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Searches for Higgs flavour violating couplings at ATLAS and CMS

Shikma Bressler

Flavour violating couplings

Harnik, Kopp, Zupan 1209.1397

$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots$$

fermion mass term Higgs-fermion coupling

If the mass basis and the interaction basis are different

$\Leftrightarrow$

In this notation, if Y_{ij} is not diagonal

$\Rightarrow$

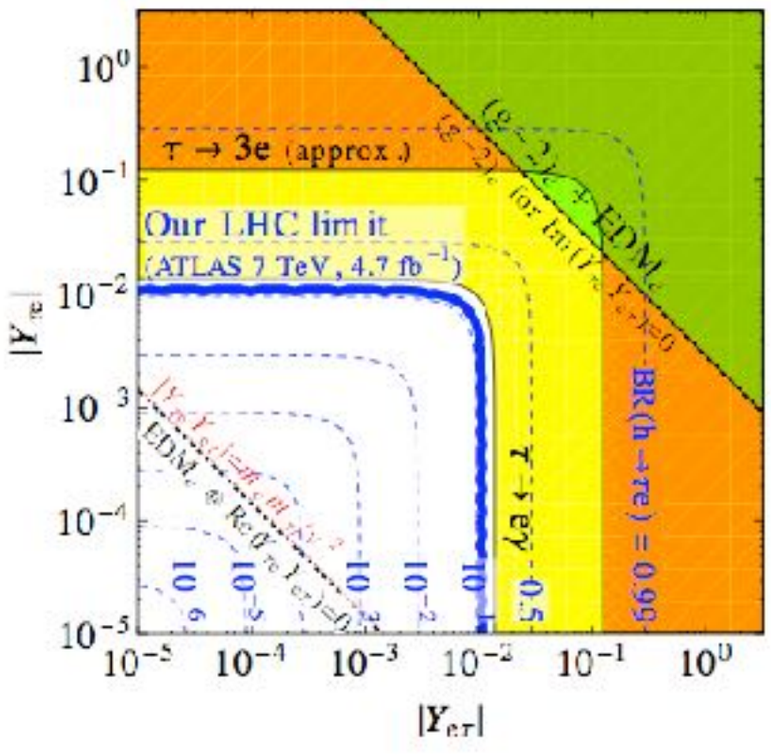
Flavour violating couplings

Can easily occur in extensions of the SM

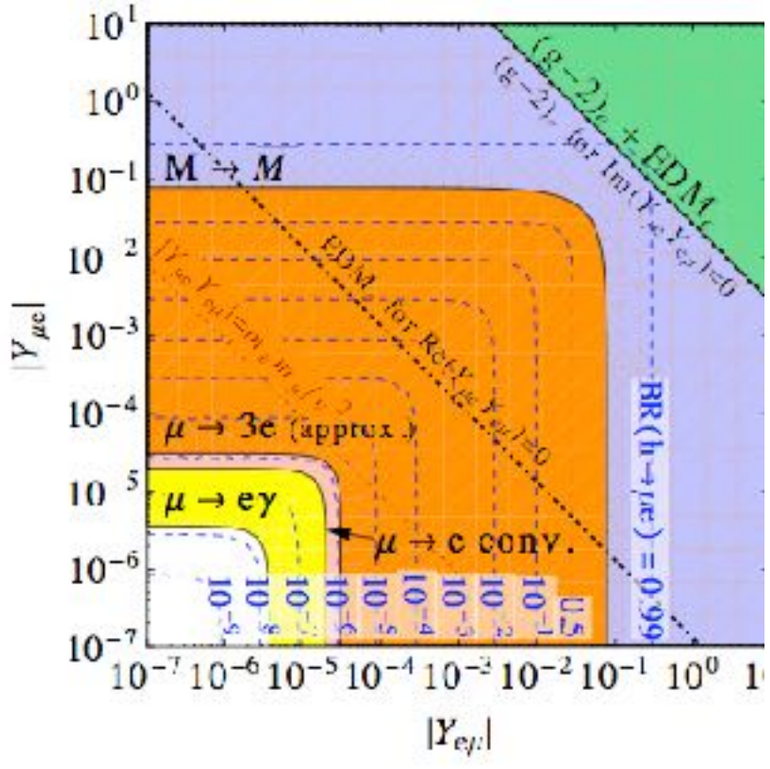
Pre-LHC results: indirect bounds

Harnik, Kopp, Zupan 1209.1397

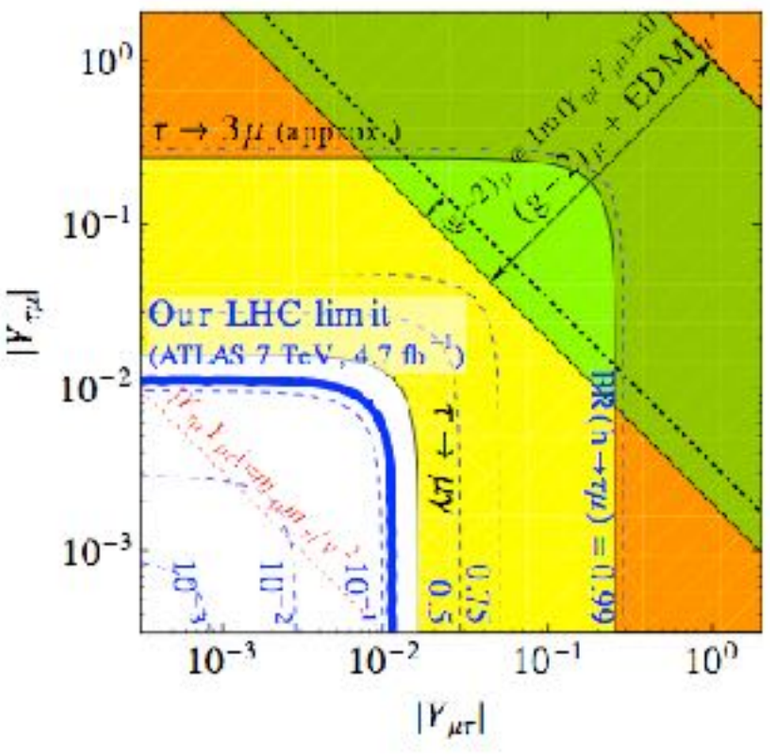
Lepton sector



BR(H→τe) ~ 15%
is allowed



No sensitivity
at the LHC*



BR(H→τμ) ~ 15%
is allowed

*Up to loop level cancelations

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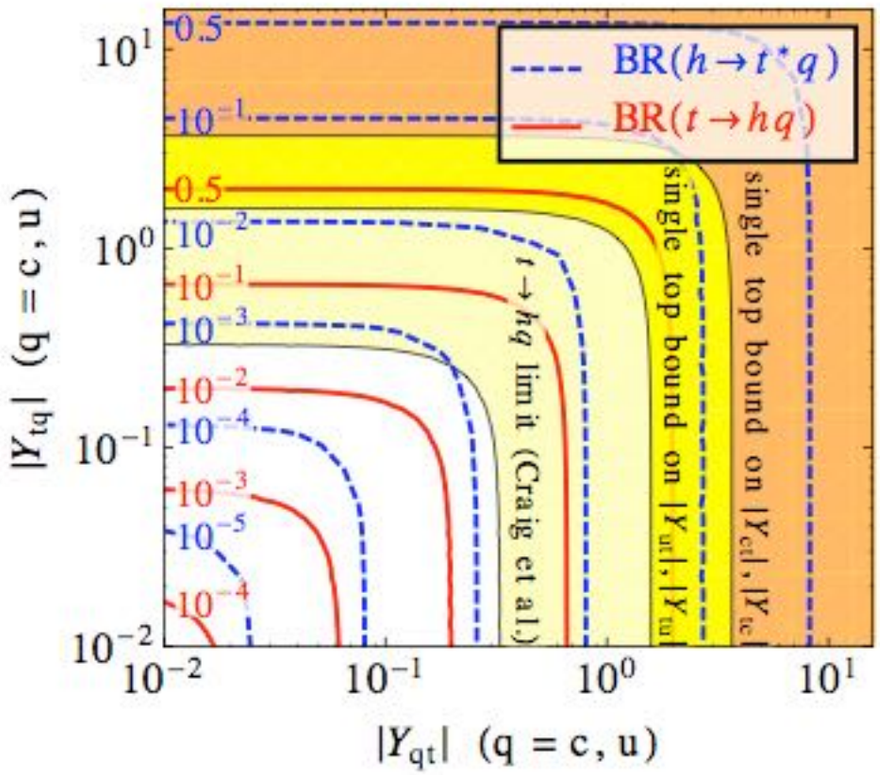
Pre-LHC results: indirect bounds

Harnik, Kopp, Zupan 1209.1397

Quark sector

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc} Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db} Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb} Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$



BR(t→qH) ~ 10% are allowed

Couplings not involving the top quark are highly suppressed

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Lepton sector

Experiment		Process	√s [TeV]	∫L [fb^{-1}]
CMS	1502.07400	H→τμ	8	20
CMS	1607.03561	H→eμ H→eτ	8	20
CMS	PAS HIG 16 005	H→τμ	**13**	2.3
ATLAS	1508.03372	H→τμ	8	20
ATLAS	1601.03567	**τ→3μ**	8	20
ATLAS	1604.07737	H→τμ H→τe	8	20

Quark sector

Experiment		Process	√s [TeV]	∫L [fb^{-1}]
CMS	1410.2751	t→Hc	8	20
CMS	1610.04857	t→Hc t→Hu	8	20
ATLAS	1403.6293	t→Hq	7,8	5,20
ATLAS	1509.06047	t→Hc t→Hu	8	20

Executive summary - November 2016

Lepton sector

Process	CMS	ATLAS
$H\to\tau\mu$	BR<1.20%	BR<1.40%
$H\to\tau e$	BR<0.69%	BR<1.04%
$H\to e\mu$	BR<0.048%	-
$\tau\to 3\mu$	-	BR<3.76×10^{-7} 90% CL

Quark sector

Process	CMS	ATLAS
$t\to cH$	BR<0.4%	BR<0.46%
$t\to uH$	BR<0.55%	BR<0.55%

Lepton sector

- Complementary efforts are made by both collaborations
- Different methods are being employed ⇒ stringent cross checks
  - General approaches
  - Estimation of mis-identified leptons
- Detector performance plays a leading role
  - Steep lepton reconstruction turn-on curves
  - High lepton p_T resolution
  - Misidentified lepton rate ⇒ the lower the better

CMS H→τμ

CMS 1502.07400 ➠ $Y_{\tau\mu}$

CMS H→τμ

CMS 1502.07400 ➠ $Y_{\tau\mu}$

Two search channels

- H→μτ_{had}
- H→μτ_e

Three jet categories

- 0-jets ⇒ targeting ggF production
- 1-jet ⇒ targeting ggF production
- 2-jets ⇒ targeting VBF production

Mass estimator

- Collinear mass

Background

- Z→ττ
  - Embedding
- Misidentified leptons (w+jets, QCD)
  - Based on reverse isolation criteria
  - Validated in a same-sign region

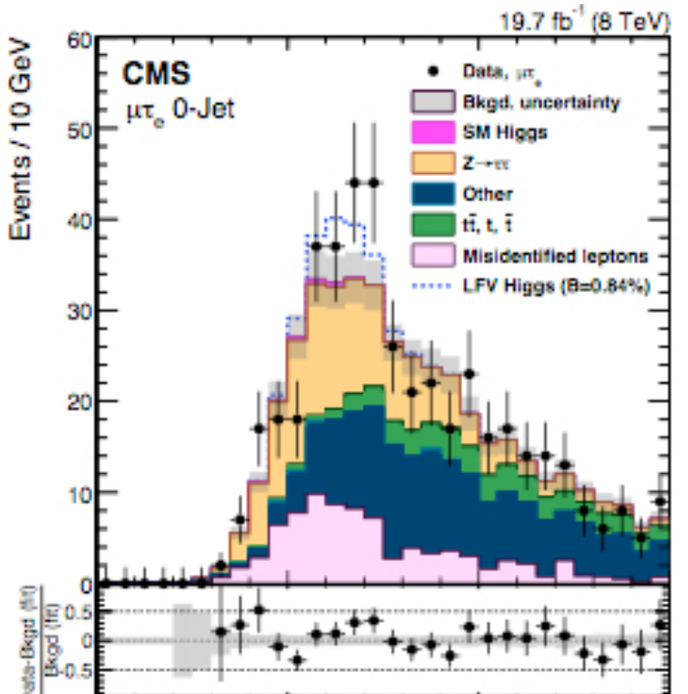
Region I	Region II
$\ell_1^{\pm}$(isolated)	$\ell_1^{\pm}$(isolated)
$\ell_2^{\mp}$(isolated)	$\ell_2^{\mp}$(isolated)
Region III	**Region IV**
$\ell_1^{\pm}$(isolated)	$\ell_1^{\mp}$(isolated)
$\ell_2^{\mp}$(not-isolated)	$\ell_2^{\pm}$(not-isolated)

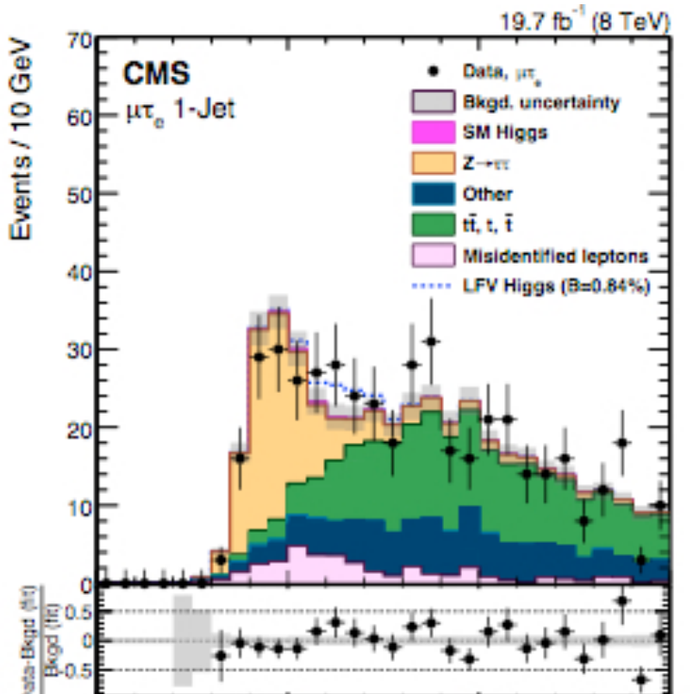
- Other (ttbar, H→ττ, WW, ZZ…)
  - From simulation

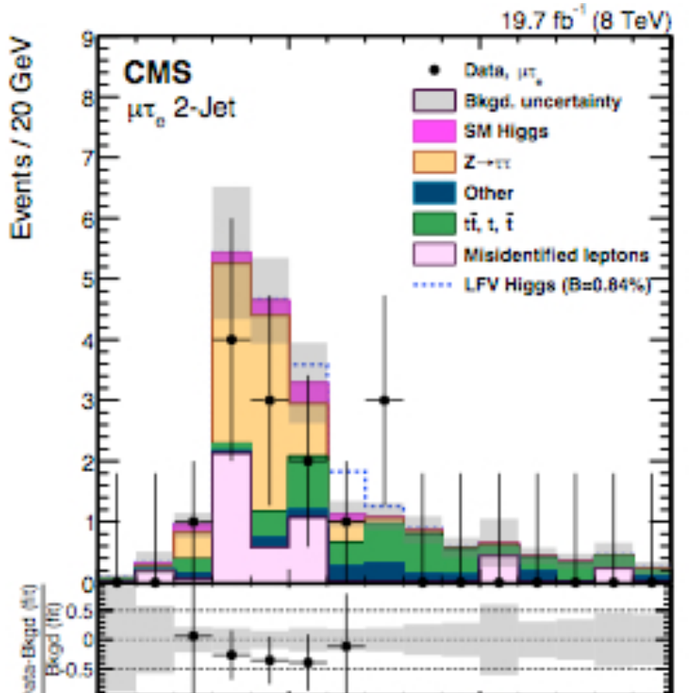
8 TeV Lepton sector CMS H→τμ

CMS 1502.07400 ➠ $Y_{\tau\mu}$

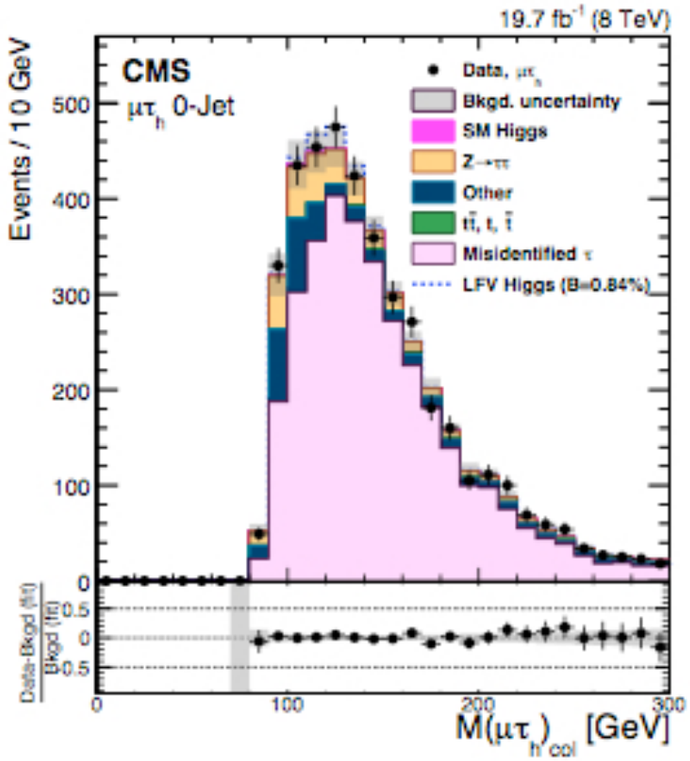
$H\to\mu\tau_e$

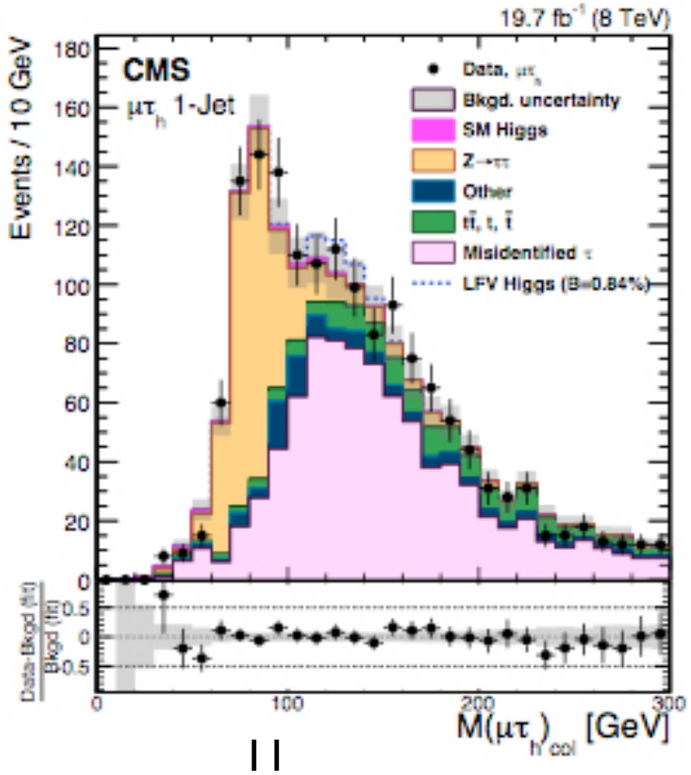


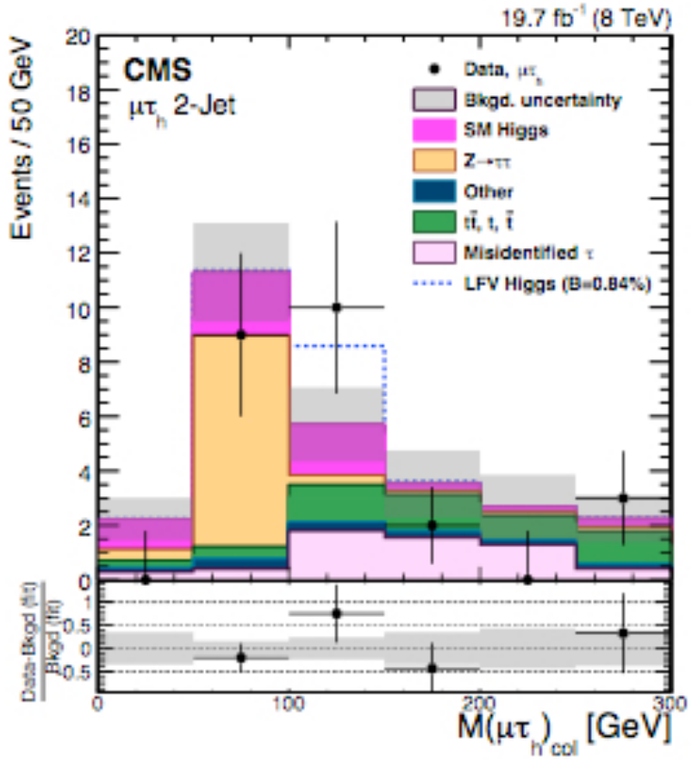




$H\to\mu\tau_{had}$





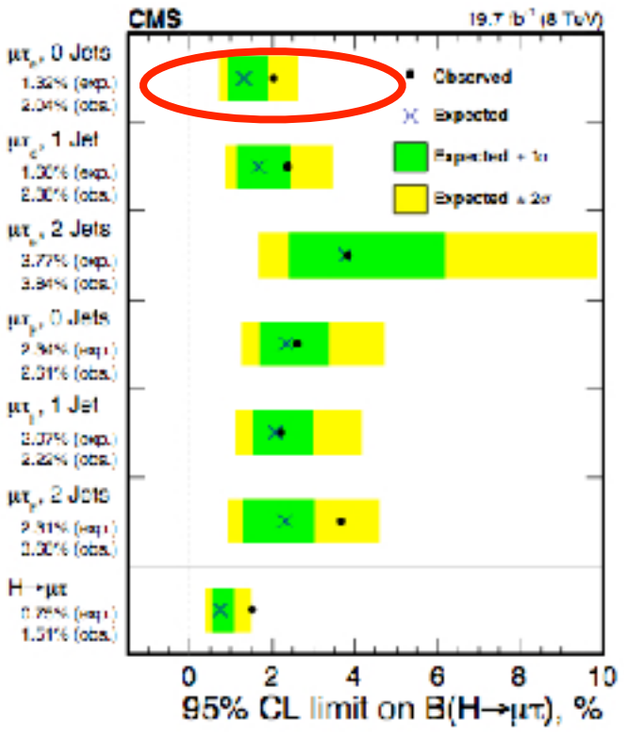


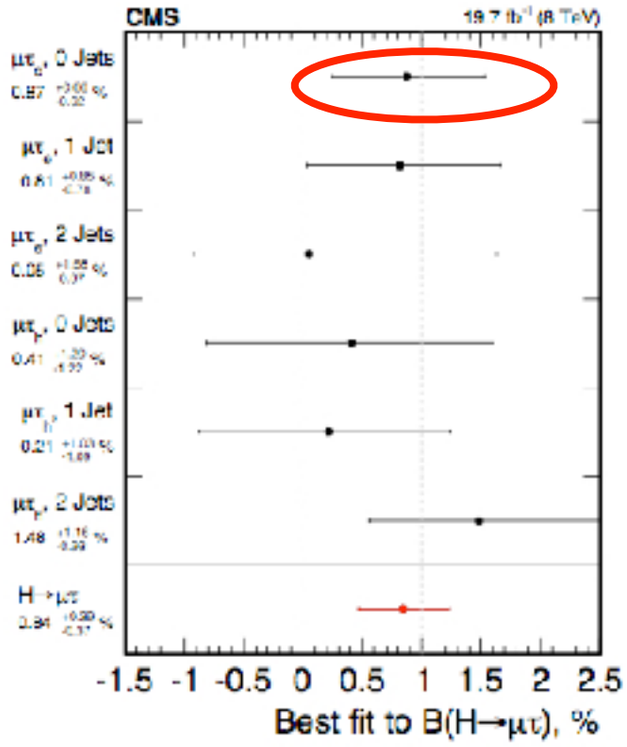
CMS H→τμ

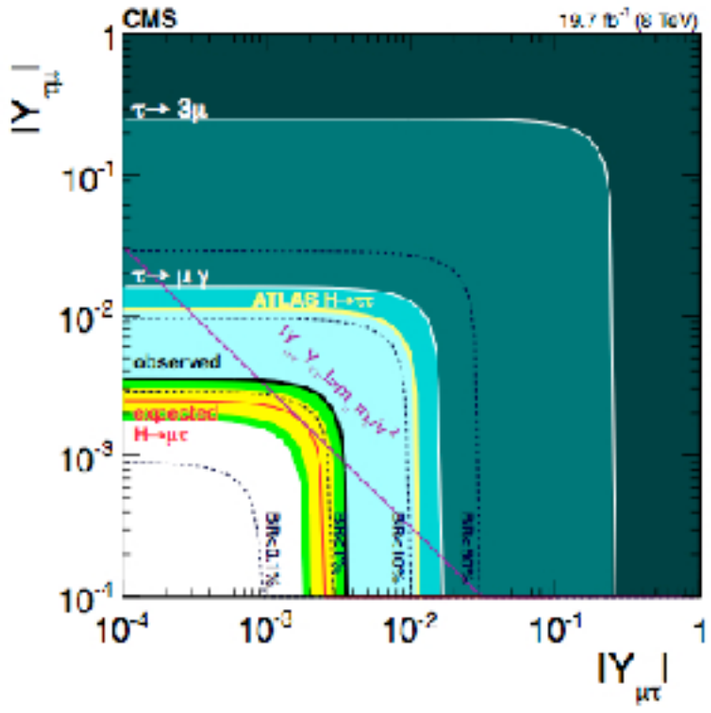
CMS 1502.07400 ➠ $Y_{\tau\mu}$

$H\to\mu\tau_e$

$H\to\mu\tau_{had}$







Expected Limits			
	0-Jet (%)	1-Jet (%)	2-Jets (%)
$\mu\tau_e$	<1.32 (±0.67)	<1.66 (±0.85)	<3.77 (±1.92)
$\mu\tau_h$	<2.34 (±1.19)	<2.07 (±1.06)	<2.31 (±1.18)
$\mu\tau$	<0.75 (±0.38)		
Observed Limits			
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$	<1.51		
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$		$0.84^{+0.39}_{-0.37}$	

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$

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ATLAS $H \to \tau_{had}\mu$

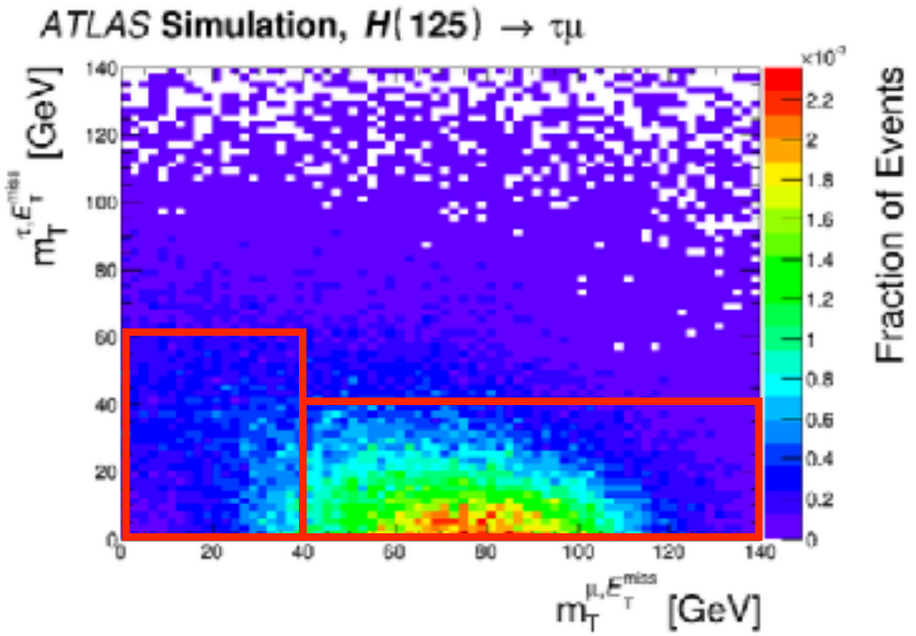
ATLAS 1508.03372 ➠ $Y_{\tau\mu}$

8 TeV Lepton sector ATLAS $H\to\tau_{had}\mu$

One search channels

- $H\to\mu\tau_{had}$

Two signal regions



Mass estimator

- MMC

Background

ATLAS 1508.03372 ➠ $Y_{\tau\mu}$

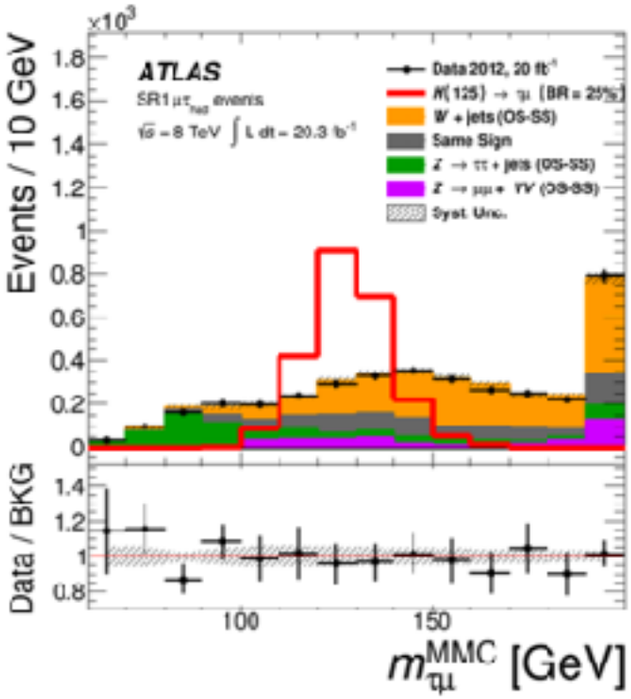
$$N_{OS}^{bkg} = r_{QCD}\cdot N_{SS}^{data} + N_{OS-SS}^{Z\to\tau\tau} + N_{OS-SS}^{Z\to\mu\mu} + N_{OS-SS}^{W+jets} + N_{OS-SS}^{top} + N_{OS-SS}^{VV} + N_{OS-SS}^{H\to\tau\tau},$$

- $r_{QCD} = N_{OS}^{multi-jet}/N_{SS}^{multi-jet}$

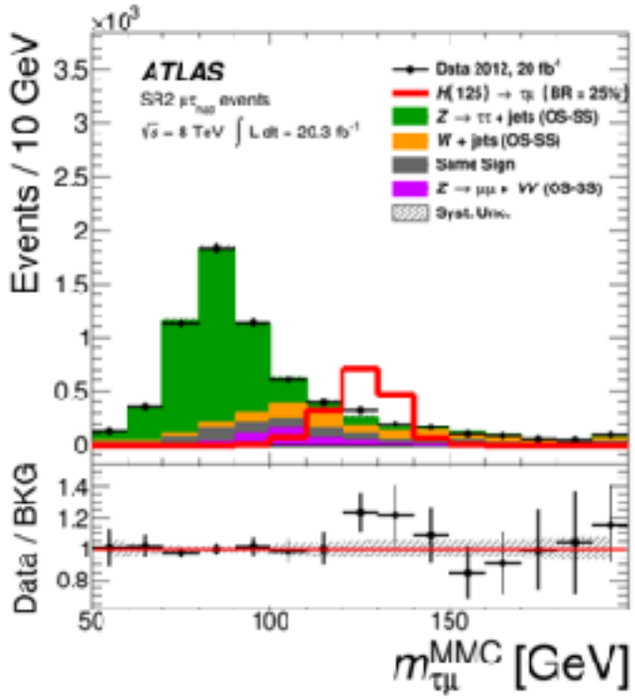
- $Z\to\tau\tau$
  - Embedding
- Misidentified leptons (w+jets, QCD)
  - By r_{QCD}
- Other (ttbar, $H\to\tau\tau$, WW, ZZ…)
  - From simulation

8 TeV Lepton sector

ATLAS $H \to \tau_{had}\mu$

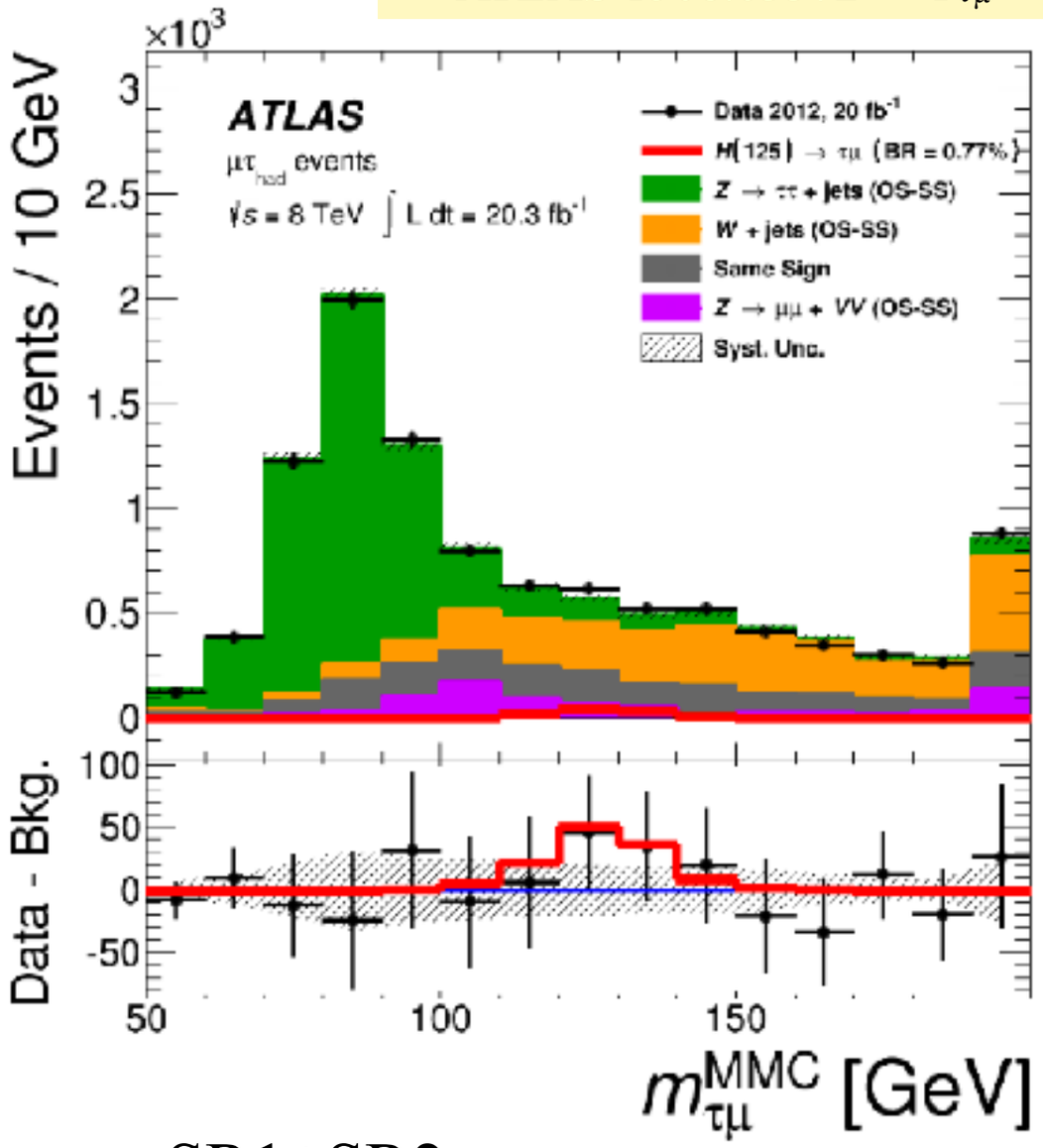


SR1



SR2

ATLAS 1508.03372 ➠ $Y_{\tau\mu}$



SR1+SR2

	SR1	SR2	Combined
Expected limit on Br($H \to \mu\tau$) [%]	$1.60^{+0.64}_{-0.45}$	$1.75^{+0.71}_{-0.49}$	$1.24^{+0.50}_{-0.35}$
Observed limit on Br($H \to \mu\tau$) [%]	1.55	3.51	1.85
Best fit Br($H \to \mu\tau$) [%]	$-0.07^{+0.81}_{-0.86}$	$1.94^{+0.92}_{-0.89}$	0.77±0.62

ATLAS H→τμ/τe

ATLAS 1604.07737 ➠ $Y_{\tau\mu}$ & $Y_{\tau e}$

8 TeV Lepton sector ATLAS H→τμ/τe

ATLAS 1604.07737 ➠ $Y_{\tau\mu}$ & $Y_{\tau e}$

Two searches & search channels

- H→eτ_{had}
- H→μτ_e & H→eτ_μ

H→eτ_{had}

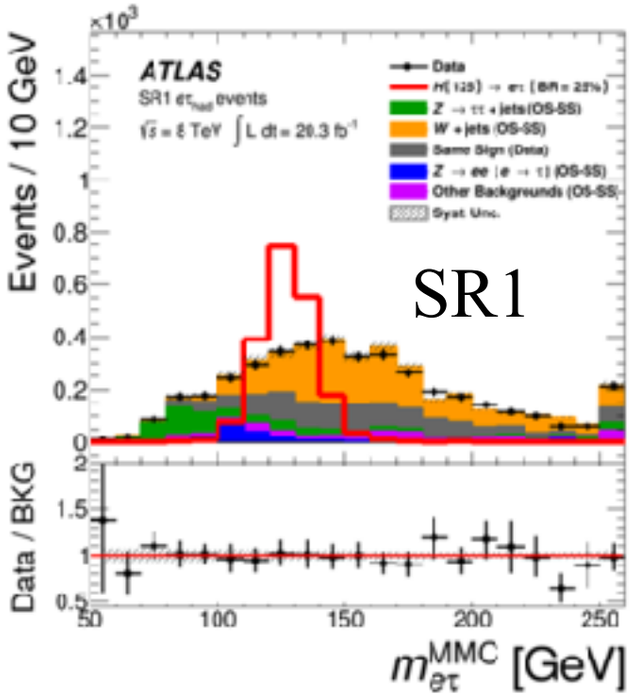
- Similar to H→μτ_{had}

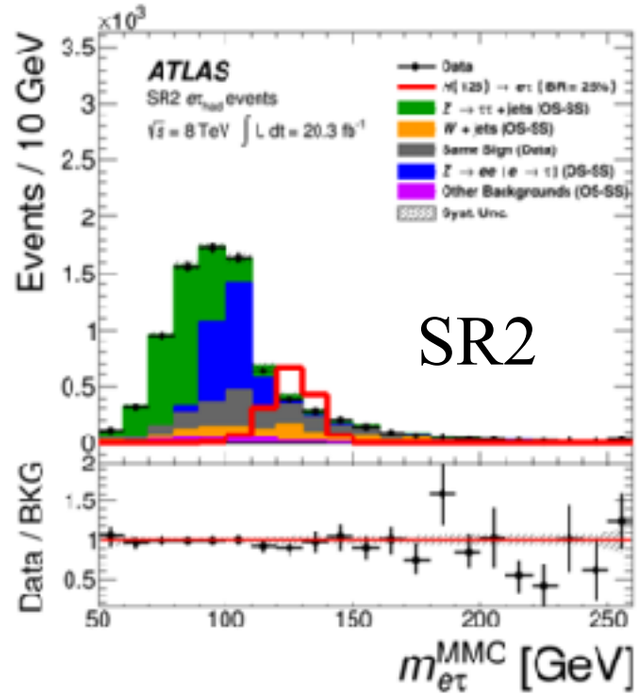
Mass estimator

- MMC

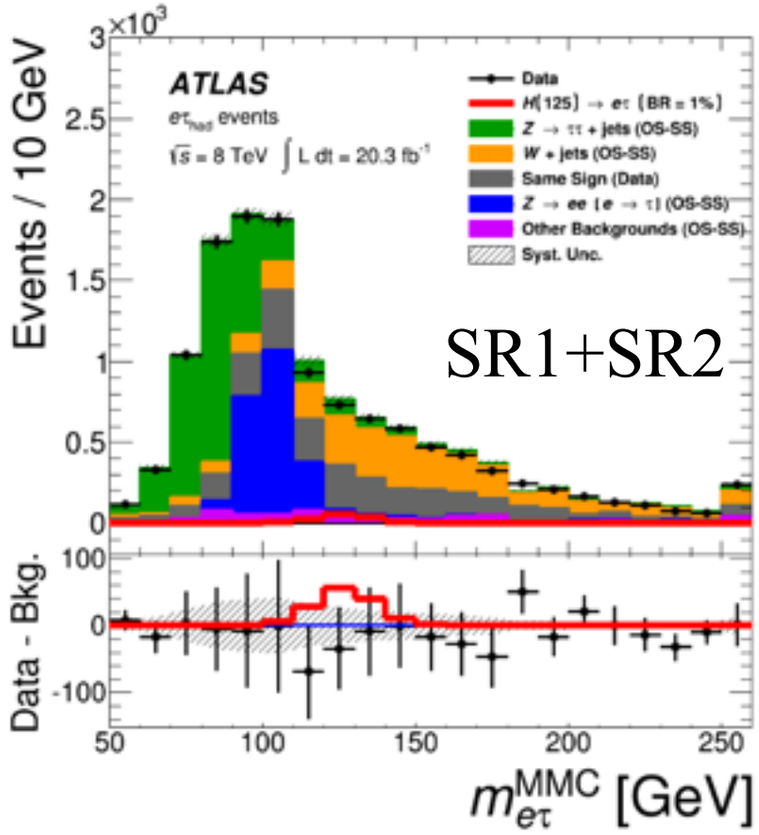
Background estimation

$$N_{OS}^{bkg} = r_{QCD} \cdot N_{SS}^{data} + N_{OS-SS}^{Z\to\tau\tau} + N_{OS-SS}^{Z\to\mu\mu} + N_{OS-SS}^{W+jets} + N_{OS-SS}^{top} + N_{OS-SS}^{VV} + N_{OS-SS}^{H\to\tau\tau},$$





H→eτ_{had}



8 TeV Lepton sector ATLAS H→τμ/τe

ATLAS 1604.07737 ➠ $Y_{\tau\mu}$ & $Y_{\tau e}$

$H\rightarrow\mu\tau_e$ & $H\rightarrow e\tau_\mu$

Mass estimator

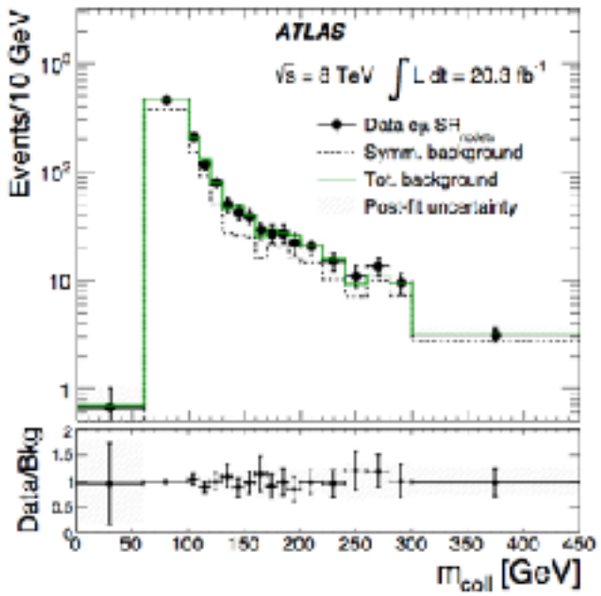
- Collinear mass

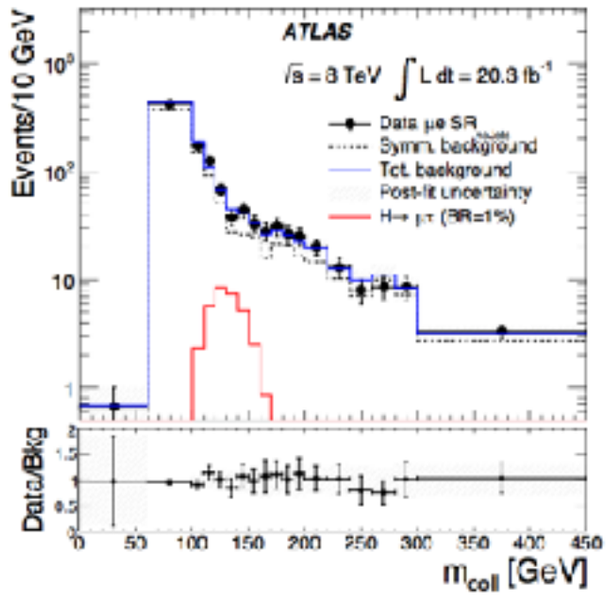
Two signal regions

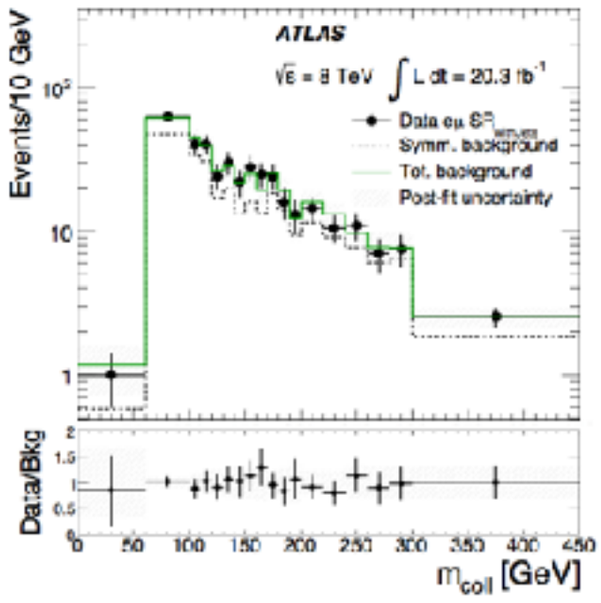
- SR_{noJets}
- SR_{jets}

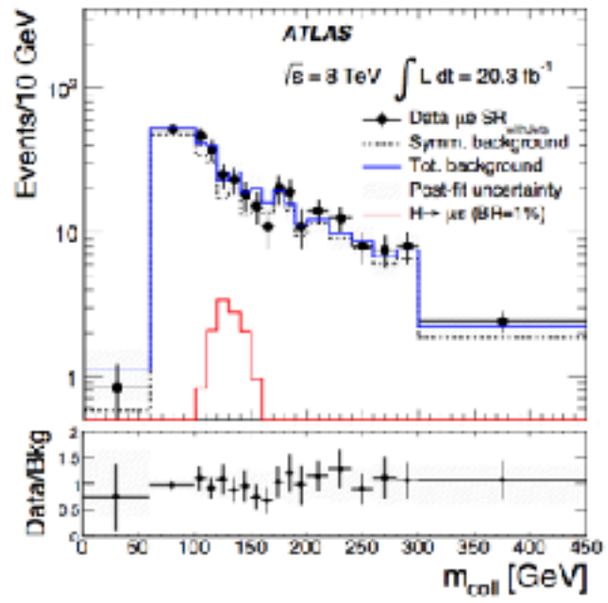
Background - the symmetry assumption

- Comparing eμ and μe events
- SM events are symmetric to the replacement of prompt electron with prompt muons
- Signal events break this symmetry
- Correction for asymmetric componenets
  - Fake and non prompt leptons
  - p_T dependent effects



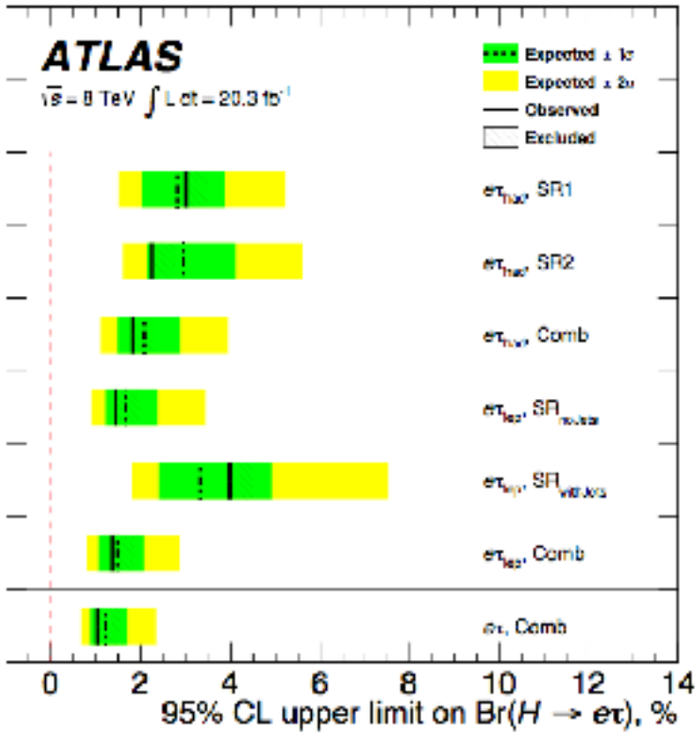


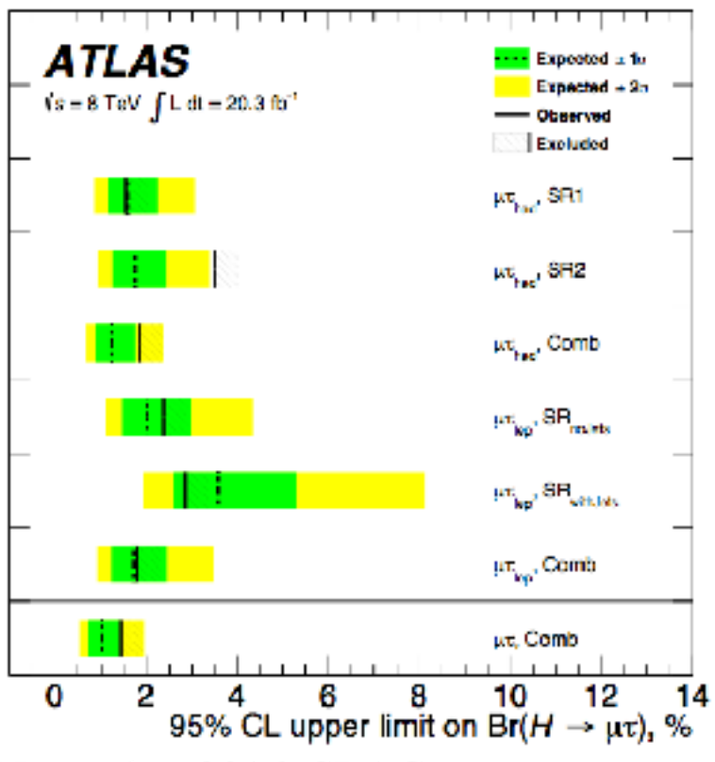




8 TeV Lepton sector ATLAS H→τμ/τe

ATLAS 1604.07737 ➠ $Y_{\tau\mu}$ & $Y_{\tau e}$





Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to e\tau_{\text{had}}$	SR1	$2.81^{+1.06}_{-0.79}$	3.0	$0.33^{+1.48}_{-1.59}$
	SR2	$2.95^{+1.16}_{-0.82}$	2.24	$-1.33^{+1.56}_{-1.80}$
	Combined	$2.07^{+0.82}_{-0.58}$	1.81	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{\text{lep}}$	$\text{SR}_{\text{noJets}}$	$1.66^{+0.72}_{-0.46}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$\text{SR}_{\text{withJets}}$	$3.33^{+1.50}_{-0.93}$	3.99	$0.74^{+1.59}_{-1.62}$
	Combined	$1.48^{+0.50}_{-0.42}$	1.36	$-0.26^{+0.79}_{-0.82}$
$H \to e\tau$	Combined	$1.21^{+0.49}_{-0.34}$	1.04	$-0.34^{+0.64}_{-0.66}$
$H \to \mu\tau_{\text{had}}$	SR1	$1.60^{+0.54}_{-0.45}$	1.55	$-0.07^{+0.81}_{-0.86}$
	SR2	$1.75^{+0.71}_{-0.49}$	3.51	$1.94^{+0.92}_{-0.89}$
	Combined	$1.24^{+0.50}_{-0.35}$	1.85	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{\text{lep}}$	$\text{SR}_{\text{noJets}}$	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$\text{SR}_{\text{withJets}}$	$3.57^{+1.74}_{-1.00}$	2.85	$-1.03^{+1.66}_{-1.82}$
	Combined	$1.73^{+0.74}_{-0.49}$	1.79	$0.03^{+0.88}_{-0.86}$
$H \to \mu\tau$	Combined	$1.01^{+0.40}_{-0.29}$	1.43	$0.53^{+0.51}_{-0.51}$

CMS H→τe/eμ

CMS 1607.03561 ➠ $Y_{e\mu}$ & $Y_{\tau e}$

8 TeV Lepton sector

CMS H→τe/eμ

Two searches

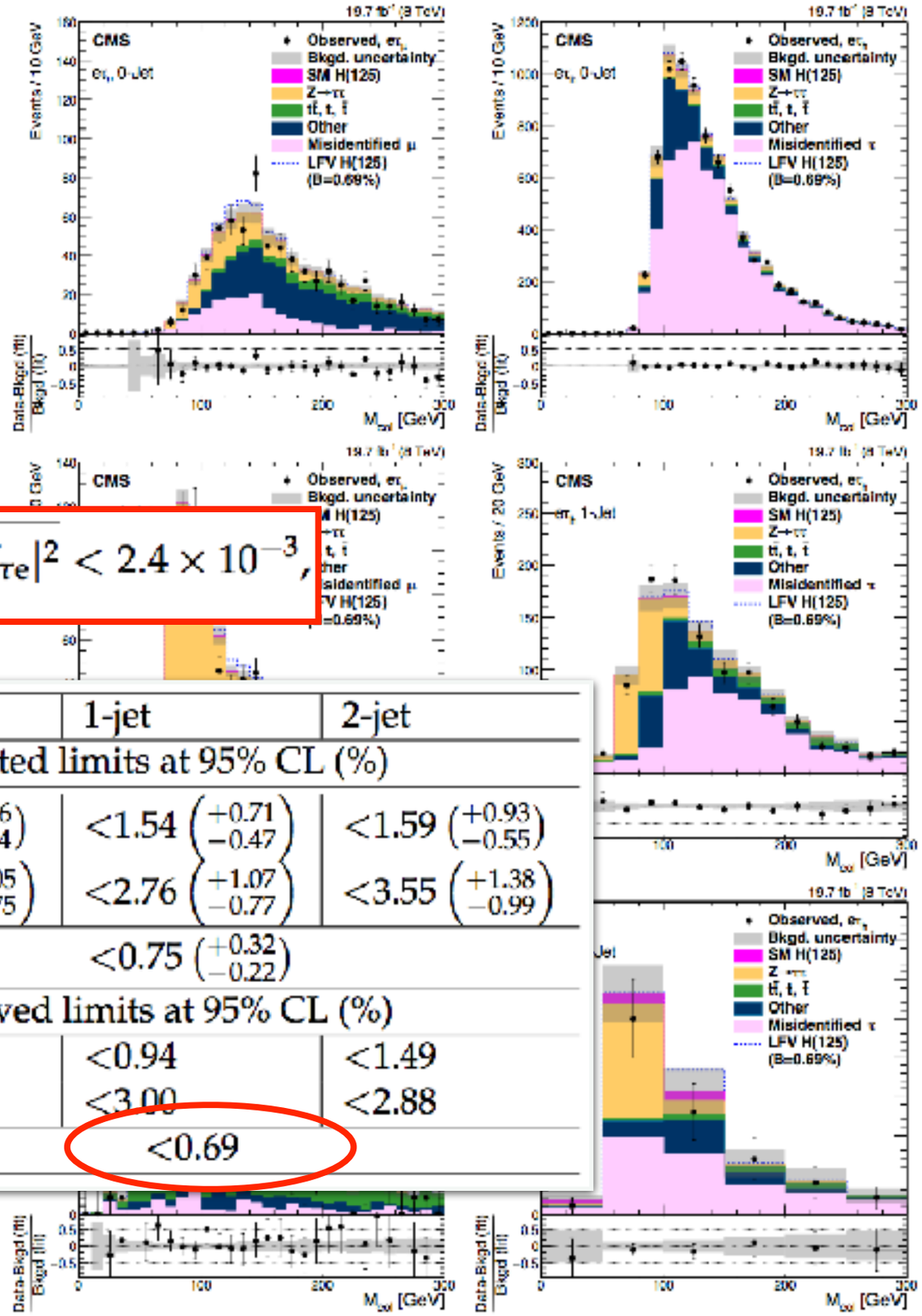
- H→eτ
- H→eμ

H→eτ

- Similar to H→μτ

- Collinear mass
- N_{Jet}-based categories
- Background
  - Z→ττ - embedded sample
  - Misidentified leptons scaling from sample with reversed isolation
  - Other - MC

CMS 1607.03561 ➠ $Y_{e\mu}$ & $Y_{\tau e}$



$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.4 \times 10^{-3},$$

	0-jet	1-jet	2-jet
Expected limits at 95% CL (%)			
$e\tau_\mu$	$<1.63\ ^{+0.66}_{-0.44}$	$<1.54\ ^{+0.71}_{-0.47}$	$<1.59\ ^{+0.93}_{-0.55}$
$e\tau_h$	$<2.71\ ^{+1.05}_{-0.75}$	$<2.76\ ^{+1.07}_{-0.77}$	$<3.55\ ^{+1.38}_{-0.99}$
$e\tau$	$<0.75\ ^{+0.32}_{-0.22}$		
Observed limits at 95% CL (%)			
$e\tau_\mu$	<1.83	<0.94	<1.49
$e\tau_h$	<3.92	<3.00	<2.88
$e\tau$		<0.69	

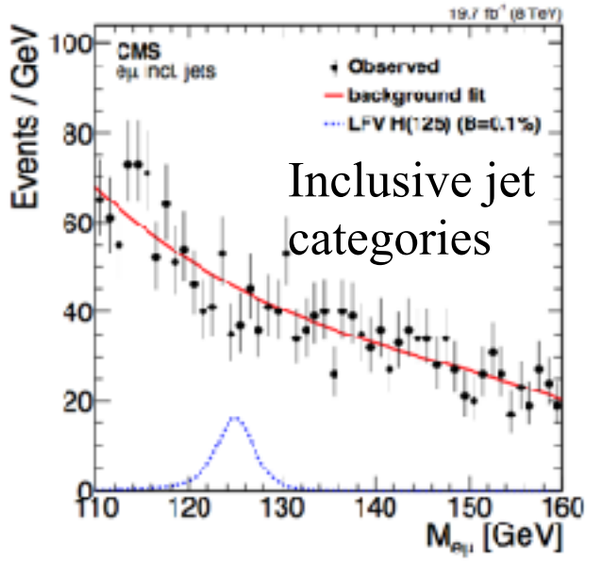
CMS H→τe/eμ

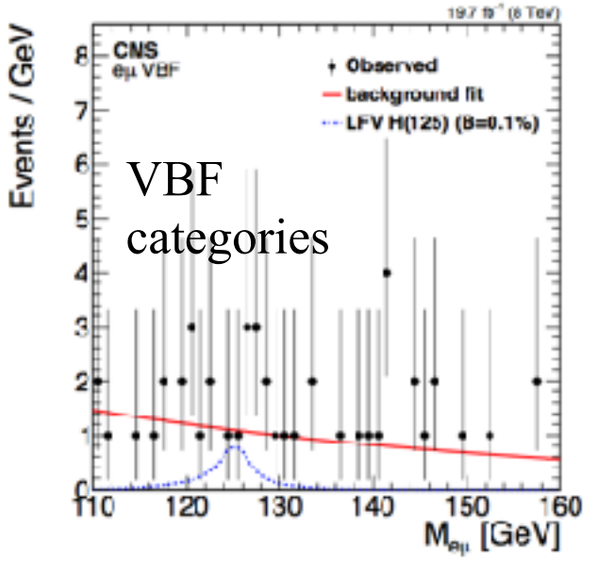
CMS 1607.03561 ➠ $Y_{e\mu}$ & $Y_{\tau e}$

H→eμ

11 categories

- Motivated by detector performance
  - Signal mass resolution varied with lepton region
  - Background composition dictated by the number of jets

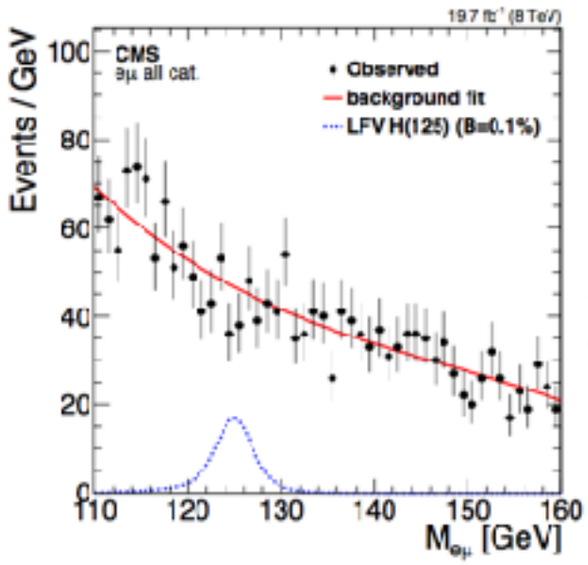




Background

- Functional fit

Category	Description	N-jets	p_T^ℓ [GeV]	E_T^{miss} [GeV]	Background model	
					Function	Order
0	$e_B\mu_B$	0	>25	<30	polynomial	4
1	$e_B\mu_B$	1	>22	<30	polynomial	4
2	$e_B\mu_B$	2	>25	<25	power law	1
3	$e_B\mu_{EC}$	0	>20	<30	polynomial	4
4	$e_B\mu_{EC}$	1	>22	<20	exponential	1
5	$e_B\mu_{EC}$	2	>20	<30	exponential	1
6	$e_{EC}\mu_{B\text{ or }EC}$	0	>20	<30	polynomial	4
7	$e_{EC}\mu_{B\text{ or }EC}$	1	>22	<20	power law	1
8	$e_{EC}\mu_{B\text{ or }EC}$	2	>20	<30	polynomial	4
9	VBF Tight	2	>22	<30	exponential	1
10	VBF Loose	2	>22	<25	exponential	1



All categories combined

$$\mathcal{B}(H \to e\mu) < 0.048\% \text{ at } 95\%$$

$$\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 5.4 \times 10^{-4}$$

CMS H→τμ

PAS HIG 16 005 ➠ $Y_{\tau\mu}$

CMS H→τμ

PAS HIG 16 005 ➠ $Y_{\tau\mu}$

Analysis similar to run-1 analysis

- One exception -
  Z→ττ model also from MC
- Deficit in the H mass window

Expected limits				
	0-jet (%)	1-jet (%)	2-jets (%)	Combined (%)
$\mu\tau_h$	<4.17	<4.89	<6.41	<2.98
$\mu\tau_e$	<2.24	<4.36	<7.31	<1.96
$\mu\tau$	<1.62 %			
Observed limits				
	0-jet (%)	1-jet (%)	2-jets (%)	Combined (%)
$\mu\tau_h$	<4.24	<6.35	<7.71	<3.81
$\mu\tau_e$	<1.33	<3.04	<8.99	<1.15
$\mu\tau$	<1.20 %			
Best-fit branching fractions				
	0-jet (%)	1-jet (%)	2-jets (%)	Combined (%)
$\mu\tau_h$	$0.12^{+2.02}_{-1.91}$	$1.70^{+2.41}_{-2.52}$	$1.54^{+3.12}_{-2.71}$	$1.12^{+1.45}_{-1.40}$
$\mu\tau_e$	$-2.11^{+1.30}_{-1.89}$	$-2.18^{+1.99}_{-2.05}$	$2.04^{+2.96}_{-3.31}$	$-1.81^{+1.07}_{-1.32}$
$\mu\tau$	$-0.76^{+0.81}_{-0.84}$ %			

CMS 1502.07400 ➠ $Y_{\tau\mu}$

Expected Limits			
	0-Jet (%)	1-Jet (%)	2-Jets (%)
$\mu\tau_e$	<1.32 (±0.67)	<1.66 (±0.85)	<3.77 (±1.92)
$\mu\tau_h$	<2.34 (±1.19)	<2.07 (±1.06)	<2.31 (±1.18)
$\mu\tau$	<0.75 (±0.38)		
Observed Limits			
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$	<1.51		
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$	$0.84^{+0.39}_{-0.37}$		

ATLAS $\tau \rightarrow 3\mu$

ATLAS 1601.03567 ➠ $Y_{\tau\mu}$

8 TeV Lepton sector ATLAS $\tau \rightarrow 3\mu$

Search channel

- $W \rightarrow \tau\nu$; $\tau \rightarrow 3\mu$

Main discriminators

- 3 near by muons
- $m_T = \sqrt{2p_T^{3\mu} E_T^{miss}(1 - \cos\Delta\phi)}$,
- τ lifetime $\Rightarrow$ muons originating from a secondary vertex
- $m_{3\mu} \sim m_\tau$

Strategy

ATLAS 1601.03567 ➠ $Y_{\tau\mu}$

- Step 1: event selection based on the discriminators
- Step 2: BDT - with loose selections
  - To ensure enough statistics
  - 16 input variables
- Step 3: tight cuts on the BDT output score
- Step 4: optimize selection based on estimation in the sideband region

Region	Range in $m_{3\mu}$ [MeV]
Signal region	[1713, 1841]
Blinded region	[1690, 1870]
Sideband region	[1450, 1690] and [1870, 2110]
Training region	[750, 1450] and [2110, 2500]

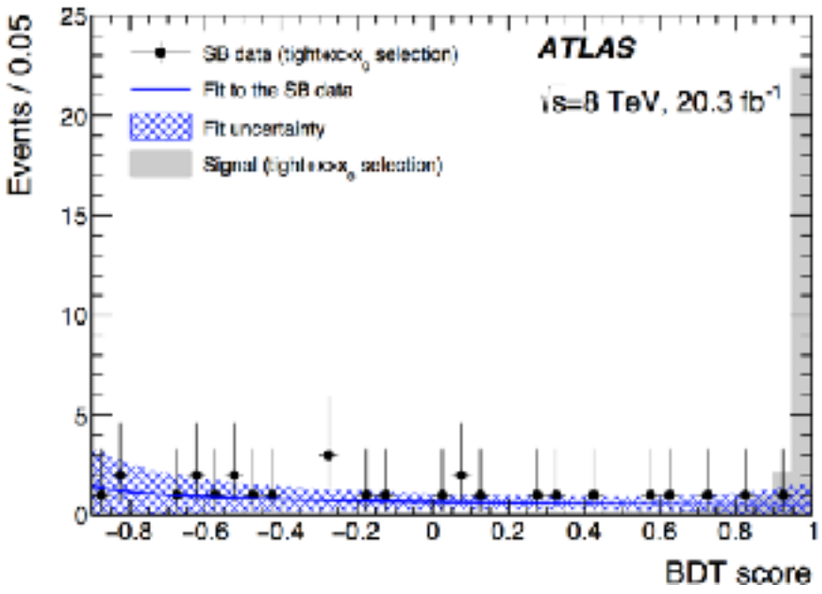
Background

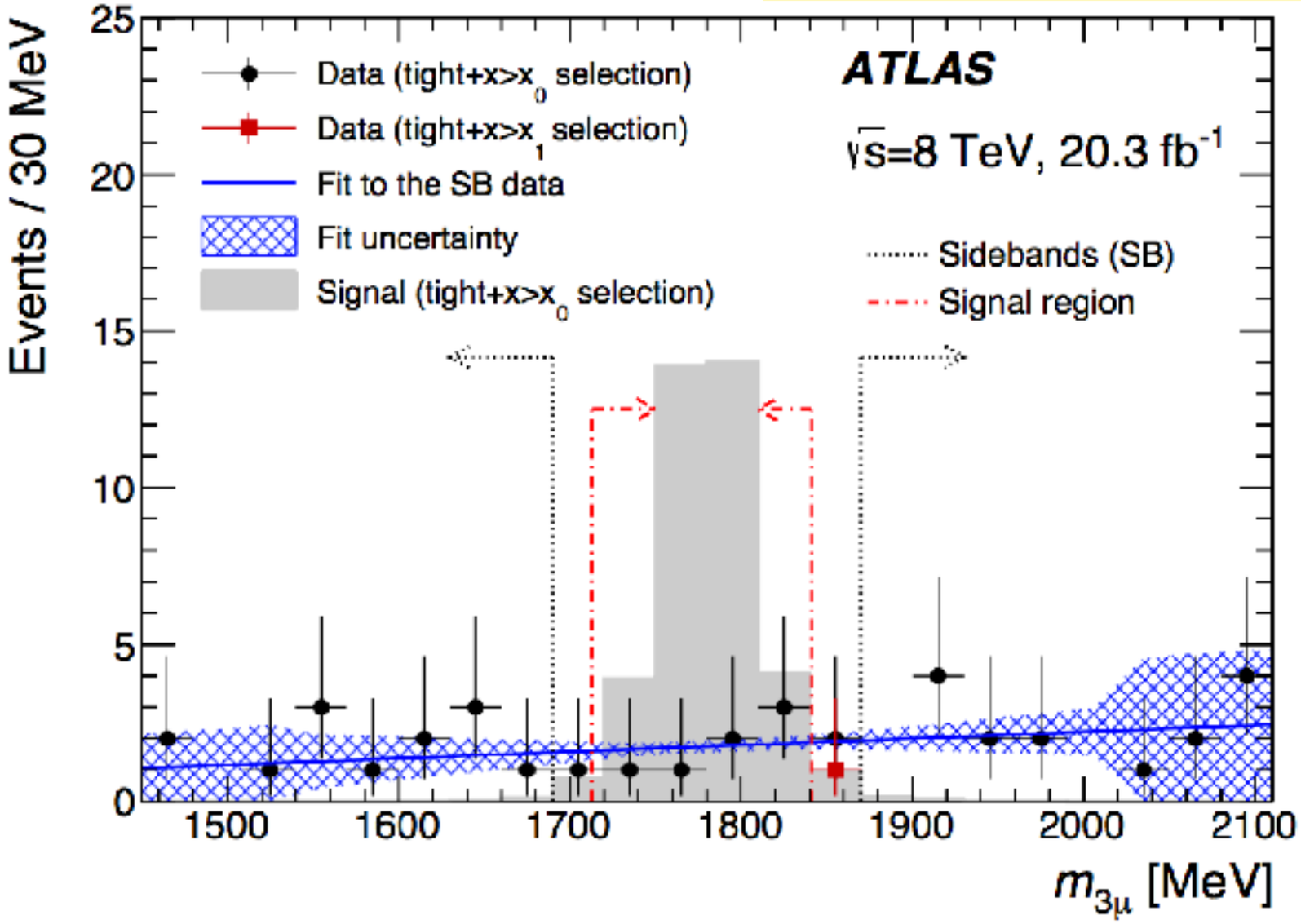
- Main source: Heavy Flavour decays
- Extrapolated from the sideband region

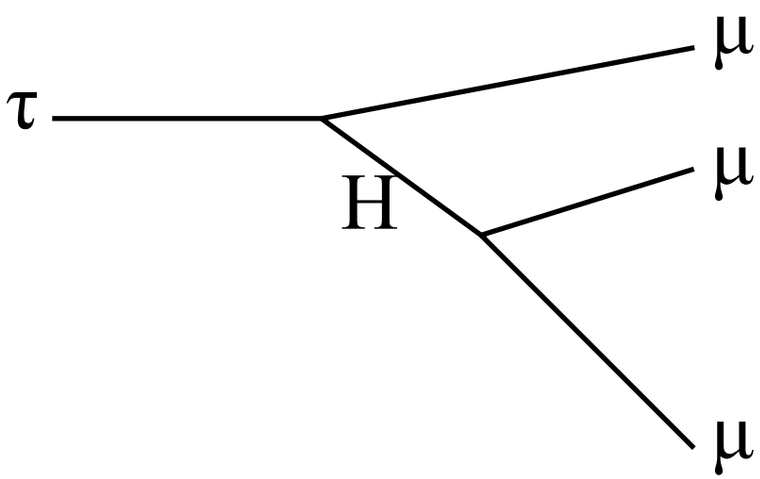
8 TeV Lepton sector

ATLAS $\tau \rightarrow 3\mu$

ATLAS 1601.03567 ➠ $Y_{\tau\mu}$







3.76×10^{-7} (3.94×10^{-7}) on Br($\tau \rightarrow 3\mu$) at 90% CL

Quark sector

Quark sector

- Complementary efforts are made by both collaborations
- Different methods are being employed ⇒ stringent cross checks
- Analyses become more and more complicated
  - Combination of different channels

ATLAS t→qH

ATLAS 1403.6293 ➠ Y_{tq}

8 TeV Quark sector ATLAS t→qH(γγ)

One search channels

- [t][tbar]→[Wb][Hq]→bWqγγ

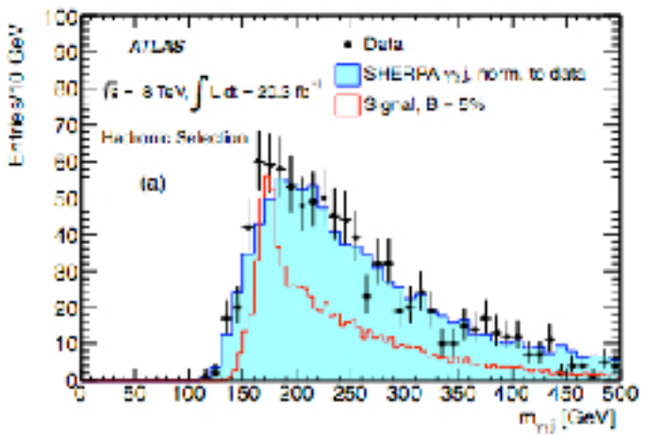
Two signal regions

similar to H→γγ

- Fully hadronic W: no leptons
- Semi-leptonic W: one isolated lepton

Strategy

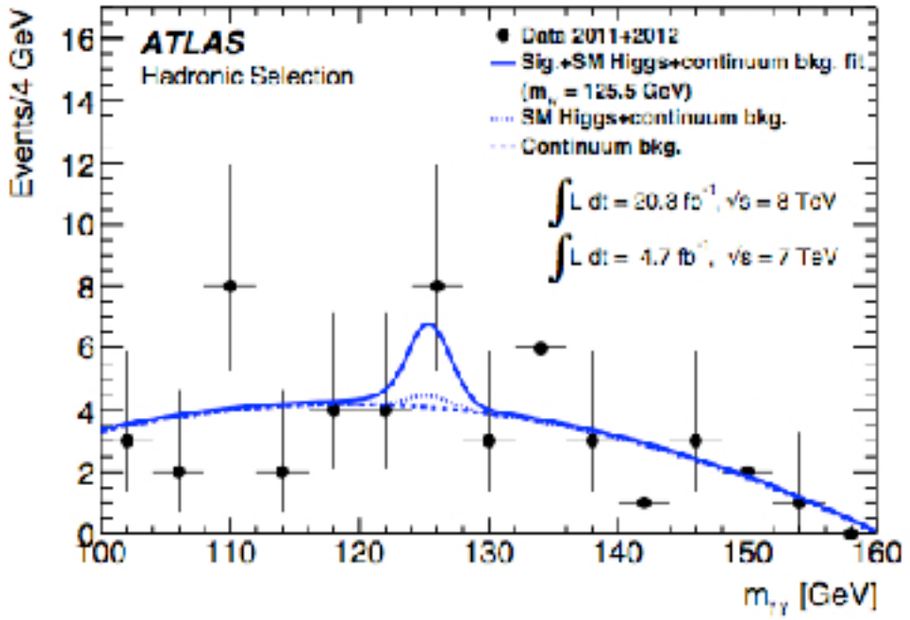
- Looking for ttbar topology: based on $M_{jγγ}$ and M_{jjj} + 1 b-tag
- The top mass is a discriminator
- Look for peak in $m_{γγ}$



Background

ATLAS 1403.6293 ➠ Y_{tq}

- Hadronic channel
  - Functional fit for smoothes $m_{γγ}$ distribution
  - Smoothing using pseudo data
- Semi-leptonic channel
  - Transfer factor from a control region with similar kinematics



Observed: BR(t→qH) ≤ 0.79 %

Expected: BR(t→qH) ≤ 0.51 %

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$

ATLAS t→qH(bbbar)

ATLAS 1509.06047 ➠ Y_{tq}

8 TeV Quark sector ATLAS t→qH(bbbar)

One new search channels

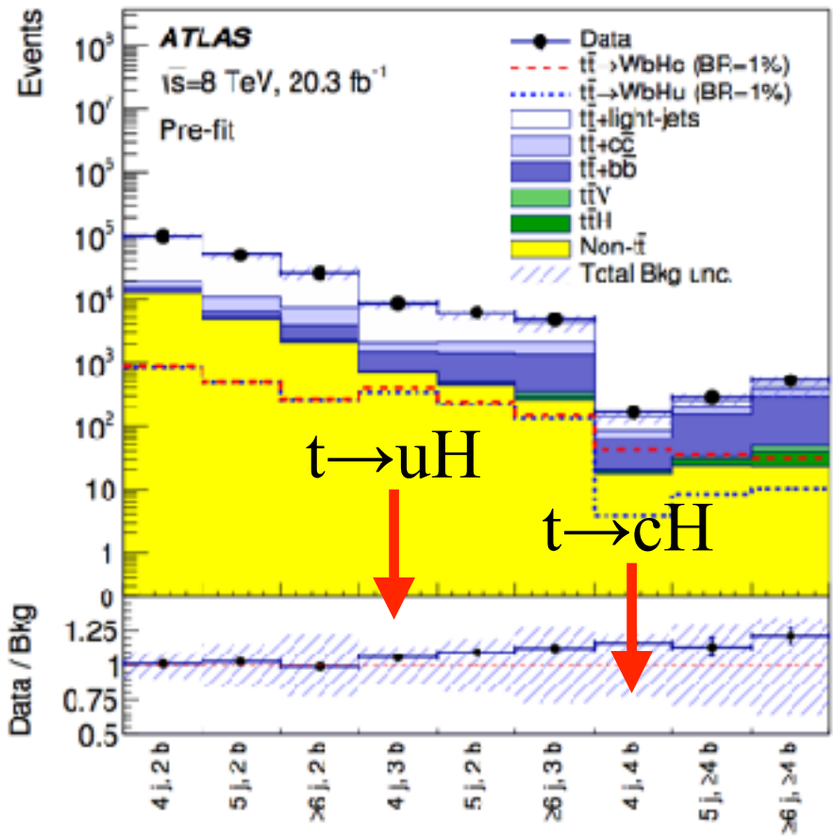
- [t][tbar]→[Wb][Hq]→bWqbb

One signal region

- Semi-leptonic W: one isolated lepton

Categories

- Based on the number of jets and b-jets



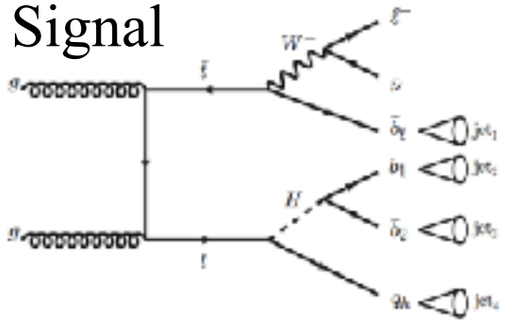
Main discriminant

ATLAS 1509.06047 ➠ Y_{tq}

$$D(\mathbf{x}) = \frac{P^{\text{sig}}(\mathbf{x})}{P^{\text{sig}}(\mathbf{x}) + P^{\text{bkg}}(\mathbf{x})}$$

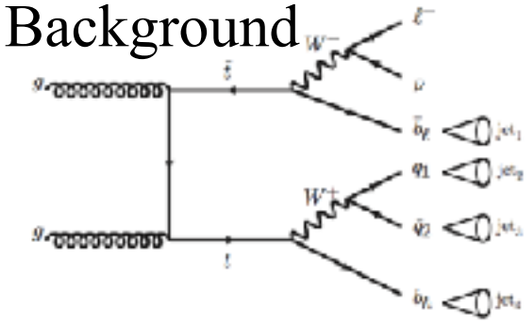
- Related to the probability of an event to be signal and background
- Exploits the various resonances in each category

Signal



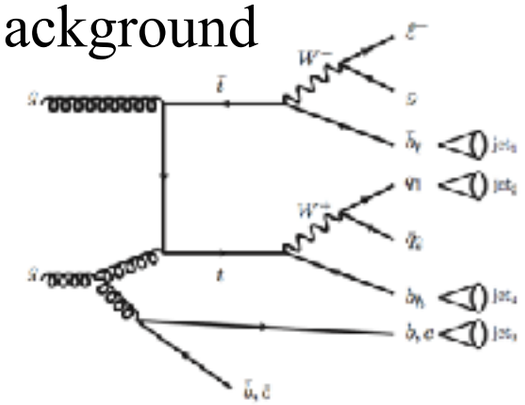
(a)

Background



(b)

Background



(c)

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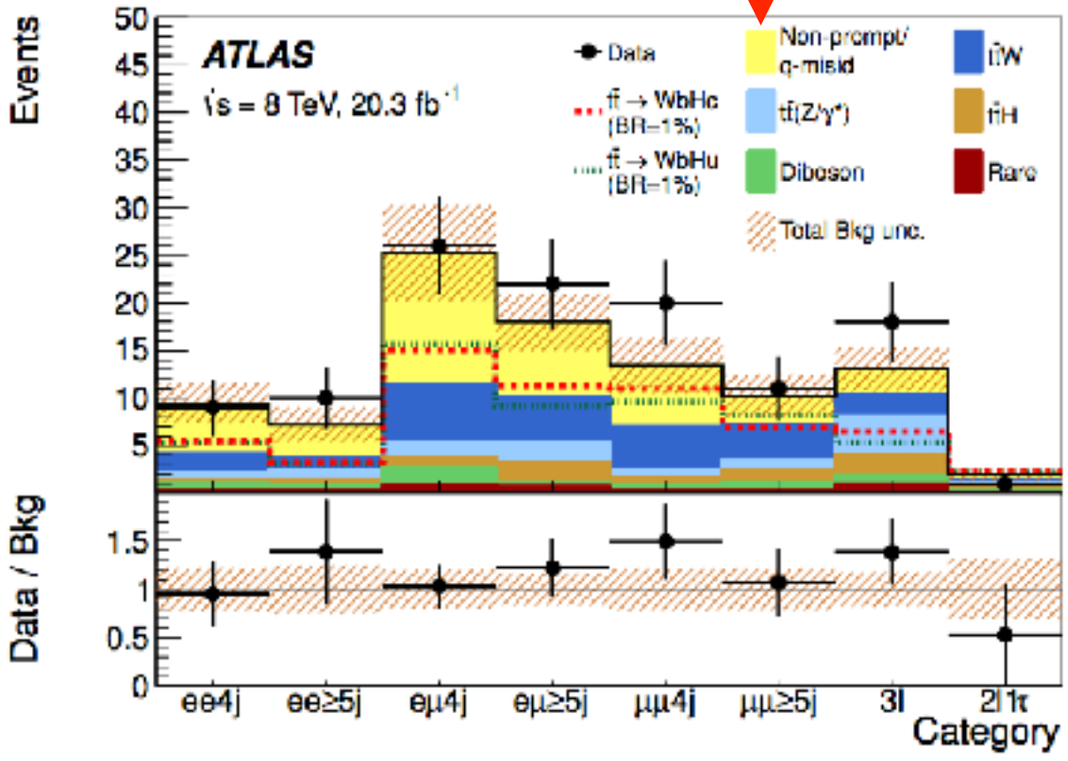
8 TeV Quark sector ATLAS t→qH(comb.)

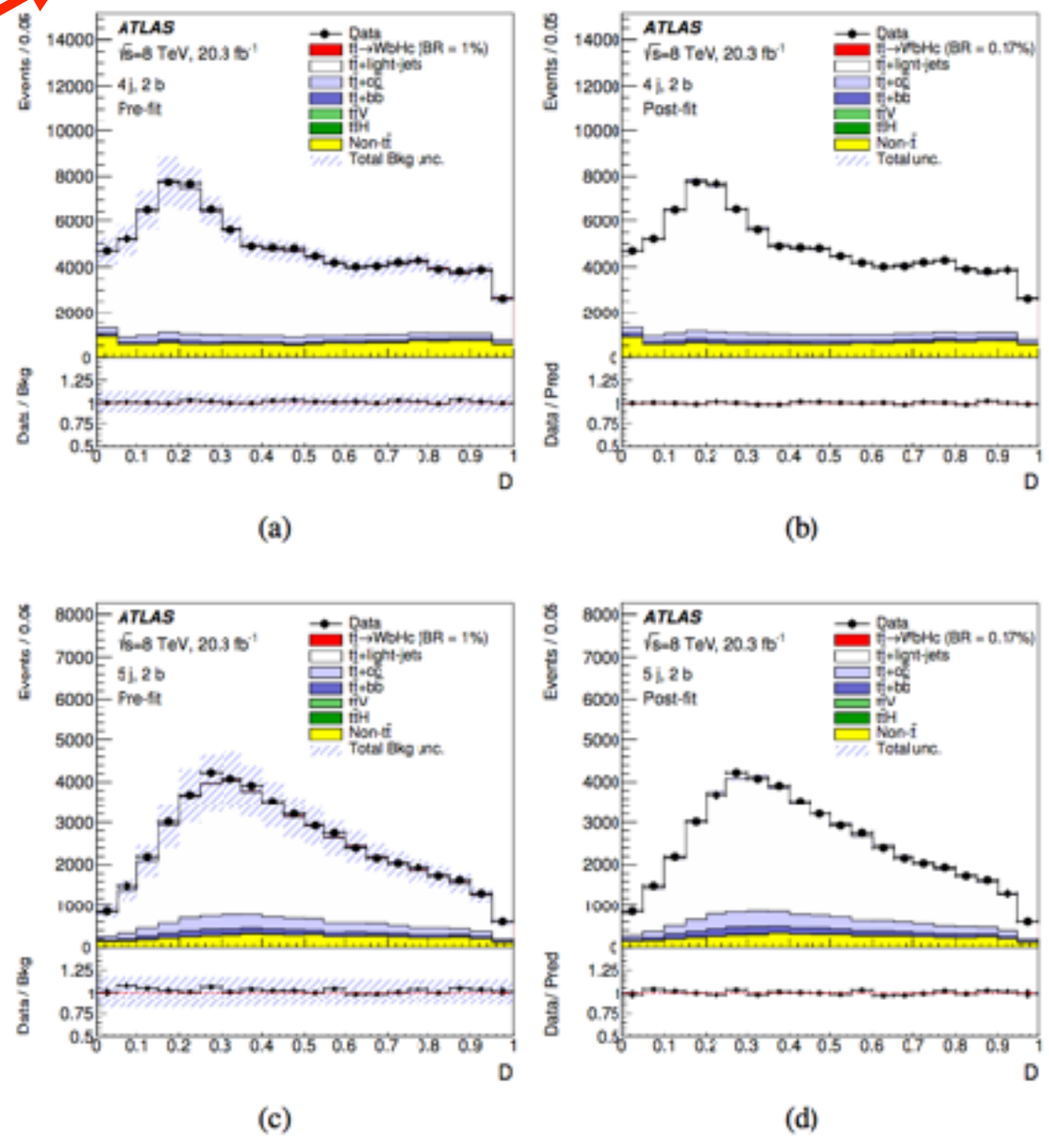
ATLAS 1509.06047 ➠ Y_{tq}

Re-interpretation of ttH measurements & combination

- [t][tbar]→[Wb][Hq]→bWqbb (this channel)
- [t][tbar]→[Wb][Hq]→bWq$\gamma\gamma$ (1403.6293)
- [t][tbar]→[Wb][Hq]→bWq[WW/$\tau\tau$] (ttH)
  - Multi channel analysis



First 2 categories



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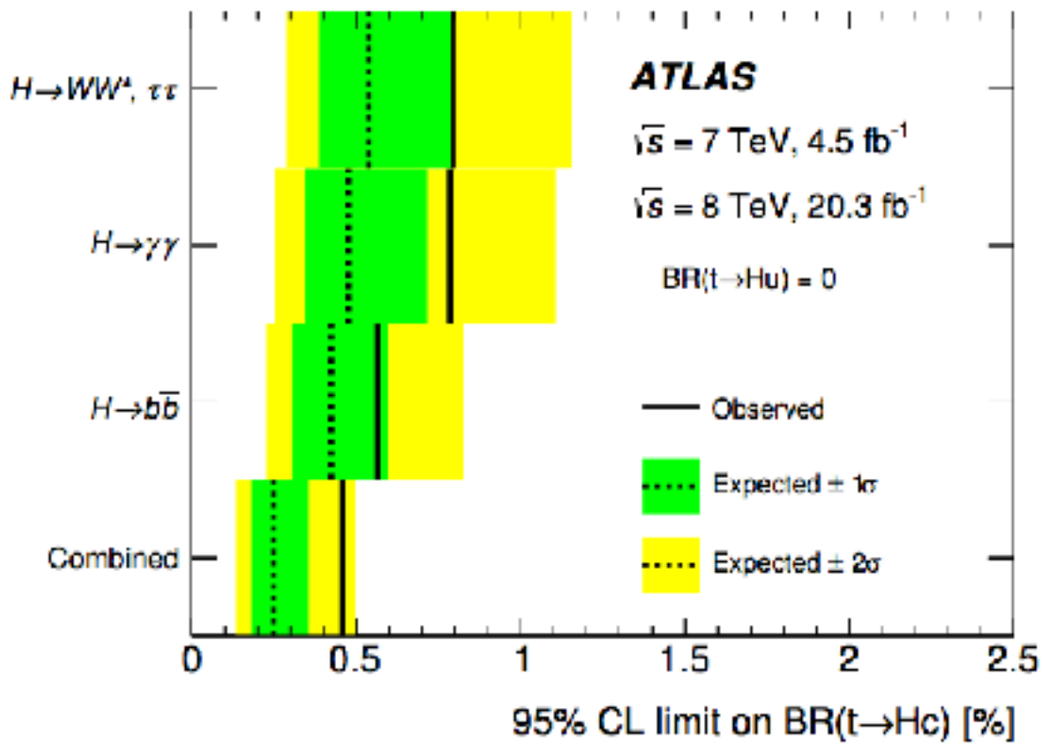
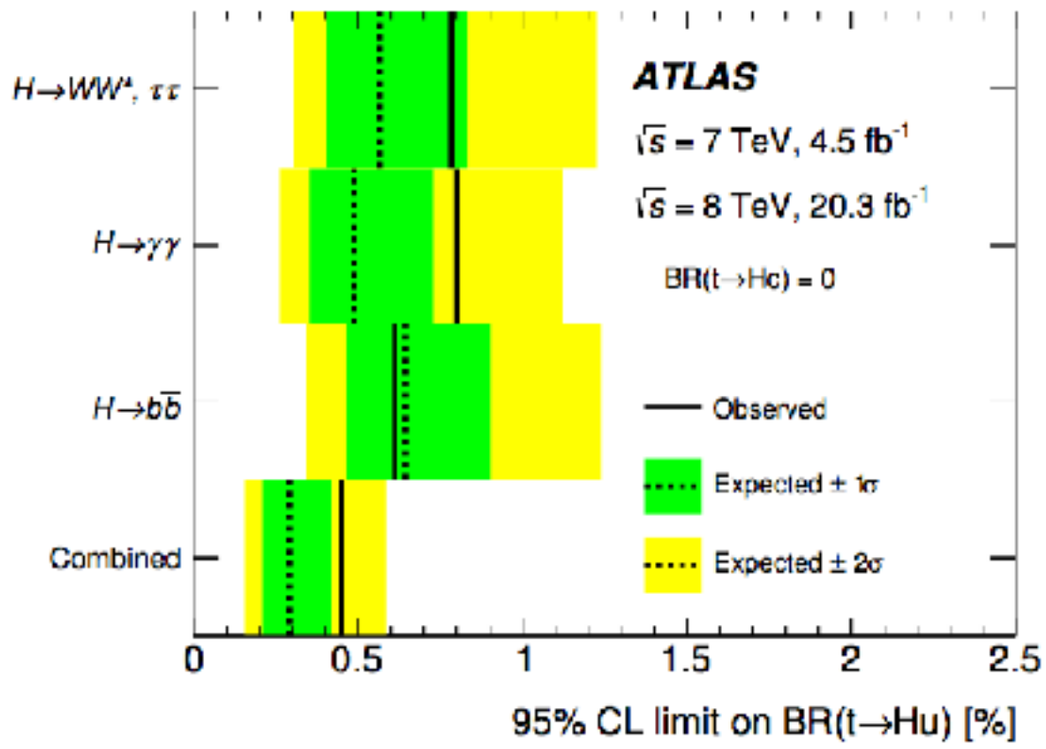
8 TeV Quark sector ATLAS t→qH(comb.)

ATLAS 1509.06047 ➠ Y_{tq}





$$\mathrm{BR}(t \to Hc) < 0.46\%\,(0.25\%) \text{ and } \mathrm{BR}(t \to Hu) < 0.45\%\,(0.29\%)$$

Separation between t→cH and t→uH

- Based on b tagging efficiency and purity

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CMS t→cH(comb.)

CMS 1410.2751 ➠ Y_{tc}

8 TeV Quark sector CMS t→cH(comb.)

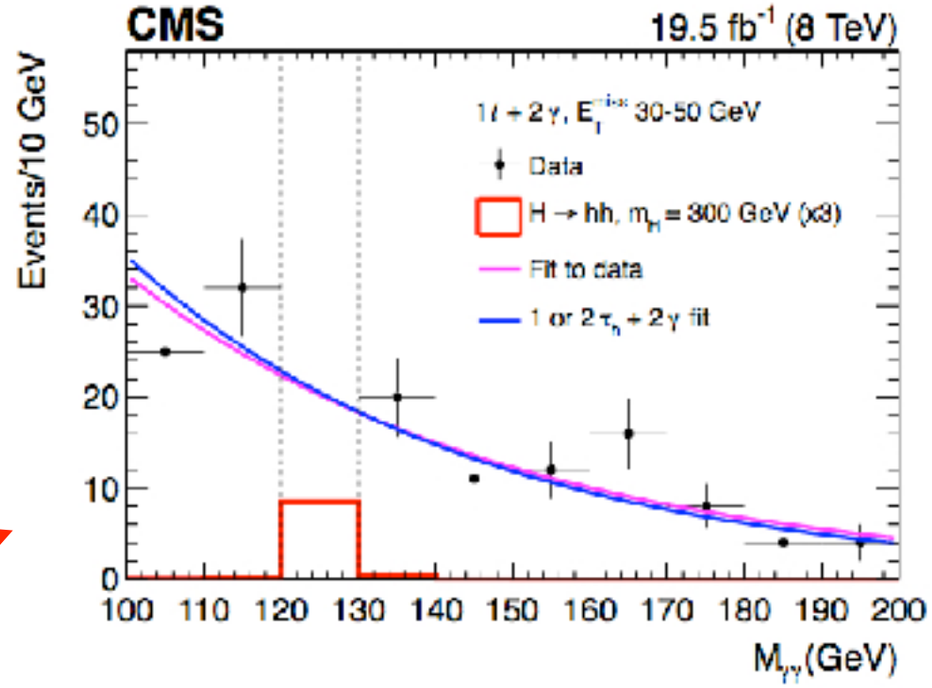
CMS 1410.2751 ➠ Y_{tc}

Search channels

- [t][tbar]→[Wb][Hc]
  ⇒ H→WW/ZZ/ττ or γγ

Two signal regions

- lepton + 2γ
- multi-lepton
  - Many categories



Background

- lepton + 2γ: side band fit
- multi-lepton
  - Irreducible - all leptons are prompt
    - Estimated from MC normalized to data in dedicated control regions
  - Reducible - 1 or 2 fake or non-prompt leptons
    - Estimated using data-driven techniques

CMS t→cH(comb.)

CMS 1410.2751 ➠ Y_{tc}

Channel	E_T^{miss} (GeV)	N_b	Obs.	Exp.	Sig.
$\gamma\gamma\ell$	(50, 100)	≥1	1	2.3 ± 1.2	2.88 ± 0.39
	(30, 50)	≥1	2	1.1 ± 0.6	2.16 ± 0.30
	(0, 30)	≥1	2	2.1 ± 1.1	1.76 ± 0.24
	(50, 100)	0	7	9.5 ± 4.4	2.22 ± 0.31
	(100, ∞)	≥1	0	0.5 ± 0.4	0.92 ± 0.14
	(100, ∞)	0	1	2.2 ± 1.0	0.94 ± 0.17
$\ell\ell\ell$ (OSSF1, below-Z)	(50, 100)	≥1	48	48 ± 23	9.5 ± 2.3
	(0, 50)	≥1	34	42 ± 11	5.9 ± 1.2
$\ell\ell\ell$ (OSSF0)	(50, 100)	≥1	29	26 ± 13	5.9 ± 1.3
	(0, 50)	≥1	29	23 ± 10	4.3 ± 1.1

Observed: BR(t→cH) ≤ 0.56 %

Expected: BR(t→cH) ≤ 0.65 %

CMS t→qH(comb.)

CMS 1610.04857 ➠ Y_{tq}

8 TeV Quark sector CMS t→qH(comb.)

CMS 1610.04857 ➠ Y_{tq}

Search channels

- [t][tbar]→[Wb][Hq]

Many categories

Decay channels	Leptons	Photons	Jets	b jets	Category
$H \to WW, ZZ, \tau\tau$ & $W \to \ell\nu$	eee, eeμ, e$\mu\mu$, $\mu\mu\mu$	—	≥2	—	trilepton
$H \to WW, ZZ, \tau\tau$ & $W \to \ell\nu$	$e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$	—	≥2	—	dilepton SS
$H \to \gamma\gamma$ & $W \to \ell\nu$	$e^{\pm}$, $\mu^{\pm}$	≥2	≥2	=1	diphoton + lepton
$H \to \gamma\gamma$ & $W \to q_1q_2$	—	≥2	≥4	=1	diphoton + hadron
$H \to b\bar{b}$ & $W \to \ell\nu$	$e^{\pm}$, $\mu^{\pm}$	—	≥4	≥3	b jet + lepton

	$\mathcal{B}_{obs}(t \to Hc)$	$\mathcal{B}_{exp}(t \to Hc)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
Trilepton	1.26	1.33	1.87	0.95
Same-sign dilepton	0.99	0.93	1.26	0.68
Multilepton combined	0.93	0.89	1.22	0.65
Diphoton hadronic	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
Diphoton combined	0.47	0.67	1.06	0.44
b jet + lepton	1.16	0.89	1.37	0.60
Full combination	0.40	0.43	0.64	0.30
	$\mathcal{B}_{obs}(t \to Hu)$	$\mathcal{B}_{exp}(t \to Hu)$	$\mathcal{B}_{exp}+\sigma$	$\mathcal{B}_{exp}-\sigma$
Trilepton	1.34	1.47	2.09	1.05
Same-sign dilepton	0.93	0.85	1.16	0.62
Multilepton combined	0.86	0.82	1.14	0.60
Diphoton hadronic	1.26	1.33	1.87	0.95
Diphoton leptonic	0.99	0.93	1.26	0.68
Diphoton combined	0.42	0.60	0.96	0.39
b jet + lepton	1.92	0.84	1.31	0.57
Full combination	0.55	0.40	0.58	0.27

Observed: BR(t→cH) ≤ 0.40 %
Expected: BR(t→cH) ≤ 0.43 %

Observed: BR(t→uH) ≤ 0.55 %
Expected: BR(t→uH) ≤ 0.40 %

Next steps

- Analyses will be repeated when more data become available
- Optimization and improvements will be done in parallel
- Exploit multivariate techniques

- …
- The track is pretty well defined
- Are we missing anything?