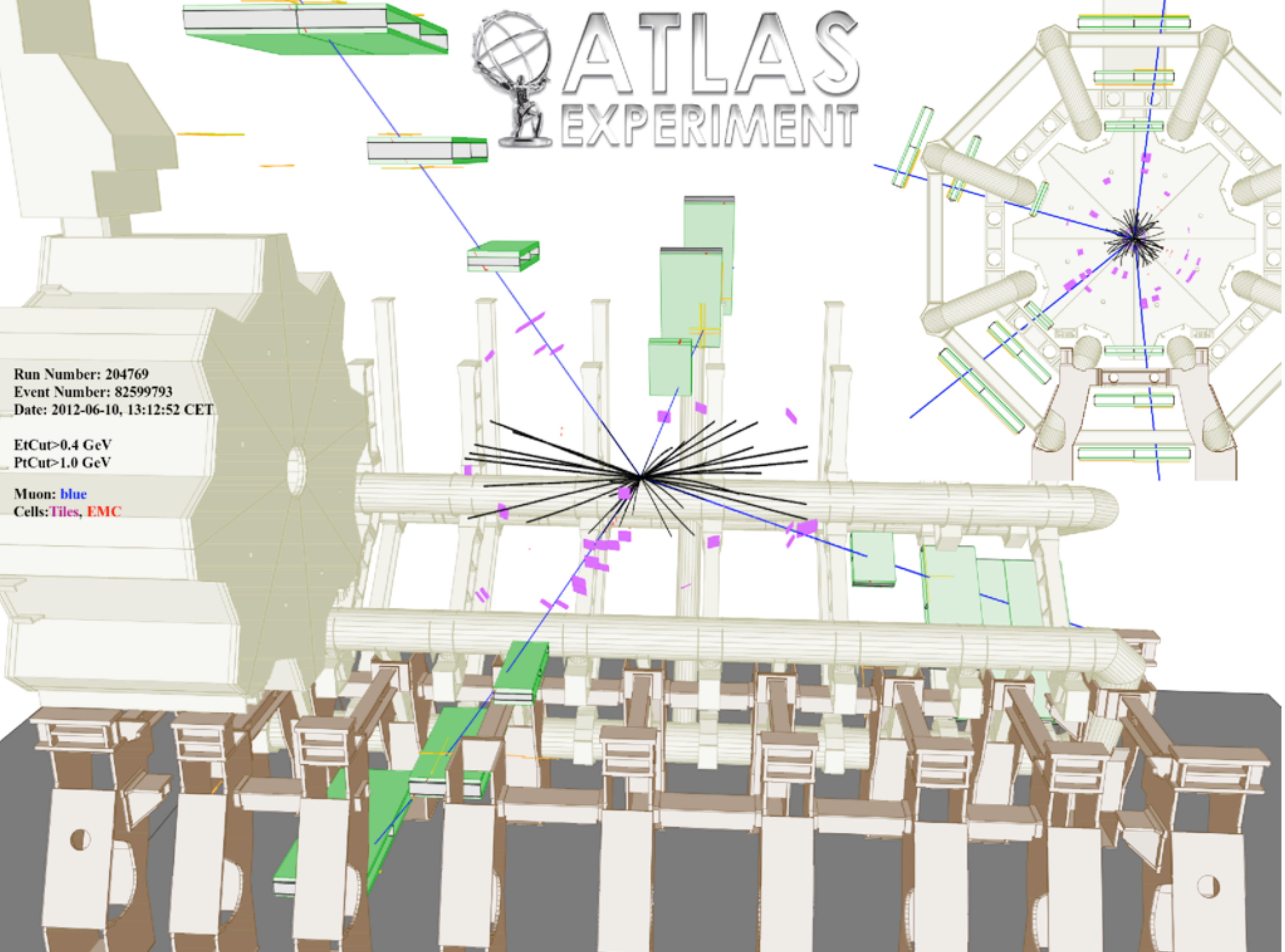


Higgs and Z boson rare decays in quarkonium + photon

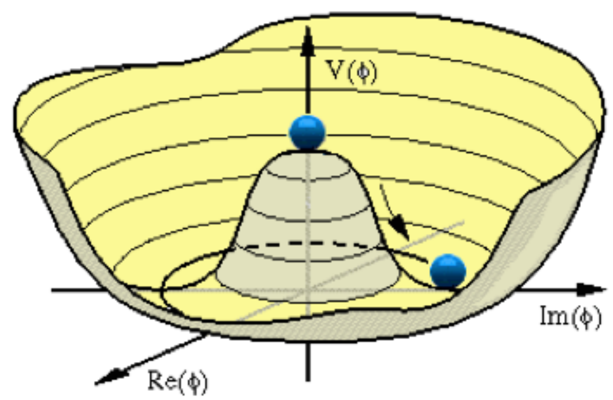
K. Nikolopoulos
University of Birmingham

UNIVERSITY OF BIRMINGHAM

New Possibilities in Physics of Quarkonia
24th September 2015, Institut Henri Poincaré, France

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)

The Standard Model Higgs boson



→ Unification of electromagnetic and weak interactions through $SU(2)_L \otimes U(1)_Y$ local gauge symmetry; massless carriers

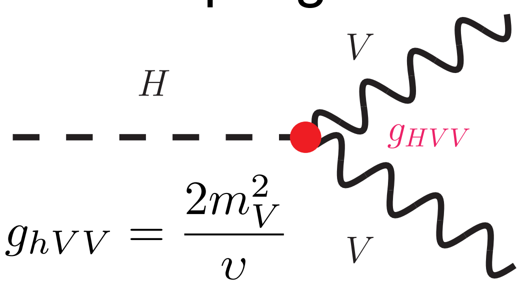
→ Symmetry spontaneously broken - non-zero VEV of the Higgs field

→ Three degrees of freedom of Higgs field → longitudinal polarizations of the vector bosons [Mod.Phys.Lett. A29 (2014) 1450046], fourth is the Higgs boson.

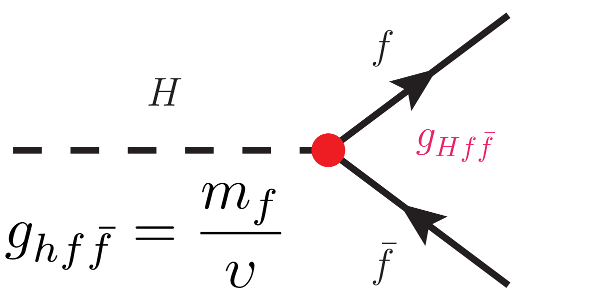
•H→VV defined by symmetry breaking

•H→ffbar is ad hoc Yukawa coupling $\propto m_f$

[Phys.Rev.Lett. 19 (1967) 1264]



$$g_{hVV} = \frac{2m_V^2}{v}$$



$$g_{hf\bar{f}} = \frac{m_f}{v}$$

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

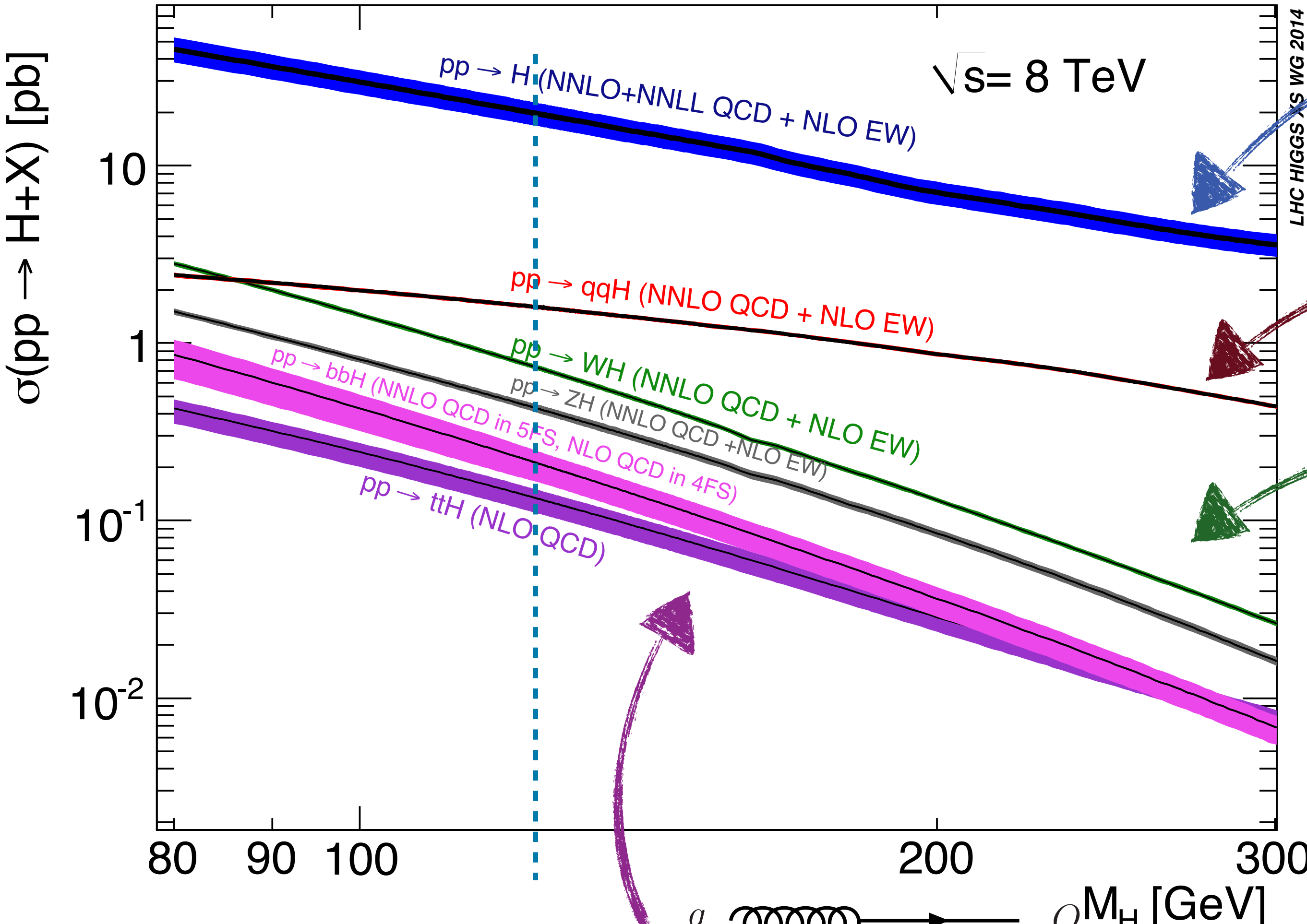
BUT the Yukawa couplings are ad hoc:

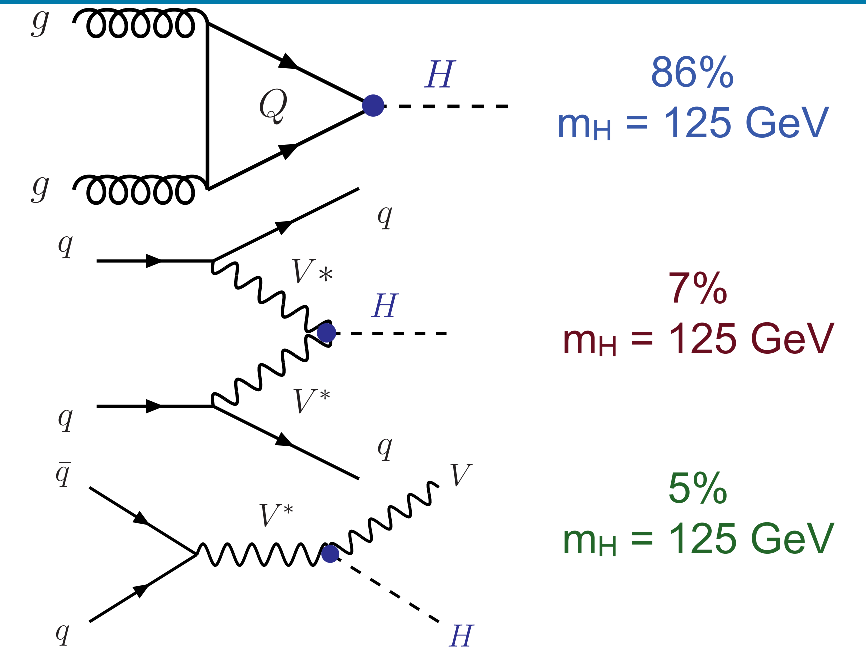
- BSM scenarios predict enhanced Yukawa couplings
- Unitarity bounds (through EFT) for fermion mass generation scale (1st/2nd gen) Λ<20TeV $\Lambda \sim \sqrt{\frac{v^3}{m_f}}$

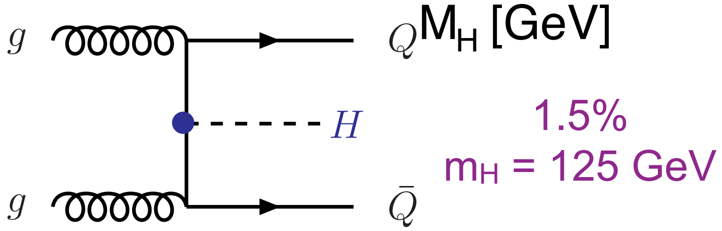
[Phys. Rev. Lett. 59, 2405 (1987); Phys.Rev. D71 (2005) 093009]

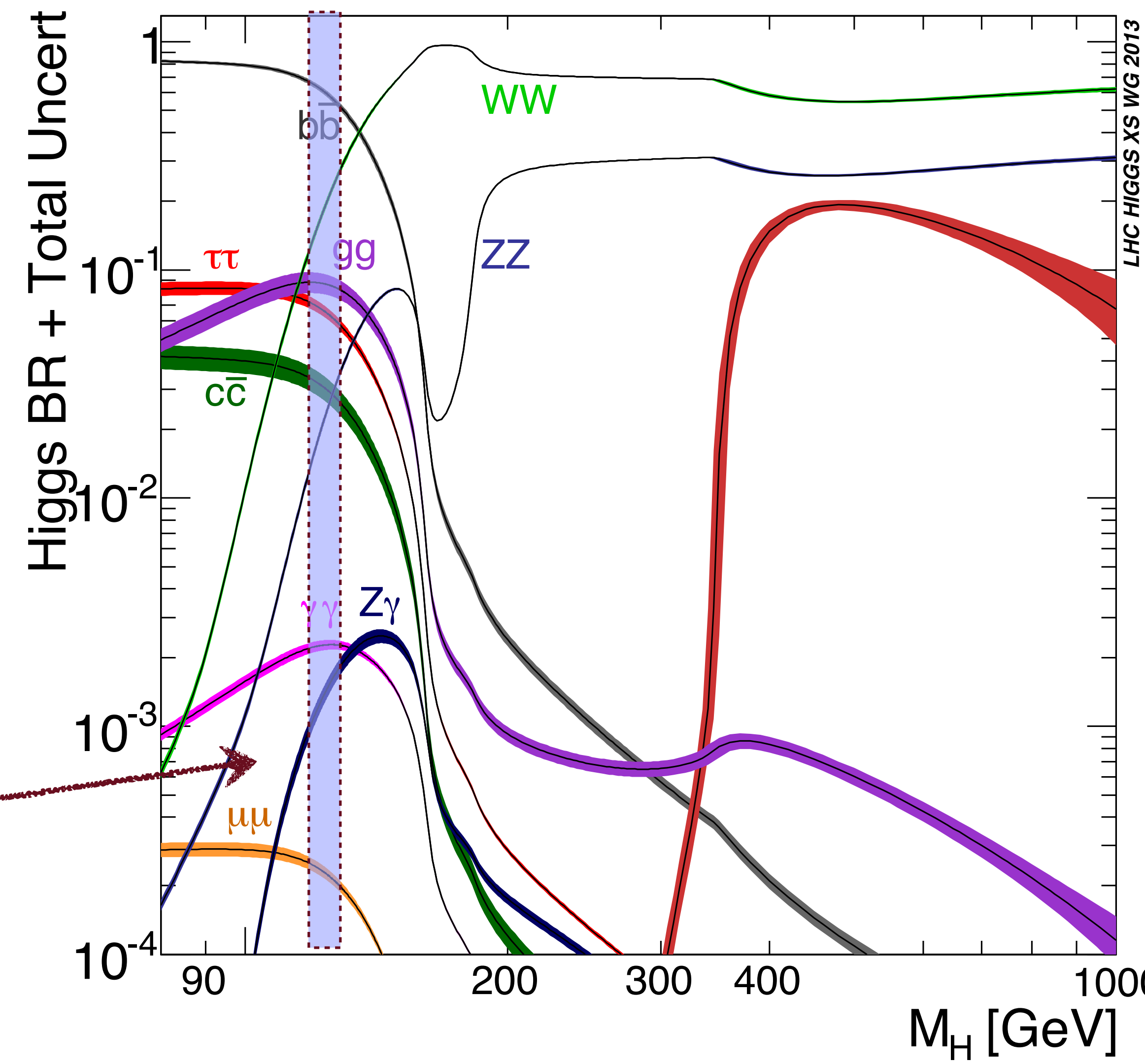
The Higgs boson, was discovered in July 2012, about 115 years after the electron!

SM Higgs boson production and decay at the LHC









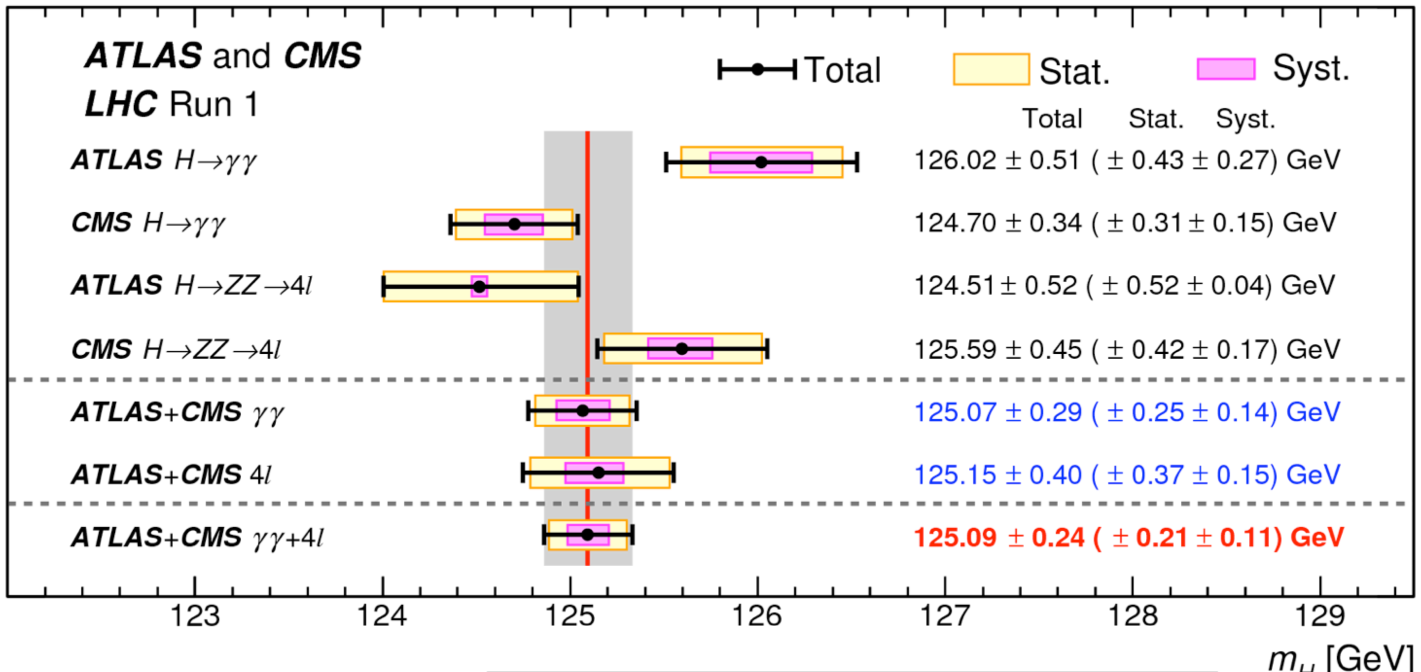
m_H~125 GeV gives access to several decay channels
Gauge bosons: γγ, ZZ*, WW*, Zγ
Fermions: bb, ττ, μμ

The Standard Model Higgs boson

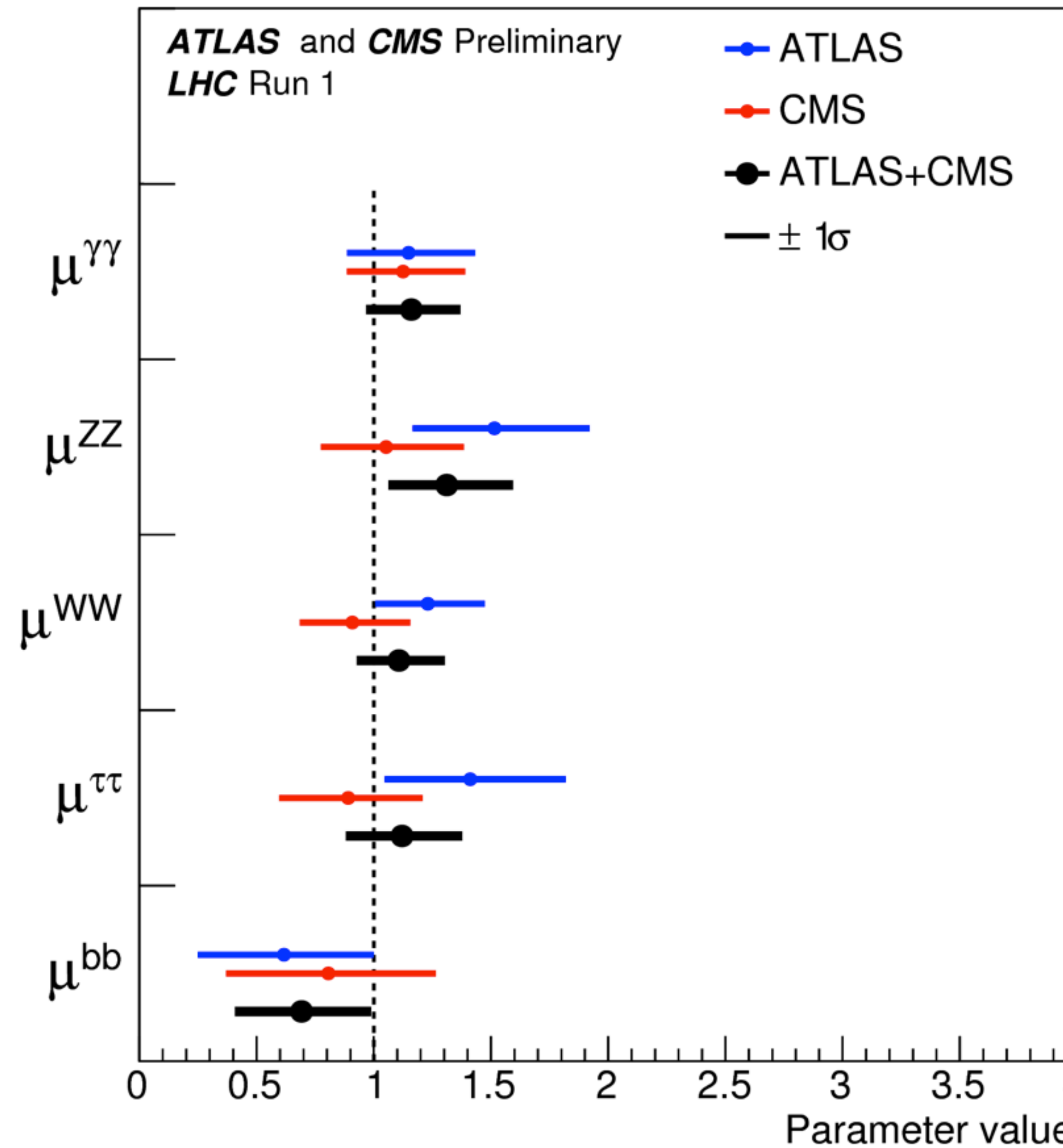
ATLAS-CMS Higgs boson mass combination; 0.19% precision

- 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

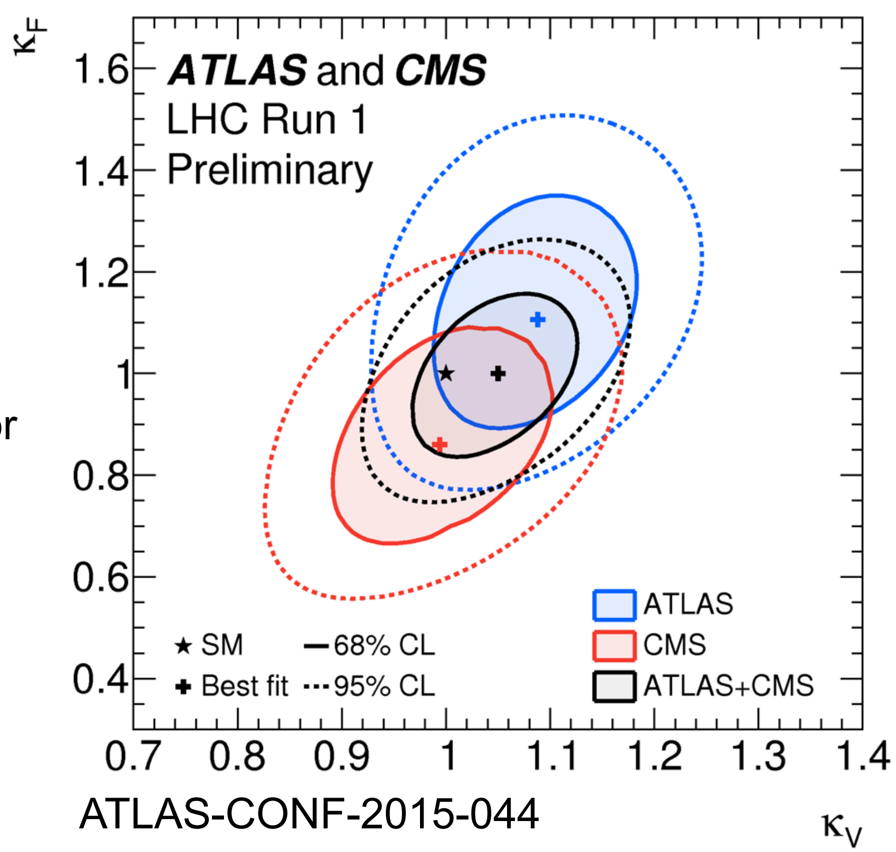
Phys.Rev.Lett 114 (2015) 191803



ATLAS-CONF-2015-044



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

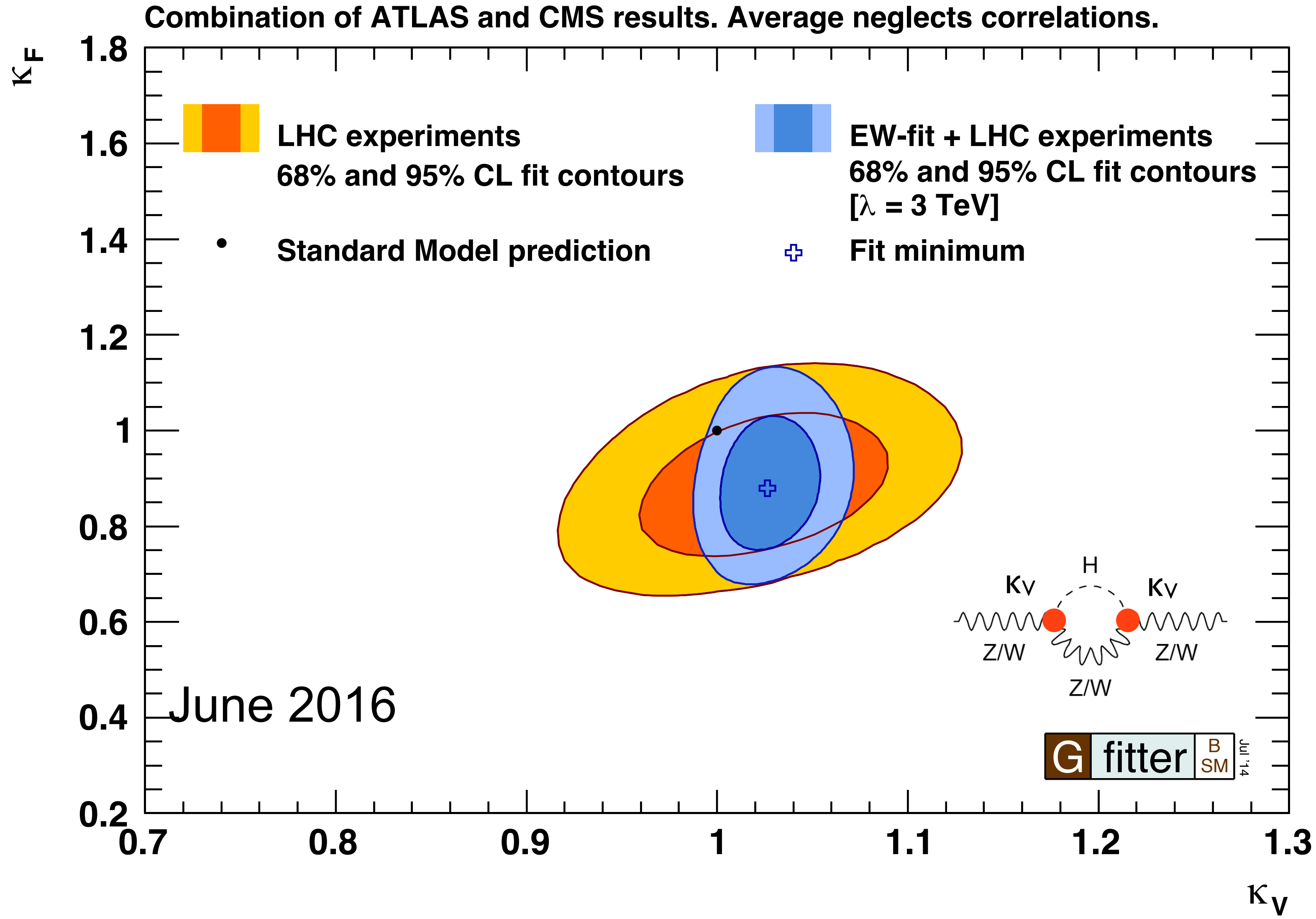


ATLAS-CONF-2015-044

This was not unexpected, given the level of agreement of the SM predictions with the precision electroweak data

Higgs boson and precision electroweak observables

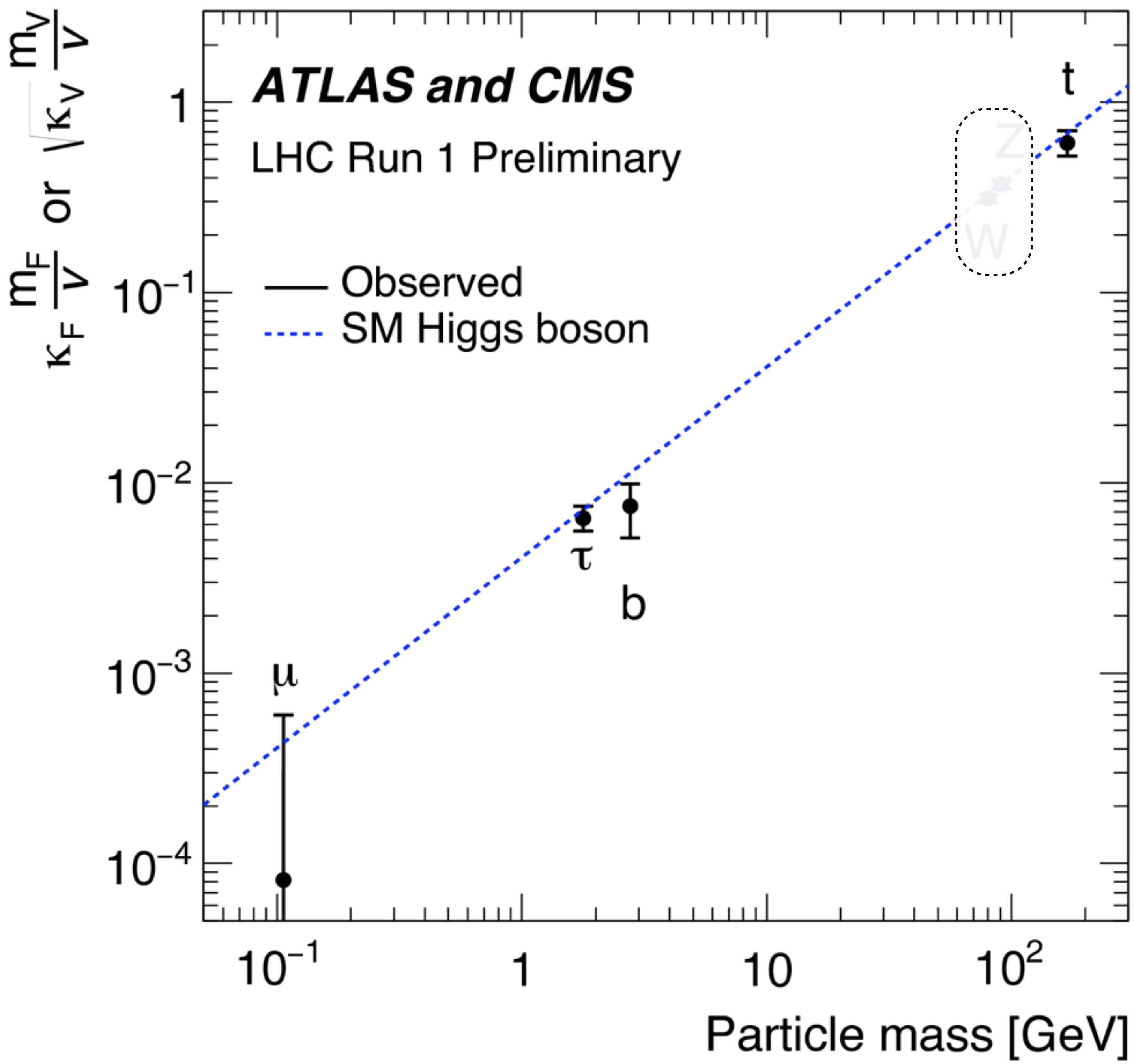
Common coupling scaling for all Fermions (κ_F) and for all Bosons (κ_V); no BSM contributions



Global EW fit still more precise for κ_V than Higgs boson measurements
κ_V>1 preferred (many BSM scenarios require κ_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!

Yukawa couplings so far...



ATLAS-CONF-2015-044

→ 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

Charm-quark Yukawa coupling

Charm-quark Yukawa coupling

Recent substantial activity on probing the charm-quark Yukawa coupling at the LHC.
Two lines of attack (non-exhaustive list of references):

→ Charm-tagging either at decays h→ccbar or production pp→hc
[Phys.Rev. D89 (2014) 3, 033014; Phys.Rev. D92 (2015) 033016, arXiv:1507.0291]

→ Exclusive decays h→Qγ
[Phys.Lett. B82 (1979) 411; Phys.Rev. D27 (1983) 2762; Yad.Fiz. 46, 864 (1987); Phys.Rev. D88 (2013) 053003; Phys.Rev. D90 (2014) 113010, JHEP 1508 (2015) 012]

These searches are sensitive to BSM physics
[arXiv:1508.01501, arXiv:1504.04022, Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79]

Charm Tagging

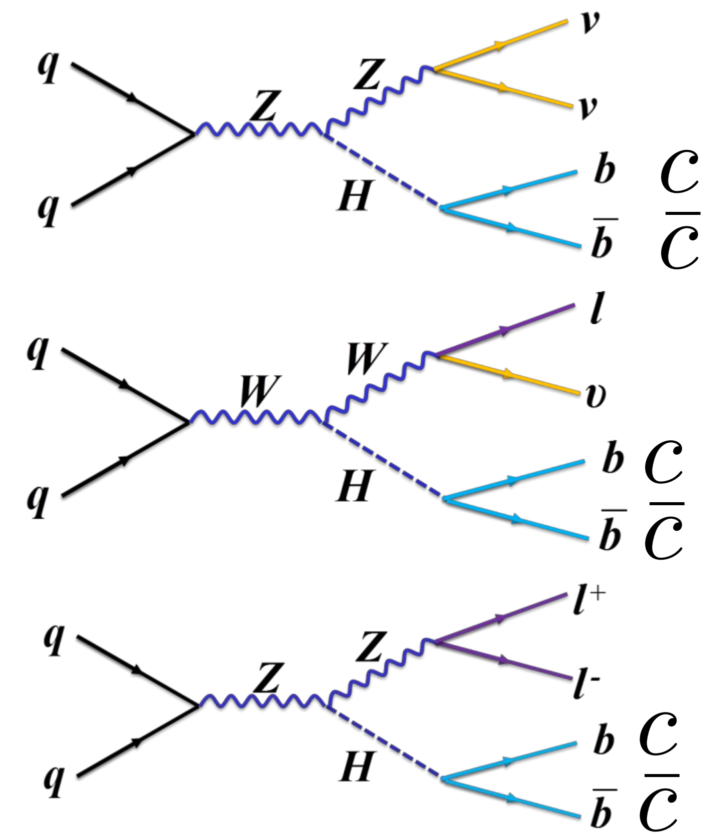
One may "re-interpret" the h→bbbar search
for anomalous h→ccbar production

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

→ Enhancement Y_c: ↑BR(h→ccbar), ↓BR(h→bbbar) [through ↑Γ_h]

→ Constrains only a linear combination of μ_b and μ_c

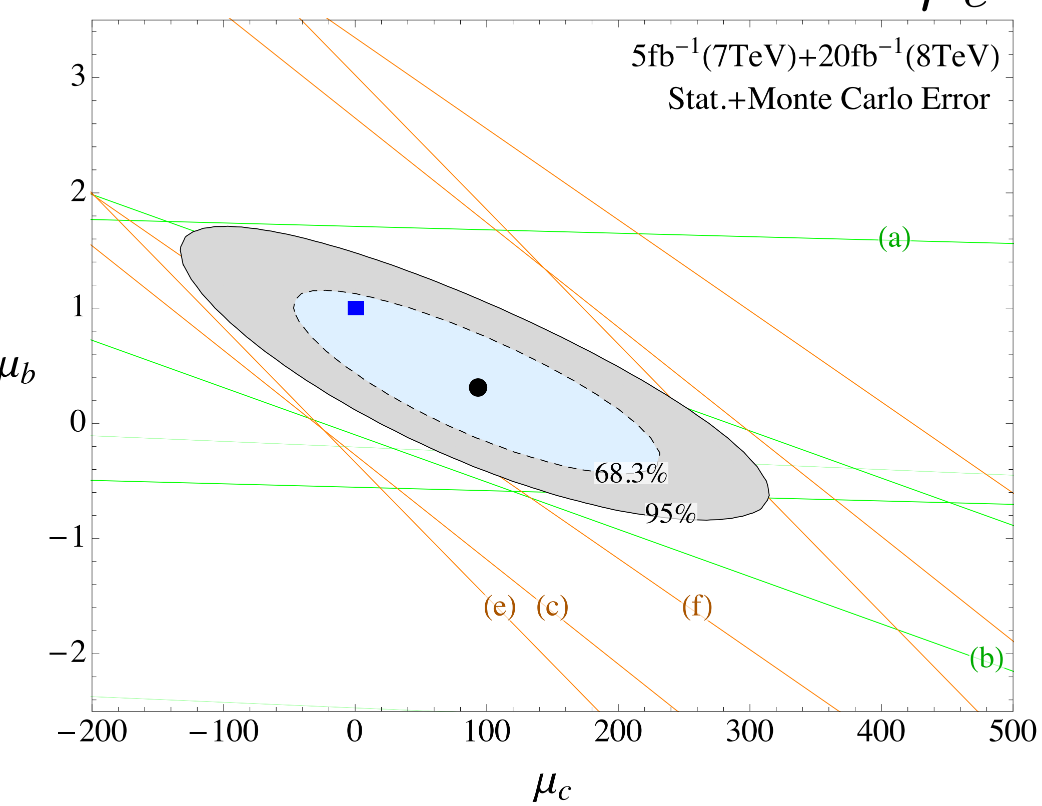
→ Need multiple b-tagging points



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

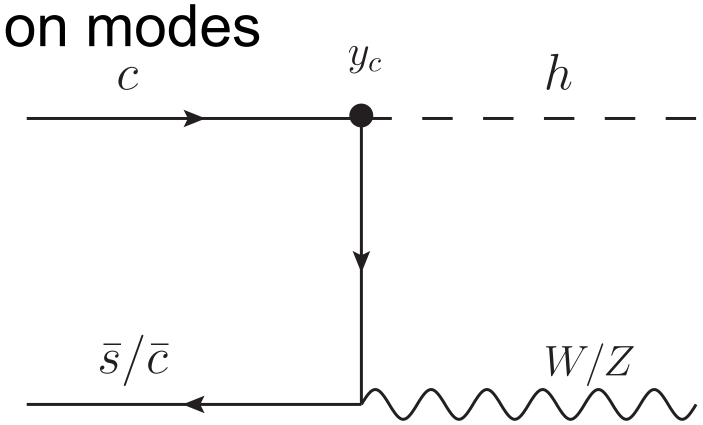
$$= \mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar{c}}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar{b}}}\,\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\;\mu_c\,,$$

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



[Phys.Rev. D92 (2015) 033016]

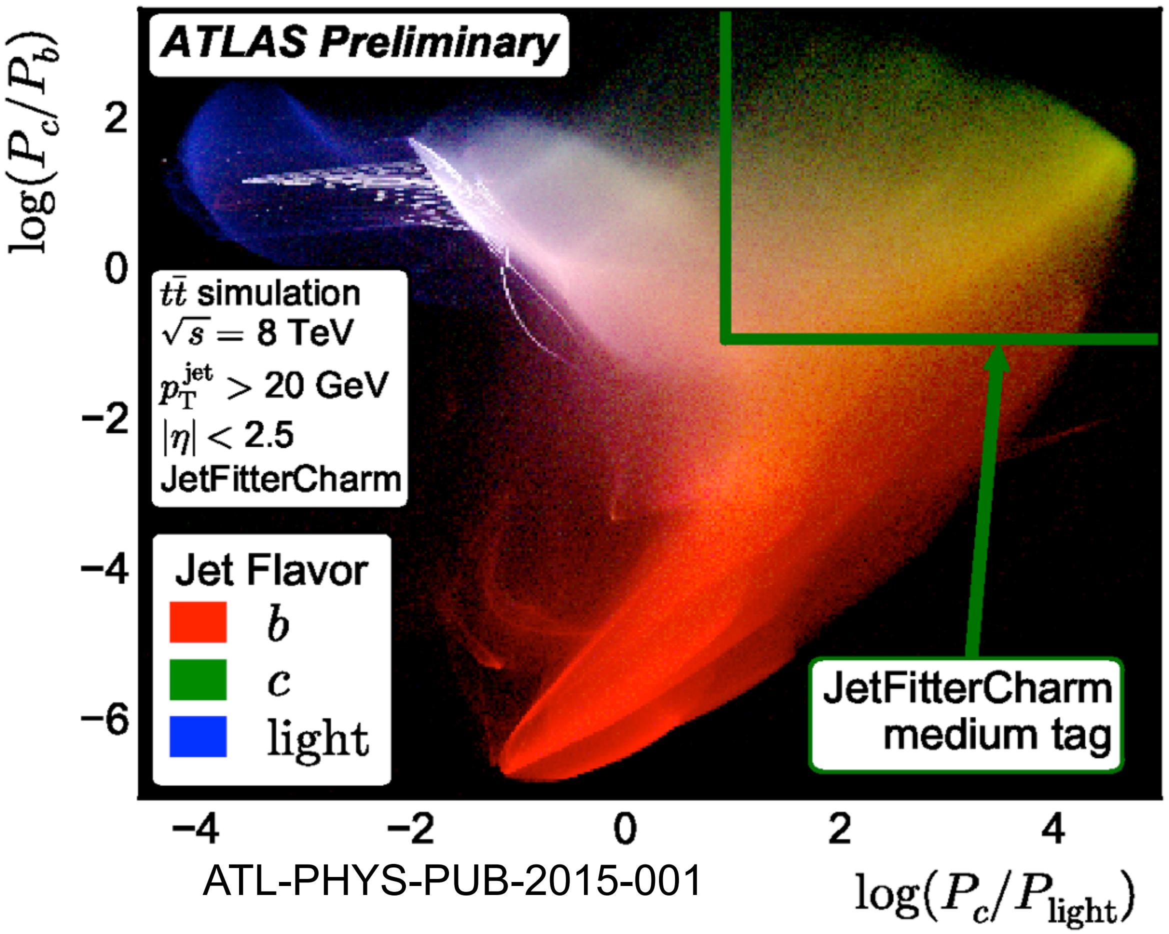
→ Extracting info about Yukawa couplings:
account for new production modes

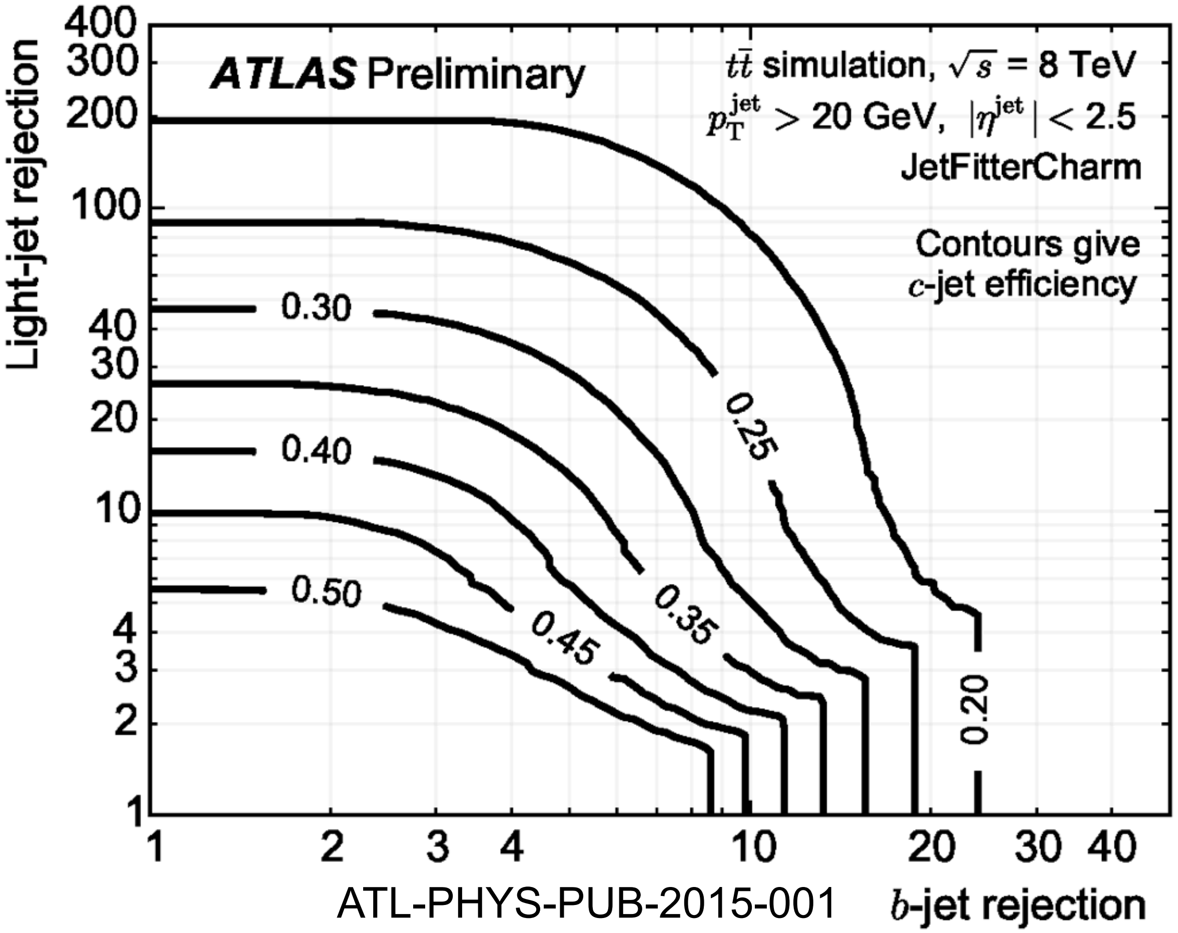


$$\kappa_c \lesssim 234 \text{ at } 95\% \text{ CL}\,,$$

→ No detailed experimental analysis performed yet!

Charm Tagging





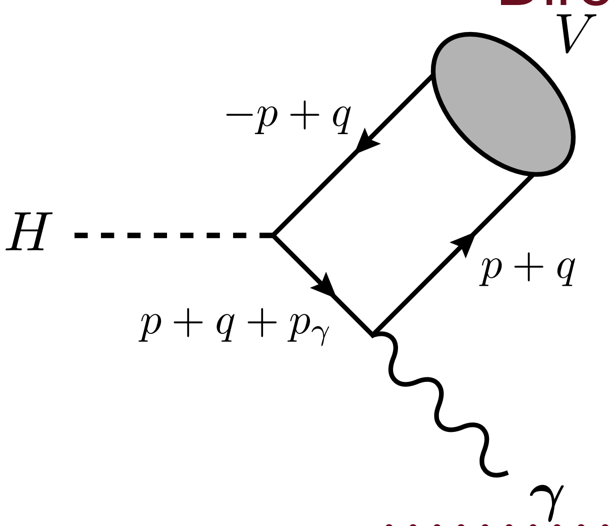
To resolve the two contributions improved c-tagging is needed
→ ideally completely separate b- and c-jets
Future H→ccbar searches will benefit from dedicated c-tagging (ATL-PHYS-PUB-2015-001), already applied in ATLAS scalar-charm search. [Phys.Rev.Lett. 114 (2015) 161801]

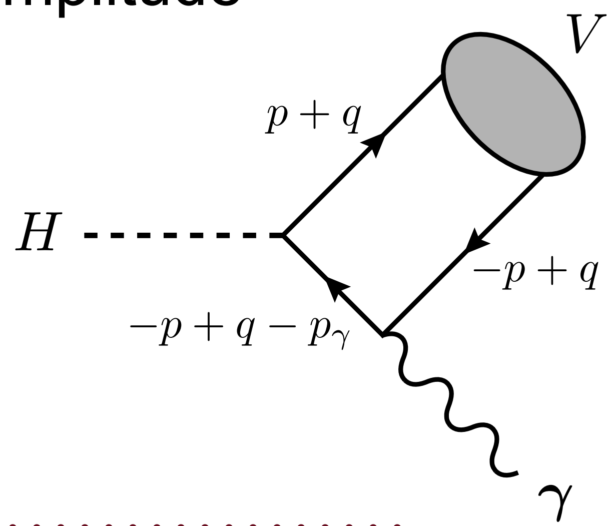
However:
- complicated analysis with large QCD backgrounds
- signal sits on top of large (×20) h→bbbar "background"
- sensitivity to systematics of b/c-tagging efficiency
- need dedicated simulations for decay and production

Exclusive Decays h→Qγ

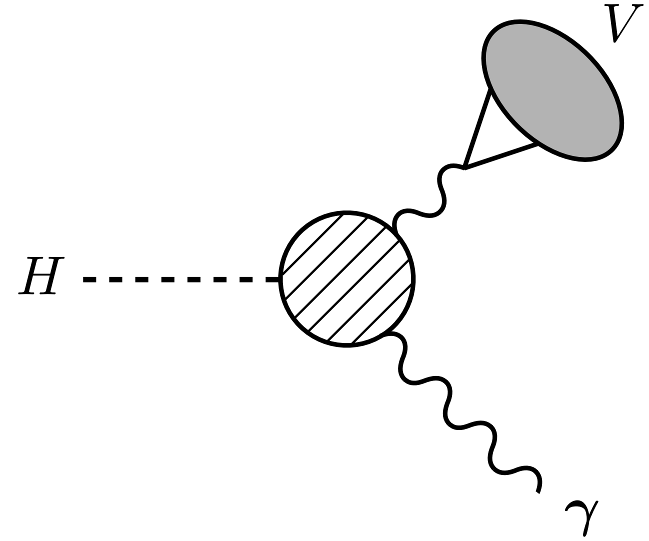
Exclusive decays lead to distinct experimental signatures
→ High-pT quarkonium back-to-back with a high-pT photon.

"Direct" amplitude





"Indirect" contribution



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

Phys.Rev. D88 (2013) 5, 053003

Indirect amplitude: significant contribution, larger than direct amplitude
Destructive interference between the two → resolve coupling sign-ambiguity

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

Phys.Rev. D90 (2014) 11, 113010

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

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

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

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

JHEP 1508 (2015) 012

Exclusive Decays $Z \to Q\gamma$: J/ψ and Υ

→ Analogous Z boson decays also attracting significant attention
[Nucl. Phys. B 174, 317 (1980), Theor. Math. Phys. 170, 39 (2012), Phys.Rev. D92 (2015) 014007, 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
→ Also possibility to study potentially FCNC processes (constrained only indirectly)

Recently, a number of numerical results have appeared, for these decay rates.

JHEP 1504 (2015) 101

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

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)

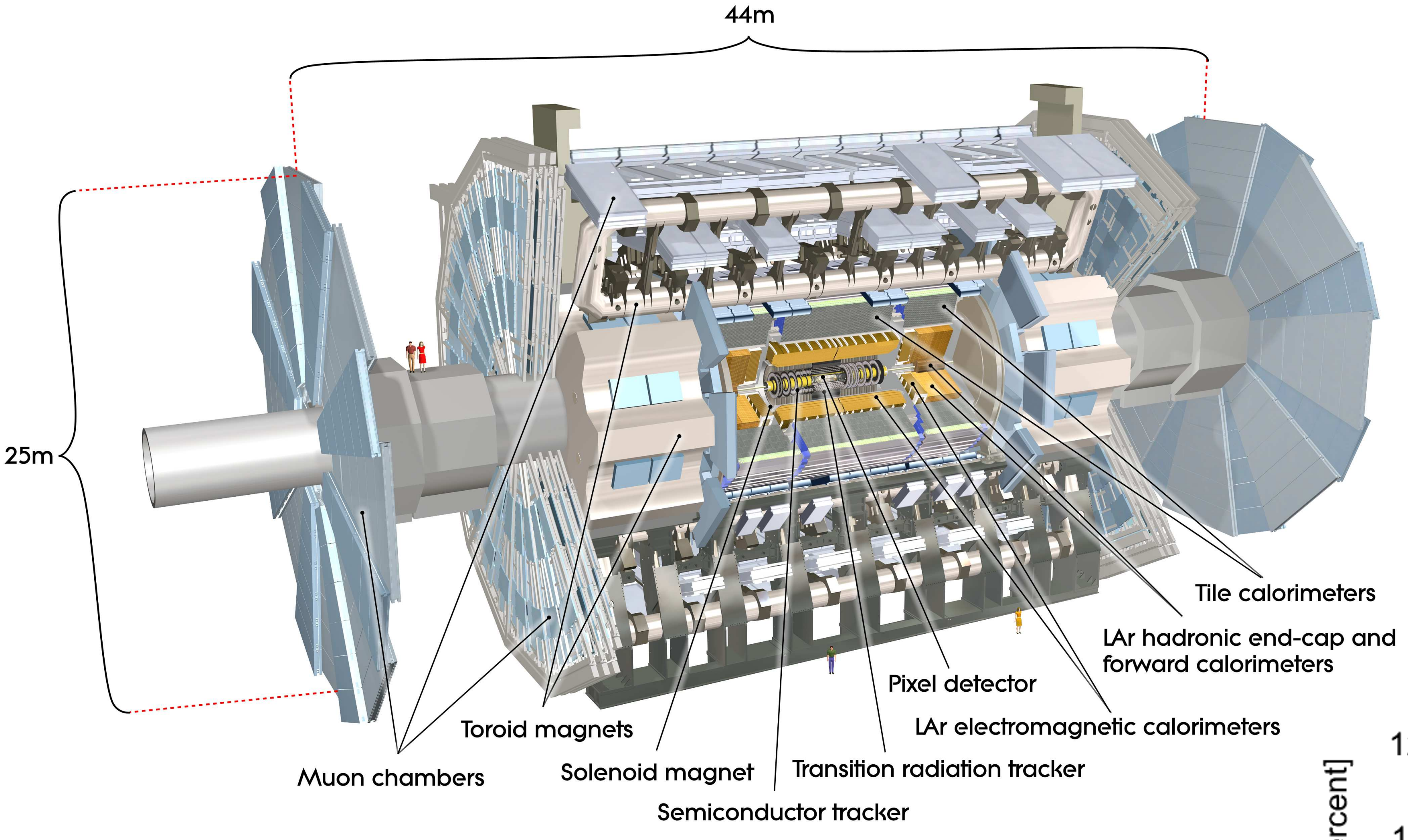
(Received 15 January 2015; published 26 March 2015)

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 Y(nS), n=1,2,3

A Toroidal LHC ApparatuS

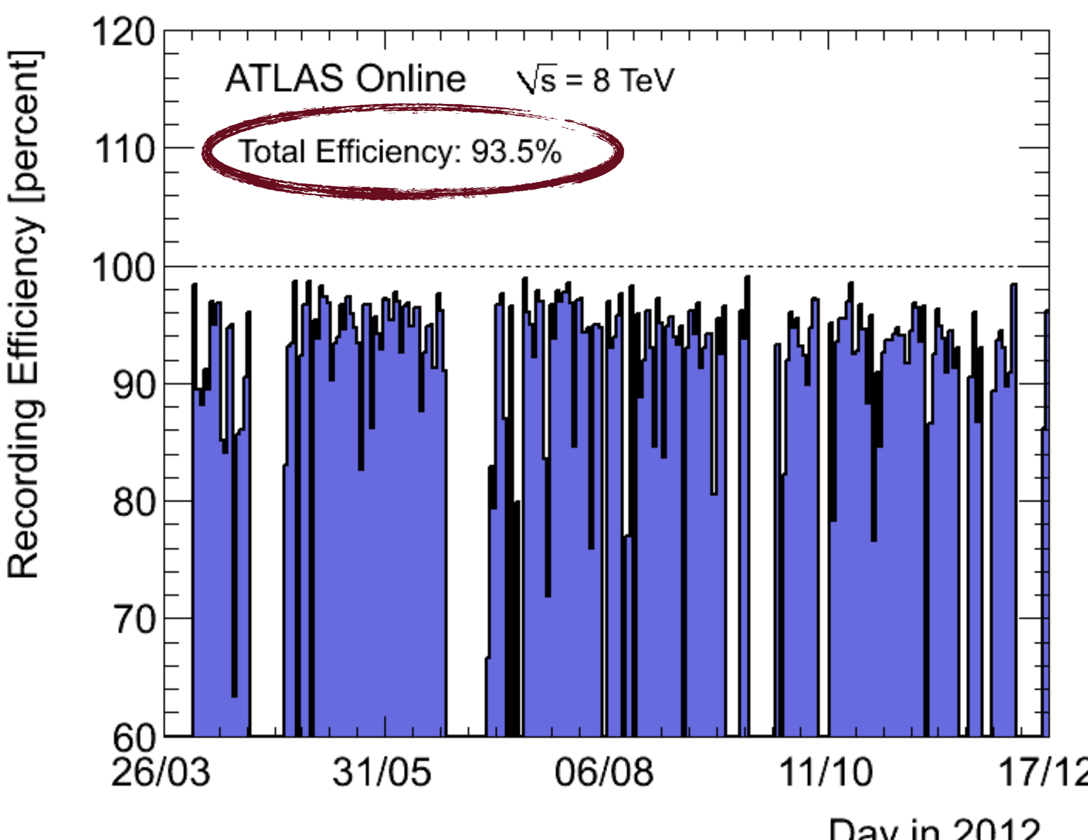


	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling Liquid Argon
Hadron Calorimetry	plastic scintillator (barrel) Liquid Argon(endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 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 $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.



$h \to J/\psi\gamma$ and $h \to \Upsilon(ns)\gamma$

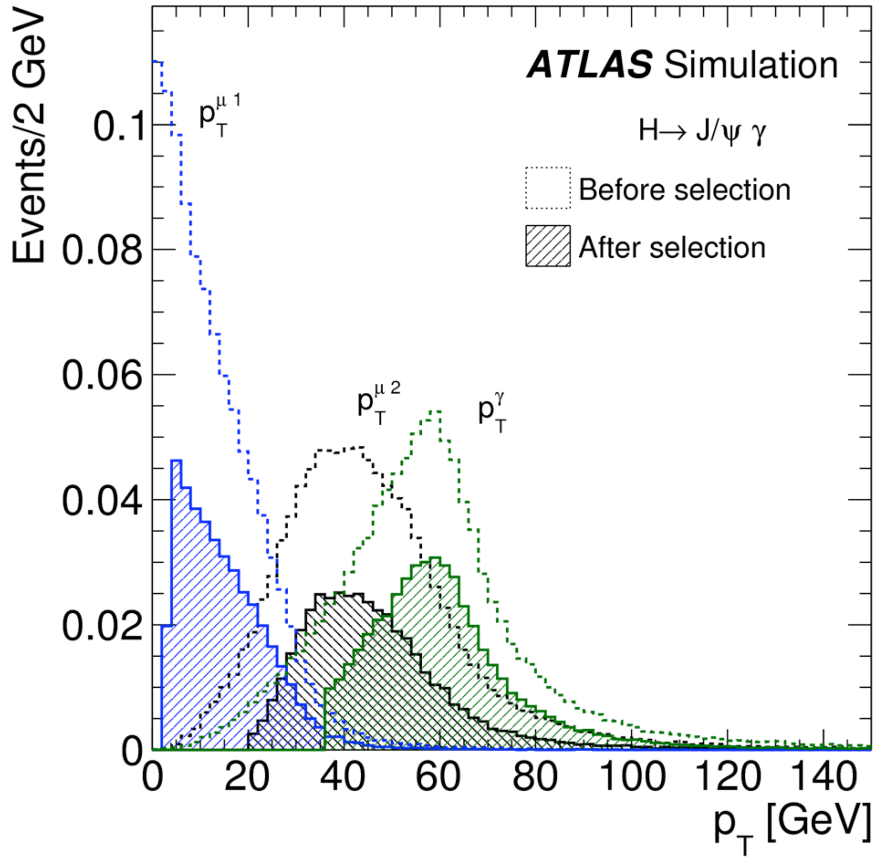
Phys.Rev.Lett. 114 (2015) 121801

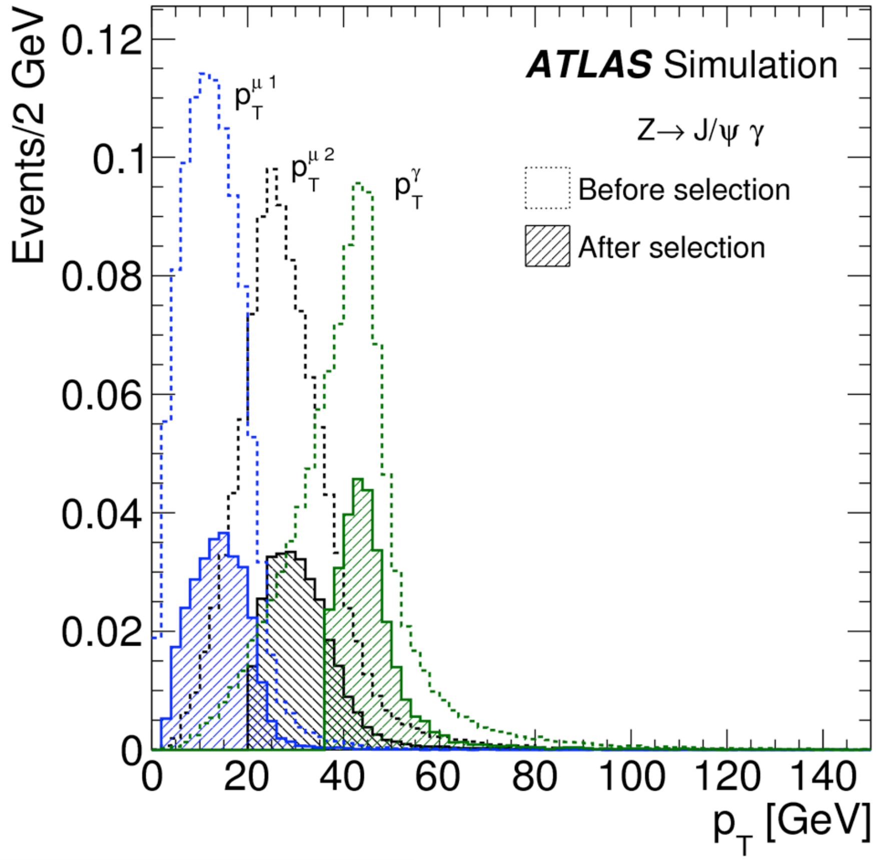
Signature: $\mu^+\mu^-+\gamma$

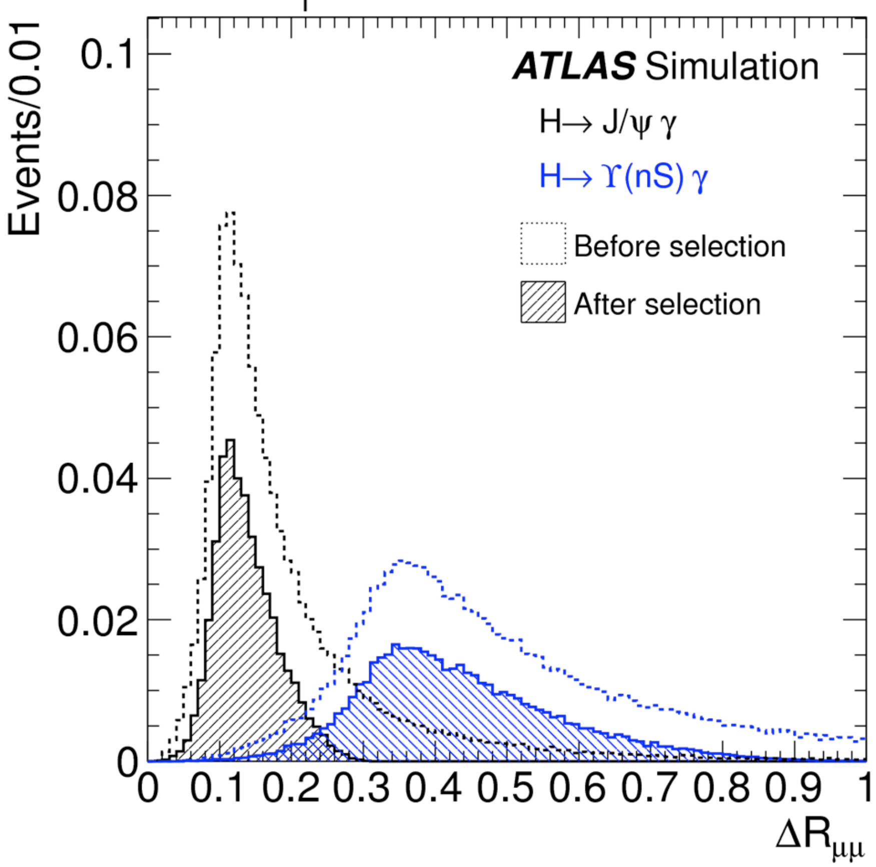
→ event selection:
- single(di)-muon trigger
- $pT_\mu > 20{,}3$ GeV,
- $pT_{\mu\mu} > 36$ GeV,
- $pT_\gamma > 36$ GeV
- $\mu\mu$ and γ isolation,
- [J/ψ mass requirement]
- L_{xy} significance,
- $\Delta\varphi(\mu\mu,\gamma) > 0.5$

→ total signal acceptance/efficiency
- $H(Z) \to J/\psi\gamma \to \mu^+\mu^-+\gamma$ ~ 22% (12%)
- $H(Z) \to \Upsilon\gamma \to \mu^+\mu^-+\gamma$ ~ 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/Z→J/ψγ and h/Z→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 121801

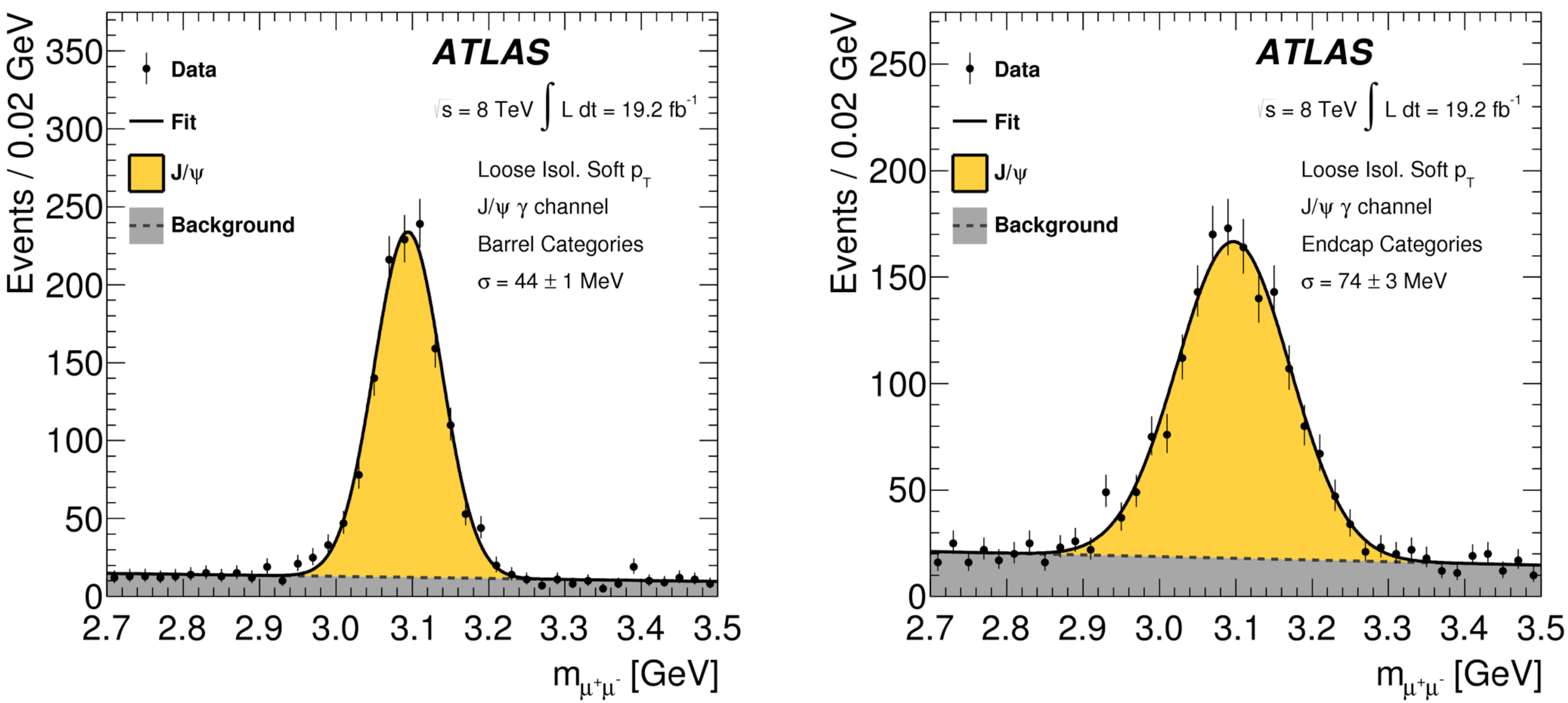
Categories

For this search simple - detector performance driven categorisation

→ Muon pseudo-rapidity

→ Both Central/One Non-Central

→ Photon Unconverted/Converted

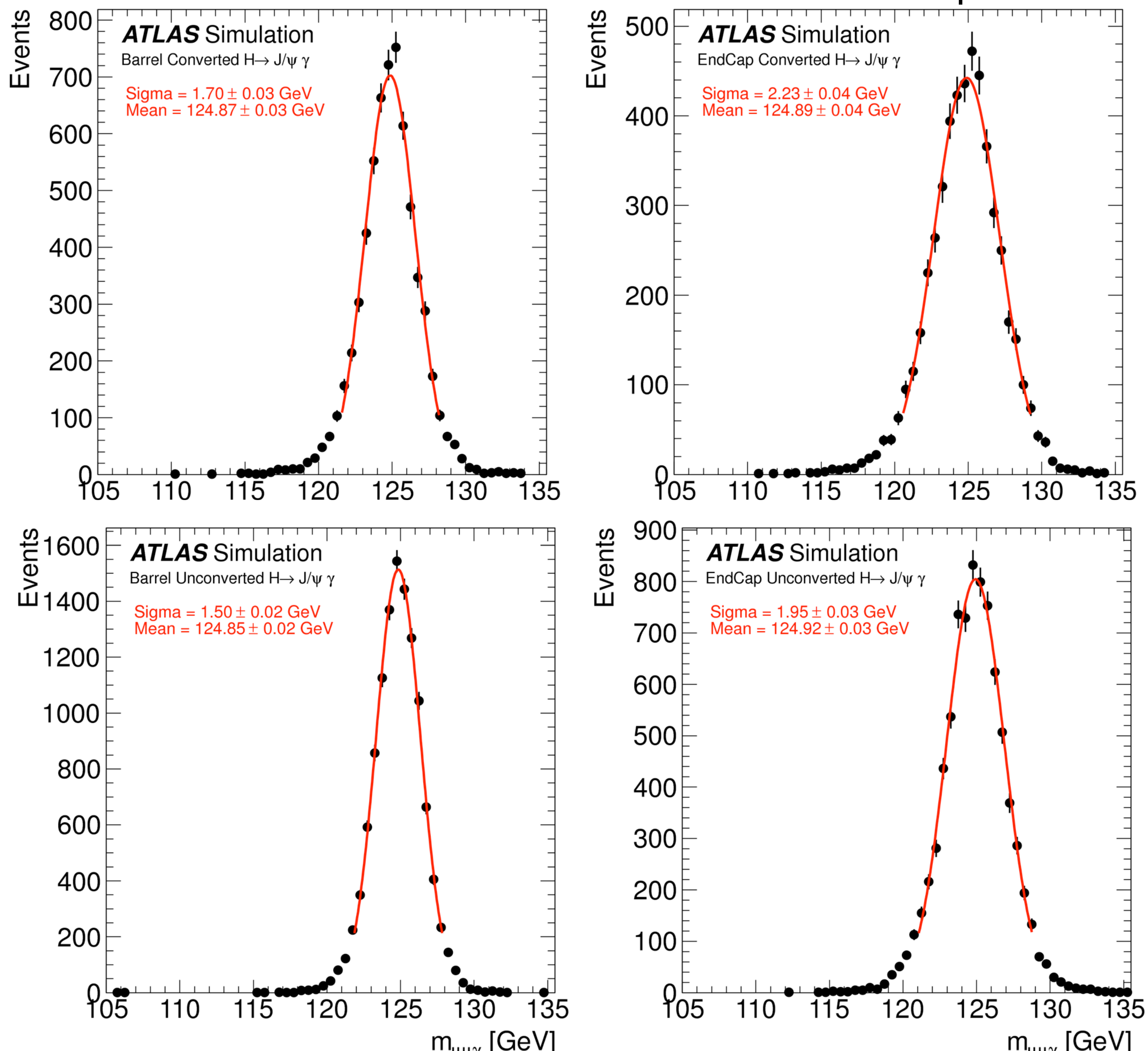


h→J/ψγ and h→Y(ns)γ: Mass Resolution

barrel | endcap

converted photon

unconverted photon



h/Z→J/ψγ and h/Z→Υ(ns)γ

Phys.Rev.Lett. 114 (2015) 121801

Category	Observed (Expected Background) All	Mass Range [GeV] 80–100		115–135		Signal Z $\mathcal{B}$ [10^{-6}]	Signal H $\mathcal{B}$ [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

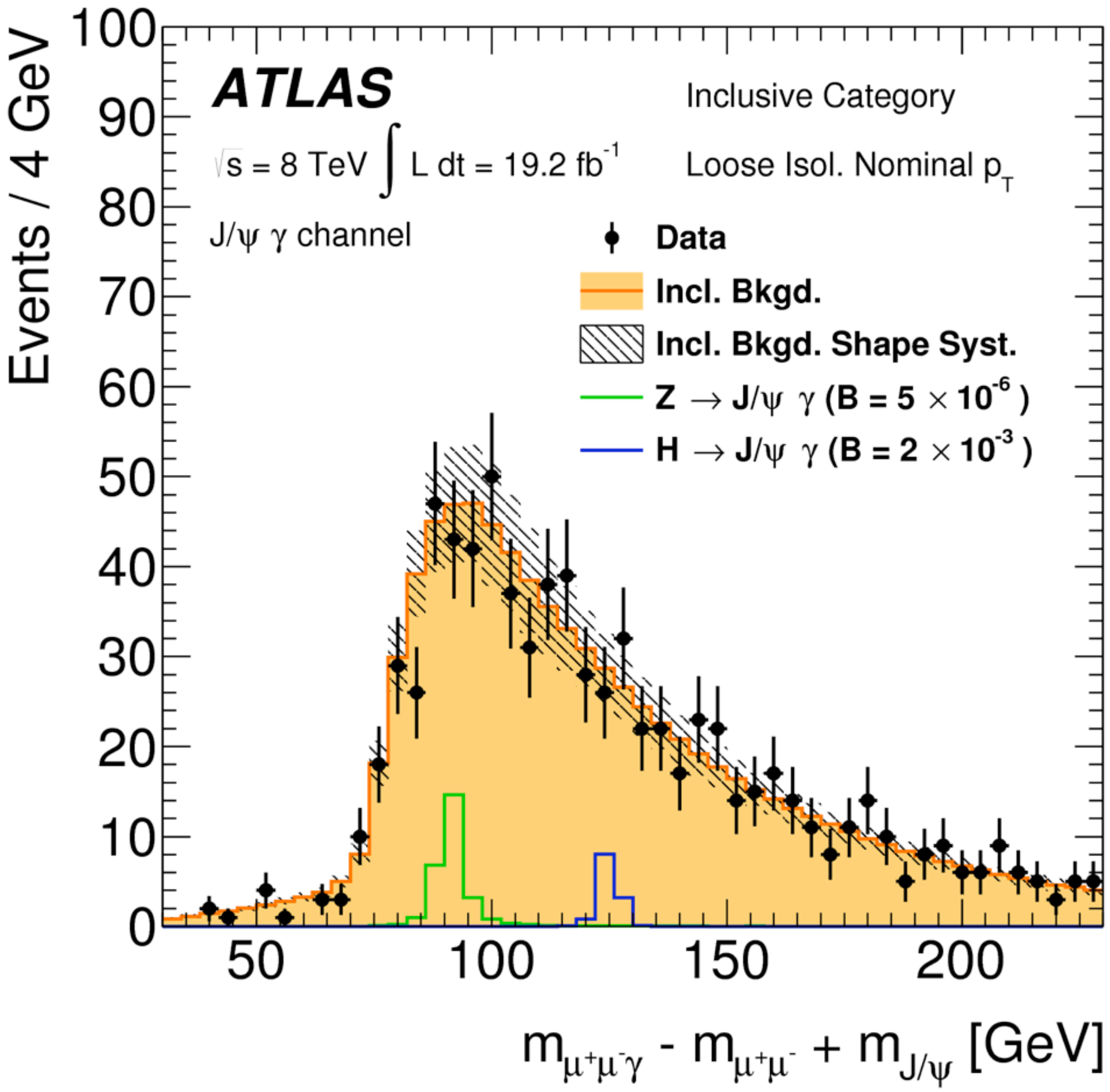
Background

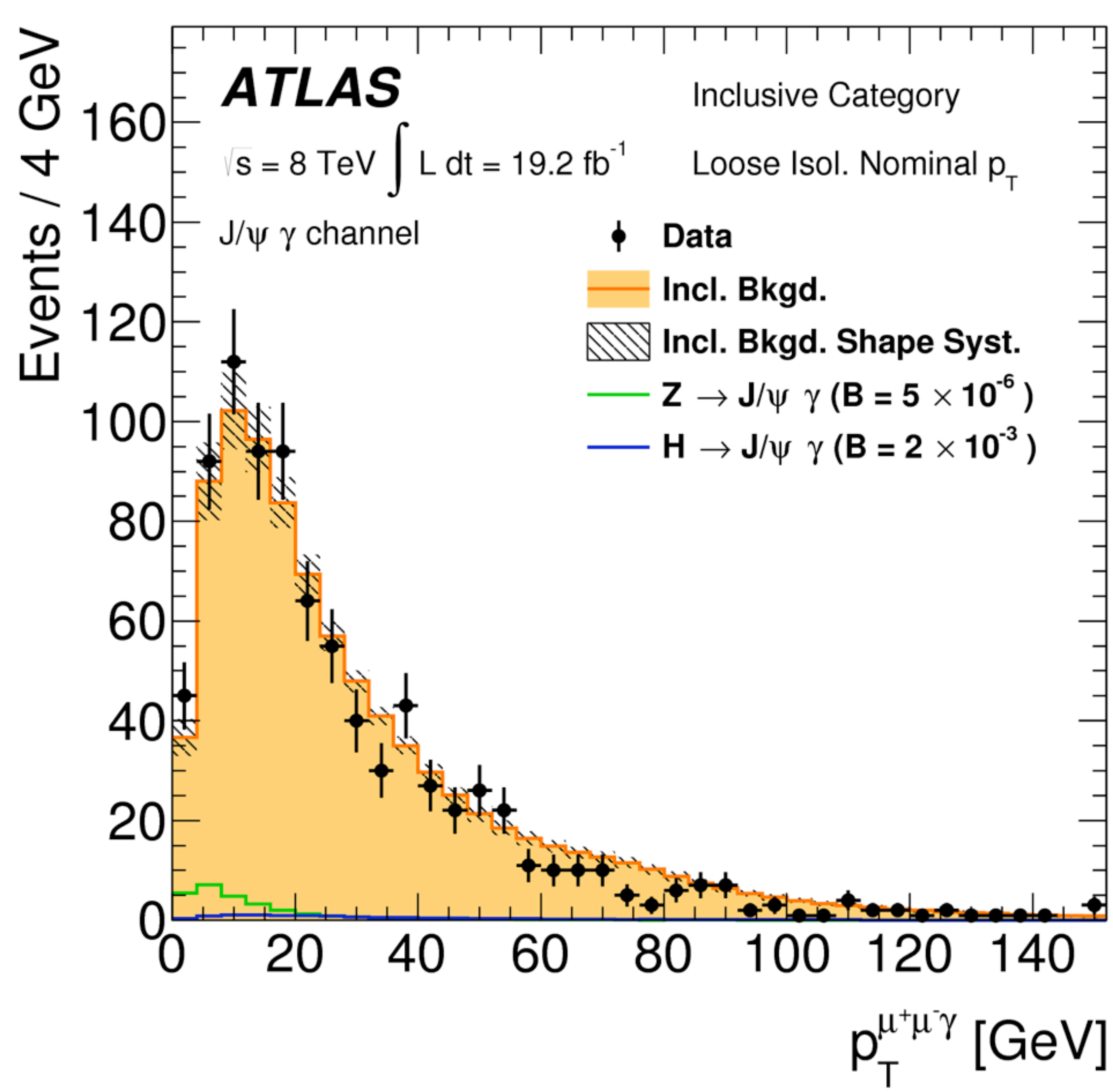
→ mostly inclusive quarkonium with jet "seen" as γ

→ small component of combinatoric

→ Non-parametric data-driven background estimation

→ for Υ(nS)γ also $Z\to\mu\mu\gamma_{FSR}$ from side-band fit

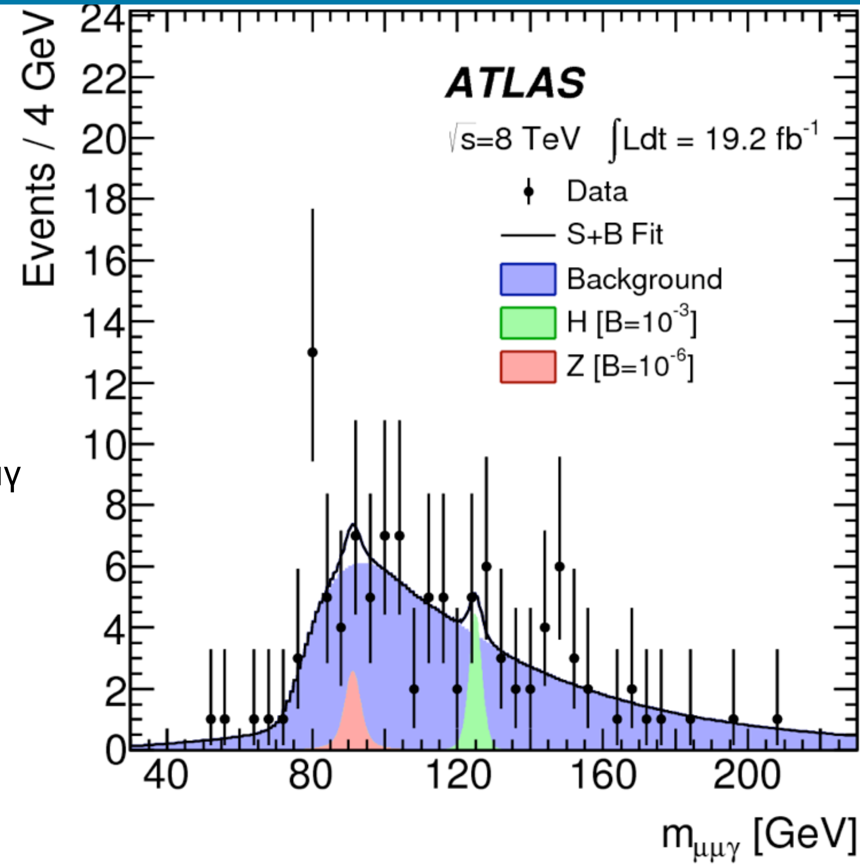


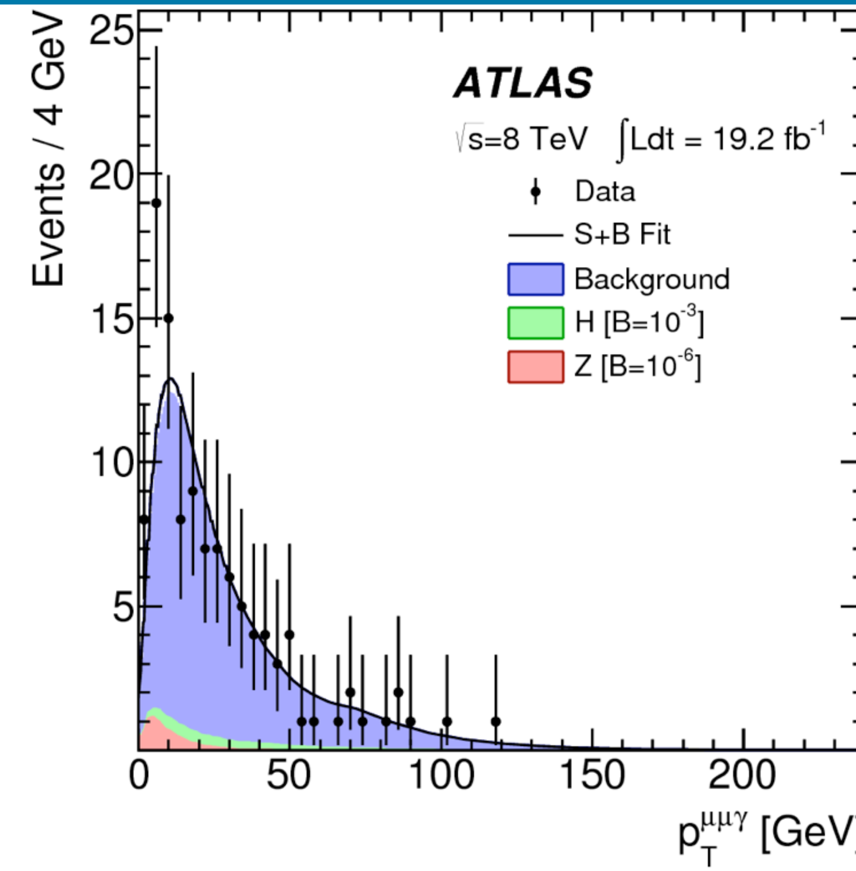


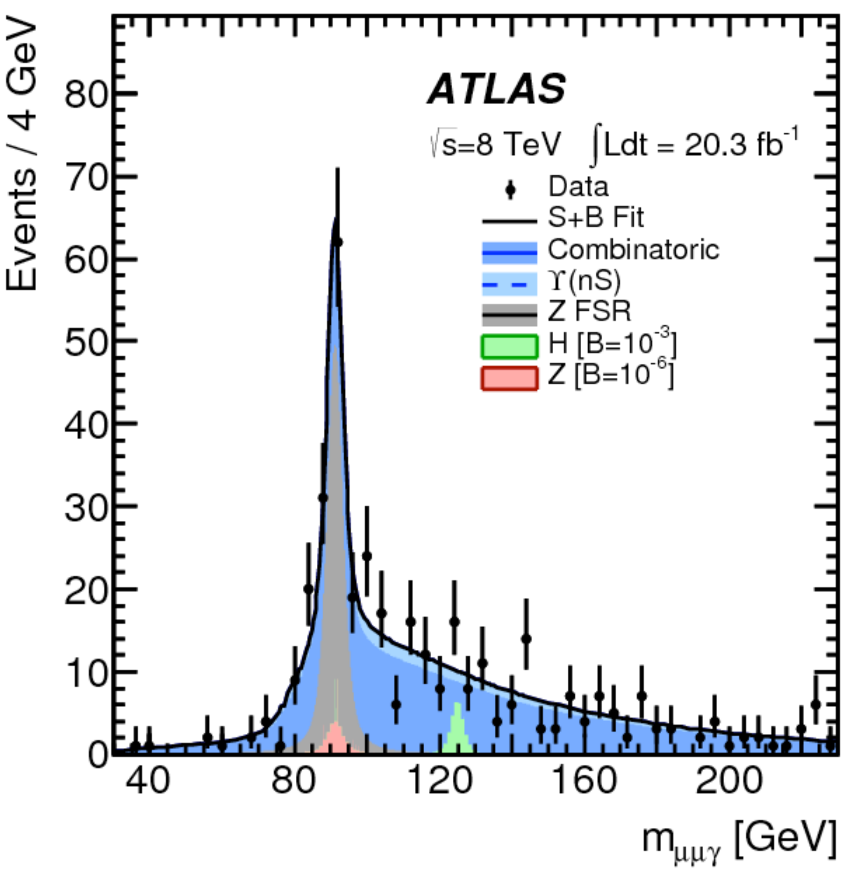
h/Z→J/ψγ and h/Z→Υ(ns)γ: Results

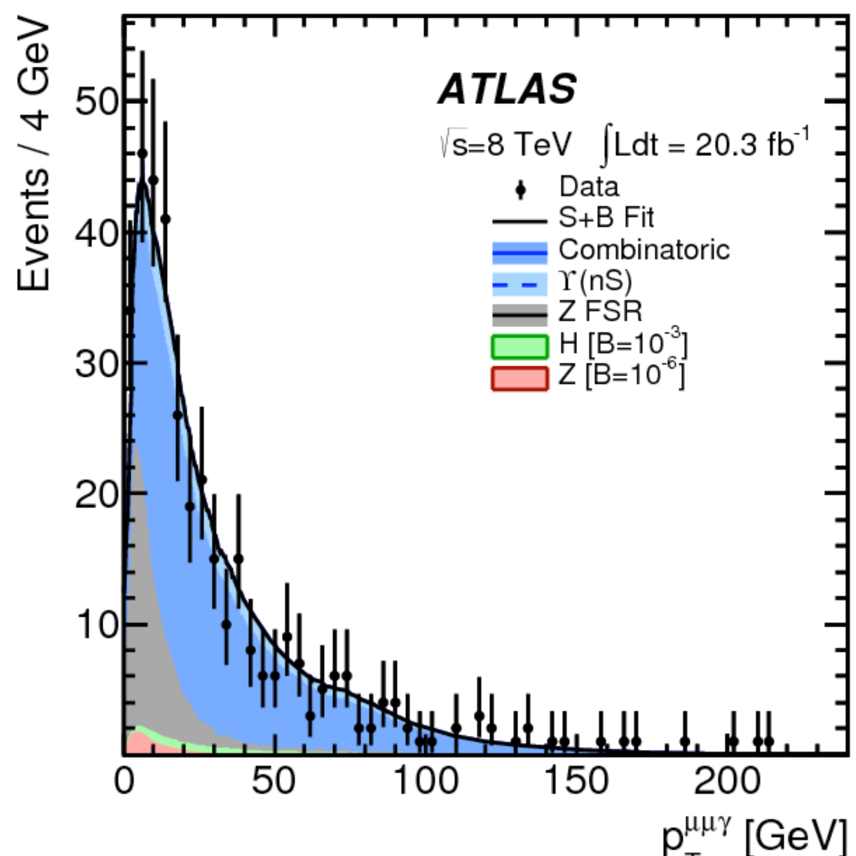
Phys.Rev.Lett. 114 (2015) 1121801

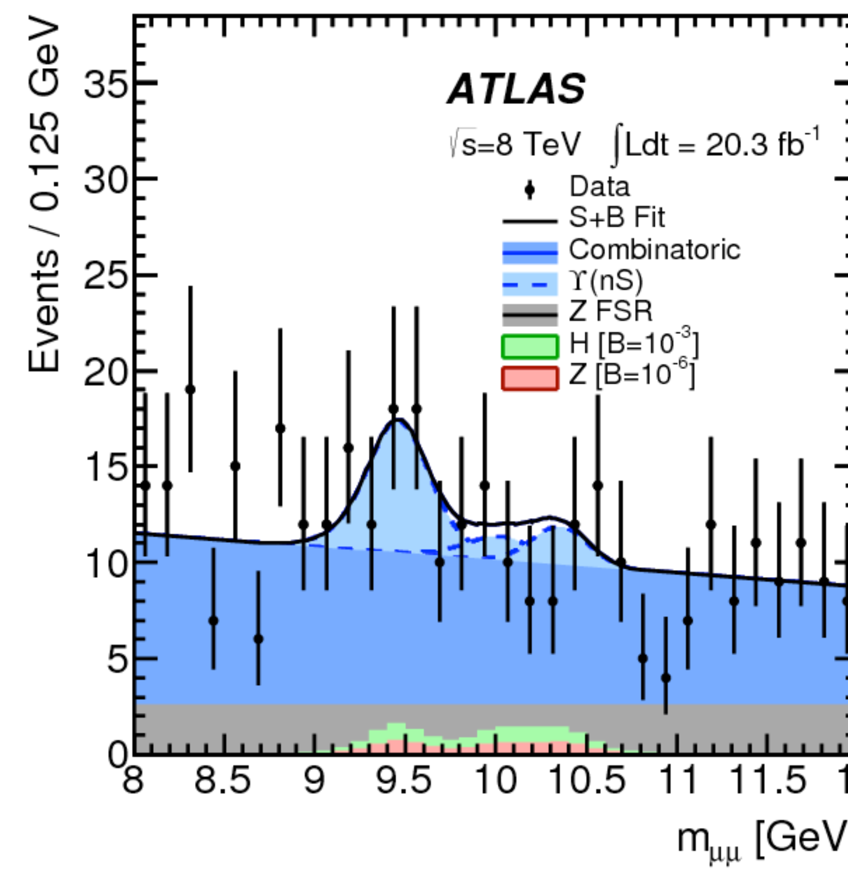
→ Multi-observable fit to $m_{\mu\mu\gamma}$, $pT_{\mu\mu\gamma}$
→ also $m_{\mu\mu}$ for Υ(nS)γ
→ No significant excess above background observed



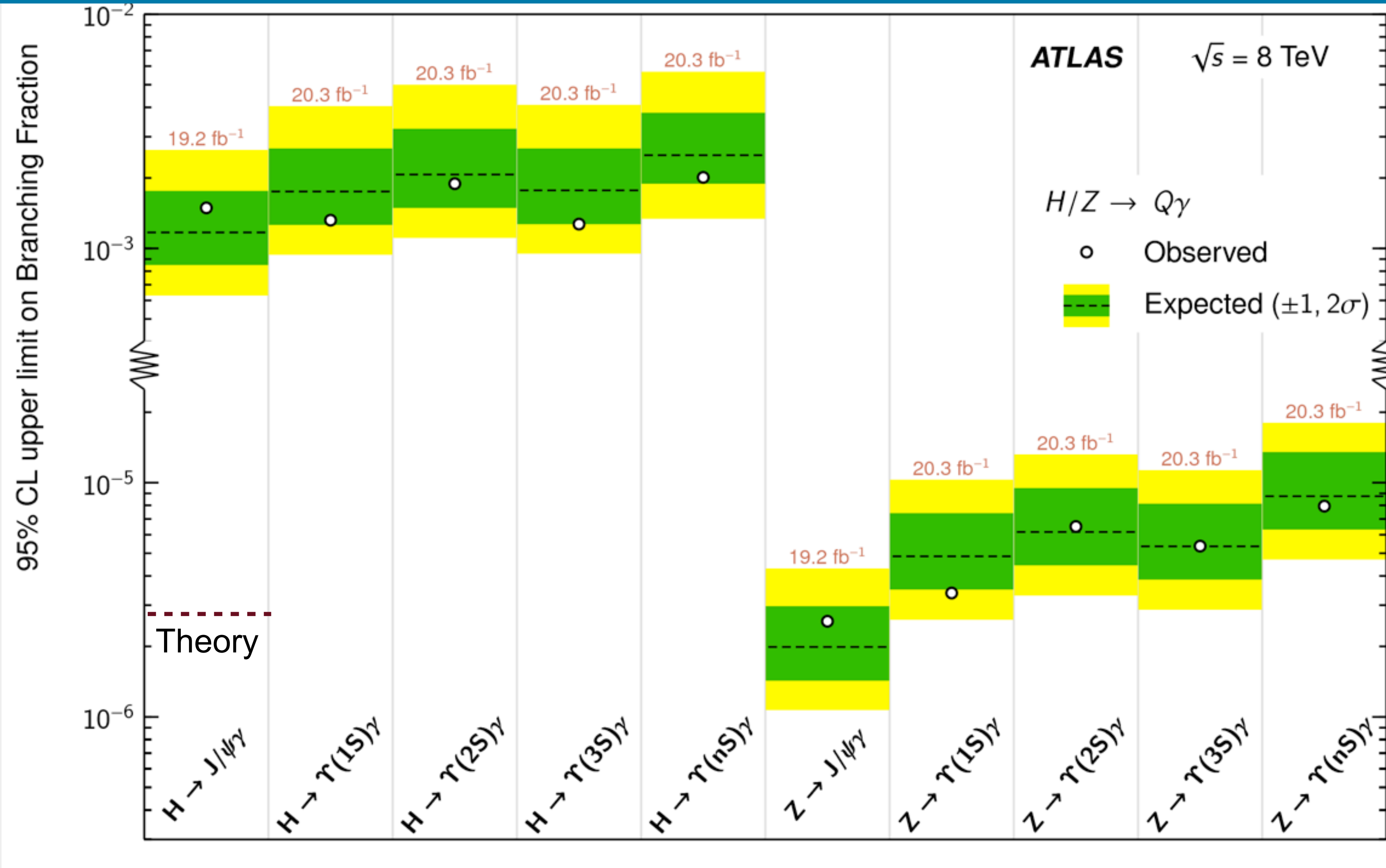








h/Z→J/ψγ and h/Z→Υ(ns)γ: Results



	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

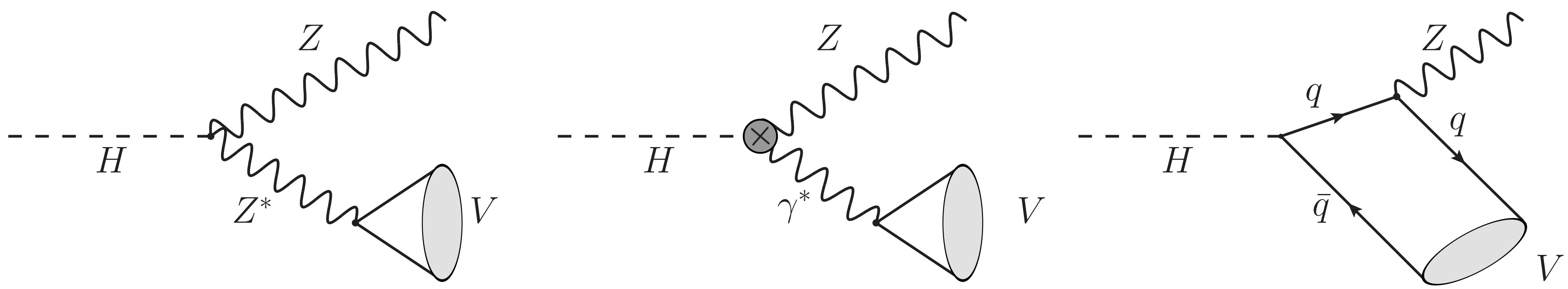
Phys.Rev.Lett. 114 (2015) 12, 121801

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

CMS recently obtained 95% CL upper limit on BR[H→(J/ψ)γ] < 1.5×10^{-3} [arXiv:1507.03031]

h→ZJ/ψ and h→ZΥ(nS)



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

$\mathcal{B}r(H \to ZV)$	$J/\psi(1S)$	$\Upsilon(1S)$
$\mathcal{B}r_{\Gamma_1}$	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}

arXiv:1411.2210

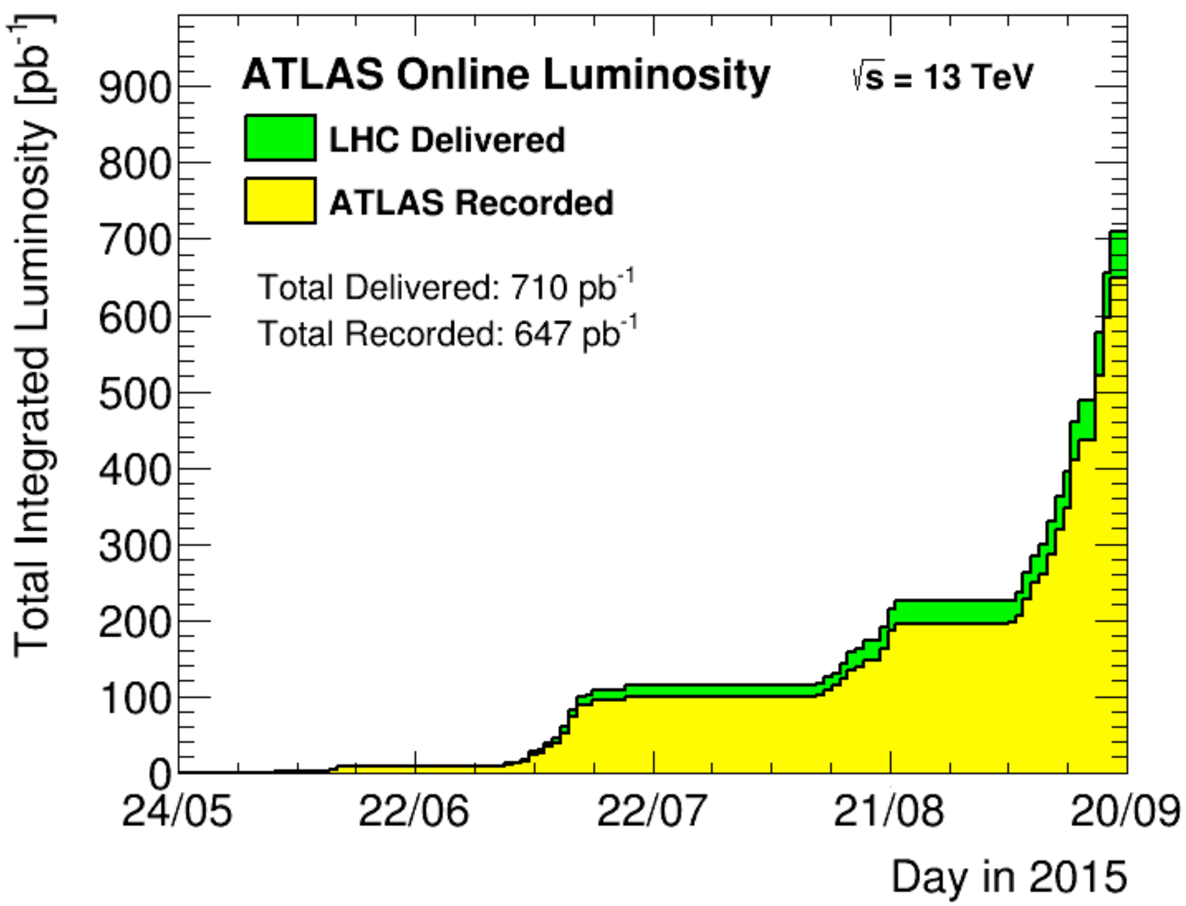
$$\Gamma = \Gamma_1 \kappa_V^2 + \Gamma_2 \kappa_{Z\gamma}^2 + \Gamma_3 \kappa_Q^2 + \Gamma_{12} \kappa_V \kappa_{Z\gamma} + \Gamma_{13} \kappa_V \kappa_Q + \Gamma_{23} \kappa_{Z\gamma} \kappa_Q$$

$\boxed{\mathrm{BR_{SM}}(h \to J/\psi\gamma) \simeq \mathrm{BR_{SM}}(h \to ZJ/\psi)}$

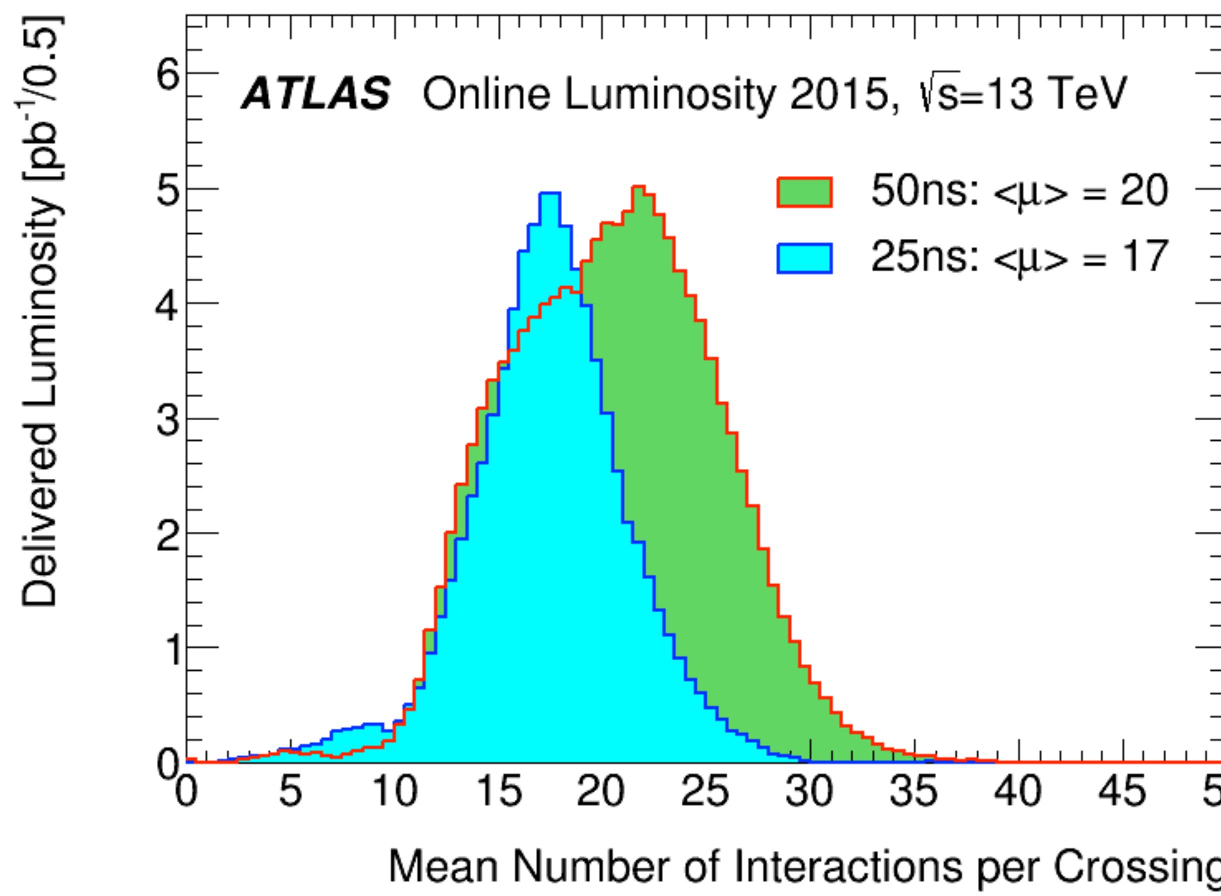
alas, need to account for additional BR(Z→ee/μμ) ~6% and properly evaluate S/B

LHC Run II

LHC Page1
Fill: 4402
E: 6500 GeV
t(SB): 00:46:54
21-09-15 21:47:16
PROTON PHYSICS: STABLE BEAMS
Energy:
6500 GeV
I(B1):
1.24e+14
I(B2):
1.23e+14



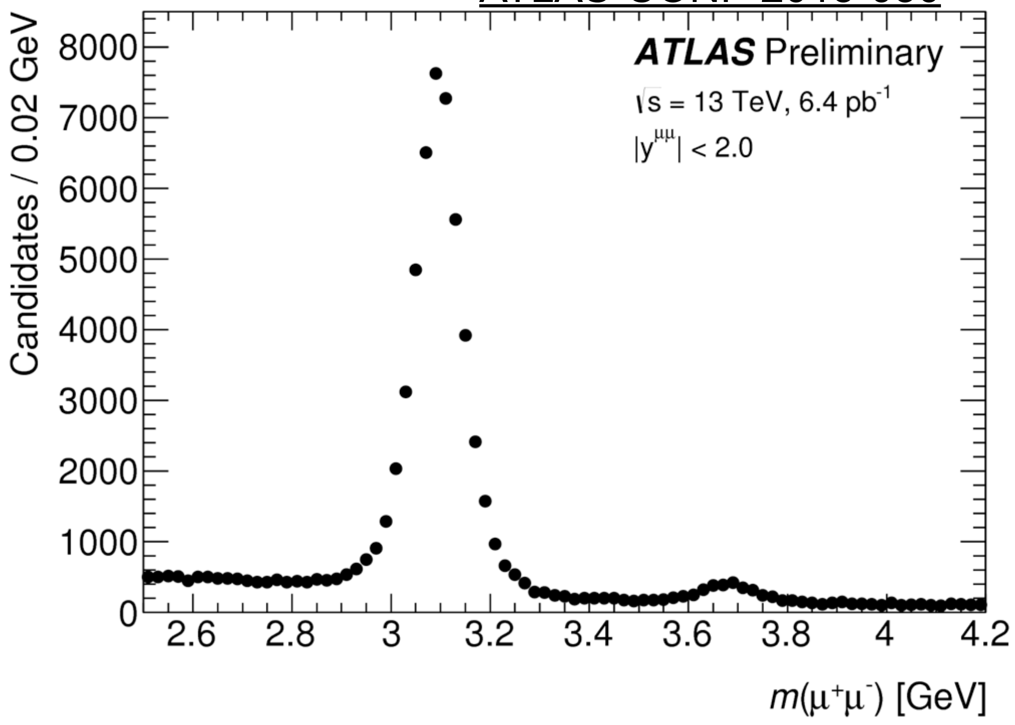
ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 710 pb⁻¹
Total Recorded: 647 pb⁻¹
Total Integrated Luminosity [pb⁻¹]
Day in 2015
24/05
22/06
22/07
21/08
20/09



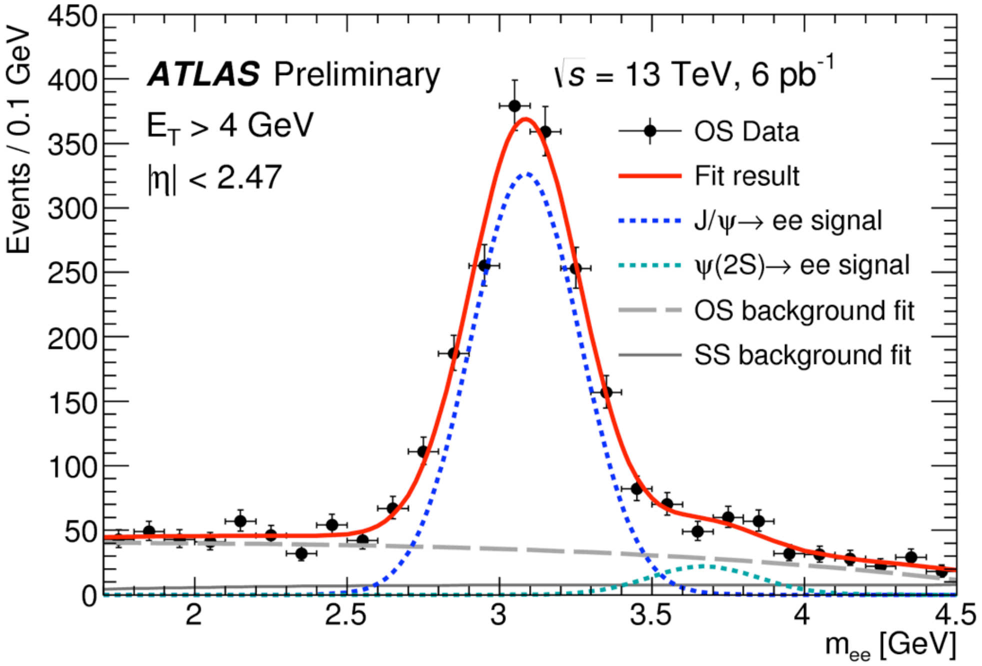
ATLAS Online Luminosity 2015, √s=13 TeV
50ns: <μ> = 20
25ns: <μ> = 17
Delivered Luminosity [pb⁻¹/0.5]
Mean Number of Interactions per Crossing

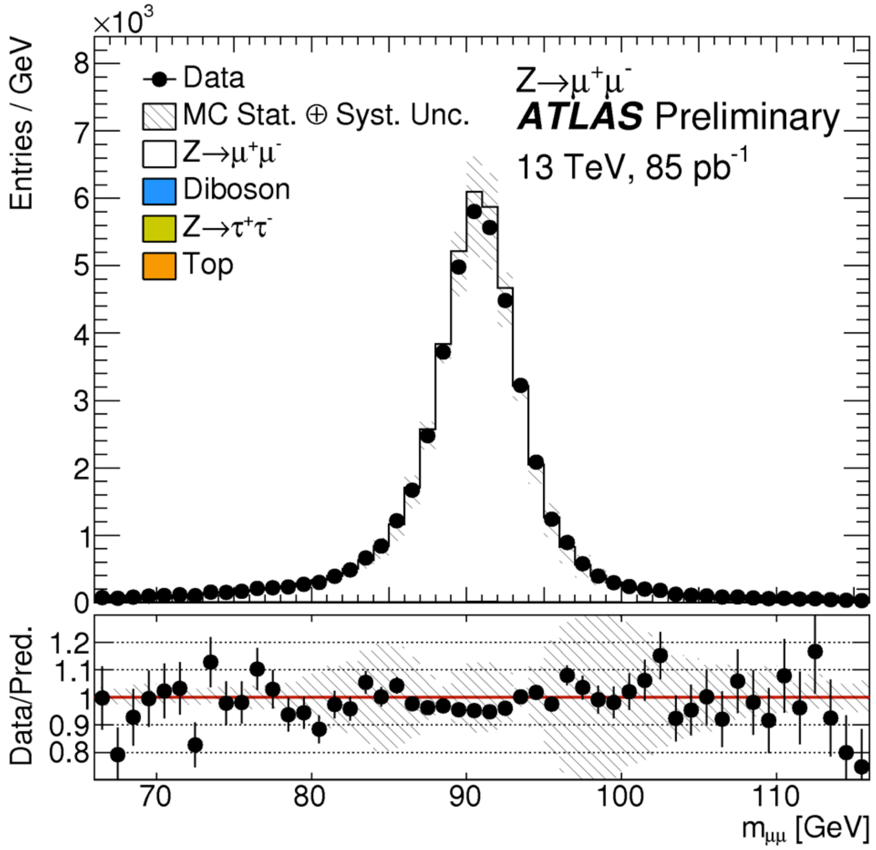
First resonances in Run II

ATLAS-CONF-2015-030

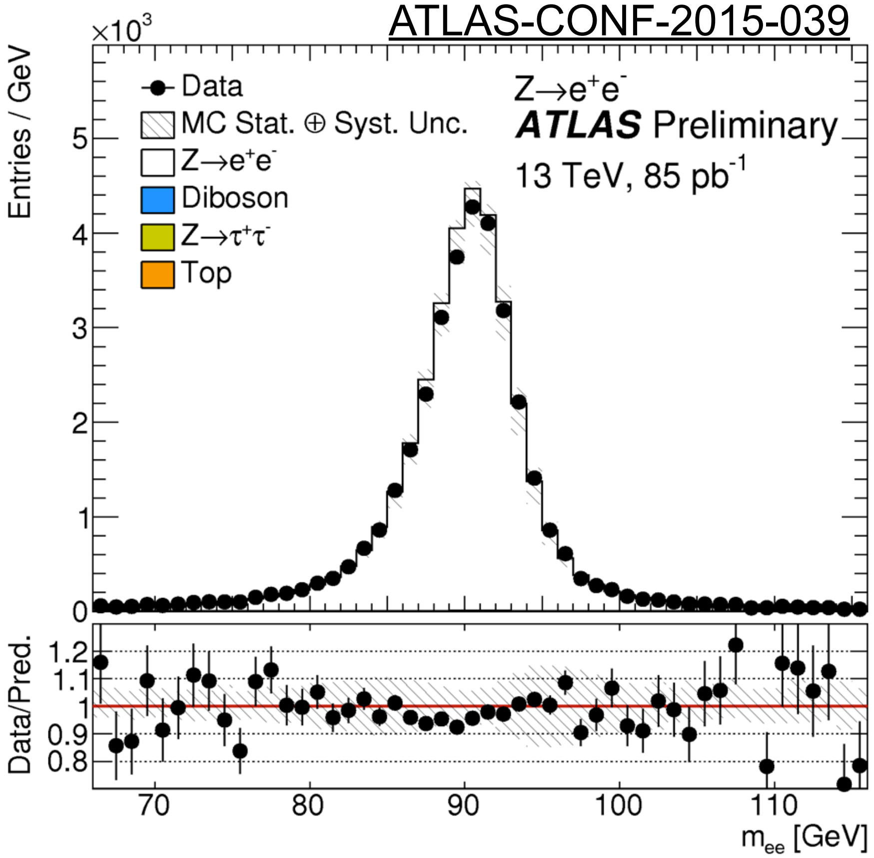


EGAM-2015-003

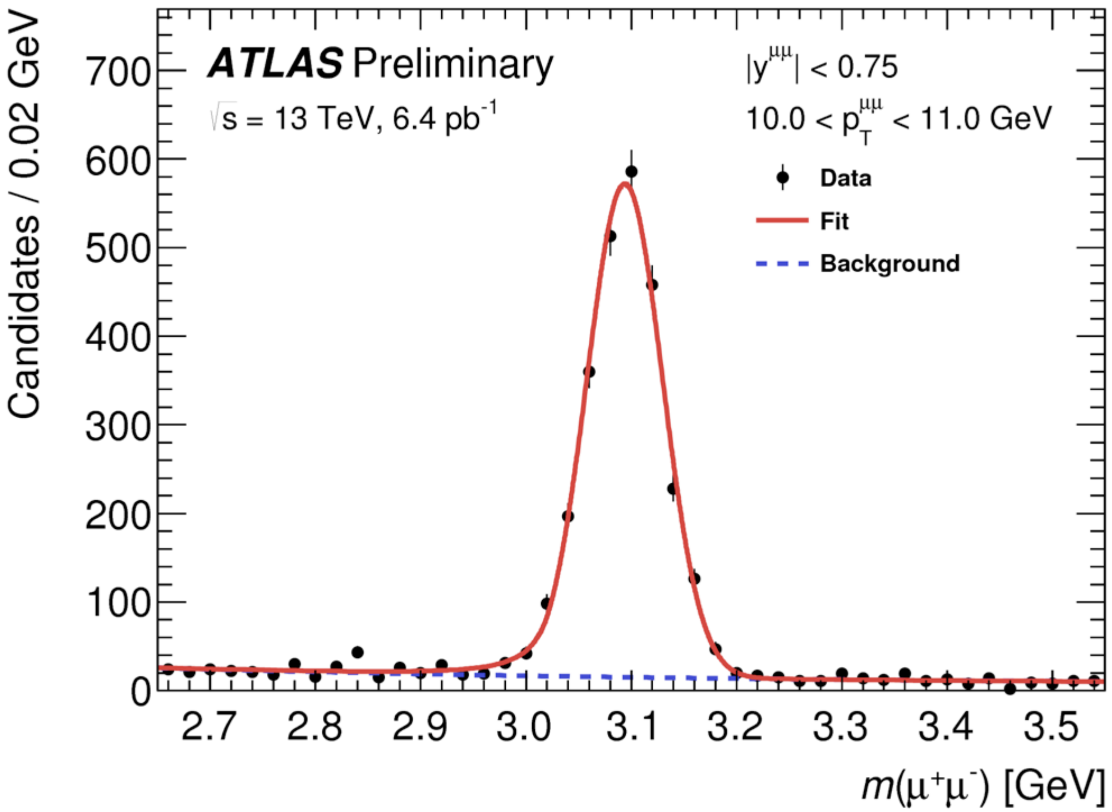


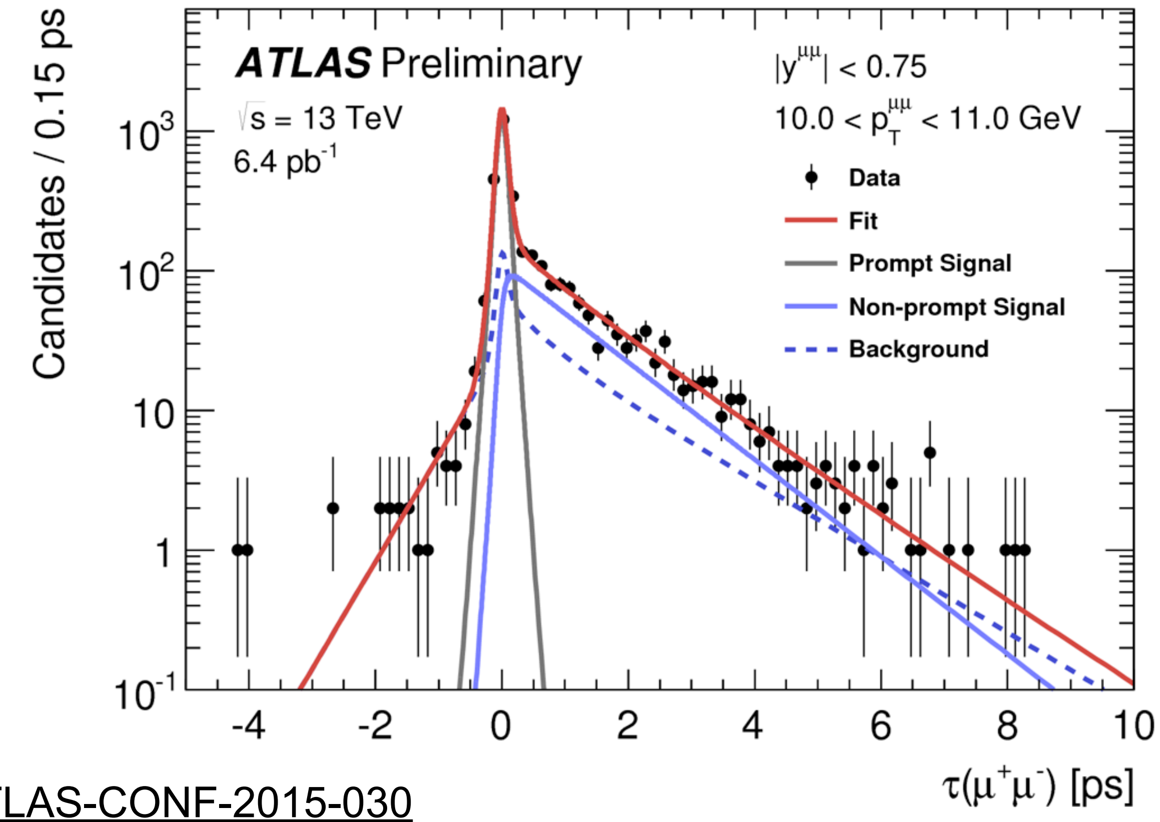


ATLAS-CONF-2015-039

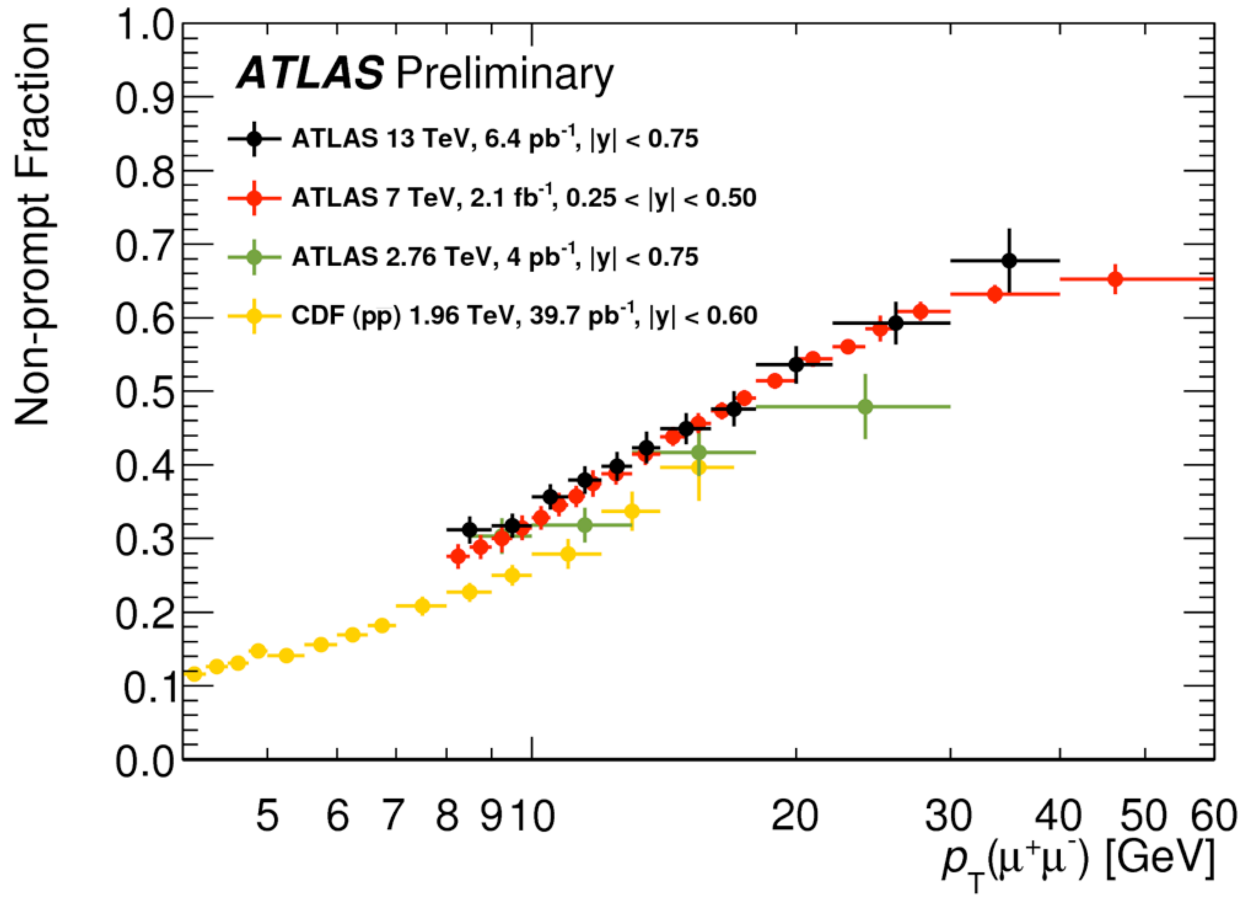


J/ψ production at 13 TeV: prompt vs non-prompt fraction

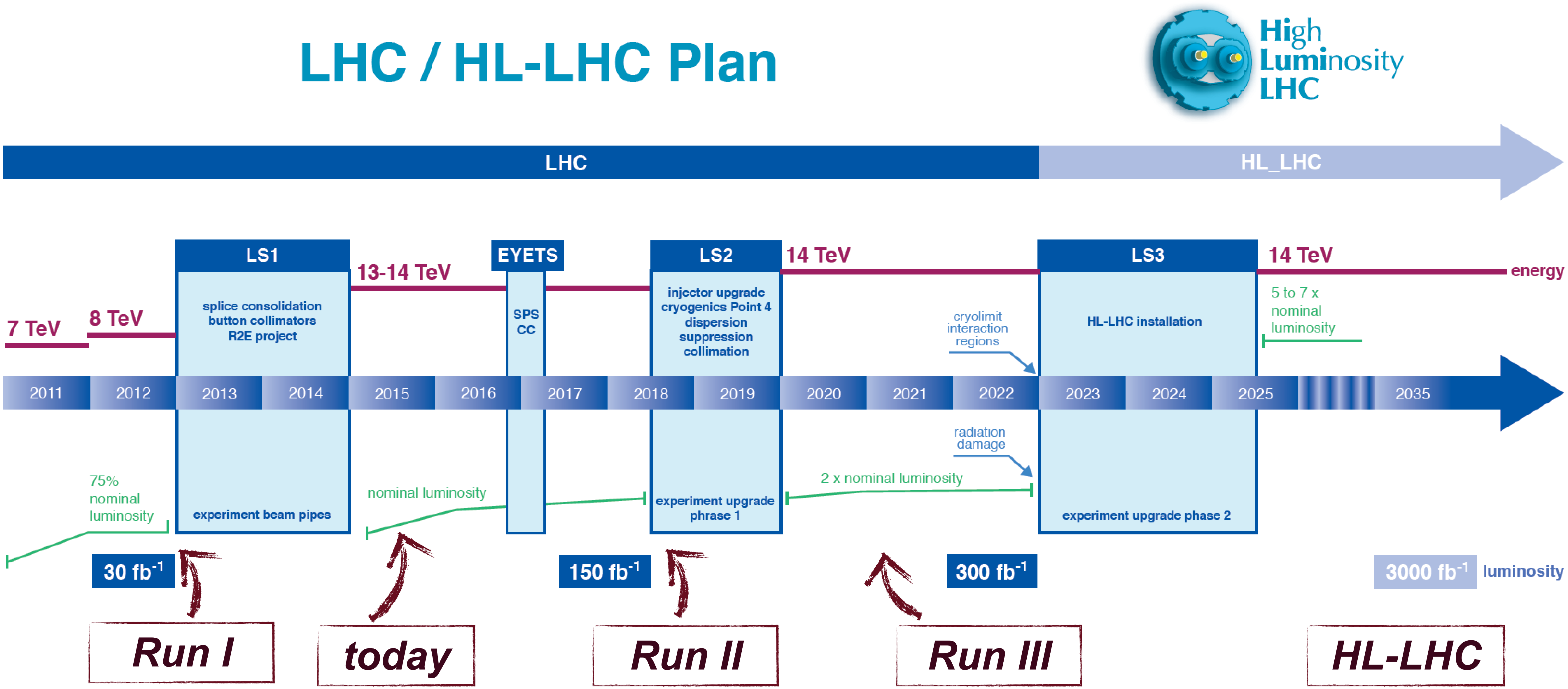




ATLAS-CONF-2015-030

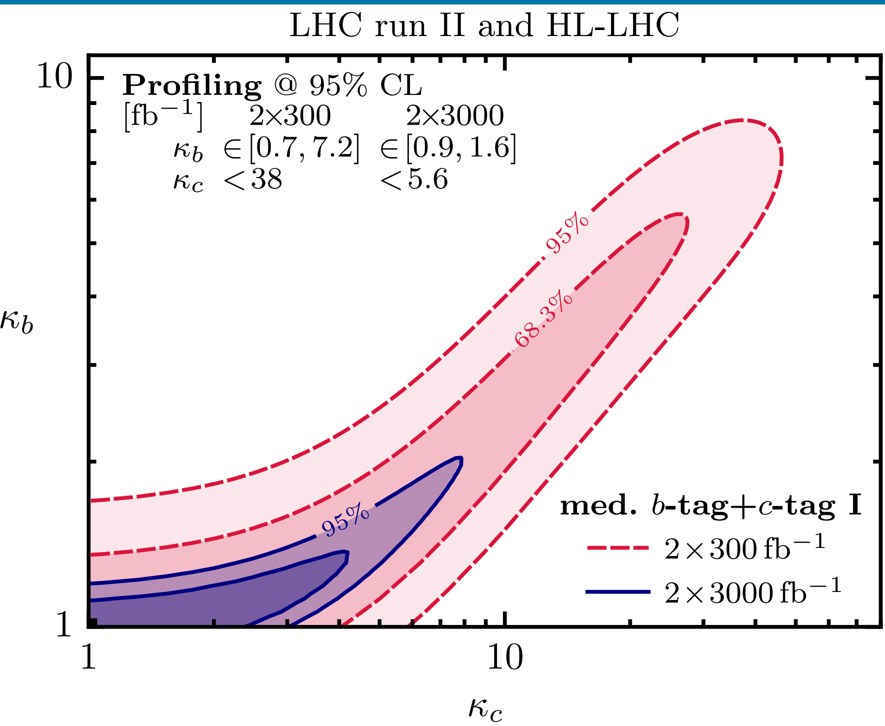


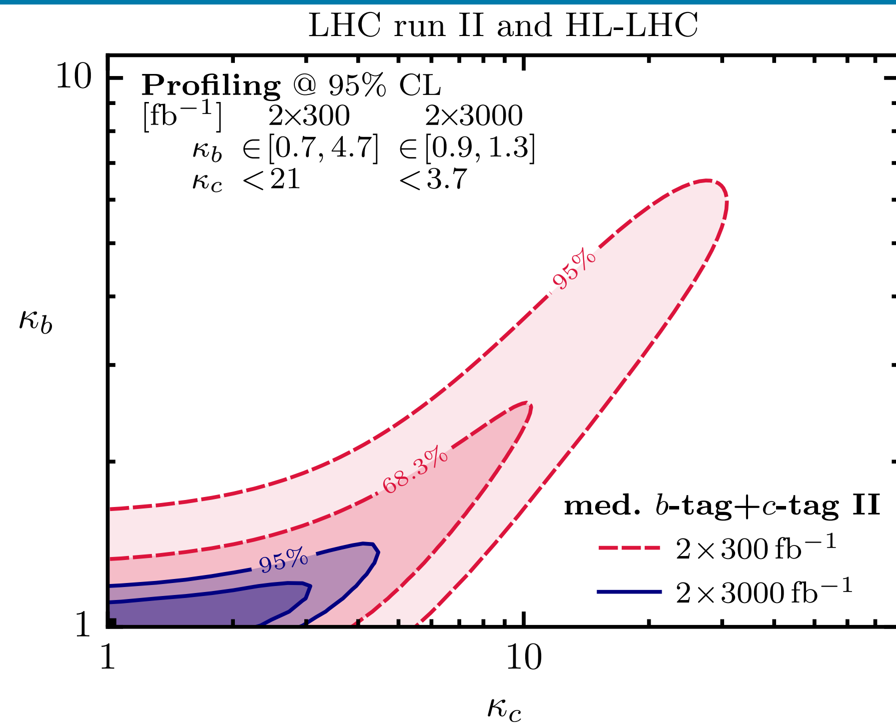
LHC/HL-LHC Plan



- 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

Charm Tagging in HL-LHC



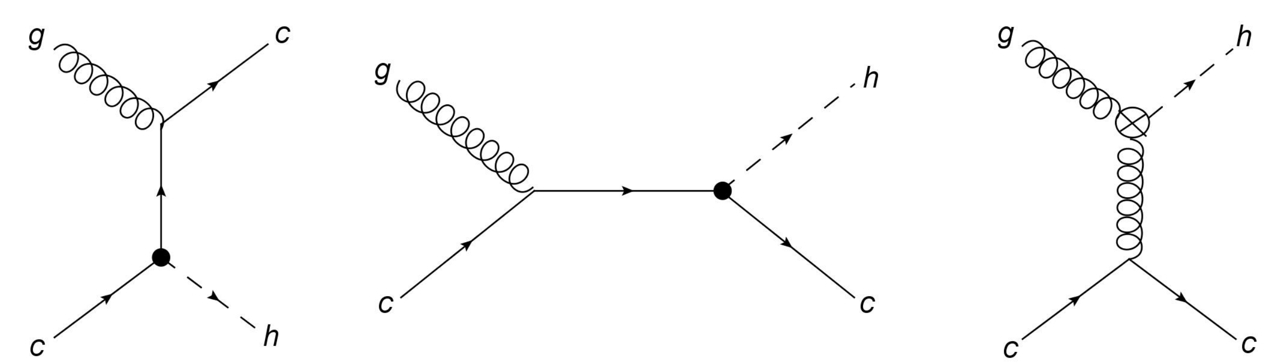


	ϵ_b	ϵ_c	ϵ_l
b-tagging	70%	20%	1.25%
c-tagging I	13%	19%	0.5%
c-tagging II	20%	30%	0.5%
c-tagging III	20%	50%	0.5%

2×3000 fb^{-1}
$|\kappa_c|\lesssim 2.5$-5.5 at 95%CL
depending on the
c-tagging scenario

arXiv:1507.0291

For the HL-LHC the pp→hc could be potentially employed (using high purity Higgs boson decays) to probe the charm Yukawa coupling
SM cross section σ(pp→hc)~166 fb



pp→ch(→γγ) 3000 fb^{-1}

κ_c	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
S	874	877	885	899	917	941	973	1008	1052

κ_c	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5
S	1097	1148	1206	1276	1350	1424	1504	1590	1683	1786

Main backgrounds are
pp→hg (σ~12pb) [with g→cc (~55fb)] and
pp→hb (σ~200fb)
2×3000 fb^{-1} $|\kappa_c|\lesssim 2$ at 95%CL
[p_{Tj}>20 GeV, $|\eta_j|$<5, DR(j_1,j_2)>0.4, ε_c=0.4, $\varepsilon_{g\to c}$=1%, $\varepsilon_{b\to c}$=30%]

h/Z→J/ψγ and h/Z→Υ(ns)γ: at Run II/III and HL-LHC

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 and Z→μμγ
3) This channel is also affected by potential "anomalies" in the h→γγ loop

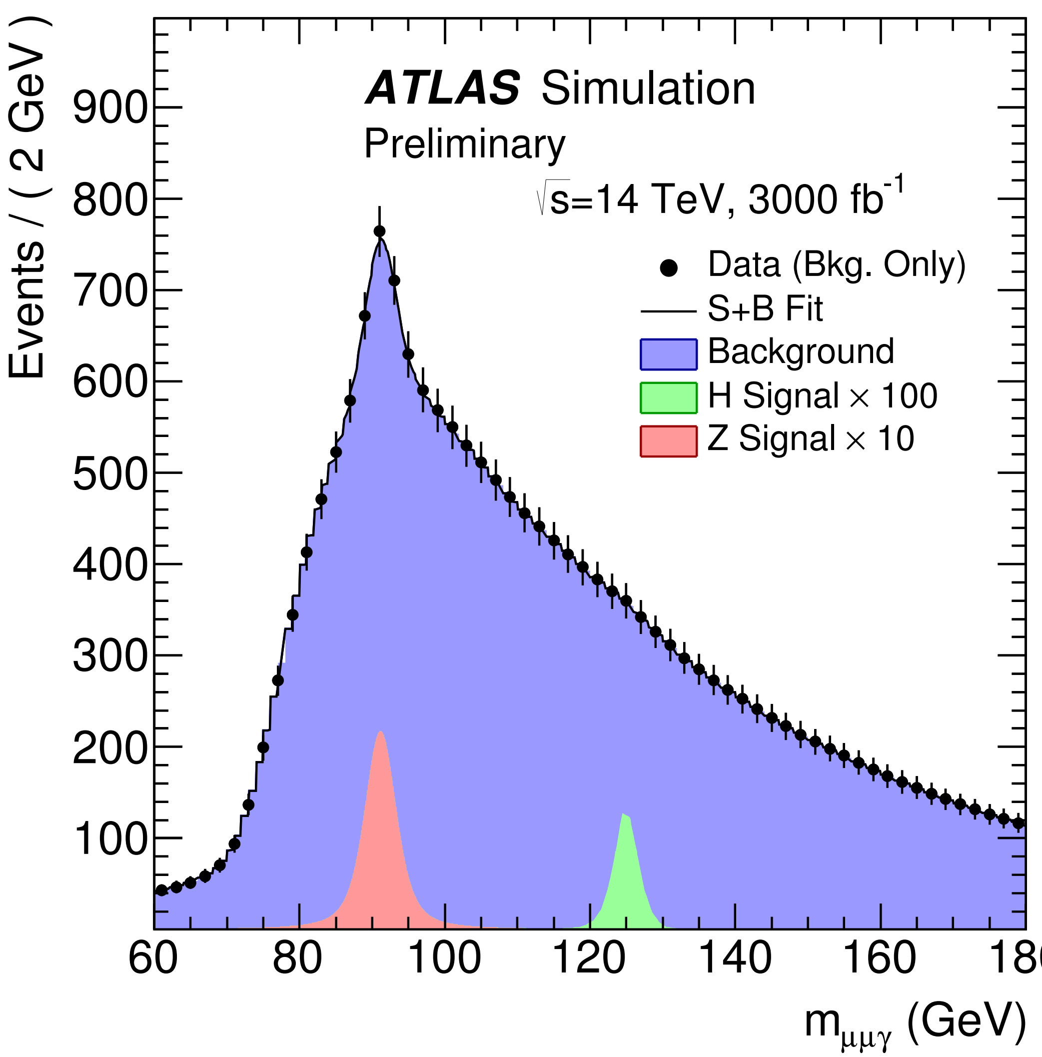
3000 fb^{-1} @ 14 TeV

$J/\psi\,\gamma$ Final state

	Expected Background				Signal	
	Inclusive QCD Mass Range [GeV]		Other Backgrounds			
	80-100	115-135	$Z \to \mu^+\mu^-\gamma$	$H_{\gamma^*\gamma} \to \mu^+\mu^-\gamma$	Z	H
Cut Based Analysis	7800±500	3500±400	780 ±100	15.1 ±1.4	62±3	3.1±0.1
Multivariate Analysis		1700±200		13.7 ±1.3		2.8±0.1

	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

	Standard Model expectation	
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$	$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	2.9 ± 0.2	0.80 ± 0.05



Light-Quark Yukawa couplings

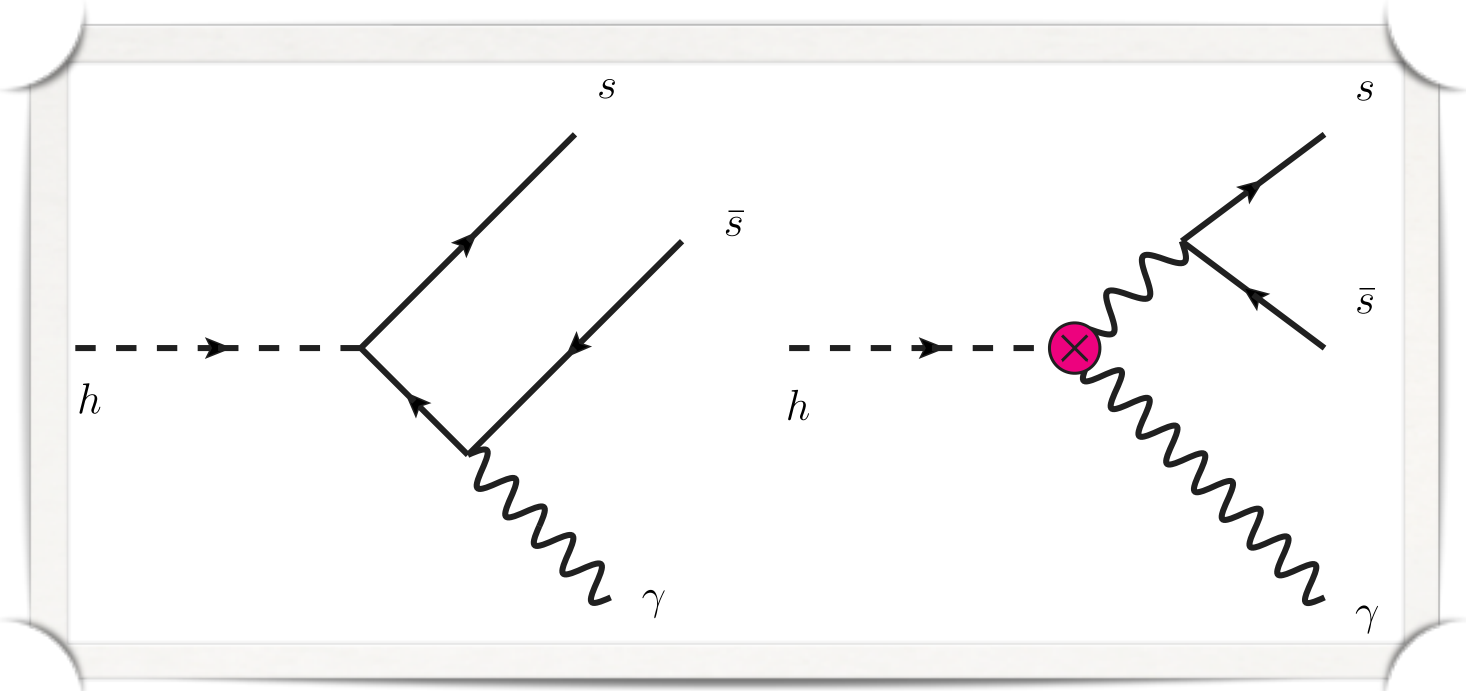
Initially, considered impossible at the LHC, recent activity on its feasibility:

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

[Phys.Rev.Lett. 114 (2015) 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) 101802

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

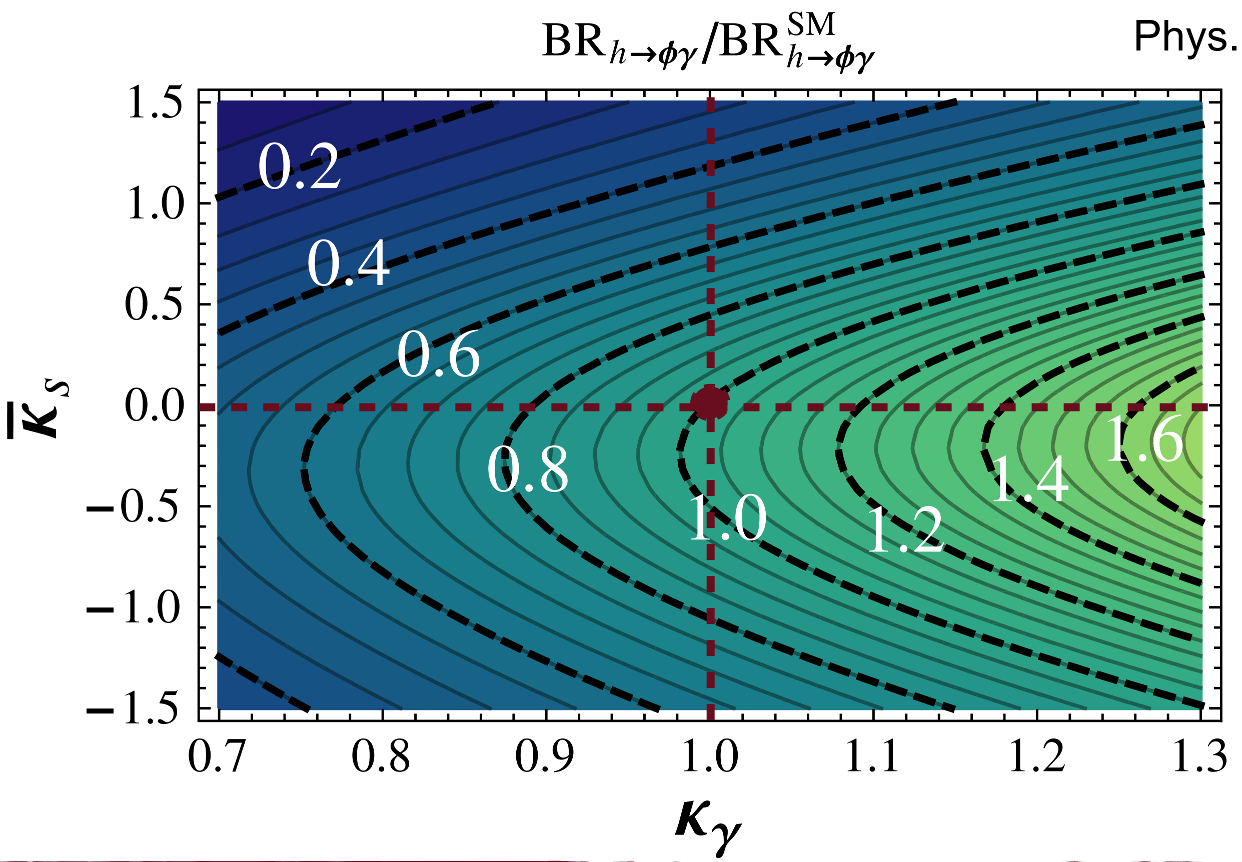
$$\mathrm{Br}(h\to\omega\gamma) = (1.48\pm0.03_{f_\omega}\pm0.07_{h\to\gamma\gamma})\cdot10^{-6},$$

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

JHEP 1508 (2015) 012

Light-Quark Yukawa couplings

Phys.Rev.Lett. 114 (2015) 101802



$\varphi \to K^+K^-$ (BR=48.9%), ~8 events 100 fb^{-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

arXiv:1505.06689

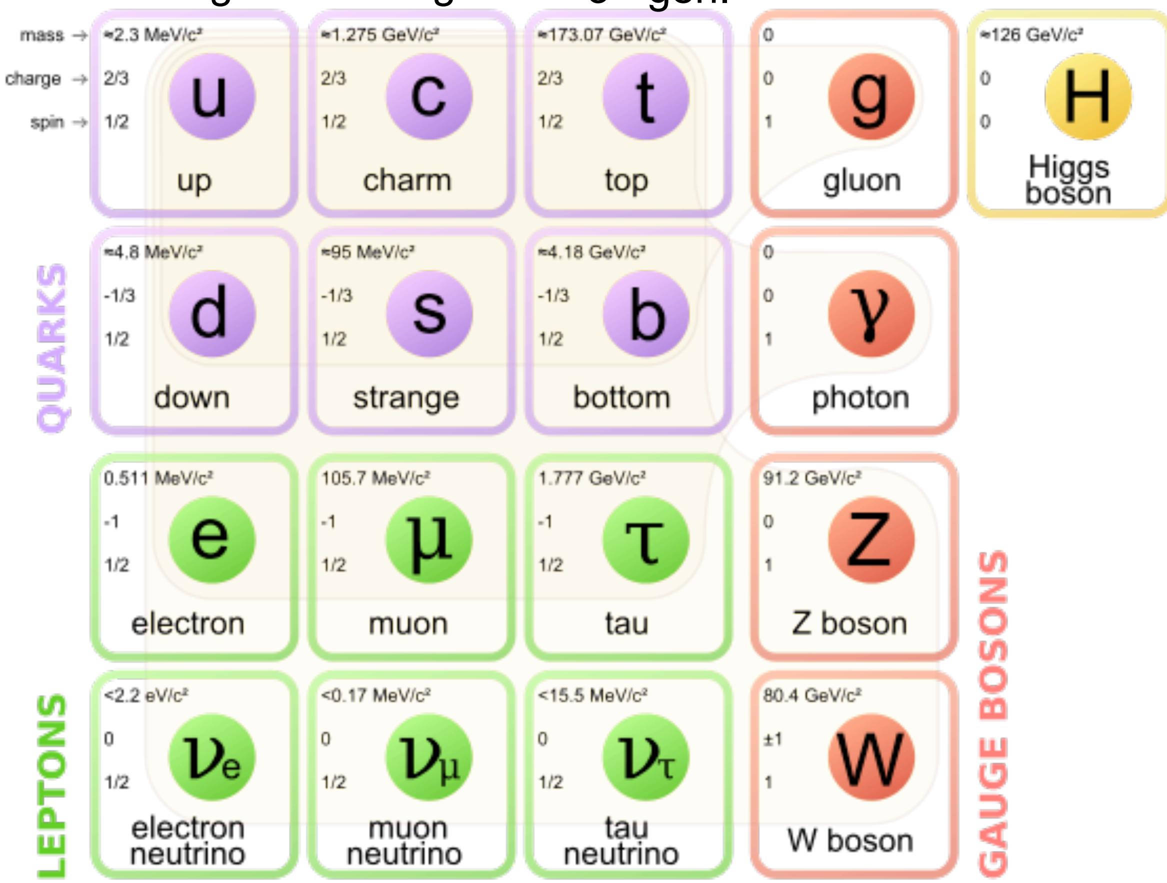
Preliminary "back-of-the-envelope" study gives pessimistic prospects of $\kappa_c < \mathcal{O}(2000)$ at the HL-LHC

Summary

Yukawa Couplings

1st gen. 2nd gen. 3rd gen.

EWSB



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

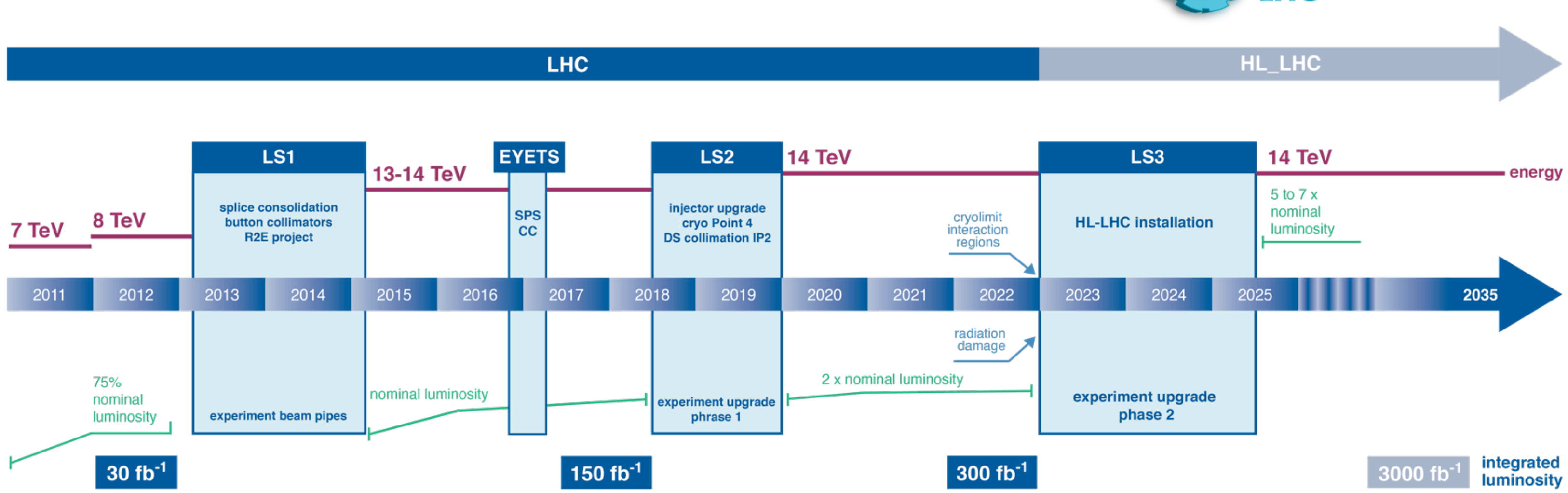
A wealth of information has been collected over the last few years on the nature of the Higgs boson
→ Yukawa sector still relatively unconstrained

New Physics could be lurking here!

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

LHC / HL-LHC Plan

High Luminosity LHC



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

Additional Slides

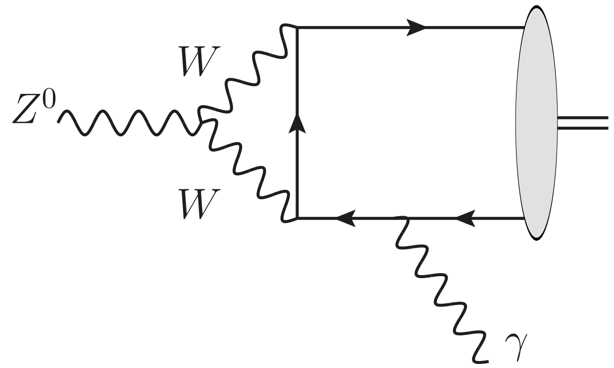
h/Z→J/ψγ and h/Z→Υ(ns)γ: Systematics

Source	Signal Yield Uncertainty	Estimated From
Total H cross section	12%	QCD scale variation and PDF uncertainties
Total Z cross section	4%	
Integrated Luminosity	2.8%	Calibration observable and vdM scan uncertainties†
Trigger Efficiency	1.7%	Data driven techniques with $Z \to \ell^+\ell^-$, $Z \to \ell^+\ell^-\gamma$ and $J/\psi \to \mu^+\mu^-$ events
Photon ID Efficiency	Up to 0.7%	
Muon ID Efficiency	Up to 0.4%	
Photon Energy Scale	0.2%	
Muon Momentum Scale	Negligible	

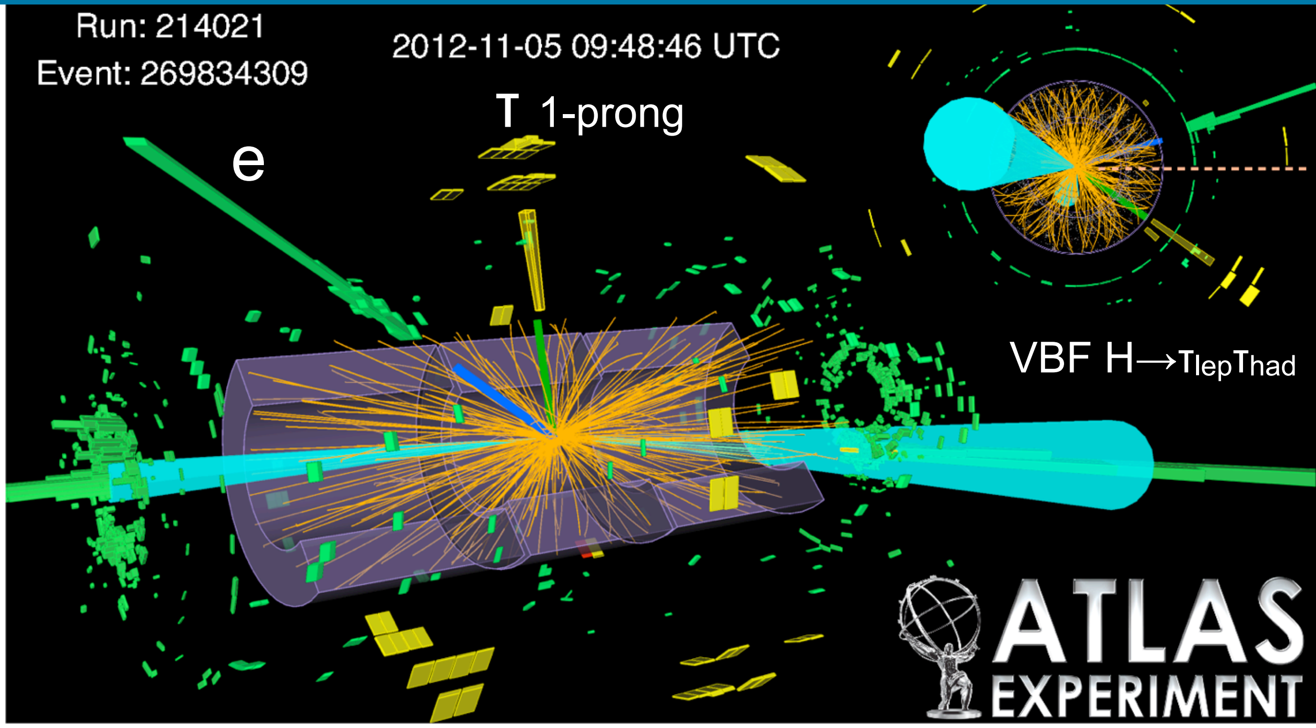
FCNC Z→Qγ decays

relative to new physics contributions

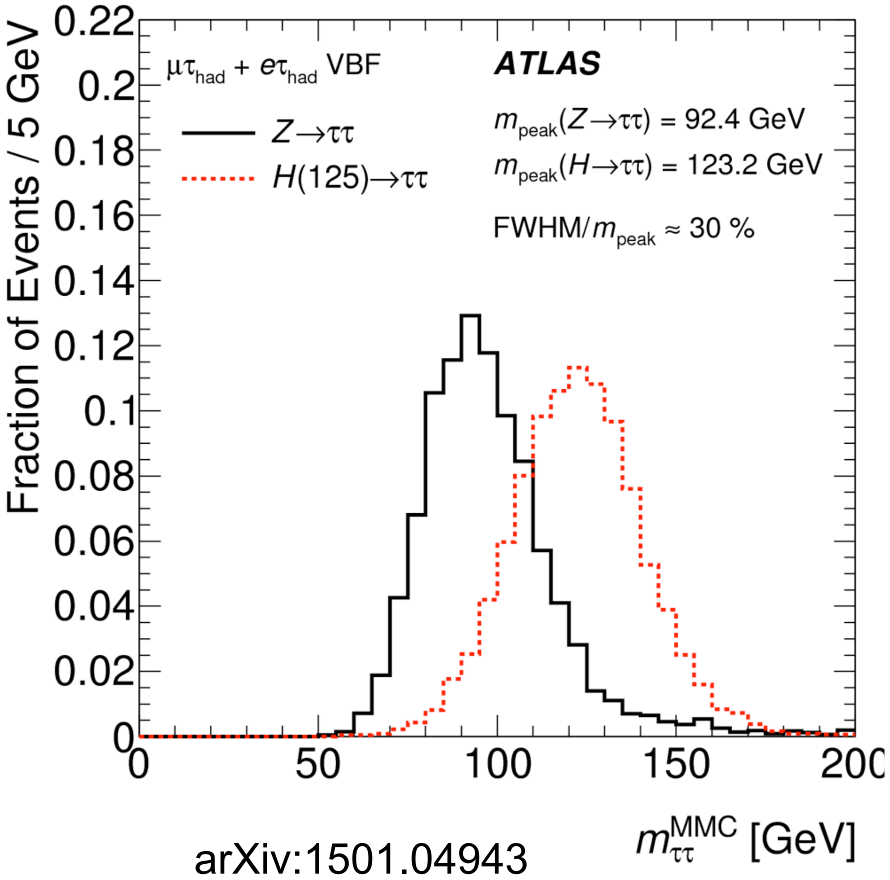
Decay mode	Branching ratio	SM background
$Z^0 \to K^0\gamma$	$\left[(7.70 \pm 0.83)\,\lvert v_{sd}\rvert^2 + (0.01 \pm 0.01)\,\lvert a_{sd}\rvert^2\right] \cdot 10^{-8}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to D^0\gamma$	$\left[(5.30\,^{+0.67}_{-0.43})\,\lvert v_{cu}\rvert^2 + (0.62\,^{+0.36}_{-0.23})\,\lvert a_{cu}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 2 \cdot 10^{-3}$
$Z^0 \to B^0\gamma$	$\left[(2.08\,^{+0.59}_{-0.41})\,\lvert v_{bd}\rvert^2 + (0.77\,^{+0.38}_{-0.26})\,\lvert a_{bd}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^3}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 8 \cdot 10^{-5}$
$Z^0 \to B_s\gamma$	$\left[(2.64\,^{+0.82}_{-0.52})\,\lvert v_{bs}\rvert^2 + (0.87\,^{+0.51}_{-0.33})\,\lvert a_{bs}\rvert^2\right] \cdot 10^{-7}$	$\frac{\lambda^2}{\sin^2\theta_W}\,\frac{\alpha}{\pi} \sim 4 \cdot 10^{-4}$



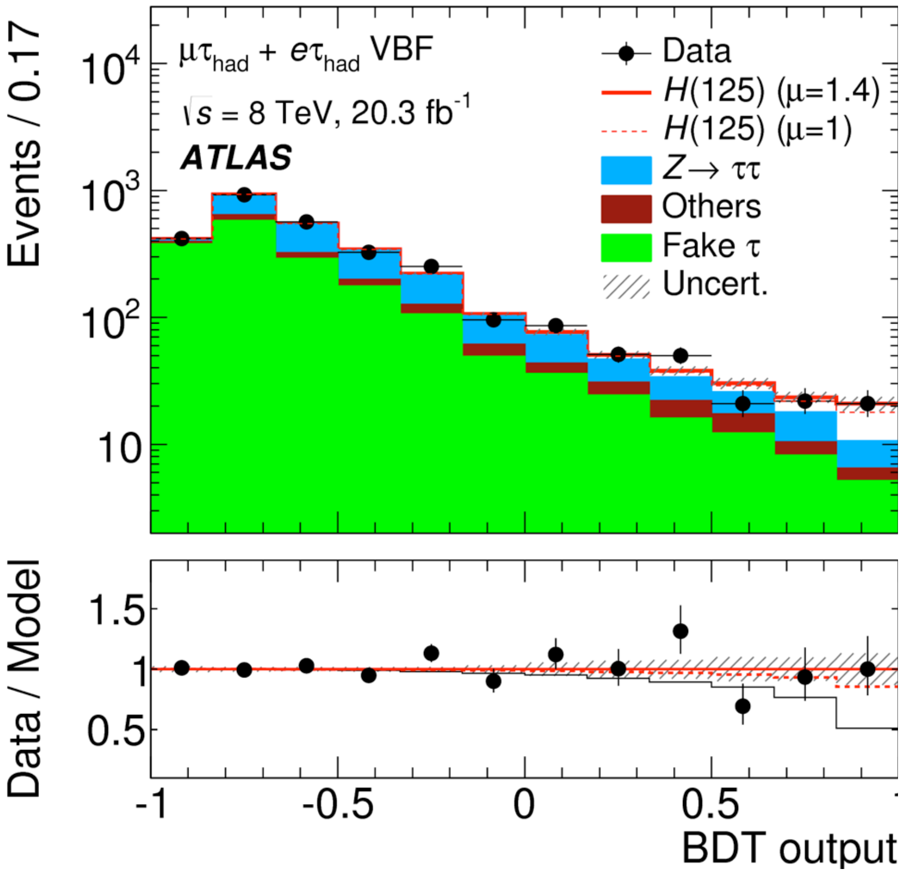
- Most promising for down-type fermion/lepton couplings
- Backgrounds
  - Z → ττ dominant [embedding]
  - "Fakes": Multijet, W+jets, top [data-driven]
  - "Other": Dibosons/H->WW* [MC]
- Three sub-channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Two exclusive categories/final 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, ...)

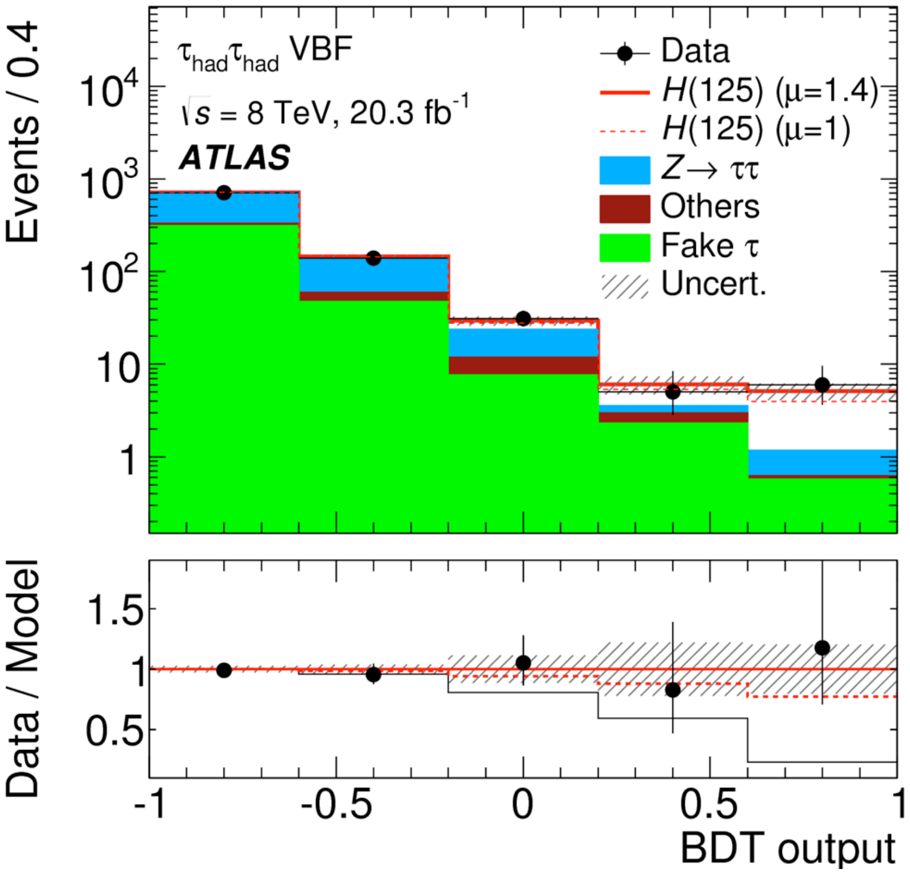


$e\,p_T$ = 56 GeV, τ_{had} p_T = 27 GeV, MET=113 GeV, $m_{j1,j2}$=1.53 TeV, $m_{\tau\tau}^{MMC}$=129 GeV, BDT score = 0.99. S/B ratio of this bin 1.0

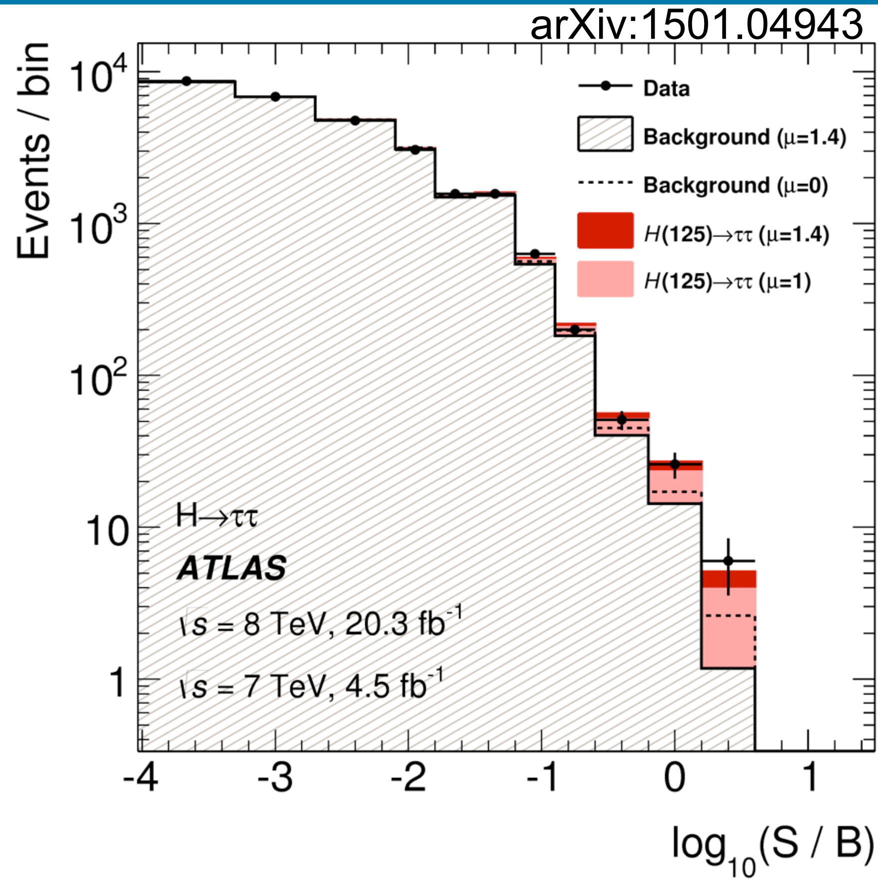


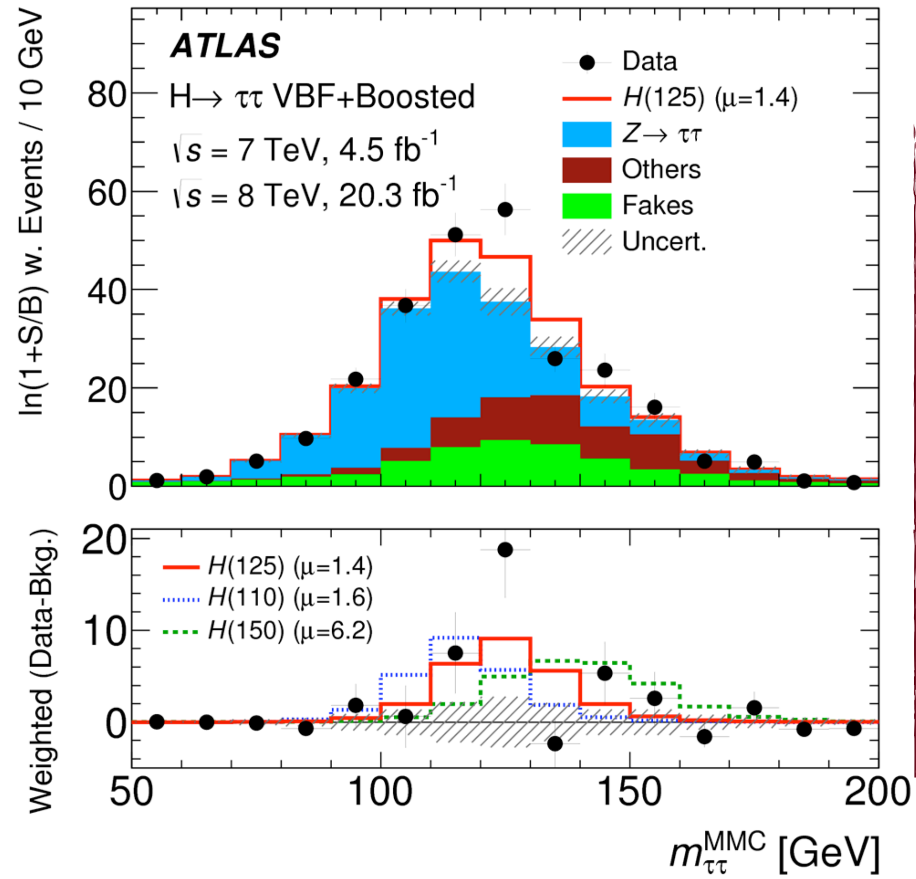
arXiv:1501.04943





H→ττ: Results





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)

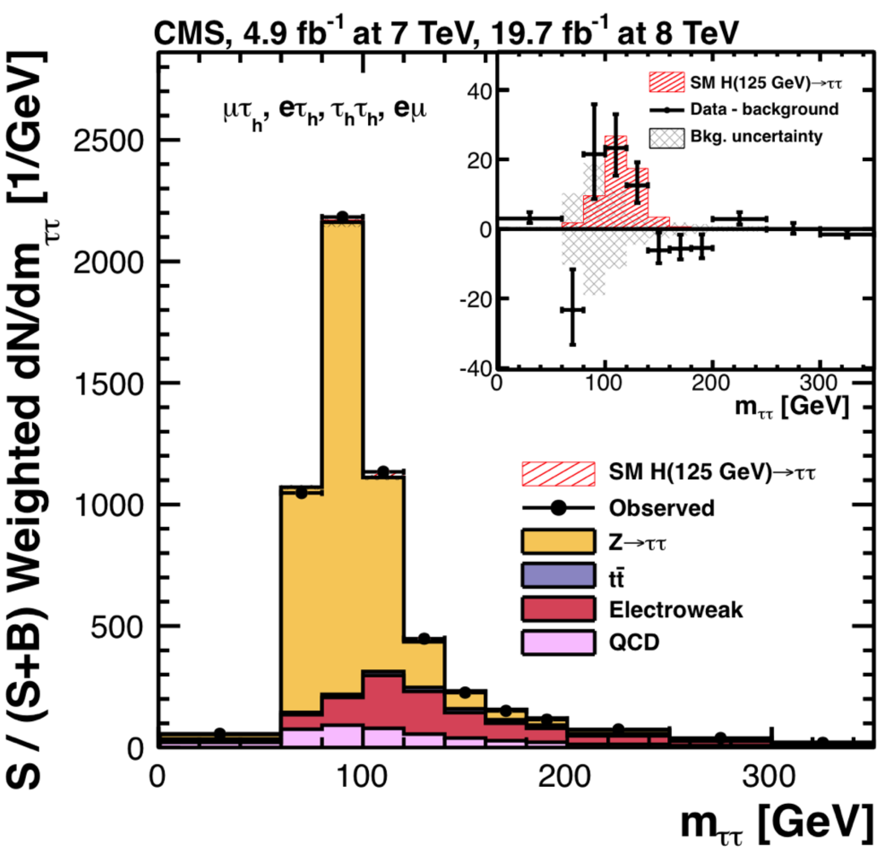
<u>Rate measurement</u>

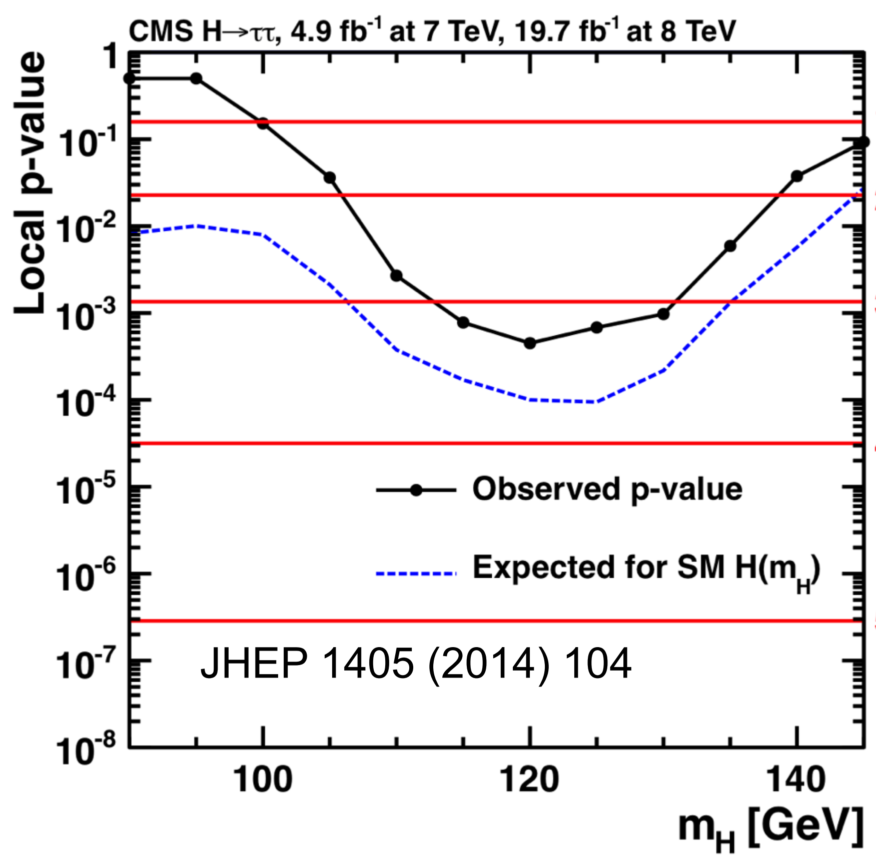
ATLAS $\mu=1.43^{+0.27}_{-0.26}$(stat) $^{+0.32}_{-0.25}$(syst) ± 0.09 (theo syst)

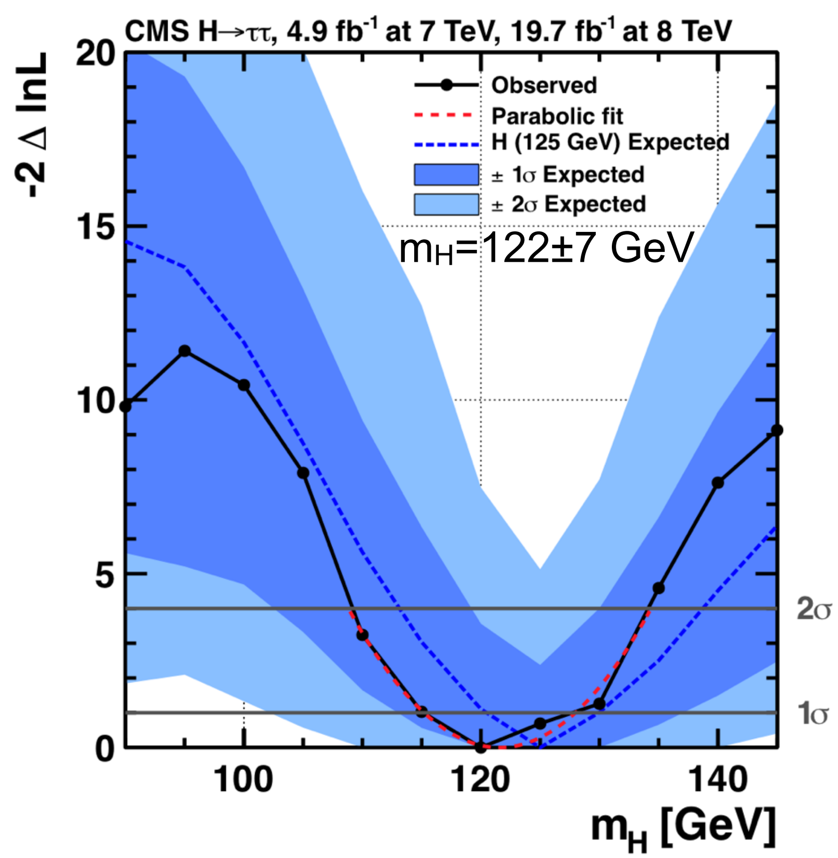
[@ m_H=125.36 GeV]

CMS μ=0.78 ± 0.27

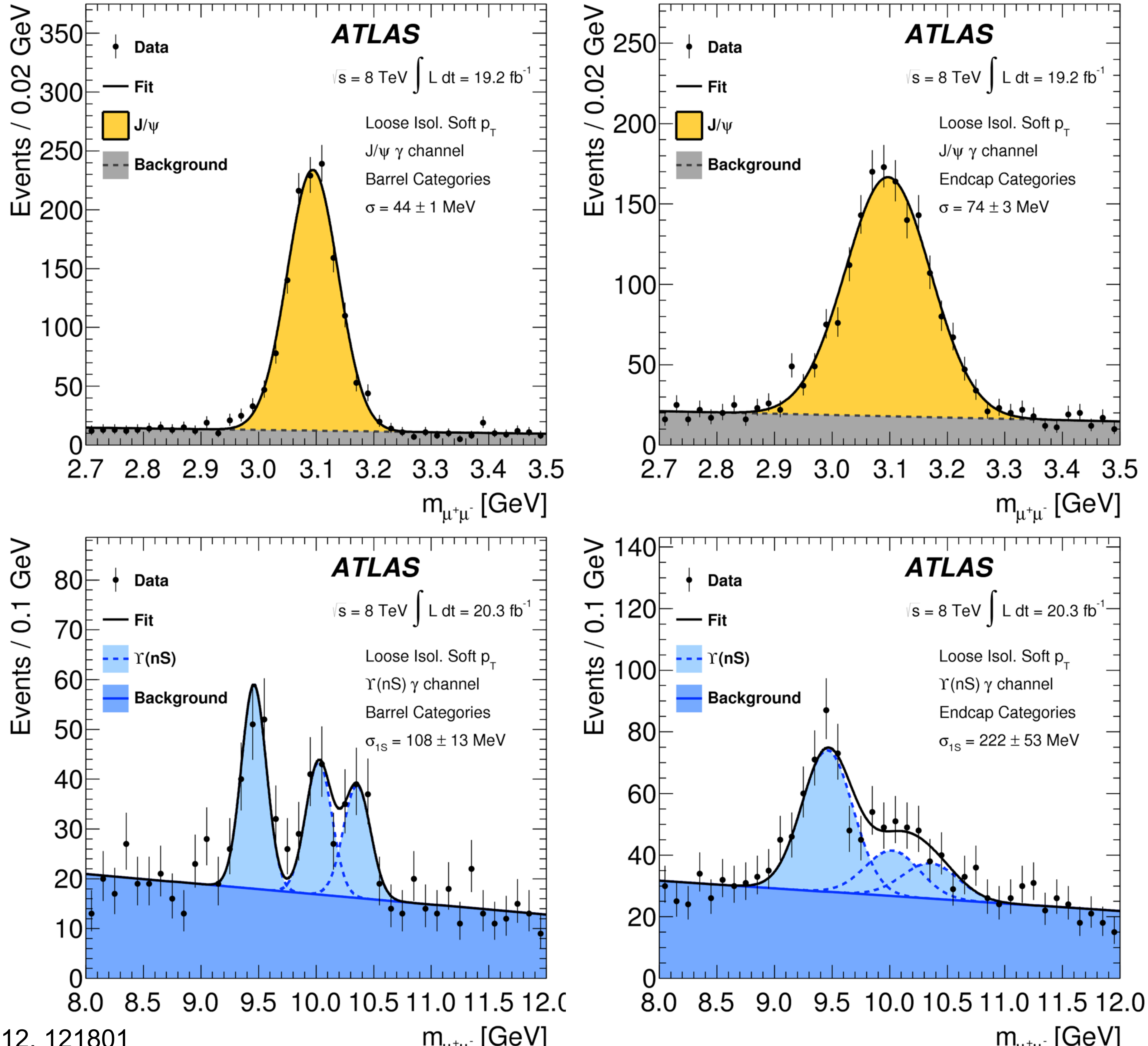
[@ m_H=125.00 GeV]







H→J/ψγ and H→Υ(ns)γ



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H→J/ψγ and H→Υ(ns)γ

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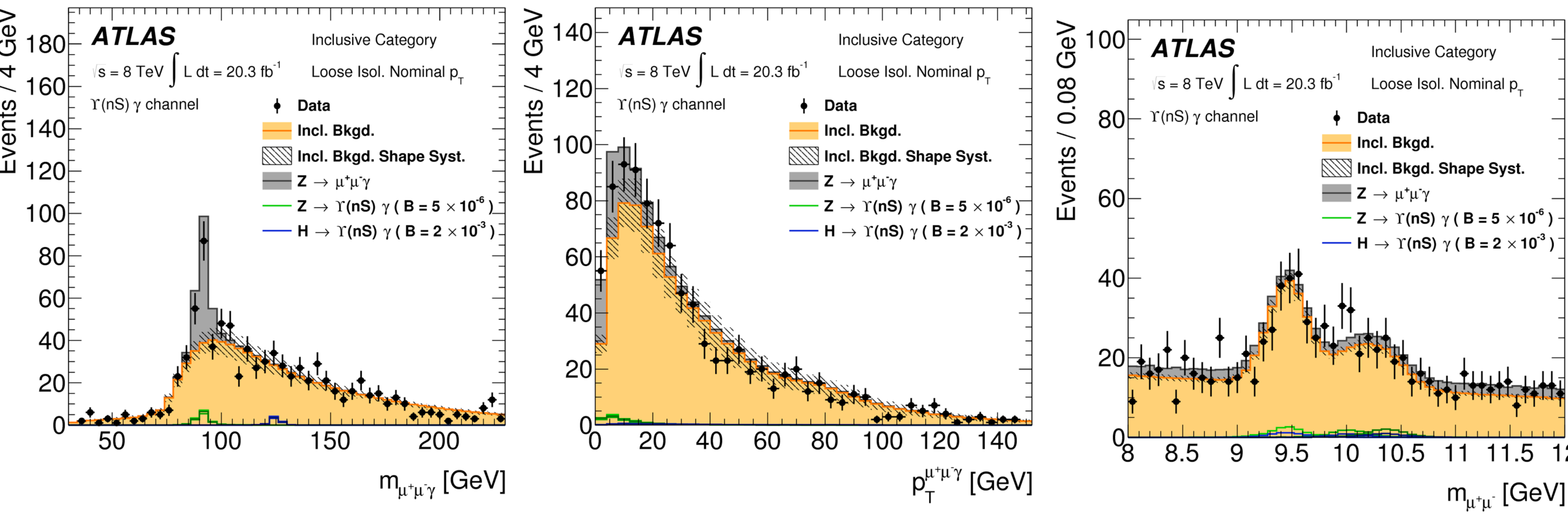
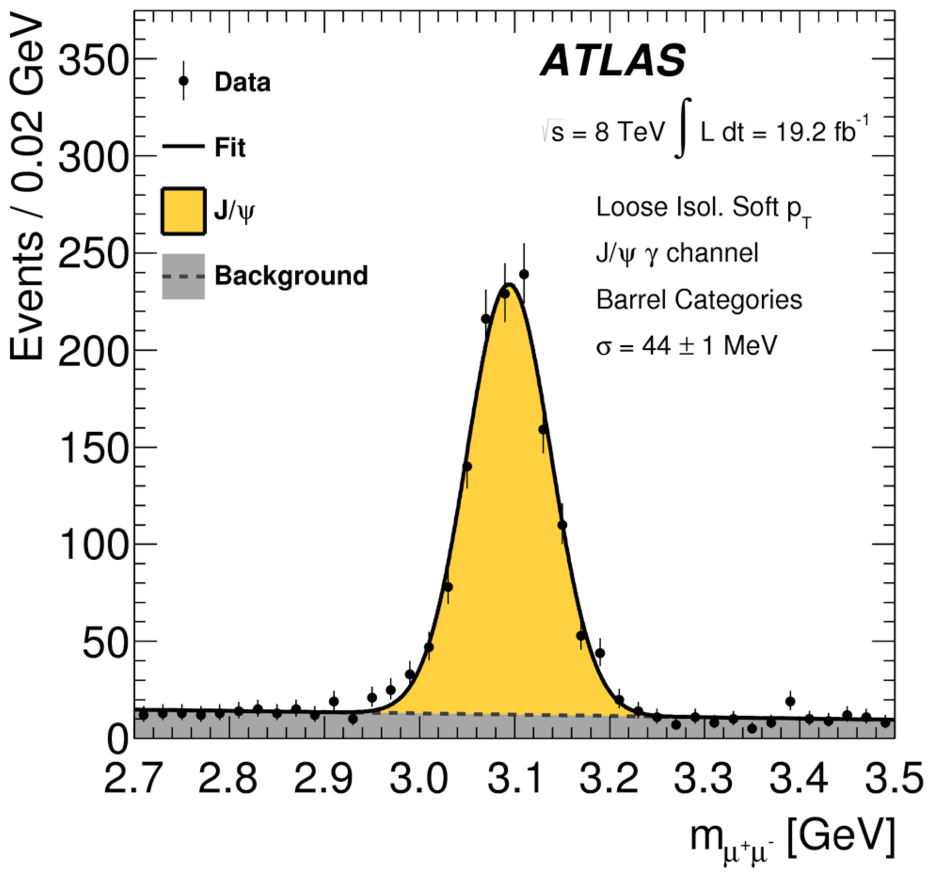
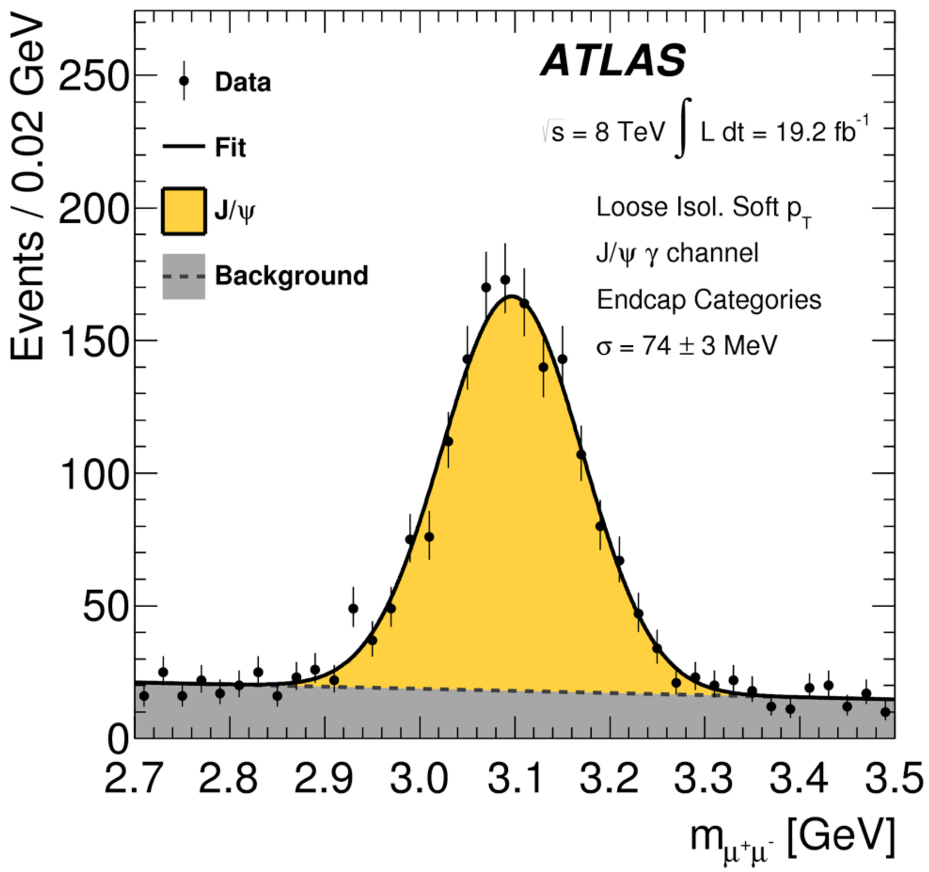
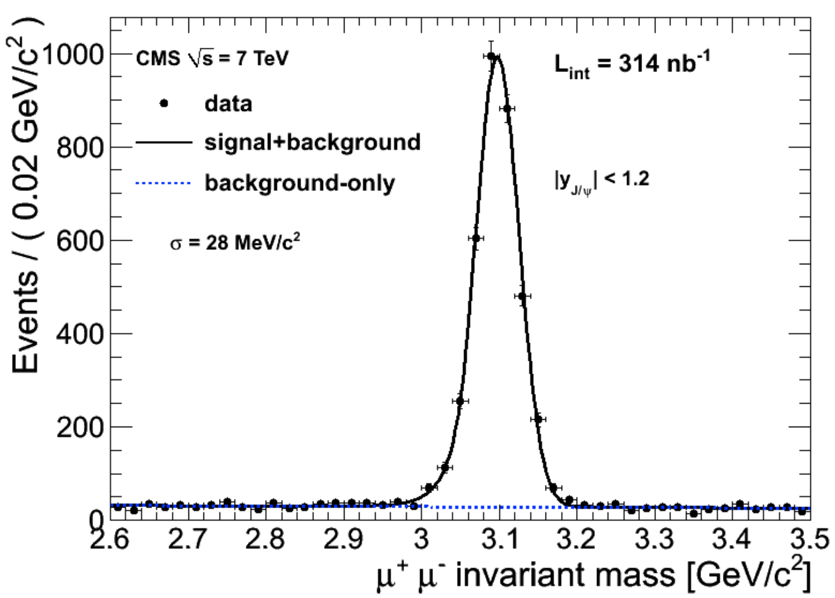
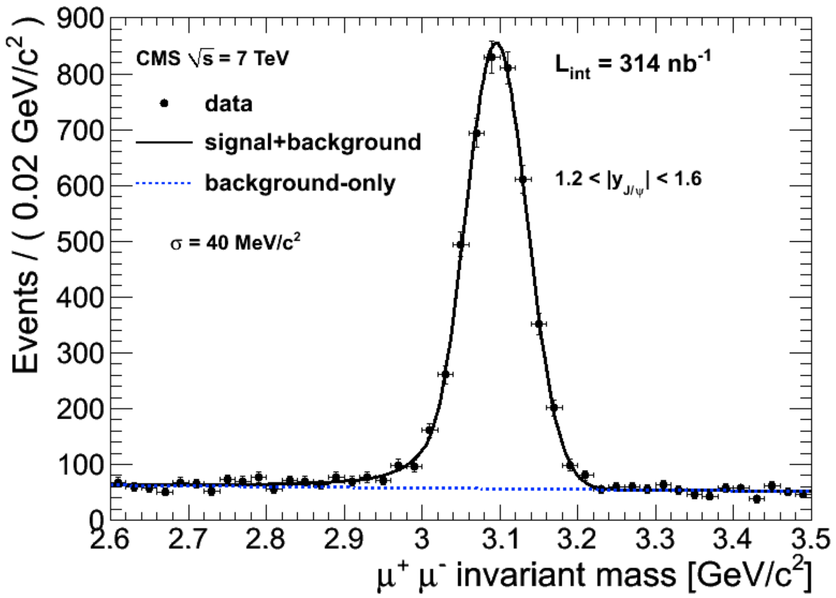


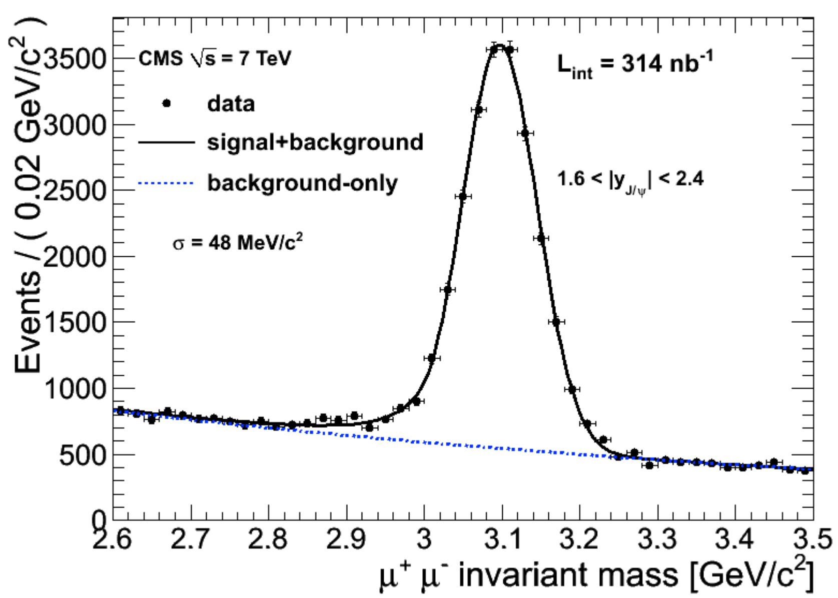
H→J/ψγ and H→Y(ns)γ











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]

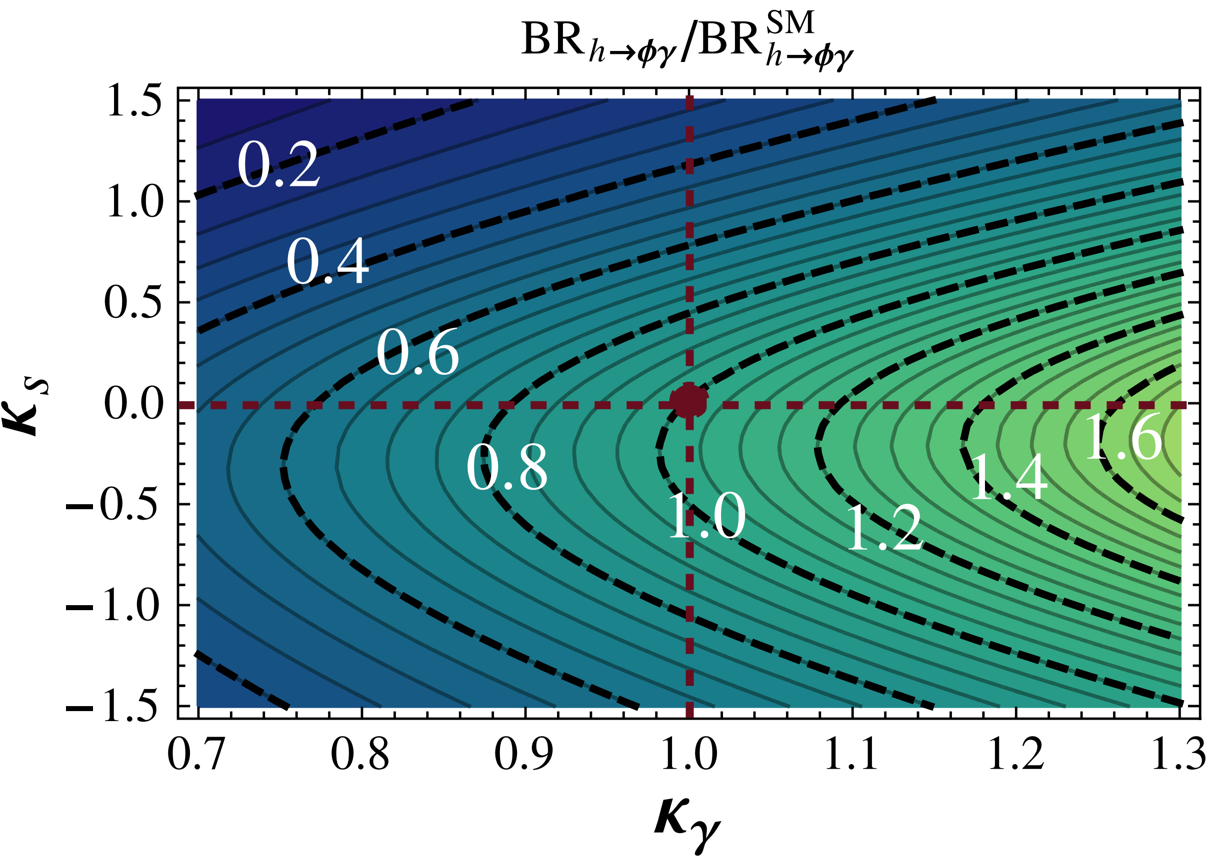
→ Sensitive to BSM physics [Phys. Rev. D 80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022]

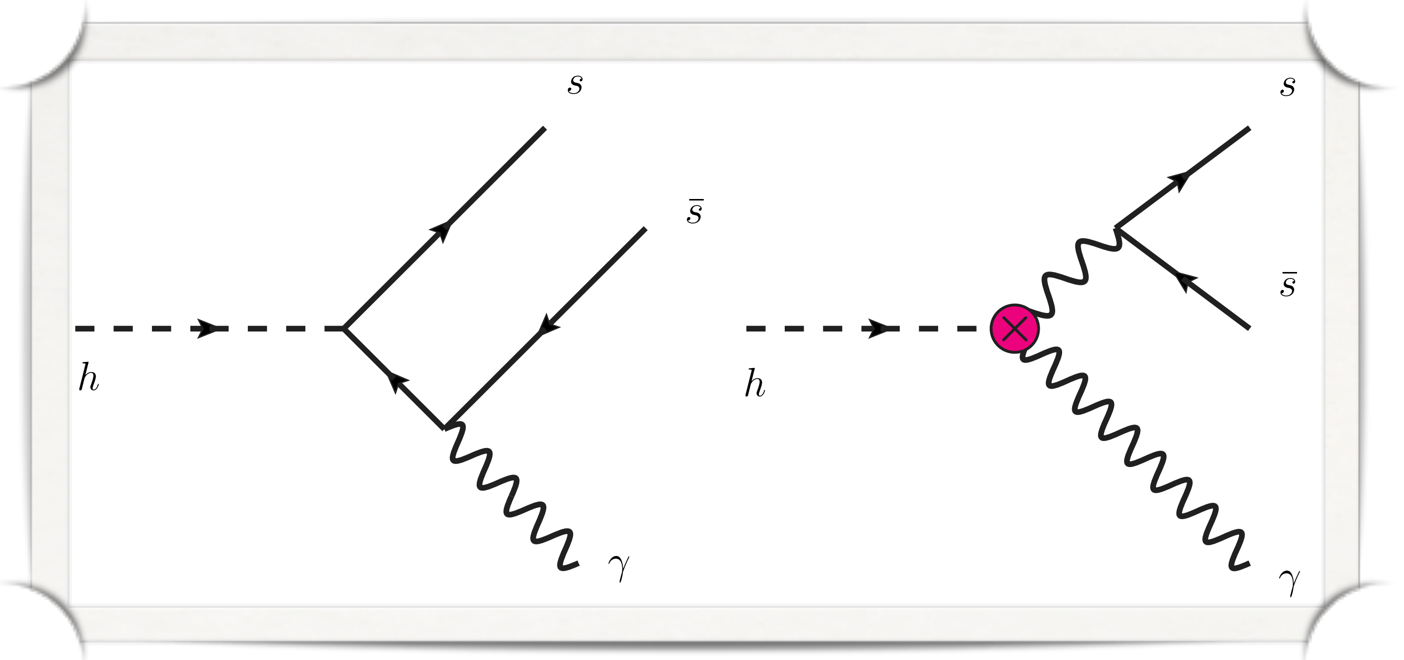
The idea is to benefit from the interference of the "direct" and "indirect" amplitudes!

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

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

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





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

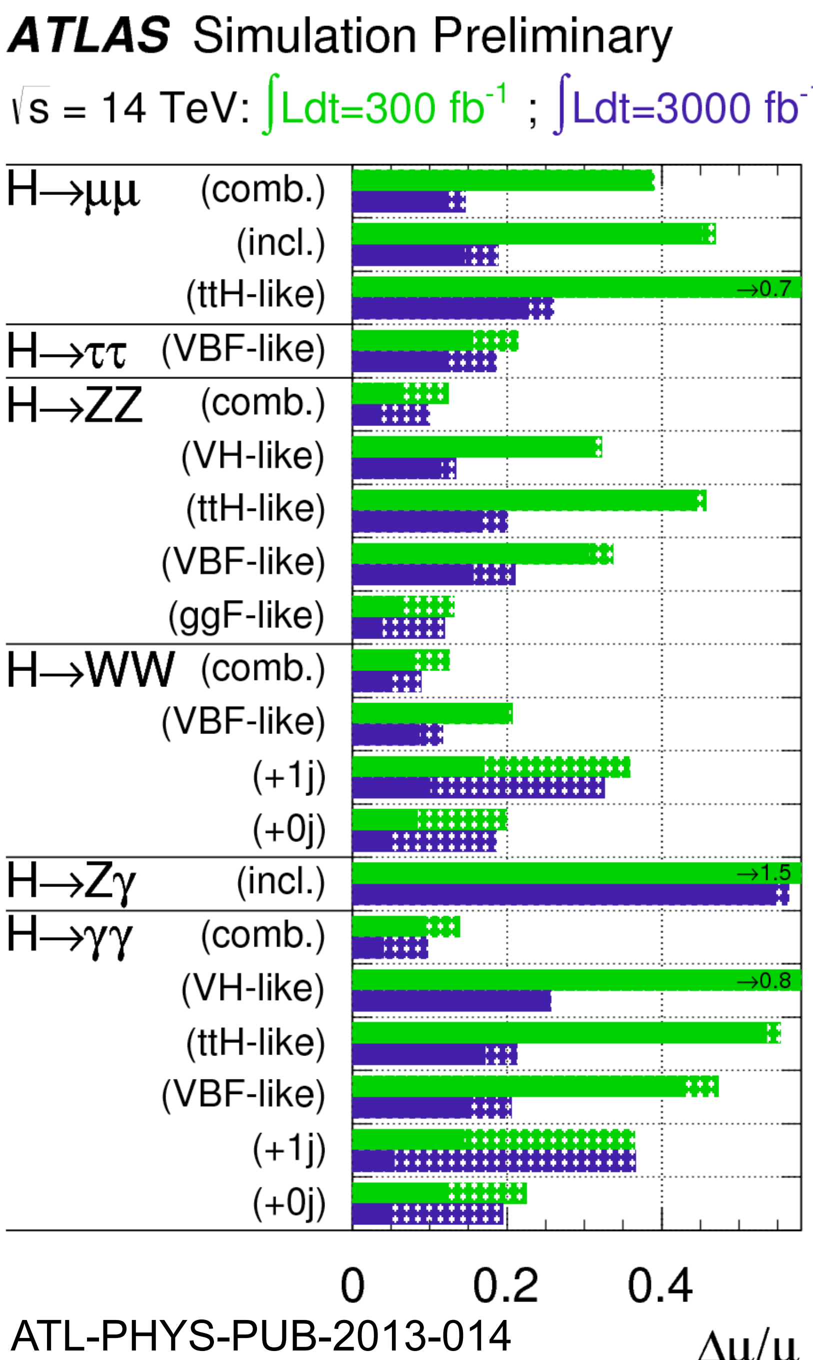
$$BR^{SM}_{h\to\phi\gamma} \approx 3\cdot10^{-6}$$
$$BR^{SM}_{h\to\rho\gamma} \approx 1.9\cdot10^{-5}$$
$$BR^{SM}_{h\to\omega\gamma} \approx 1.6\cdot10^{-6}$$

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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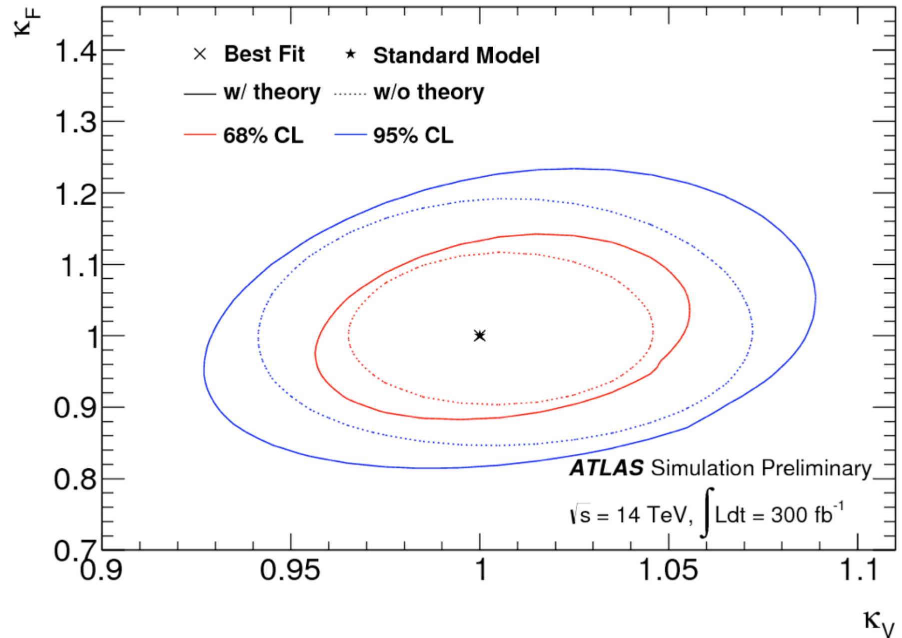

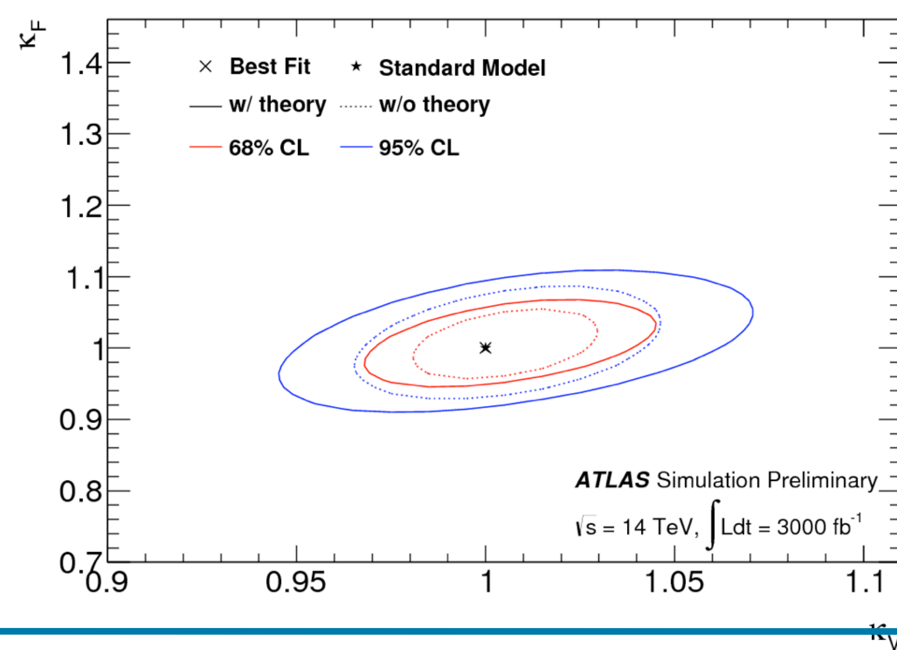

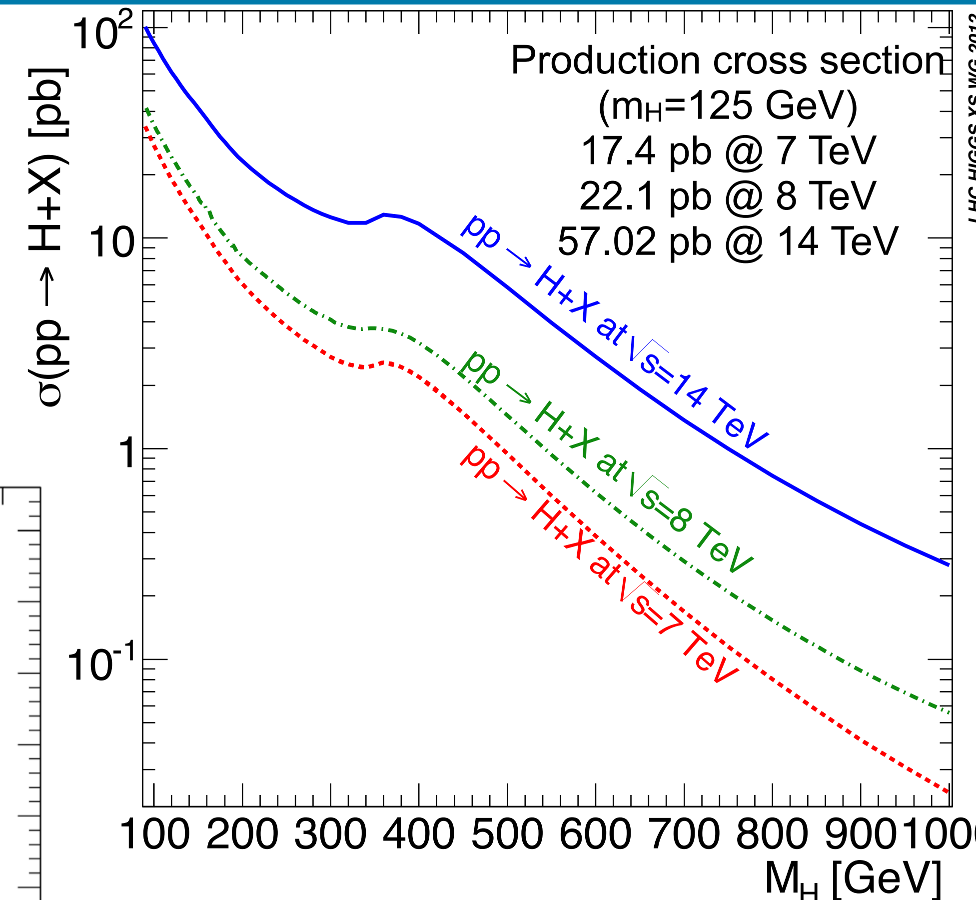

Several open topics in the Higgs sector for future studies:

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

Prospects for Run II/III and HL-LHC

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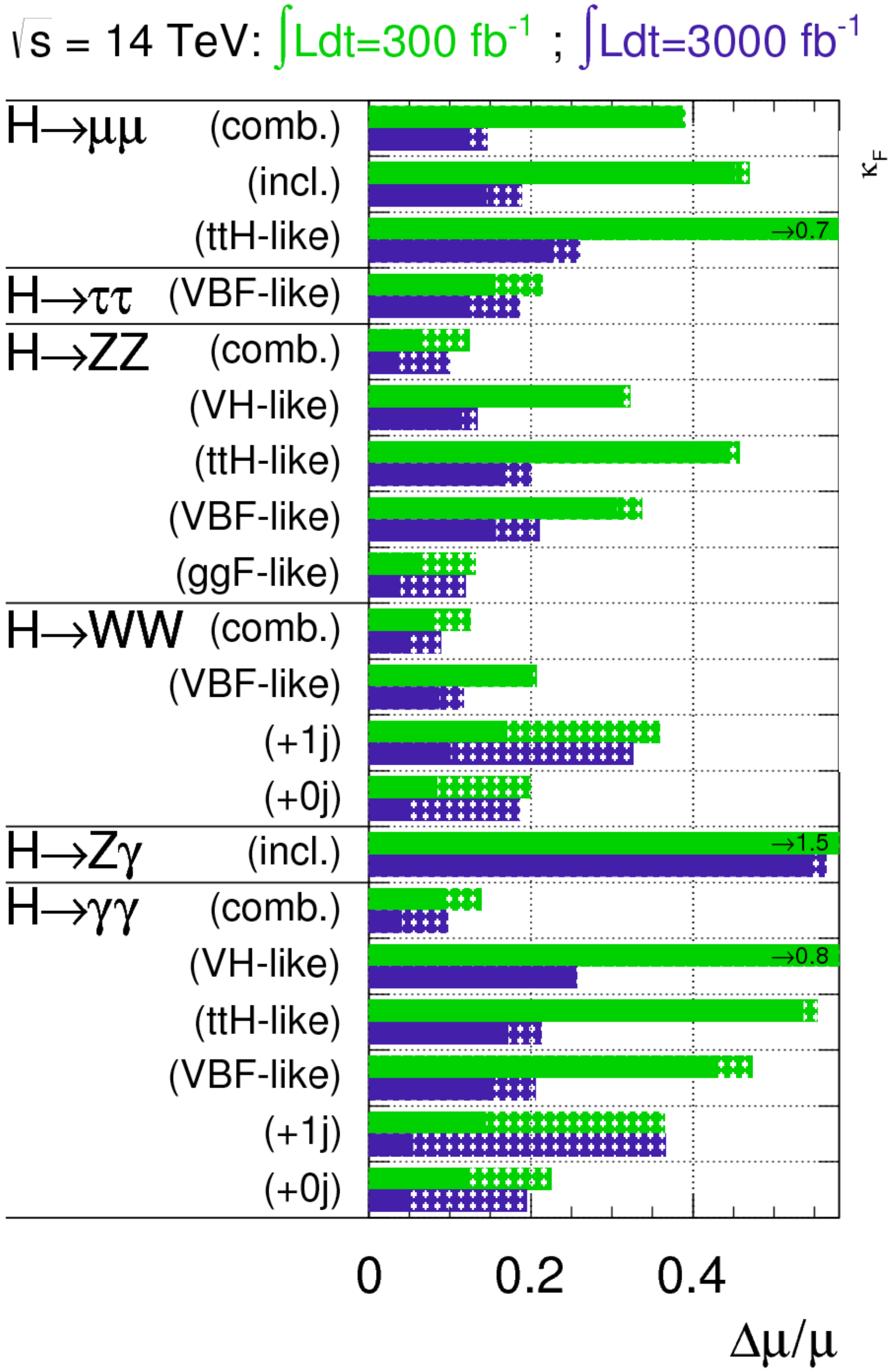

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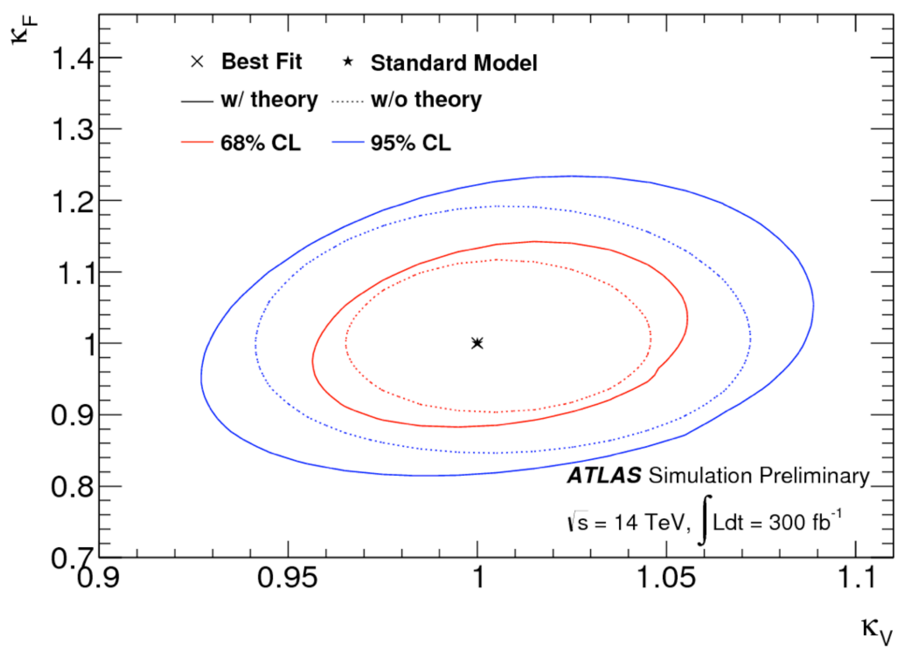

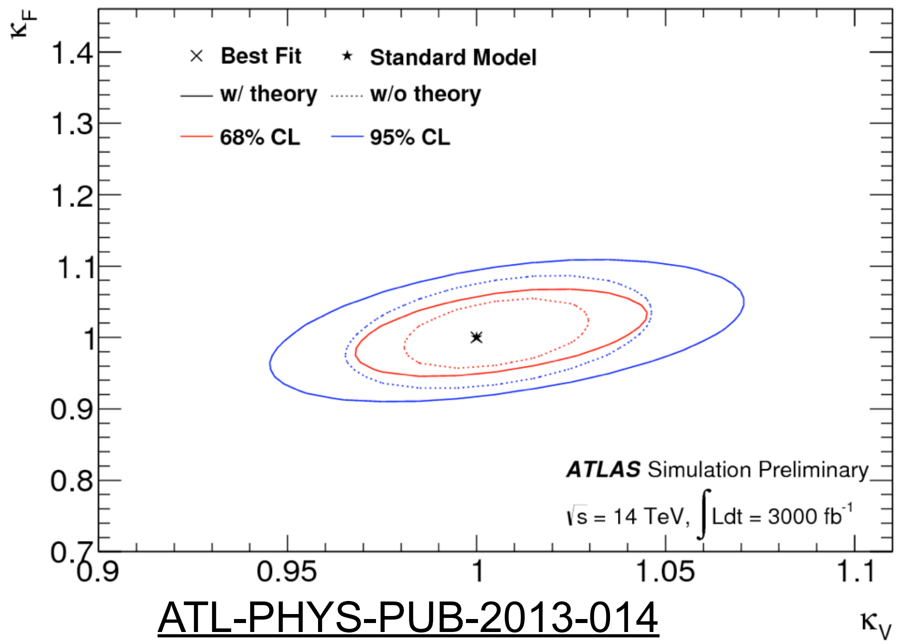

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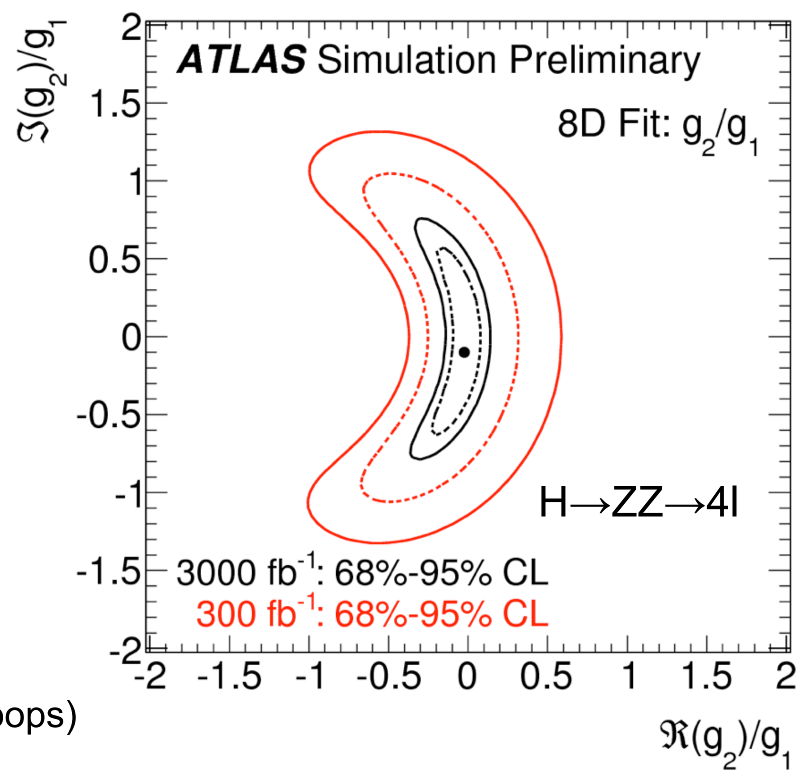

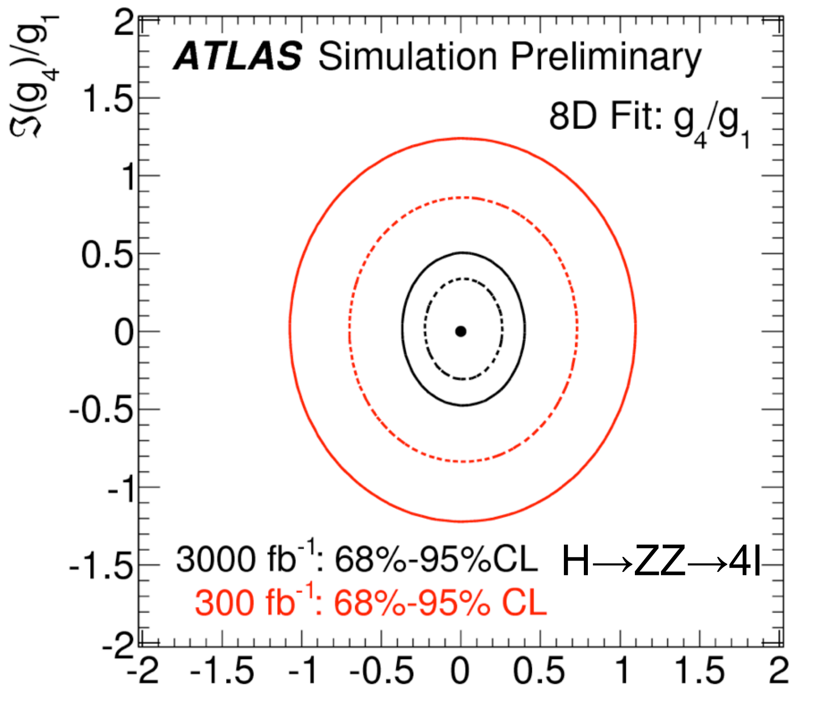

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g_1 CP-even HZZ coupling
g_2 CP-even HZZ coupling (loops)
g_4 CP-odd HZZ coupling