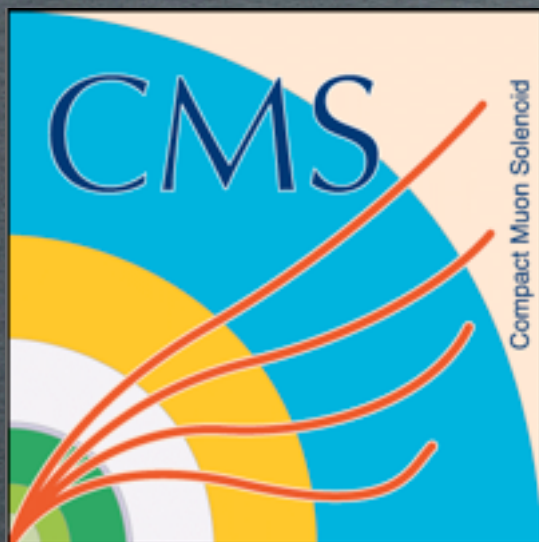
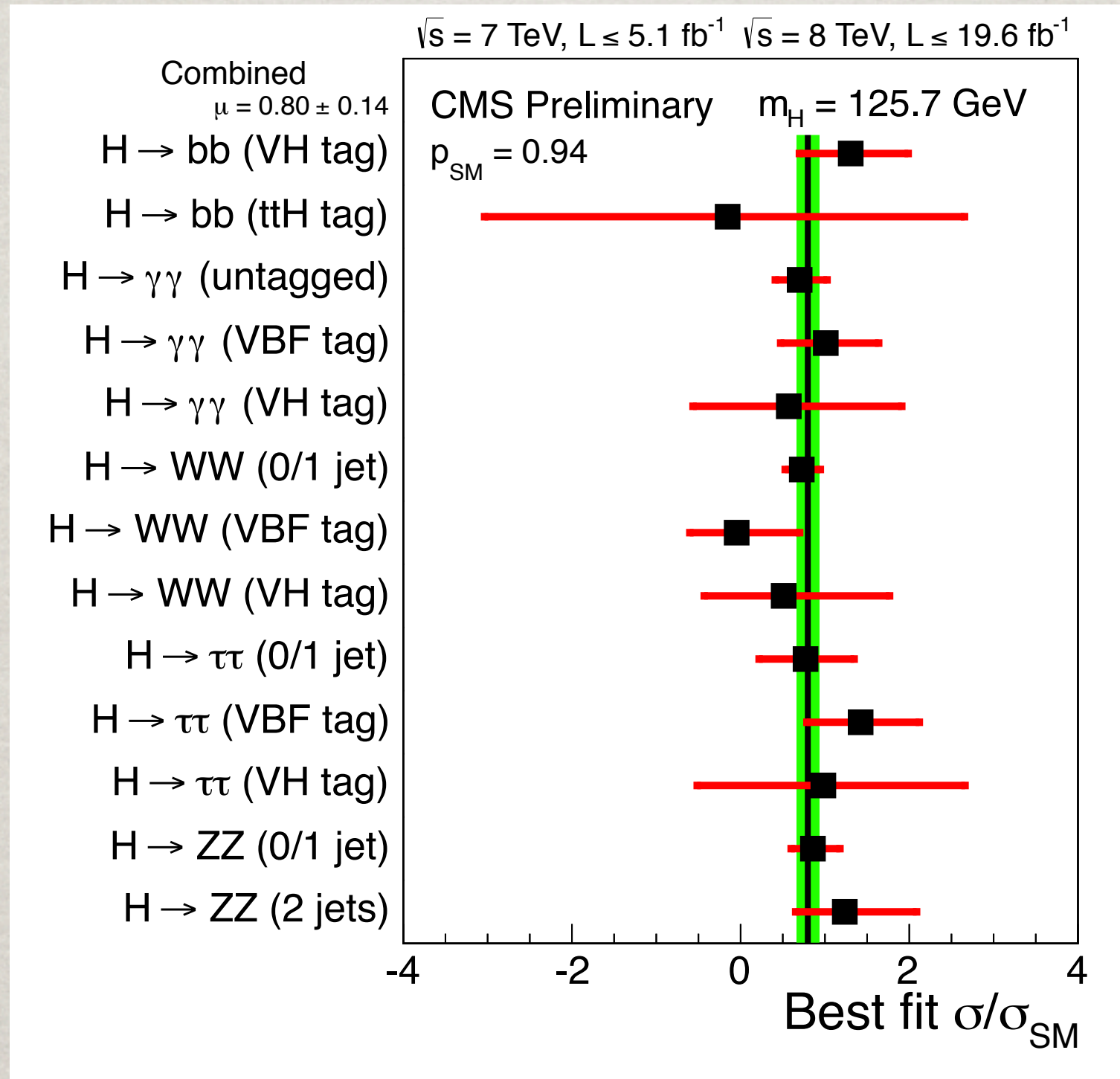


THE SEARCH FOR THE HIGGS BOSON PRODUCED IN ASSOCIATION WITH A TOP QUARK PAIR

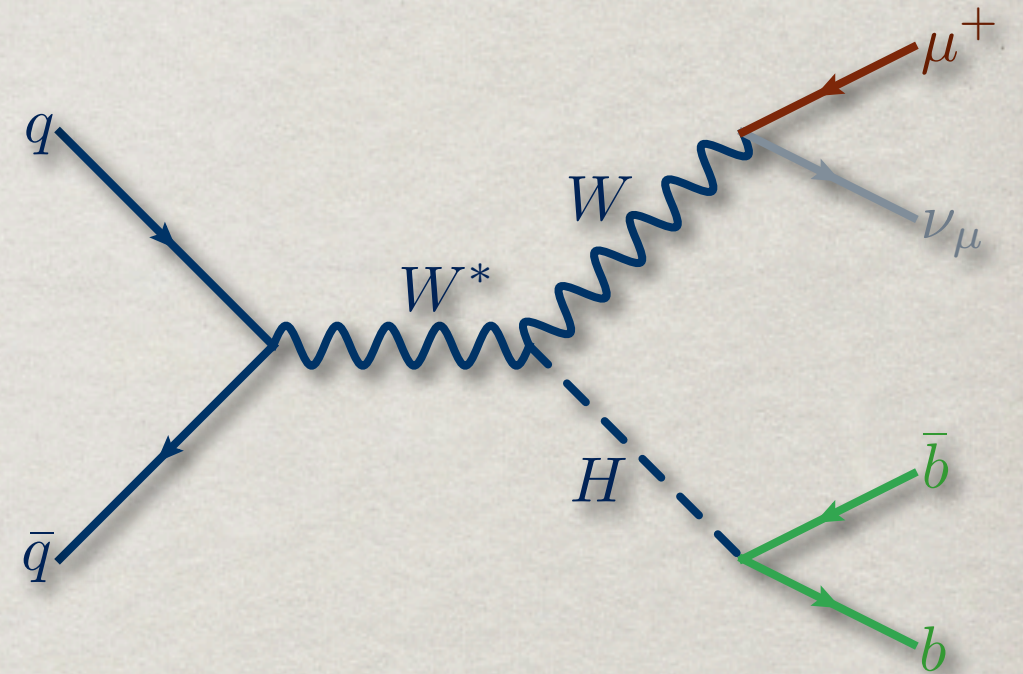
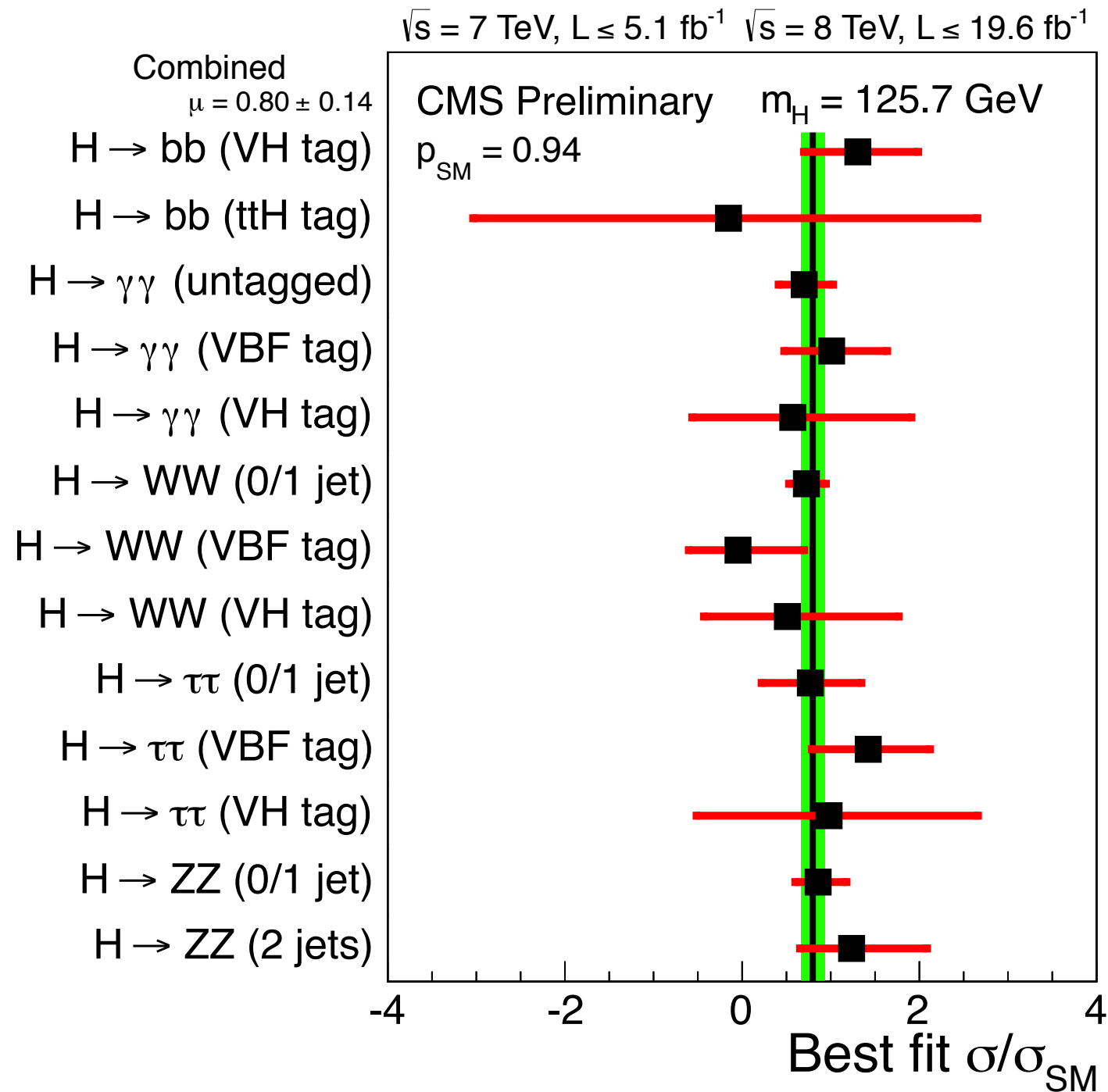
KEVIN LANNON



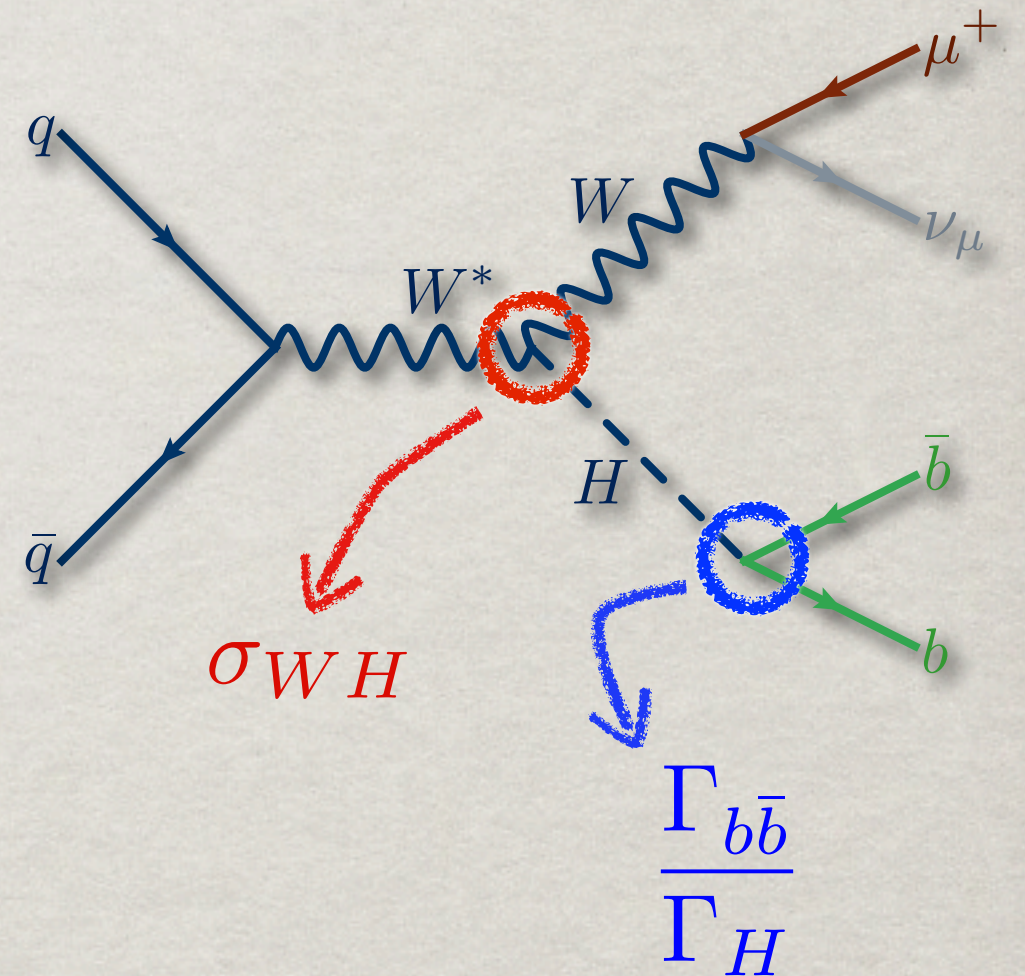
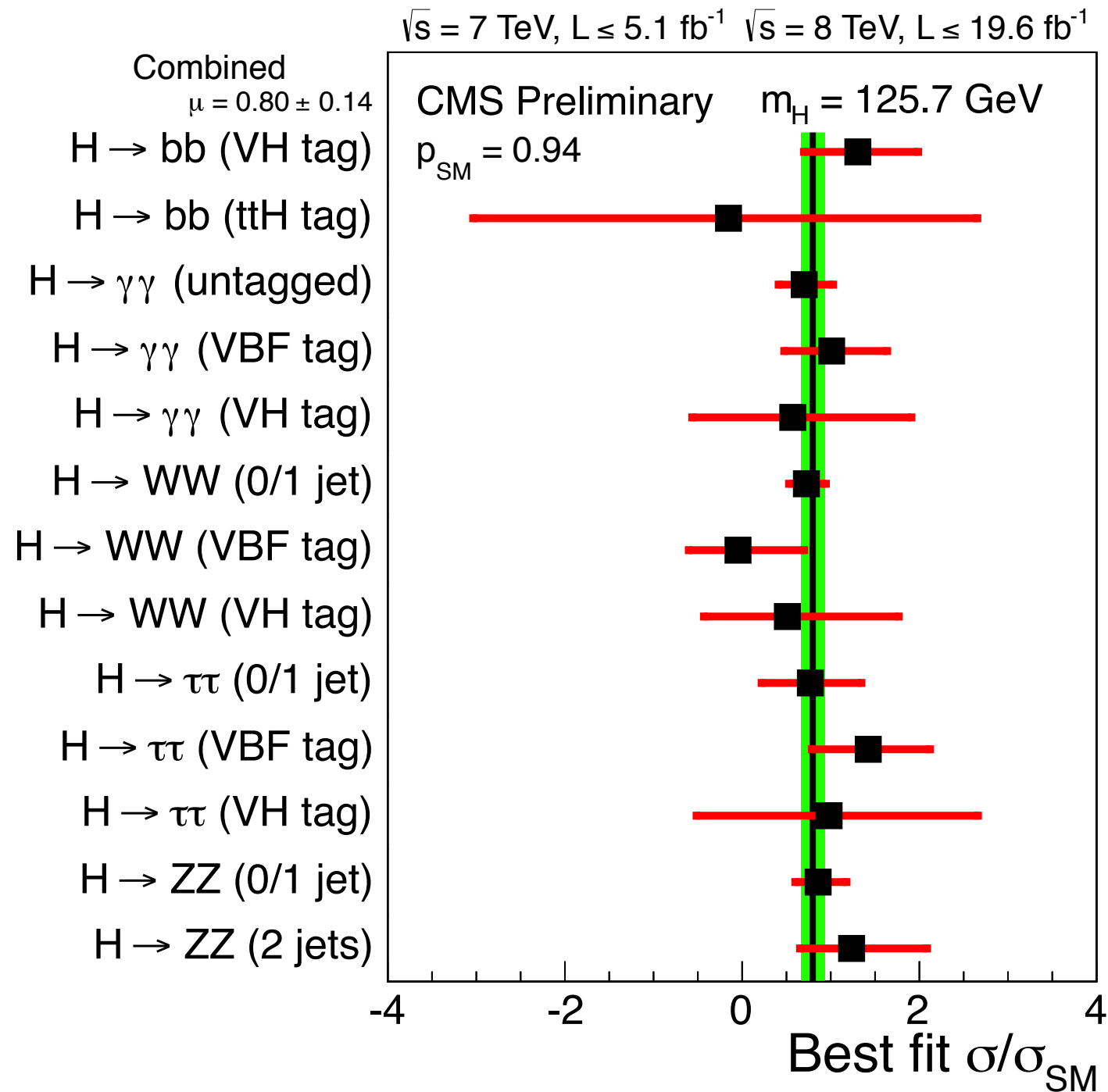
HIGGS COUPLINGS



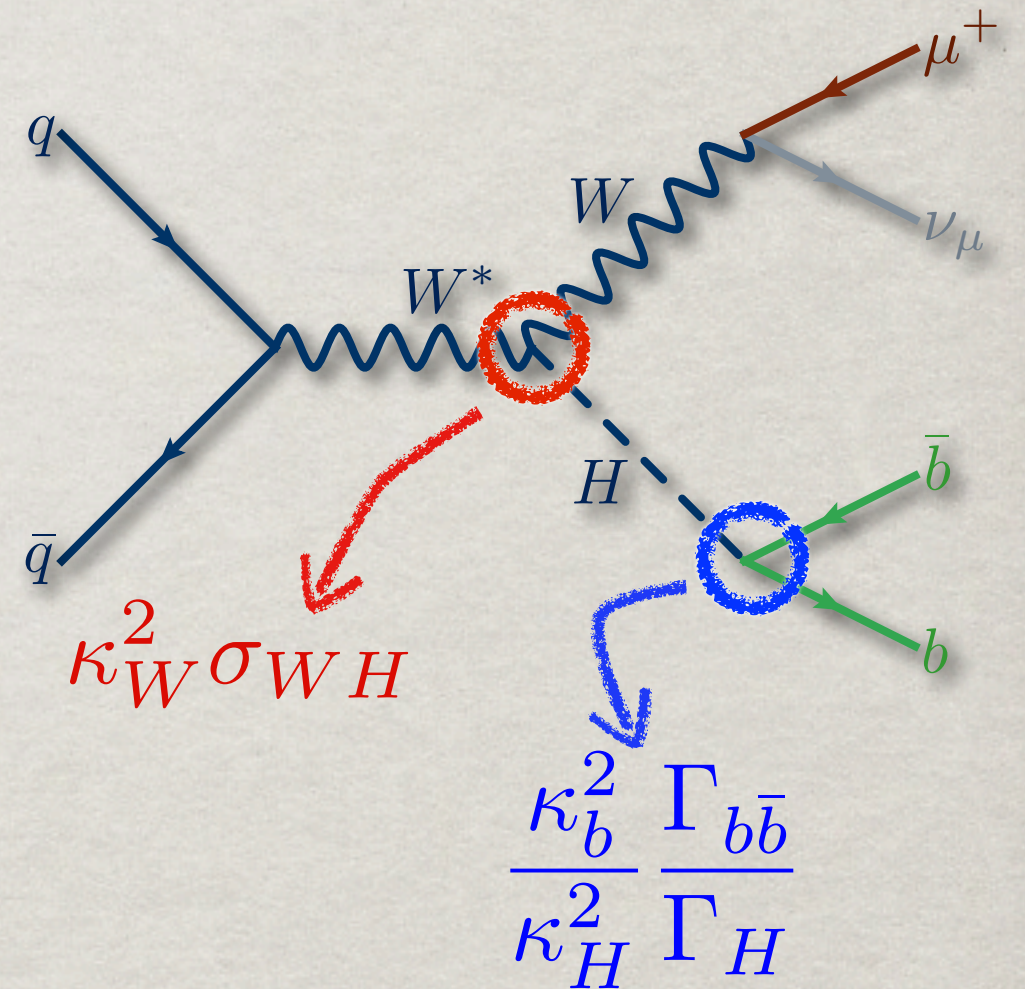
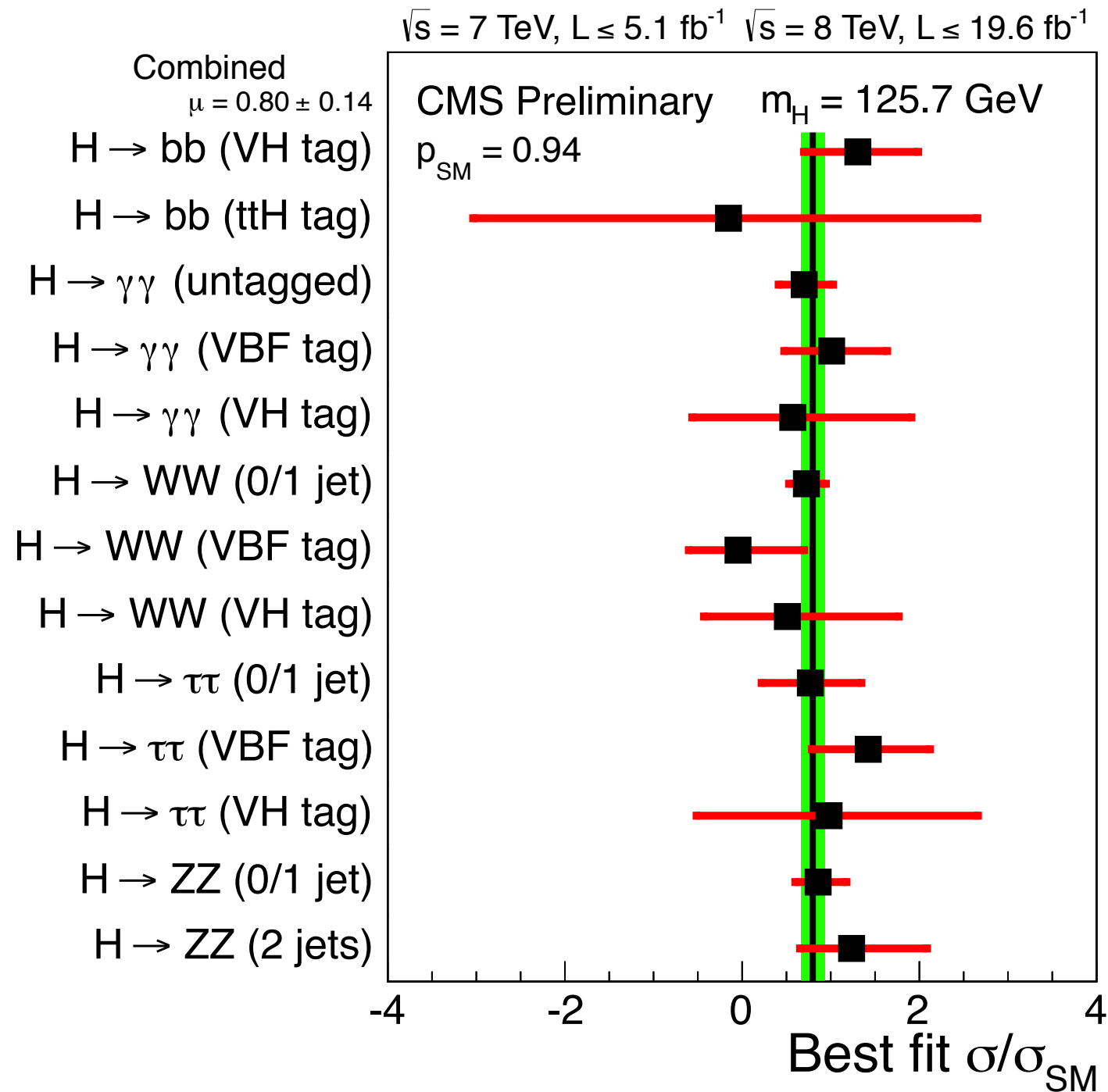
HIGGS COUPLINGS



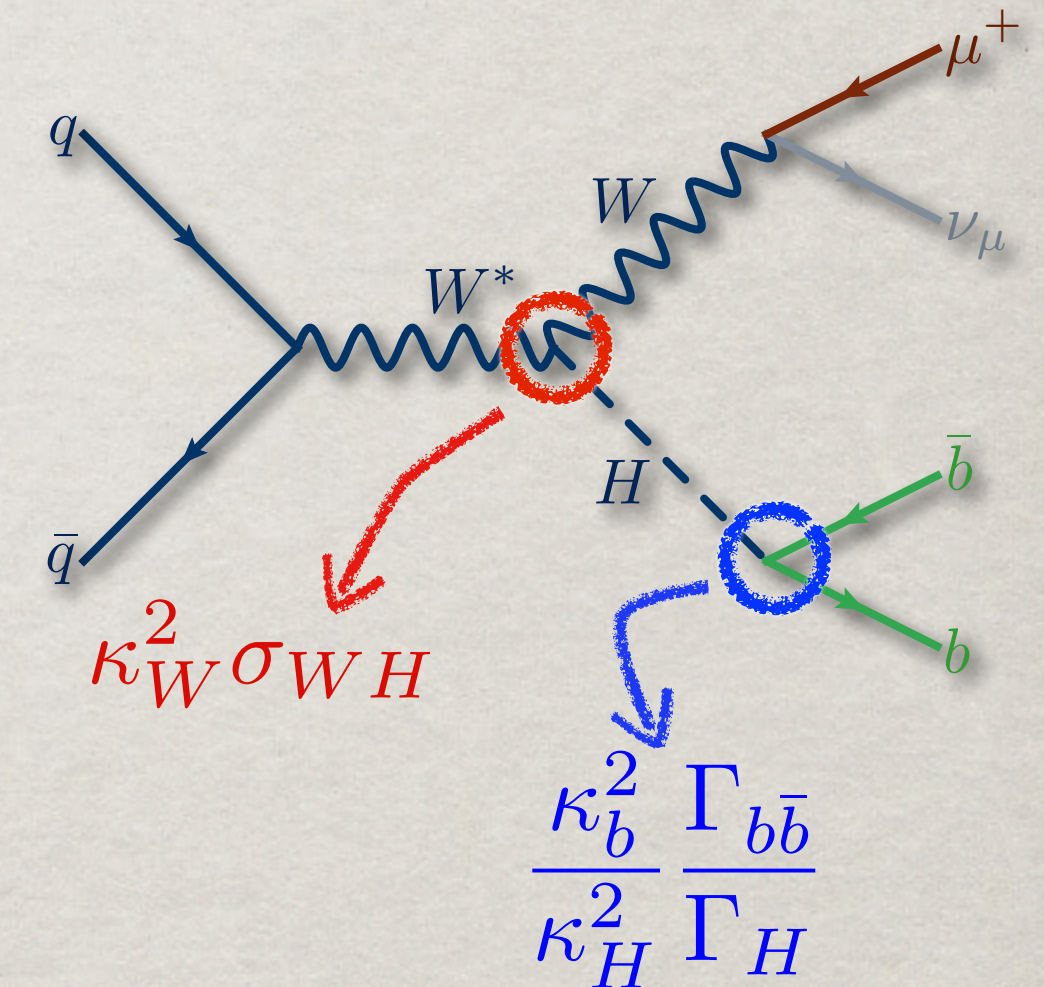
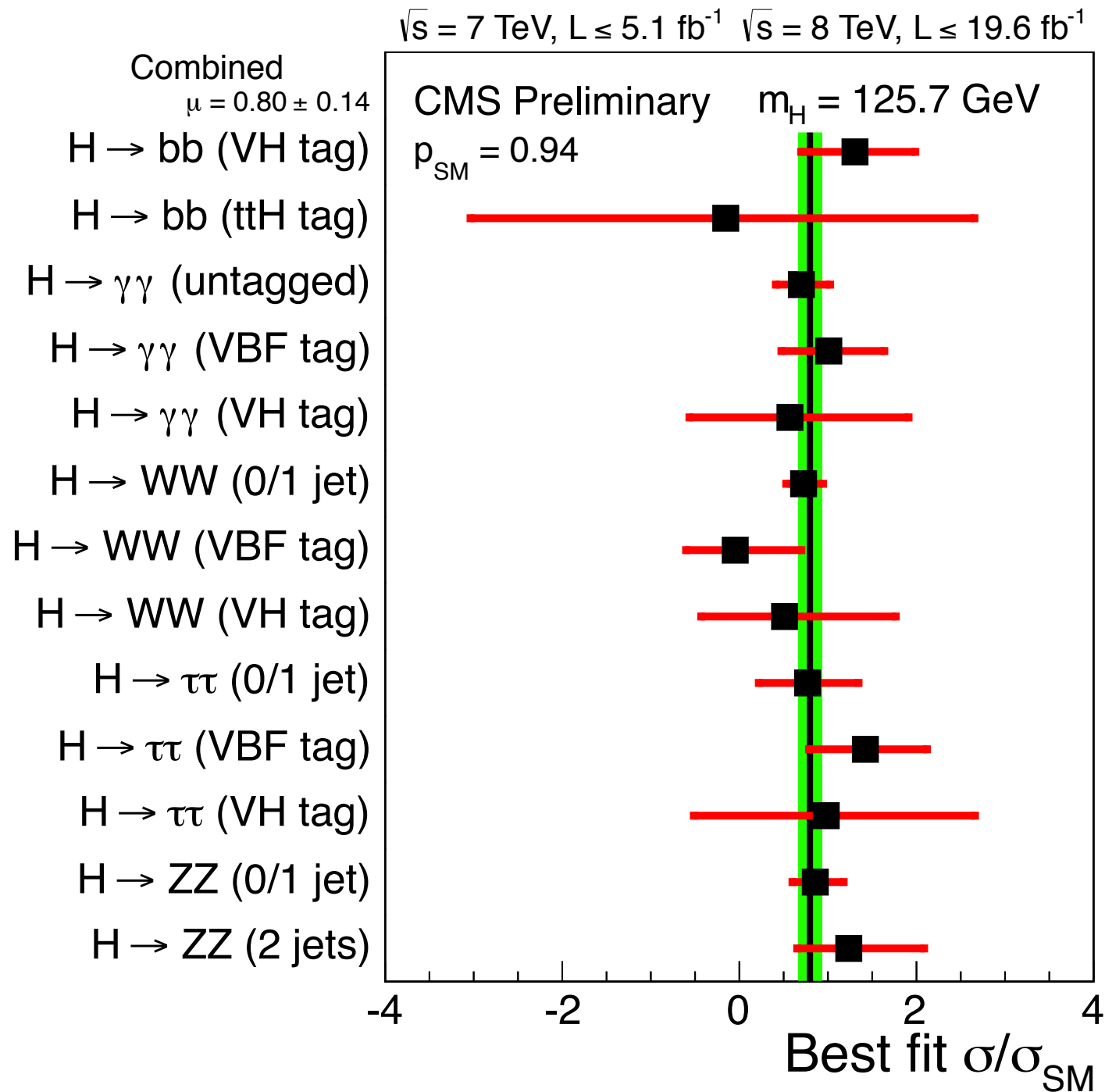
HIGGS COUPLINGS



HIGGS COUPLINGS

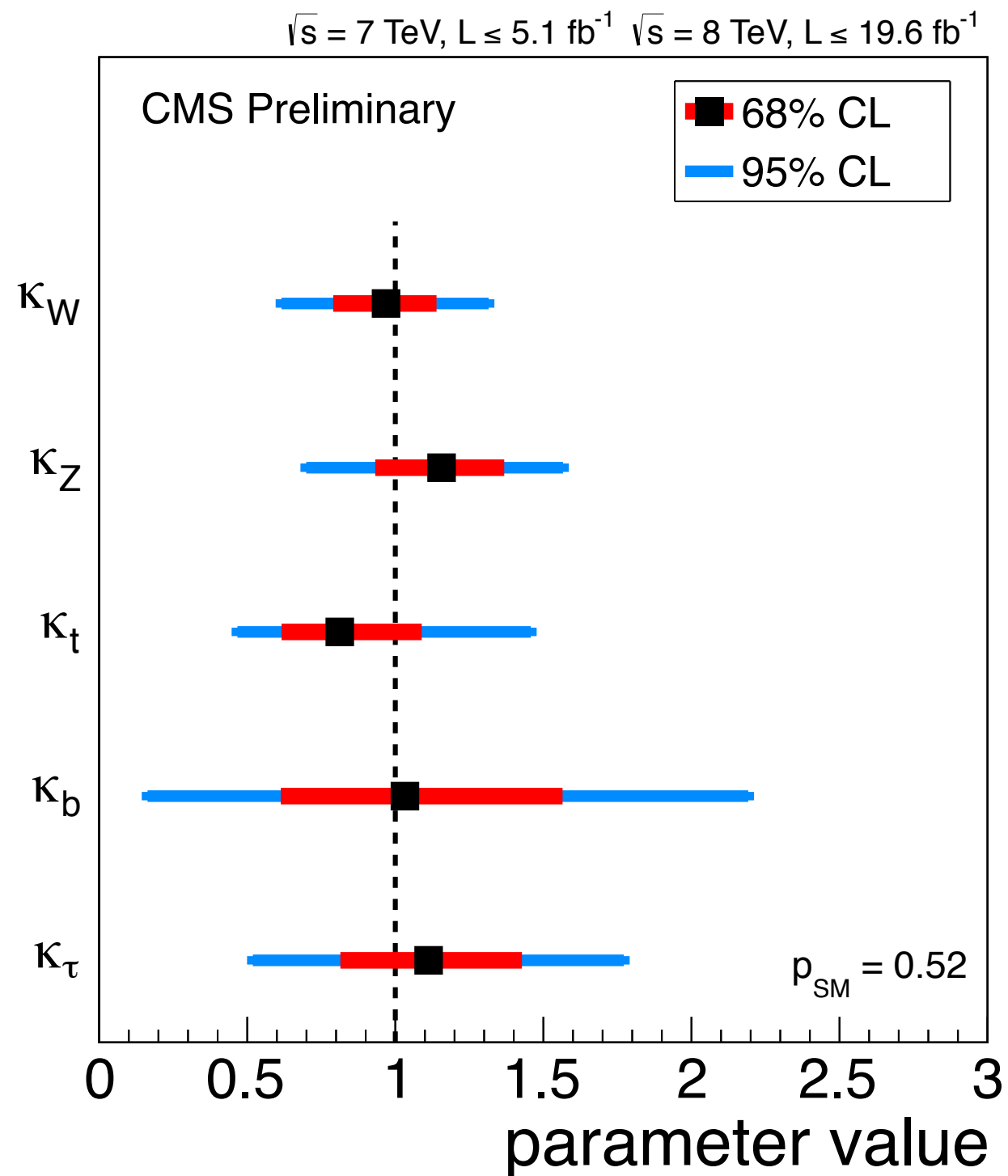


HIGGS COUPLINGS

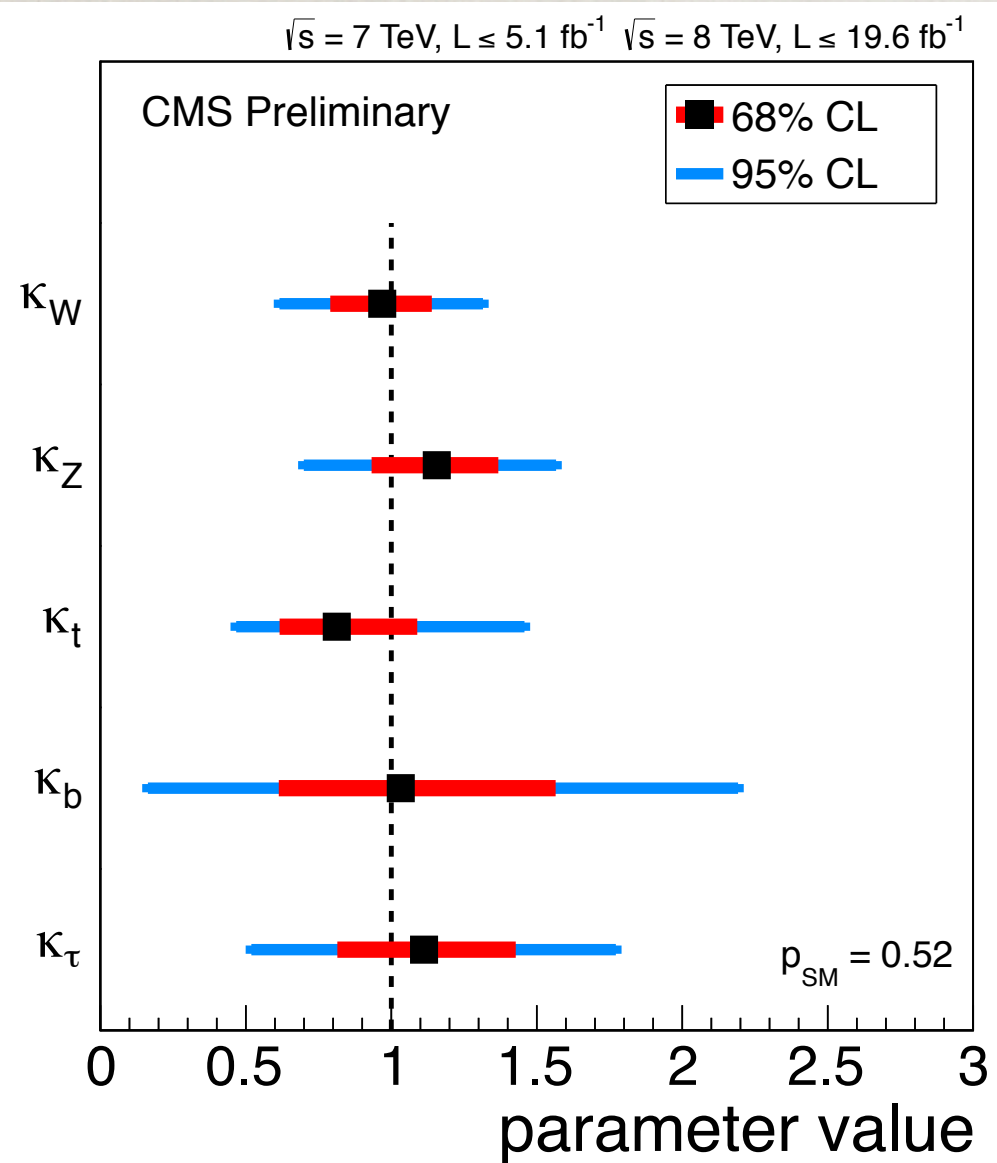


$$\mu \equiv \frac{\sigma_{WH} \times BR_{b\bar{b}}}{\sigma_{WH,SM} \times BR_{b\bar{b},SM}} = \frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

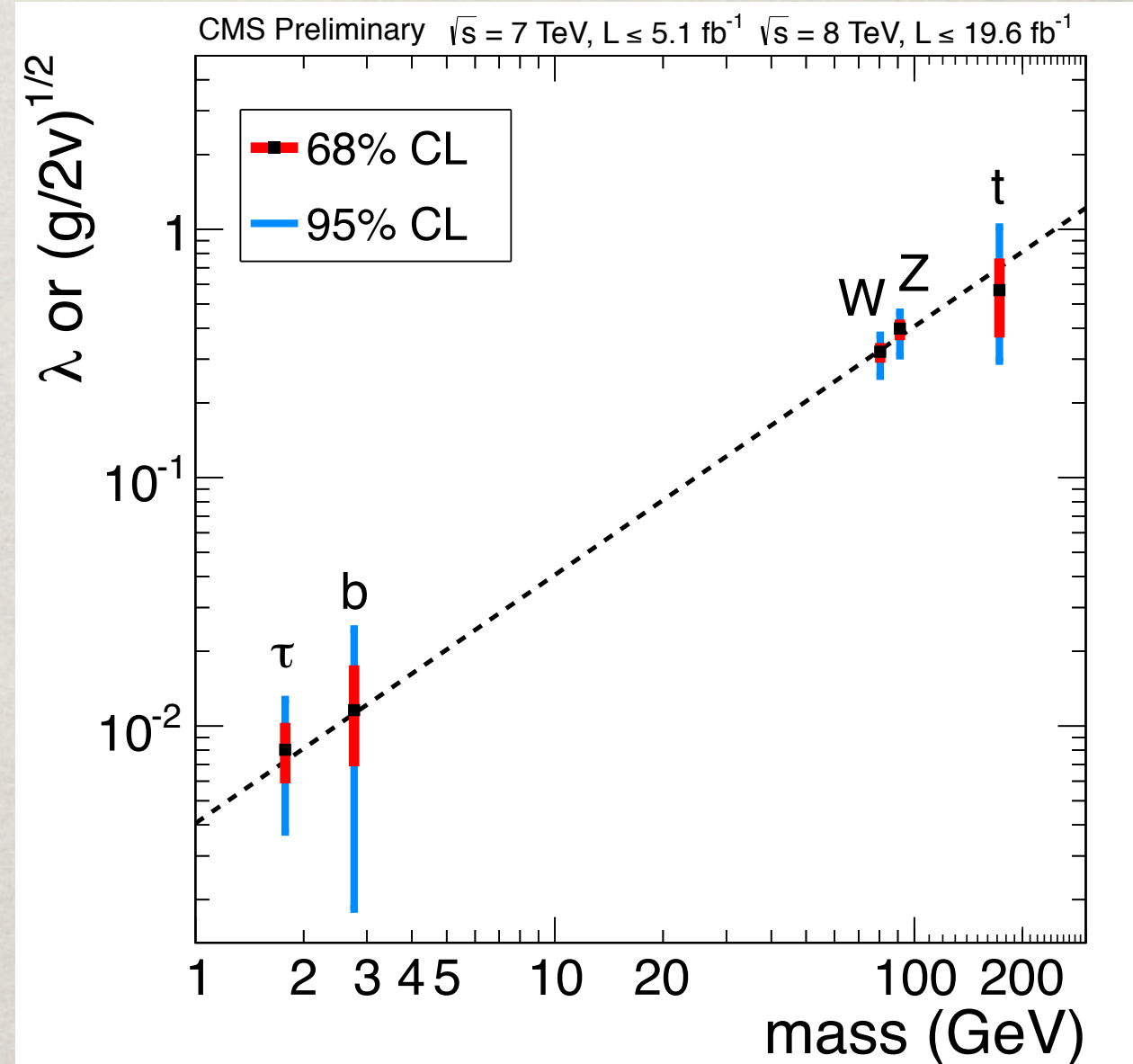
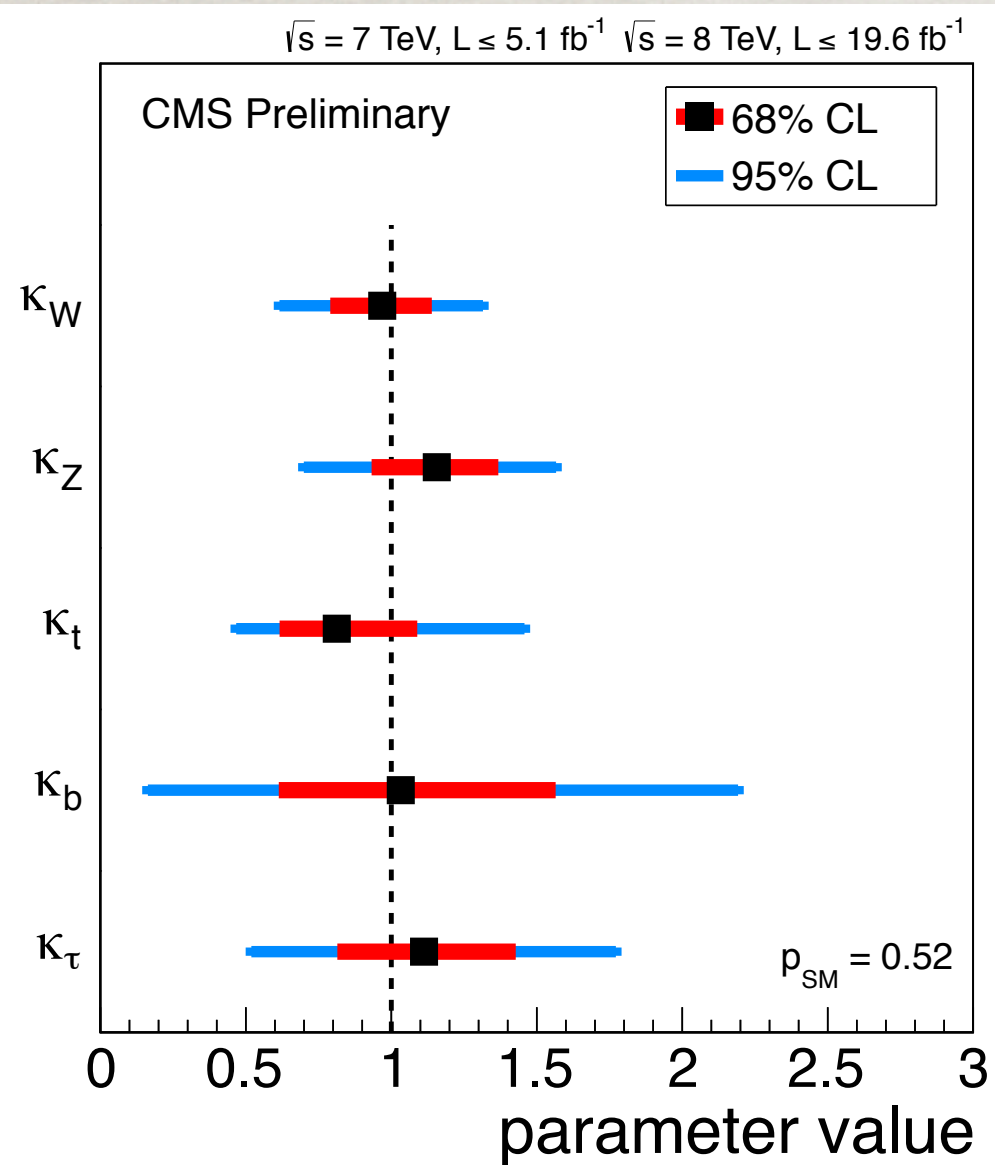
COUPLINGS



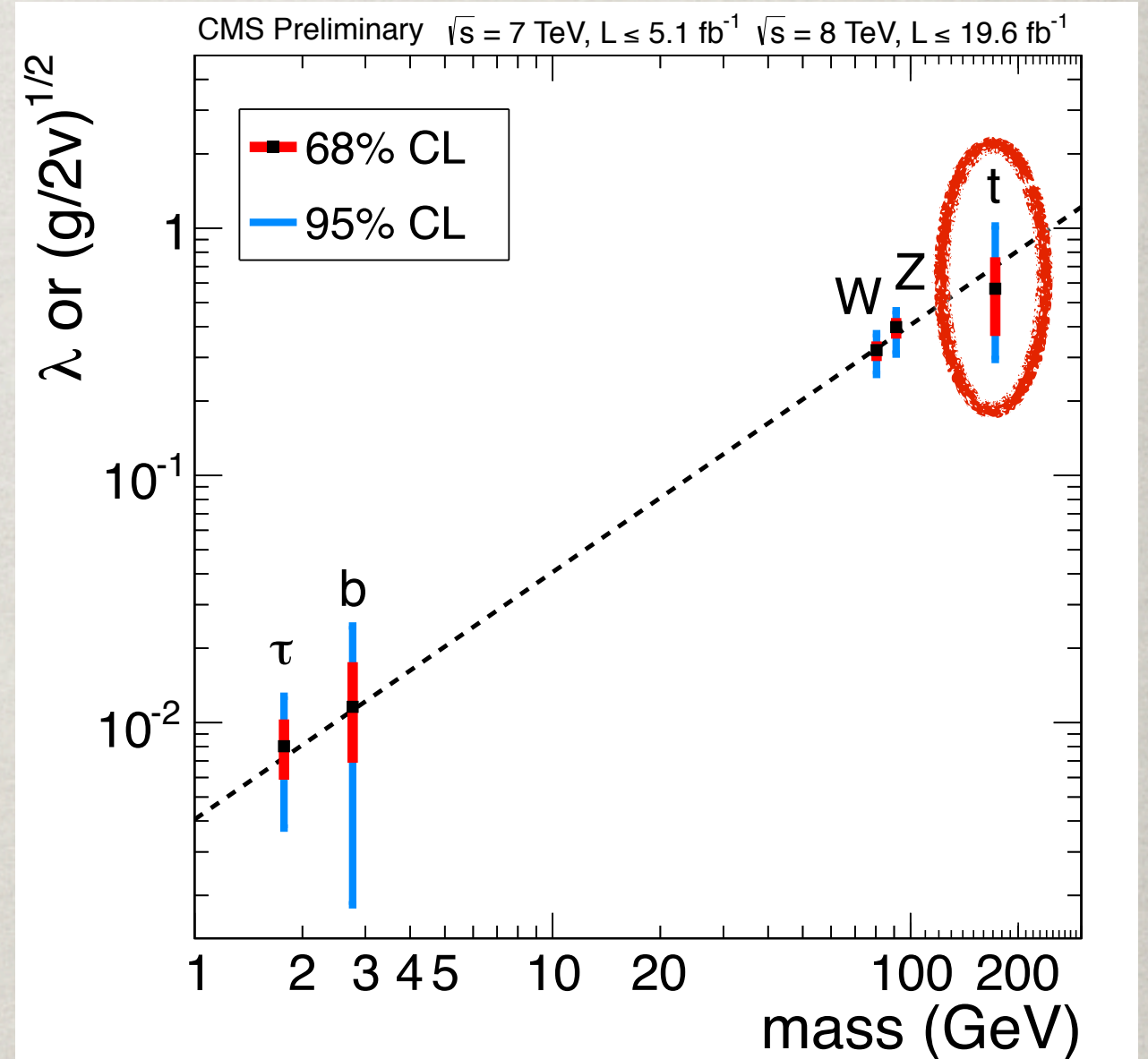
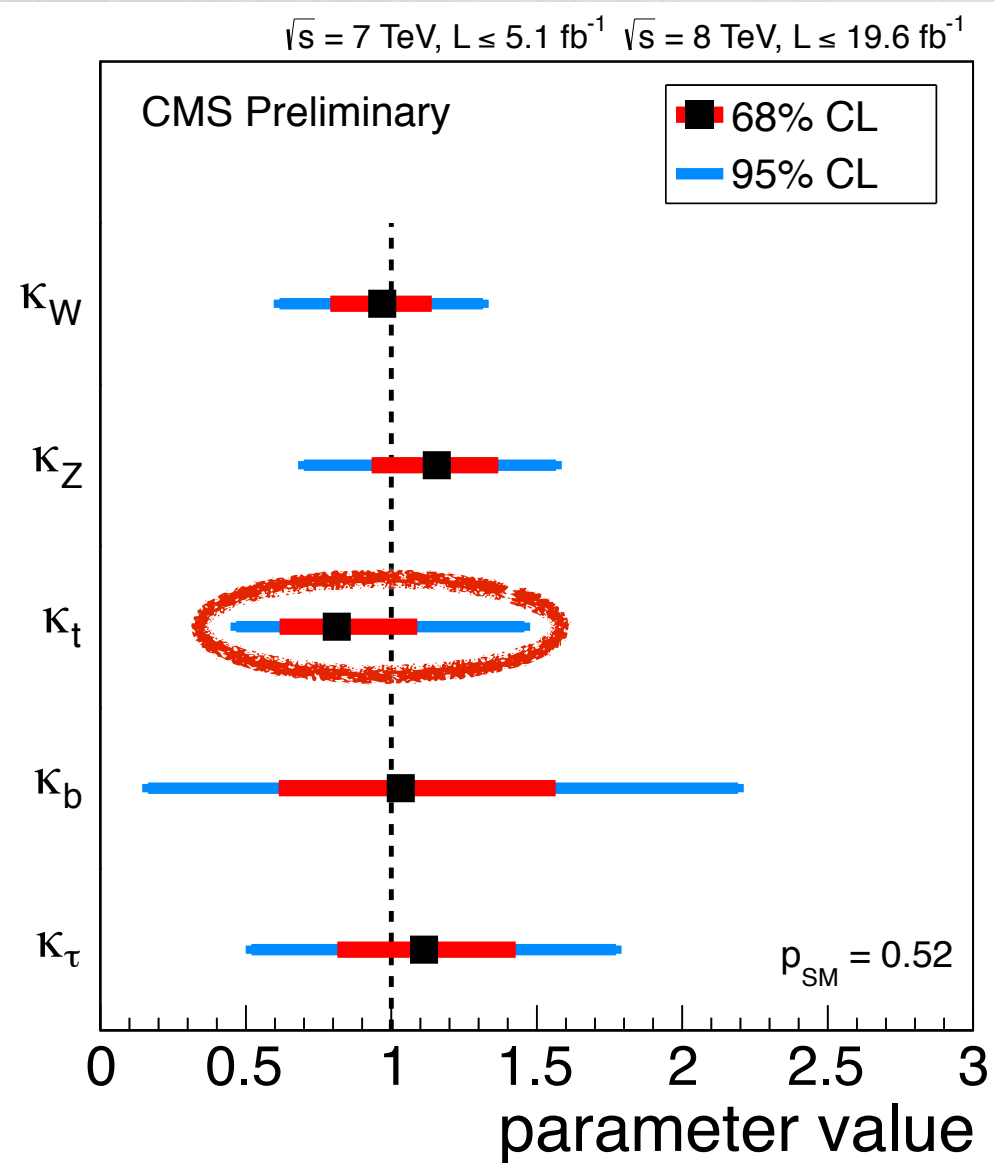
COUPLINGS



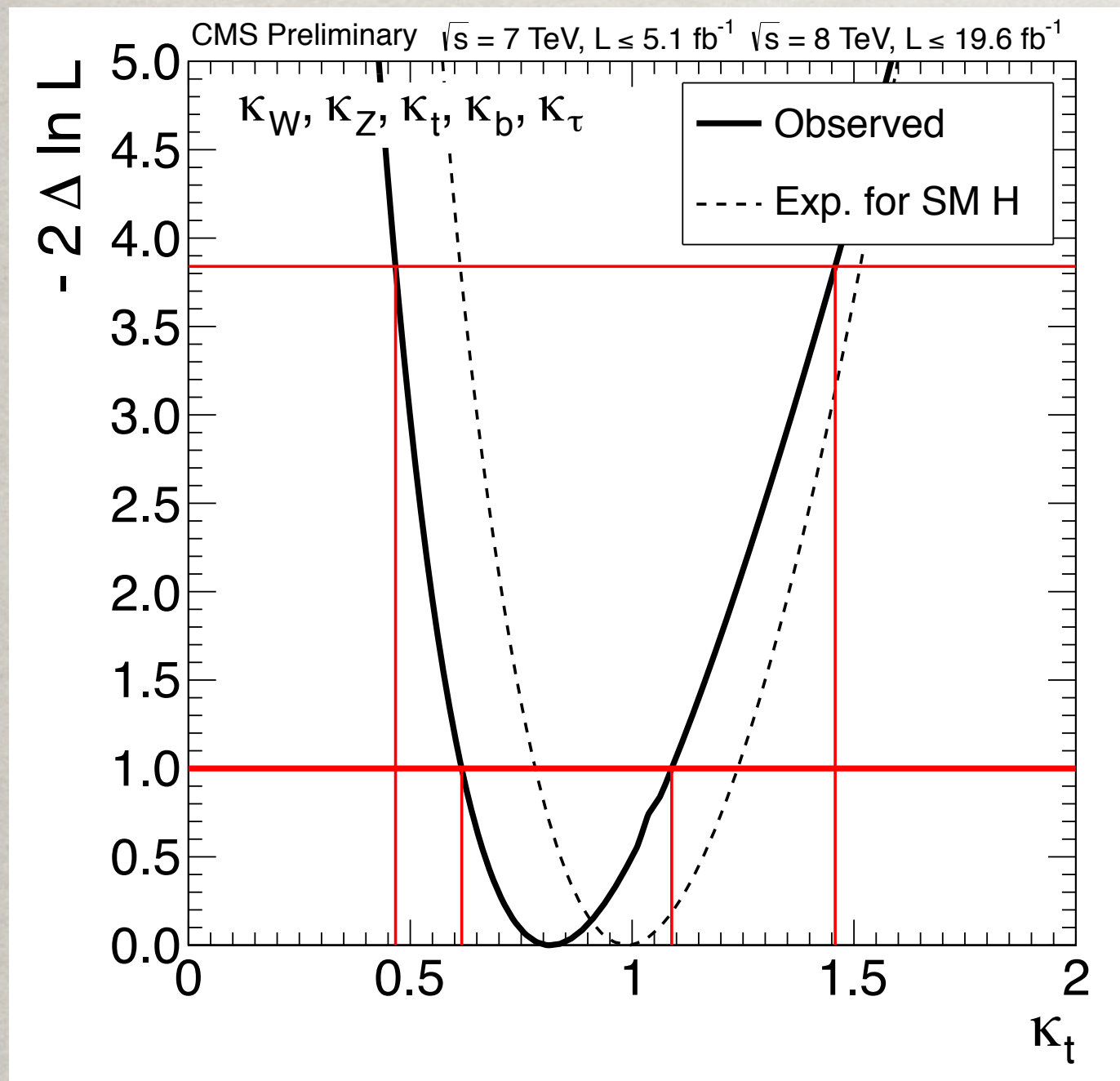
COUPLINGS



COUPLINGS

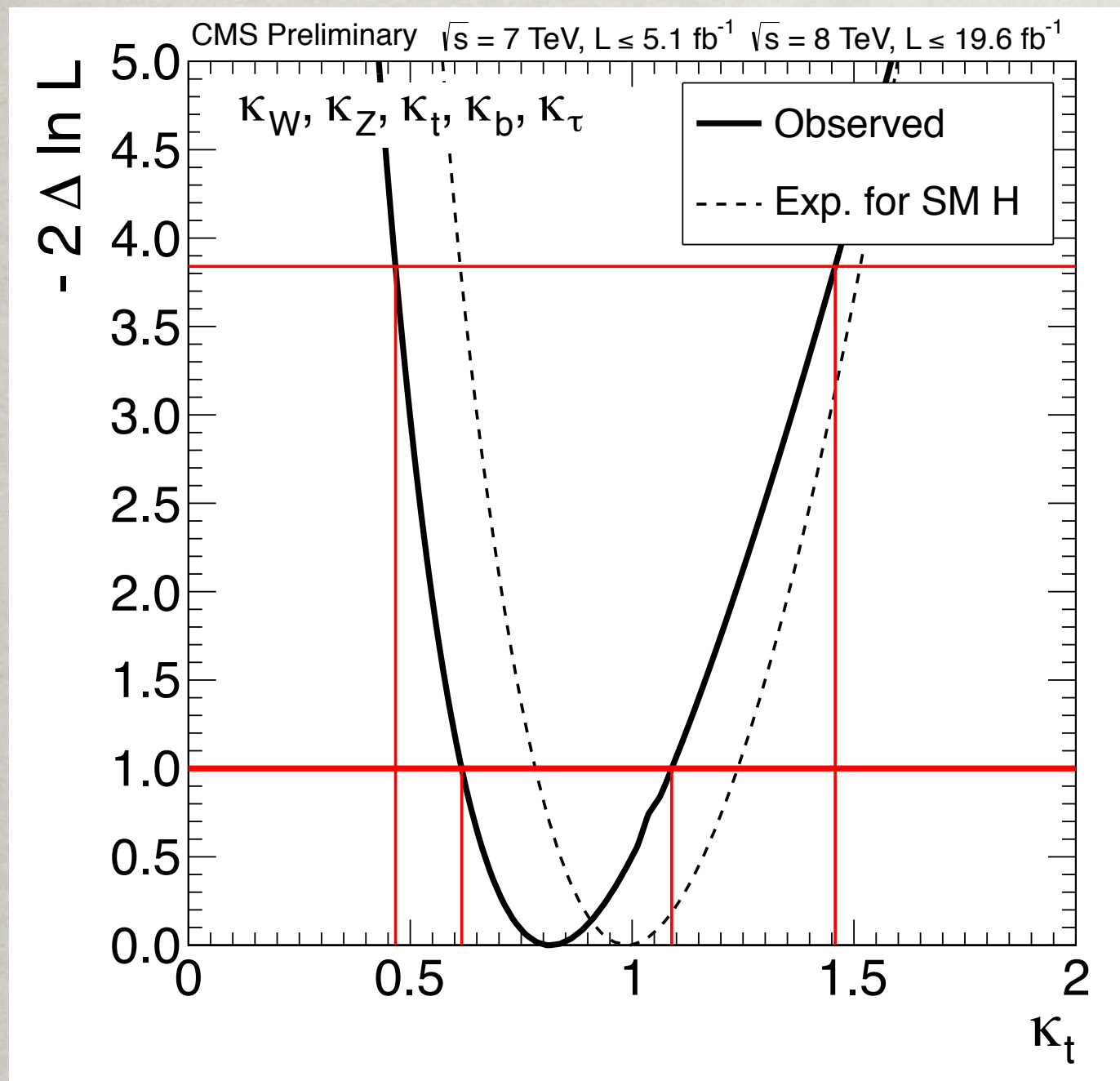


TOP COUPLING

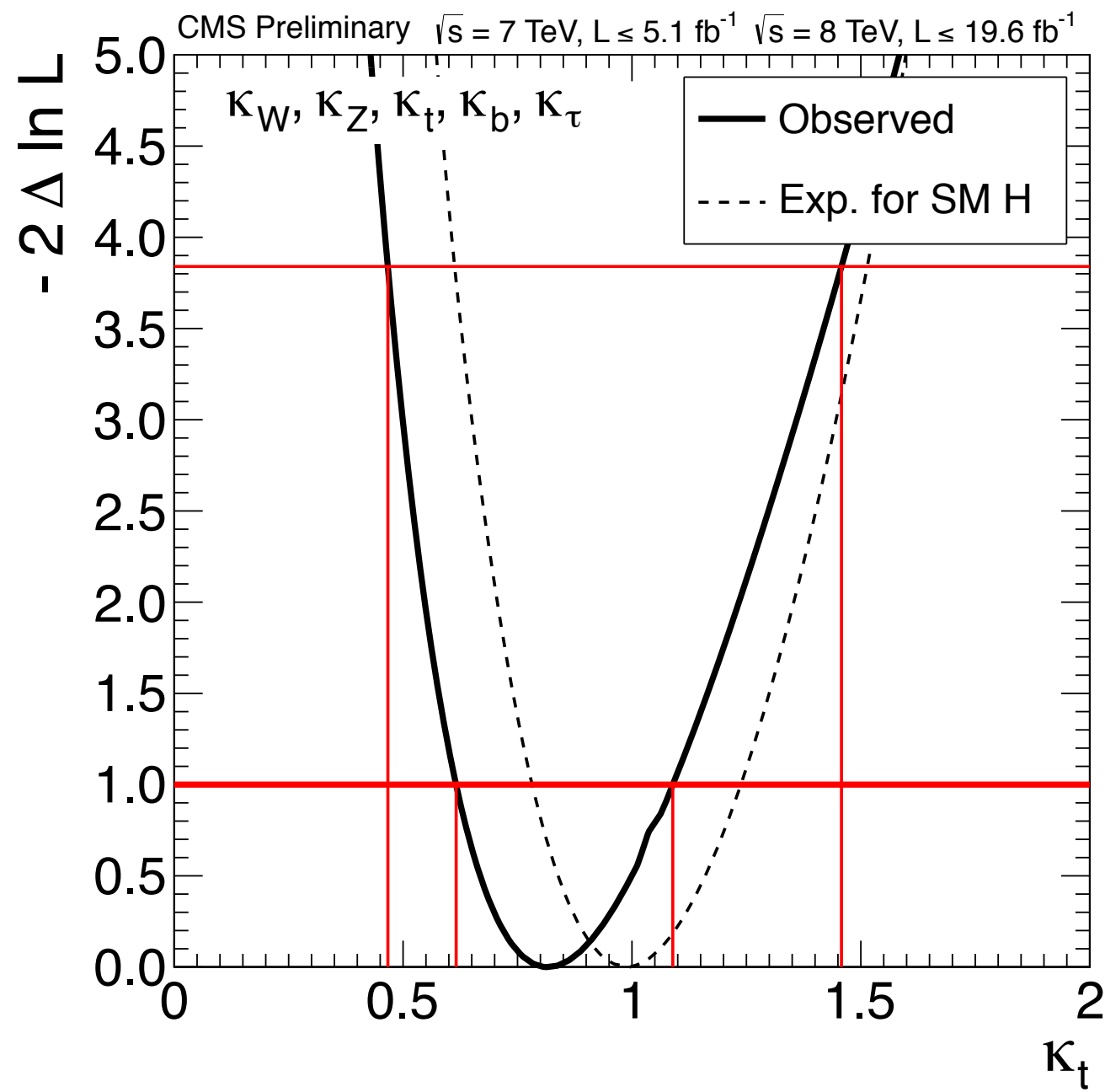


TOP COUPLING

✱ Other scaling factors profiled

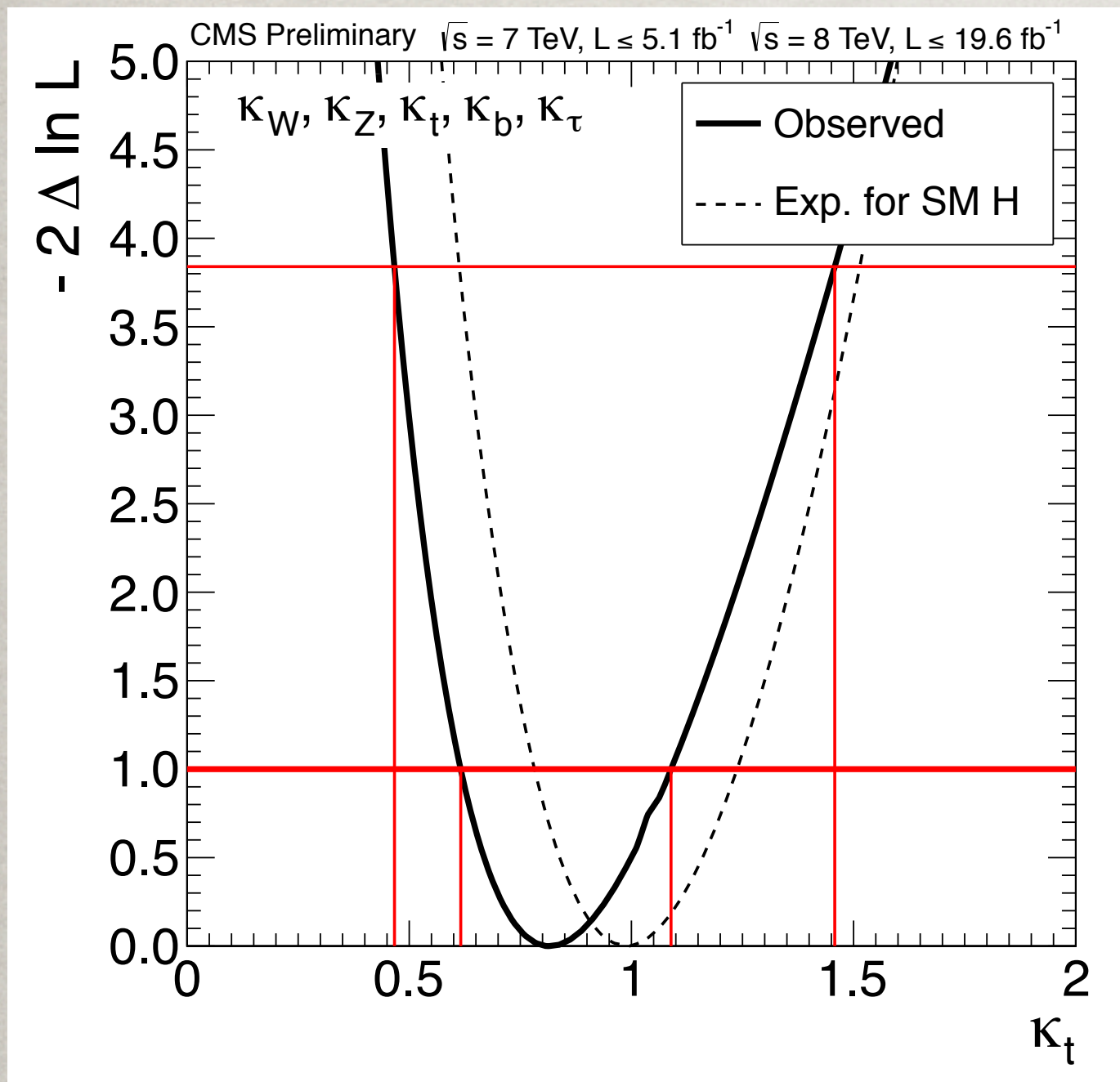


TOP COUPLING

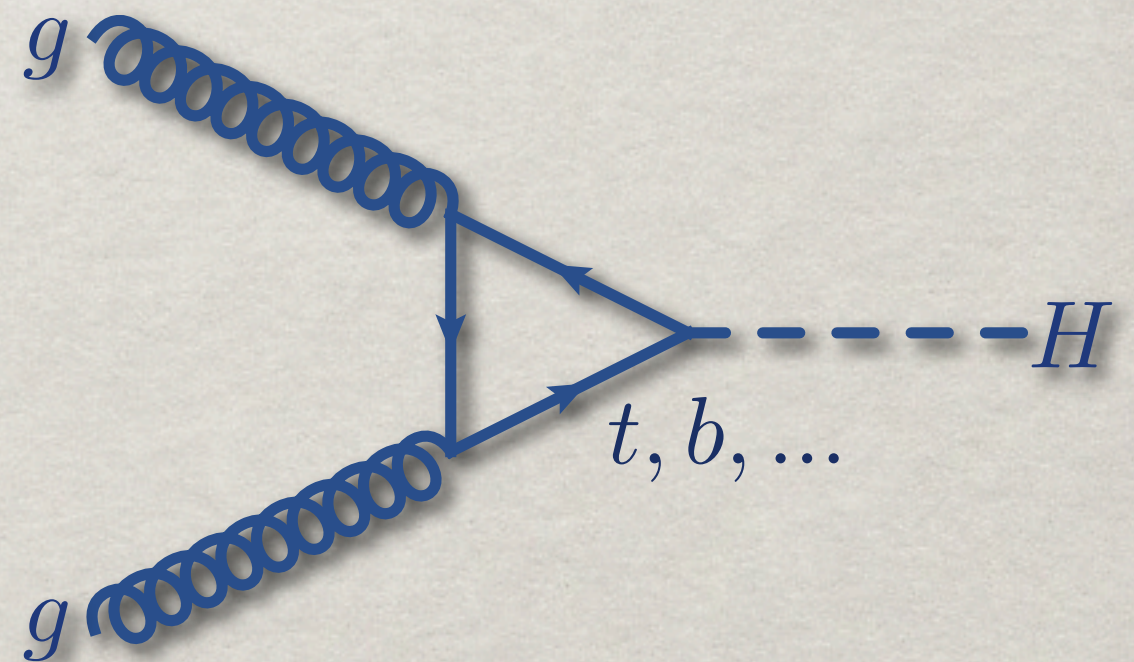


- ✱ Other scaling factors profiled
- ✱ No scaling factors for g or γ ...

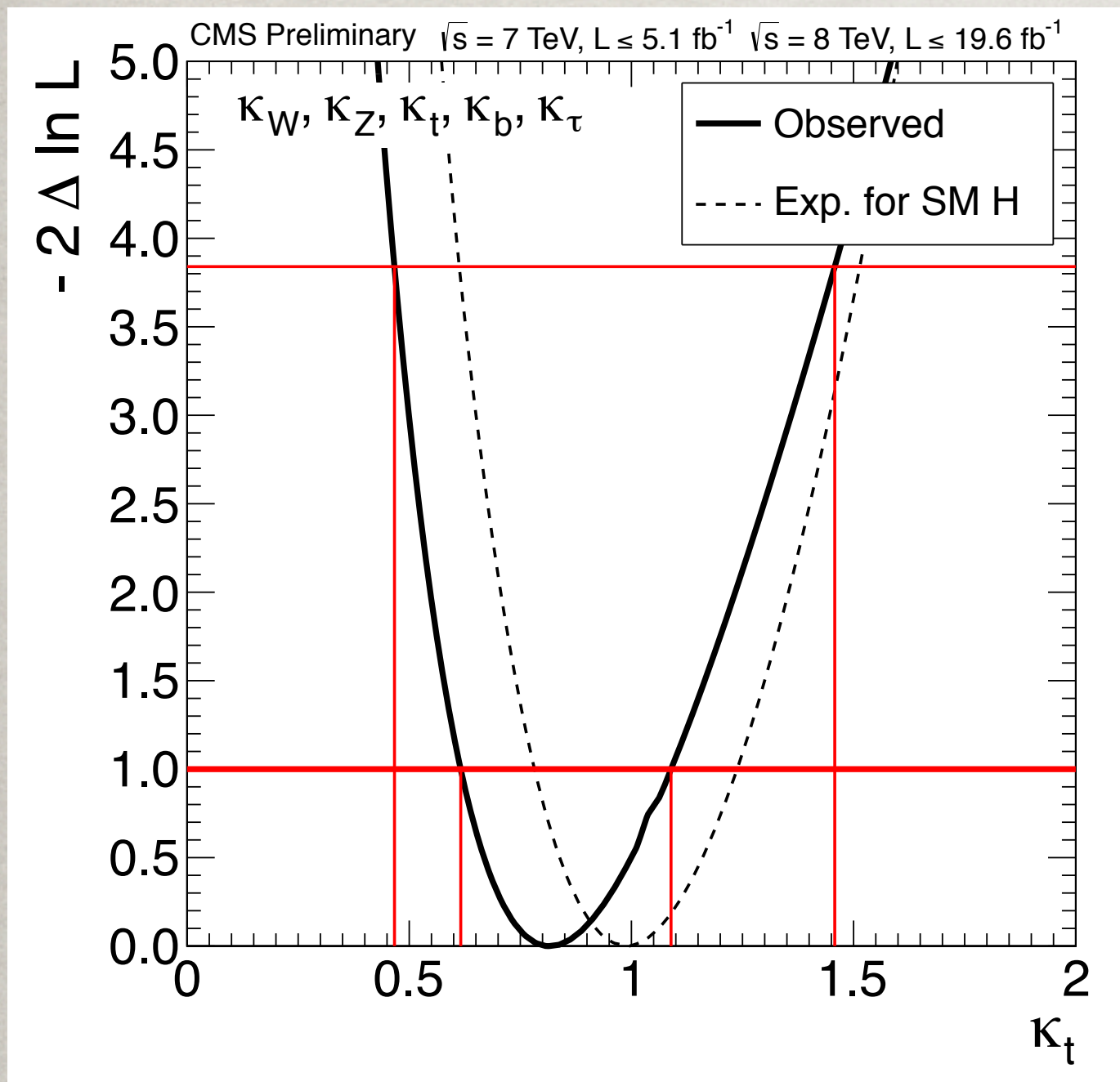
TOP COUPLING



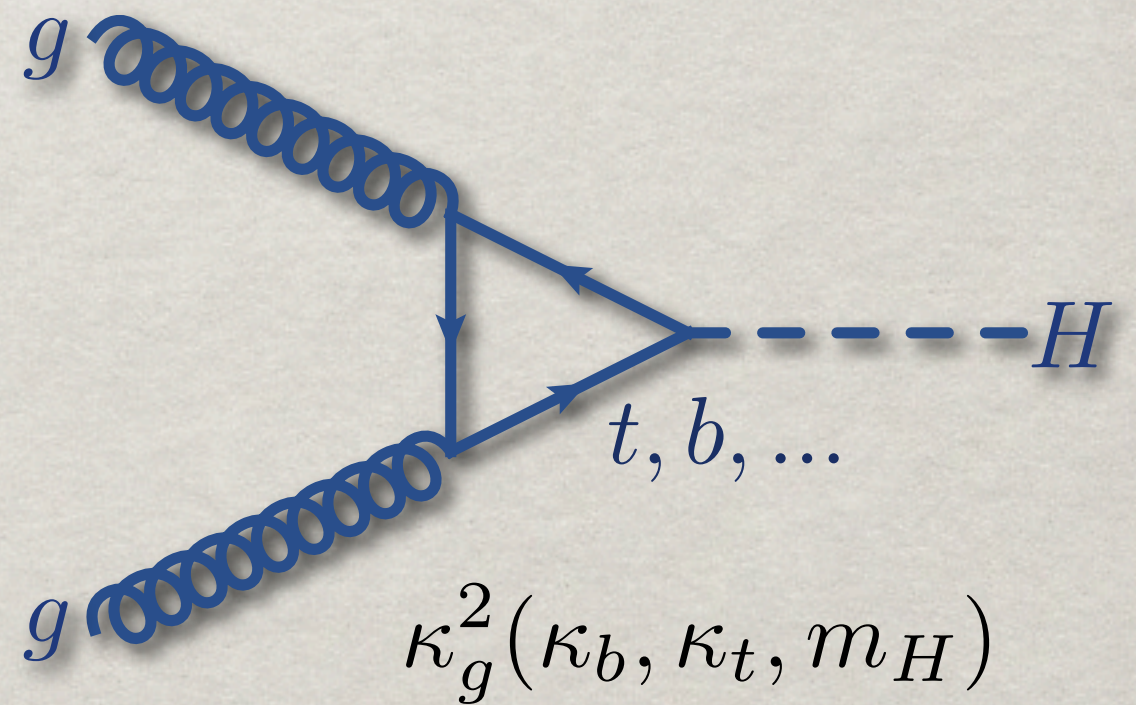
- ✱ Other scaling factors profiled
- ✱ No scaling factors for g or γ ...



TOP COUPLING

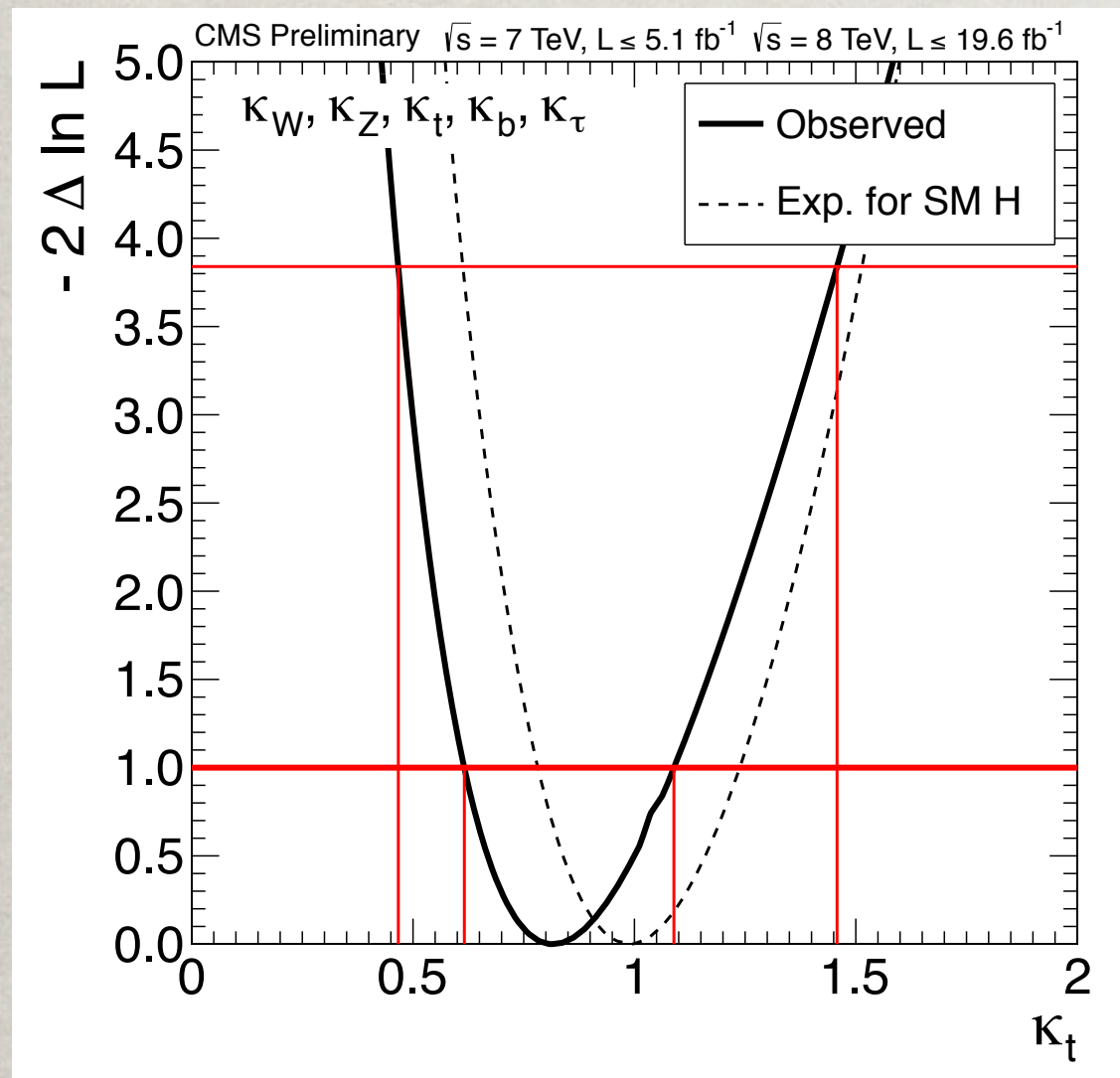


- ✱ Other scaling factors profiled
- ✱ No scaling factors for g or γ ...



TOP COUPLING

☼ Allow non-standard gluon and photon couplings

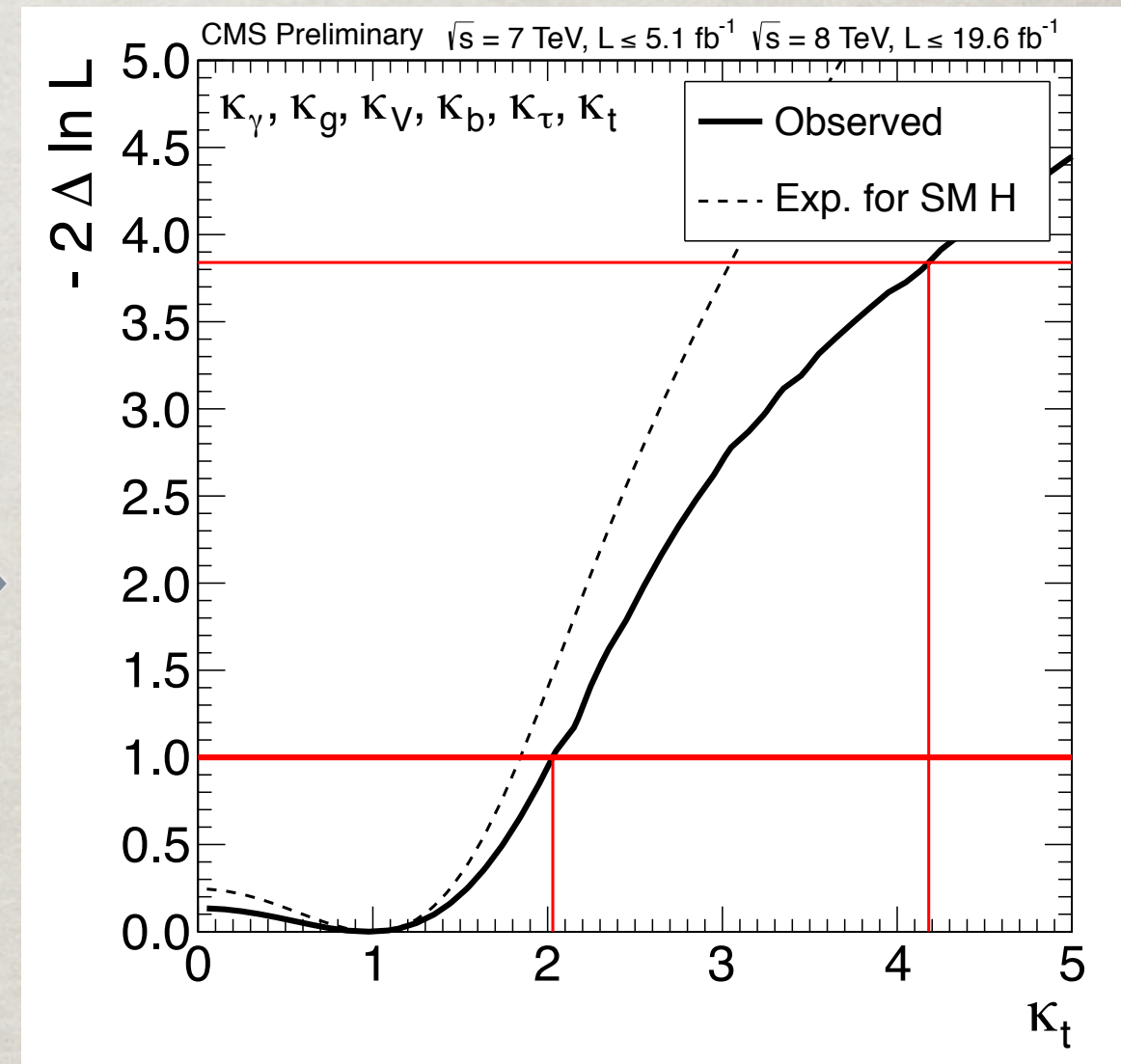
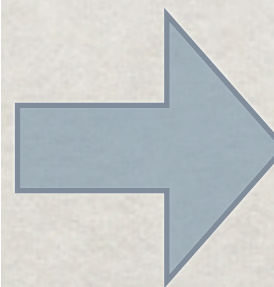
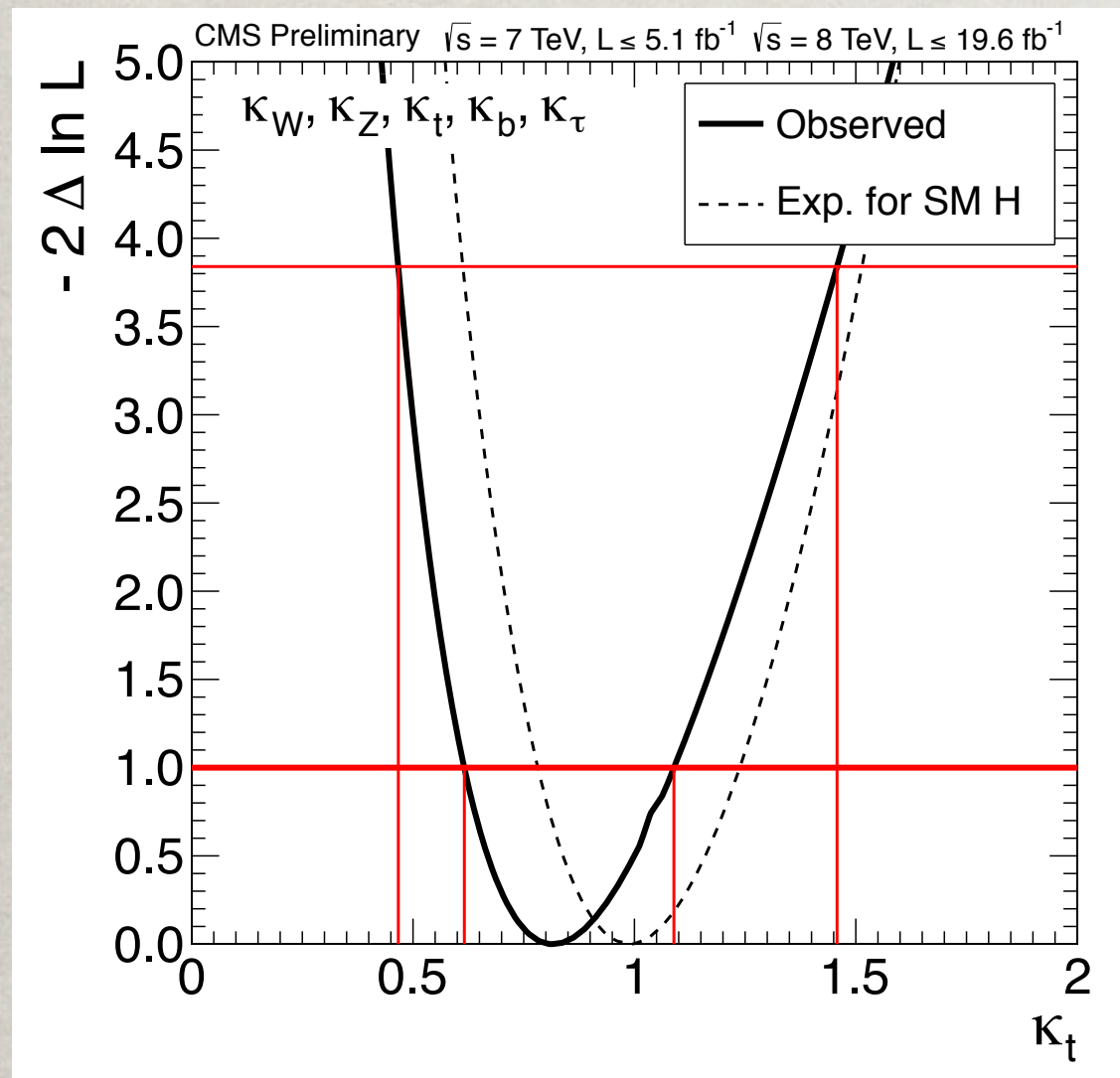


$$\kappa_g^2(\kappa_b, \kappa_t, m_H)$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H)$$

TOP COUPLING

☼ Allow non-standard gluon and photon couplings



$$\kappa_g^2(\kappa_b, \kappa_t, m_H)$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H)$$

$$\kappa_g, \kappa_\gamma$$

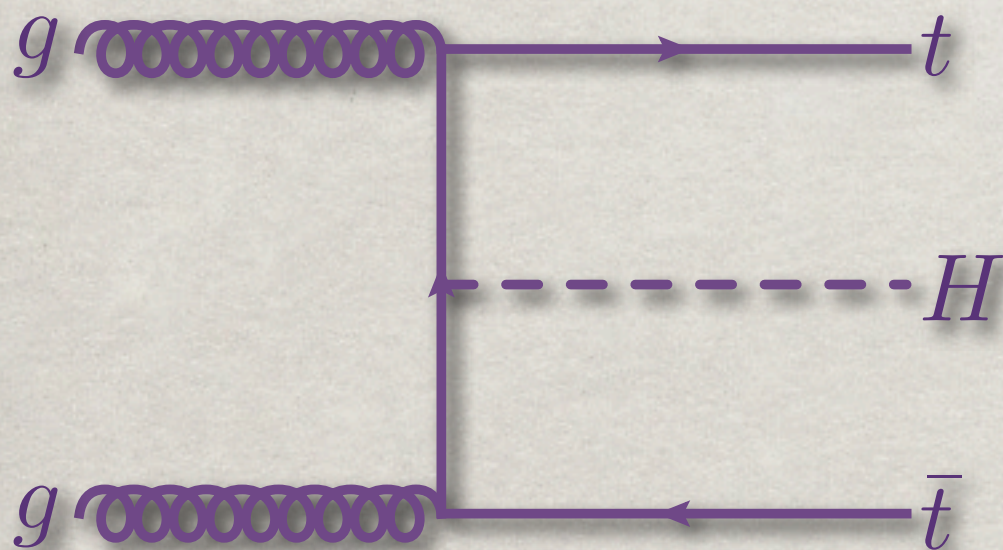
MEASURING TTH

MEASURING TTH

- ✱ Measuring rate of Higgs produced in association with top quark pair only way to directly measuring coupling

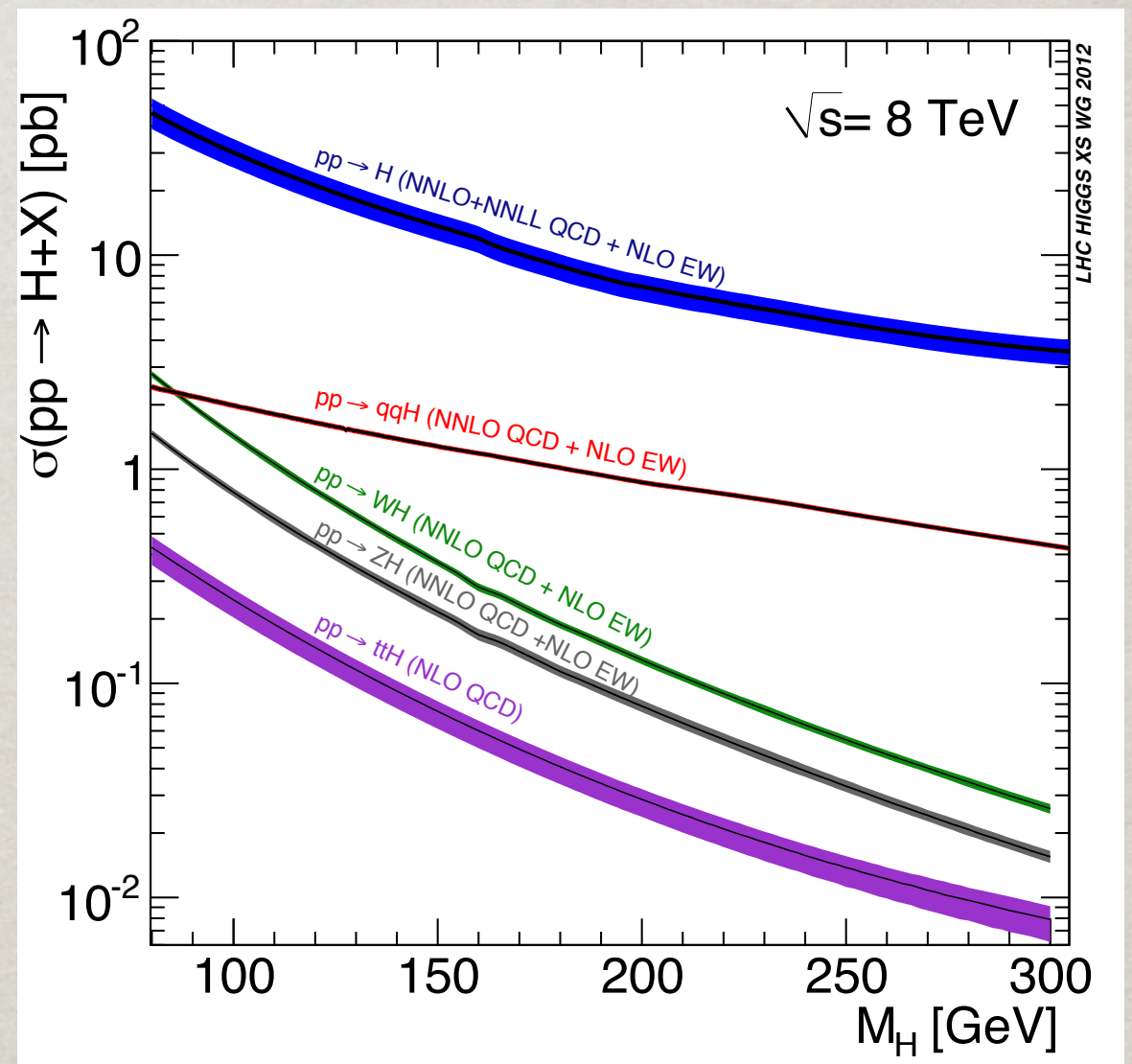
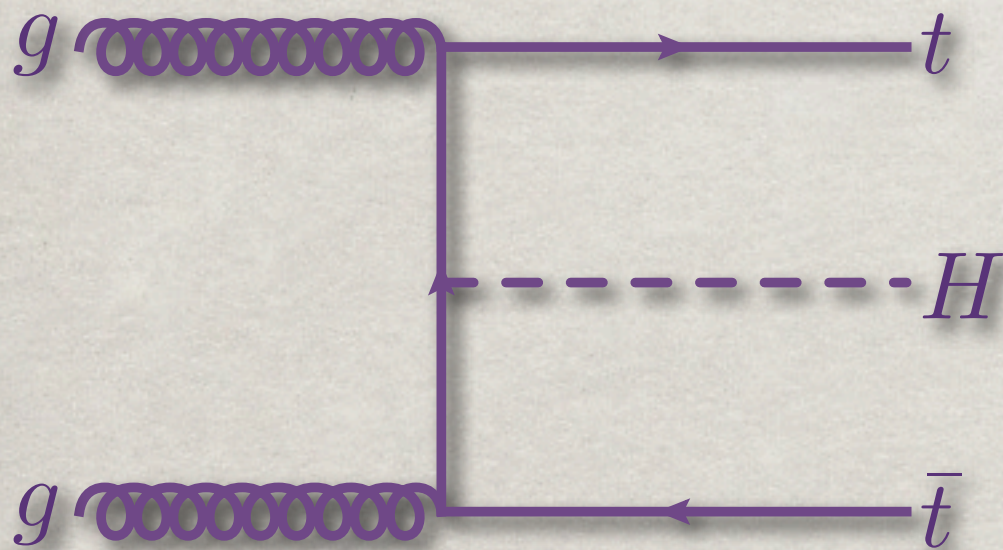
MEASURING TTH

- ✱ Measuring rate of Higgs produced in association with top quark pair only way to directly measuring coupling



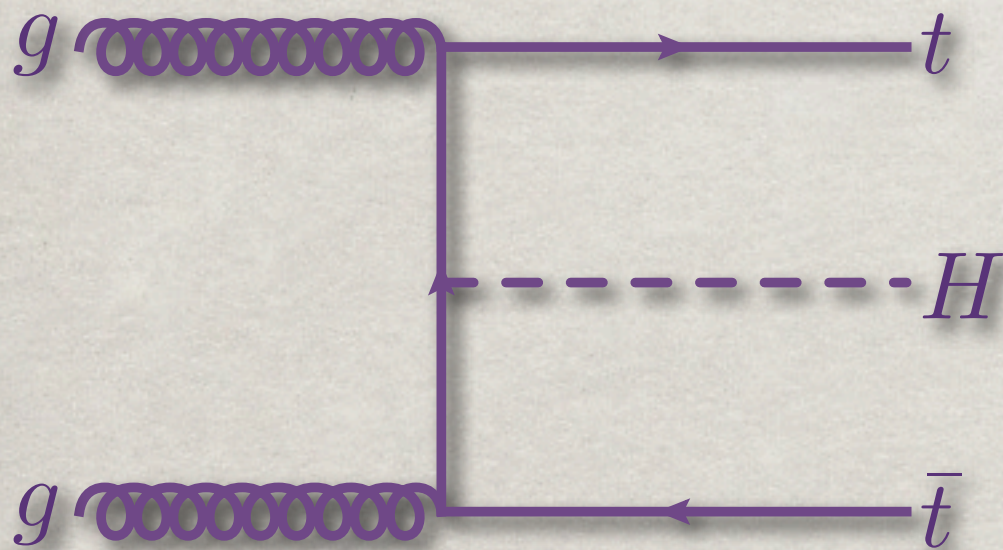
MEASURING TTH

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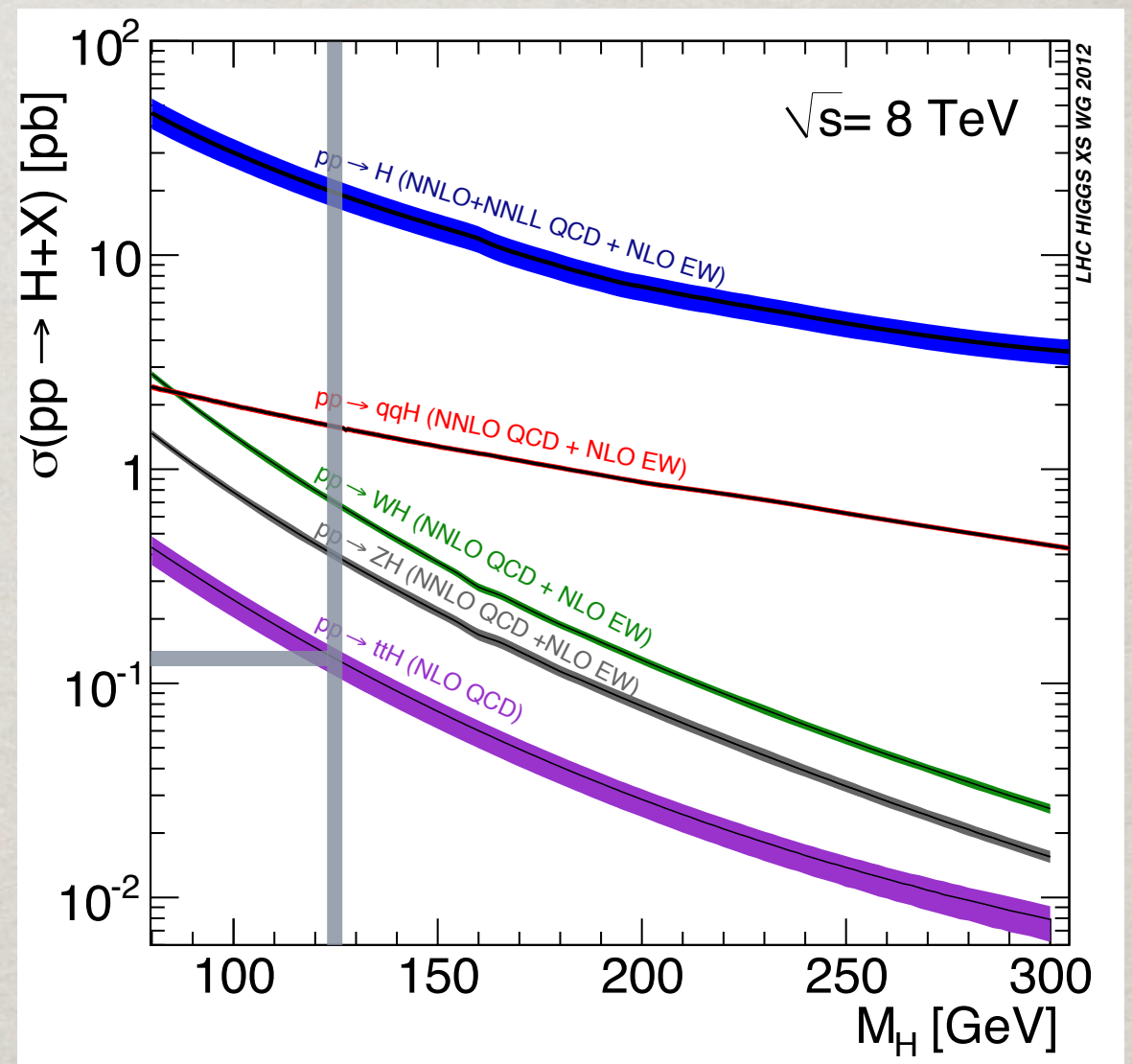
MEASURING TTH

- Measuring rate of Higgs produced in association with top quark pair only way to directly measuring coupling



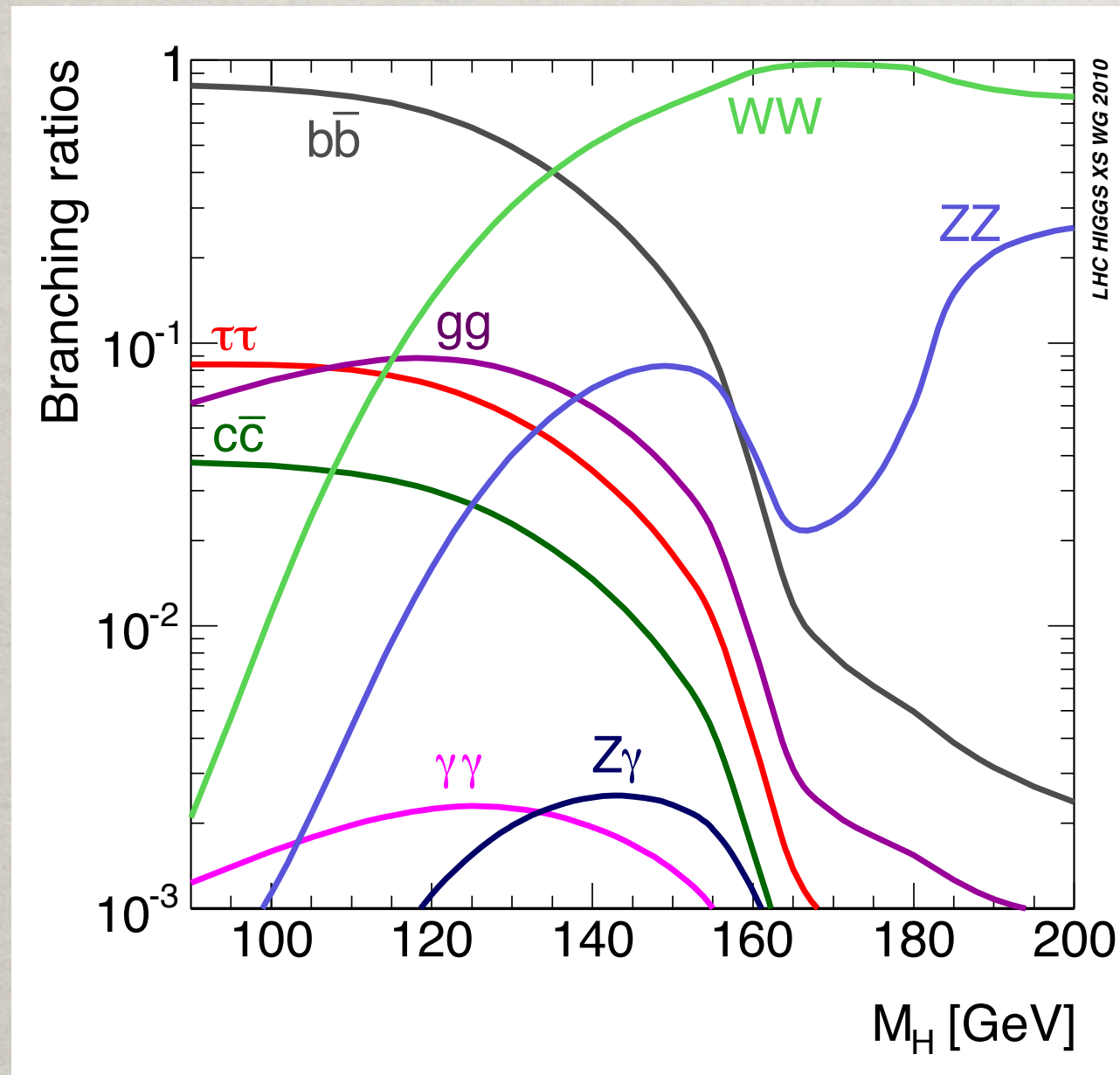
At 8 TeV: $\sigma_{t\bar{t}H} = 127.1 \text{ fb}$

At 7 TeV: $\sigma_{t\bar{t}H} = 84.9 \text{ fb}$

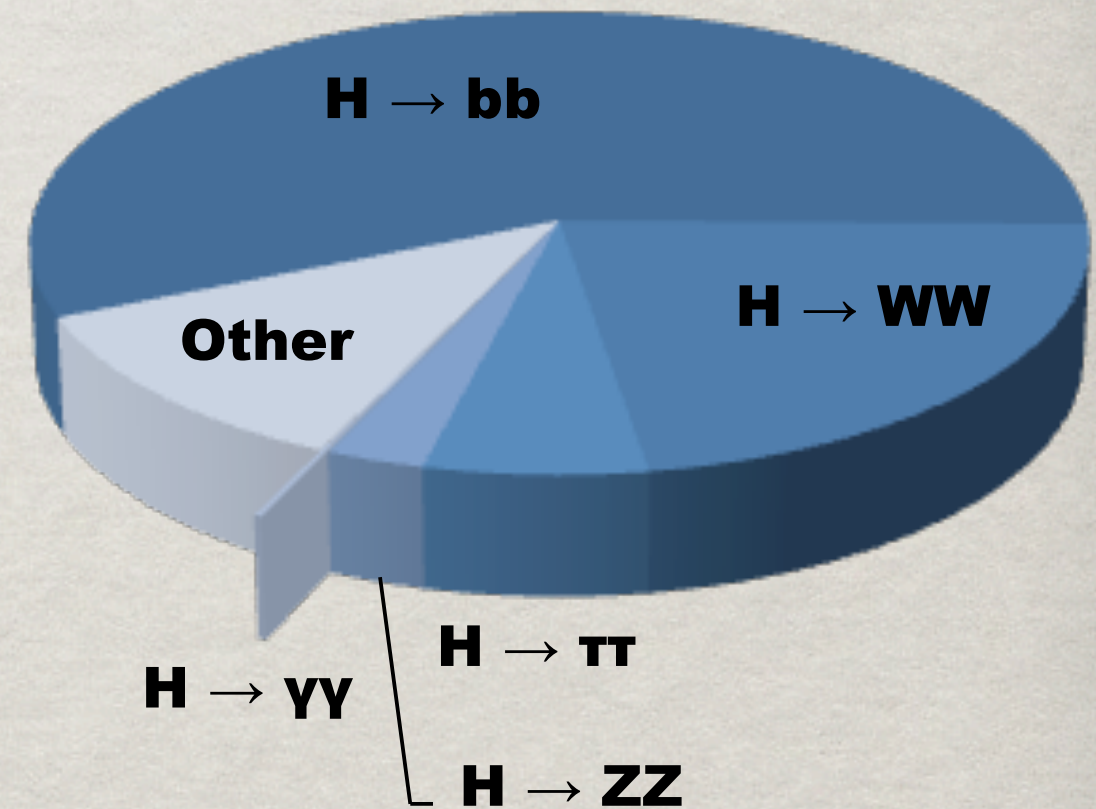
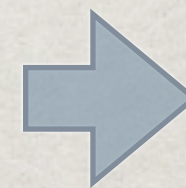
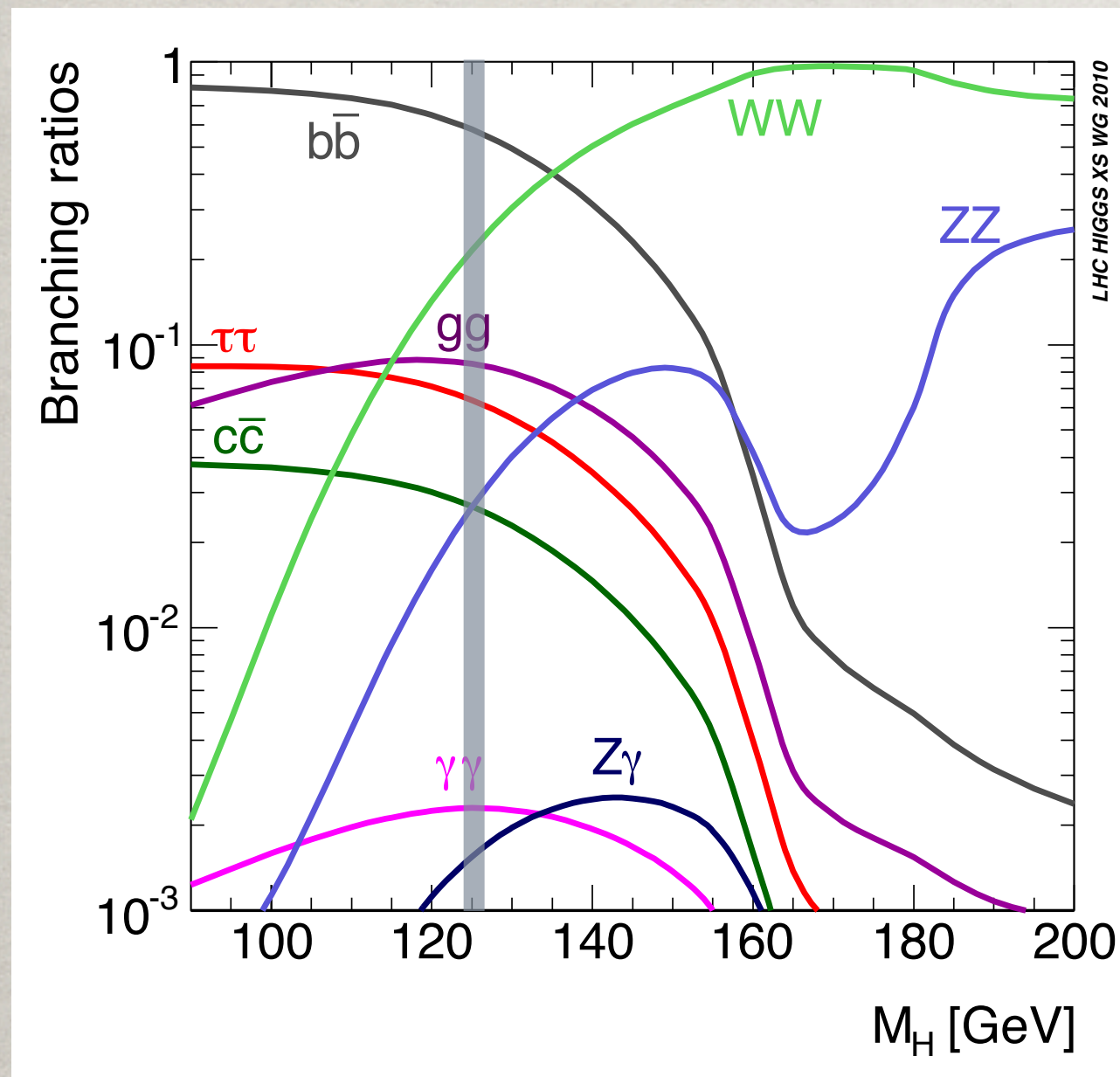


HIGGS DECAYS

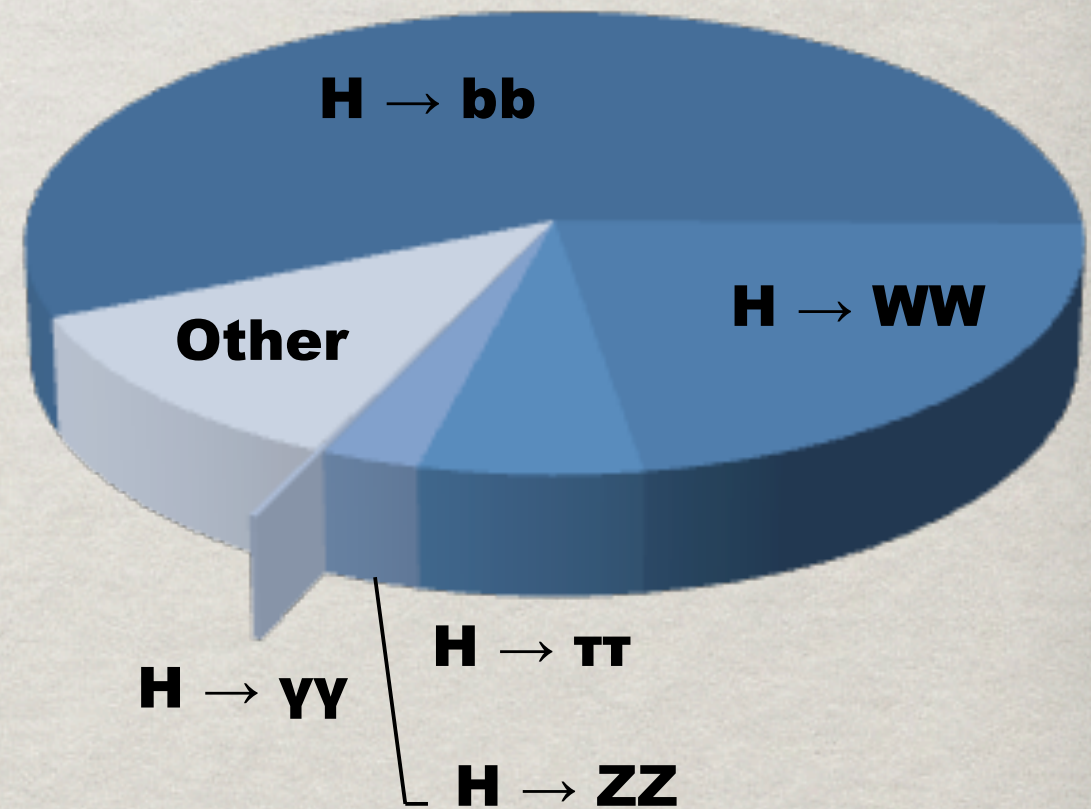
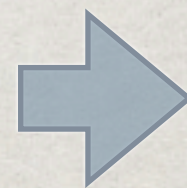
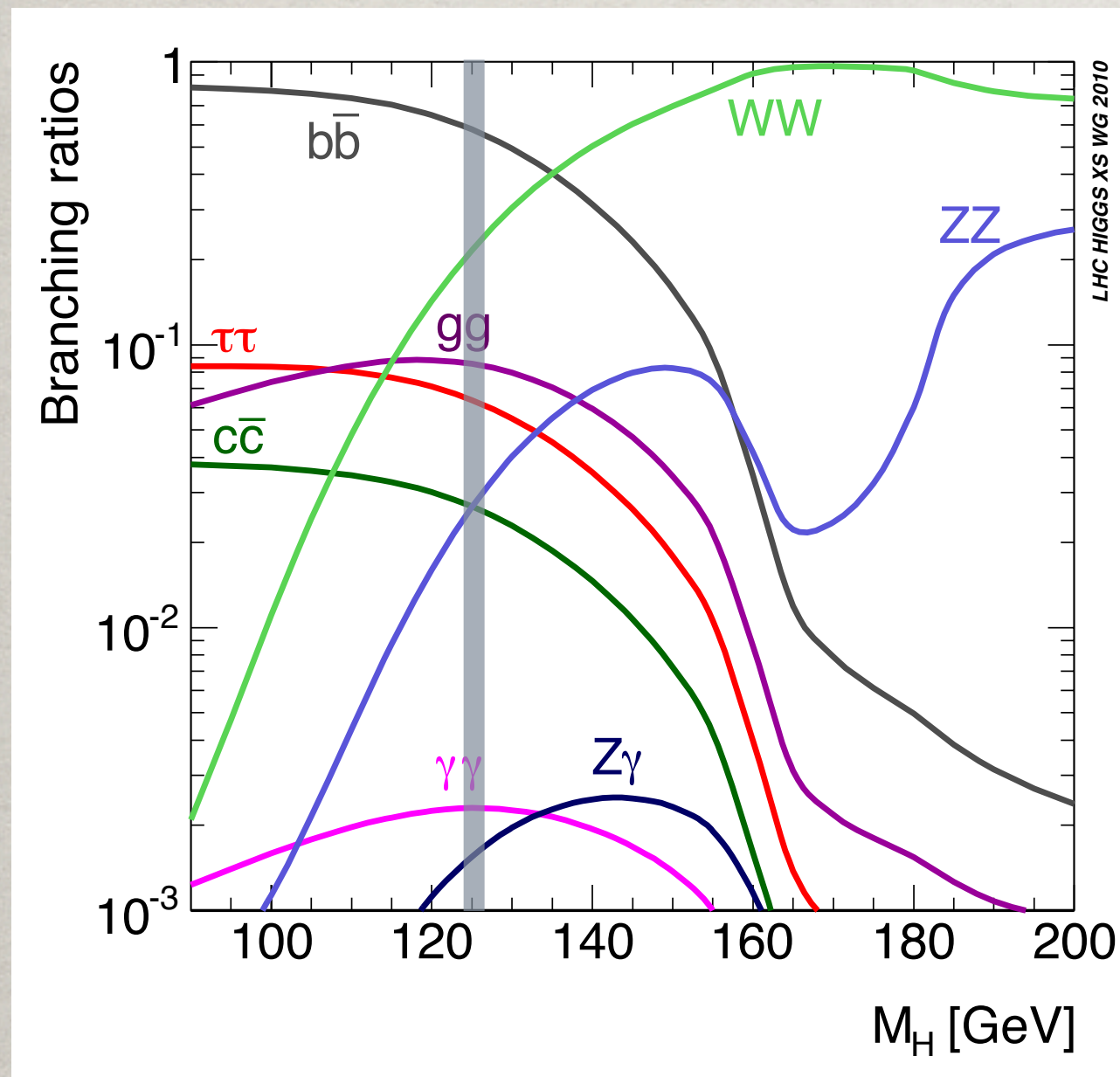
HIGGS DECAYS



HIGGS DECAYS



HIGGS DECAYS

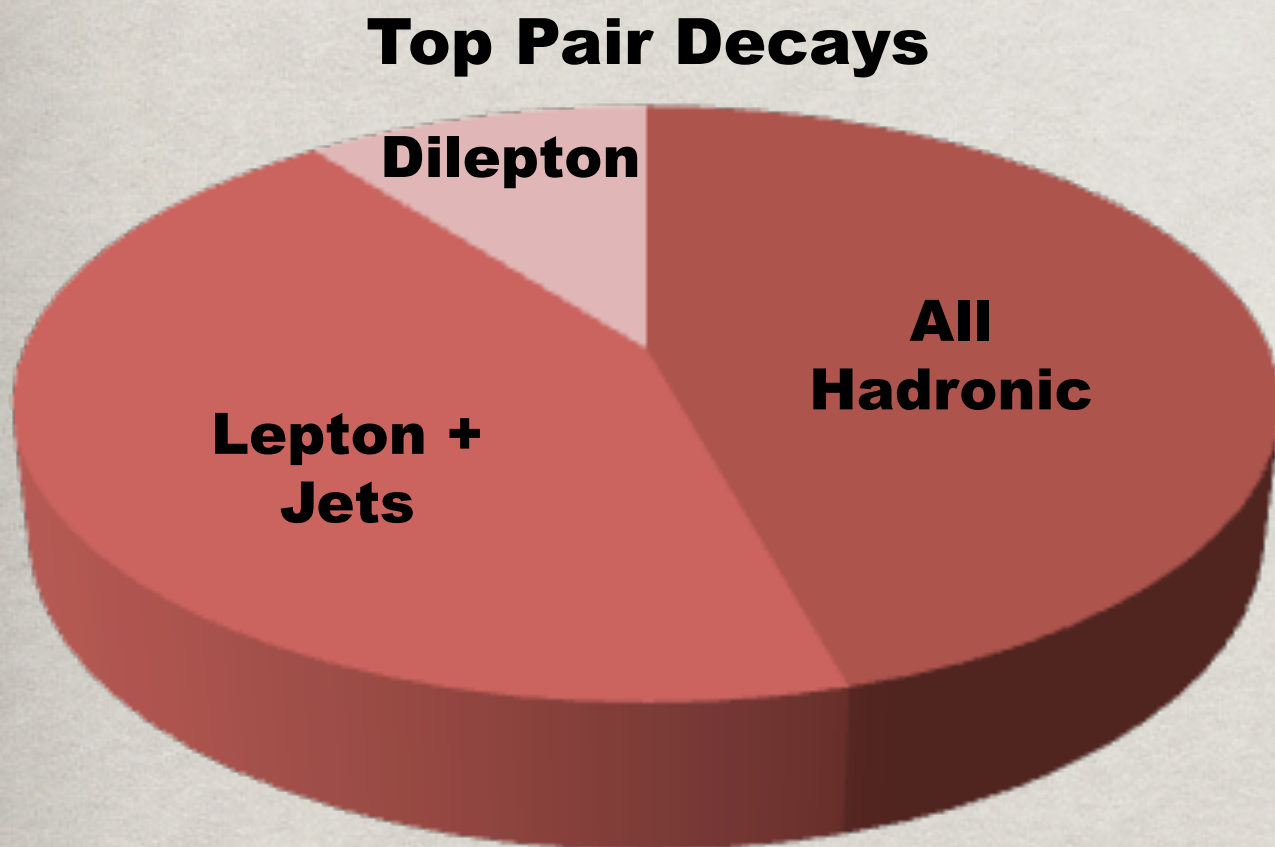


✿ With $M_H = 125-126$ GeV, many different decay modes available

EXP. SIGNATURES

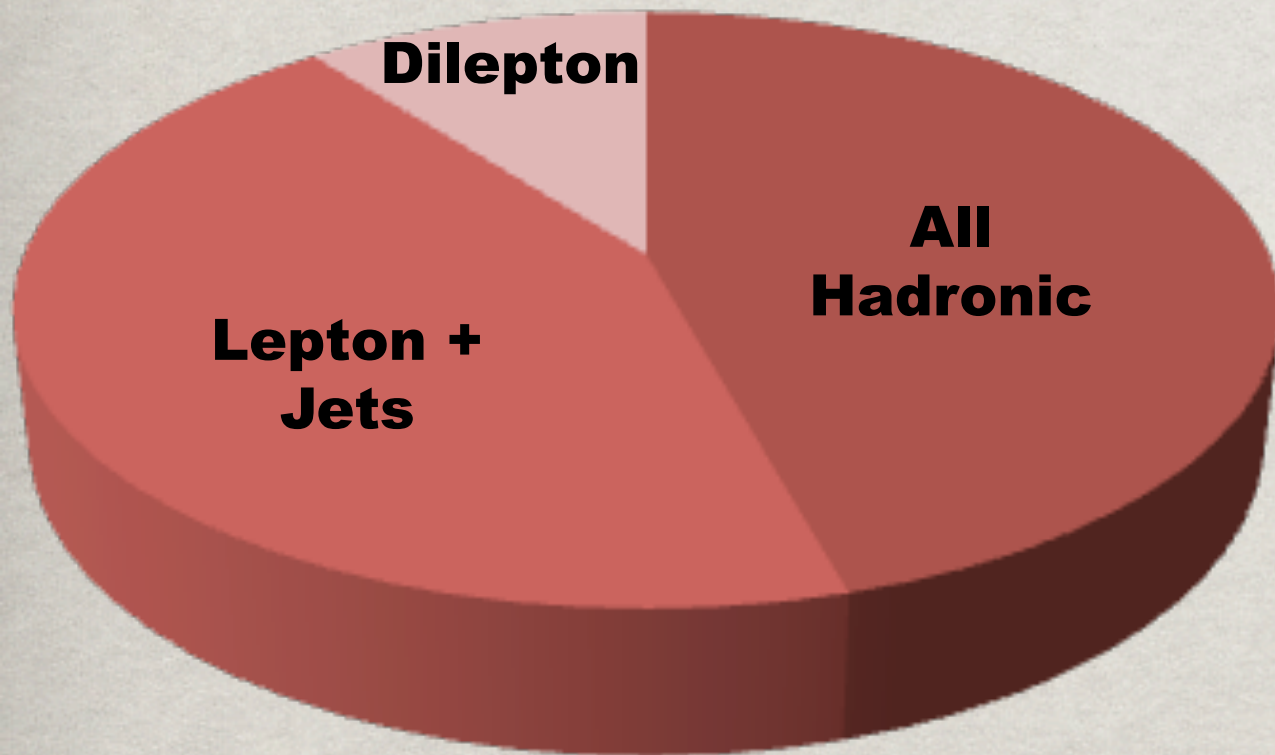


EXP. SIGNATURES



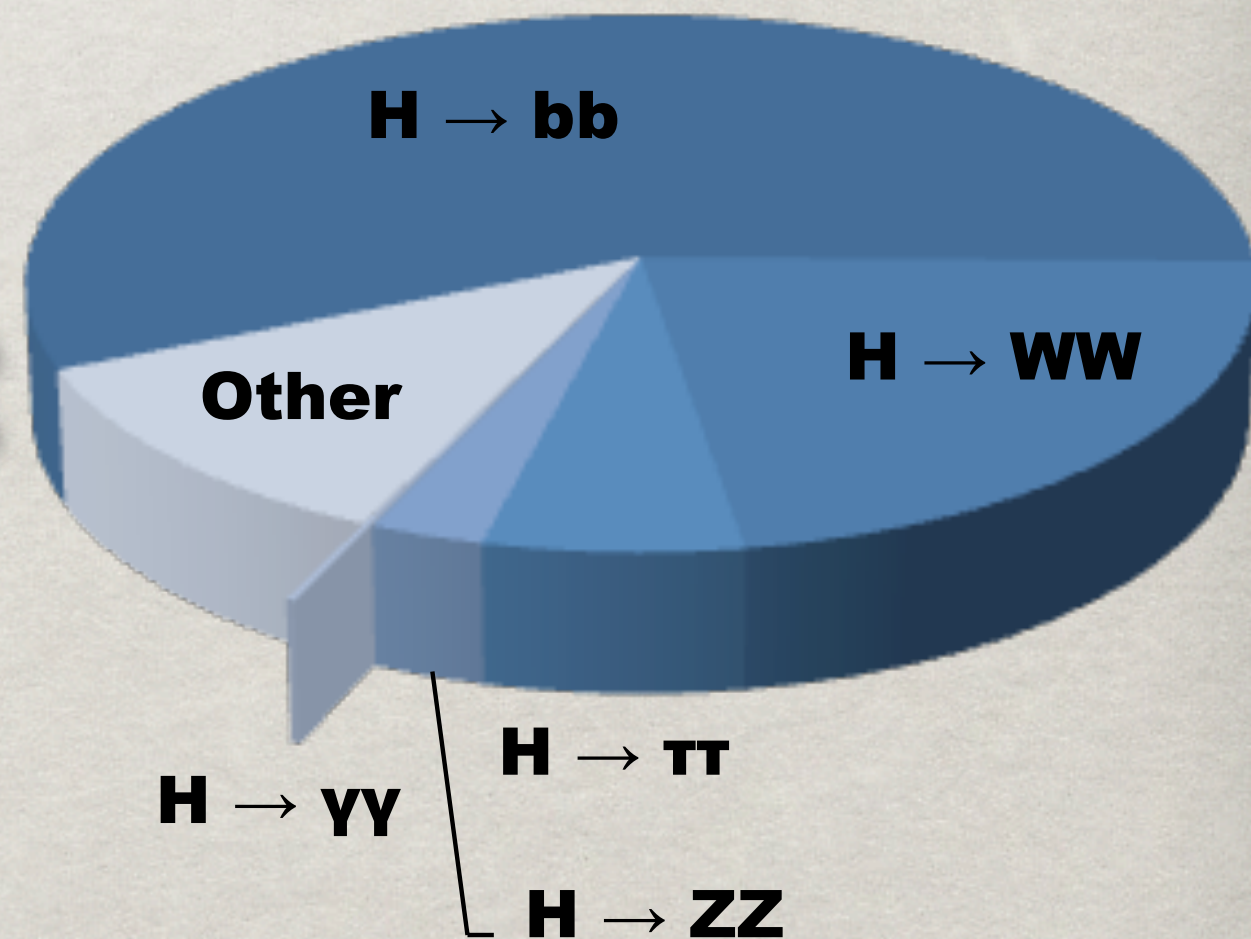
EXP. SIGNATURES

Top Pair Decays



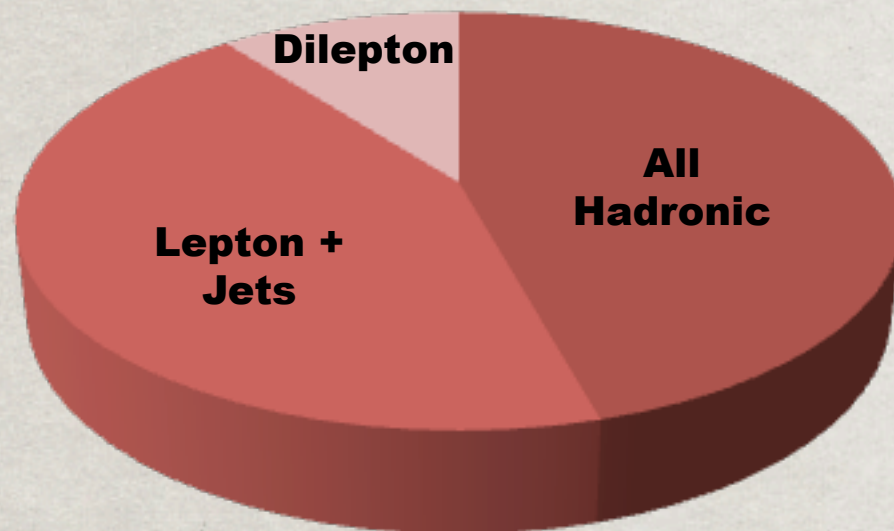
X

Higgs Decays



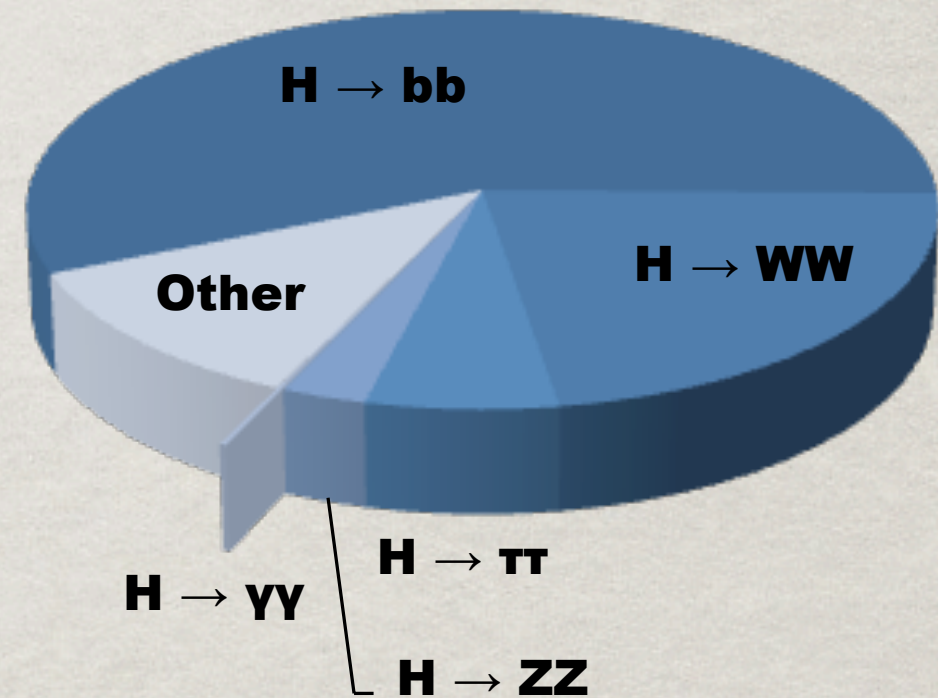
EXP. SIGNATURES

Top Pair Decays



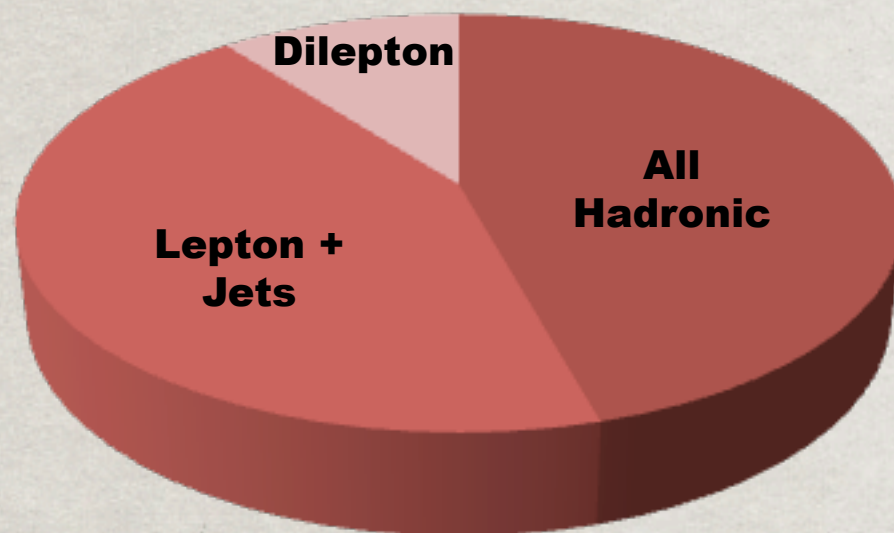
X

Higgs Decays

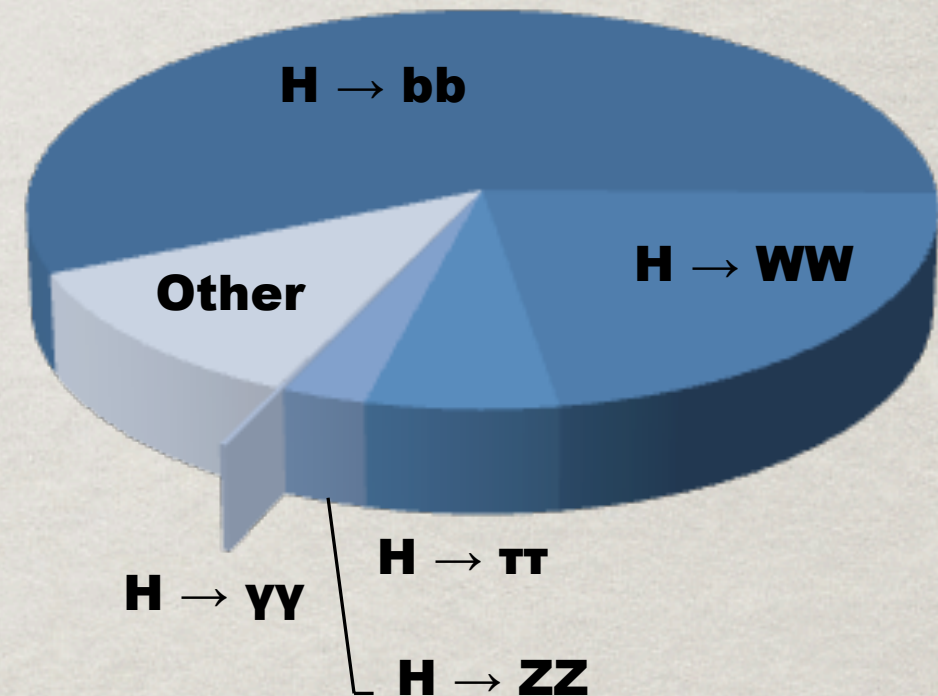


EXP. SIGNATURES

Top Pair Decays



Higgs Decays

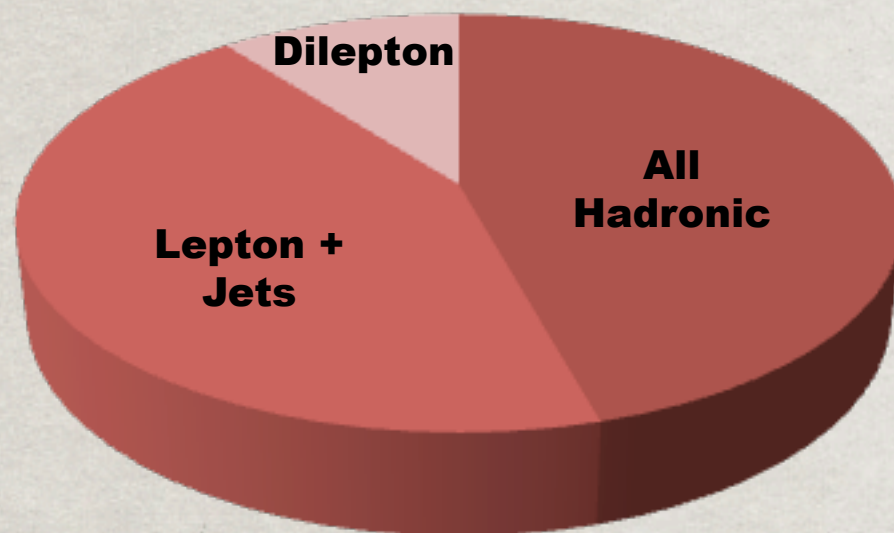


✱ Results in final states with one or more of the following:

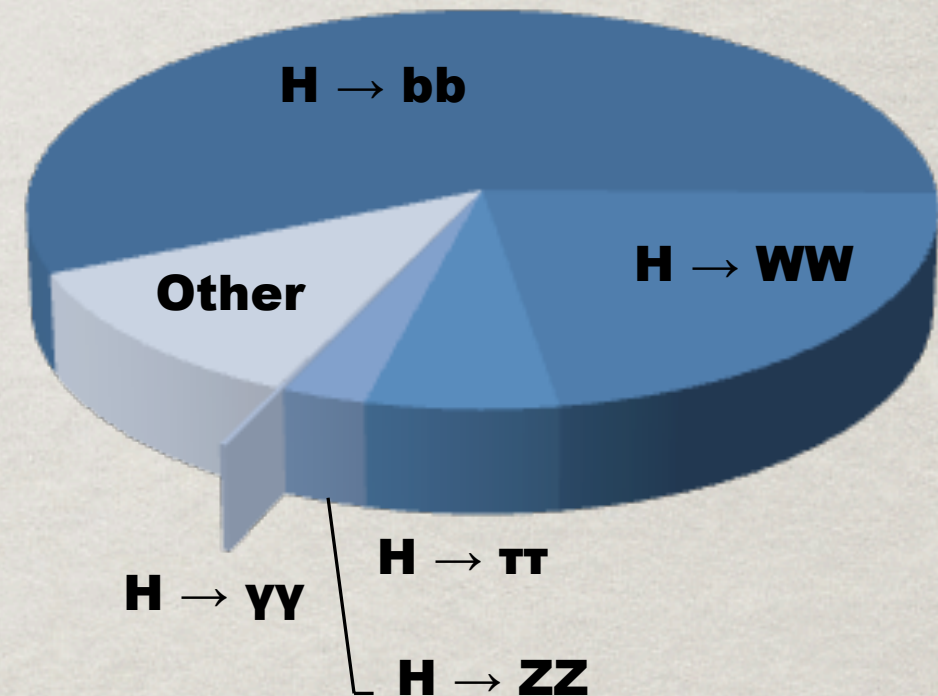
- ✱ Multiple jets (multiple b or τ tags)
- ✱ Multiple leptons (e, μ , τ)
- ✱ Photons
- ✱ Missing transverse energy

EXP. SIGNATURES

Top Pair Decays



Higgs Decays



- ✱ Results in final states with one or more of the following:
 - ✱ Multiple jets (multiple b or τ tags)
 - ✱ Multiple leptons (e, μ , τ)
 - ✱ Photons
 - ✱ Missing transverse energy
- ✱ Spectacular signatures requiring different techniques and tools for backgrounds depending on final state

EXPLORED SO FAR

	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow WW$	$H \rightarrow ZZ$
LJ					
DIL					
HAD					

EXPLORED SO FAR

	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow WW$	$H \rightarrow ZZ$
LJ	   				
DIL					
HAD					

EXPLORED SO FAR

	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow WW$	$H \rightarrow ZZ$
LJ	   				
DIL					
HAD					

EXPLORED SO FAR

	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow WW$	$H \rightarrow ZZ$
LJ	   	 			
DIL		 			
HAD		 			

EXPLORED SO FAR

	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow WW$	$H \rightarrow ZZ$
LJ	   	 	 (Hadronic $\tau\tau$ final state)		
DIL		 			
HAD		 			

EXPLORED SO FAR

	$H \rightarrow b\bar{b}$	$H \rightarrow \gamma\gamma$	$H \rightarrow \tau\tau$	$H \rightarrow WW$	$H \rightarrow ZZ$
LJ	   	 	 (Hadronic $\tau\tau$ final state)  (Leptonic final states)		
DIL		 			
HAD		 			



CMS



LHCb



ATLAS



ALICE

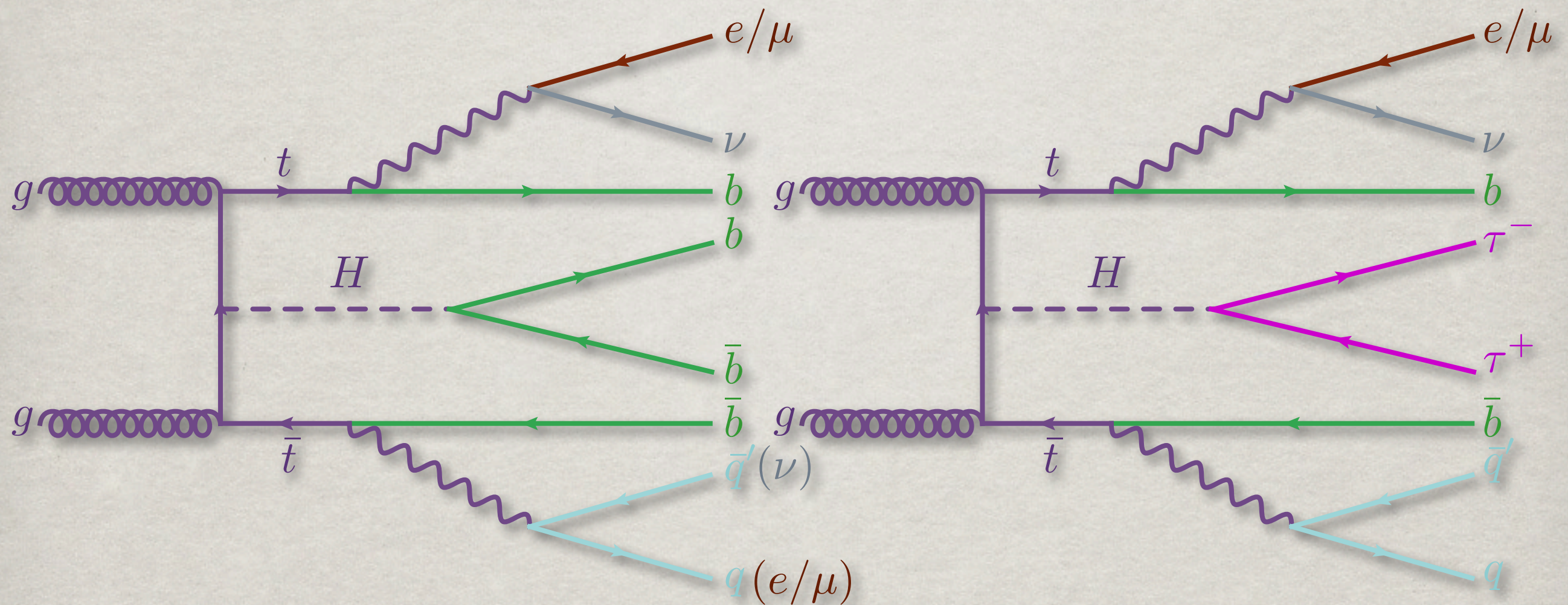


$H \rightarrow BB$

AND

$H \rightarrow \tau\tau$

SIGNATURES



✱ Many different objects:

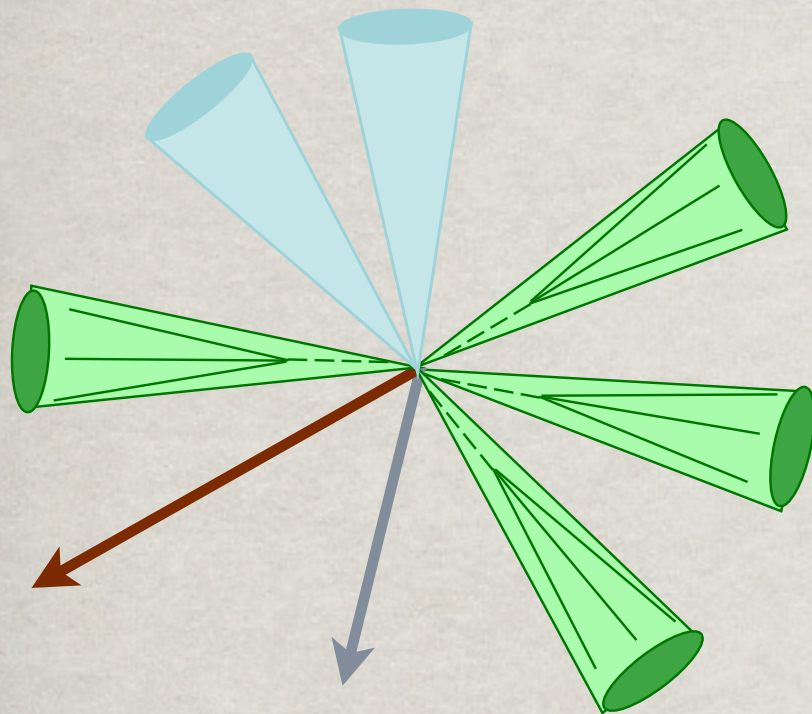
✱ 1-2 charged leptons (e, μ)

✱ 2-4 b jets

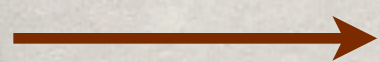
✱ 0 or 2 light flavor jets

✱ 0 or 2 hadronic τ 's

SIGNATURES



Lepton + Jets (LJ)



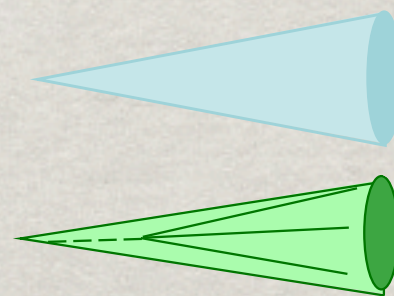
Electron:

Tight: $p_T > 25$ GeV;
 $|\eta| < 2.47$; 90% efficient
 isolation cut



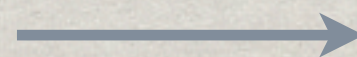
Muon:

Tight: $p_T > 20$ GeV;
 $|\eta| < 2.5$; Isolation: < 4 GeV
 calo, < 2.5 GeV tracks



Jet: $p_T > 30$ GeV; $|\eta| < 2.4$

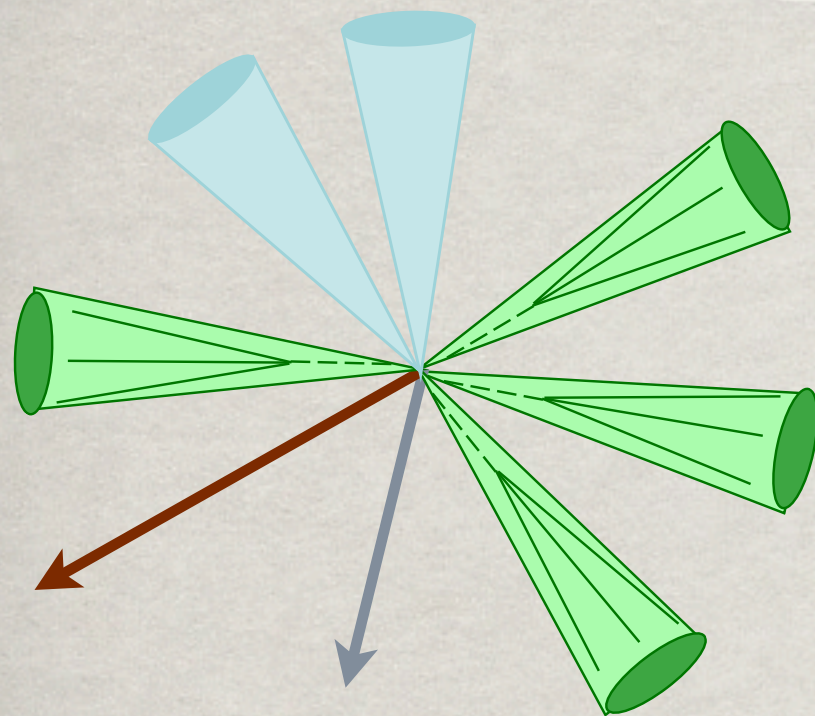
b-Jet: As above tagged
 ($\epsilon_b \approx 70\%$, $\epsilon_{LF} \approx 1\%$)



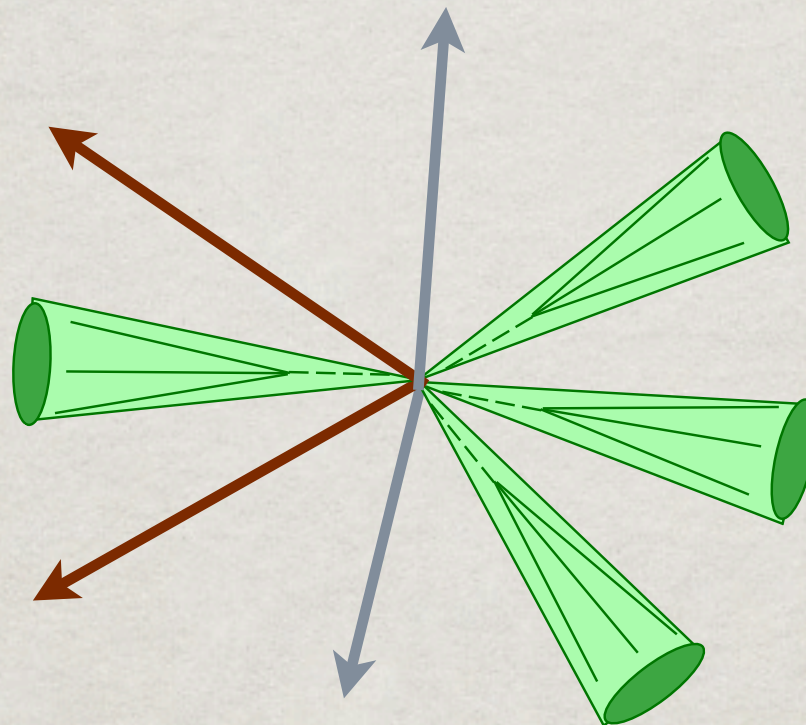
MET:

Electrons: $MET > 30$ GeV,
 $M_T > 30$ GeV
 Muons: $MET > 20$ GeV,
 $MET + M_T > 60$ GeV

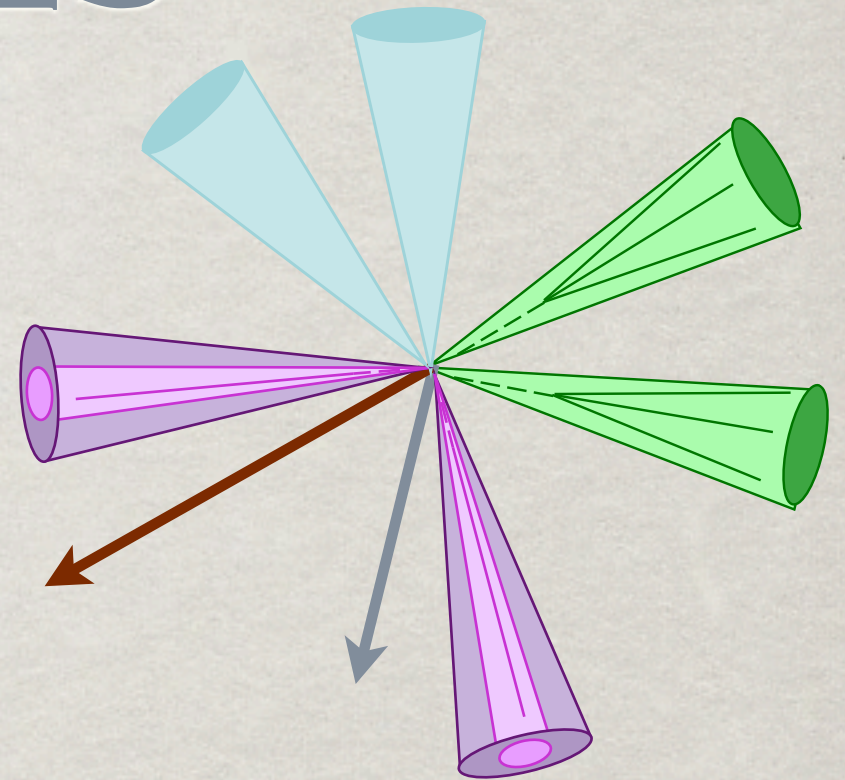
SIGNATURES



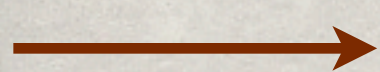
Lepton + Jets (LJ)



Dilepton (DIL)



Hadronic τ (TAU)



Electron:

Tight: $p_T > 30$ (20) GeV;

$|\eta| < 2.5$; Iso < 0.1

Loose: $p_T > 10$ GeV;

$|\eta| < 2.5$; Iso < 0.2

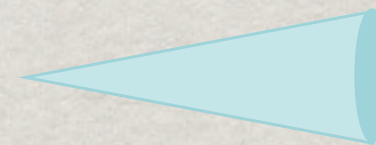
Muon:

Tight: $p_T > 30$ (20) GeV;

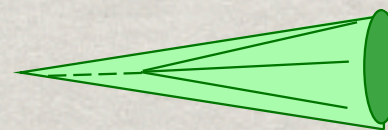
$|\eta| < 2.1$; Iso < 0.12

Loose: $p_T > 10$ GeV;

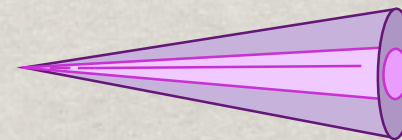
$|\eta| < 2.4$; Iso < 0.2



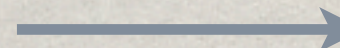
Jet: $p_T > 30$ GeV; $|\eta| < 2.4$



b -Jet: As above tagged by CSV ($\epsilon_b \approx 70\%$, $\epsilon_{LF} \approx 1\%$)



Hadronic τ : $p_T > 20$ GeV;
 $|\eta| < 2.1$; Isolated (MVA)

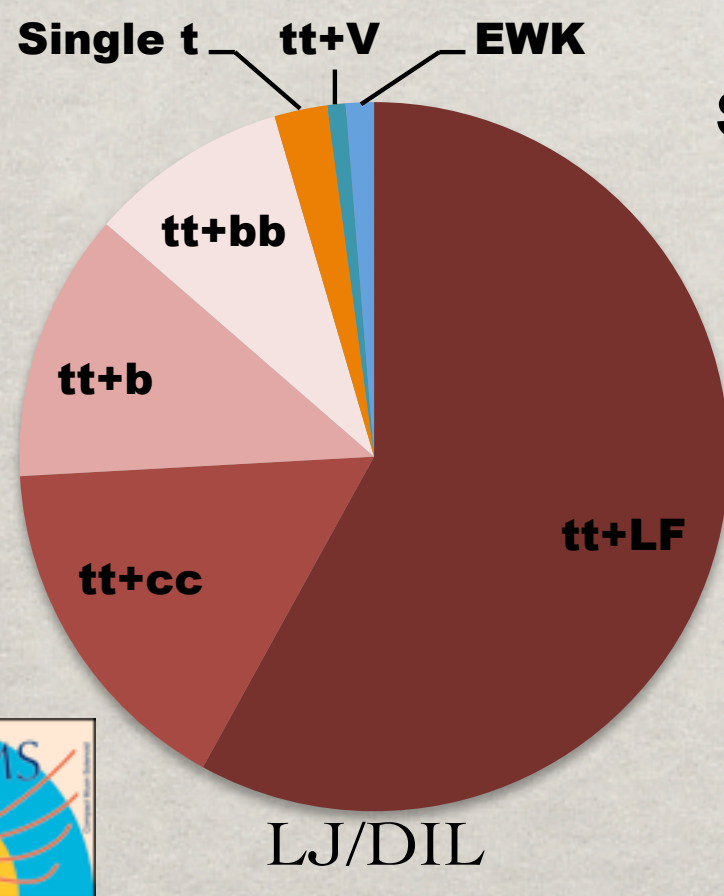


MET: No cut

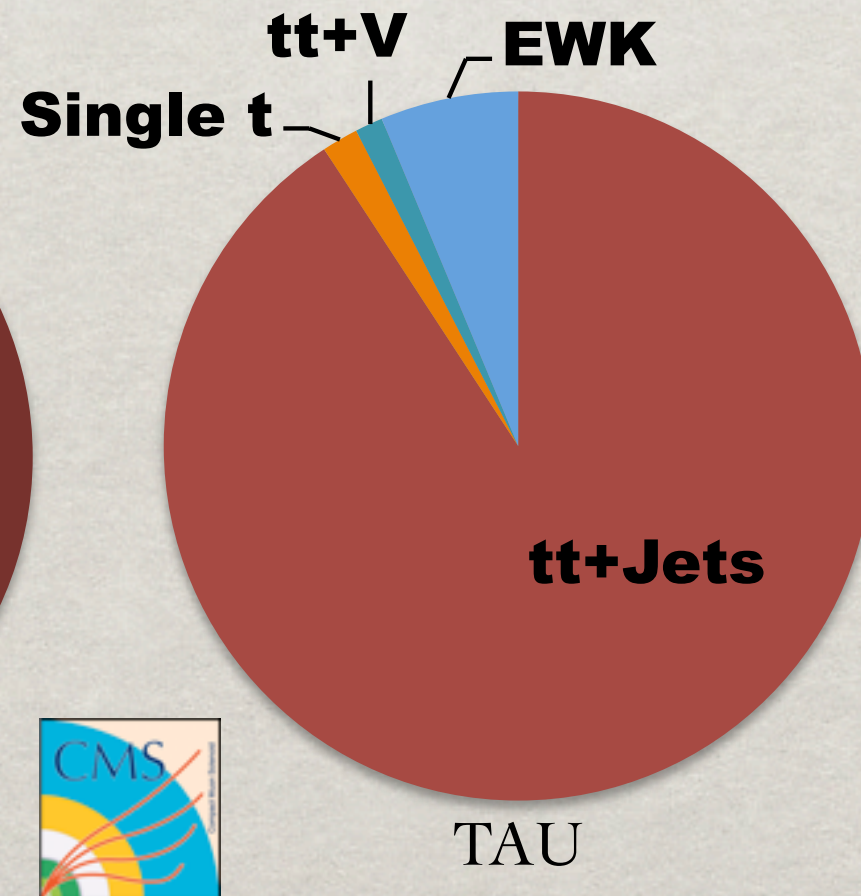


BACKGROUNDS

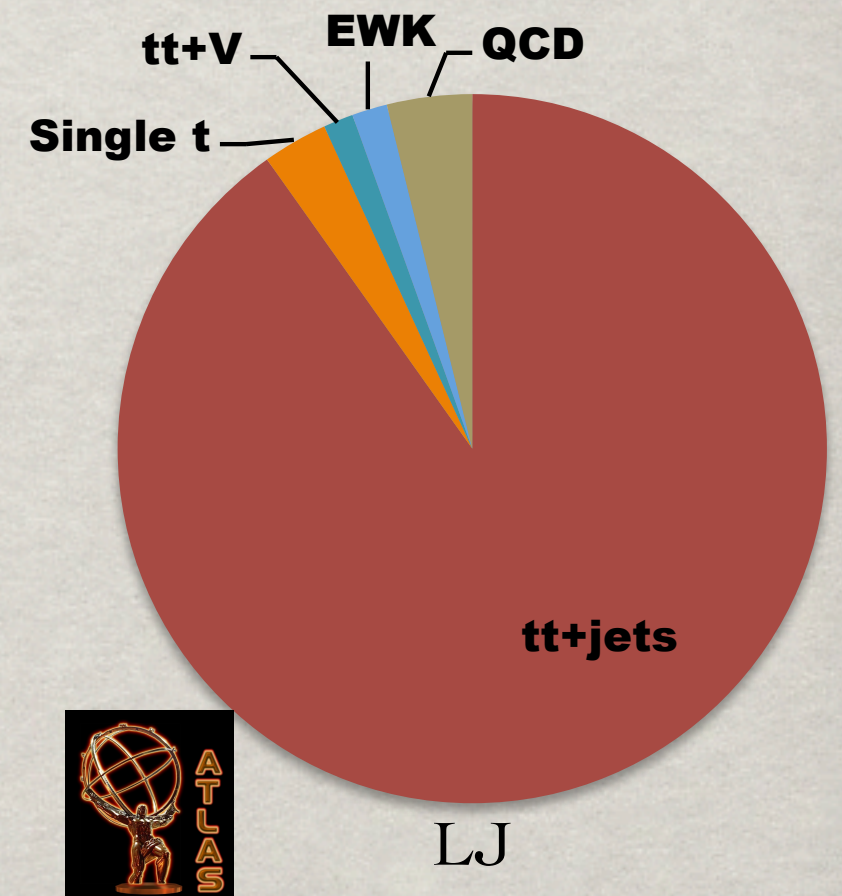
- ✱ Spectacular signal = Challenging backgrounds
 - ✱ Most have real top quarks!
 - ✱ Normalize to (N)NLO inclusive cross section prediction
 - ✱ Model (N_{jets} , kinematics) using ME+PS MC or NLO+PS



LJ/DIL

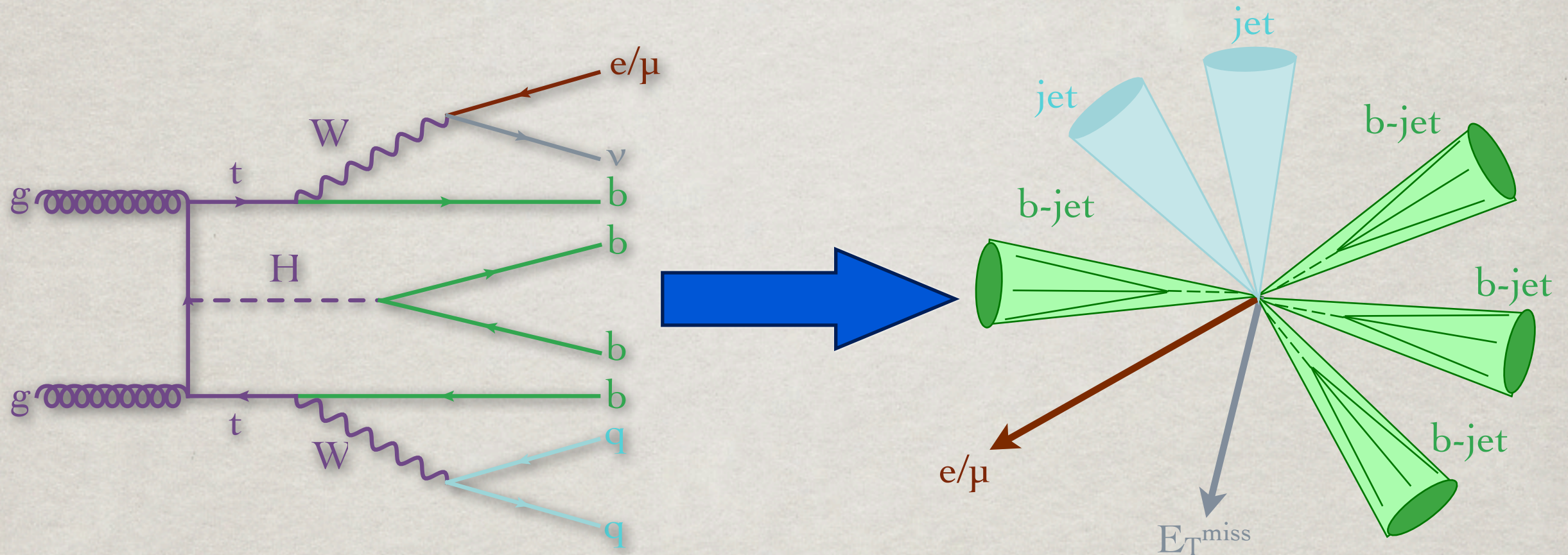


TAU



LJ

EVENT CATEGORIZATION

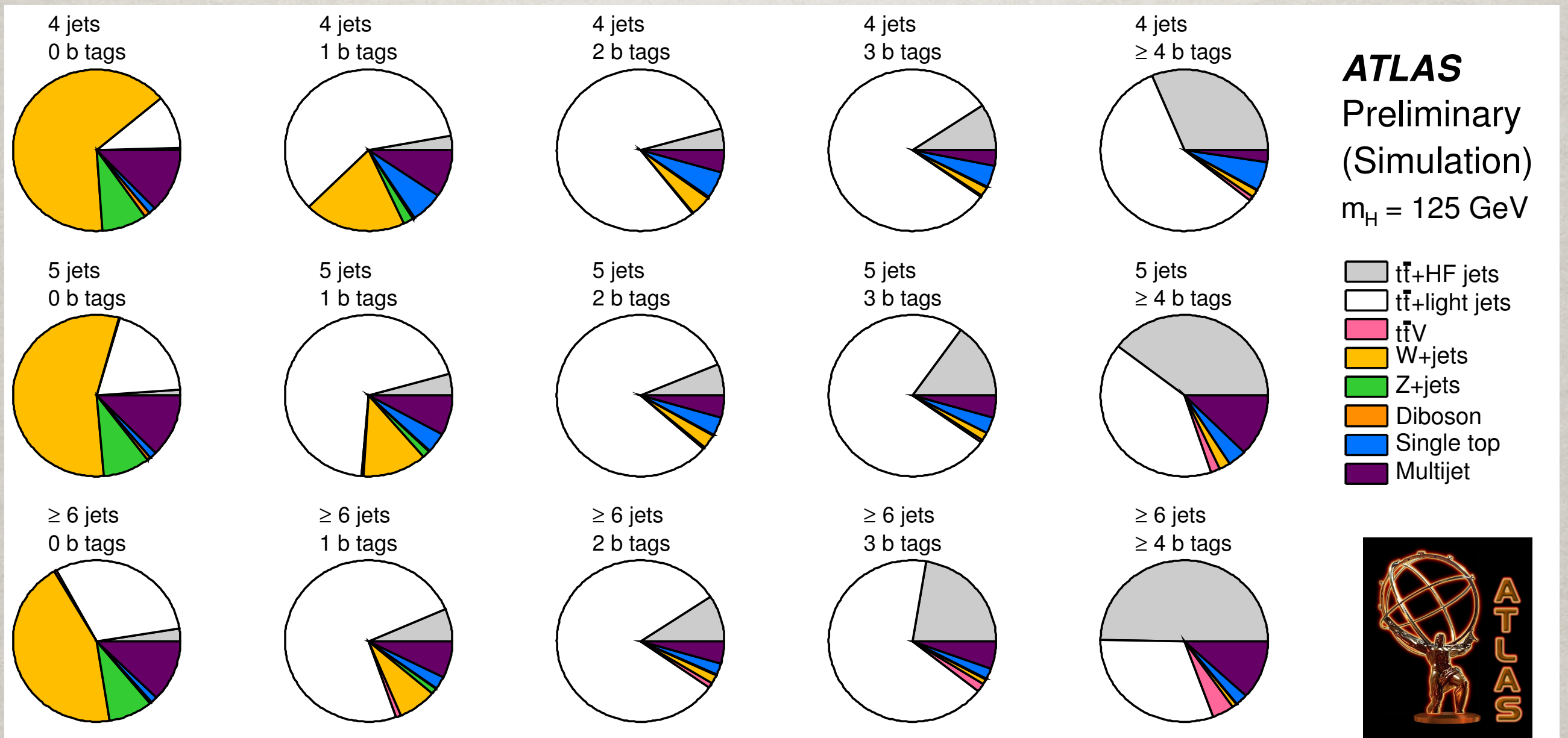


Signals and backgrounds contribute at different levels in different categories

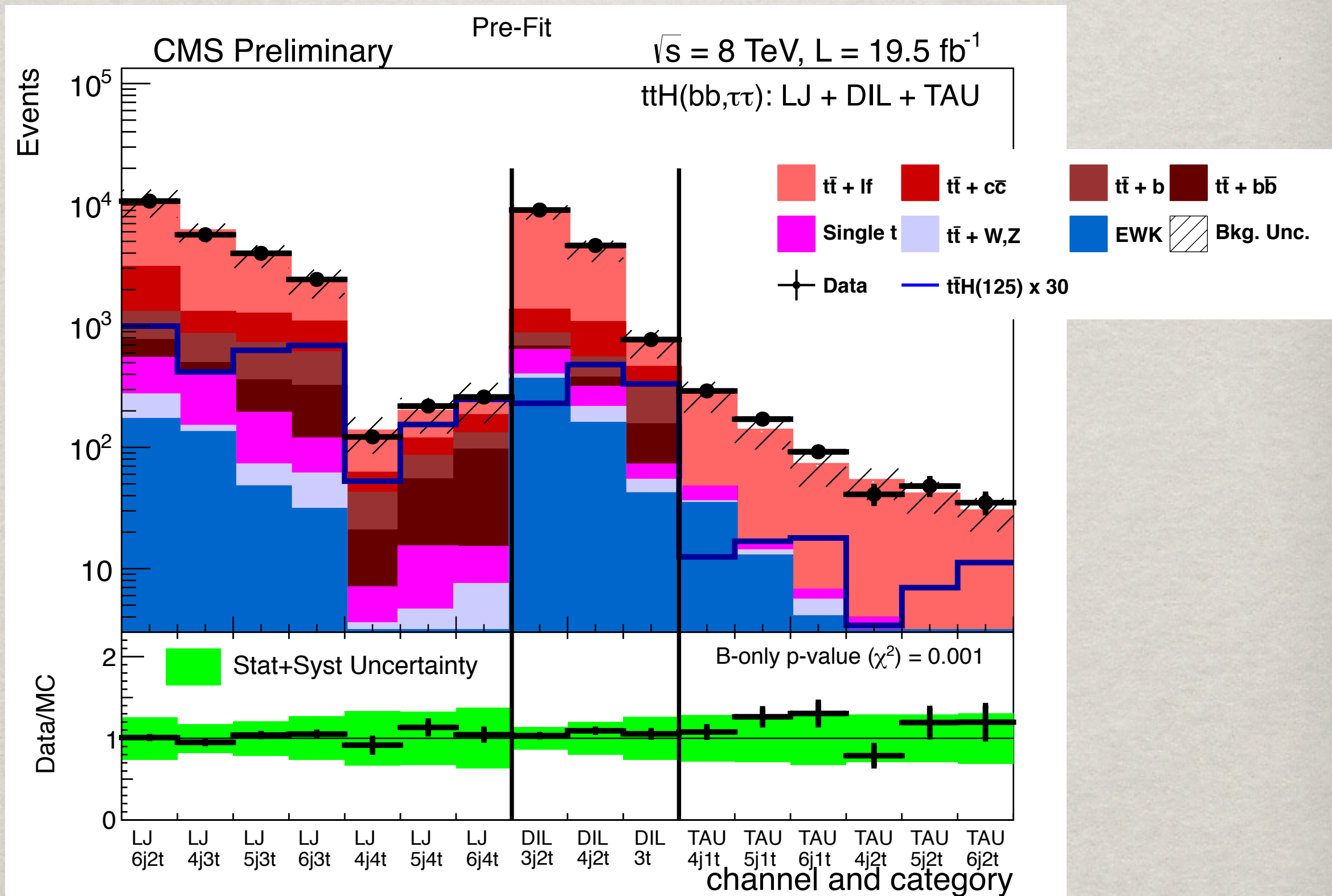
CMS has dilepton and hadronic ditau channels also

	0 Tag	1 Tag	2 Tag	3 Tag	≥ 4 Tag
4 Jet				 	 
5 Jet				 	 
≥ 6 Jet			 	 	 

ATLAS BKG COMPOSITION

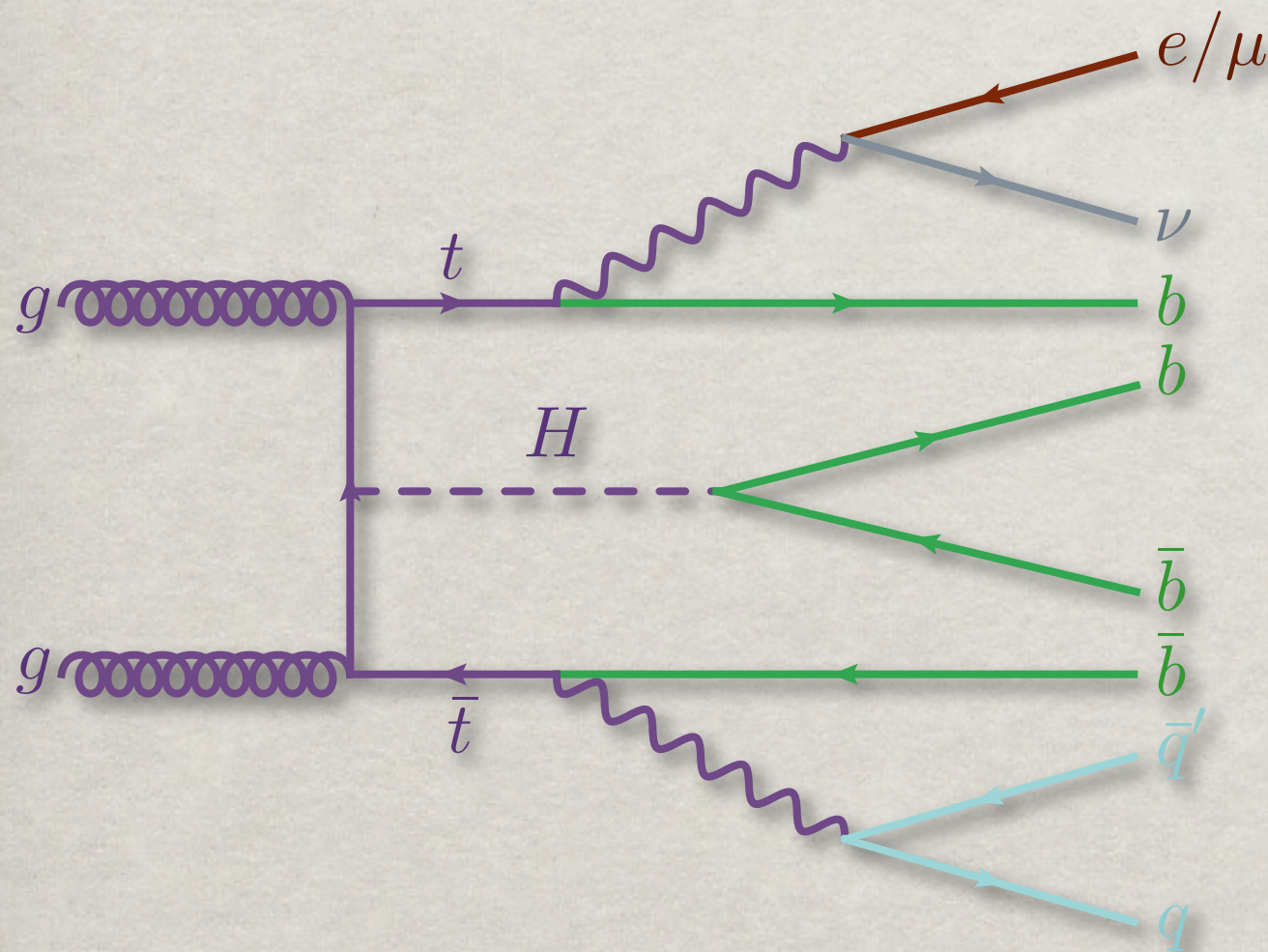


CMS BKG COMPOSITION



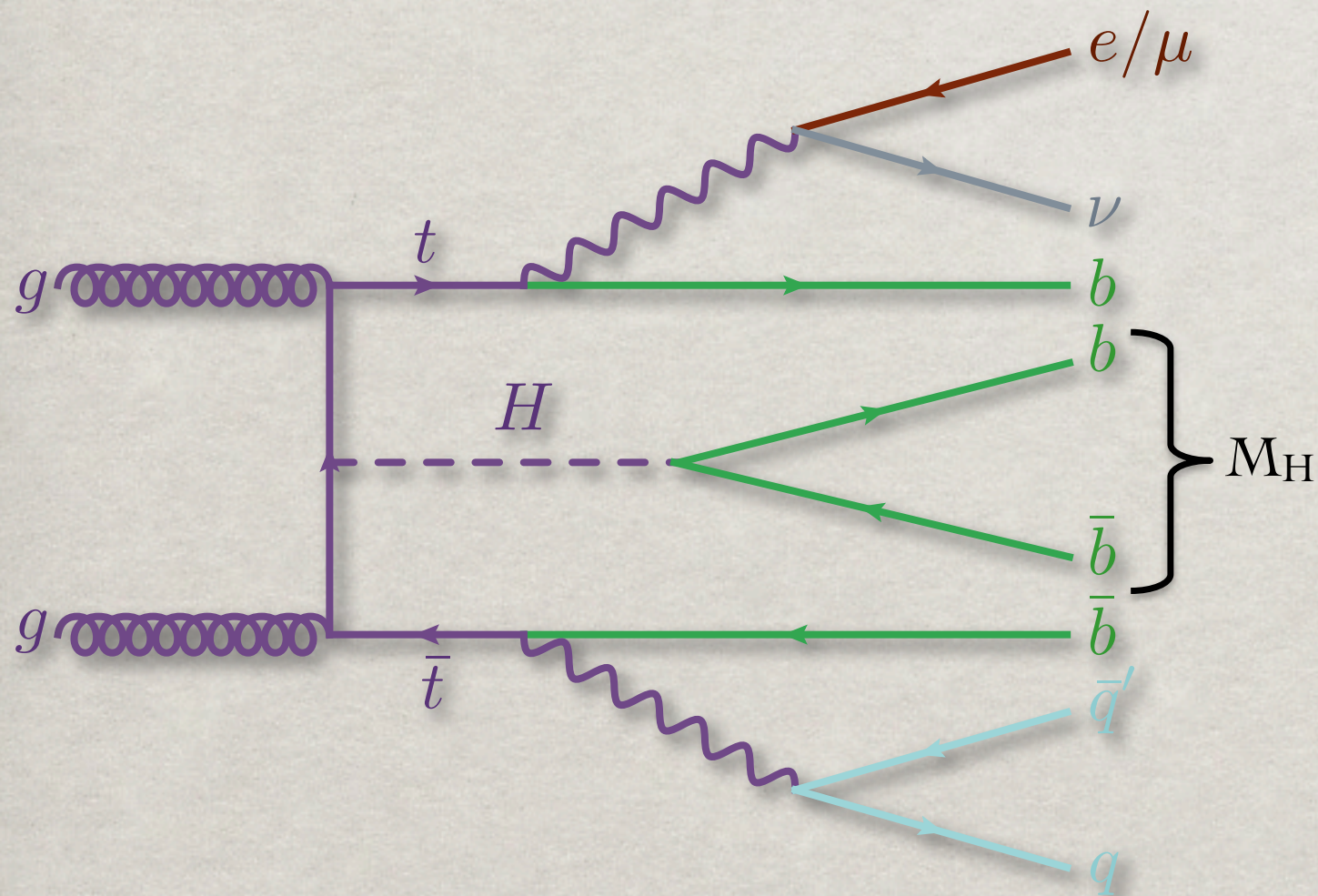
SEPARATING S FROM B

- ✱ Traditional approach: Look for bump in “ M_H ” distribution



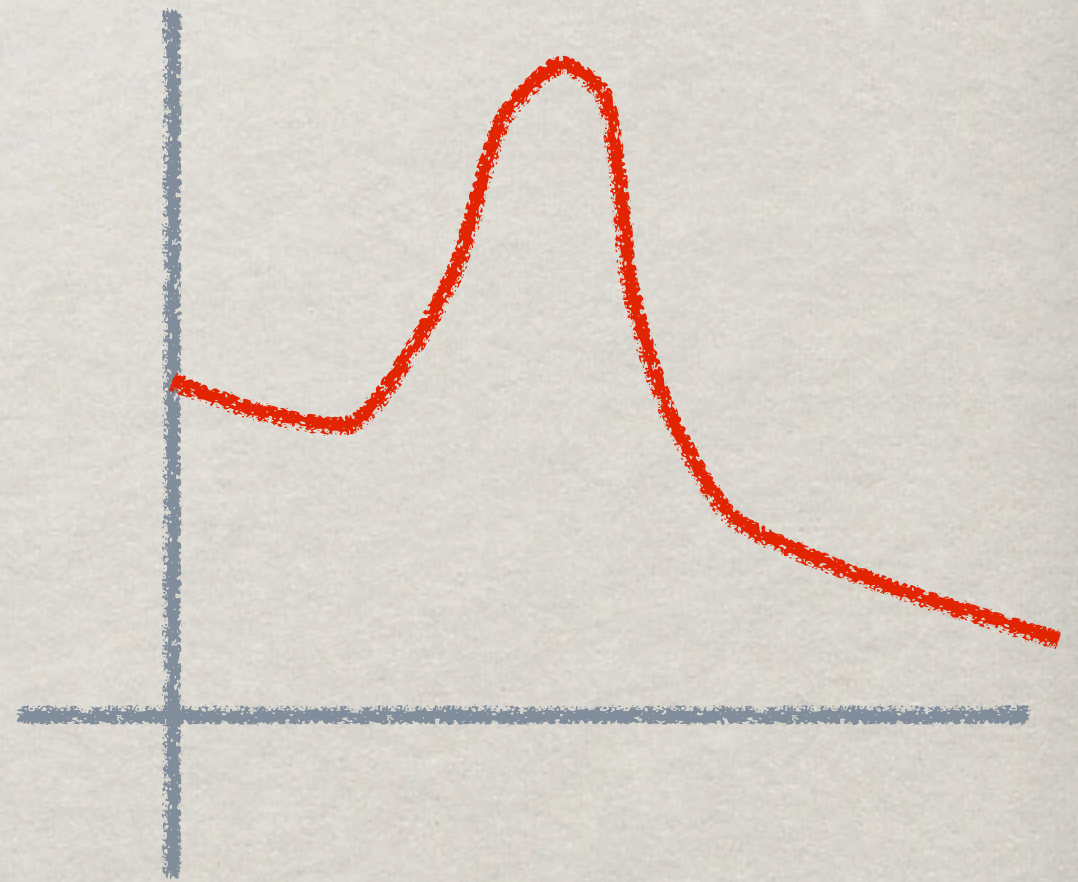
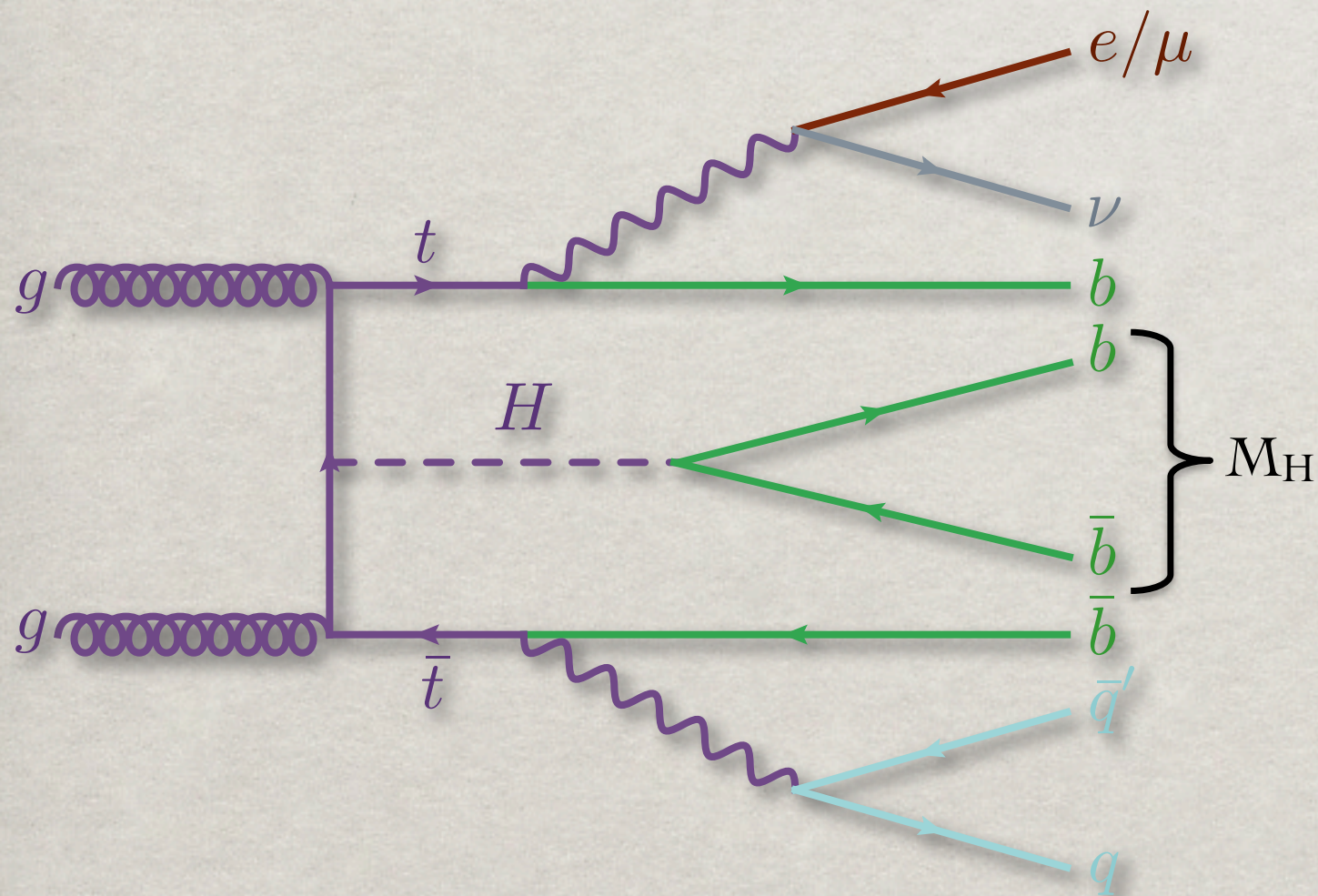
SEPARATING S FROM B

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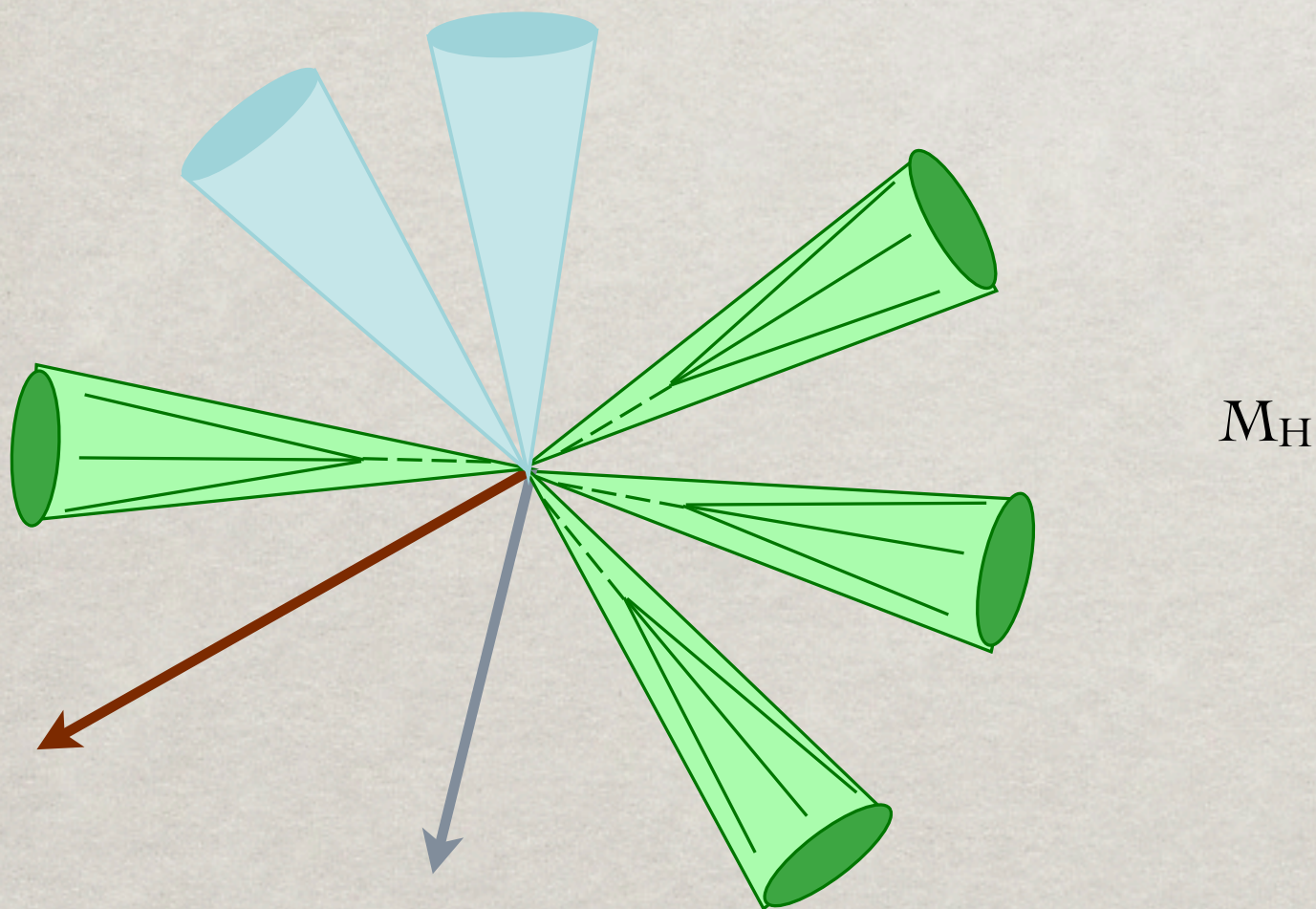
SEPARATING S FROM B

- ✱ Traditional approach: Look for bump in “ M_H ” distribution



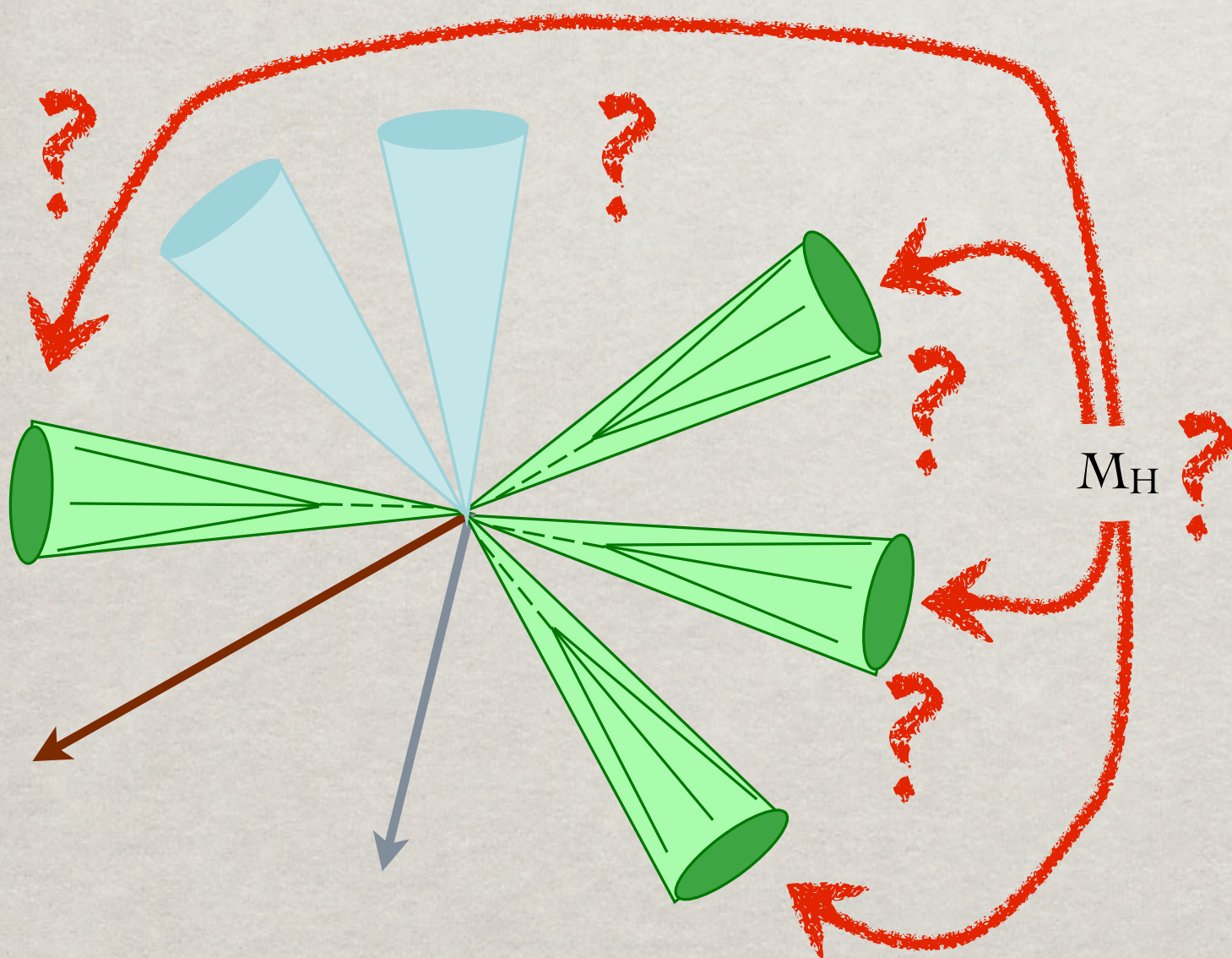
SEPARATING S FROM B

- ✱ Traditional approach: Look for bump in “ M_H ” distribution



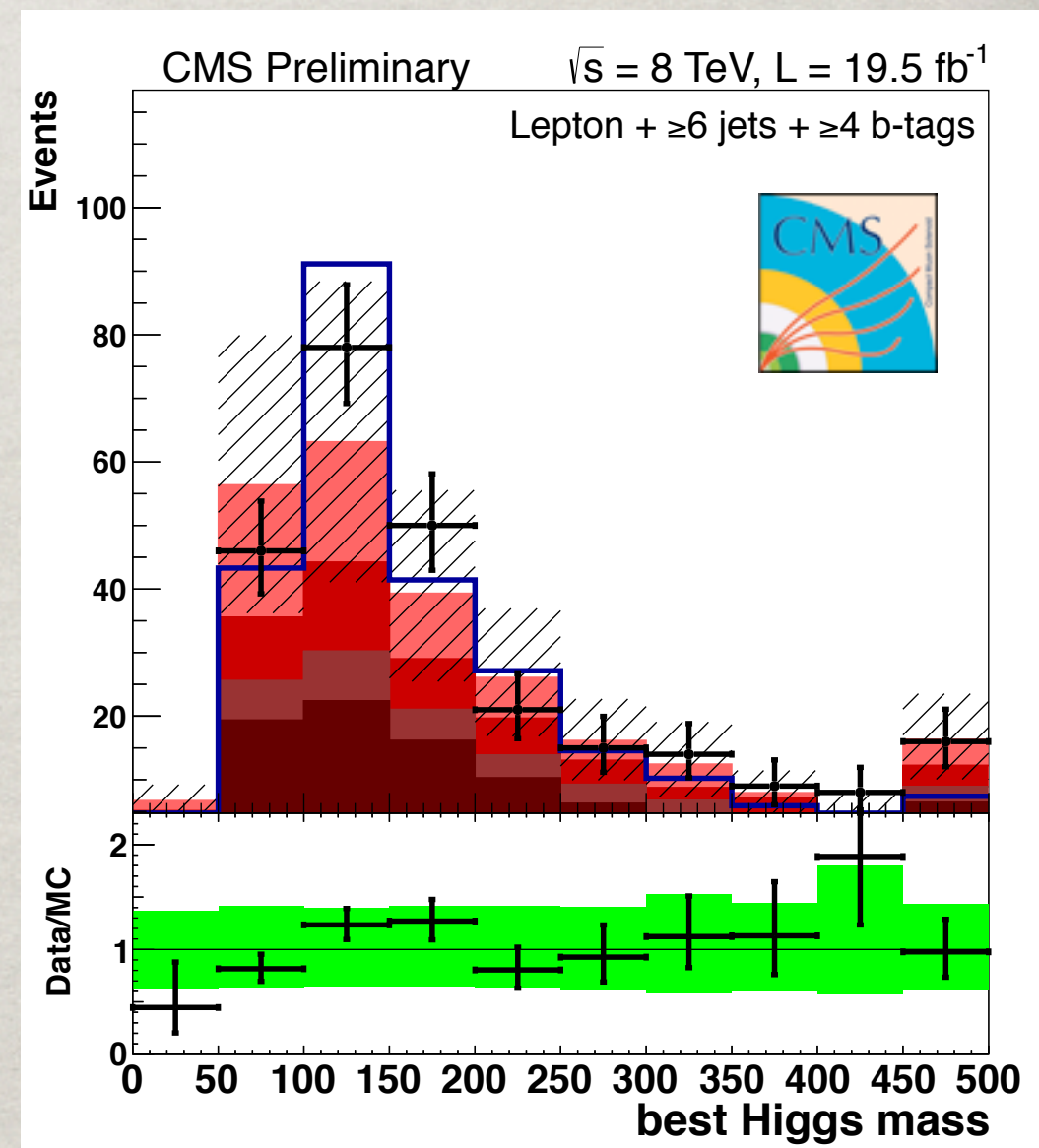
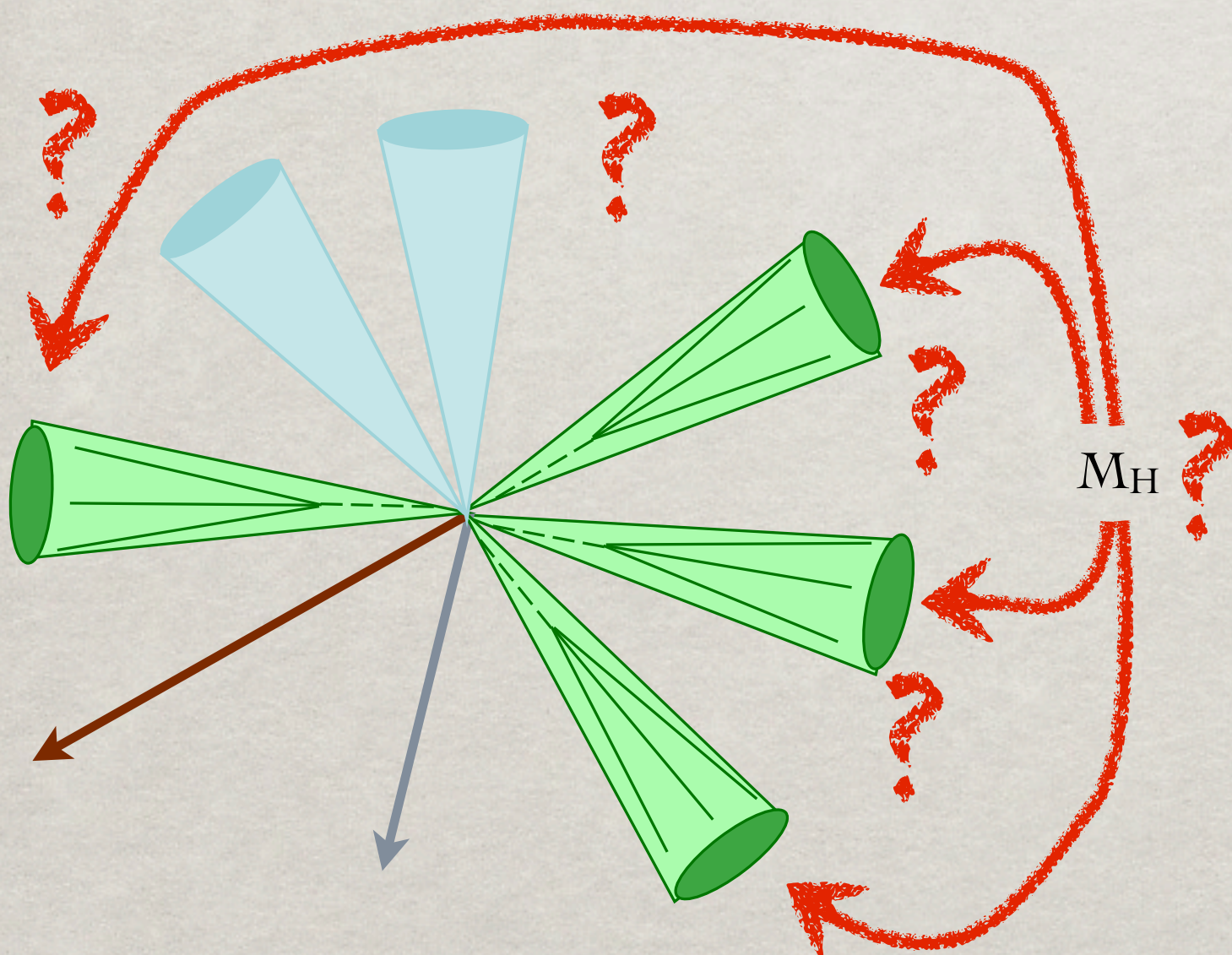
SEPARATING S FROM B

- ✱ Traditional approach: Look for bump in “ M_H ” distribution



SEPARATING S FROM B

- Traditional approach: Look for bump in “ M_H ” distribution



SIGNAL DISCRIMINATION

☼ ATLAS:



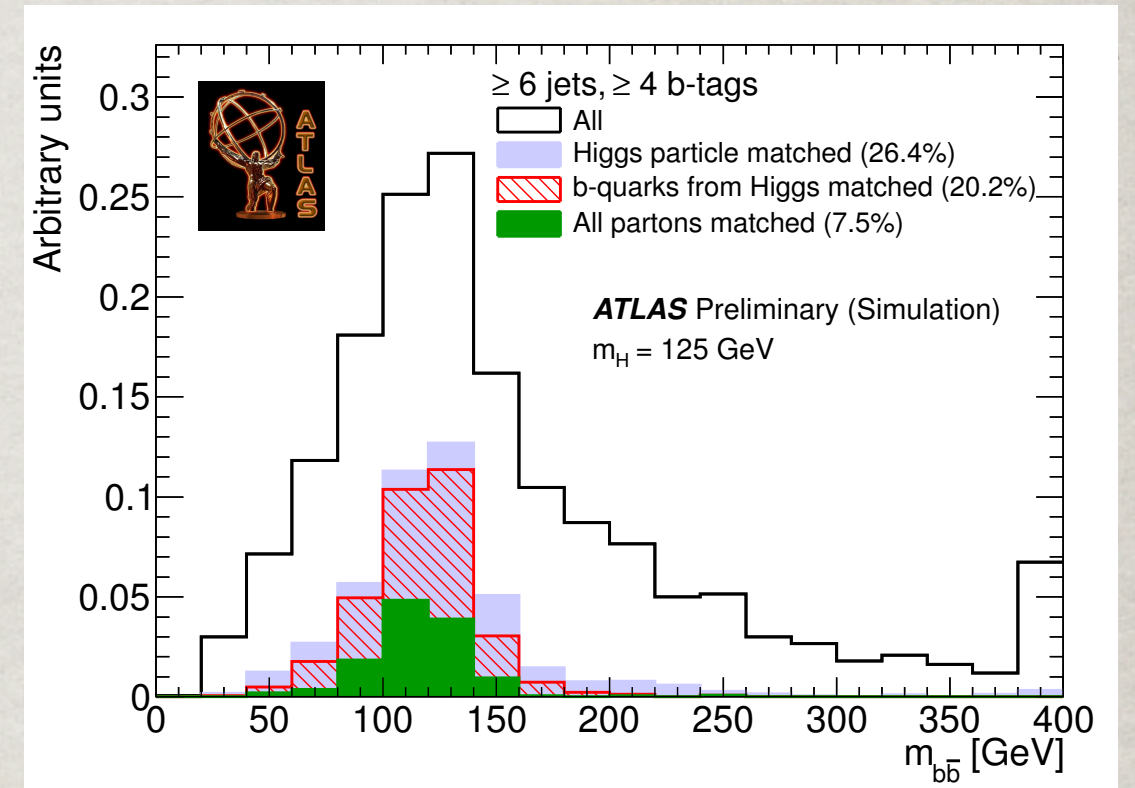
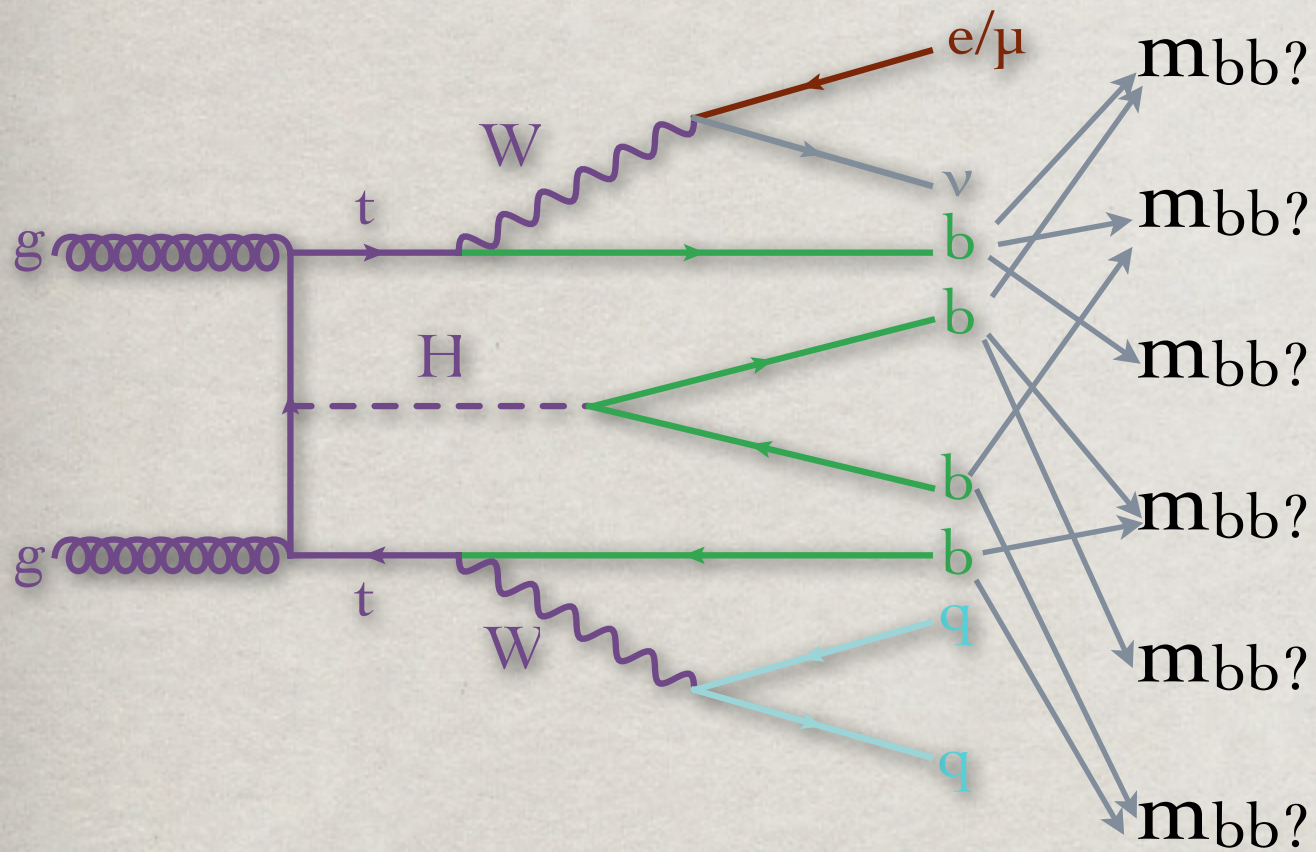
- ☼ For bkg rich categories: Use global event variable H_T
- ☼ For ≥ 6 jet, 3 tag and ≥ 6 jet, 4 tag, use reconstructed invariant mass (likelihood technique)

☼ CMS:



- ☼ Use MVA: BDT using kinematic, angular, and b-tagging variables
- ☼ Separate dedicated MVA to discriminate against $t\bar{t} + b\bar{b}$

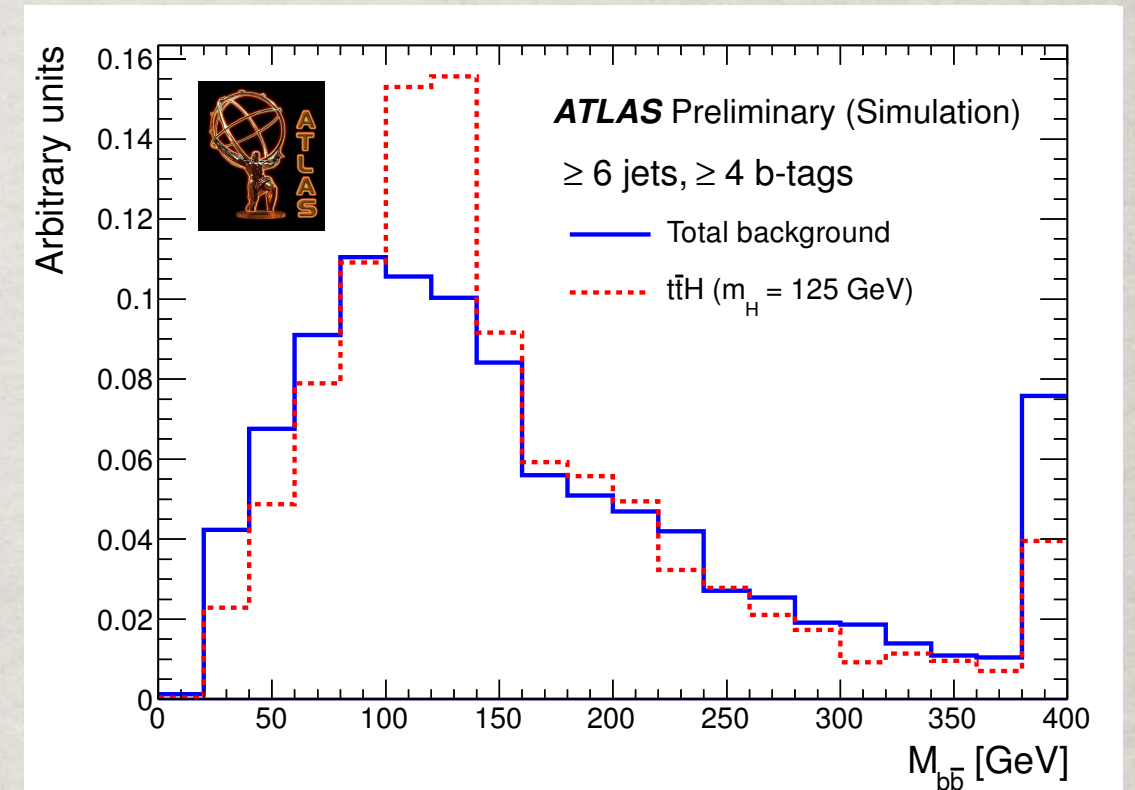
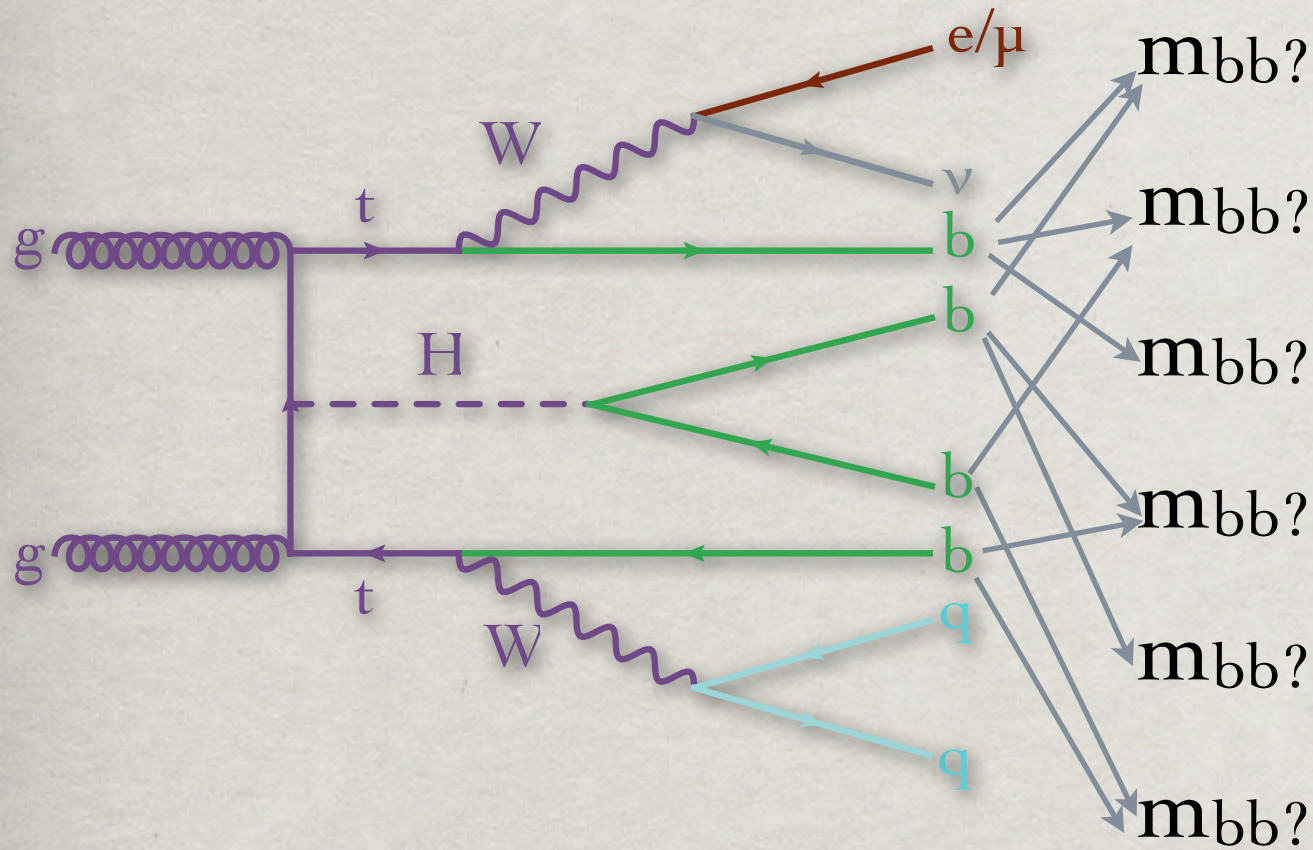
MASS RECONSTRUCTION



$$\begin{aligned}
 \mathcal{L} = & T_J(\tilde{E}_{\text{jet}_1} | E_{b_{\text{had}}}) \times T_J(\tilde{E}_{\text{jet}_2} | E_{b_{\text{lep}}}) \times T_J(\tilde{E}_{\text{jet}_3} | E_{q_1}) \times T_J(\tilde{E}_{\text{jet}_4} | E_{q_2}) \times T_J(\tilde{E}_{\text{jet}_5} | E_b) \times T_J(\tilde{E}_{\text{jet}_6} | E_{\bar{b}}) \\
 & \times T_{\text{miss}}(\tilde{E}_x^{\text{miss}} | p_x^\nu) \times T_{\text{miss}}(\tilde{E}_y^{\text{miss}} | p_y^\nu) \times \left\{ \begin{array}{l} T_e(\tilde{E}_e | E_e) \\ T_\mu(\tilde{p}_{T,\mu} | p_{T,\mu}) \end{array} \right\} \\
 & \times BW\{m_{q_1 q_2} | m_W, \Gamma_W\} \times BW\{m_{l\nu} | m_W, \Gamma_W\} \\
 & \times BW\{m_{q_1 q_2 b_{\text{had}}} | m_{\text{top}}, \Gamma_{\text{top}}\} \times BW\{m_{l\nu b_{\text{lep}}} | m_{\text{top}}, \Gamma_{\text{top}}\}
 \end{aligned} \tag{3}$$

KLFilter

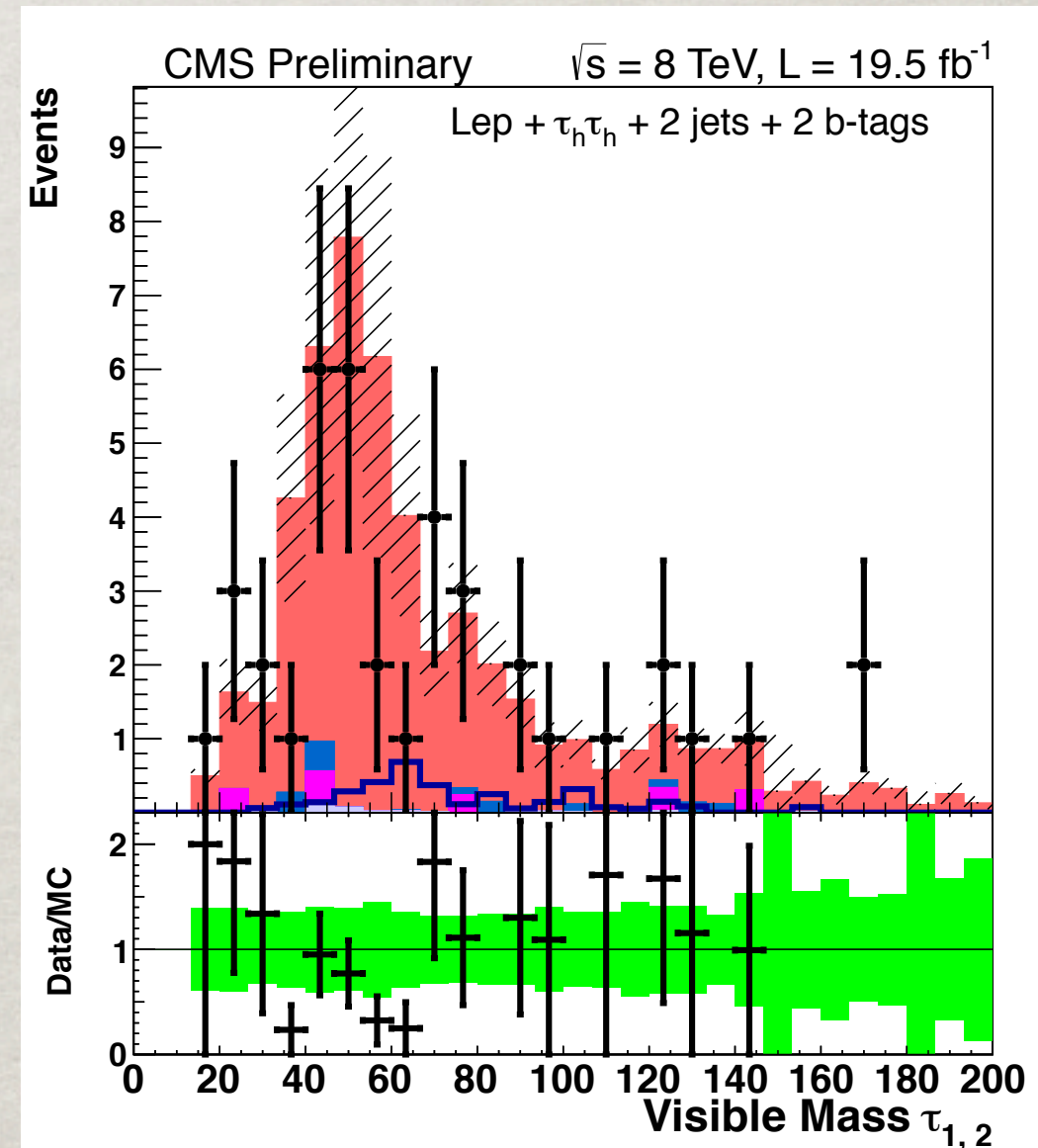
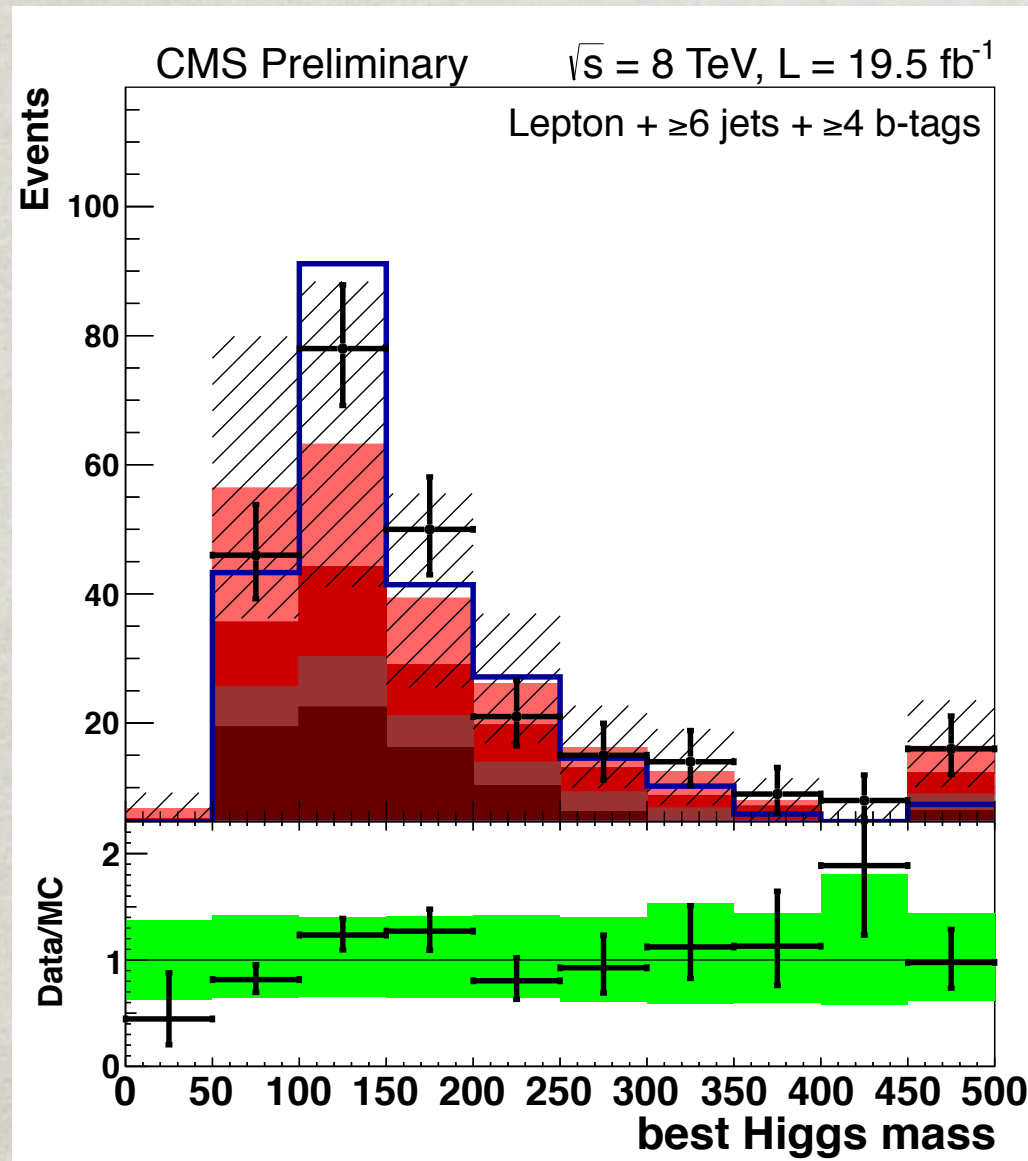
MASS RECONSTRUCTION



$$\begin{aligned}
 \mathcal{L} = & T_J(\tilde{E}_{\text{jet}_1} | E_{b_{\text{had}}}) \times T_J(\tilde{E}_{\text{jet}_2} | E_{b_{\text{lep}}}) \times T_J(\tilde{E}_{\text{jet}_3} | E_{q_1}) \times T_J(\tilde{E}_{\text{jet}_4} | E_{q_2}) \times T_J(\tilde{E}_{\text{jet}_5} | E_b) \times T_J(\tilde{E}_{\text{jet}_6} | E_{\bar{b}}) \\
 & \times T_{\text{miss}}(\tilde{E}_x^{\text{miss}} | p_x^\nu) \times T_{\text{miss}}(\tilde{E}_y^{\text{miss}} | p_y^\nu) \times \left\{ \begin{array}{l} T_e(\tilde{E}_e | E_e) \\ T_\mu(\tilde{p}_{T,\mu} | p_{T,\mu}) \end{array} \right\} \\
 & \times BW\{m_{q_1 q_2} | m_W, \Gamma_W\} \times BW\{m_{l\nu} | m_W, \Gamma_W\} \\
 & \times BW\{m_{q_1 q_2 b_{\text{had}}} | m_{\text{top}}, \Gamma_{\text{top}}\} \times BW\{m_{l\nu b_{\text{lep}}} | m_{\text{top}}, \Gamma_{\text{top}}\}
 \end{aligned} \tag{3}$$

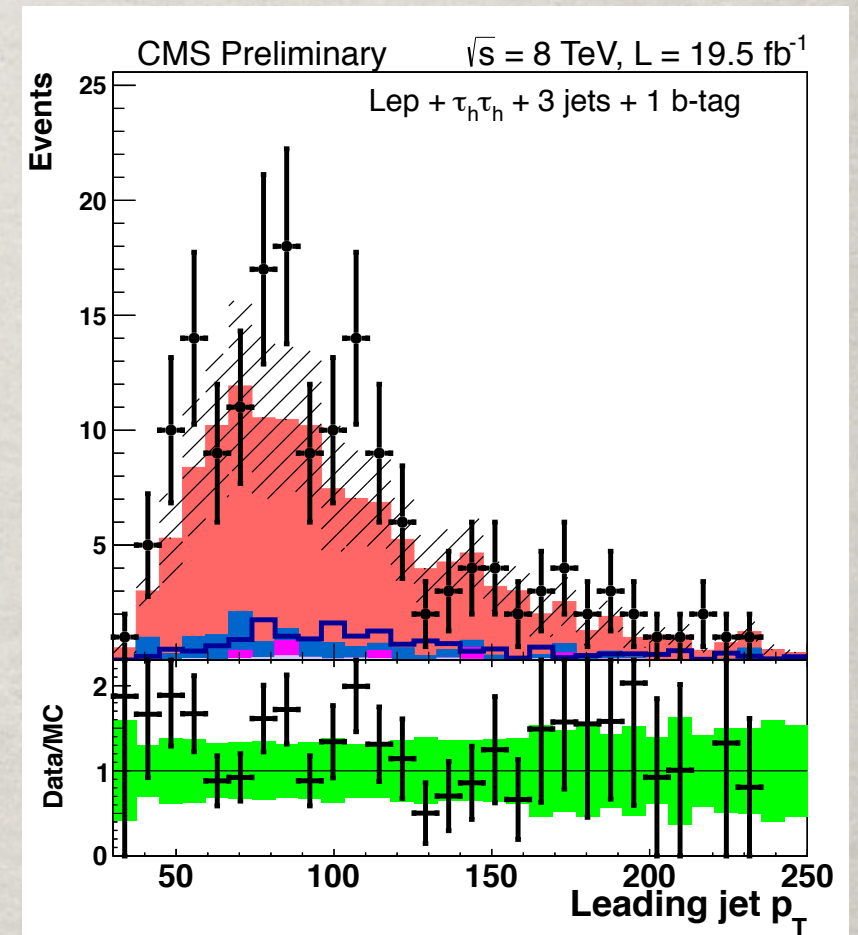
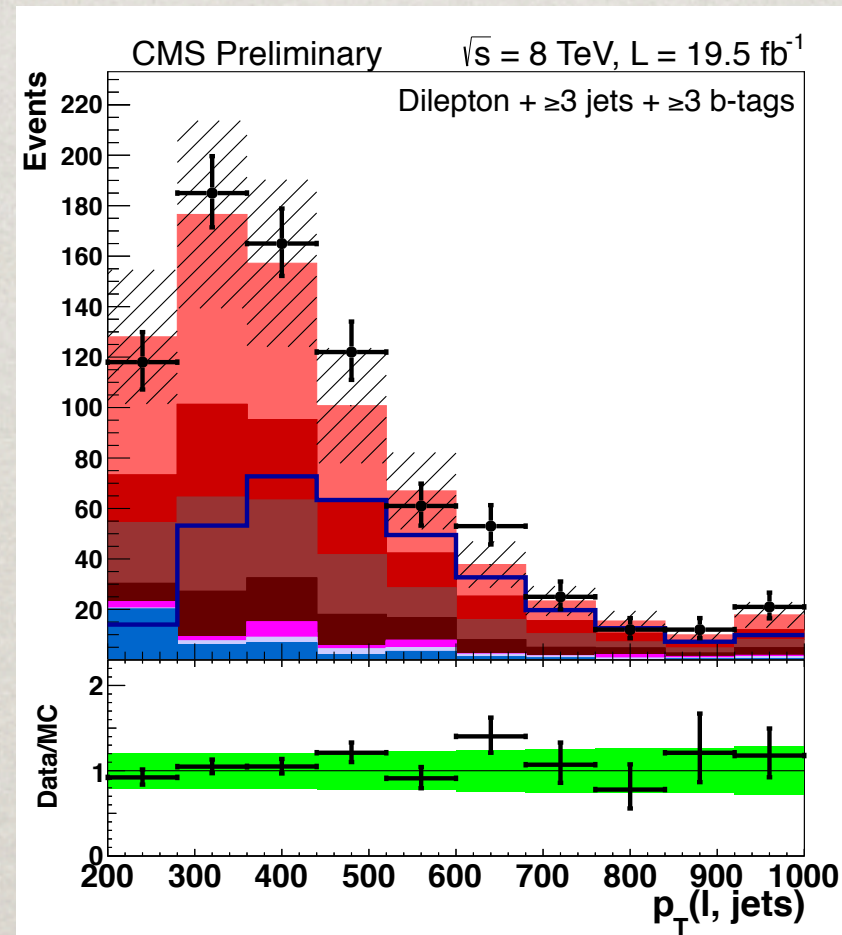
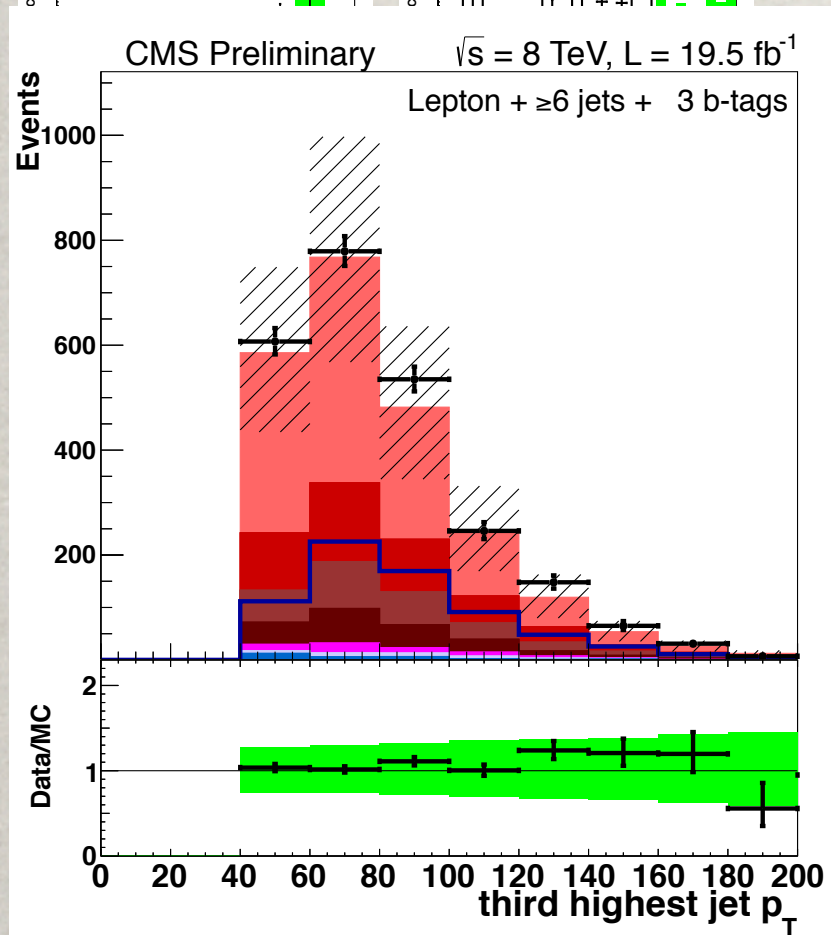
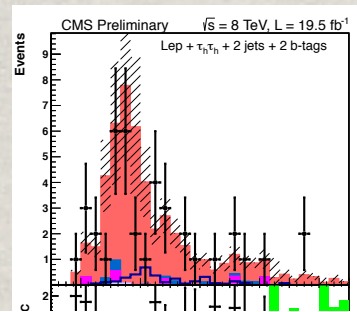
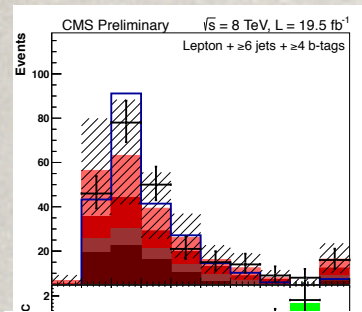
KL Fitter

MULTIVARIATE APPROACH



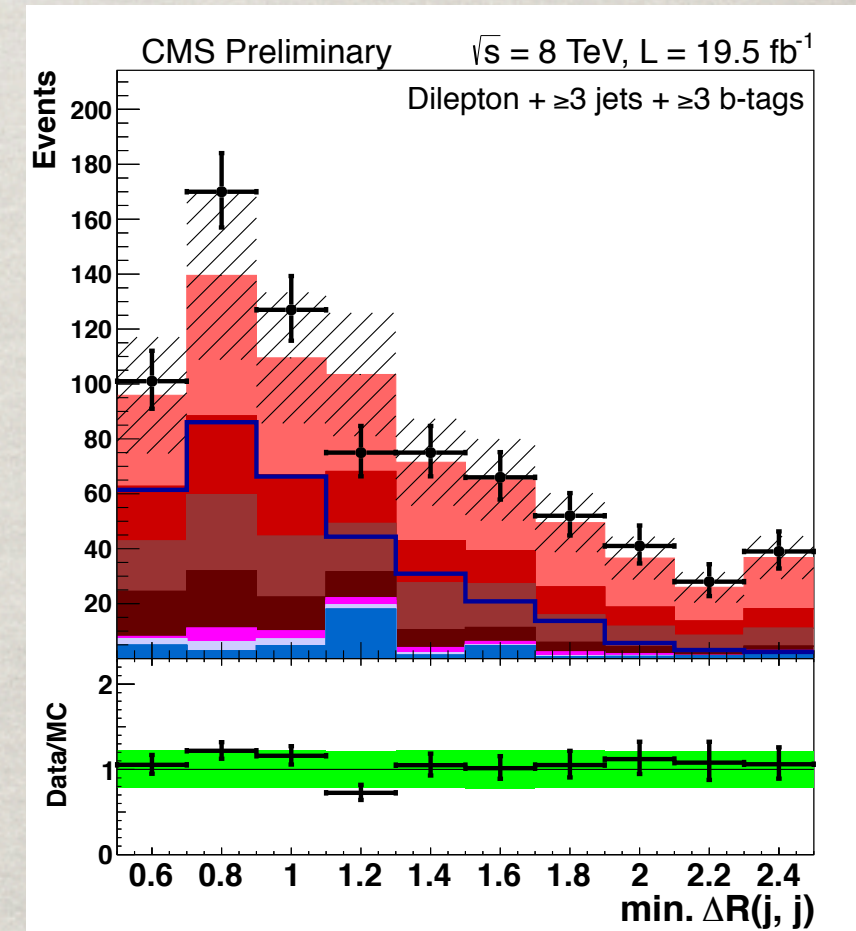
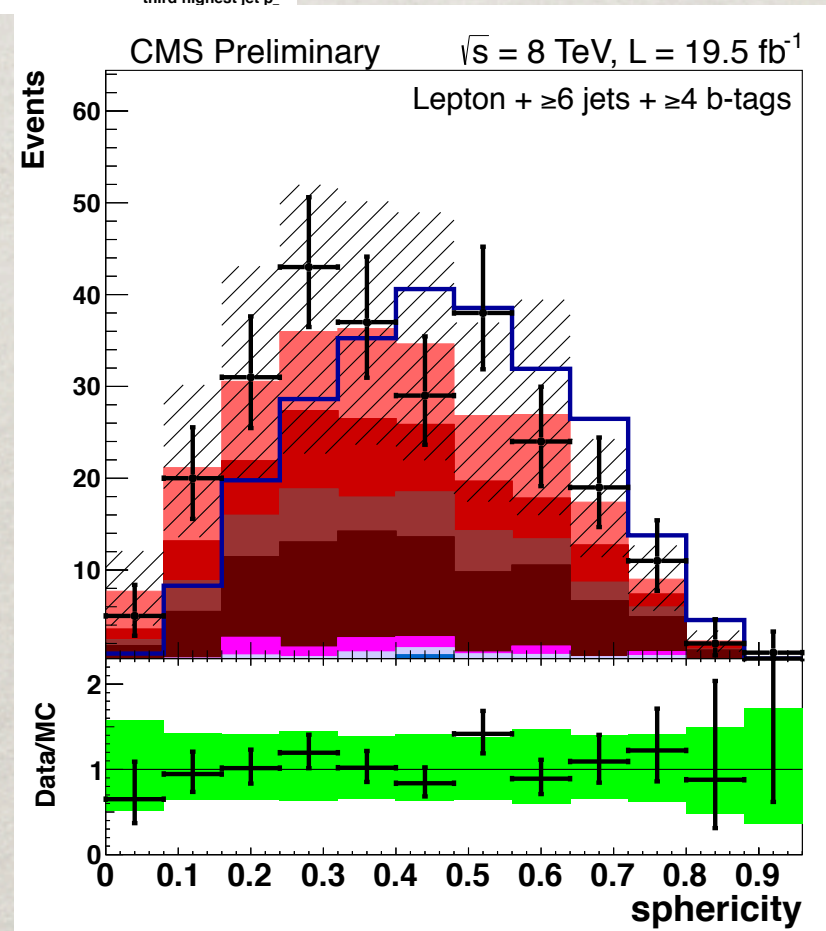
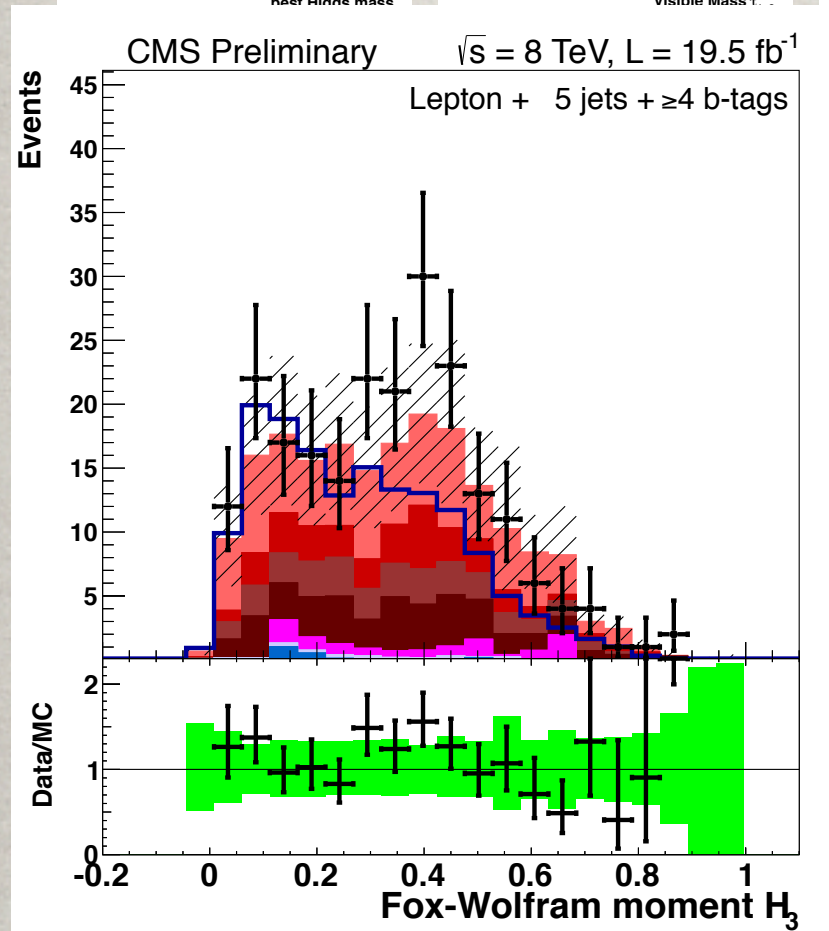
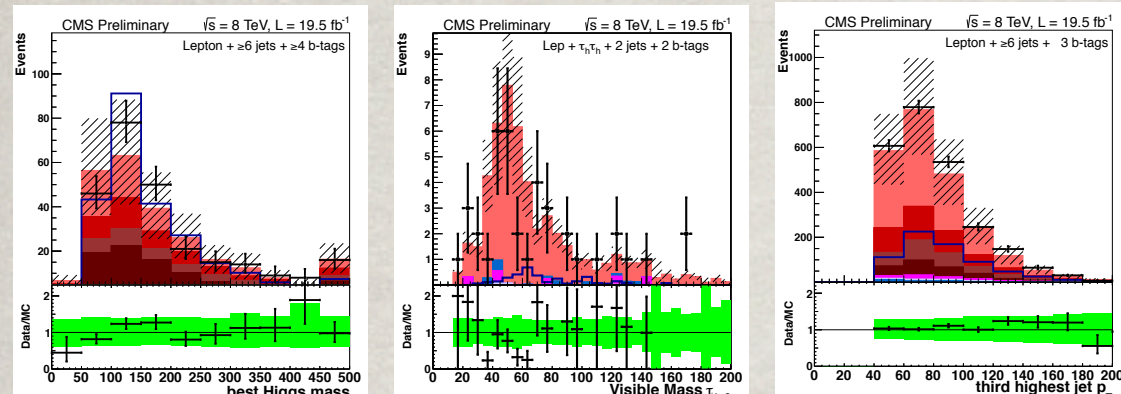
Variables related to Higgs invariant mass

MULTIVARIATE APPROACH



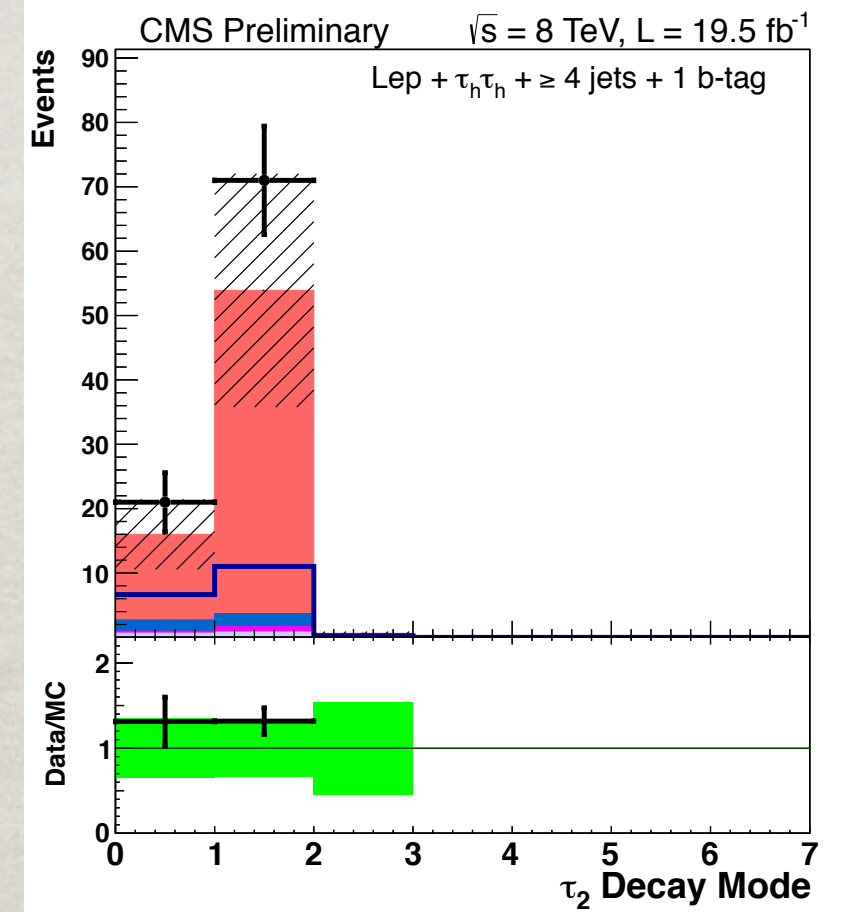
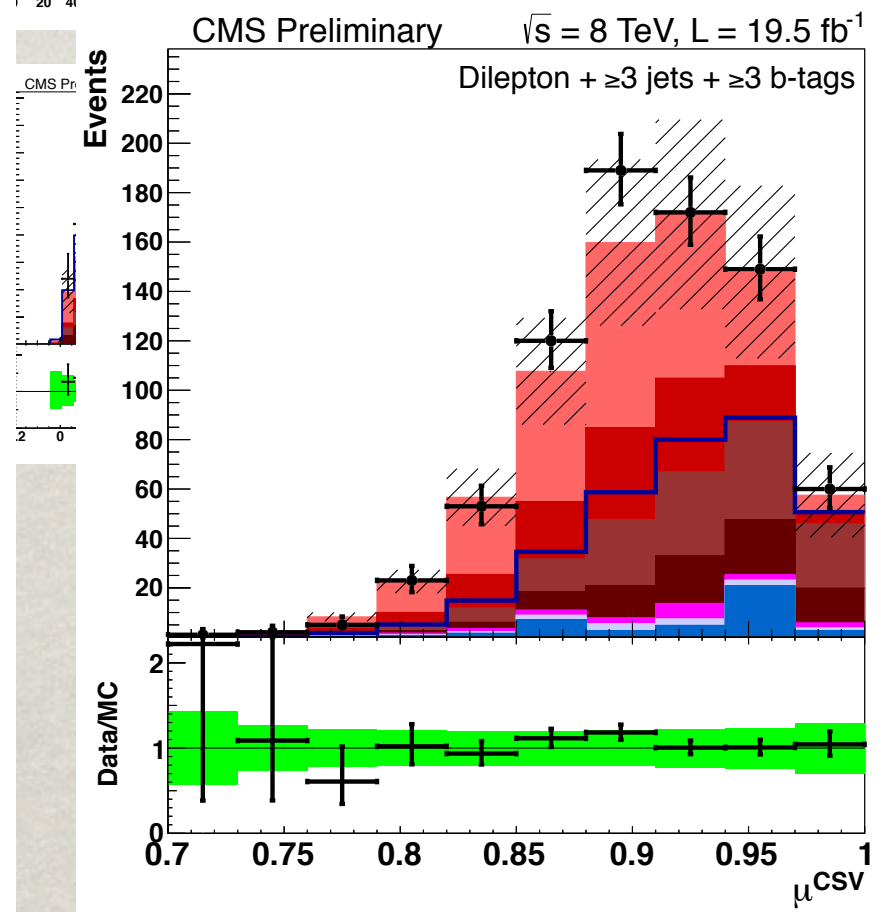
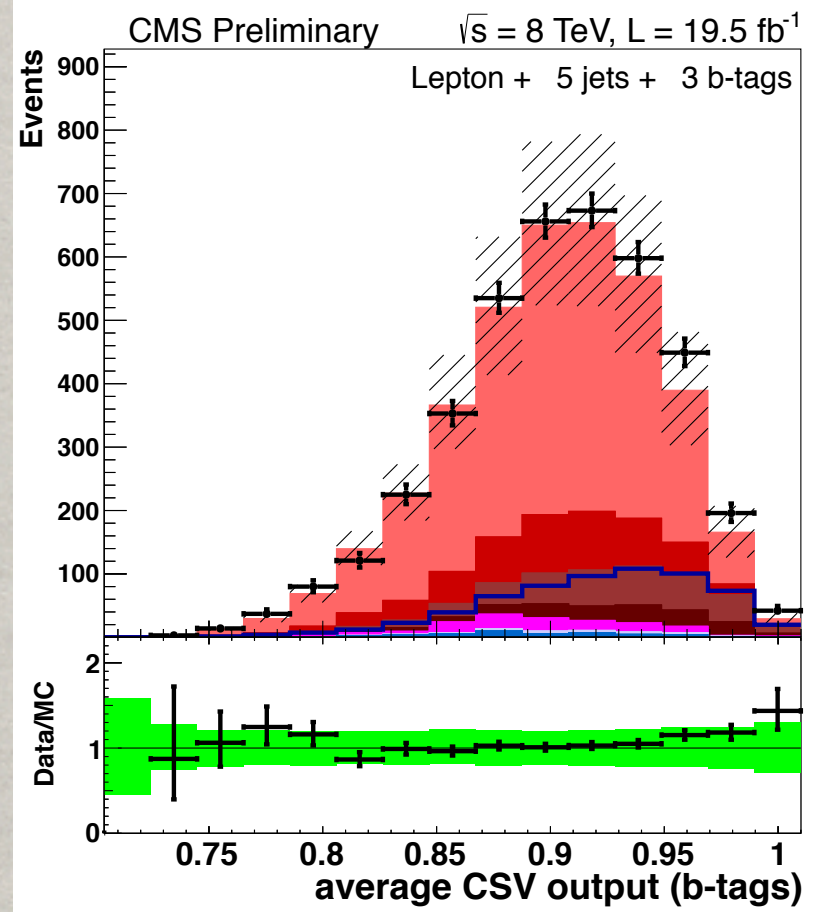
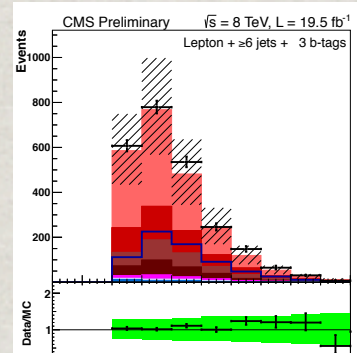
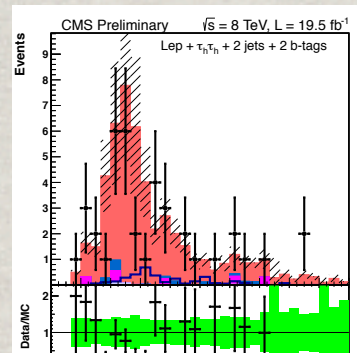
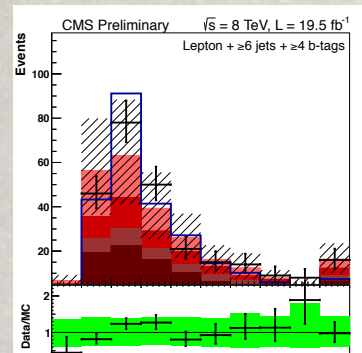
Variables connected with object p_T 's

MULTIVARIATE APPROACH



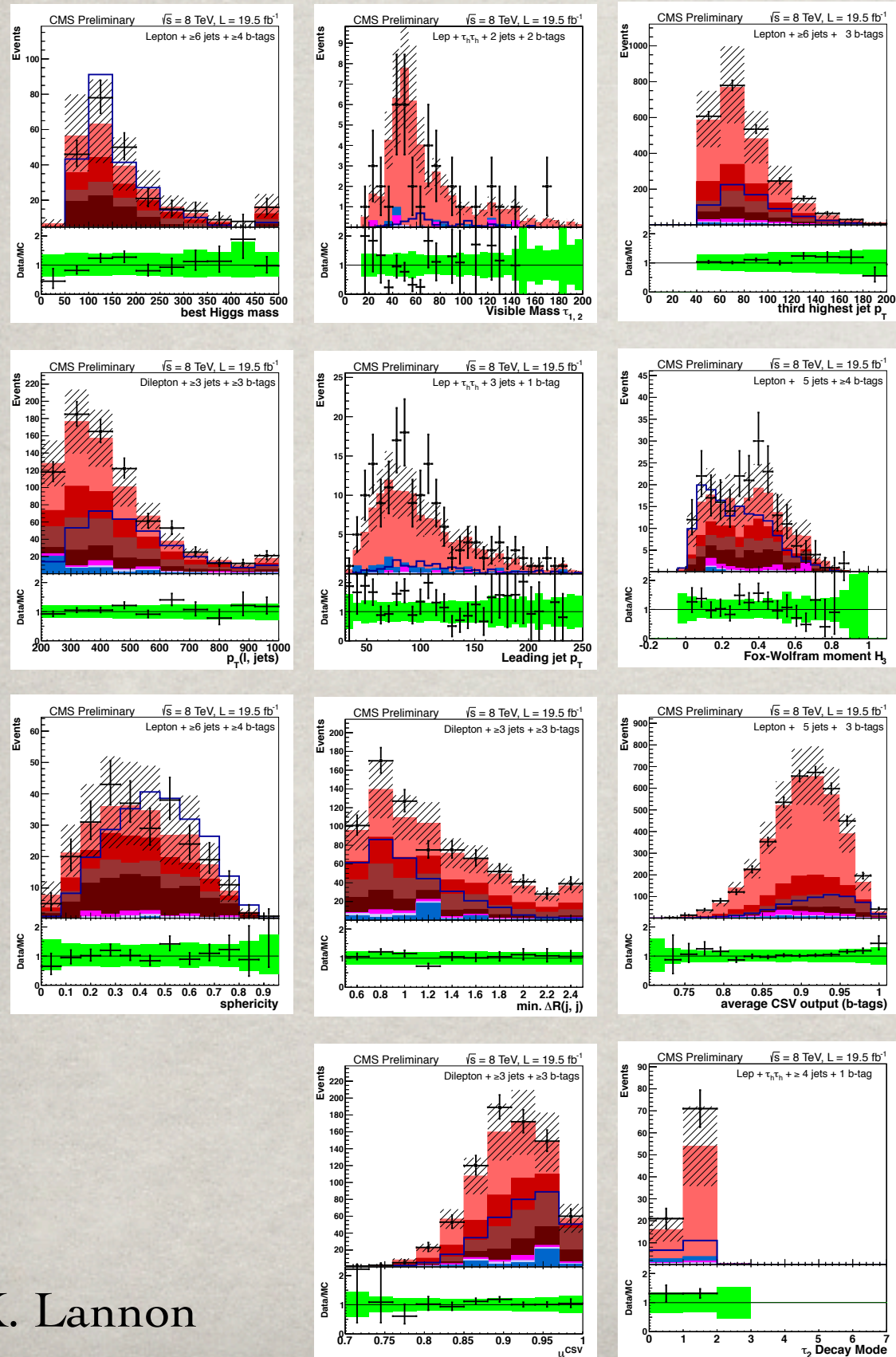
Event shape and angular variables

MULTIVARIATE APPROACH



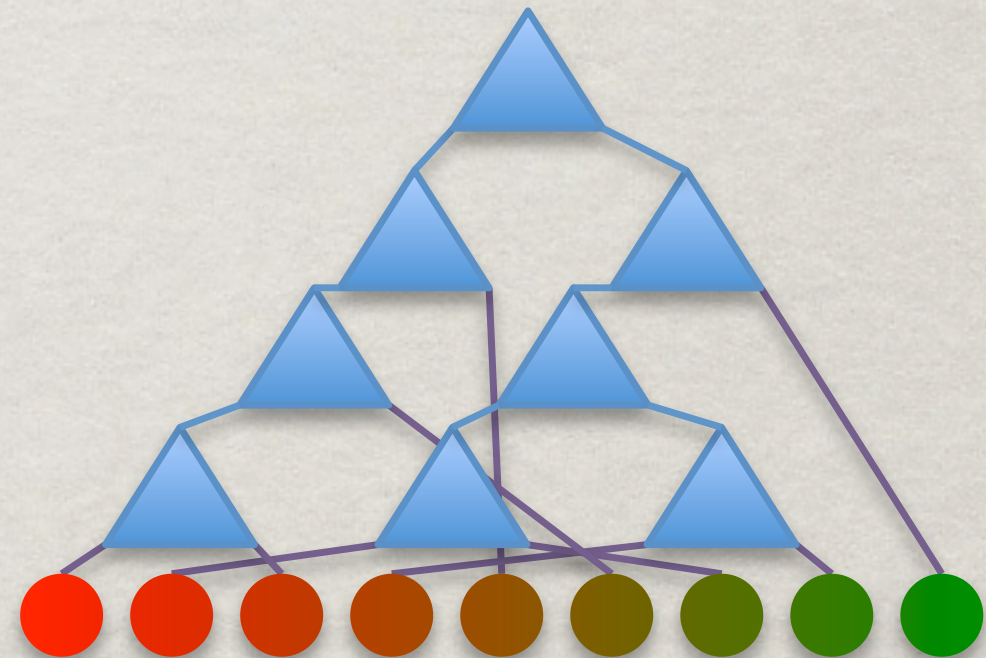
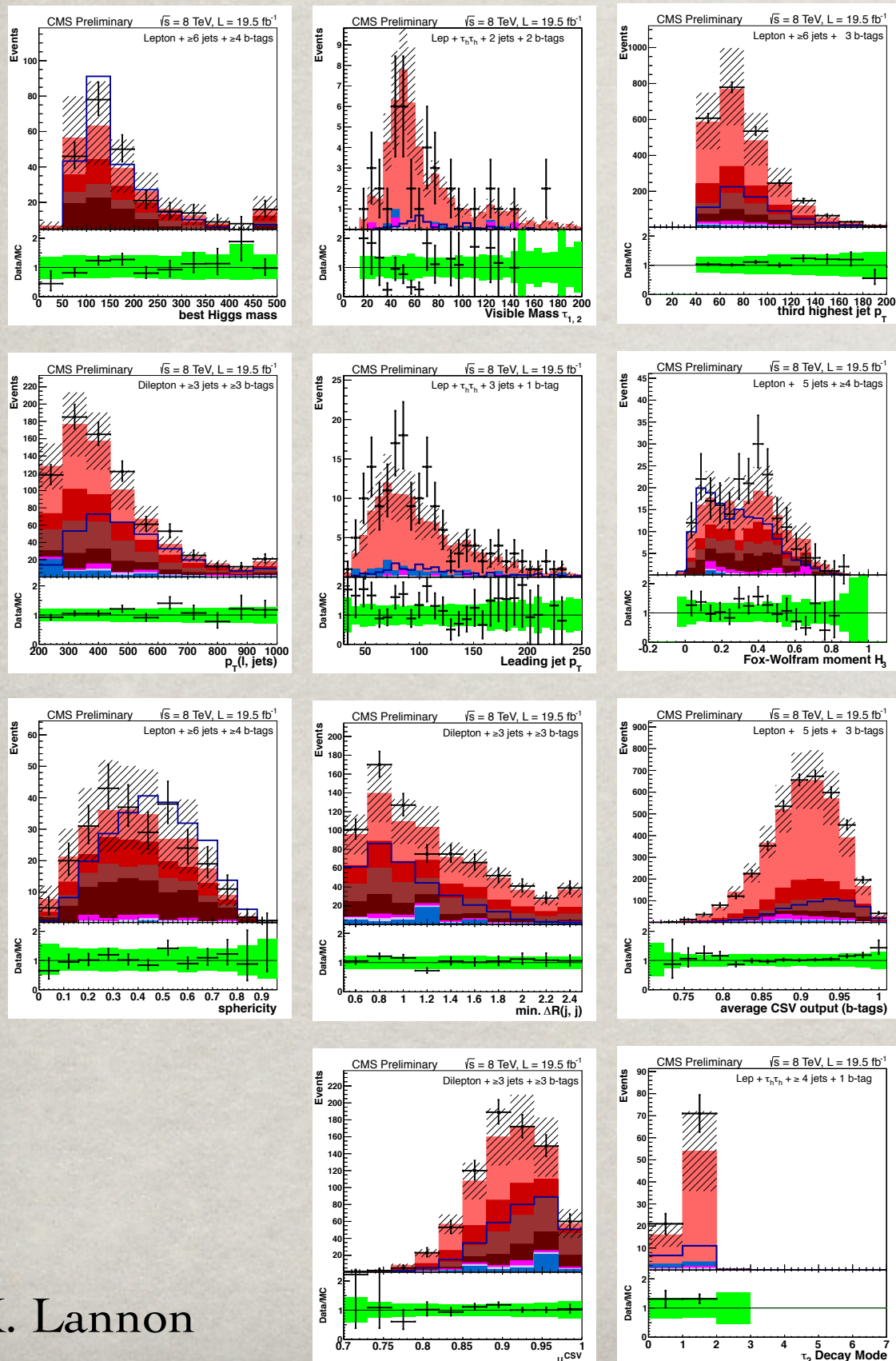
b-Tagging or τ -ID Variables

MULTIVARIATE APPROACH

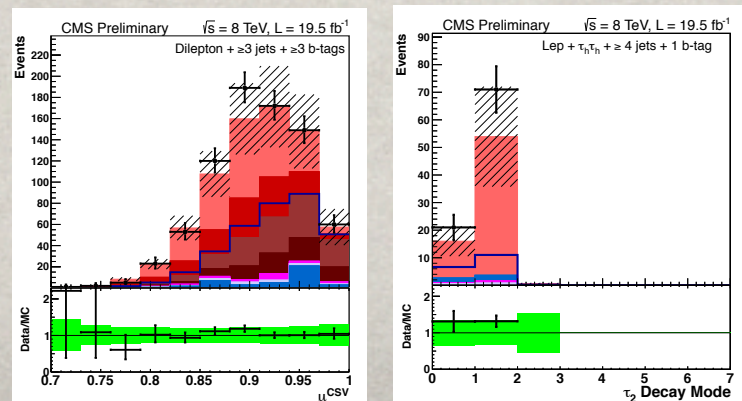
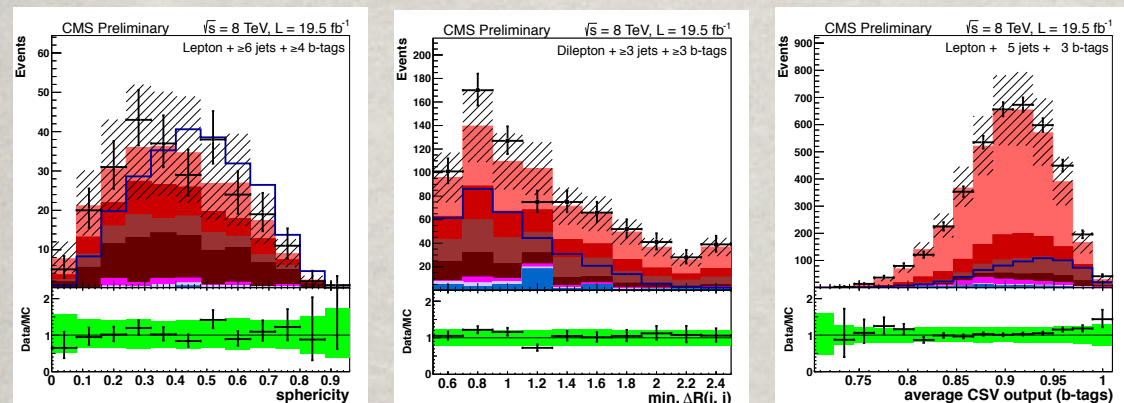
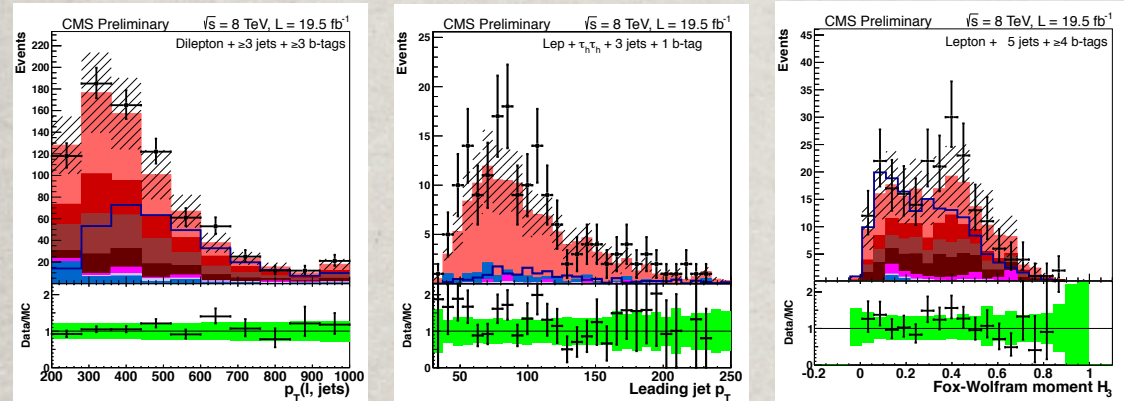
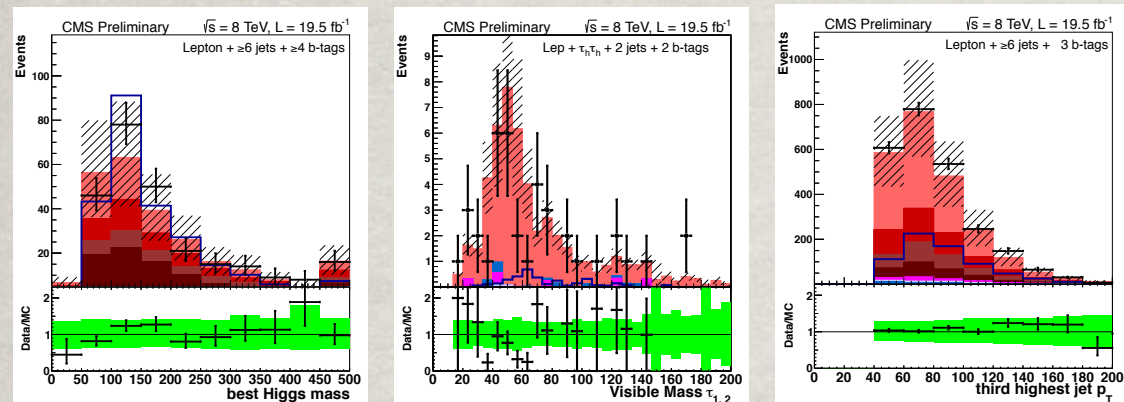


MULTIVARIATE APPROACH

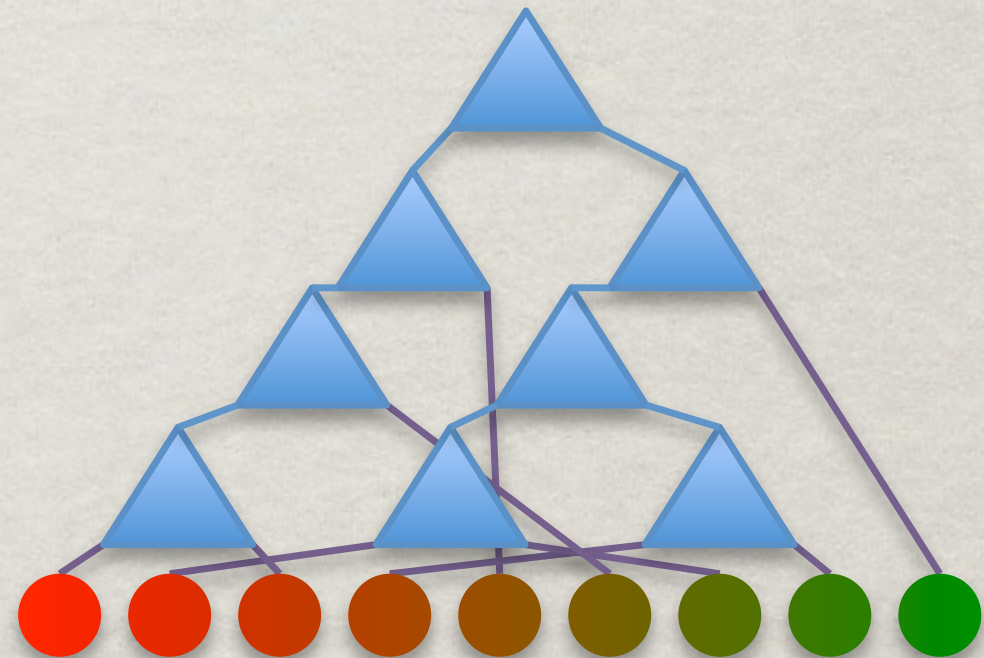
Combine multiple variables using a boosted decision tree (BDT)



MULTIVARIATE APPROACH

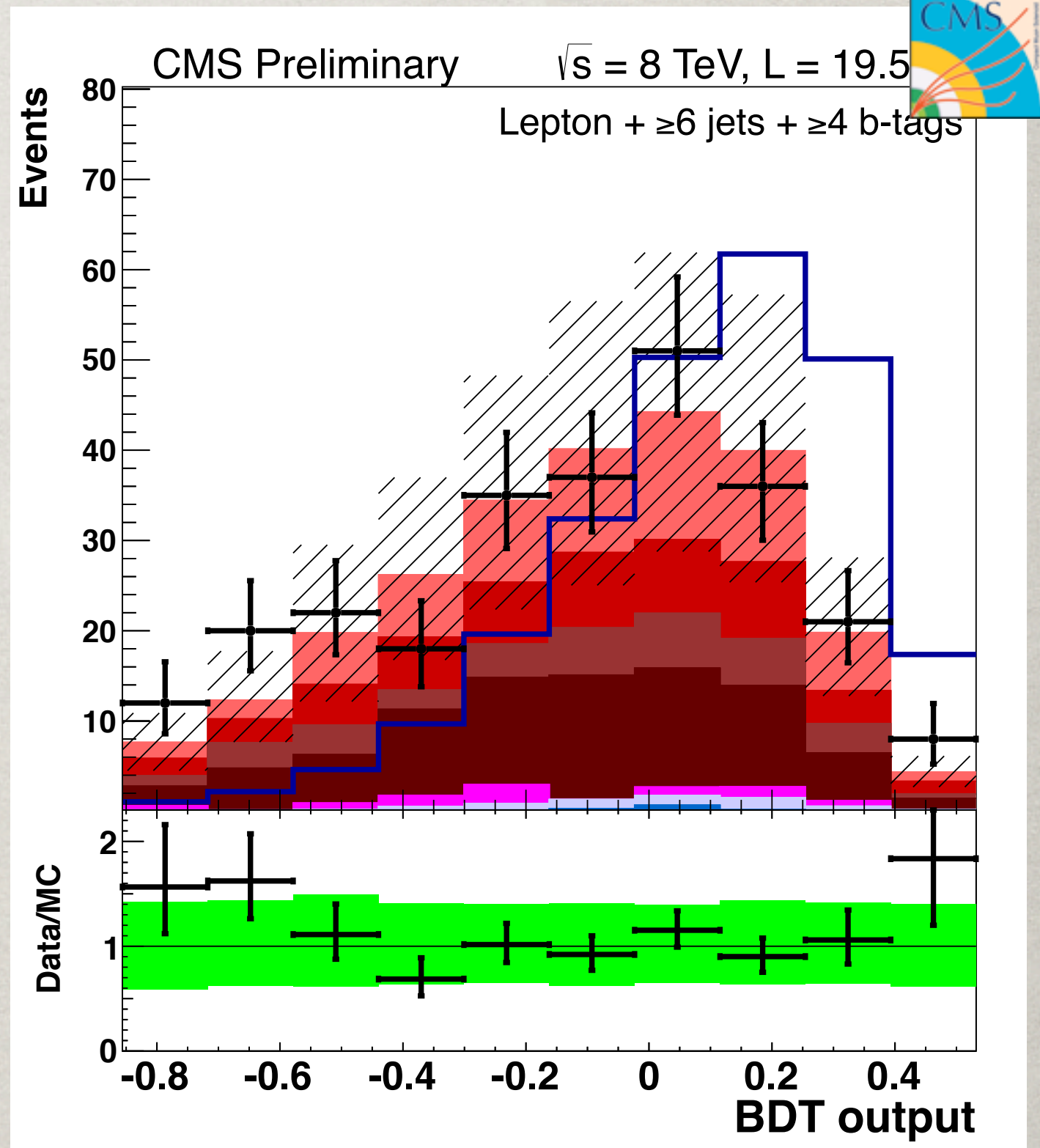
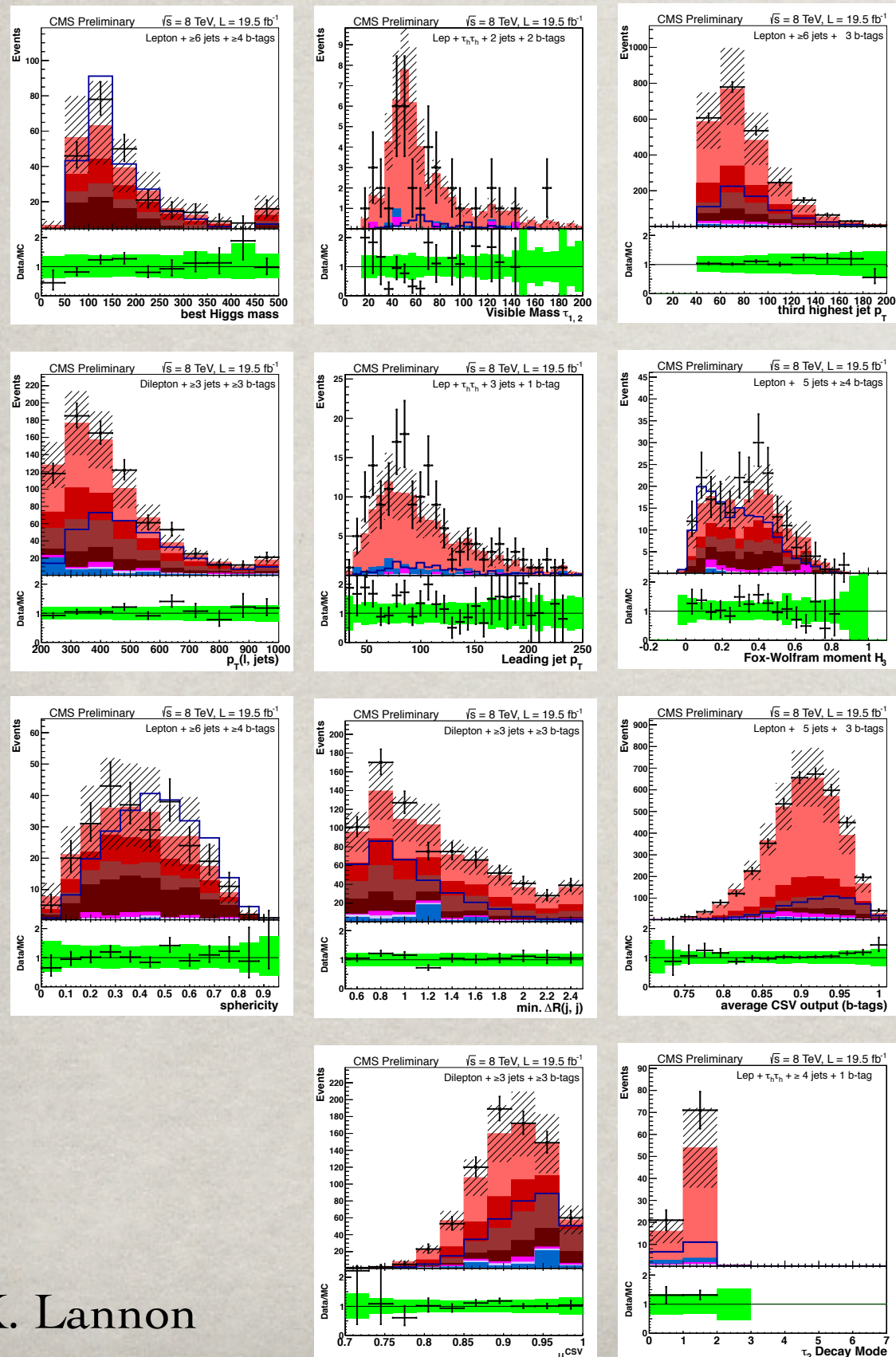


Combine multiple variables using a boosted decision tree (BDT)

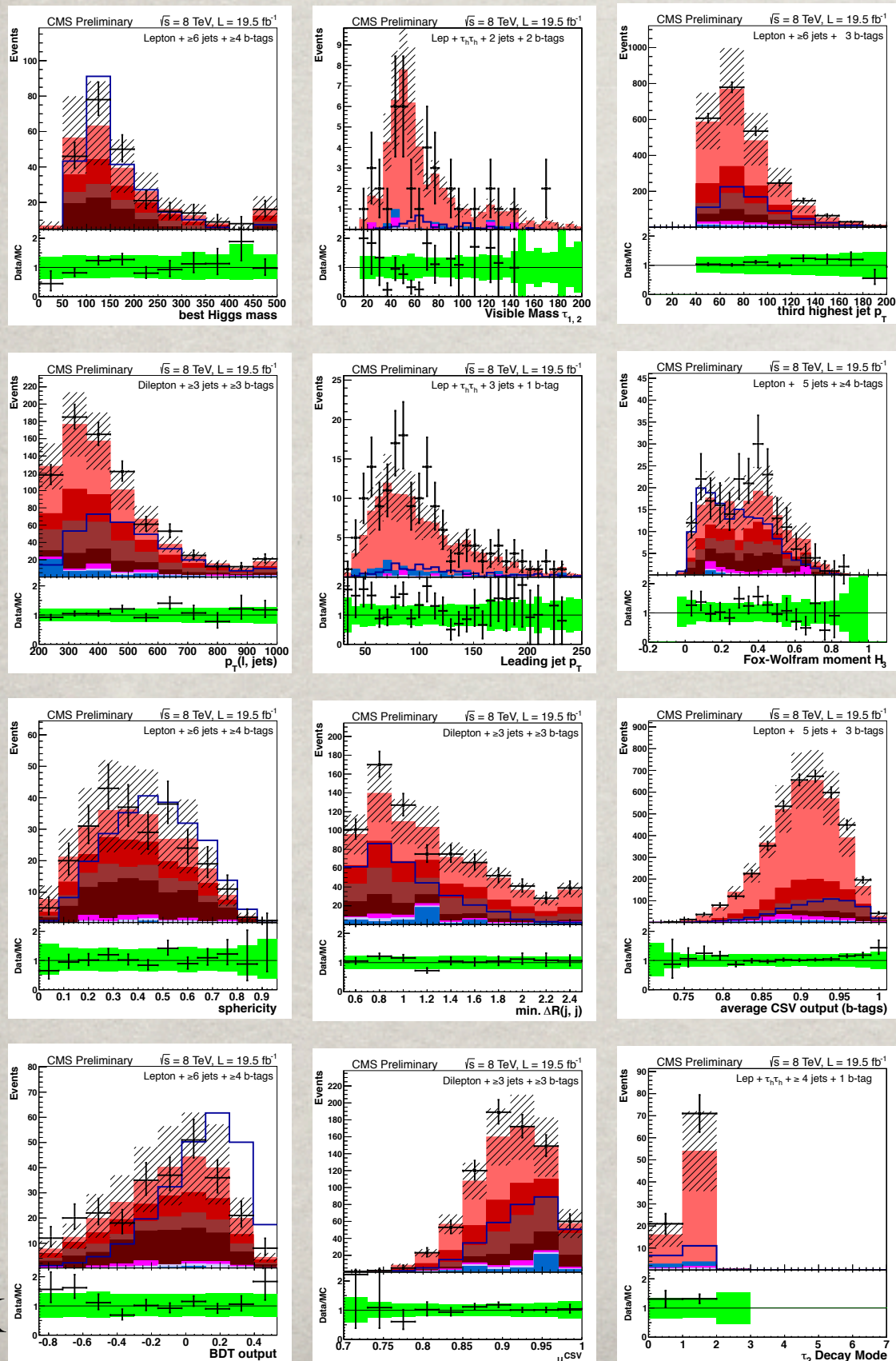


Train separate BDT for ttH vs $ttbb$ separation

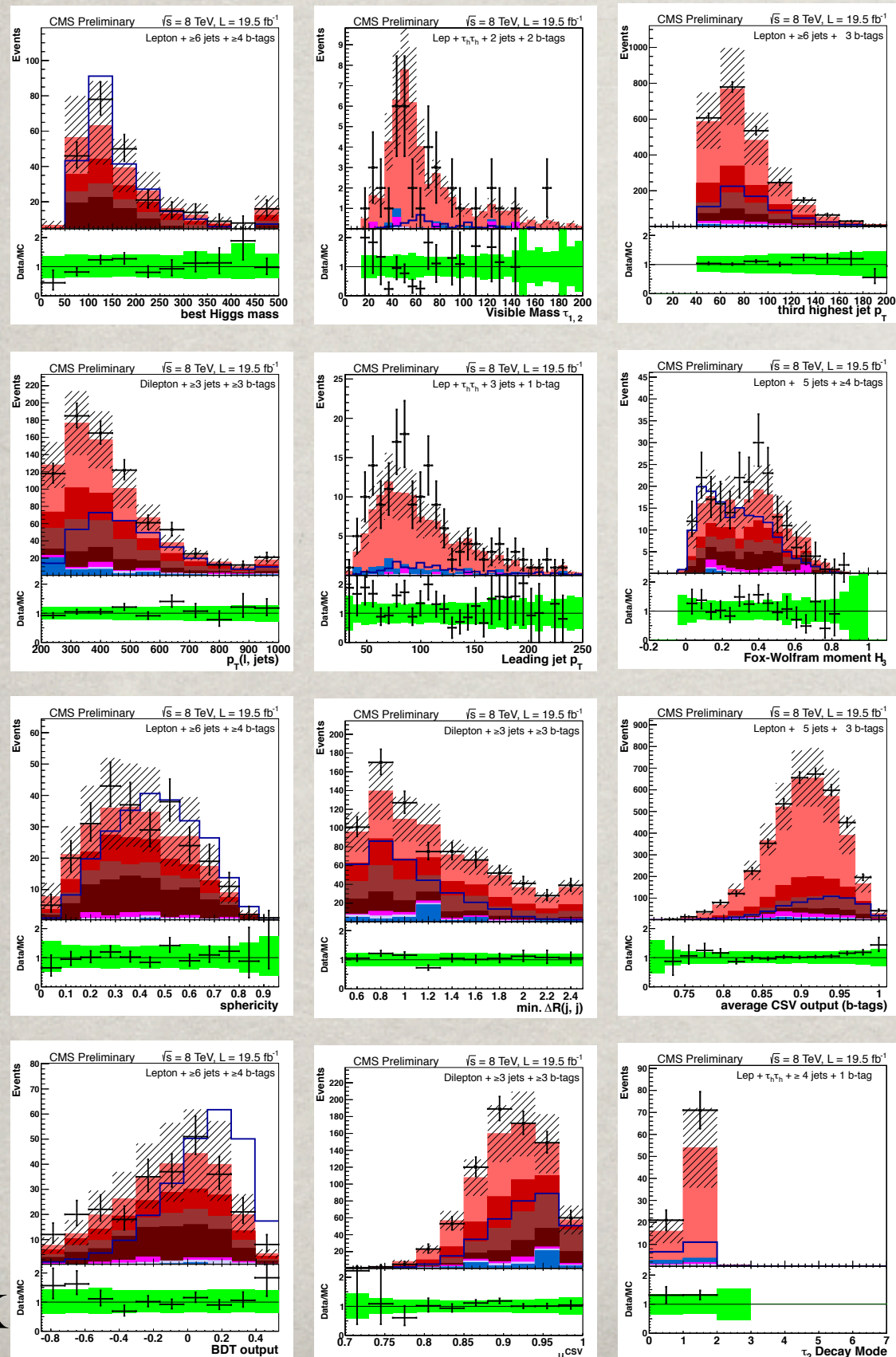
MULTIVARIATE APPROACH



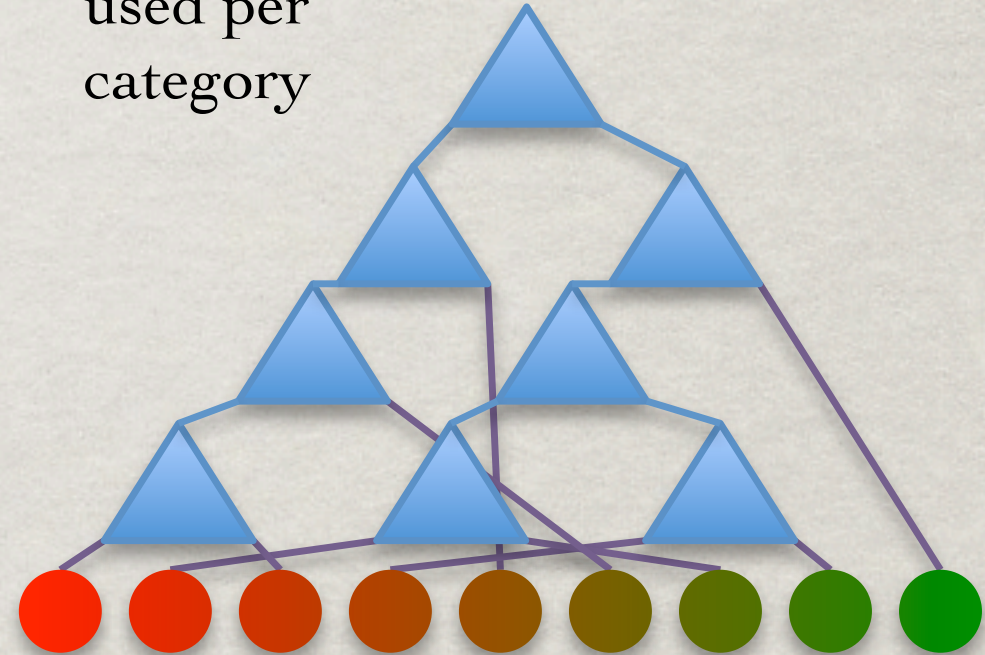
MULTIVARIATE APPROACH



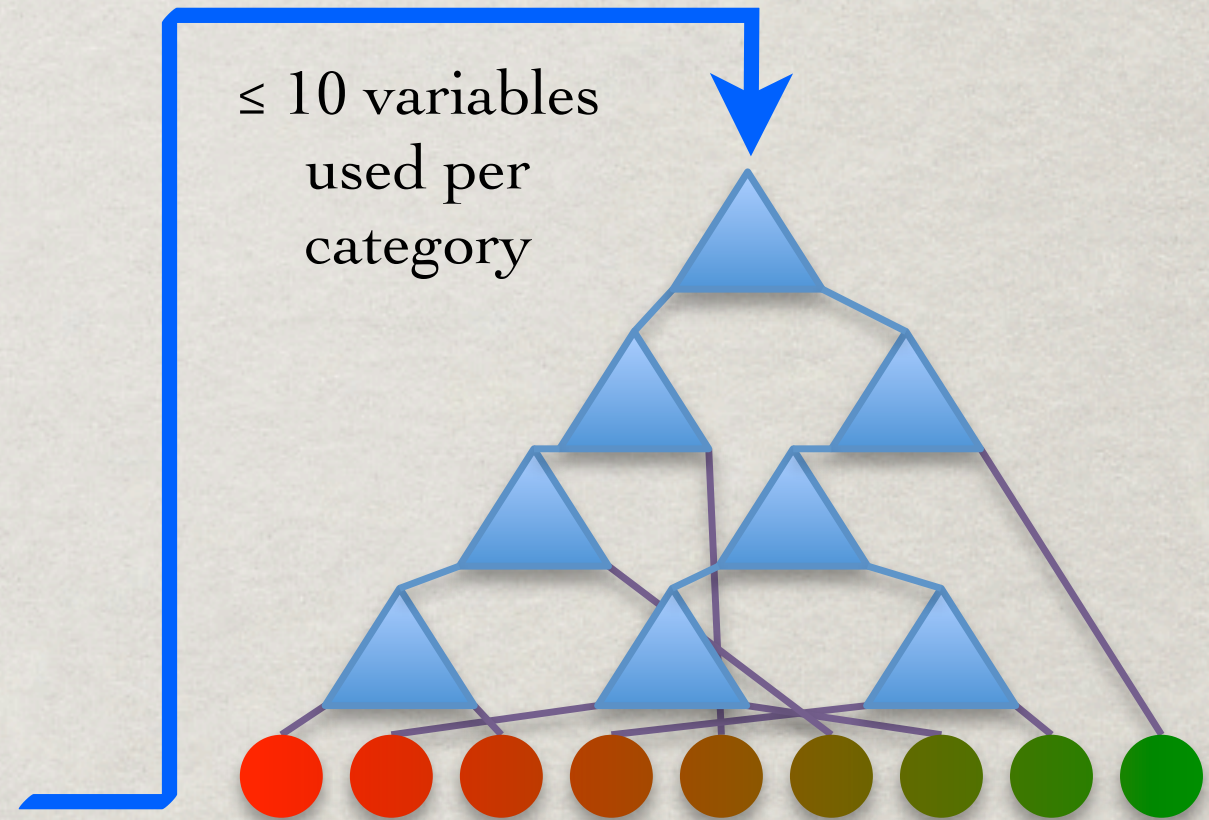
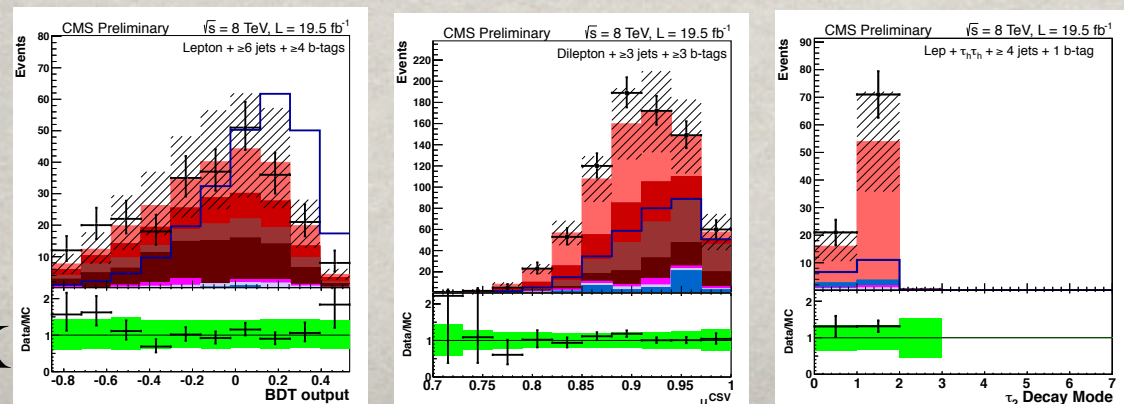
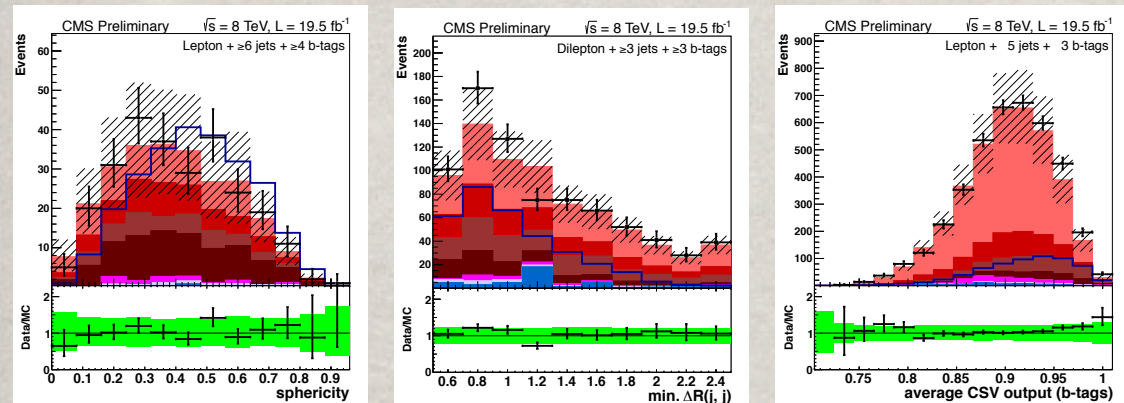
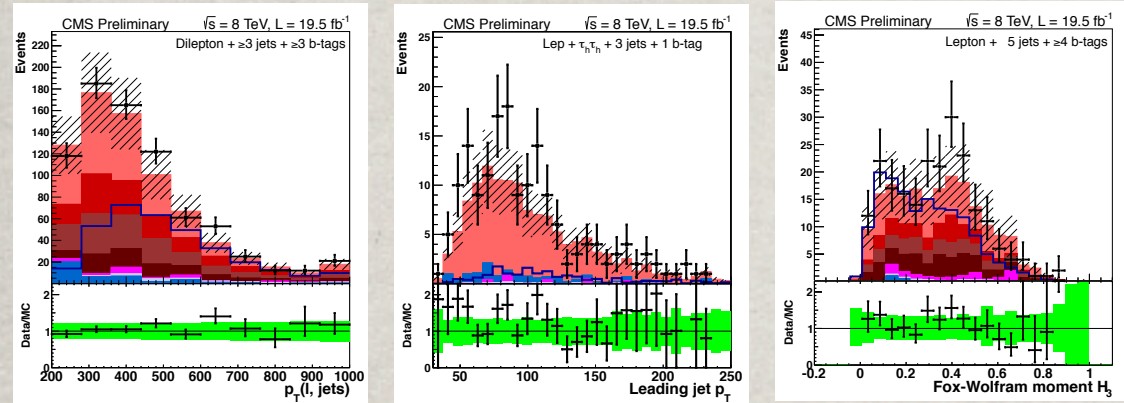
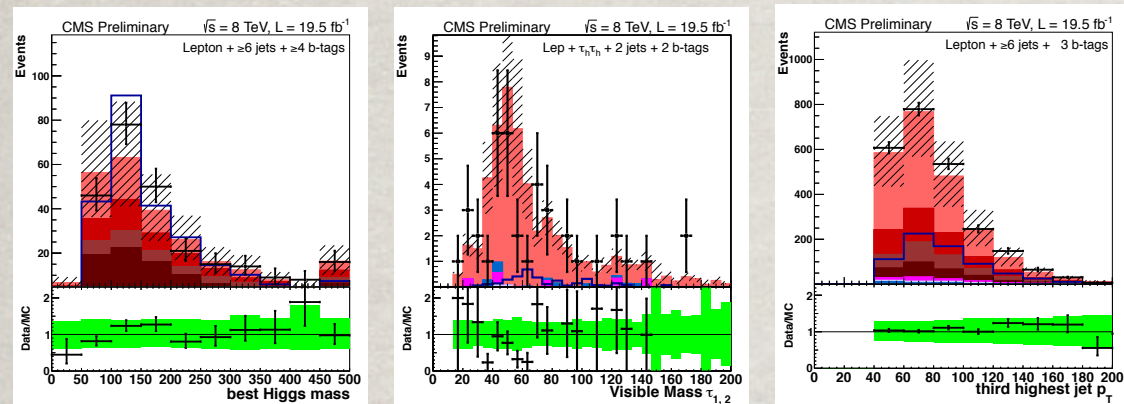
MULTIVARIATE APPROACH



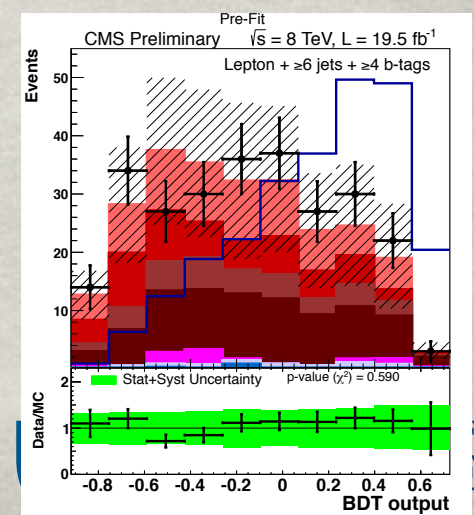
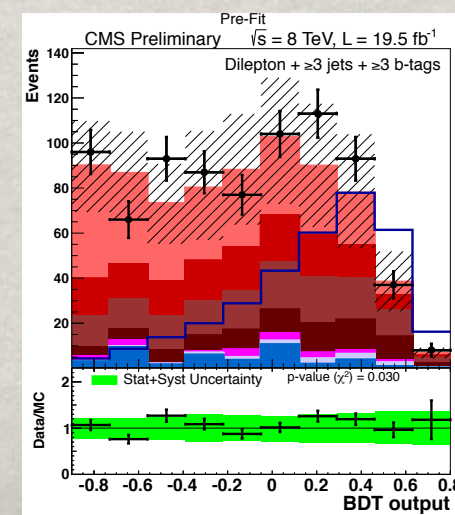
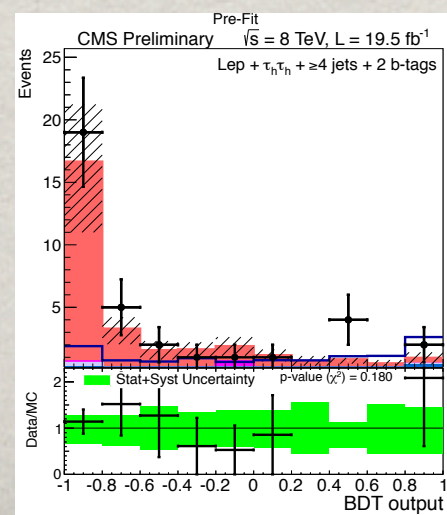
≤ 10 variables
used per
category



MULTIVARIATE APPROACH



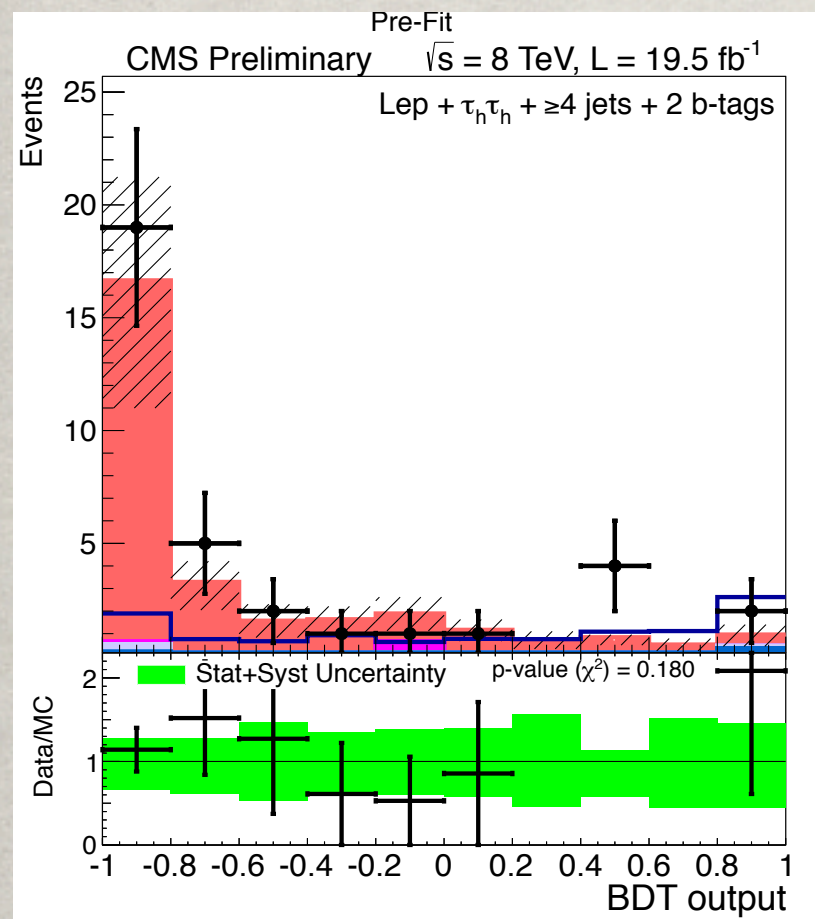
Optimized BDT
for each category
(16 in all)



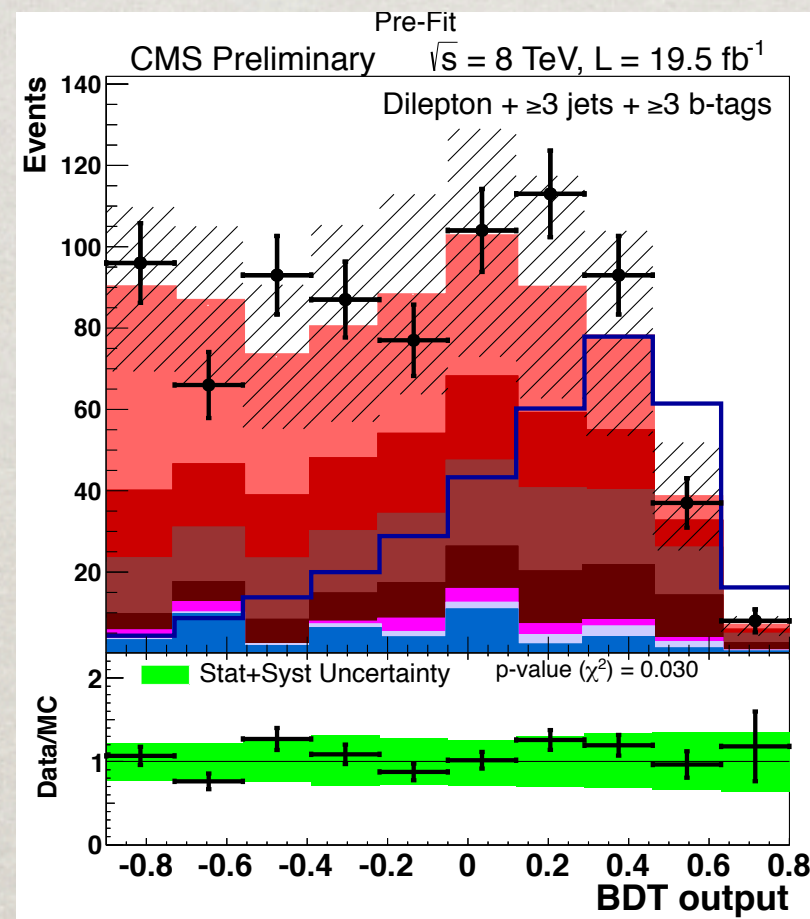
MULTIVARIATE APPROACH



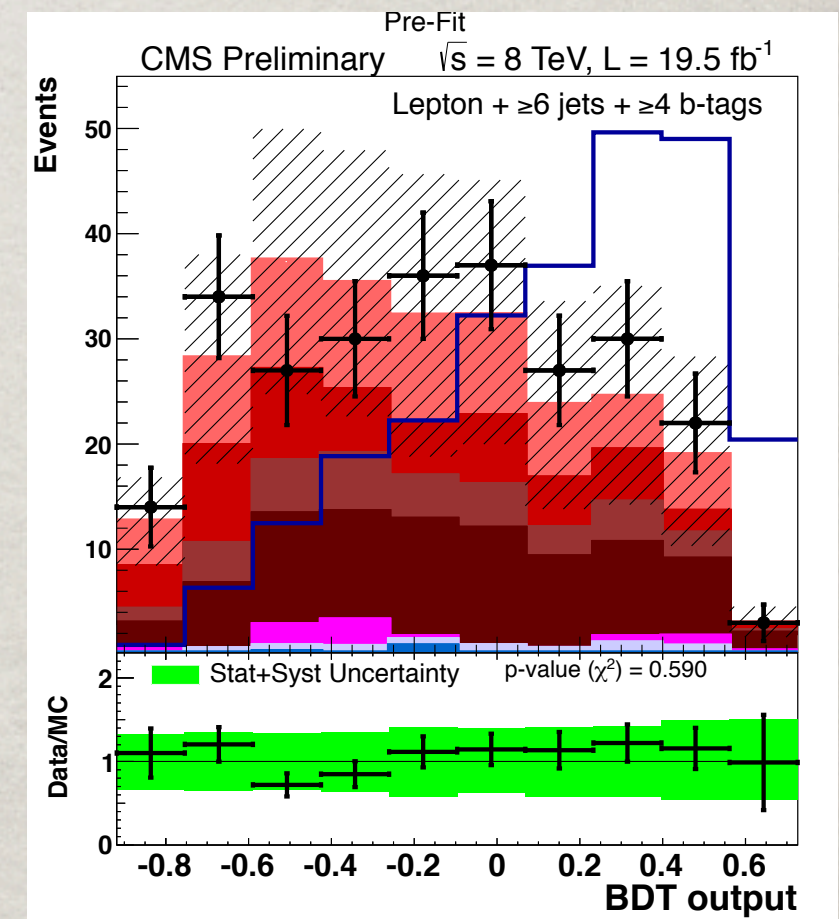
BDT for most sensitive categories for each channel



TAU



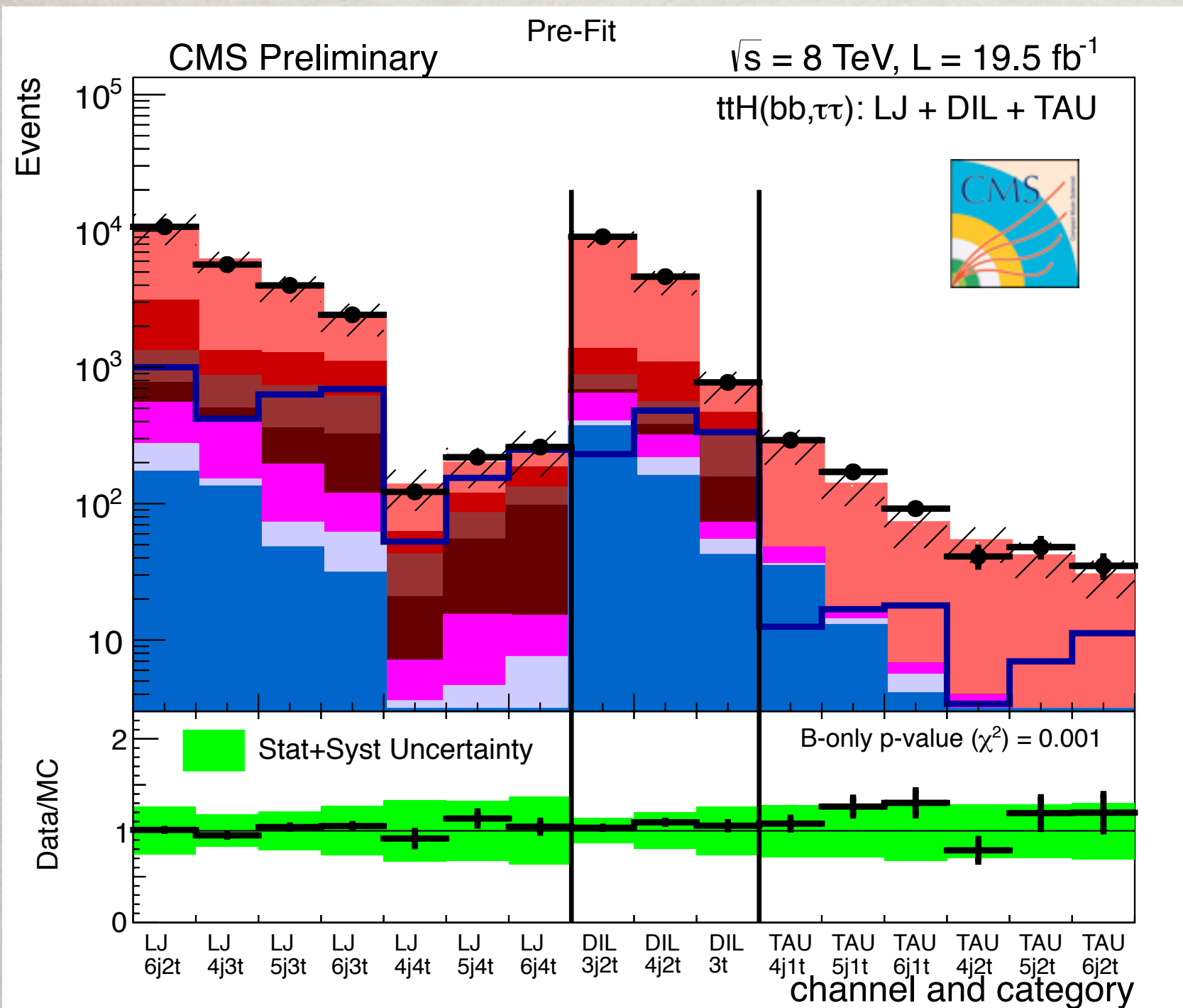
DIL



LJ

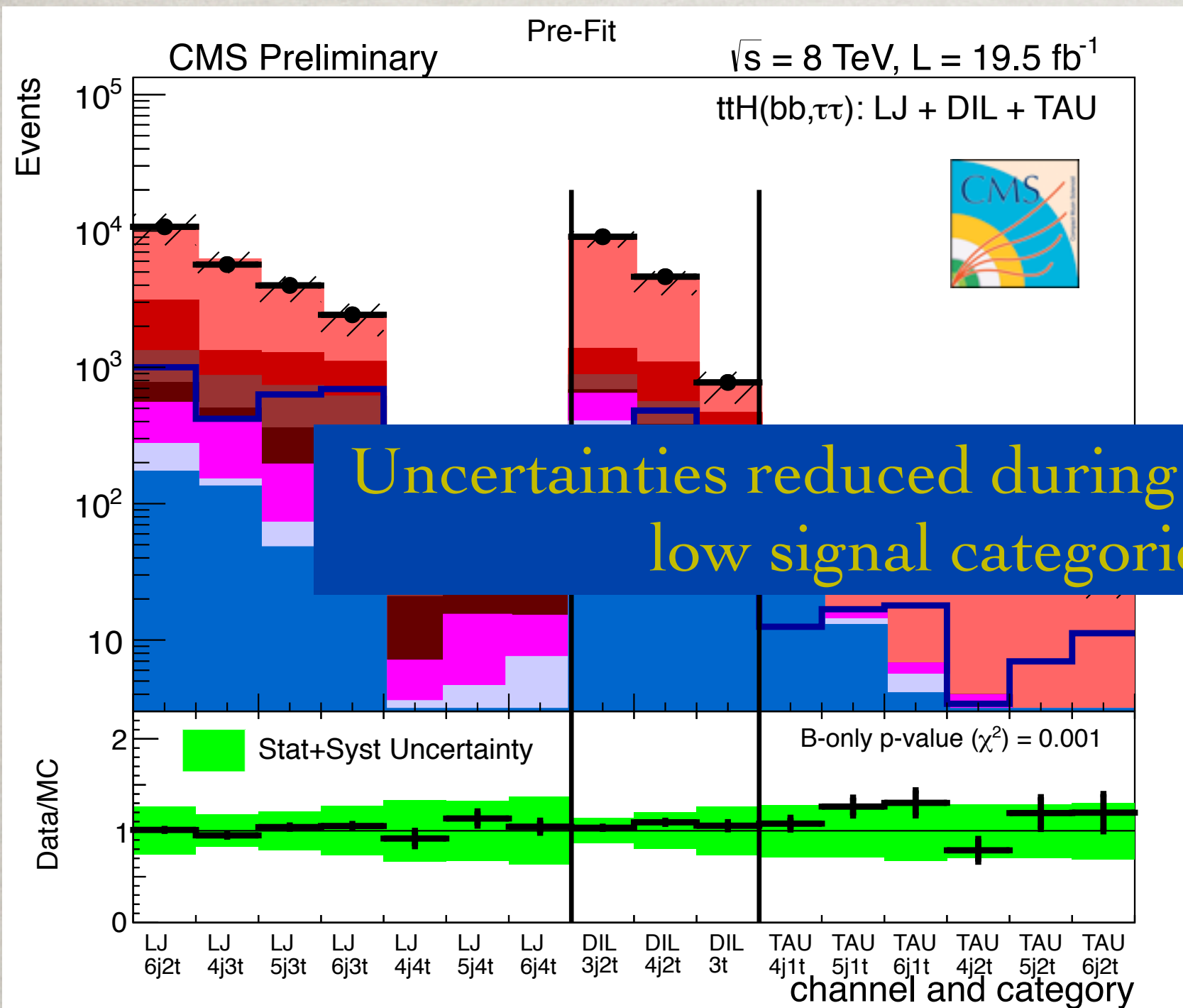


SYSTEMATICS



- ✱ Leading systematic uncertainties
- ✱ tt +HF uncertainty
- ✱ b -tagging uncertainties
- ✱ JES
- ✱ $t\bar{t}$ Modeling

SYSTEMATICS



Leading systematic uncertainties

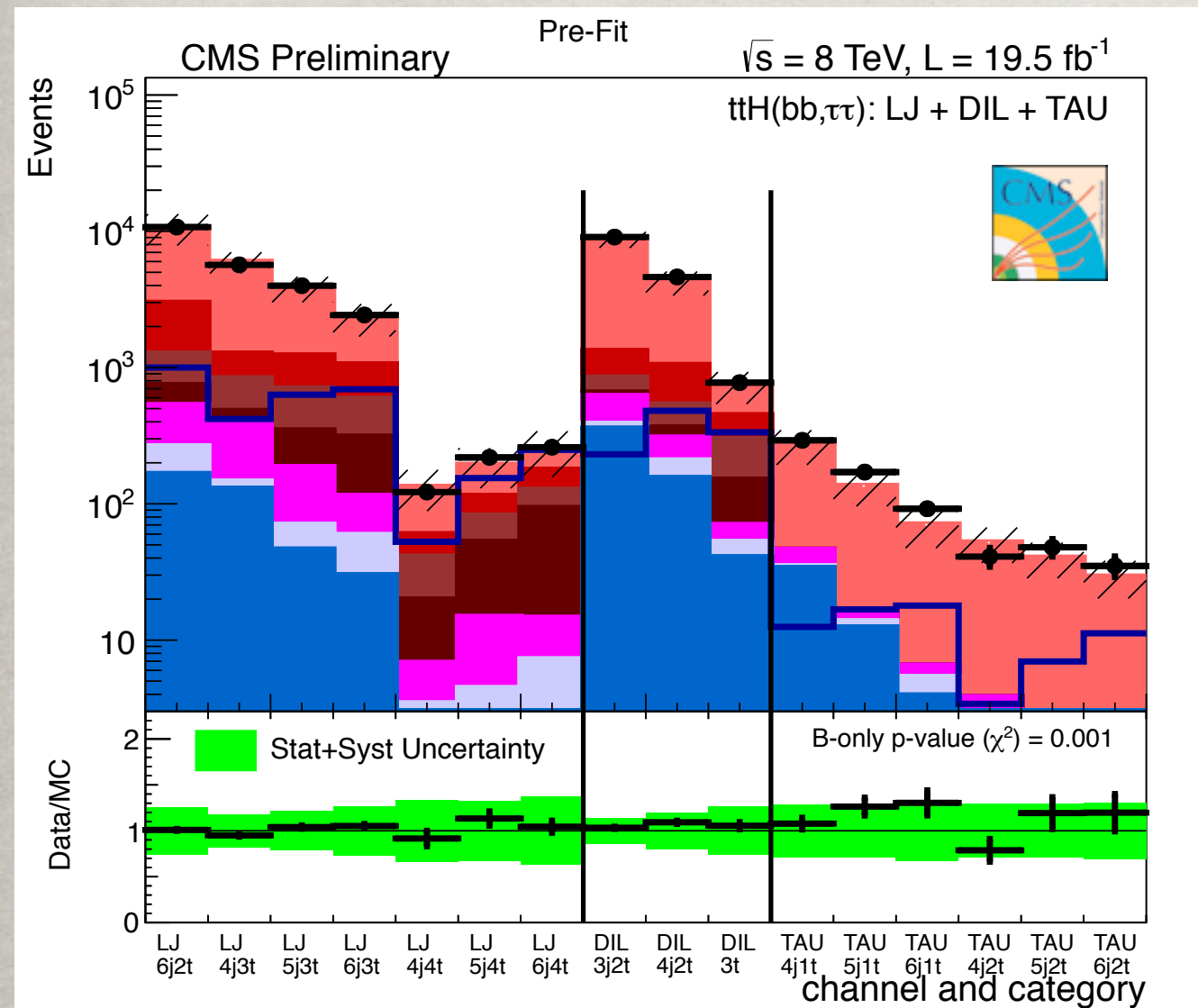
b -tagging uncertainties

JES

$t\bar{t}$ Modeling

SYSTEMATICS

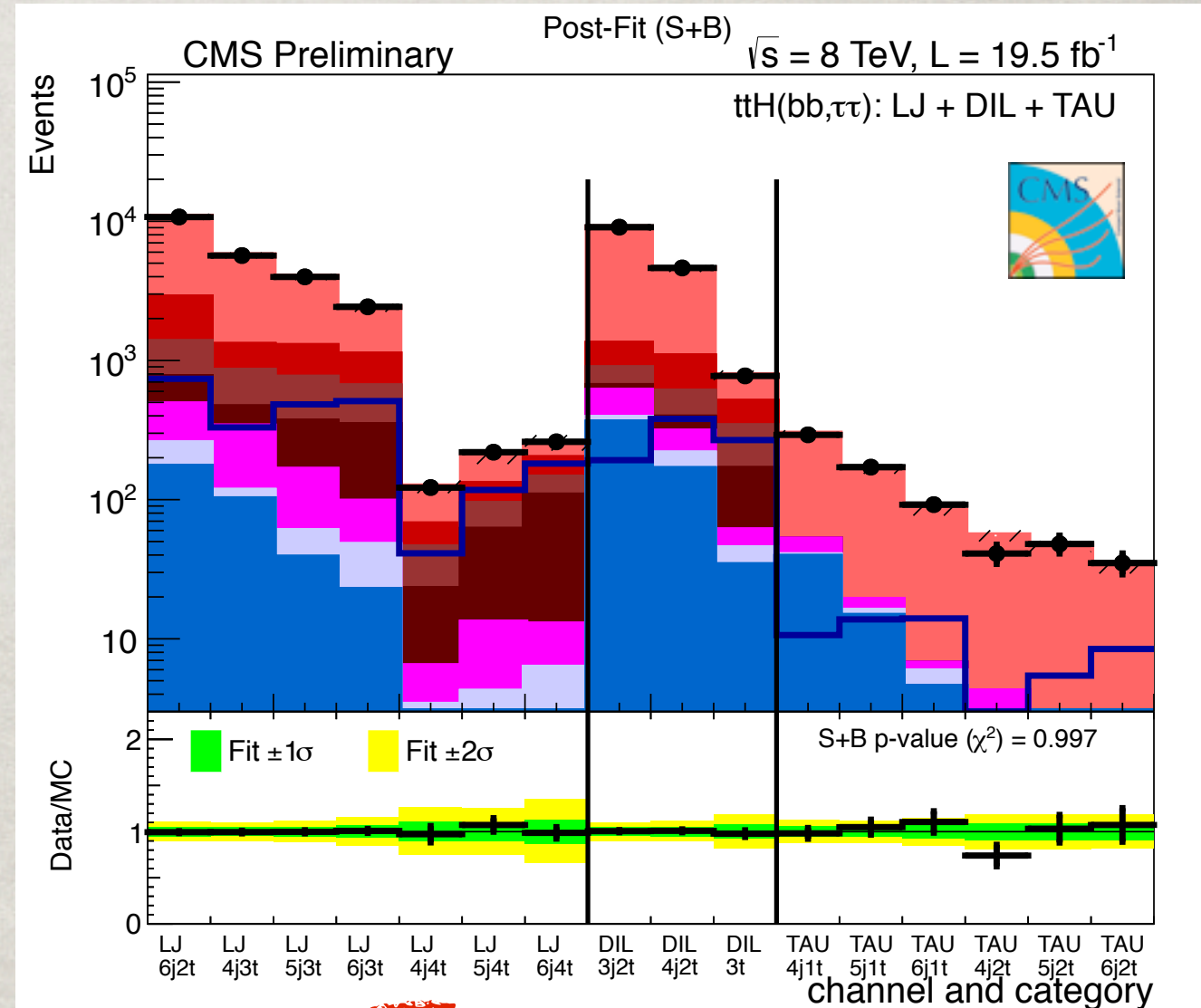
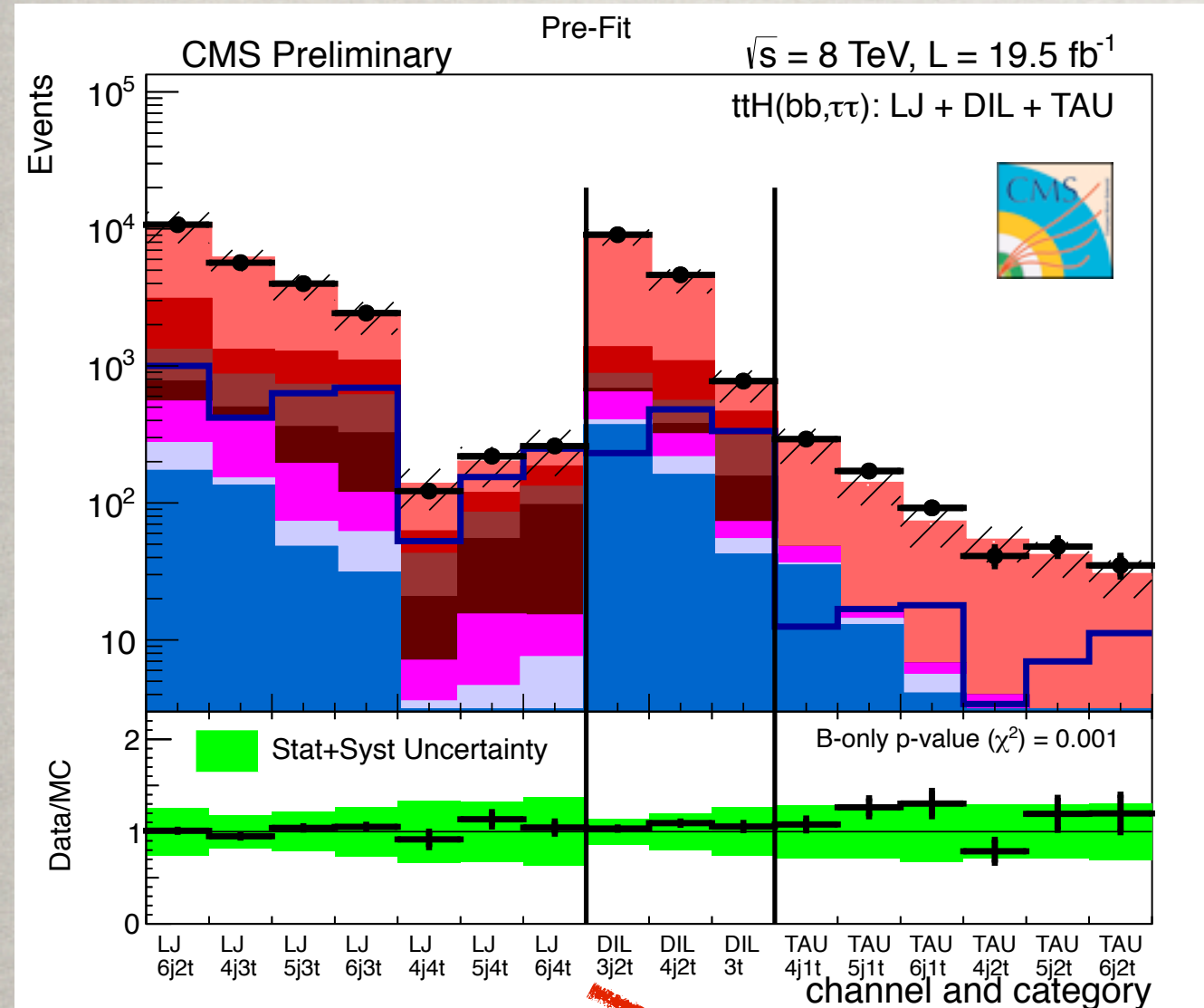
Pre-Fit



SYSTEMATICS

Pre-Fit

Post-Fit

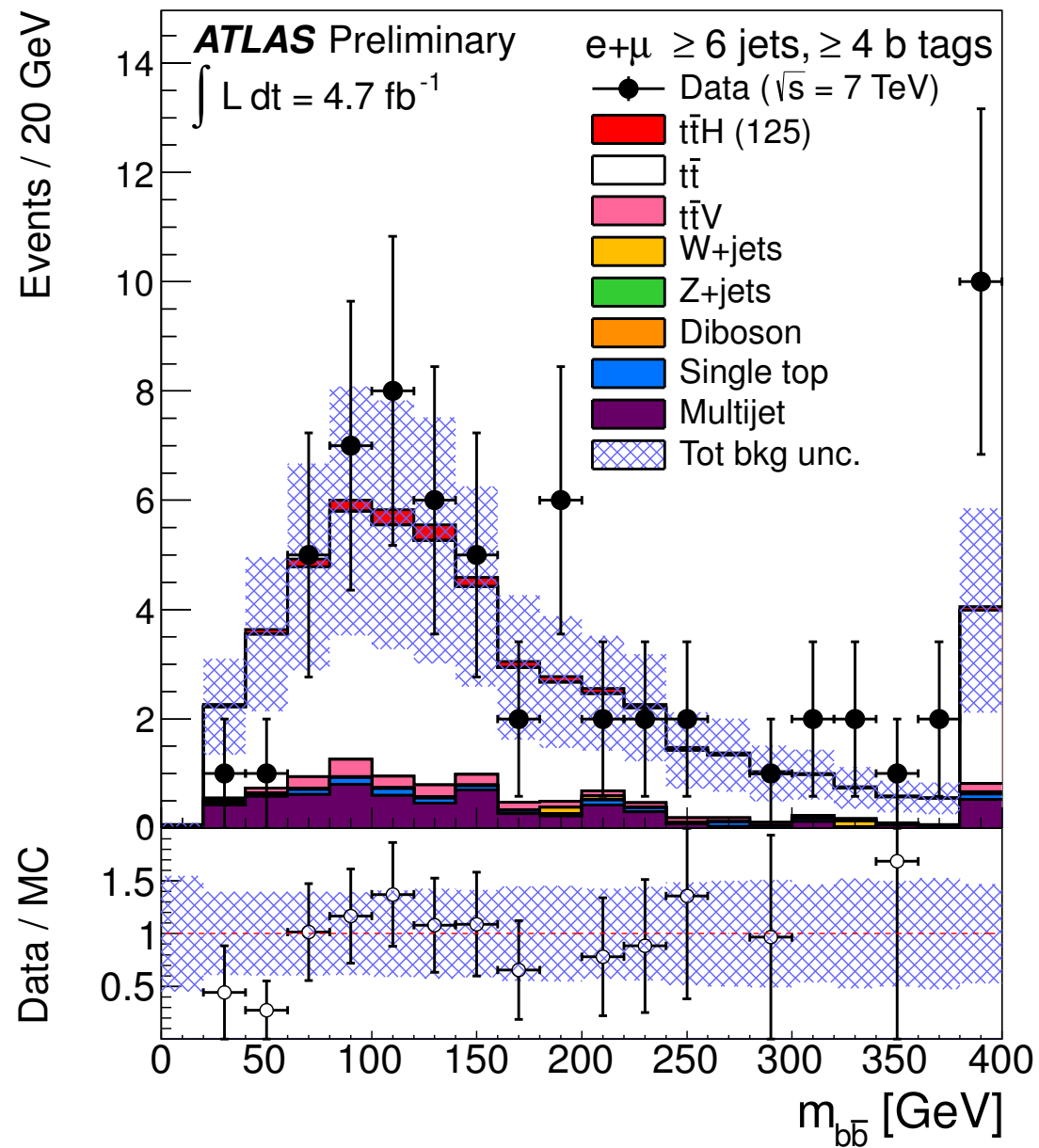


Uncertainties reduced

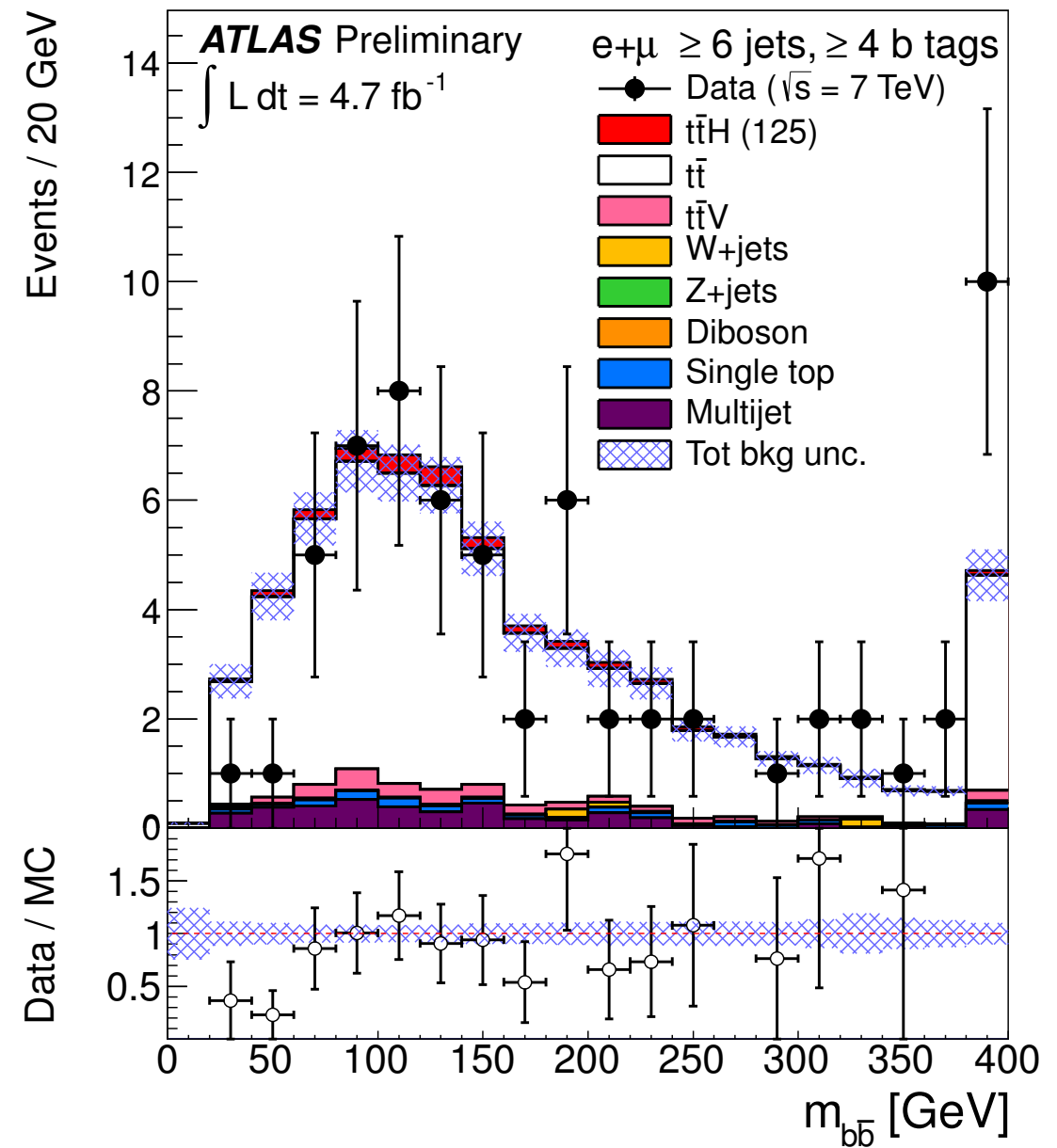
SYSTEMATICS



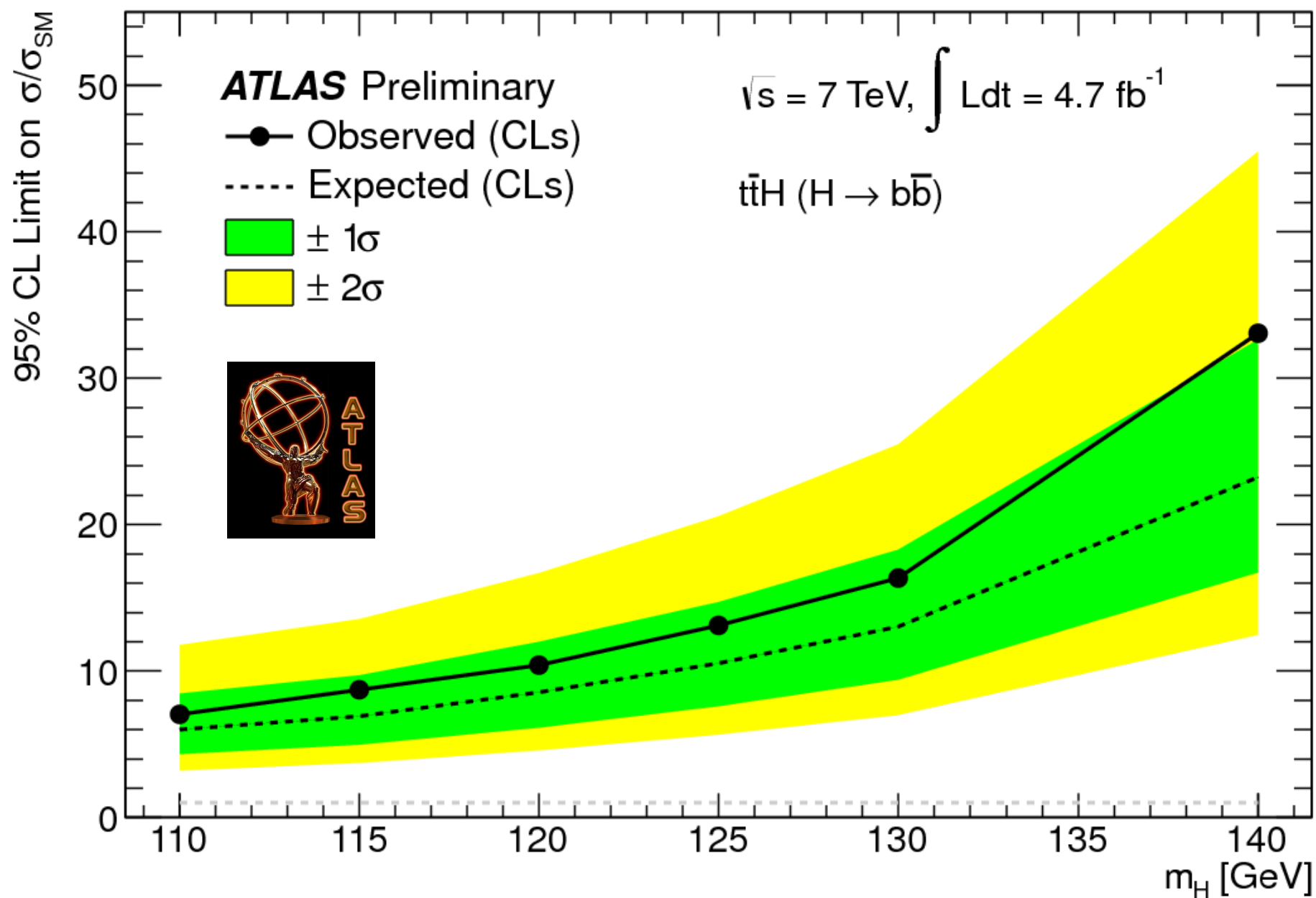
Pre-Fit



Post-Fit



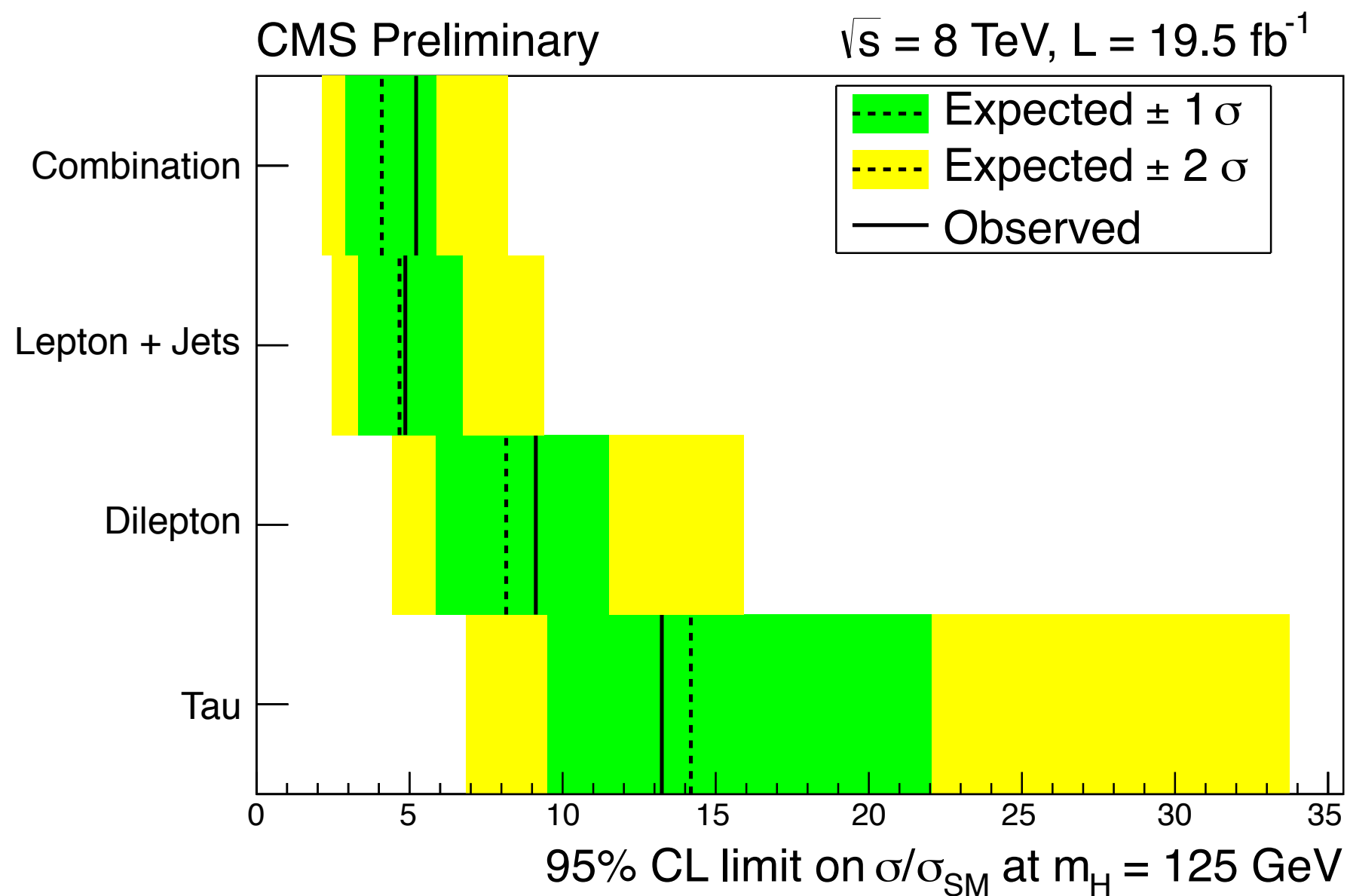
ATLAS RESULTS



Exp: 10.5, Obs: 13.1 @ $M_H = 125 \text{ GeV}$



CMS RESULTS

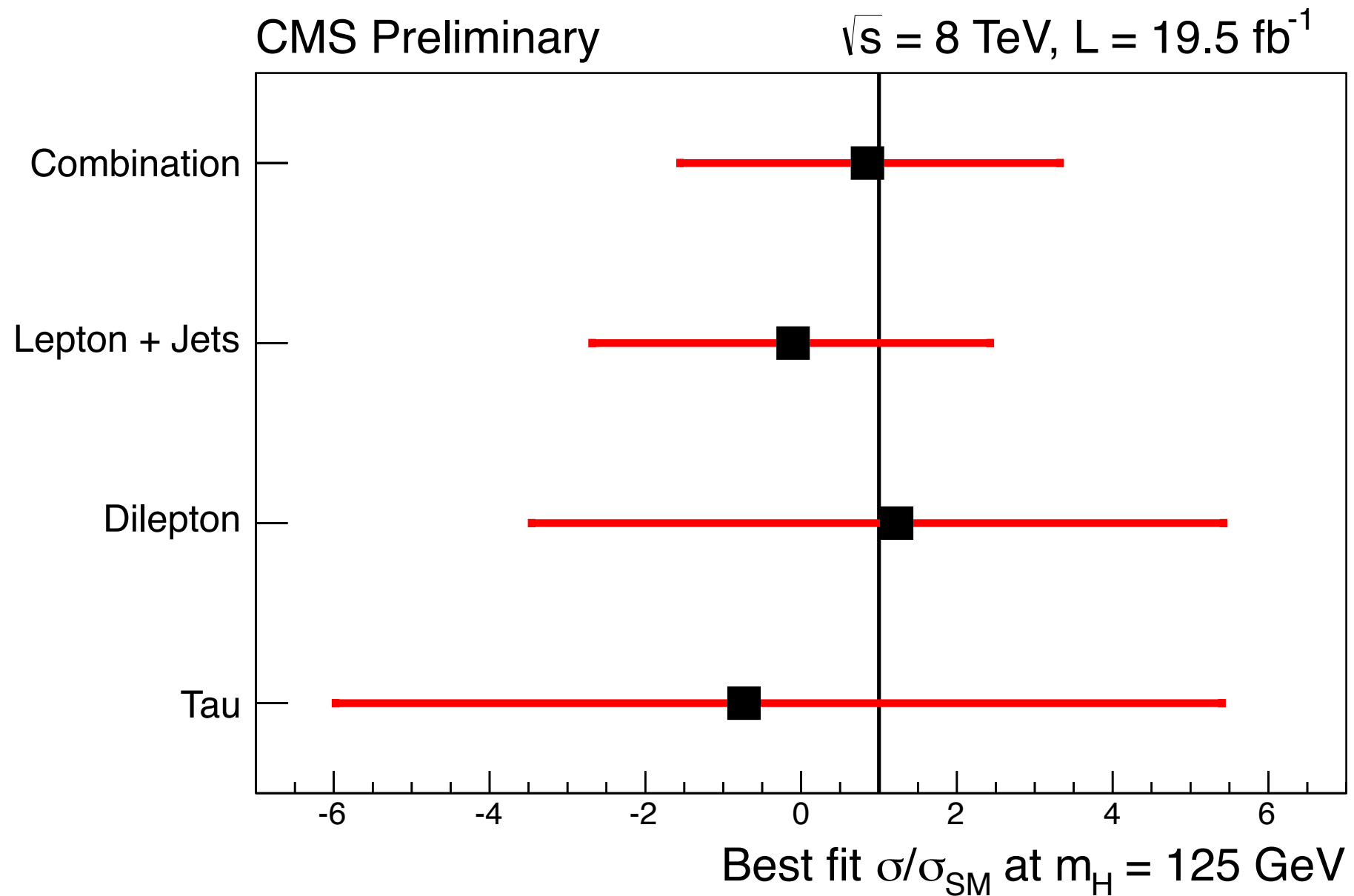
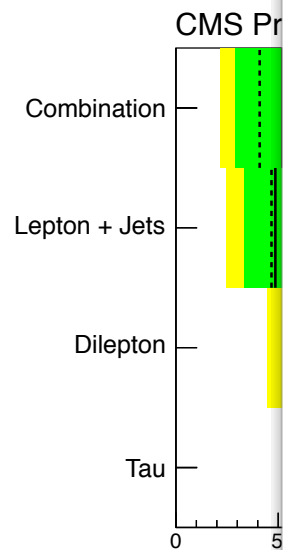


Combined: Exp (Obs) Limit = 4.1 (5.2) $\times$ SM





CMS RESULTS

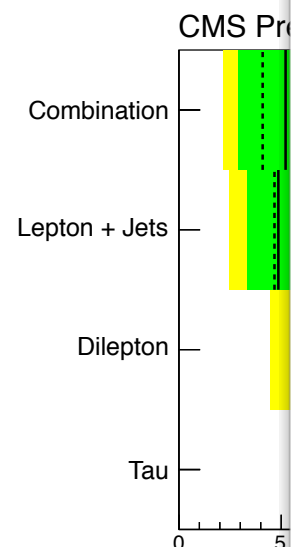


Consistency among results

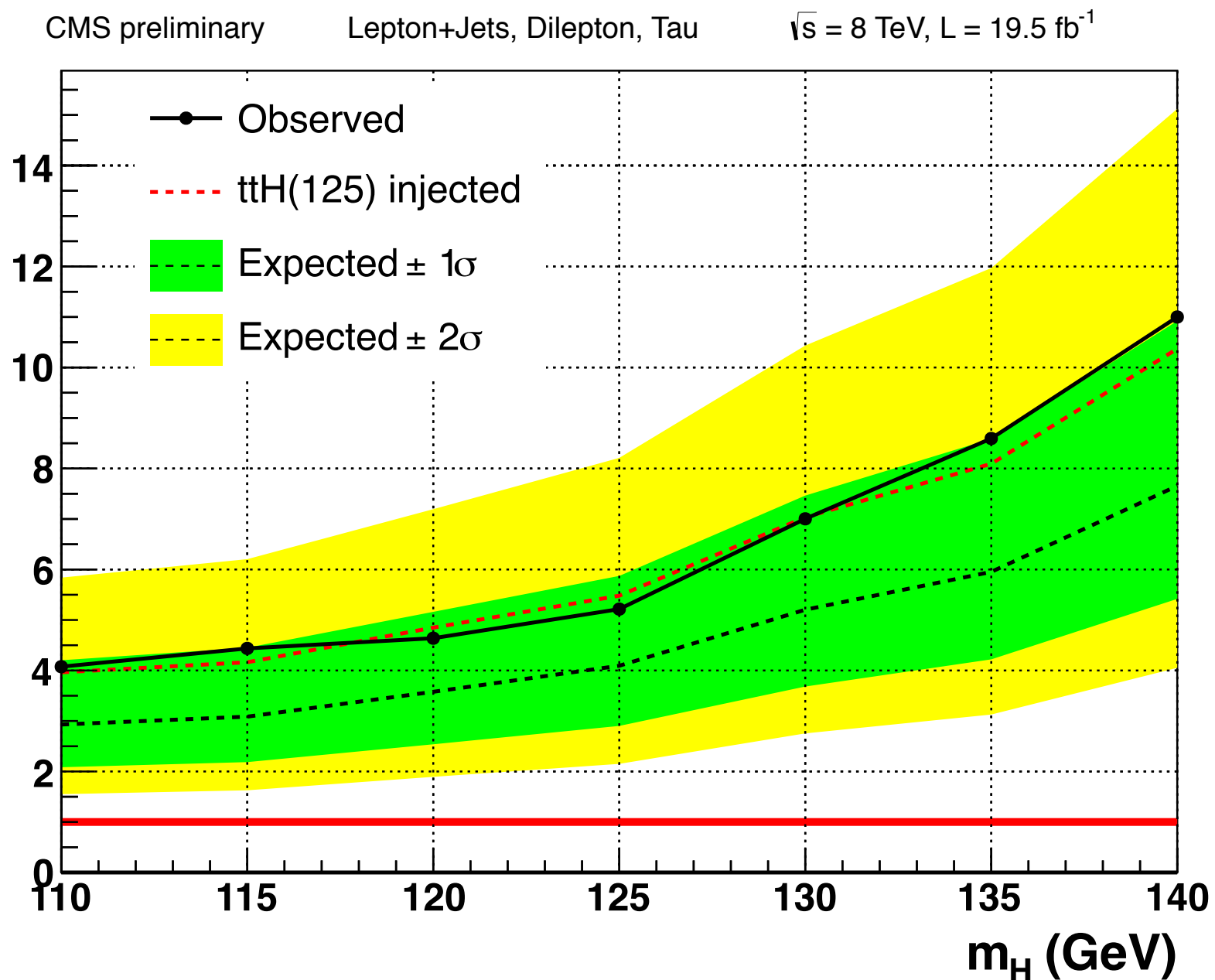




CMS RESULTS



95% CL limit on $\sigma/\sigma_{\text{SM}}$

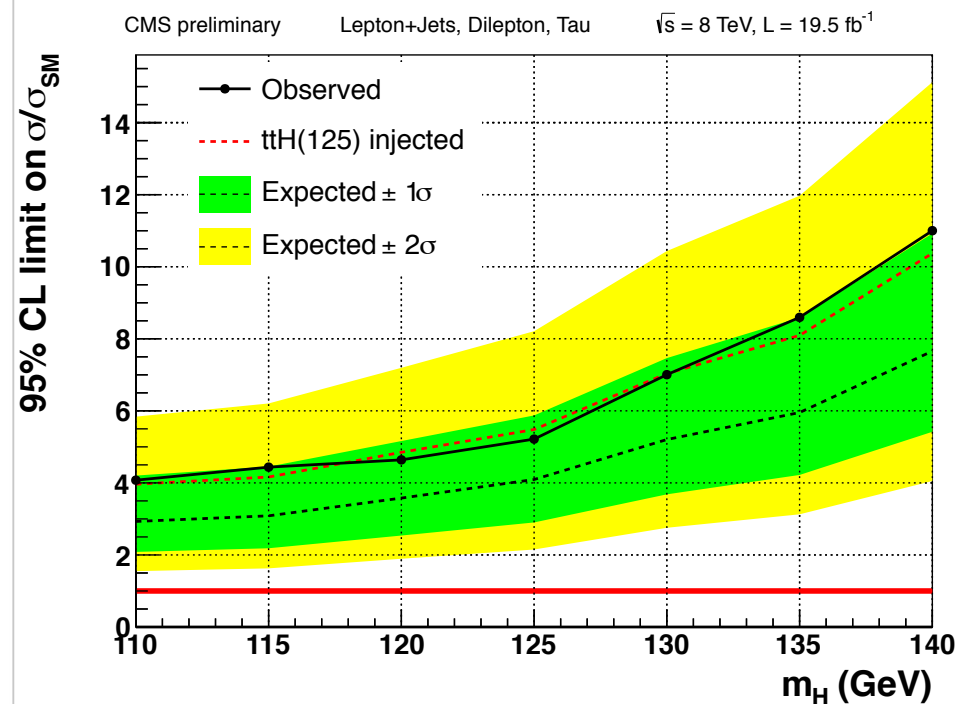
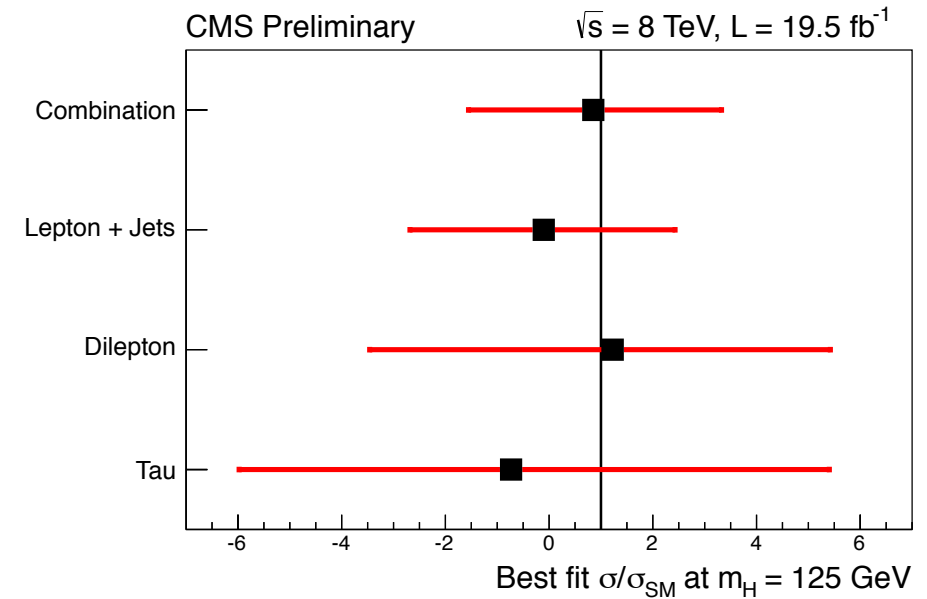
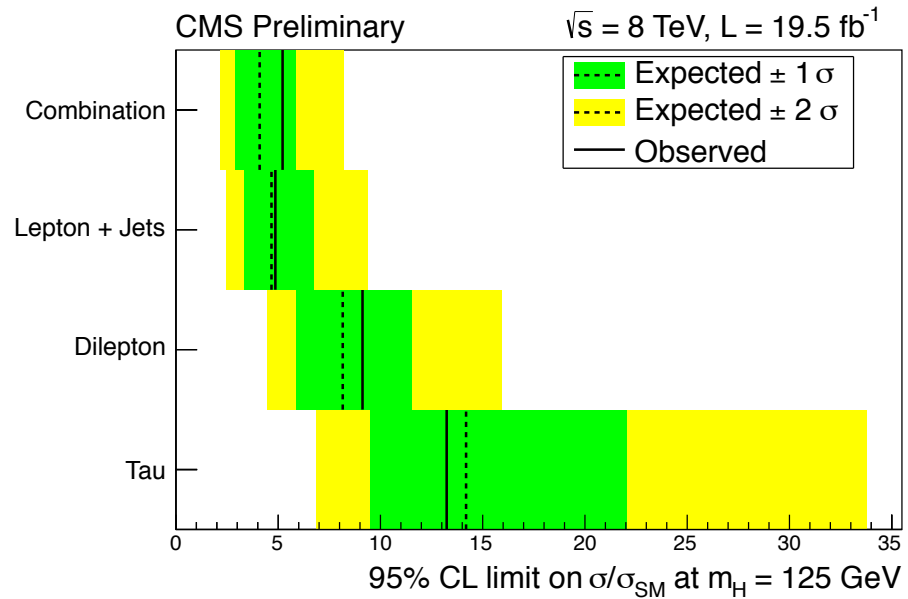


No real mass sensitivity





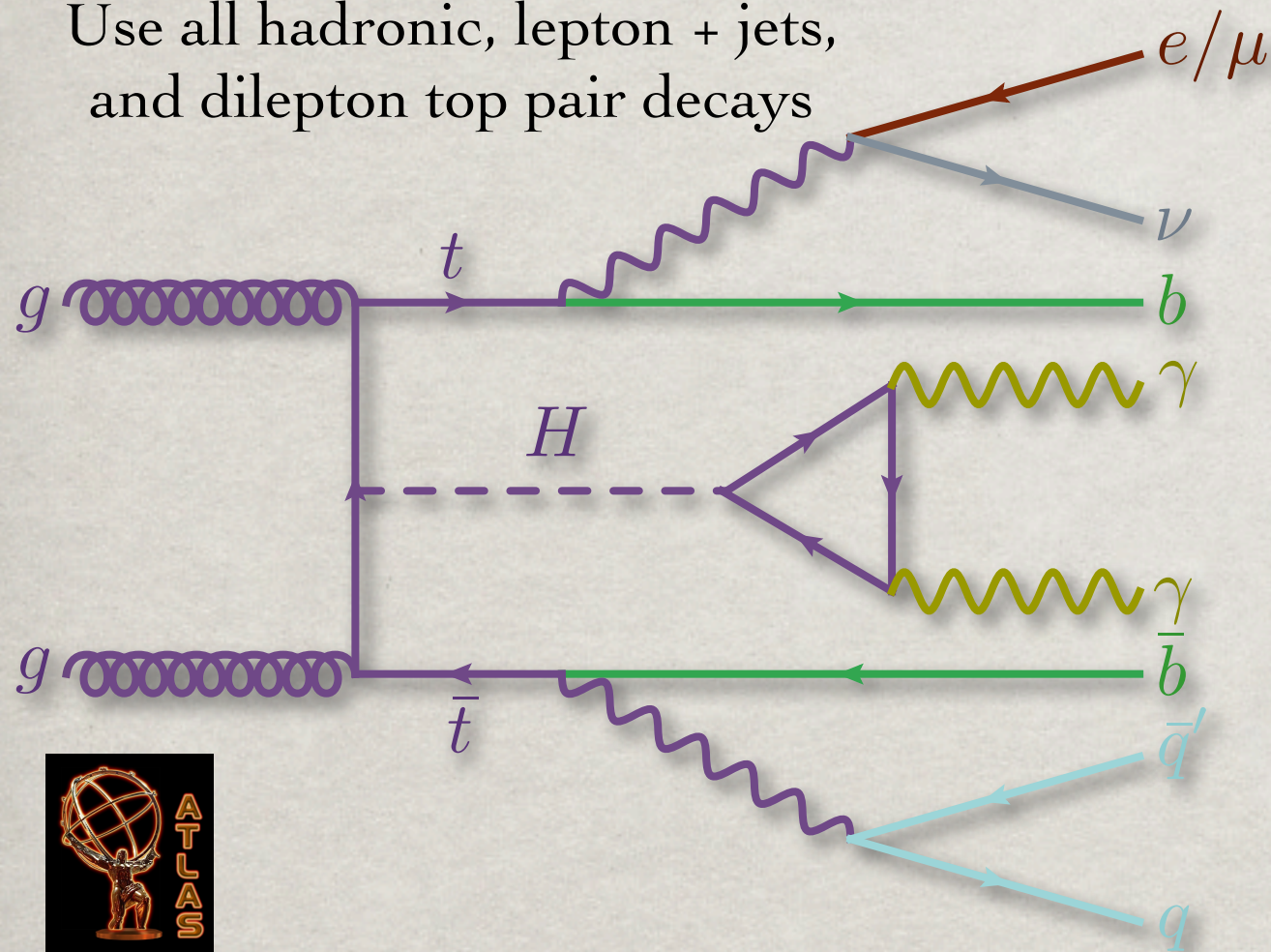
CMS RESULTS



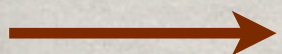
$$H \rightarrow \gamma\gamma$$

SIGNATURE

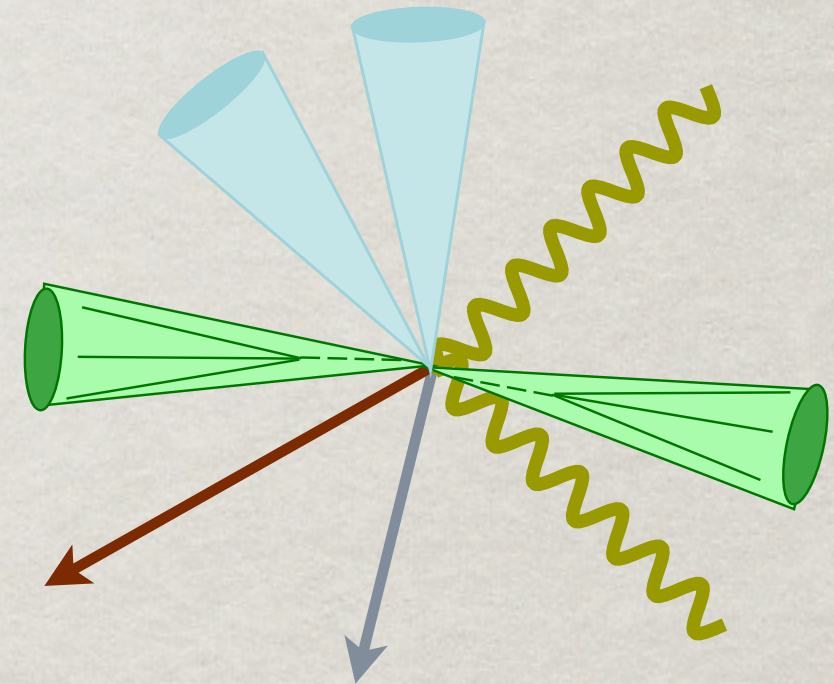
Use all hadronic, lepton + jets,
and dilepton top pair decays



Photon: $|\eta| < 2.37$, isolated
Leading: $p_T > 40$ GeV
Subleading: $p_T > 30$ GeV

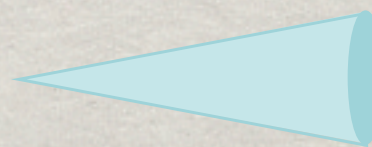


Electron (Muon):
 $p_T > 15$ (10) GeV;
 $|\eta| < 2.47$ (2.7); isolated

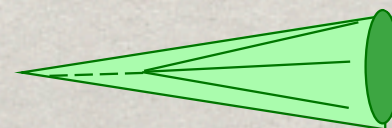


All-Hadronic: 0 leptons; ≥ 6 jets (≥ 2 b -tag)

Lepton+Jets/Dilepton: ≥ 1 lepton;
 ≥ 1 b -tagged jets; $MET \geq 30$ GeV



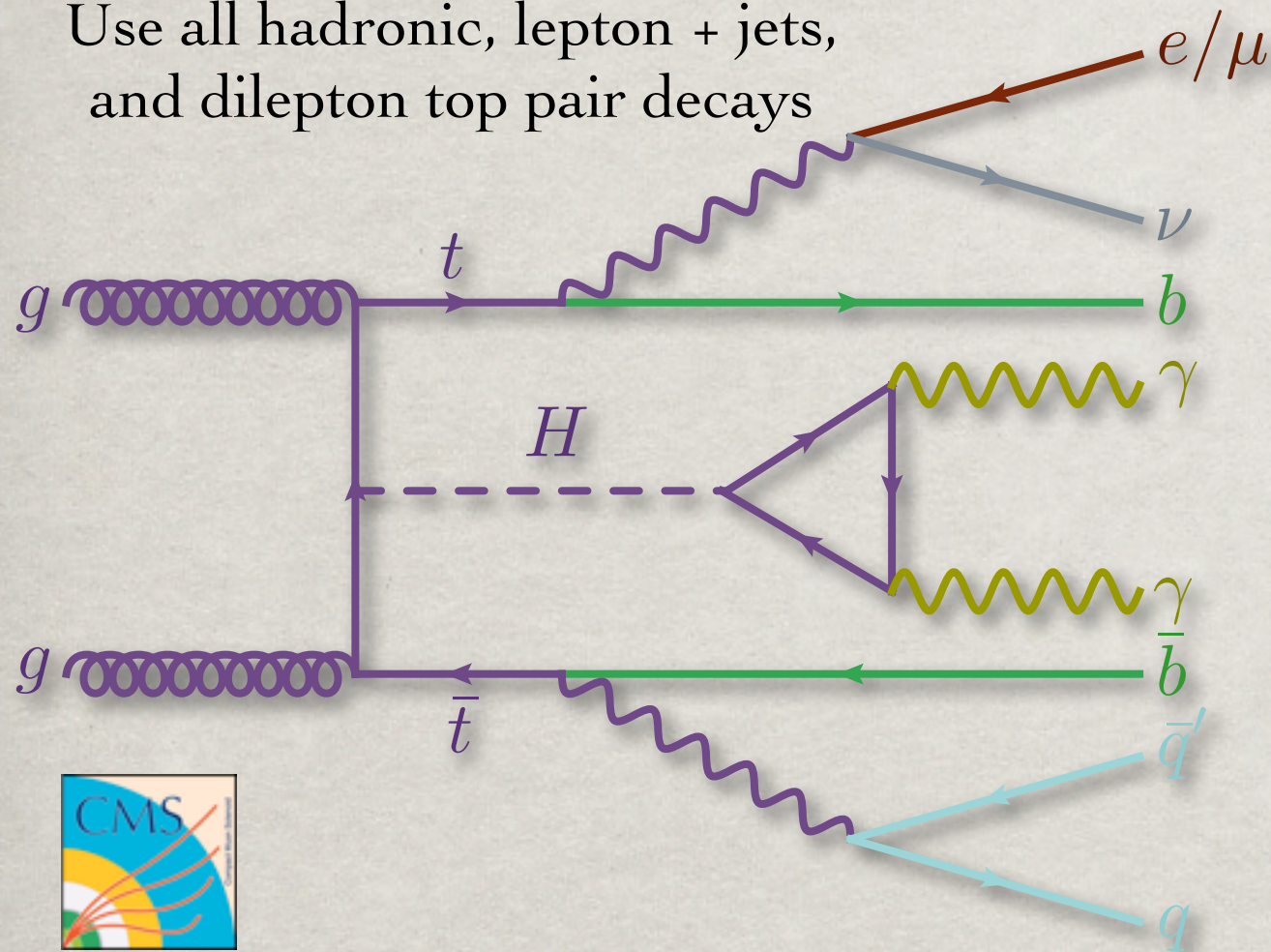
Jet: $p_T > 25$ GeV; $|\eta| < 2.5$



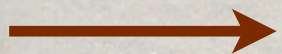
b -Jet: As above tagged by
CSV ($\epsilon_b \approx 70\%$, $\epsilon_{LF} \approx 1\%$)

SIGNATURE

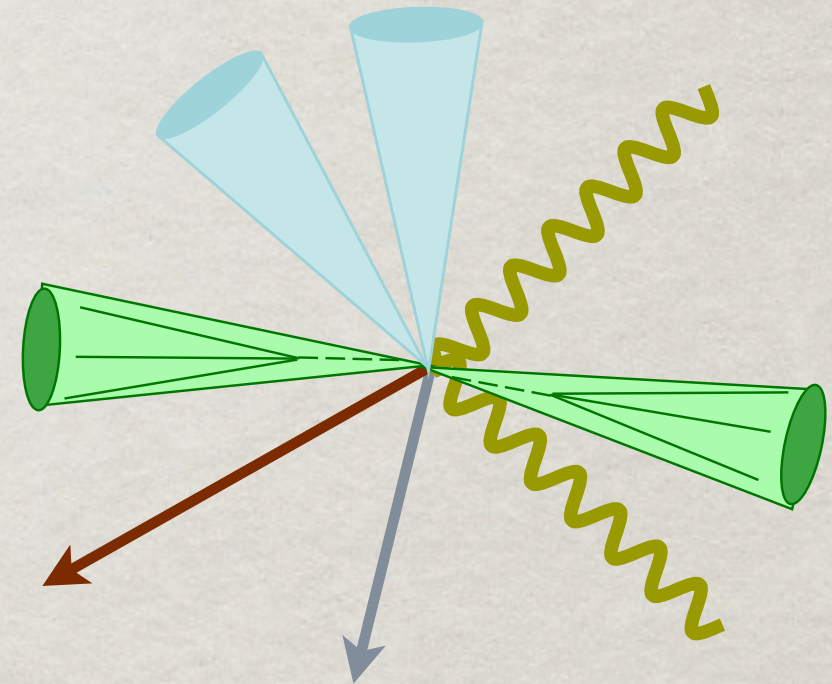
Use all hadronic, lepton + jets,
and dilepton top pair decays



Photon: $|\eta| < 2.5$, isolated
Leading: $p_T > 60 \times (m_{\gamma\gamma}/120 \text{ GeV}) \text{ GeV}$
Subleading: $p_T > 25 \text{ GeV}$

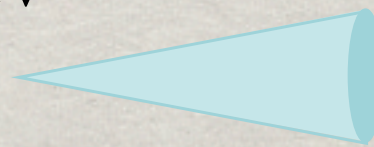


Electron (Muon):
 $p_T > 20 \text{ GeV}$; $|\eta| < 2.5$ (2.4);
isolated

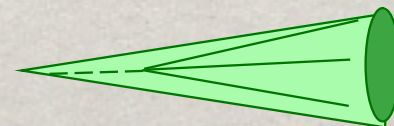


All-Hadronic: 0 leptons; ≥ 4 jets (≥ 1 b -tag)

Lepton+Jets/Dilepton: ≥ 1 lepton; ≥ 2 jets
(≥ 1 b -tag)

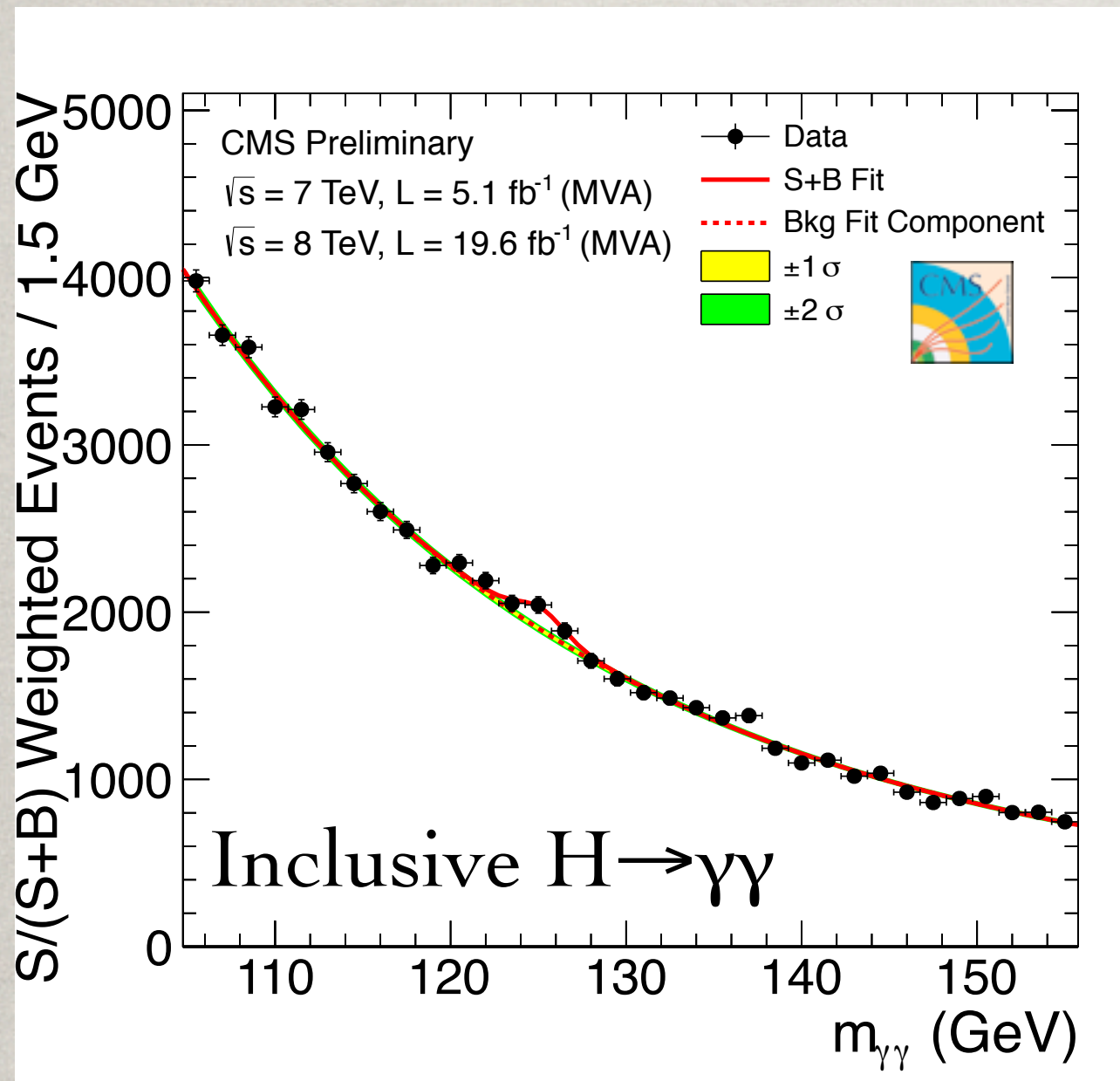


Jet: $p_T > 25 \text{ GeV}$; $|\eta| < 2.4$



b -Jet: As above tagged by
CSV ($\epsilon_b \approx 70\%$, $\epsilon_{LF} \approx 1\%$)

BACKGROUND

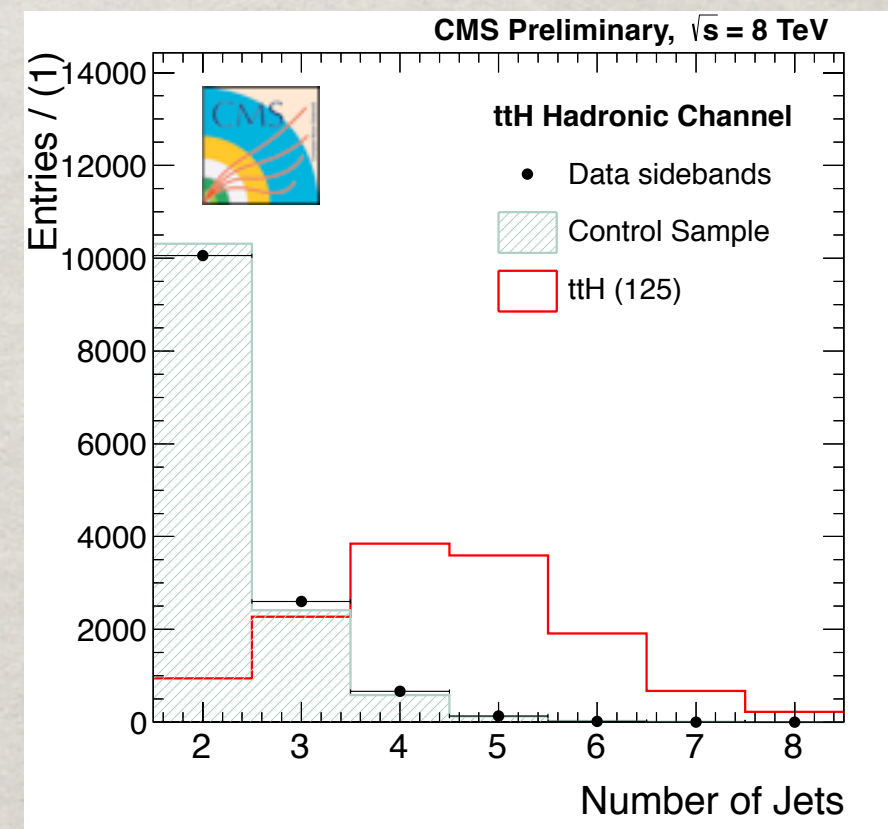
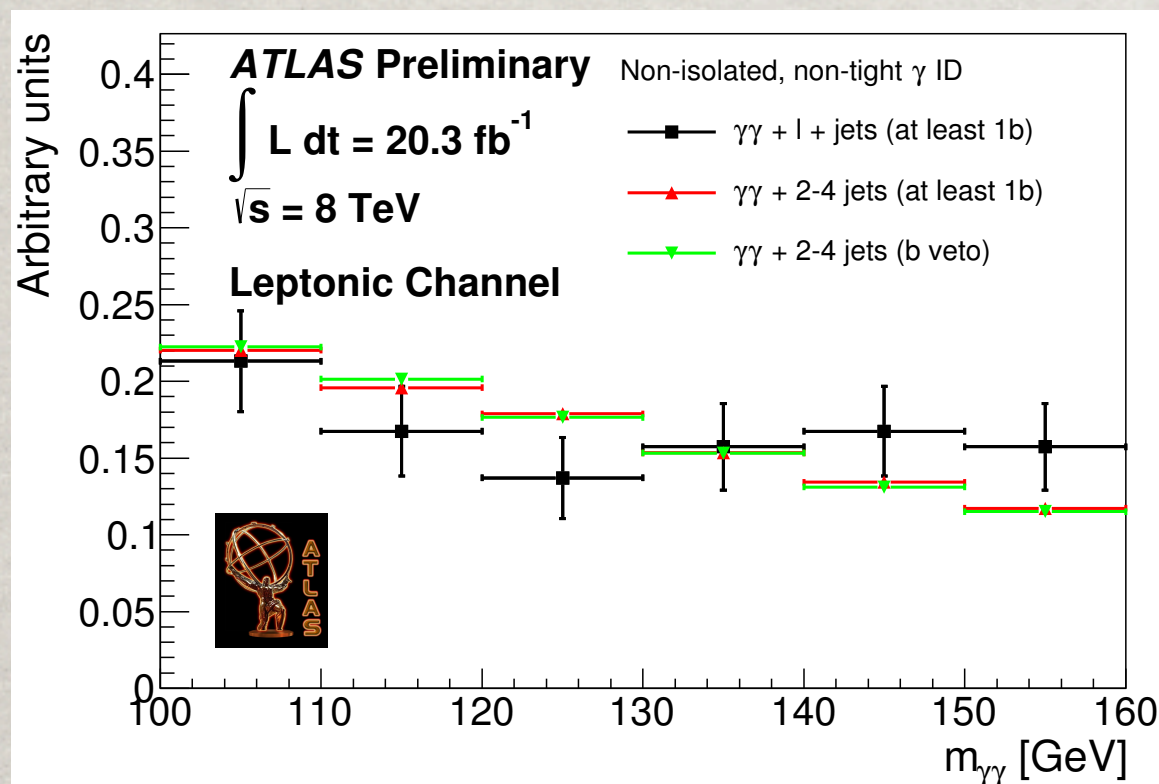


ttH has much fewer events!

- ✱ Main backgrounds:
 - ✱ tt +photons
 - ✱ tt +jets ($\rightarrow$ fake photons)
- ✱ Estimate model backgrounds
 - ✱ Take advantage of excellent mass resolution
 - ✱ Backgrounds should be smoothly falling distribution

CONTROL REGIONS

- Low statistics in signal region makes fitting background challenging
- Validate background fitting function in control region with more statistics
- Control region defined by inverting photon ID requirements for at least one of the two photons



HIGGS AS BACKGROUND!

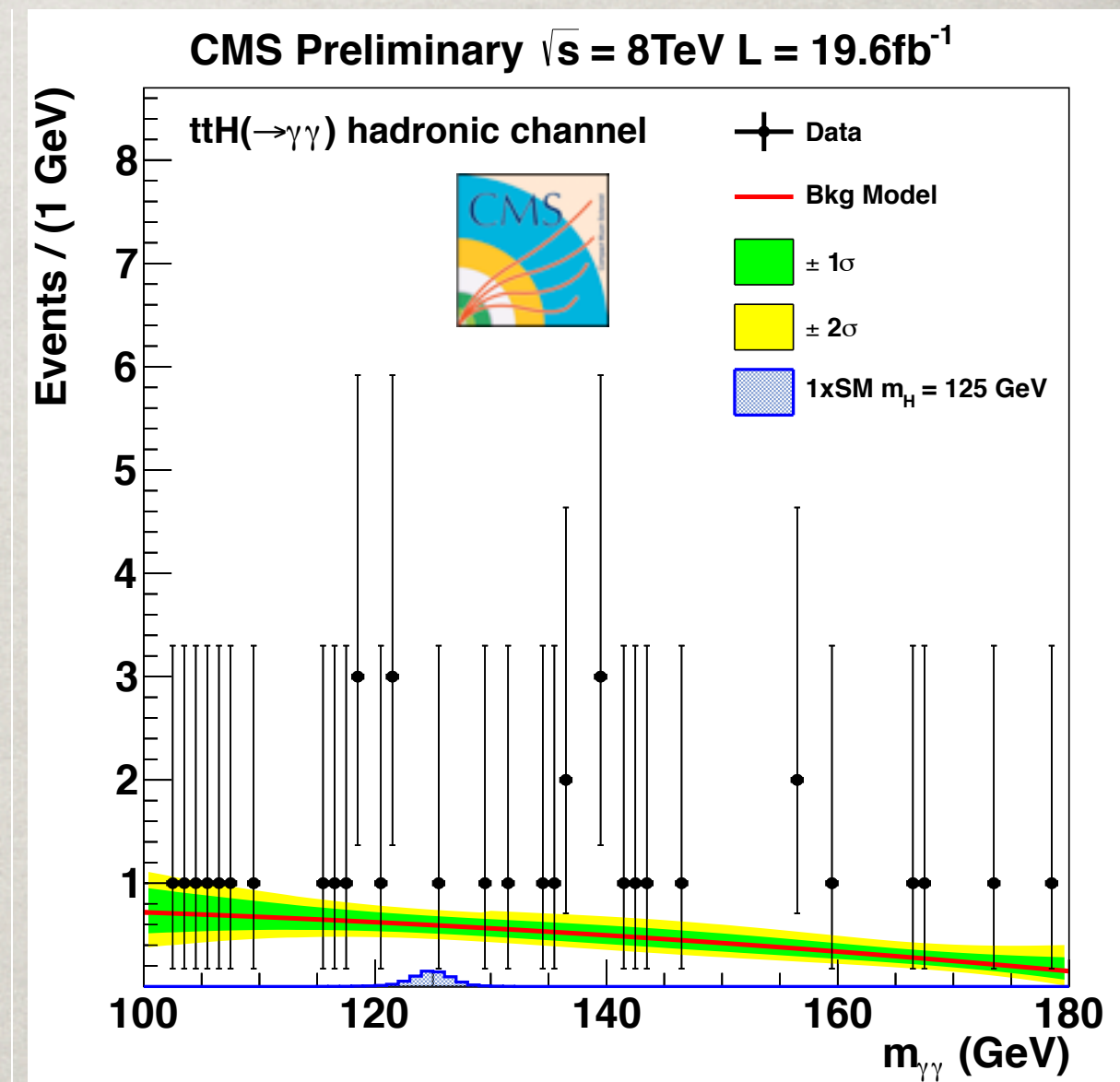
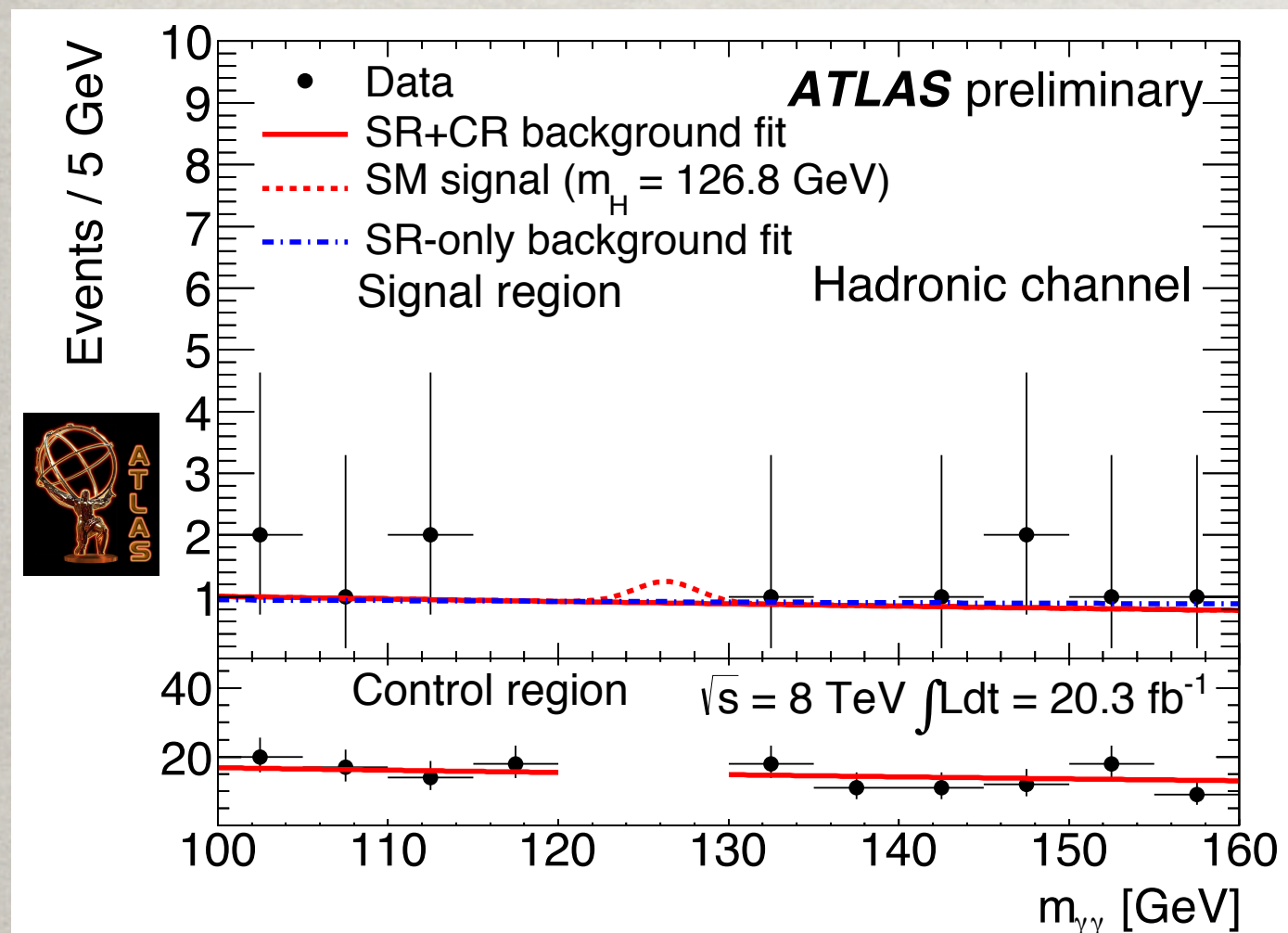


Channel	N_S	$ggF(\%)$	$VBF(\%)$	$WH(\%)$	$ZH(\%)$	$tH(\%)$	$t\bar{t}H(\%)$	Process	Hadronic Channel	Leptonic Channel
Leptonic	0.55	0.6	0.3	7.7	2.4	6.1	82.8	$t\bar{t}H$	0.567 (87%)	0.429 (97%)
Hadronic	0.36	5.3	1.1	1.1	1.3	—	91.2	$gg \rightarrow H$	0.059 (9%)	0 (0%)
								$VBF H$	0.006 (1%)	0 (0%)
								WH/ZH	0.019 (3%)	0.013 (3%)
								Total signal	0.65	0.44

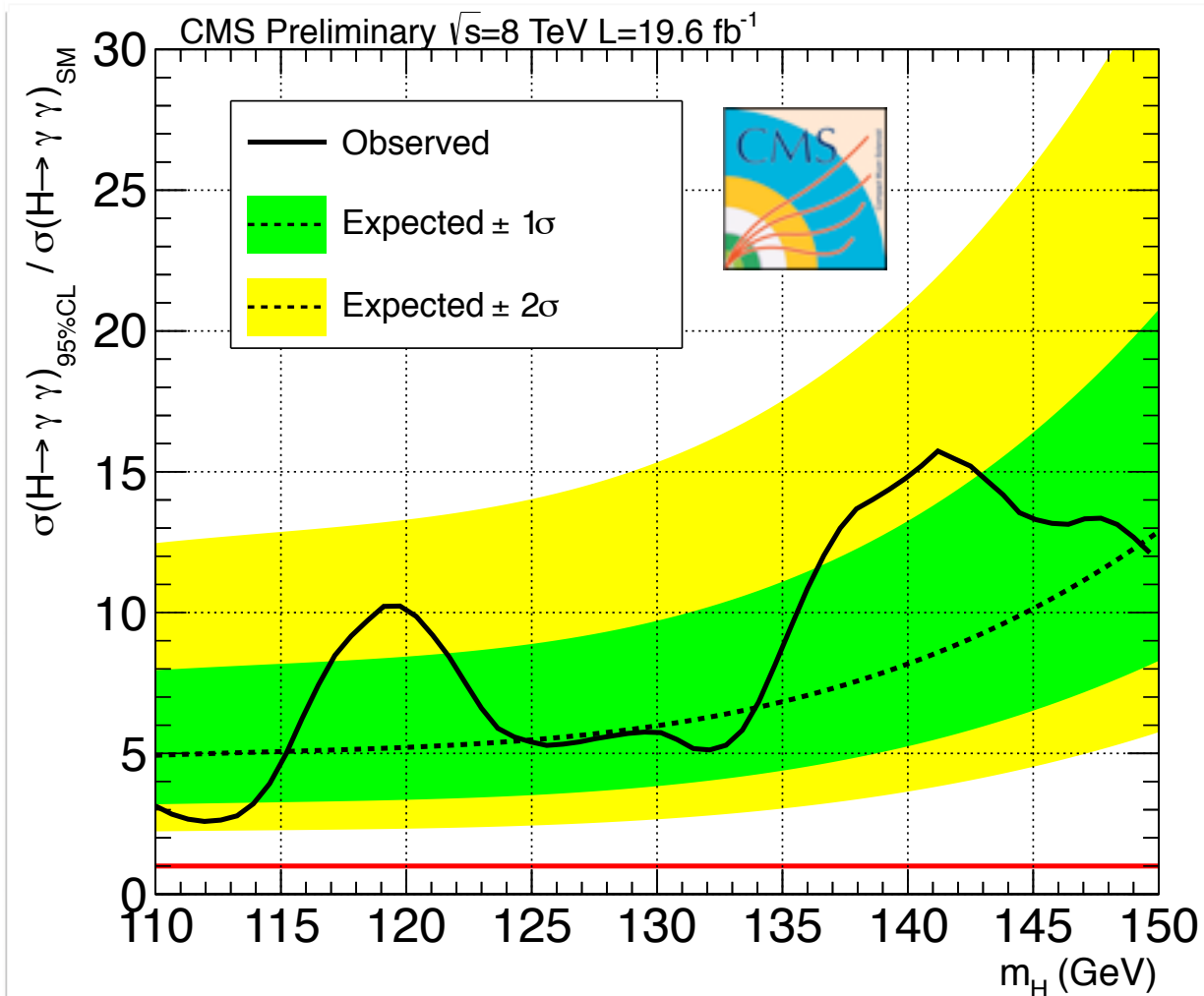
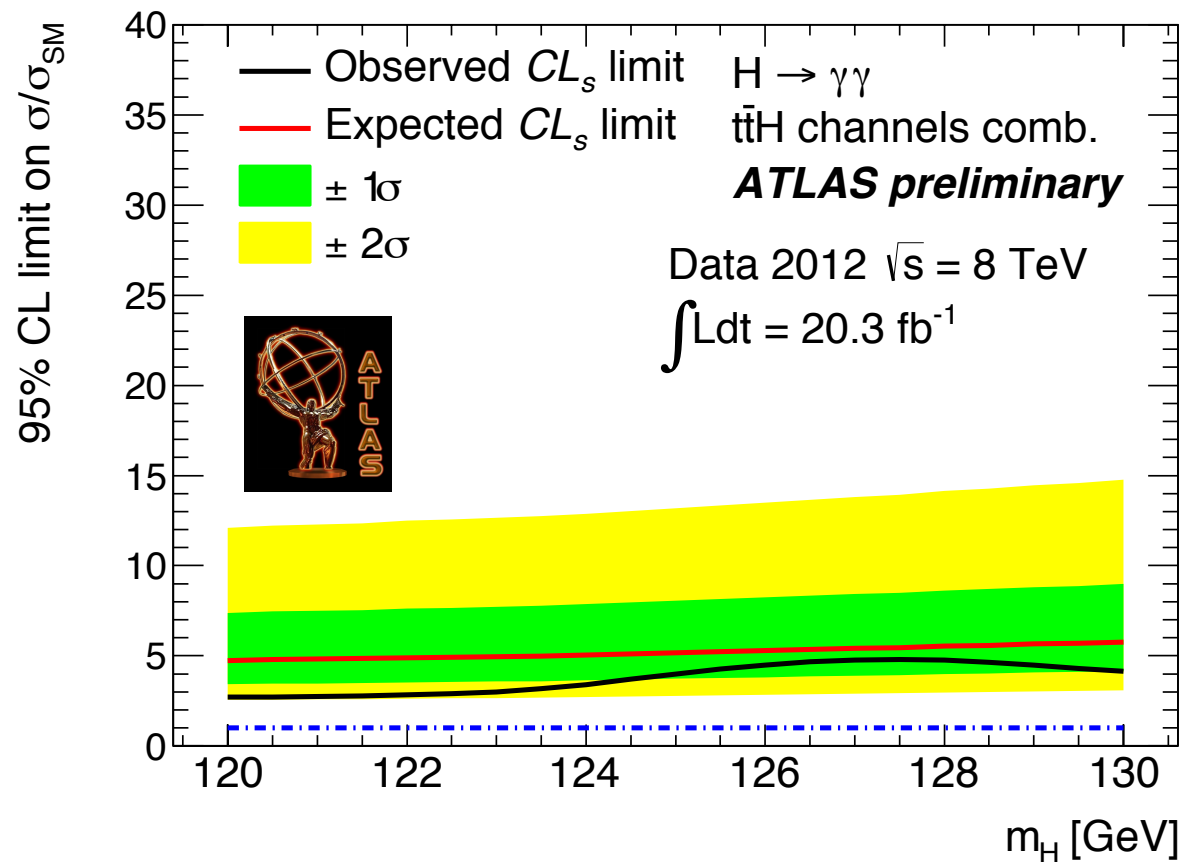
- Other Higgs production mechanisms can be treated as signal or background depending on question you're trying to answer
- Prediction based on same MC used for signal modeling in other Higgs analyses
 - Challenge: Need to consider signal with extra jets/b-tags
 - Uncertainties on prediction combine theoretical and experimental constraints
 - Standard uncertainties on (N)NLO predictions
 - Additional uncertainties extracted from studies of $t\bar{t}$ +jets/ $t\bar{t}$ +bb

MODELING

- ✱ Smooth fit function chosen: Exponential (CMS All-had is 2nd-order polynomial)
- ✱ Background function fit simultaneously with signal extraction



RESULTS

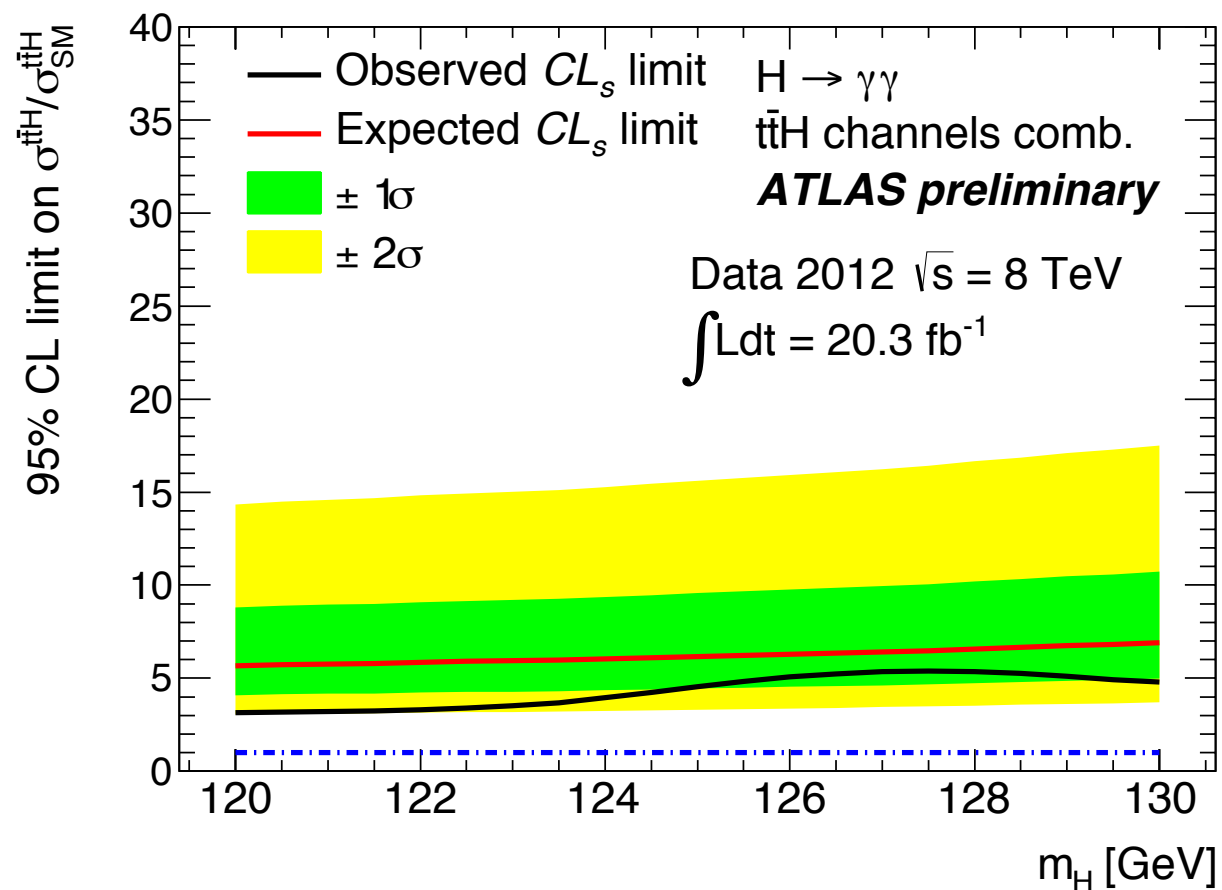


Exp: 5.4, Obs: 4.7 @ $M_H = 126.8 \text{ GeV}$

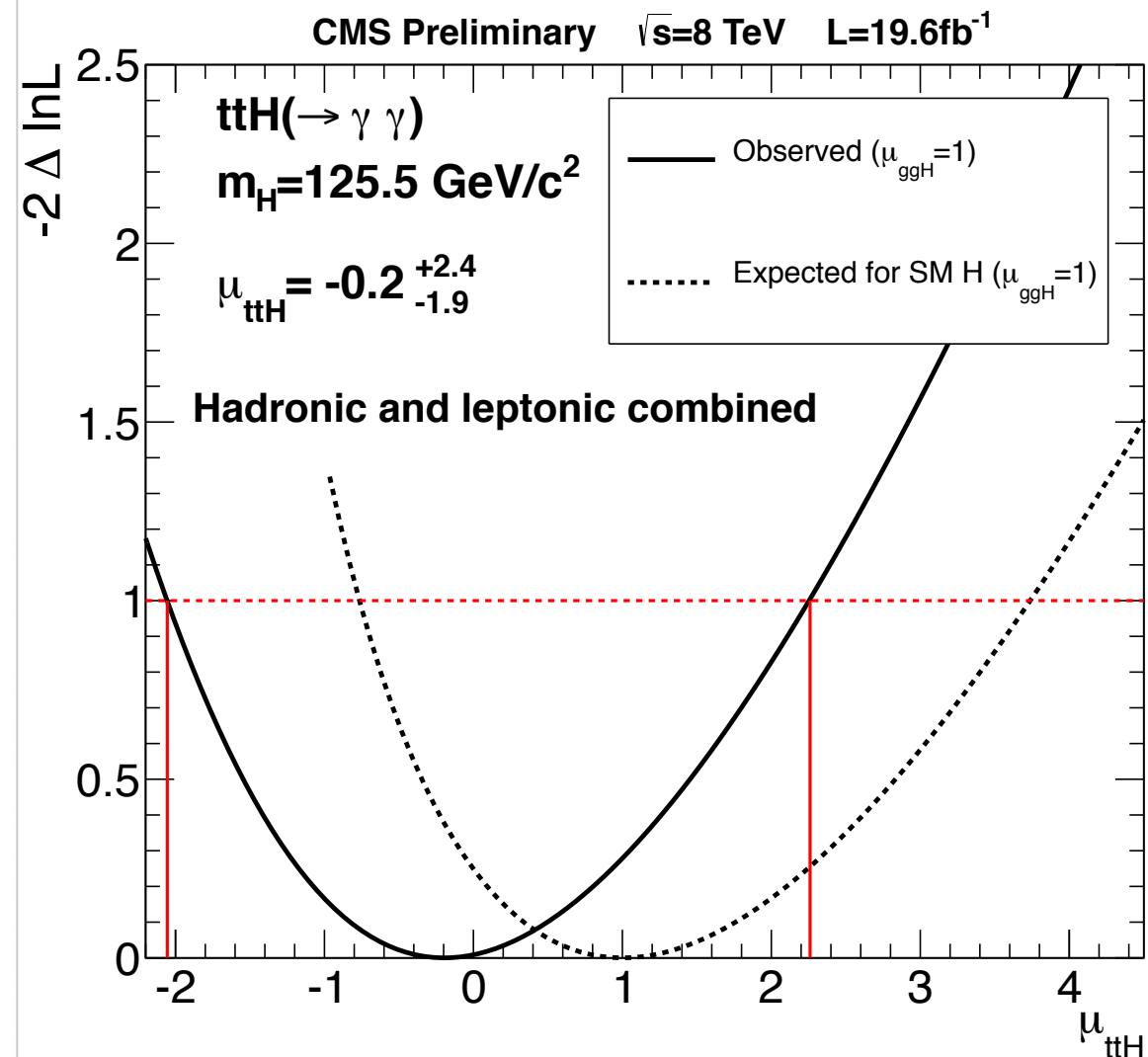
Exp: 5.3, Obs: 5.4 @ $M_H = 126.8 \text{ GeV}$

Limit set on overall Higgs production

RESULTS



Exp: 6.4, Obs: 5.3 @ $M_H = 126.8$ GeV



Fixing other Higgs production to SM expectation.

Electron

Jets

Muon

Photons

MET

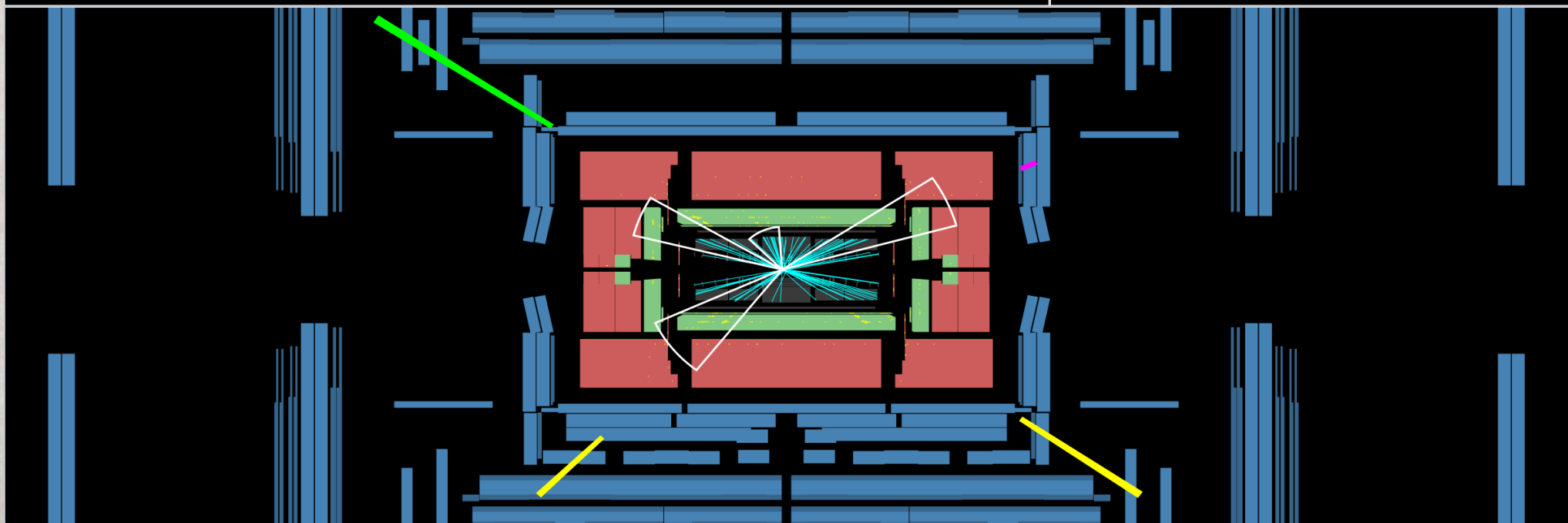


ATLAS

EXPERIMENT

Run Number: 206971, Event Number: 40173184

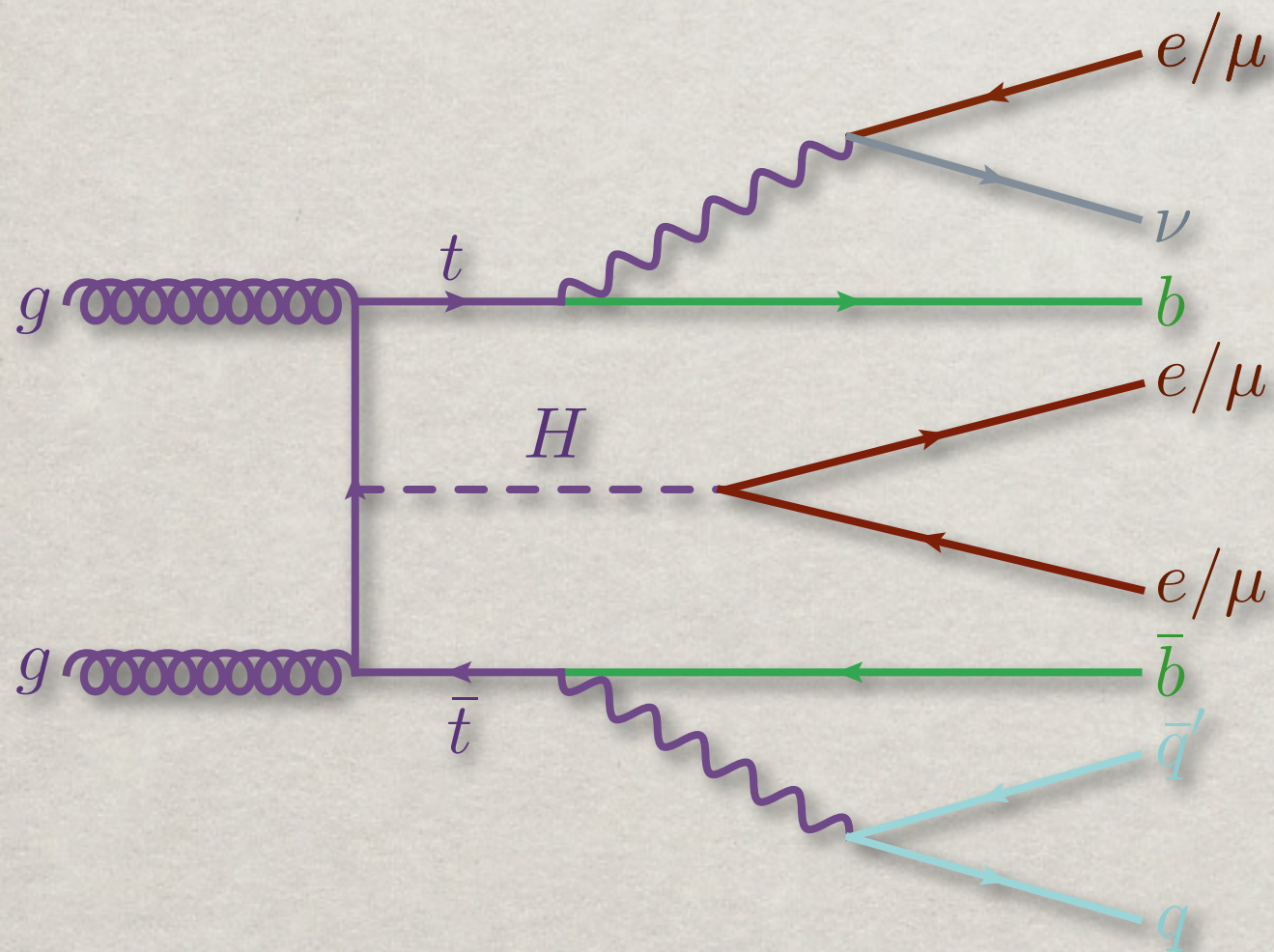
Date: 2012-07-14 23:57:00 CEST



$H \rightarrow \text{LEPTONS}$

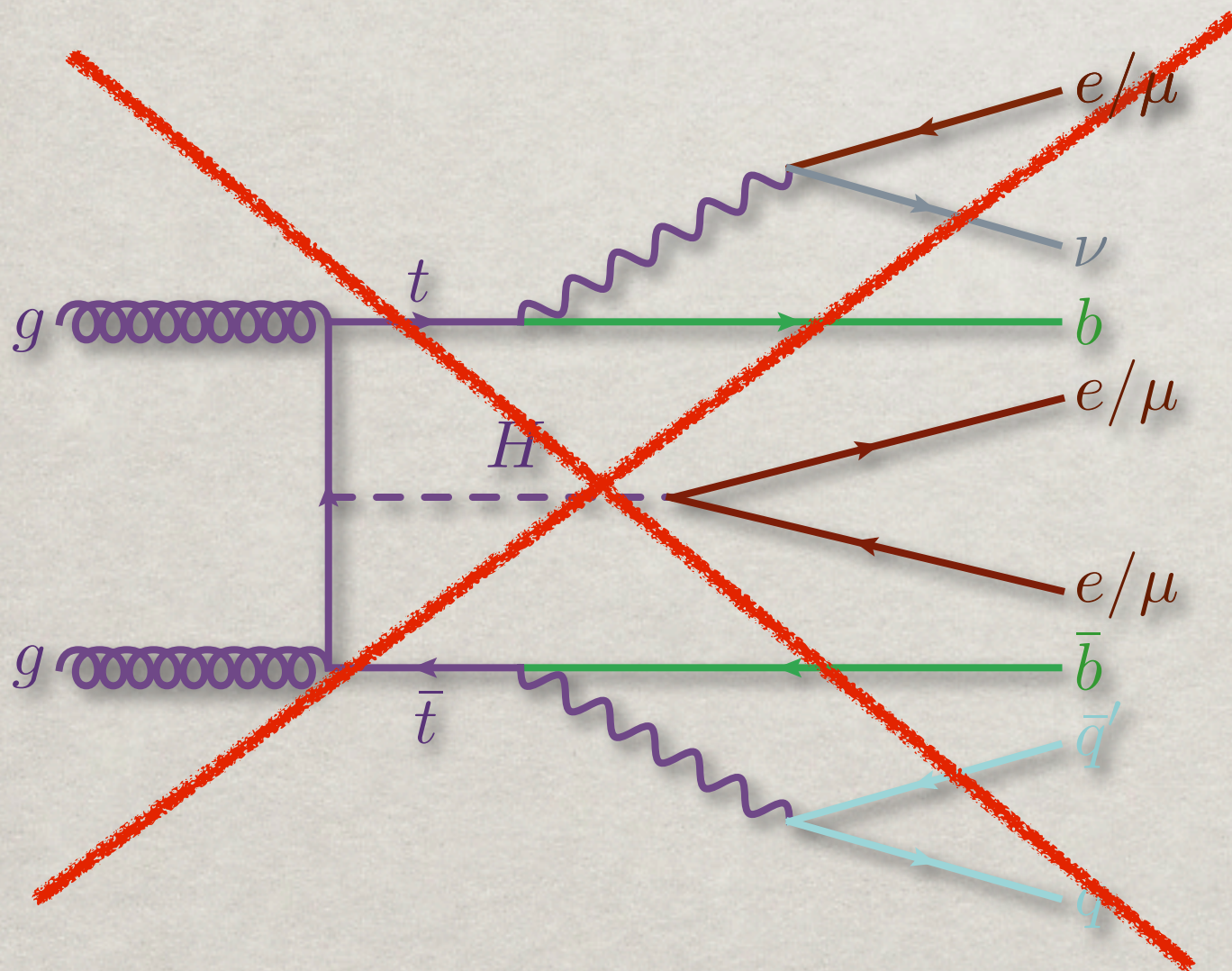
SIGNATURES

- ✱ Higgs decaying **directly** to leptons (e , or μ) too rare (for this luminosity anyway...)



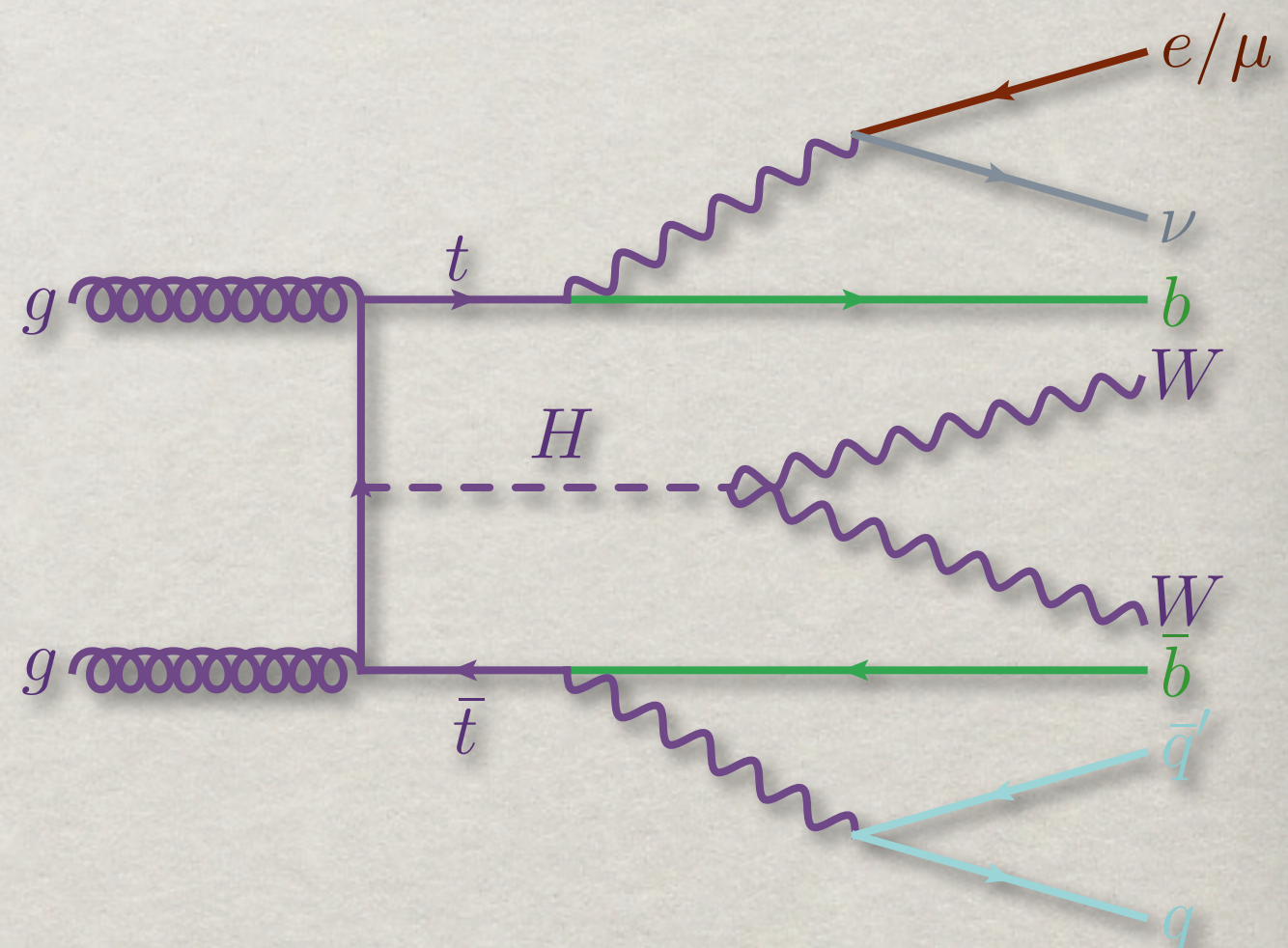
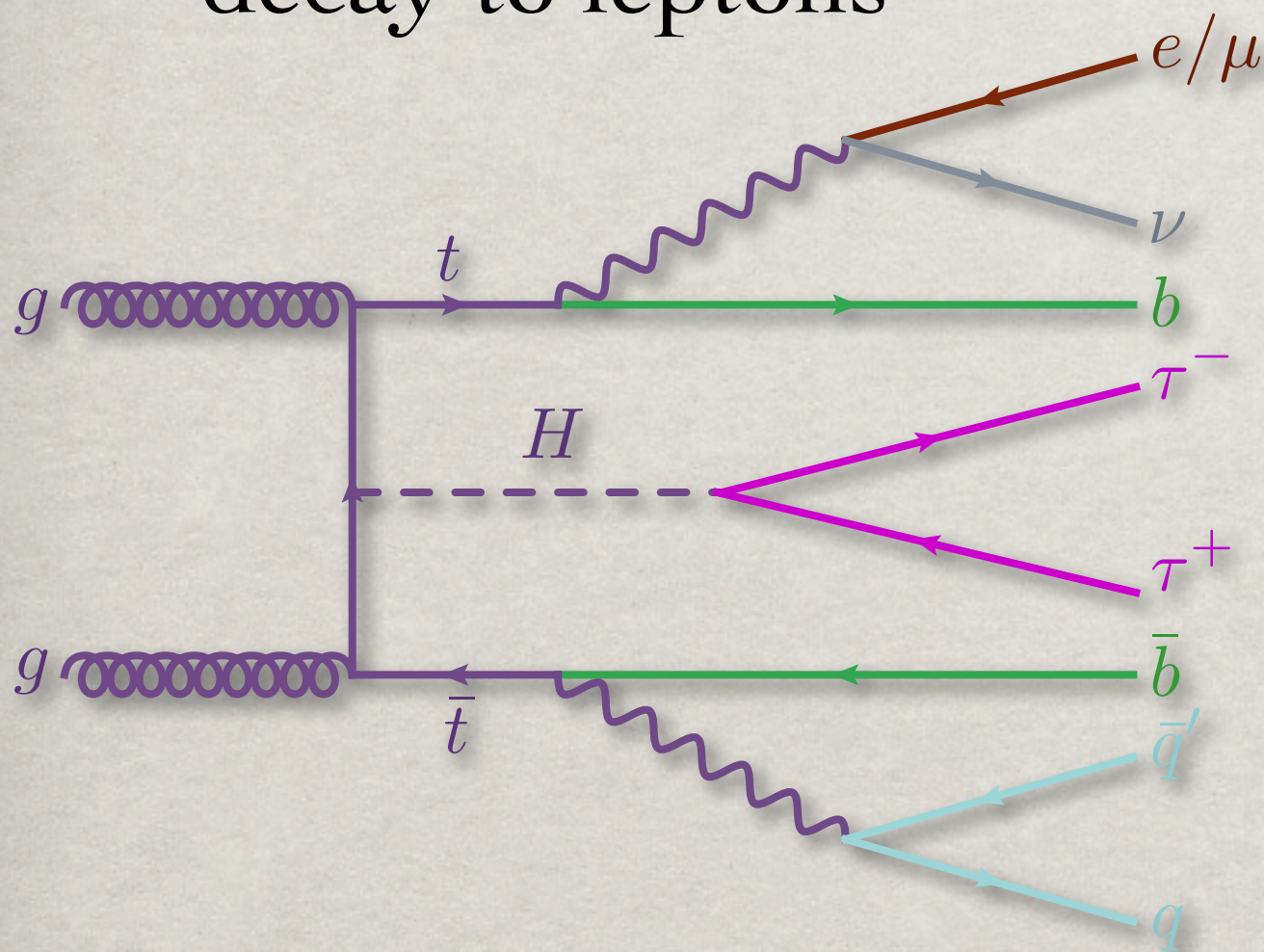
SIGNATURES

- ✱ Higgs decaying **directly** to leptons (e , or μ) too rare (for this luminosity anyway...)



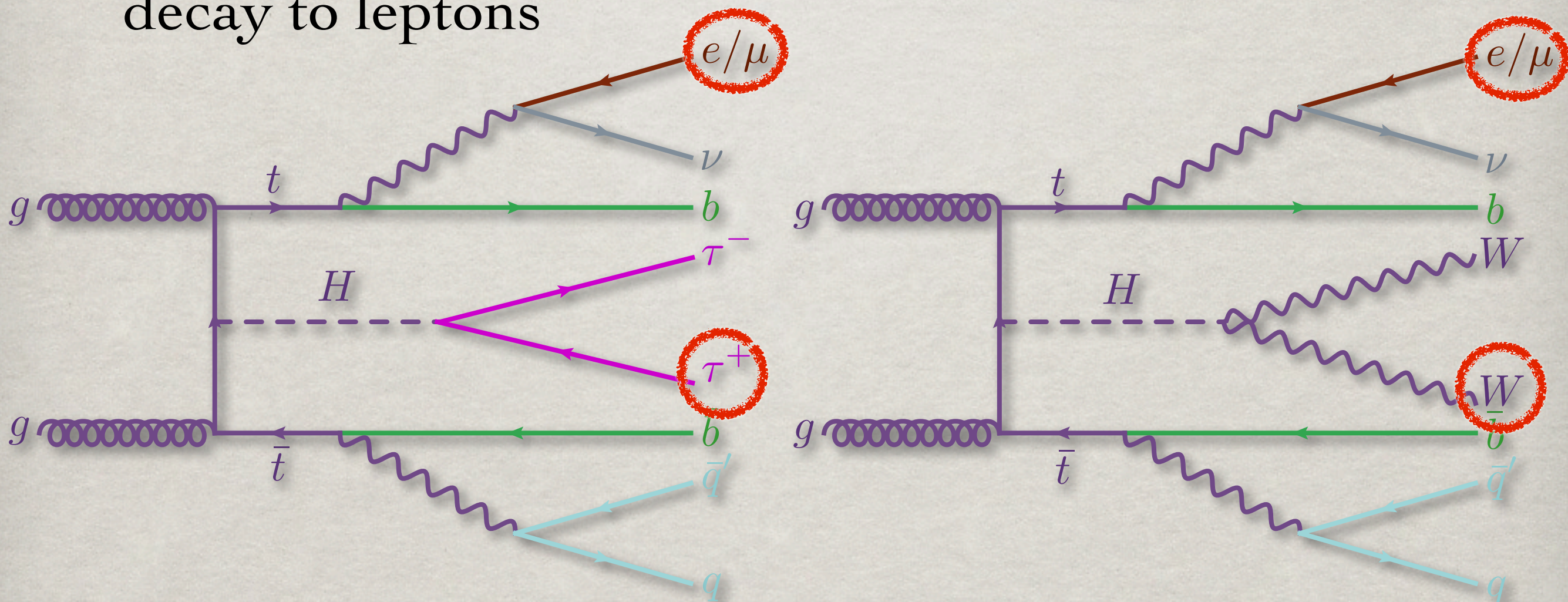
SIGNATURES

- ✱ There are several Higgs final states that subsequently decay to leptons



SIGNATURES

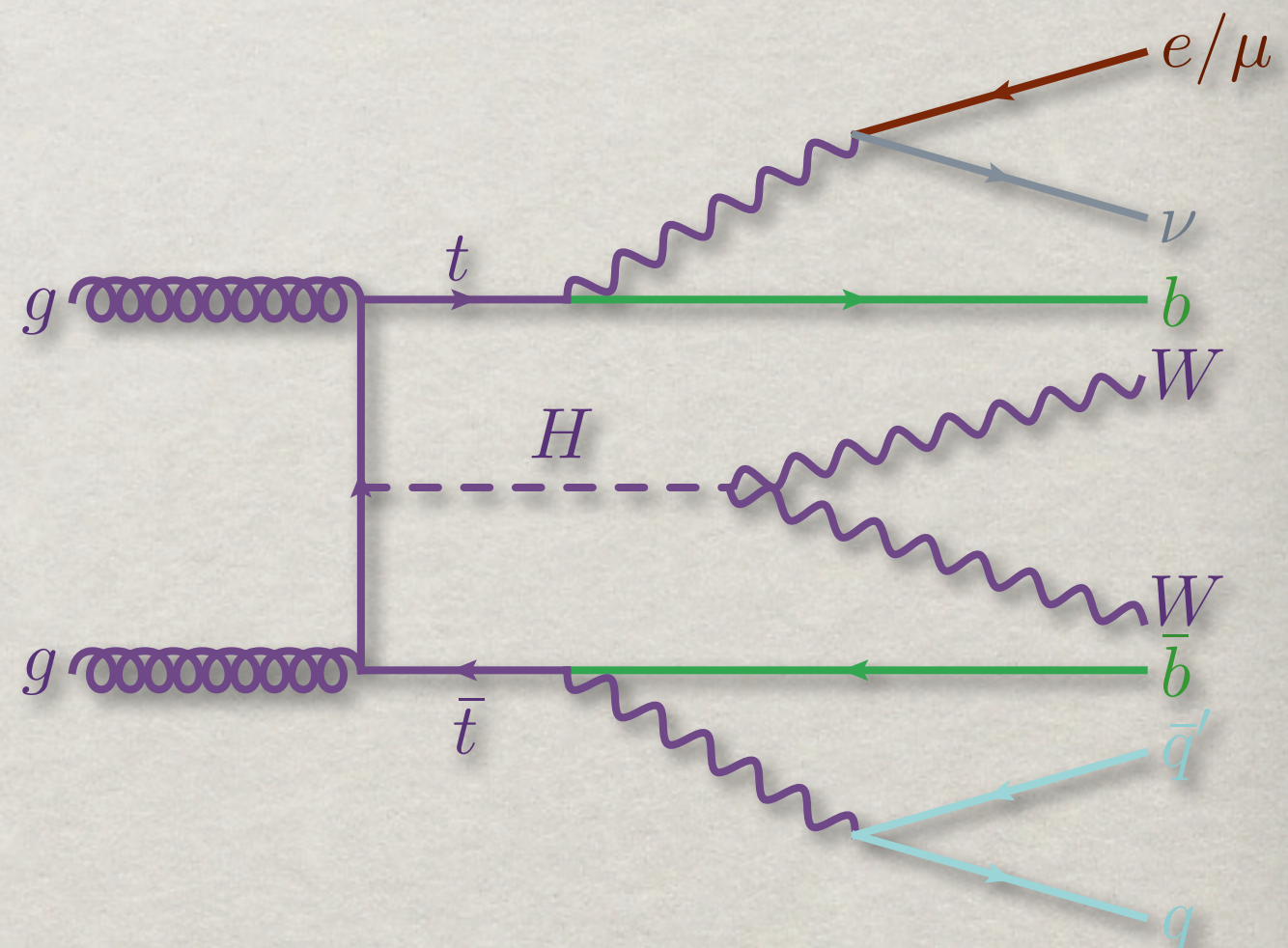
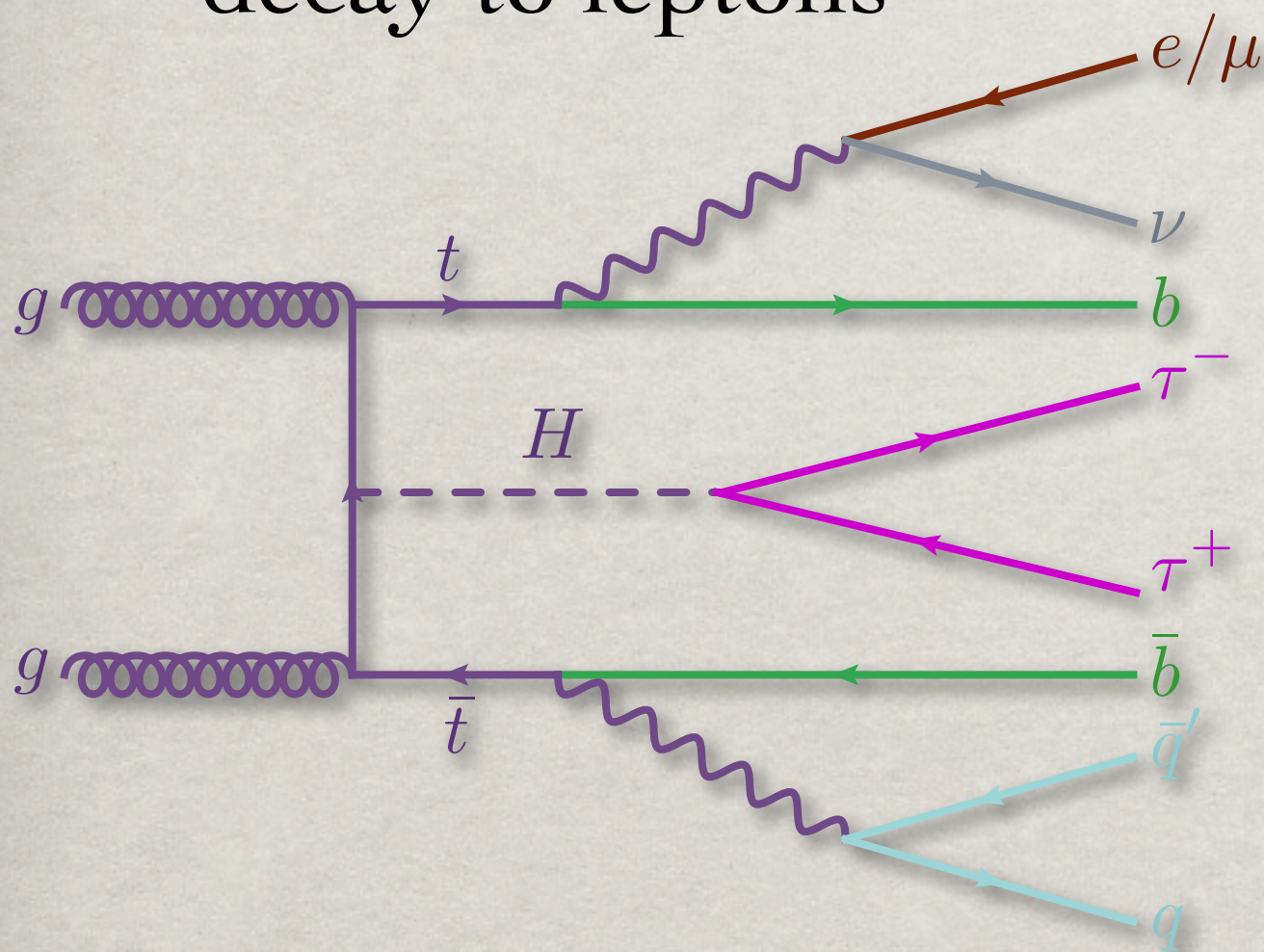
- There are several Higgs final states that subsequently decay to leptons



One lepton from top decay, one lepton from Higgs:
SS lepton pair + 2 b -jets + 3-4 other jets

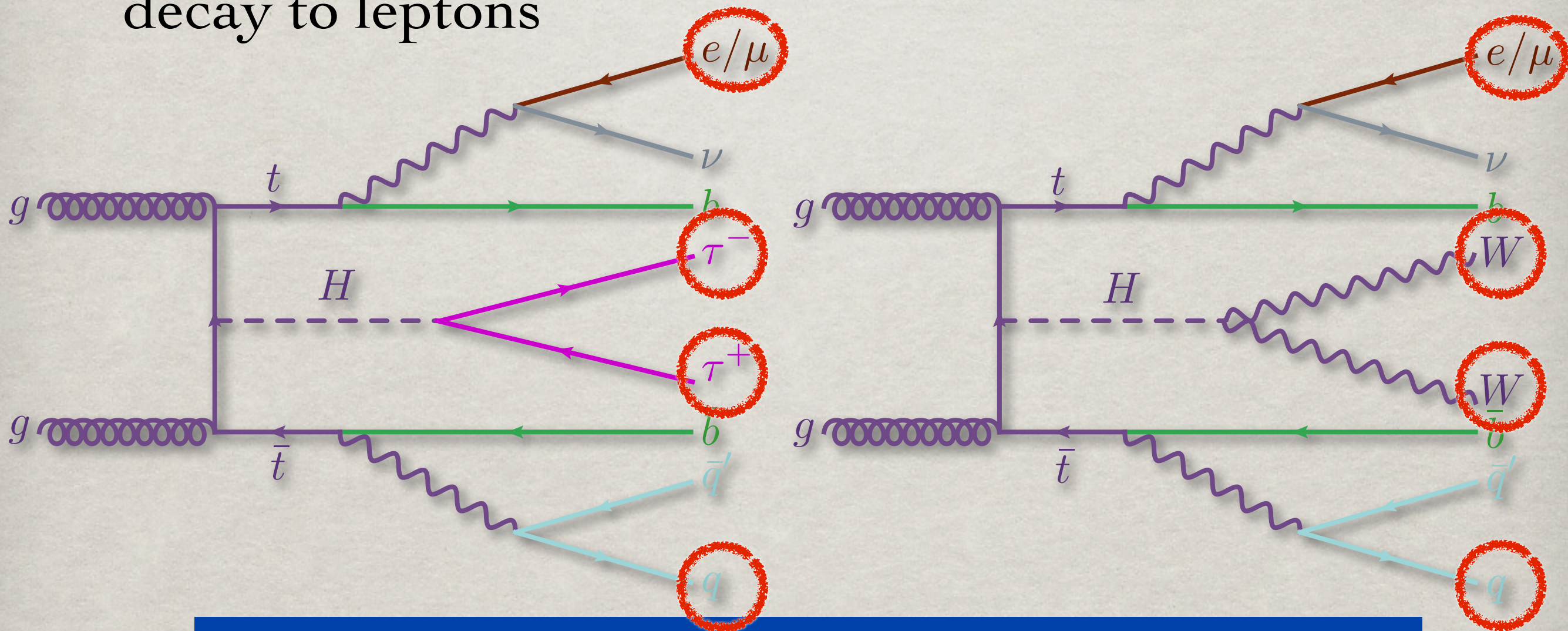
SIGNATURES

- There are several Higgs final states that subsequently decay to leptons



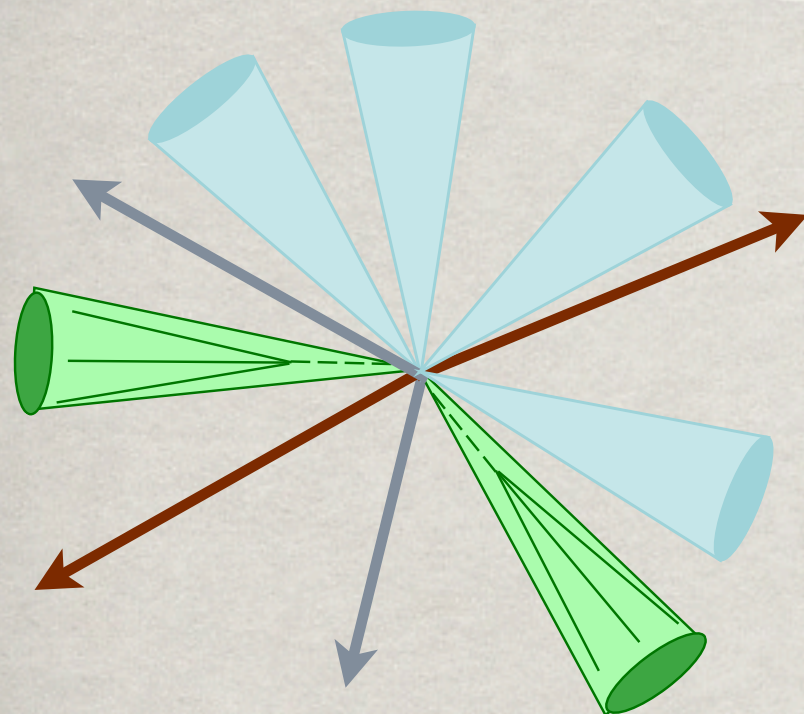
SIGNATURES

- There are several Higgs final states that subsequently decay to leptons

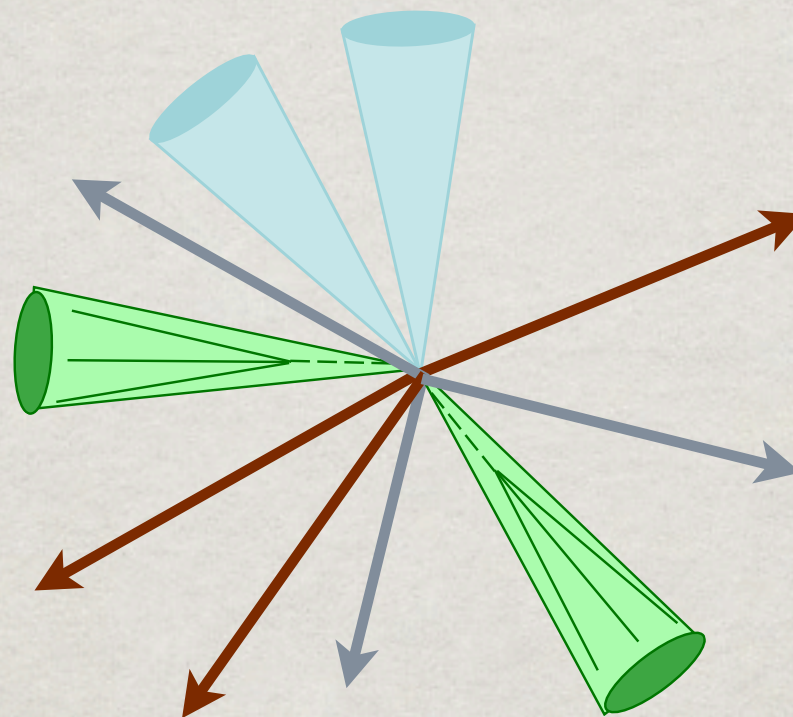


1-2 leptons from top decay, 1-2 leptons from Higgs:
3-4 lepton pair + 2 b -jets + 0-2 other jets

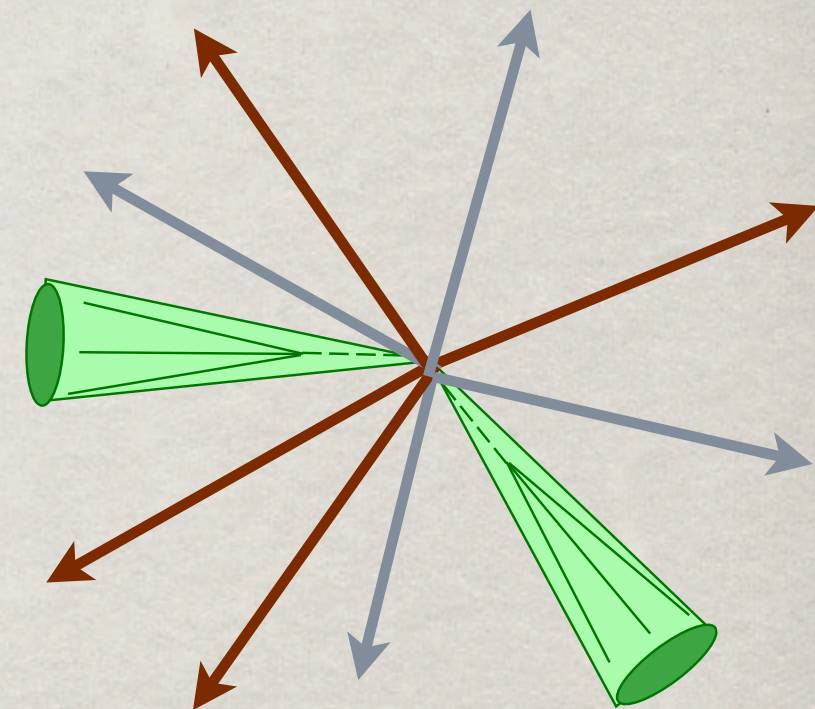
SIGNATURES



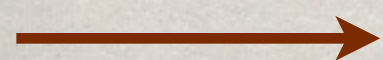
SS 2ℓ



3ℓ



4ℓ



Electron: $p_T > 7 \text{ GeV}$; $|\eta| < 2.5$;
Iso < 0.4

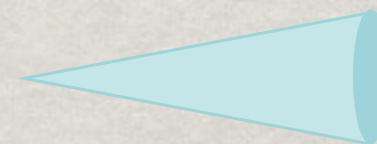
Muon: $p_T > 5 \text{ GeV}$; $|\eta| < 2.5$;
Iso < 0.4

To satisfy trigger:

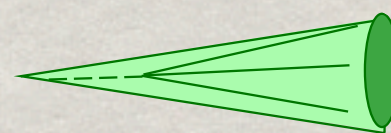
Leading: $p_T > 20 \text{ GeV}$

2nd: $p_T > 10 \text{ GeV}$ (20 GeV for
SS 2ℓ)

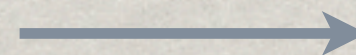
Lepton MVA to reject fakes



Jet: $p_T > 25 \text{ GeV}$; $|\eta| < 2.4$



b -Jet: As above tagged by CSV
(Med.: $\epsilon_b \approx 70\%$, $\epsilon_{LF} \approx 1\%$;
Loose: $\epsilon_b \approx 85\%$, $\epsilon_{LF} \approx 10\%$)



LD using E_T^{miss} and H_T^{miss}

BACKGROUNDS

BACKGROUNDS

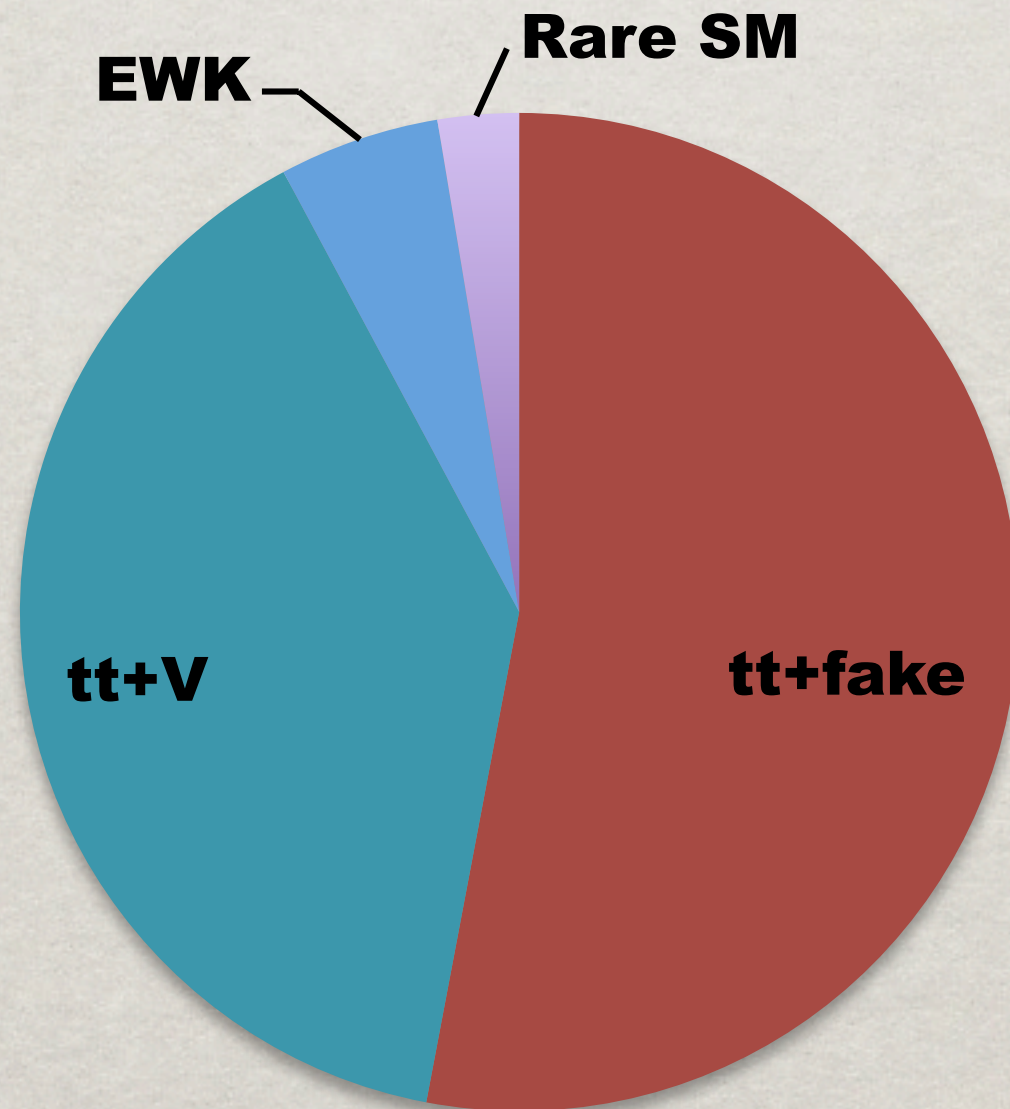
☼ Pro: Lowest amount of background of any channel

BACKGROUNDS

- ✱ Pro: Lowest amount of background of any channel
- ✱ Con: Hardest to estimate/model

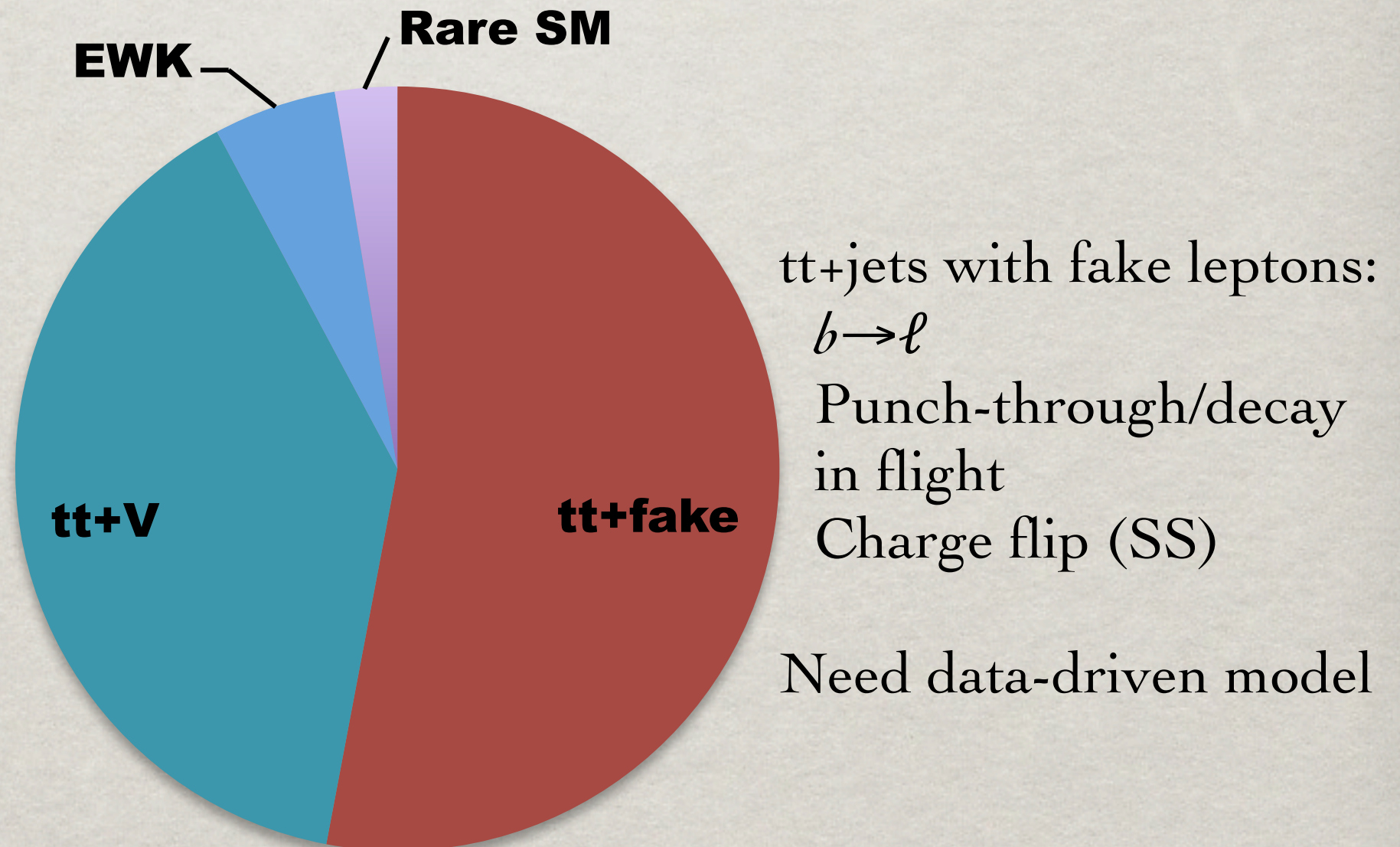
BACKGROUNDS

- ✱ Pro: Lowest amount of background of any channel
- ✱ Con: Hardest to estimate/model



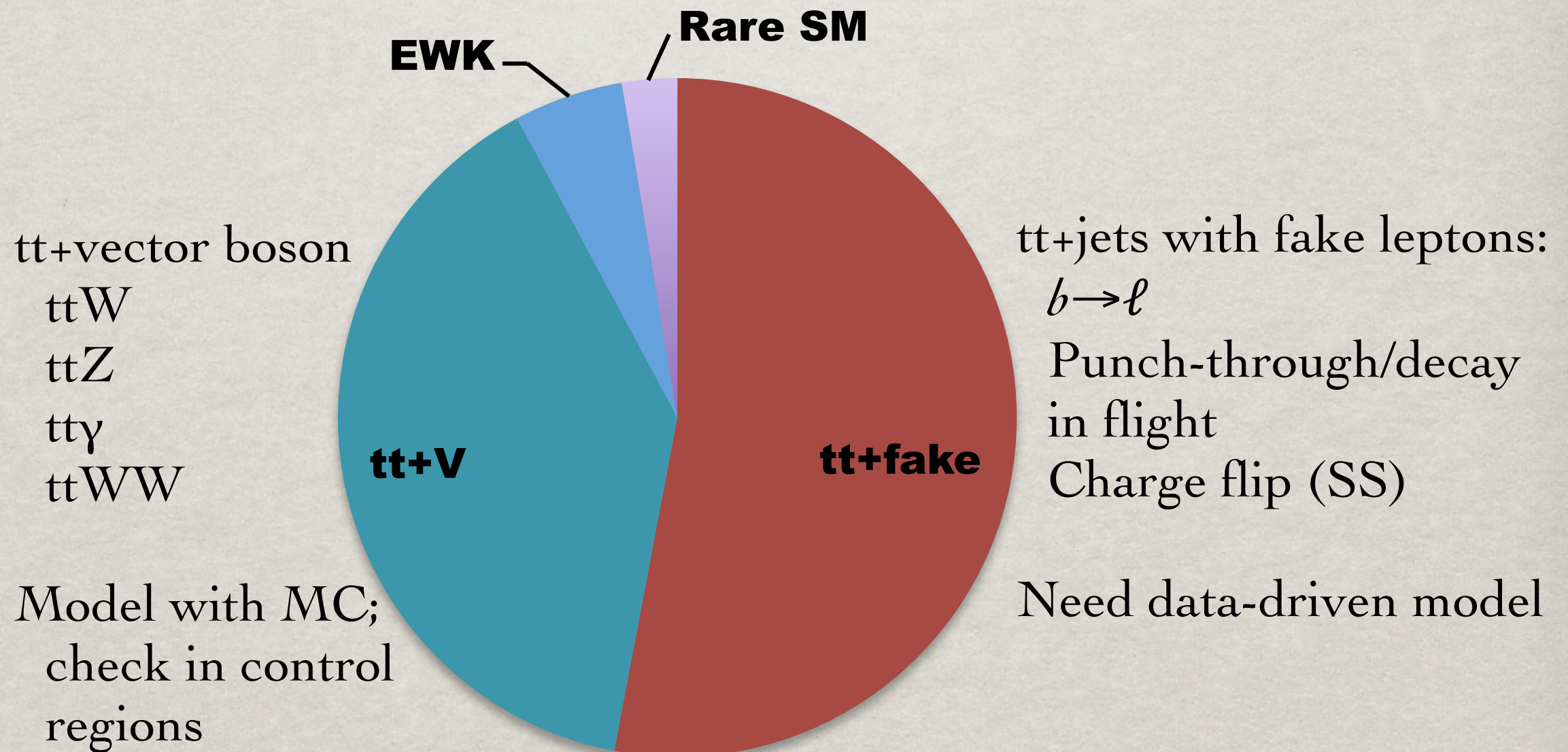
BACKGROUNDS

- ✱ Pro: Lowest amount of background of any channel
- ✱ Con: Hardest to estimate/model



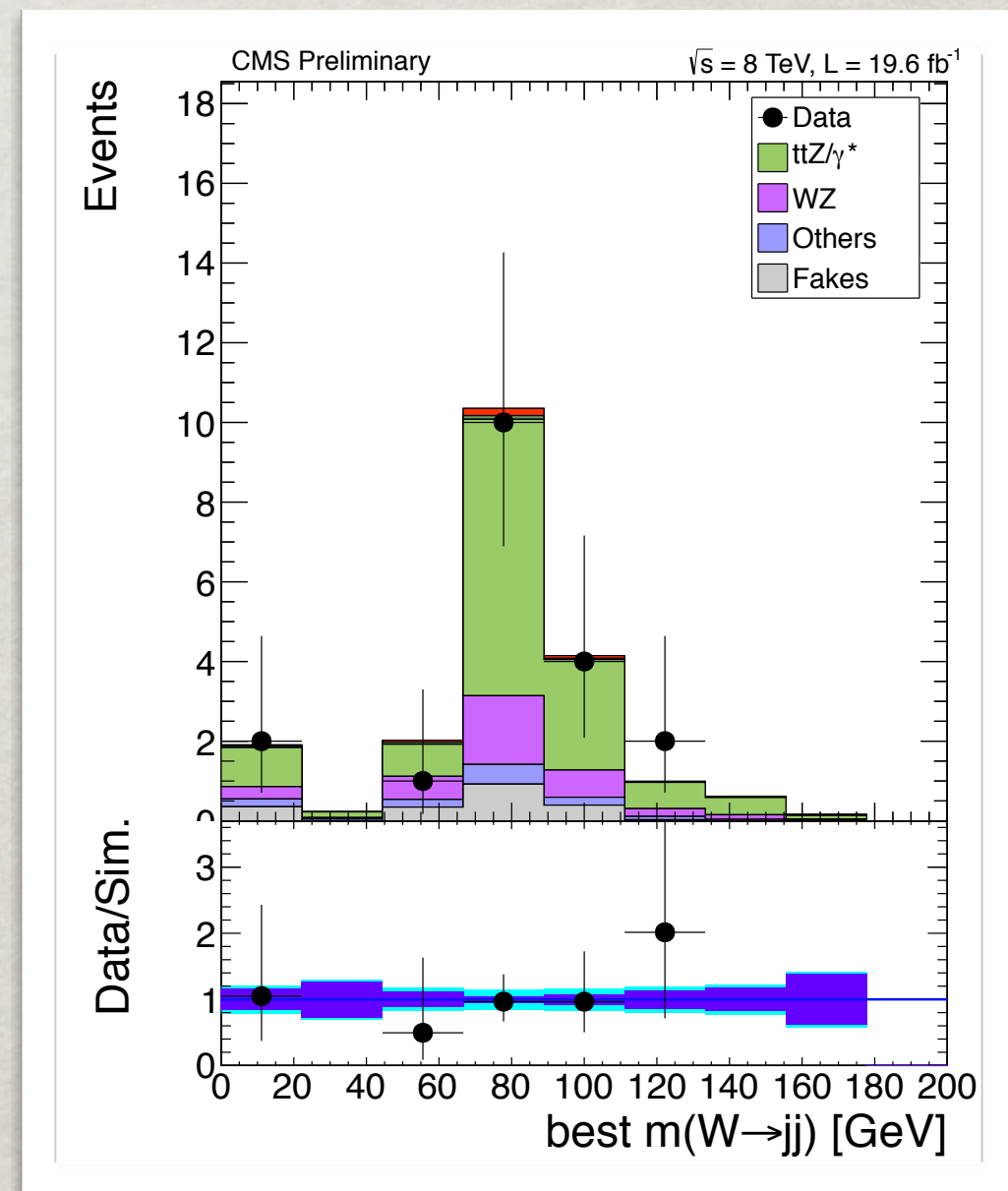
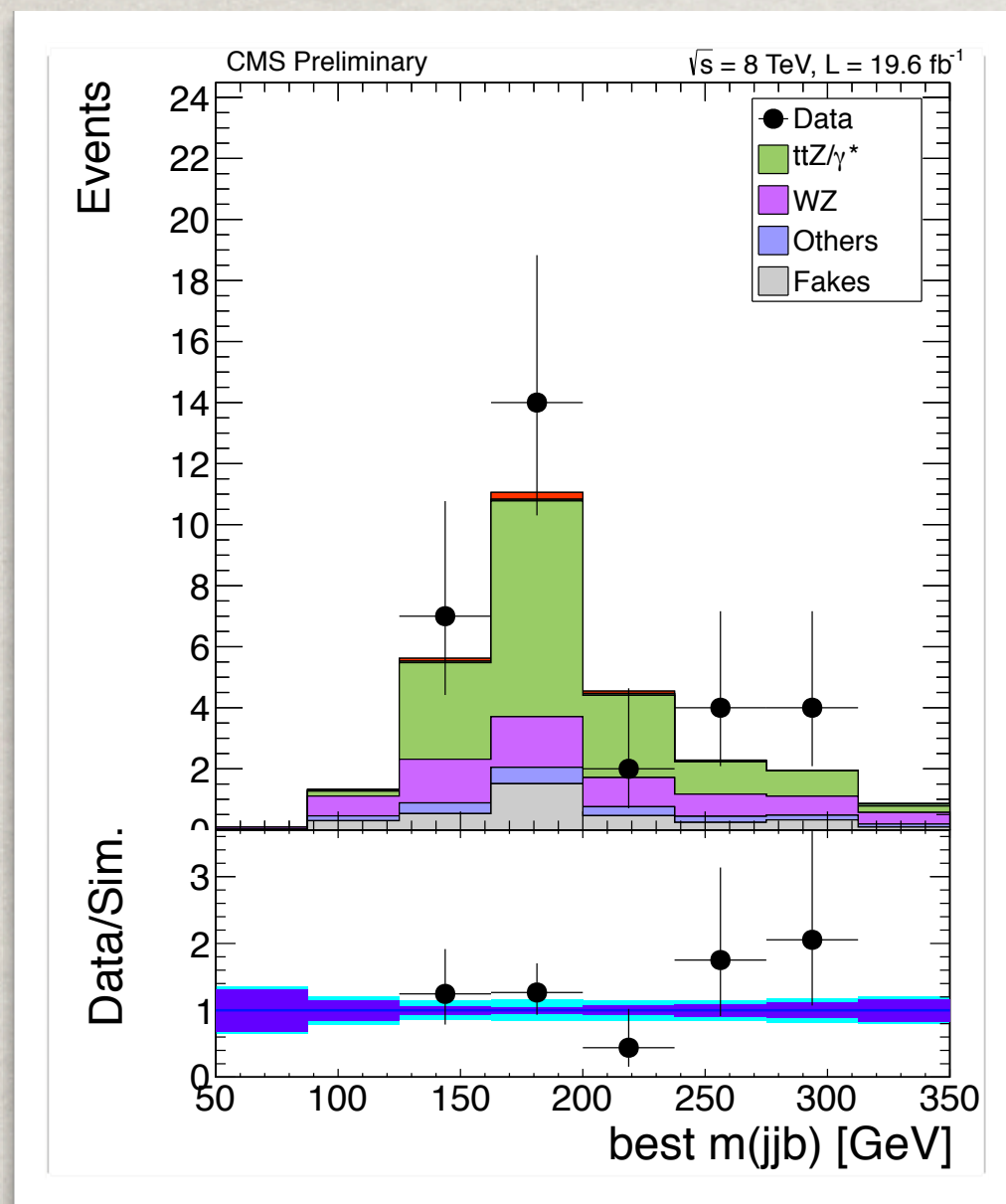
BACKGROUNDS

- ✱ Pro: Lowest amount of background of any channel
- ✱ Con: Hardest to estimate/model



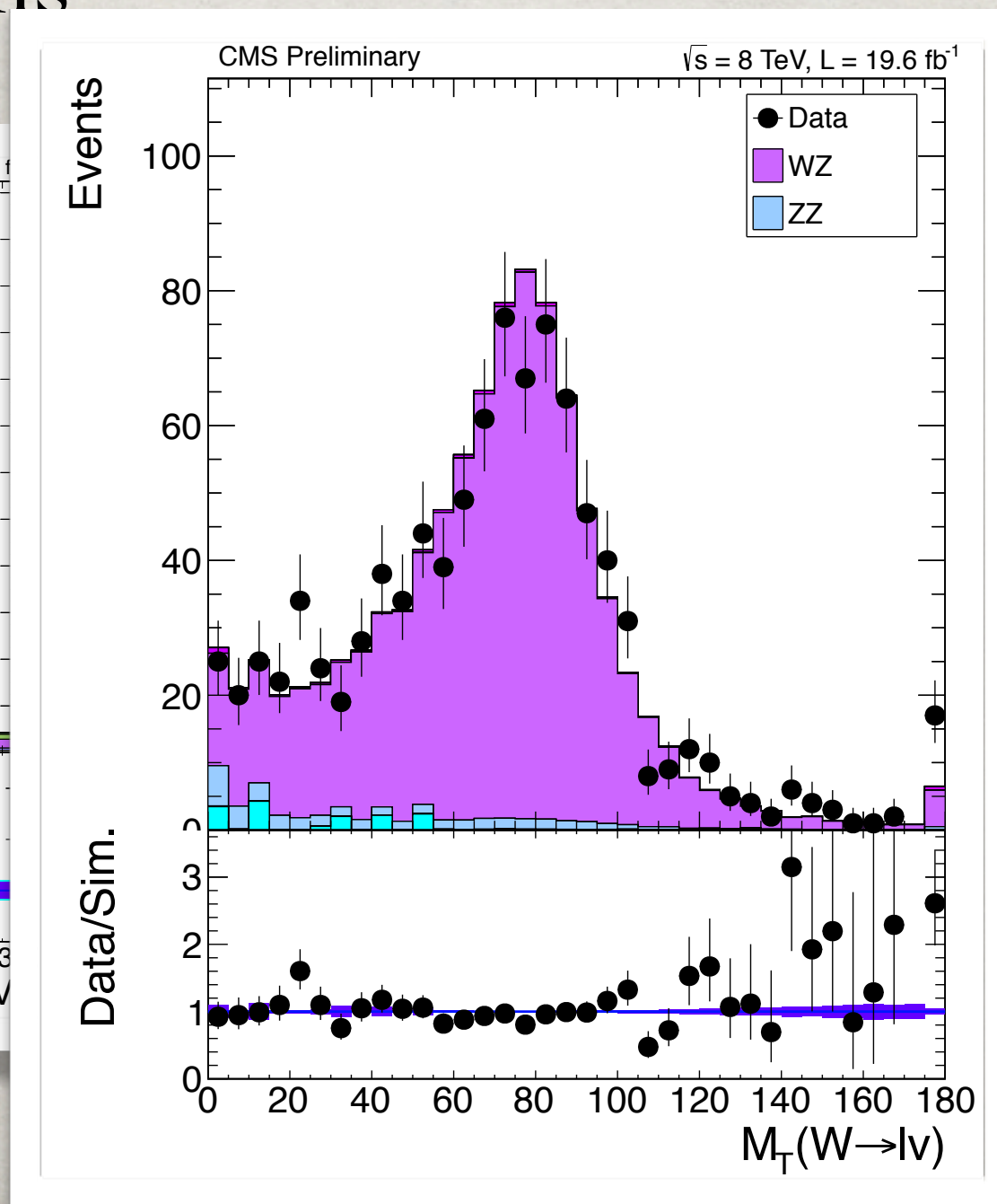
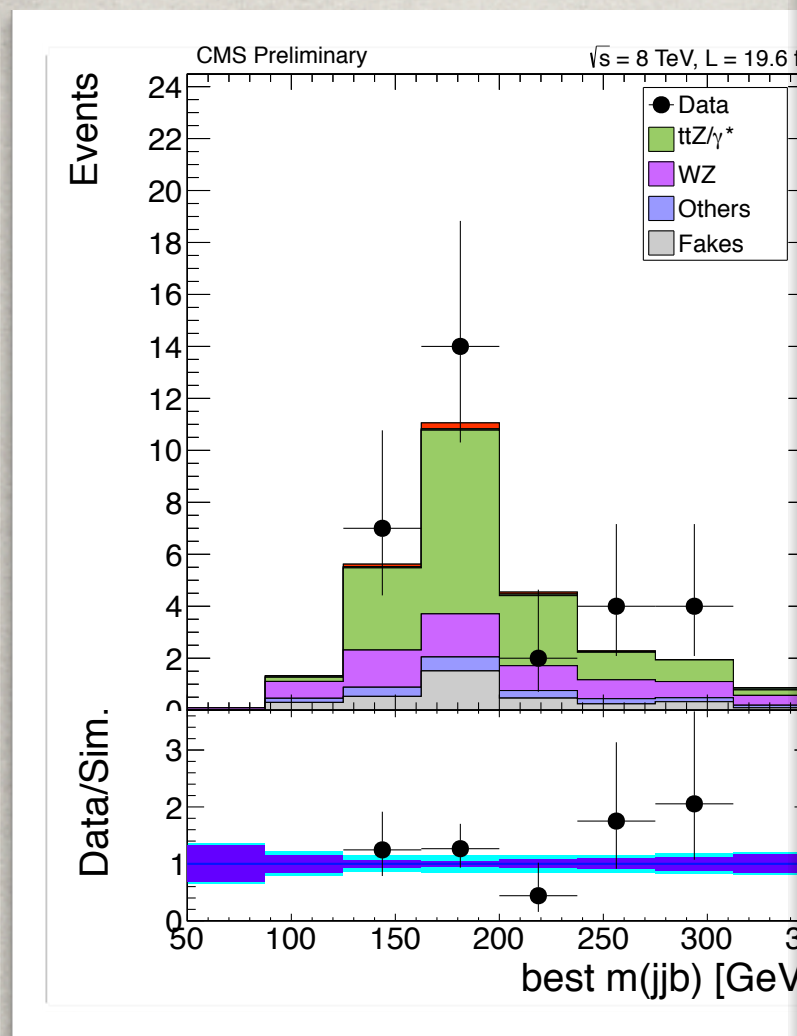
TTV/DIBOSON

- Estimated/Modeled from MC, but checked in data control regions



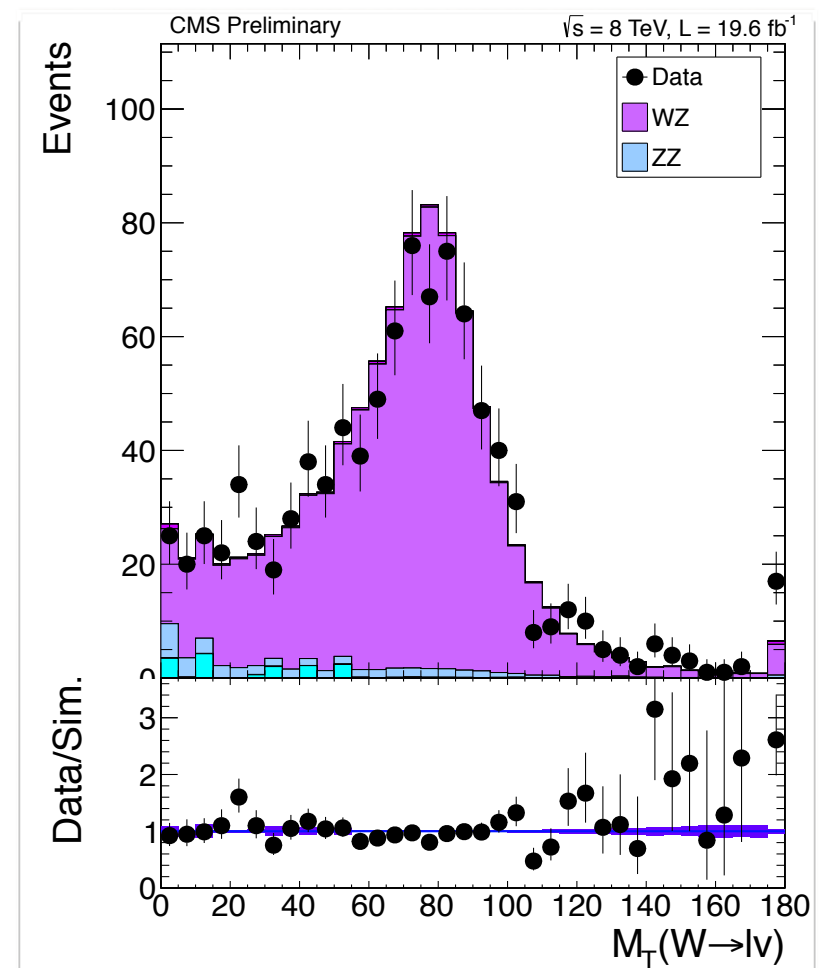
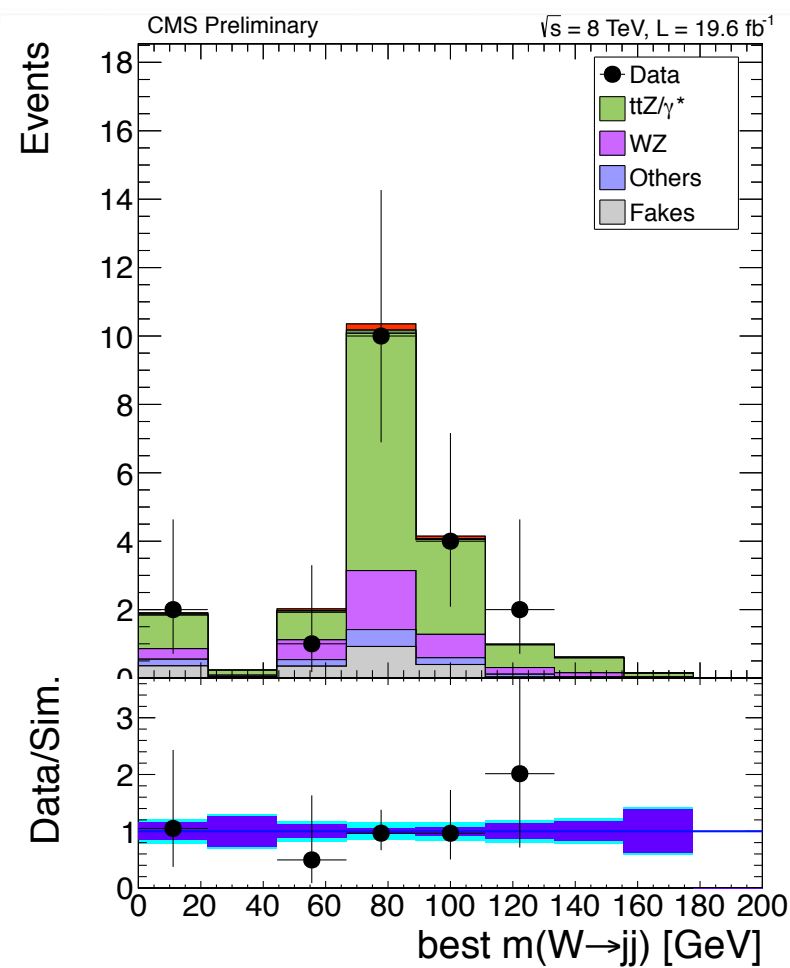
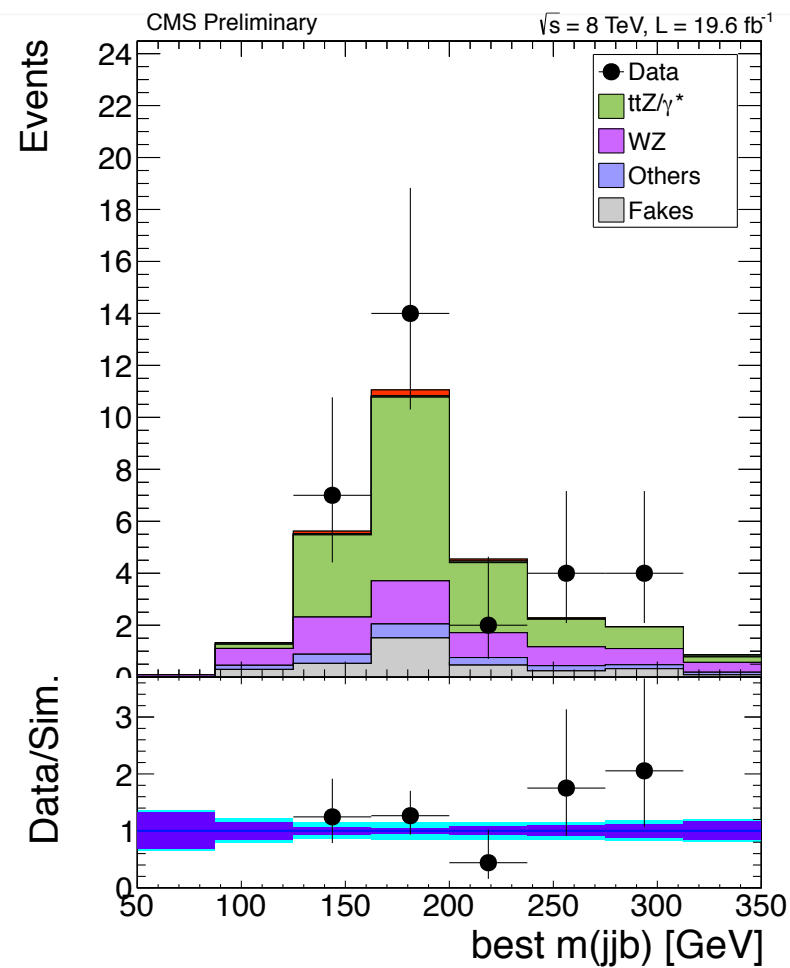
TTV/DIBOSON

☼ Estimated/Modeled from MC, but checked in data control regions



TTV/DIBOSON

☼ Estimated/Modeled from MC, but checked in data control regions

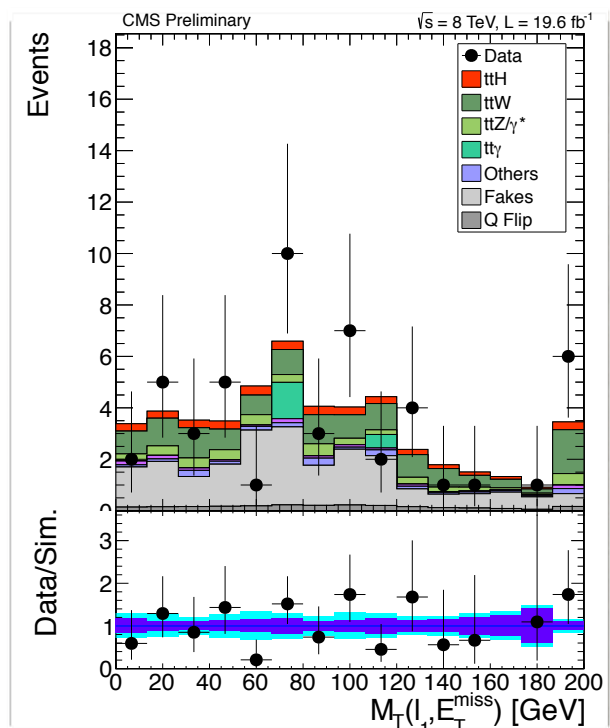
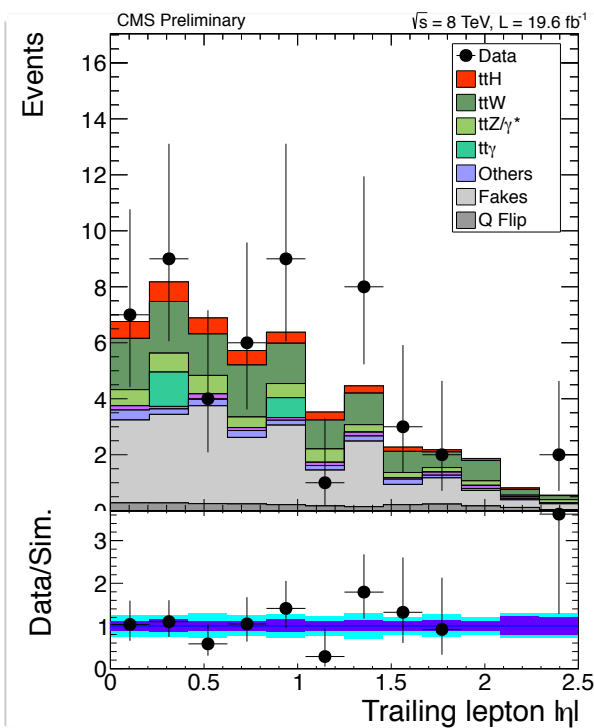
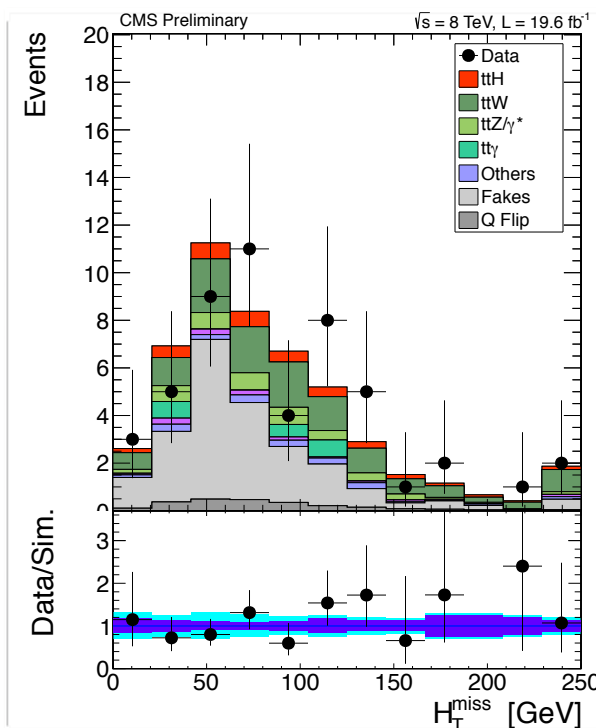
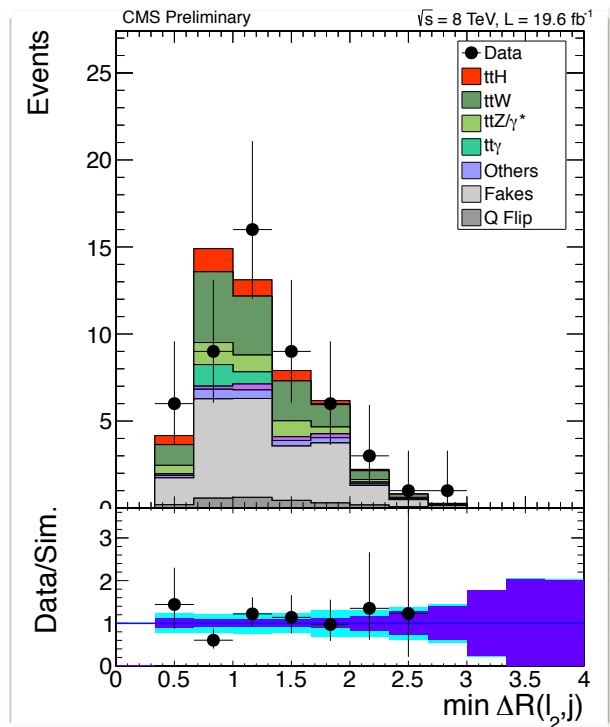
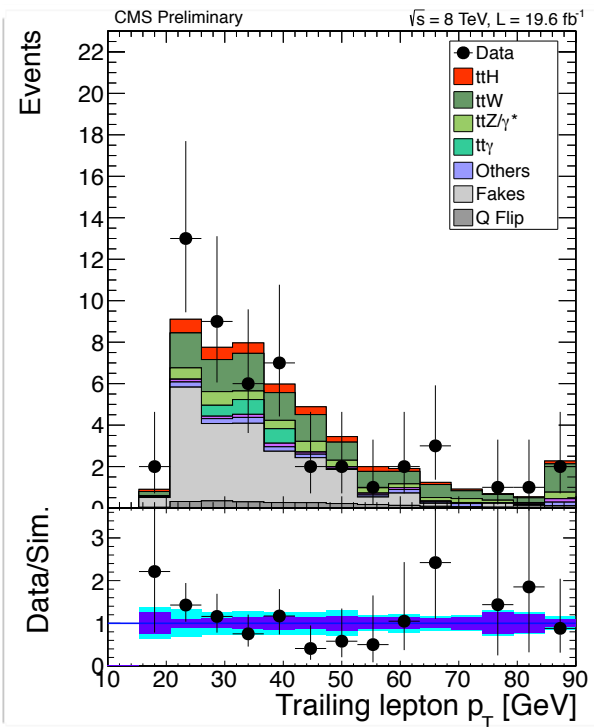
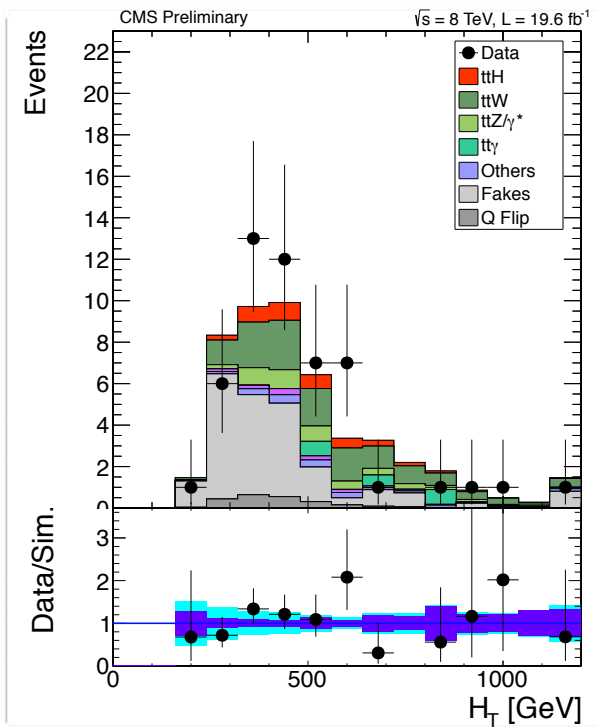


SEPARATING S FROM B

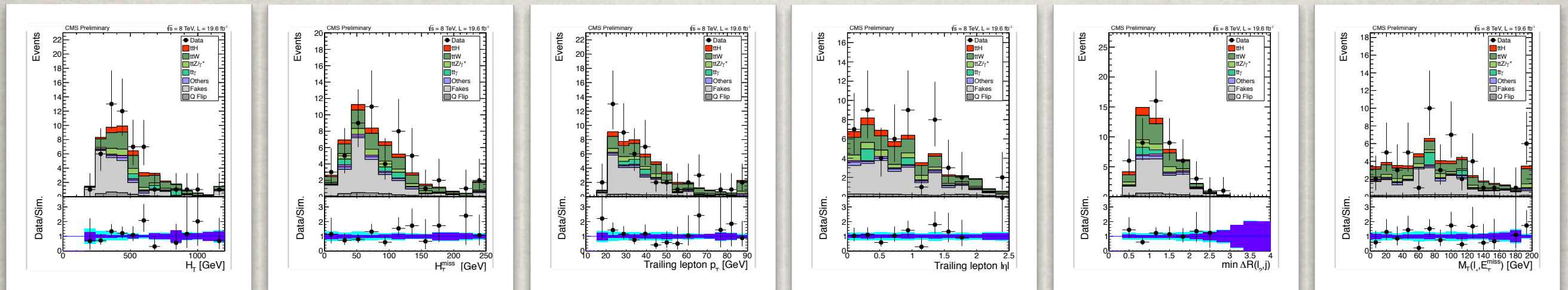
SEPARATING S FROM B

For SS 2ℓ : Select variables to discriminate between ttH and fakes

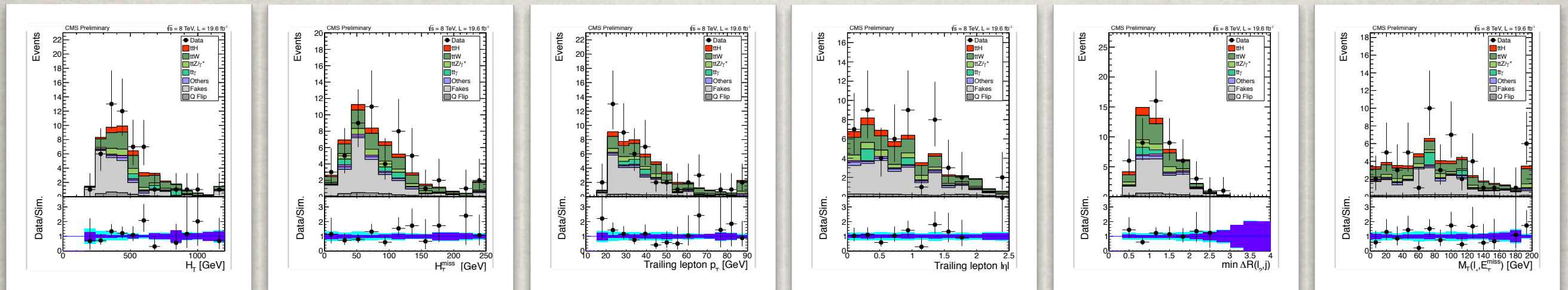
SEPARATING S FROM B



SEPARATING S FROM B

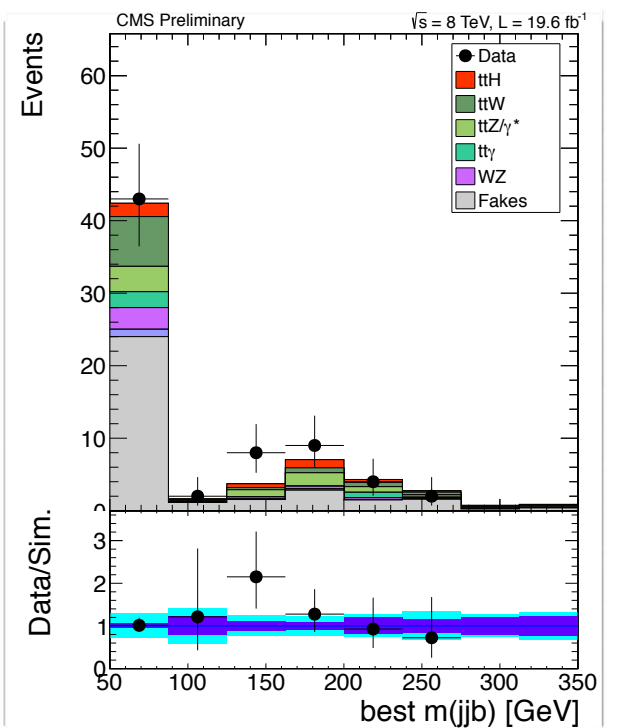
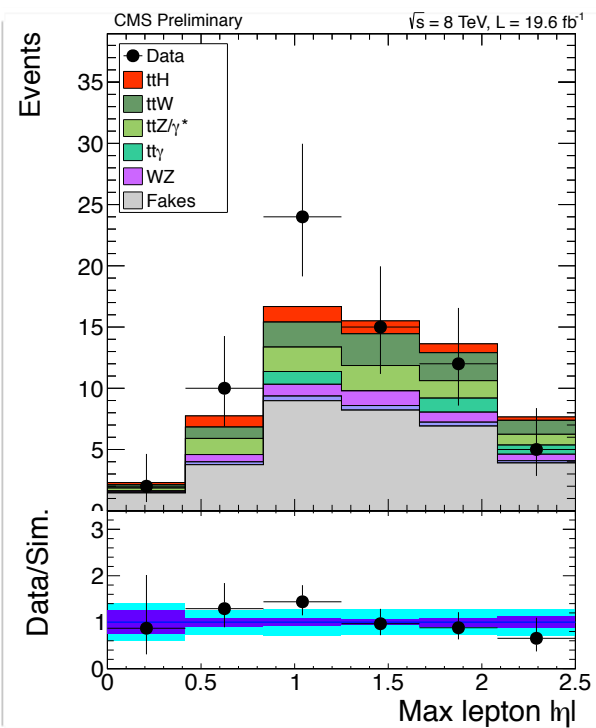
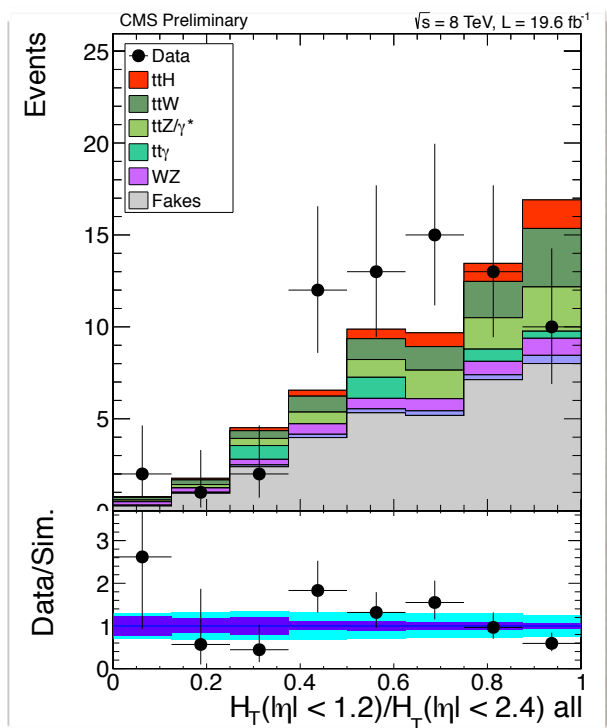
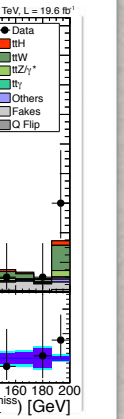
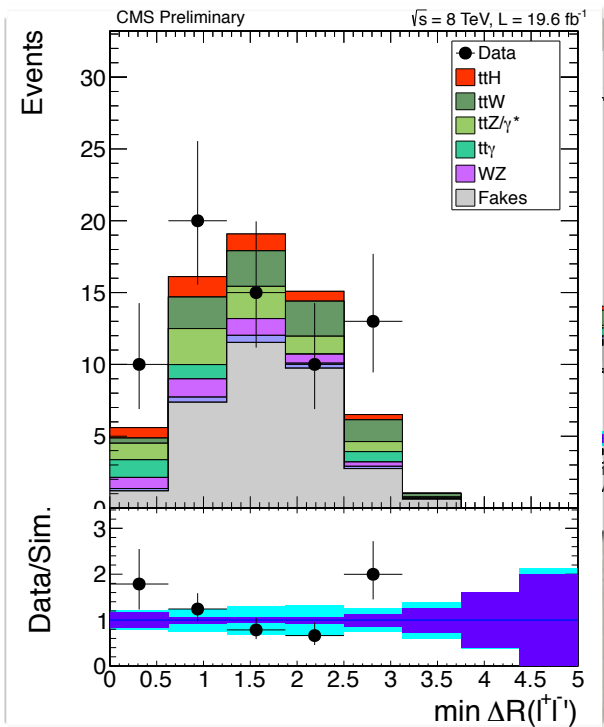
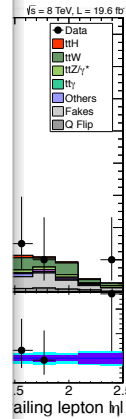
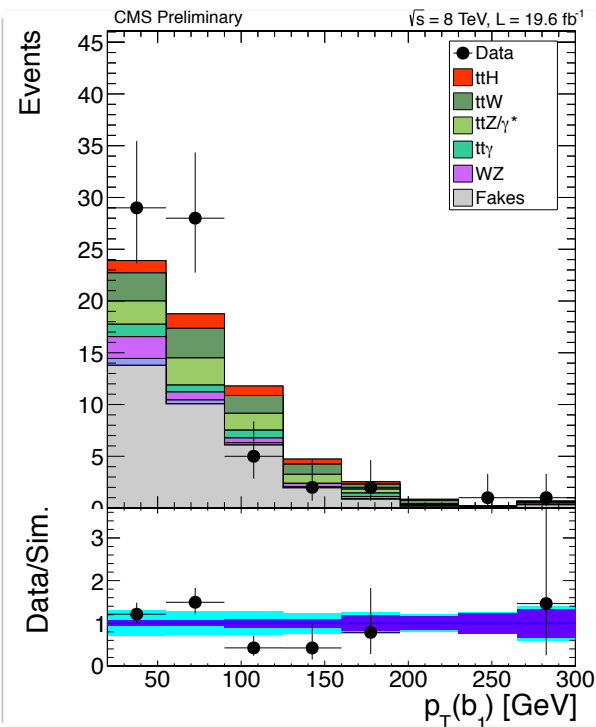
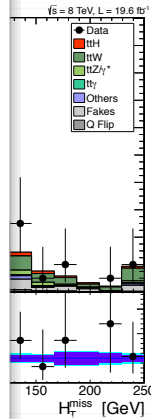
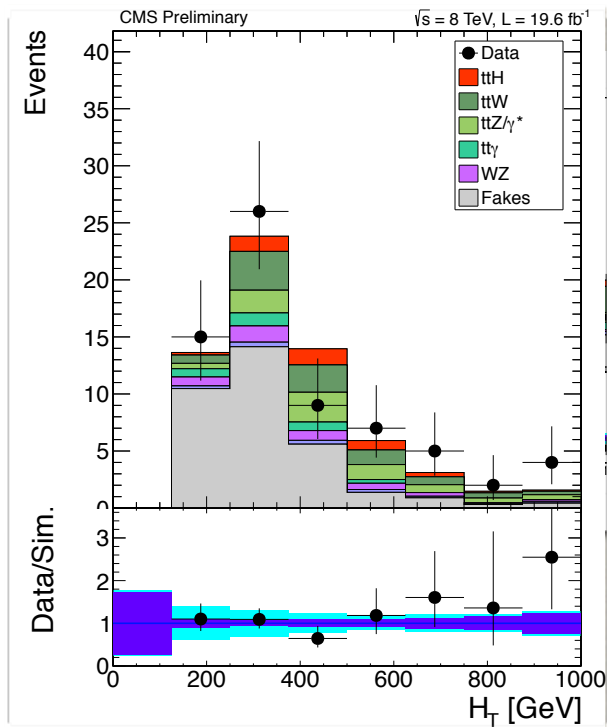


SEPARATING S FROM B

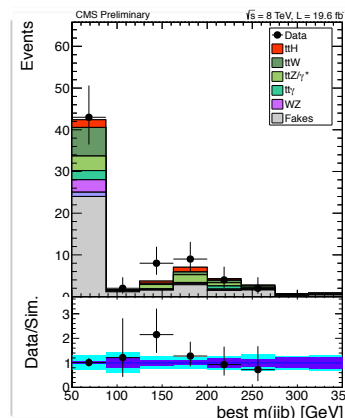
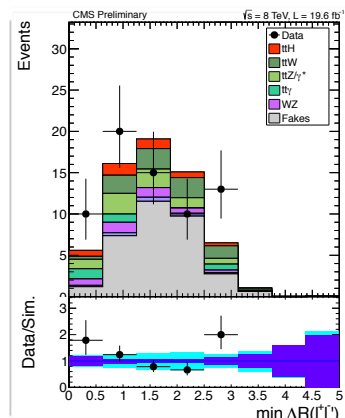
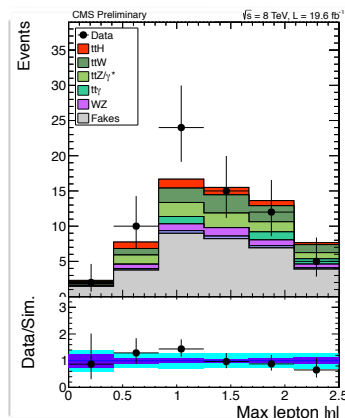
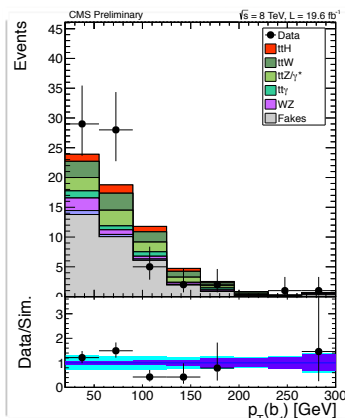
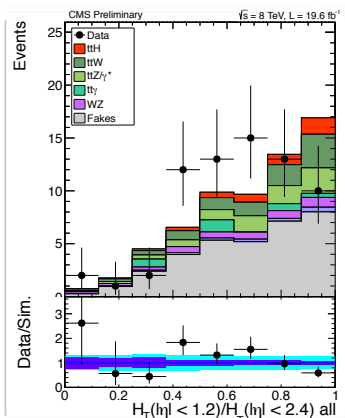
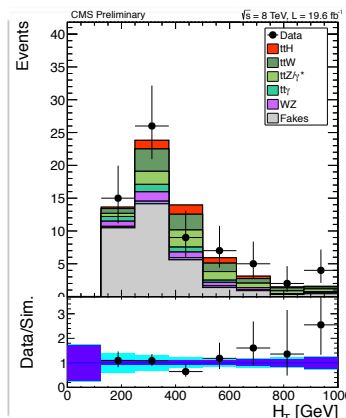
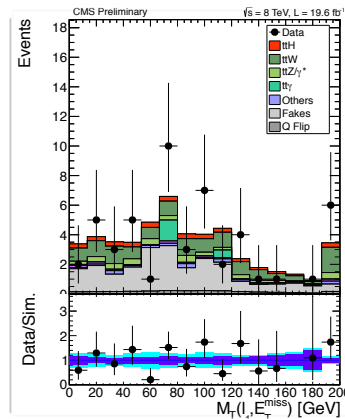
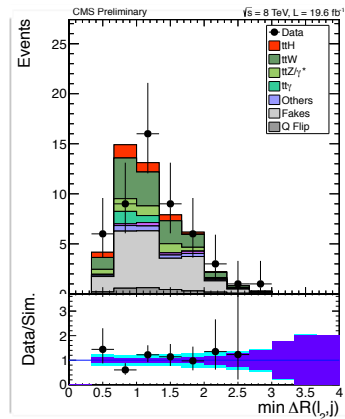
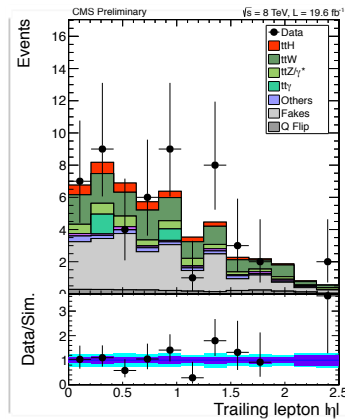
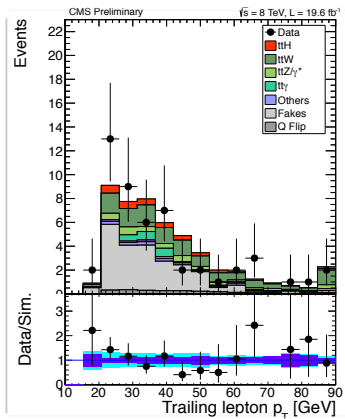
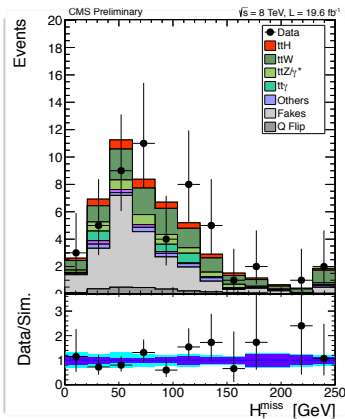
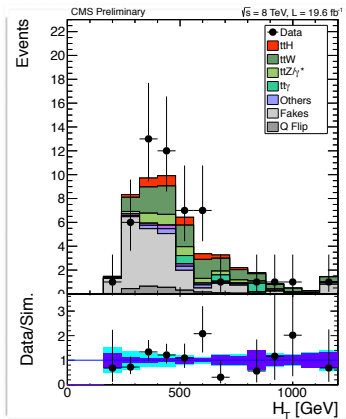


For 3ℓ : Select variables to discriminate between ttH and ttV

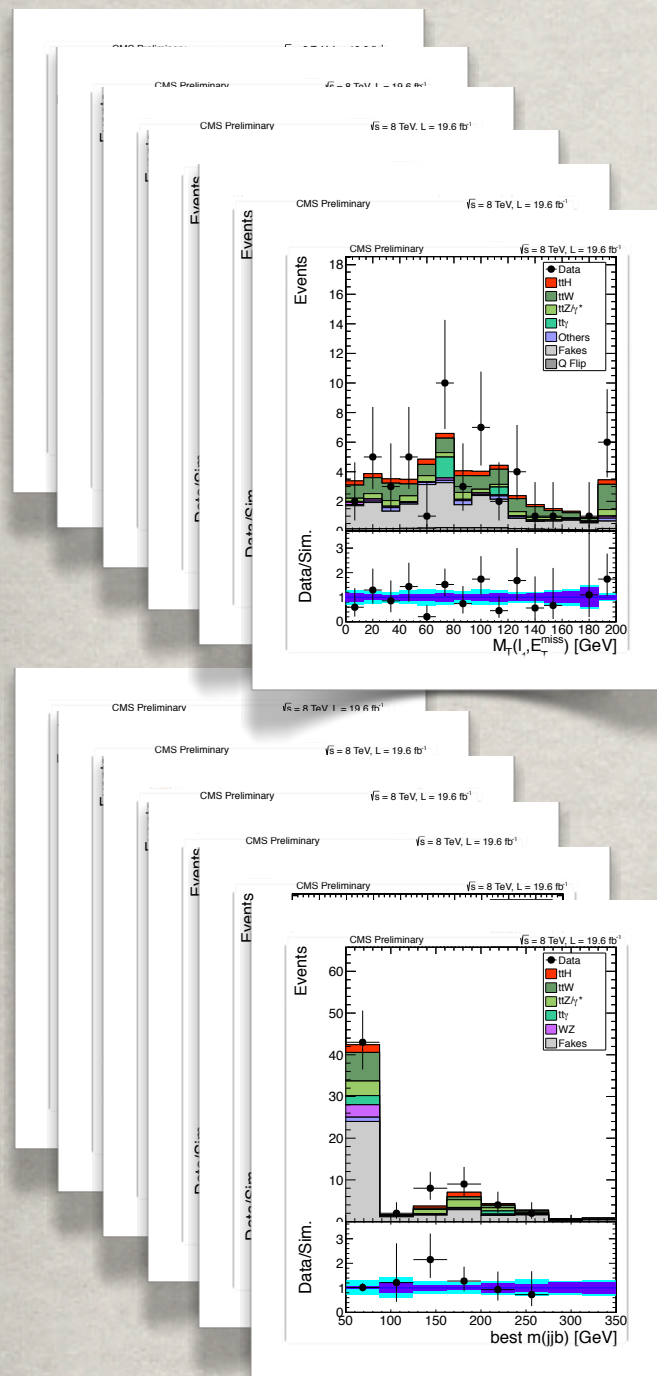
SEPARATING S FROM B



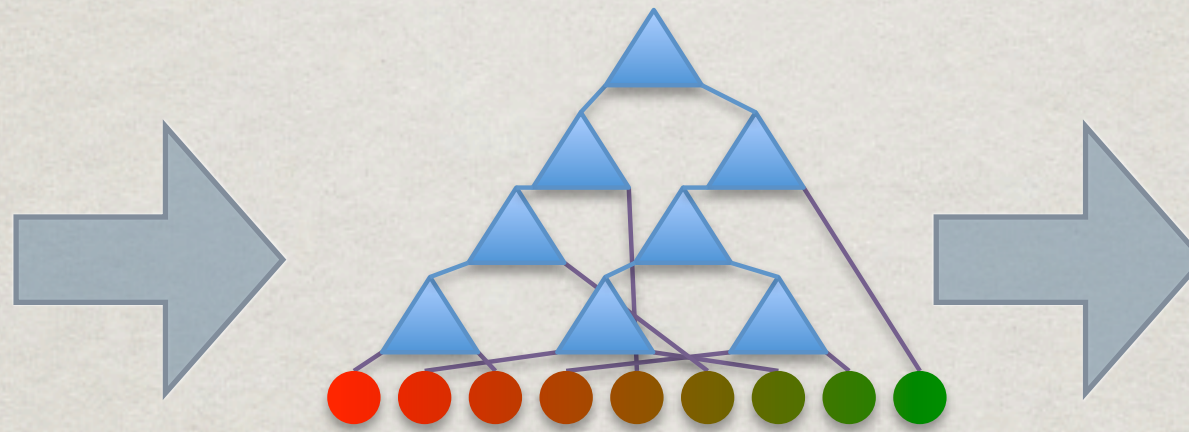
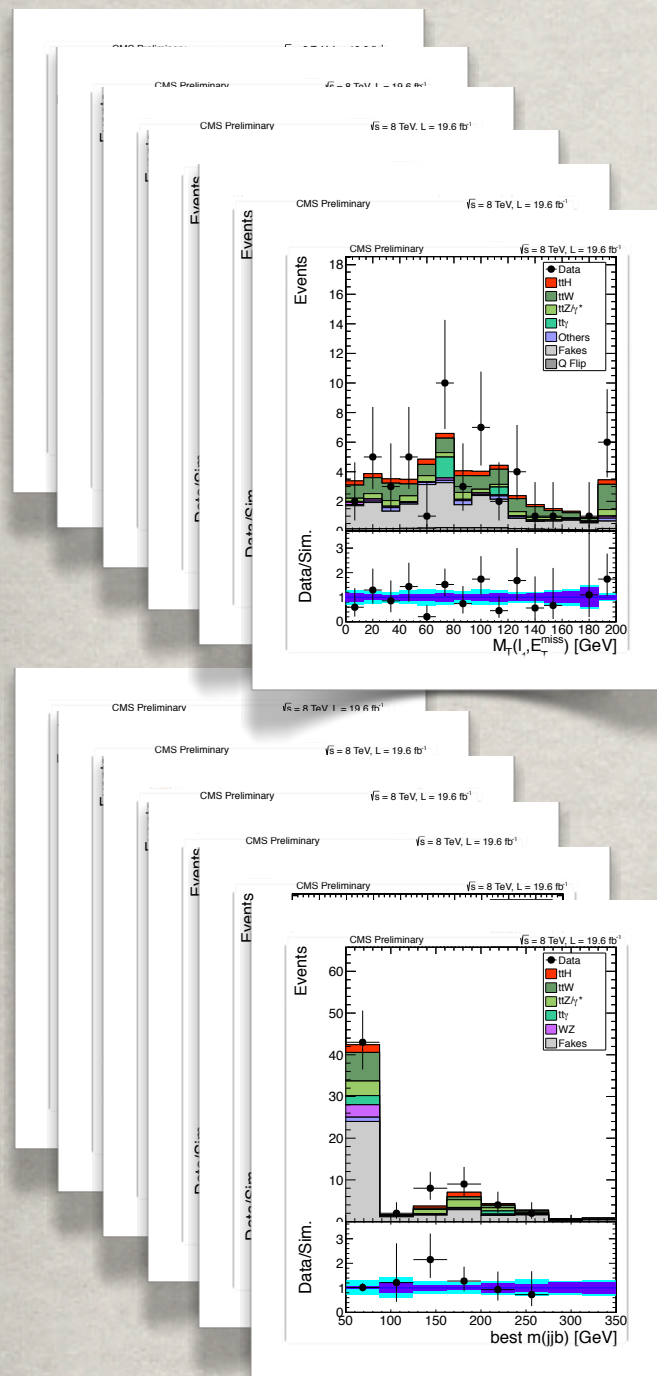
SEPARATING S FROM B



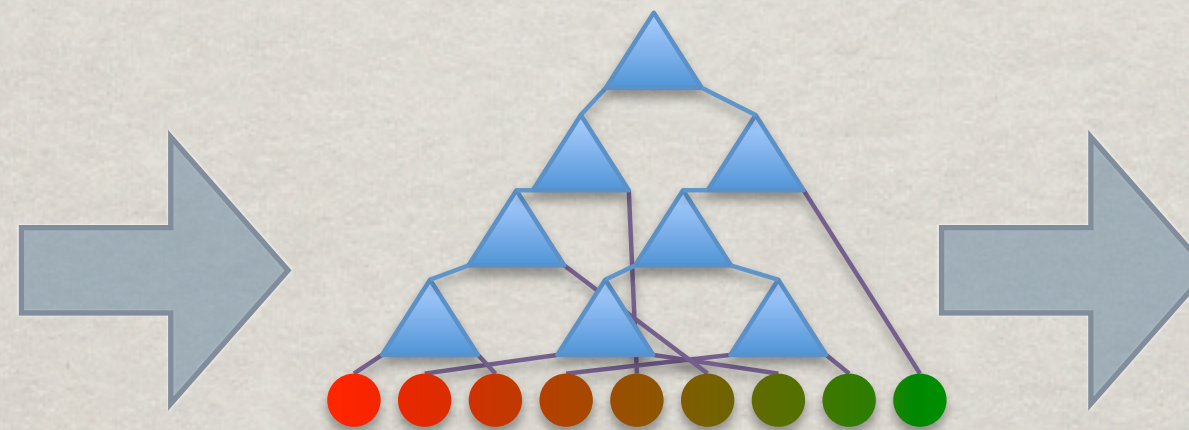
SEPARATING S FROM B



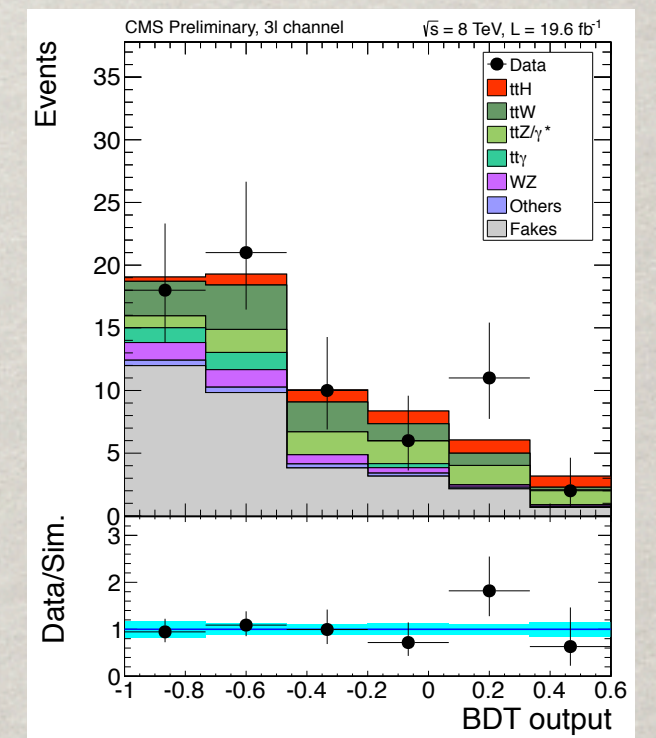
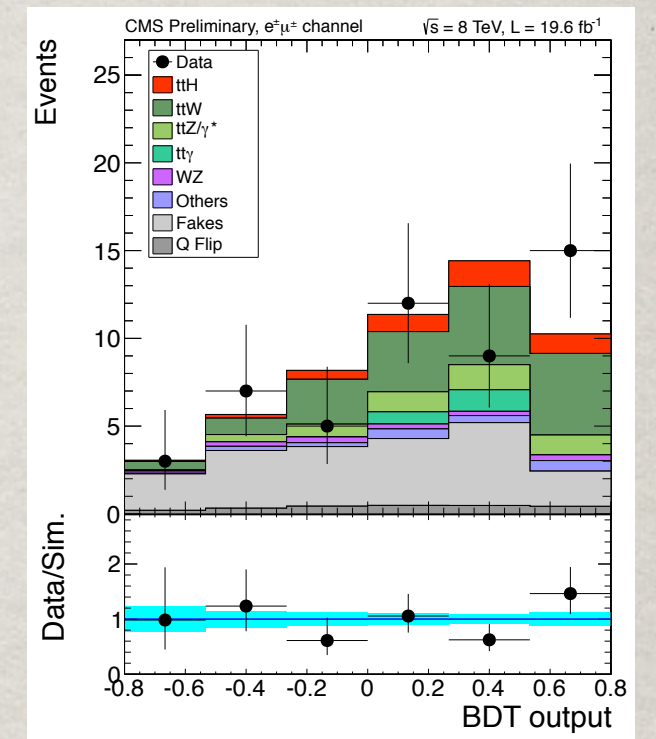
SEPARATING S FROM B



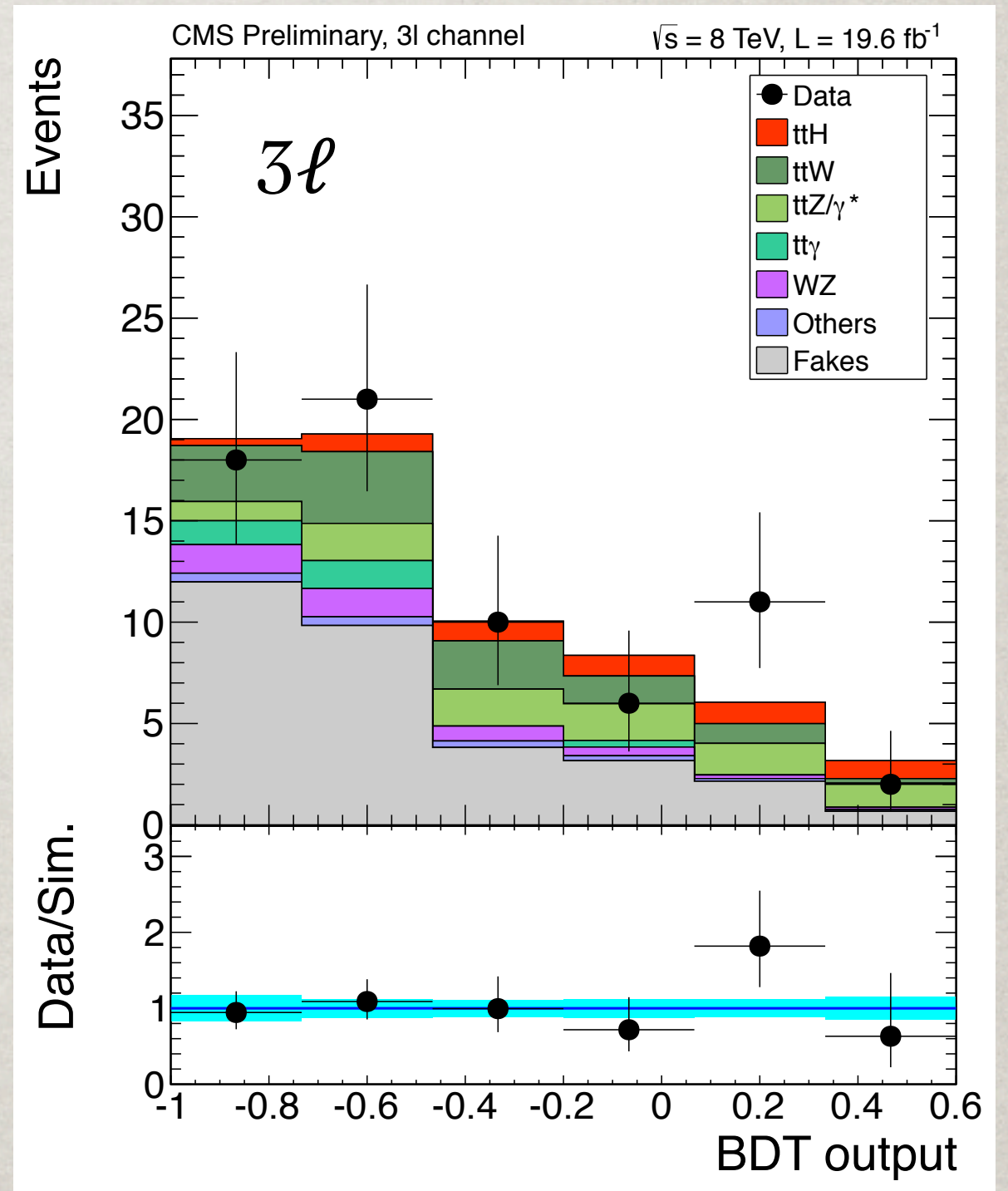
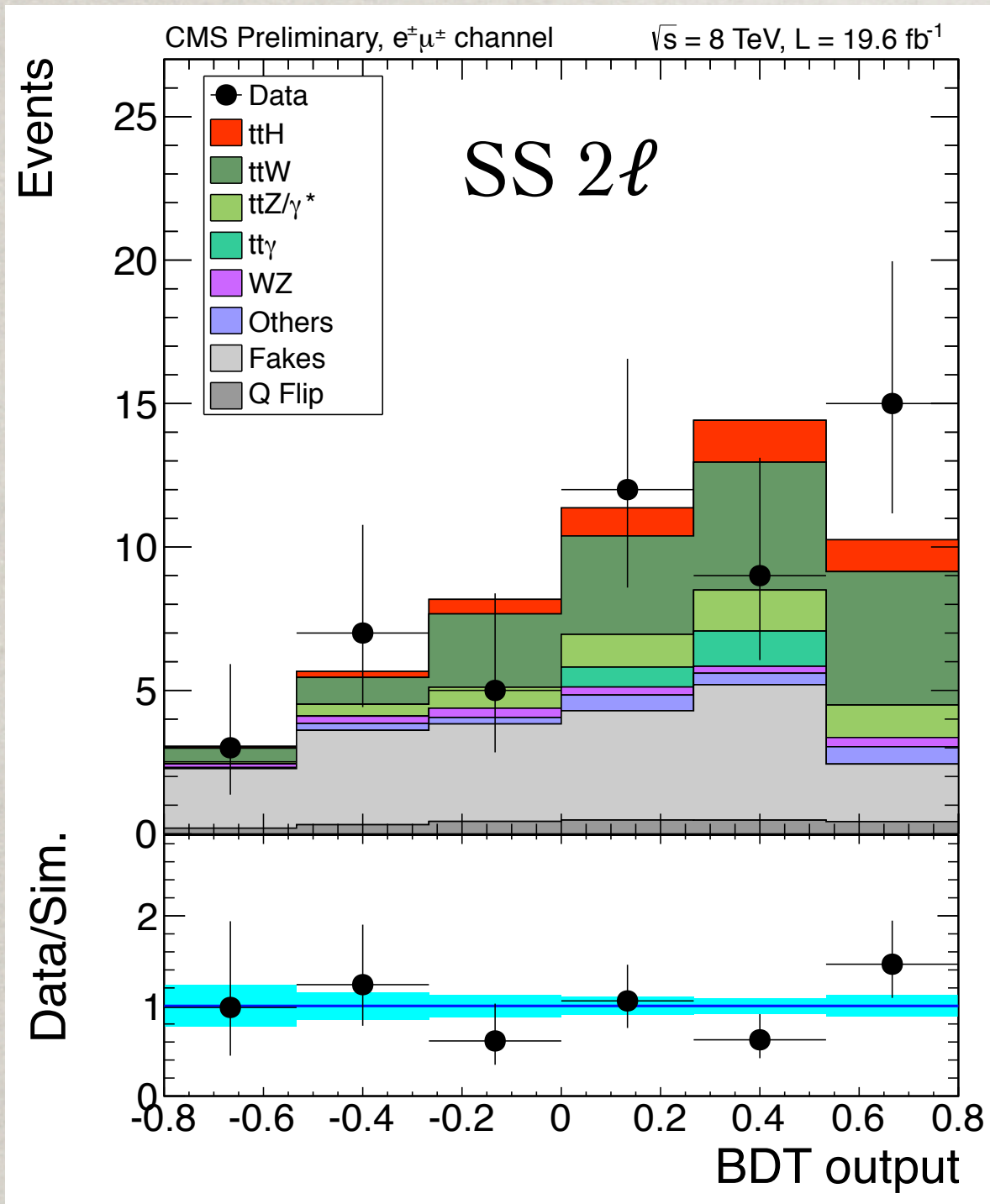
Trained against tt +fake



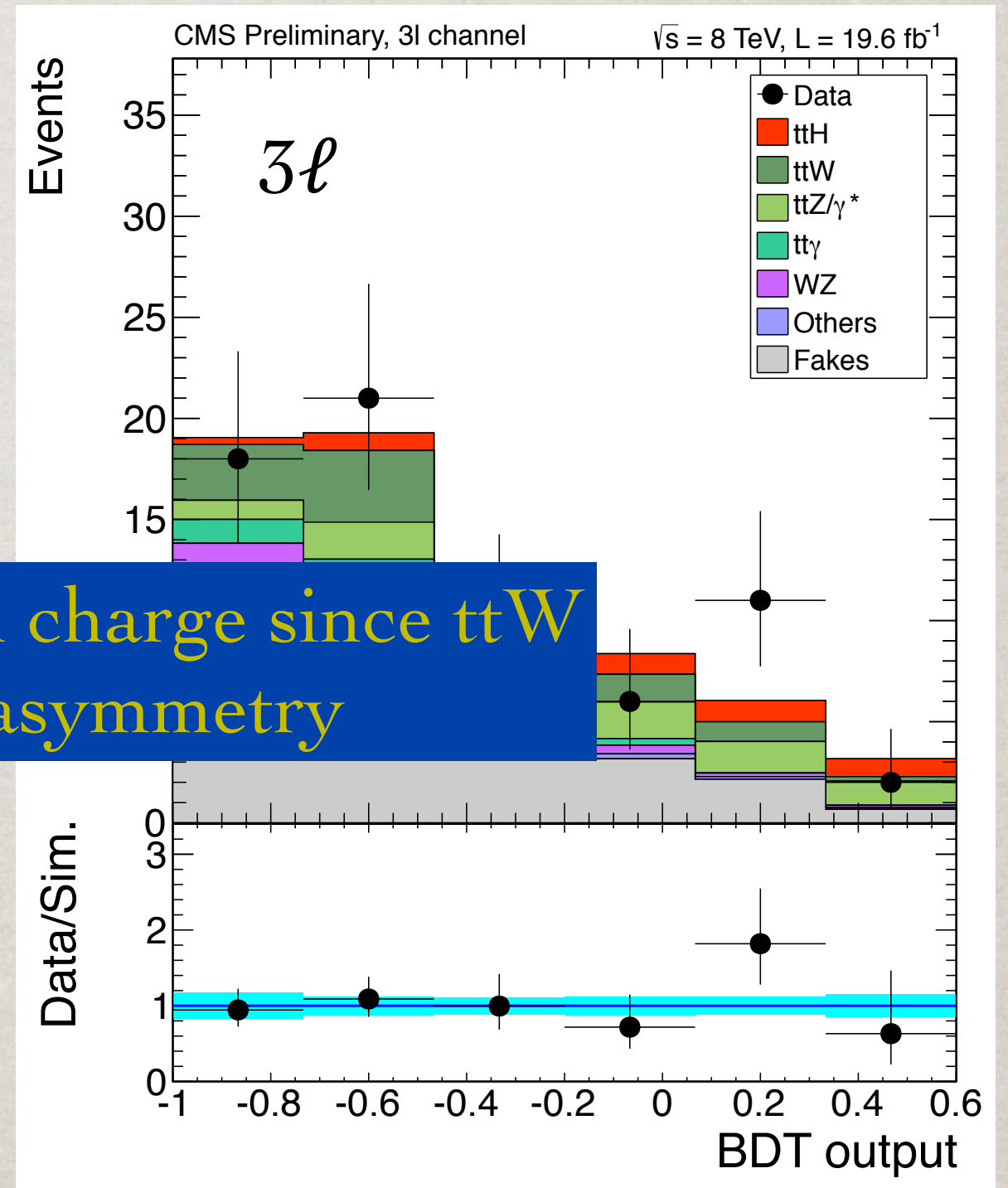
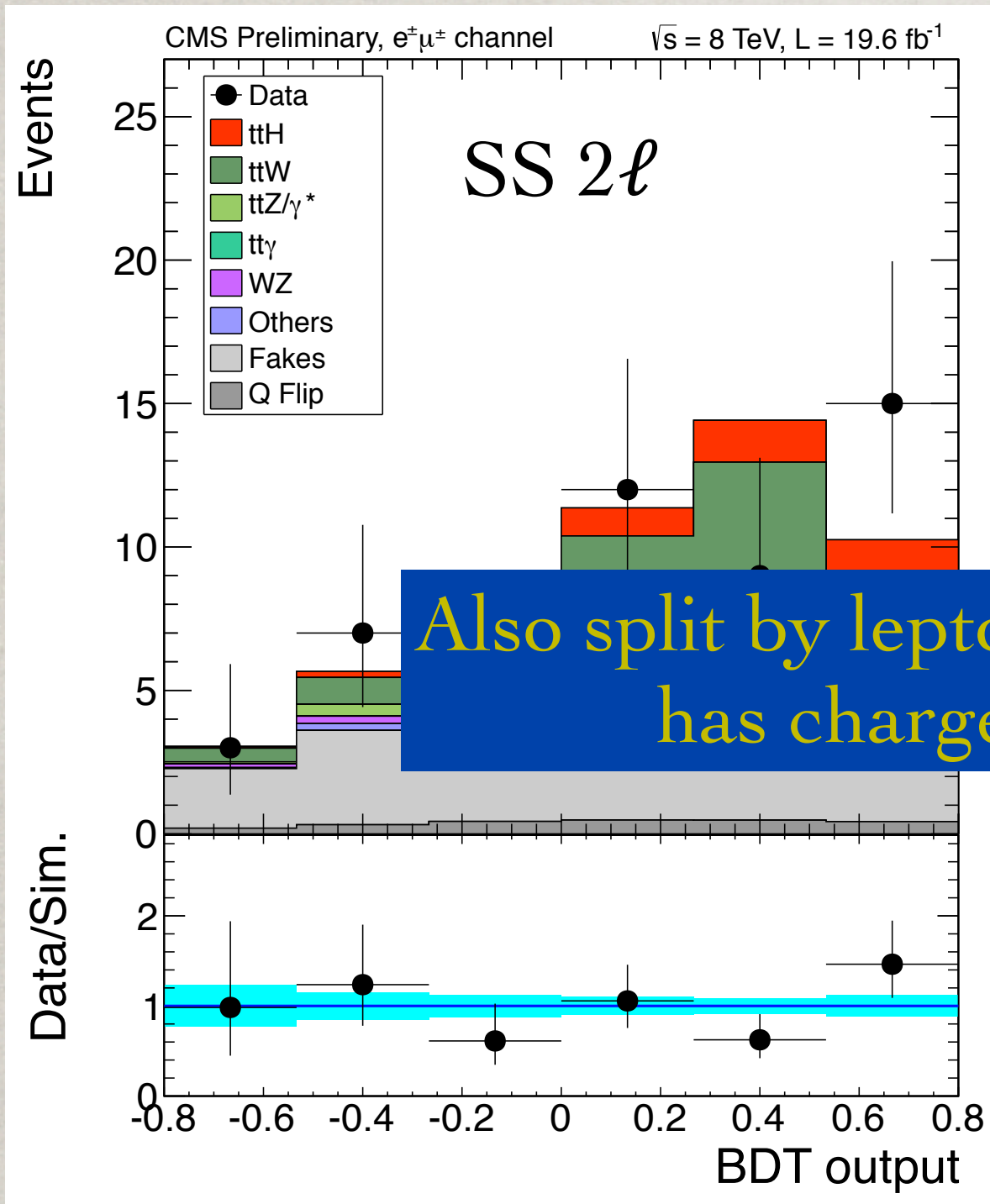
Trained against tt +V



SEPARATING S FROM B

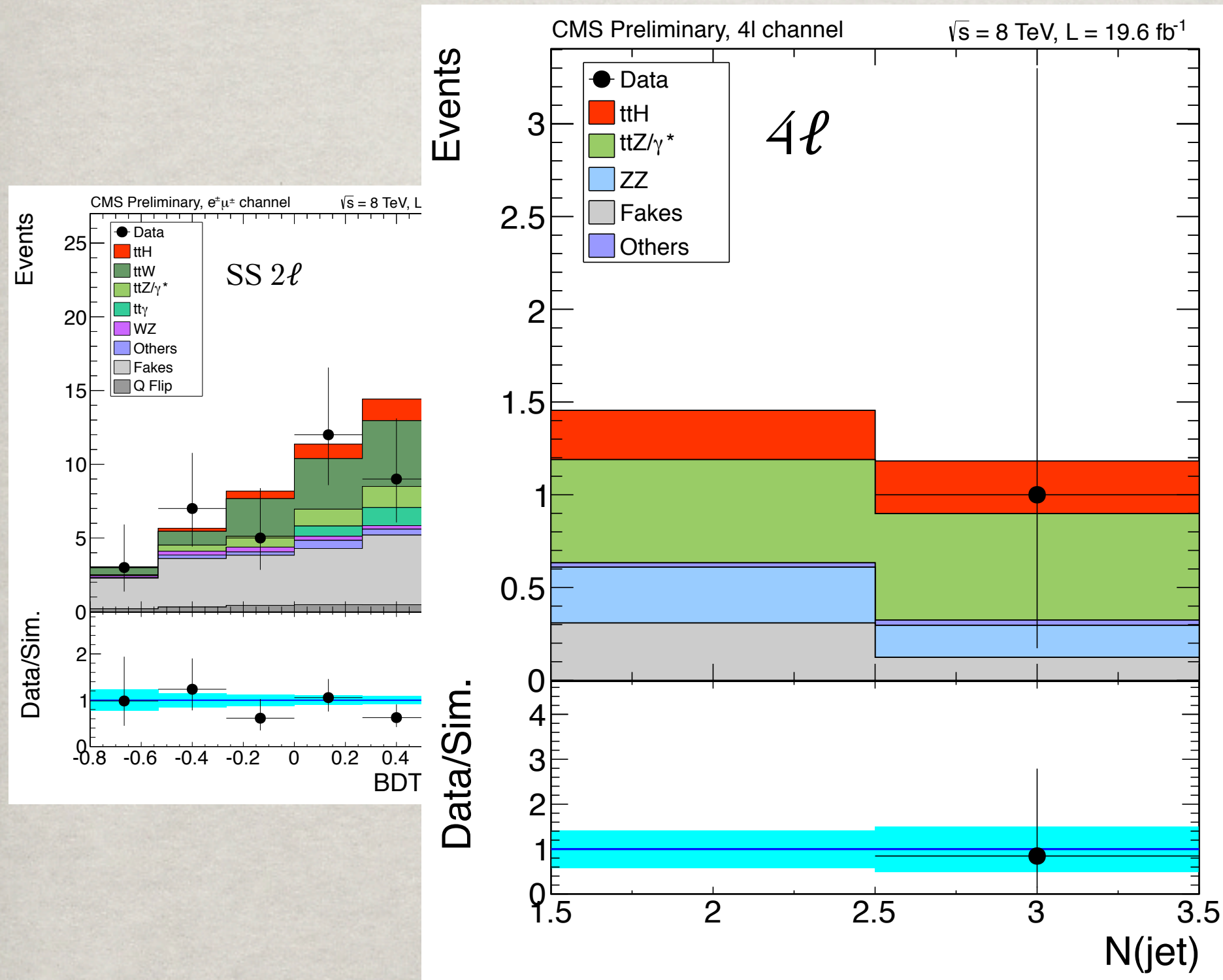


SEPARATING S FROM B



Also split by lepton charge since ttW has charge asymmetry

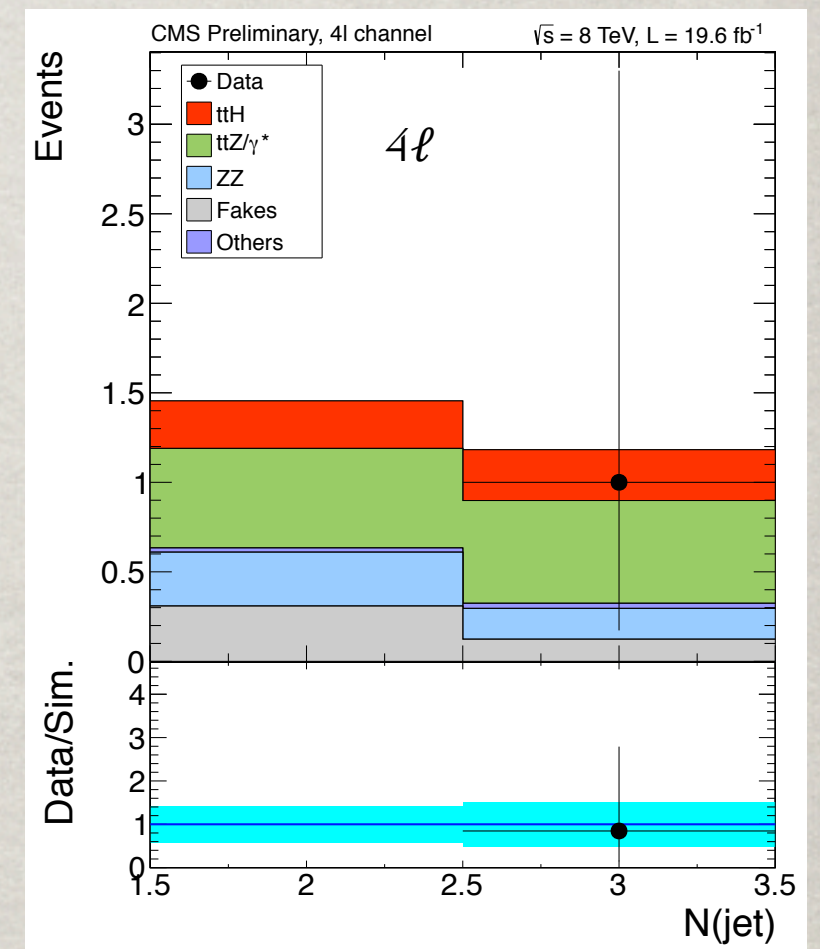
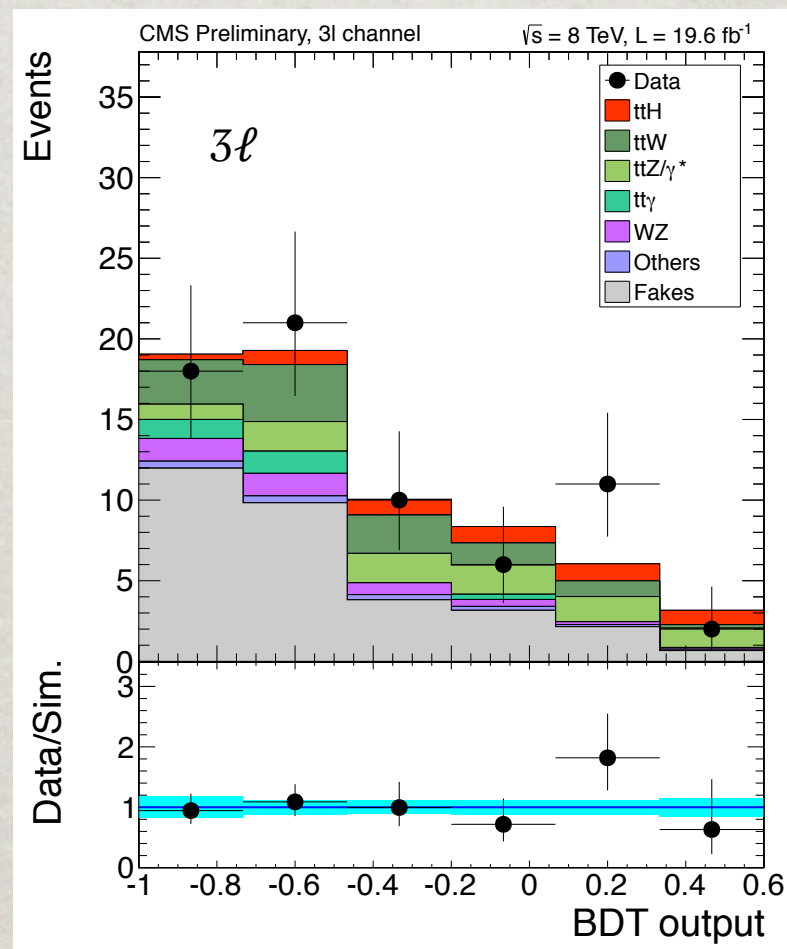
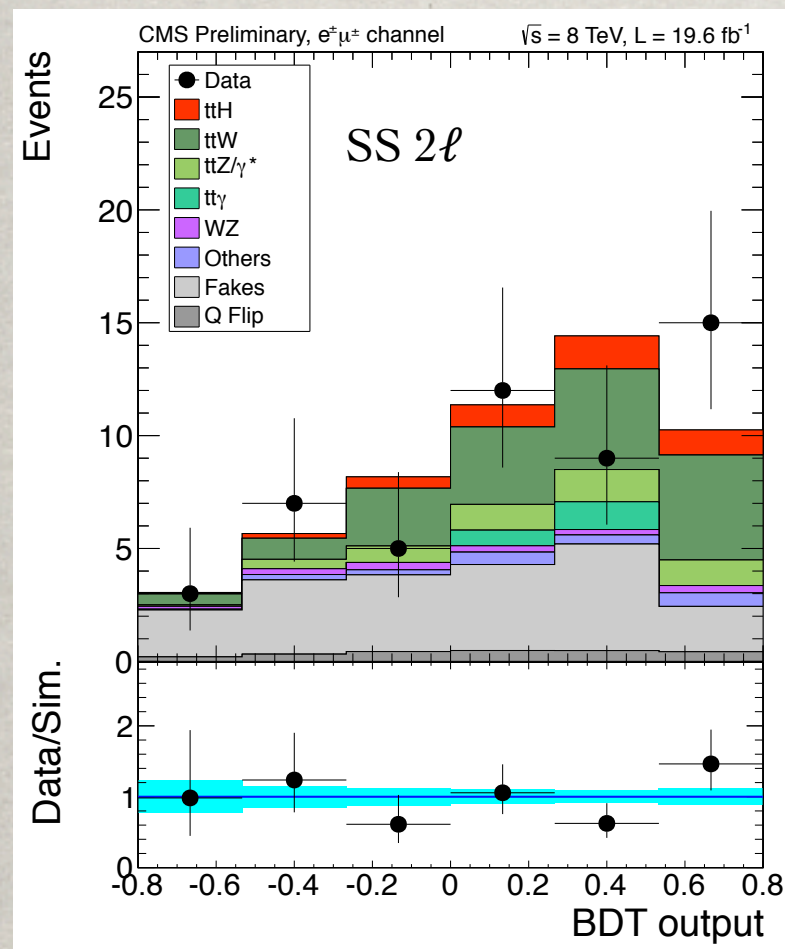
SEPARATING S FROM B



Use N_{jets} as discriminant

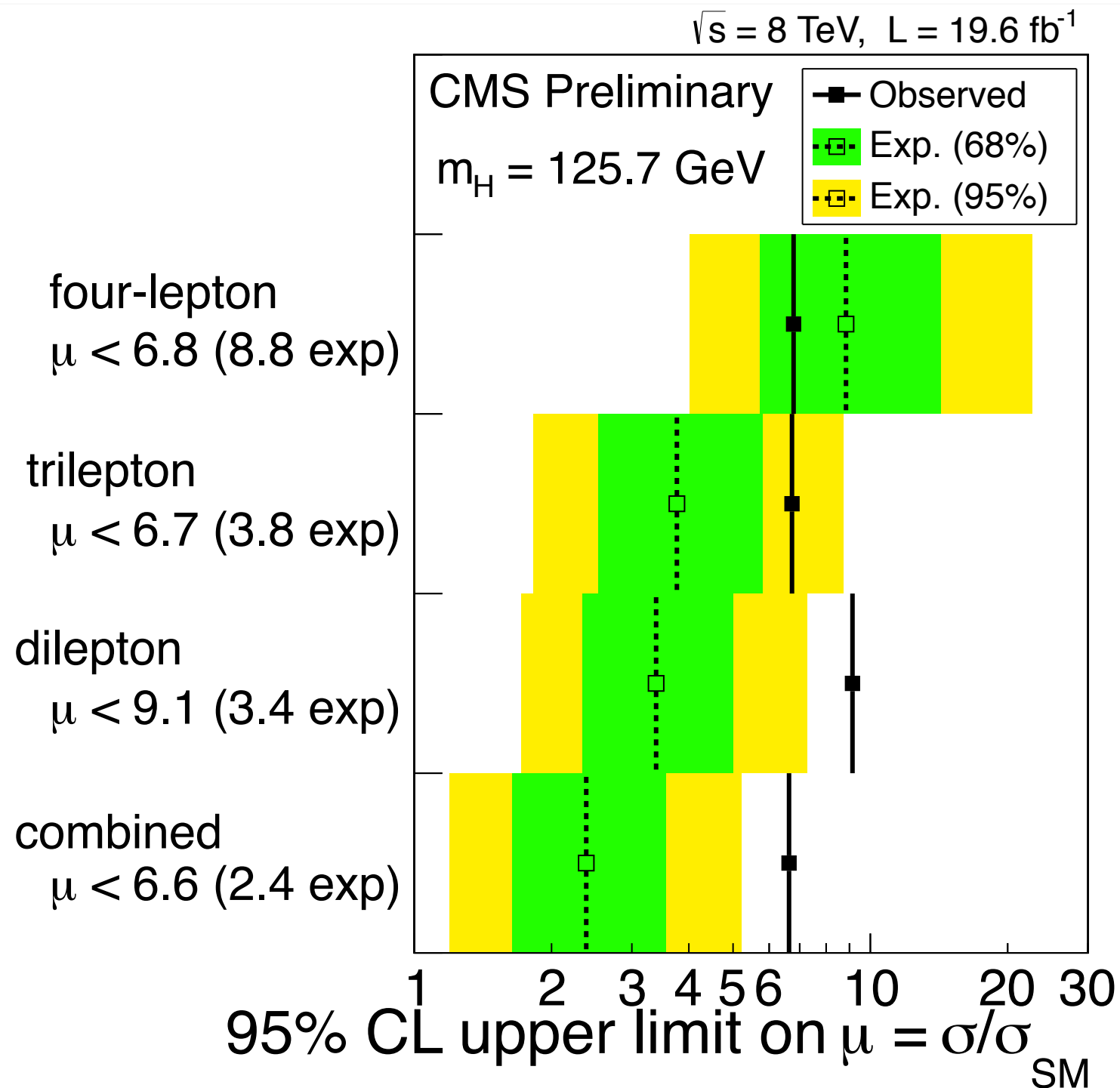
SEPARATING S FROM B

Fit to extract signal

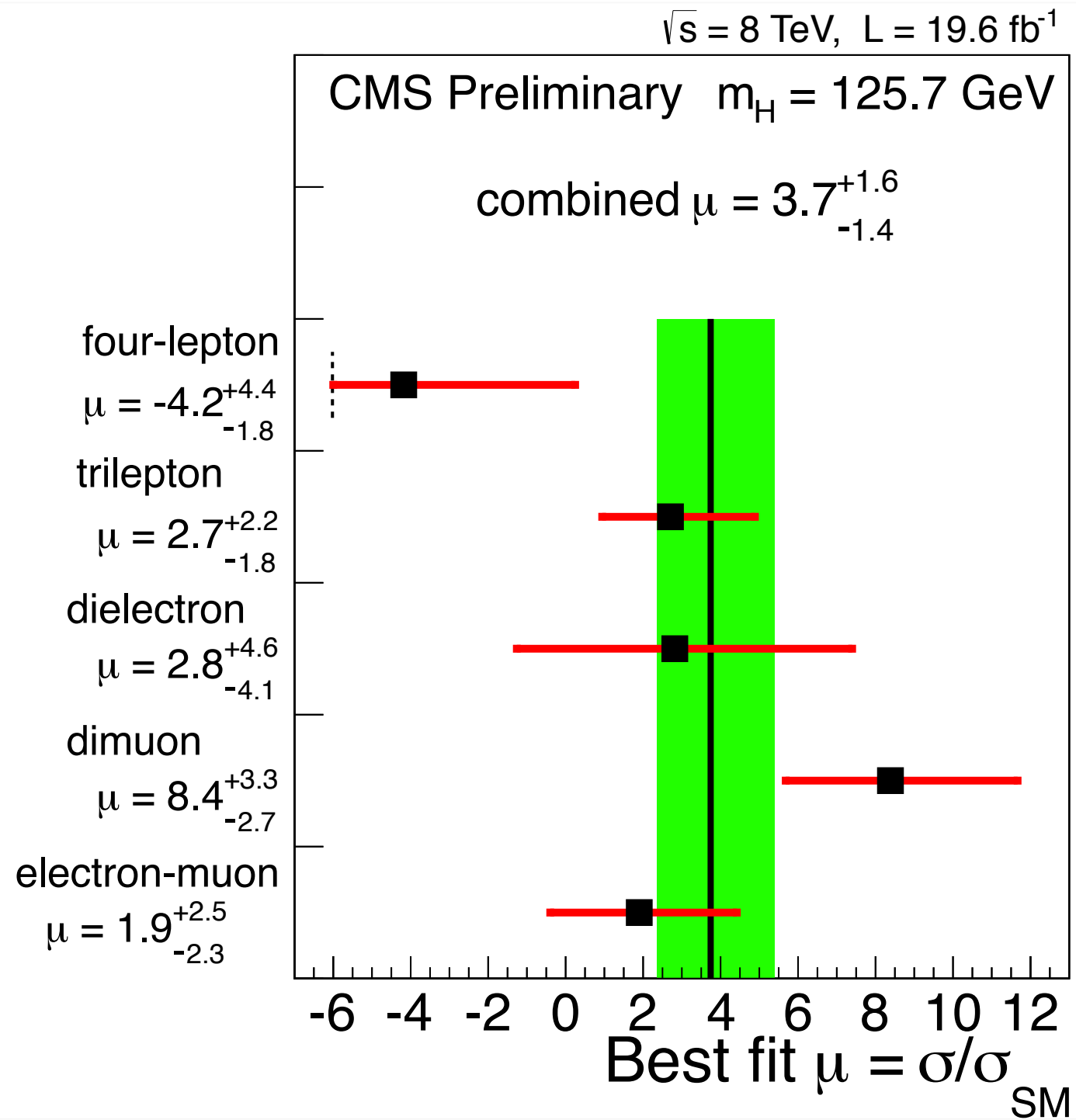
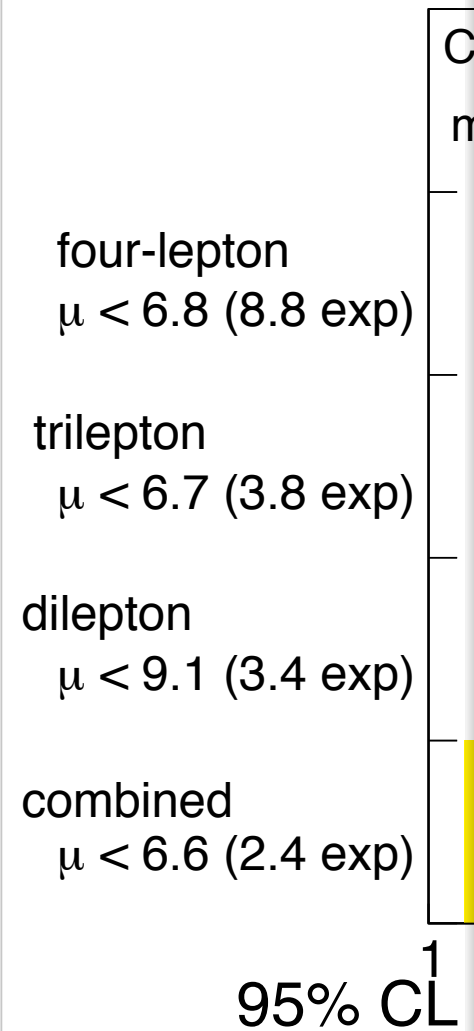


Leading systematic: Fake rate uncertainty

RESULTS



RESULTS



RESULTS

$\sqrt{s} = 8 \text{ TeV}, L = 19.6 \text{ fb}^{-1}$

CMS Preliminary

$m_H = 125.7 \text{ GeV}$

—■— Observed
—□— Exp. (68%)
—□— Exp. (95%)

four-lepton
 $\mu < 6.8$ (8.8 exp)

trilepton
 $\mu < 6.7$ (3.8 exp)

dilepton
 $\mu < 9.1$ (3.4 exp)

combined
 $\mu < 6.6$ (2.4 exp)

95% CL upper limit on $\mu = \sigma/\sigma_{\text{SM}}$

$\sqrt{s} = 8 \text{ TeV}, L = 19.6 \text{ fb}^{-1}$

CMS Preliminary $m_H = 125.7 \text{ GeV}$

combined $\mu = 3.7^{+1.6}_{-1.4}$

four-lepton
 $\mu = -4.2^{+4.4}_{-1.8}$

trilepton
 $\mu = 2.7^{+2.2}_{-1.8}$

dielectron
 $\mu = 2.8^{+4.6}_{-4.1}$

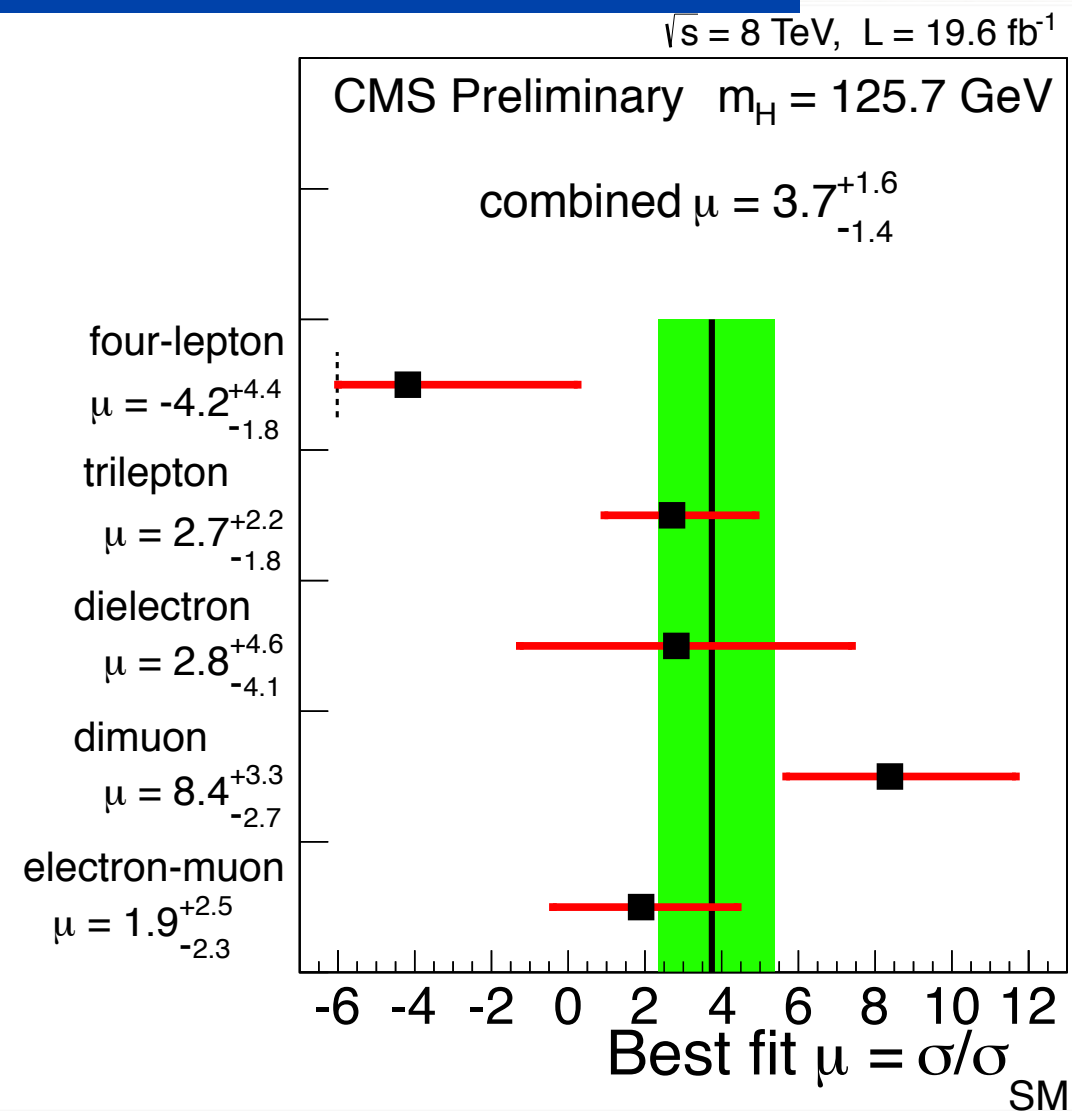
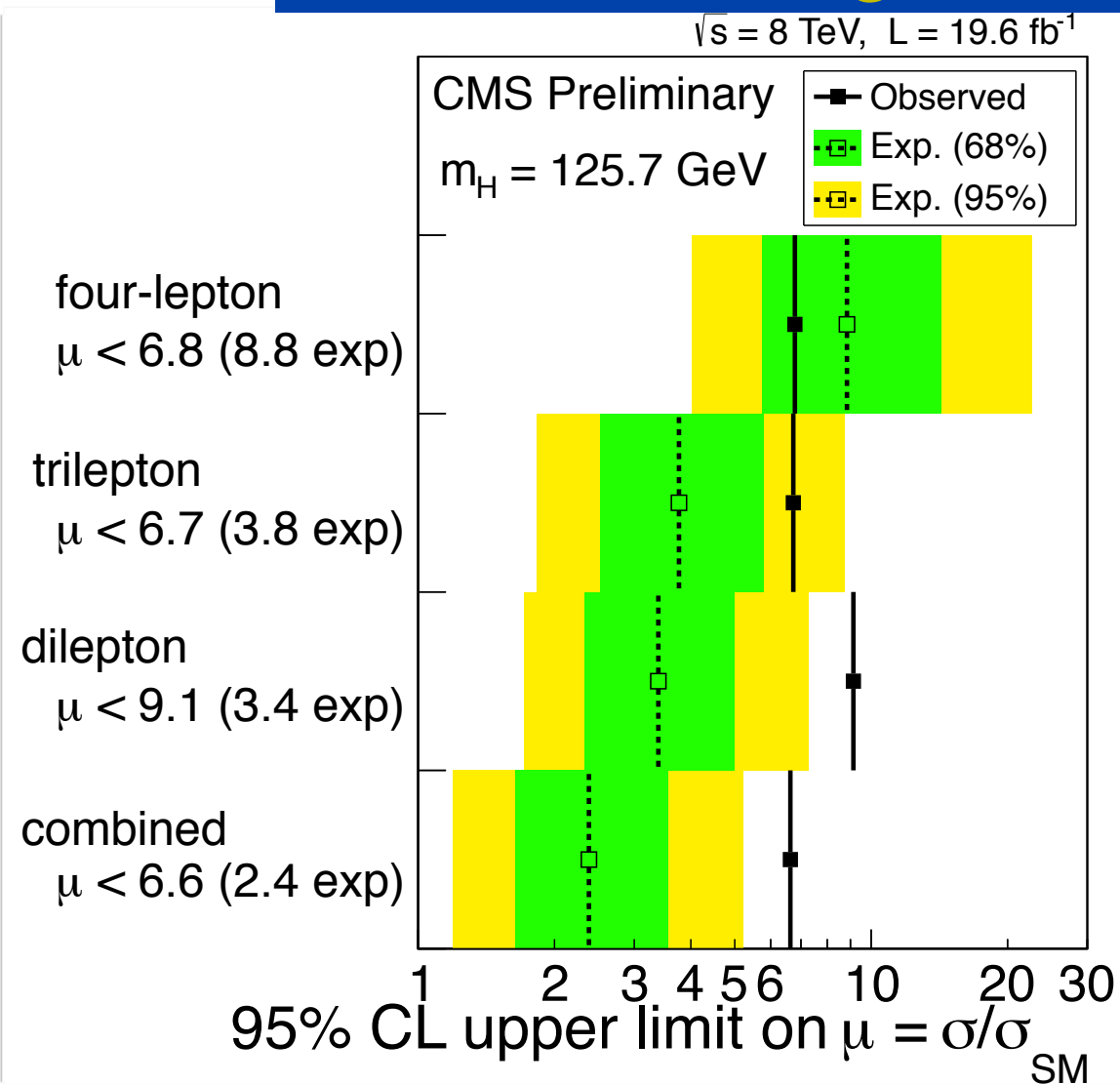
dimuon
 $\mu = 8.4^{+3.3}_{-2.7}$

electron-muon
 $\mu = 1.9^{+2.5}_{-2.3}$

Best fit $\mu = \sigma/\sigma_{\text{SM}}$

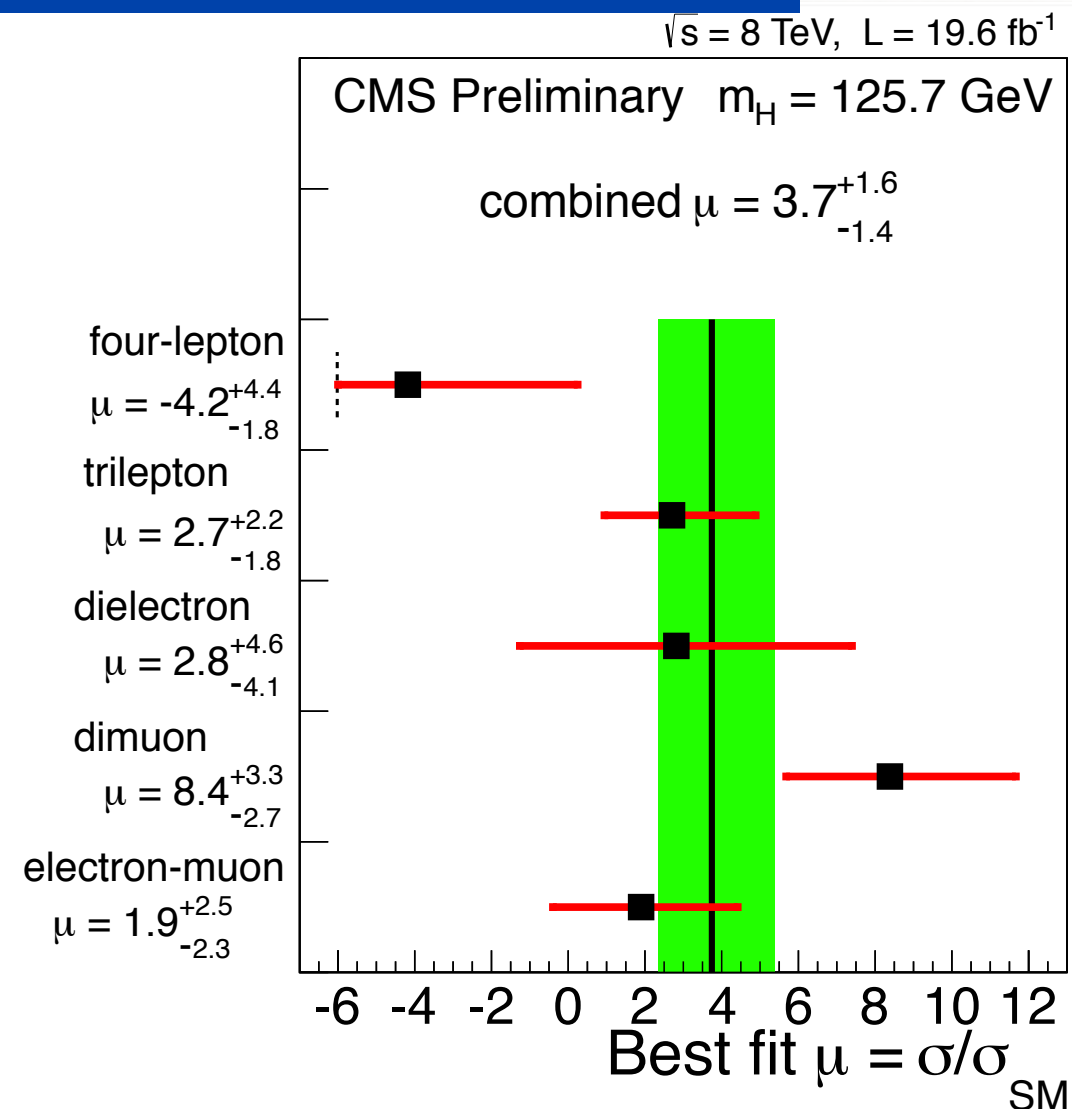
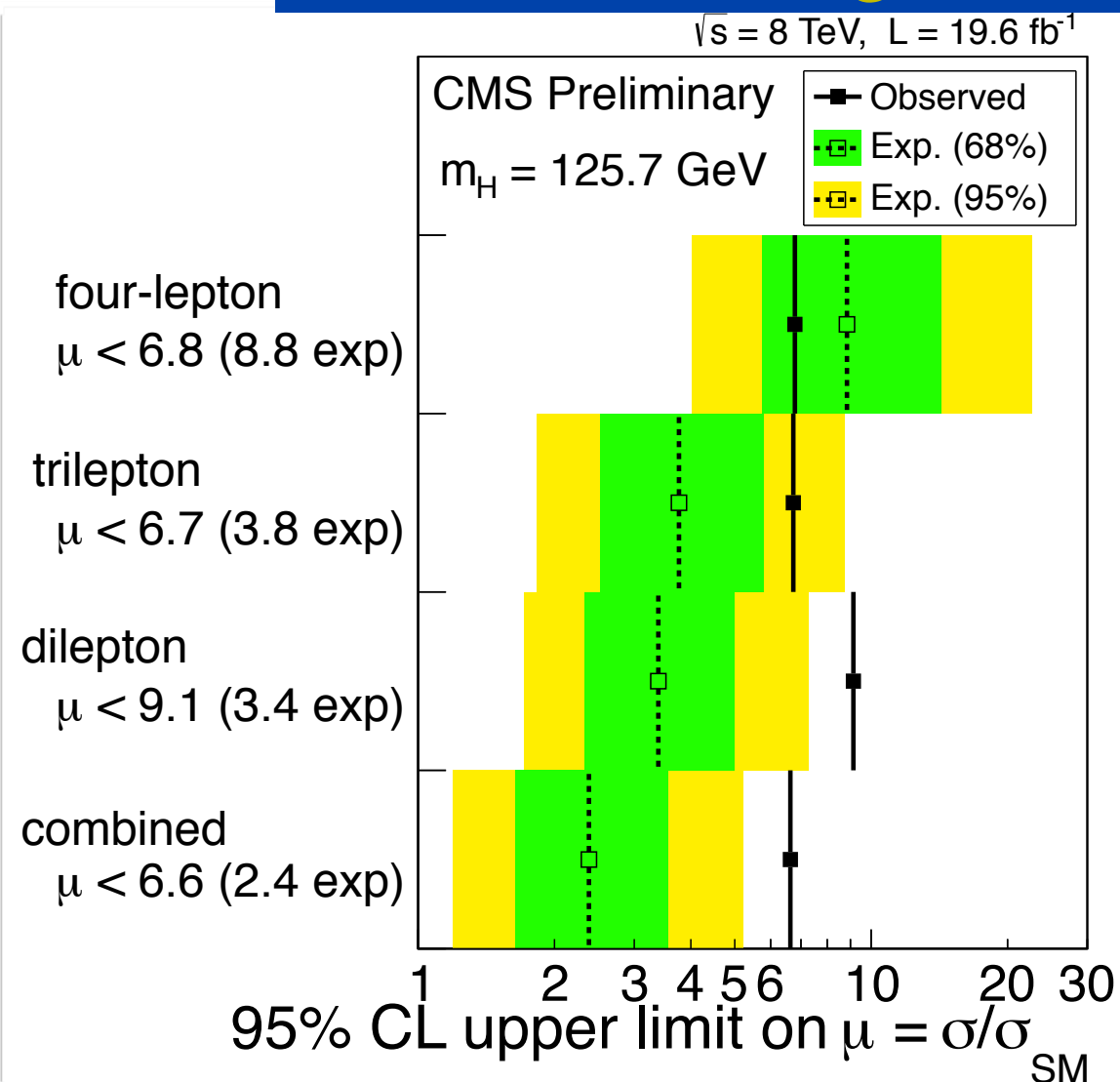
RESULTS

Excess of signal is approximately 1.9σ
(including SM expectation for ttH)



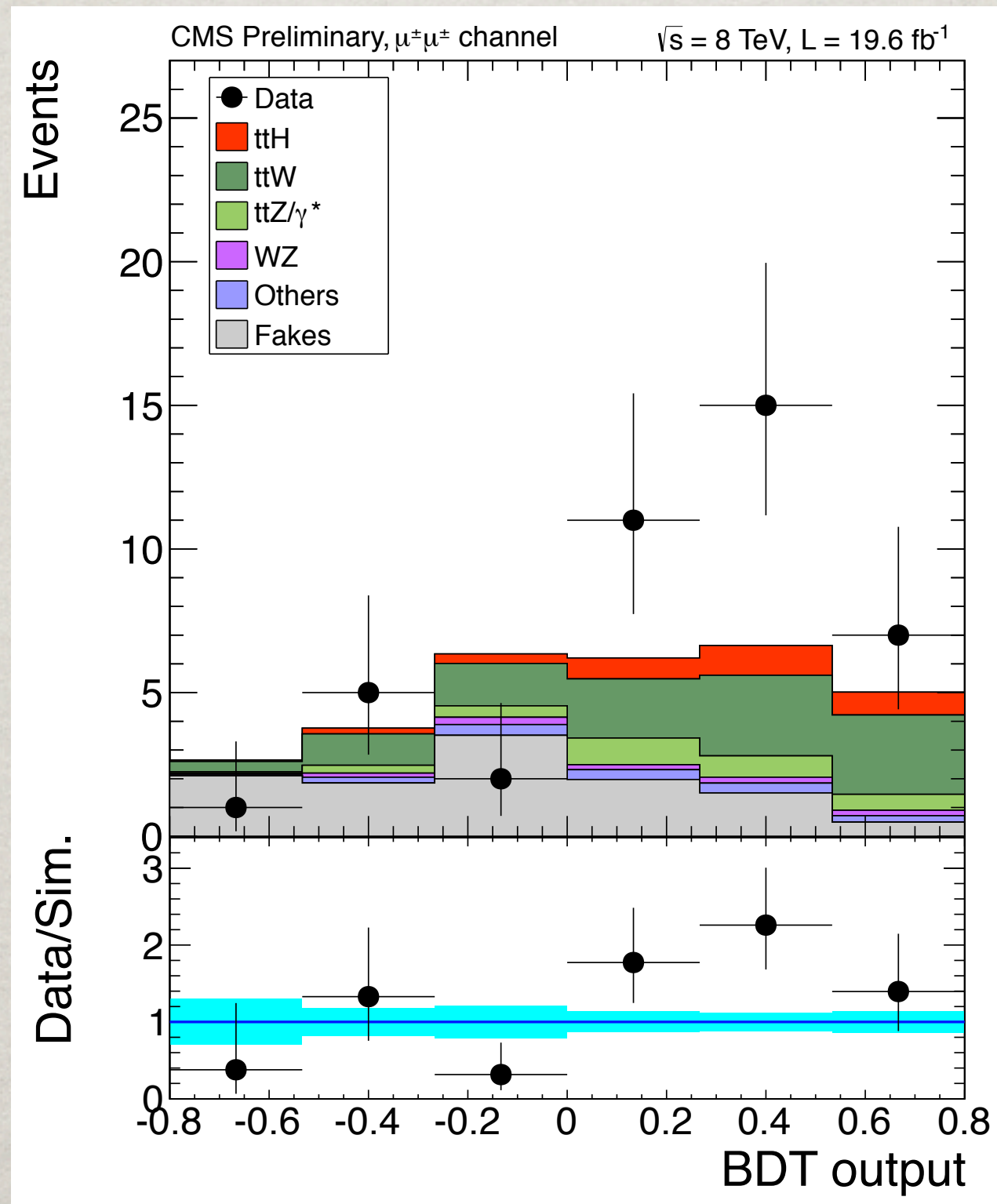
RESULTS

Excess of signal is approximately 1.9σ
(including SM expectation for ttH)



Many cross checks (esp. on dimuon); no problems uncovered

DIMUON DISTRIBUTION



Excess consistent
with isolated,
signal-like muons

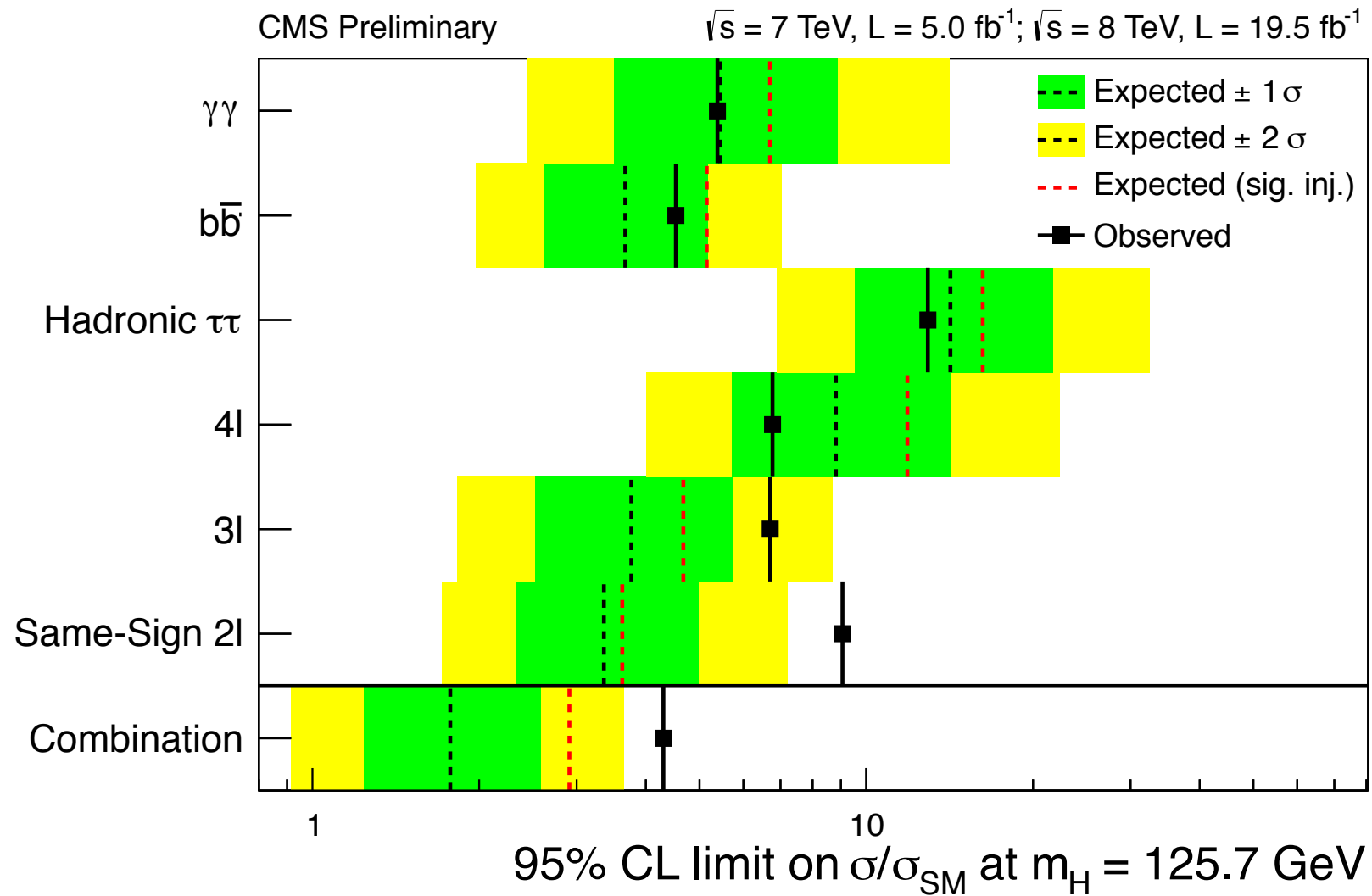
Excess persists
through several
cross checks

Still consistent
with statistical
fluctuation

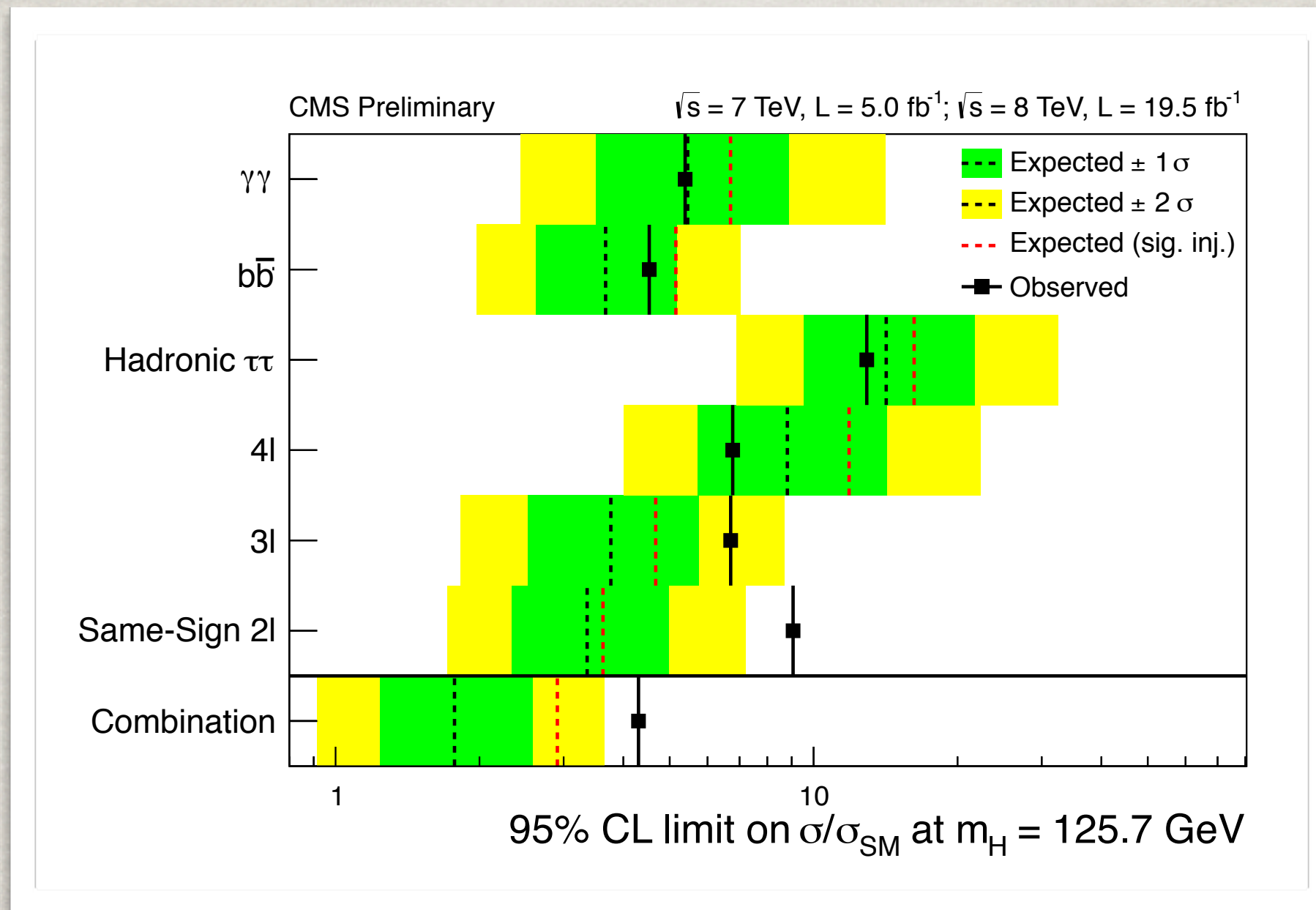
COMBINATION

RESULTS

RESULTS

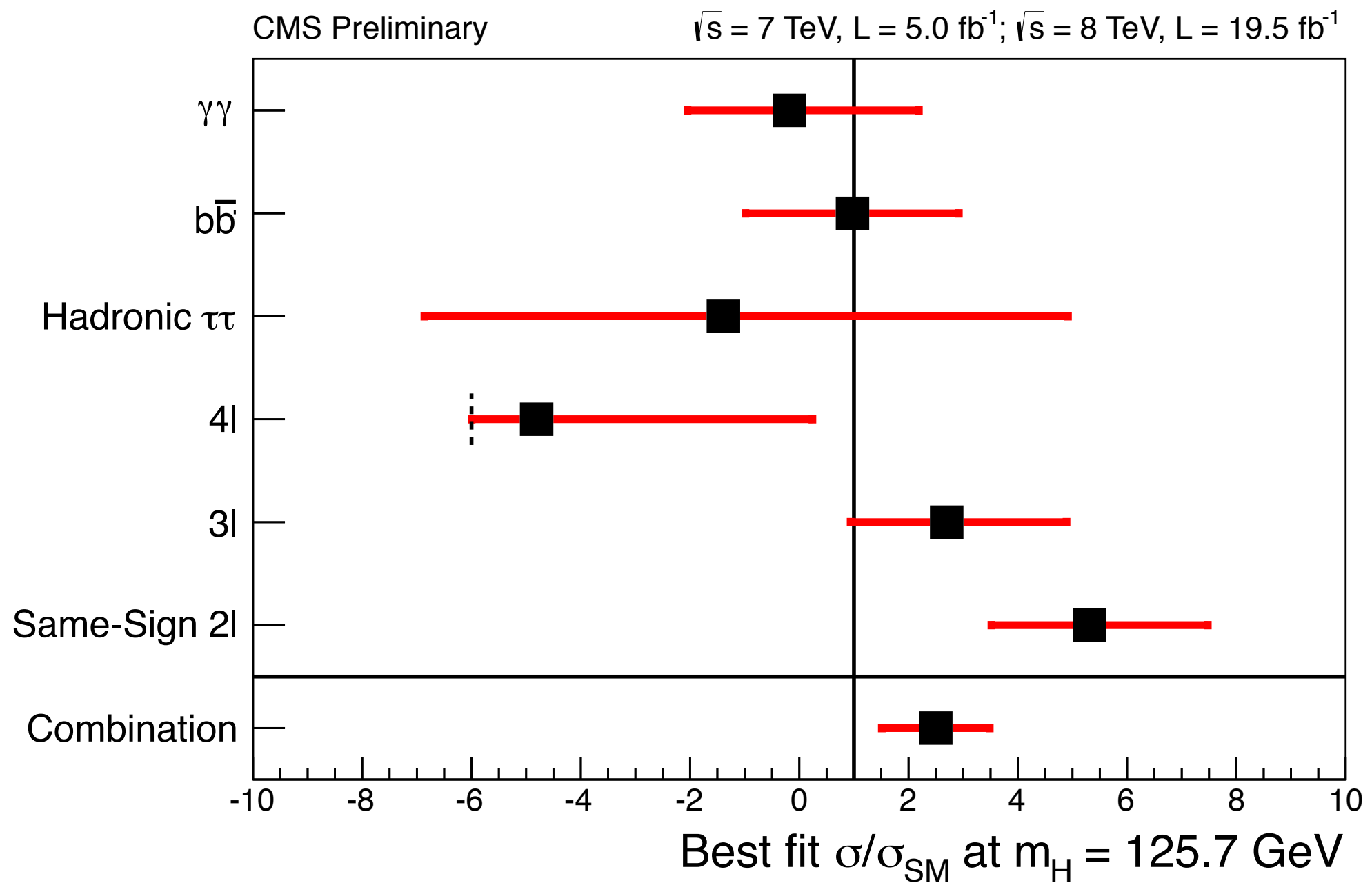


RESULTS

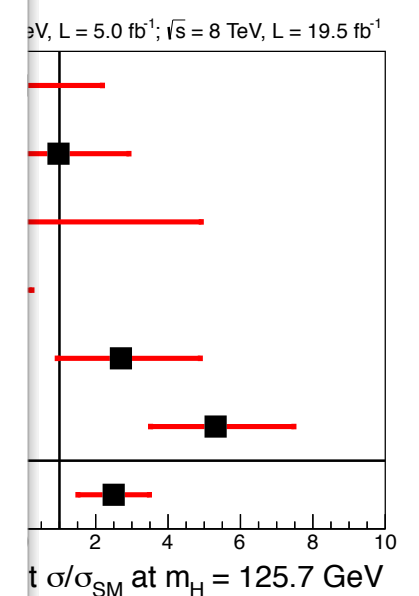
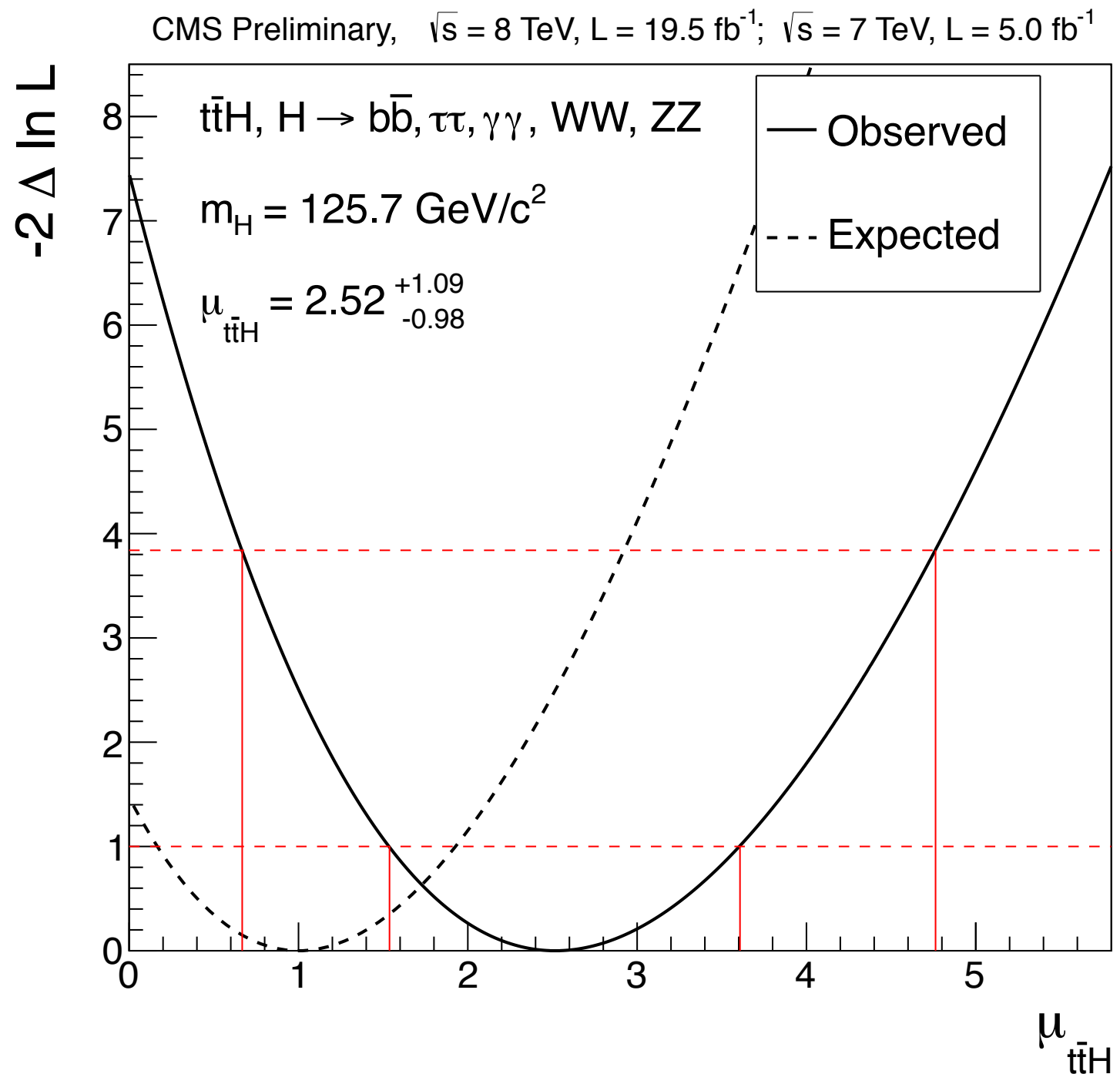
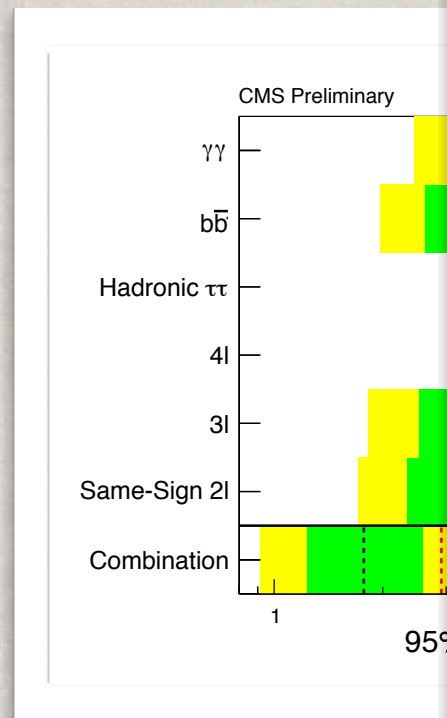


Median Exp. (no sig.) = $1.8 \times \text{SM}$; Median Exp. (sig.) = $2.9 \times \text{SM}$; Obs. = 4.3

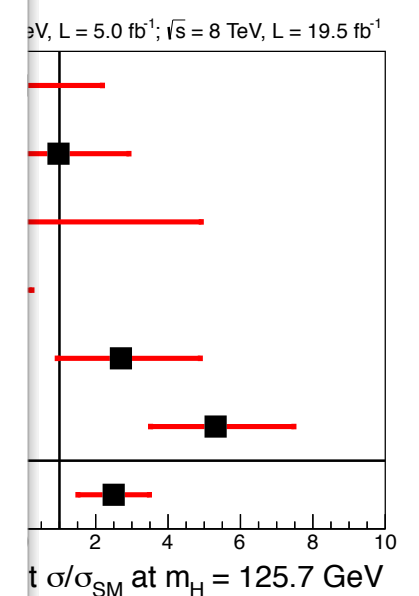
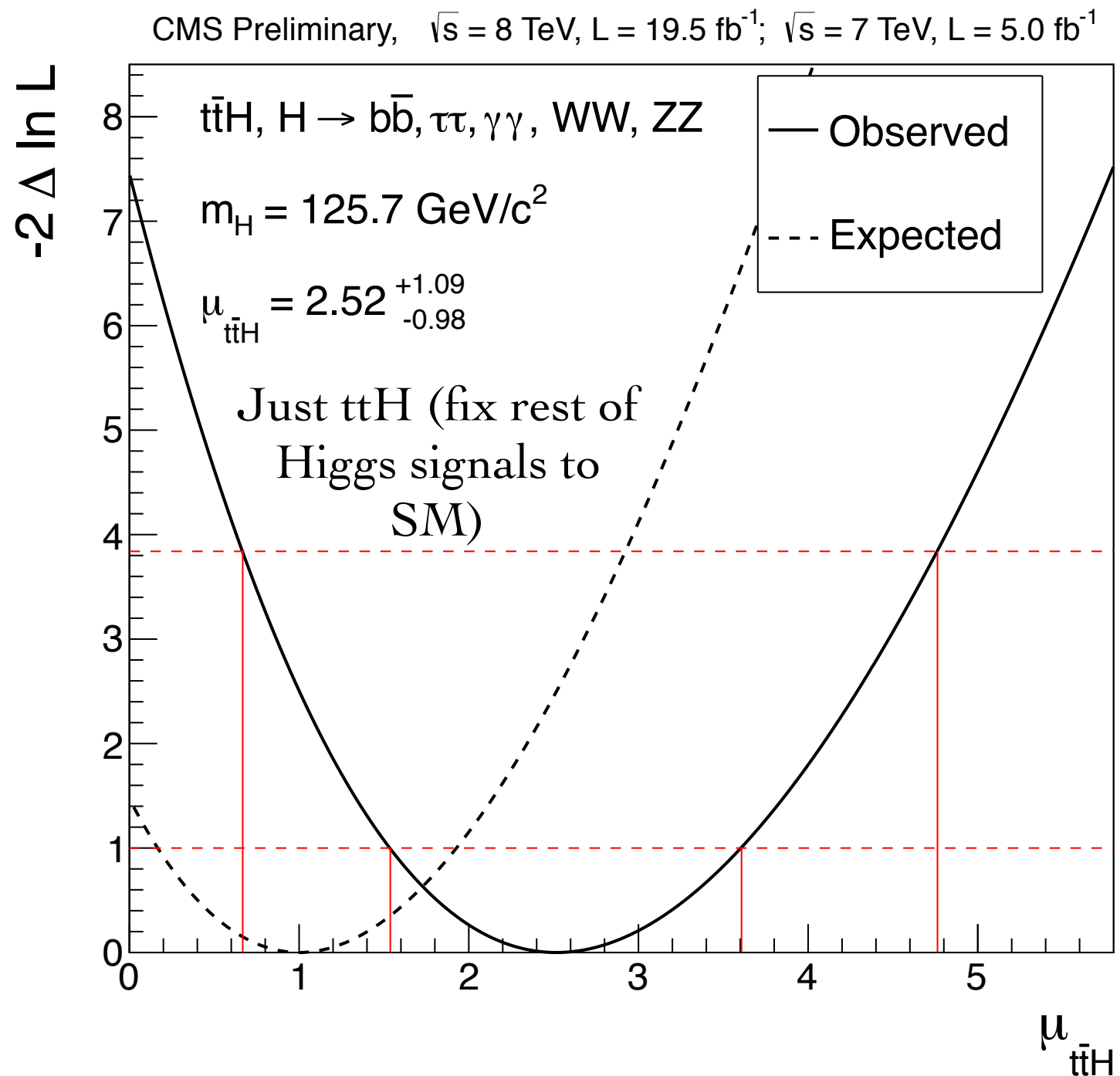
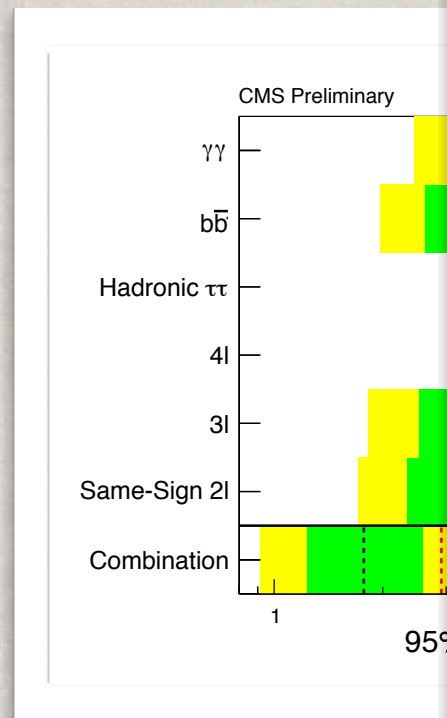
RESULTS



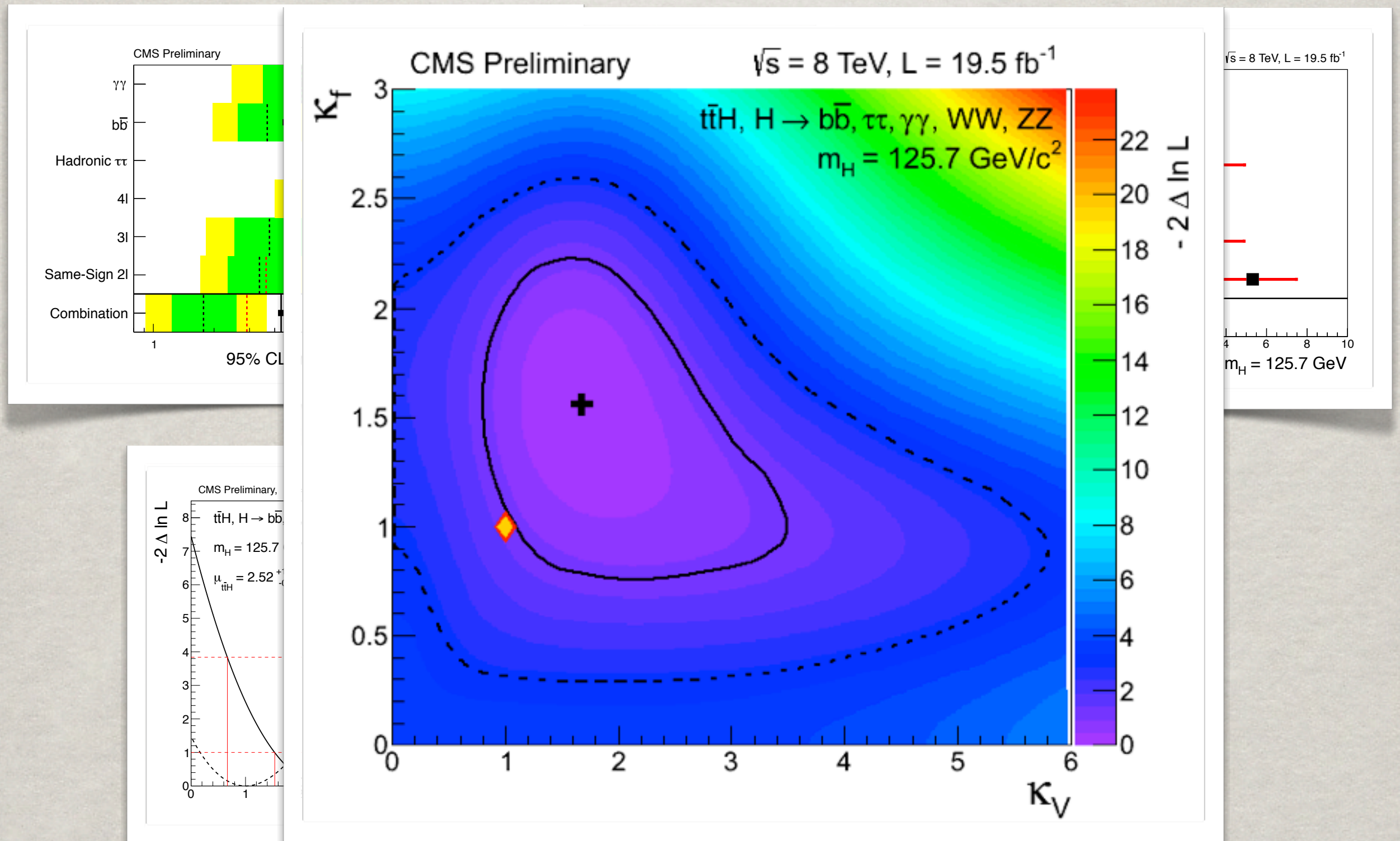
RESULTS



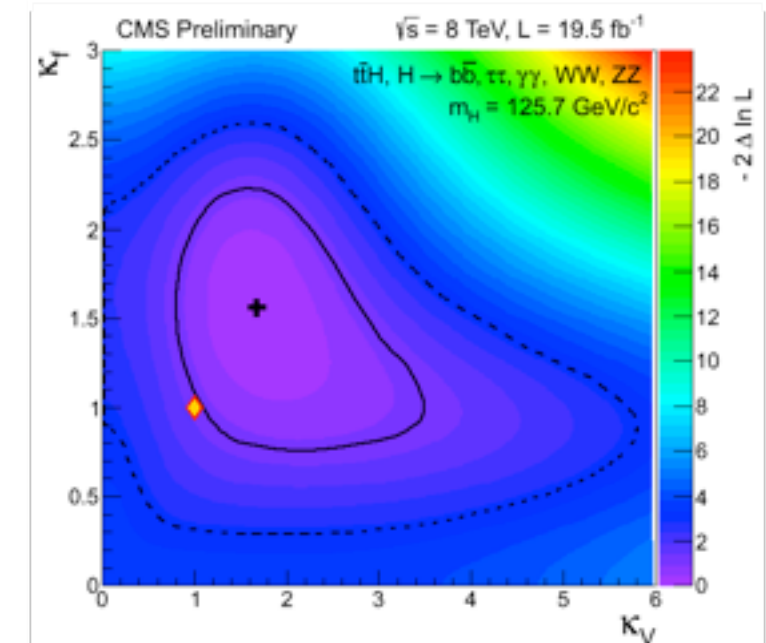
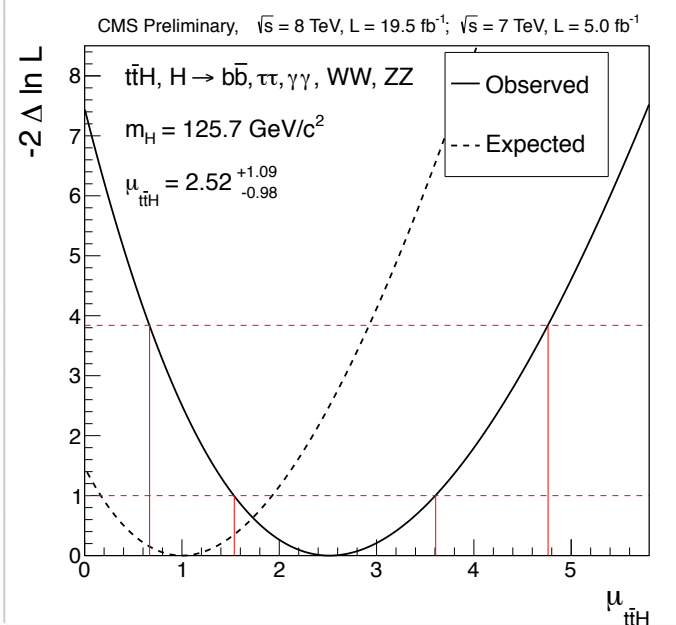
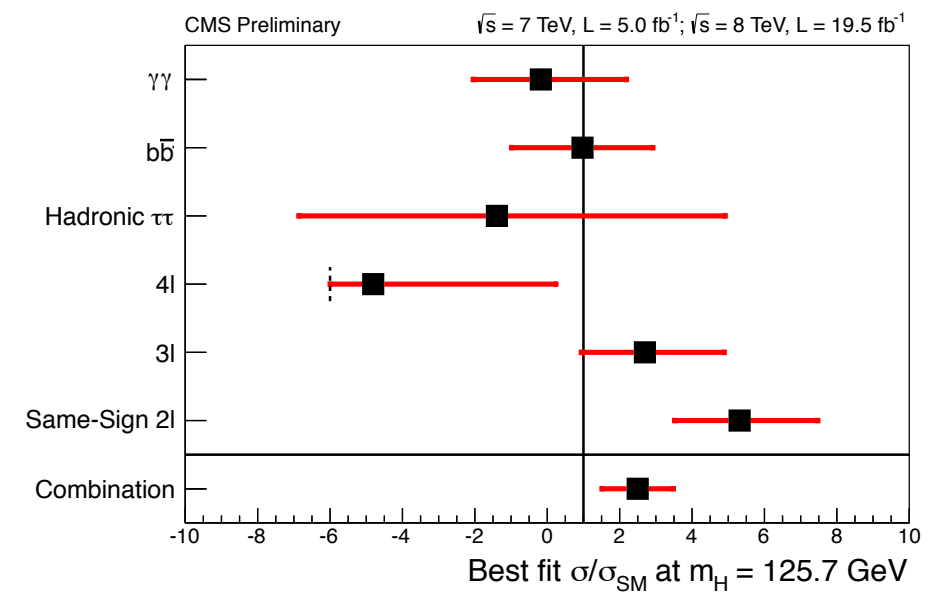
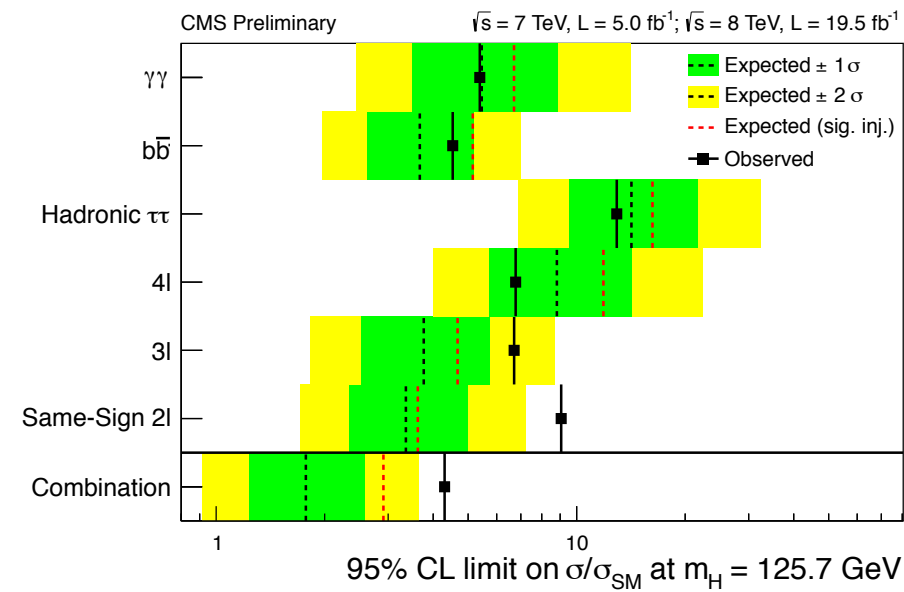
RESULTS



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CONCLUSIONS

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- ✱ Search for $t\bar{t}H$ is well underway
 - ✱ Leveraging multiple signatures
 - ✱ Still more to explore
 - ✱ New channels: All-hadronic with $H \rightarrow b\bar{b}$, etc.
 - ✱ Additional techniques: ME discriminants, boosted topologies
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- ✱ Top quark looks to be exciting signature for new physics
 - ✱ Natural SUSY $\Rightarrow$ (multi-)top quark signatures
 - ✱ Heavy resonances decaying to top pairs
 - ✱ etc.