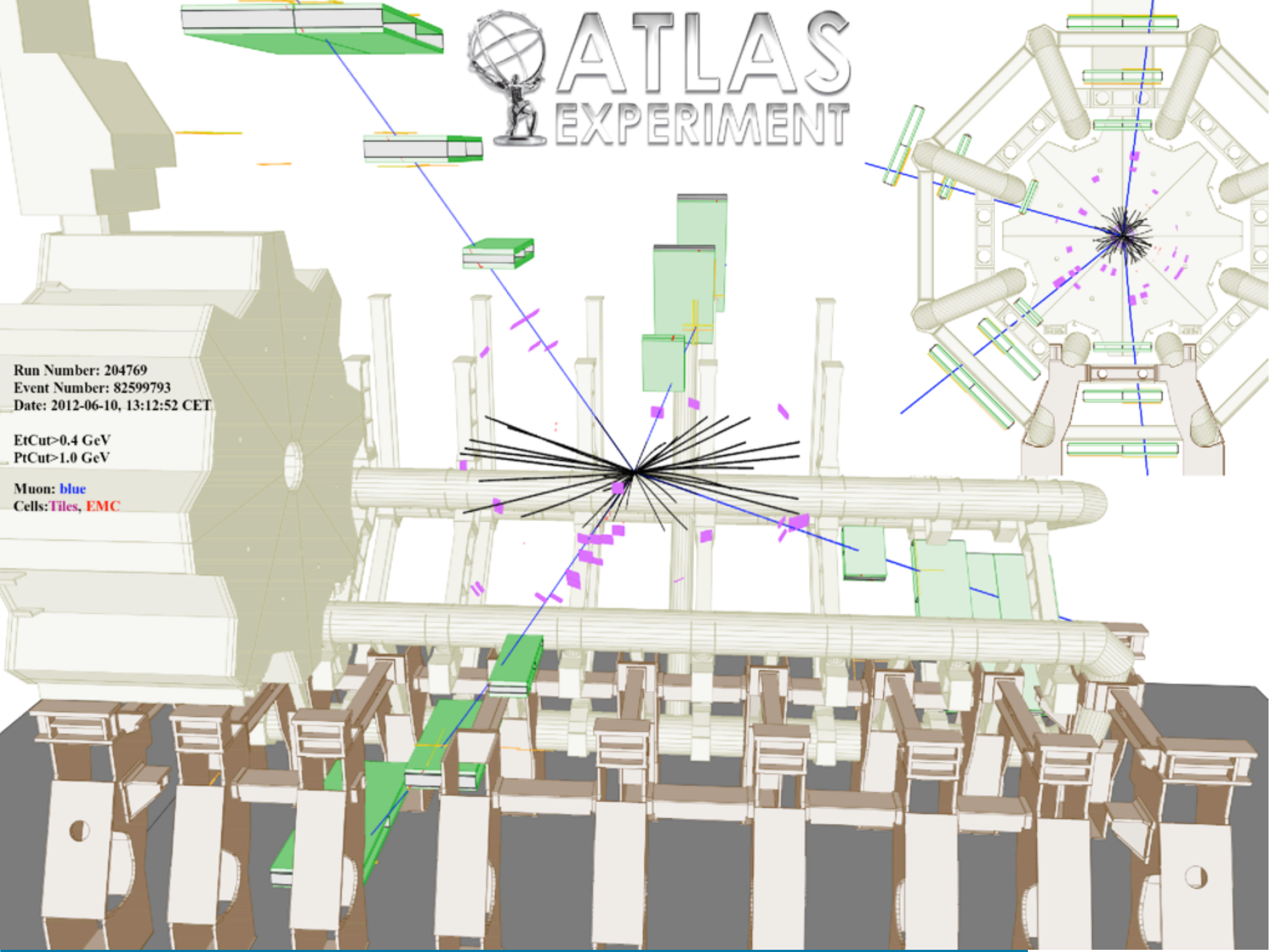


Higgs boson Rare Decays

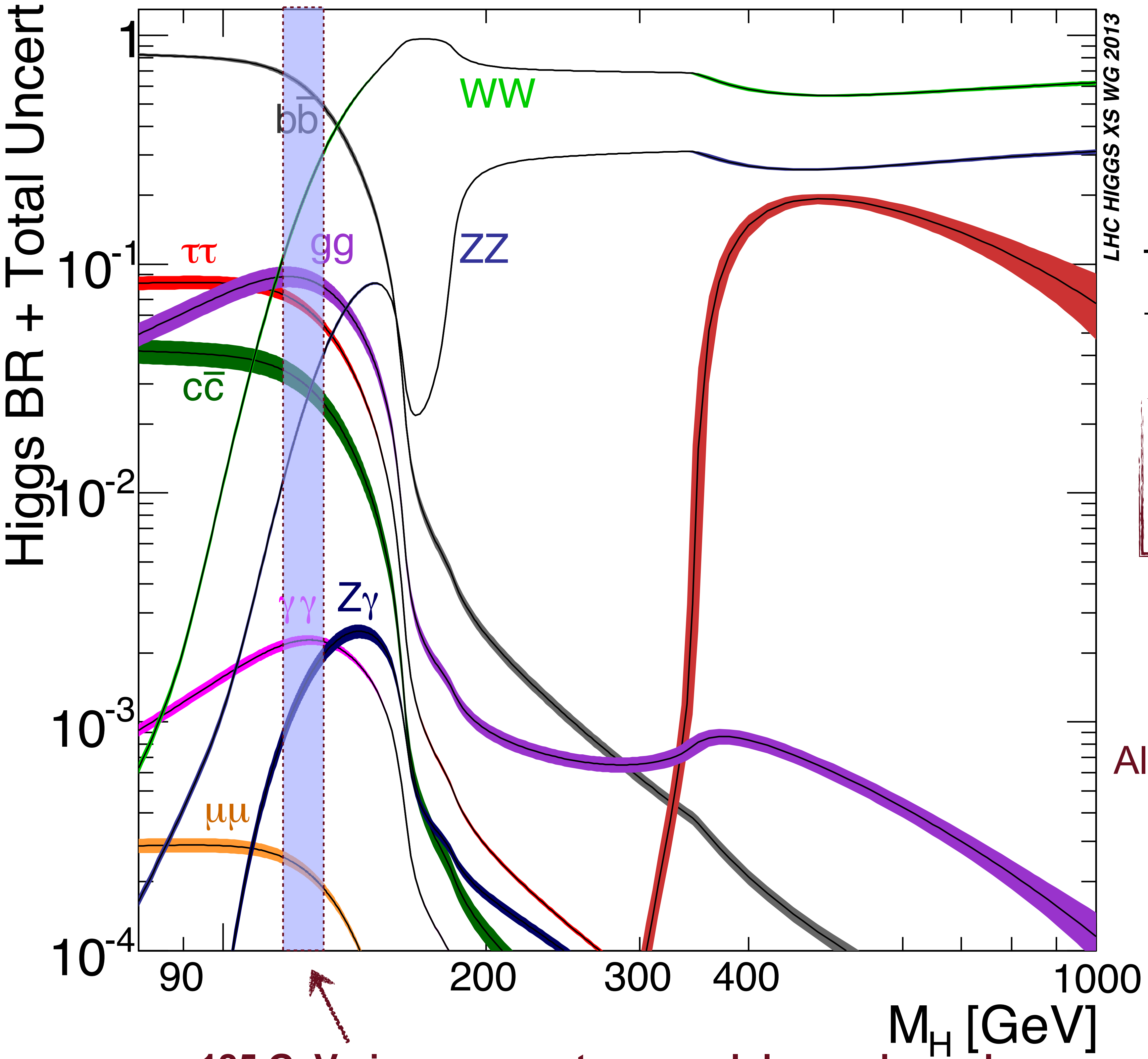
K. Nikolopoulos
University of Birmingham

LHC Higgs Cross Section WG
WG3 Rare Decays
22nd May 2015, Fermilab, USA

UNIVERSITY OF
BIRMINGHAM

This project has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration under grant agreement no 334034 (EWSB)

Standard Model Higgs boson decays



m_h~125 GeV gives access to several decay channels
Gauge bosons: γγ, ZZ*, WW*, Zγ
Fermions: bb, ττ, μμ

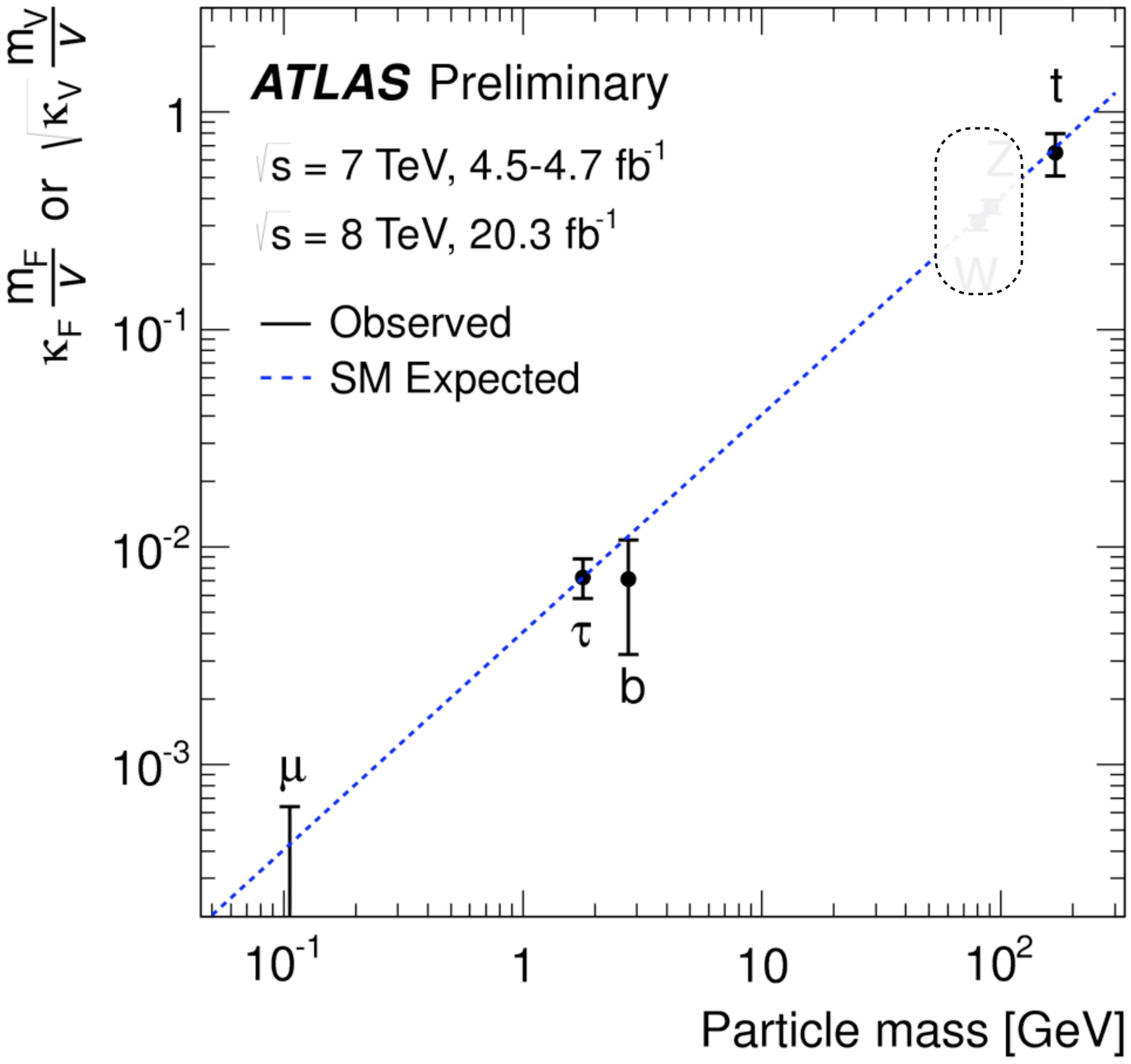
The talk title is a bit too wide:
→ Many “rare” Higgs boson decays

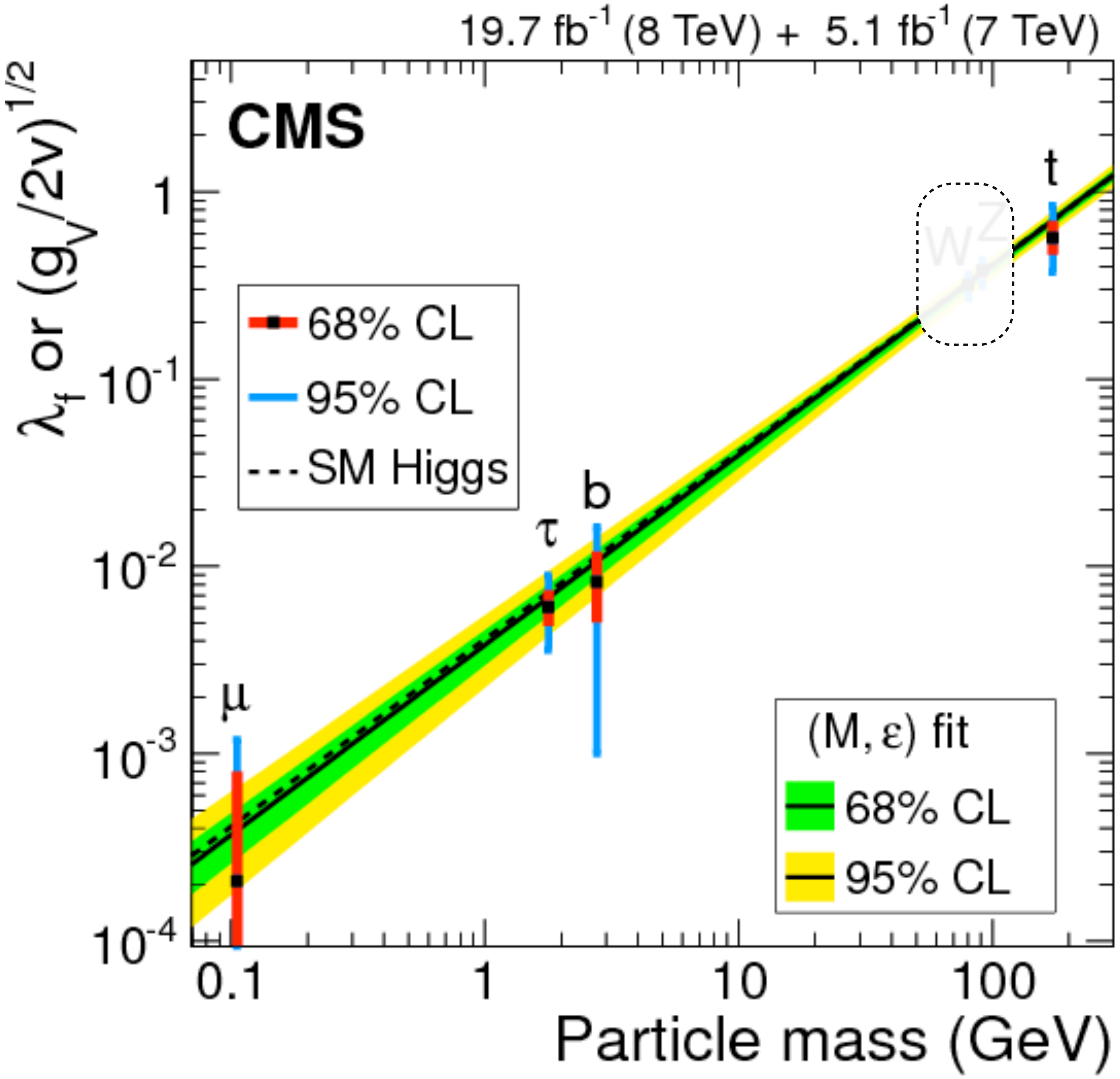
Focus on exclusive Higgs boson decays that carry information on (light) fermion Yukawa couplings

Concentrate on ATLAS results, but when relevant/available CMS plots also shown
Also relevant theory results presented

As suggested, will not focus on the results, but try to give an idea of the experiment/theory issues

Yukawa couplings so far...



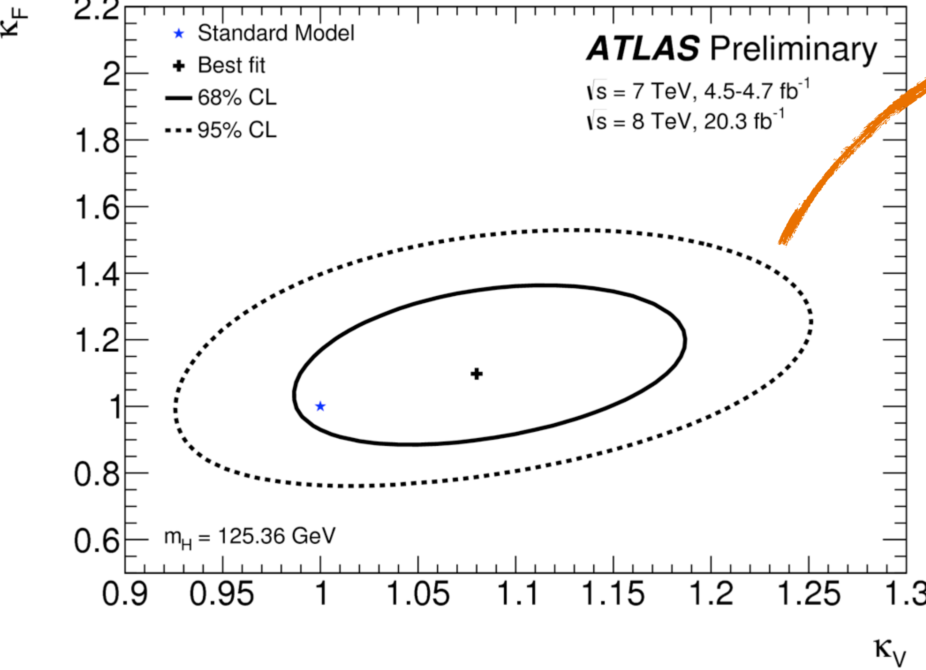


→ Currently, with the exception of h→ττ, no conclusive direct evidence for h→ffbar
  → Indications for h→bb and tth, to be followed up in LHC Run II
→ Indirectly; Higgs boson should be coupling to top-quark in the gluon fusion loop

Higgs boson and precision electroweak observables

Common coupling scaling for all Fermions (κ_F) and for all Bosons (κ_V); no BSM contributions

ATLAS-CONF-2015-007

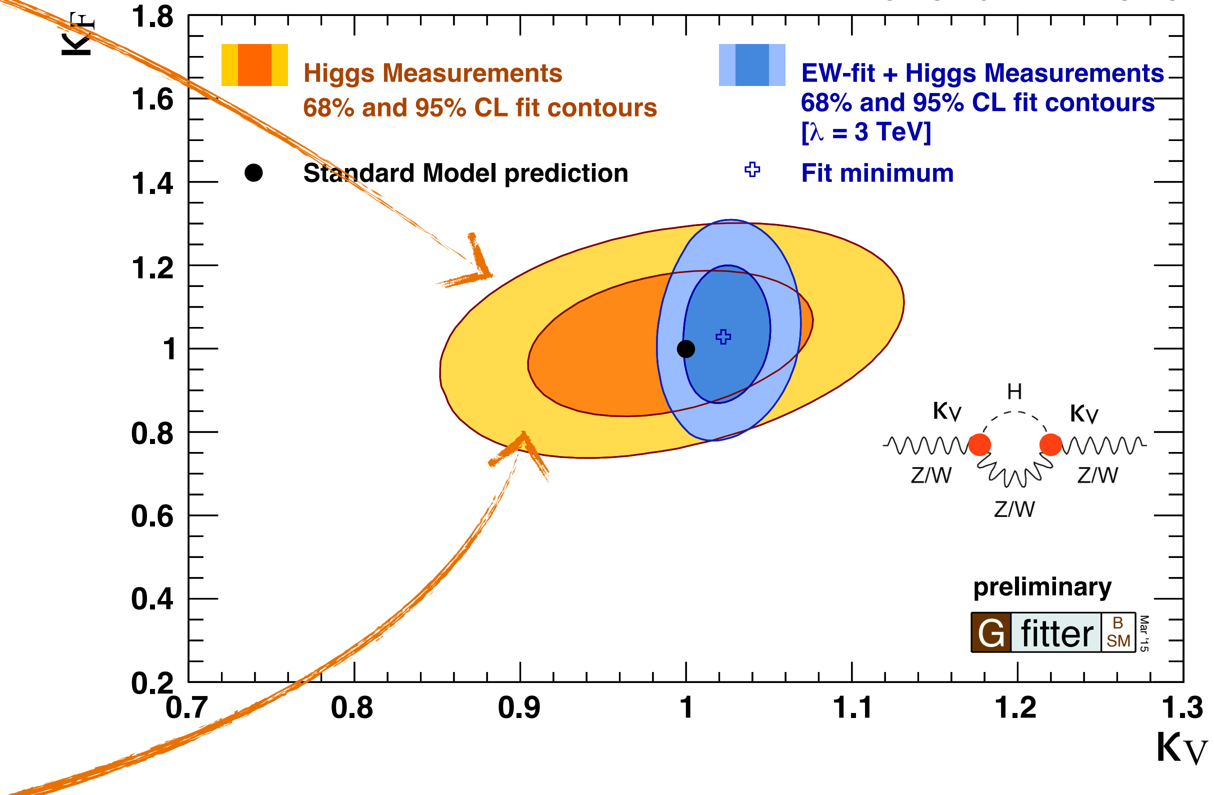


Higgs coupling measurements:

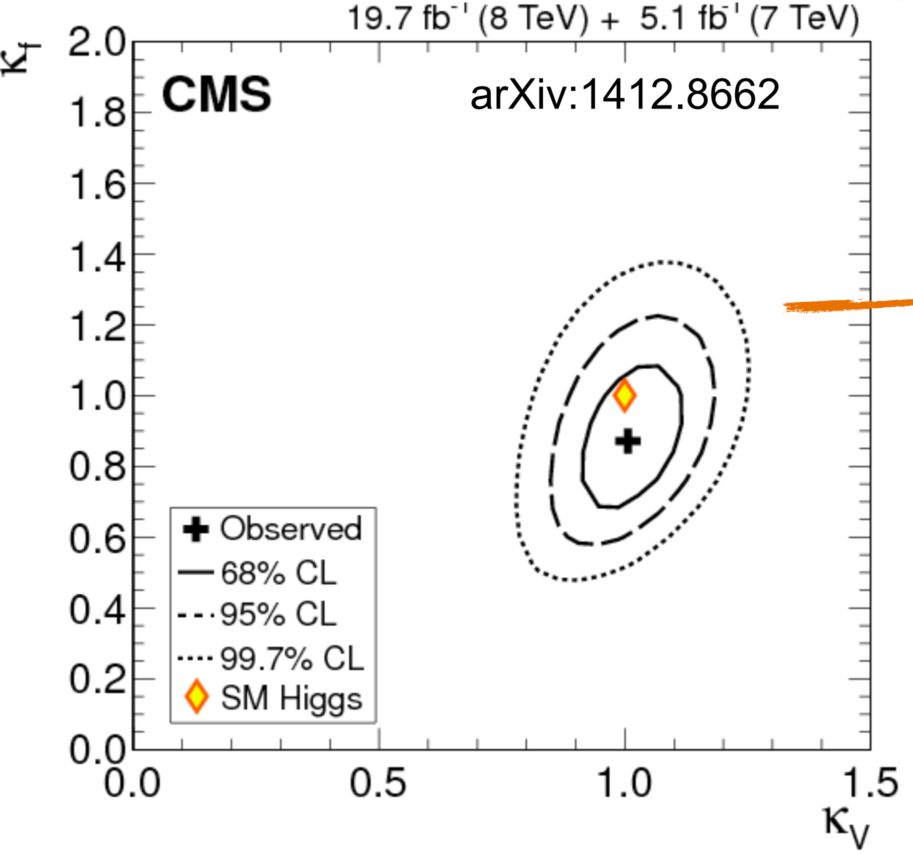
- $\kappa_V = 0.99 \pm 0.08$
- $\kappa_F = 1.01 \pm 0.17$

- **Combined result:**
- $\kappa_V = 1.03 \pm 0.02$ ($\lambda = 3$ TeV)
- implies NP-scale of $\Lambda \geq 13$ TeV

Moriond EW 2016



Roman Kogler 16 The global electroweak fit



arXiv:1412.8662

- Global EW fit more precise for κ_V than coupling measurements
- $\kappa_V > 1$ preferred (many BSM scenarios require $\kappa_V < 1$)
- Global EW fit has ~no effect on determination of κ_F

Experimental information on Yukawa couplings essential to fully characterize the observed Higgs boson!

$h \to \mu\mu$

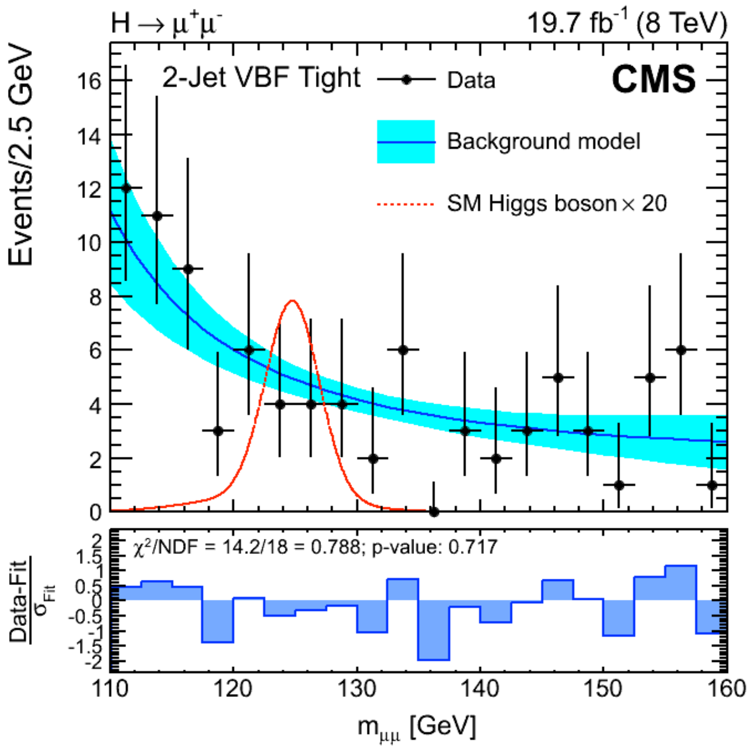
- Attainable probe for 2nd gen. Yukawa
- $BR_{SM} \sim 2 \cdot 10^{-4}$(125GeV);S/B ~0.2%

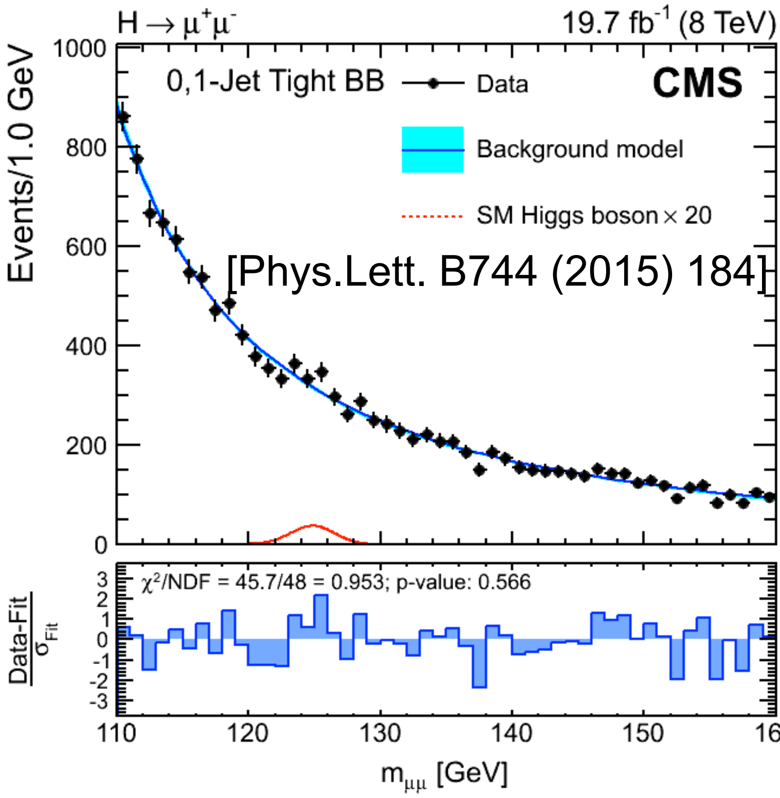
Simple Final State

(ATLAS analysis)

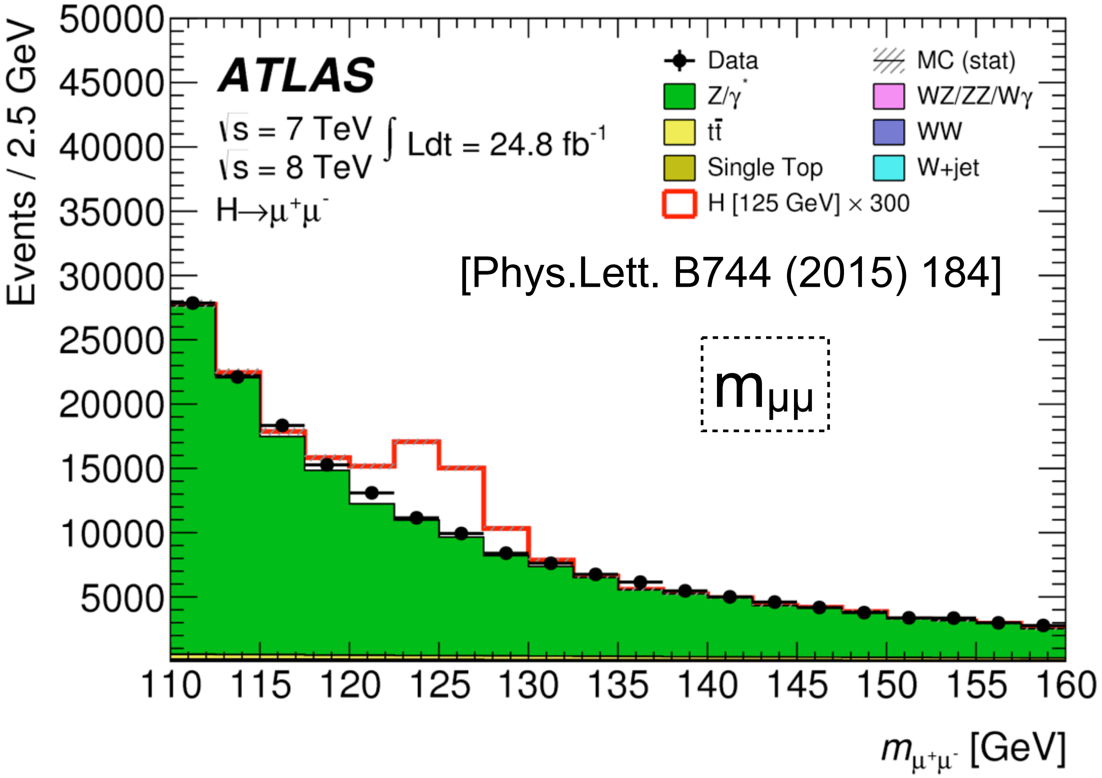
- $\mu^+\mu^-$ (p_T>25,15 GeV, $p_{T\mu\mu}$>15 GeV)
- backgrounds: $Z/\gamma^* \to \mu\mu$, top, dibosons
- Categorization: central/non-central muons
- Parametric background Model: BW+Expo
- 95% CL upper limit @m_H=125 GeV:
  - ATLAS : 9.8 (8.2)xSM
  - CMS : 7.4 (6.5)xSM

no universal Higgs coupling to fermions





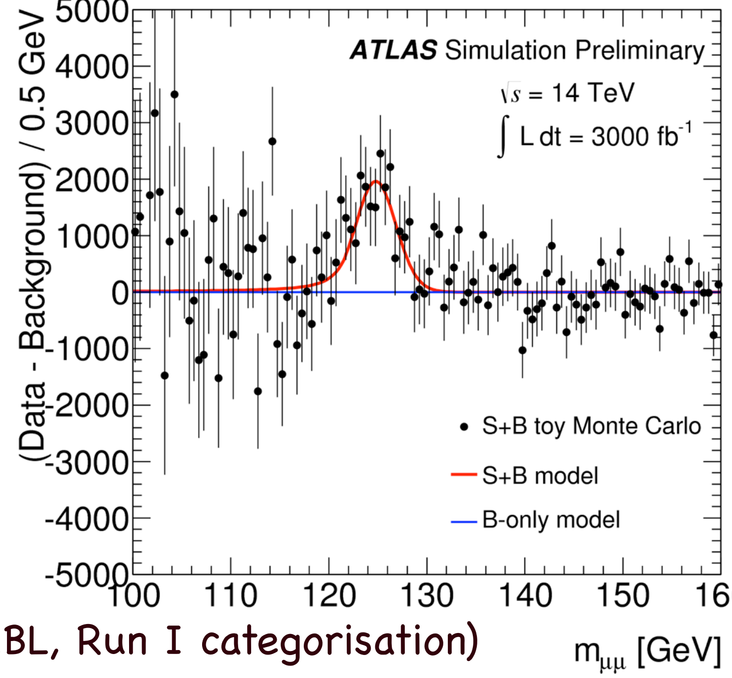
[Phys.Lett. B744 (2015) 184]



[Phys.Lett. B744 (2015) 184]

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

ATLAS-PHYS-PUB-2013-014



conservative extrapolation (no IBL, Run I categorisation)

Room for analysis improvements.
Will benefit from detector upgrades.

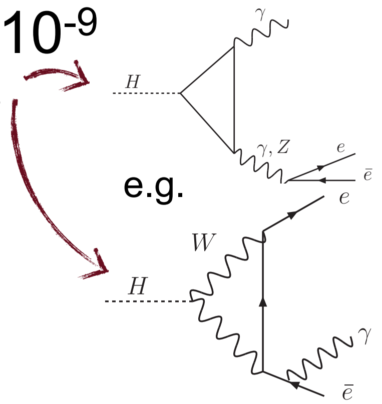
h→ee

Very rare decay of the SM Higgs BR~5·10^{-9}

[“direct” process non-Yukawa suppressed contributions need to be included Phys.Lett. B727 (2013) 424]

- $BR_{SM}(h\to\tau\tau)/BR_{SM}(h\to ee) \sim 1.3\cdot 10^{7}$

Not promising to constrain the electron SM Yukawa coupling meaningfully

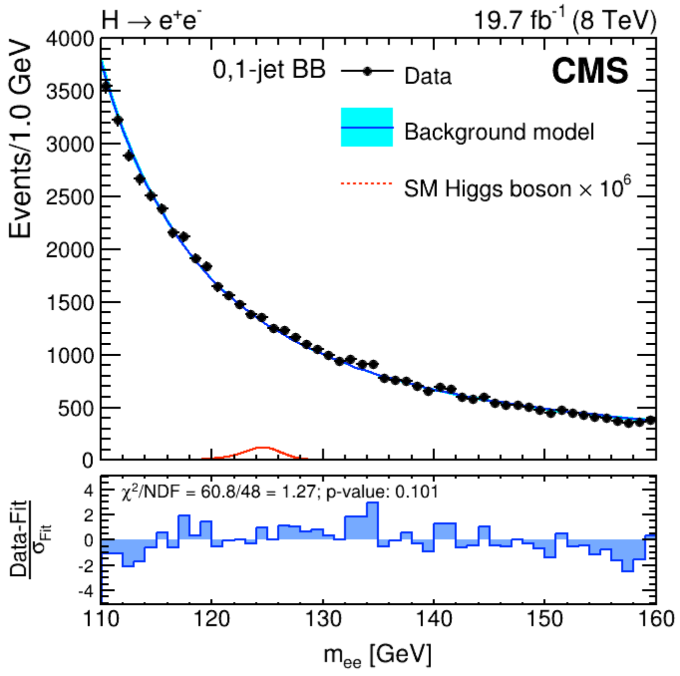


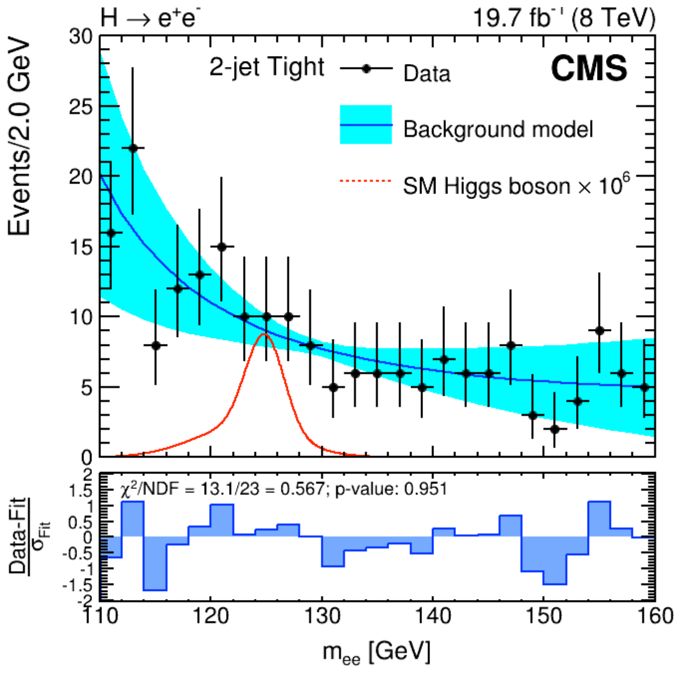
Performed by CMS, together with h→μμ

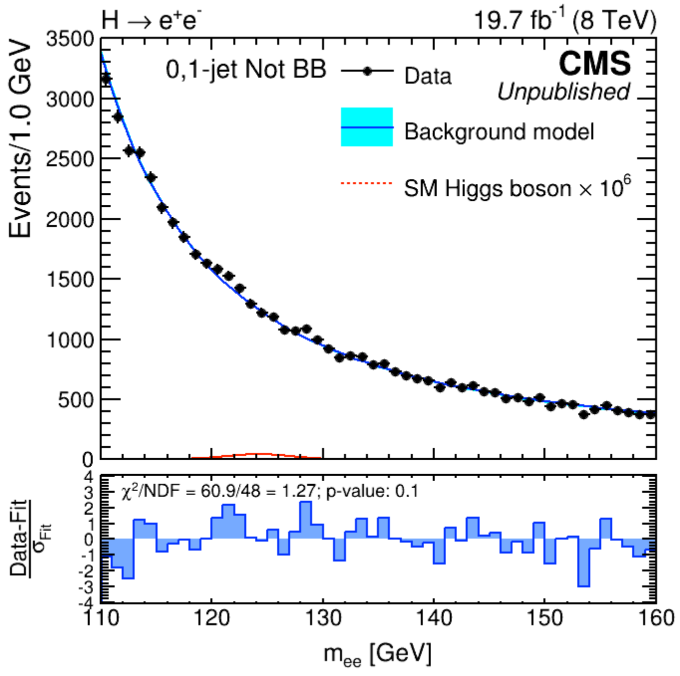
- simple final state:
  electron-positron pair, pT>25GeV
- backgrounds: Z/γ*→ee, and some ttbar
- Categorization:

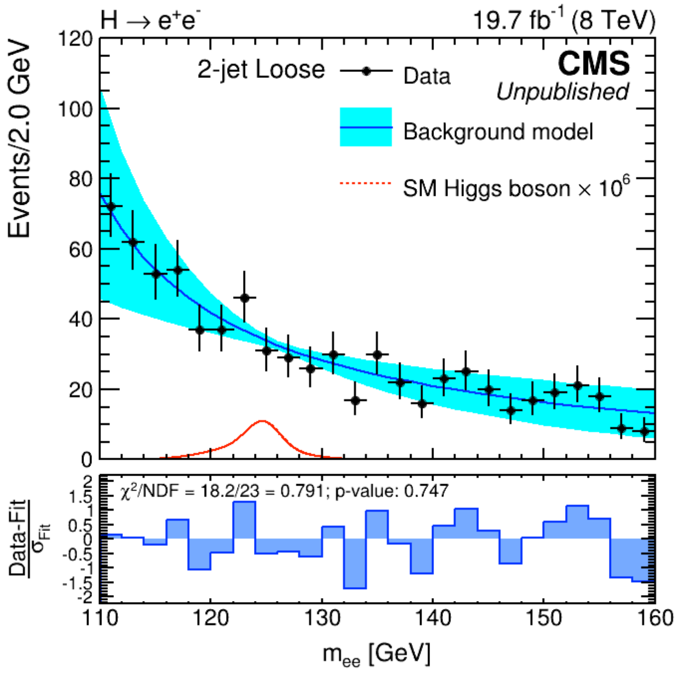
central/non-central electrons + 2 jet categories

- Parametric Background Model
- 95% CL upper limit BR(h→ee)<1.9·10^{-3}

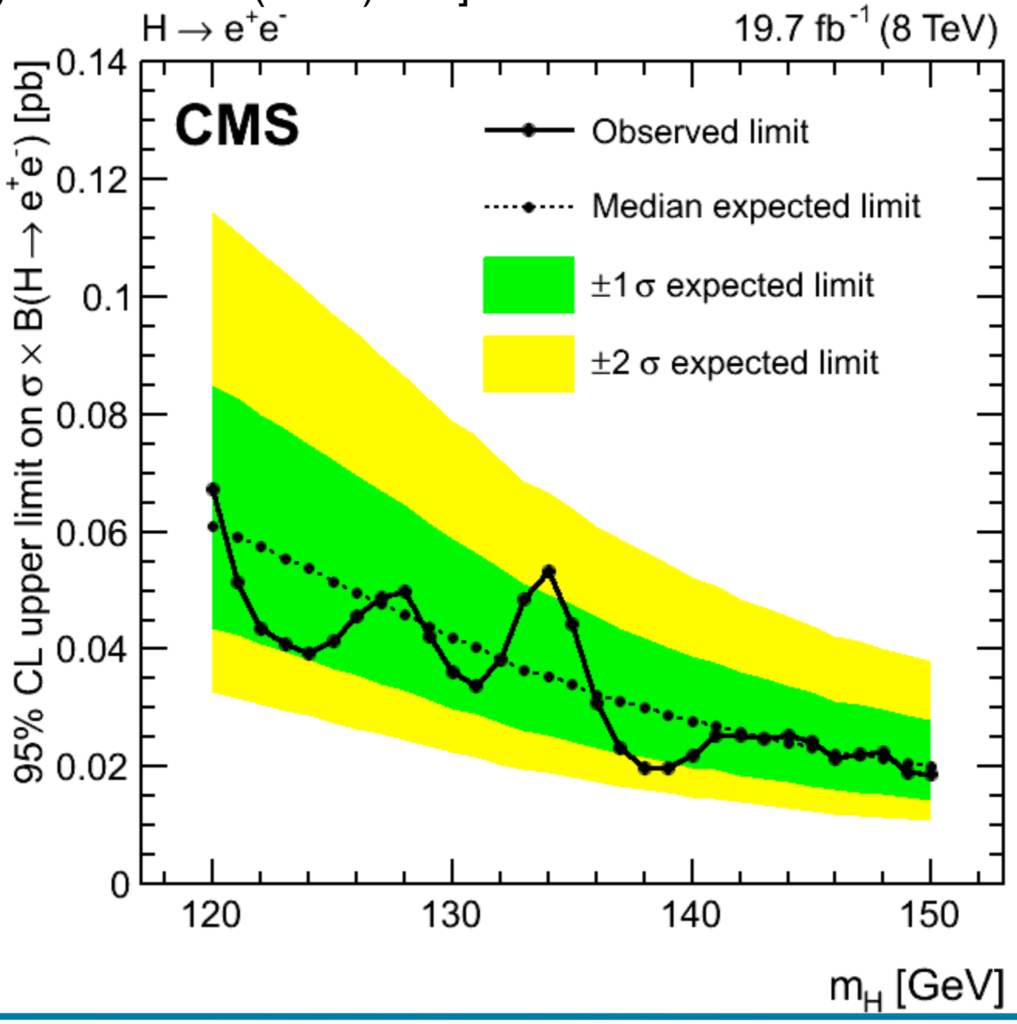








[Phys.Lett. B744 (2015) 184]



Charm-quark Yukawa coupling

Substantial recent activity on probing directly the charm-quark Yukawa coupling at the LHC.
Two lines of attack (non-exhaustive list of references):
→ Look for H→ccbar using charm-tagging, in a manner similar to the H→bbbar
[Phys.Rev. D89 (2014) 3, 033014; arXiv:1503.00290]
→ Exploit the exclusive decays H→Qγ as direct probe to the quark Yukawa couplings
[arXiv:1505.03870, Phys.Lett. B82 (1979) 411; Phys.Rev. D27 (1983) 2762; Yad.Fiz. 46, 864 (1987); Phys.Rev. D88 (2013) 5, 053003; Phys.Rev. D90 (2014) 11, 113010, arXiv:1505.03870 [hep-ph]]
→ Sensitive to BSM physics [arXiv:1504.04022, Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79]

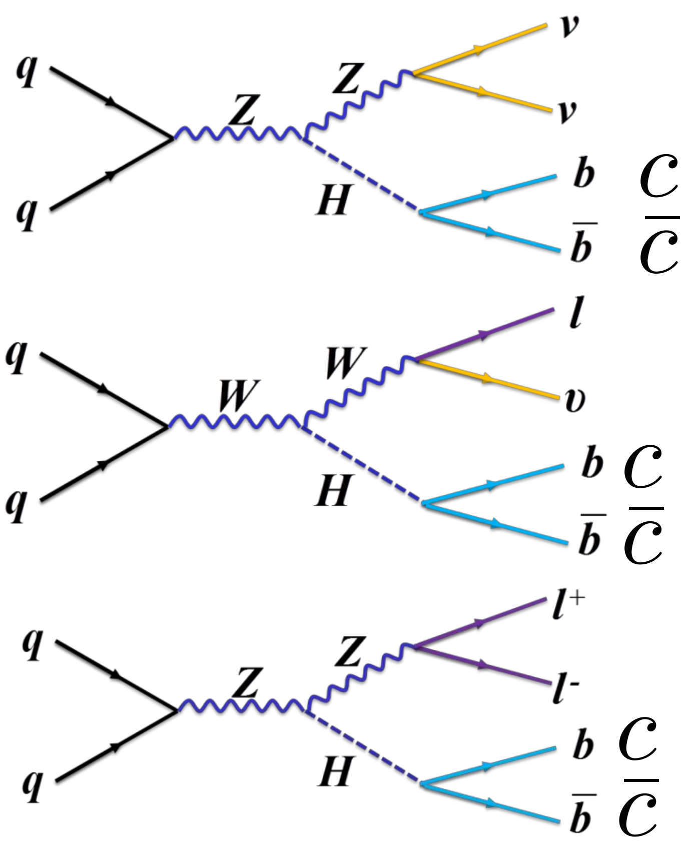
Charm Tagging

One may “re-interpret” the h→bbbar search to include the possibility of anomalous h→ccbar production

→ In the SM BR(h→ccbar)/BR(h→bbbar) ~ 5.1%

→ Enhancement in the charm Yukawa: ↑BR(h→ccbar), ↓BR(h→bbbar) [through ↑Γ_h]

→ Constrains only a linear combination of μ_b and μ_c → need multiple b-tagging points

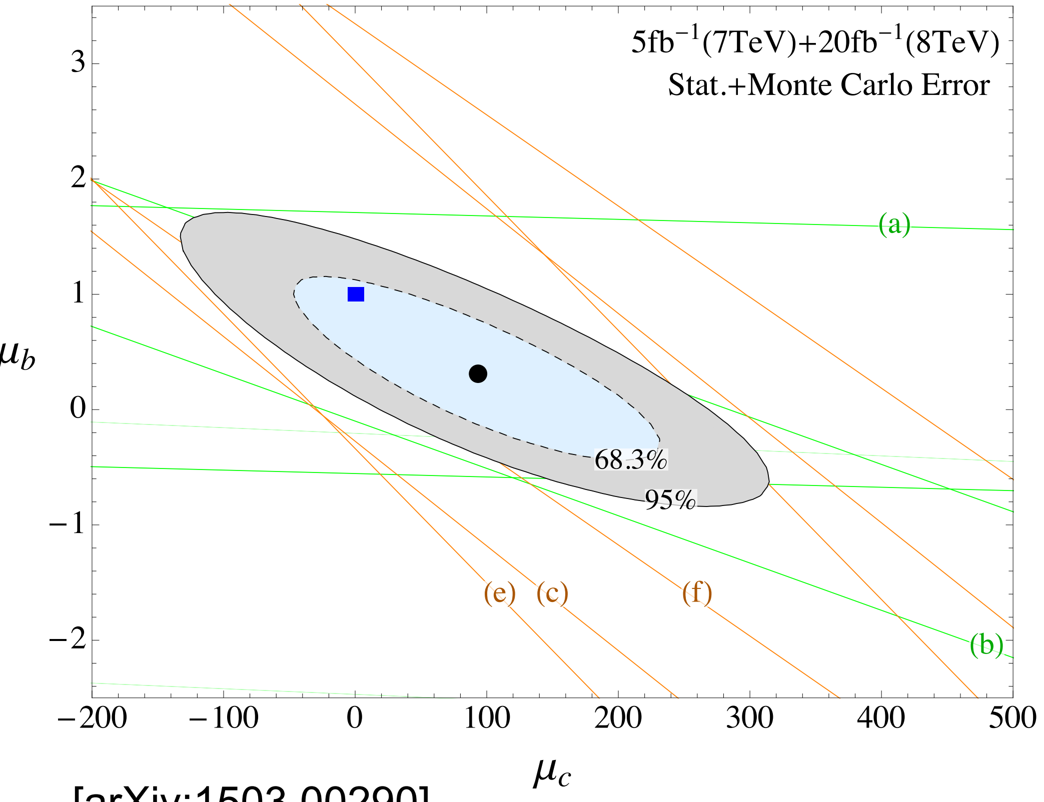


$$\mu_b = \frac{\sigma\,\mathrm{BR}_{b\bar{b}}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}} \to \frac{\sigma\,\mathrm{BR}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma\,\mathrm{BR}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}}{\sigma_{\mathrm{SM}}\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2}}$$

$$= \mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\,\mu_c\,,$$

[arXiv:1503.00290]

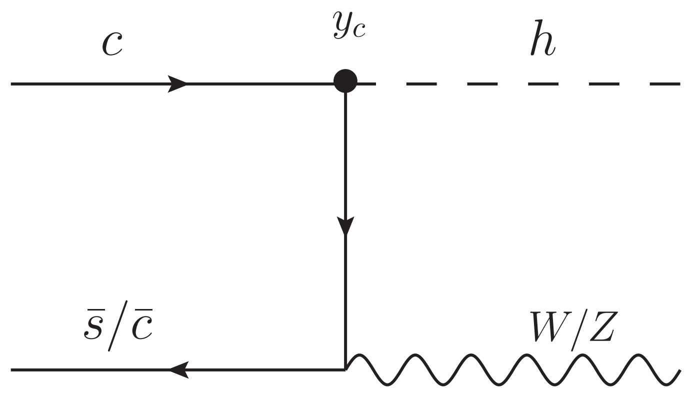
$$\mu_c = 95^{+90(175)}_{-95(180)} \text{ at } 68.3(95)\% \text{ CL.}$$



[arXiv:1503.00290]

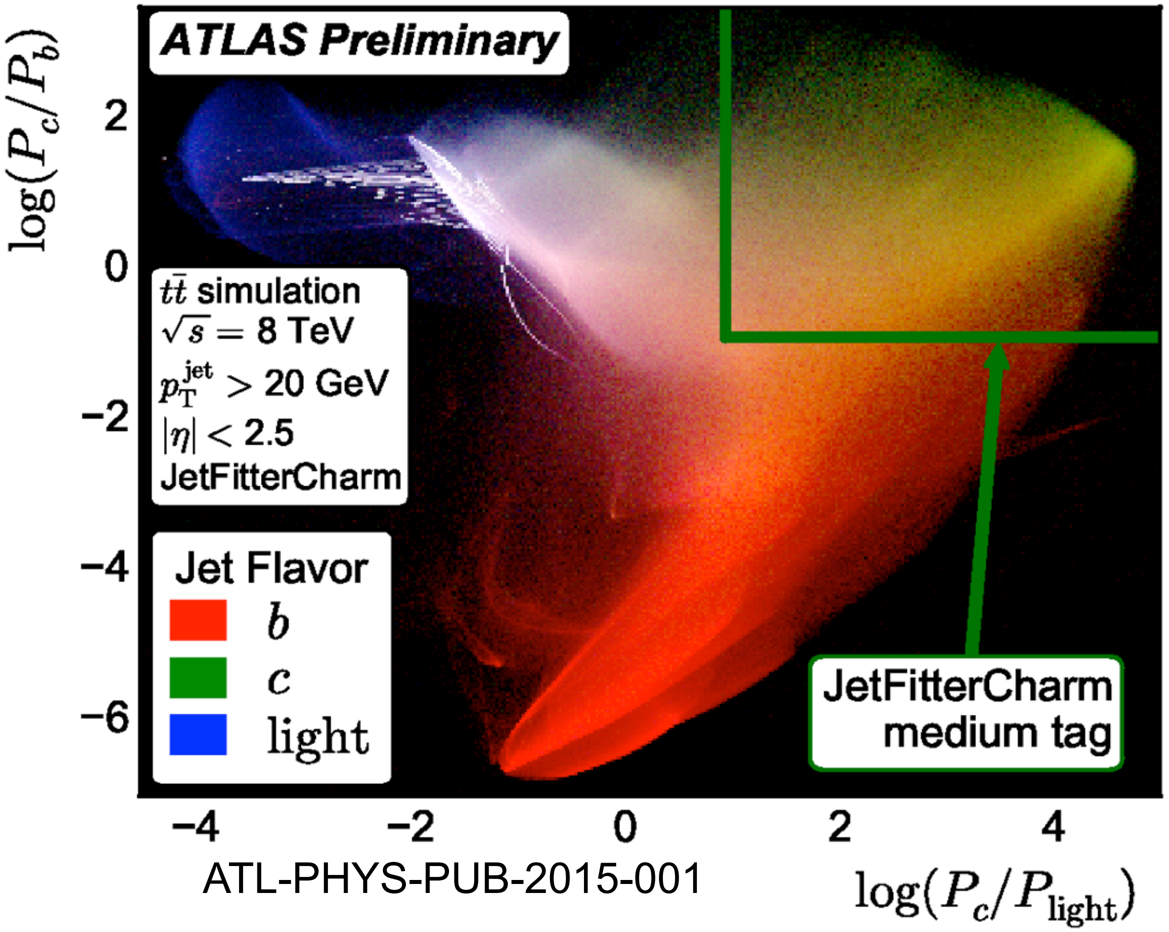
→ Extracting info about Yukawa couplings: account for new production modes

$$\kappa_c \lesssim 234 \text{ at } 95\% \text{ CL}\,,$$



→ No experiment has performed this analysis yet!

Charm Tagging



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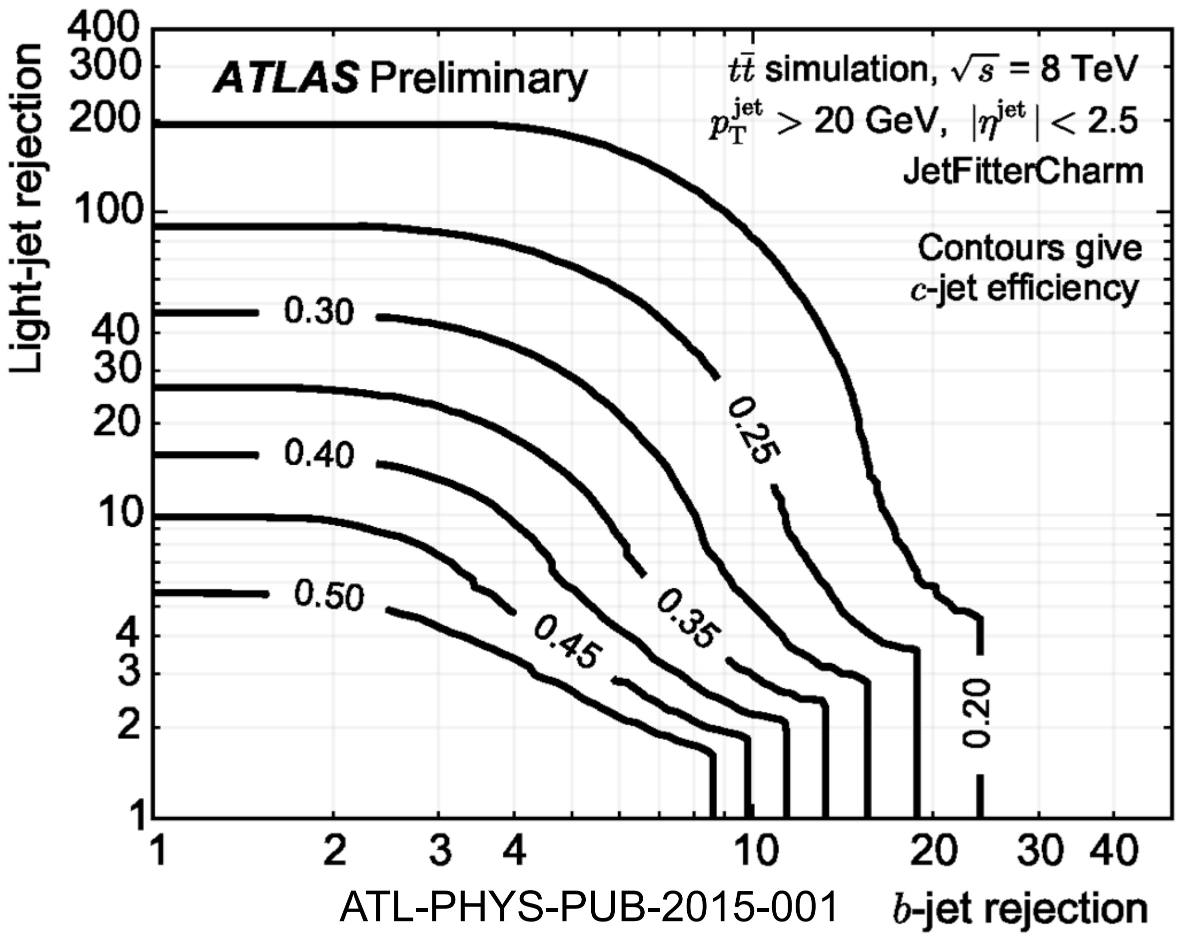


ATL-PHYS-PUB-2015-001

To resolve the two contributions improved c-tagging is needed
[ideally you would like to completely separate b- and c-jets

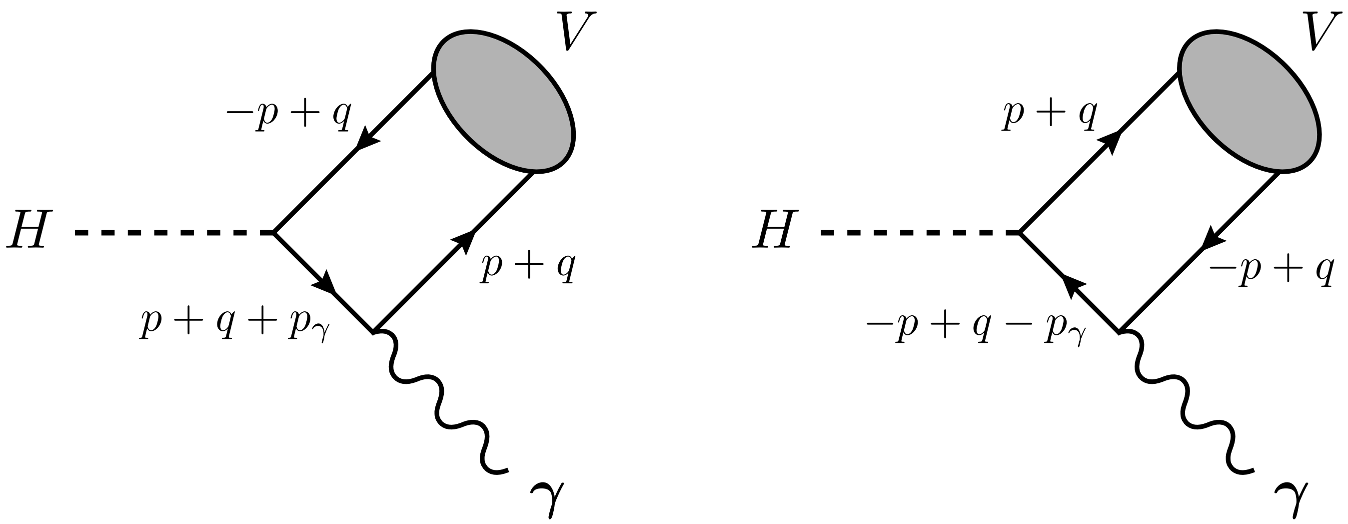
→ Future H→ccbar searches will benefit from dedicated c-tagging, already applied in ATLAS scalar-charm search. [arXiv:1501.01325]

However:
- complicated analysis with large QCD backgrounds
- signal sits on top of large (x20) h→bb “background”
- sensitivity to systematics of b/c-tagging efficiency
- need dedicated simulations for decay and production

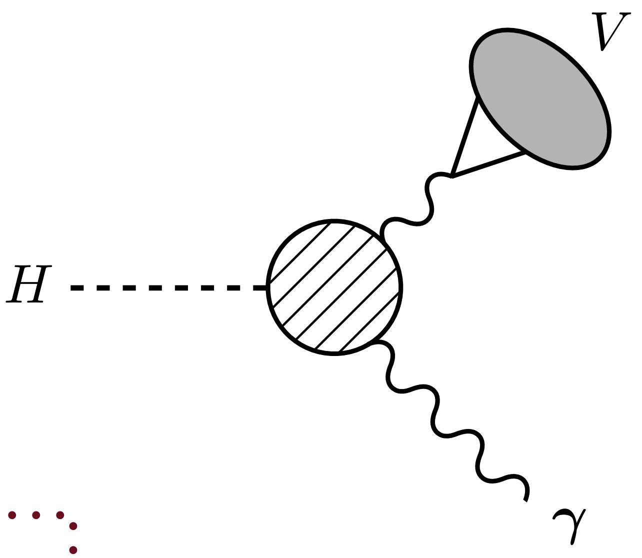
Exclusive Decays h→Qγ

These exclusive decays can lead to quite distinct experimental signatures:
→ Decay of a high-pT Quarkonium back-to-back with a high-pT photon.

“Direct” amplitude



“Indirect” contribution



Phys.Rev. D88 (2013) 5, 053003

Direct amplitude alone:
→ $\mathrm{BR}_{\mathrm{SM}}(H\to J/\psi\gamma) = 5.48\cdot 10^{-8}$
→ $\mathrm{BR}_{\mathrm{SM}}(H\to \Upsilon\gamma) = 3.84\cdot 10^{-7}$

However, the indirect amplitude corresponds to a significant contribution
→ Larger than the direct amplitude
→ Negative interference between the two amplitudes could help resolve coupling sign-ambiguity

$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

$$\mathcal{B}_{\mathrm{SM}}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6},$$

$$\mathcal{B}_{\mathrm{SM}}[H \to \Upsilon(1S) + \gamma] = 6.11^{+17.41}_{-6.11} \times 10^{-10},$$

$$\mathcal{B}_{\mathrm{SM}}[H \to \Upsilon(2S) + \gamma] = 2.02^{+1.86}_{-1.28} \times 10^{-9},$$

$$\mathcal{B}_{\mathrm{SM}}[H \to \Upsilon(3S) + \gamma] = 2.44^{+1.75}_{-1.30} \times 10^{-9}.$$

Phys.Rev. D90 (2014) 11, 113010

$$\mathrm{Br}(h \to J/\psi\,\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\mathrm{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

$$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\,{}^{+\,1.75}_{-\,1.21}\,{}_{\mathrm{direct}} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

$$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma) = (2.34 \pm 0.04_{f_{\Upsilon(2S)}}\,{}^{+\,0.75}_{-\,0.99}\,{}_{\mathrm{direct}} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-9}\,,$$

$$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma) = (2.13 \pm 0.04_{f_{\Upsilon(3S)}}\,{}^{+\,0.75}_{-\,1.12}\,{}_{\mathrm{direct}} \pm 0.10_{h\to\gamma\gamma}) \cdot 10^{-9}\,.$$

arXiv:1505.03870 [hep-ph]

Exclusive Decays Z→Qγ: J/ψ and Υ

→ The analogous Z boson decays also attracting significant attention [Nucl. Phys. B 174, 317 (1980), Theor. Math. Phys. 170, 39 (2012), arXiv:1411.5924, JHEP 1504 (2015) 101]

→ These exclusive final states are experimentally unconstrained

→ Could be sensitive to BSM contributions

→ LEP has accurately measured couplings to b- and c-quarks (~1%), but couplings to light quarks less constrained.

Recently, a number of numerical results have appeared, regarding the predictions on these decay rates.

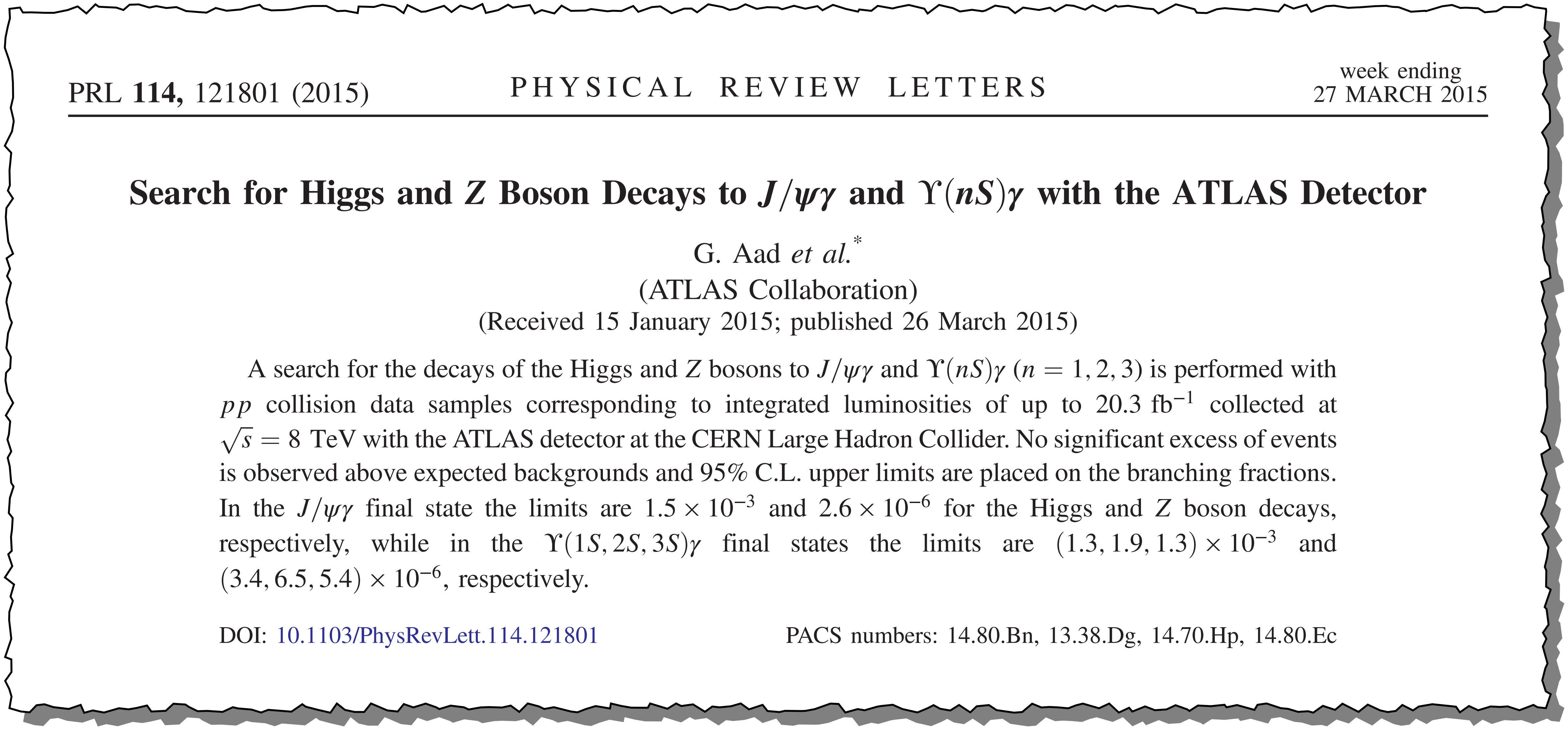
arXiv:1411.5924

$$\boxed{\begin{aligned} B_{SM}(Z \to J/\psi + \gamma) &= (9.96 \pm 1.86) \times 10^{-8}, \\ B_{SM}(Z \to \Upsilon(1S) + \gamma) &= (4.93 \pm 0.51) \times 10^{-8}, \\ B_{SM}(Z \to \phi + \gamma) &= (1.17 \pm 0.08) \times 10^{-8}. \end{aligned}}$$

JHEP 1504 (2015) 101

Decay mode	Branching ratio
$Z^0 \to \pi^0\gamma$	$(9.80\,{}^{+0.09}_{-0.14}{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,{}^{+0.04}_{-0.06}{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,{}^{+0.03}_{-0.05}{}_{\mu} \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$
$Z^0 \to \phi\gamma$	$(8.63\,{}^{+0.08}_{-0.13}{}_{\mu} \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$
$Z^0 \to J/\psi\,\gamma$	$(8.02\,{}^{+0.14}_{-0.15}{}_{\mu} \pm 0.20_f\,{}^{+0.39}_{-0.36}{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(1S)\,\gamma$	$(5.39\,{}^{+0.10}_{-0.10}{}_{\mu} \pm 0.08_f\,{}^{+0.11}_{-0.08}{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(4S)\,\gamma$	$(1.22\,{}^{+0.02}_{-0.02}{}_{\mu} \pm 0.13_f\,{}^{+0.02}_{-0.02}{}_{\sigma}) \cdot 10^{-8}$
$Z^0 \to \Upsilon(nS)\,\gamma$	$(9.96\,{}^{+0.18}_{-0.19}{}_{\mu} \pm 0.09_f\,{}^{+0.20}_{-0.15}{}_{\sigma}) \cdot 10^{-8}$

consistent when rescaled to up-to-date value of f_ϕ



PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with pp collision data samples corresponding to integrated luminosities of up to 20.3 fb^{-1} collected at $\sqrt{s} = 8$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are 1.5×10^{-3} and 2.6×10^{-6} for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.

DOI: 10.1103/PhysRevLett.114.121801 PACS numbers: 14.80.Bn, 13.38.Dg, 14.70.Hp, 14.80.Ec

ATLAS performed the first search for these exclusive decays of the Higgs and Z bosons
H/Z→Qγ, where Q = J/ψ or Υ(nS), n=1,2,3

$h\rightarrow J/\psi\gamma$ and $h\rightarrow Y(ns)\gamma$

Phys.Rev.Lett. 114 (2015) 12, 121801

Signature: $\mu^+\mu^-+\gamma$

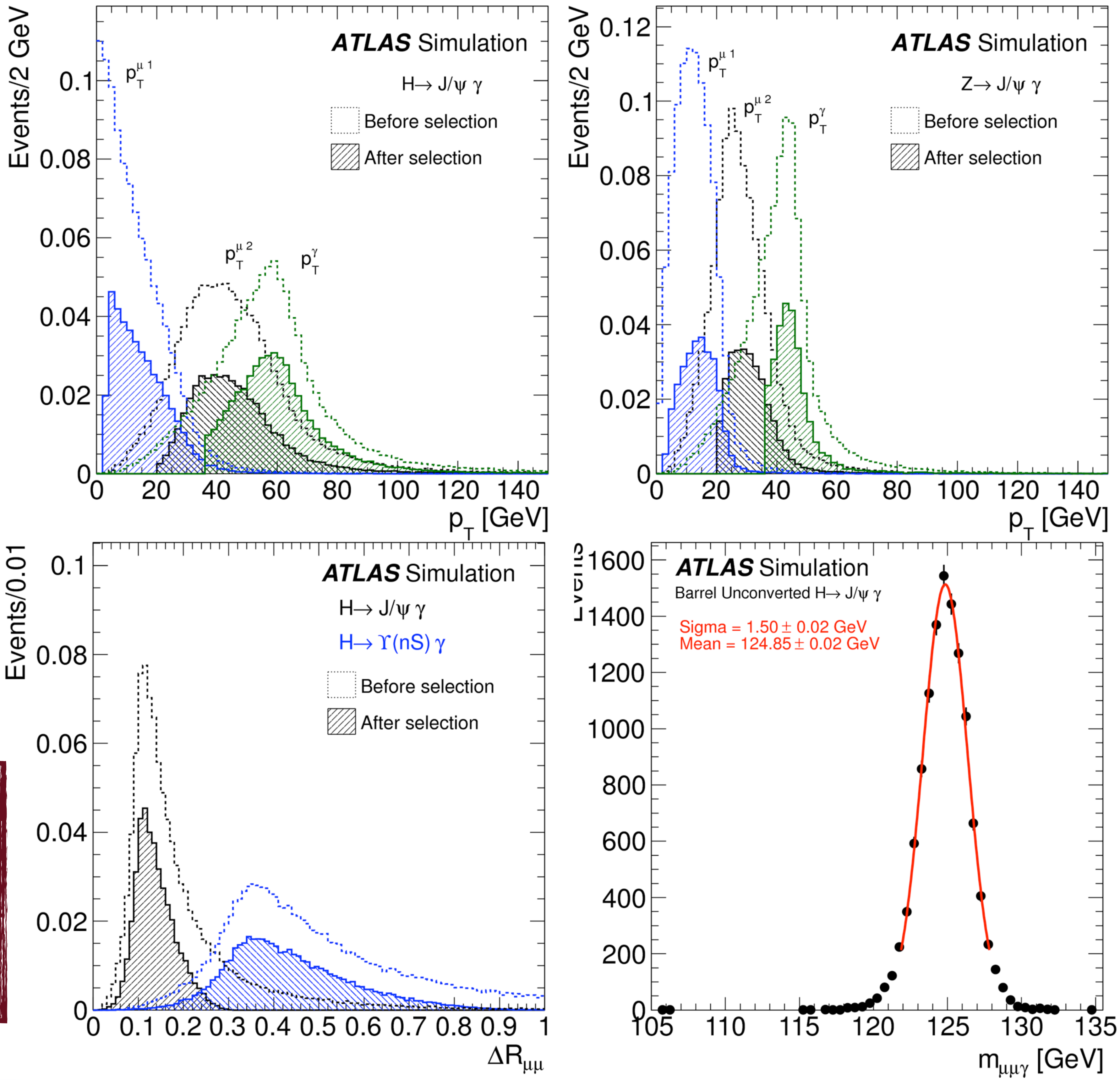
→ event selection:
  single(di)-muon trigger
  $pT_\mu>20,3$ GeV,
  $pT_{\mu\mu}>36$ GeV,
  $pT_\gamma>36$ GeV
  $\mu\mu$ and γ isolation,
  [J/ψ mass requirement]
  L_{xy} significance,
  $\Delta\varphi(\mu\mu,\gamma)>0.5$

→ total signal acceptance/efficiency
  $H(Z)\rightarrow J/\psi\gamma\rightarrow\mu^+\mu^-+\gamma$ ~ 22% (12%)
  $H(Z)\rightarrow Y\gamma\rightarrow\mu^+\mu^-+\gamma$ ~ 28% (15%)

→ $m_{\mu\mu\gamma}$ mass resolution ~1.2-1.8%

$e^+e^-+\gamma$

experimentally more challenging
- dedicated reconstruction for nearby electrons
- poorer mass resolution/efficiency
- typically larger backgrounds



h→J/ψγ and h→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 12, 121801

Categories

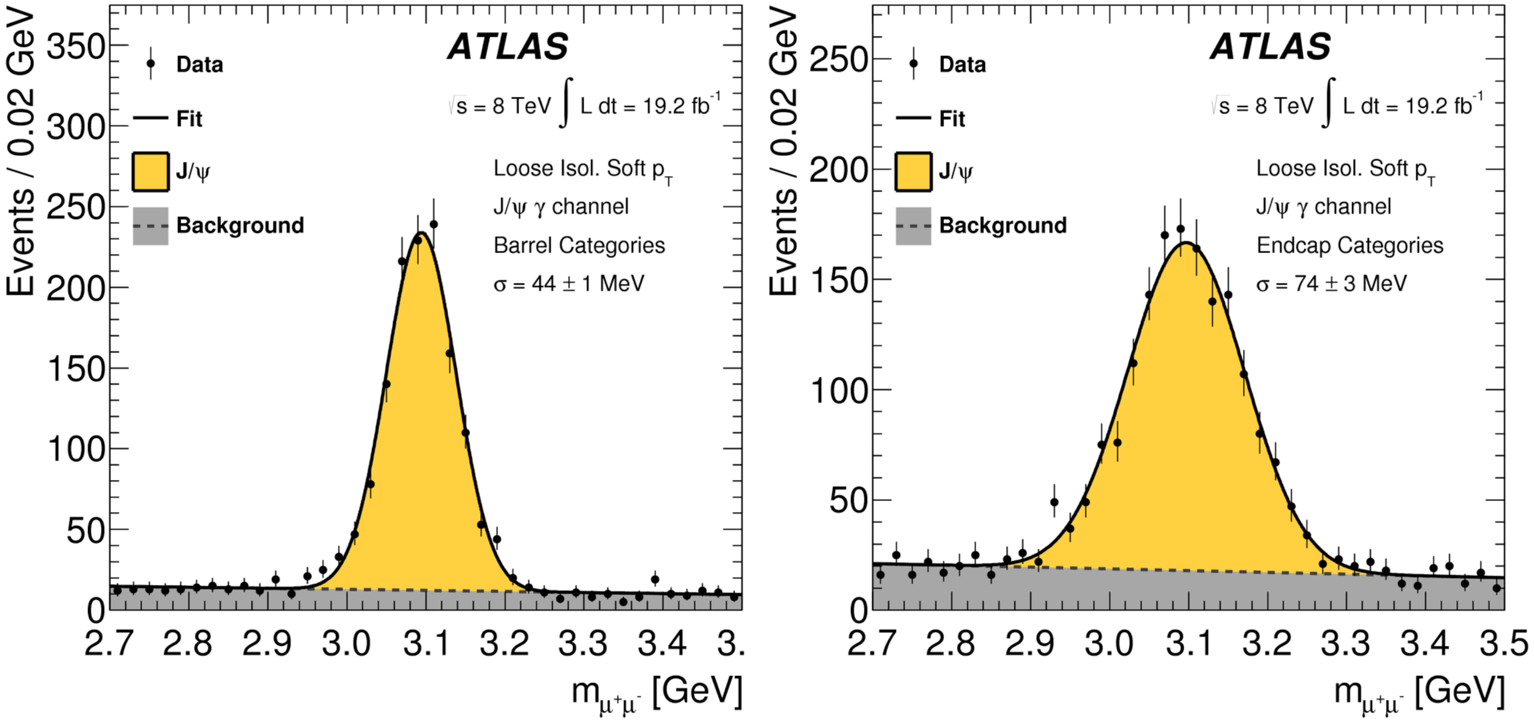
For this search simple - detector performance driven categorisation

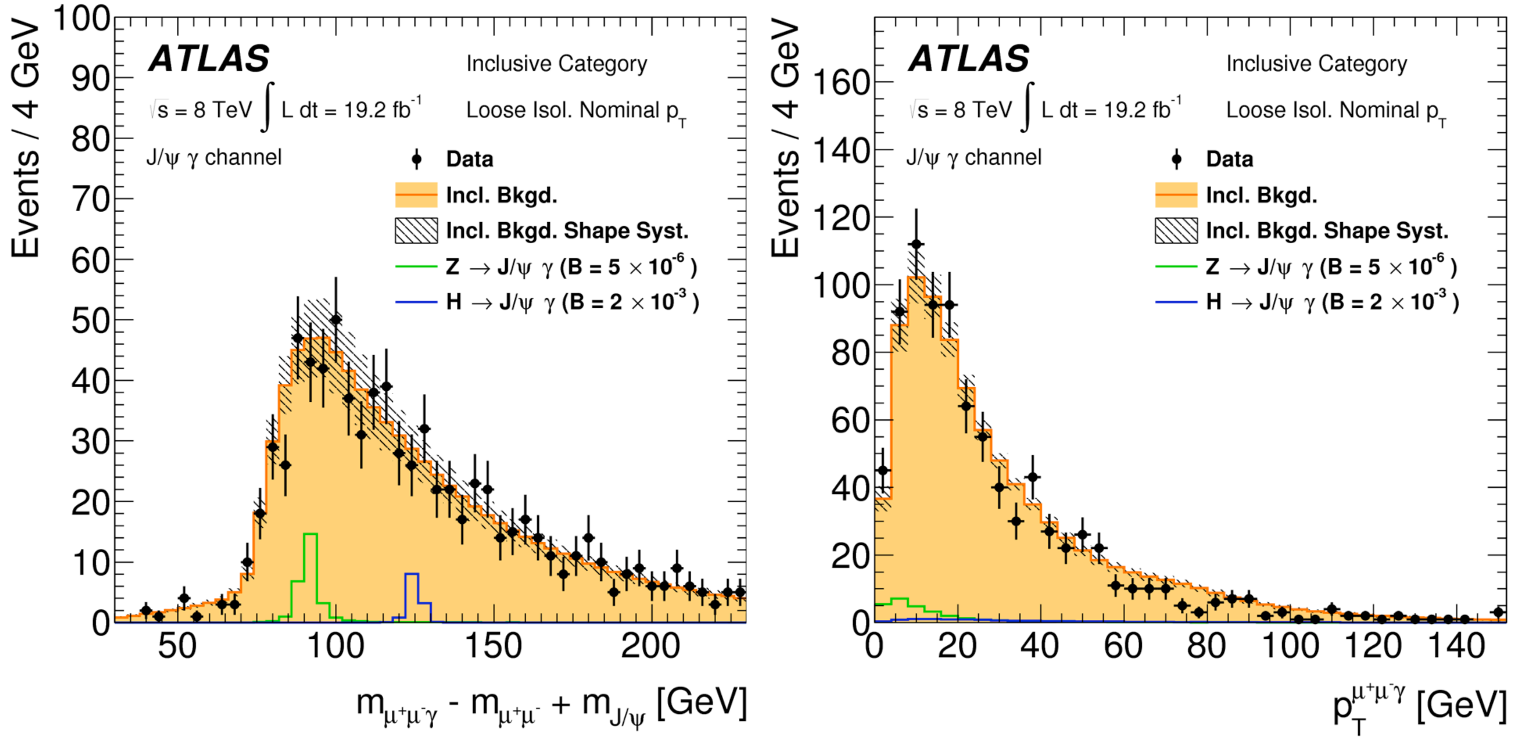
→ Muon pseudo-rapidity
  → Both Central/One Non-Central
→ Photon Unconverted/Converted

Background

→ inclusive Quarkonium with jet “seen” as γ
  → small component of combinatoric
→ Non-parametric data-driven background estimation
→ for Υ(nS)γ also Z→μμγ_{FSR} from side-band fit

Category	Observed (Expected Background)					Signal	
		Mass Range [GeV]				Z	H
	All	80–100		115–135		$\mathcal{B}$ $[10^{-6}]$	$\mathcal{B}$ $[10^{-3}]$
				$J/\psi\,\gamma$			
BU	30	9	(8.9±1.3)	5	(5.0±0.9)	1.29±0.07	1.96±0.24
BC	29	8	(6.0±0.7)	3	(5.5±0.6)	0.63±0.03	1.06±0.13
EU	35	8	(8.7±1.0)	10	(5.8±0.8)	1.37±0.07	1.47±0.18
EC	23	6	(5.6±0.7)	2	(3.0±0.4)	0.99±0.05	0.93±0.12
				$\Upsilon(nS)\,\gamma$			
BU	93	42	(39±6)	16	(12.9±2.0)	1.67±0.09	2.6±0.3
BC	71	32	(27.7±2.4)	5	(9.7±1.2)	0.79±0.04	1.45±0.18
EU	125	49	(47±6)	16	(17.8±2.4)	2.24±0.12	2.5±0.3
EC	85	31	(31±5)	18	(12.3±1.9)	1.55±0.08	1.60±0.20

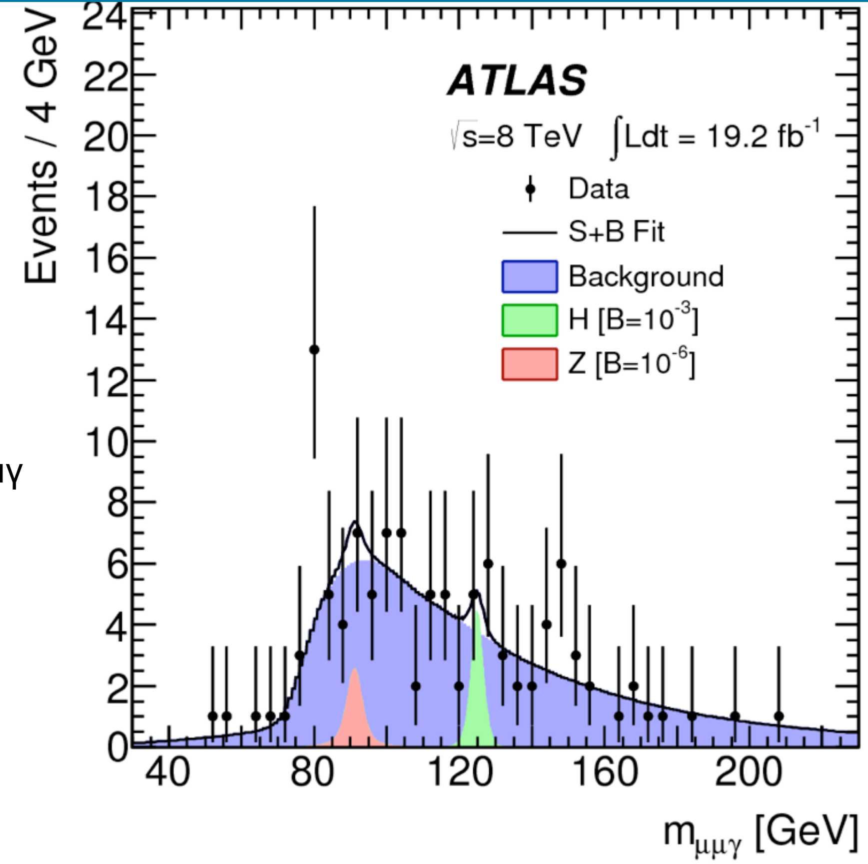


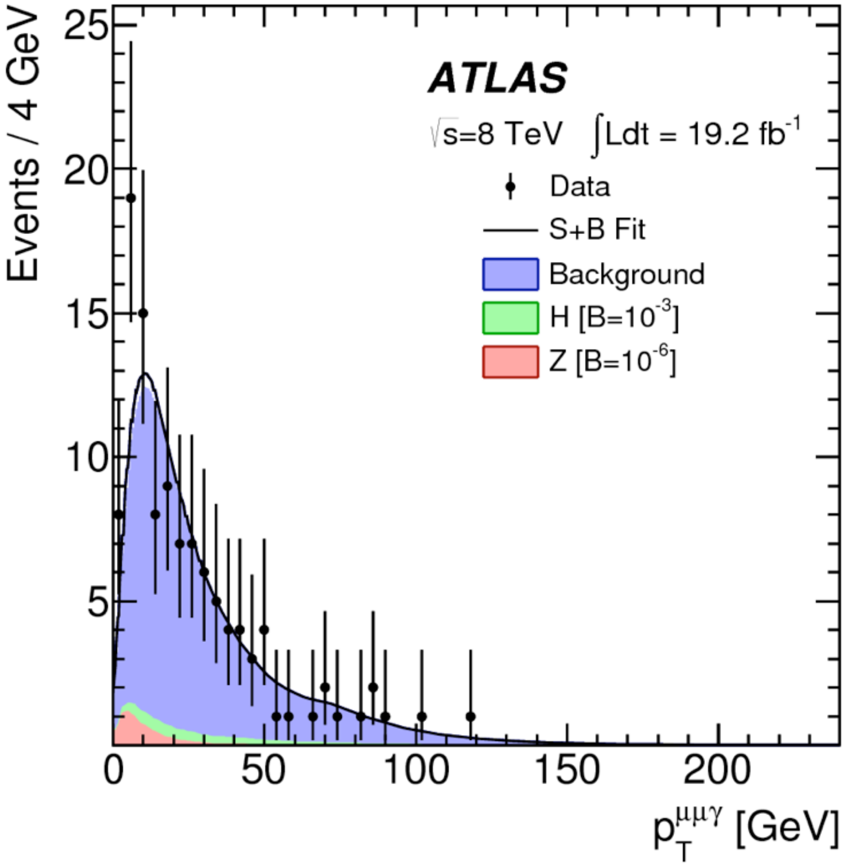


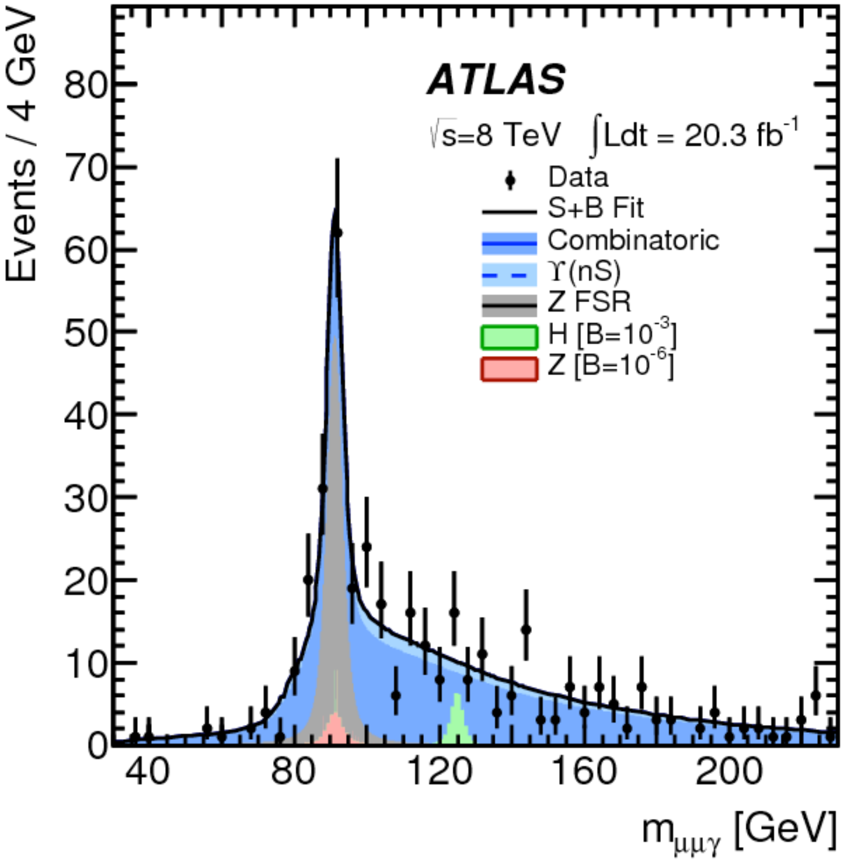
h→J/ψγ and h→Y(ns)γ: Results

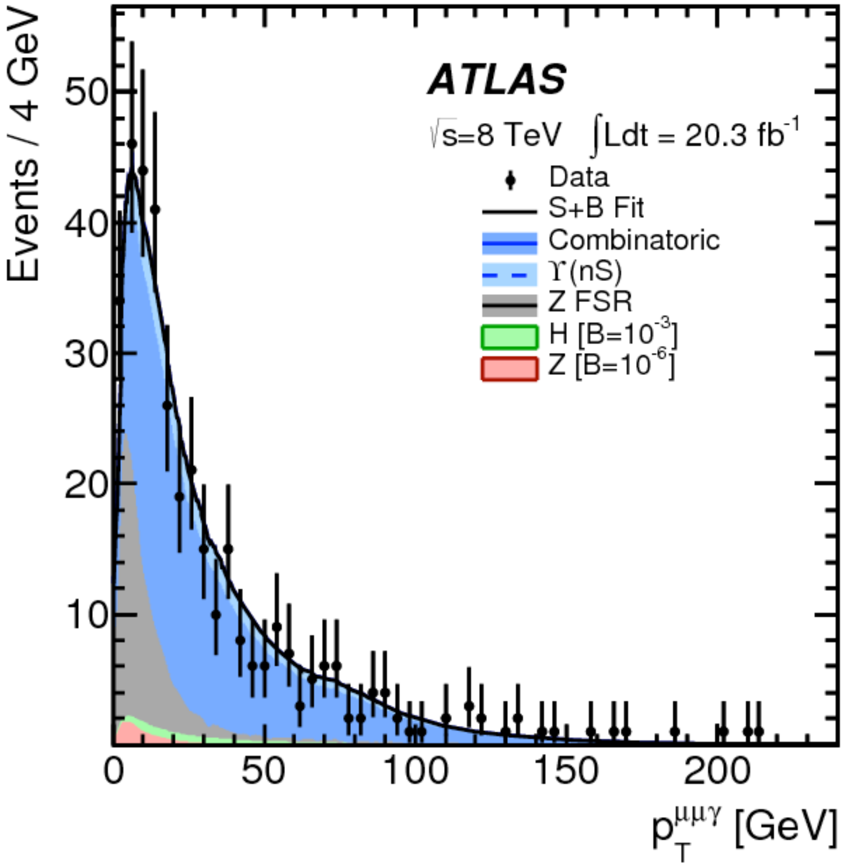
Phys.Rev.Lett. 114 (2015) 12, 121801

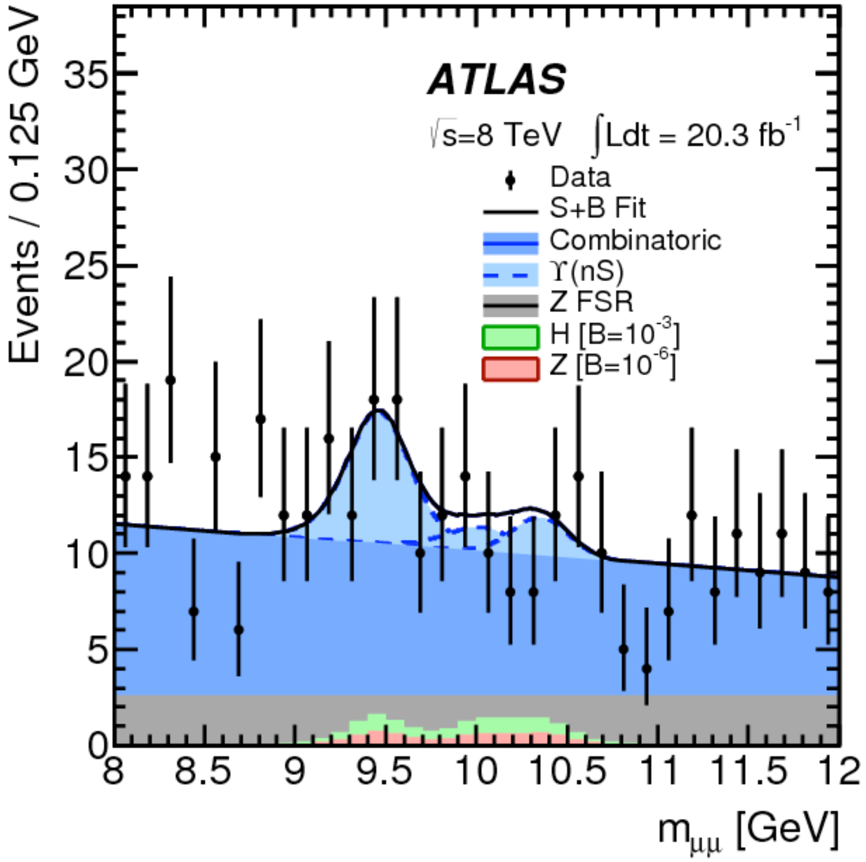
→ Multi-observable fit to $m_{\mu\mu\gamma}$, $pT_{\mu\mu\gamma}$
  → also $m_{\mu\mu}$ for Y(nS)γ
→ No significant excess above background observed





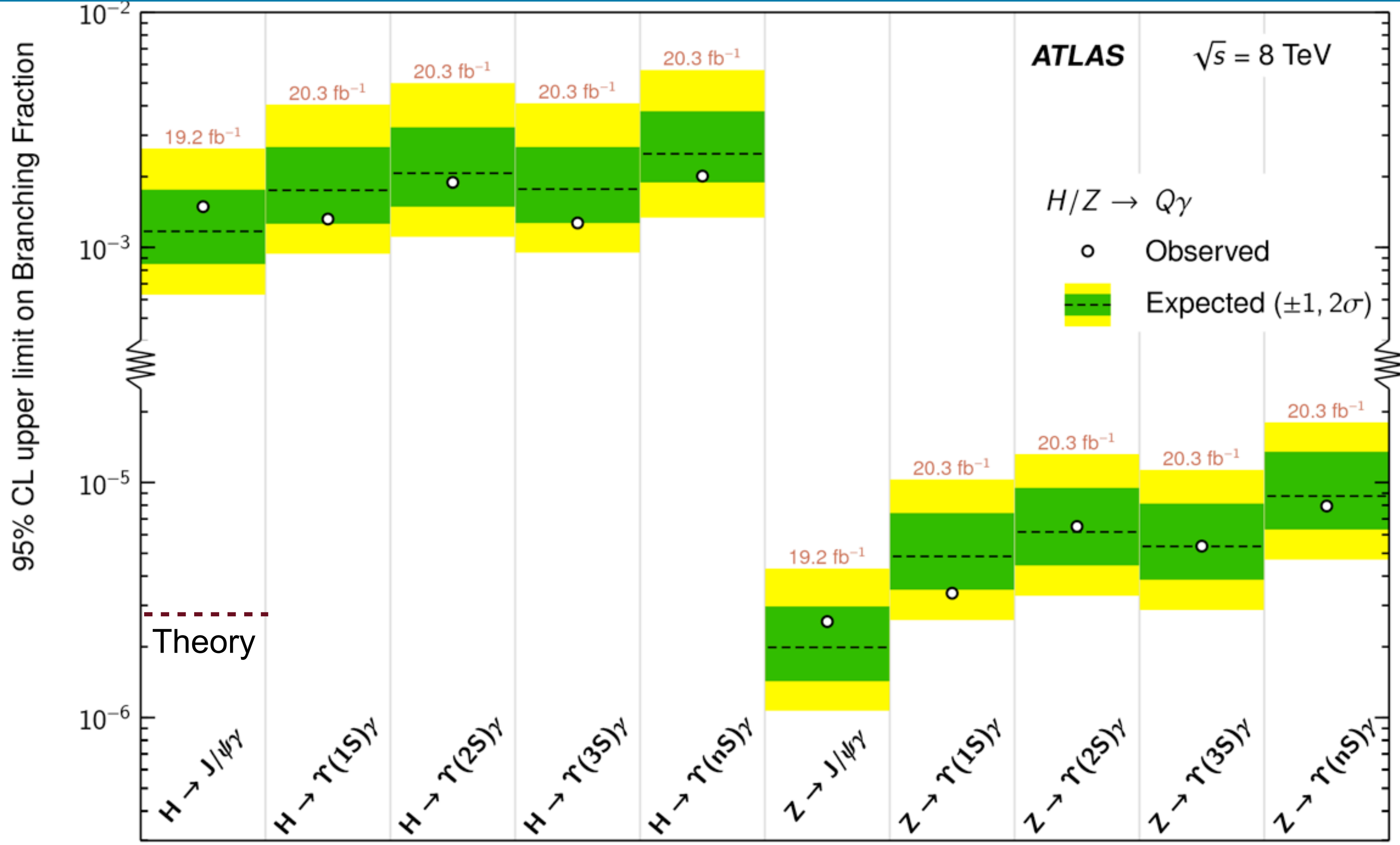






h→J/ψγ and h→Υ(ns)γ: Results

Phys.Rev.Lett. 114 (2015) 12, 121801



First search for H/Z→Qγ, will constitute the basis for Run 2 and HL-LHC extrapolations

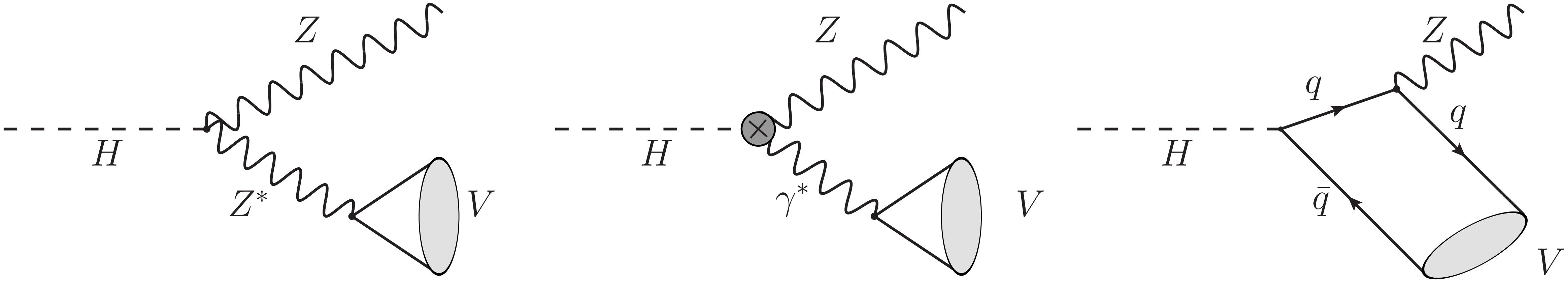
BR 95% CLs upper limits: ~10^{-3} level for Higgs boson (SM production) decays and ~10^{-6} for the Z boson decays

	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

This is a nice and, relatively, clean final state.
Fun and interesting thing to do!
A few drawbacks of these exclusive decays:
1) Small branching ratio,
a handful of events expected even at HL-LHC
2) At SM sensitivity significant contribution from non-resonant h→μμγ ~3×h→J/ψγ
3) This channel is also affected by potential “anomalies” in the h→γγ loop

h→ZJ/ψ and h→ZY(nS): A short note

arXiv:1411.2210



h→ZQ could be another way to approach the charm/ bottom Yukawa couplings, quite similar to the exclusive h→Qγ decays discussed earlier.

arXiv:1411.2210

$\mathcal{B}r(H \to ZV)$	$J/\psi(1S)$	$\Upsilon(1S)$
$\mathcal{B}r_{\Gamma_1}$	1.75×10^{-6}	1.68×10^{-5}
$\mathcal{B}r_{\Gamma_2}$	1.14×10^{-6}	8.33×10^{-8}
$\mathcal{B}r_{\Gamma_3}$	8.52×10^{-9}	5.80×10^{-7}
$\mathcal{B}r_{\Gamma_{12}}$	4.50×10^{-7}	1.10×10^{-6}
$\mathcal{B}r_{\Gamma_{13}}$	3.89×10^{-8}	2.89×10^{-6}
$\mathcal{B}r_{\Gamma_{23}}$	1.97×10^{-7}	4.40×10^{-7}

$$\Gamma = \Gamma_1 \kappa_V^2 + \Gamma_2 \kappa_{Z\gamma}^2 + \Gamma_3 \kappa_Q^2 + \Gamma_{12} \kappa_V \kappa_{Z\gamma} + \Gamma_{13} \kappa_V \kappa_Q + \Gamma_{23} \kappa_{Z\gamma} \kappa_Q$$

BR$_{SM}$(h→J/ψγ) ≃ BR$_{SM}$(h→ZJ/ψ)

unfortunately,
need to account for the additional
BR(Z→ee/μμ) ~6%
and properly evaluate S/B

Light-Quark Yukawa couplings

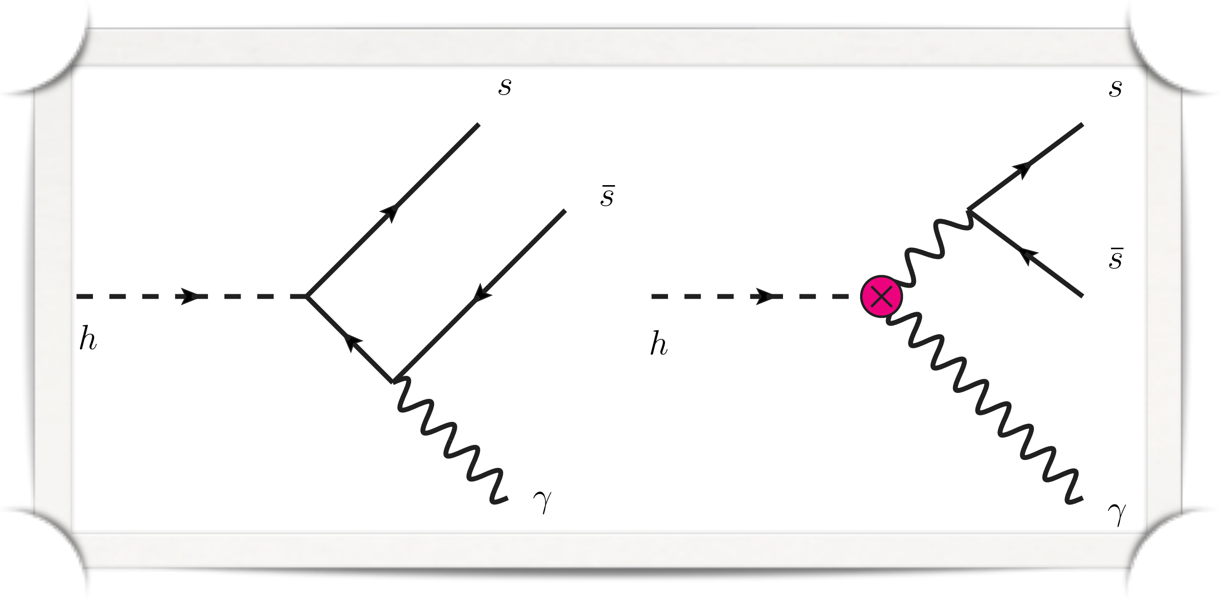
Initially, considered impossible at the LHC, recent activity on its feasibility:

→ Exploit the exclusive decays H→Qγ as direct probe to the quark Yukawa couplings

[Phys.Rev.Lett. 114 (2015) 10, 101802]

→ Sensitive to BSM physics [Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022]

The idea is to benefit from the interference of the “direct” and “indirect” amplitudes!



$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(3.0\pm0.3)\kappa_\gamma-0.78\bar{\kappa}_s]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.9\pm0.2)\kappa_\gamma-0.24\bar{\kappa}_u-0.12\bar{\kappa}_d]\times10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.6\pm0.2)\kappa_\gamma-0.59\bar{\kappa}_u-0.29\bar{\kappa}_d]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$

Phys.Rev.Lett. 114 (2015) 10, 101802

$$BR^{SM}_{h\to\phi\gamma}\approx 3\cdot10^{-6}$$

$$BR^{SM}_{h\to\rho\gamma}\approx 1.9\cdot10^{-5}$$

$$BR^{SM}_{h\to\omega\gamma}\approx 1.6\cdot10^{-6}$$

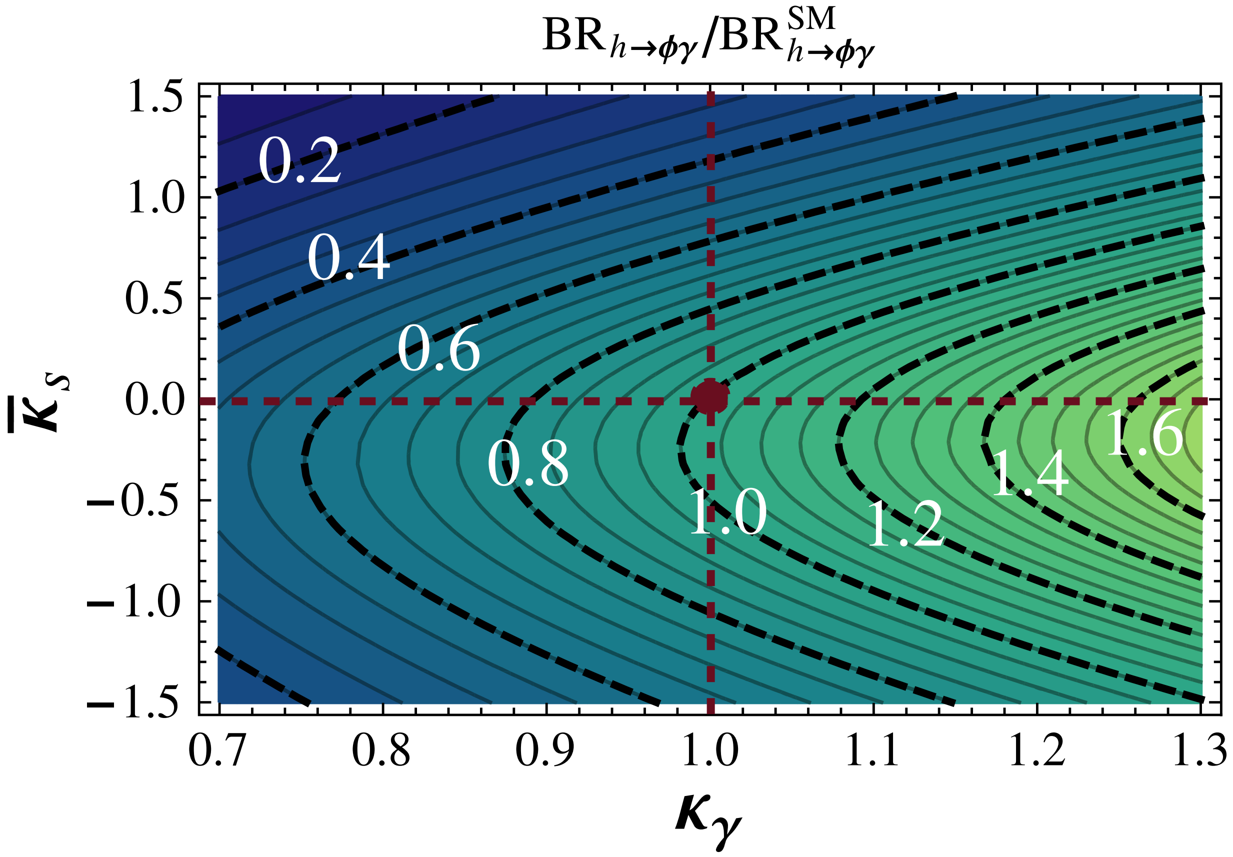
$$\mathrm{Br}(h\to\rho^0\gamma)=(1.68\pm0.02_{f_\rho}\pm0.08_{h\to\gamma\gamma})\cdot10^{-5},$$

$$\mathrm{Br}(h\to\omega\gamma)=(1.48\pm0.03_{f_\omega}\pm0.07_{h\to\gamma\gamma})\cdot10^{-6},$$

$$\mathrm{Br}(h\to\phi\gamma)=(2.31\pm0.03_{f_\phi}\pm0.11_{h\to\gamma\gamma})\cdot10^{-6},$$

arXiv:1505.03870 [hep-ph]

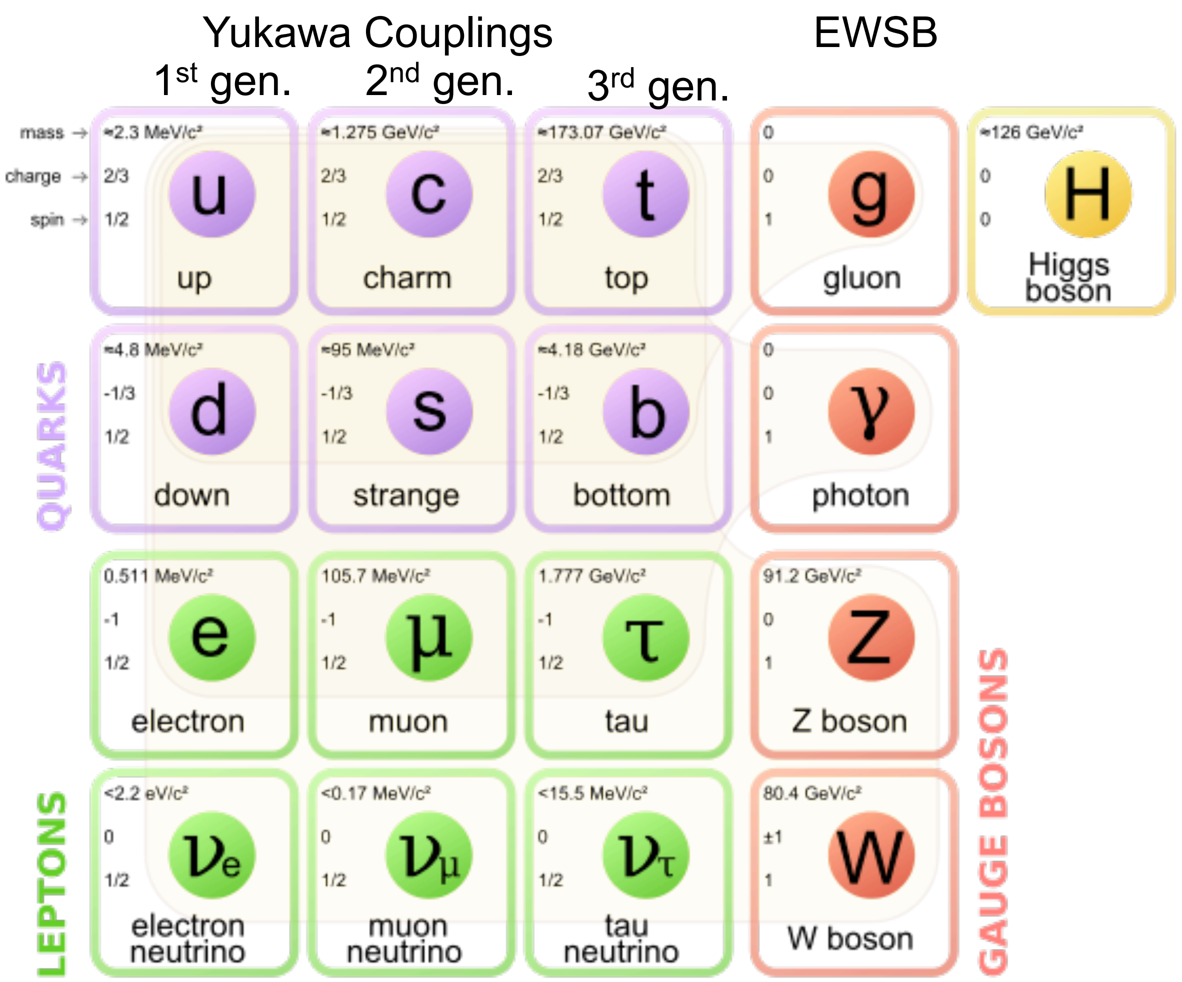
Light-Quark Yukawa couplings



$\varphi\to K^+K^-$ (BR=48.9%), ~8 events 100fb^{-1} @14 TeV!
$\omega\to\pi^+\pi^-\pi^0$ (BR=89.2%) similar rate
$\rho\to\pi^+\pi^-$ (BR~100%) expect ~100 events!

Interesting/experimentally challenging topologies!
-triggering on a photon + narrow hadronic jet
→ will benefit from ATLAS FTK
- boosted decays but overwhelming QCD backgrounds,
- Γ_ρ and ω-ρ interference

Summary



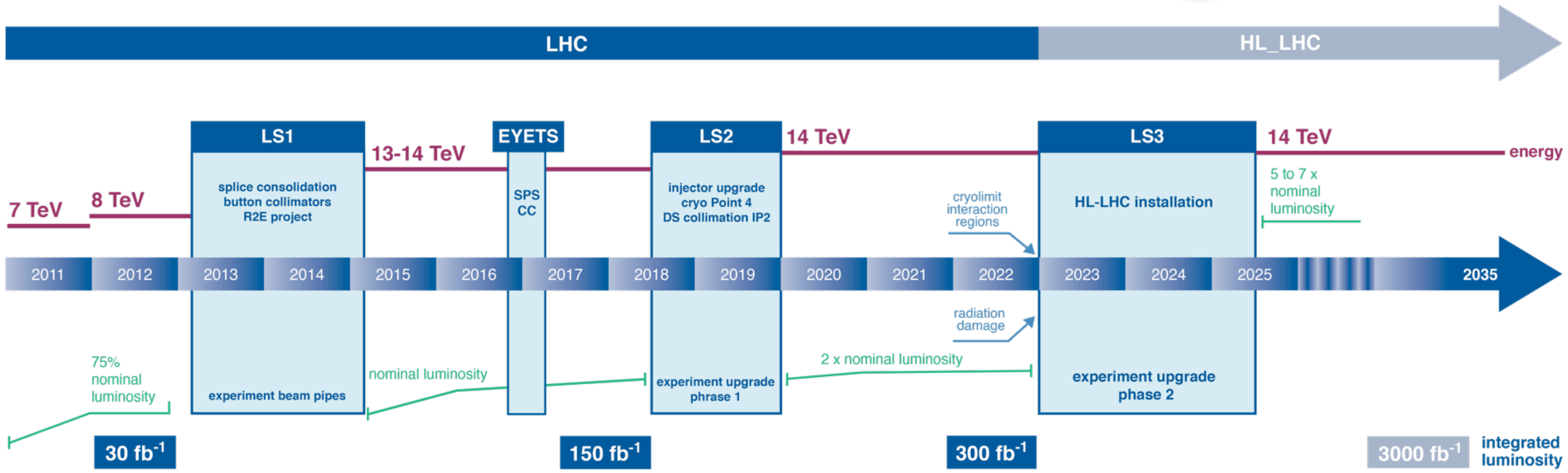
Yukawa sector likely the least theoretically motivated and constrained part of the Standard Model
→ Particularly true for 1st/2nd generation.

New Physics could be lurking here!

A wealth of information has been collected over the last few years on the nature of the Higgs boson
→ Yukawa sector still relatively unconstrained

Currently, under intense phenomenological and experimental focus; new results
(H→J/ψγ, H→Υγ, etc)
and new ideas/approaches to probe this sector at the LHC appear!

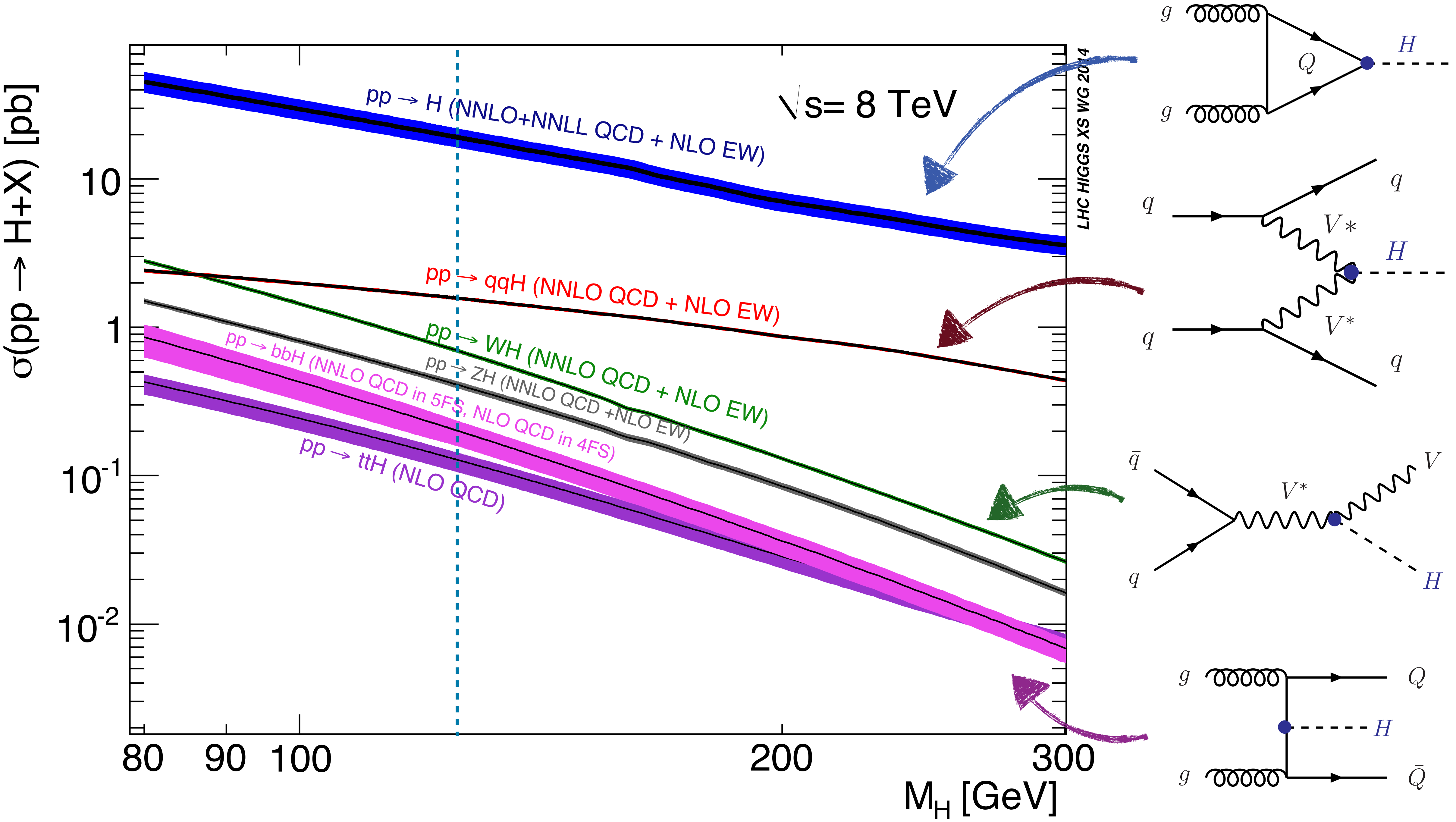
LHC / HL-LHC Plan



Most importantly:
ingenuity, both from both theory and experiment, will be crucial to achieve such an enhancement of the LHC physics potential

Additional Slides

SM Higgs boson production at the LHC



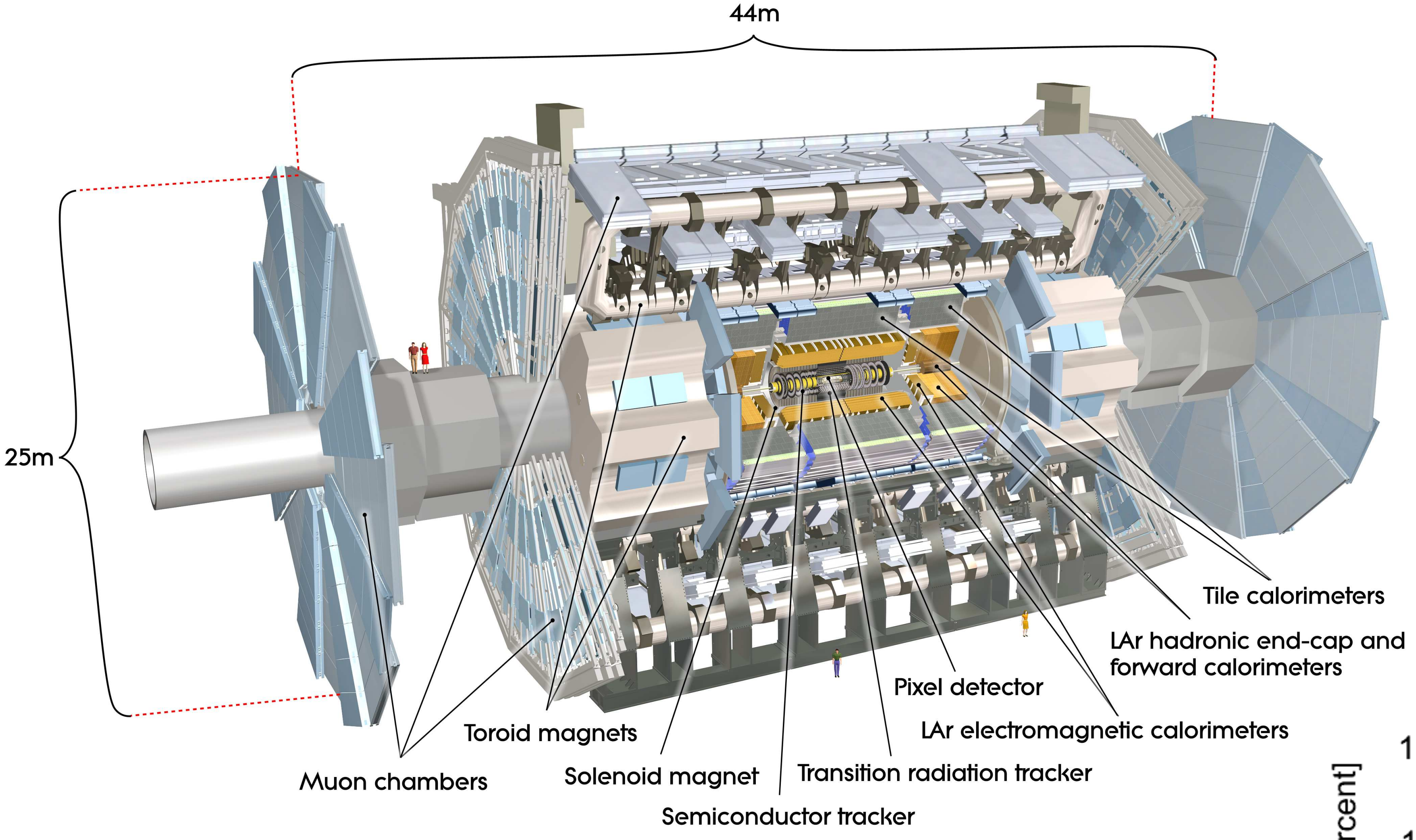
86%
m_H = 125 GeV

7%
m_H = 125 GeV

5%
m_H = 125 GeV

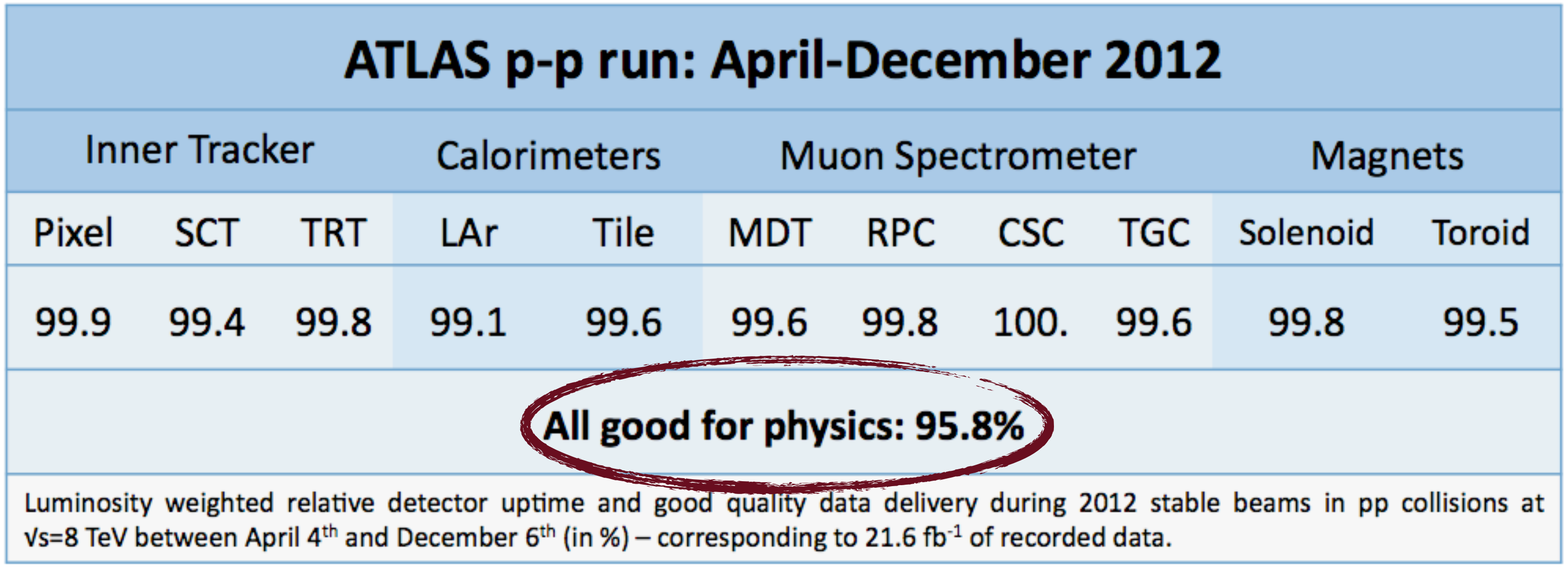
1.5%
m_H = 125 GeV

A Toroidal LHC ApparatuS



	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling Liquid Argon
Hadron Calorimetry	plastic scintillator (barrel) Liquid Argon(endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

⇒ General purpose detector designed for the harsh LHC environment

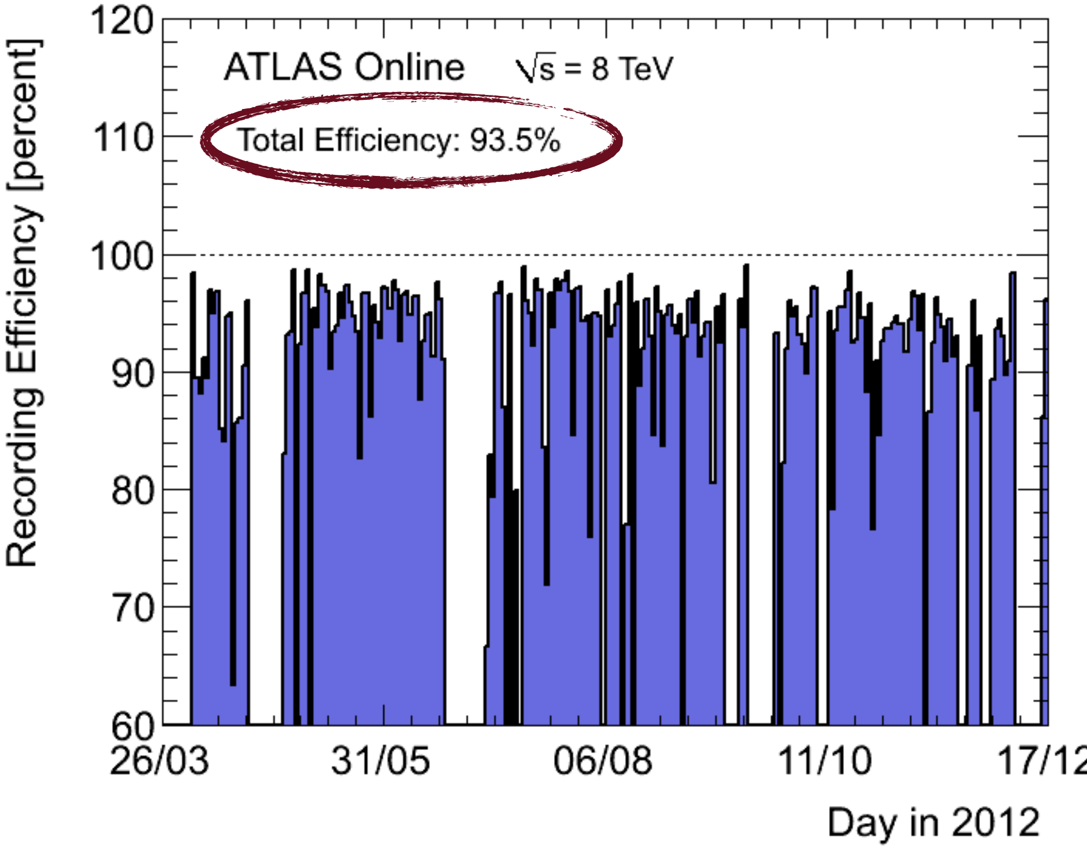


ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

All good for physics: 95.8%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

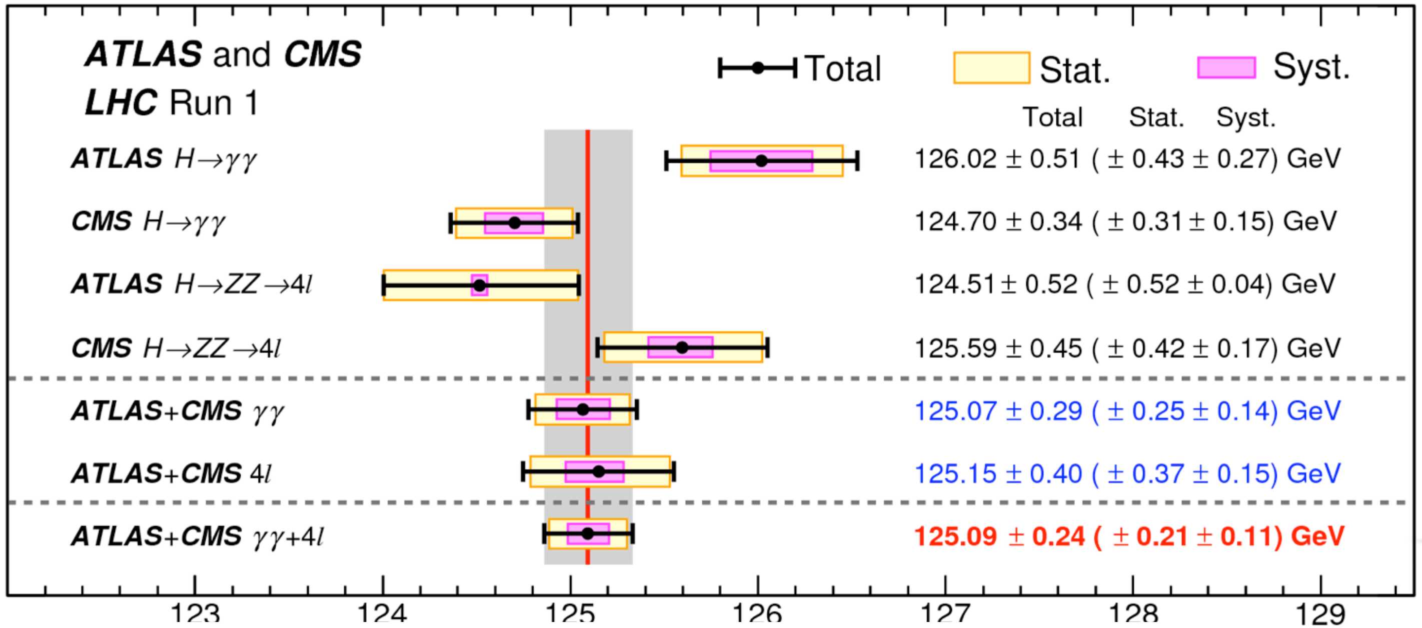


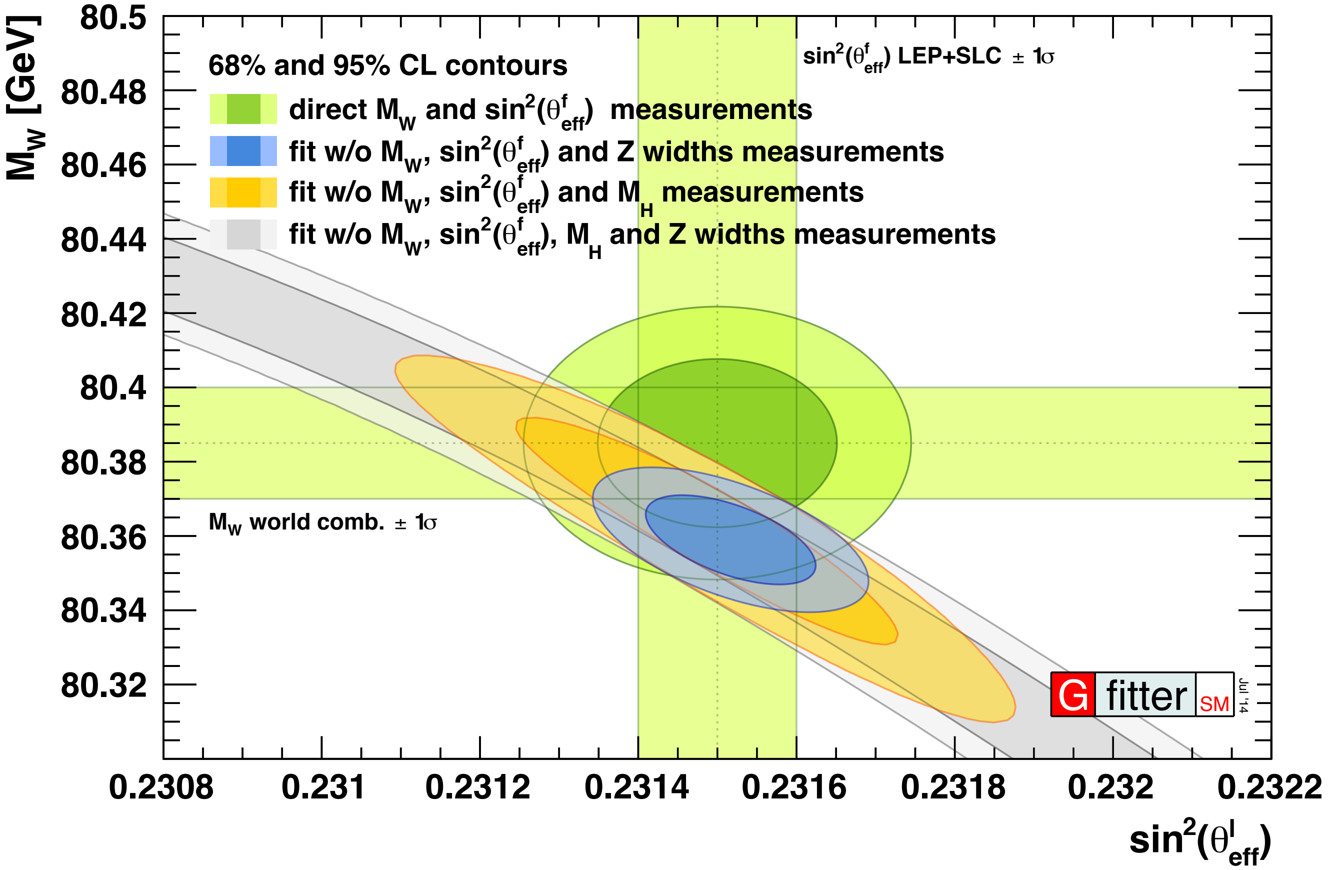
The Standard Model Higgs boson

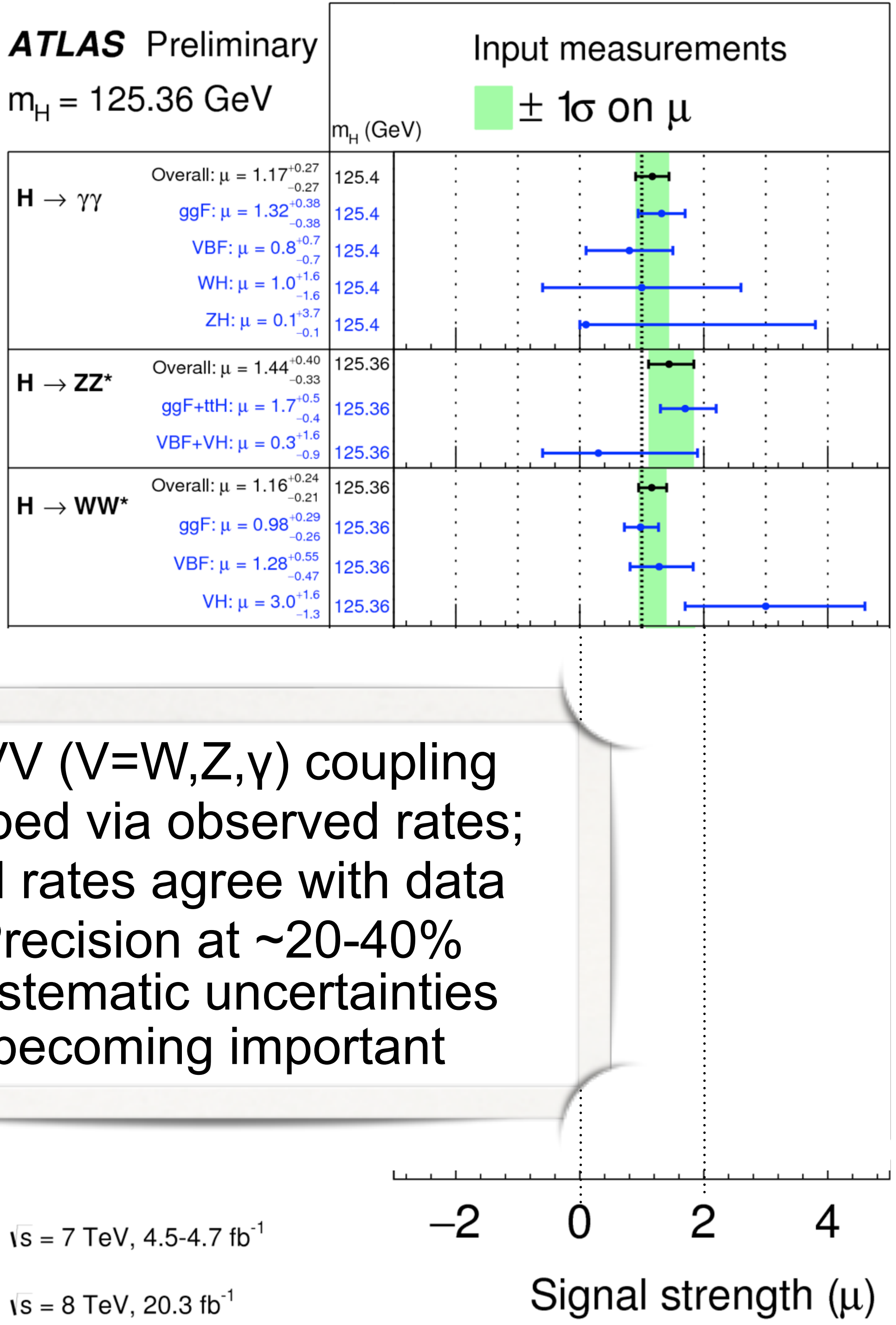
Substantial progress made in understanding its nature

ATLAS-CMS Higgs boson mass combination; 0.19% precision

- ATLAS measurement: 125.36 $^{+0.37}$ (stat) $^{+0.18\ 0.41}_{-0.15}$ (syst) GeV
- CMS measurement: 125.02 $^{+0.26}_{-0.27}$ (stat) $^{+0.14}_{-0.15}$ (syst) GeV



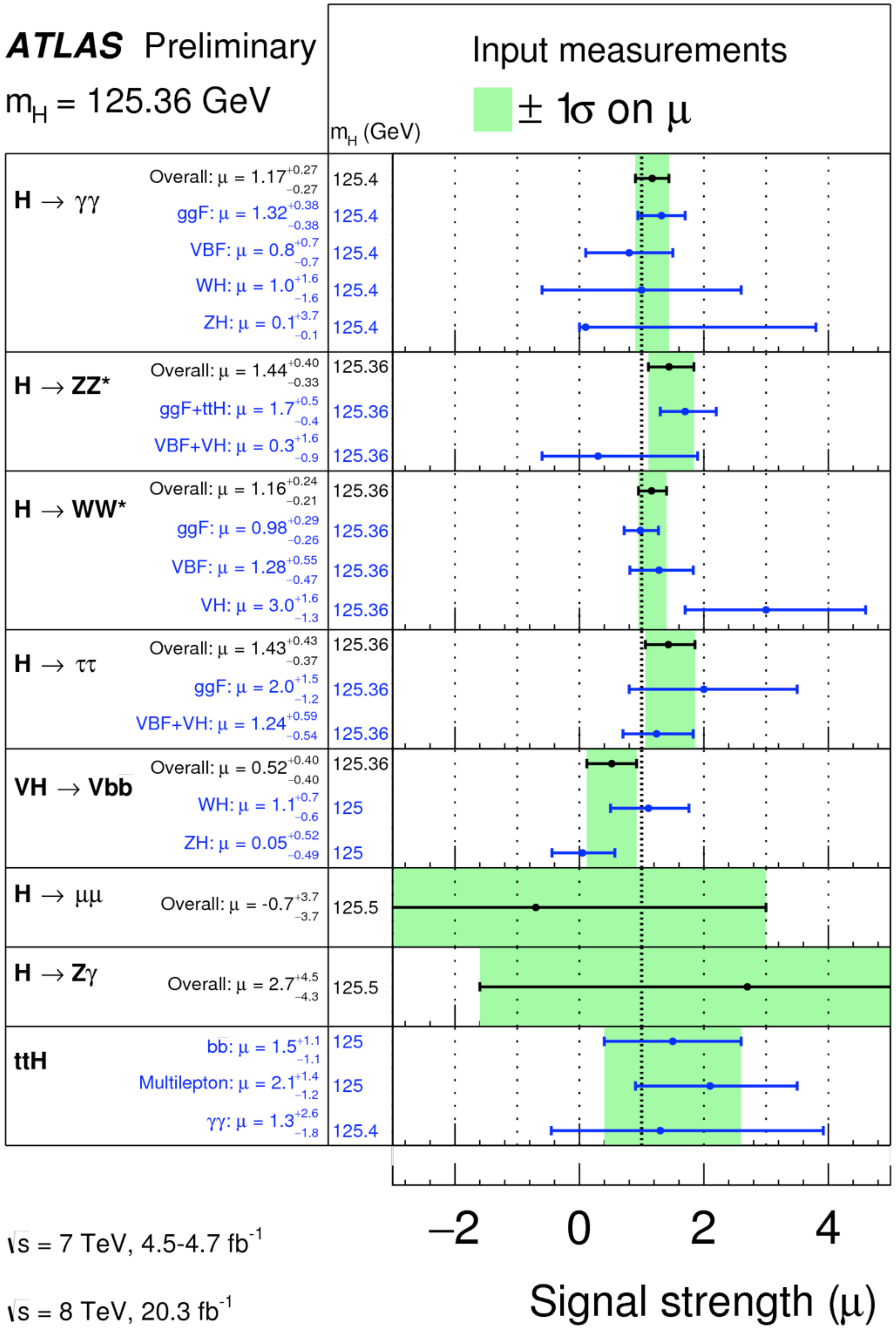




HVV (V=W,Z,γ) coupling probed via observed rates;
SM rates agree with data
Precision at ~20-40%
Systematic uncertainties becoming important

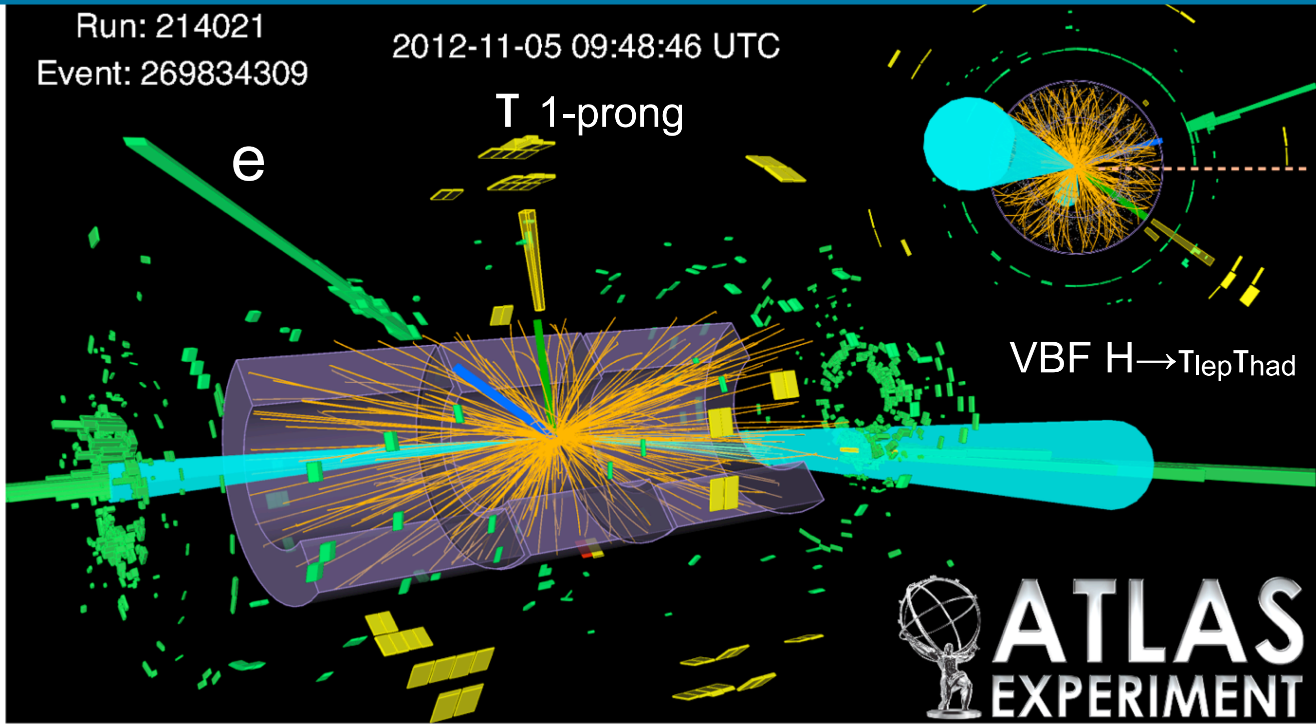
This was not unexpected, given the level of agreement of the SM predictions with the observed precision electroweak data (even w/o knowledge of m_H)

Overview of rate measurements

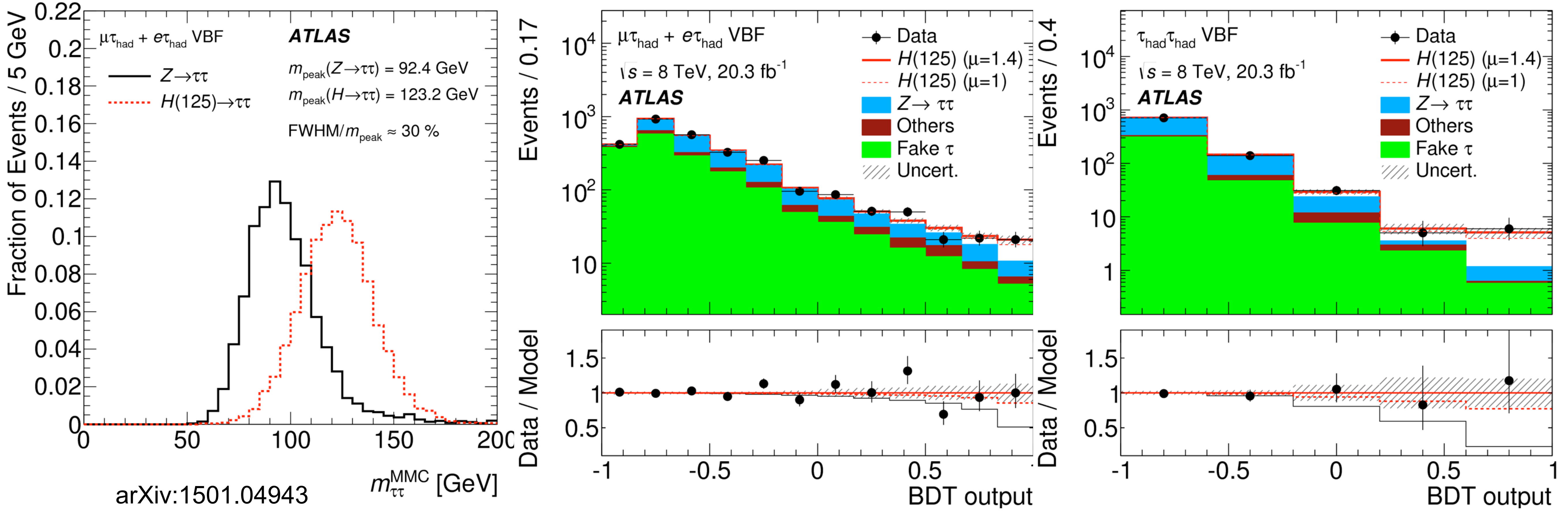


$H\to\tau\tau$

- Most promising for down-type fermion/lepton couplings
- Backgrounds
  - Z → ττ dominant [embedding]
  - "Fakes": Multijet, W+jets, top [data-driven]
  - "Other": Dibosons/H->WW* [MC]
- Three sub-channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Two exclusive categories/final state: *VBF* (2 jets with large Δη) and *Boosted* (large di-tau pT)
- BDT for each category: *di-tau properties* ($m_{\tau\tau}$, $\Delta R_{\tau\tau}$, ...), *jet topology* (m_{jj}, $\Delta\eta_{jj}$, ...), *event activity/topology* (scalar/vector pT sum, object centralities, ...)



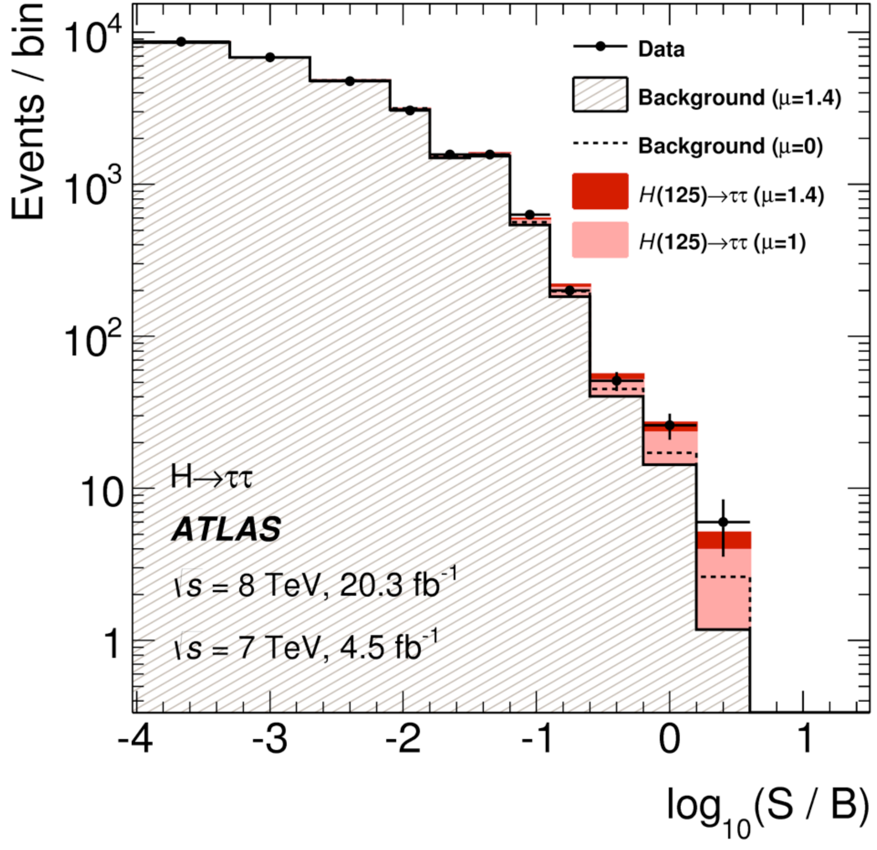
e p_T = 56 GeV, τ_{had} p_T = 27 GeV, MET=113 GeV, $m_{j1,j2}$=1.53 TeV, $m_{\tau\tau}^{MMC}$=129 GeV, BDT score = 0.99. S/B ratio of this bin 1.0

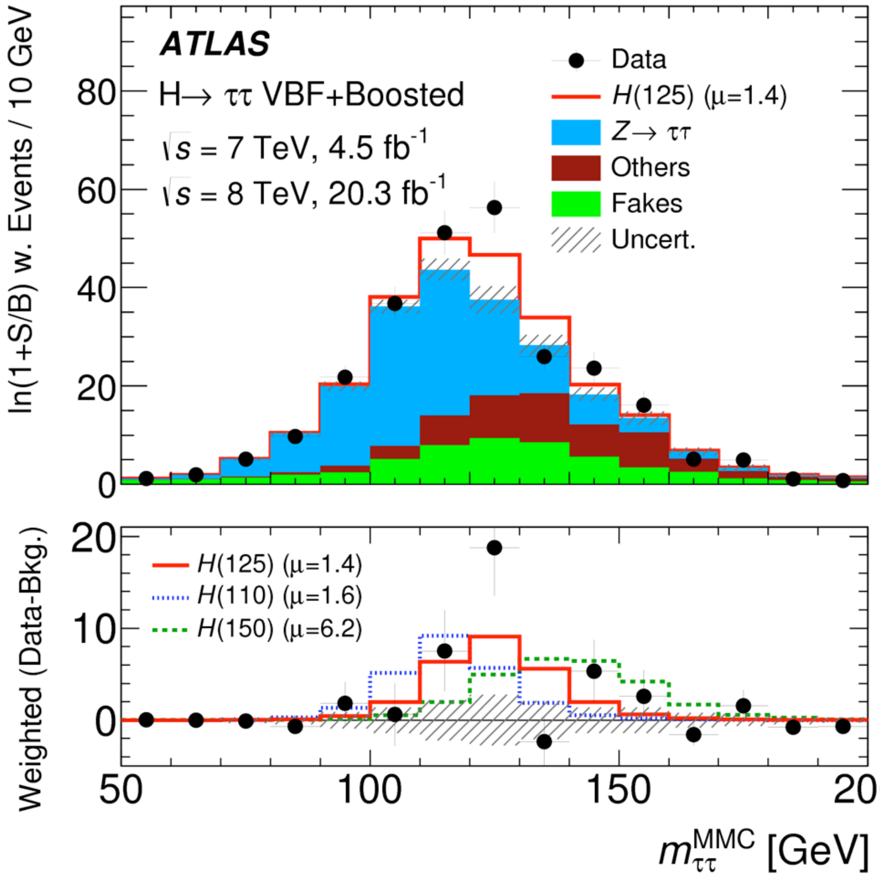


arXiv:1501.04943

H→ττ: Results

arXiv:1501.04943





Evidence observed for Higgs boson decays to τ-leptons

<u>significance at 125 GeV</u>

ATLAS: 4.5σ (3.4σ)

CMS: 3.2σ (3.5σ)

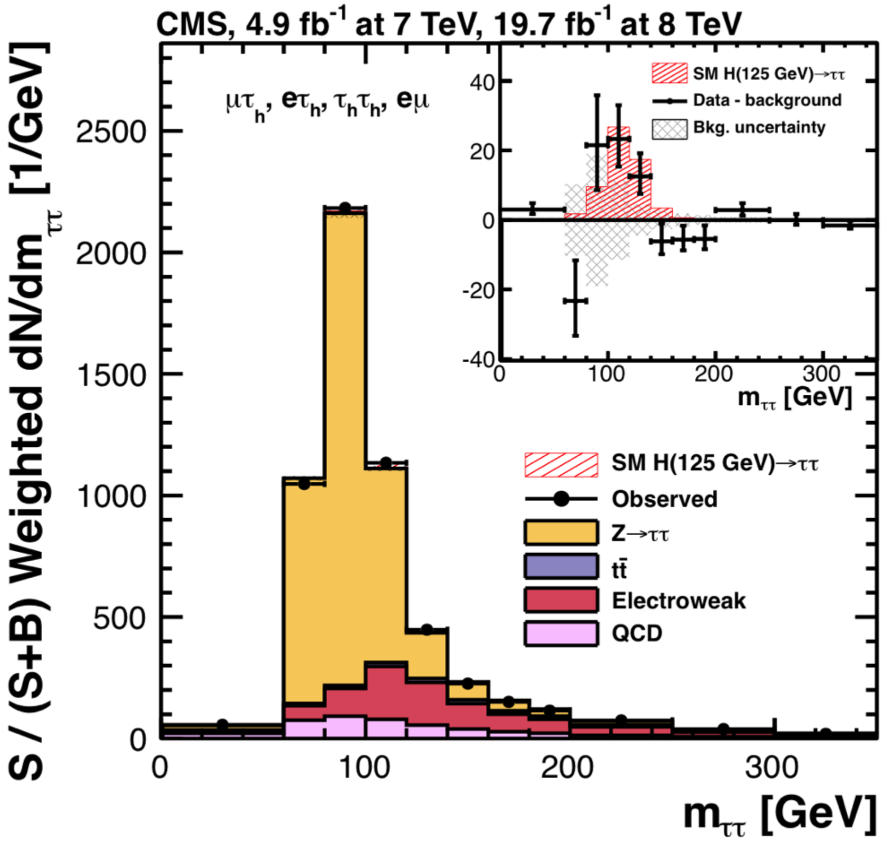
<u>Rate measurement</u>

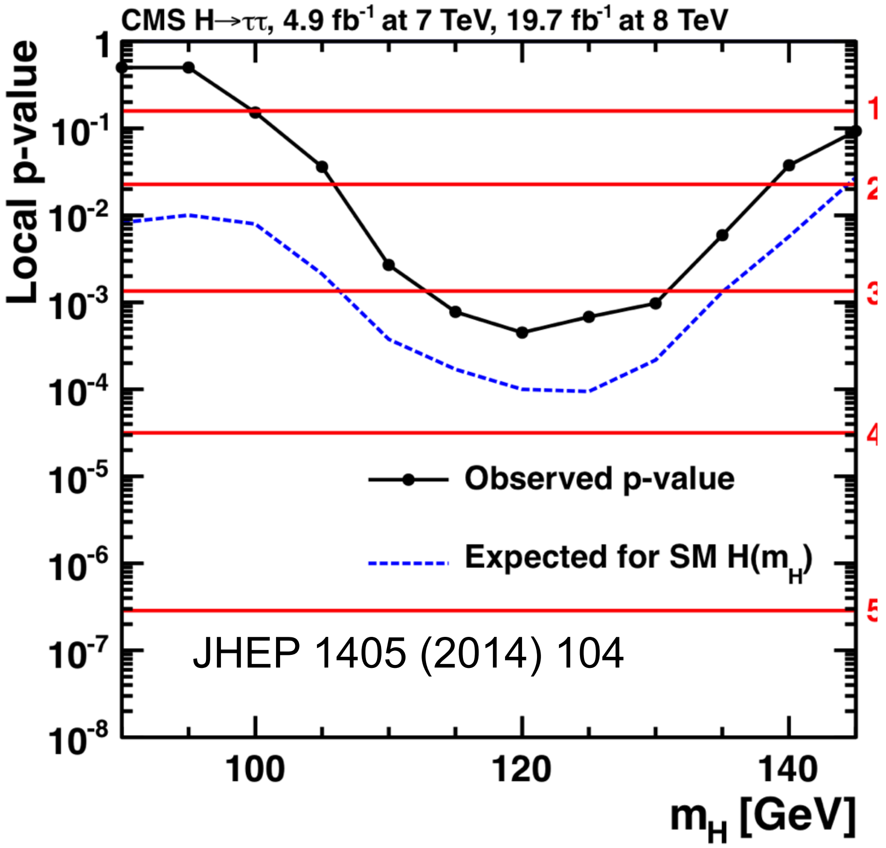
ATLAS $\mu=1.43^{+0.27}_{-0.26}$(stat) $^{+0.32}_{-0.25}$(syst) ± 0.09 (theo syst)

[@ m_H=125.36 GeV]

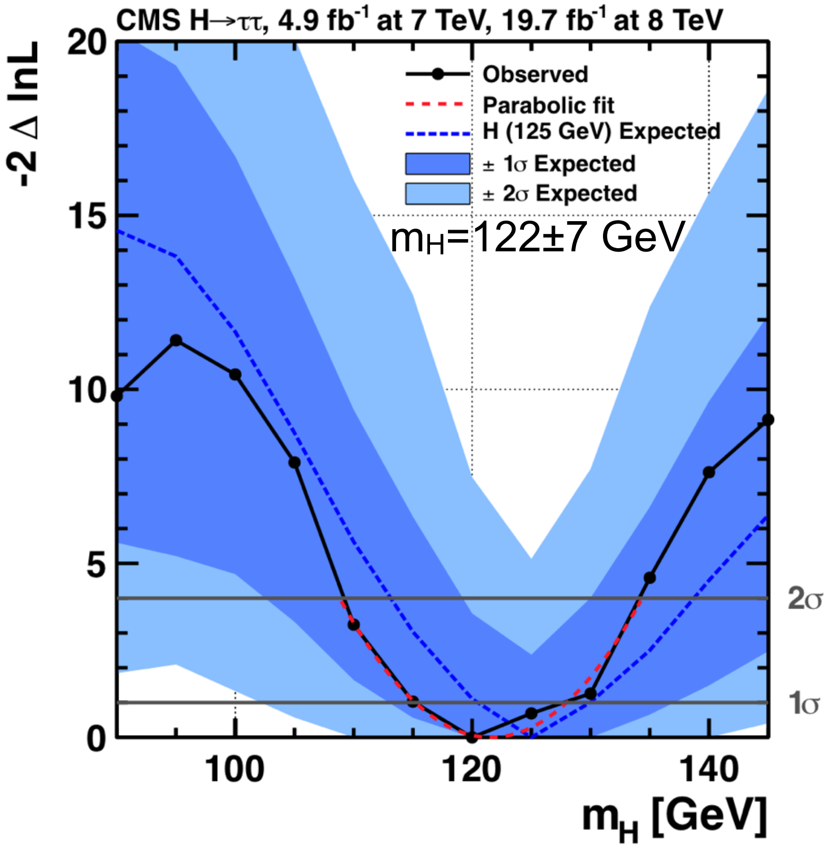
CMS μ=0.78 ± 0.27

[@ m_H=125.00 GeV]



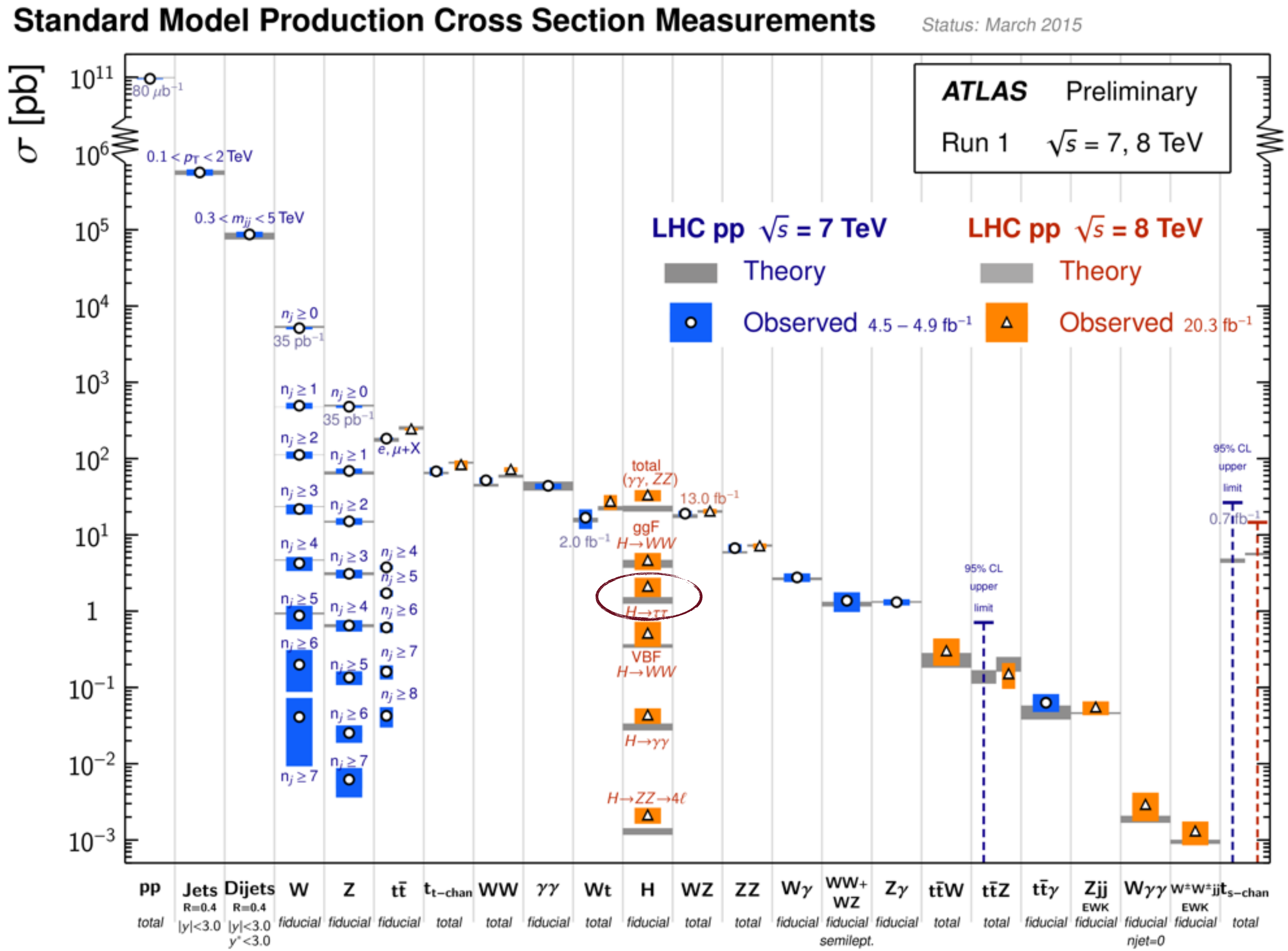


JHEP 1405 (2014) 104



m_H=122±7 GeV

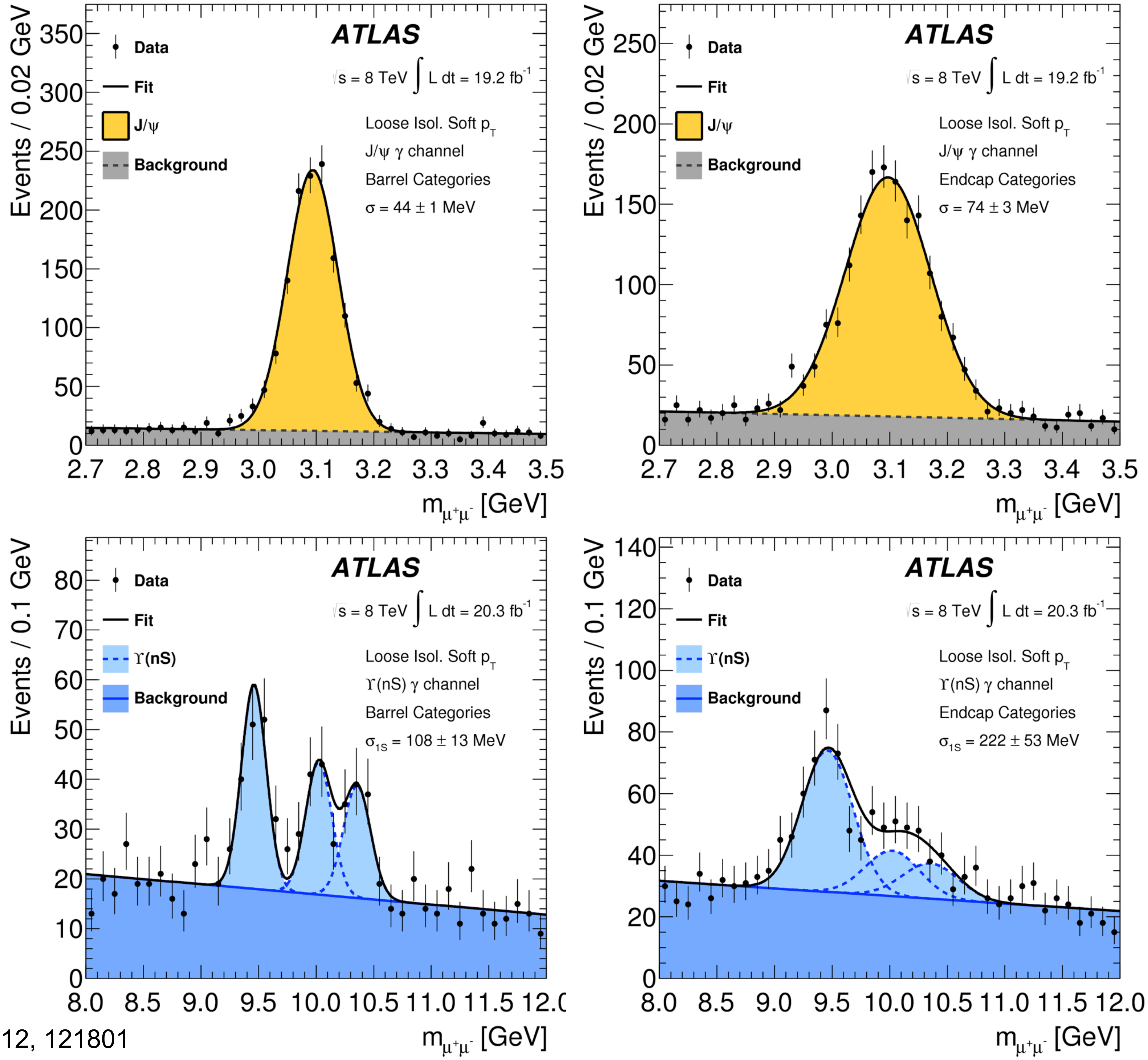
H→ττ



Standard Model Production Cross Section Measurements

Status: March 2015

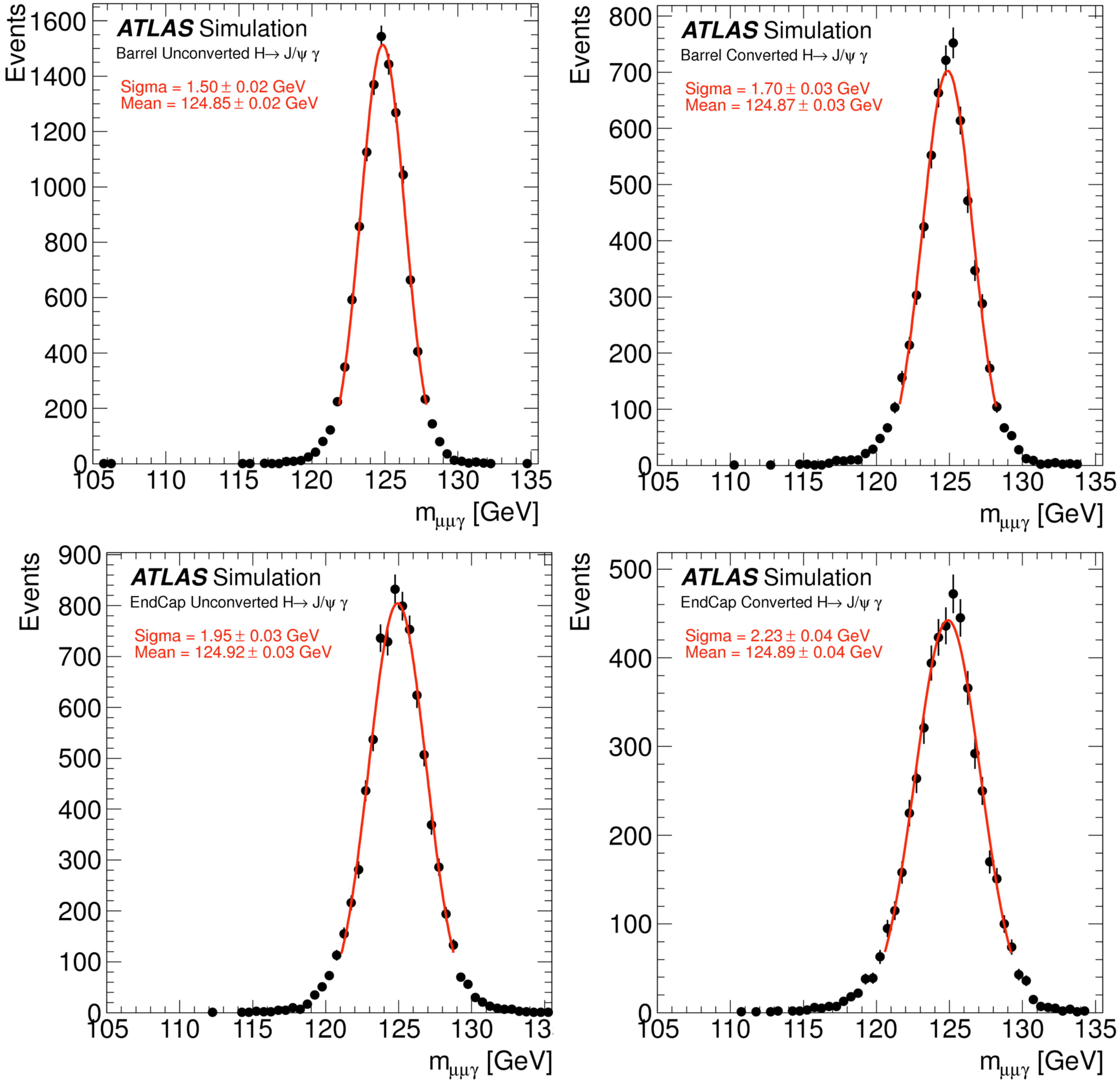
H→J/ψγ and H→Y(ns)γ



Phys.Rev.Lett. 114 (2015) 12, 121801

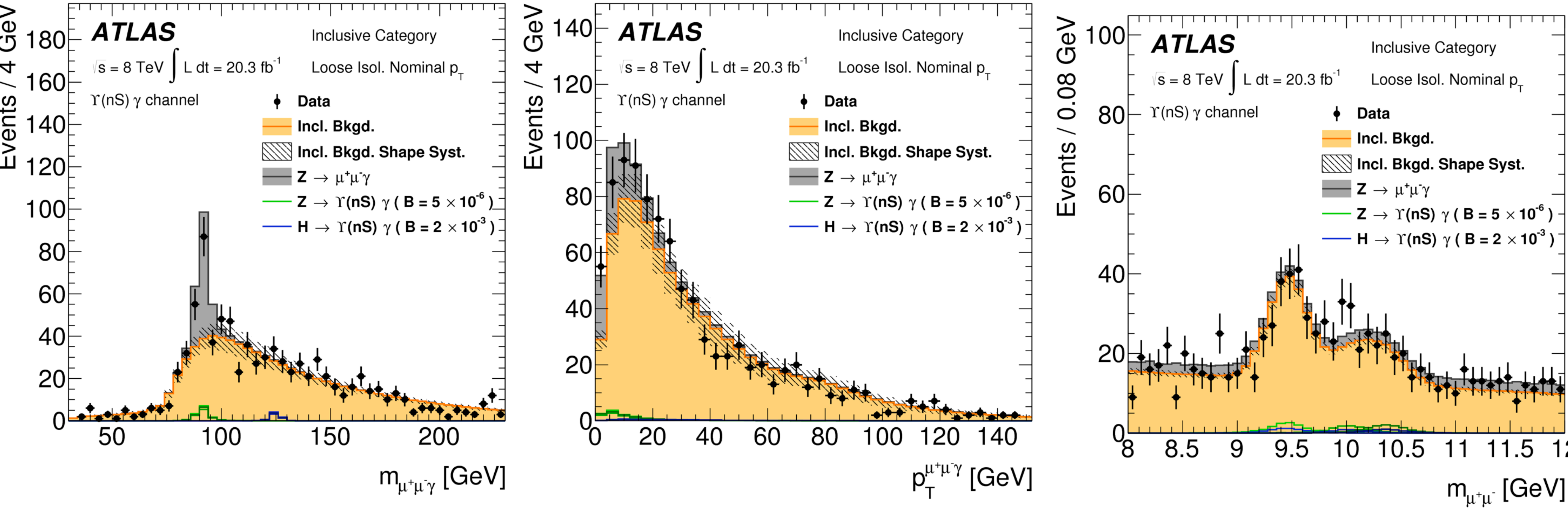
H→J/ψγ and H→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 12, 121801

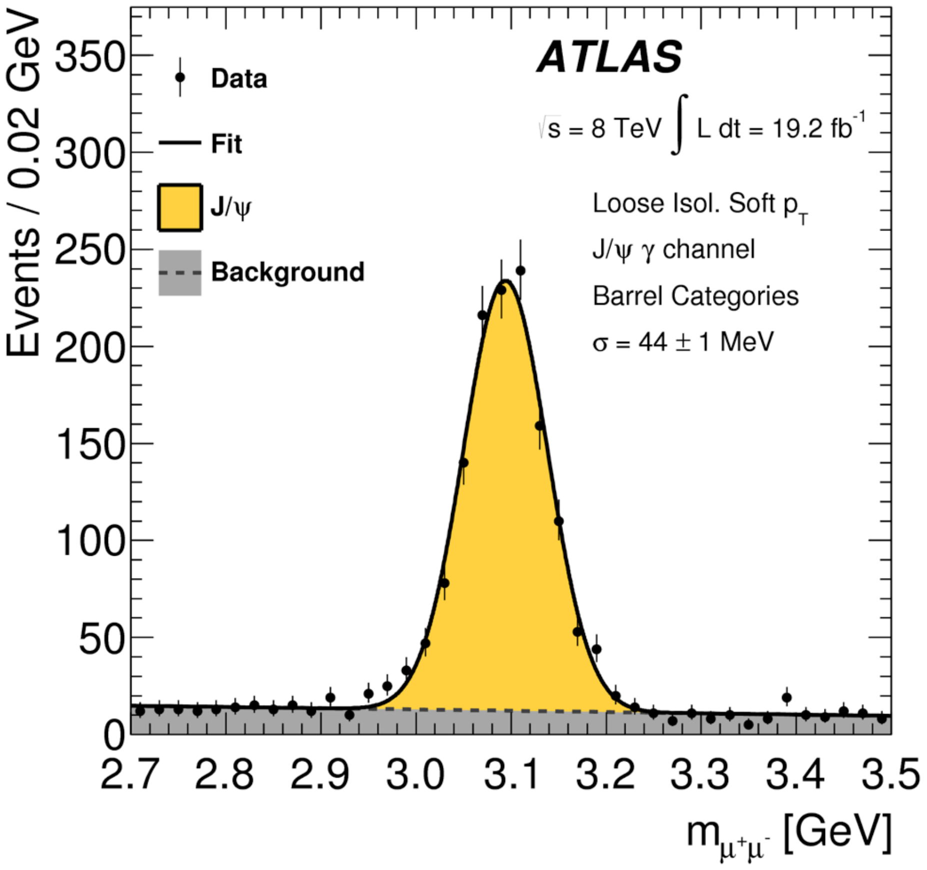


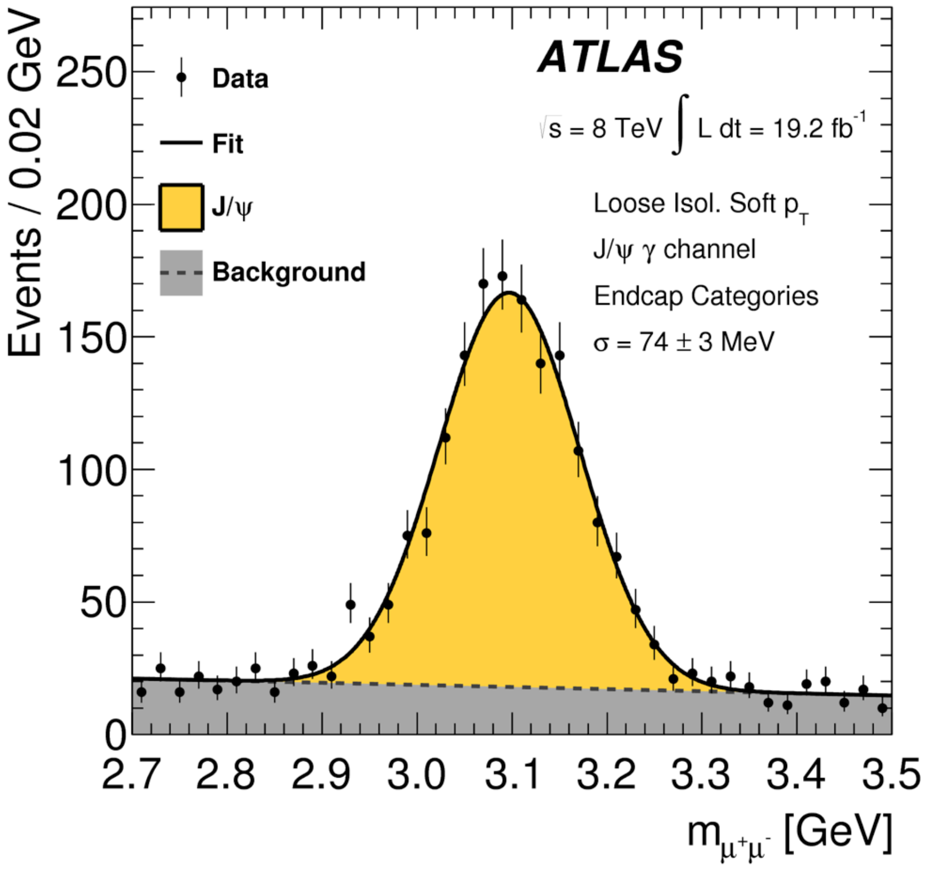
H→J/ψγ and H→Y(ns)γ

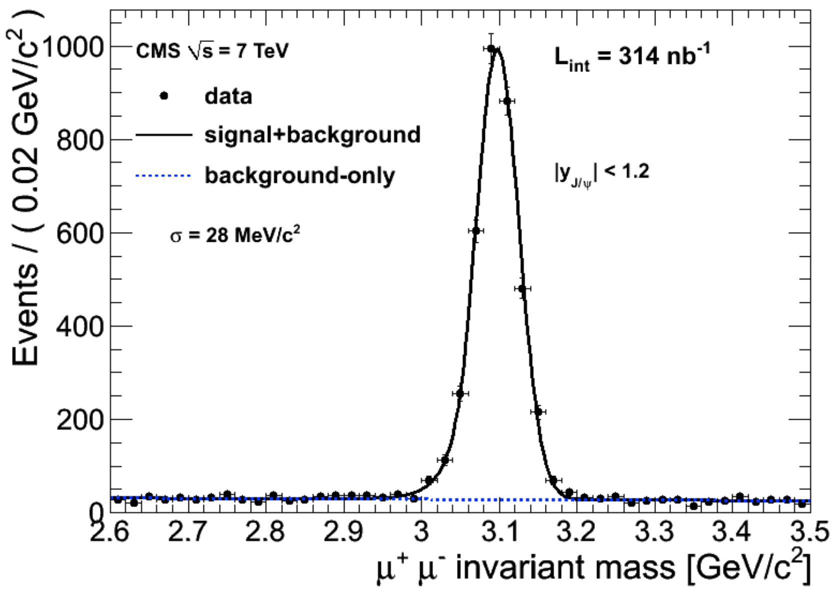
Phys.Rev.Lett. 114 (2015) 12, 121801

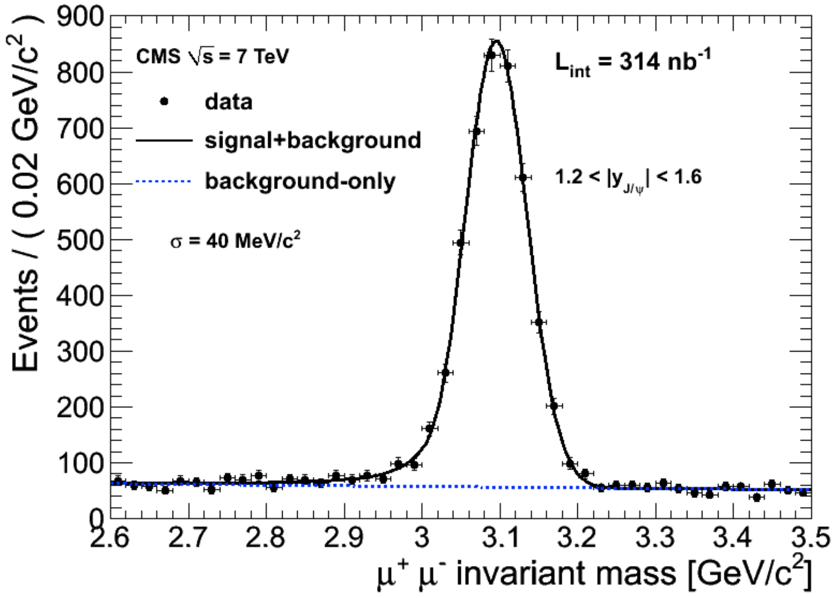


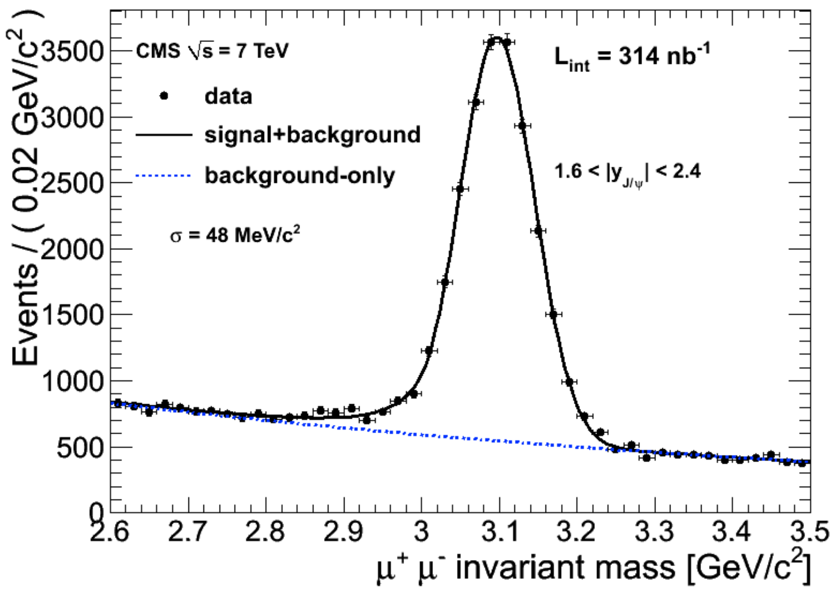
H→J/ψγ and H→Υ(ns)γ











Light-Quark Yukawa couplings

This was also considered impossible for the LHC. Recent activity on its feasibility:

→ Exploit the exclusive decays H→Qγ as direct probe to the quark Yukawa couplings

[Phys.Rev.Lett. 114 (2015) 10, 101802]

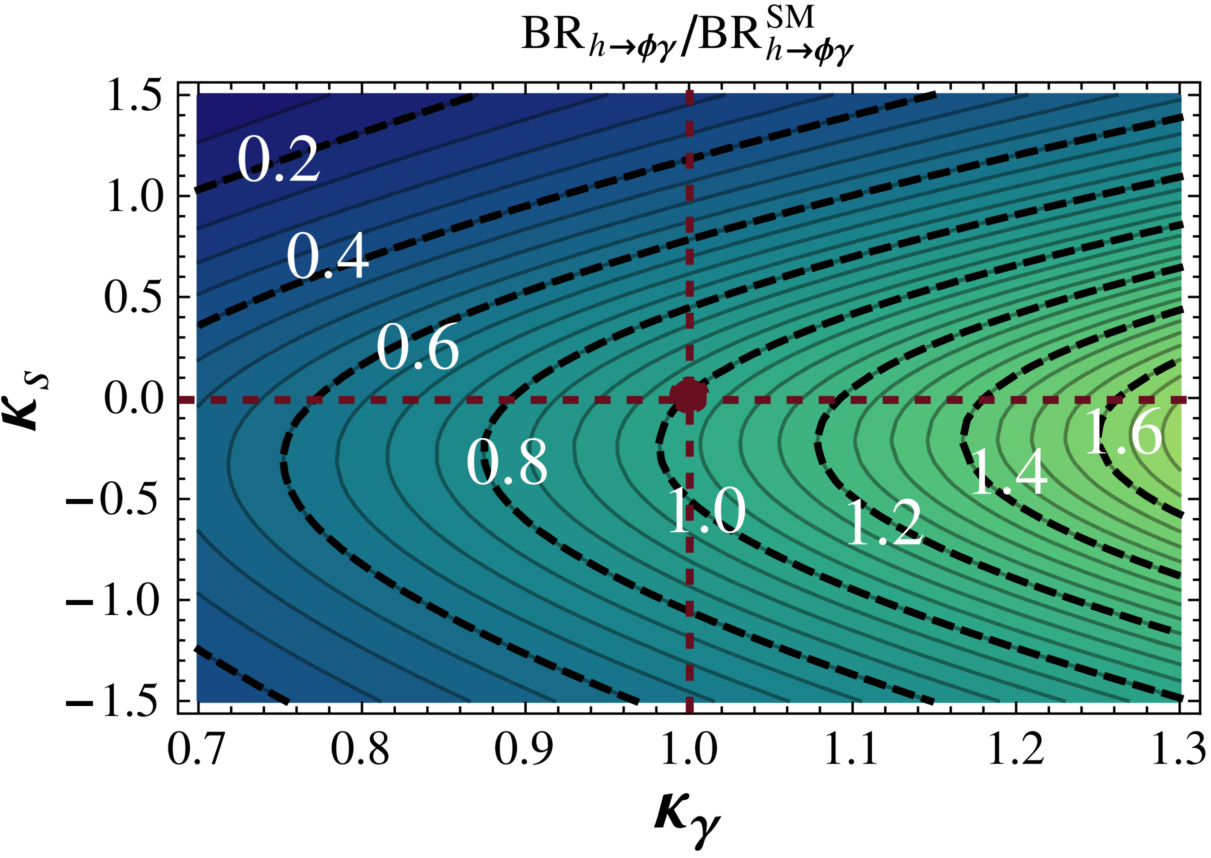
→ Sensitive to BSM physics [Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022]

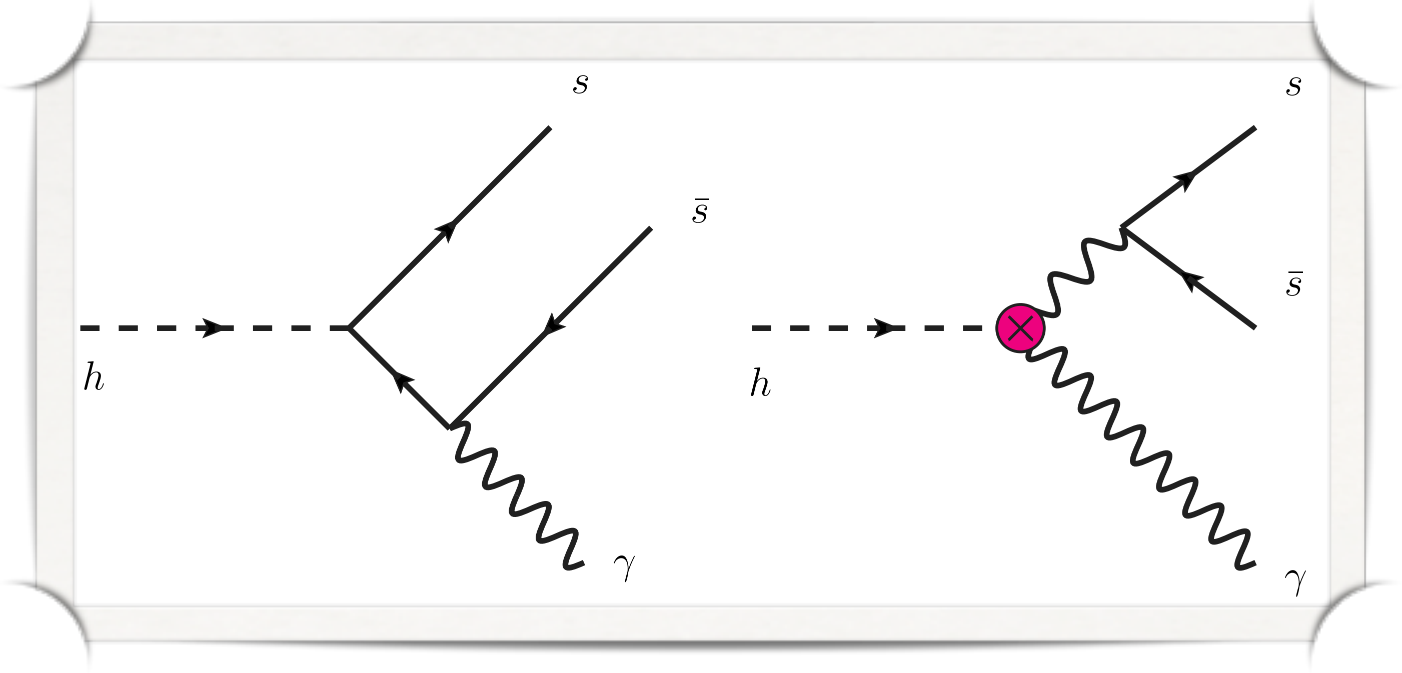
The idea is to benefit from the interference of the “direct” and “indirect” amplitudes!

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(3.0\pm0.3)\kappa_\gamma-0.78\bar{\kappa}_s]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.9\pm0.2)\kappa_\gamma-0.24\bar{\kappa}_u-0.12\bar{\kappa}_d]\times10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}}=\frac{\kappa_\gamma[(1.6\pm0.2)\kappa_\gamma-0.59\bar{\kappa}_u-0.29\bar{\kappa}_d]\times10^{-6}}{0.57\bar{\kappa}_b^2},$$



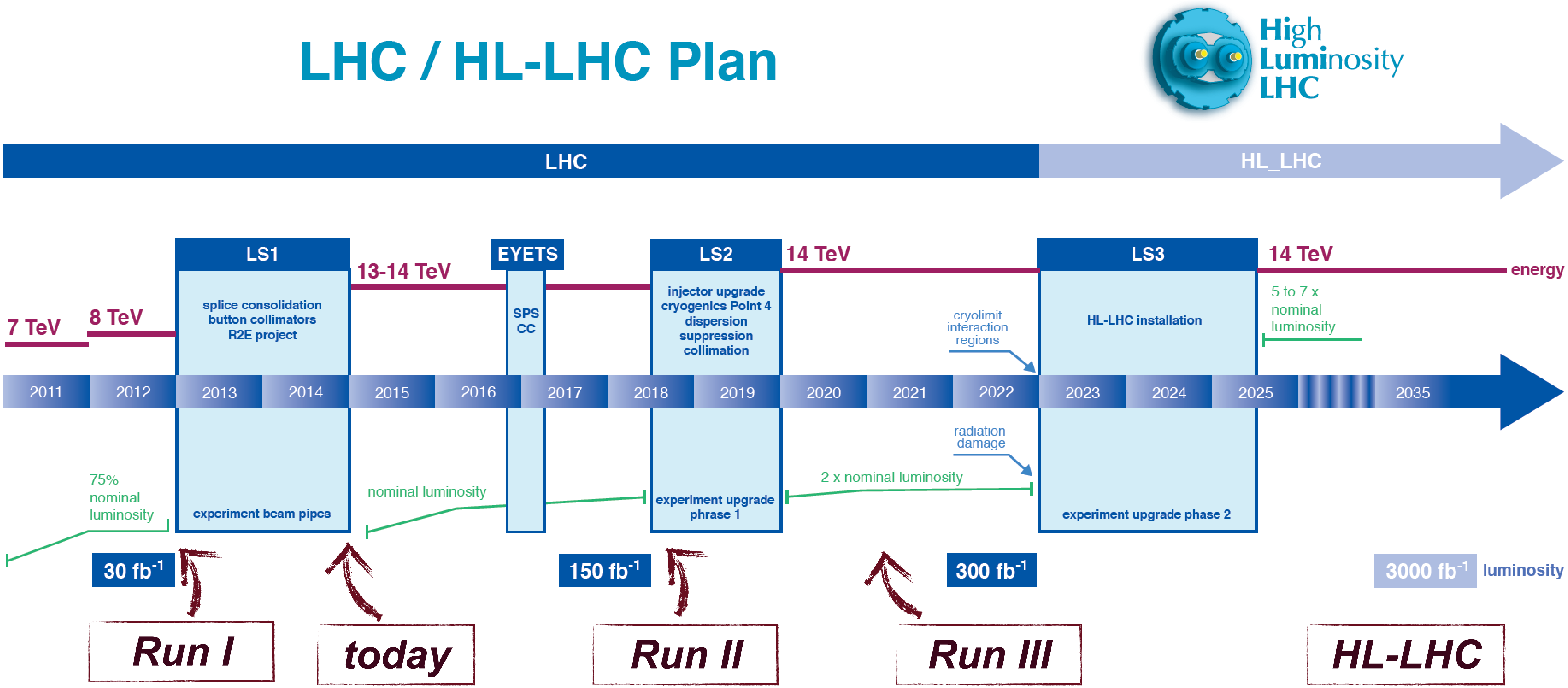


Phys.Rev.Lett. 114 (2015) 10, 101802

$$\bar{\kappa}_s = m_s/m_b \approx 0.02$$
$$\bar{\kappa}_d = m_d/m_b \approx 1\cdot10^{-3}$$
$$\bar{\kappa}_u = m_u/m_b \approx 4.7\cdot10^{-4}$$

$$BR^{SM}_{h\to\phi\gamma} \approx 3\cdot10^{-6}$$
$$BR^{SM}_{h\to\rho\gamma} \approx 1.9\cdot10^{-5}$$
$$BR^{SM}_{h\to\omega\gamma} \approx 1.6\cdot10^{-6}$$

LHC/HL-LHC Plan



- Run II will provide ×5-6 more integrated luminosity compared to Run I
- Aiming for 3000 fb^{-1} by 2035
- Experiments will be upgraded ATLAS to go for an new all Si tracker

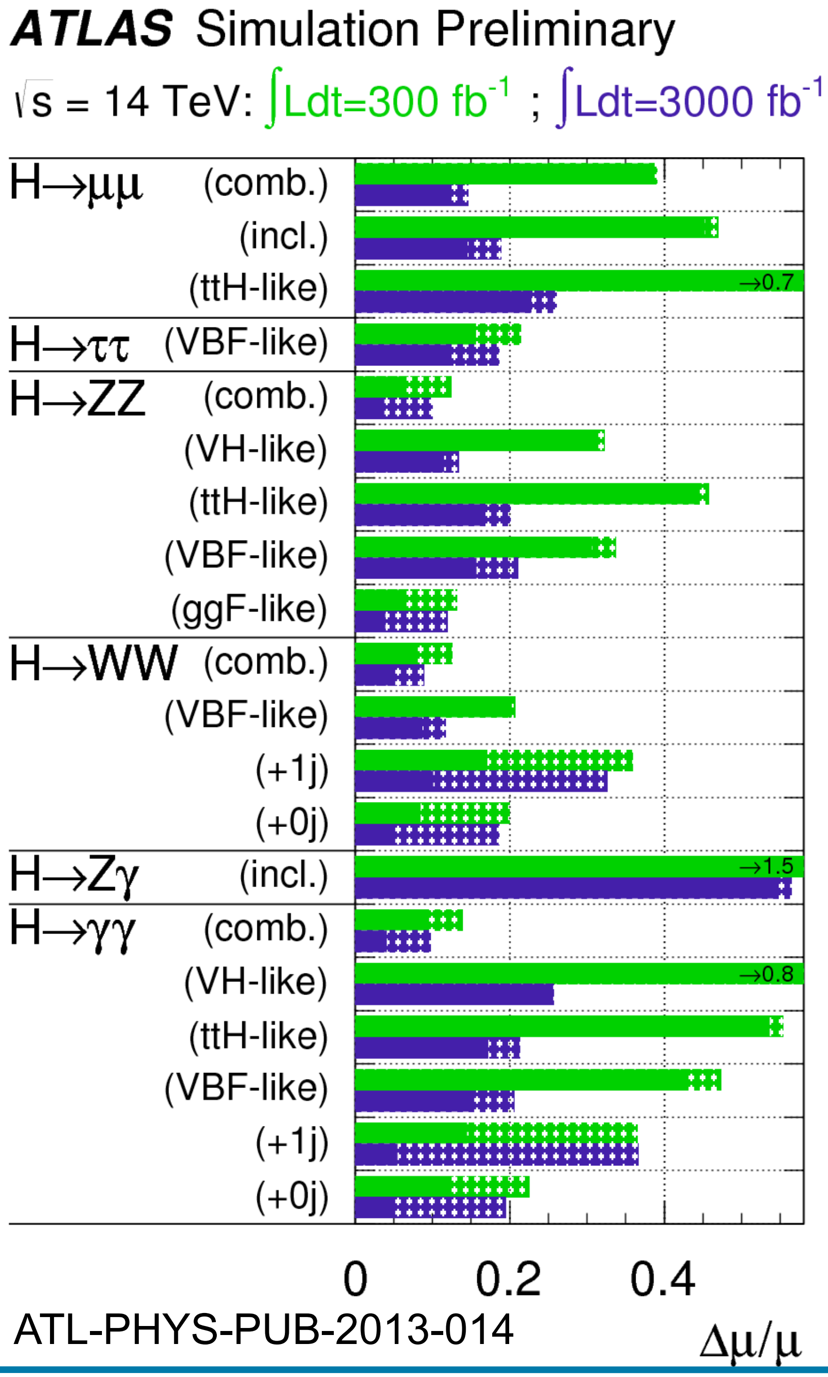
Higgs in Run II and beyond

The LHC is a Higgs Factory

- Run II ×5-6 more integrated luminosity compared to Run I
- ×2.3 - 3.9 increase in Higgs production cross section from 8TeV to 13TeV
- ×3.4-5 improvement in statistical sensitivity

In Run II several Higgs analysis may become systematics limited

need to work on reducing those



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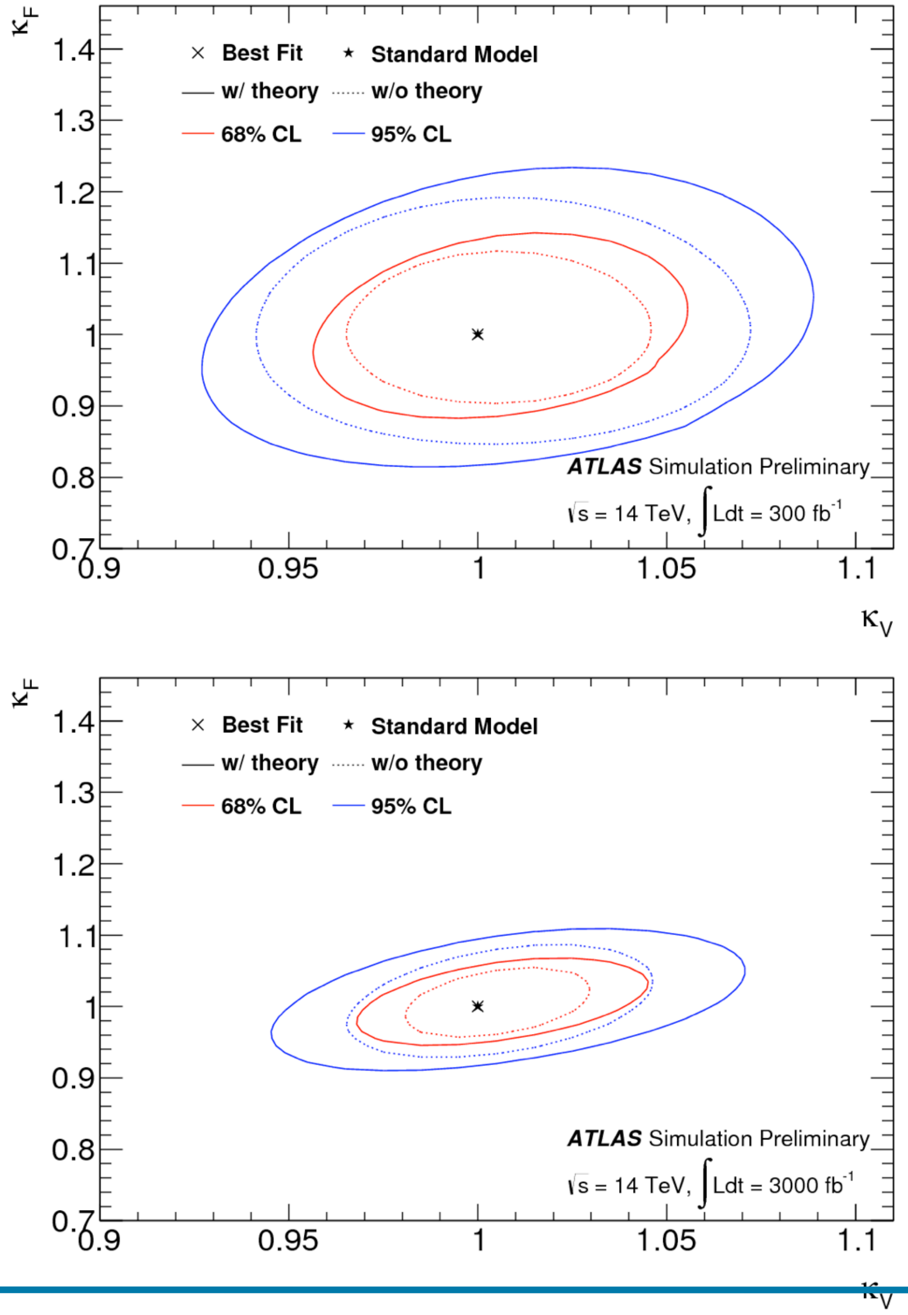
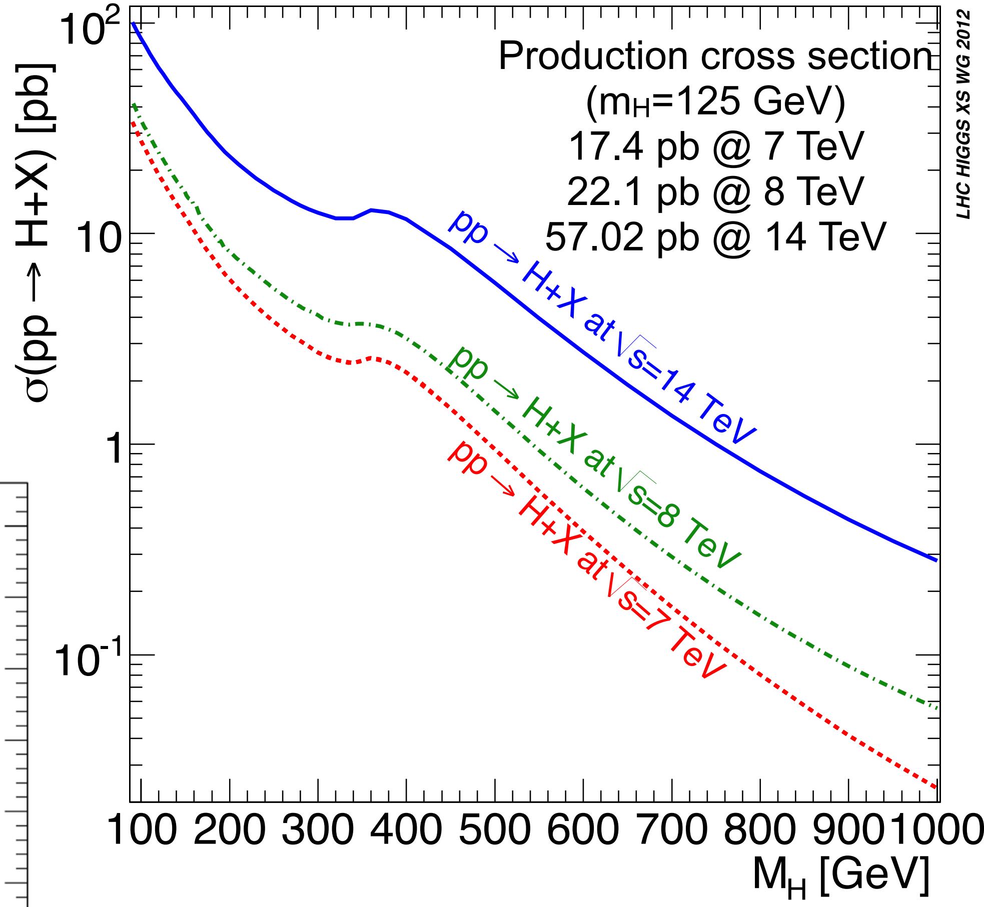




Several open topics in the Higgs sector for future studies:

- Rare decays & Couplings
- CP studies
- BSM Higgs boson searches
- Higgs boson pair production

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Fiducial/Differential cross sections

fiducial cross-section

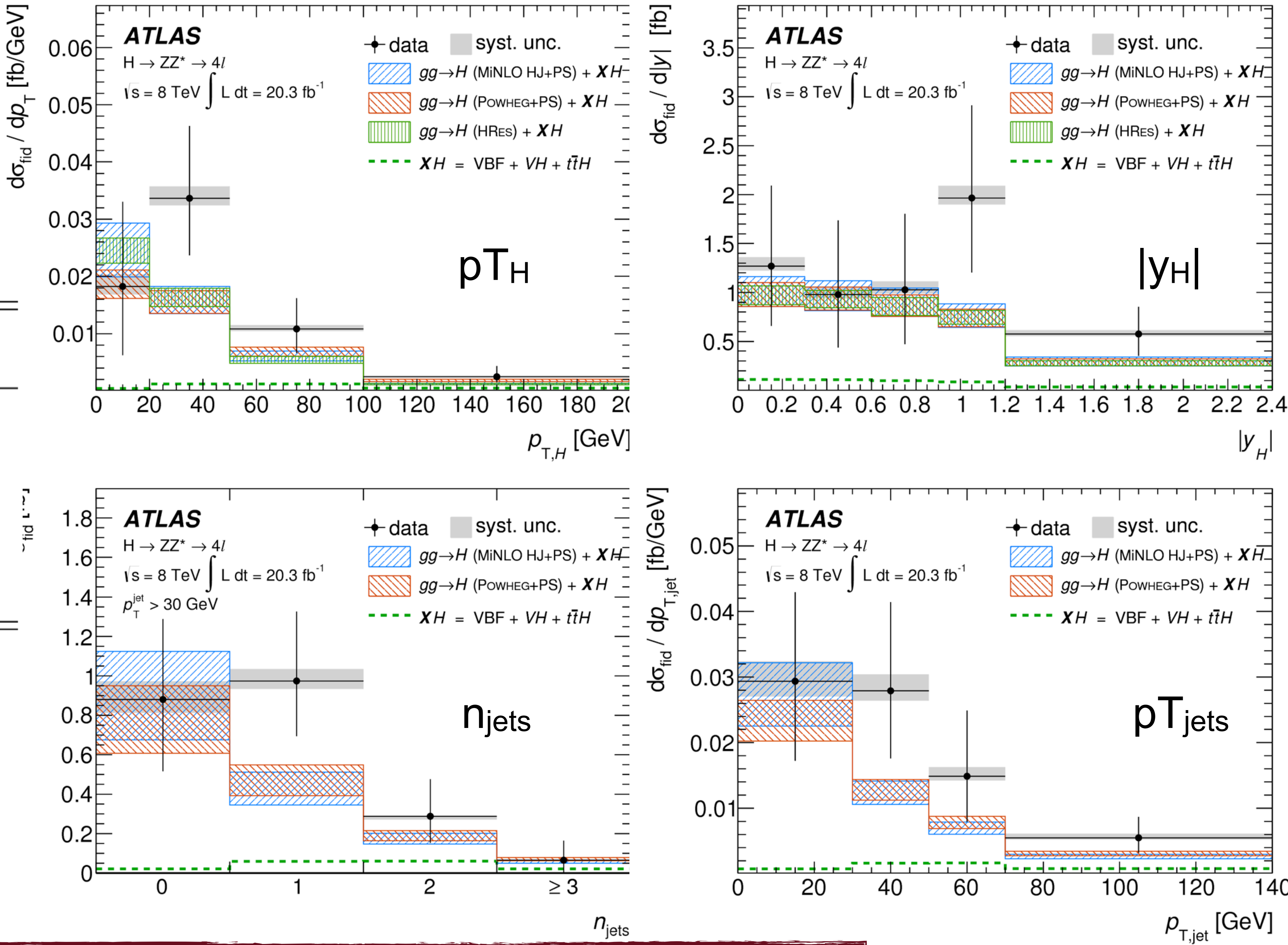
6 differential cross sections

$$\sigma^{\rm fid}_{\rm tot} = 2.11^{+0.53}_{-0.47}({\rm stat})^{+0.08}_{-0.08}({\rm syst})\ {\rm fb}$$

SM prediction at 125.4GeV = 1.30 ± 0.13 fb

Procedure ($120<m_{4l}<130$ GeV):
- expected background subtracted from observed events in bins of interesting variable
- bin-by-bin unfolding

Variable	POWHEG	MINLO	HRES2
	p-values		
$p_{\mathrm{T},H}$	0.30	0.23	0.16
$\lvert y_H \rvert$	0.37	0.45	0.36
m_{34}	0.48	0.60	-
$\lvert \cos\theta^* \rvert$	0.35	0.45	-
n_{jets}	0.37	0.28	-
$p_{\mathrm{T,jet}}$	0.33	0.26	-



First result/statistics limited → No large surprise

BSM examples

The properties of the observed Higgs boson already constraint BSM contributions

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Additional EW singlet field

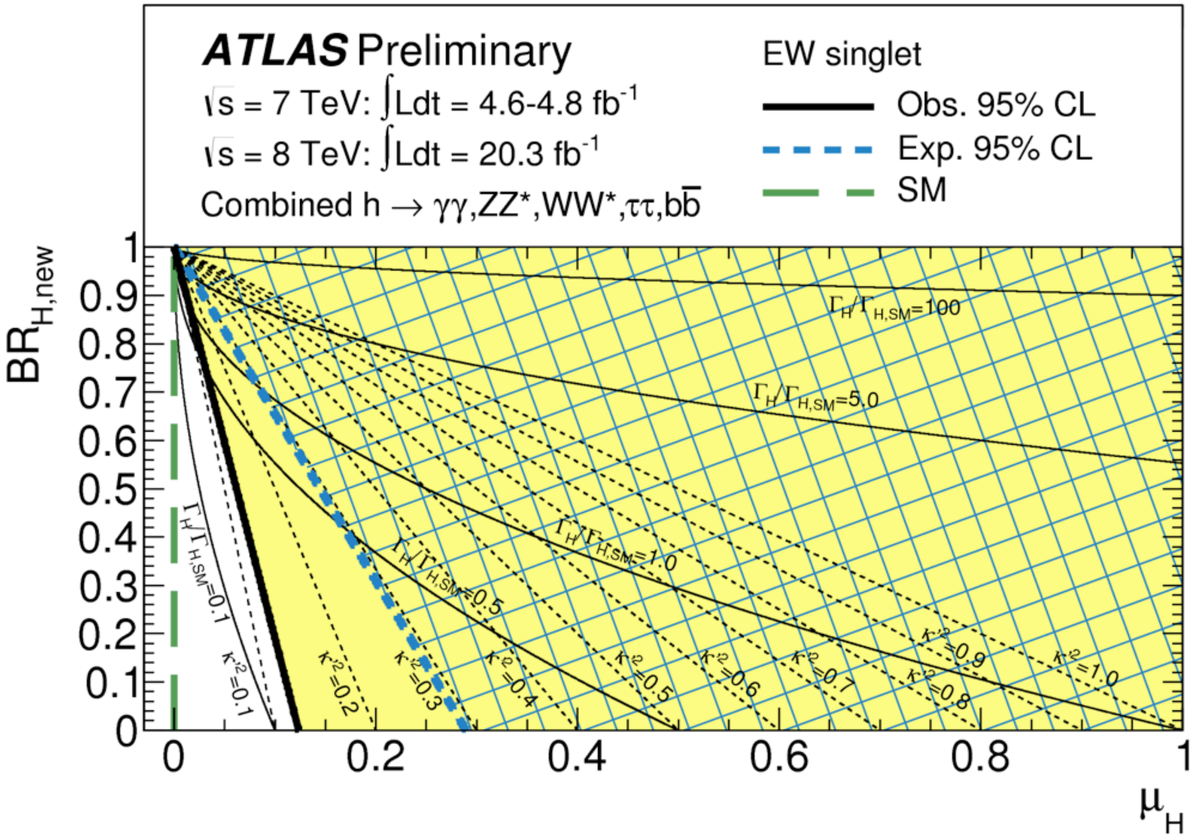
Simplest extension of SM Higgs sector

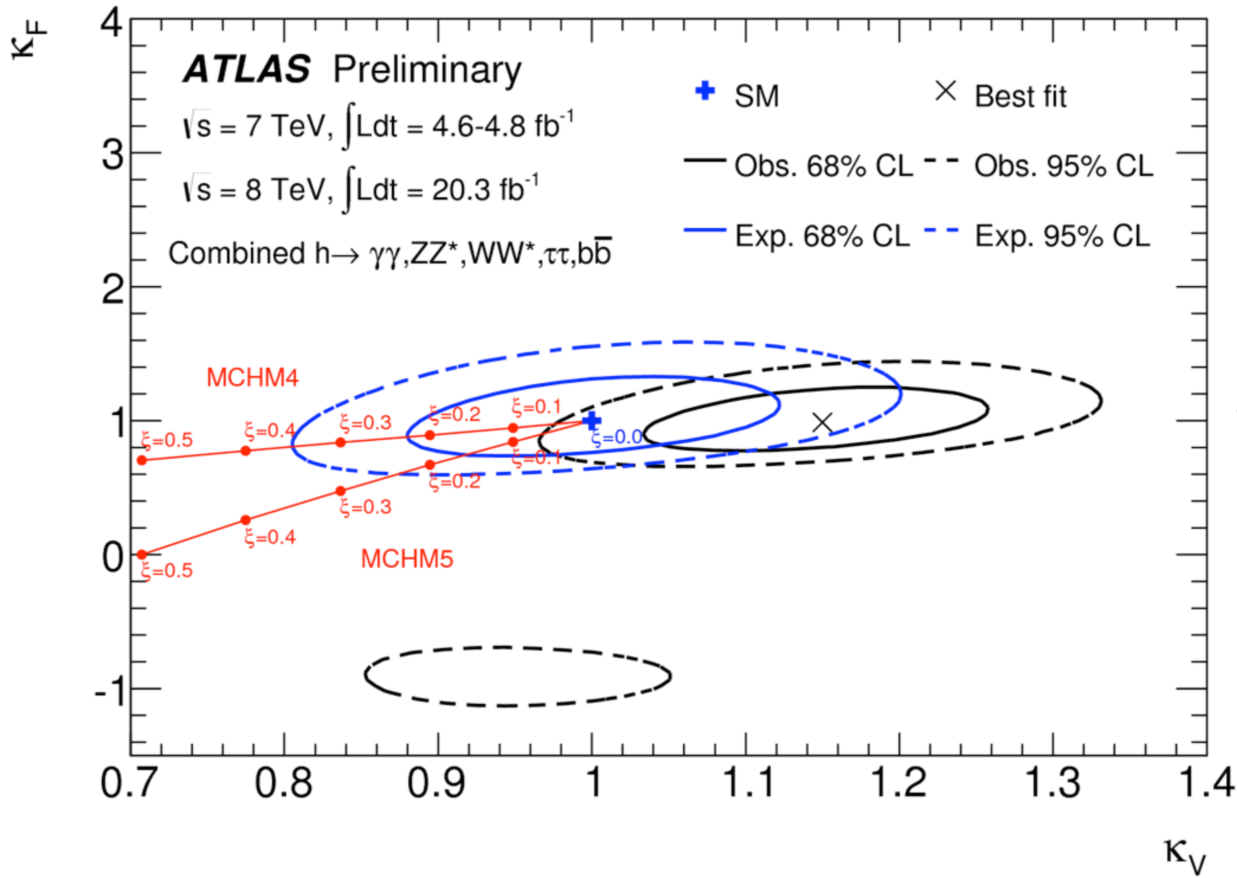
Results in two CP-even Higgs bosons: h, H (assumed non degenerate)

Couplings similar to SM Higgs boson, but each scaled by common factor, denoted as κ (κ') for h(H).
From unitarity: $\kappa^2+\kappa'^2=1$

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$





Minimal Composite Higgs Model

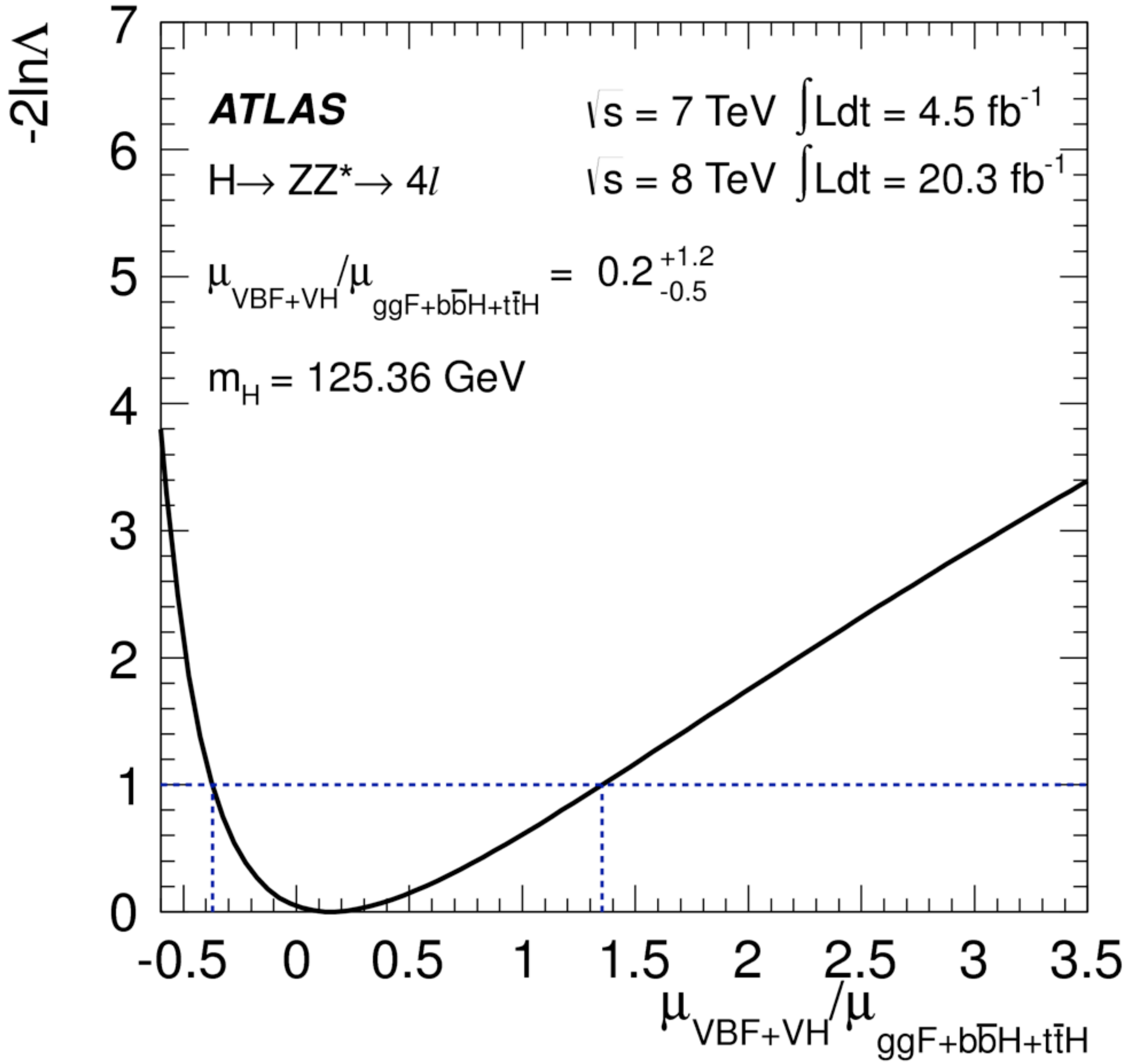
Higgs is pseudo Nambu-Goldstone boson

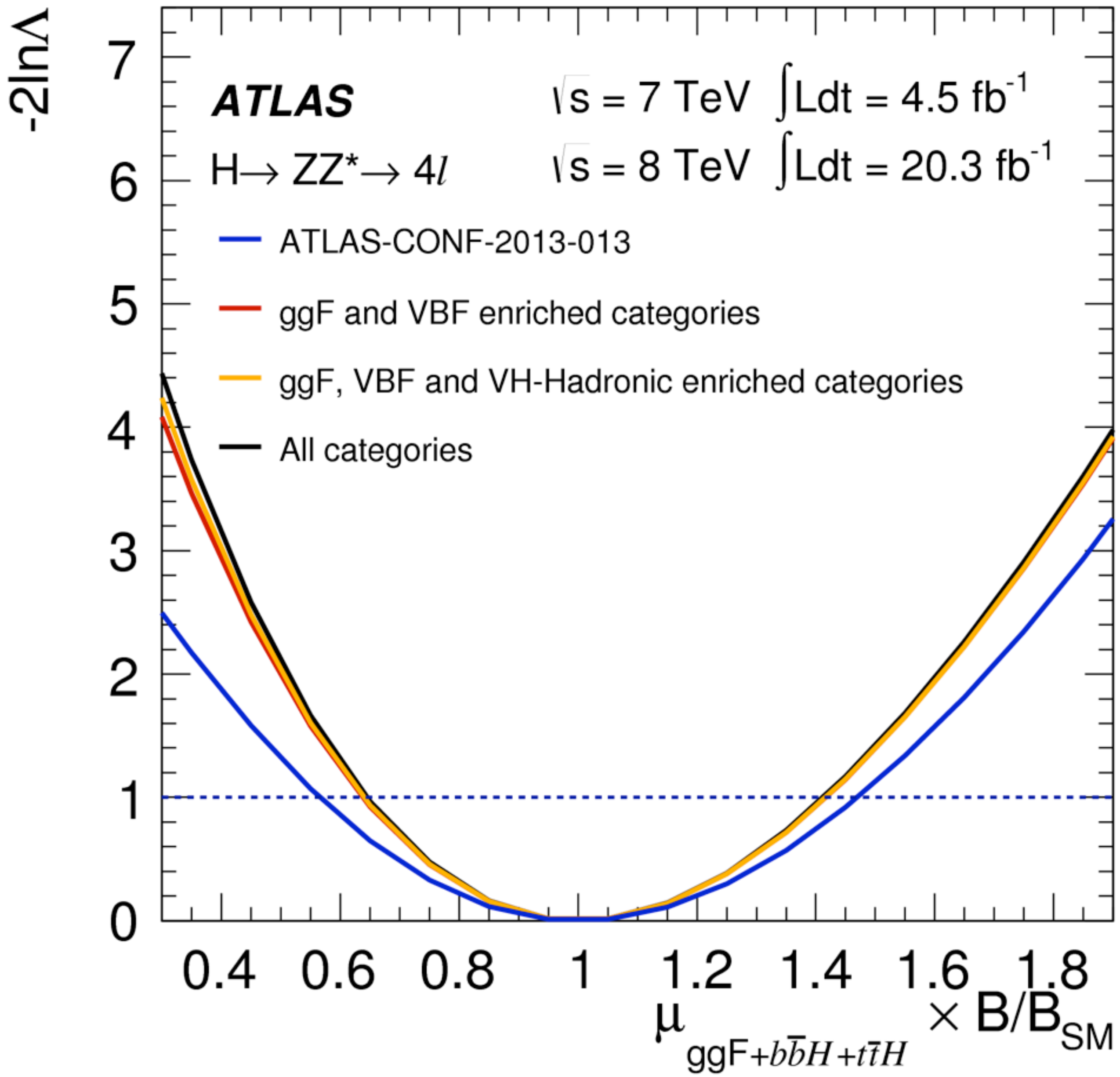
Neglecting contributions from new heavy resonances the Higgs couplings modified wrt SM as a function of compositeness scale: $\xi = v^2/f^2$

MCHM4: $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$ f>710 (460) GeV at 95%CL

MCHM5: $\kappa_V = \sqrt{1-\xi}$, $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$. f>640 (550) GeV at 95%CL

$H \to ZZ^{(*)} \to 4l$: Coupling Results





Prospects for Run II/III and HL-LHC

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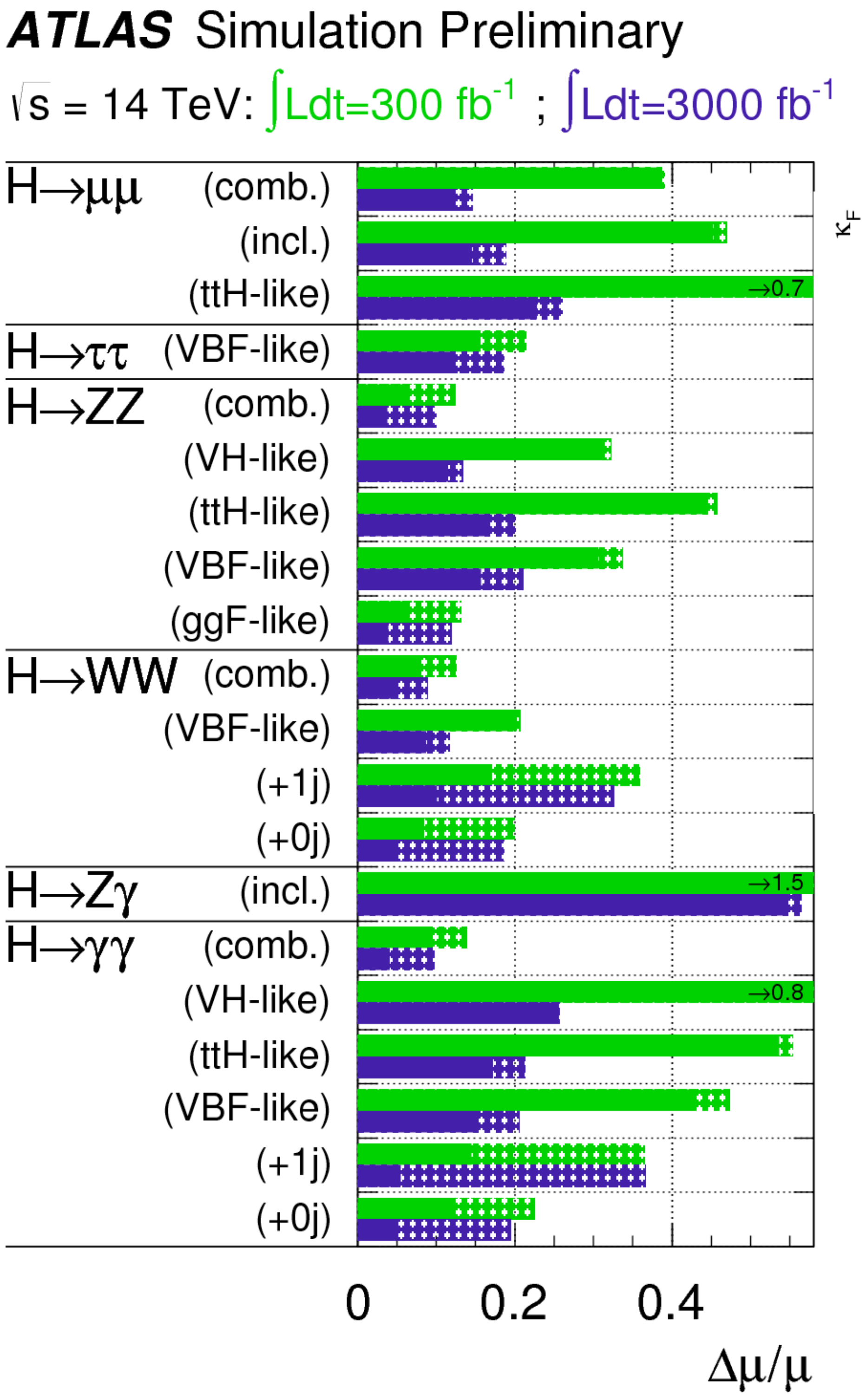

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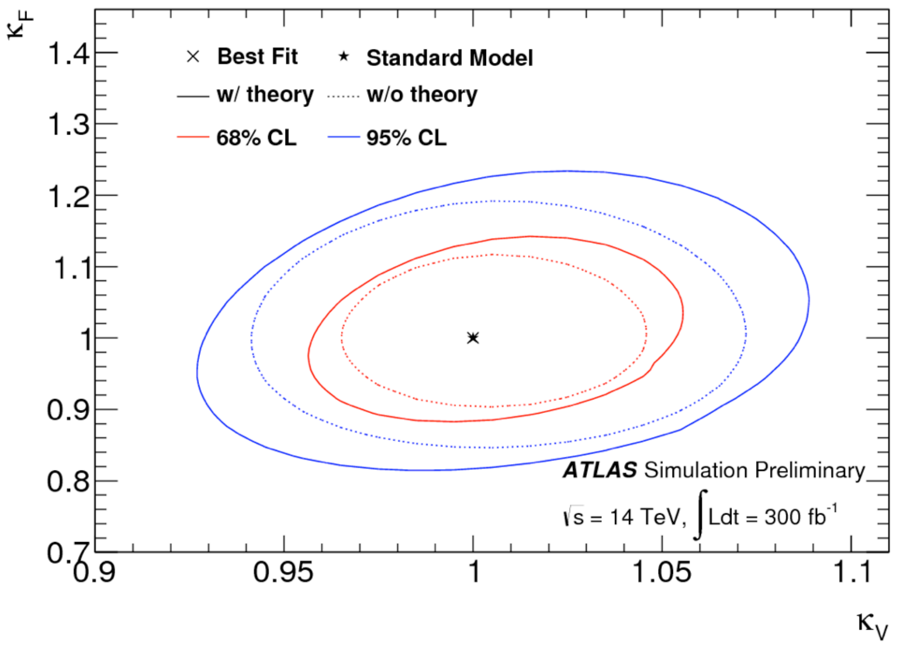

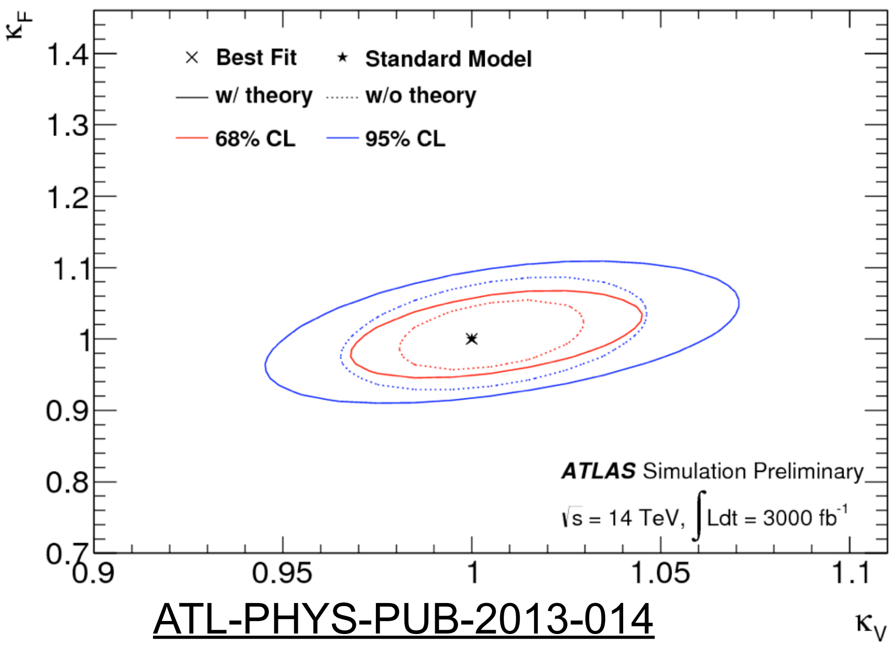

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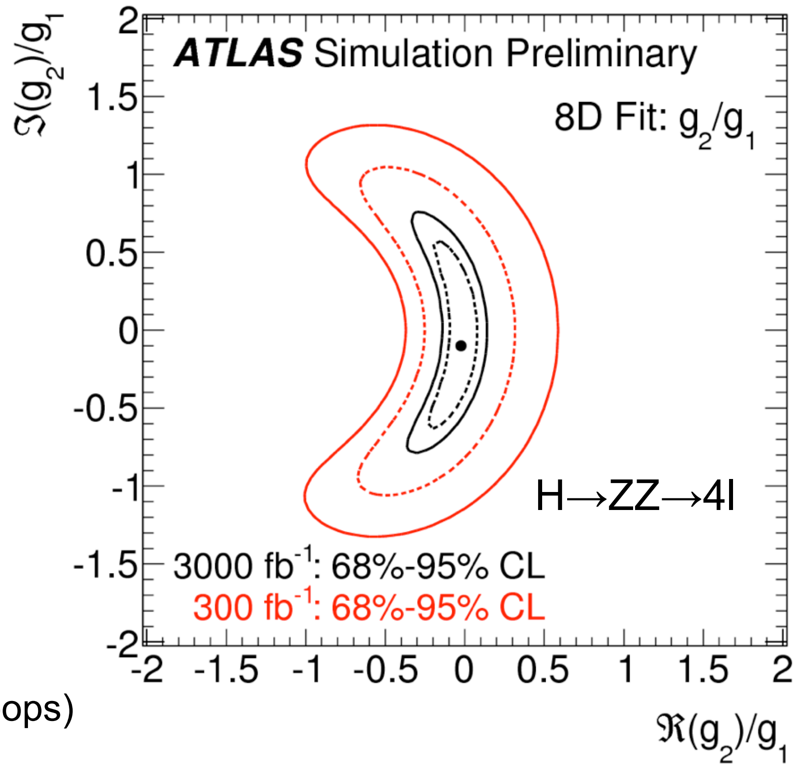

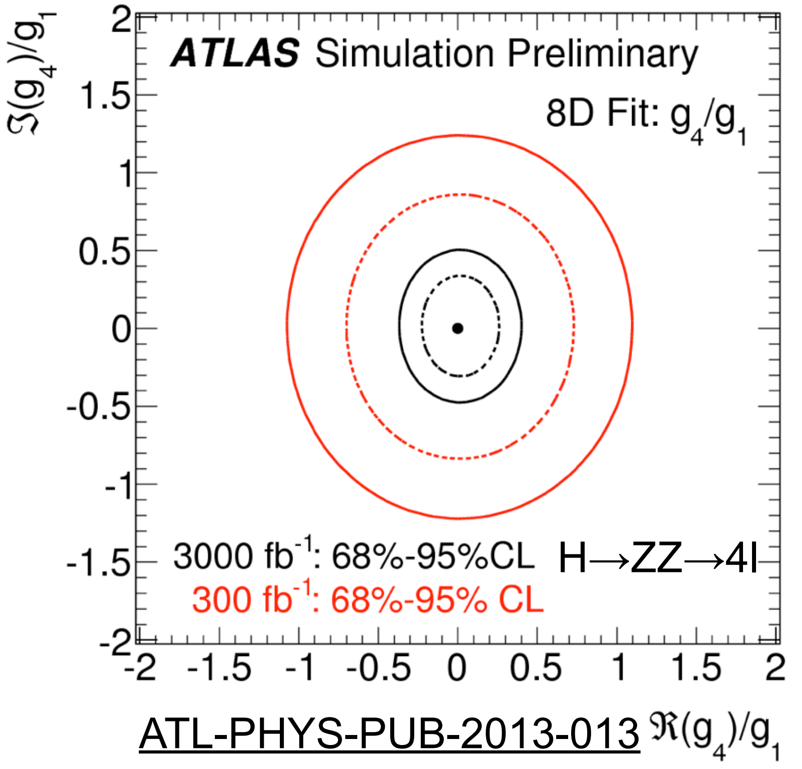

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g_1 CP-even HZZ coupling

g_2 CP-even HZZ coupling (loops)

g_4 CP-odd HZZ coupling