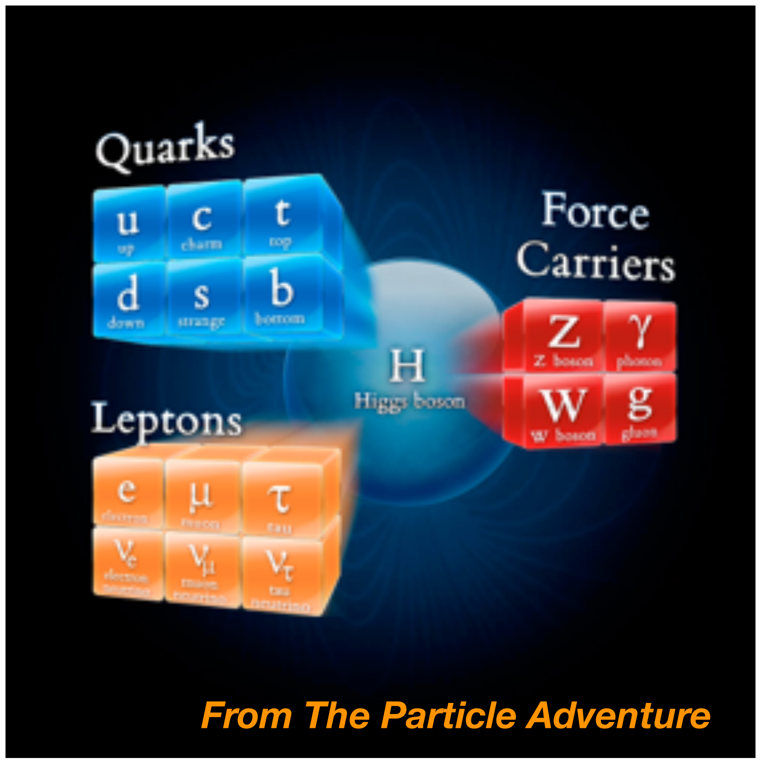
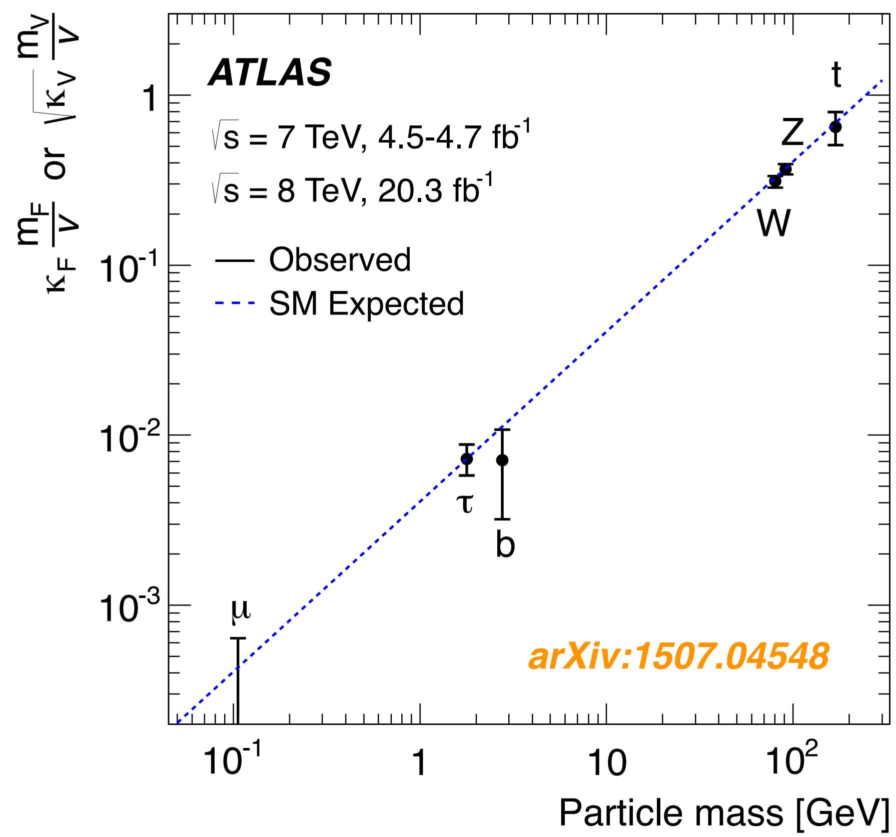
Higgs Boson & Flavors at the ATLAS & CMS Experiments

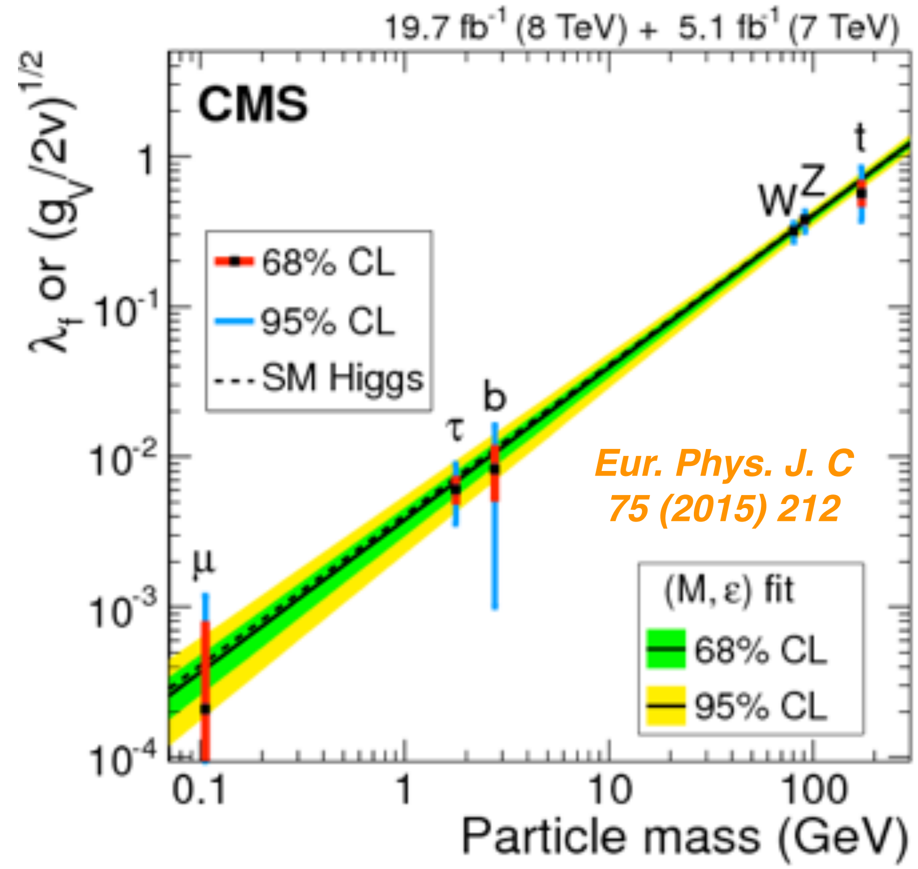
SUSY 2015, August 29, 2015

Hideki Okawa (University of Tsukuba)
on behalf of ATLAS & CMS Collaborations

Higgs Discovery & Beyond

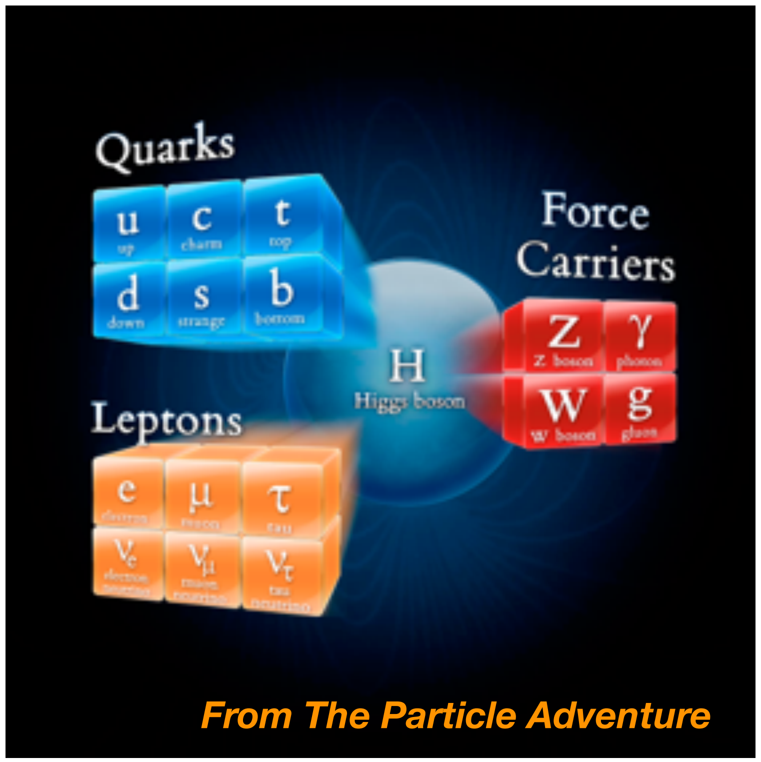


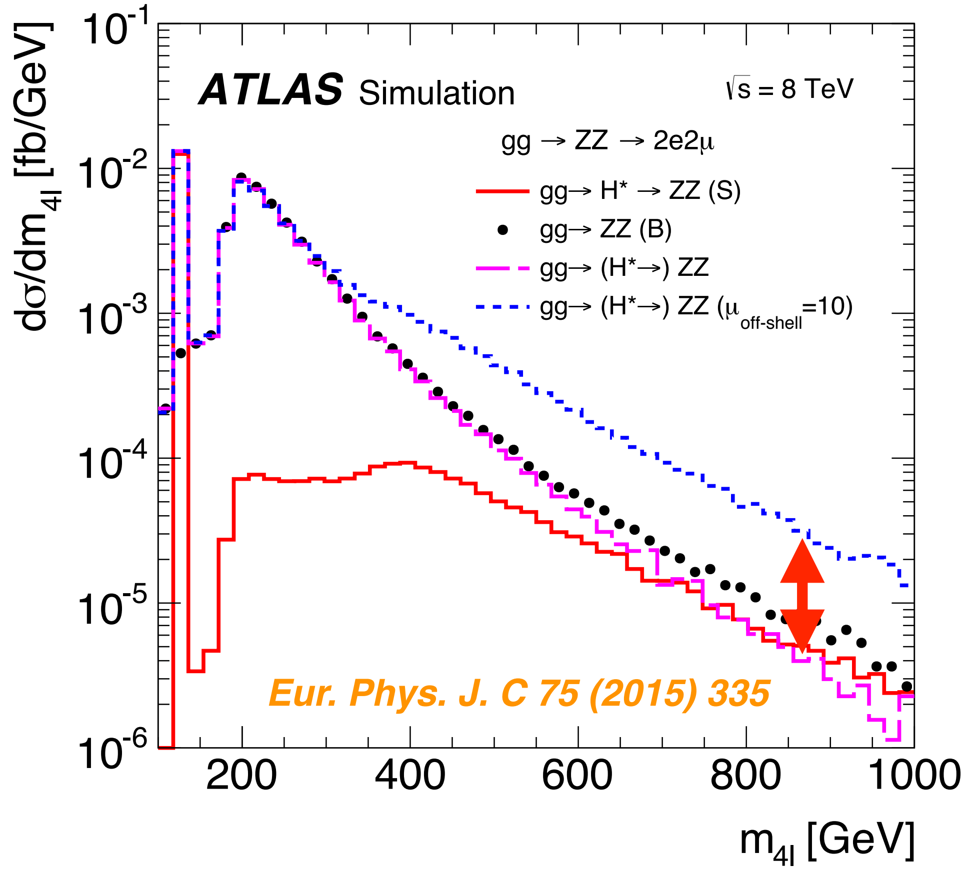


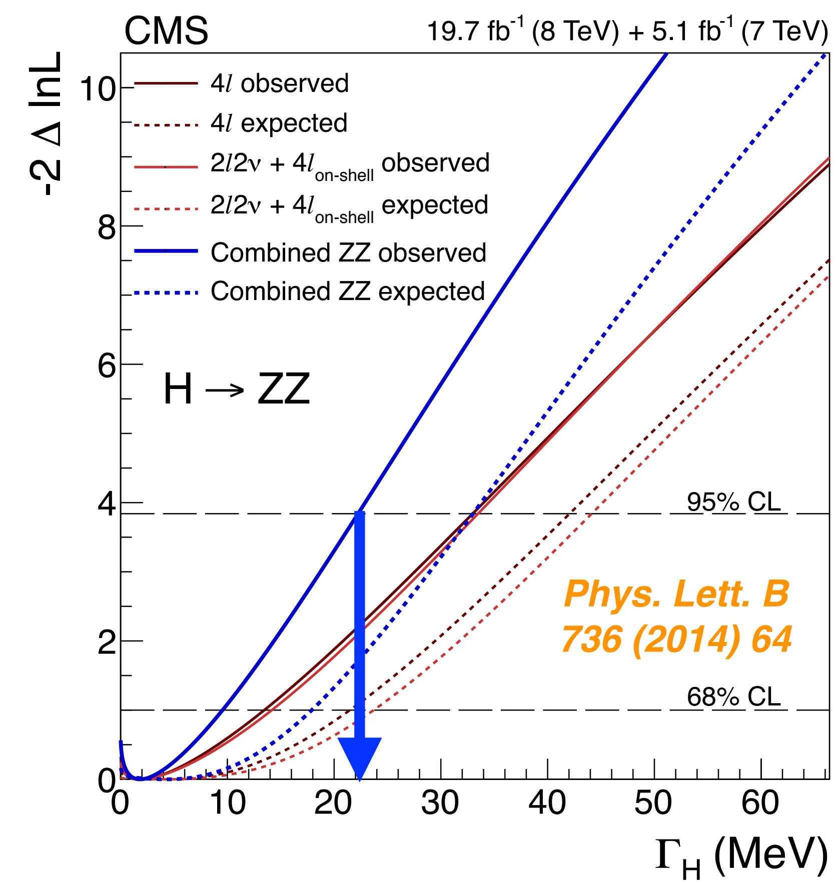


- We have discovered a Higgs boson in 2012. So far, the particle shows properties consistent with the Standard Model (→Attilio Andreazza's talk).

Higgs Discovery & Beyond







- However, current constraints on the Higgs total width is rather loose: **<~5×Γ_H^{SM}** & **there is still room for BSM decays**.
- We are at the stage to further investigate & understand **the properties of the Higgs boson/Yukawa couplings, and the electroweak sector as a whole.**
- I will present an overview of such studies **from a flavor perspective** in particular.

Tristan du Pree will cover the other BSM decays.

Outline

- **Flavor violation**
  - **Lepton Flavor Violation (LFV)**
    - $H\to\mu\tau_e$, $e\tau_\mu$, $e\tau_h$, $e\mu$ (CMS), $H\to\mu\tau_h$ (ATLAS, CMS)
    - $Z\to e\mu$ (ATLAS, CMS)
    - Z', $\tilde{\nu}_\tau\to e\mu$, $e\tau$, $\mu\tau$ (ATLAS), $e\mu$ (CMS)
    - $Z'\to\tau\tau$ (ATLAS)
    - $W'\to\tau\nu_\tau$ (CMS)
    - RPV $\tilde{t}\,\tilde{t}^*\to b\ell\, b\ell$ (ATLAS)

→ Dai Kobayashi's talk

© Particle Zoo

- MFV dark matter search (mono-b)

→ Priscilla Pani's talk

  - **Flavor Changing Neutral Currents (FCNC)**
    - $t\to qH(\to\gamma\gamma)$ (ATLAS, CMS)
    - $t\to qH(\to$multi-lepton) & combination (CMS)

- $t\to qZ$, $q\gamma$ (ATLAS, CMS)
- BSM single top (ATLAS, CMS)

→ Sridhara Dasu's & Sandro Palestini's talks

- **Light-flavor Yukawa couplings**
  - $H\to ee$ (CMS), $\mu\mu$ (ATLAS, CMS)
  - $H\to J/\psi\gamma$ (ATLAS, CMS), $\Upsilon(nS)\gamma$ (ATLAS)
- **Run-2 Prospects**

Flavor Violation

Why Flavor Violation?

R.Harnik, J.Kopp, J.Zupan, JHEP 03 (2013) 026

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

Higgs-fermion coupling

- Standard Model Higgs boson conserves the flavor symmetry (Y_{ij} is diagonal).
- **In general, Y_{ij} can be non-diagonal, which leads to a flavor violation.** Flavor violation itself would be a discovery of BSM physics.
  - Naturally occurs in models with more than one Higgs doublet.
  - Can arise in SUSY, composite Higgs models, Randall-Sundrum, etc.

Lepton Flavor Violation

- $H \to \mu\tau$, $e\tau$, $e\mu$
- $Z \to e\mu$
- Z', $\nu_\tau \to e\mu$, $e\tau$, $\mu\tau$
- Non-universal $Z' \to \tau\tau$, $W' \to \tau\nu_\tau$
- RPV $\tilde{t}\,\tilde{t}^* \to b\,\ell\,b\,\ell$

Charged lepton flavor violation may have different origin from the neutrino oscillation.

Flavor Changing Neutral Current

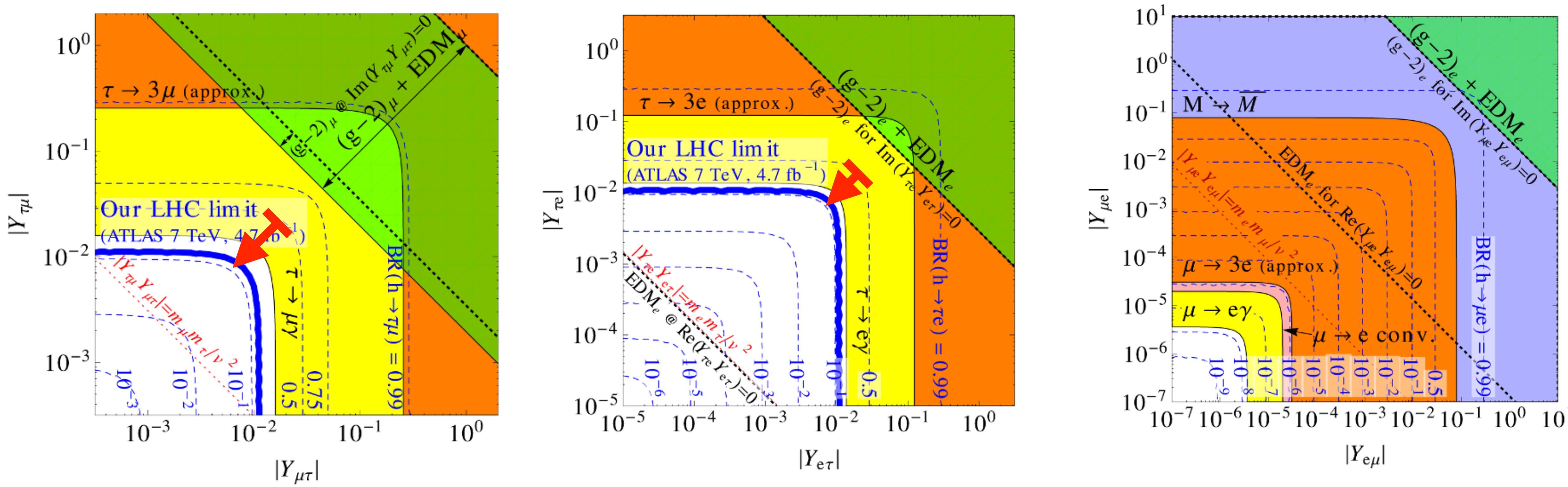
- $t \to qH$

LHC has high sensitivity for FCNC for the top quark→Higgs.

H→μτ,eτ,eμ Searches

- Indirect constraints from previous experiments are stringent for μ→e, **but <u>rather</u>** **<u>moderate for τ-related FV.</u>** ⇒ BR(H→μe)<Ơ(10^{-8}), **<u>BR(H→μτ, eτ)<Ơ(10%).</u>**

R.Harnik, J.Kopp, J.Zupan, JHEP 03 (2013) 026



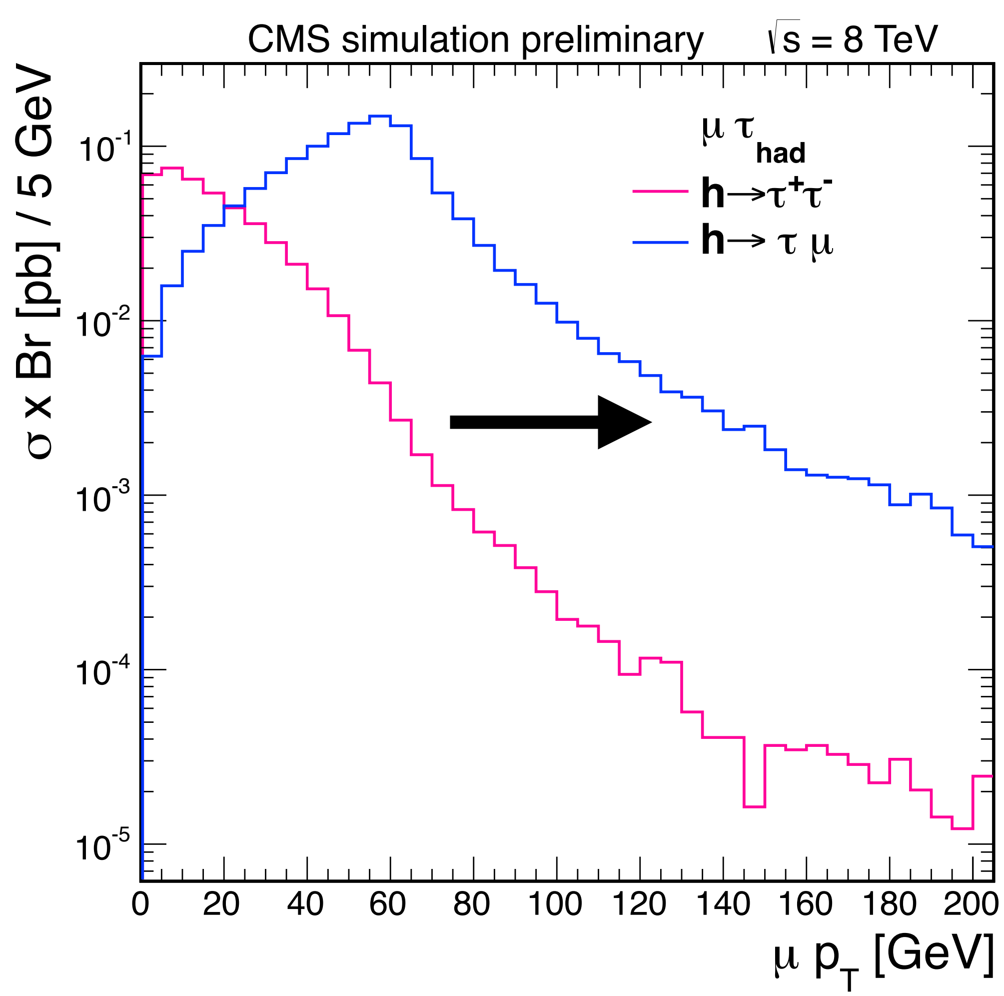
- Direct searches are performed for H→μτ, eτ, eμ (CMS), H→μτ_h (ATLAS)

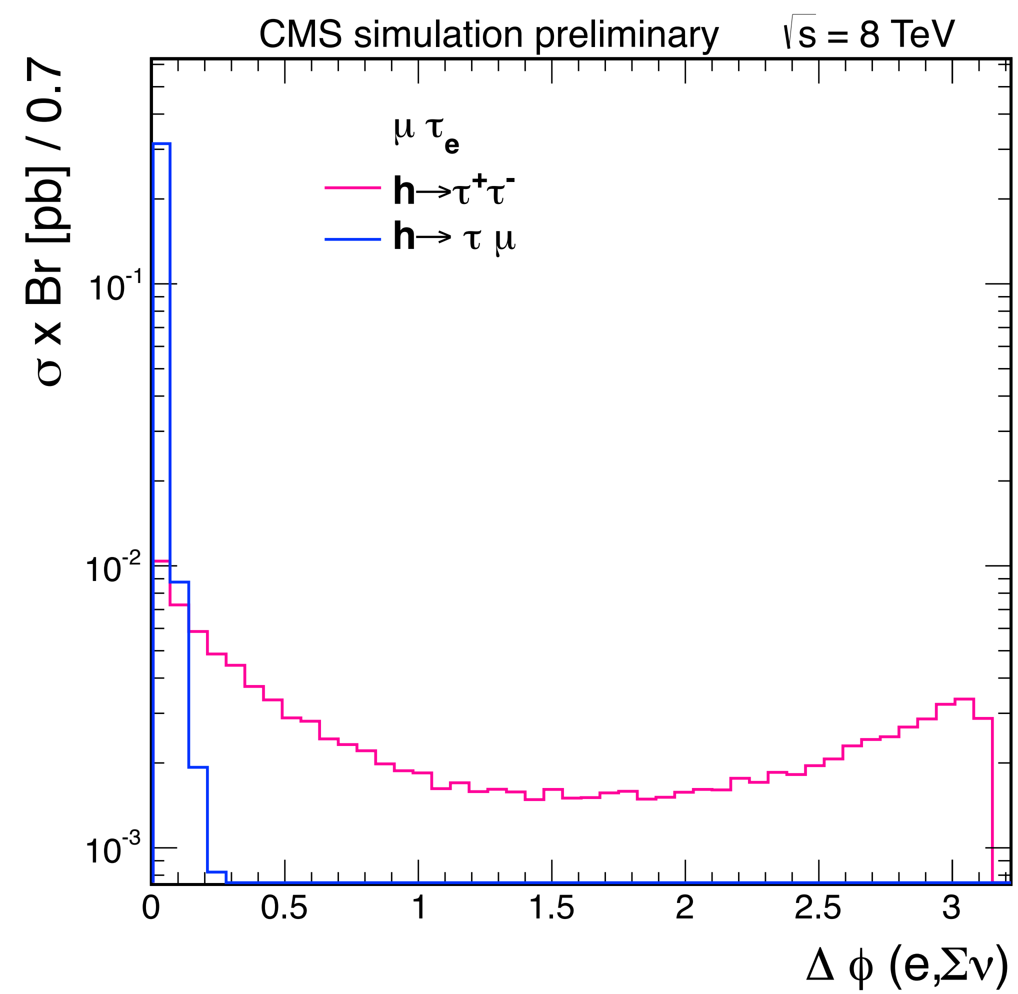
- **Similar signatures as the SM H→ ττ, but with a prompt/higher-p_T muon & different Missing E_T event topologies.**

- Similar selections/strategies between CMS & ATLAS for H→μτ_h. Some differences in the kinematic cuts, jet binning & mass reconstruction (collinear vs Missing Mass Calculator).

$H\rightarrow\mu\tau, e\tau, e\mu$ Searches

CMS-PAS-HIG-14-005

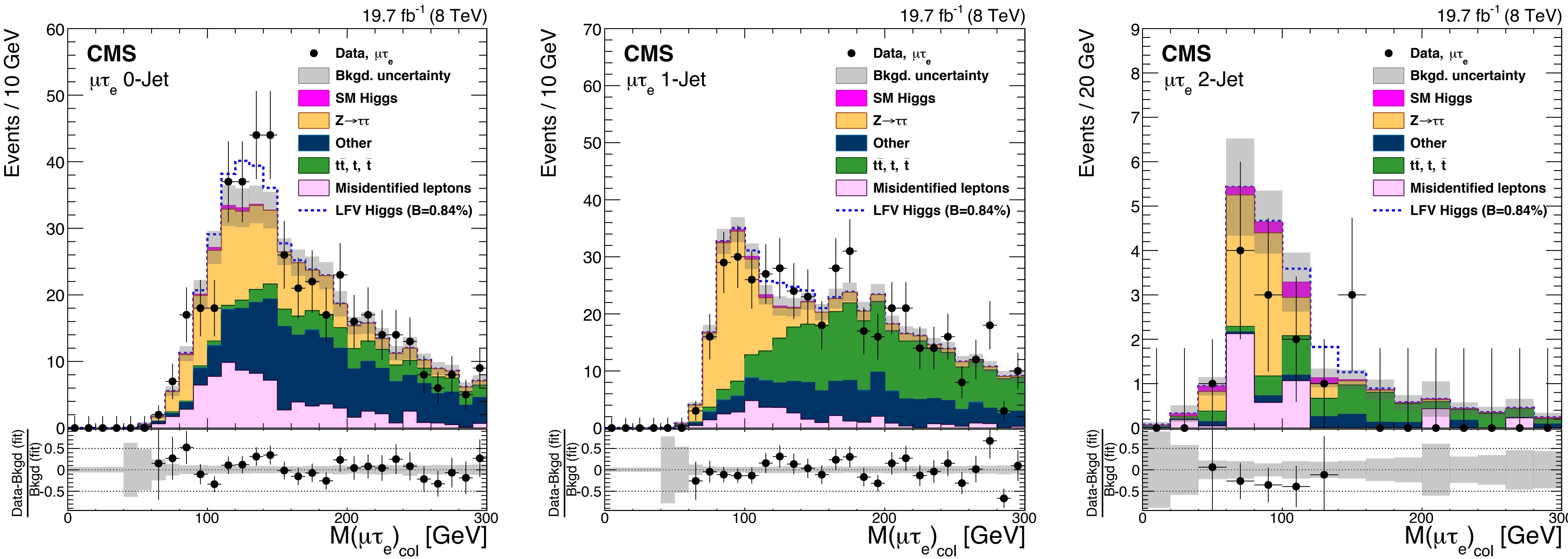




- **Similar signatures as the SM $H\rightarrow\tau\tau$, but with a prompt/higher-p_T muon & different Missing E_T event topologies.**
- Similar selections/strategies between CMS & ATLAS for $H\rightarrow\mu\tau_h$. Some differences in the kinematic cuts, jet binning & mass reconstruction (collinear vs Missing Mass Calculator).

$H \to \mu\tau_e$ Channel

Phys. Lett. B 749 (2015) 337

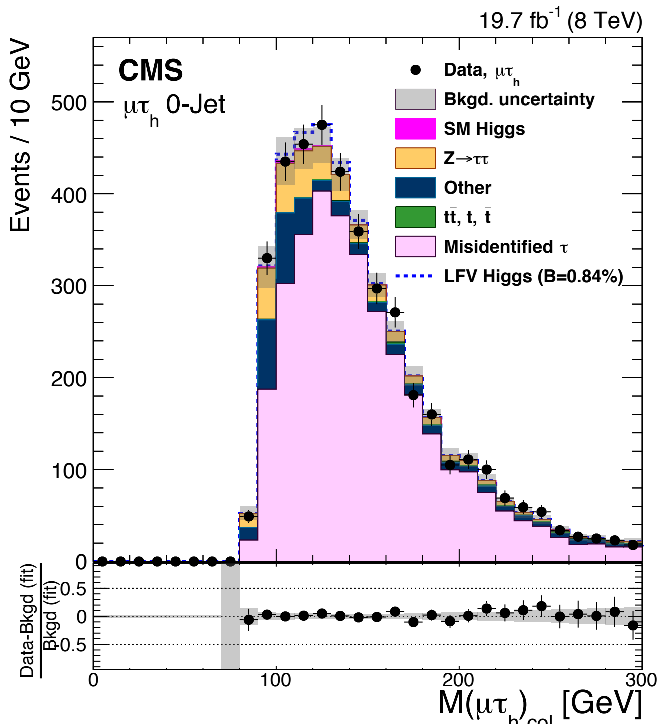


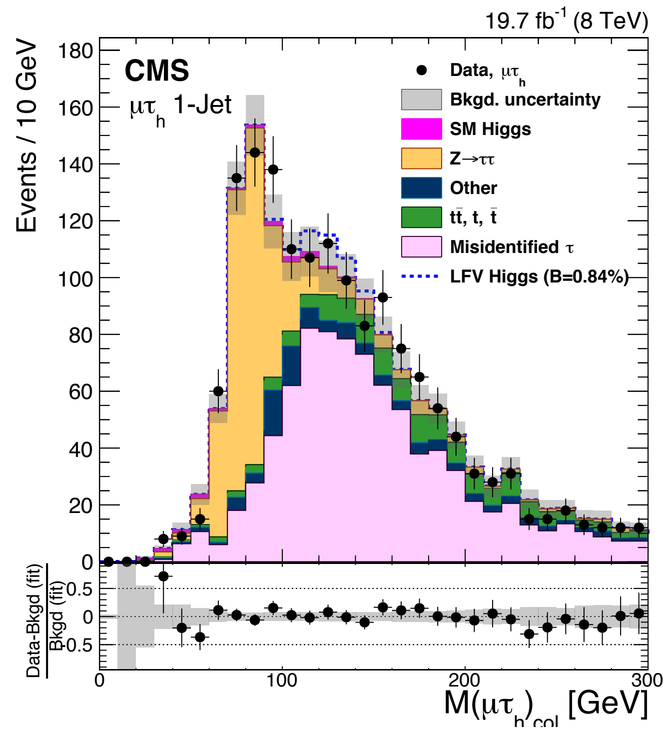
- Dominant BG ⇒ $Z \to \tau_\mu\tau_e$, mis-ID leptons, dibosons. $Z \to \tau_\mu\tau_e$ estimated from embedding technique from $Z \to \mu\mu$ ($Z \to \mu\mu$ data with μ's replaced by simulated τ decays.)
- Data agree with the expectation within uncertainty.

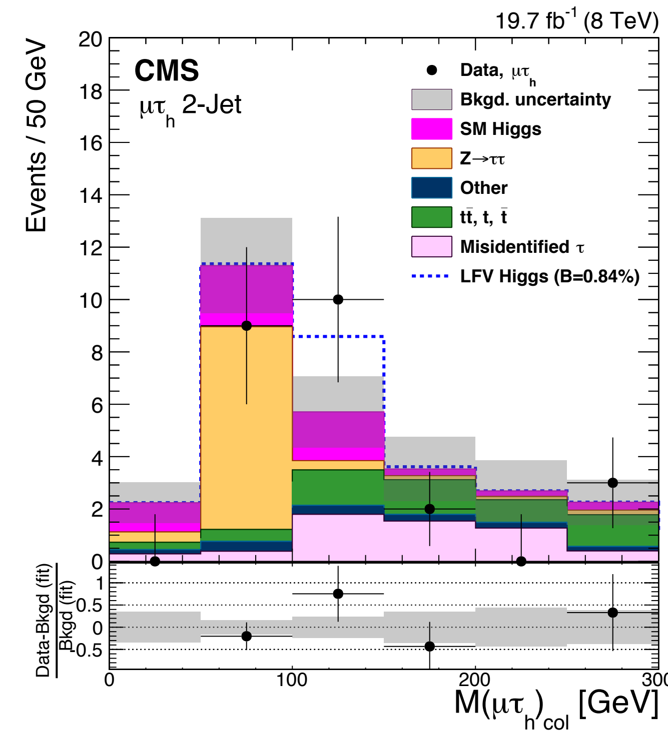
	0-jet	1-jet	2-jets
sum of backgrounds	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	23 ± 6	13 ± 3	1.2 ± 0.3
data	180	128	6

H→μτ$_h$ Channel

Phys. Lett. B 749 (2015) 337, arXiv:1508.03372

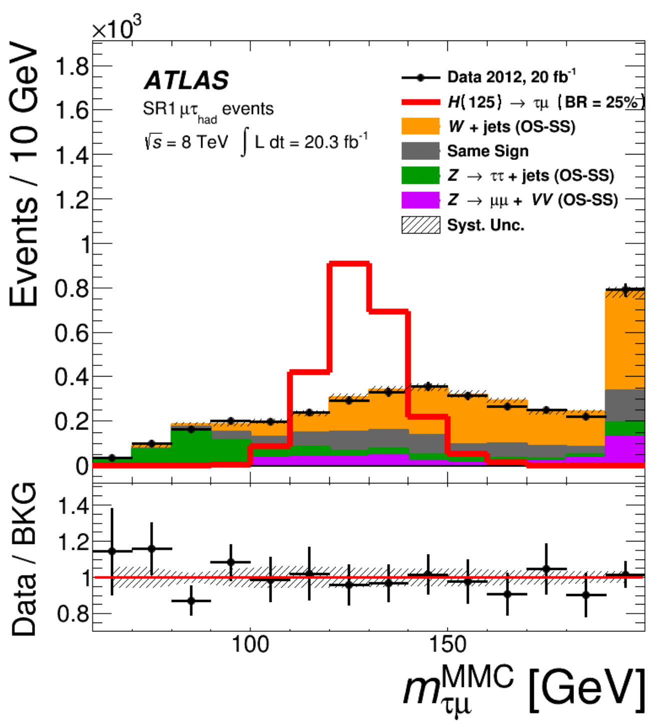


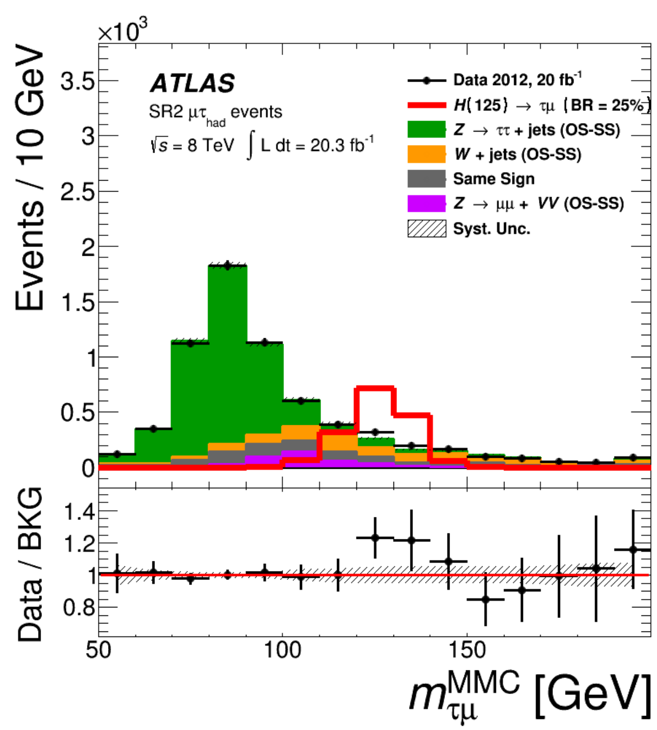




Dominant BG ⇒

Fake τ BG from W +jets, Z→τ$_μ$τ$_h$, multijet, ttbar.





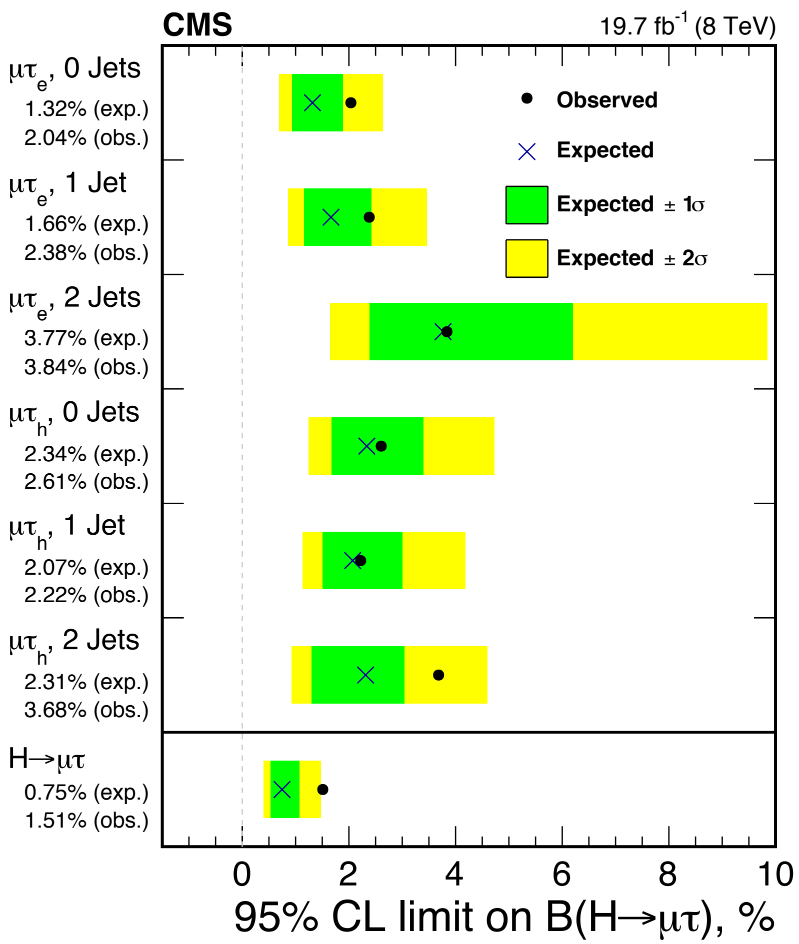
CMS (100<M_{col}<150 GeV)	0-jet	1-jet	2-jets
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1
data	2147	511	10

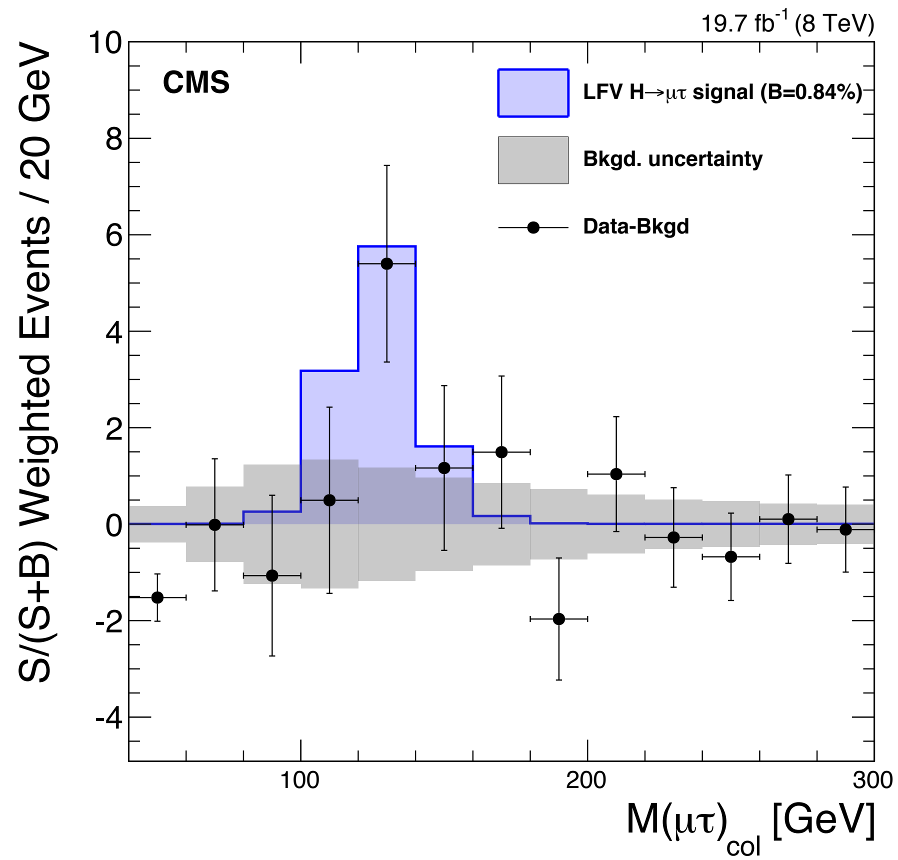
ATLAS	SR1 $m_T(μ,E_T^{miss})$>40 GeV	SR2 $m_T(μ,E_T^{miss})$<40 GeV
Total background	1224 ± 62 ± 63	1021 ± 51 ± 49
Data	1217	1075

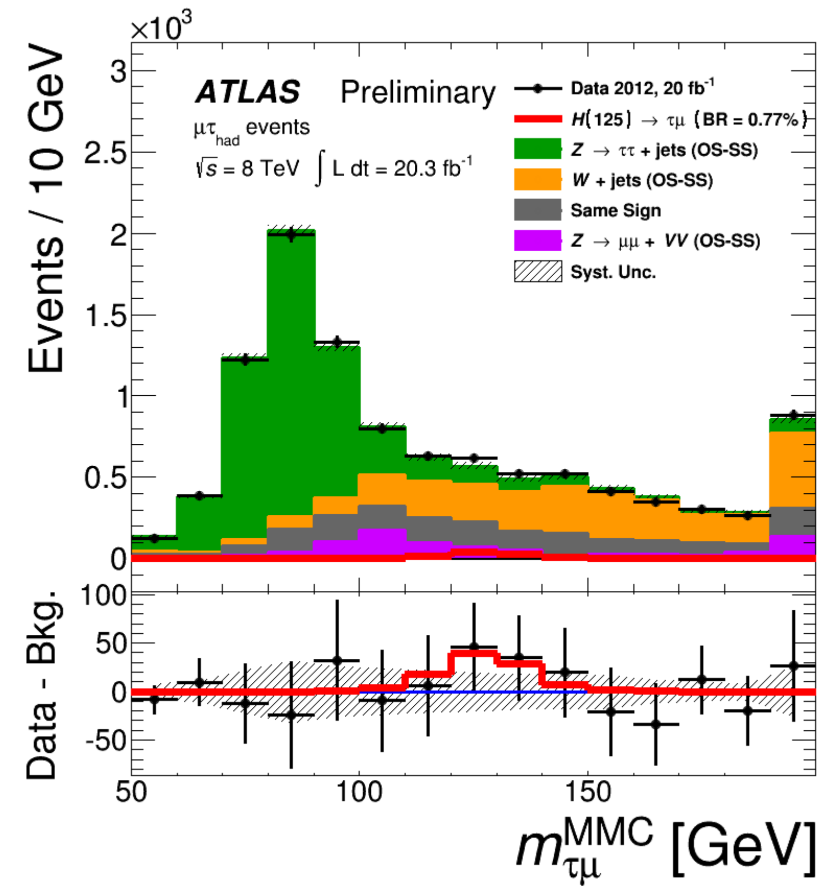
- Slight excess in the 2-jet bin for CMS.

H→μτ$_e$,μτ$_h$ Results

Phys. Lett. B 749 (2015) 337, arXiv:1508.03372



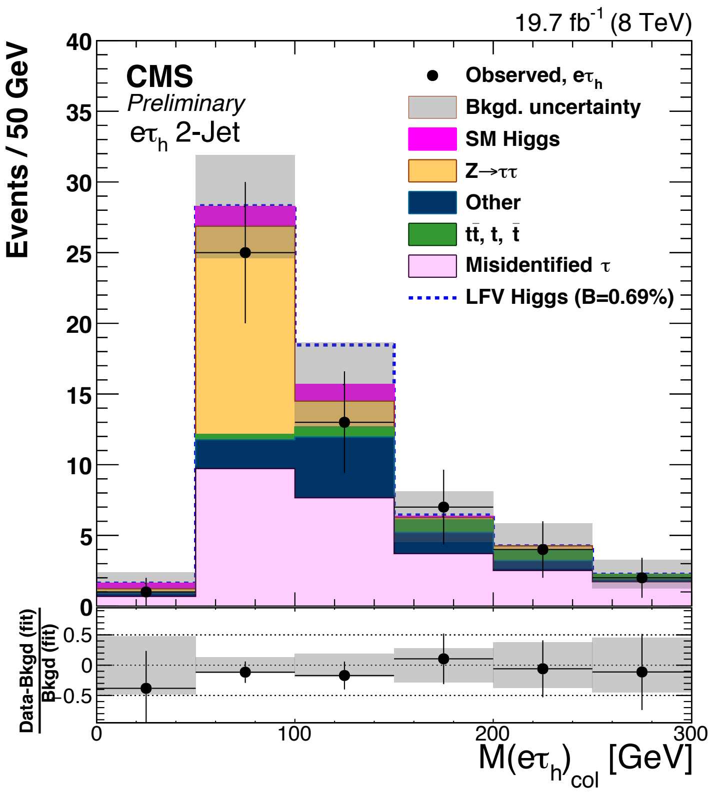


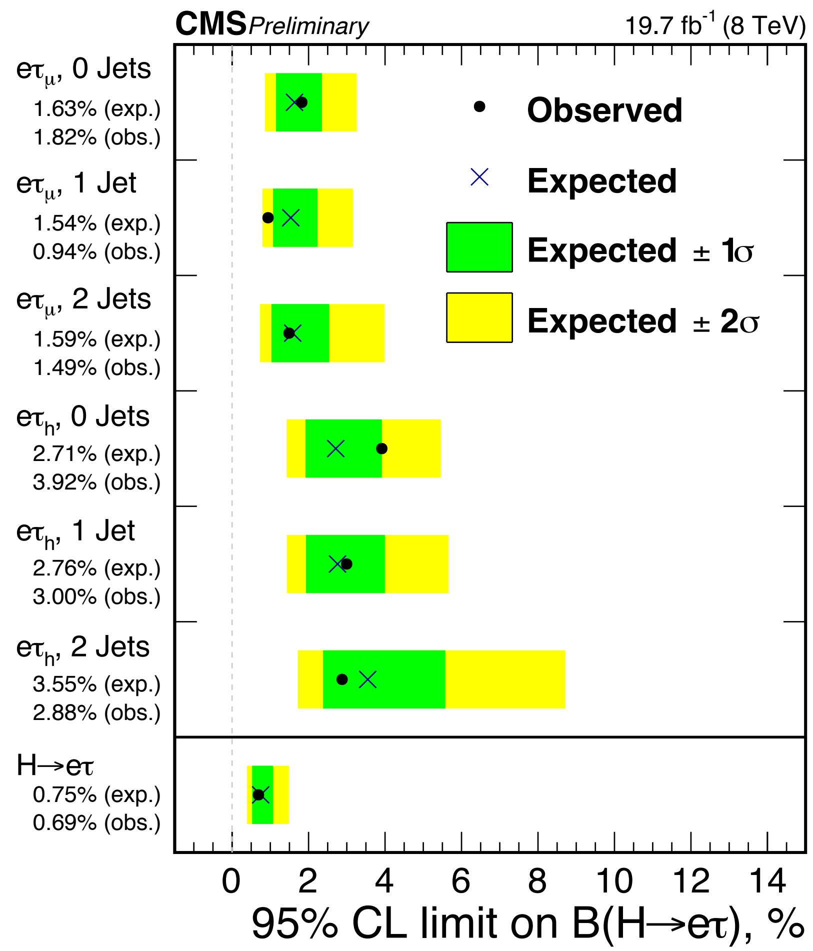


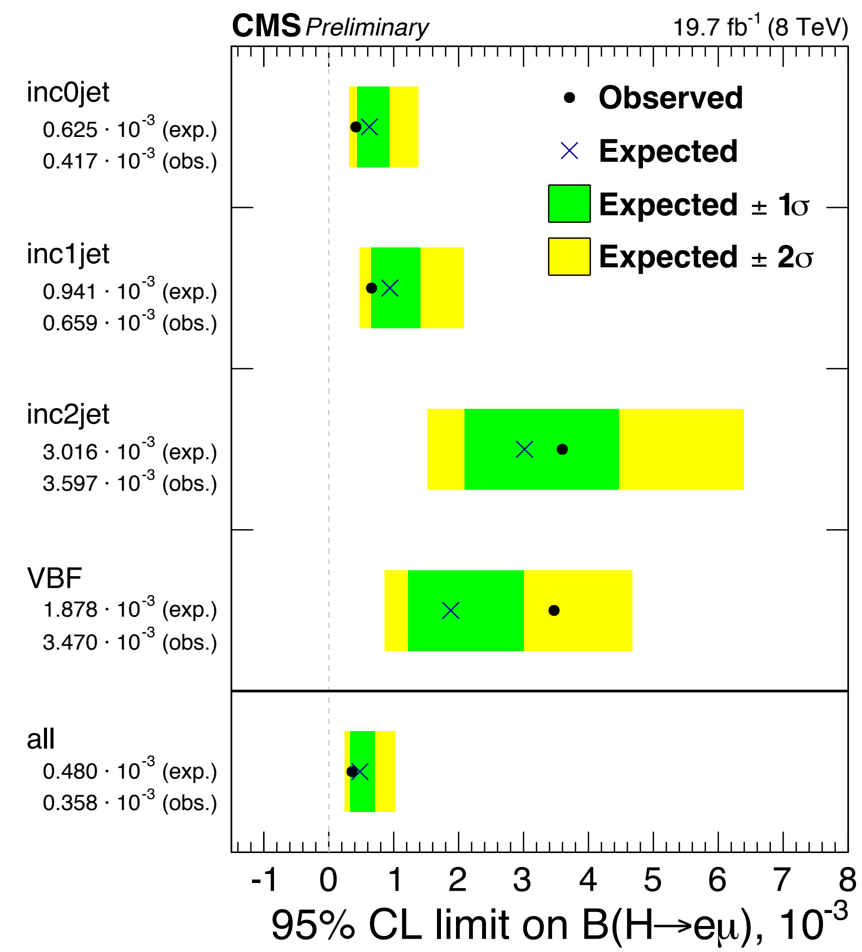
- Slight excess of **2.4σ significance** is observed in CMS (1.3σ in ATLAS).
- **Best fit BR(H→μτ) = 0.84$^{+0.39}_{-0.37}$% [CMS], 0.77±0.62% [ATLAS]**
- Limit: **BR(H→μτ) < 1.51% obs** (0.75% exp) [CMS], **1.85%** (1.24%) [ATLAS]@95%CL

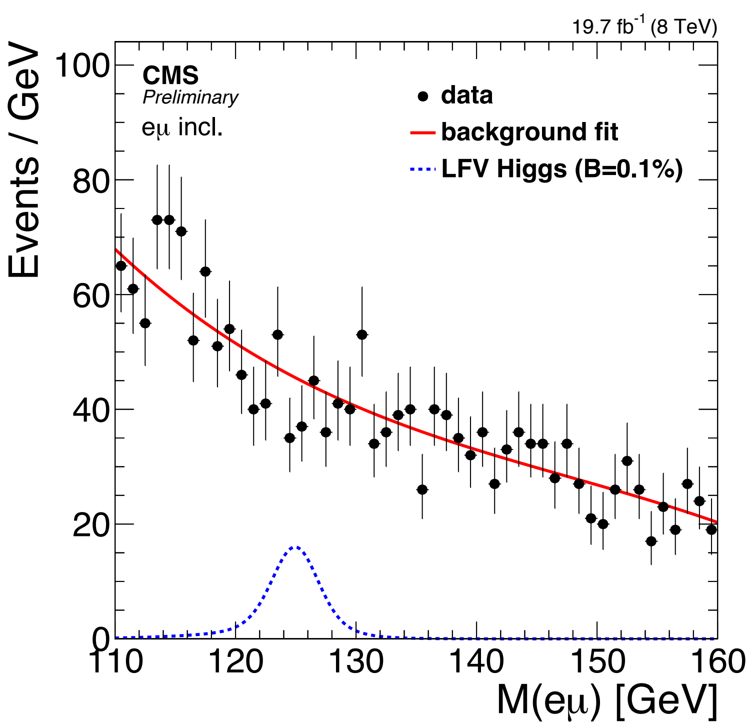
H→eτ,eμ Results

CMS-PAS-HIG-14-040







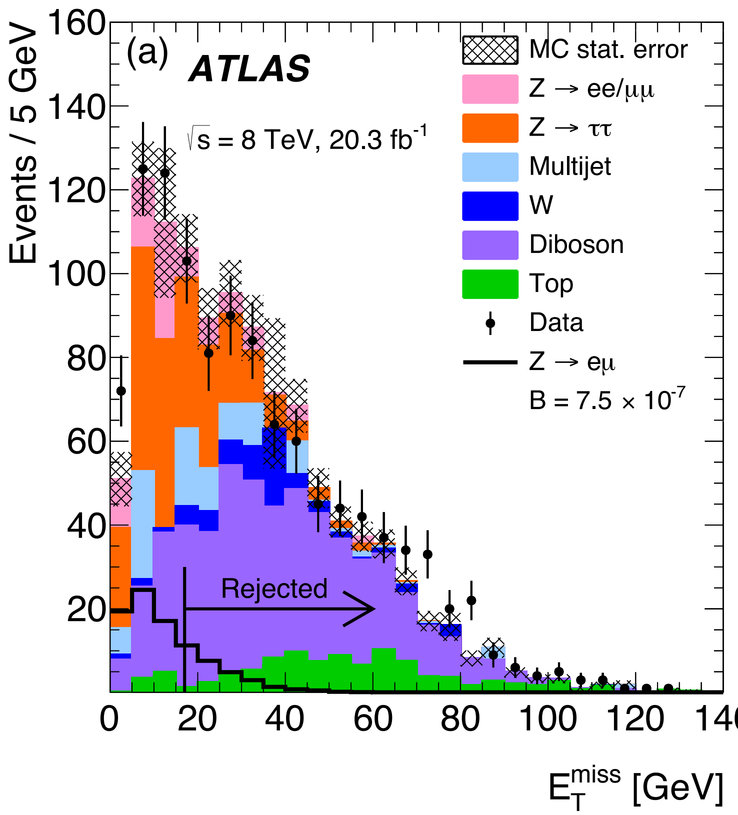


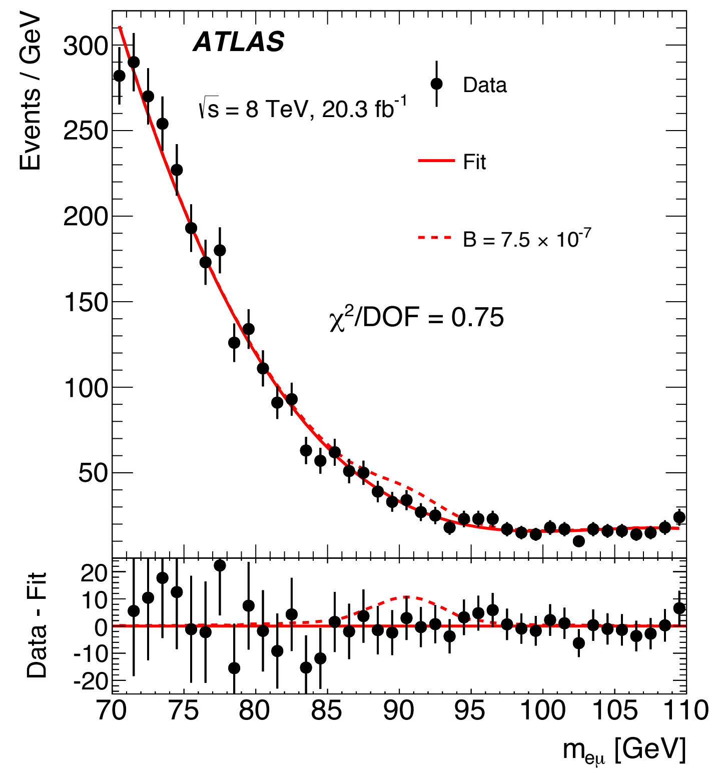
- No excess observed in H→eτ$_μ$,eτ$_h$, eμ channels for all categories.
- **BR(H→eτ) < 0.70%@95%CL. Best fit -0.10.**
- BR(H→eμ) < 0.036%@95%CL.

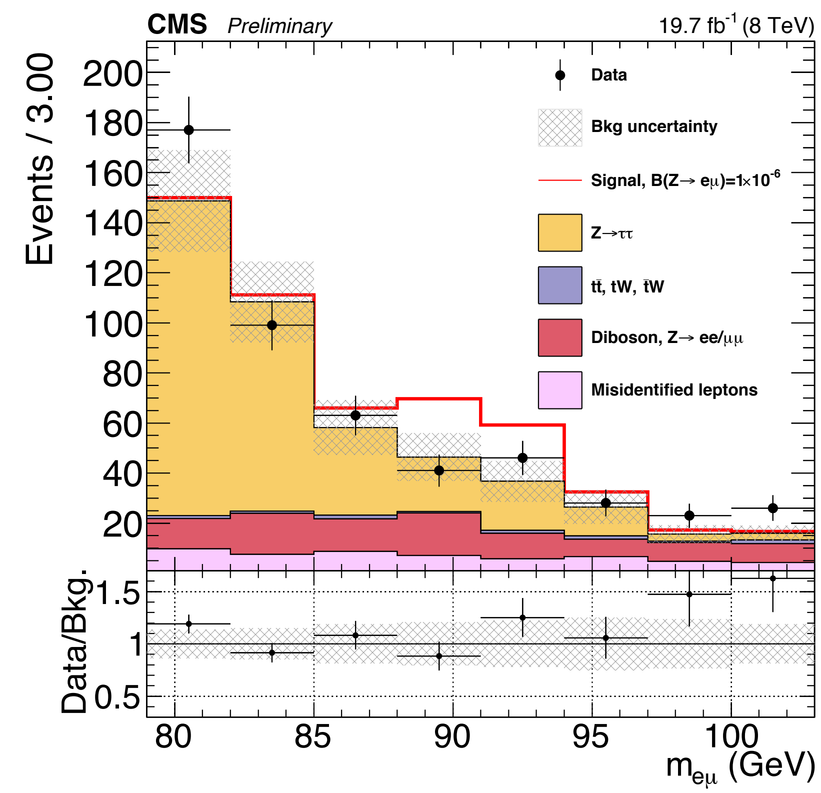
Z→eμ Search

- Indirect limits: BR(Z→eμ) < 10^{-12} (μ→3e), 10^{-10} (μ→eγ)

Phys. Rev. D 90, 072010 (2014), CMS-PAS-EXO-13-005



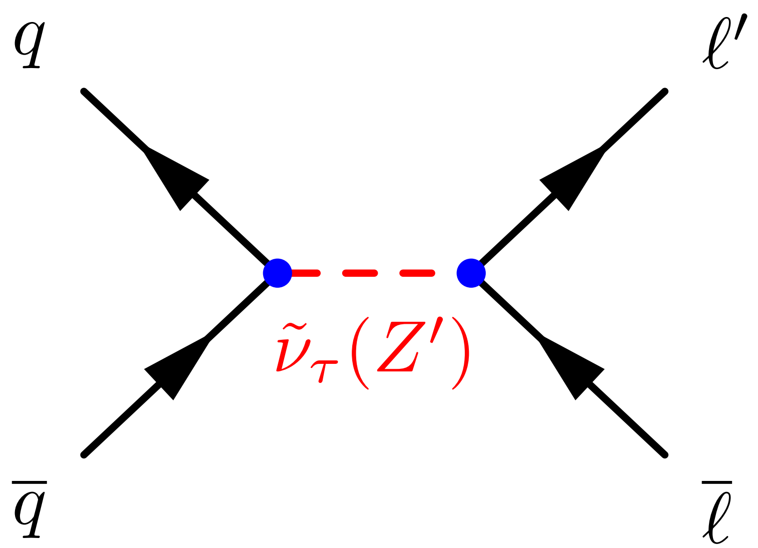




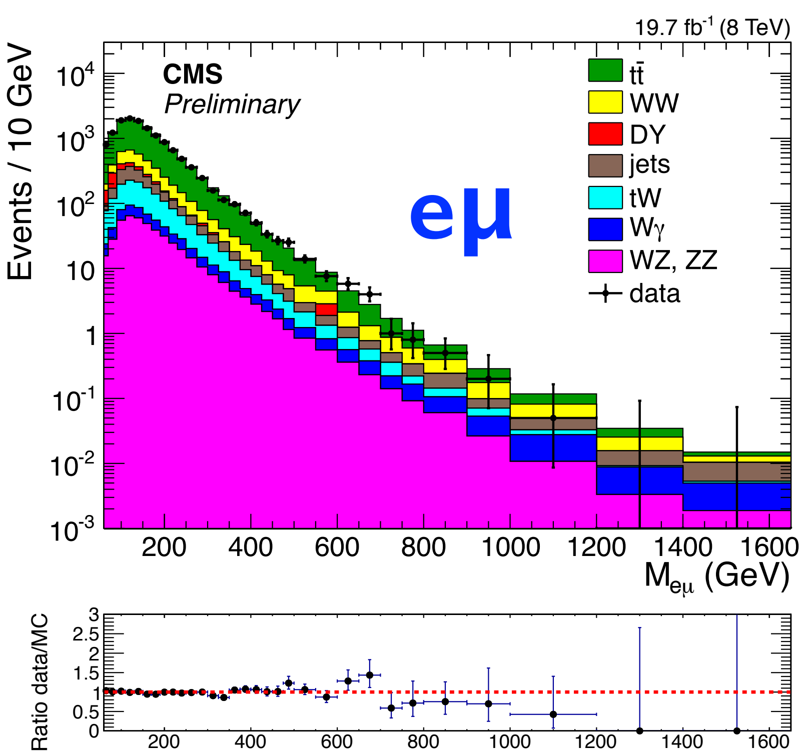
- Require low E_T^{miss} & veto jets to suppress the Z→ττ, diboson, and ttbar BGs.
- Dominant BG: Z→ττ.
- **BR(Z→eμ) < 7.5 × 10^{-7} (ATLAS)**, **7.3 × 10^{-7} (CMS)** @ 95%CL. Surpassing the previously most stringent direct limit from LEP (< 1.7 × 10^{-6}).

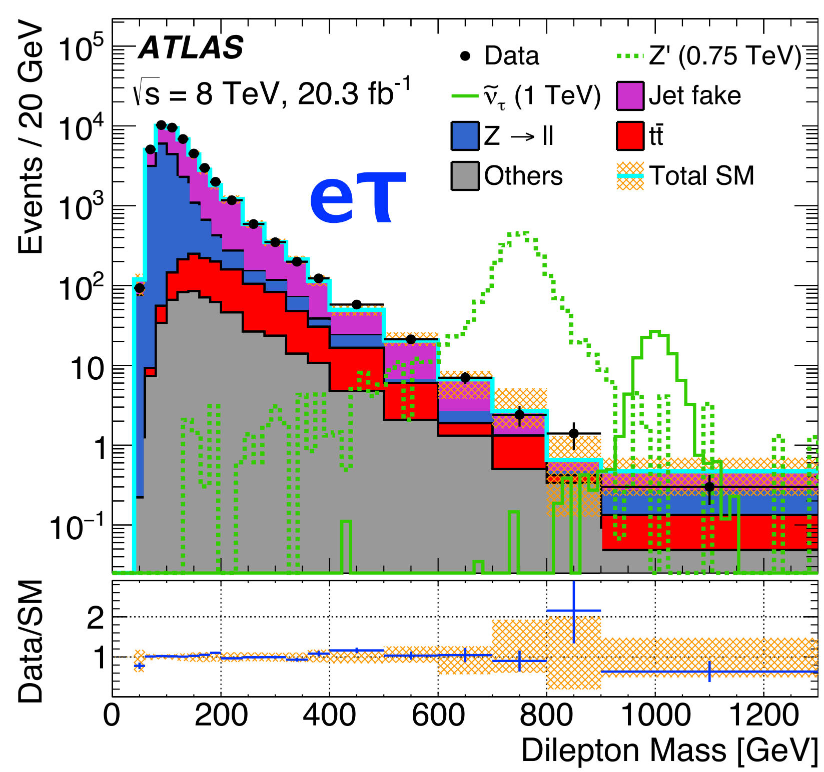
Z′→eμ,eτ,μτ Search

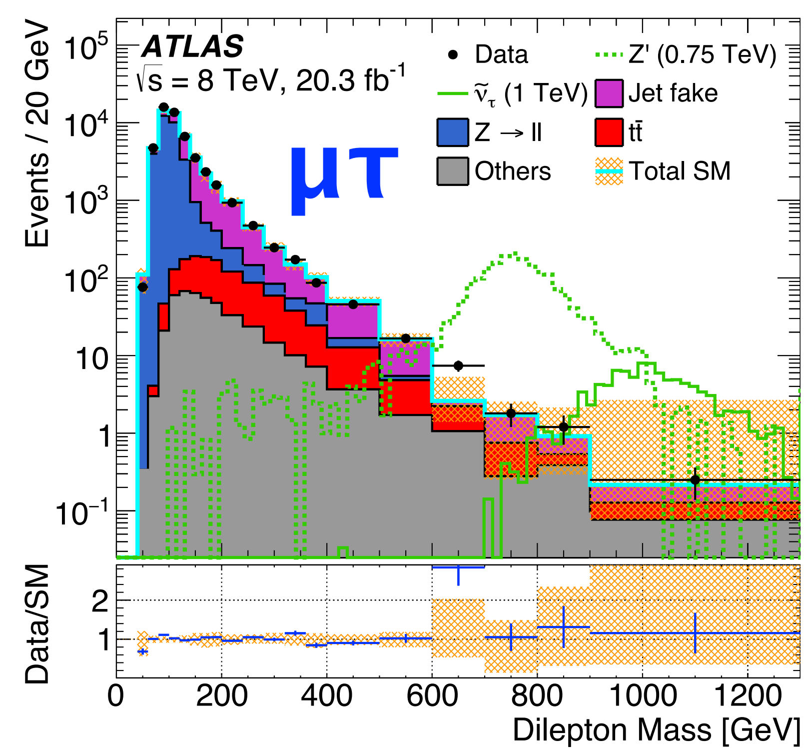
Phys. Rev. Lett. 115, 031801 (2015), CMS-PAS-EXO-13-002



- Search for LFV motivated from RPV SUSY models, LFV Z′, and quantum black holes.
- Bump hunting for opposite-sign different-flavor dileptons (eμ, eτ, μτ for ATLAS; eμ for CMS).
- Collinear neutrino approximation considered for mass reconstruction in eτ/μτ channels.



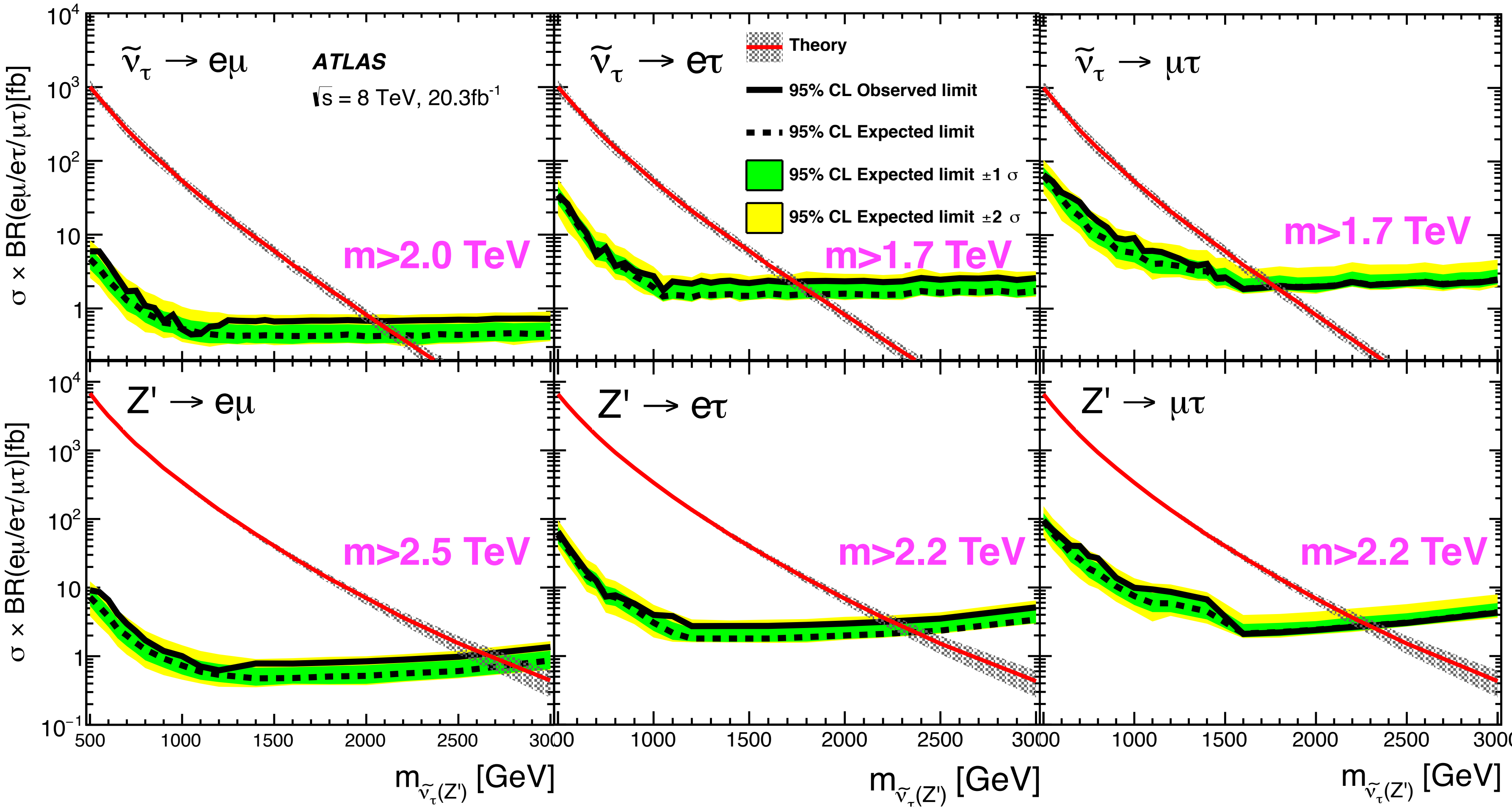


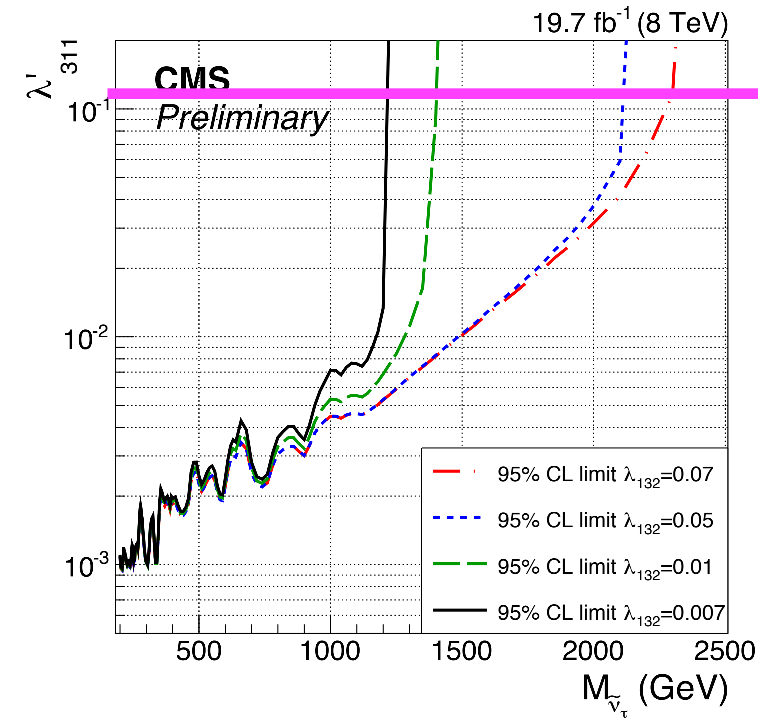


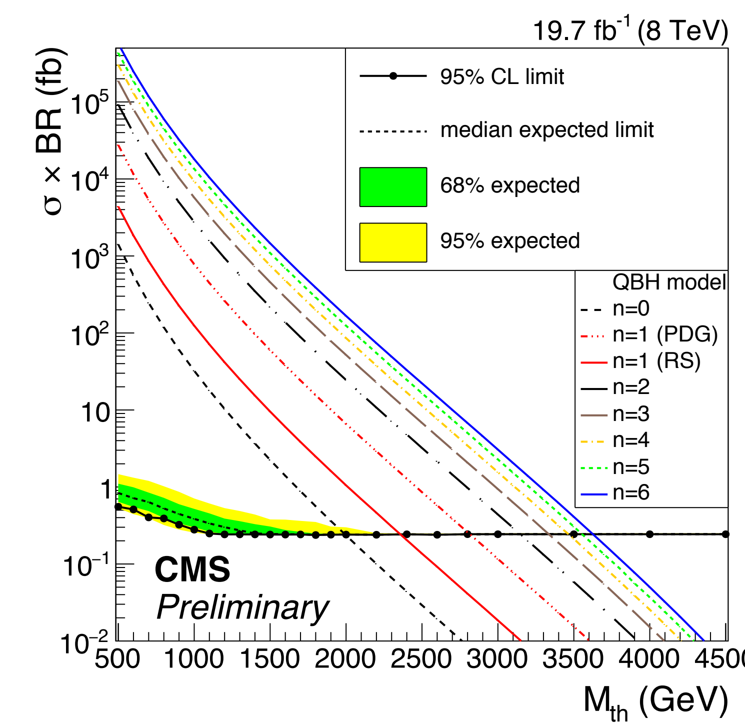
Z′→eμ,eτ,μτ Results

Phys. Rev. Lett. 115, 031801 (2015),
CMS-PAS-EXO-13-002,

λ'_{311}=0.11, λ'_{i3k}=0.07







- Limits placed on RPV SUSY, LFV Z′, or quantum BH production times branching ratio.
- **These results significantly extend constraints from previous results** from the Tevatron & LHC.

$Z' \to \tau\tau$ Search

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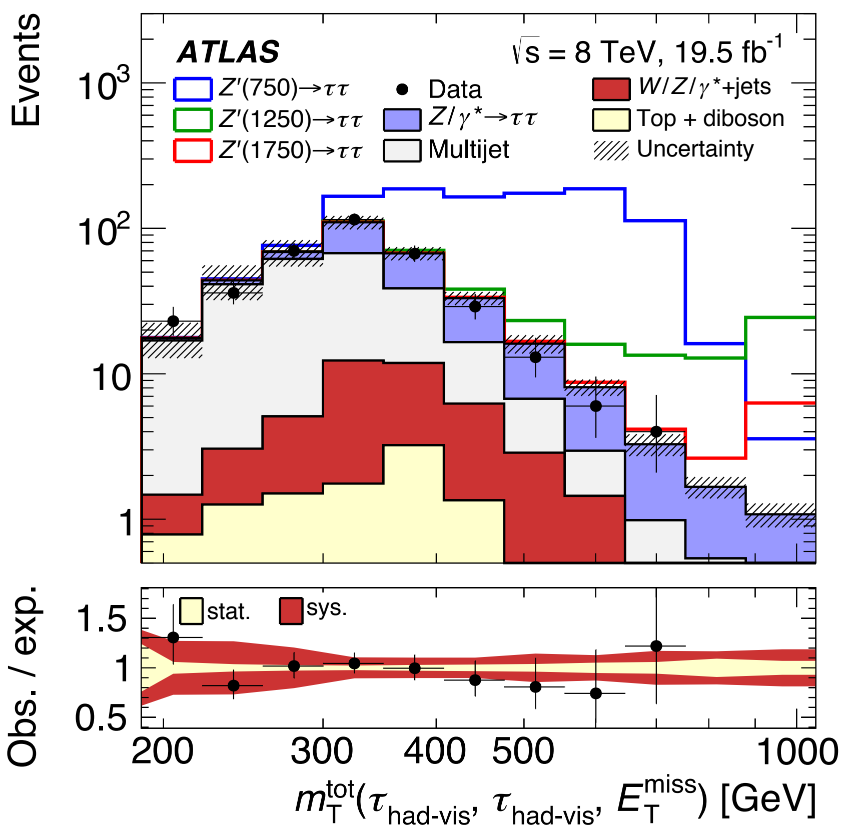
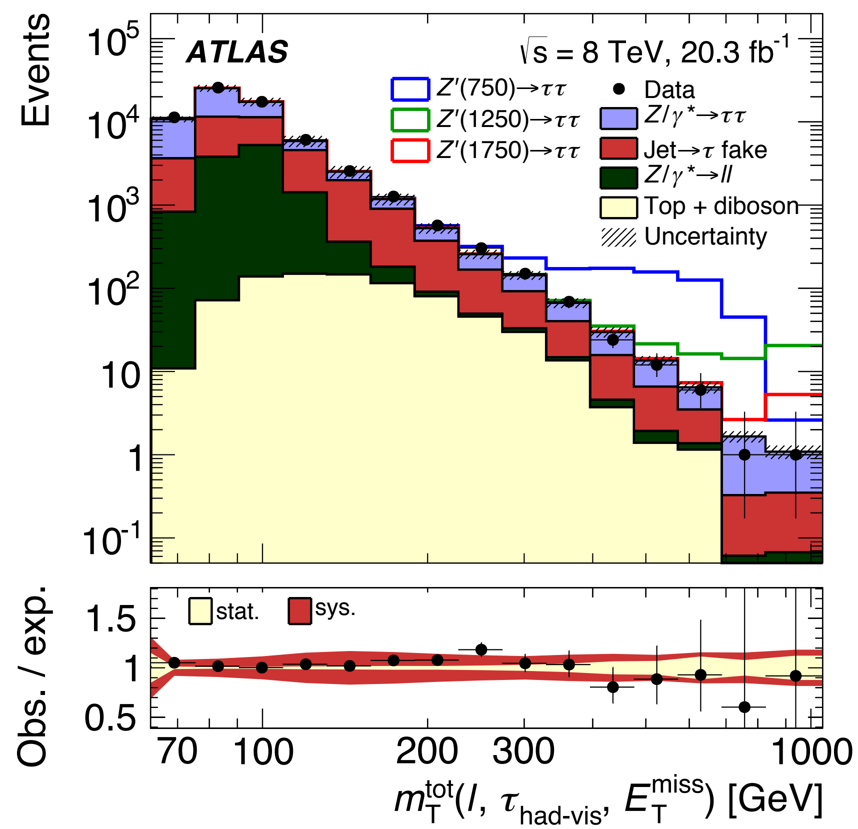
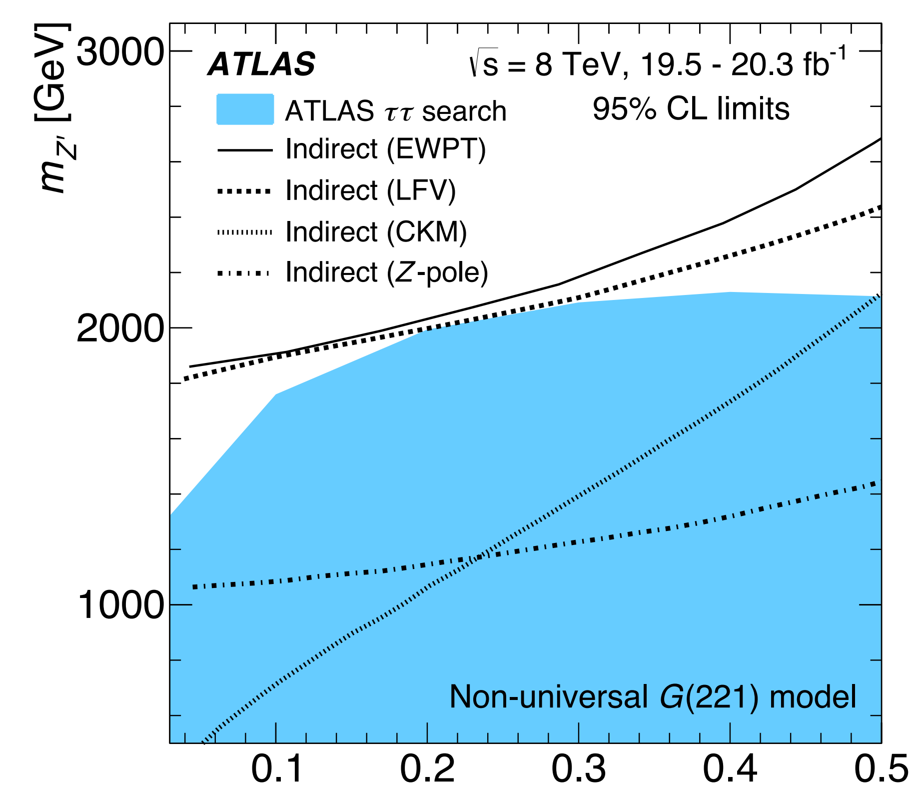
- Non-universal lepton couplings to Z′ can explain observed flavor anomalies.
  (e.g. anomalous dimuon production@D0, excess of $B \to D^{(*)}\tau^-\bar{\nu}_\tau$@BaBar, Belle)
- $\tau_{had}\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$ channels are considered.
- Main BGs: $Z \to \tau\tau$, multijet for $\tau_{had}\tau_{had}$ & $Z \to \tau\tau$, W+jets for $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$.
- No excess observed. Stronger constraints on the G(221) [SU(2)×SU(2)×SU(1)] parameter space than the indirect limits from LEP & CKM unitarity.







sin²φ

sin²φ: mixing of two extended SU(2) groups.

W′→τν Search

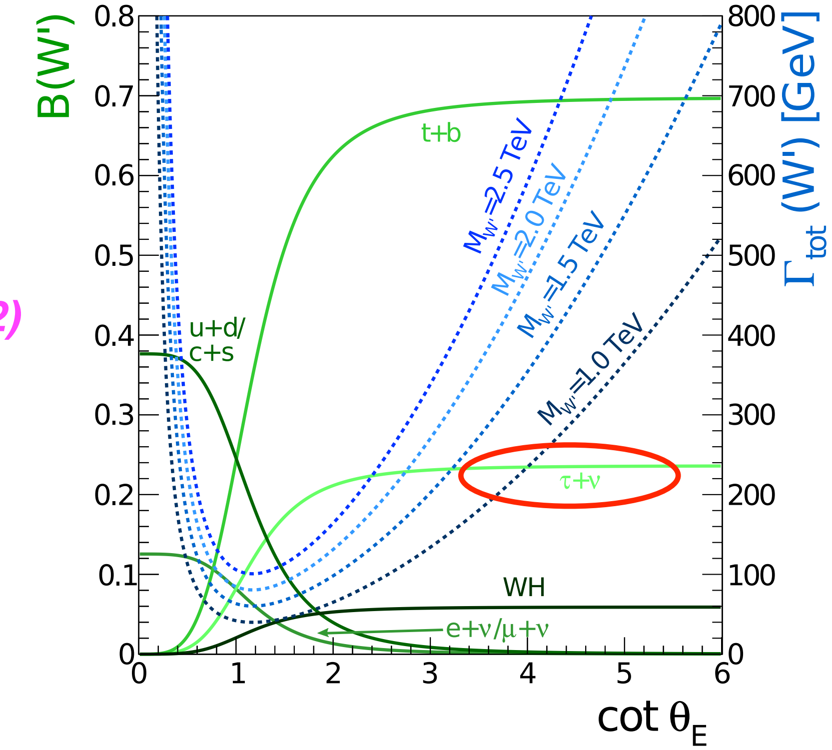
arXiv:1508.0430

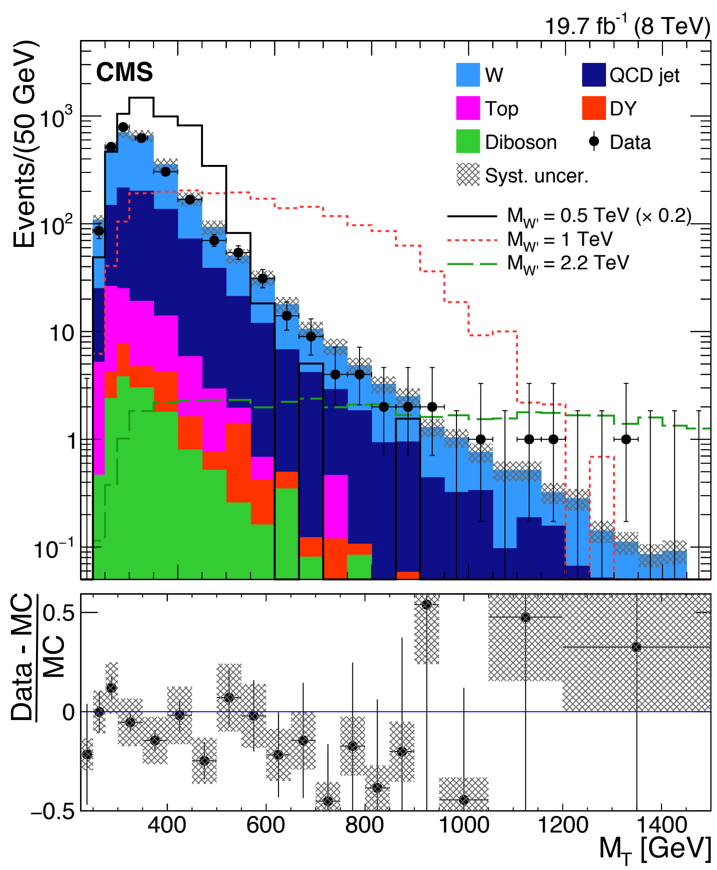
- First search for W′ decaying to τ_{had} & ν_τ.
  Decays to 3rd generation could be enhanced in case of non-universal coupling.

- Main BGs: $W \to \tau\nu_\tau$, multijet.

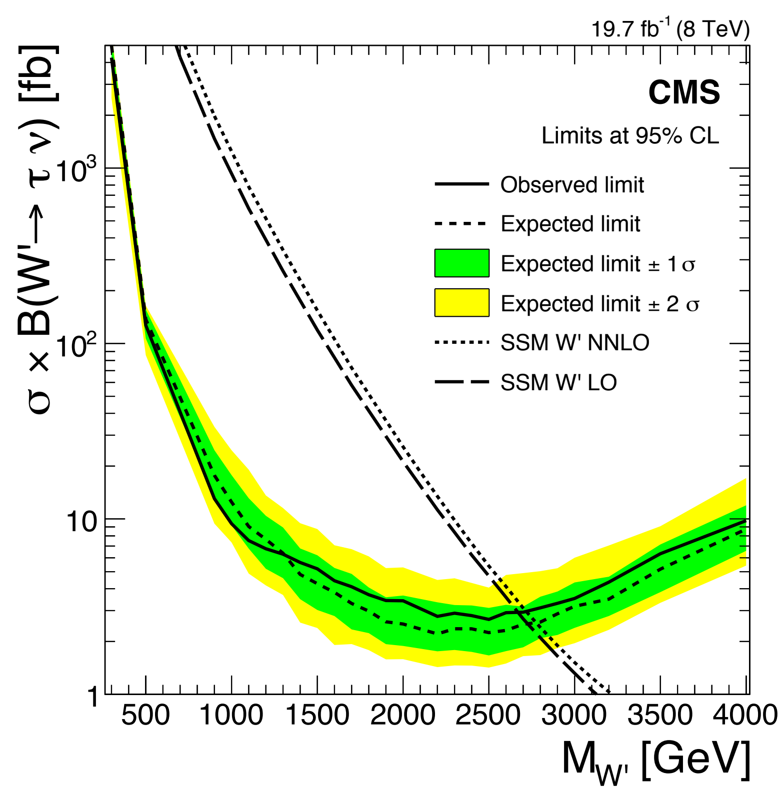
- Significantly expanding the limits for large cot θ_E.

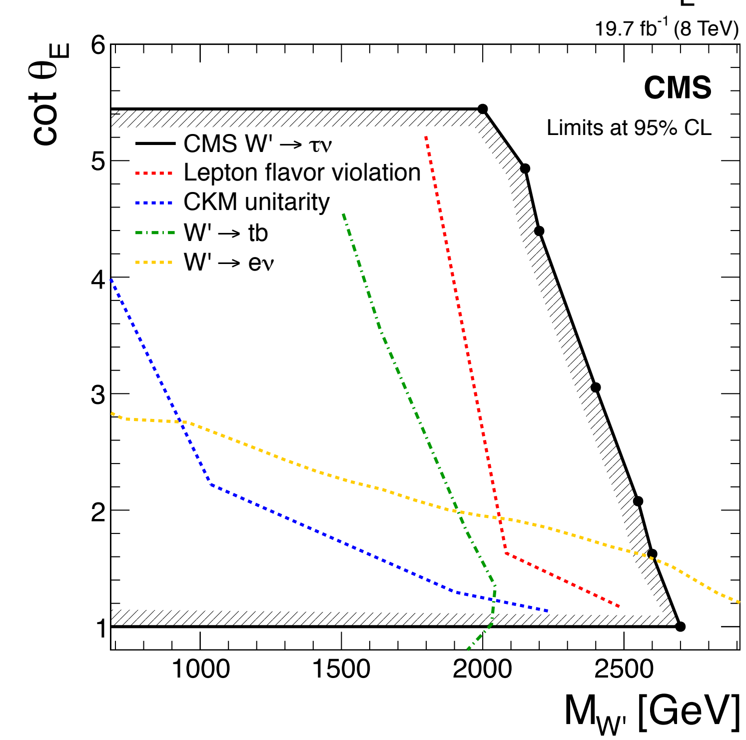
cot θ_E: mixing of two extended SU(2) groups.





$$M_T = \sqrt{2\, p_T^\tau\, E_T^{\mathrm{miss}}\, (1 - \cos\Delta\phi(\tau, \vec{p}_T^{\mathrm{miss}}))},$$

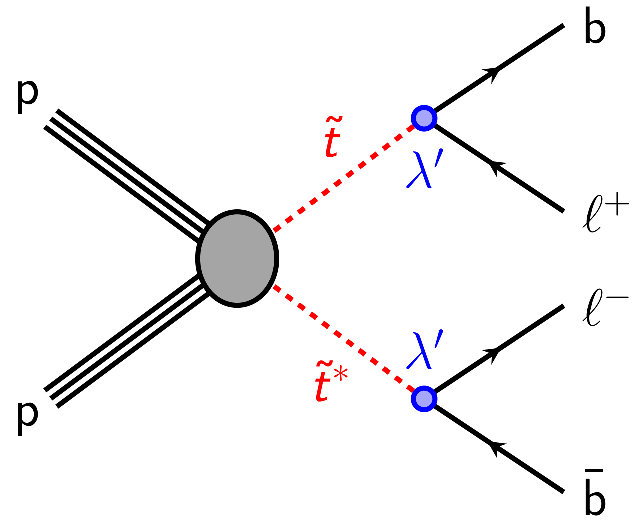


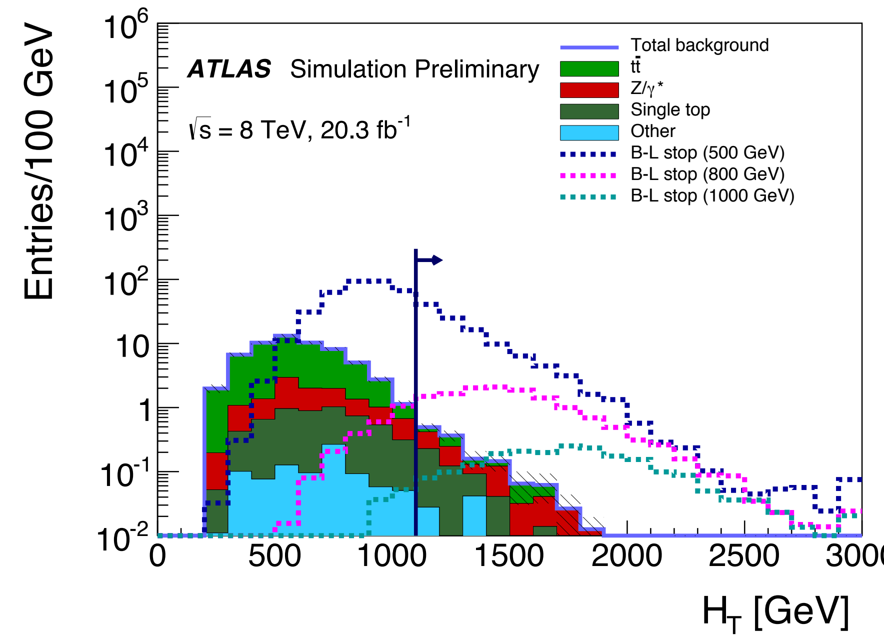


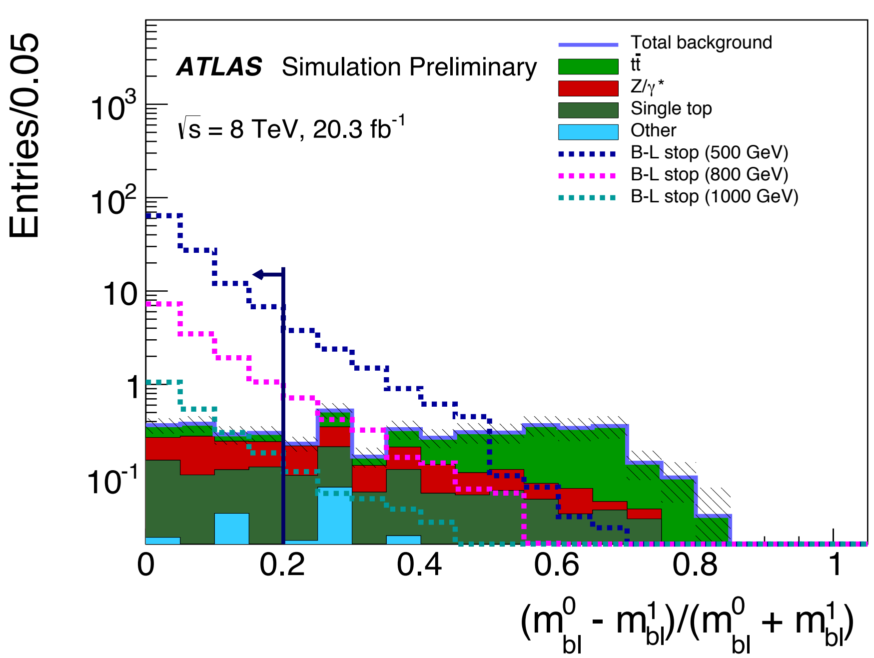
RPV Stop Search

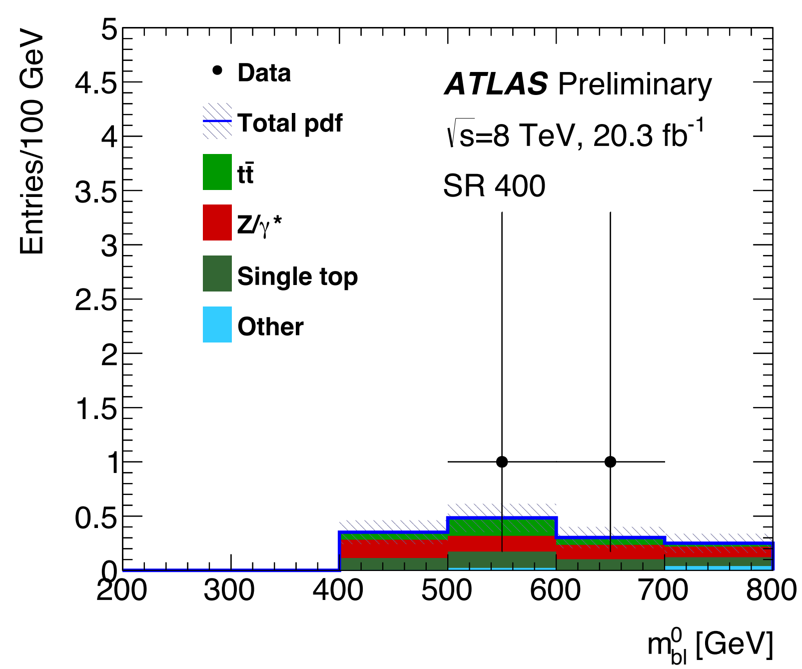
ATLAS-CONF-2015-015

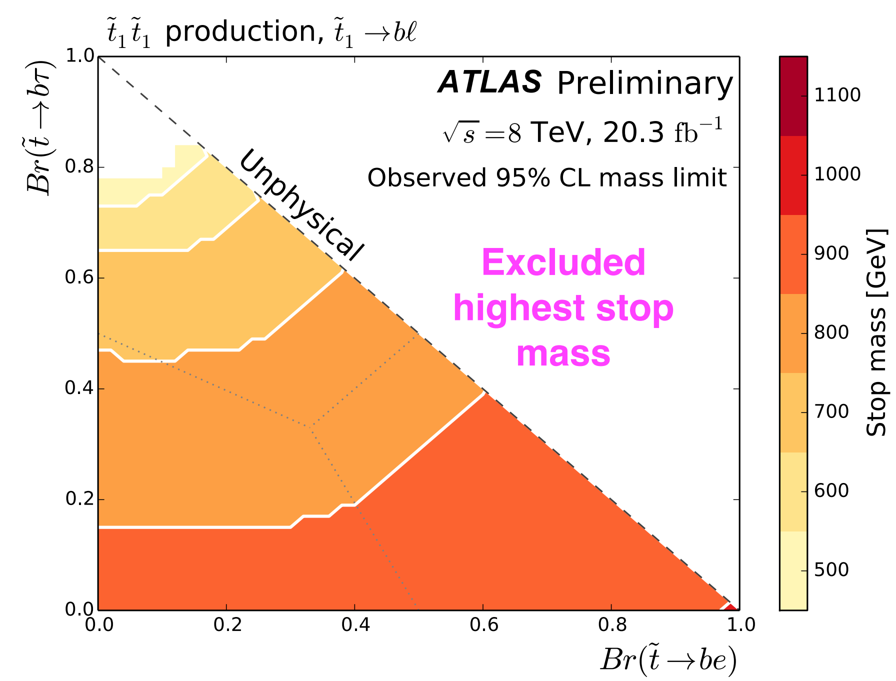
- RPV SUSY model w/ spontaneously broken local *U(1)*$_{B-L}$ symmetry. Only lepton number is violated.
- eebb,eμbb,μμbb final states considered.
- H_T>1100 GeV, m_{bl} asymmetry ≤ 0.2, Z veto on higher m_{bl} (m_{bl}^0).





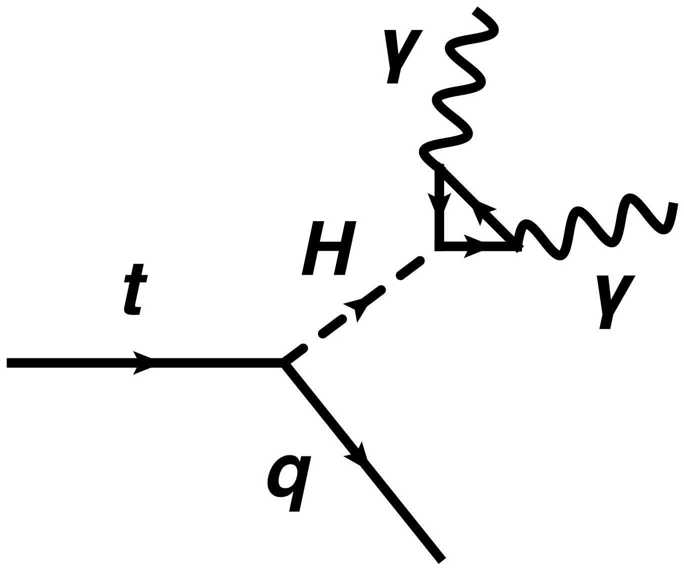




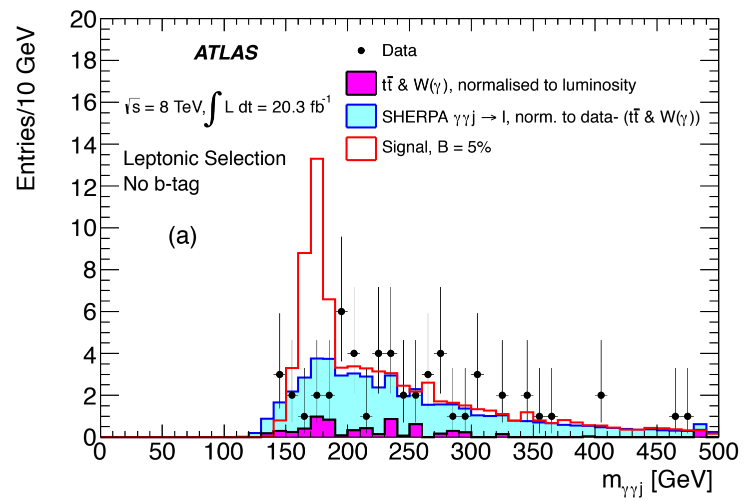


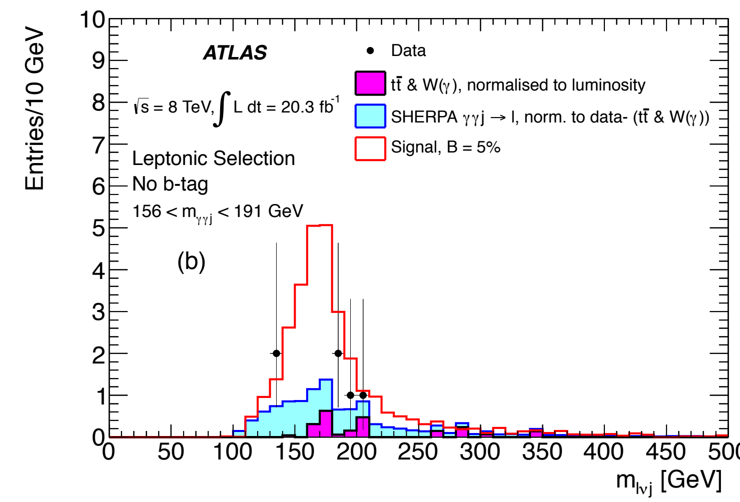
FCNC t→qH(→γγ) Search

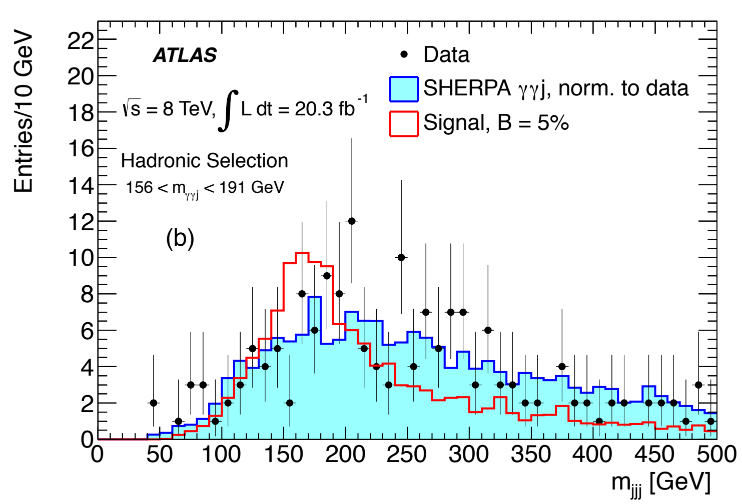
JHEP 06 (2014) 008, CMS-PAS-TOP-14-019

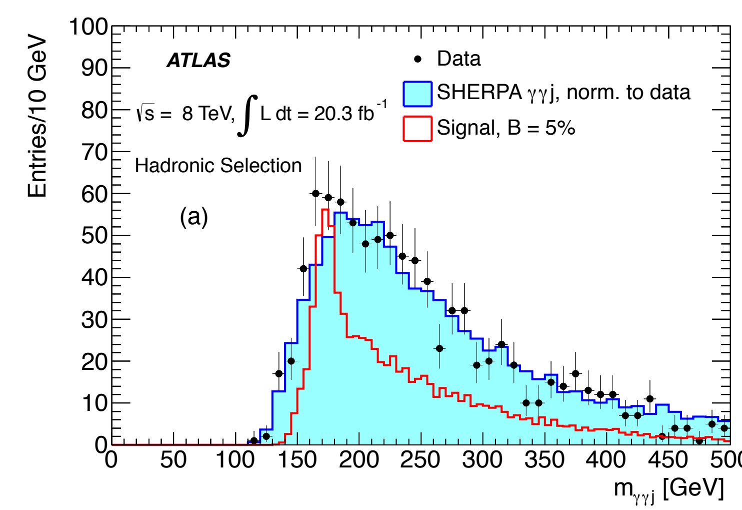


- Seach for flavor-changing neutral currents in top decays using ttbar processes. Look for peak at γγj invariant mass & Wj (leptonic + hadronic channels).







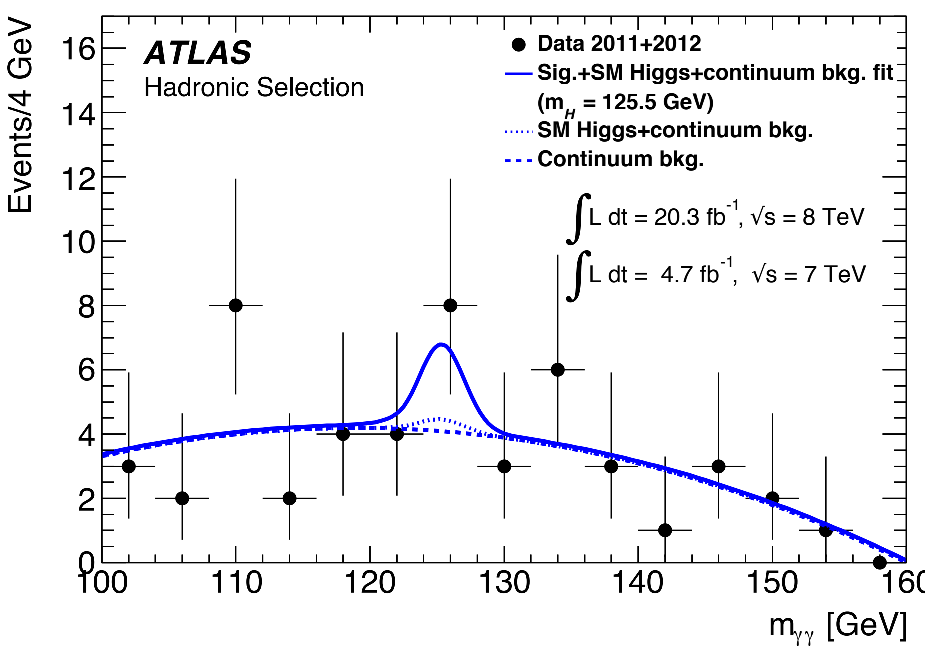


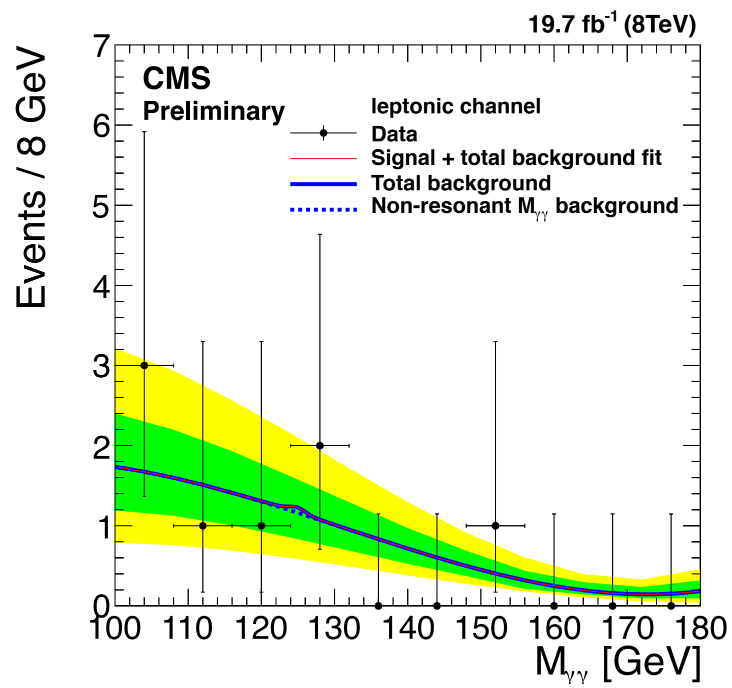
Backgrounds

- **Leptonic channel:** non-resonant γγ production, multijet, ttbar, Wγ, real Higgs decay.
- **Hadronic channel:** non-resonant γγ production, multijet, real Higgs decay.

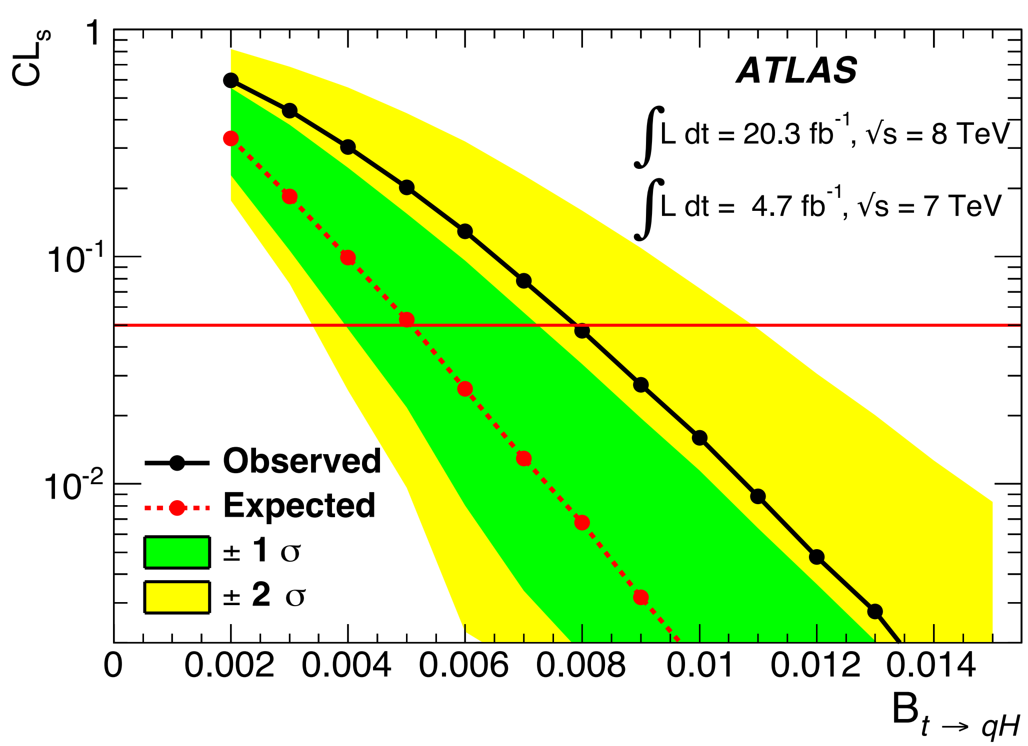
$t \to qH(\to \gamma\gamma)$ Results

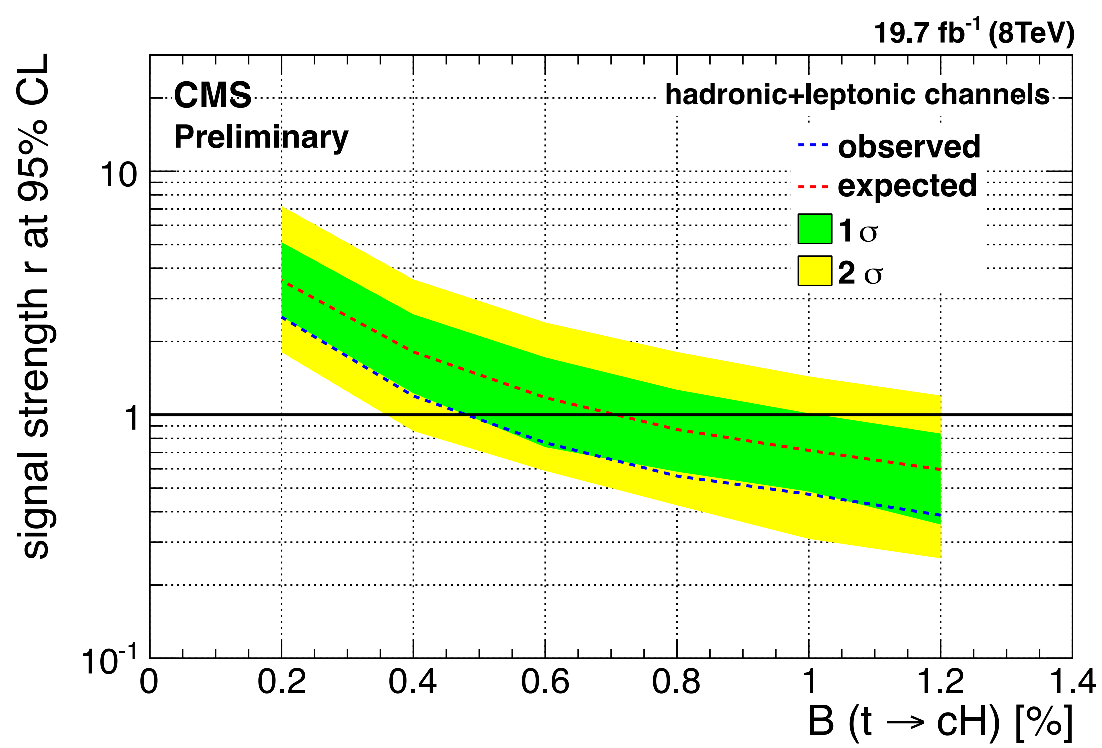
JHEP 06 (2014) 008, CMS-PAS-TOP-14-019





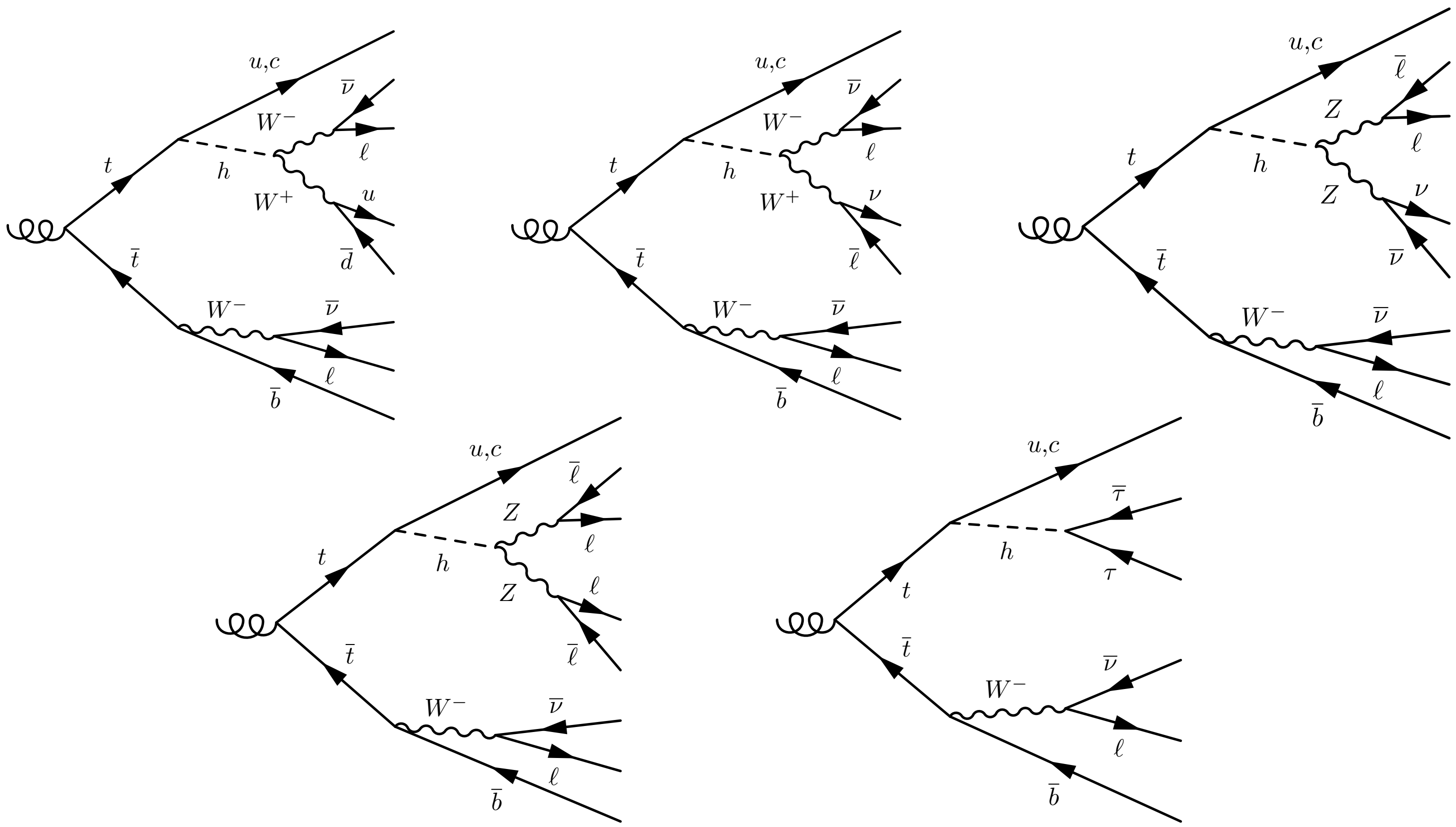
- **BR($t \to cH$) < 0.79% (0.51%)** [ATLAS], **0.71% (0.47%)** [CMS] @95%CL
- **BR($t \to uH$) < 0.65% (0.42%)** [CMS]
- **$\sqrt{(\lambda_{tcH}^2+\lambda_{tuH}^2)}$ < 0.17** [ATLAS]

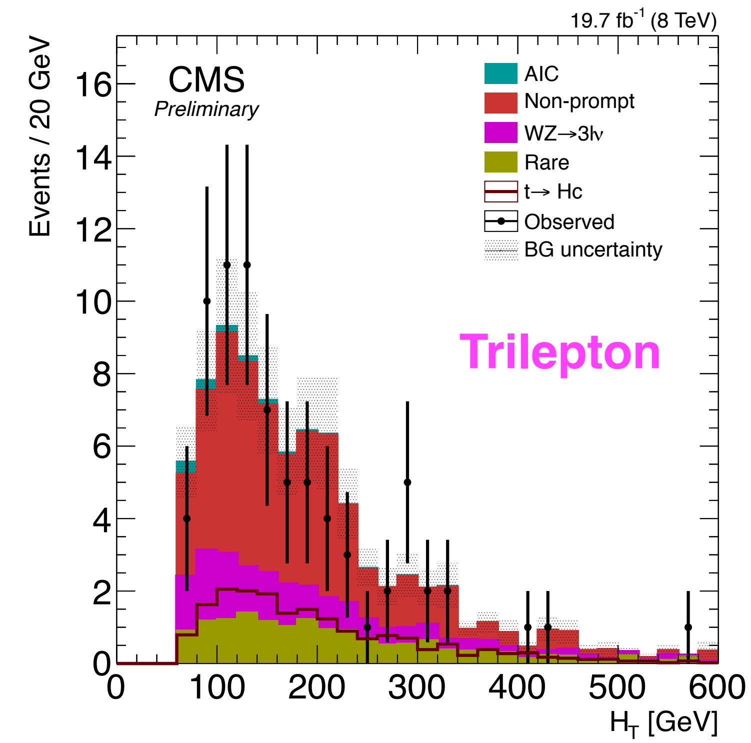


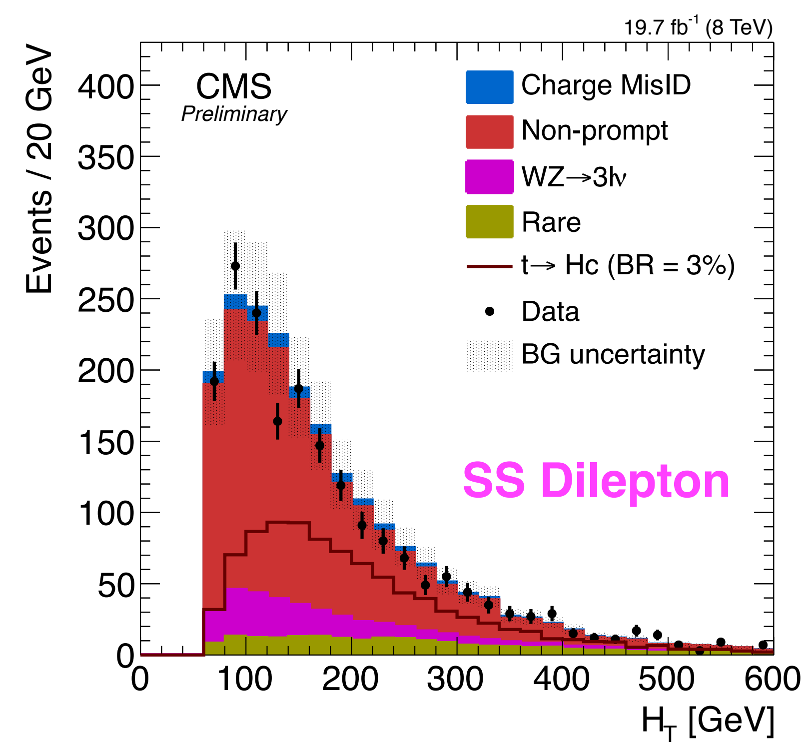


t→qH(→multilepton) & Combination

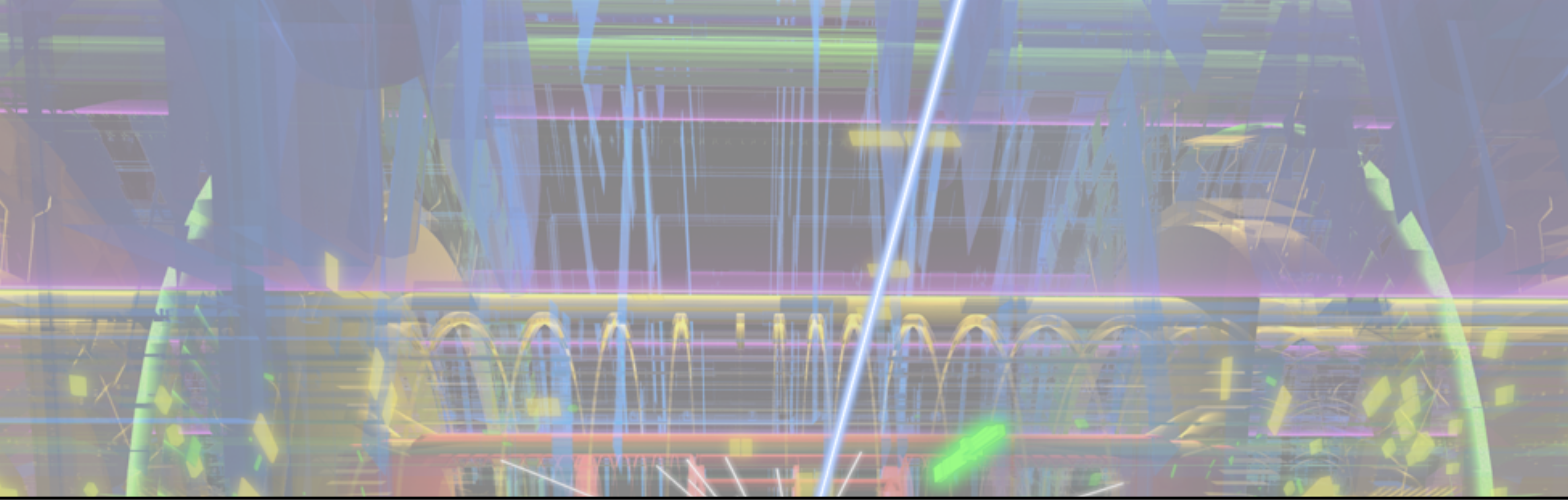
CMS-PAS-HIG-13-017, CMS-PAS-HIG-13-034



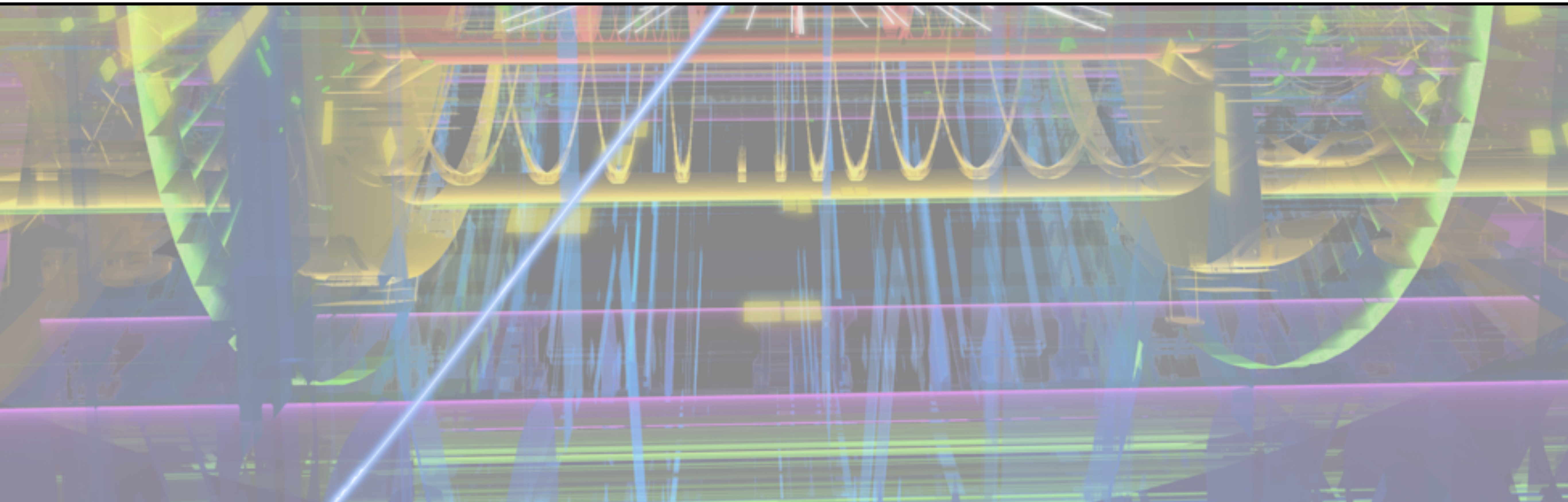




- Used same-sign dilepton & trilepton SRs.
- BR(t→cH) < 0.93% obs (0.89% exp)
- $\sqrt{(\lambda_{tcH}^2+\lambda_{tuH}^2)} < 0.18$
- Combination w/ γγ channel leads to **BR(t→cH) < 0.56%** & **$\sqrt{(\lambda_{tcH}^2+\lambda_{tuH}^2)} < 0.14$**

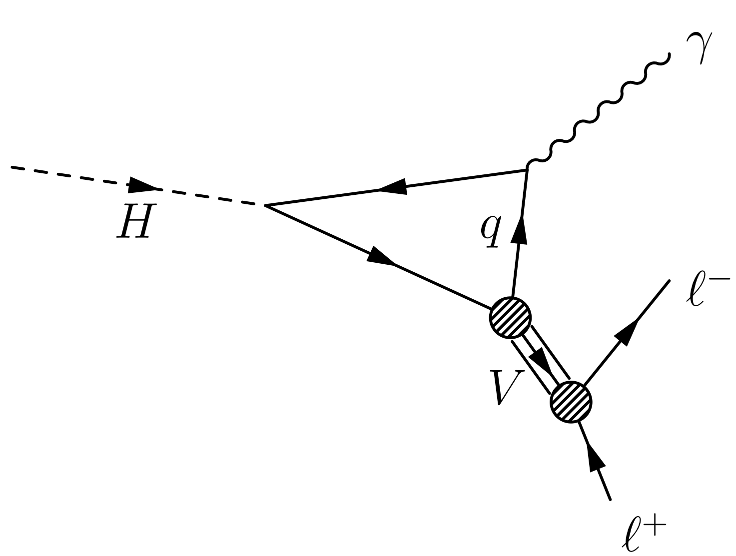


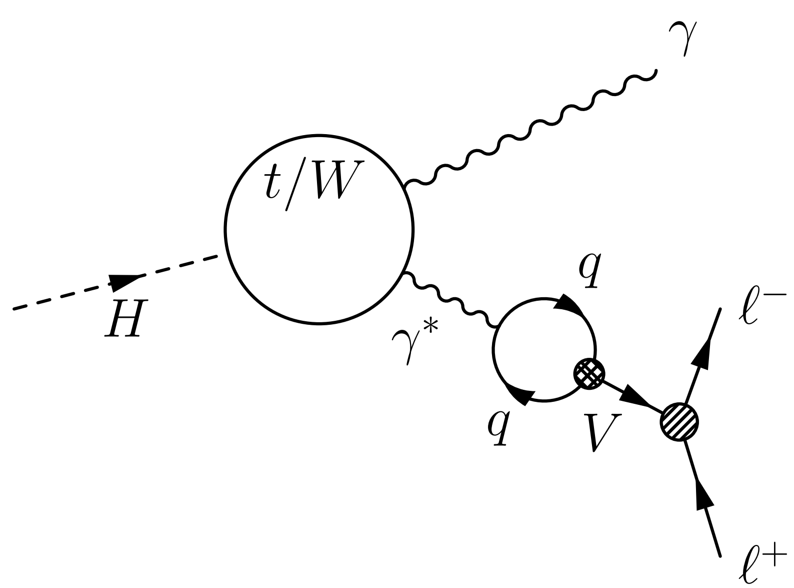
Light-Flavor Yukawa Couplings



Light-Flavor Yukawa Couplings

- Yukawa couplings are among the most arbitrary in the electroweak symmetry breaking mechanism.
- Light-flavor lepton/quark couplings to the Higgs boson provide useful insights to the nature of the Yukawa couplings.
  - **Universal or non-universal Higgs couplings to fermions.**
  - Decays to a quarkonium & γ (“exclusive approach”; cf. E.Stamou’s talk) may offer sensitivity to both magnitude & sign of the Yukawa couplings.
  - Probe for physics beyond the Standard Model.



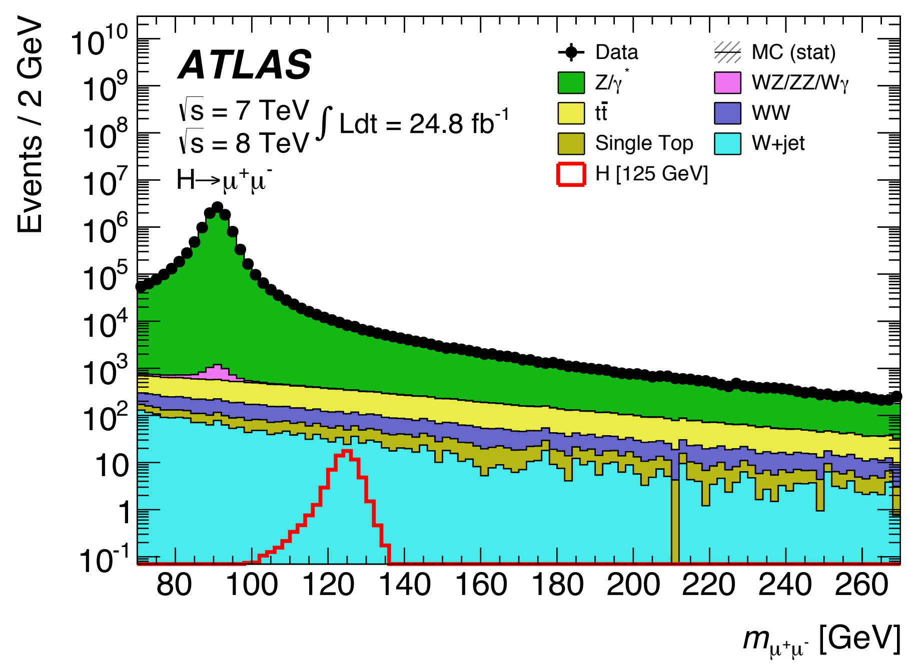


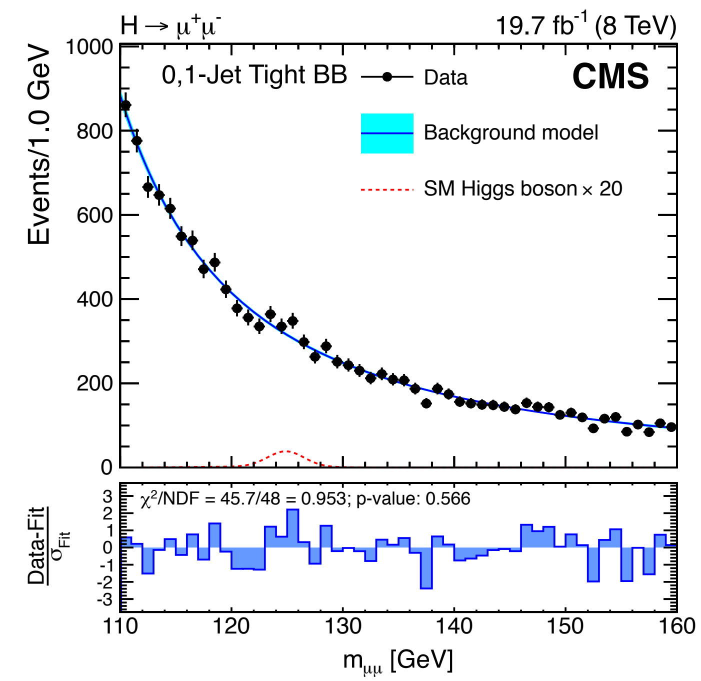
arXiv:1507.0303

$H \rightarrow \mu\mu$

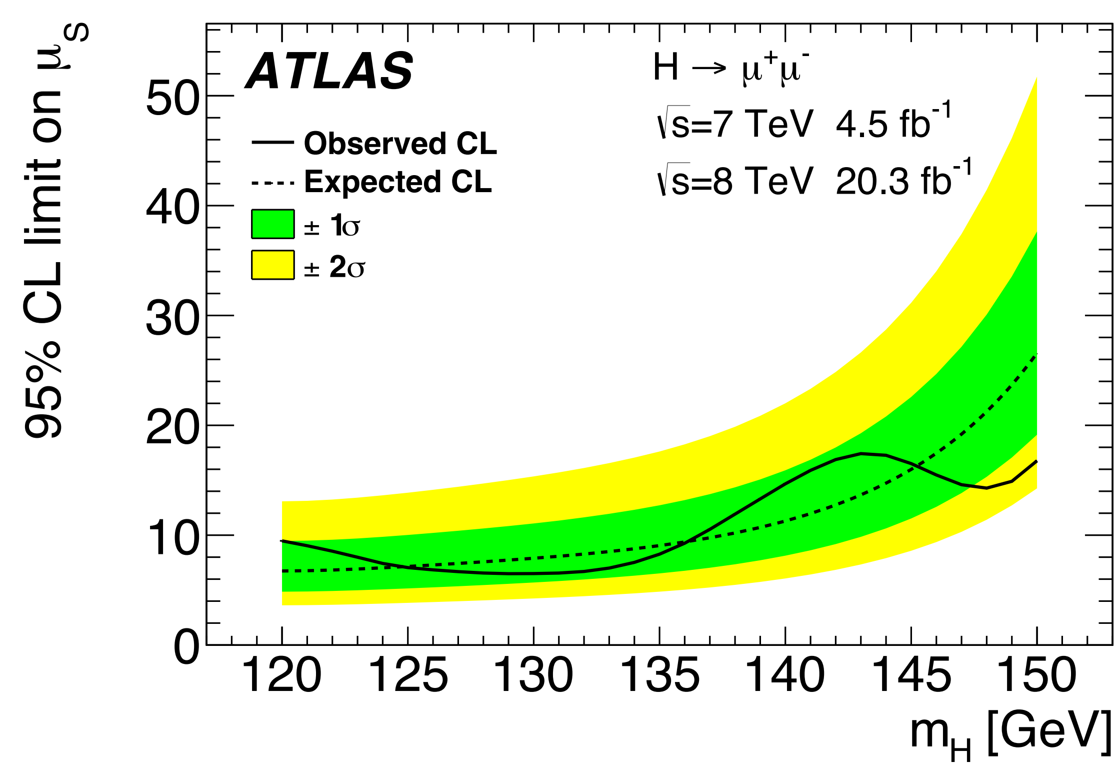
Phys. Lett. B 738 (2014) 68, Phys. Lett. B 744 (2015) 184

- ggF & VBF categories
- Analytic BG modeling similar to $\gamma\gamma$ channel.





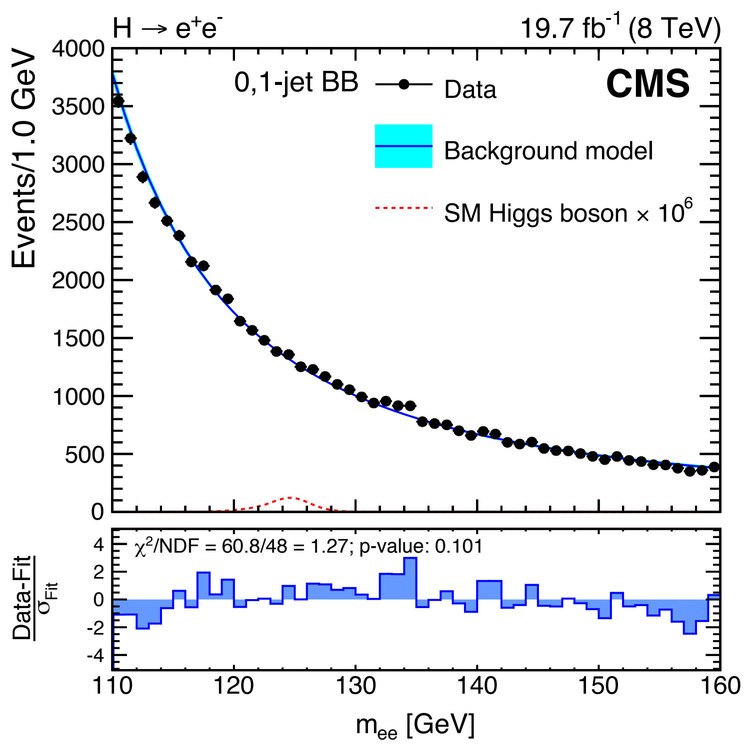
- **$\sigma \times BR < 7.0$ obs (7.2 exp) $(\sigma \times BR)_{SM}$** [ATLAS], **7.4 (6.5) $(\sigma \times BR)_{SM}$** [CMS]
- **Confirmed non-universal couplings** (~~same as the τ-lepton~~).
- Need HL-LHC data for measuring the SM $H \rightarrow \mu\mu$ process (Adrian Perieanu's talk).

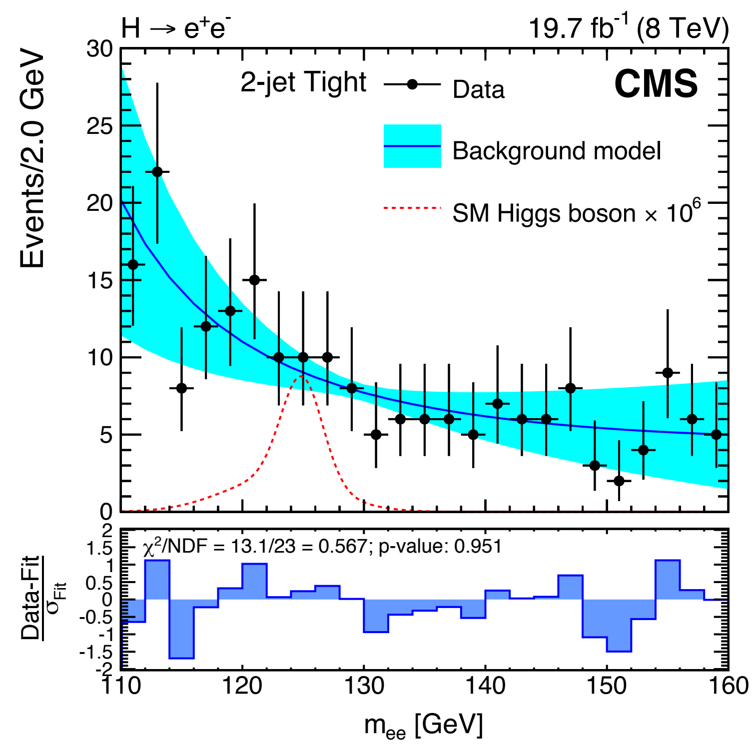


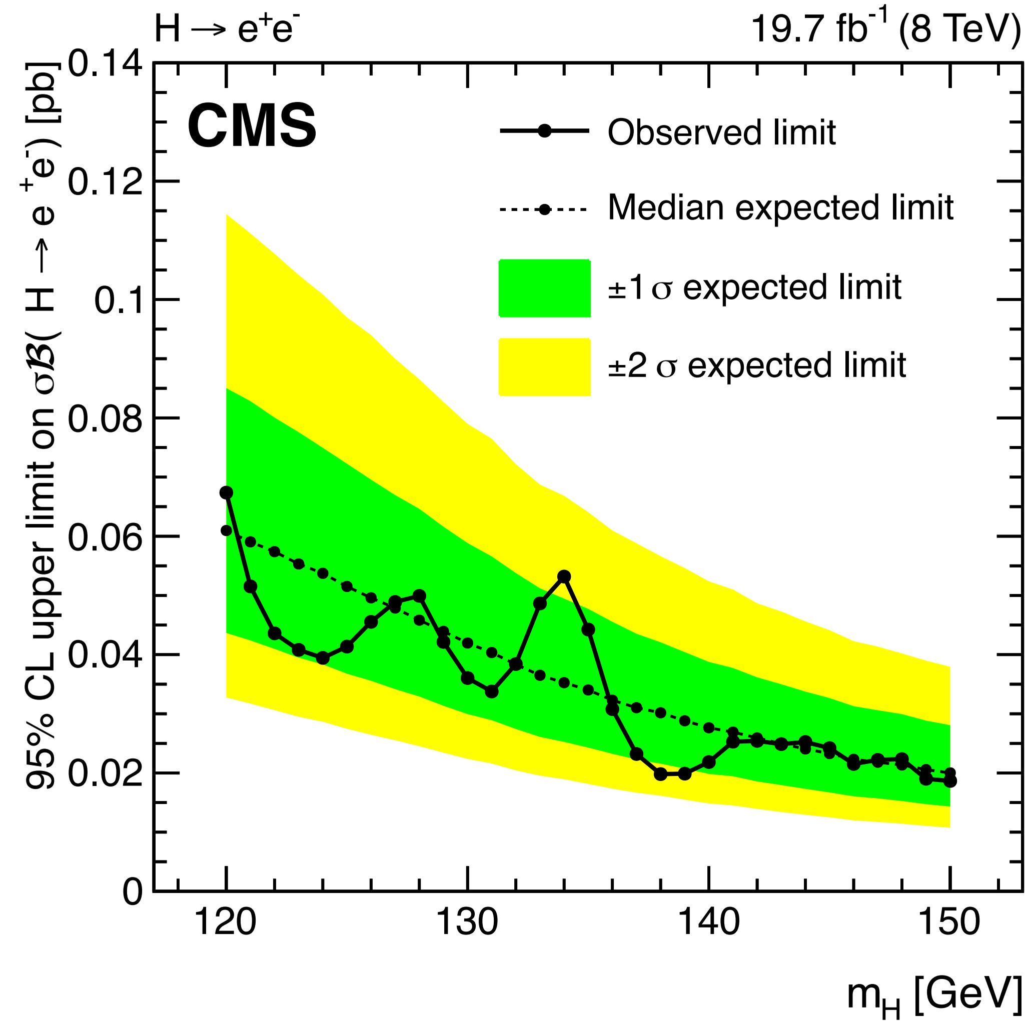
H→ee

Phys. Lett. B 744 (2015) 184

- SM BR(H→ee)~5×10^{-9}.
- *Inaccessible at the LHC.*





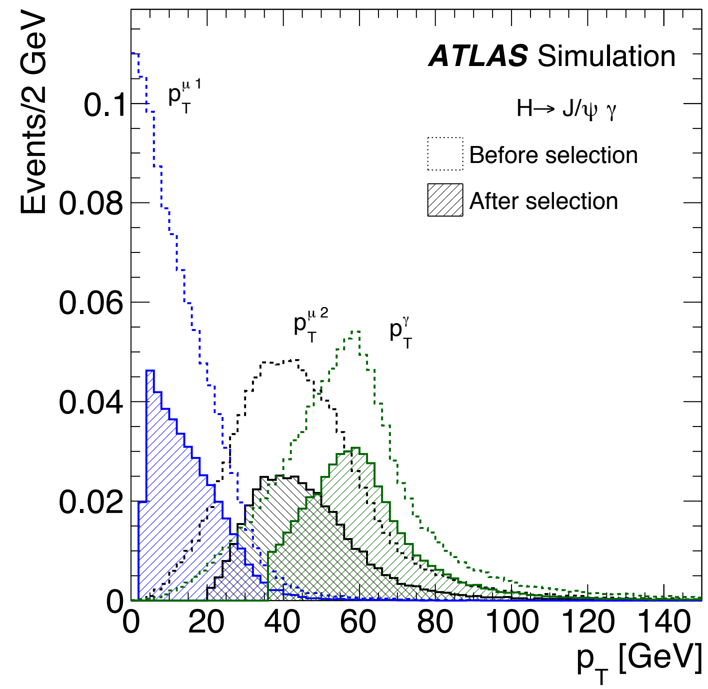


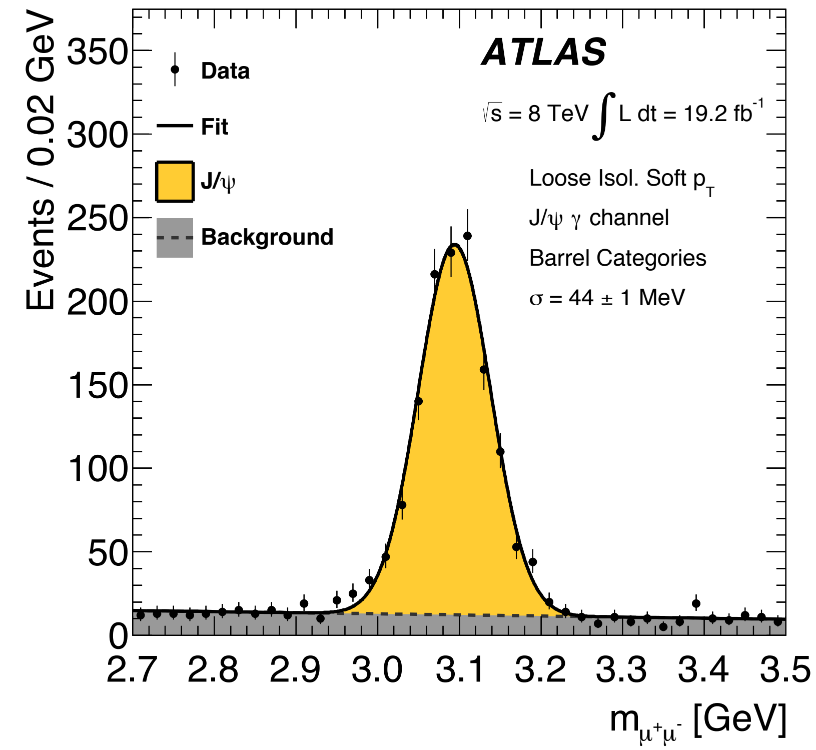
- ggF & VBF categories. Using analytic BG modeling.
- No excess from SM expectation. BR(H→ee)<1.9×10^{-3} @95% CL.
- Another confirmation of non-universal couplings of the Higgs boson.

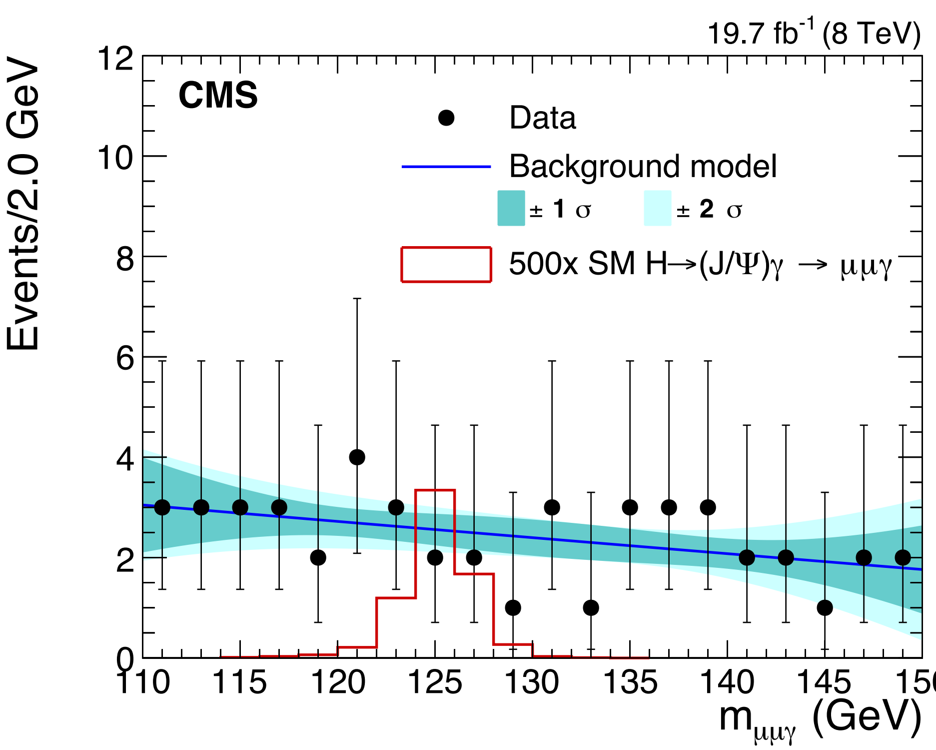
H/Z→J/ψ γ, Υ(nS)γ

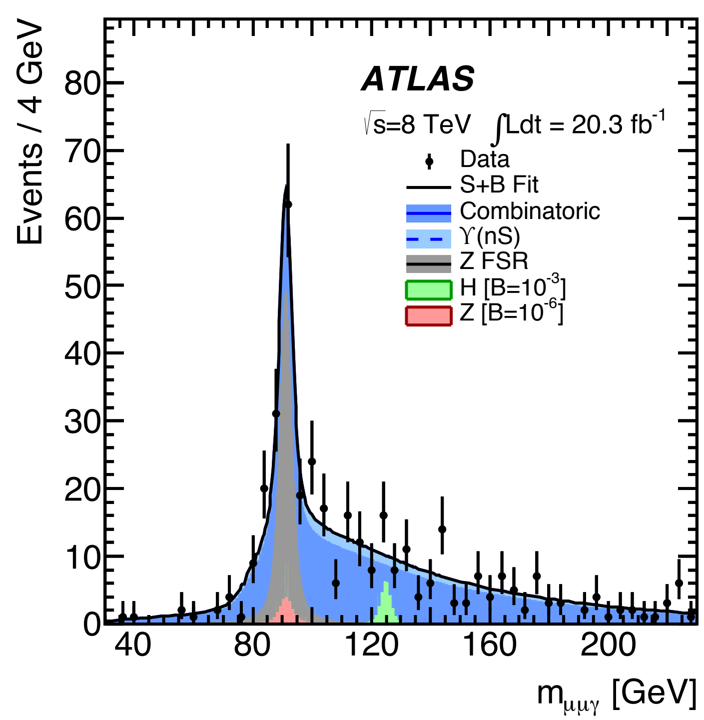
Phys. Rev. Lett. 114 (2015) 121801, arXiv:1507.0303

- SM BR(H→J/ψγ)=2.8×10^{-6},
  BR(H→Υ(nS)γ)=(6.1,2.0,2.4)×10^{-10}
- Considered $\mu^+\mu^-\gamma$ final state.
- Signal efficiency [ATLAS]:
  22% for J/ψγ, 28% for Υ(nS)γ
- $m_{\mu\mu\gamma}$ ($m_{\mu\mu}$) resolution [ATLAS]:
  1.2-1.8% (1.4-2.4%)





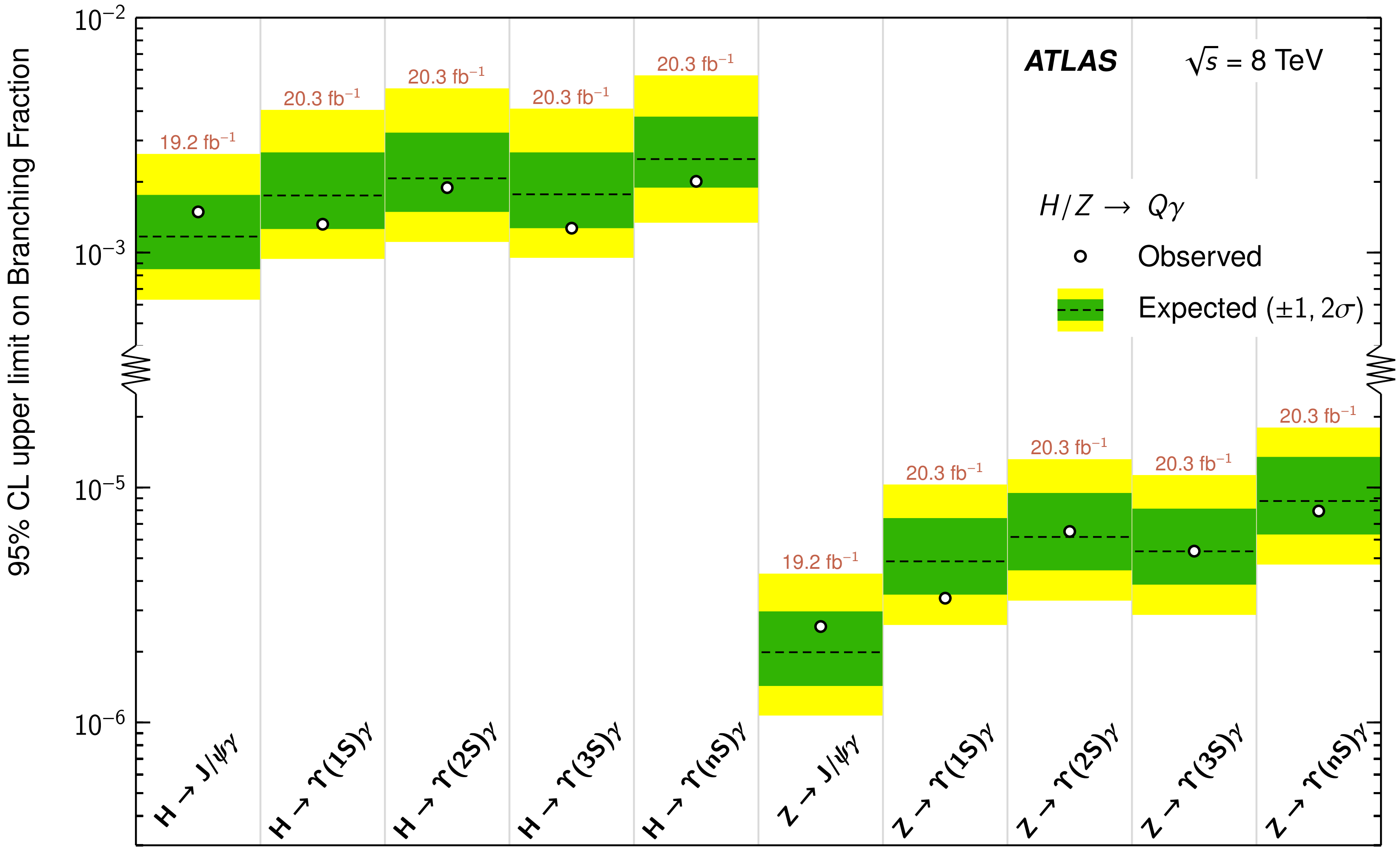




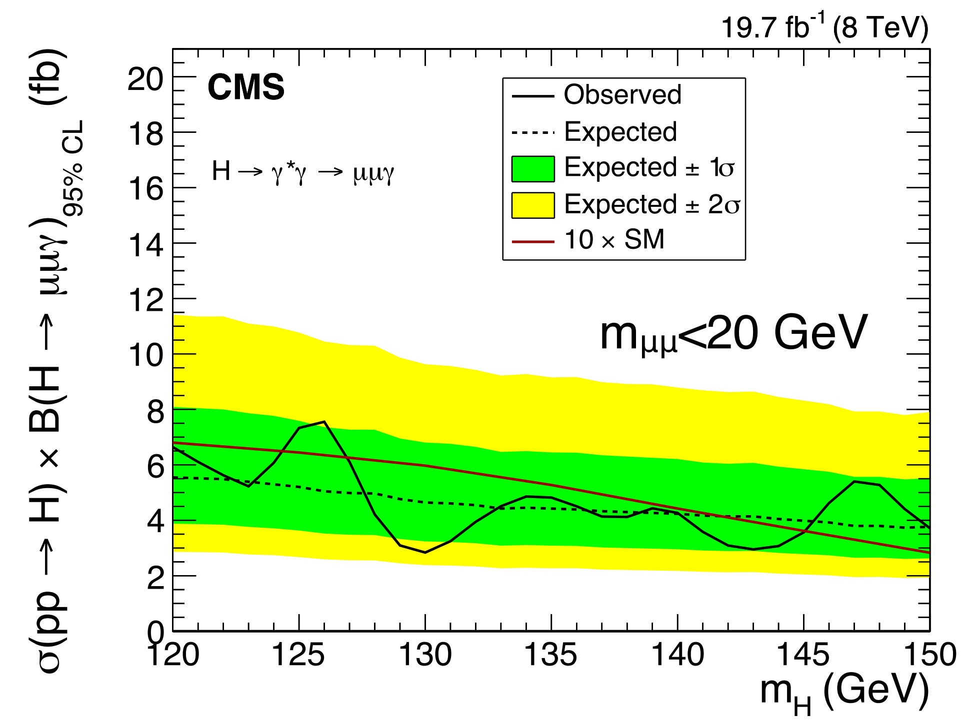
- Simultaneous fits are performed to $m_{\mu\mu\gamma}$ & $m_{\mu\mu}$ for ATLAS and to $m_{\mu\mu\gamma}$ for CMS.
- No significant H/Z→$\mathcal{Q}$γ signals are observed.

H/Z→J/ψ γ, ϒ(nS)γ

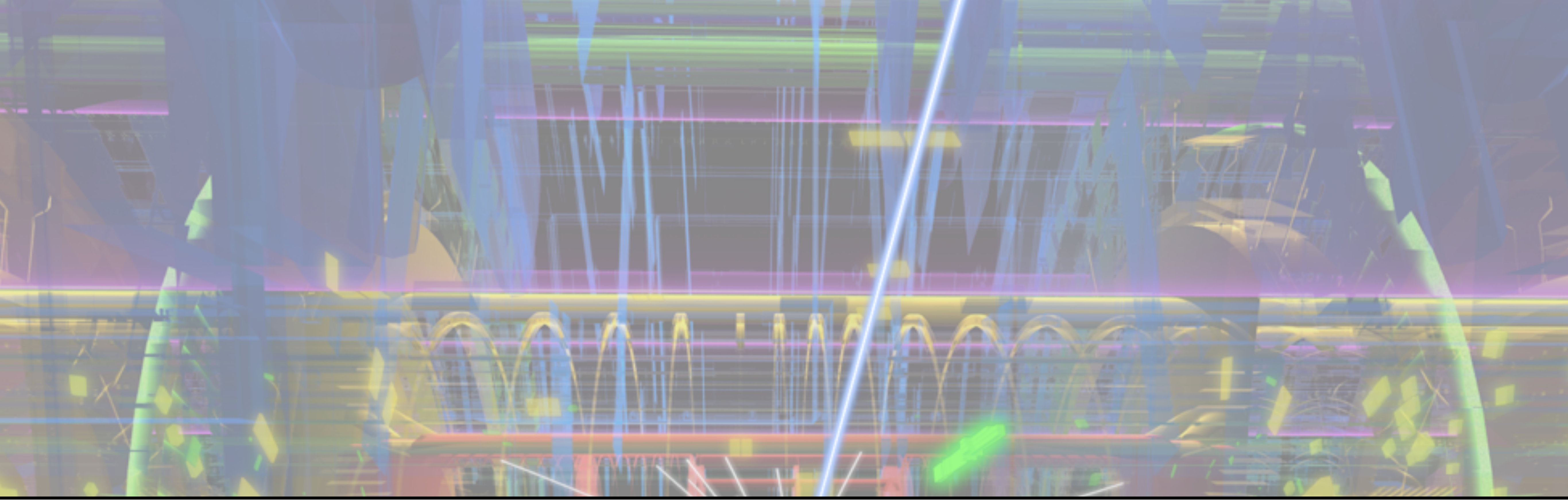
Phys. Rev. Lett. 114 (2015) 121801, arXiv:1507.0303



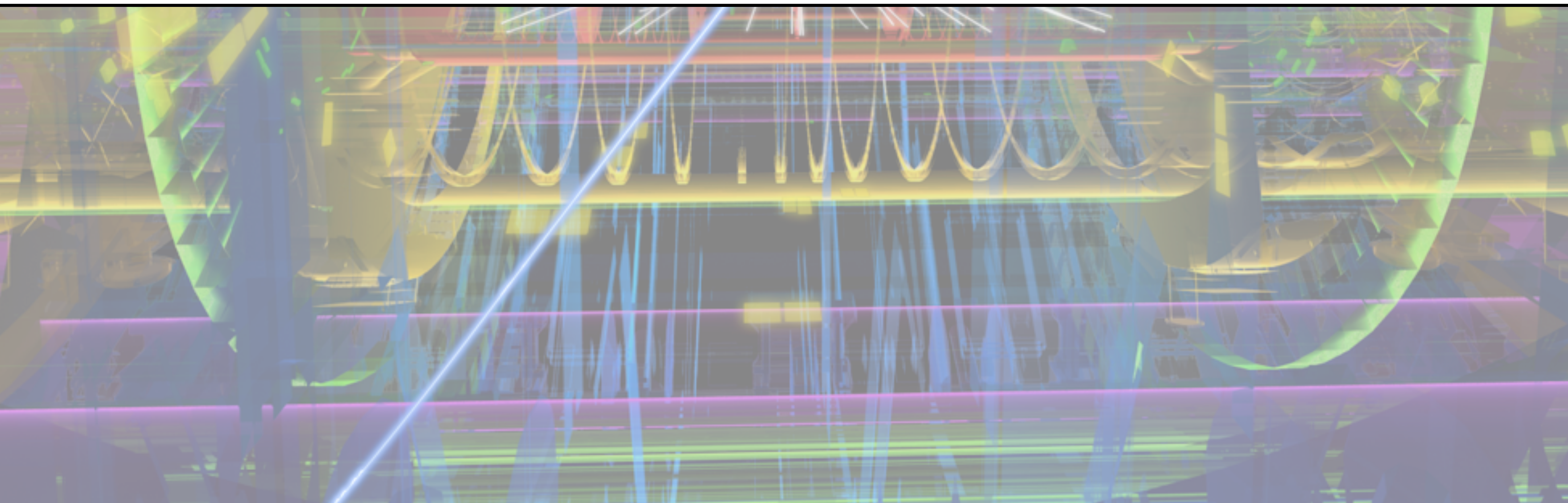
- First LHC searches for H/Z→$\mathcal{Q}$γ.
- **BR(H→J/ψγ)<1.5×10^{-3}@95%CL [ATLAS, CMS]**



- Interesting analyses, but challenging for the SM H→J/ψγ, ϒ(nS)γ due to the very low expected yields, even at the HL-LHC.
- However, **the method can also be used for general H→$\mathcal{Q}$γ, where $\mathcal{Q}$ is a meson from light quarks. It provides interesting programs for BSM search.**

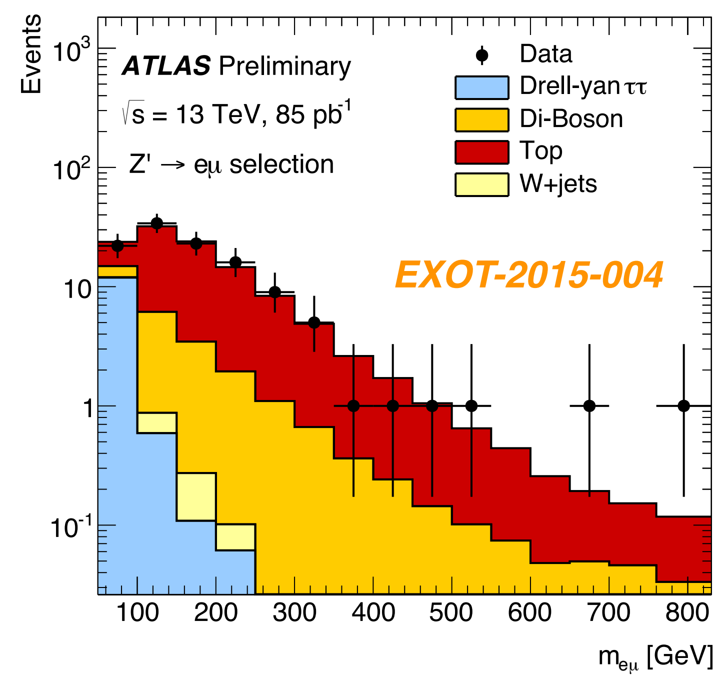


Prospects for Run-2

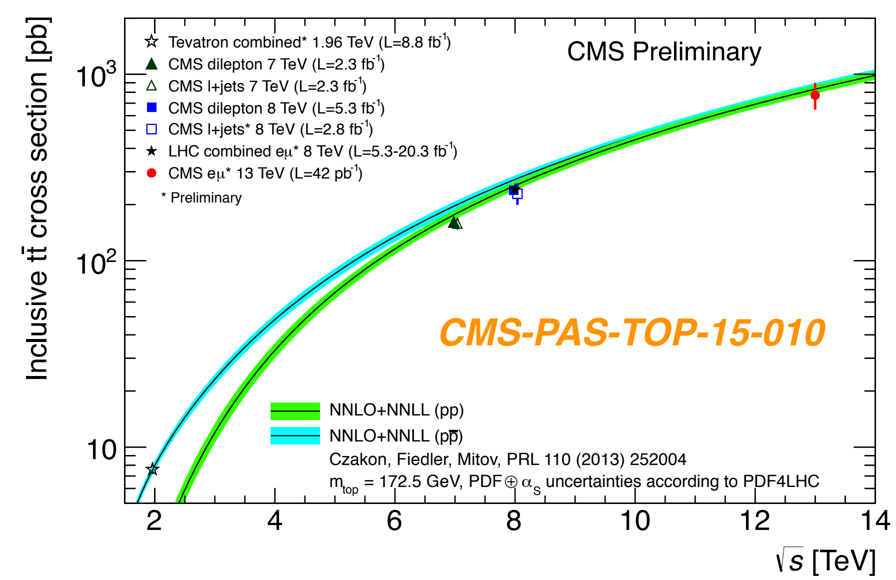


Run-2 Prospects

- Lepton flavor violation
  - CMS ($H \to \mu\tau_e$, $\mu\tau_h$, etc.): New τ-reconstruction algorithm developed for Run-2.
  - $Z' \to e\mu$: Already started looking at $m_{e\mu}$ distribution. Will make use of the significantly increased cross section in 13 TeV.



- Flavor changing neutral current
  - Will benefit from enhanced production of the ttbar process. First ttbar cross section measurements were performed w/ 13 TeV data by ATLAS/CMS (***ATLAS-CONF-2015-033, CMS-PAS-TOP-15-010***).



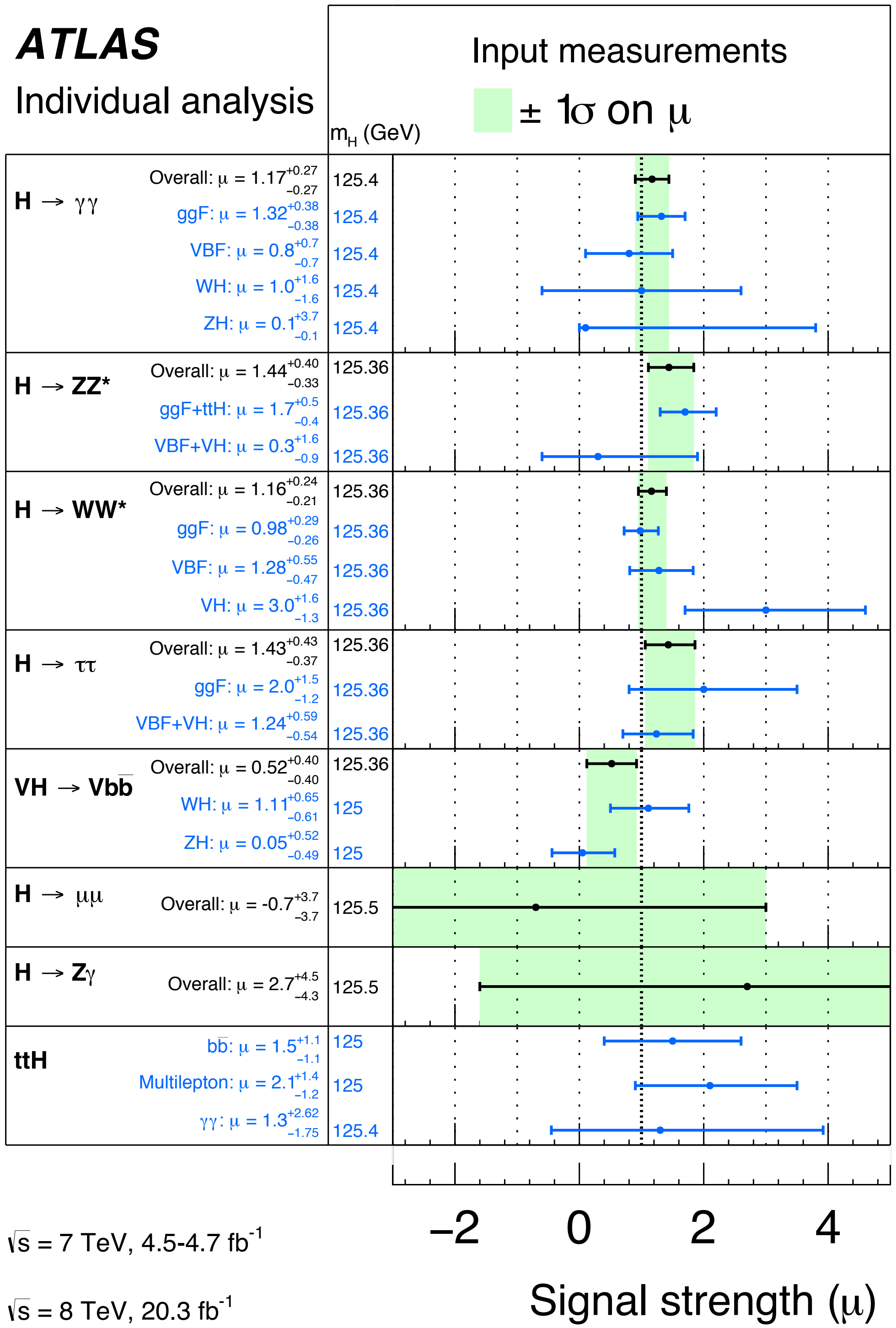
Analyses are progressing rapidly with the Run-2 data.

Summary

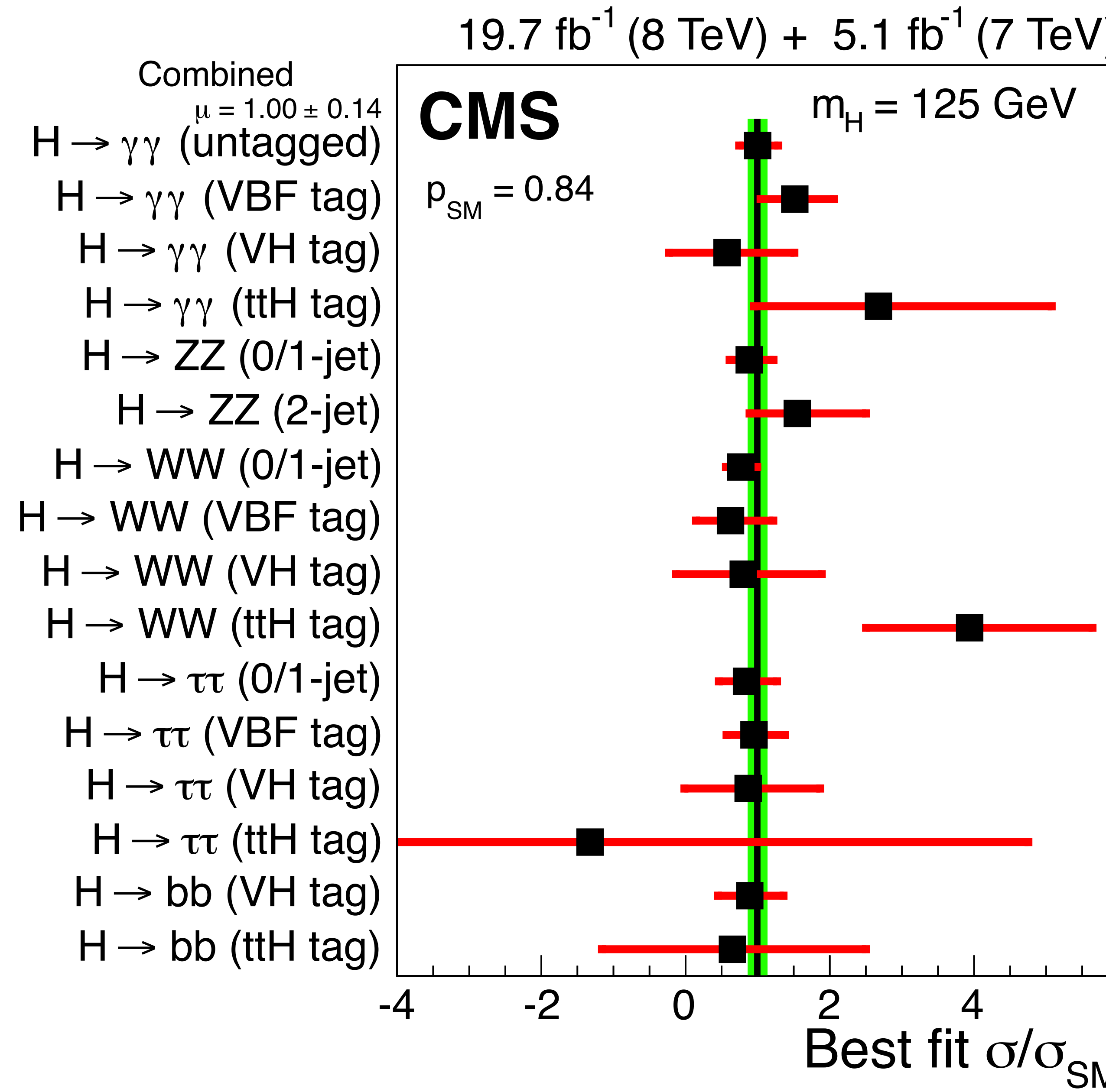
- **LHC provides rich program for flavor studies.**
- Understanding the Yukawa couplings of the Higgs boson is crucial after the discovery of a Higgs boson, and **there could be flavor violating processes in the electroweak sector**.
- No observation of charged lepton flavor violation so far. However, there is **2.4σ (1.3σ) excess in the $H \to \mu\tau$ from CMS (ATLAS)**. Further investigations are ongoing.
- We had fruitful results regarding the light-flavor Yukawa couplings as well. No sign of deviations from the Standard Model so far.
- **Analyses are rapidly progressing with Run-2 data!!**

backups

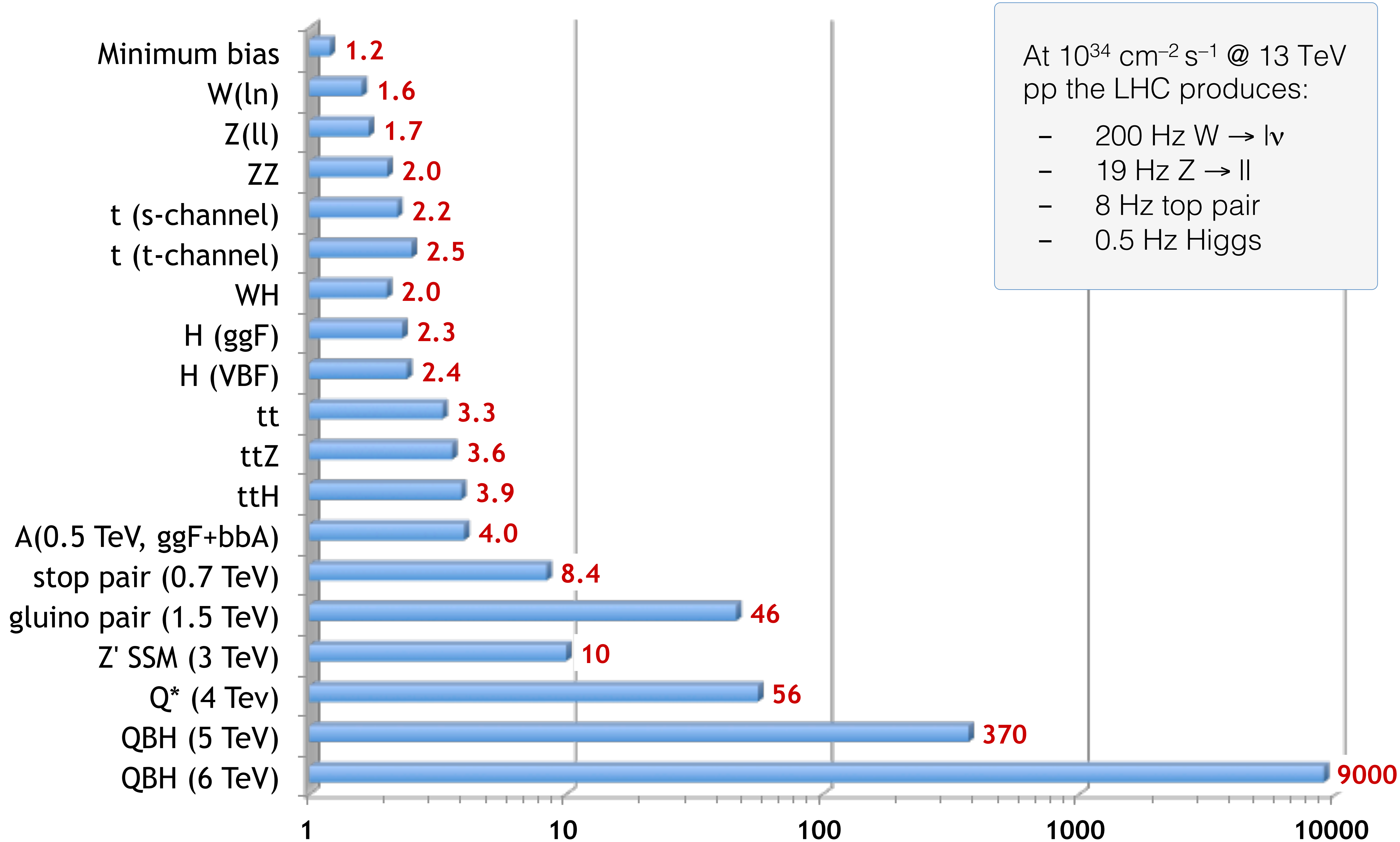
Higgs Signal Strength



arXiv:1507.04548, Eur. Phys. J. C 75 (2015) 212



13 vs 8 TeV



At 10^{34} cm^{-2} s^{-1} @ 13 TeV pp the LHC produces:

- 200 Hz $W \to l\nu$
- 19 Hz $Z \to ll$
- 8 Hz top pair
- 0.5 Hz Higgs

H→μτ Search

Phys. Lett. B 749 (2015) 337, arXiv:1508.03372

- Some differences in the kinematic selections ($\Delta\phi_{\mu,\tau}$, $\Delta\eta_{\mu,\tau}$) & discriminating variable (mass reconstruction w/ collinear approximation vs Missing Mass Calculator).

CMS

Variable [GeV]	$H \to \mu\tau_e$ 0-jet	$H \to \mu\tau_e$ 1-jet	$H \to \mu\tau_e$ 2-jet	$H \to \mu\tau_h$ 0-jet	$H \to \mu\tau_h$ 1-jet	$H \to \mu\tau_h$ 2-jet
$p_T^\mu >$	50	45	25	45	35	30
$p_T^e >$	10	10	10	—	—	—
$p_T^\tau >$	—	—	—	35	40	40
$M_T^e <$	65	65	25	—	—	—
$M_T^\mu >$	50	40	15	—	—	—
$M_T^\tau <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^\mu - \vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^e - \vec{p}_T^\mu} >$	2.7	1.0	—	—	—	—

ATLAS

Cut	SR1	SR2
$p_T(\mu)$	>26 GeV	>26 GeV
$p_T(\tau_{had})$	>45 GeV	>45 GeV
$m_T(\mu, E_T^{miss})$	>40 GeV	<40 GeV
$m_T(\tau_{had}, E_T^{miss})$	<30 GeV	<60 GeV
$\lvert\eta(\mu) - \eta(\tau_{had})\rvert$	<2	<2
N_{jet}	–	–
N_{b-jet}	0	0

H→μτ Channel (CMS)

Phys. Lett. B 749 (2015) 337

Variable	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_T^{\mu} >$	50	45	25	45	35	30
$p_T^{e} >$	10	10	10	—	—	—
$p_T^{\tau} >$	—	—	—	35	40	40
$M_T^{e} <$	65	65	25	—	—	—
$M_T^{\mu} >$	50	40	15	—	—	—
$M_T^{\tau} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^{\mu} - \vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^{e} - \vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^{e} - \vec{p}_T^{\mu}} >$	2.7	1.0	—	—	—	—

H→μτ Yields (CMS)

Phys. Lett. B 749 (2015) 337

Sample	$H \to \mu\tau_h$			$H \to \mu\tau_e$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
misidentified leptons	1770 ± 530	377 ± 114	1.8 ± 1.0	42 ± 17	16 ± 7	1.1 ± 0.7
$Z \to \tau\tau$	187 ± 10	59 ± 4	0.4 ± 0.2	65 ± 3	39 ± 2	1.3 ± 0.2
ZZ, WW	46 ± 8	15 ± 3	0.2 ± 0.2	41 ± 7	22 ± 4	0.7 ± 0.2
$W\gamma$	—	—	—	2 ± 2	2 ± 2	—
$Z \to$ ee or $\mu\mu$	110 ± 23	20 ± 7	0.1 ± 0.1	1.6 ± 0.7	1.8 ± 0.8	—
$t\bar{t}$	2.2 ± 0.6	24 ± 3	0.9 ± 0.5	4.8 ± 0.7	30 ± 3	1.8 ± 0.4
$t\bar{t}$	2.2 ± 1.1	13 ± 3	0.5 ± 0.5	1.9 ± 0.2	6.8 ± 0.8	0.2 ± 0.1
SM H background	7.1 ± 1.3	5.3 ± 0.8	1.6 ± 0.5	1.9 ± 0.3	1.6 ± 0.2	0.6 ± 0.1
sum of backgrounds	2125 ± 530	513 ± 114	5.4 ± 1.4	160 ± 19	118 ± 9	5.6 ± 0.9
LFV Higgs boson signal	66 ± 18	30 ± 8	2.9 ± 1.1	23 ± 6	13 ± 3	1.2 ± 0.3
data	2147	511	10	180	128	6

H→μτ Channel (ATLAS)

arXiv:1508.03372

Cut	SR1	SR2	WCR	TCR
$p_T(\mu)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_T(\tau_{had})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$m_T(\mu, E_T^{miss})$	>40 GeV	<40 GeV	>60 GeV	–
$m_T(\tau_{had}, E_T^{miss})$	<30 GeV	<60 GeV	>40 GeV	–
$\lvert\eta(\mu) - \eta(\tau_{had})\rvert$	<2	<2	<2	<2
N_{jet}	–	–	–	>1
N_{b-jet}	0	0	0	>0

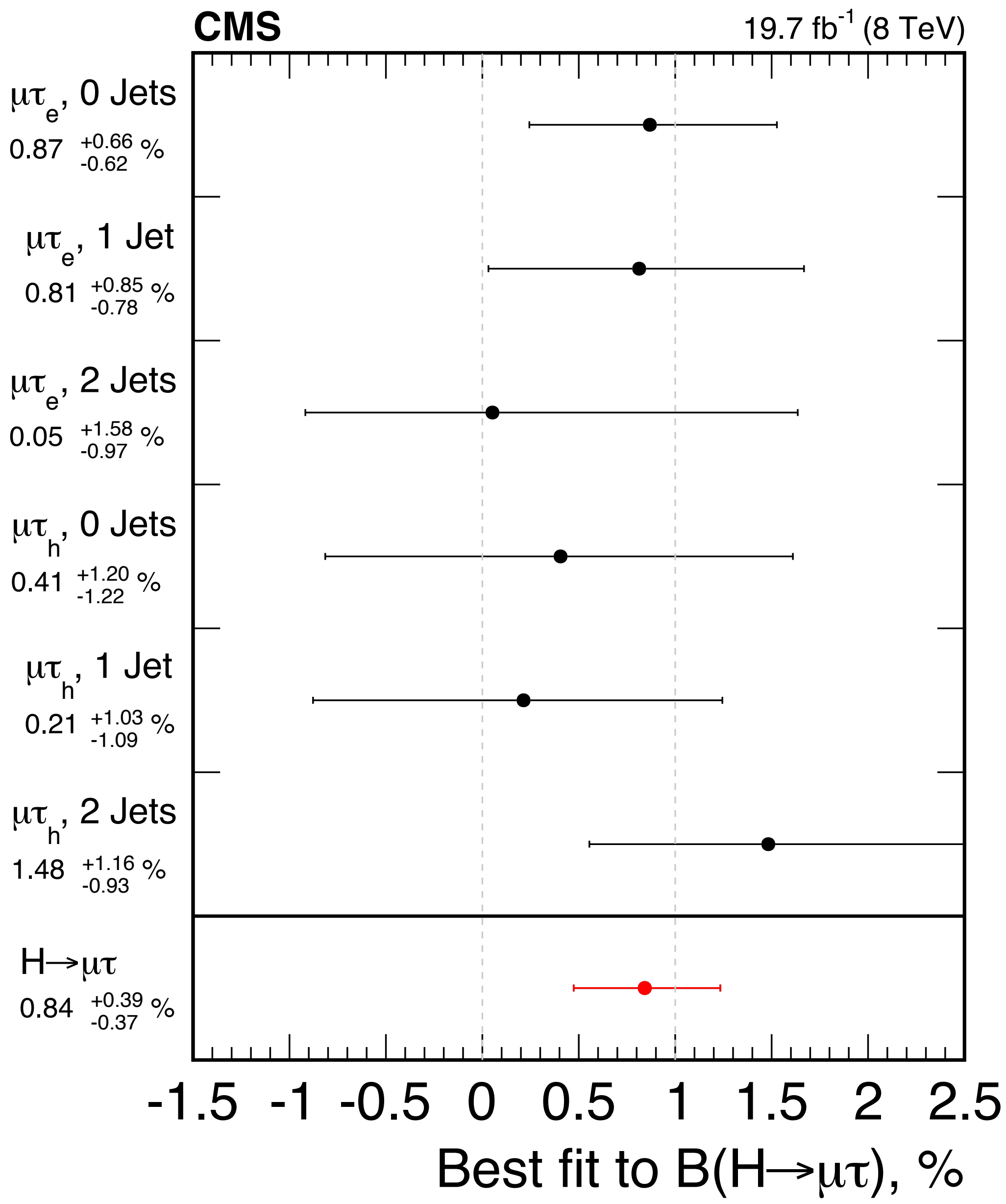
$H \to \mu\tau$ Yields (ATLAS)

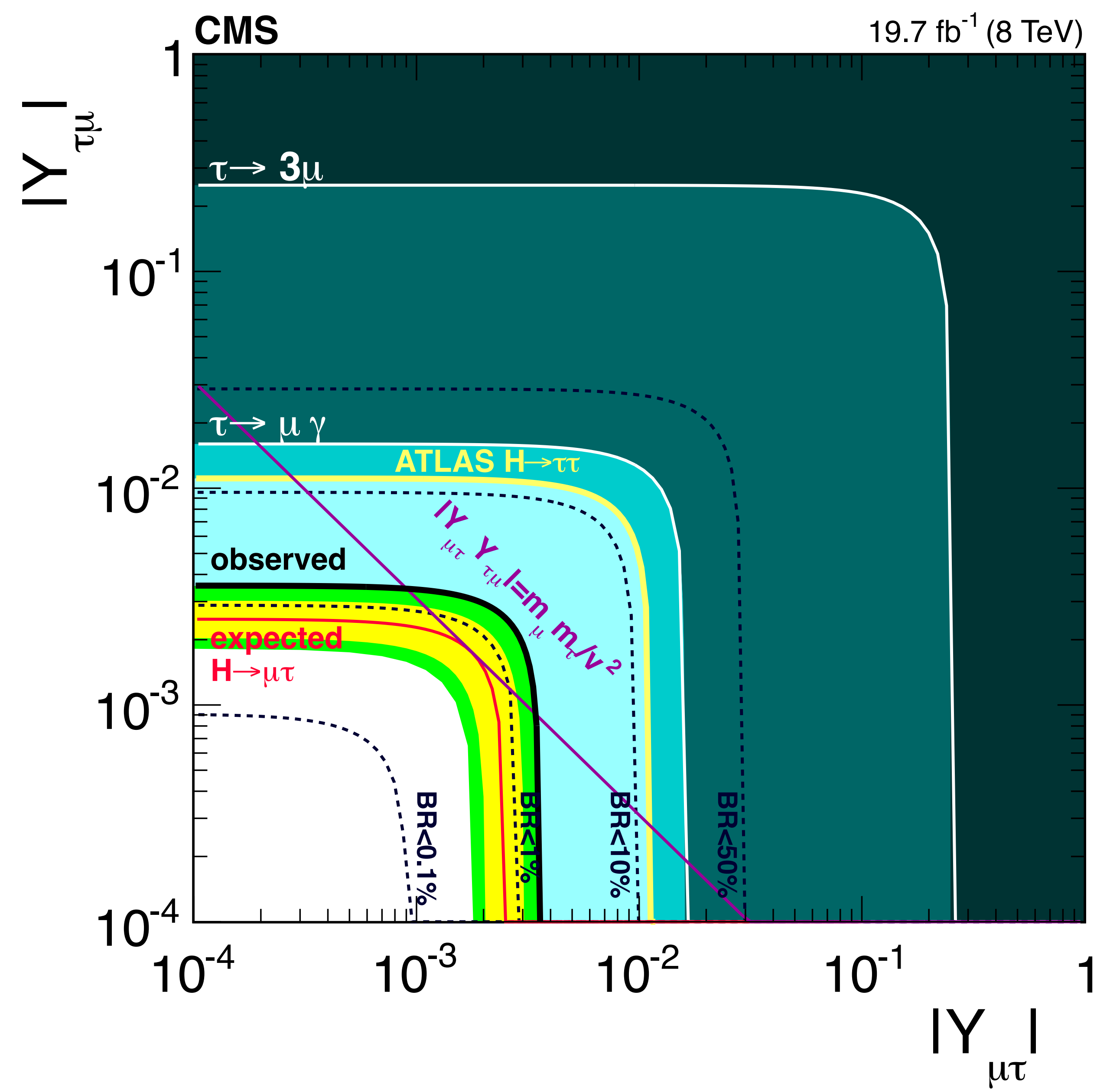
arXiv:1508.03372

	SR1	SR2
Signal	69.1 ± 0.8 ± 9.2	48.5 ± 0.8 ± 7.5
$Z \to \tau\tau$	133.4 ± 6.9 ± 9.1	262.6 ± 9.7 ± 18.6
W+jets	619 ± 54 ± 55	406 ± 42 ± 34
Top	39.5 ± 5.3 ± 4.7	19.6 ± 3.1 ± 3.3
Same–Sign events	335 ± 19 ± 47	238 ± 16 ± 34
$VV + Z \to \mu\mu$	90 ± 21 ± 16	81 ± 22 ± 17
$H \to \tau\tau$	6.82 ± 0.21 ± 0.97	13.7 ± 0.3 ± 1.9
Total background	1224 ± 62 ± 63	1021 ± 51 ± 49
Data	1217	1075

H→μτe,μτh Results

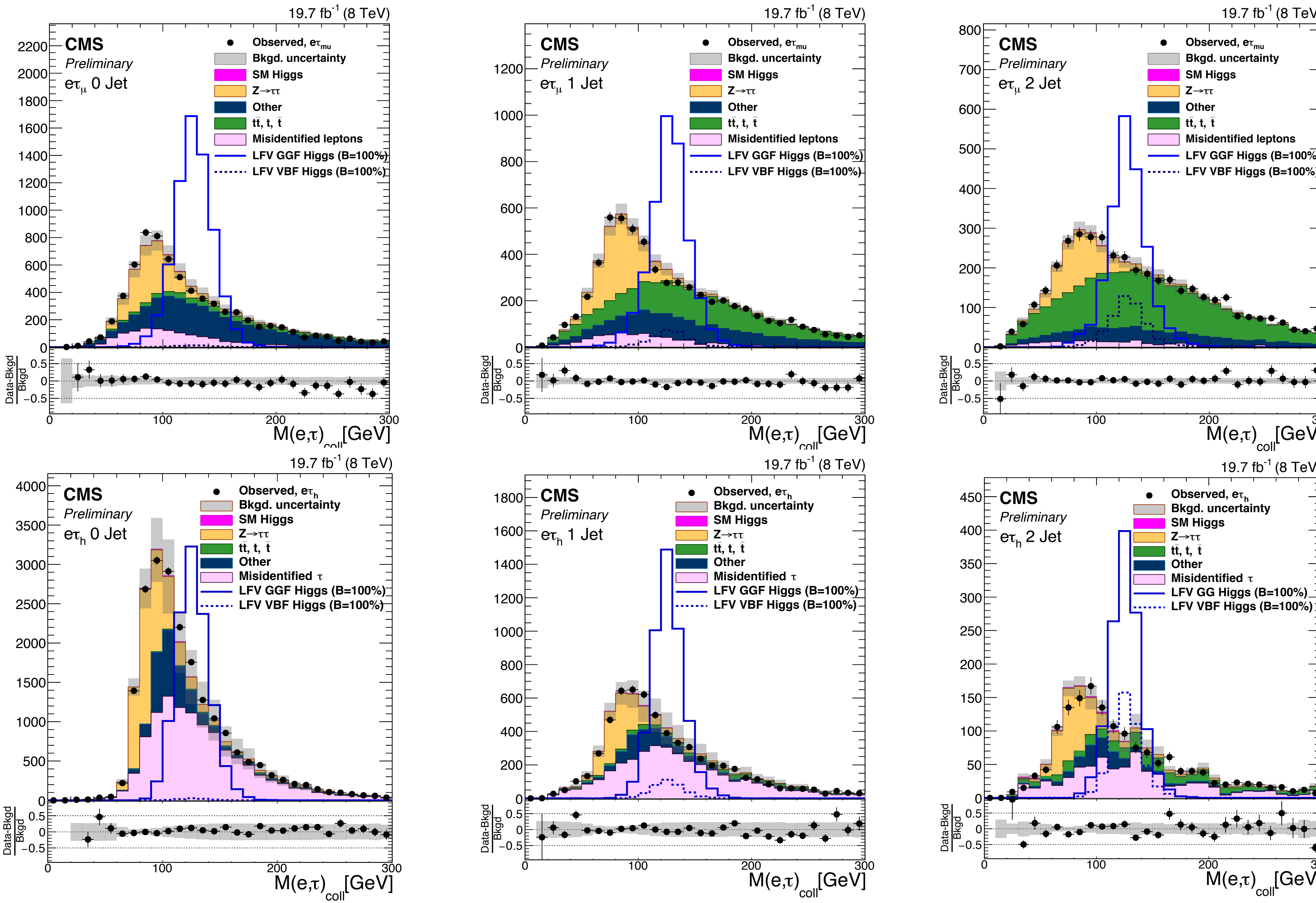
Phys. Lett. B 749 (2015) 337





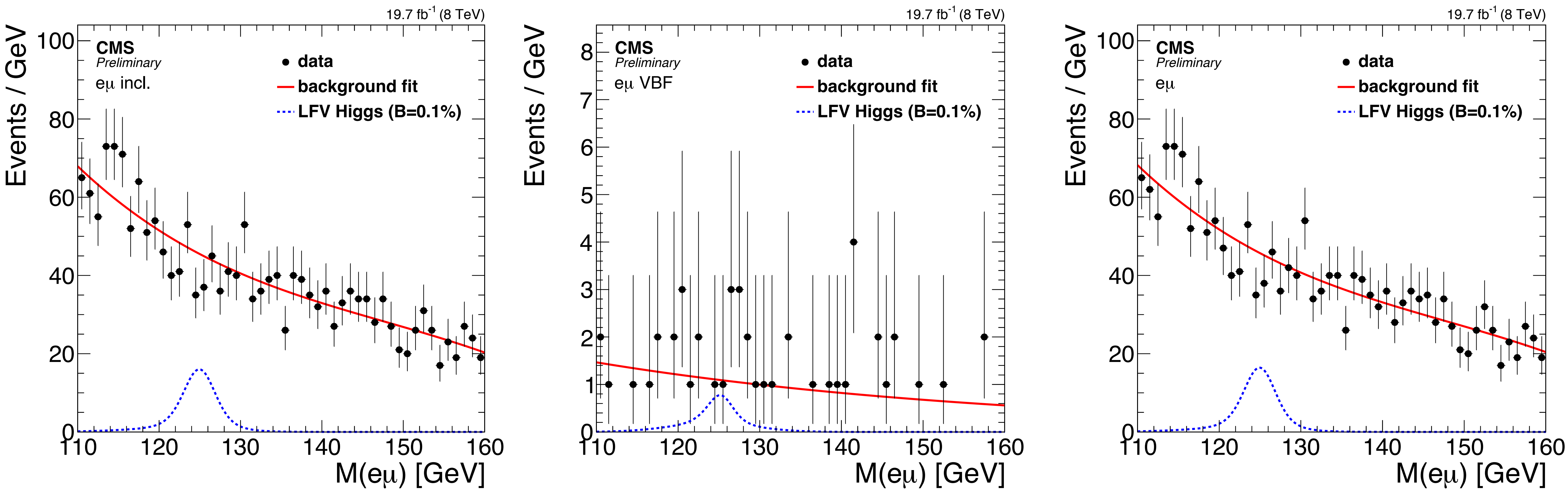
$H \to e\tau_\mu, e\tau_h$ Channels

CMS-PAS-HIG-14-040



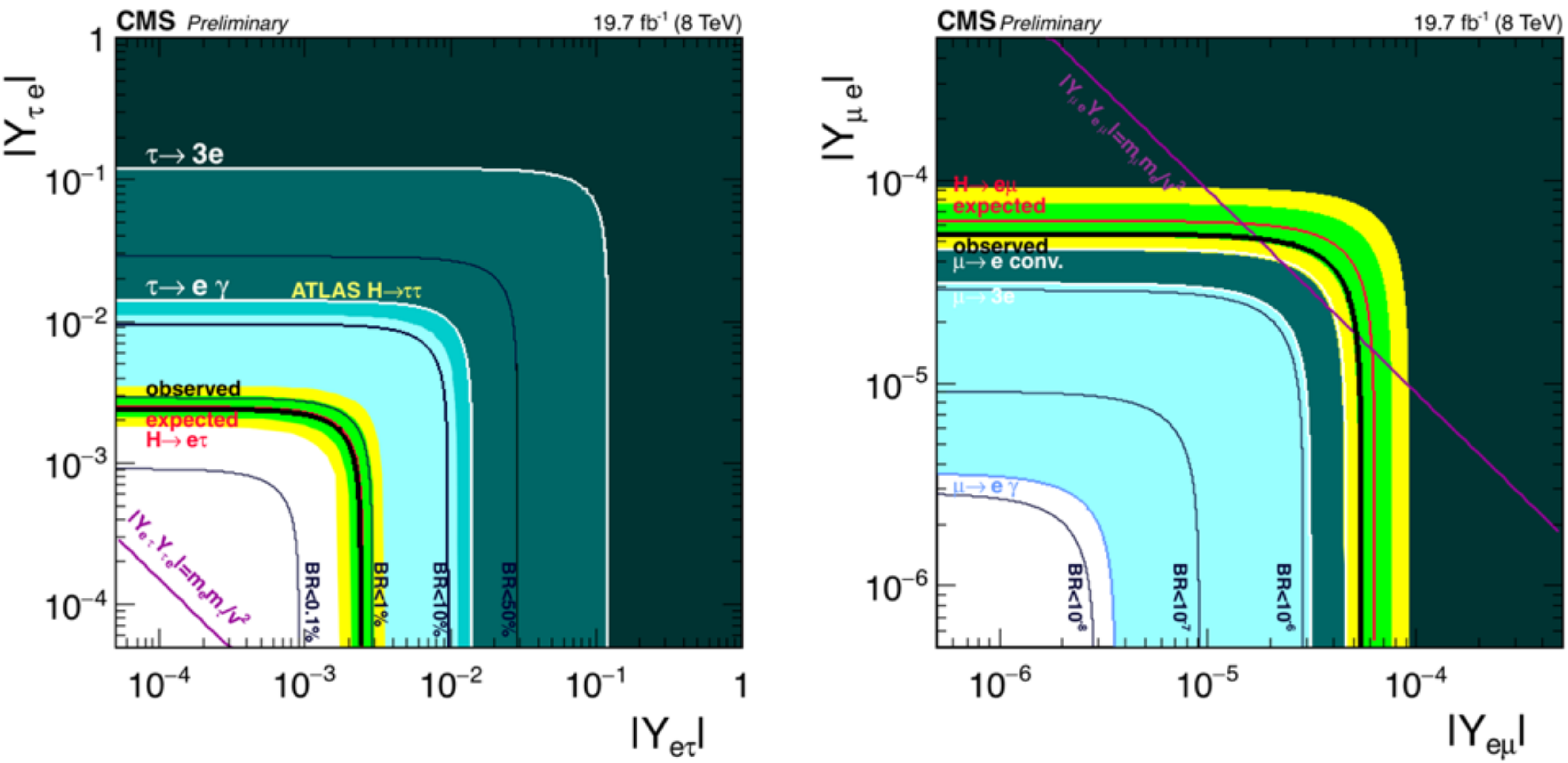
H→eμ Channel

CMS-PAS-HIG-14-040



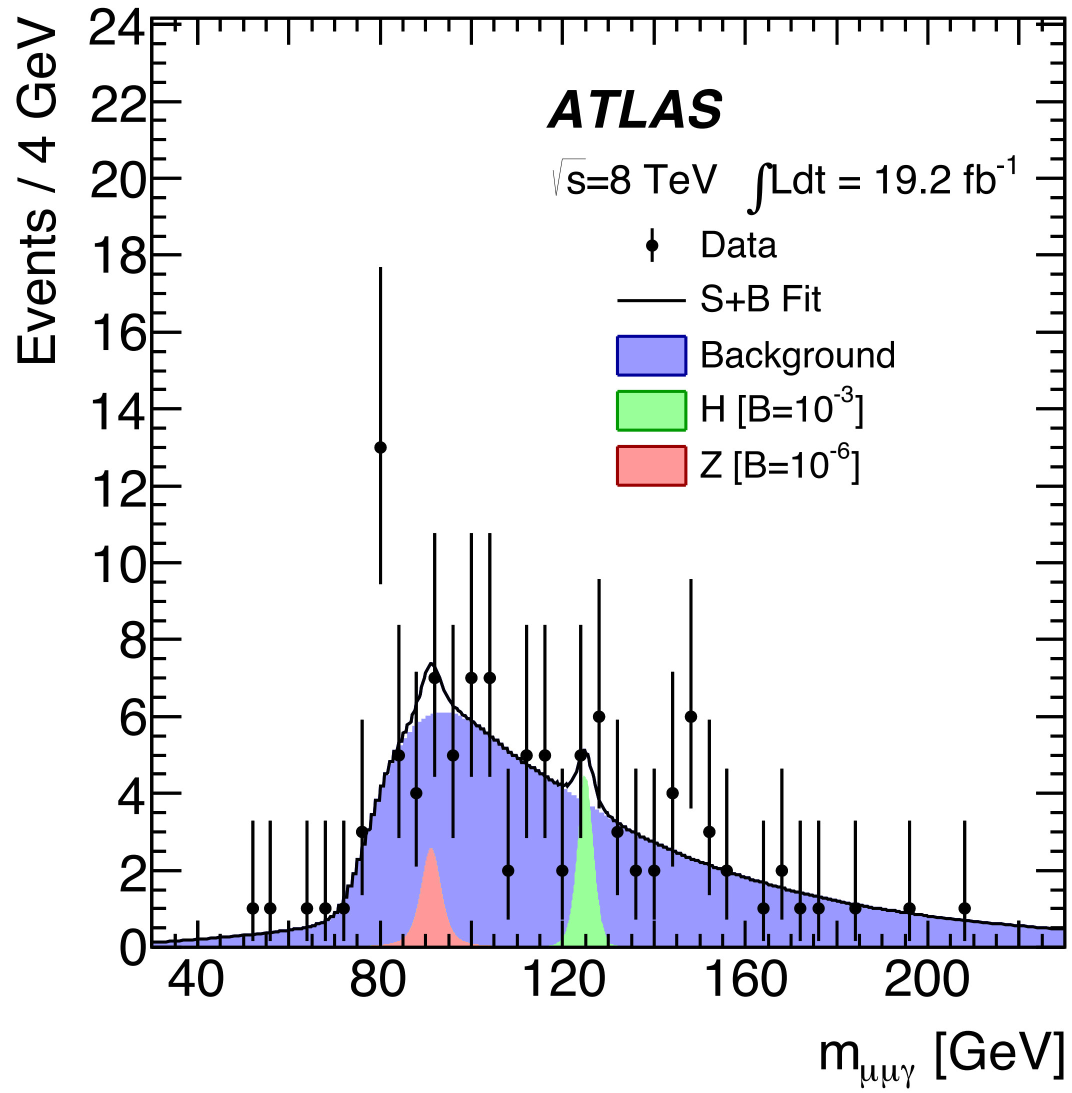
H→eτ,eμ Results

CMS-PAS-HIG-14-040



$H/Z \to J/\psi\ \gamma,\ \Upsilon(nS)\gamma$

Phys. Rev. Lett. 114 (2015) 121801



$H/Z \to J/\psi\ \gamma$, $\Upsilon(nS)\gamma$

Phys. Rev. Lett. 114 (2015) 121801, arXiv:1507.0303

	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)$ [10^{-3}]					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

$BR(H \to J/\psi\gamma) < 1.5 \times 10^{-3}$ for CMS