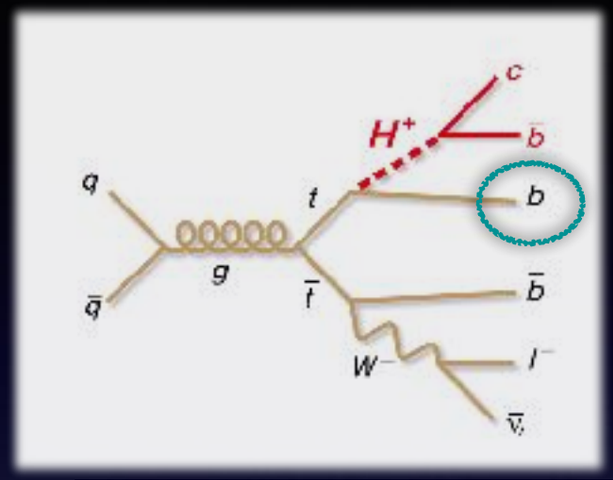


3 b-tags

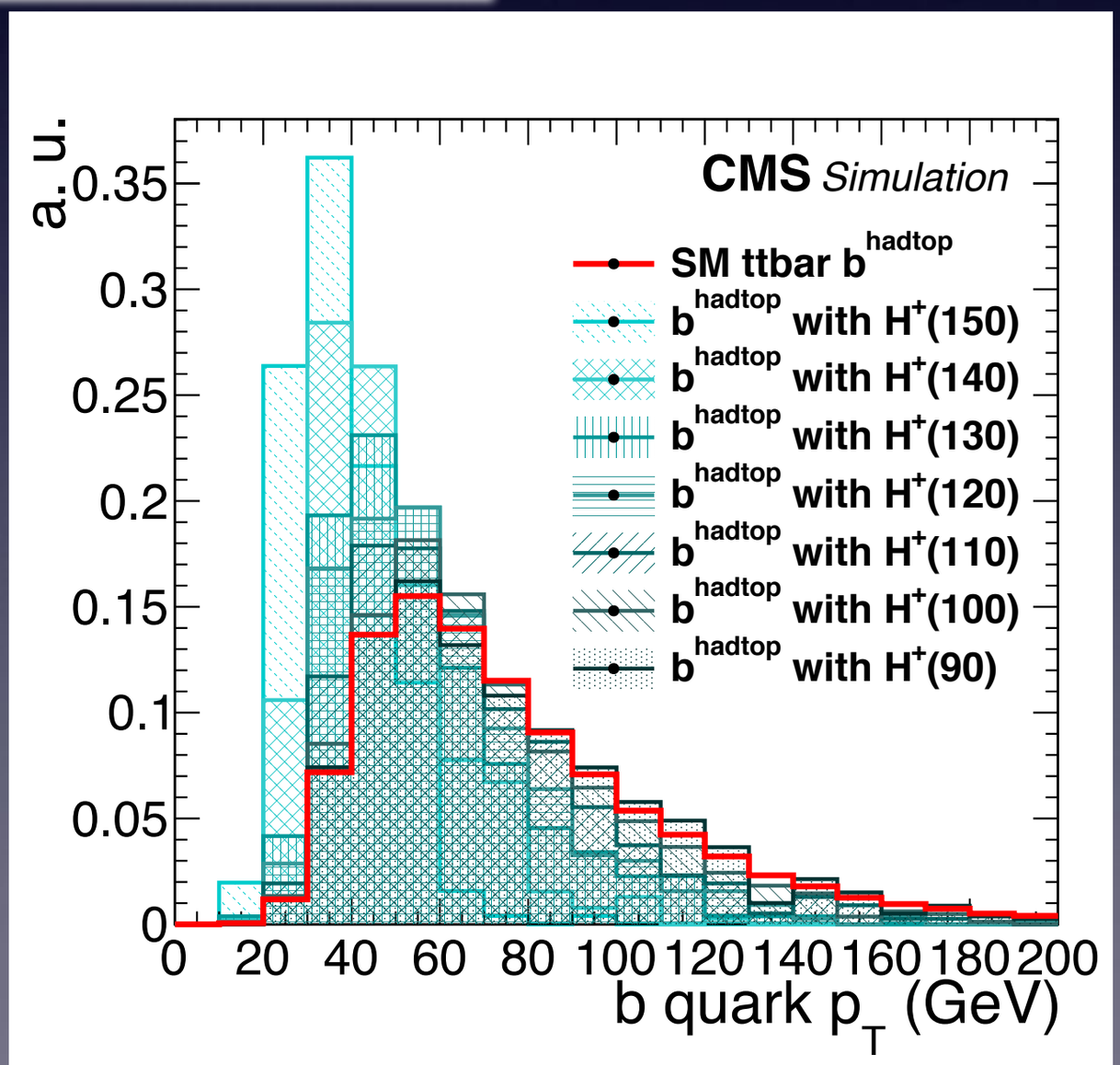




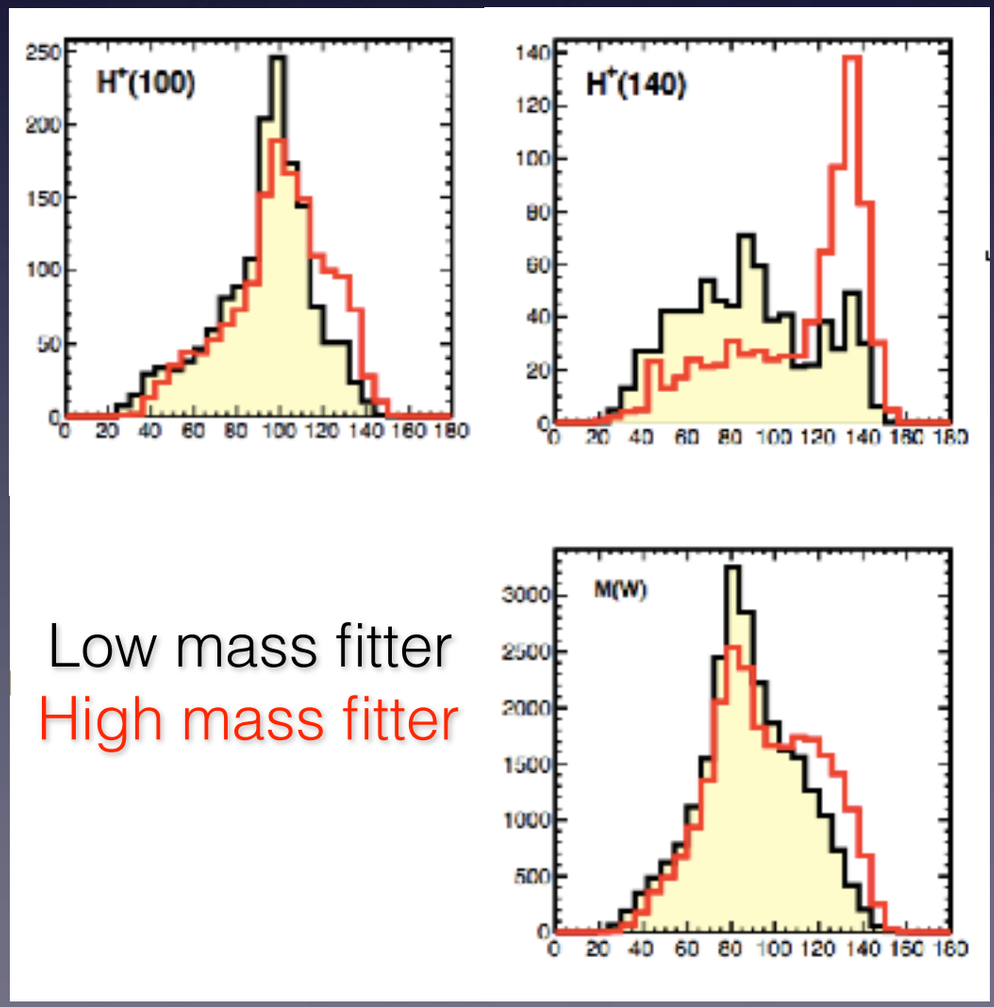
B-jet assignment (3b-jets)



Gen. b-parton p_T distribution



- In 2b-jets selection, both b-jets assigned to top-b-quarks only
- In 3b-jets
  - Two b-tagged jets assigned to direct top-b-quark and H^+ -b-quark
  - Force lower p_T b-tagged jet to direct top-b-jet (for $M(H^+) \geq 130GeV$)



Low mass fitter
High mass fitter

Issue with 3b-tag normalization

(Update for paper)

Event Yields in 3b-tag region

- >10% discrepancy in 3 b-tag region
- Known issue with ttbar modeling in terms of b-jet multiplicity
  - Could be the mis-modeling of g→bb
- ≥ 3b-tag is sensitive to the $H^+ \rightarrow c\bar{b}$ signal
  - Careful with the ttbar normalization because the excess can be from the signal contribution
  - Normalization factor came from ttbar dilepton channel where the signal contribution is negligible

PAS HIG-16-030

μ+jets	1 b-tag	2 b-tag	3 b-tag
$t\bar{t}$+jets	81622 ± 91	51823 ± 69	4755 ± 21
QCD multijet	2446 ± 42	597 ± 17	51 ± 5
Single Top	4829 ± 47	2212 ± 30	169 ± 8
W/Z+jets	11982 ± 417	1306 ± 127	64 ± 12
WW/WZ/ZZ	330 ± 6	62 ± 2	7 ± 1
$t\bar{t}$+W/Z/H	322 ± 2	195 ± 2	41 ± 1
Total Bkgd	101531 ± 431	56195 ± 149	5087 ± 26
Observed	102404	57593	5754

e+jets	1b-tag	2b-tag	3b-tag
$t\bar{t}$+jets	69289 ± 83	43592 ± 63	4007 ± 19
QCD multijet	6187 ± 87	1116 ± 33	82 ± 8
Single Top	4069 ± 43	1882 ± 28	147 ± 8
W/Z+jets	10351 ± 368	1098 ± 114	79 ± 20
WW/WZ/ZZ	290 ± 5	56 ± 2	5.4 ± 0.4
$t\bar{t}$+W/Z/H	279 ± 2	169 ± 2	35 ± 1
Total Bkgd	90464 ± 389	47911 ± 137	4355 ± 30
Observed	92877	50542	4848

Scale factor from ttbb/ttjj study

Table 4: The measured cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ and their ratio are given for the visible phase space (PS) defined as two leptons with $p_T > 20\,\text{GeV}/c$ and $|\eta| < 2.4$ plus four jets, including two b jets with $p_T > 20\,\text{GeV}/c$ and $|\eta| < 2.5$, and the full phase space, corrected for acceptance and branching fractions. The full phase space results are given for jet thresholds of $p_T > 20$ and $40\,\text{GeV}/c$. The uncertainties shown are statistical and systematic, respectively. The predictions of a NLO theoretical calculation for the full phase space and $p_T > 40\,\text{GeV}/c$ are also given [16].

Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20\,\text{GeV}/c$	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20\,\text{GeV}/c$	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40\,\text{GeV}/c$	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40\,\text{GeV}/c$	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003

TOP-13-010
PLB 746, 2015

- Direct comparison was made for the ttbb production
  - Gives a scale factor of 1.56 with an uncertainty of 42%
  - This scale factor is applied to the events when (#b-tagged jets - #b-tagged jets from W) ≥ 3 assuming it is the ttbb events

Event Yields

Fixed from paper draft

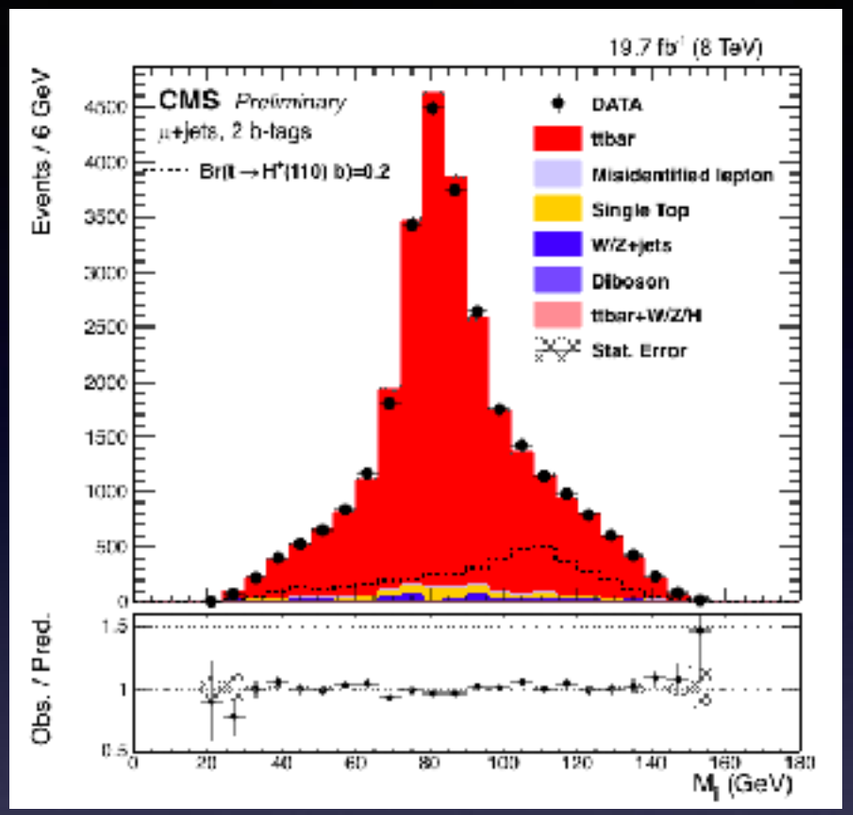
Table 1: Event yields in a muon or an electron with four jets selection from simulation samples and data corresponding to 19.7 fb ^{1} of pp collisions at $\sqrt{s} = 8$ TeV. Statistical error is considered in each yield.

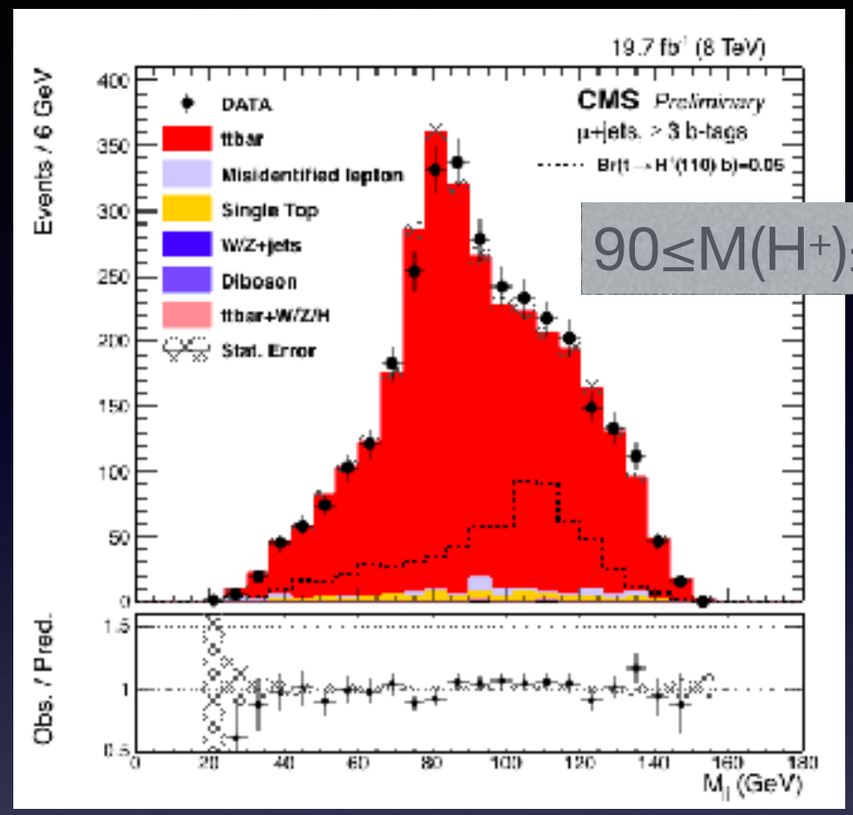
	μ+jets		e+jets	
	2 b-tags	$\geq$3 b-tags	2 b-tags	$\geq$3 b-tags
$t\bar{t}$	52236 ± 70	5582 ± 25	43935 ± 63	4692 ± 23
Single Top	2212 ± 30	169 ± 8	1882 ± 28	147 ± 8
$t\bar{t}$+W/Z/H	195 ± 2	41 ± 1	169 ± 2	35 ± 1
W/Z+jets	1305 ± 127	13 ± 7	1098 ± 114	32 ± 19
WW/WZ/ZZ	62 ± 2	5 ± 1	56 ± 2	4 ± 1
QCD multijet	554 ± 16	126 ± 14	1064 ± 33	139 ± 14
Expected	56566 ± 149	5935 ± 31	48203 ± 137	5049 ± 34
Observed	57593	5754	50542	4848

- The event yields with pre-selection (before fitter)
- ttbb, (#b-tagged jets - #b-tagged jets from W) ≥ 3, events are scaled up by 1.56

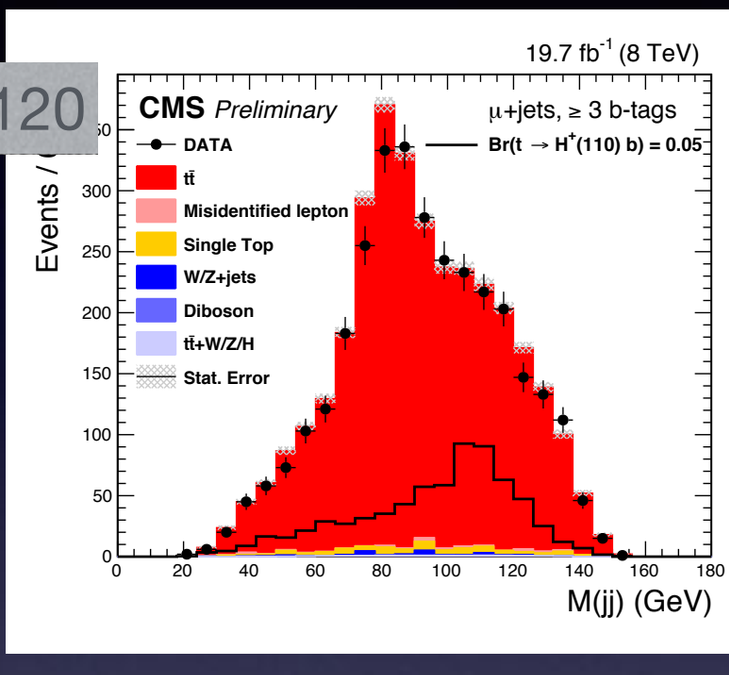
New Templates

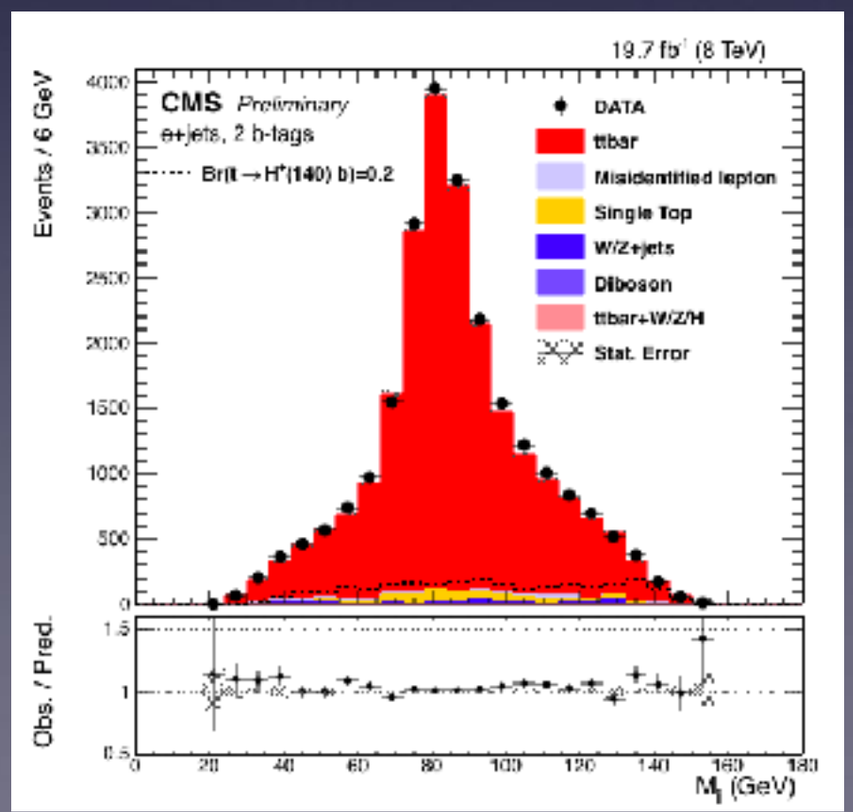
PAS

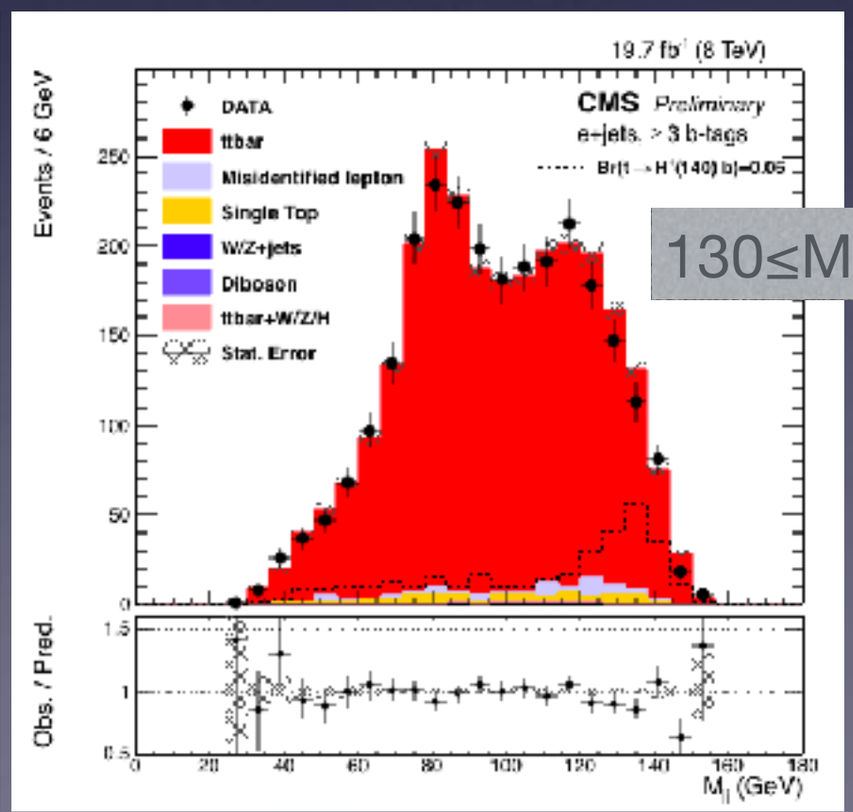




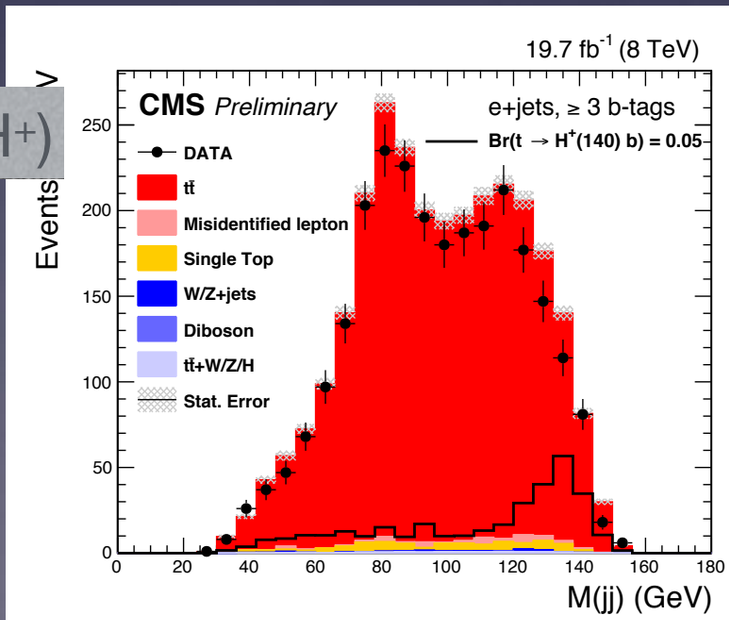
90≤M(H⁺)≤120







130≤M(H⁺)



Systematic Uncertainties

- All uncertainties are taken as shape systematics except
  - ttbar xsec, ttbb scale factor(added new), luminosity, pileup corrections to MC, scale factors (B-tagging,lepton)
- Jet-related uncertainty:
  - Jet energy correction&resolution/Flavour dependent uncertainty
- Top-related uncertainty:
  - TTbar p_T shape shift/NLO-vs-LO production/top quark mass shift
- MonteCarlo uncertainty:
  - MatrixElement event generation matching to Pythia hadronization/ Factorization scale (Q^2)/Pythia-vs-Madgraph ttbar p_T difference

Summary of Syst. Unc.

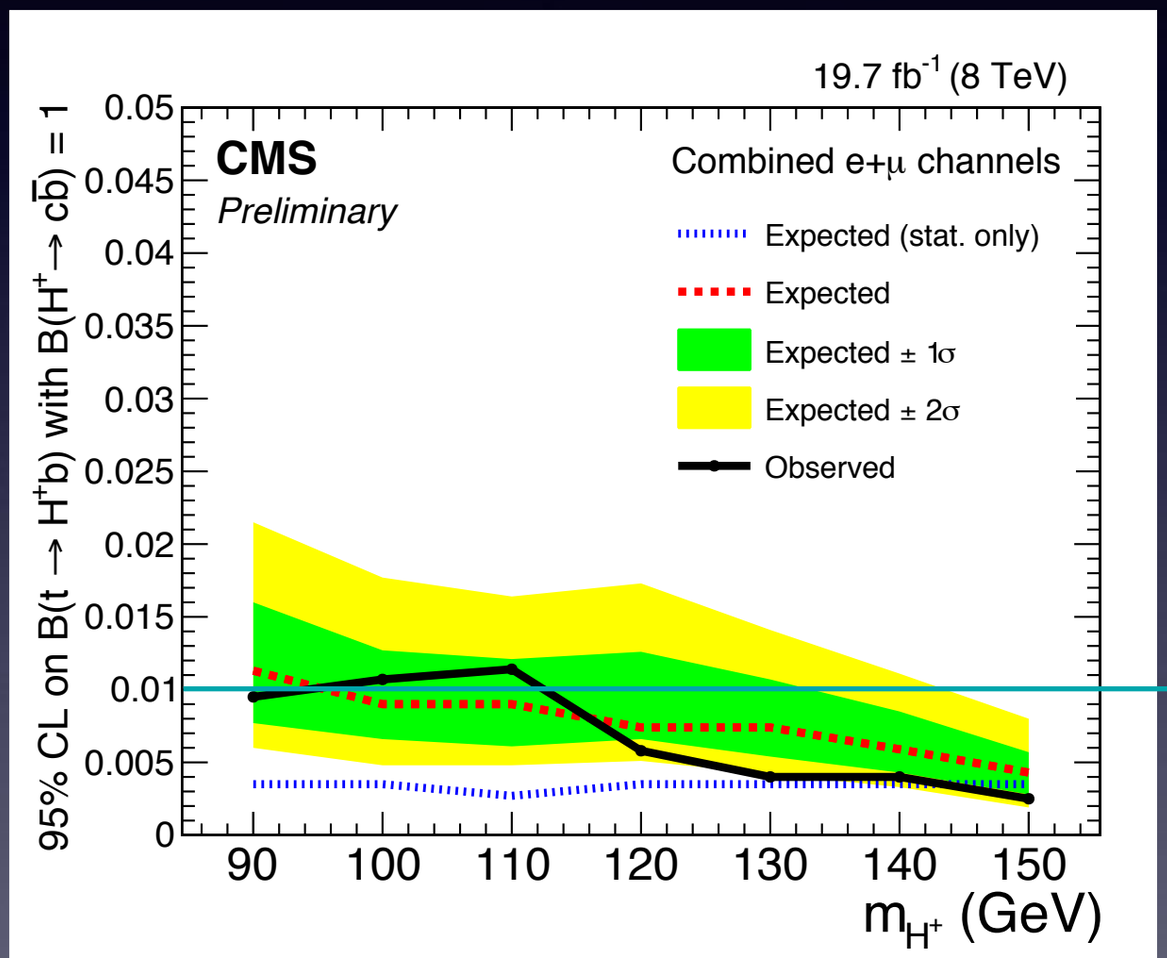
Table 2: Summary of the systematic uncertainties in the search for a charged Higgs boson covering both the μ+jet and e+jet channels. For cases where the uncertainties in the μ+jet and e+jet channels differ, range is given. Rate uncertainties for the H^+ signal, $t\bar{t}$, non-$t\bar{t}$ are listed for the 2 b-tag and 3 b-tag selections, and the uncertainties marked with (s) are used for shape systematic uncertainties.

Source of uncertainty	signal (m_{H^+} = 120)		$t\bar{t}$		non-$t\bar{t}$		QCD multijet	
	2 b-tag	3 b-tag	2 b-tag	3 b-tag	2 b-tag	3 b-tag	2 b-tag	3 b-tag
$t\bar{t}$ cross section	6.5	20	6.5	20				
Top quark mass	5 (s)	5 (s)	5 (s)	5 (s)				
$t\bar{t}$ p_T reweighting	(s)	(s)	(s)	(s)				
NLO-vs-LO shape (Powheg-vs-MadGraph)	8.5–9.0 (s)	7.6–8.8 (s)	8.3–8.5 (s)	8.0 (s)				
PYTHIA–MADGRAPH $p_T(t\bar{t})$ difference	(s)	(s)						
ME-PS matching			0.6–0.8 (s)	0.8–1.4 (s)				
ttbb production reweight			0.6 (s)	12 (s)				
Renormalization and factorization scales	4.0–4.2 (s)	6.8–7.2 (s)	1.3–1.7 (s)	1.3–2.0 (s)				
Jet energy scale (JES)	4.6–5.3 (s)	5.0–5.9 (s)	3.4 (s)	3.3 (s)	7.5–9.6 (s)	0.9–2.8 (s)		
Flavour-dependent JES (b-quark)	0.3–0.4 (s)	0.2–0.6 (s)	0.1 (s)	9.0 (s)	0.1–0.7 (s)	0.5–0.9 (s)		
Flavour-dependent JES (udsc,g)	0.9–1.2 (s)	0.4–0.6 (s)	1.0 (s)	9.0 (s)	3.1–4.1 (s)	1.1–1.8 (s)		
Jet energy resolution	0.1–0.2 (s)	0.2–0.8 (s)	0.3 (s)	0.4 (s)	1.1 (s)	1.5 (s)		
B-tag scale factor for b/c-quark jets	1.2–2.1	5.6–5.8	3.6	5.7	2.9–3.0	4.0–4.4		
Mis-tag scale factor for light quark jets	0.1–0.2	0.2–0.7	0.2	0.3–0.7	0.7–1.3	0.3–0.4		
Pileup reweighting	≈ 0.5							
Electron scale factor (e+jets)	3.0							
Muon scale factor (μ+jets)	3.0							
Luminosity	2.6							
Data-driven prediction							Shift anti-Iso_{rel} region, < 10 (s)	

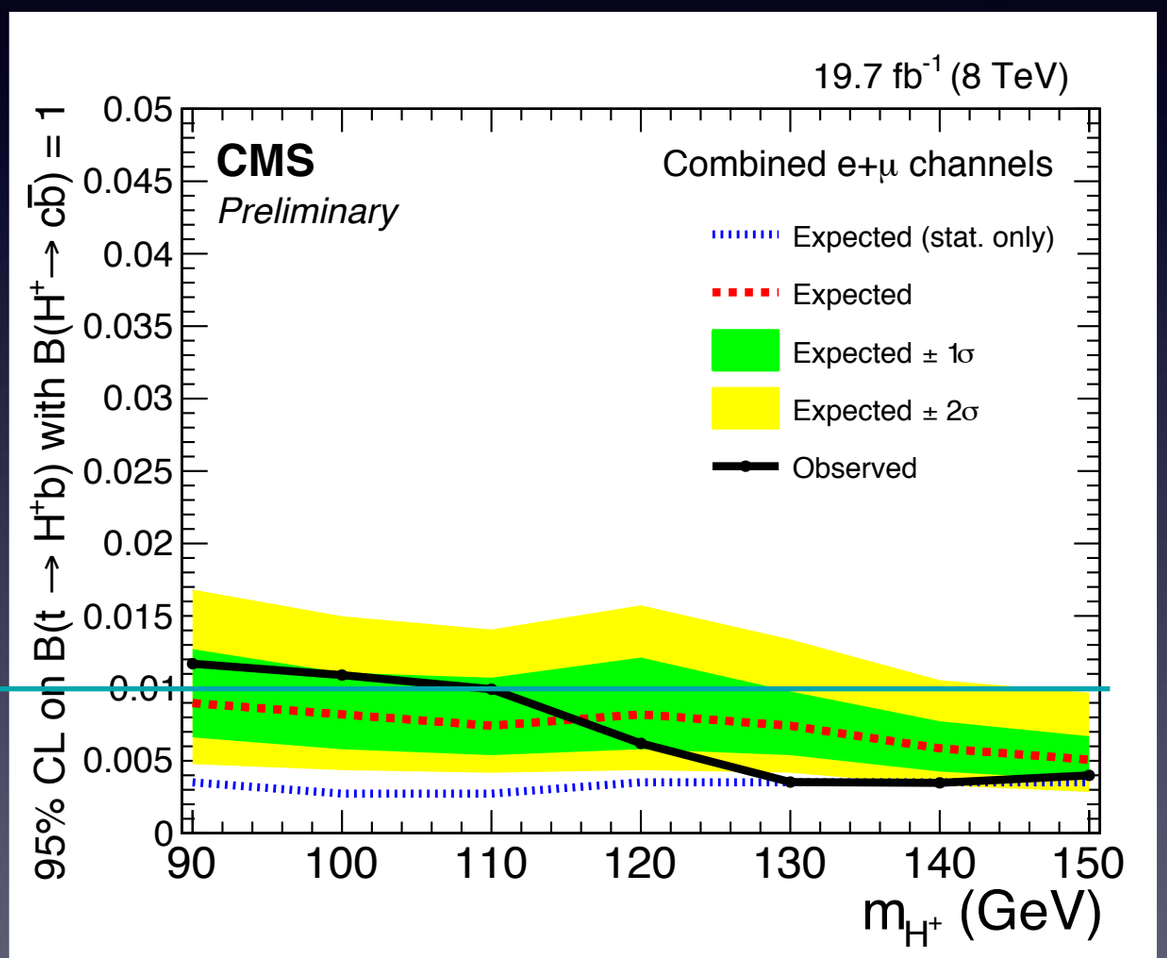
Limit Setting

Limits calculated using Asymptotic Method

PAS HIG-16-030



New limit



Update on ttbb cross section weight & systematic shape correction, expected limit on H+(90GeV) is reduced from 1.1% to 0.9%

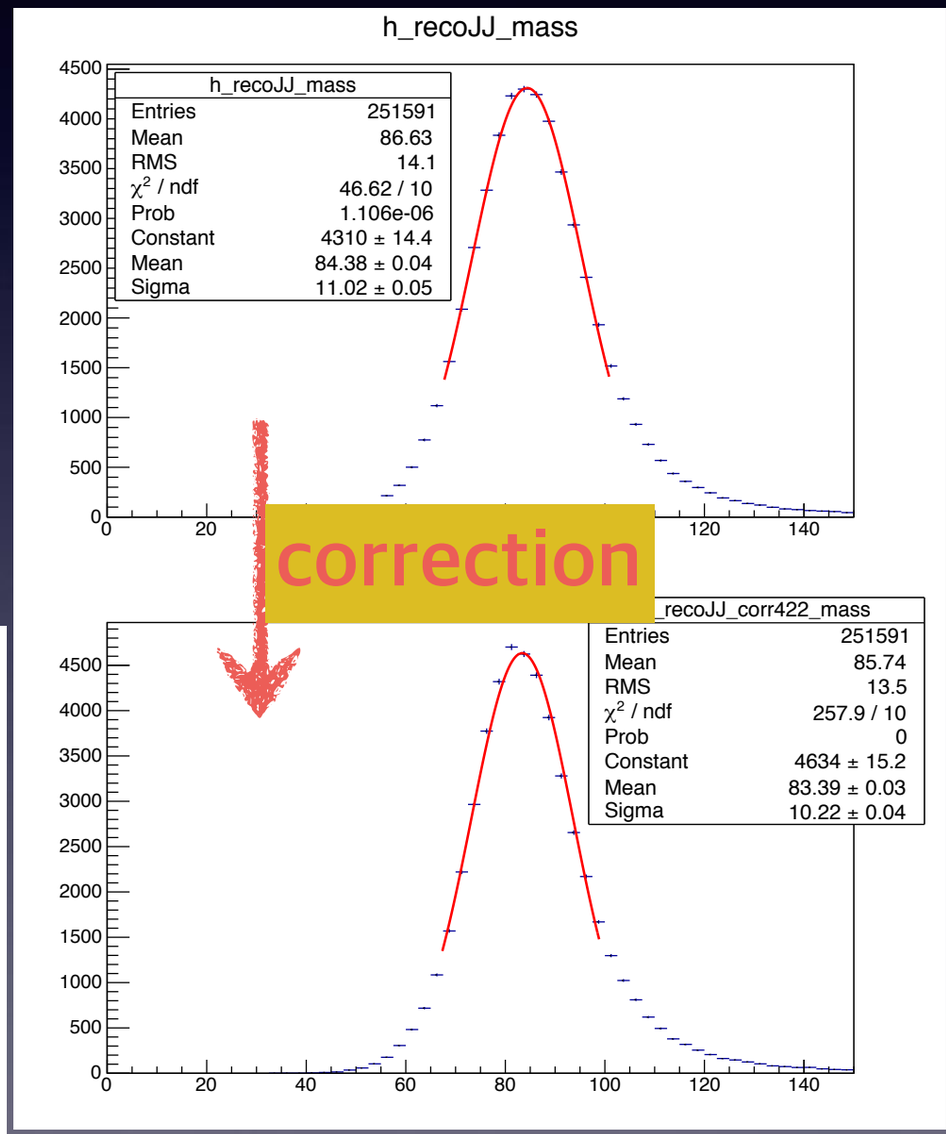
Summary

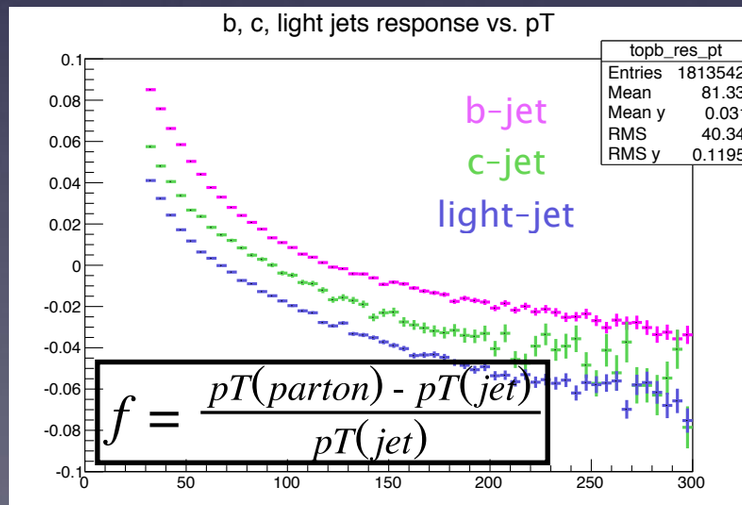
- This analysis is the first physics result on H^+ to cbbar - exotic decay expected in type-Y model other than the MSSM
  - So far this result is the most stringent limit for hadronic decay of light H^+
  - It is important to be published in a referred journal considering big interest on the H^+ among theory-community and BSM search community
  - This results are dominated by the systematic uncertainty
- Since the PAS we have a good control on the 3b-tag background
- No remaining issue on this analysis and we are ready to go
  - Paper draft is updated and AN is up to date as well

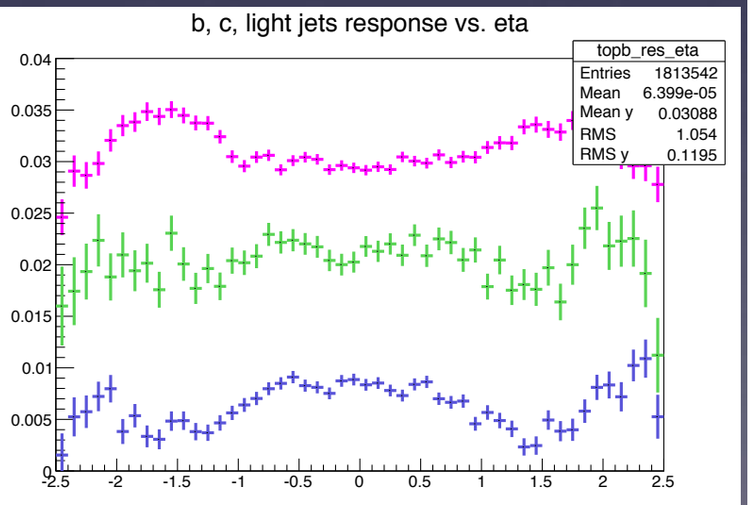
backup

Top-Specific (TS) corrections

- Particle level jets → Parton level energy
- Flavor dependent correction due to different jet constituents and detector response
- Corrections obtained from ttbar MC sample
- Jet pT response (f) is fitted to a function of pT in 9 different jet η region

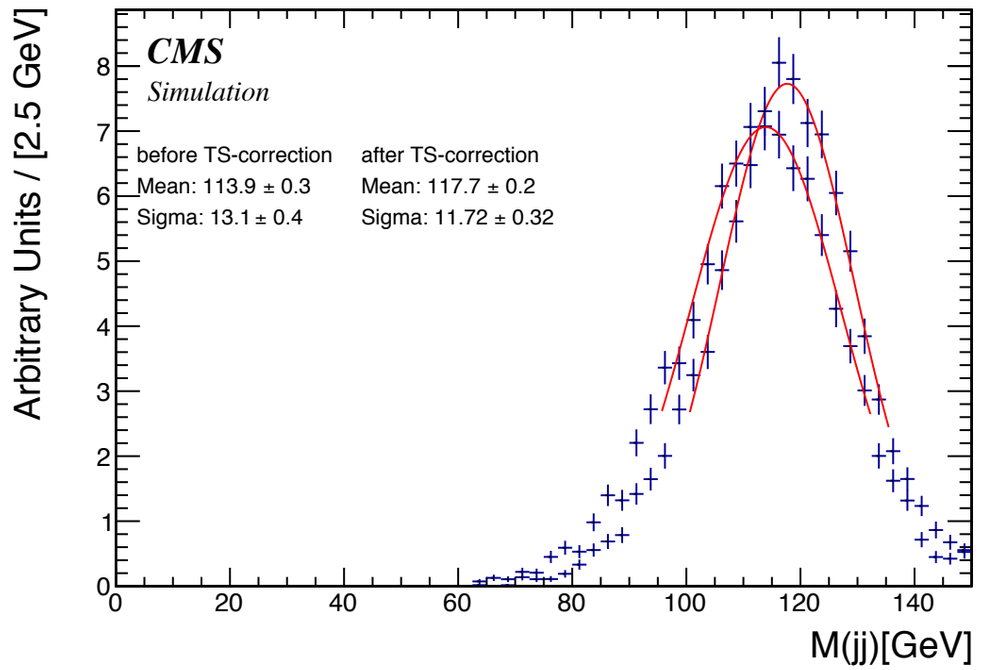


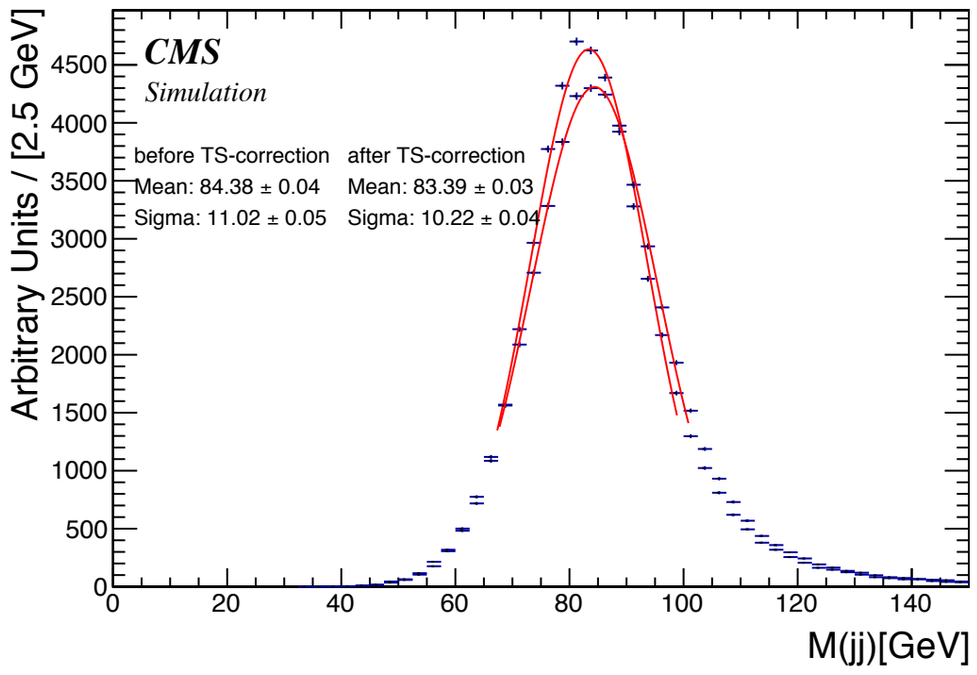


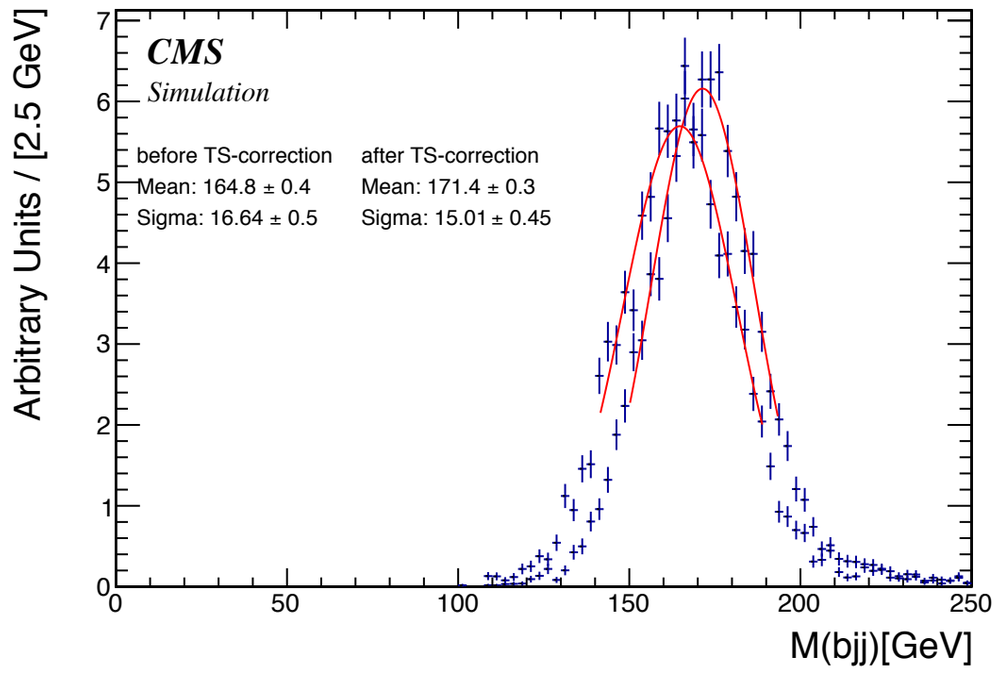


Top-specific corrections

- With this correction reconstructed mass (W^+, H^+, top) gets closer to the true value and its resolution improved by 7~9% in SM ttbar and H^+ signal
- This correction is applied to leading four jets in both MC simulation samples including H^+ signal and data



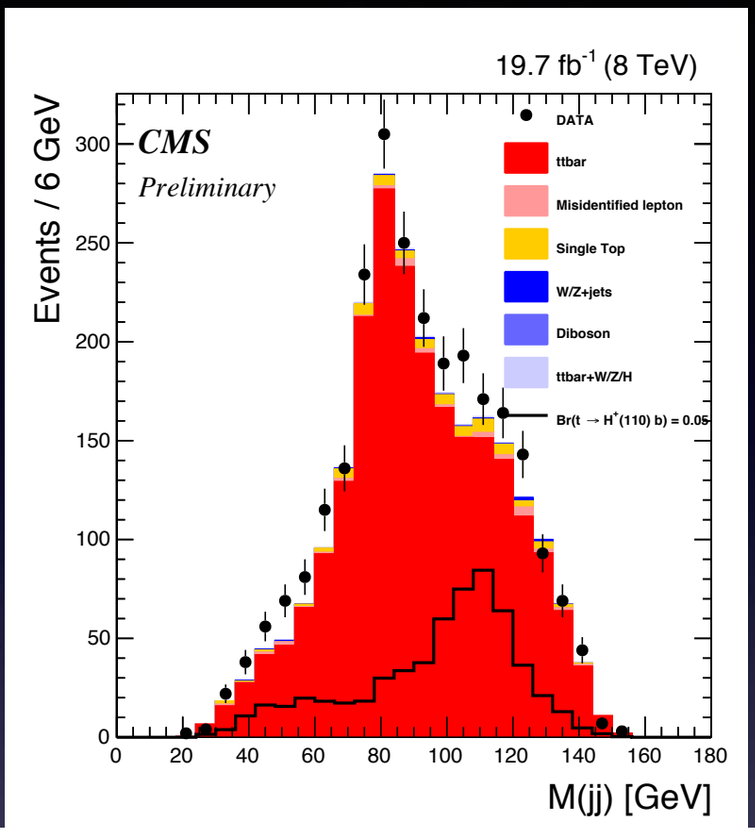




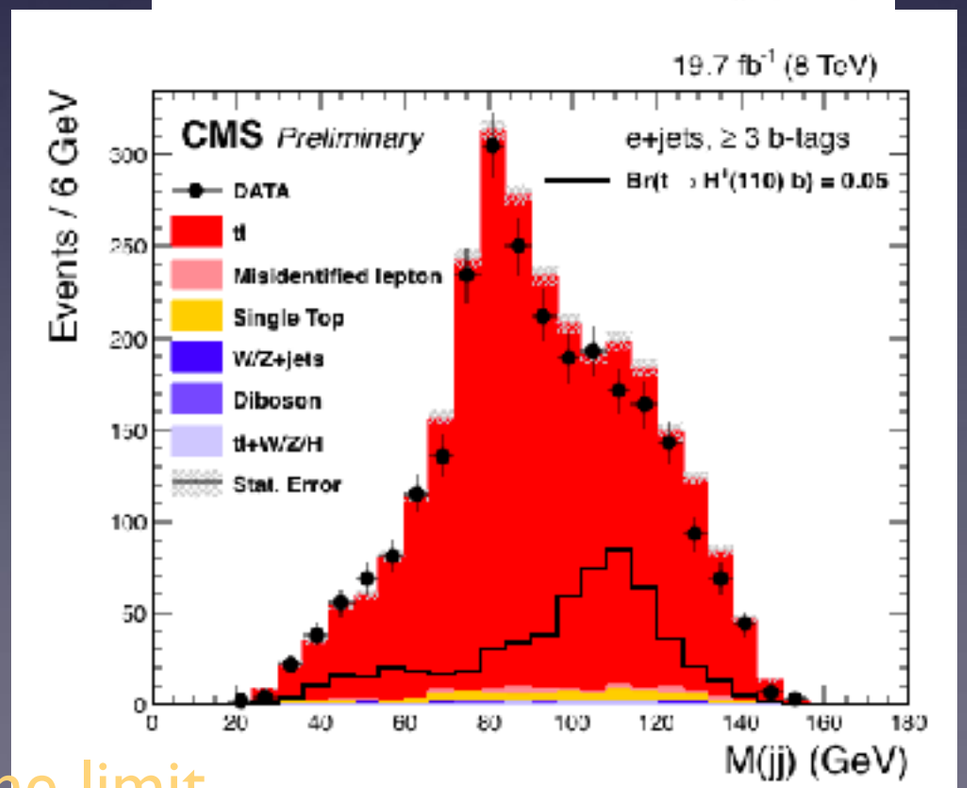
normalization in 3b-tags region (approval 2016)

- Get 3 b-tag SF from di-lepton ttbar
  - Signal Insensitive
- Among the two jets assigned to H^+
  - The SF of 1.23 was applied if extra b-jet (not from W boson) is used for the template
  - Assume this scales up ttbar+bb
- This may not be appropriate
  - It scales events based on the assigned jets not based on the production

w/o 3b SF



w/ 3b SF

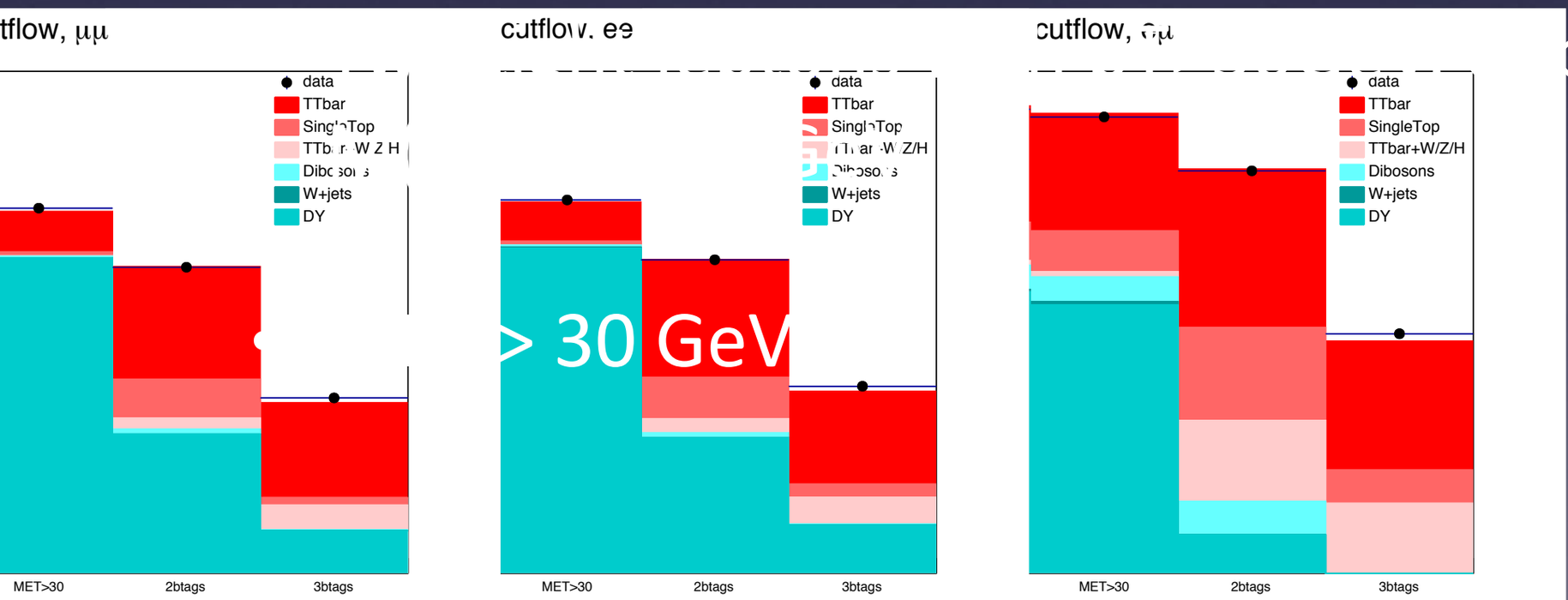


template used for the limit

3b/2b normalization from dilepton

- Dilepton events are sel… requiring:
  - at least two jets with …posite sign;

	2b-tag		3b-tag	
	MC	DATA	MC	DATA
ee	2913	3000	75	96
eμ	6146	6076	136	170
μμ	3088	3154	68	84
	12148	12230	281	348

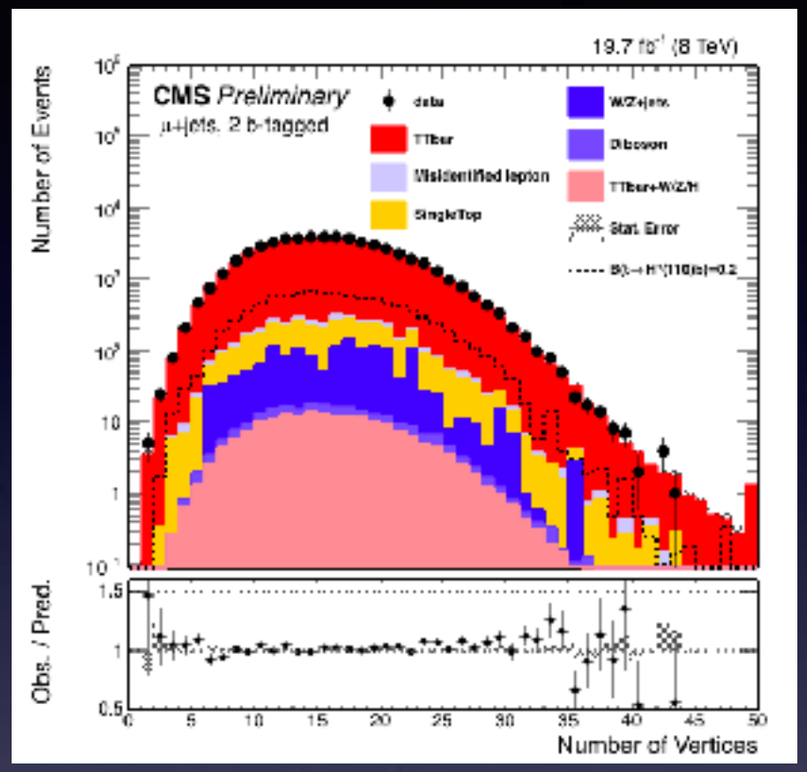


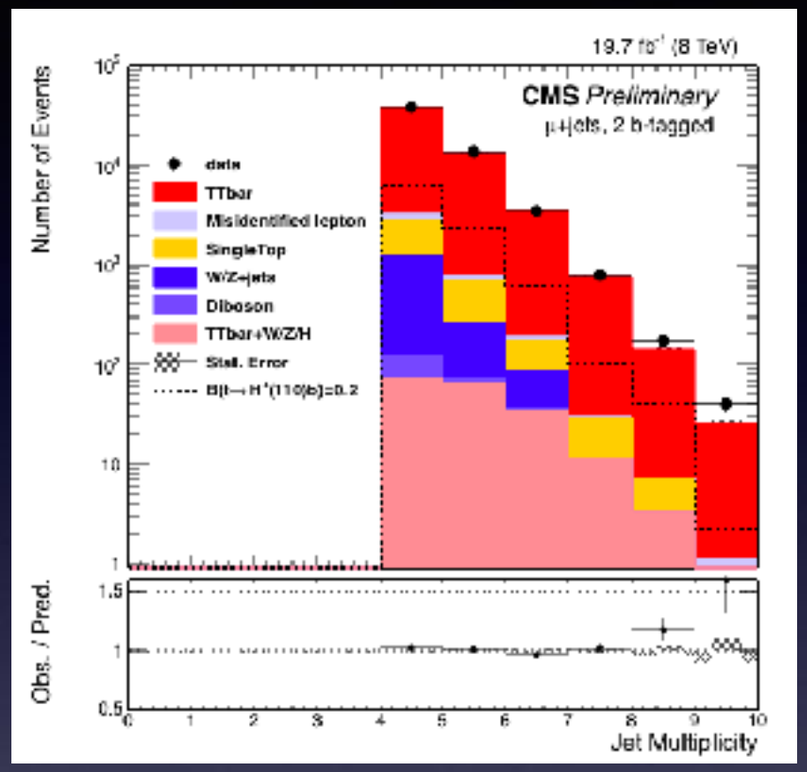
3b/2b:
data=2.8%±0.15%
MC=2.3%±0.14%
SF for MC=1.23±0.1

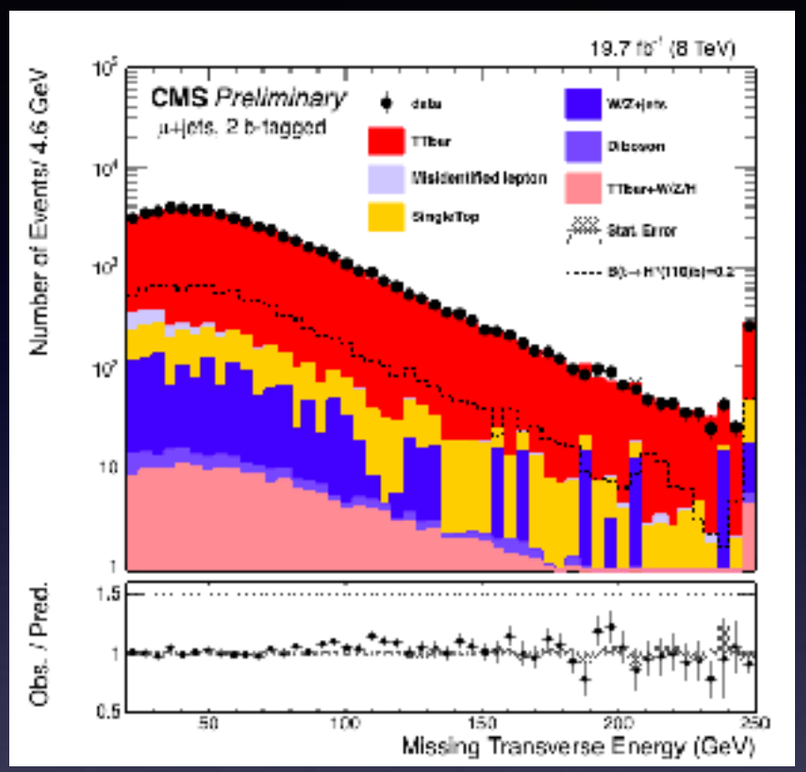
Apply this SF to 3b ttbar template

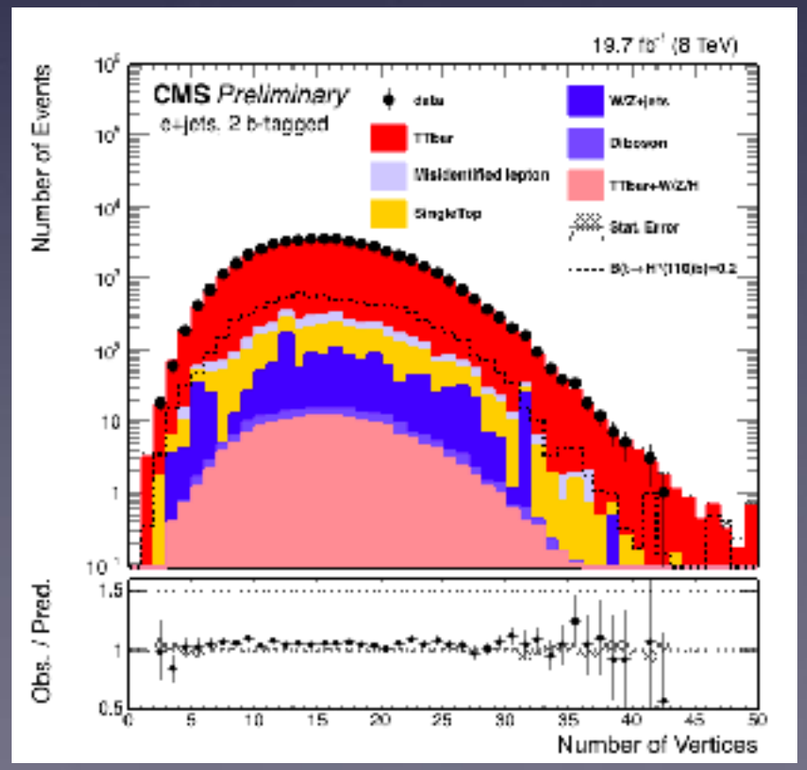
Kinematic Distribution (before fitter) 3b region renormalized

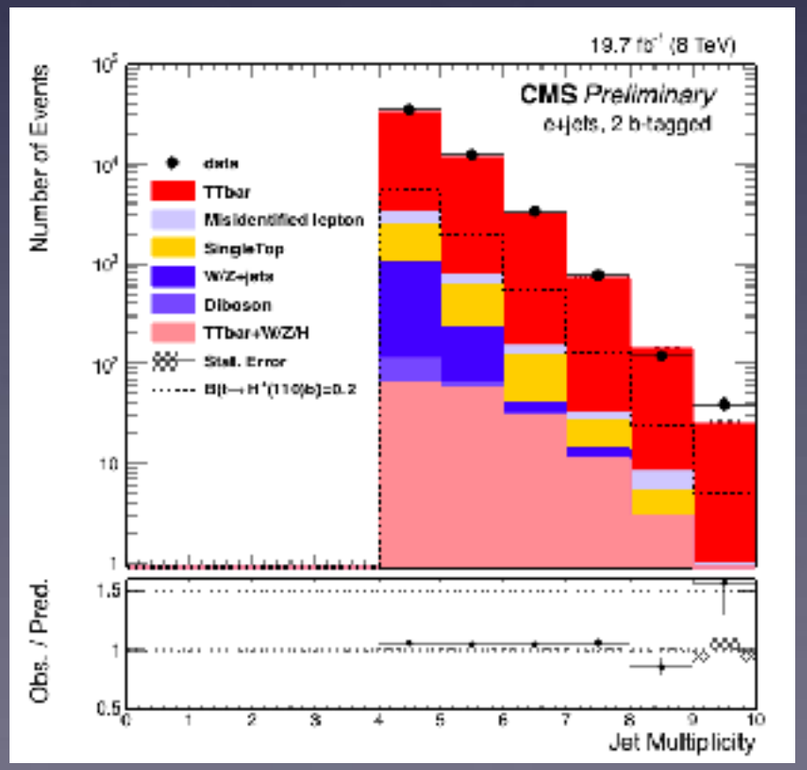
2b-tags: μ+jets(top)&e+jets(bottom)

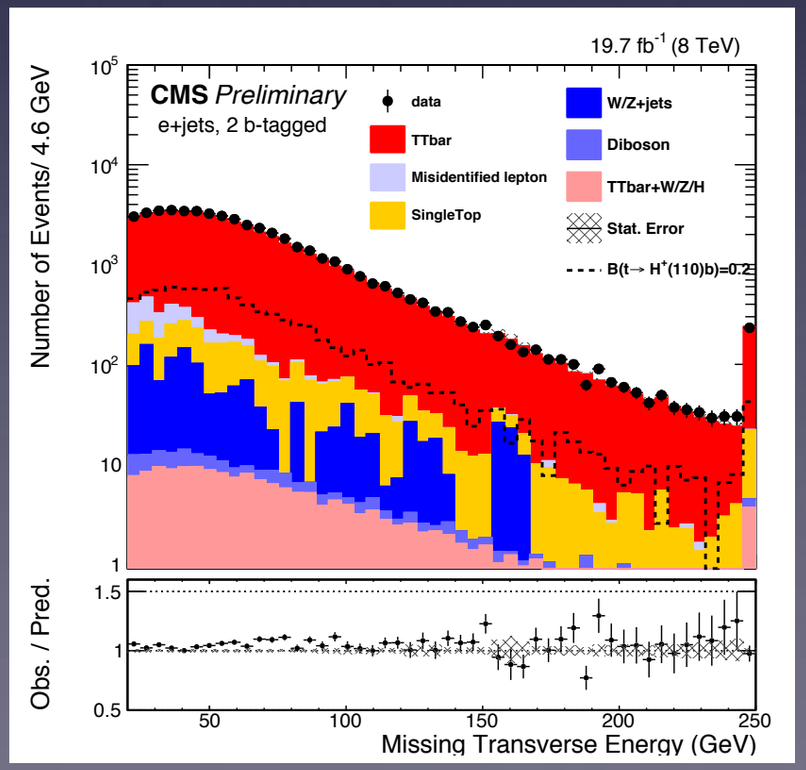




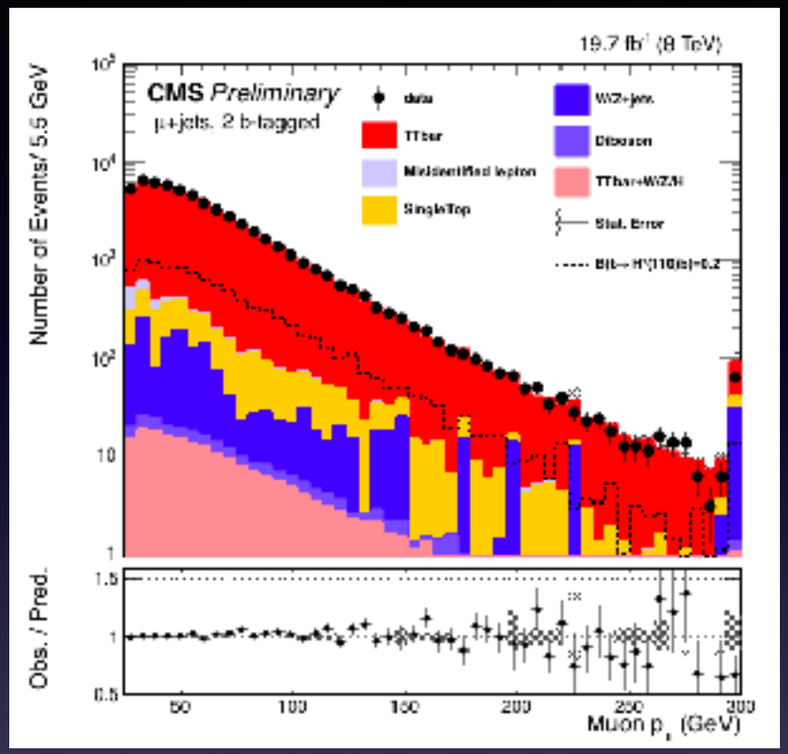


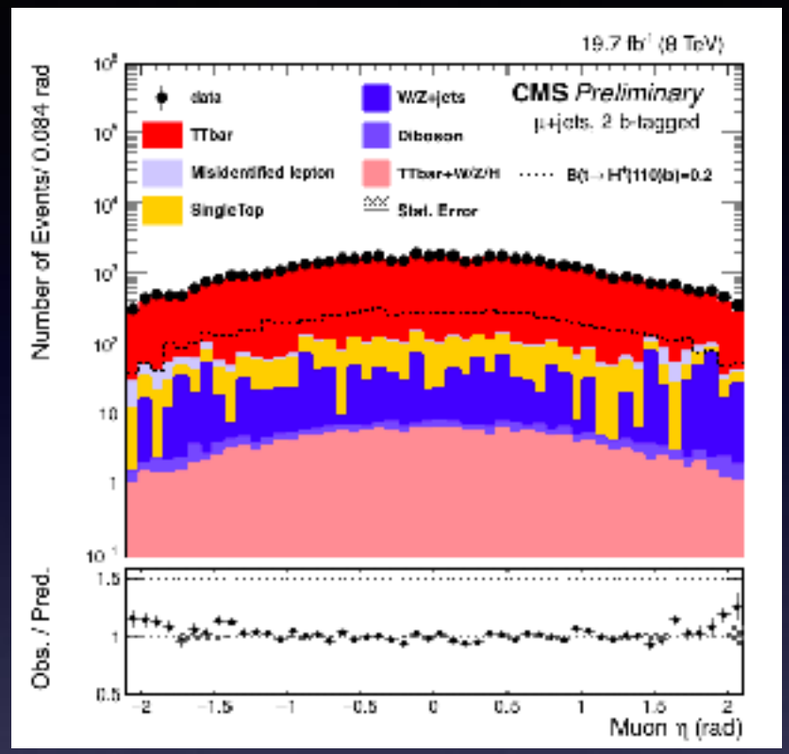


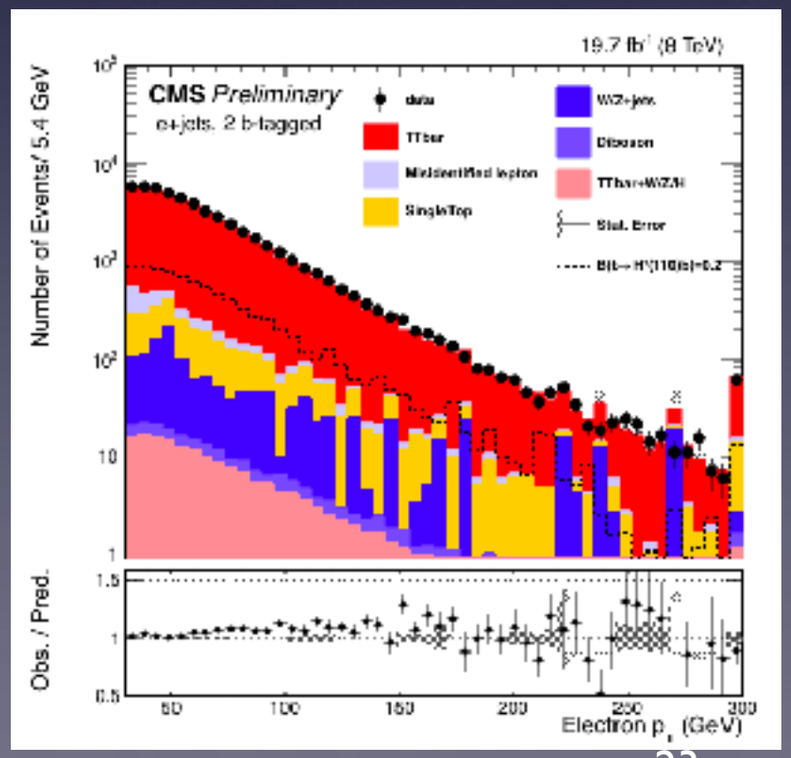


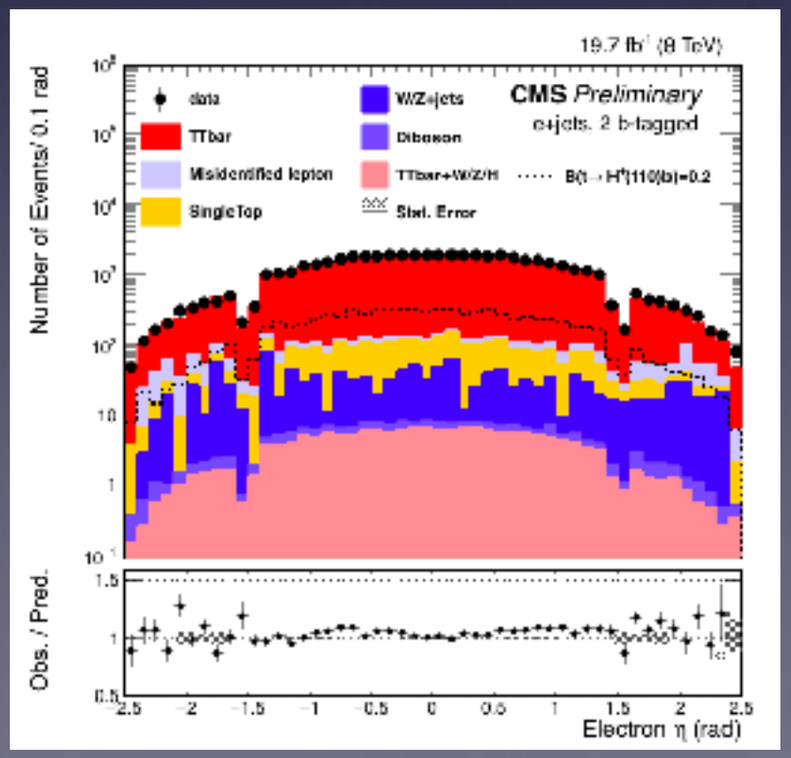


2b-tags: μ+jets(top)&e+jets(bottom)

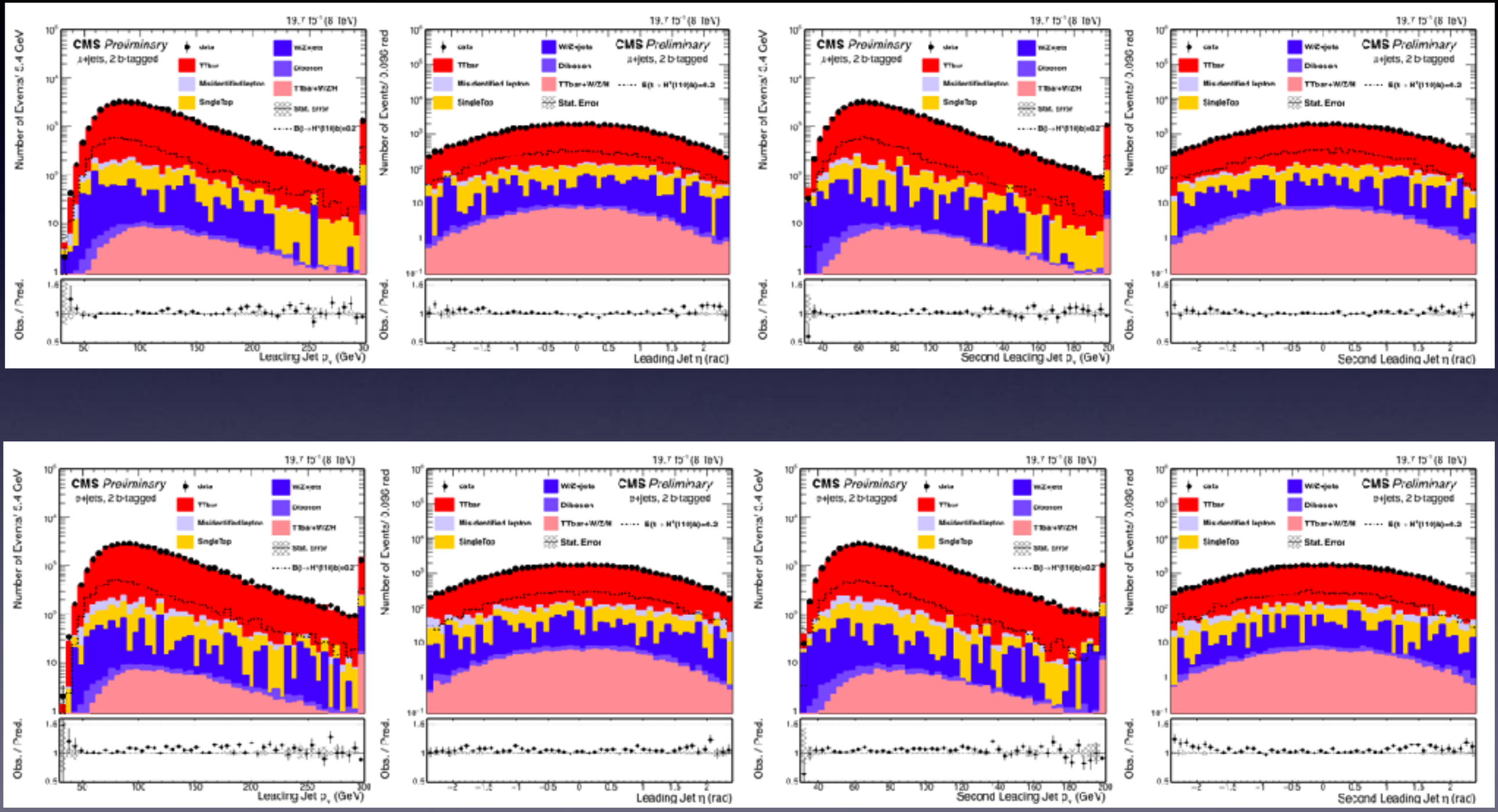




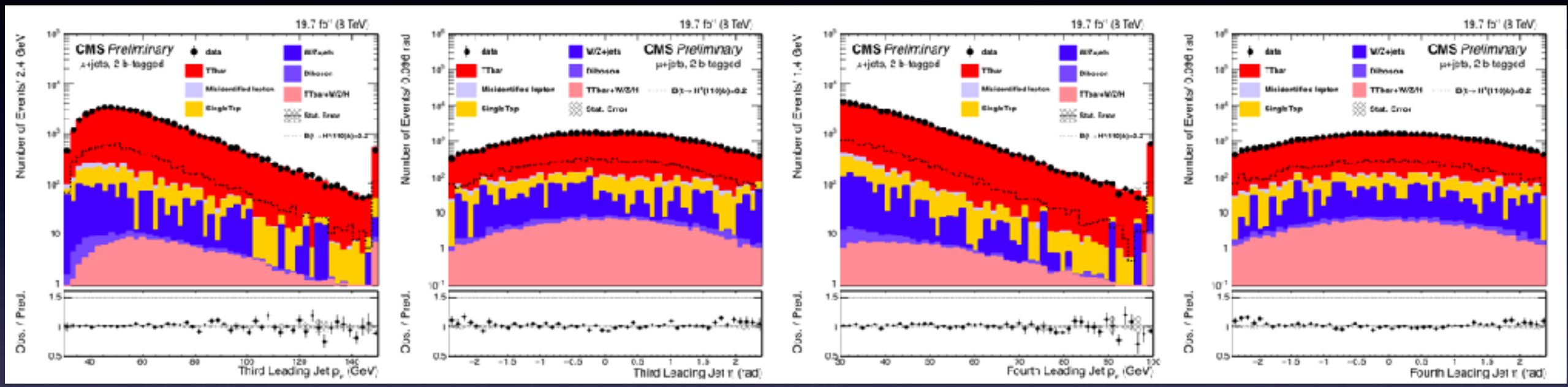


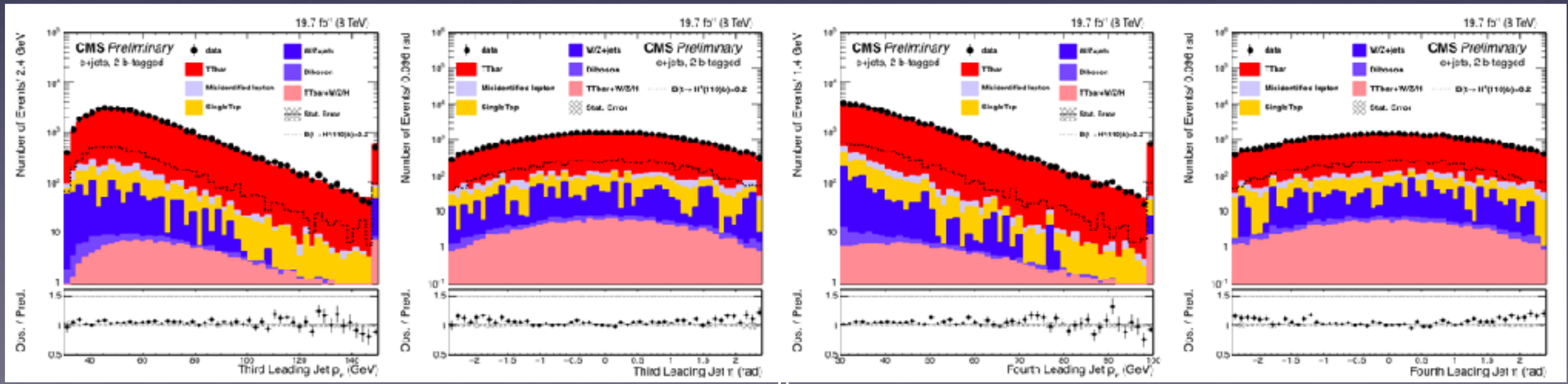


2b-tags: μ+jets(top)&e+jets(bottom)

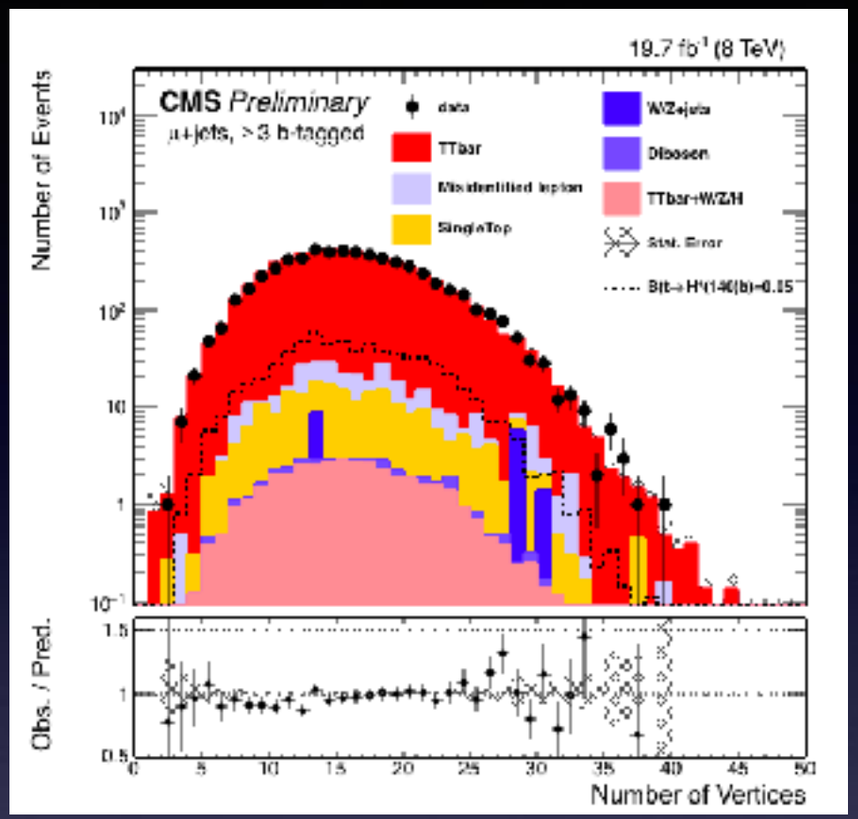


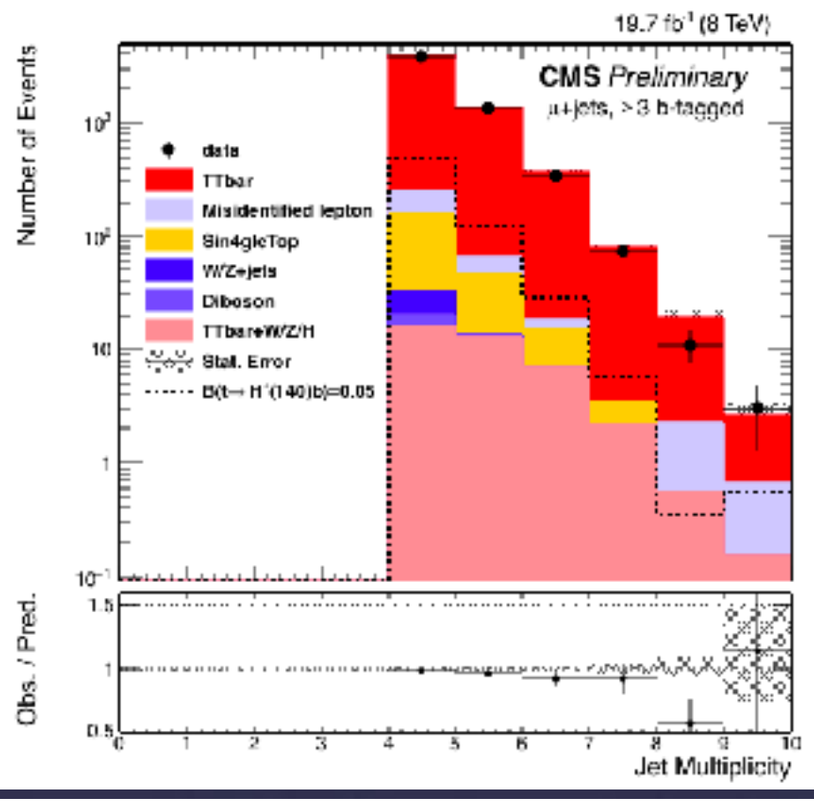
2b-tags: μ+jets(top)&e+jets(bottom)

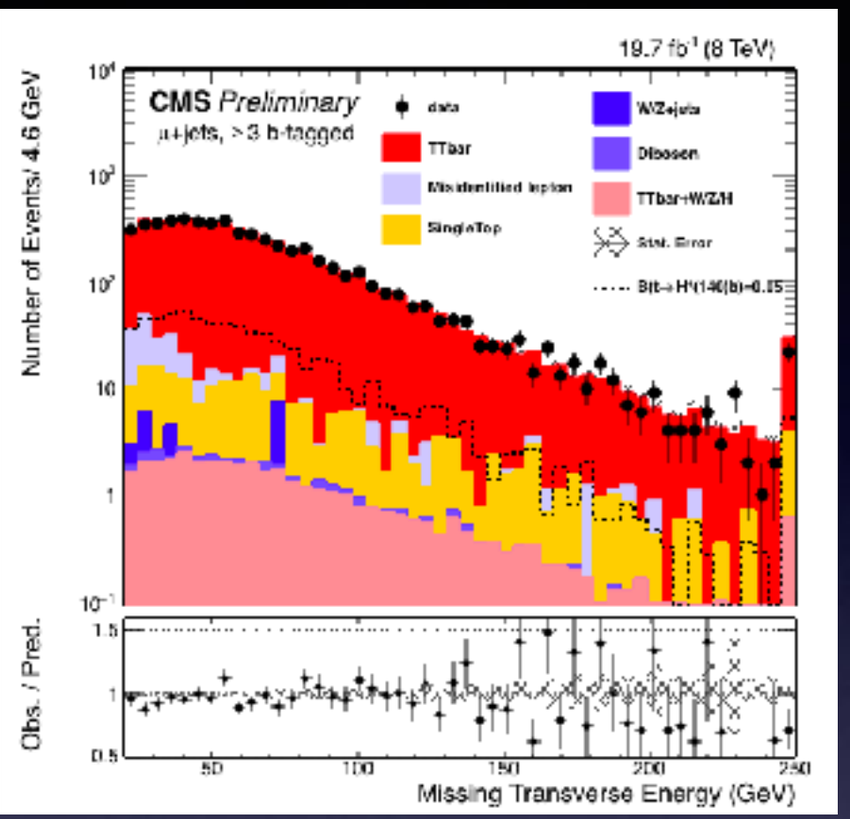


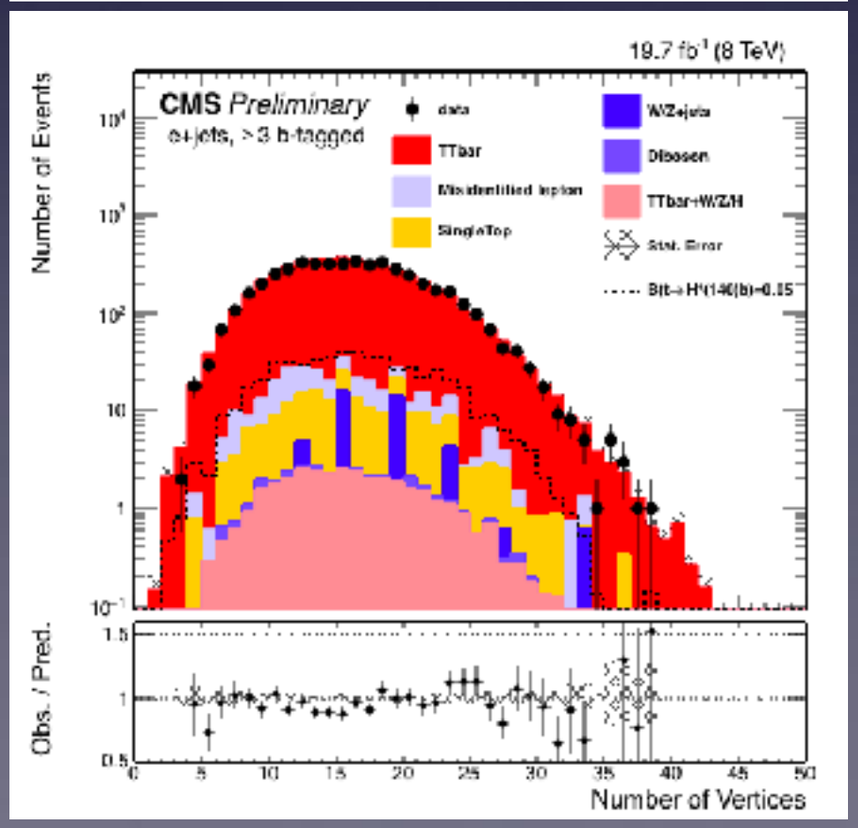


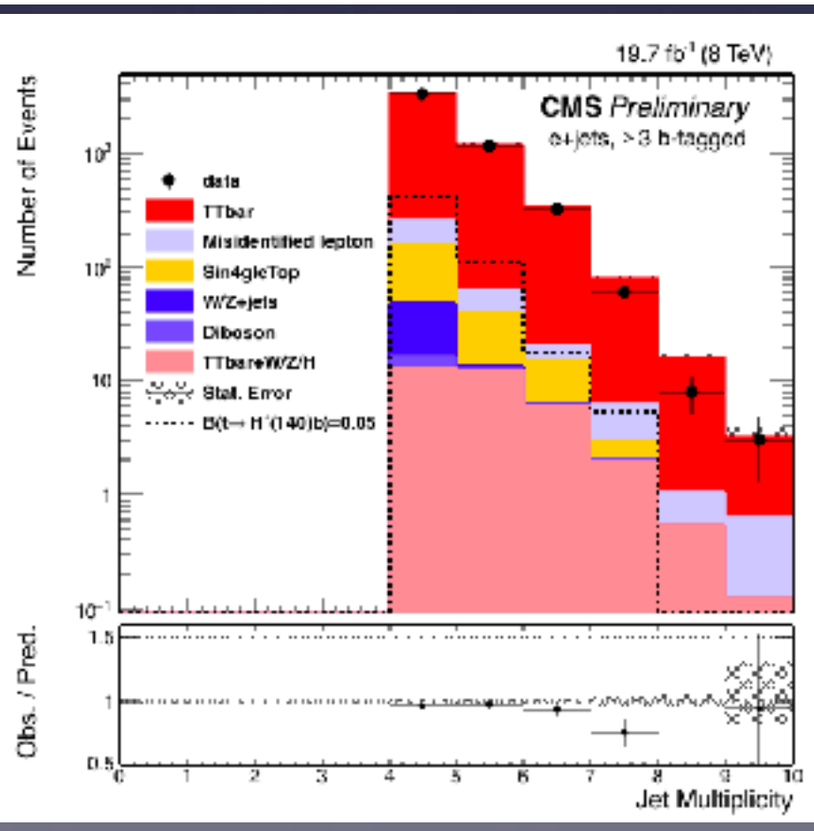
3b-tags: μ+jets(top)&e+jets(bottom)

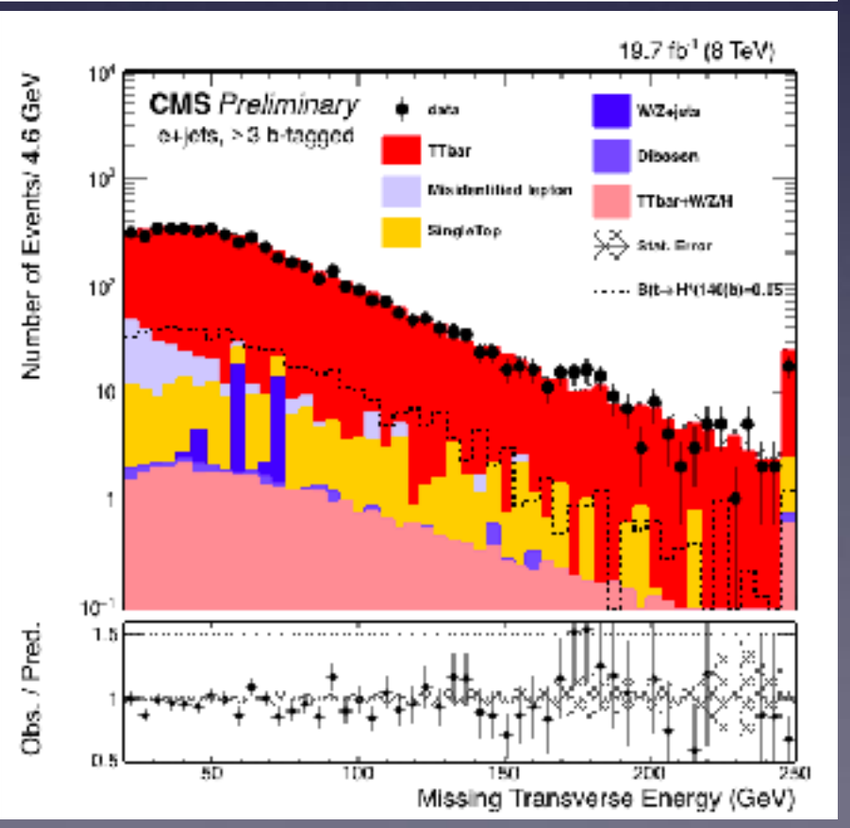




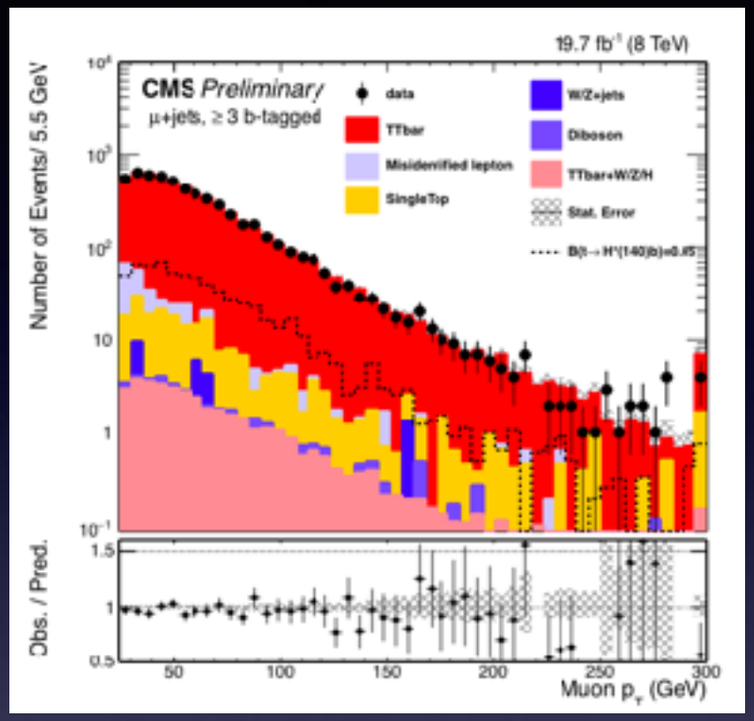


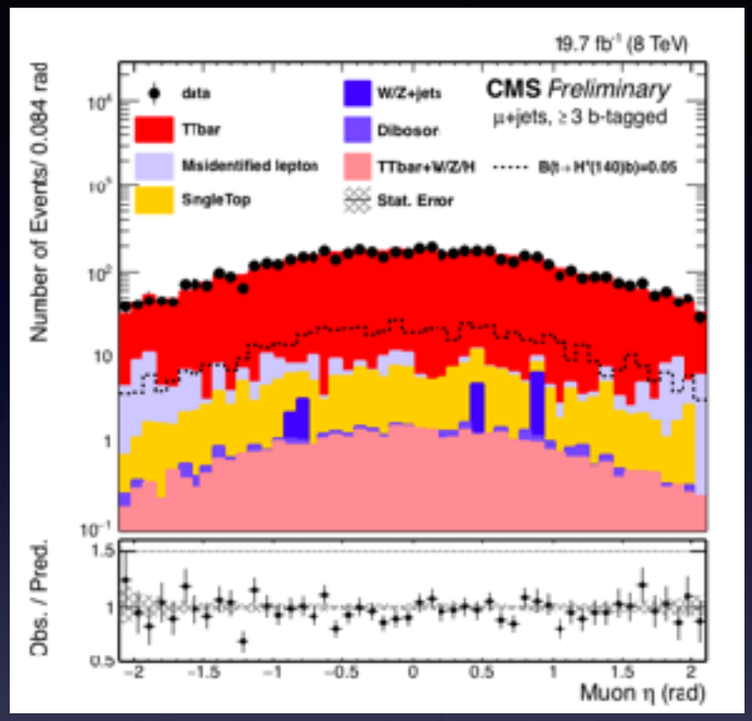


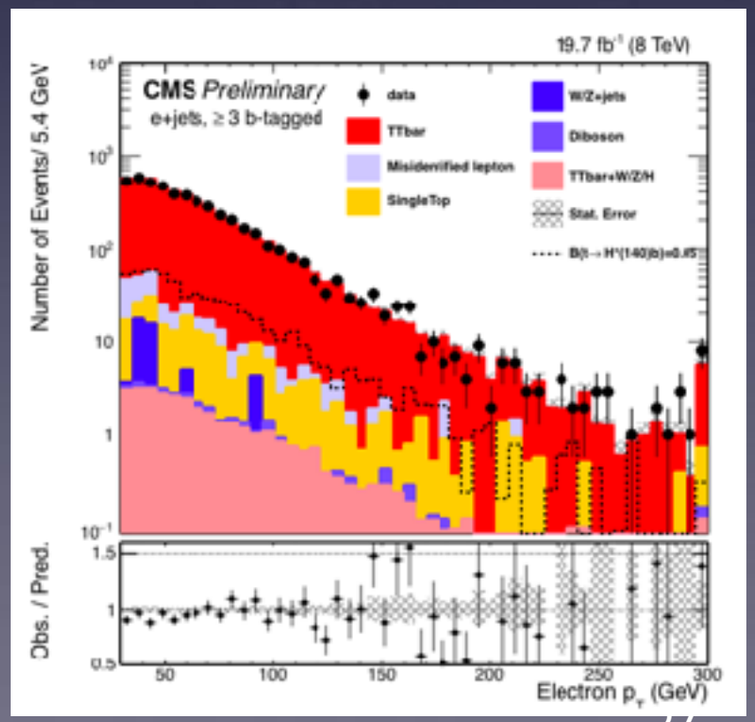


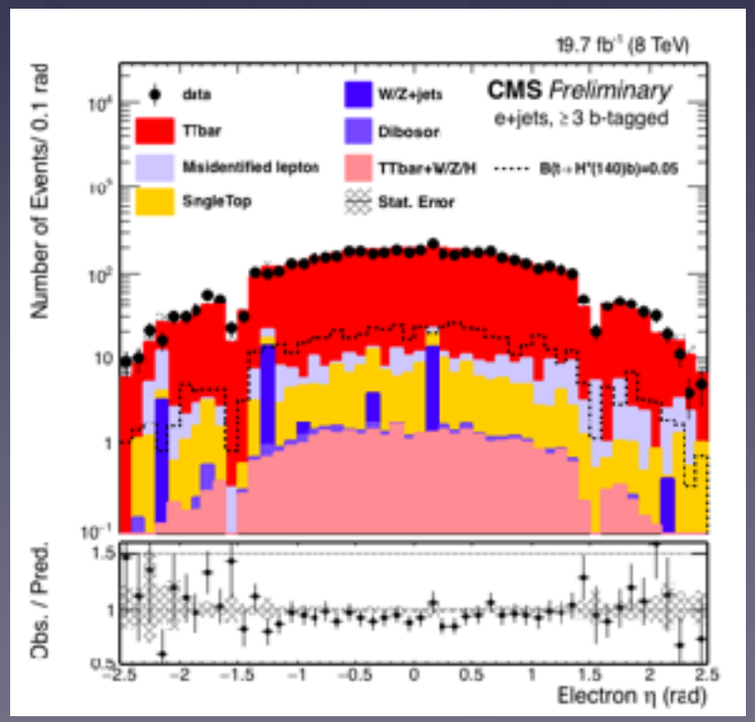


3b-tags: μ+jets(top)&e+jets(bottom)

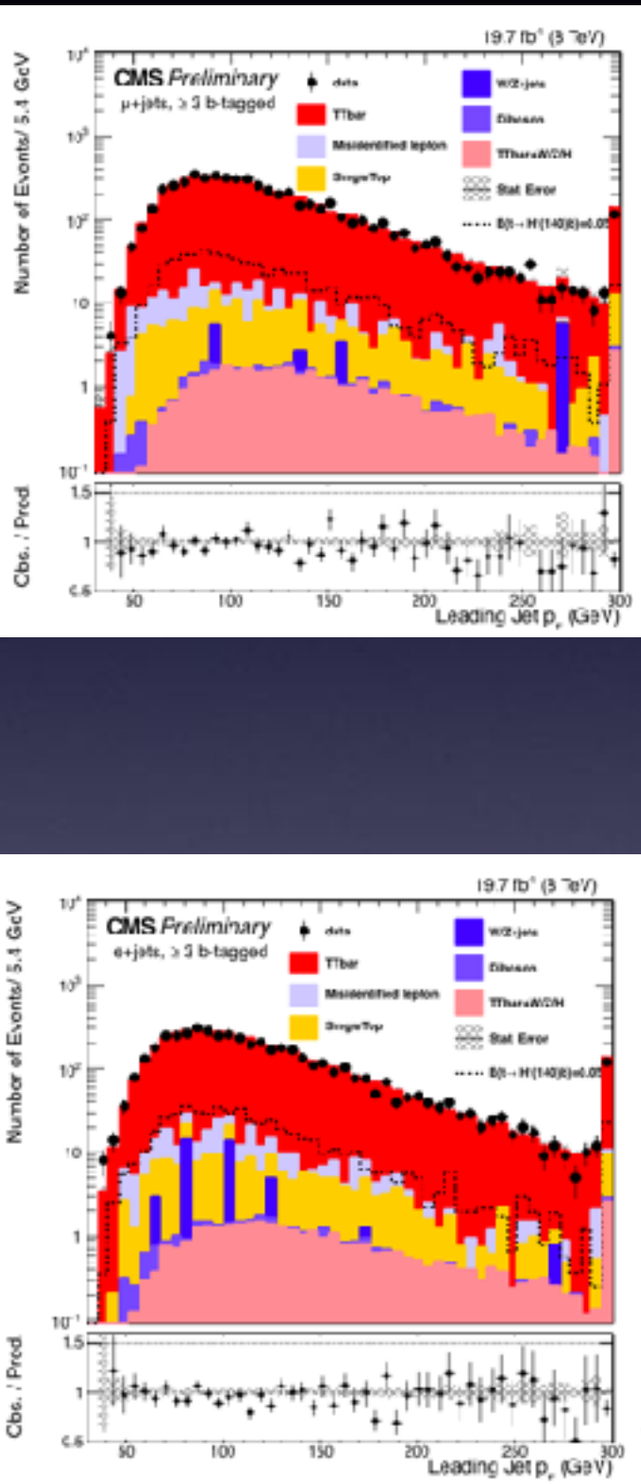


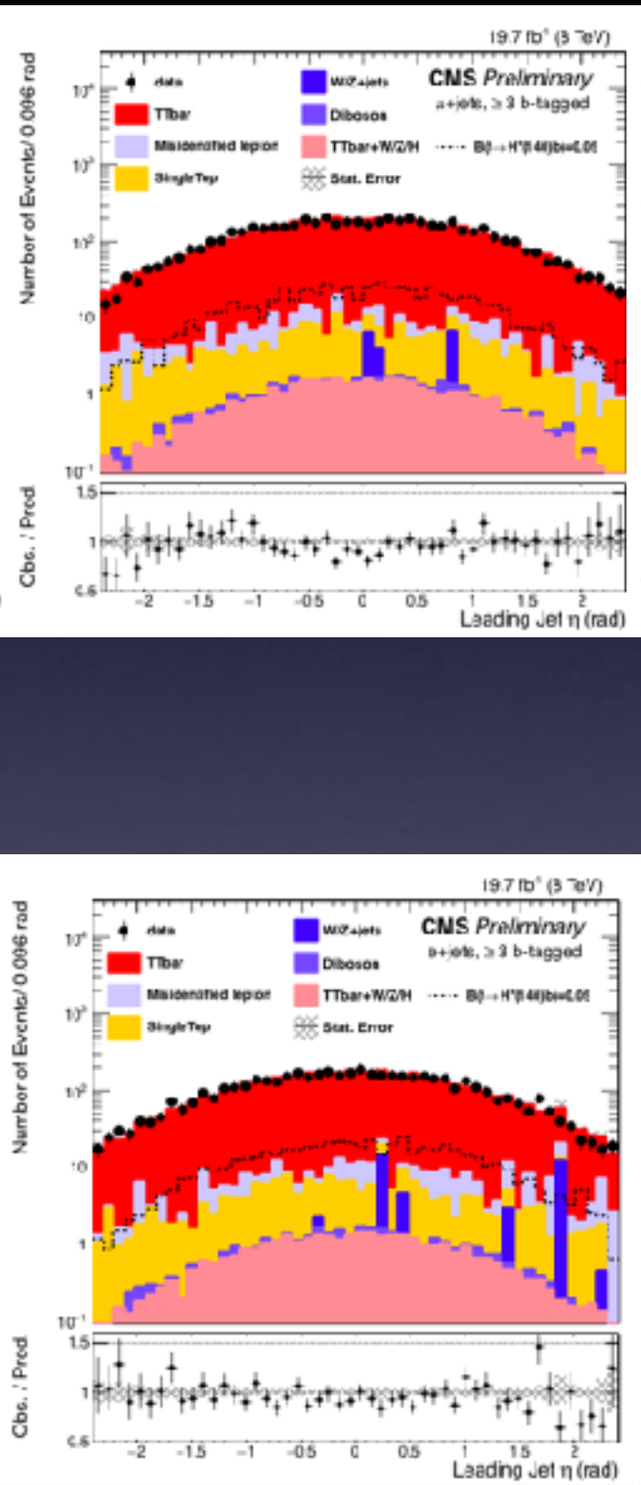


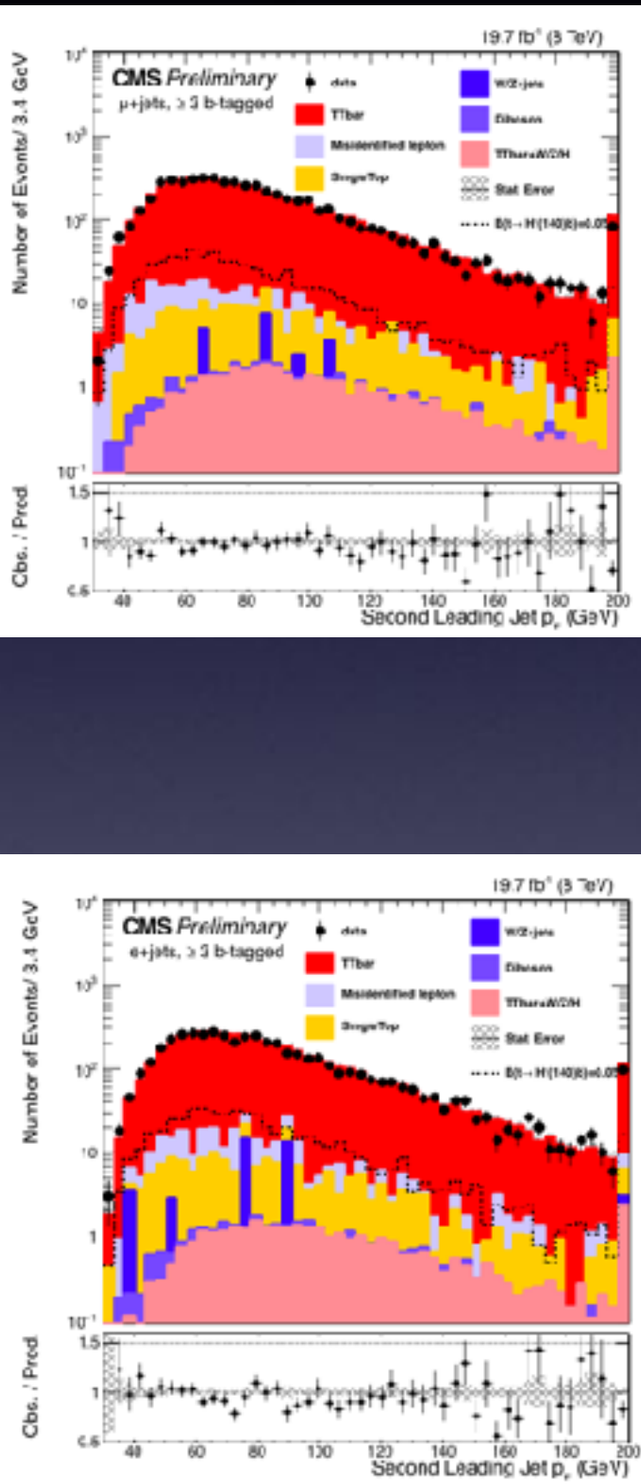


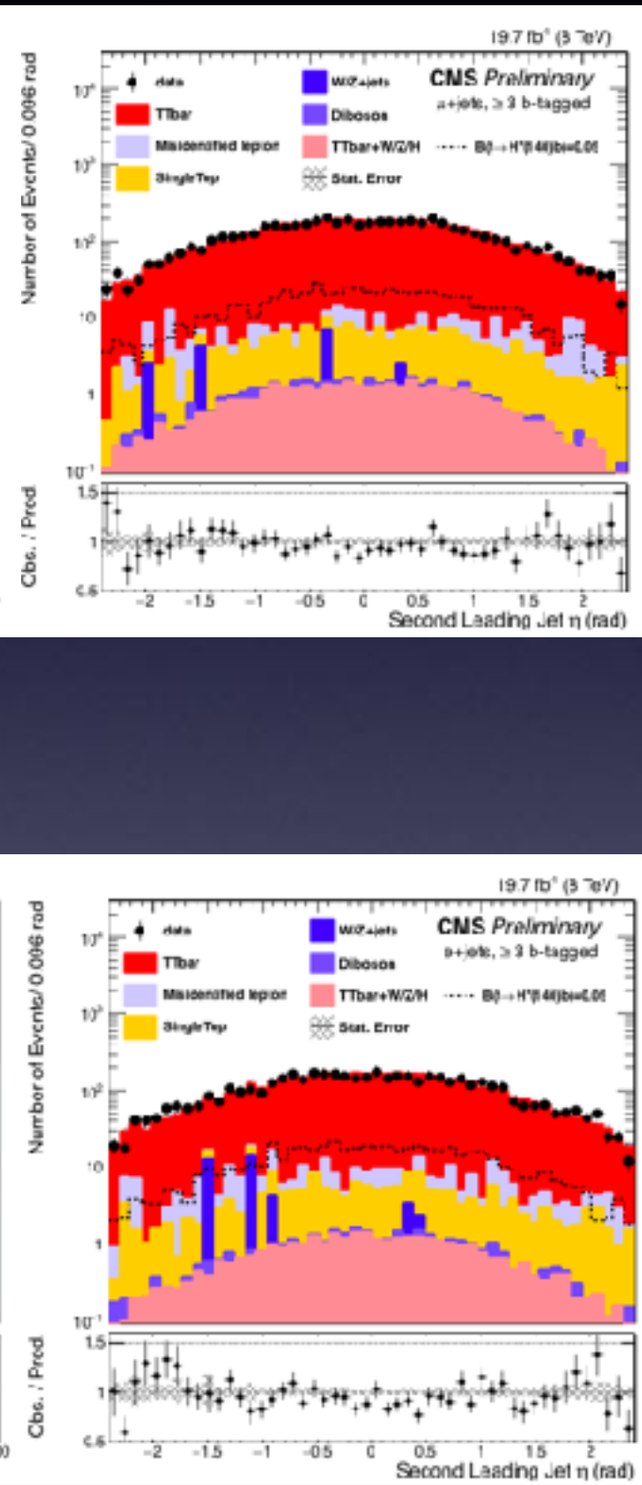


3b-tags: μ+jets(top)&e+jets(bottom)

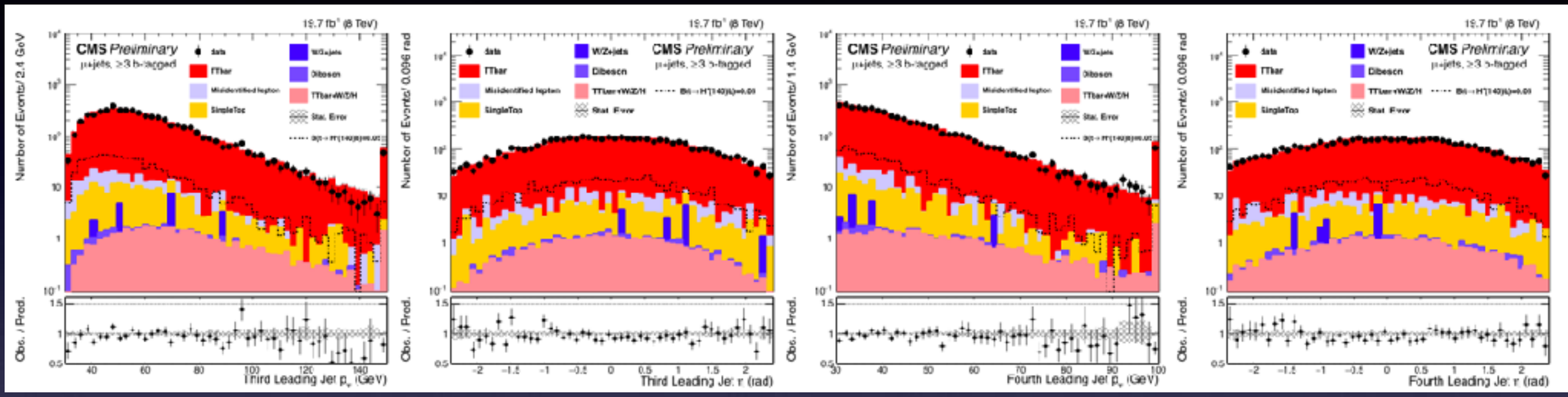


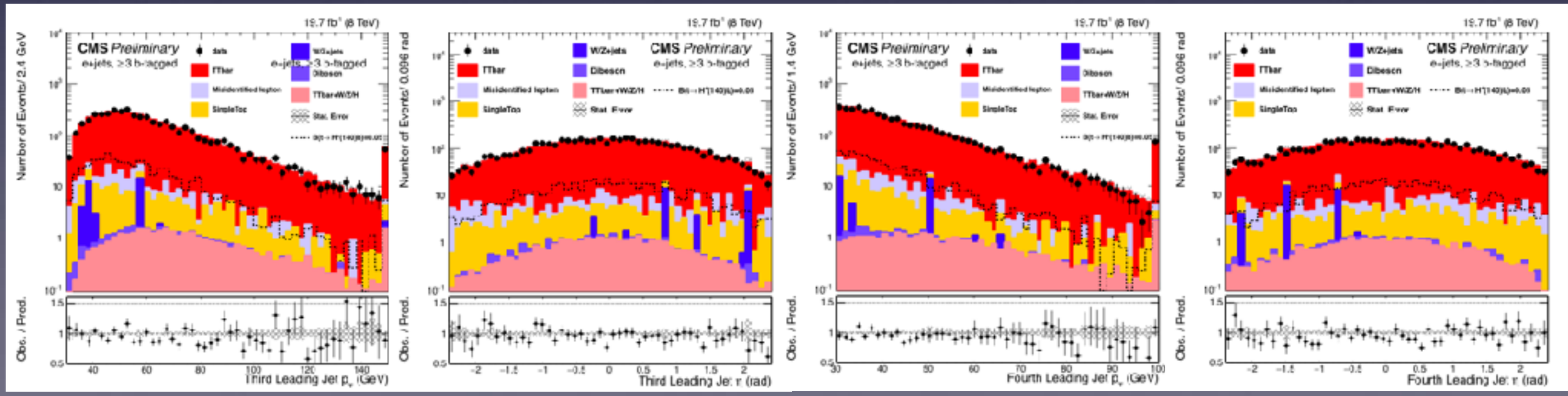






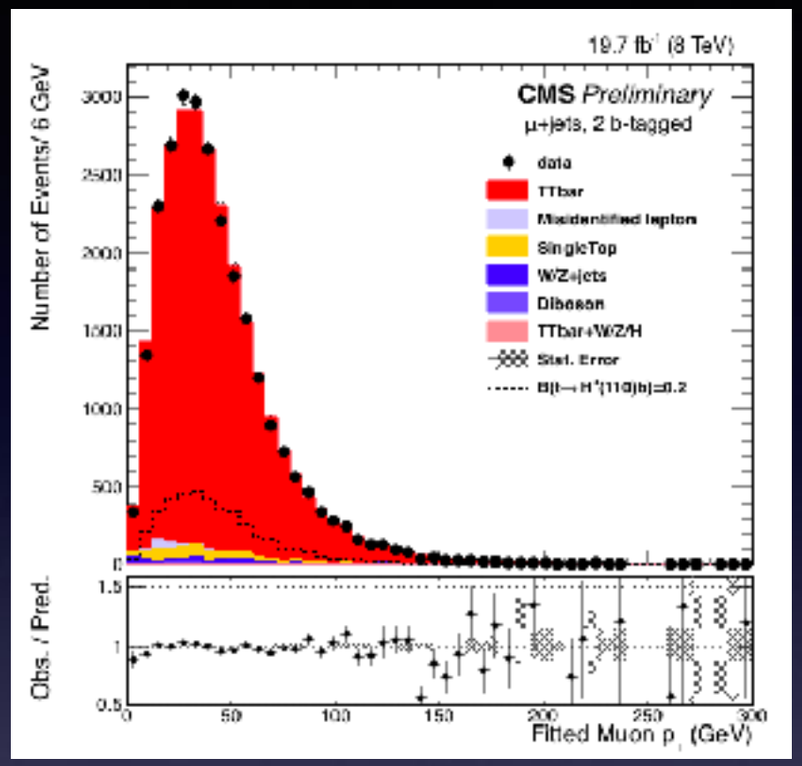
3b-tags: μ+jets(top)&e+jets(bottom)

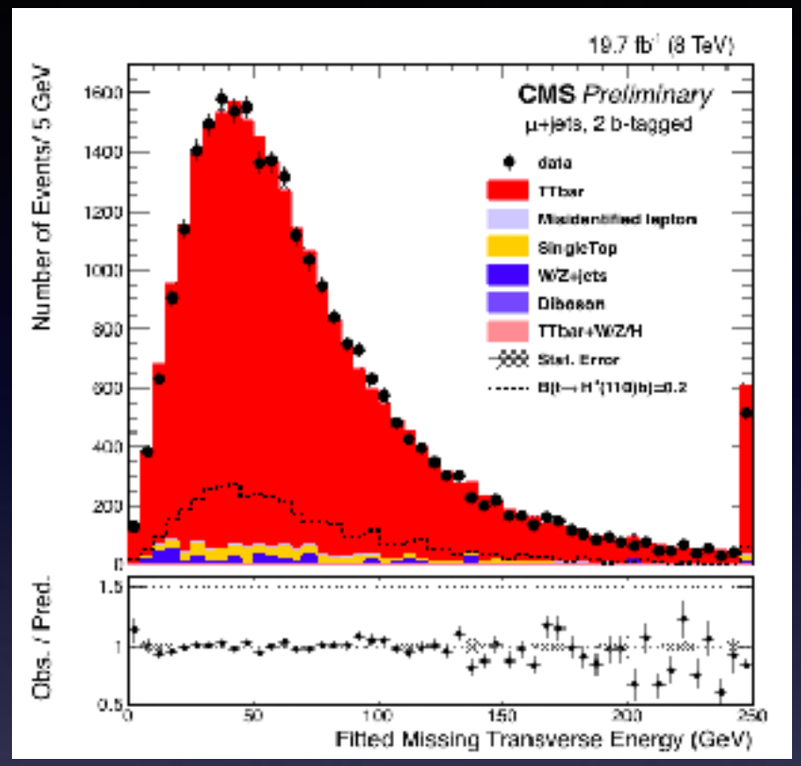


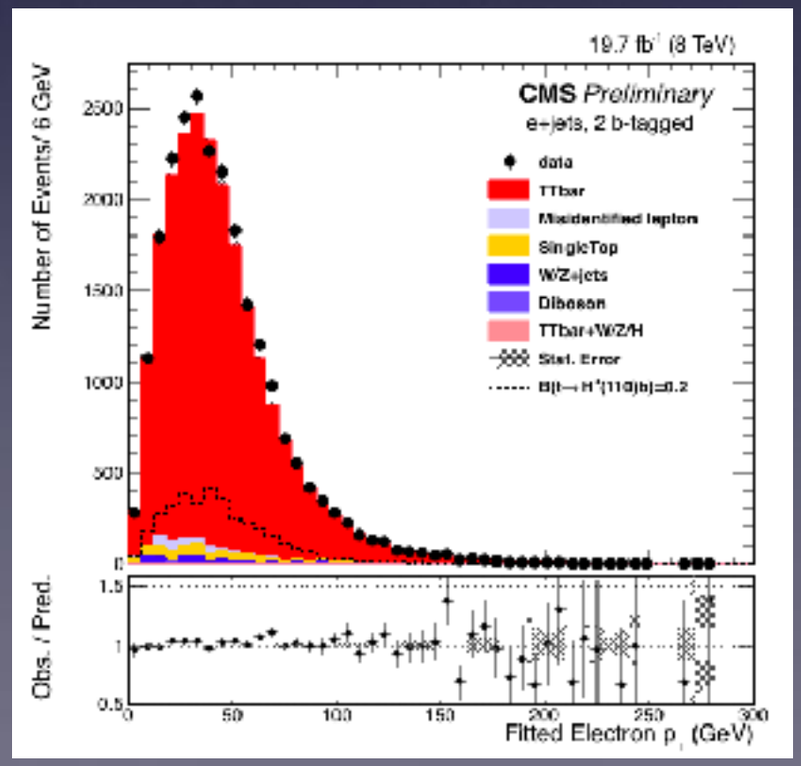


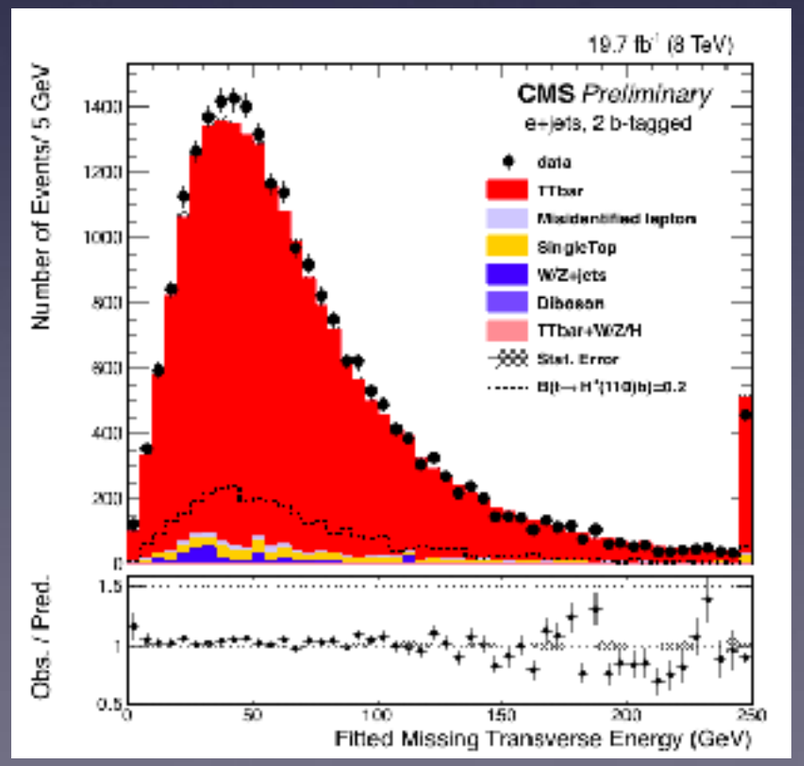
Kinematic Distribution (after fitter) 3b region renormalized

2b-tags: μ+jets(top)&e+jets(bottom)

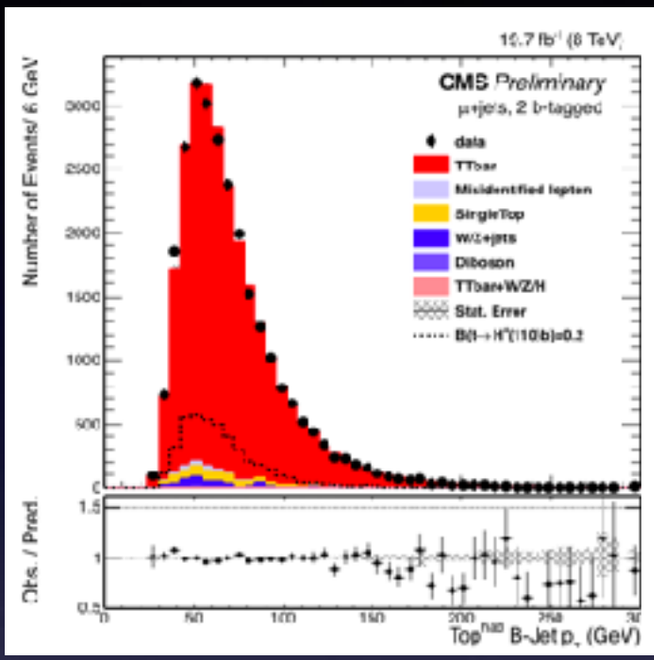


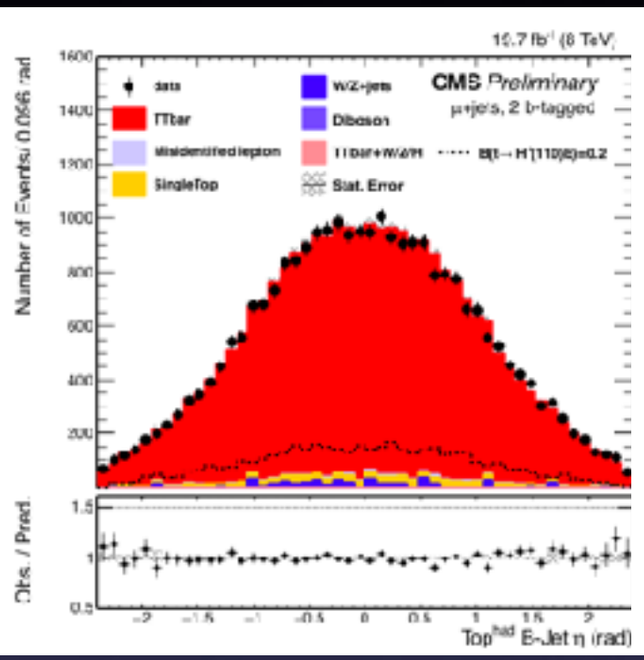


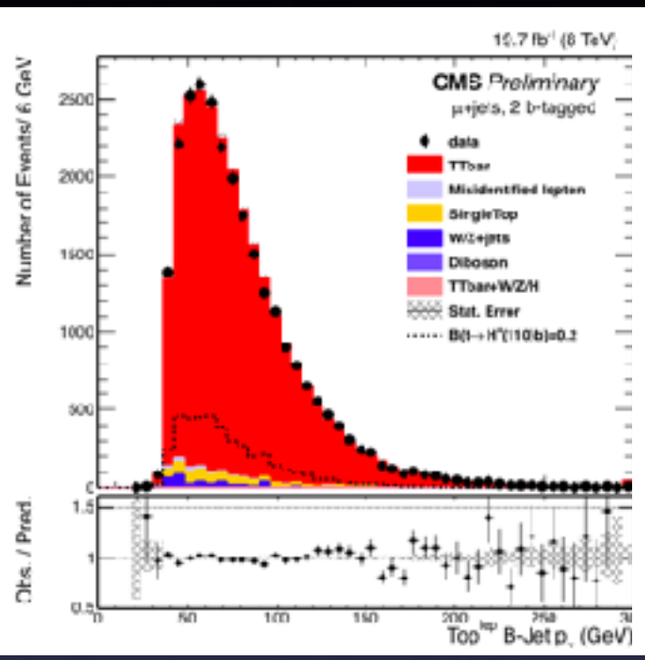


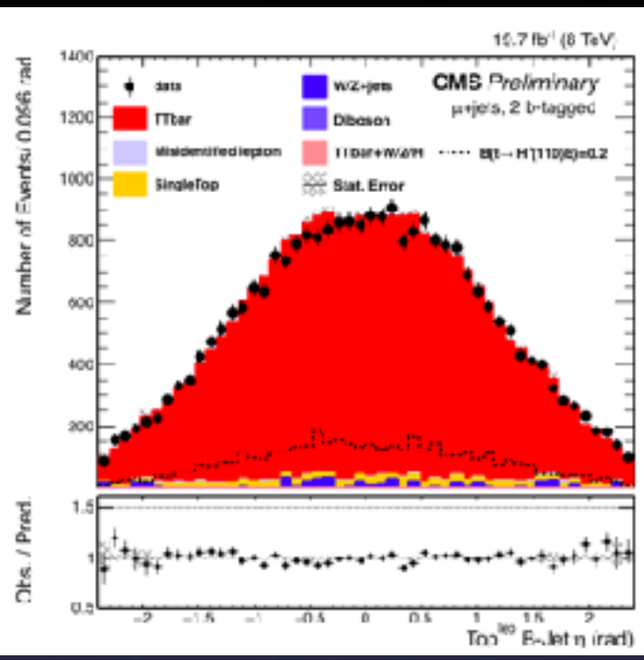


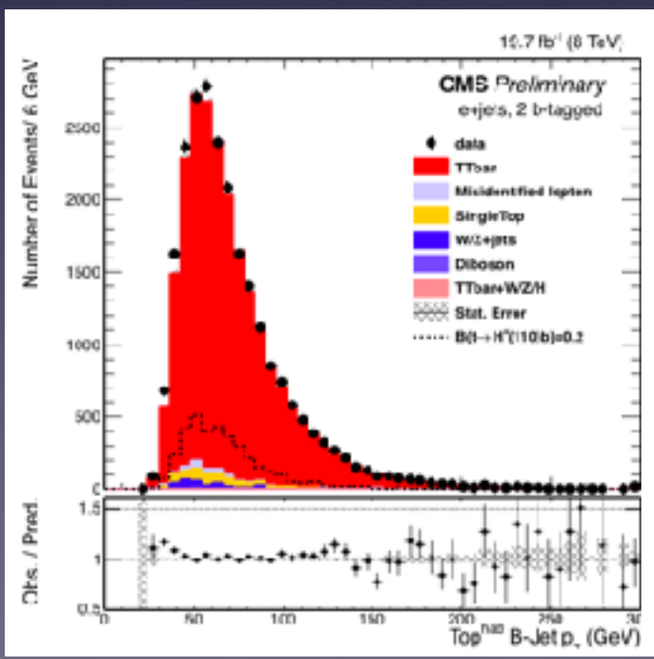
2b-tags: μ+jets(top)&e+jets(bottom)

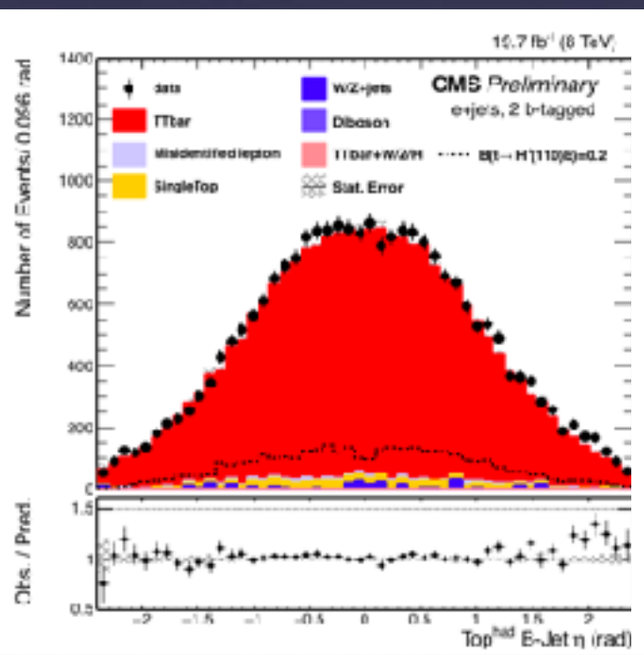


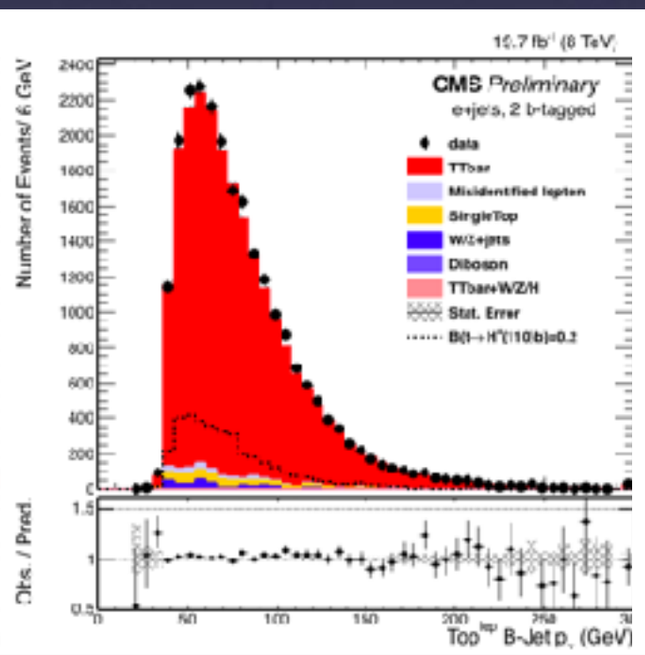


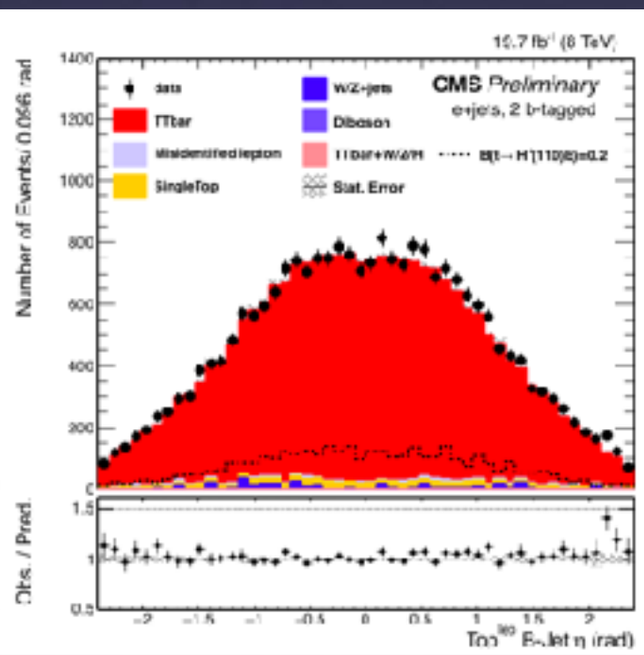




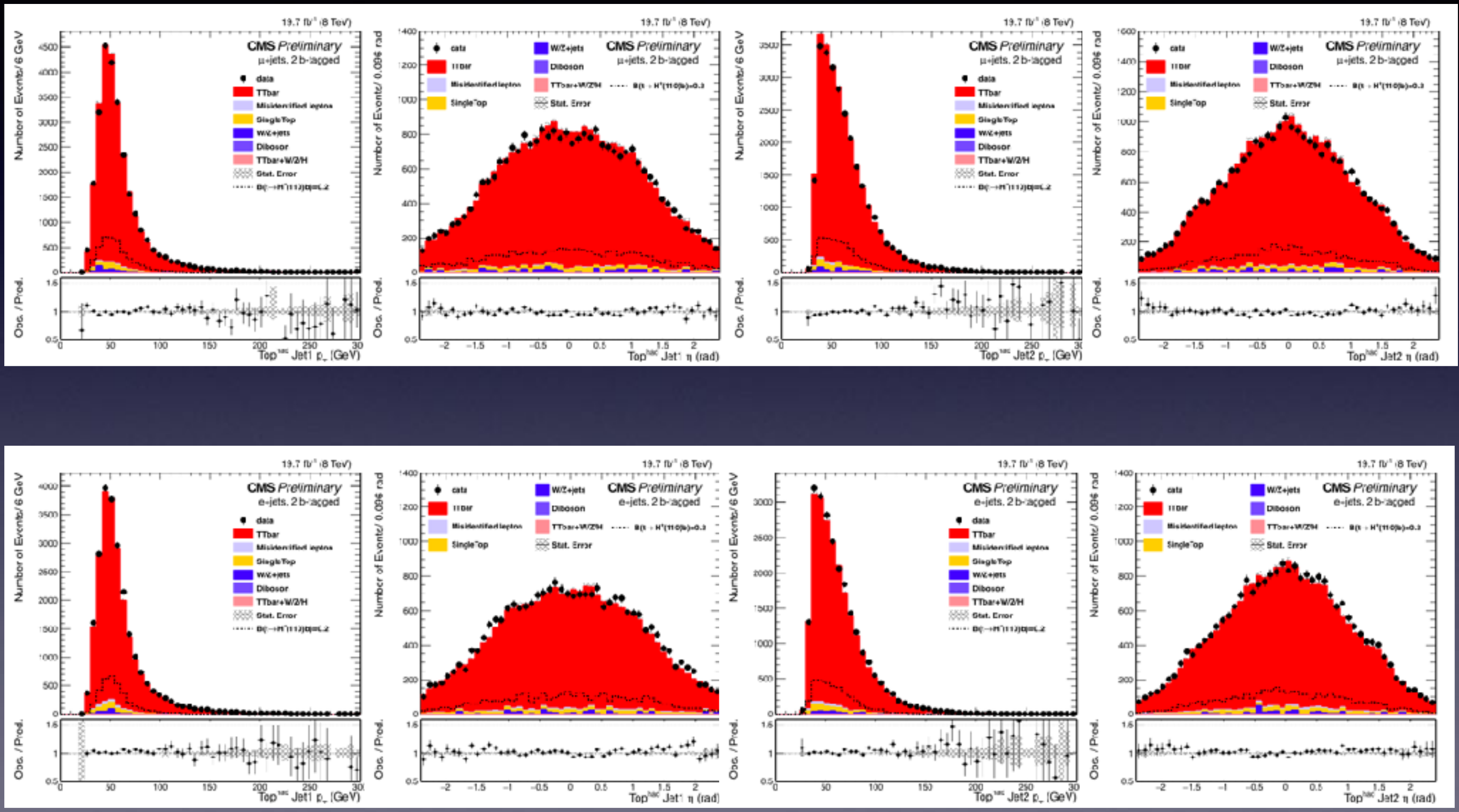




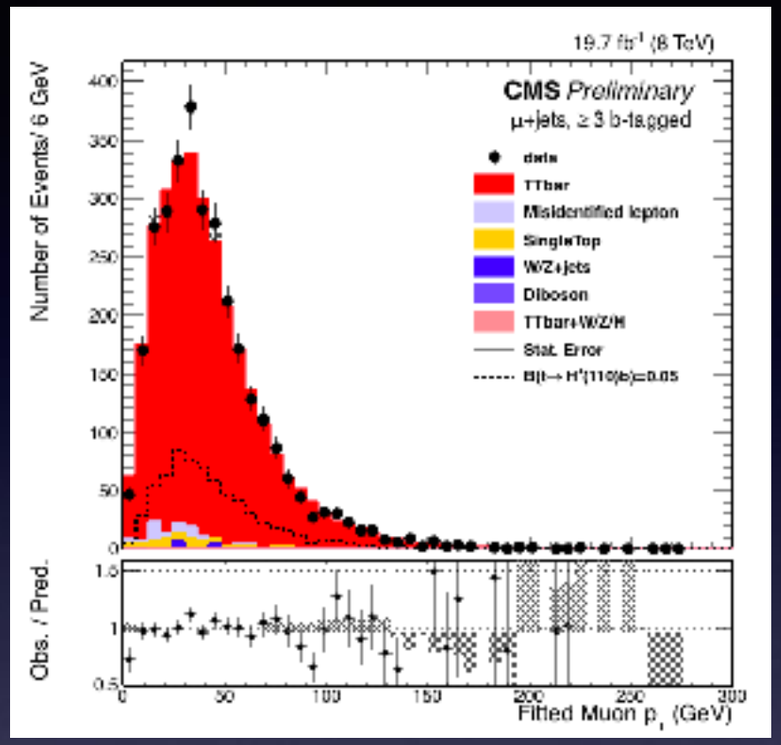


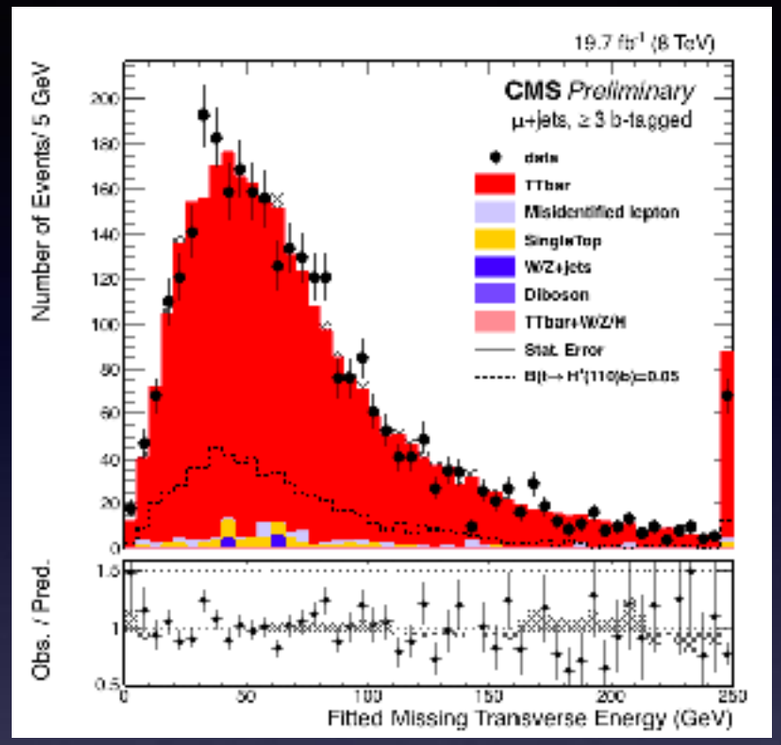


2b-tags: μ+jets(top)&e+jets(bottom)

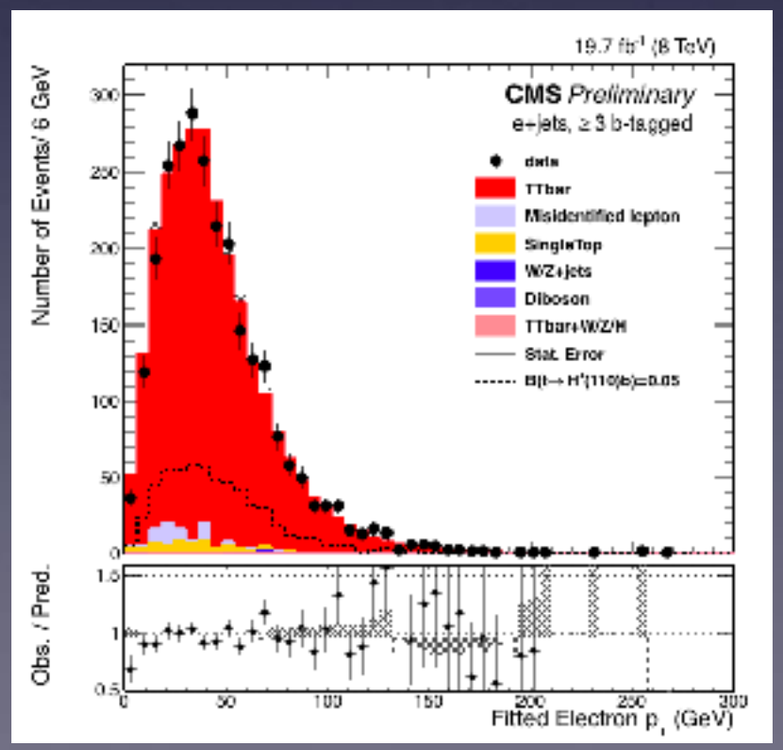


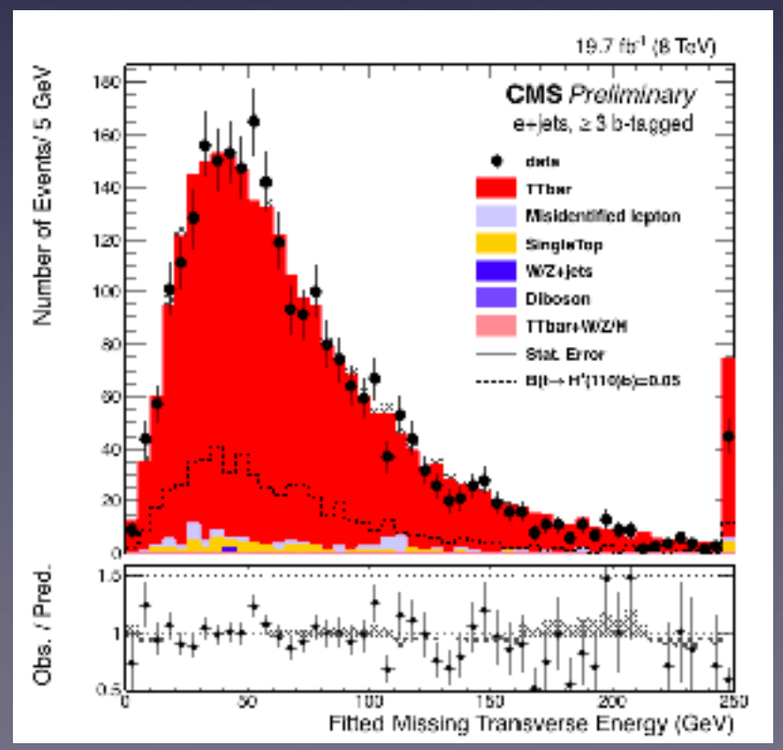
3b-tags: μ+jets(top)&e+jets(bottom)



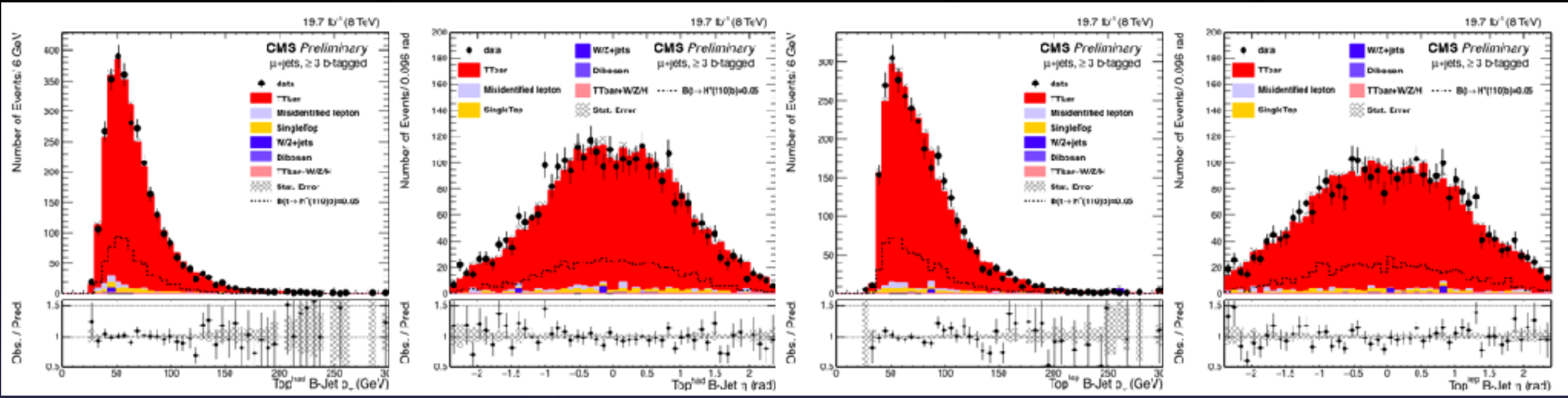


Normal Fitter:
90≤m(H+)≤120 GeV

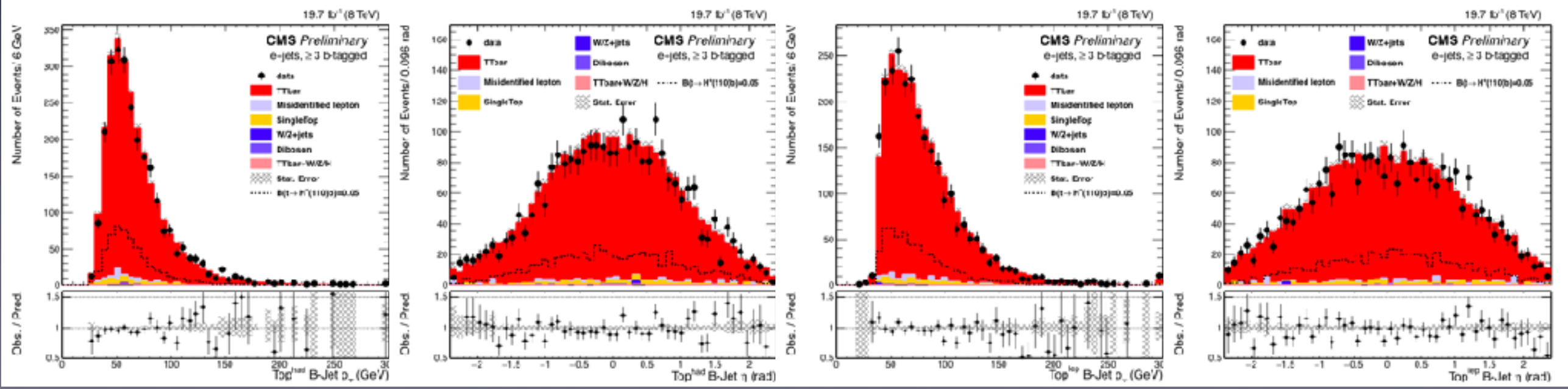




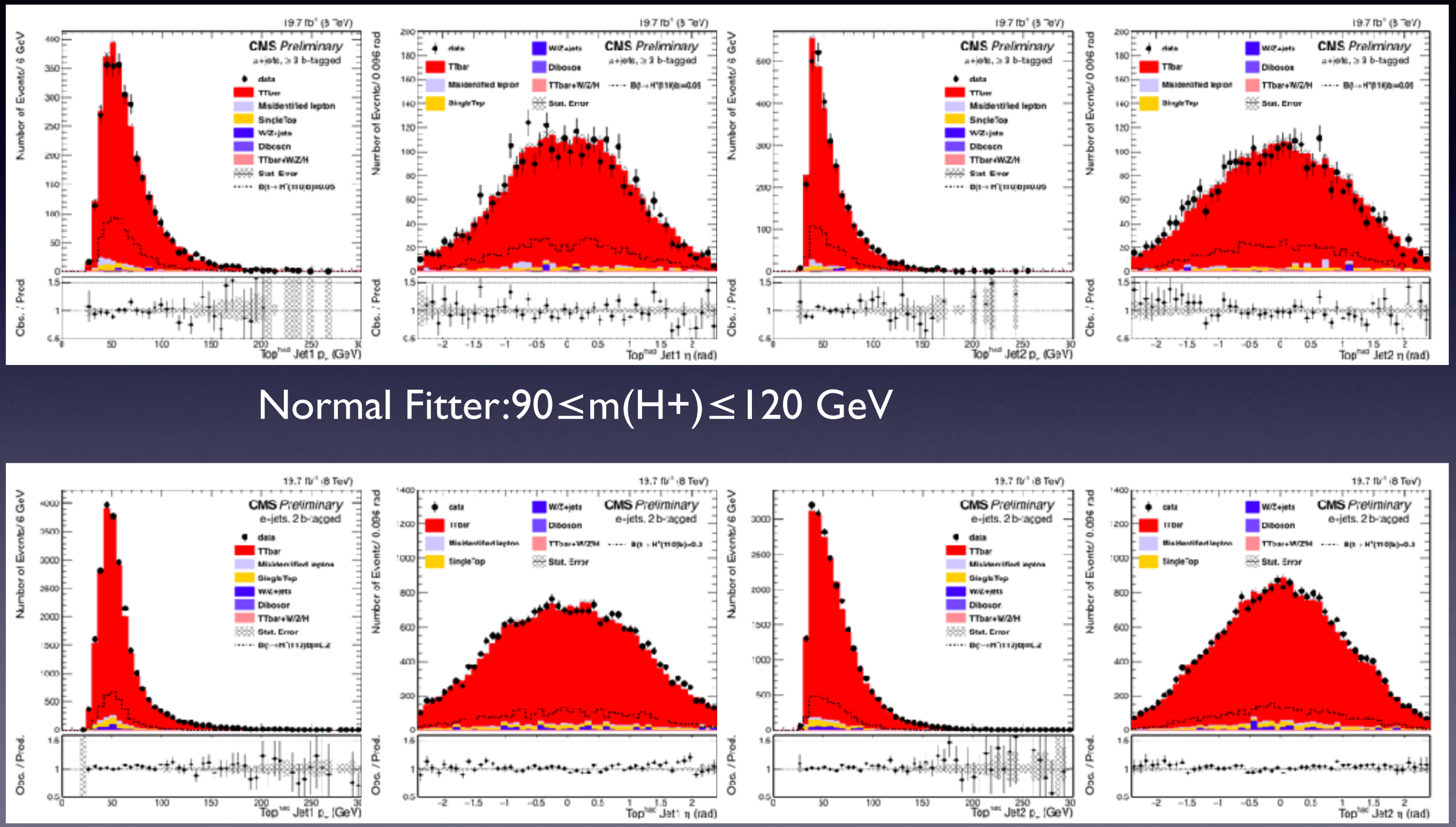
3b-tags: μ+jets(top)&e+jets(bottom)



Normal Fitter:90≤m(H+)≤120 GeV

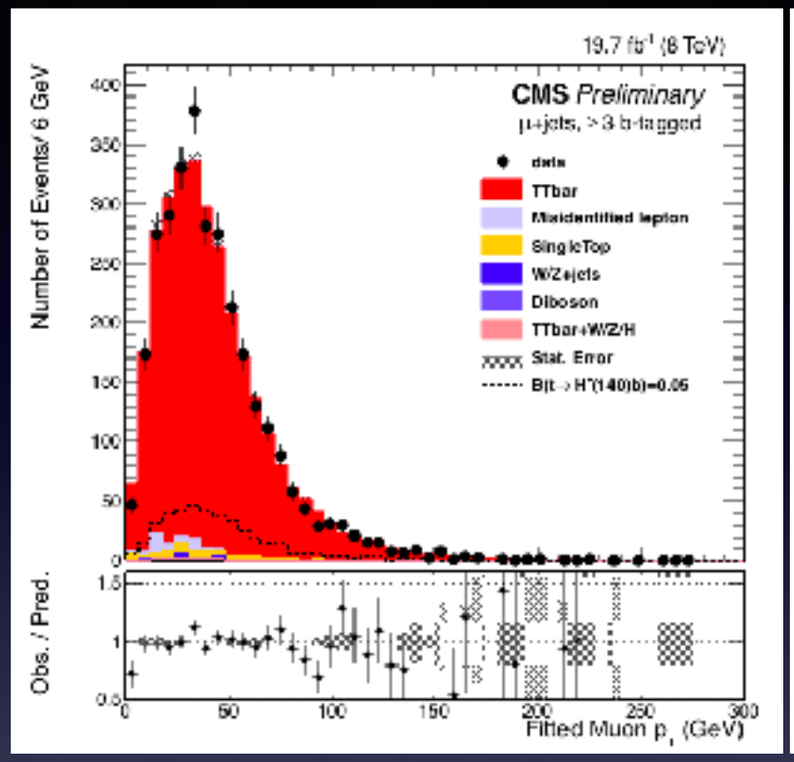


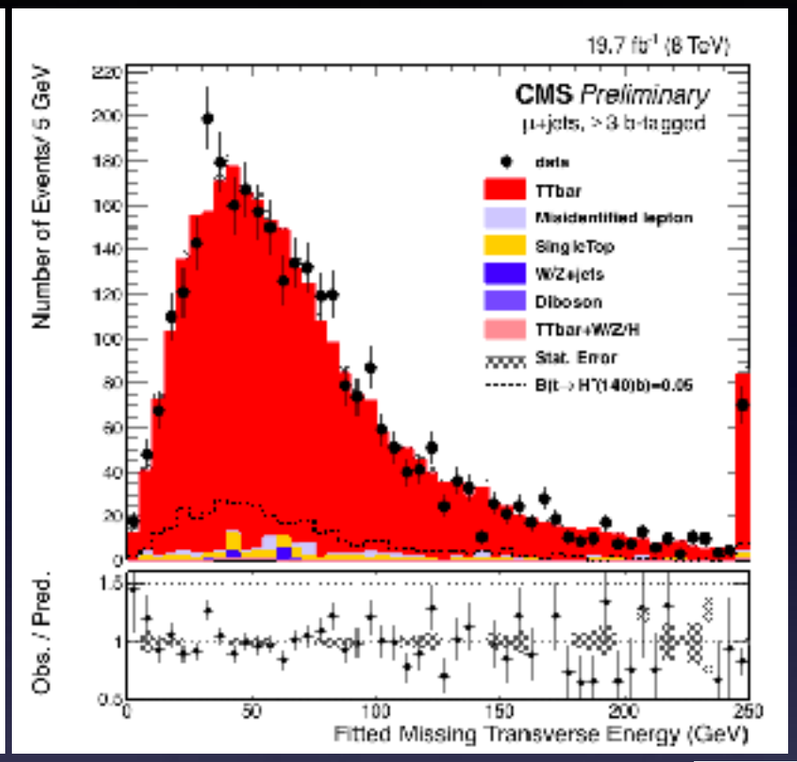
3b-tags: μ+jets(top)&e+jets(bottom)



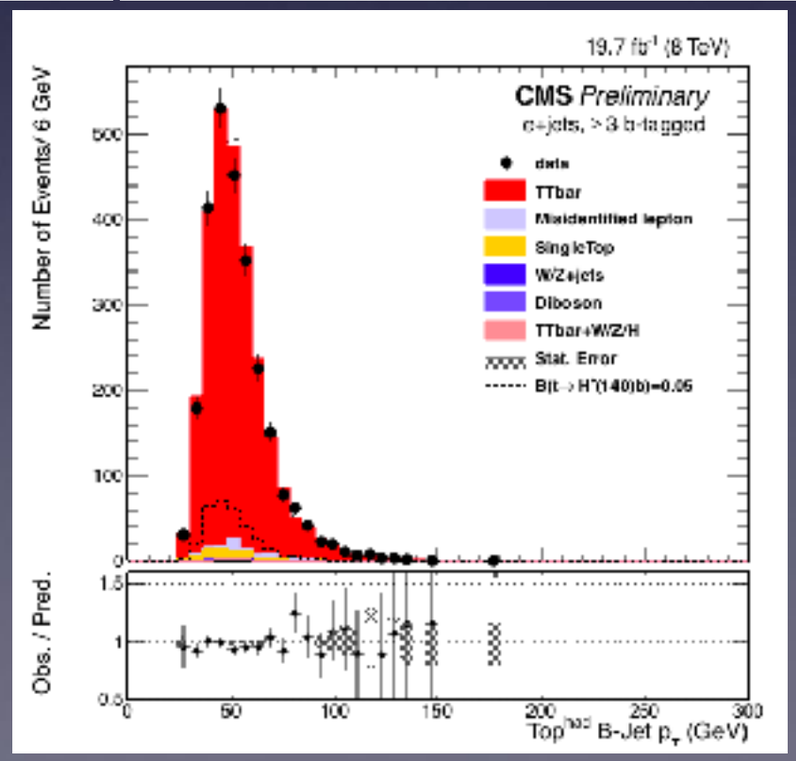
Normal Fitter: $90 \leq m(H^+) \leq 120$ GeV

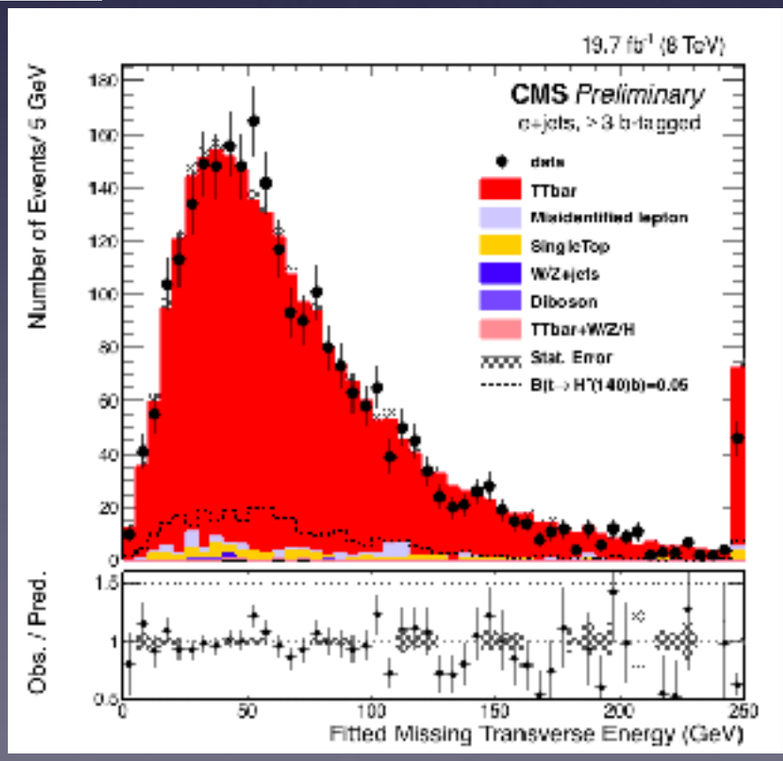
3b-tags: μ+jets(top)&e+jets(bottom)



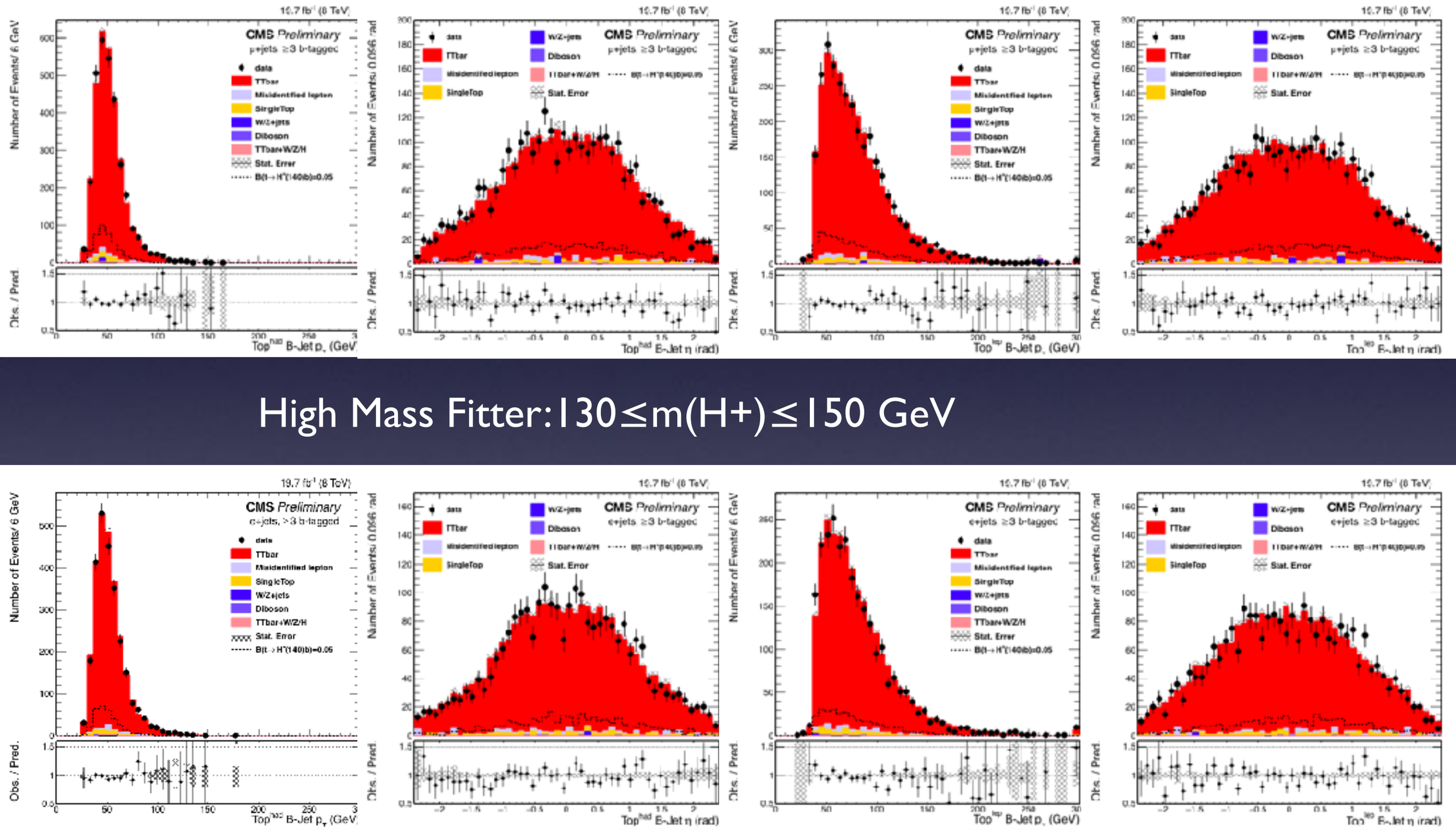


High Mass Fitter:
90≤m(H+)≤120 GeV



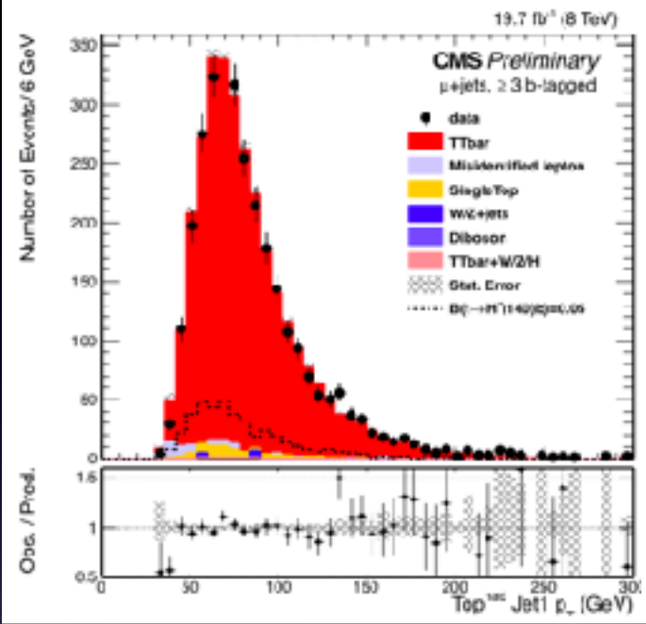


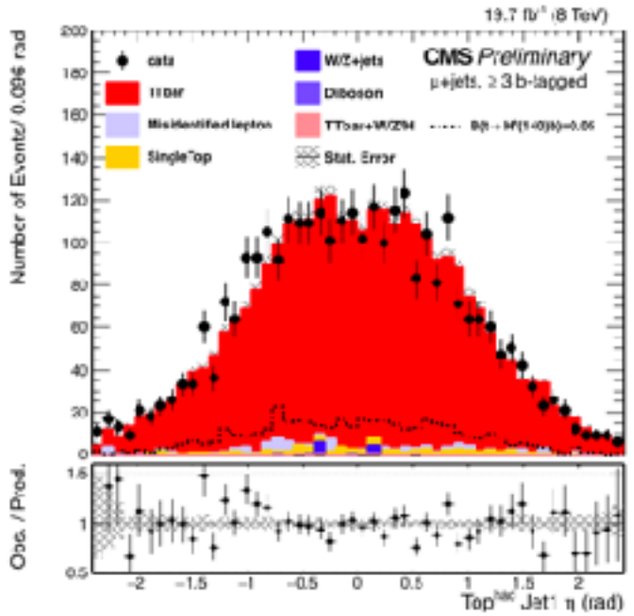
3b-tags: μ+jets(top)&e+jets(bottom)

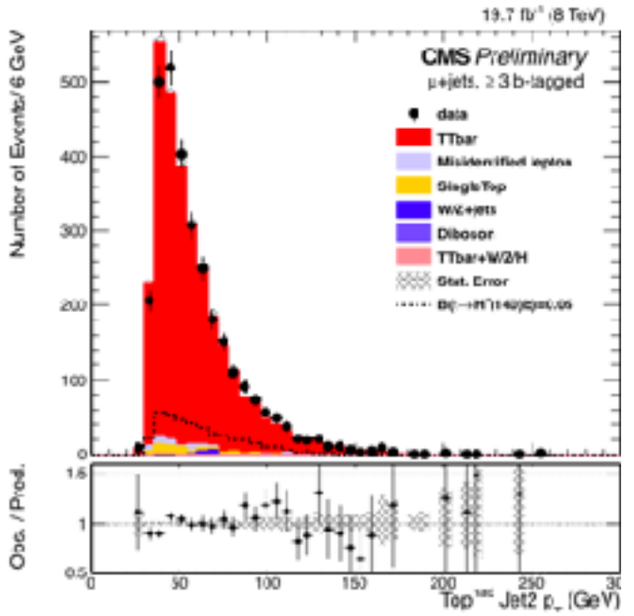


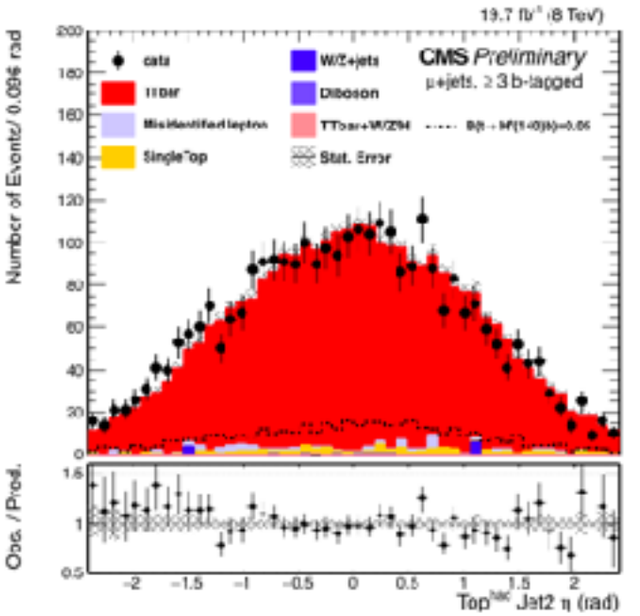
High Mass Fitter: 130≤m(H+)≤150 GeV

3b-tags: μ+jets(top)&e+jets(bottom)

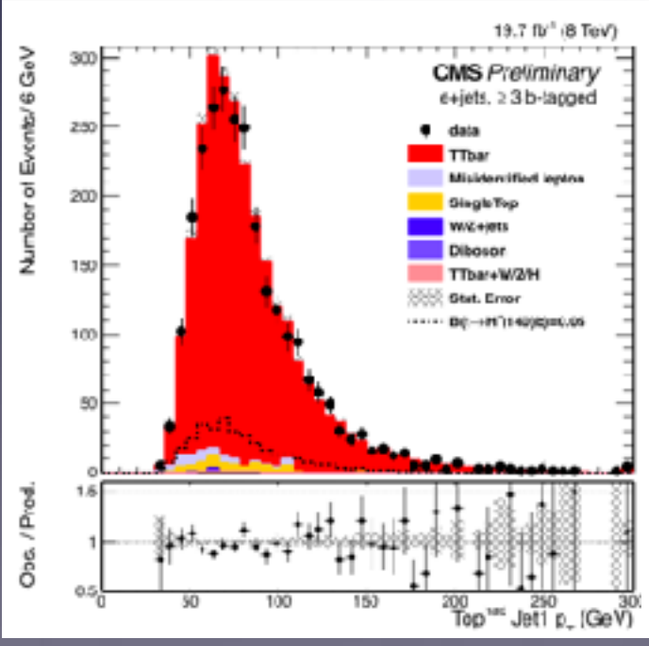


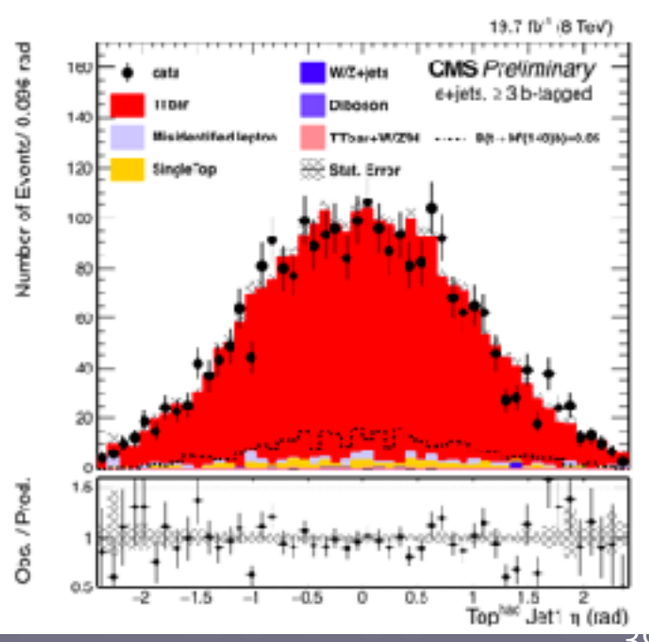


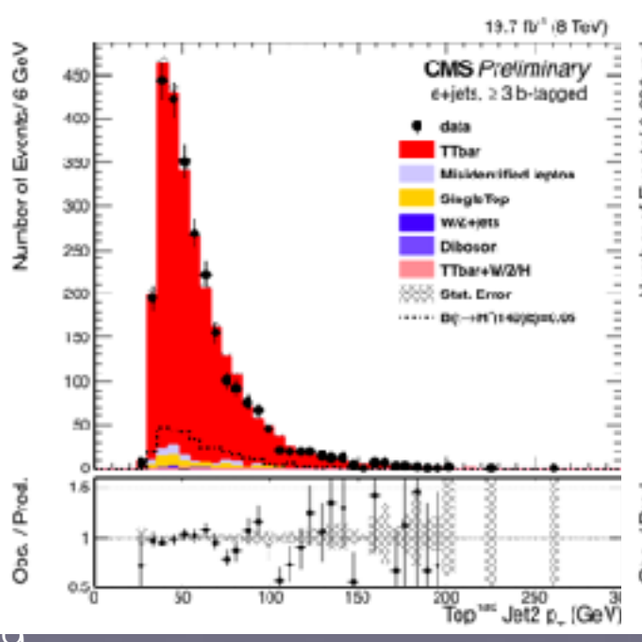


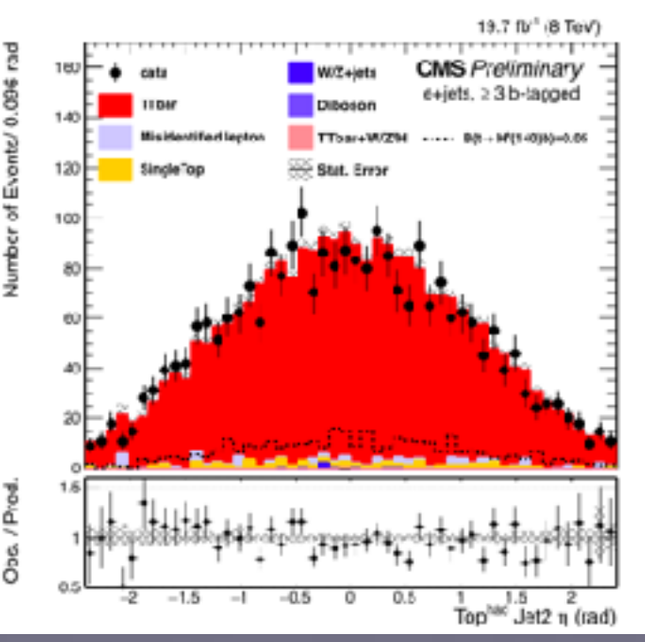


High Mass Fitter: 130≤m(H+)≤150 GeV





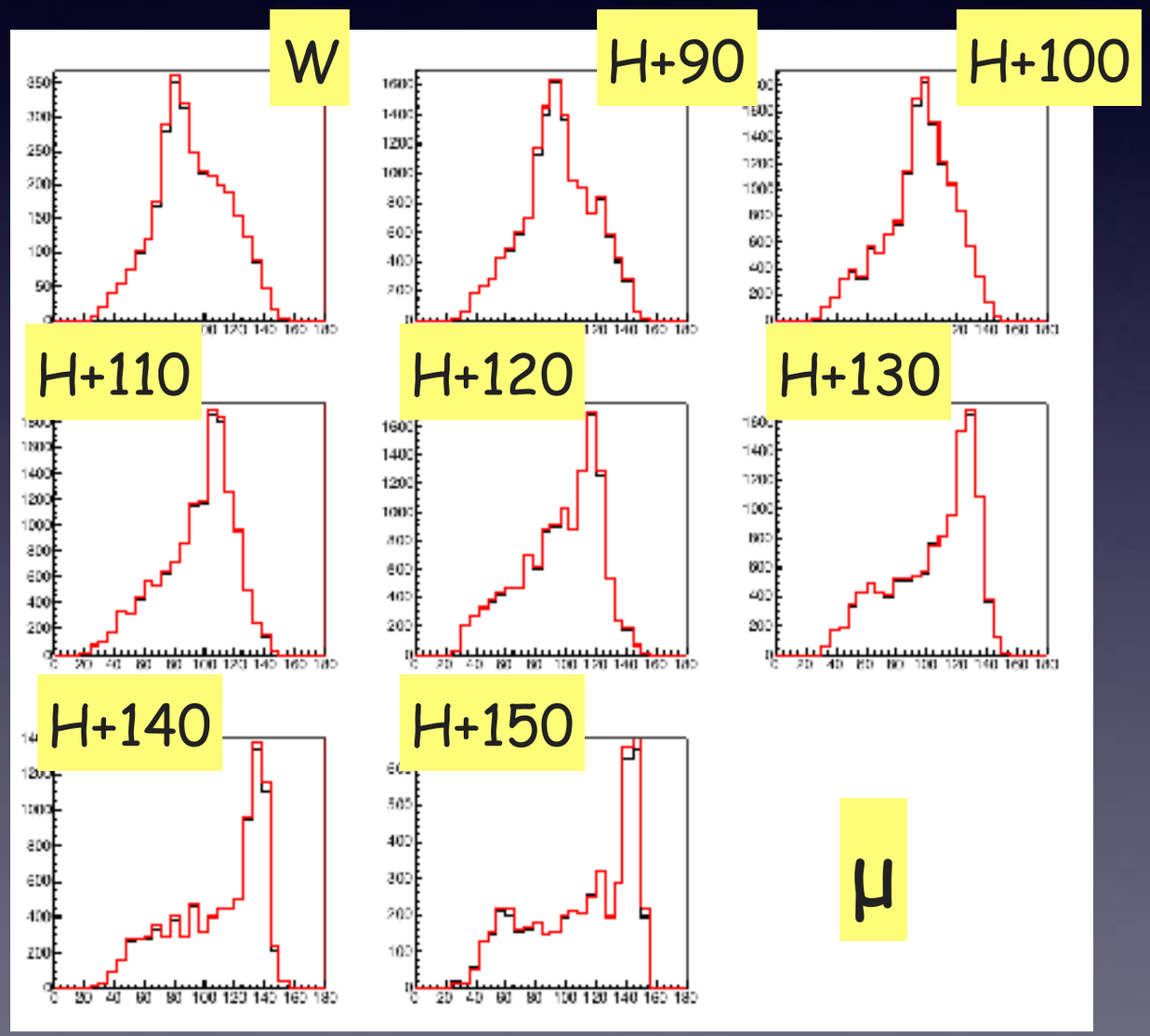


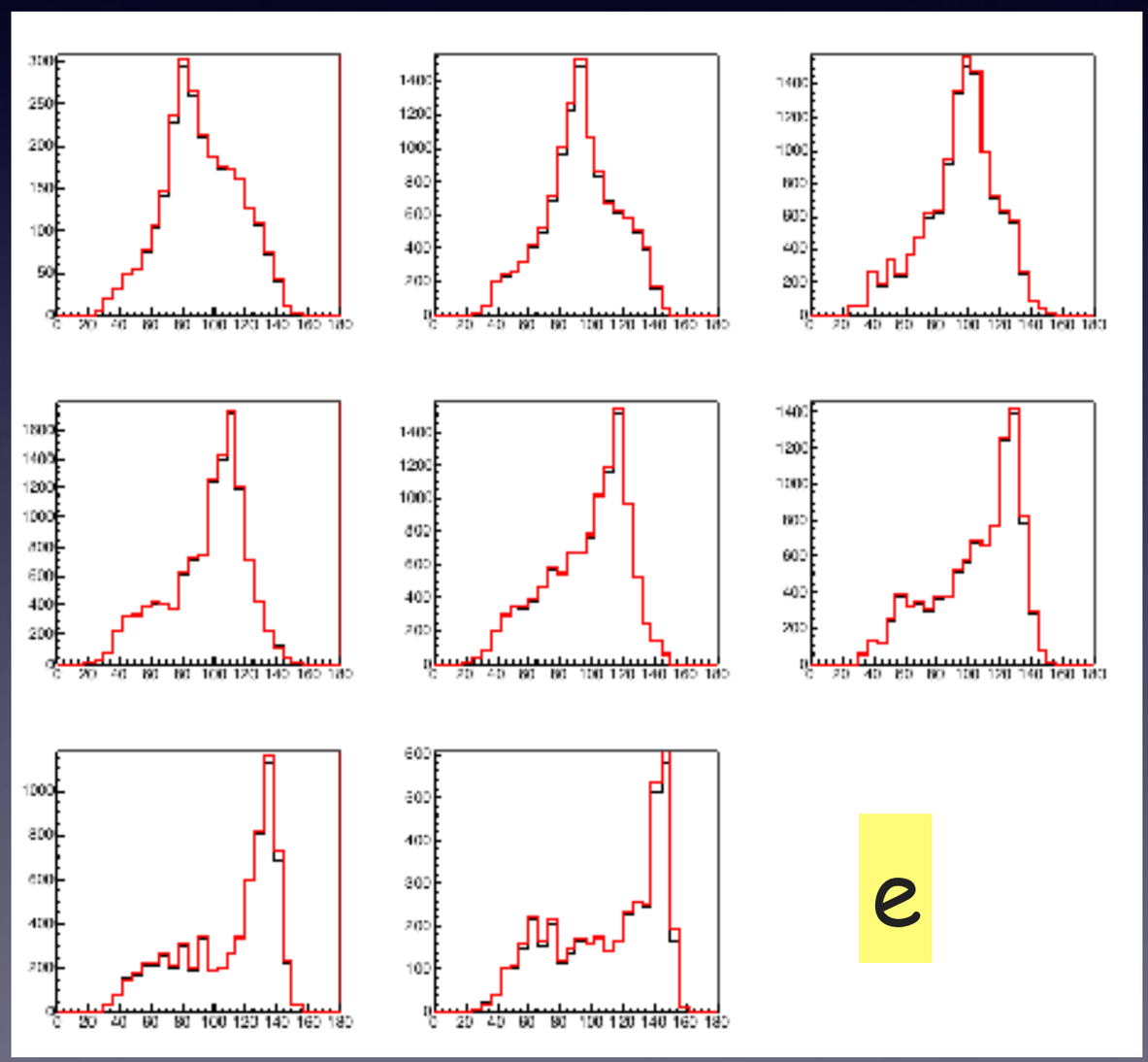


Systematic Shapes

pt(TT) reweight

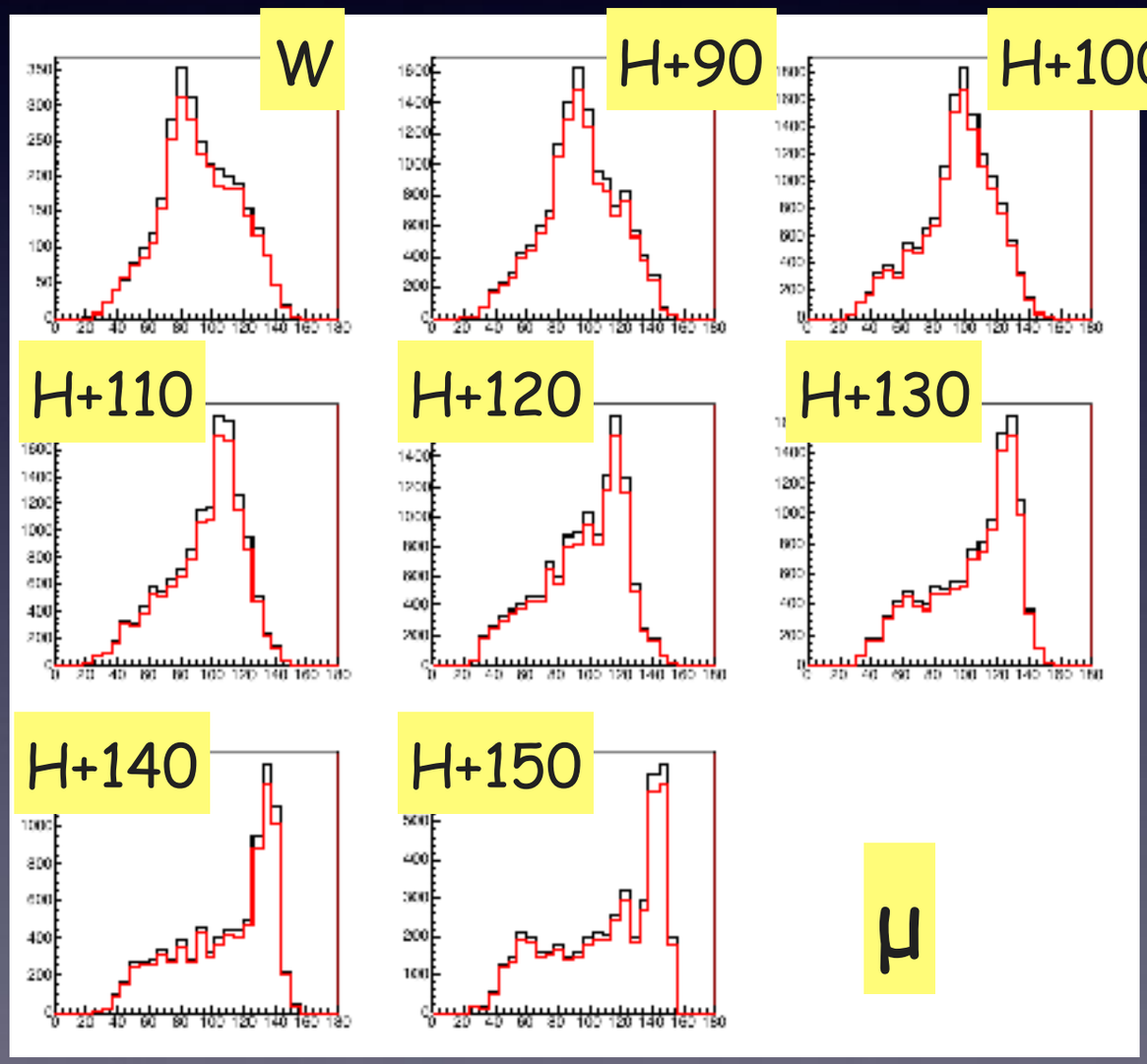
- black(template) & red(syst. template)

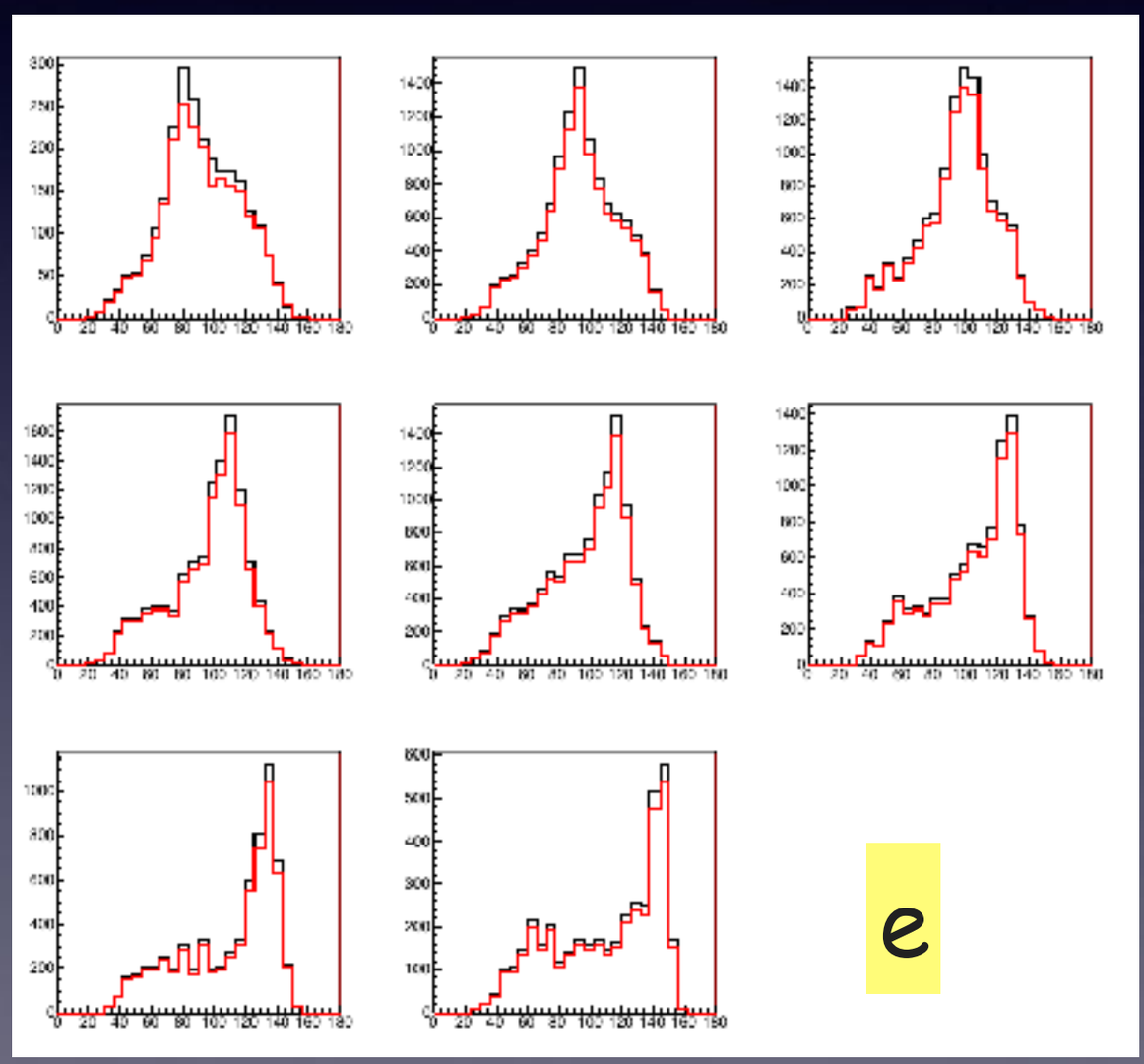




Powheg

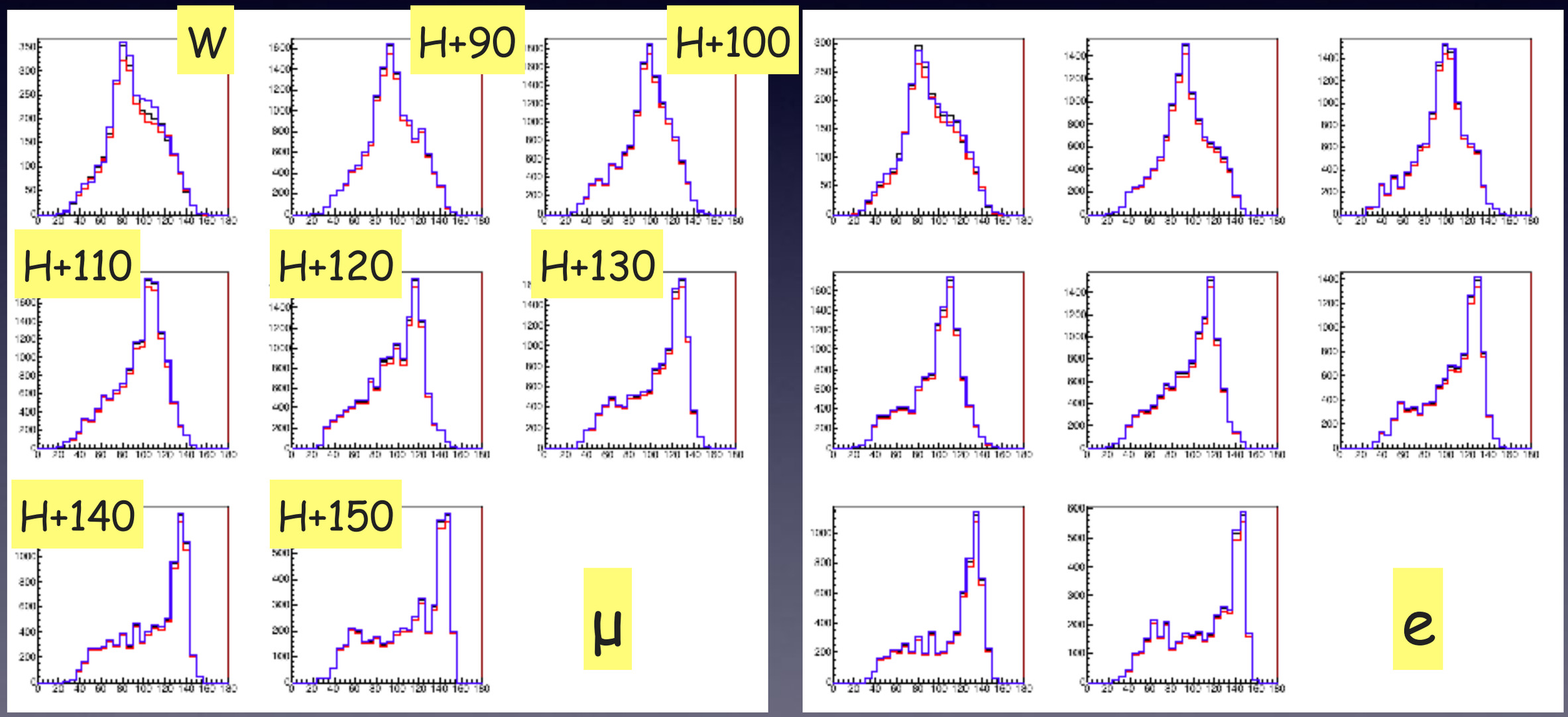
- black(template) & red(syst. template)





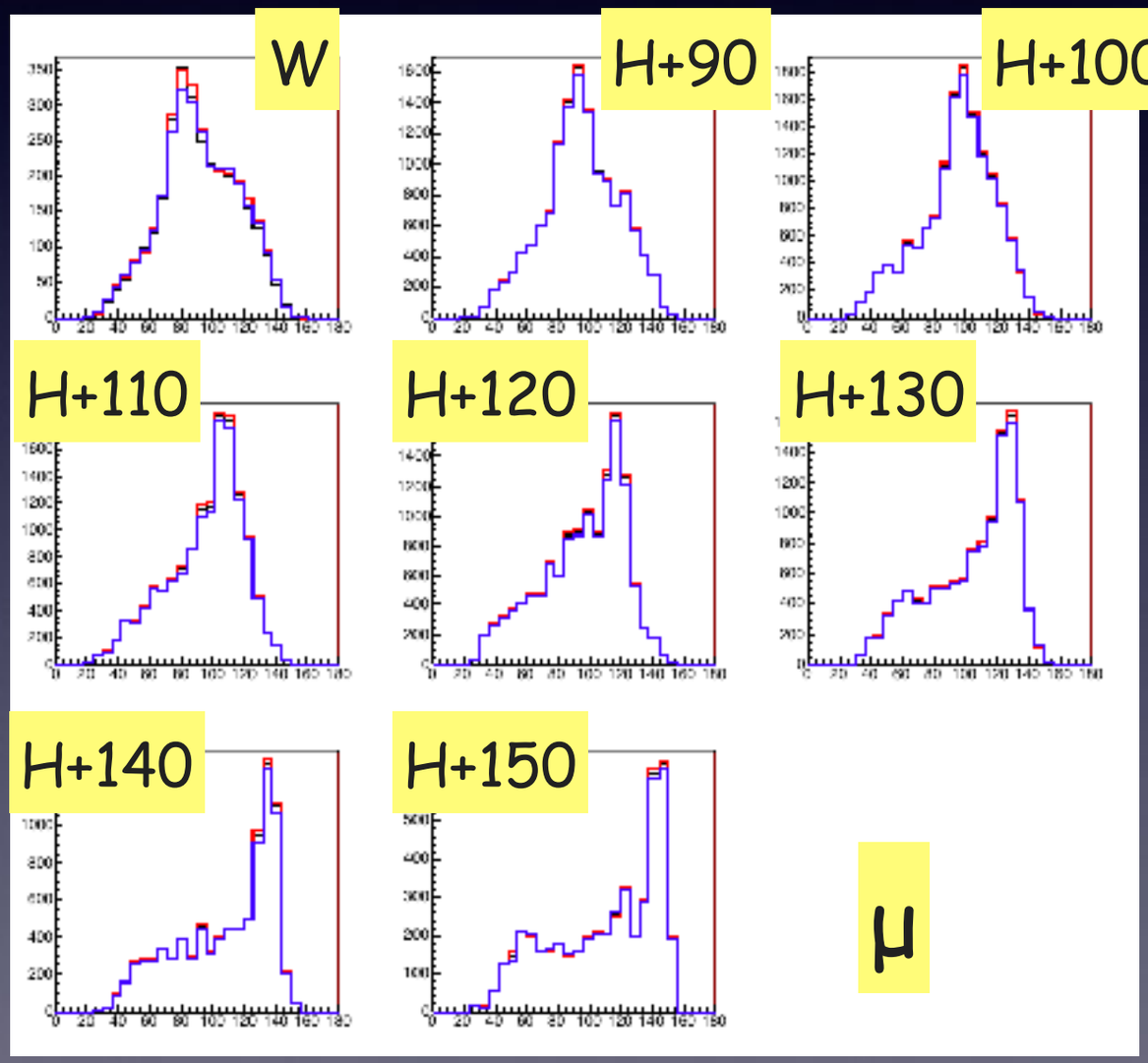
m(top) 172.5±1GeV

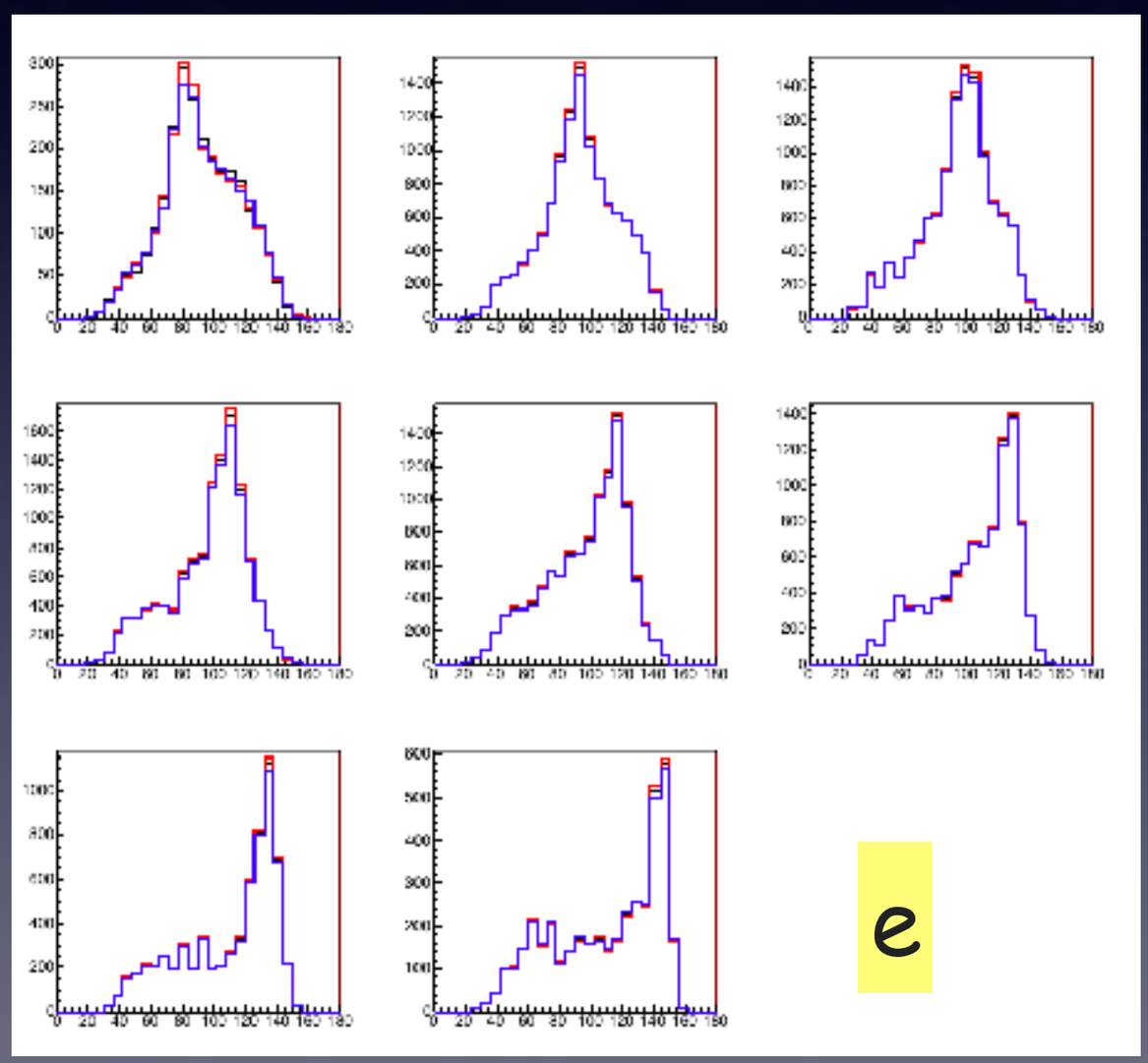
- black(template) & red(Upsyst. template) & blue(Downsyst. template)



Q^2

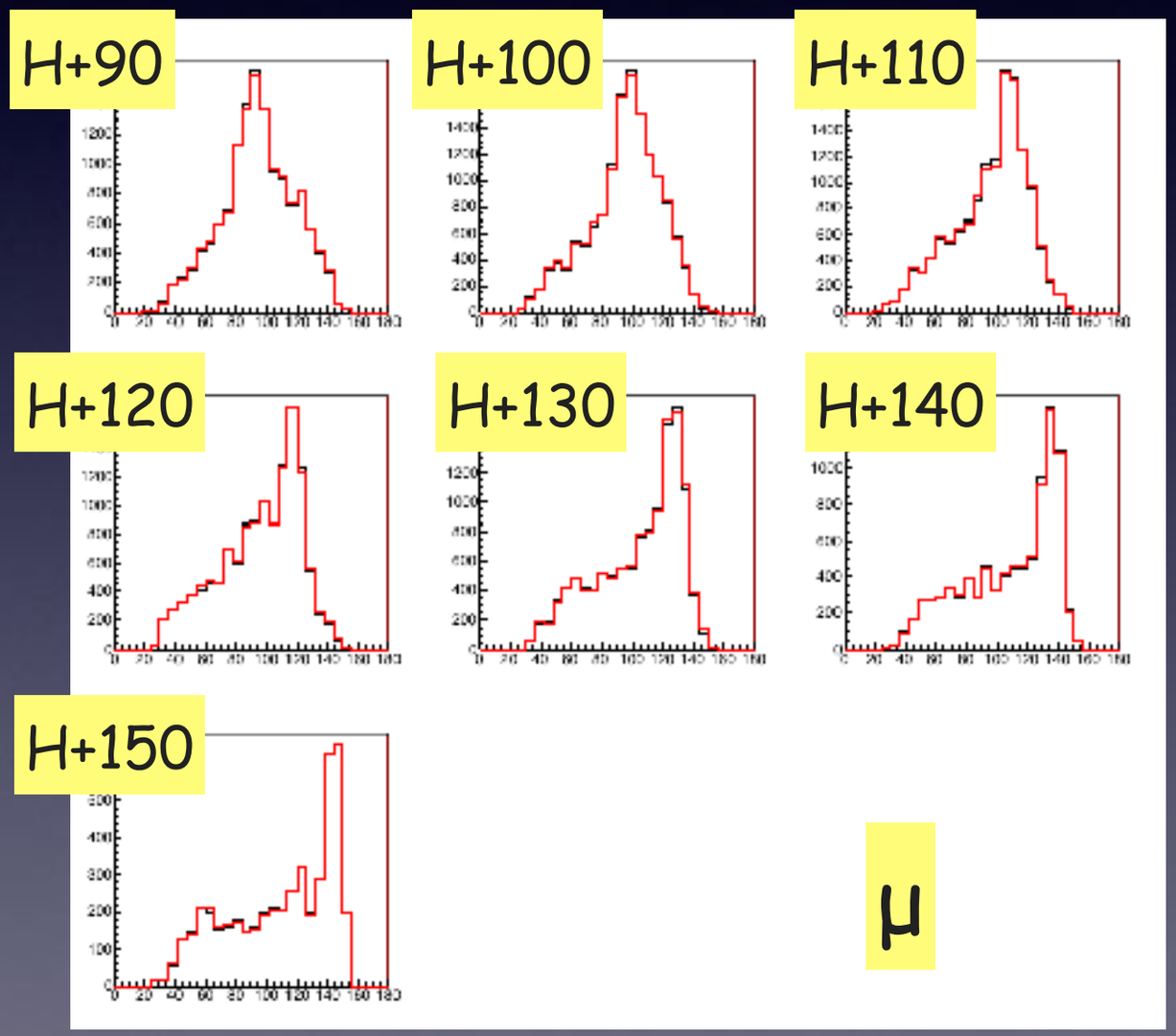
- black(template) & red(Upsyst. template) & blue(Downsyst. template)

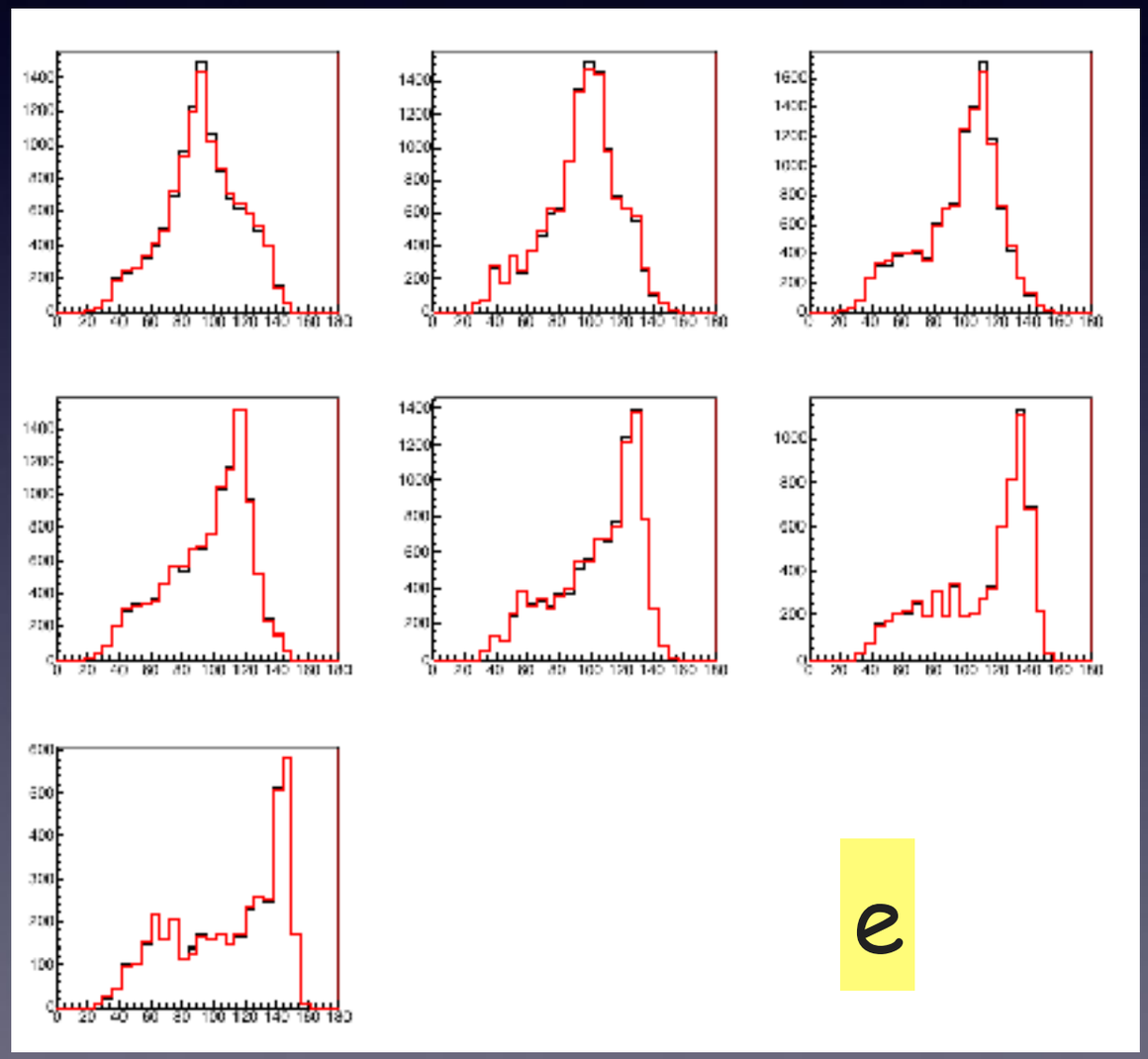




Pythia vs Madgraph (H+ signal only)

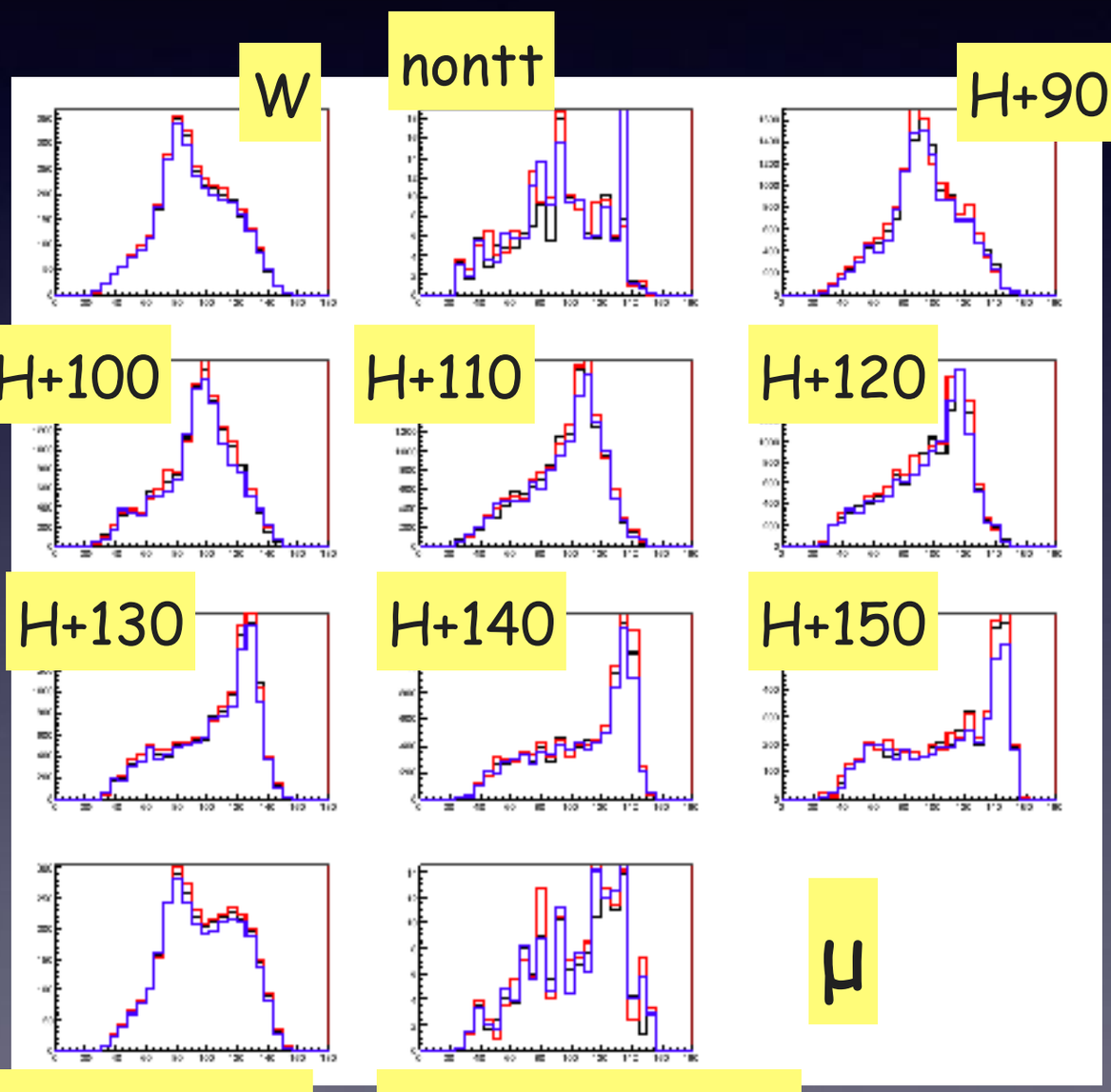
- black(template) & red(syst. template)

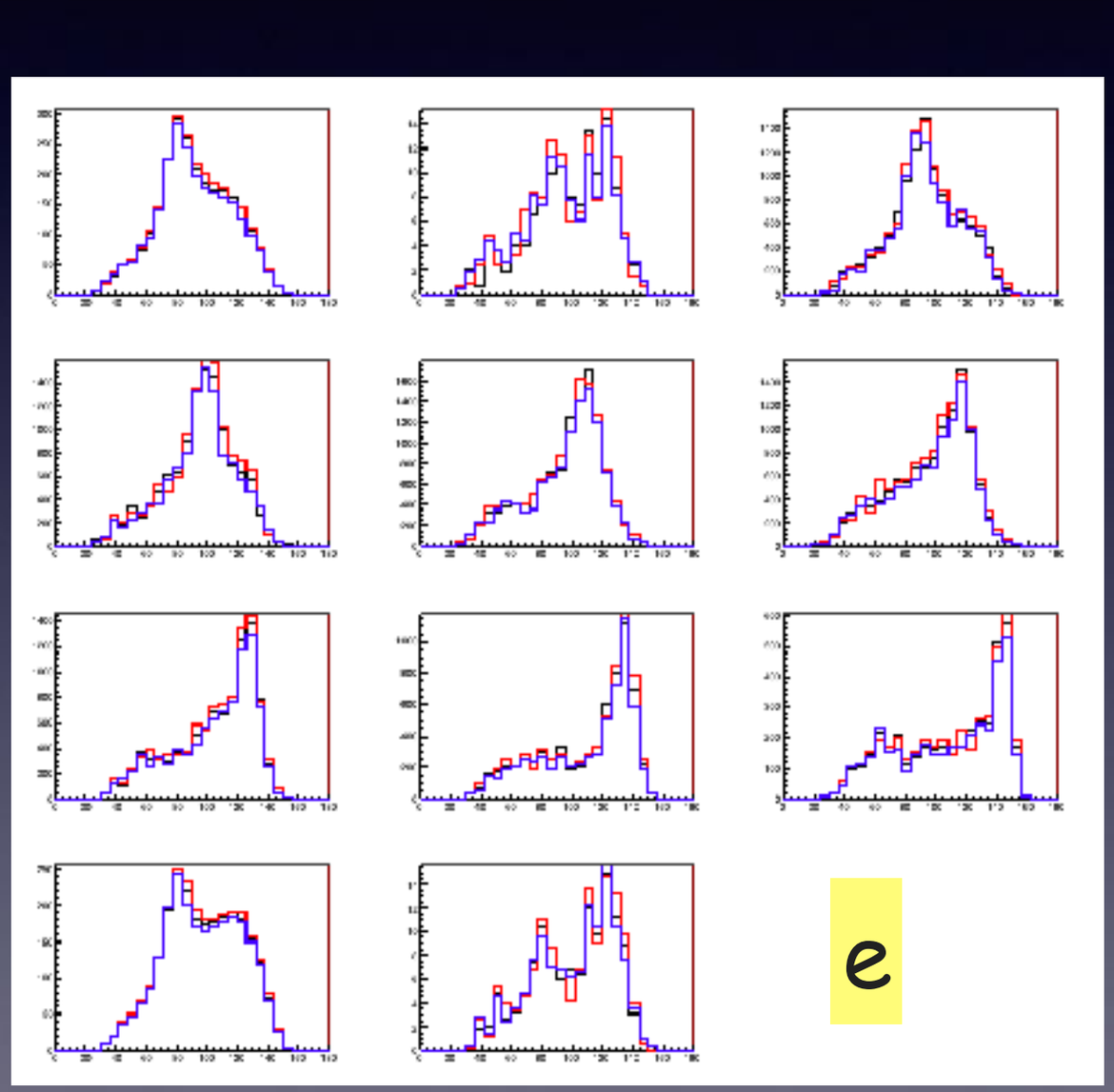




Jet Energy Scale

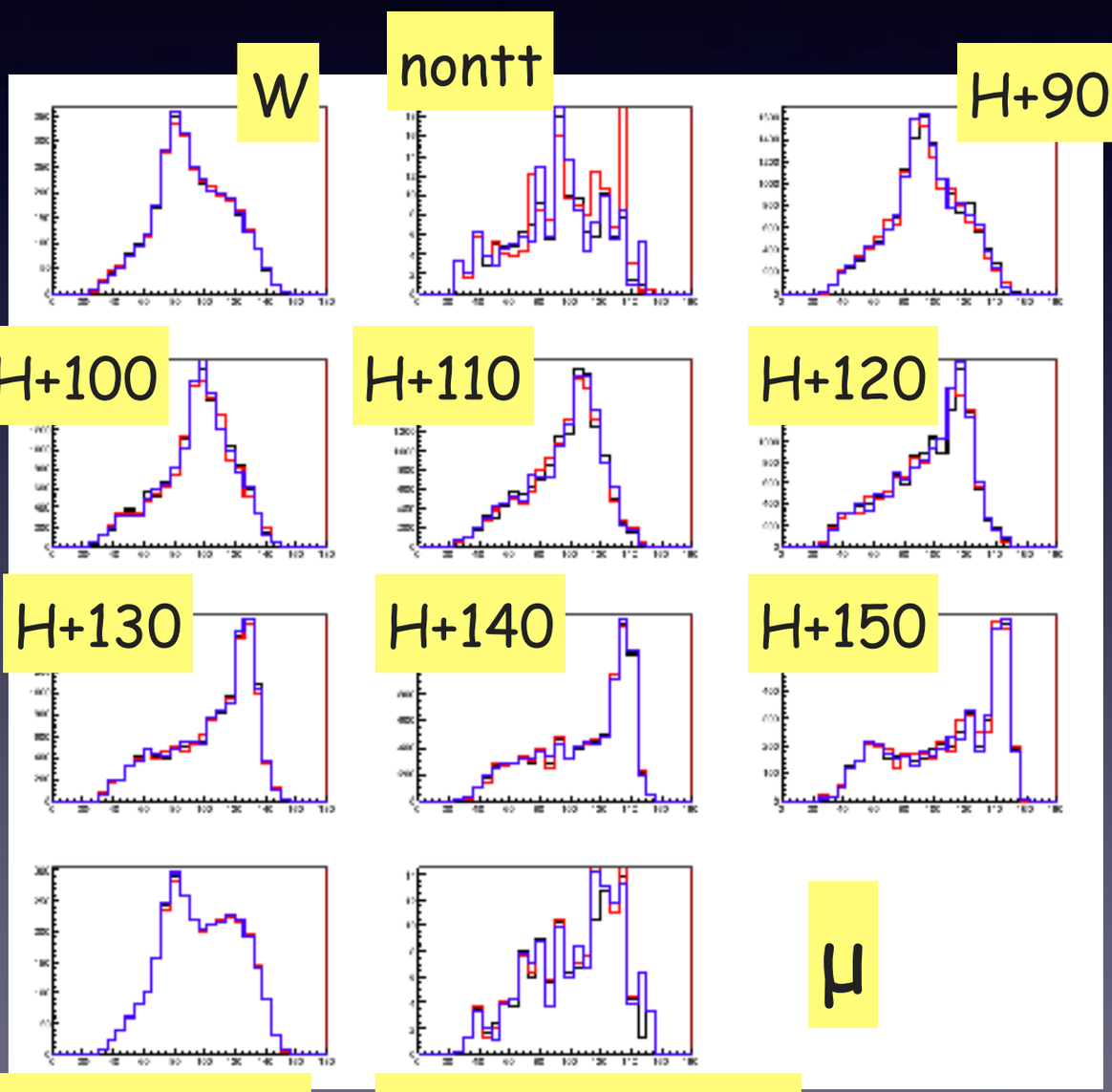
- black(template) & red(Upsyst. template) & blue(Downsyst. template)

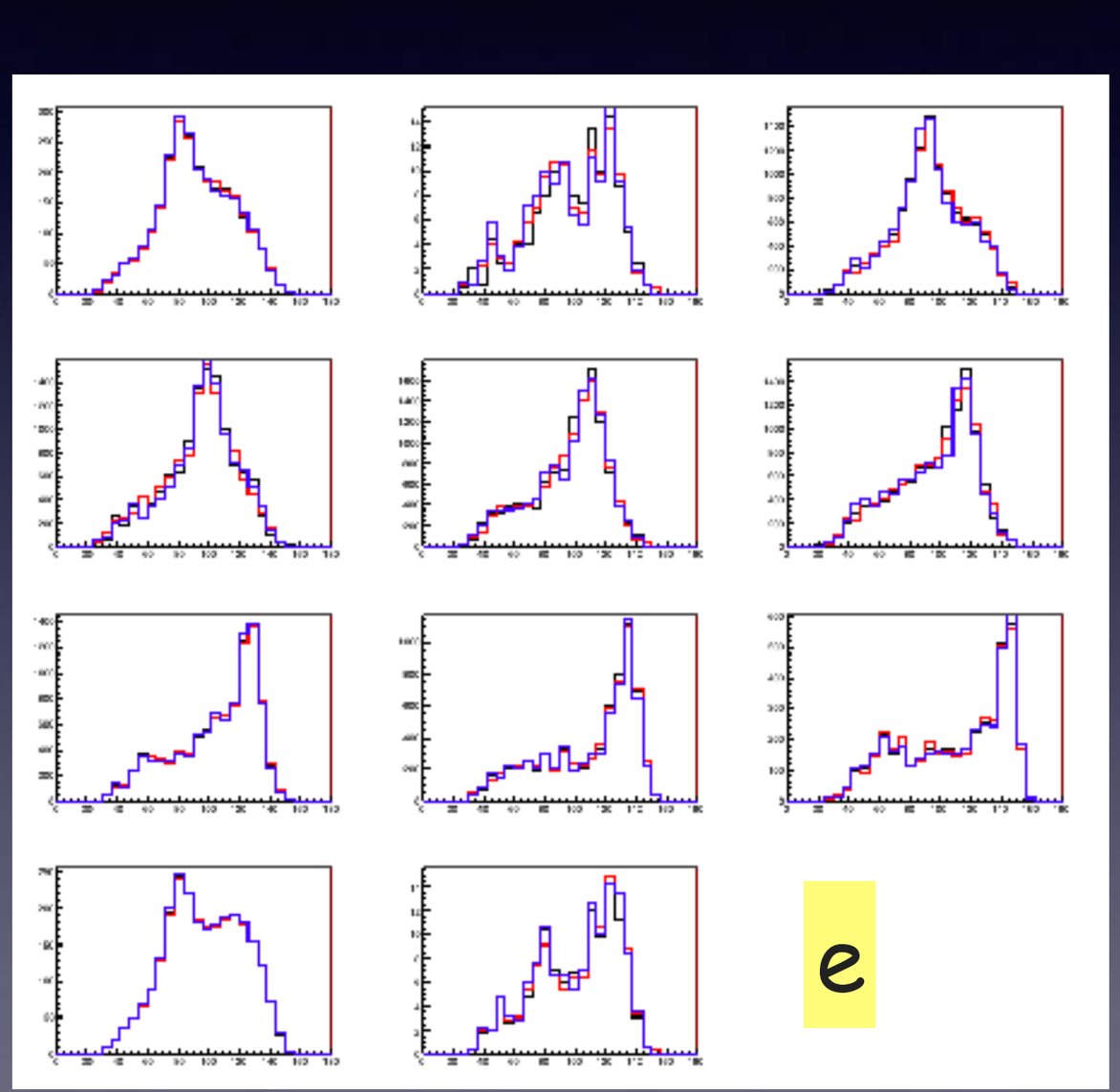




Jet Energy Resolution

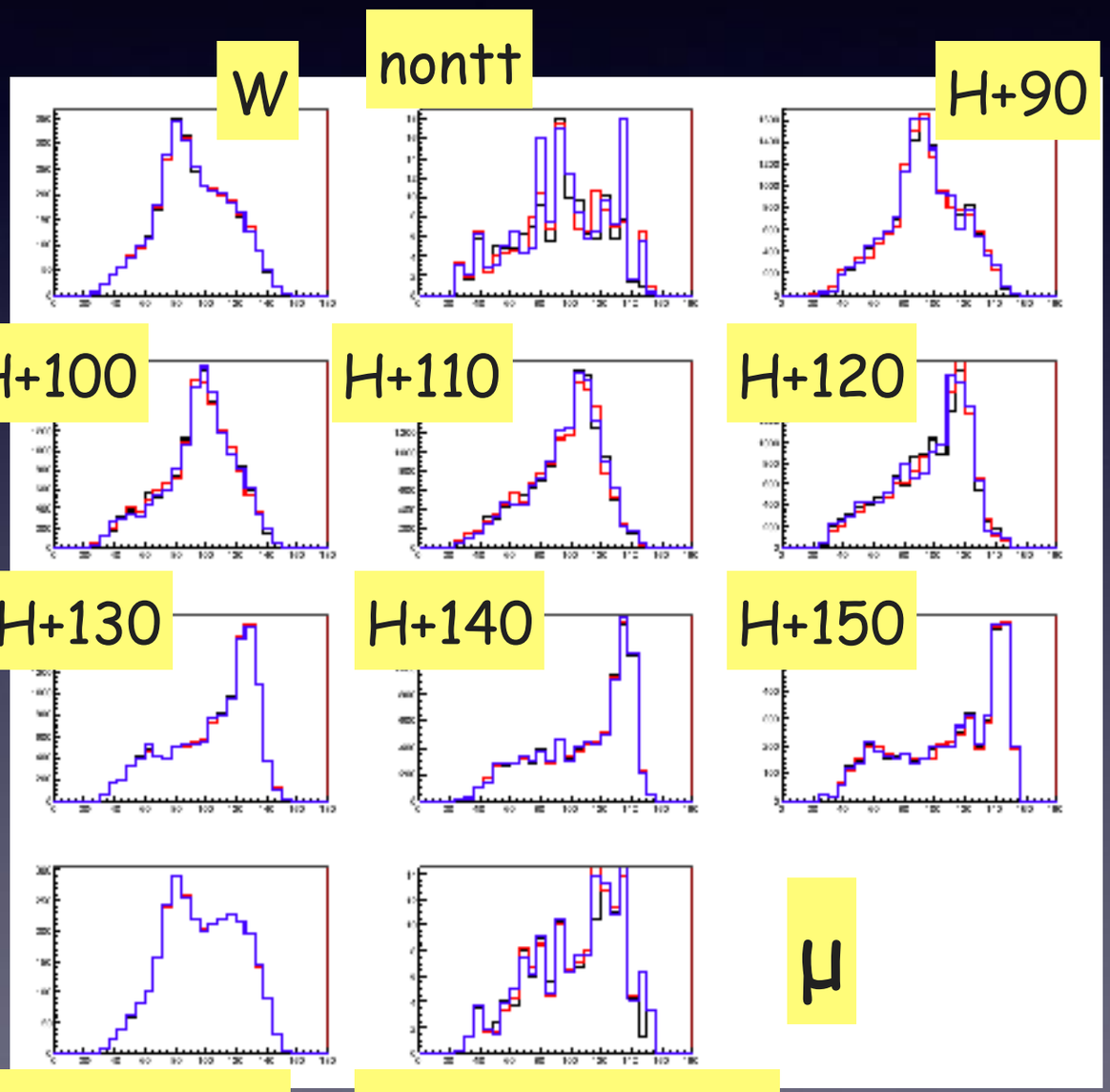
- black(template) & red(Upsyst. template) & blue(Downsyst. template)

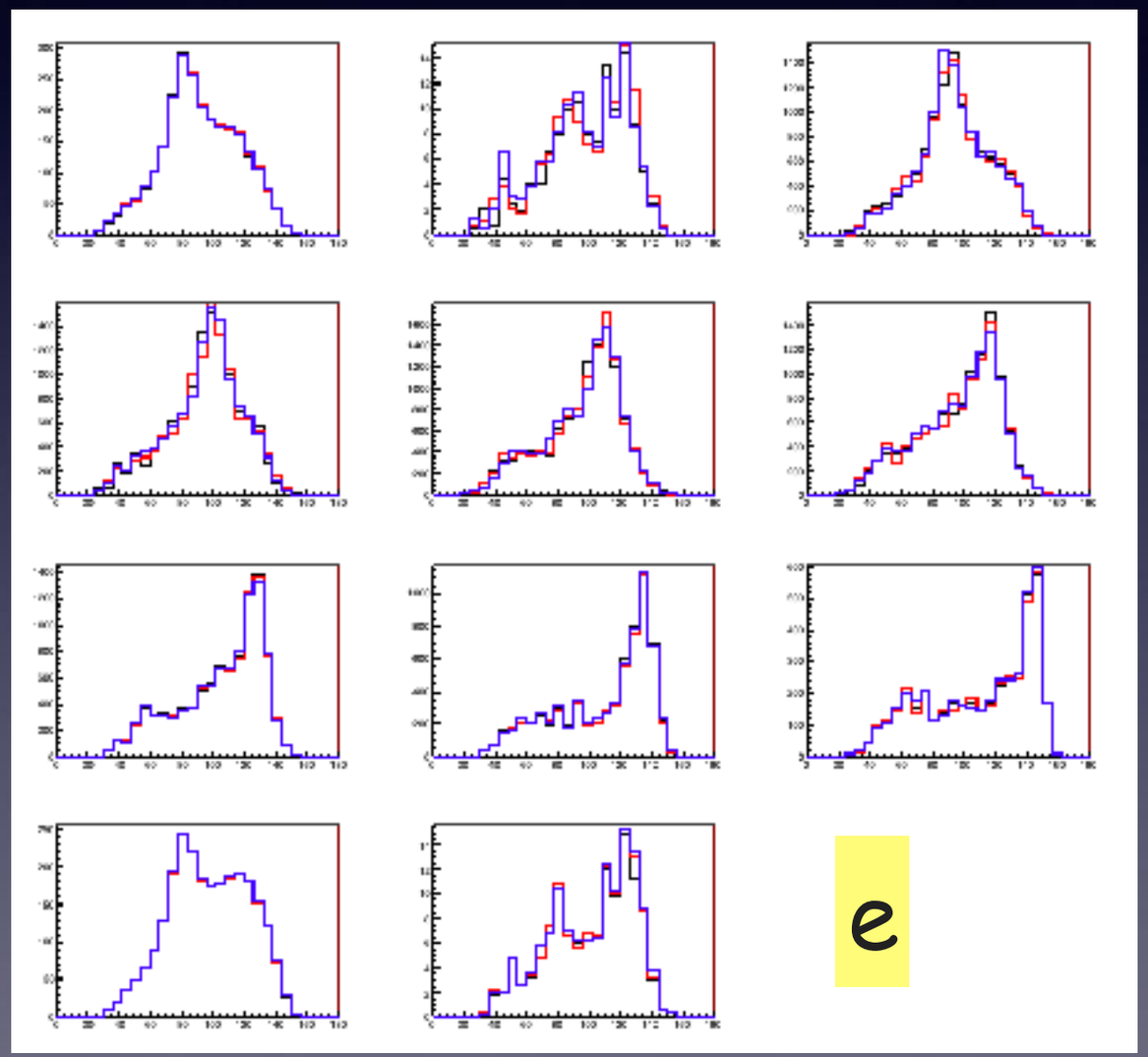




L5Buncertainty

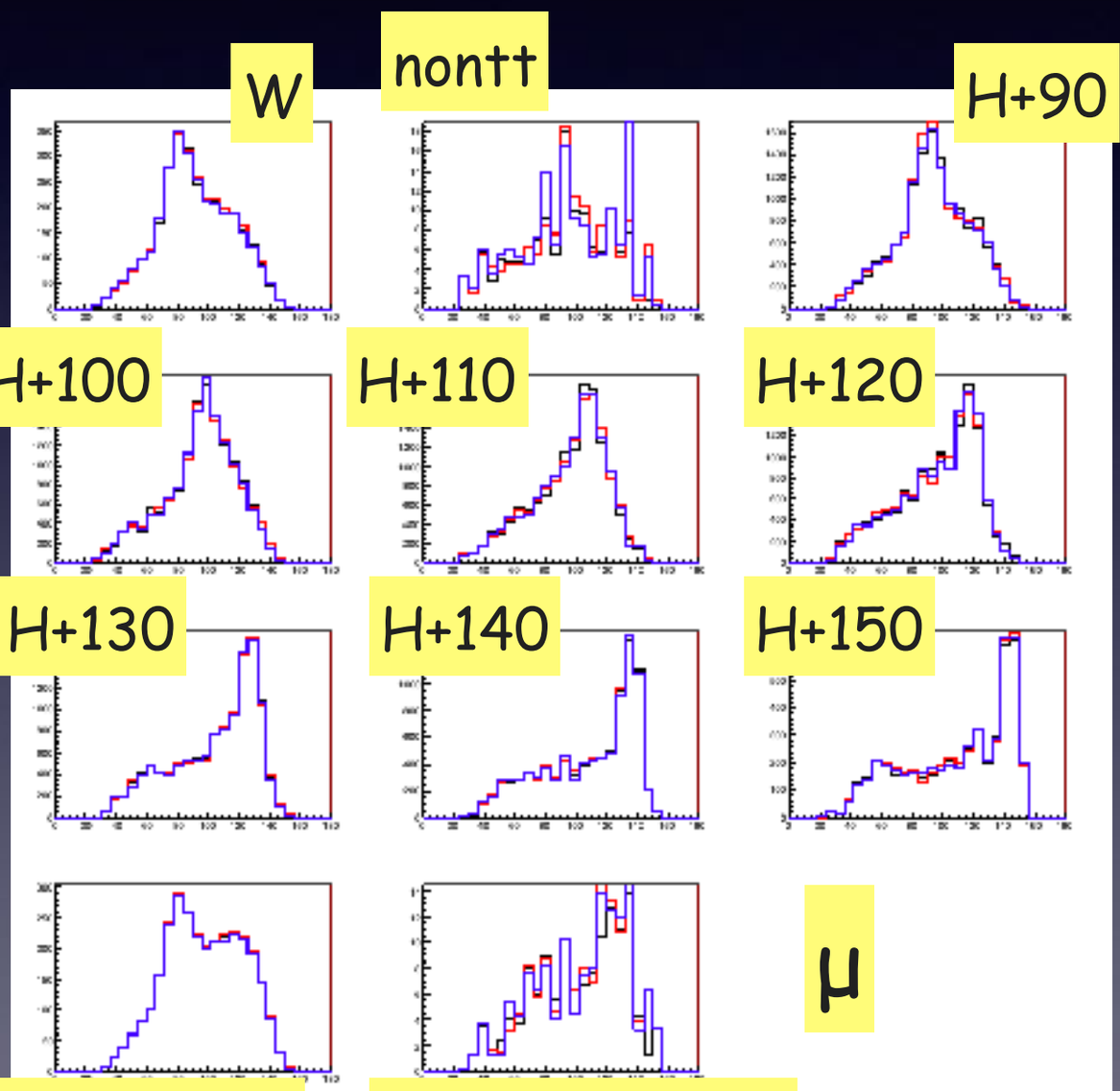
- black(template) & red(Upsyst. template) & blue(Downsyst. template)

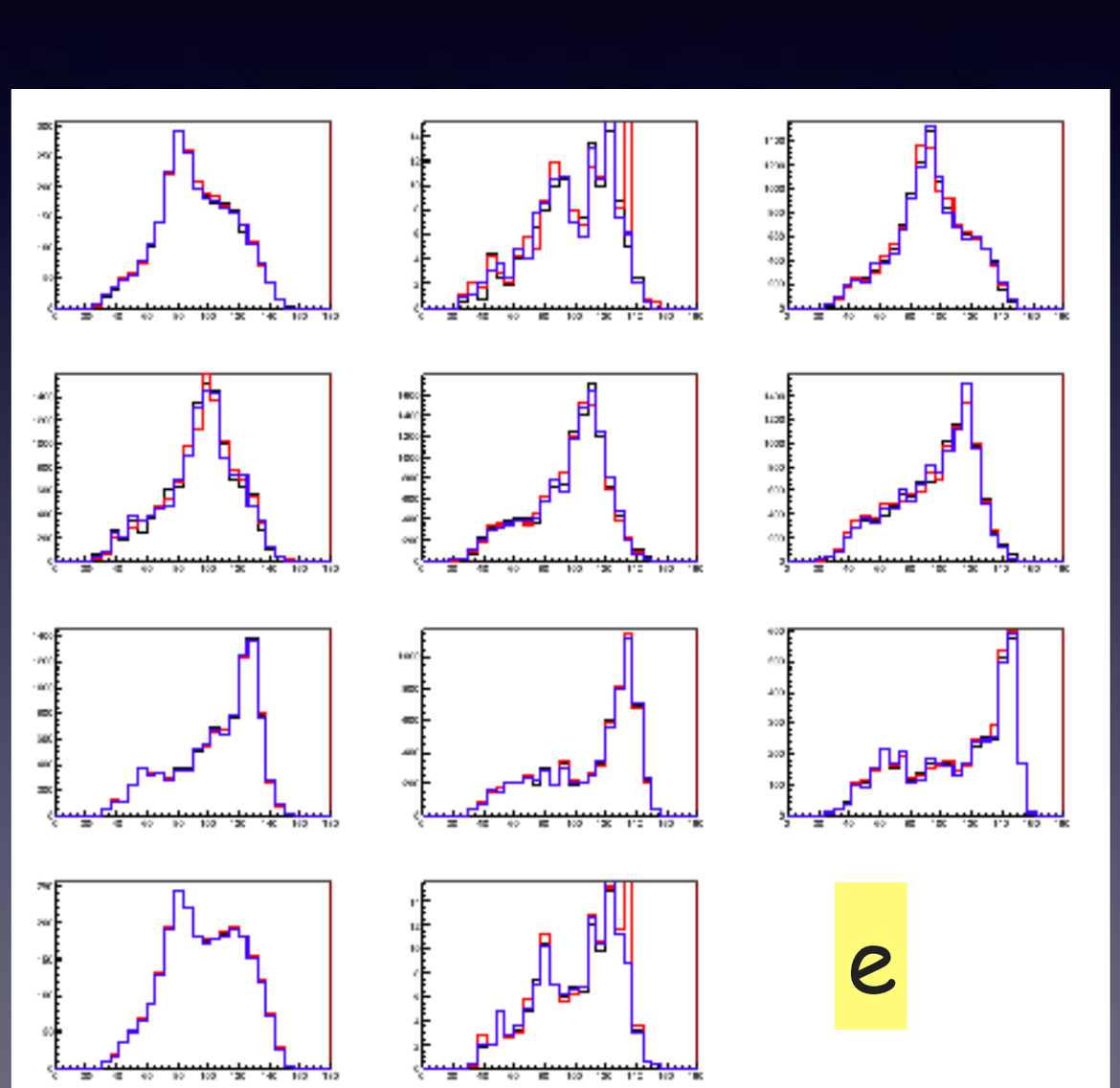




L5UDSCGuncertainty

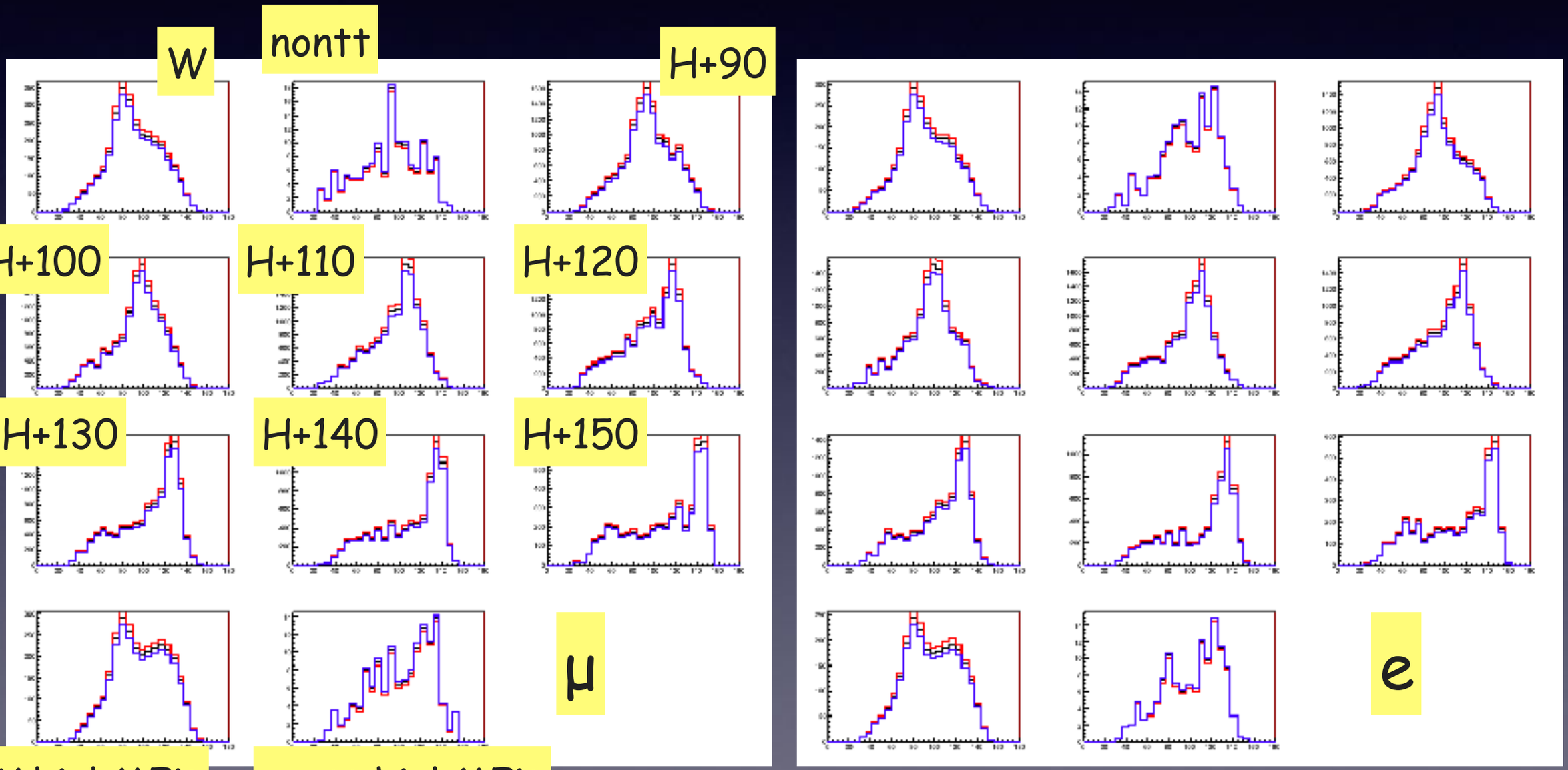
- black(template) & red(Upsyst. template) & blue(Downsyst. template)





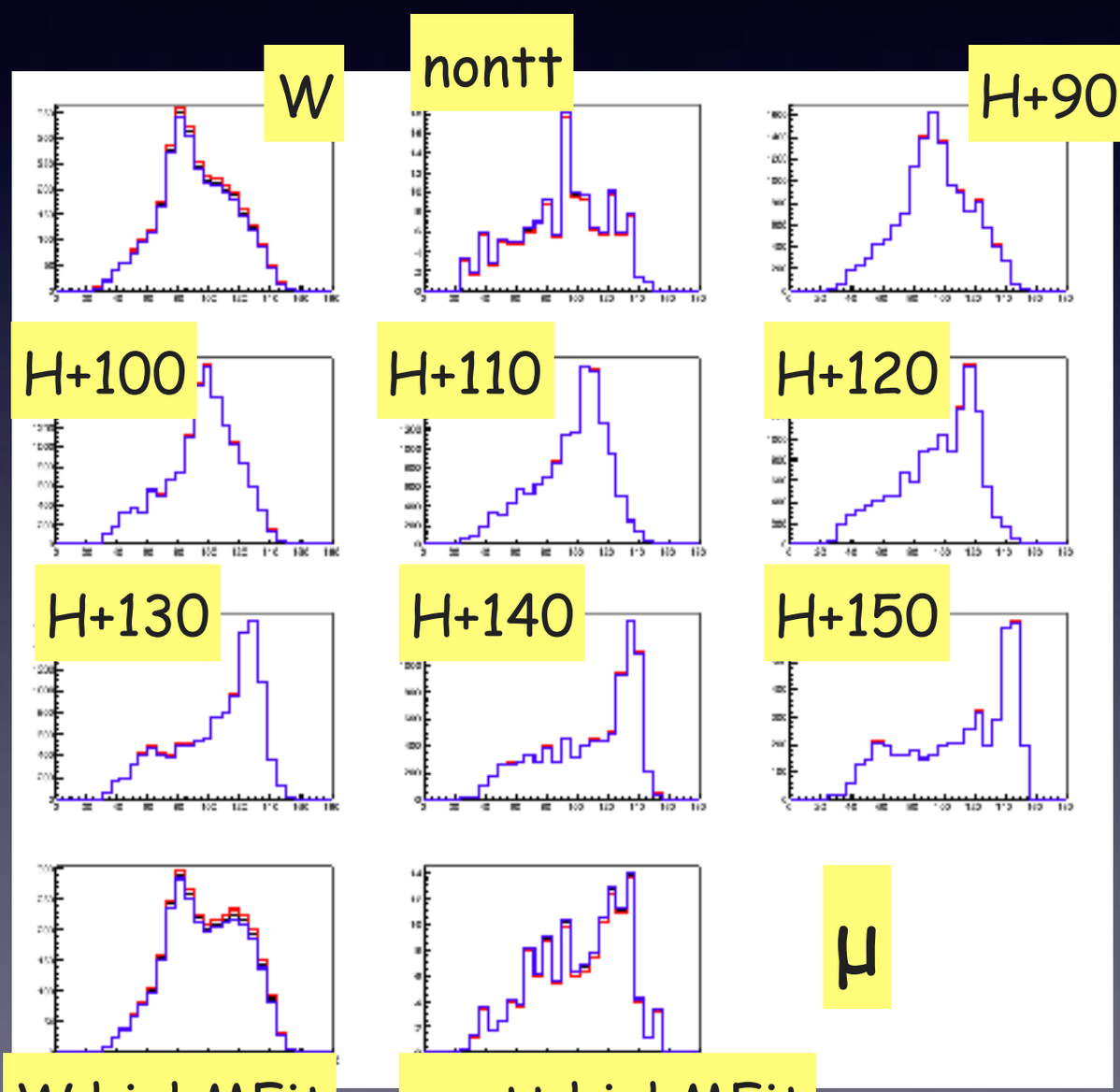
BtagSF

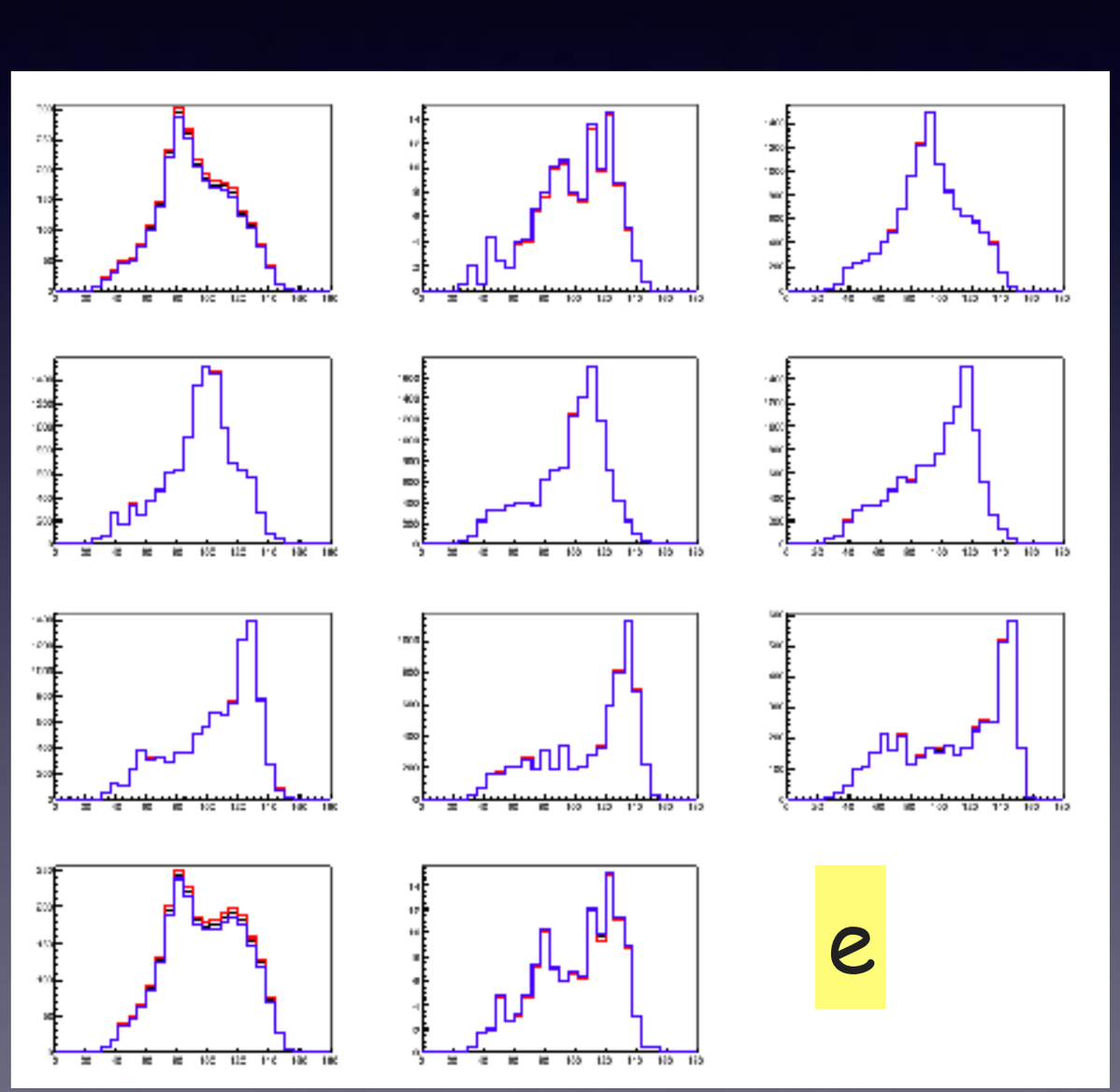
- black(template) & red(Upsyst. template) & blue(Downsyst. template)



MistagSF

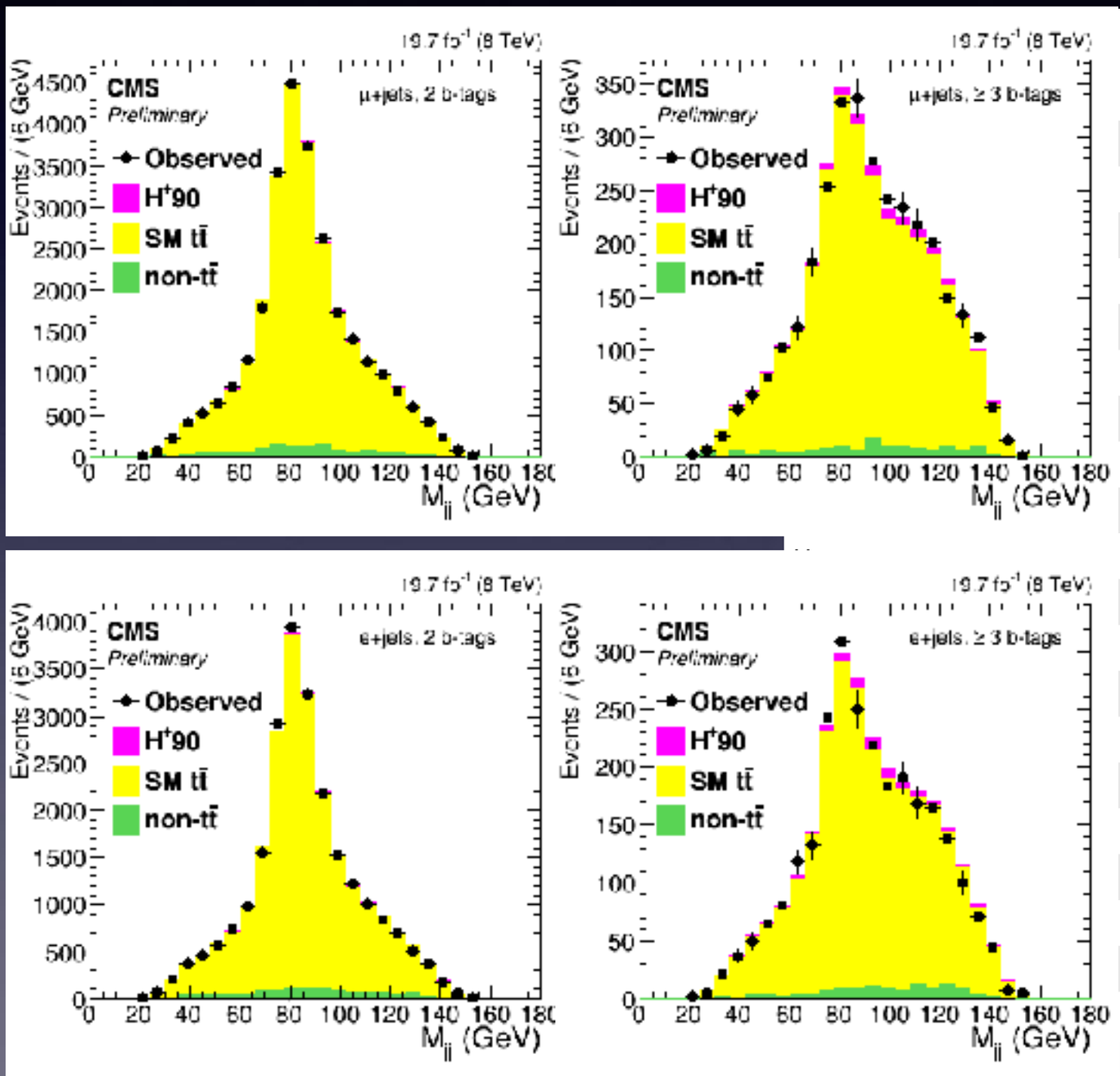
- black(template) & red(Upsyst. template) & blue(Downsyst. template)

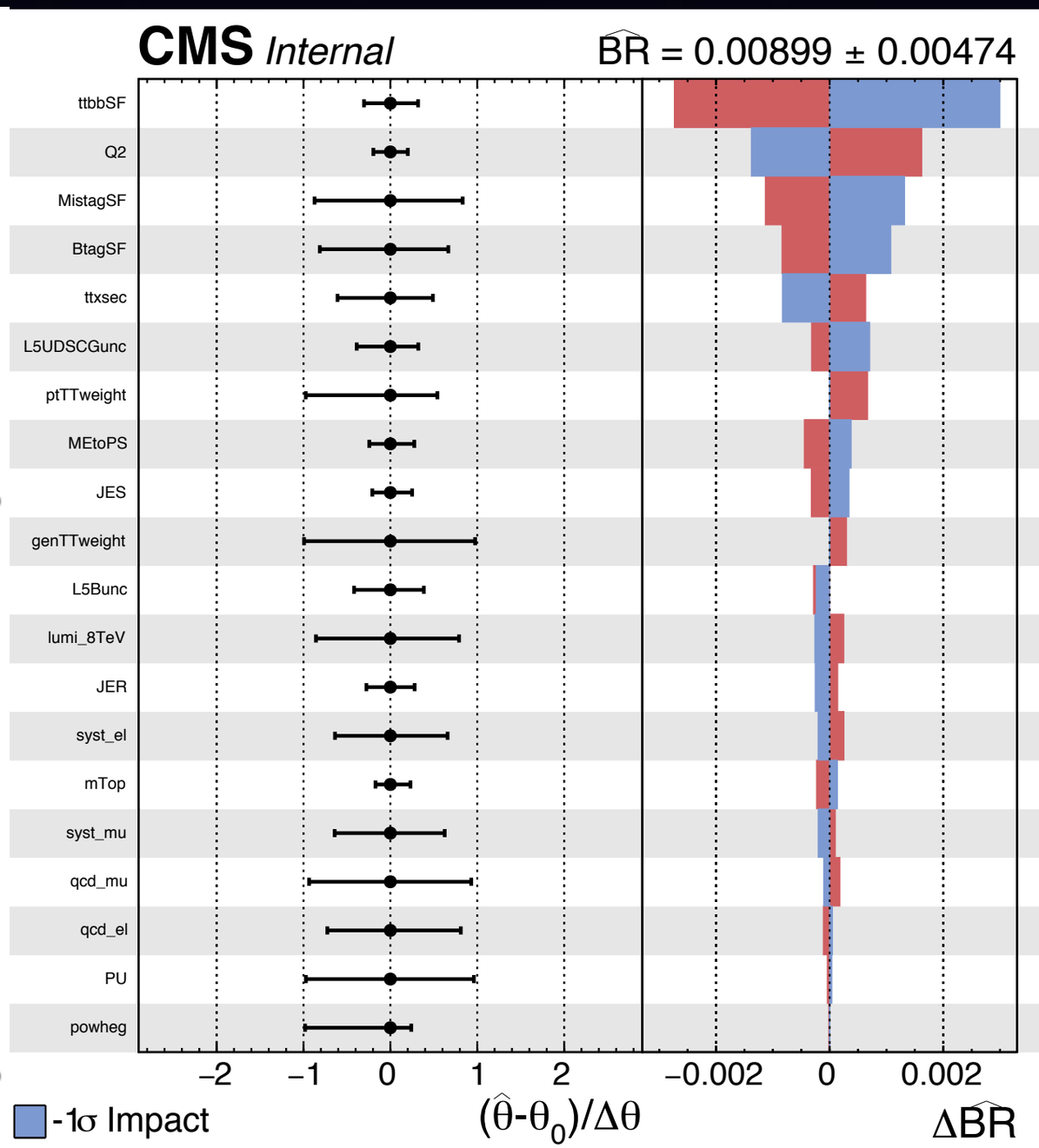




MLF & Impact (H^+ 90GeV)

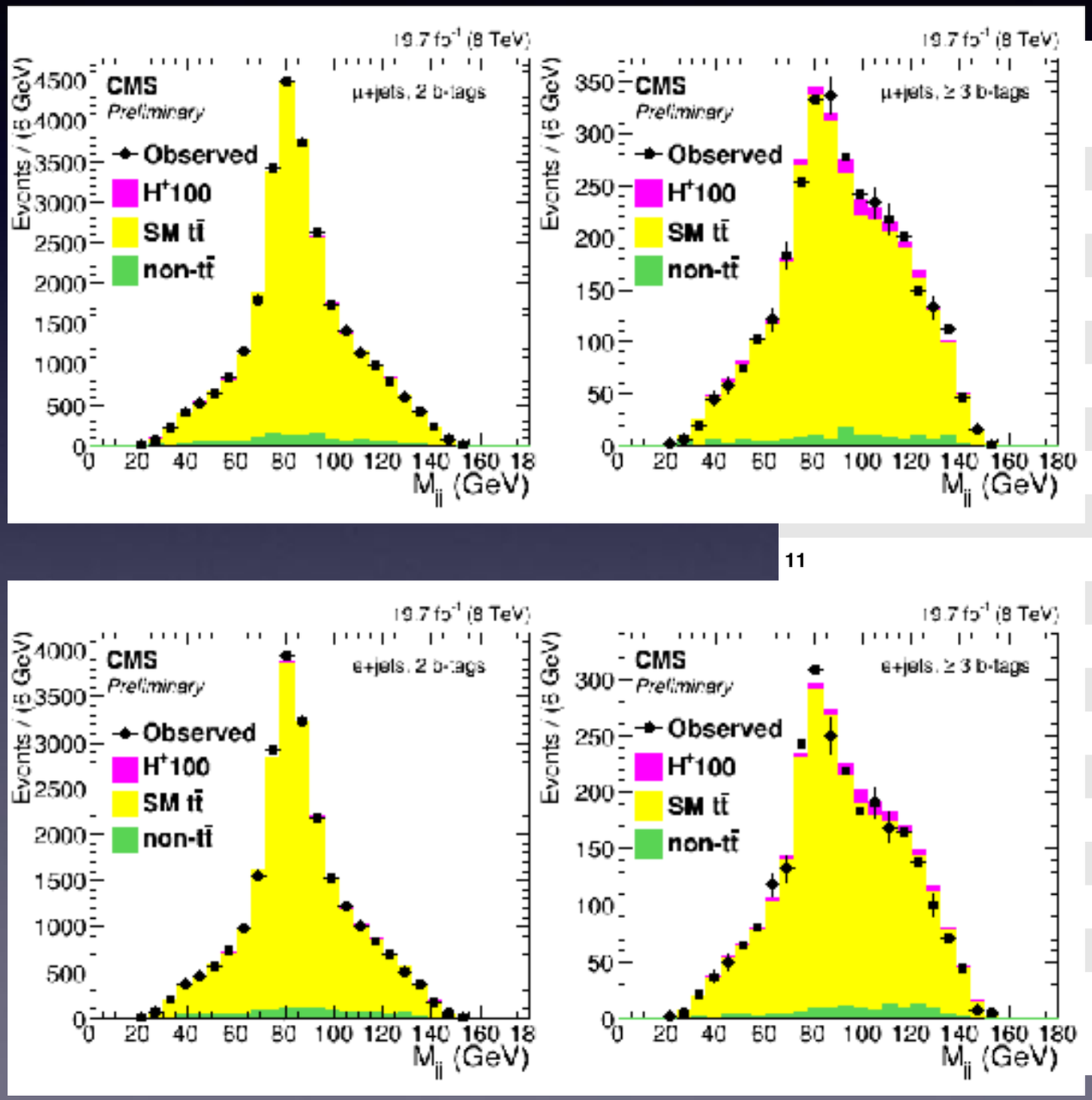
BR=0.0033 (-0.0033+0.0041)



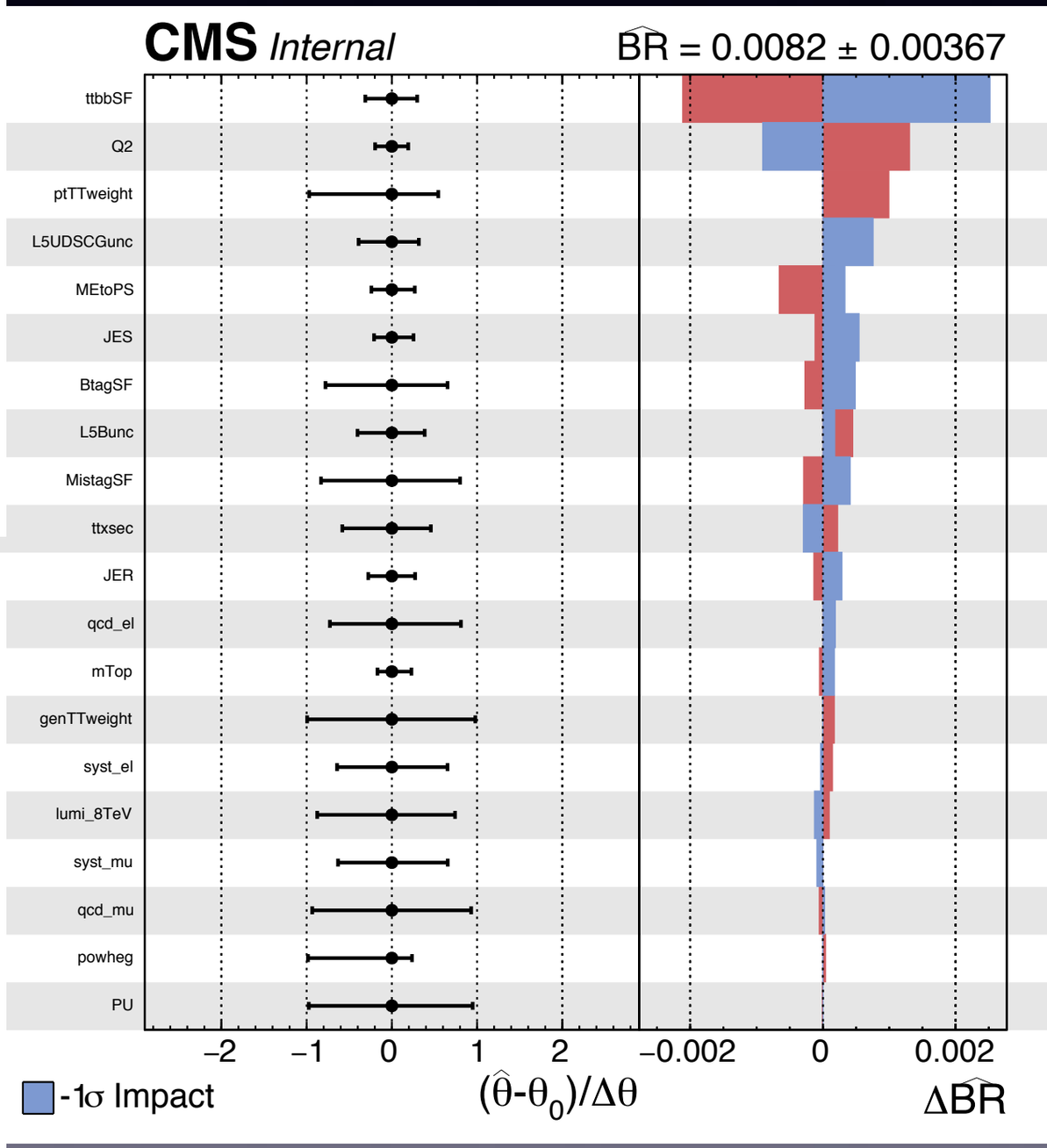


MLF & Impact (H^+ 100GeV)

BR=0.0039 (-0.0035+0.0034)

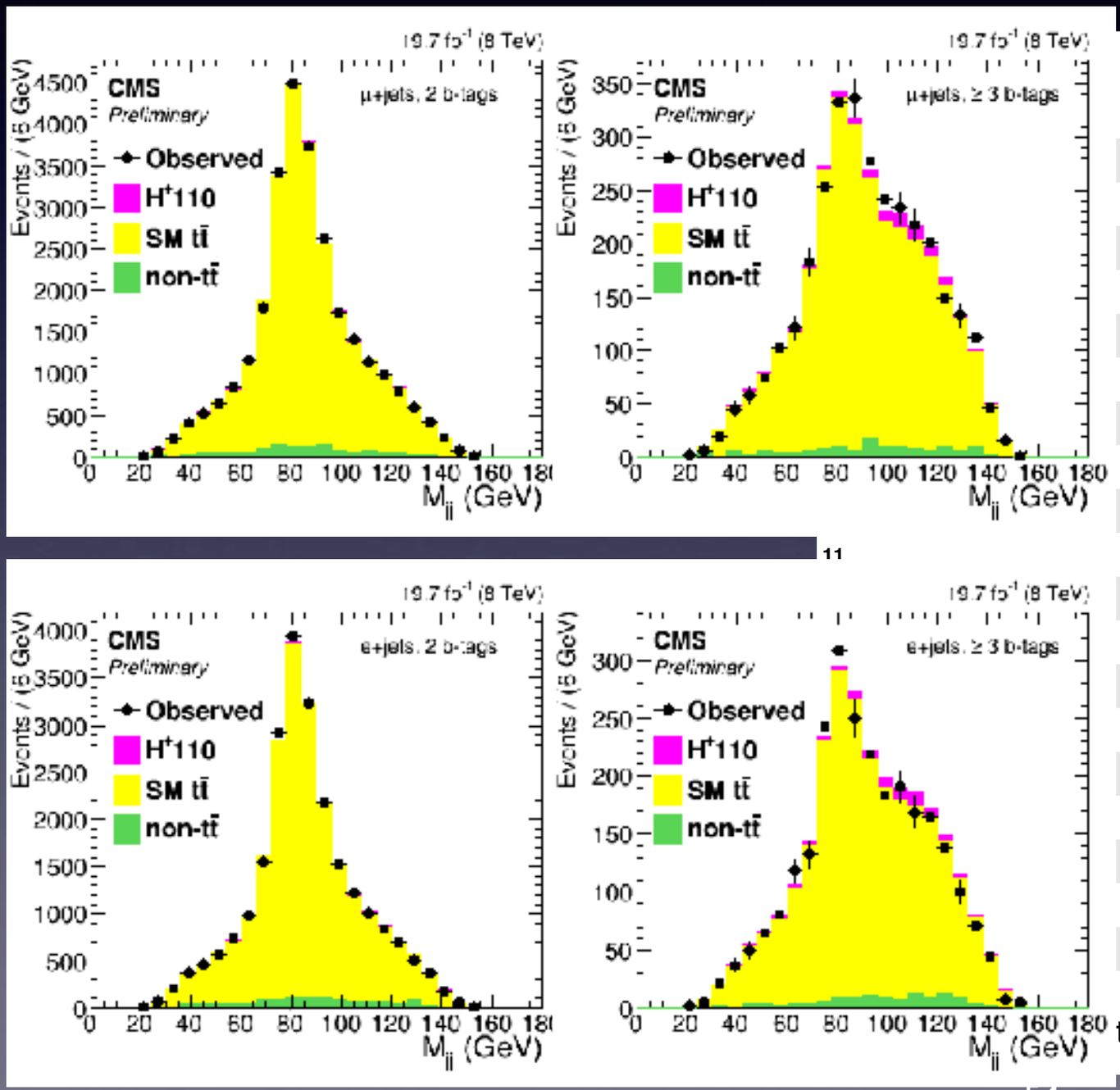


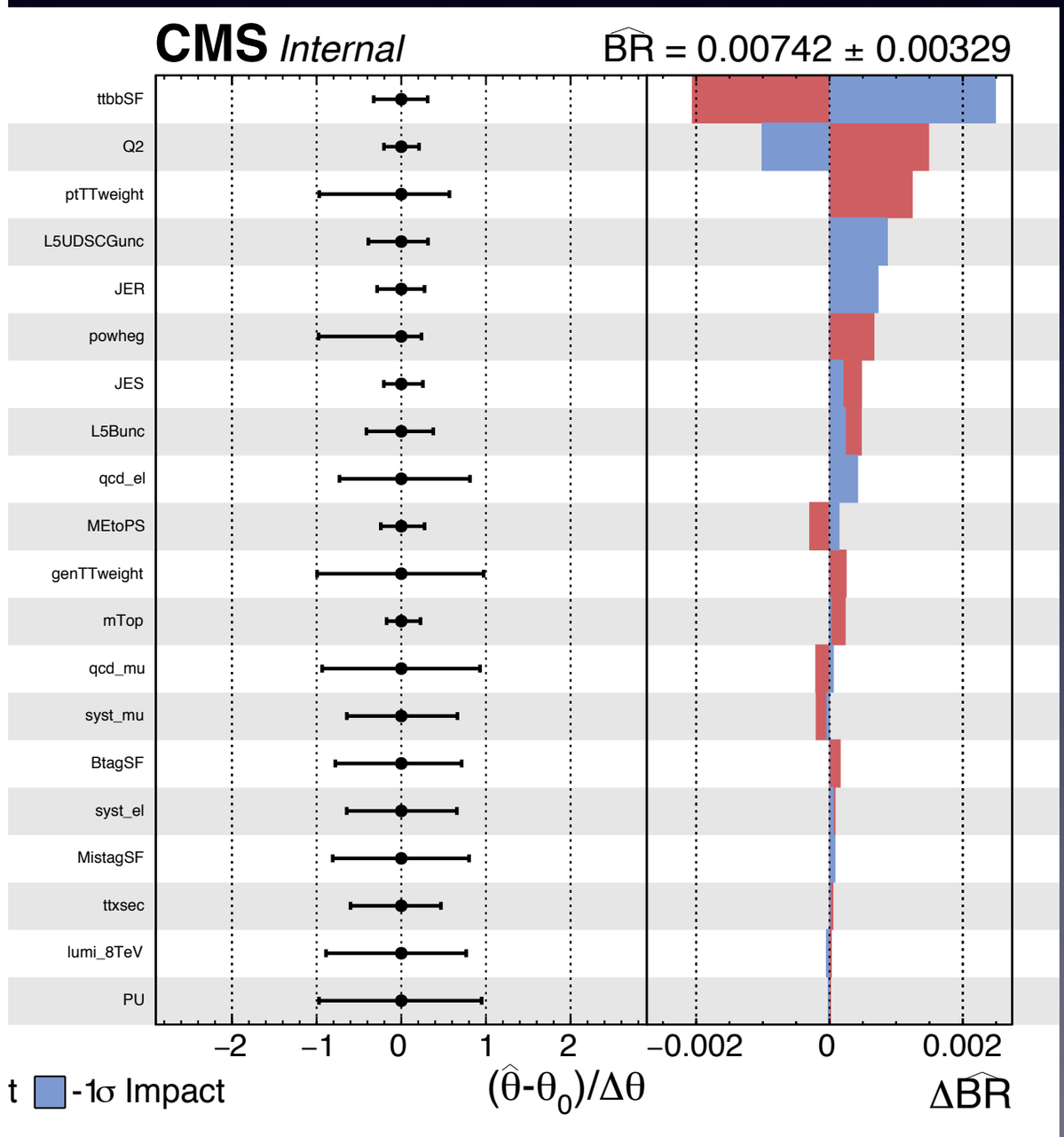
11



MLF & Impact (H^+ 110GeV)

BR=0.0036 (-0.0030+0.0039)





MLF & Impact (H^+ 140GeV)

BR=0.0000 (-0.0000+0.0009)