Search for non-standard and rare decays of the Higgs boson with the ATLAS detector

ICHEP

2016-08-05

Chicago

Davide Gerbaudo

IFAE Barcelona

on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

IFAE

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

Overview

Motivations

Exotic decays

- Lepton Flavor Violation in H decays
- $H \rightarrow$ invisible
  (see talk by Monica Trovatelli)
- $H \rightarrow$ light scalar $\rightarrow 4b, \mu\mu\tau\tau, 4\ell$
  (see talk by Lidija Zivkovic)

Rare decays

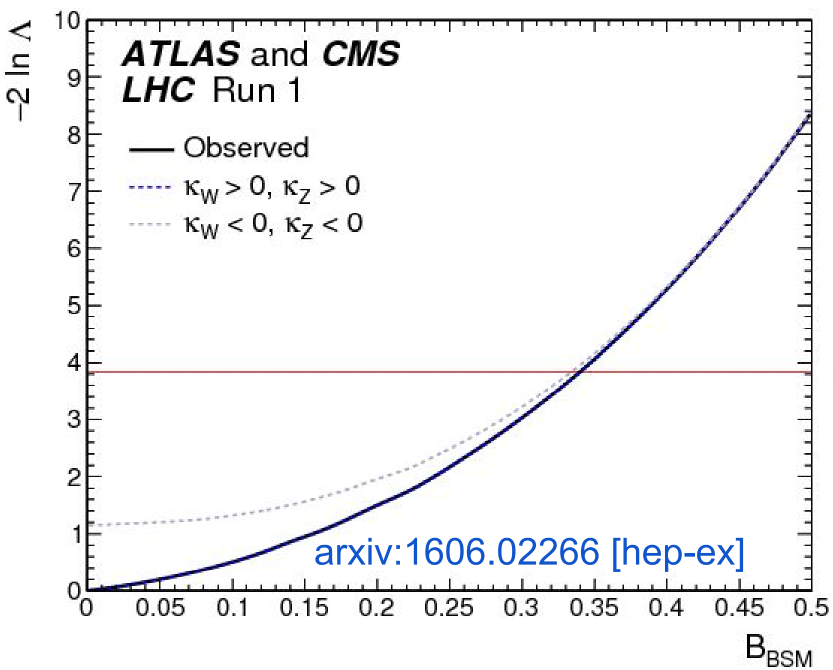
- $H \rightarrow \mu\,\mu$
  (see talk by Christian Grefe)
- $H \rightarrow Z\,\gamma$
- H and $Z \rightarrow J/\Psi\,\gamma, \Upsilon(nS)\gamma$
- H and $Z \rightarrow \varphi\gamma$ **new!**

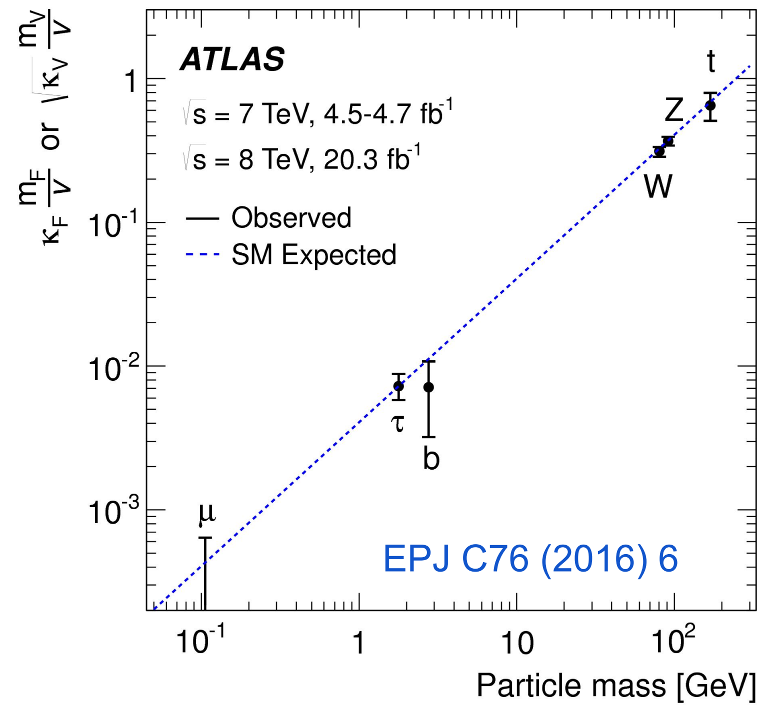
Motivations

- Although the 125GeV boson looks like the SM Higgs boson, current constraints leave room for BSM physics:

  → Br(H→BSM)<34% at 95% C.L

- Rare (SM) and Exotic (non-SM) decays have not been observed yet
- Several theories beyond the SM (such as SUSY, 2HDM, etc.) predict such decays





Higgs Boson LFV

LFV measurements are usually translated in terms of LFV interaction through the effective theory with Lagrangian:

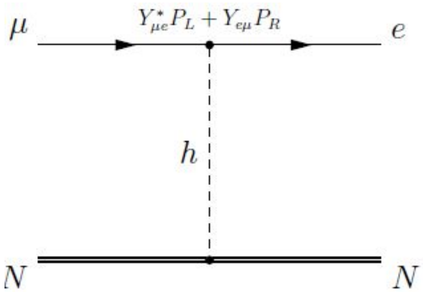
$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots$$

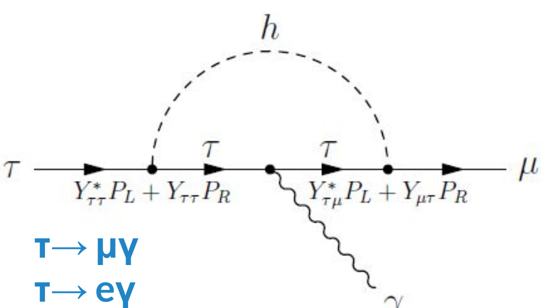
$f_L = q_L, \ell_L$ are $SU(2)_L$ doublets $\quad f_R = u_R, d_R, \nu_R, \ell_R$ the weak singlets

In the SM, Y_{ij} are diagonal; off-diagonal terms can arise in several BSM models.

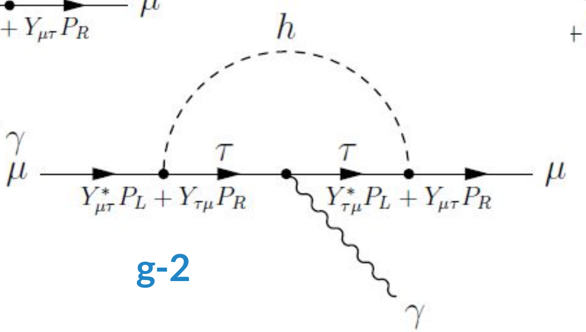
The introduction of these terms leads to diagrams such as:

μ→e conversion

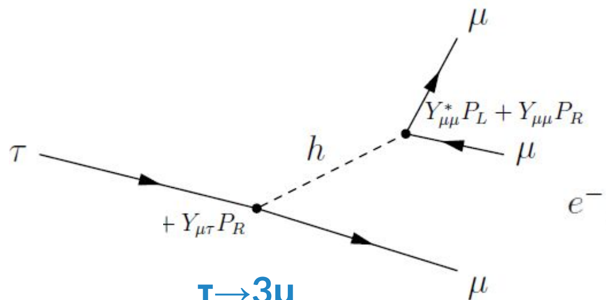




τ→ μγ
τ→ eγ

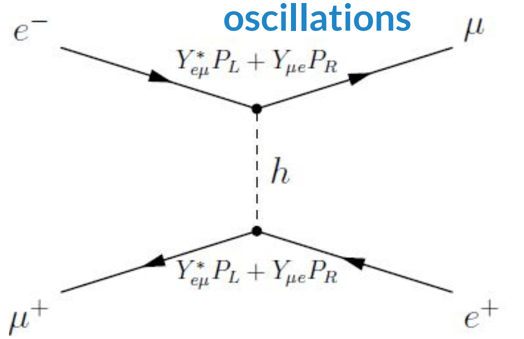


g-2



τ→3μ
τ→3e
μ→3e

M↔M oscillations

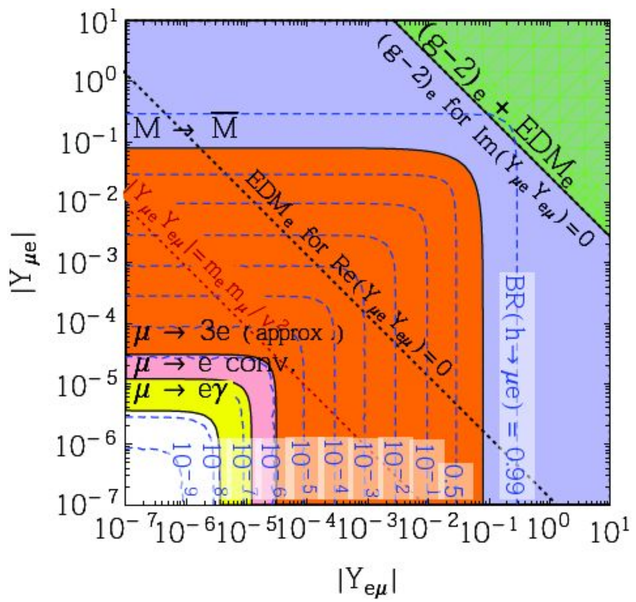


These terms can be constrained by **several (low energy) processes**.

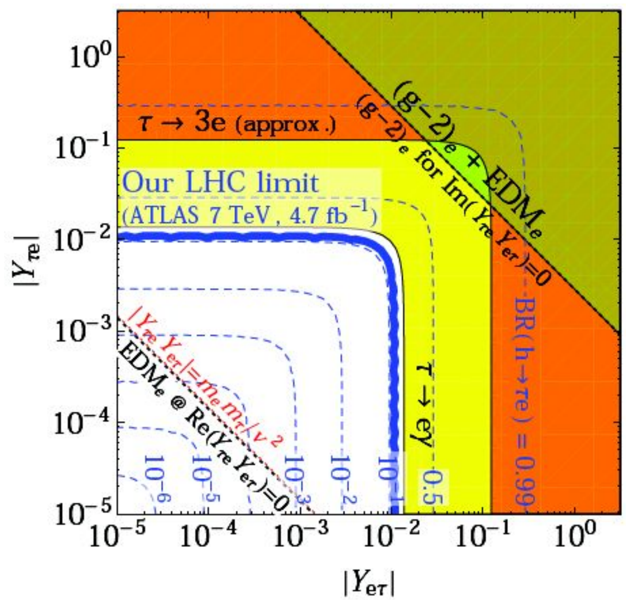
HLFV: Indirect Constraints

From JHEP 03 (2013) 026

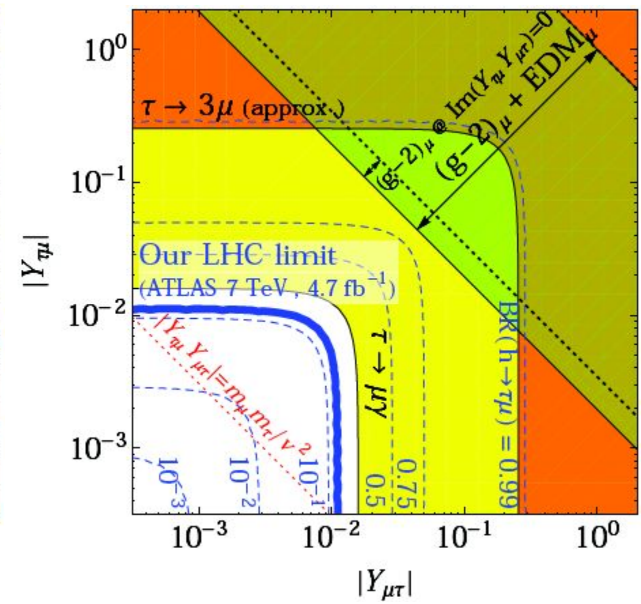
eμ



eτ



μτ



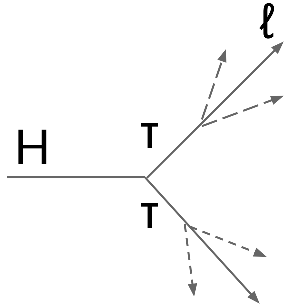
Stringent constraints from μ → eγ.
Indirect upper limit
Br(H→ μe)<O(10^{-8})
at 95% C.L.

Constraints from τ → μγ, τ → eγ.
Indirect upper limit
Br(H→ τμ) and Br(H→ τe) <O(10%) at 95% C.L.
Limits on H→ τℓ extracted from ATLAS H→ ττ

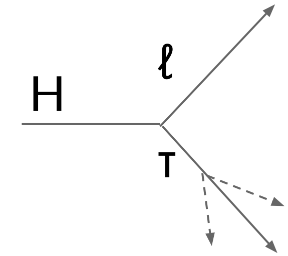
Overview of $H \rightarrow \ell\tau$ channels

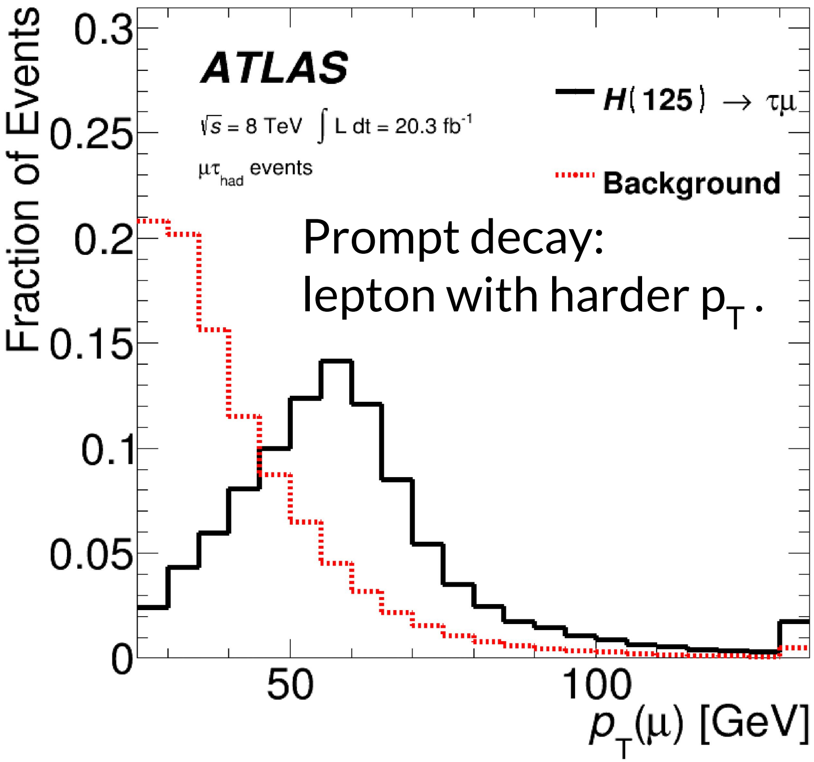
Topology similar to the one of the SM decays $H \rightarrow \tau_e \tau_\mu$ and $H \rightarrow \tau_{had}\tau_\ell$, but with important kinematic differences:

SM: $H \rightarrow \tau\tau$



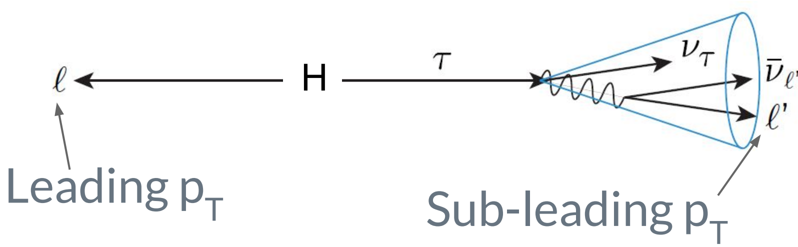
LFV: $H \rightarrow \ell\tau$





Prompt decay: lepton with harder p_T.

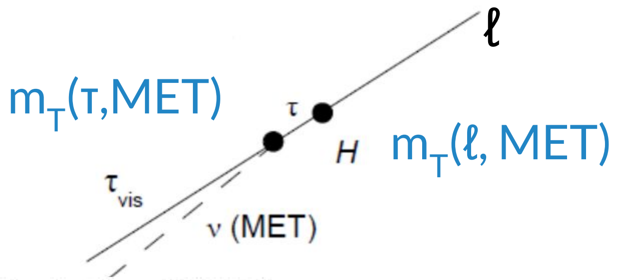
Neutrino collinear to τ

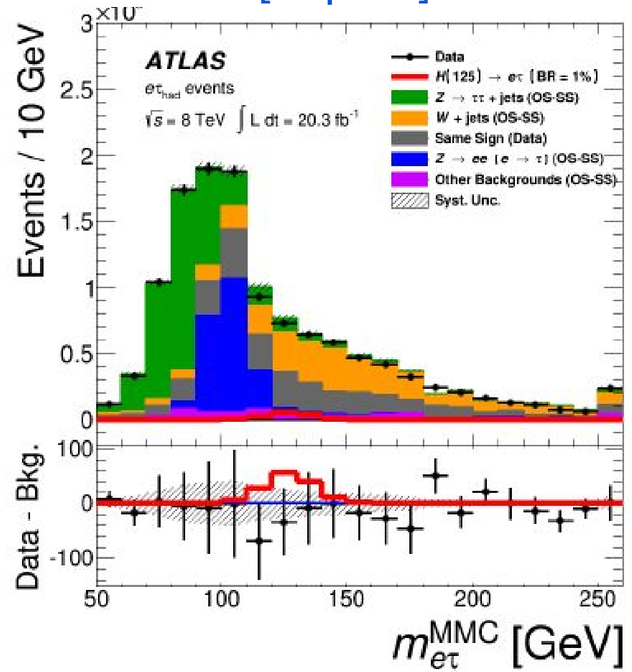


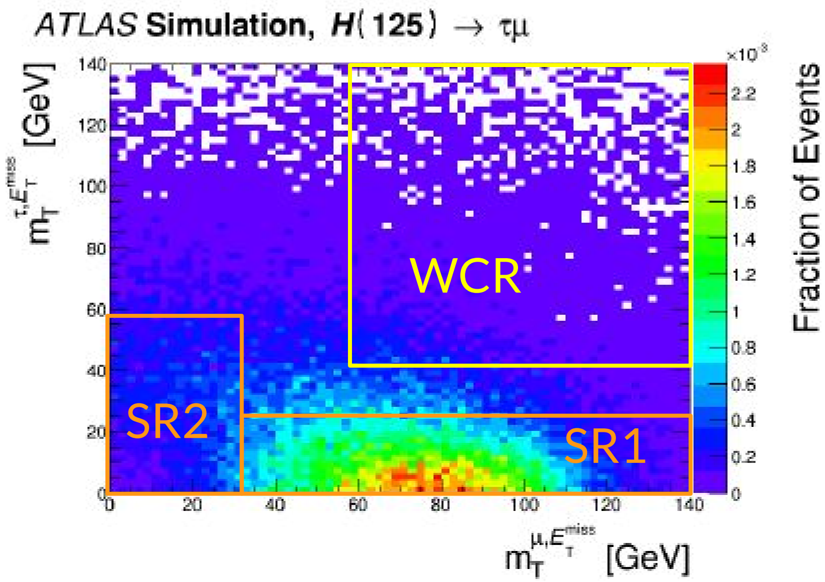
$H \to \ell\tau_{had}$

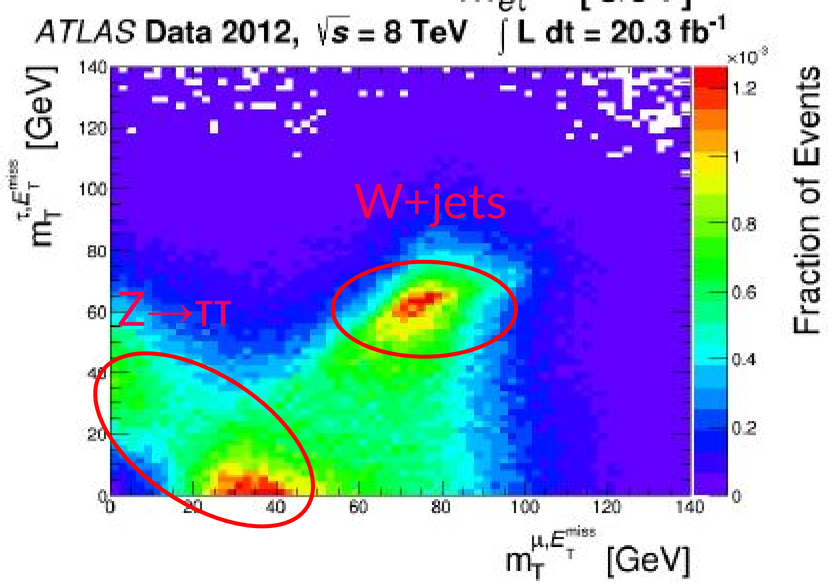
JHEP 1511 (2015) 211
arXiv:1604.07730 [hep-ex]

- Opposite-sign, well-separated ℓτ, MET
- Two signal regions based on m_T; small differences in kin. sel. b/w eτ and μτ
- Final discriminant: missing mass calculator (MMC)









Completely data-driven study, based on the data-driven asymmetry method proposed in PRD 90, 015025 (2014)

Select opposite charge e+μ sample.
Assumptions:

1. the SM processes are symmetric when we exchange e ↔ μ
2. LFV decays break this symmetry.
   E.g. $H\to\mu\tau_e$: τ and μ take ~½ p_T, e ~⅙ p_T

Subdivide the e+μ sample in two sub-samples:

- **eμ** sample, with $p_T(e) > p_T(\mu)$
- **μe** sample, with $p_T(e) < p_T(\mu)$

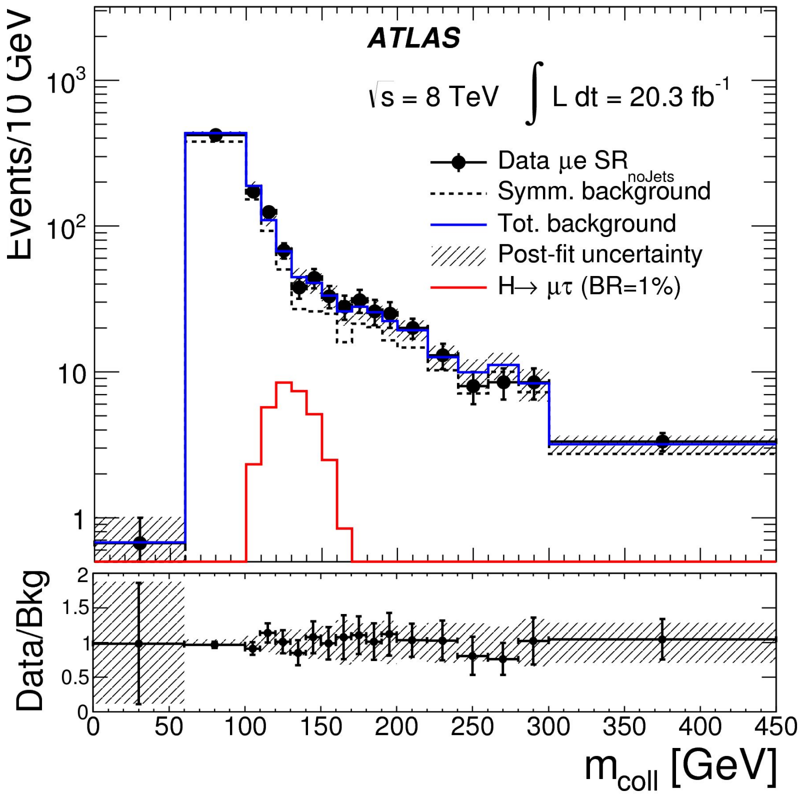
Estimate the background to $H\to\mu\tau_e$:(present only in **μe**) from the **eμ** sample & vice-versa.

This method is sensitive to:

$$|Br(H\to\mu\tau_e) - Br(H\to e\tau_\mu)|$$

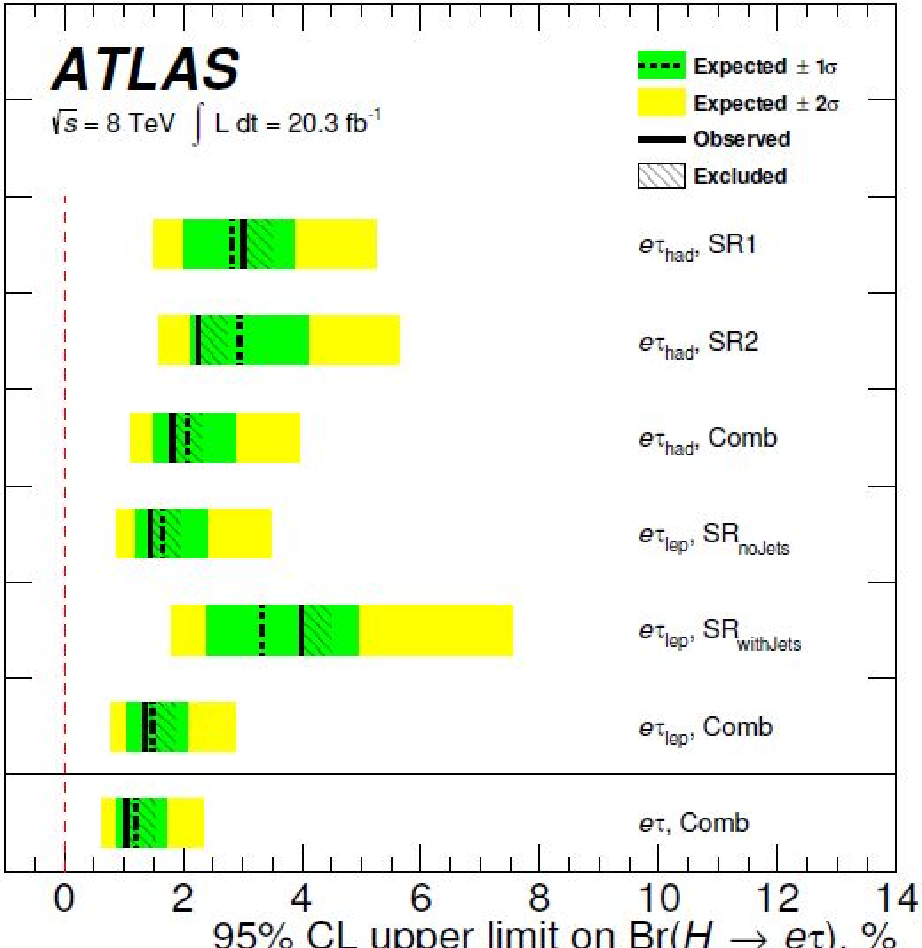
m_H estimated with collinear approx.

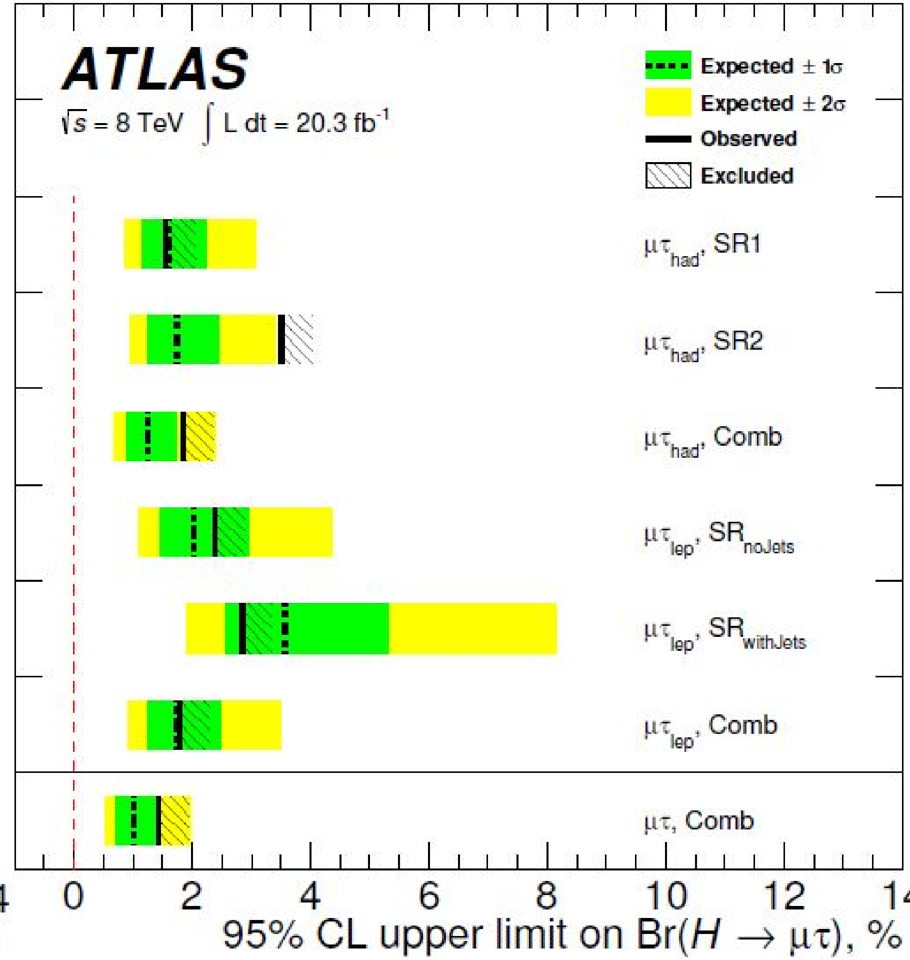
$$m_{\text{coll}} = \sqrt{2p_T^{\ell_1}\left(p_T^{\ell_2} + E_T^{\text{miss}}\right)(\cosh\Delta\eta - \cos\Delta\phi)}$$



$H \to \ell\tau$: combination

▹Improve indirect bounds by an order of magnitude: arXiv:1604.07730 [hep-ex]





Observed 95% CL upper limit

Br(H→eτ)<1.04% (1.21 exp.)

Observed 95% CL upper limit

Br(H→μτ)<1.43% (1.01 exp.)

Rare Decays

Couplings of the Higgs boson to light (or first and second generation)

leptons

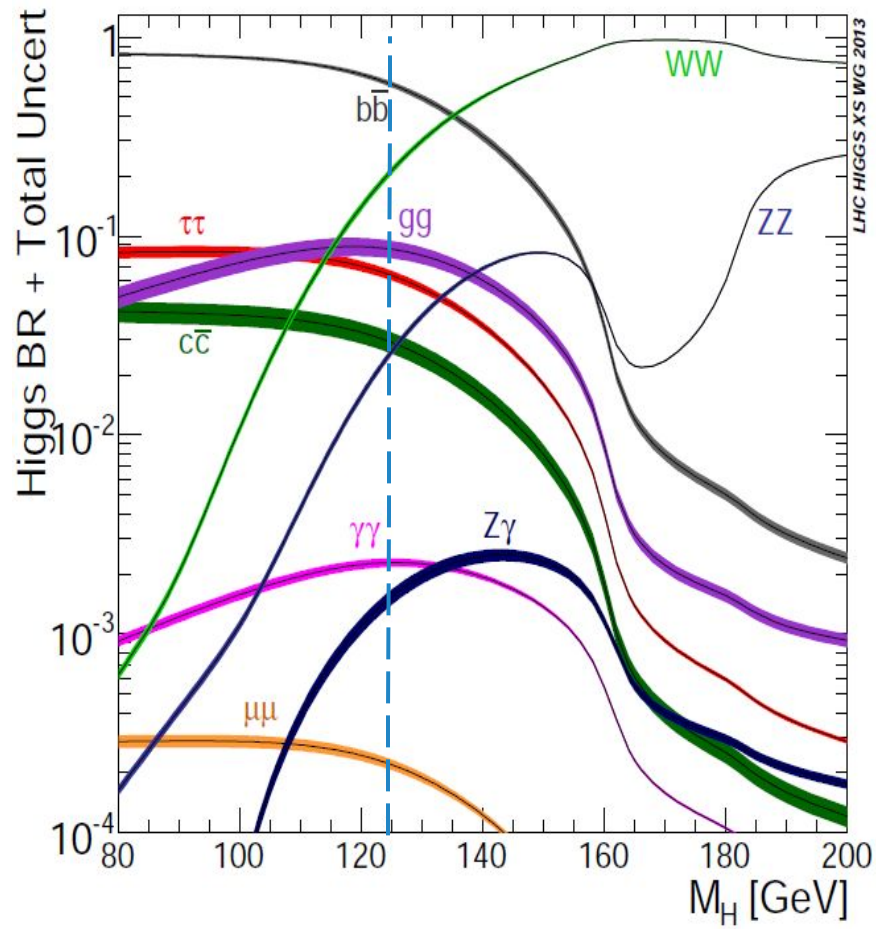
- $H \to \mu\mu$
  (see talk by Christian Grefe)
- $H \to ee$

and

quarks ($H \to X+\gamma$)

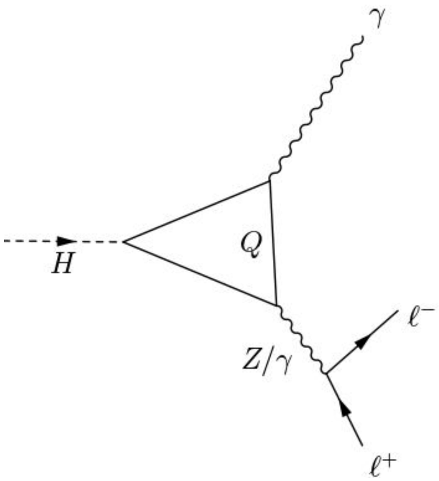
- $H \to Z/\gamma^{*} + \gamma$
- $H \to J/\Psi\gamma$, $\Upsilon(nS)\gamma$
- $H \to \varphi\gamma$

provide insights on the nature of
the
Yukawa couplings
⇒ sensitive to physics beyond the SM

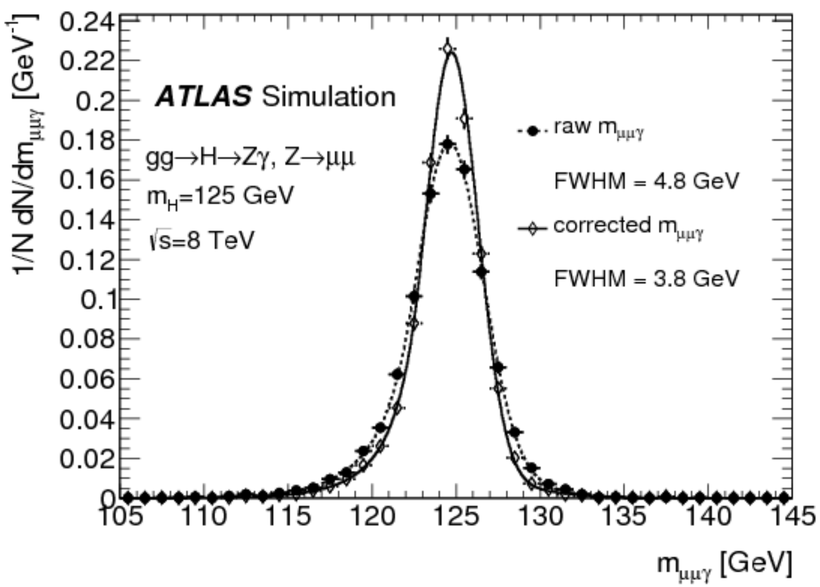


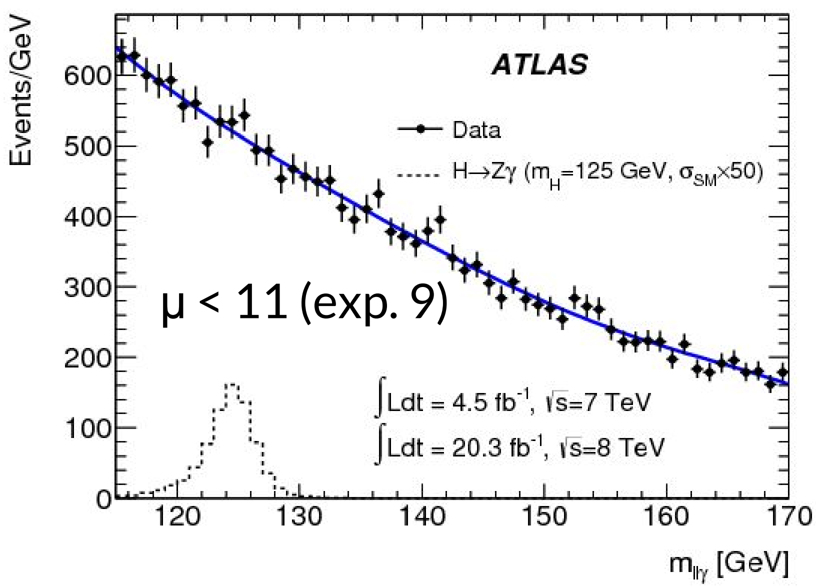
$H \to Z/\gamma^*(\to \ell\ell)+\gamma$

PLB 732 (2014) 8-27



- Small branching ratio, enhanced by heavy Q in the loop
- Isolated, same-flavor e^+e^- (p_T>10GeV) or $\mu^+\mu^-$ (p_T>15 GeV) and one γ (p_T>15GeV)
- Events categorised by lepton flavor, $\Delta|\eta|$ (Z, γ), and Higgs p_T
- Three-body inv. mass resolution improved by Z-mass constraint kinematic fit



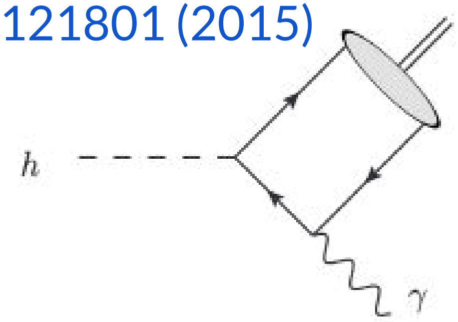


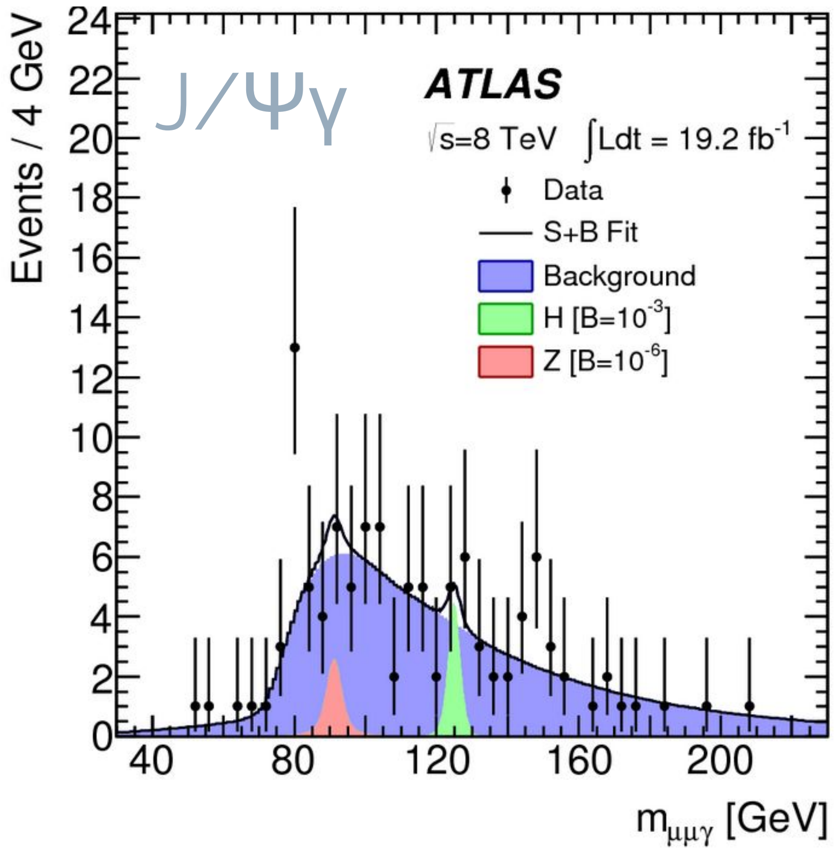
μ < 11 (exp. 9)

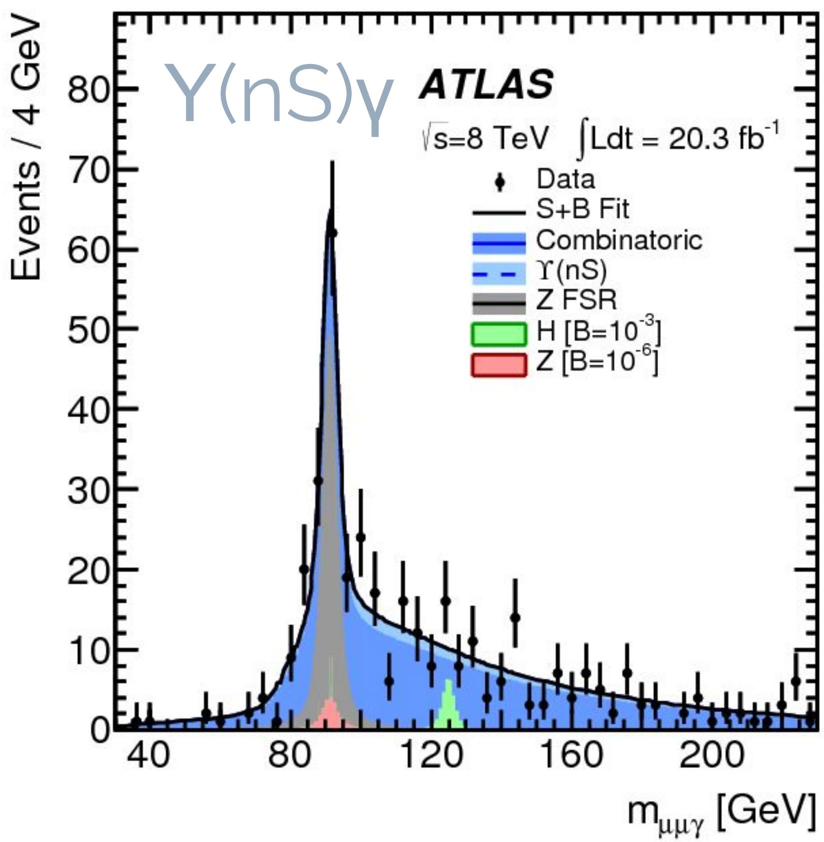
$H/Z \rightarrow J/\Psi\gamma$, $\Upsilon(nS)\gamma$

PRL 114, 121801 (2015)

- High-p_T (36 GeV) quarkonium recoiling against a high-p_T (36 GeV) photon.
- Consider only $\mu^+\mu^-\gamma$ final state ($e^+e^-\gamma$ more challenging and poorer mass res.)
- Events categorised based on μ $|\eta|$ and γ conversion.
- Simultaneous fit performed to $m(\mu\mu\gamma)$ and $m(\mu\mu)$.

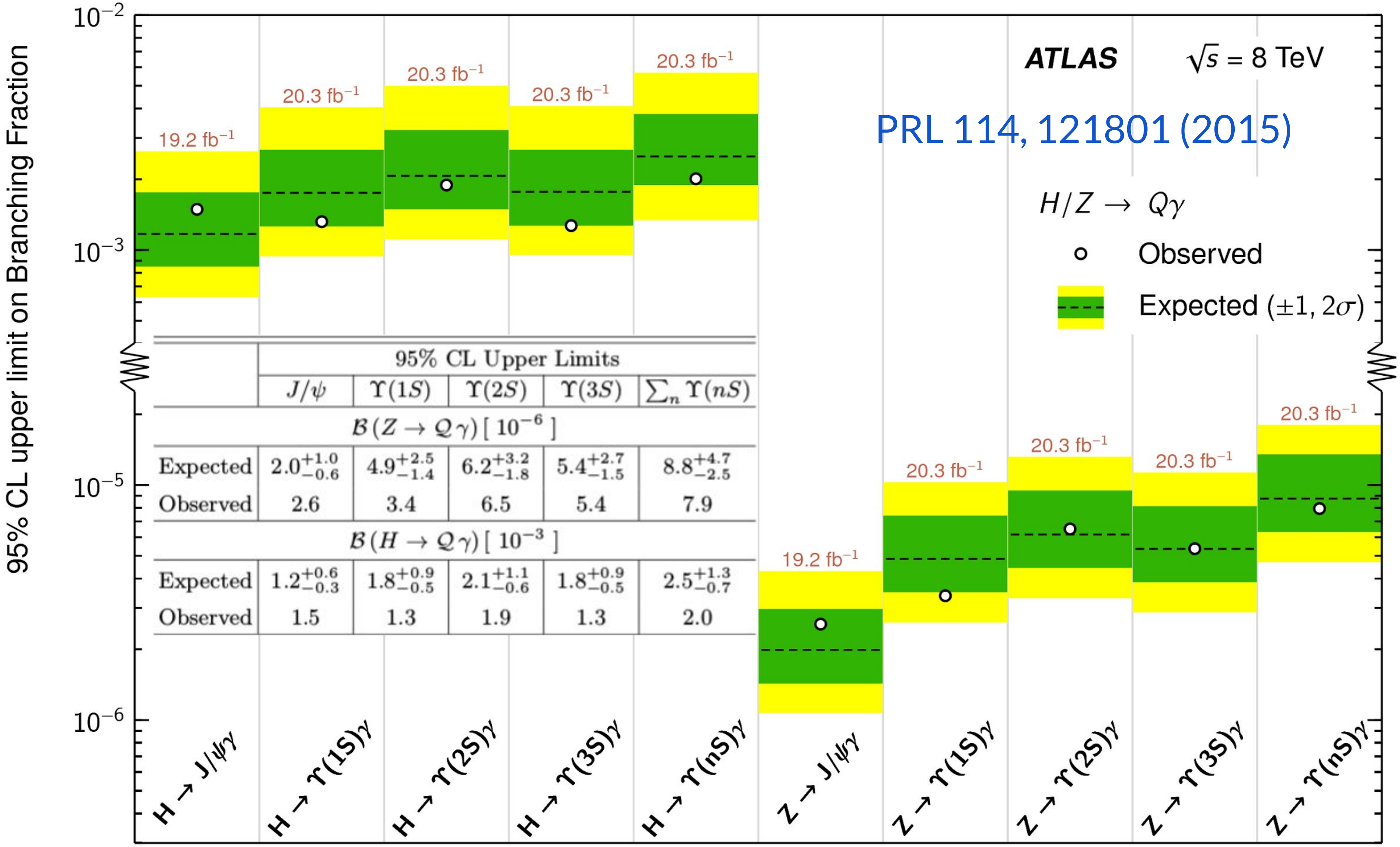






$H/Z \to J/\Psi\gamma$, $\Upsilon(nS)\gamma$

First experimental bounds on Higgs and Z boson decays to these final states.

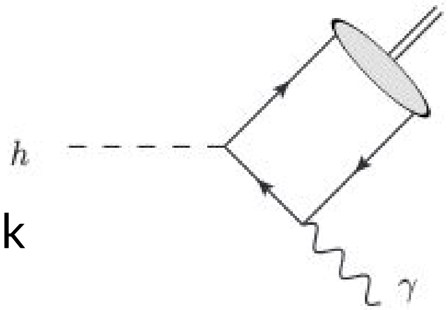


	95% CL Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)\,[10^{-6}]$					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)\,[10^{-3}]$					
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

Comparison with SM Br: ~10^{-3} for SM Higgs boson and ~10^{-6} for Z boson.

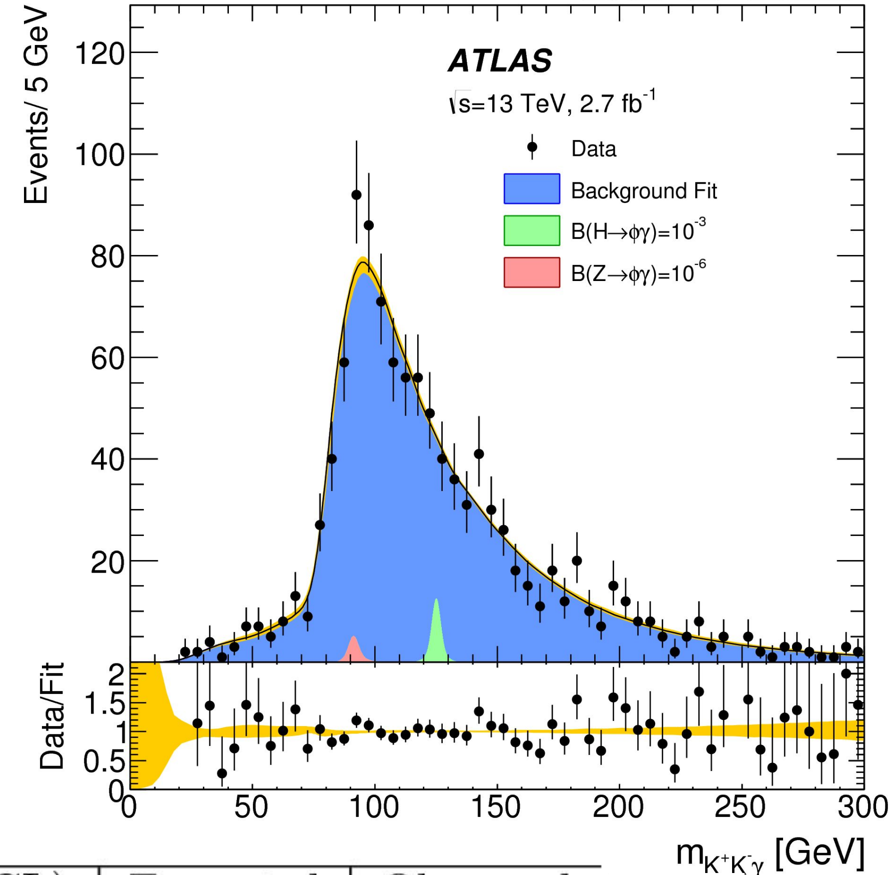
$H/Z \to \varphi\gamma$

arXiv:1607.03400 [hep-ex]



- Sensitivity to s-quark Yukawa couplings

- Reconstruct $\varphi \to K^+K^-$, $Br(\varphi \to K^+K^-)=49\%$
- Two high-p_T (20, 15 GeV) isolated collinear tracks ($\Delta R<0.05$, $m_{KK} \sim m_{\varphi}$) recoiling against γ (p_T> 35 GeV)
- Dedicated trigger (~78% efficiency wrt. offline selection)
- Data-driven template modeling of bkg



Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-3}\,]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$4.4^{+2.0}_{-1.2}$	8.3

Expected SM values:

- $\mathcal{B}(H \to \phi\gamma) = (2.3 \pm 0.1) \times 10^{-6}$ - JHEP 1508 (2015) 012 (arXiv:1505.03870)
- $\mathcal{B}(Z \to \phi\gamma) = (1.2 \pm 0.1) \times 10^{-8}$ - PRD 92, 014007 (2015) (arXiv:1411.5924)

Conclusions

▹ ATLAS has carried out several searches for rare and exotic decays of the Higgs boson cover a wide range of final states:

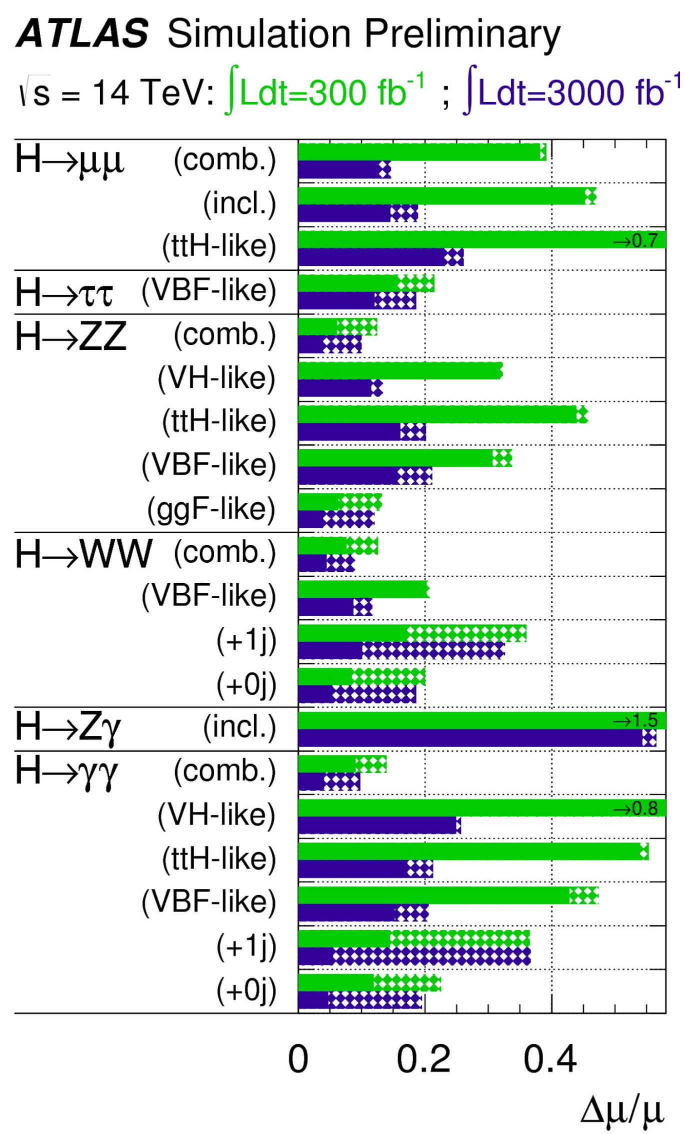
- LFV H decays
- $H \to Z/\gamma^* \gamma$
- $H/Z \to J/\Psi\gamma, \Upsilon(nS)\gamma$
- $H/Z \to \varphi\gamma$ **new!**

▹ These searches, performed at both 8TeV and 13TeV, have shown no significant excess so far.

▹ These searches will be those benefitting the most from the large datasets that will be available in the future:

- Run2: 300/fb might not be enough for evidence
- HL-LHC: 1000/fb will allow to measure such rare decays, but require significant detector upgrades

ATL-PHYS-PUB-2013-014



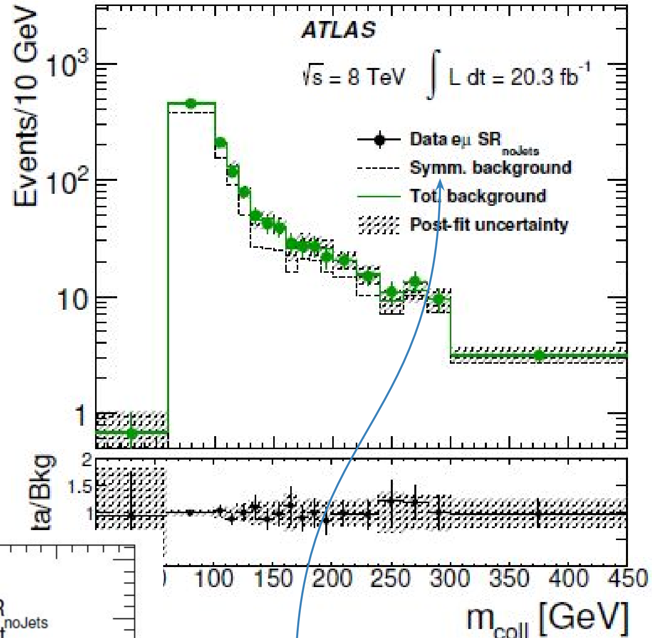
Backup

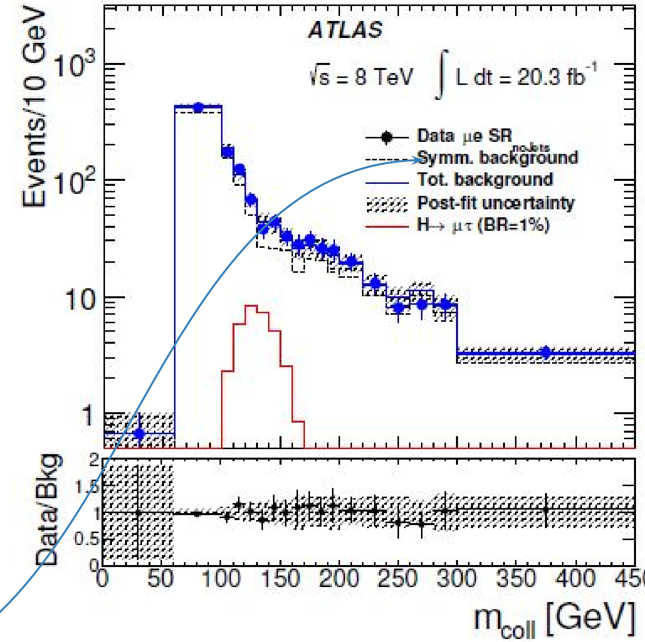
ATLAS H → ℓτ$_{\ell'}$

CERN-EP-2016-055

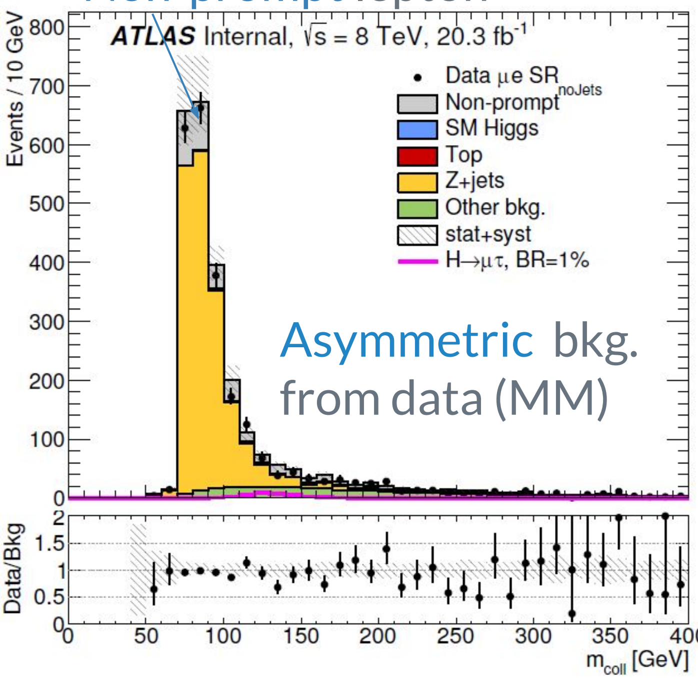
The "SM is symmetric" assumption is a good starting point → optimize jets / no-jets

But there are subtle effects to be taken into account:





Non-prompt lepton



Asymmetric bkg. from data (MM)

Residual differences between leading and subleading lepton (e.g. trigger efficiencies) → additional asymm. free term in the Lhood fit:

$f(p_T, \ell_2)$

.

95% CL upper limits

Br(H→eτ)<1.36% (1.48 exp.)

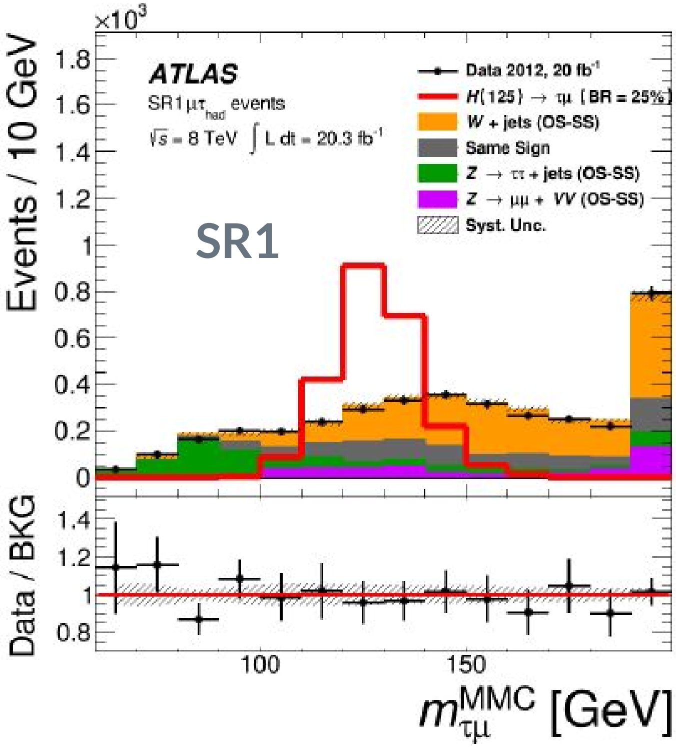
Br(H→μτ)<1.79% (1.73 exp.)

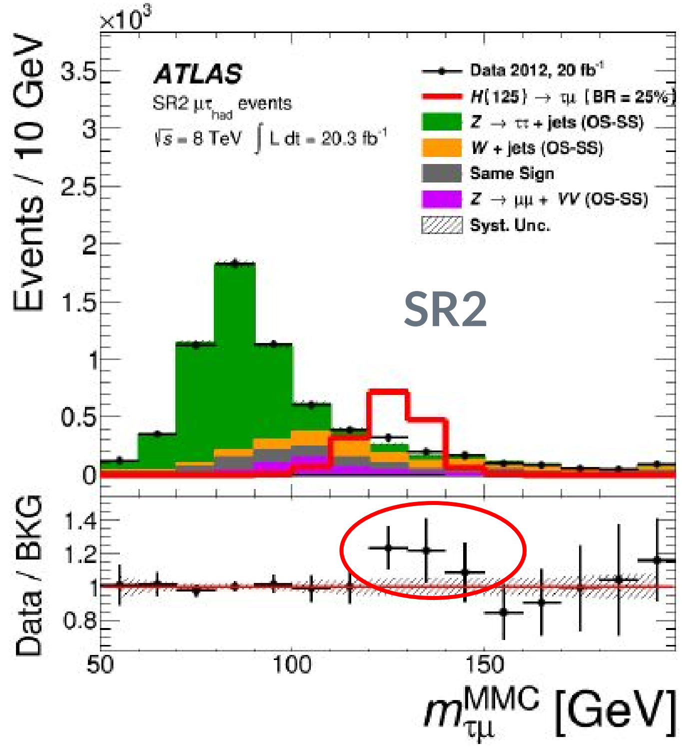
$H \rightarrow \mu\tau_{had}$

[JHEP 1511 (2015) 211]

Combined fit MMC distributions.

Main systematic uncertainties: W+jets shape & norm.





95% CL upper limit

Br(H→μτ)<1.85% (1.24 exp.)

1.3σ excess (from SR2) with best fit

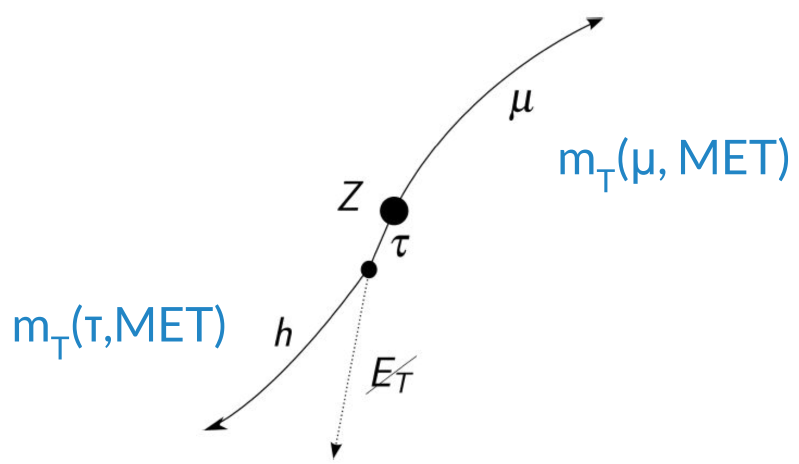
Br(H→μτ)=0.77±0.62%

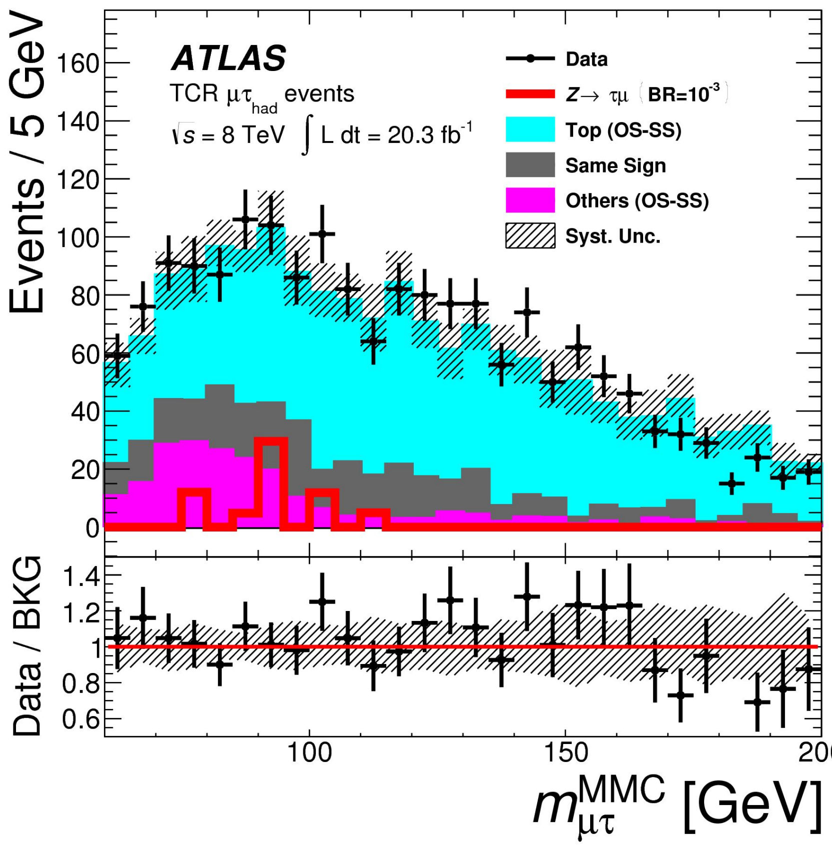
$Z \to \mu\tau_{had}$

arXiv:1508.03372 [hep-ex]

Same approach used for $H \to \ell\tau_{had}$:

- opposite-sign, well-separated $\mu\tau$, MET
- Two signal regions based on m_T
- minor differences in the kinematic selection ($m_Z < m_H \to$ softer p_T)





Previous search from LEP: Z.Phys. C73 (1997)

$Br(Z \to \mu\tau) < 1.2 \times 10^{-5}$

Large number of Z bosons produced at the LHC, but $Z \to \ell\tau$ not explored yet.

95% CL upper limit:

$Br(Z \to \mu\tau) < 1.54 \times 10^{-5}$