Search for Higgs boson decays to a meson and a photon

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on behalf of
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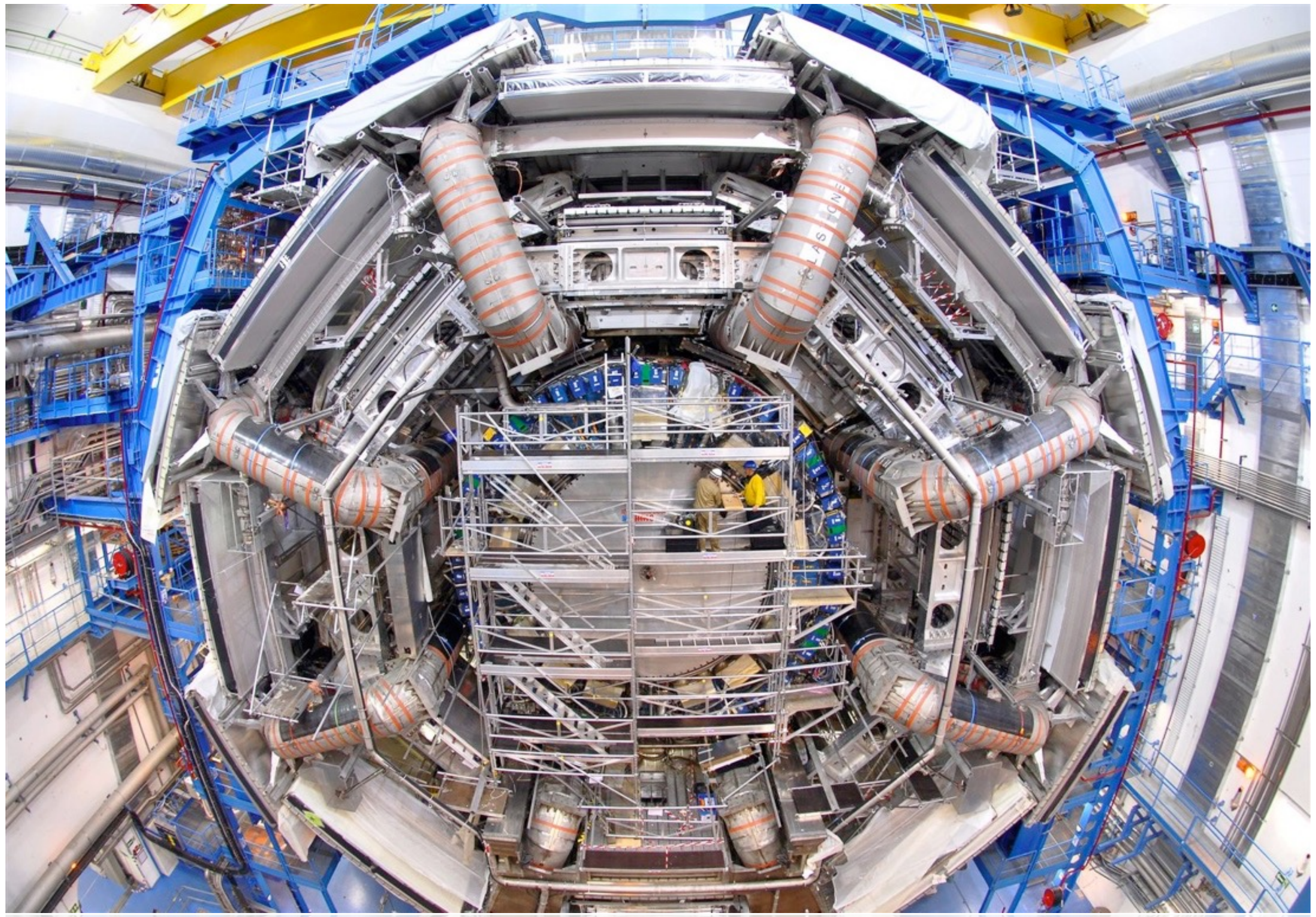

ATLAS experiment at CERN

Precision Workshop - Rencontres du Vietnam
26 September 2016, Quy Nhon, Vietnam

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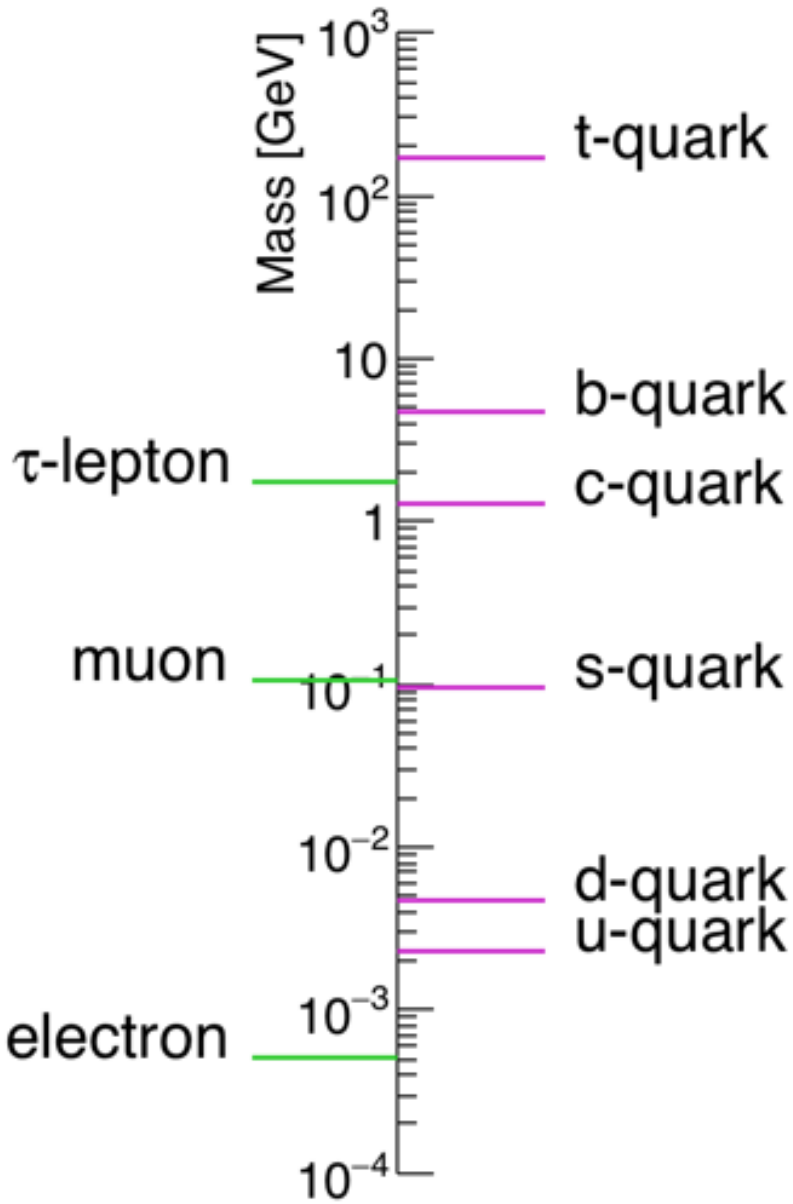
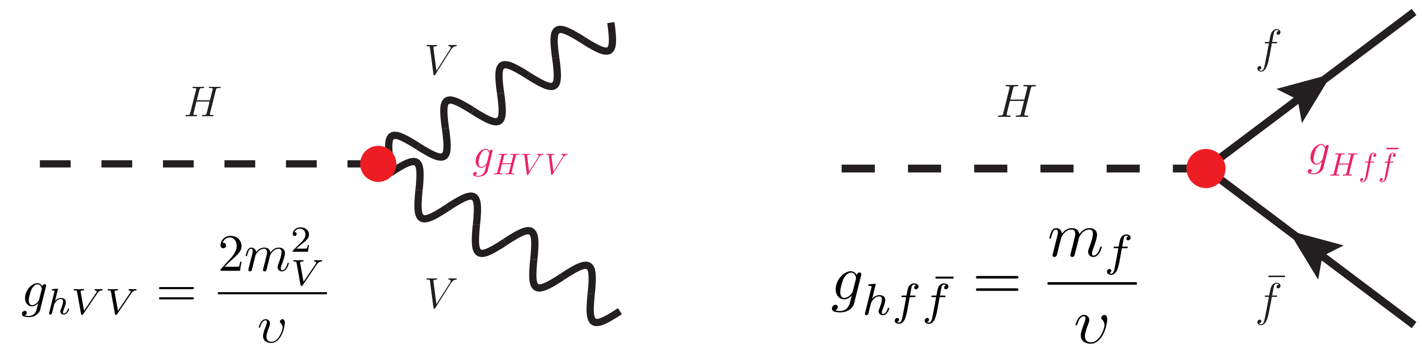
Higgs-fermion interactions: Yukawa couplings

- **Higgs interactions to vector bosons:** defined by symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$



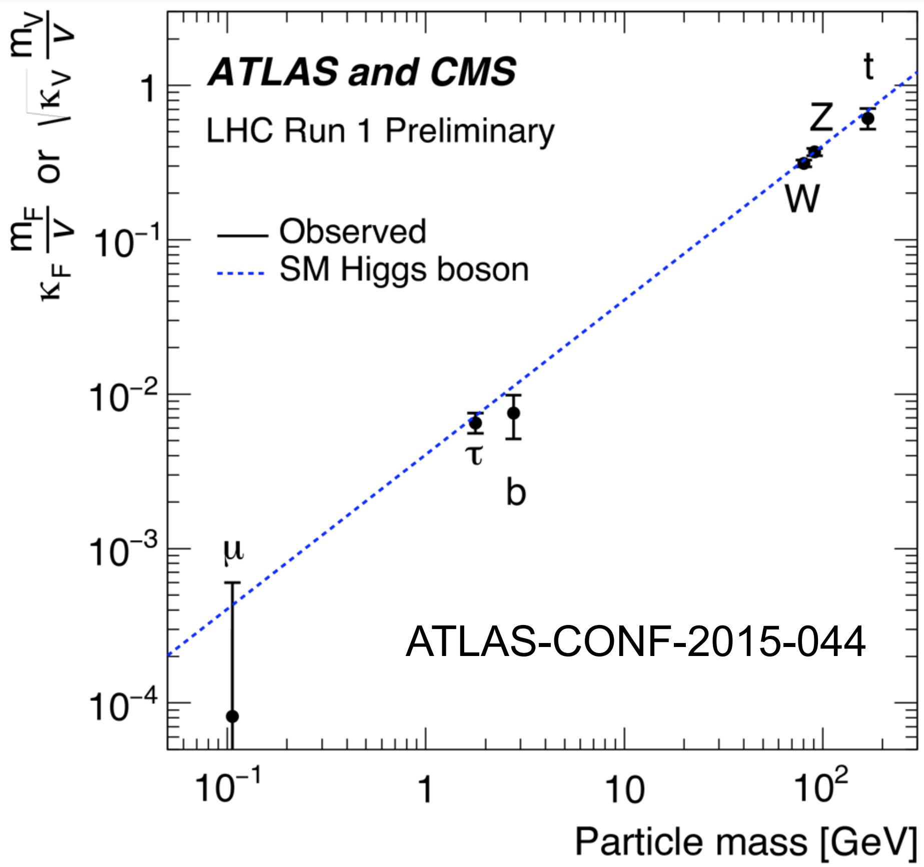


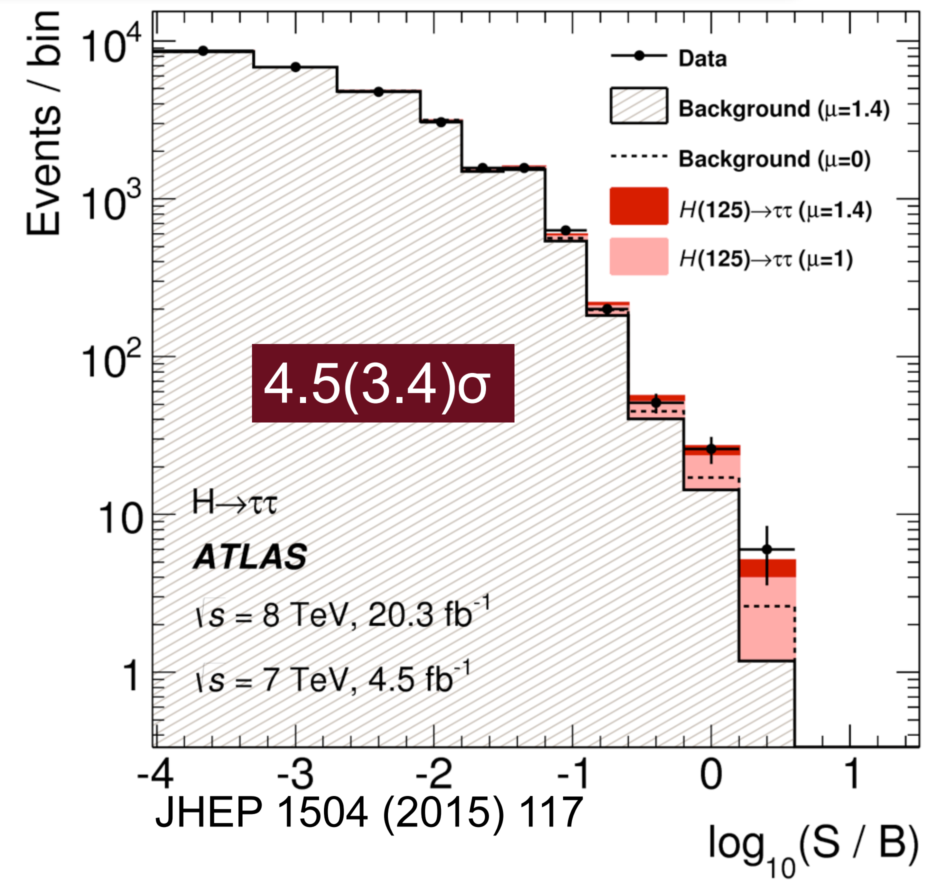
- ❑ Yukawa couplings **not** imposed by fundamental principle
- ☑ **Enhanced Yukawa couplings in BSM scenarios**
  [Phys. Rev. D80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022,…]
- ❑ **Unitarity bounds** (through EFT) for fermion mass generation scale (1st/2nd generation)

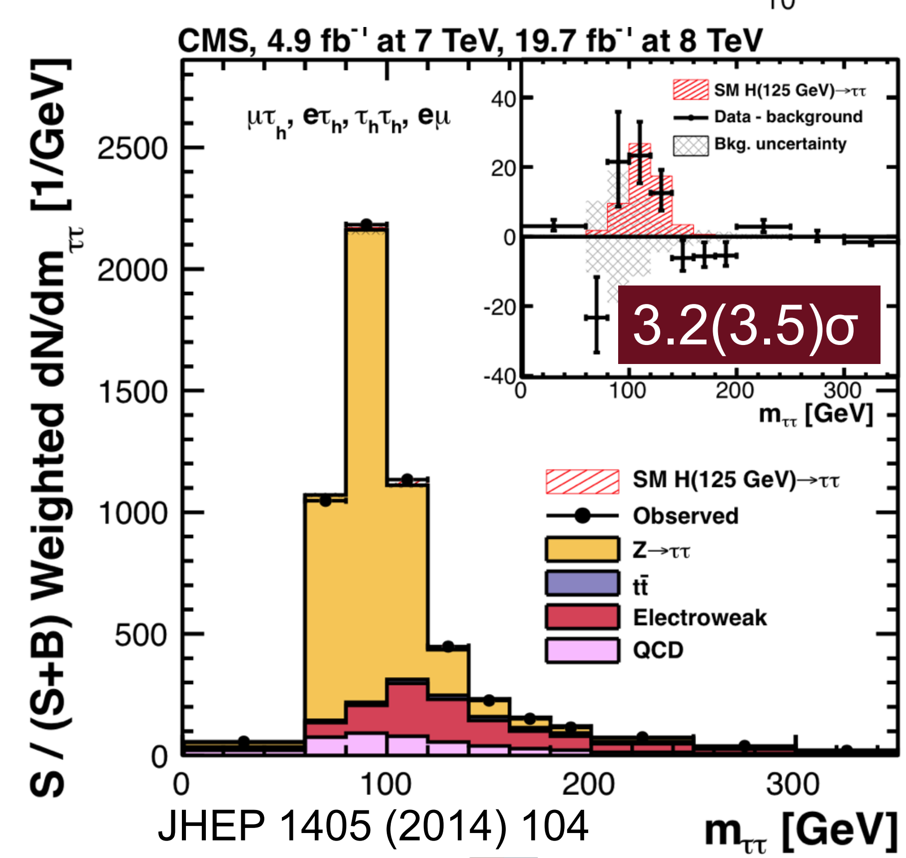
$$\Lambda \sim \sqrt{\frac{v^3}{m_f}} < 20 \text{ TeV}$$

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

Higgs-fermion interactions: The story so far







Progress in **Higgs boson properties**:

- ☑ **mass** known to 0.19%
- ☑ **bosonic decays** measured to ~20-30%

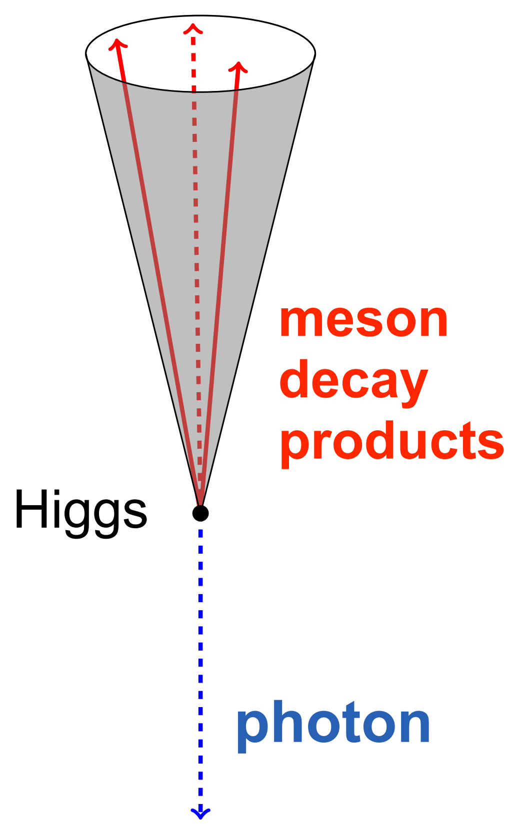
In **fermion sector**, different picture:

- ☑ **τ-lepton:** direct evidence by ATLAS and CMS for h→ττ
- ☐ **e,μ:** no evidence→non-universality
- ☑ **t-quark:** no firm evidence for ttH; indirect evidence
- ☐ **b-quark:** no evidence for h→bb in LHC; mild excesses
- ☐ **c-quark:** no direct evidence, loose bounds from h→bb
- ☐ **u/d/s-quarks:** no direct searches available

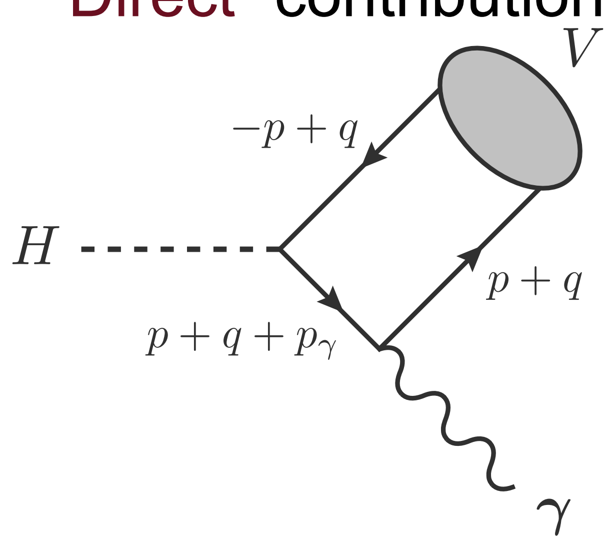
Exclusive Decays h→Qγ

- **h→Qγ decays:** a **clean probe** on Yukawa couplings of 1st and 2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two contributions:** direct and indirect amplitude
  - **Direct amplitude:** provides sensitivity to Yukawa couplings
  - **Indirect amplitude:** larger contribution than direct amplitude
  - **Destructive interference**

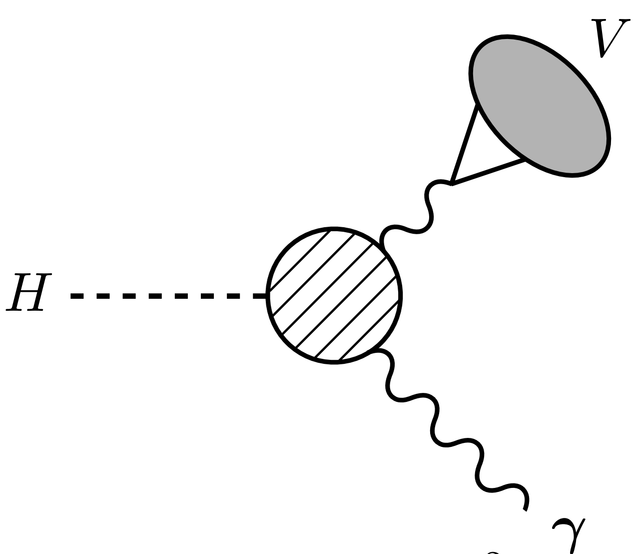
Small angular separation of decay products



"Direct" contribution



"Indirect" contribution



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

Phys.Rev. D90 (2014) 11, 113010

- **Exclusive decays** lead to **distinct experimental signatures**
  - High-p_T isolated quarkonium recoiling against high-p_T isolated photon

Exclusive Decays h→Qγ

- Substantial recent interest from the theory community regarding branching ratio estimates and feasibility:

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

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

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

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

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$$\mathrm{Br}(h \to \rho^0\gamma) = (1.68 \pm 0.02_{f_\rho} \pm 0.08_{h\to\gamma\gamma}) \cdot 10^{-5}\,,$$

$$\mathrm{Br}(h \to \omega\gamma) = (1.48 \pm 0.03_{f_\omega} \pm 0.07_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

$$\mathrm{Br}(h \to \phi\gamma) = (2.31 \pm 0.03_{f_\phi} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}\,,$$

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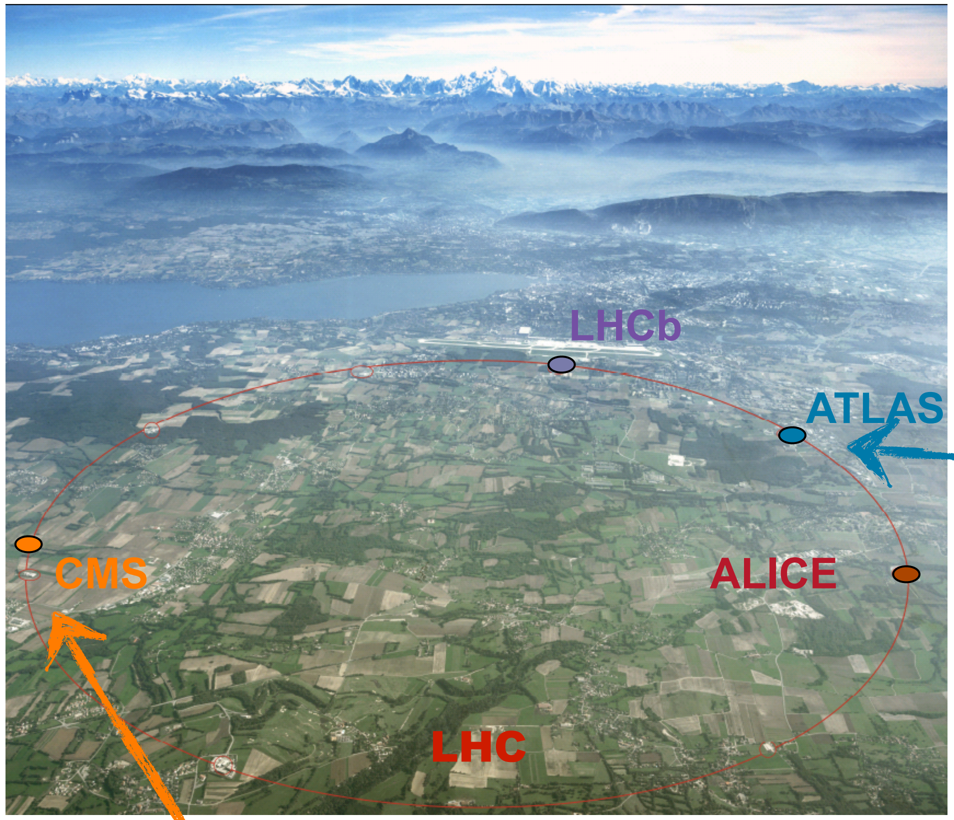
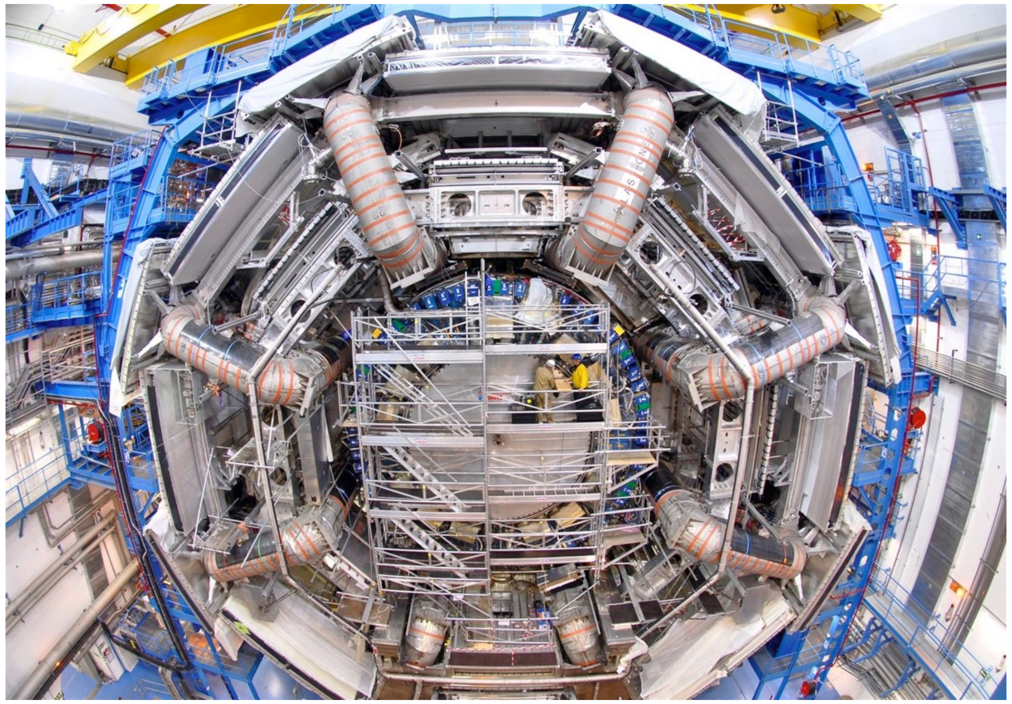
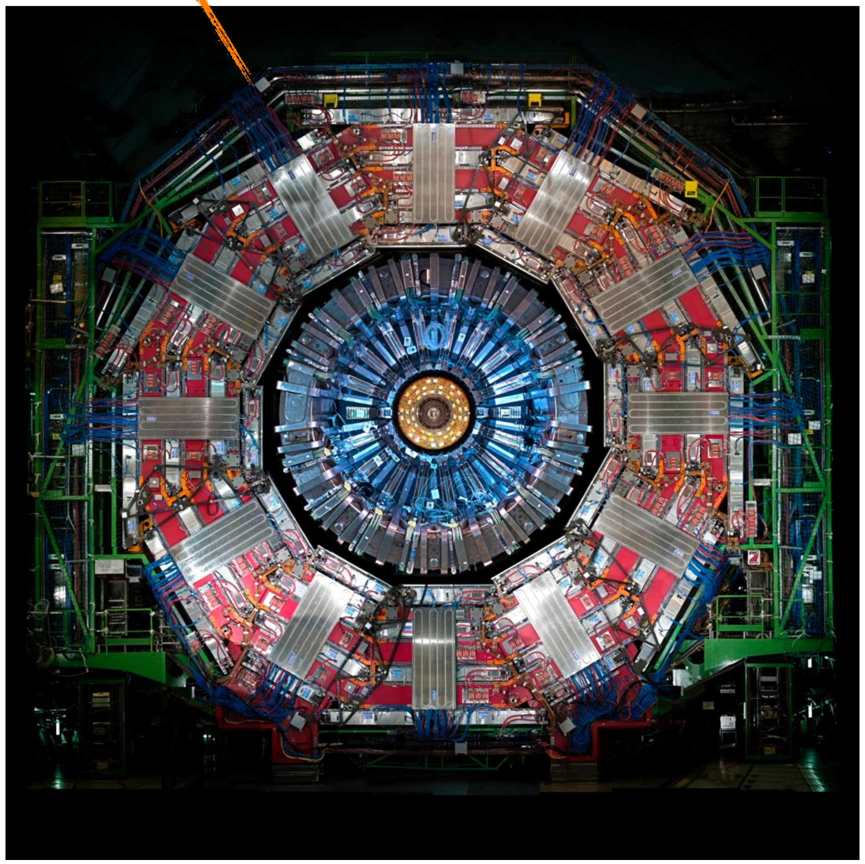
- Z→Qγ decays also interesting
- Experimentally unconstrained
  - LEP accurately measured b-/c-quark couplings (~1%)
  - light quark couplings less constrained
- Sensitive to BSM contributions

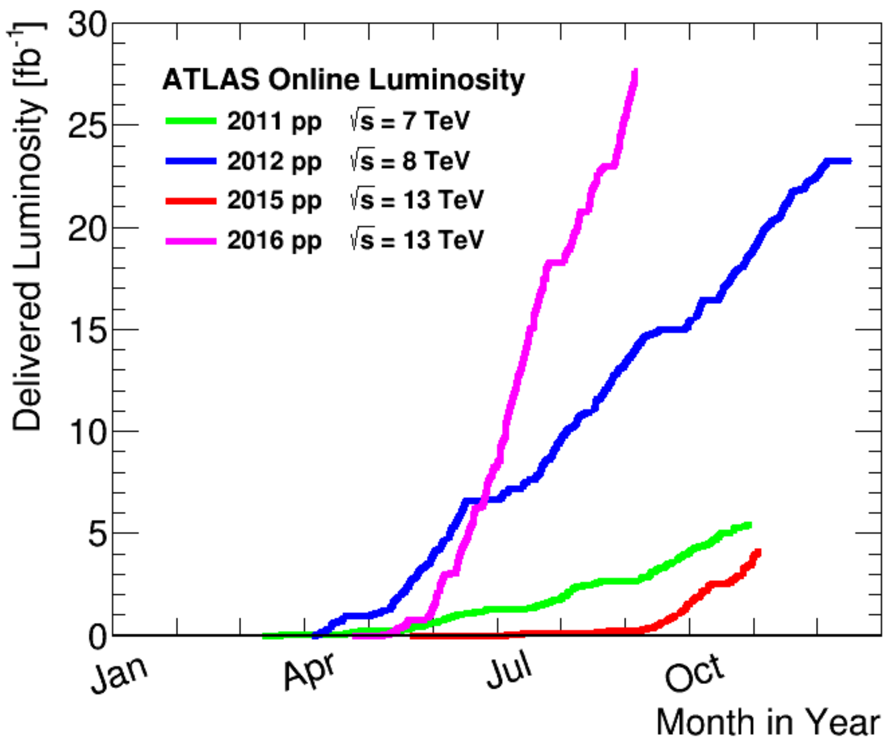
Decay mode	Branching ratio
$Z^0 \to \pi^0\gamma$	$(9.80\,{}^{+0.09}_{-0.14}{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,{}^{+0.04}_{-0.06}{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,{}^{+0.03}_{-0.05}{}_{\mu}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

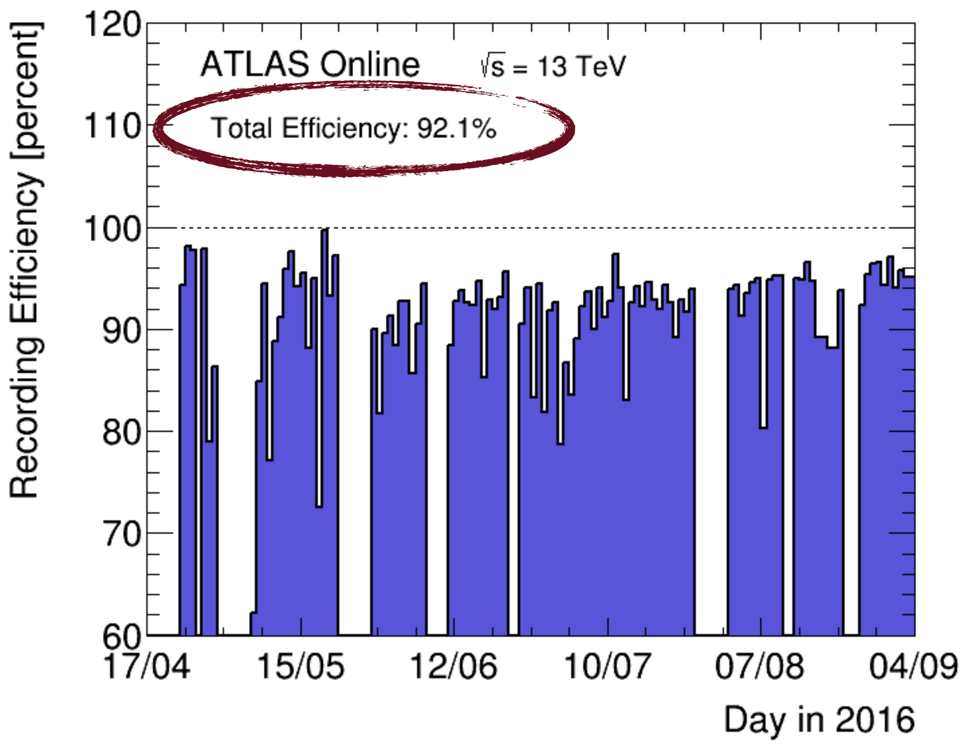
The LHC, ATLAS and CMS







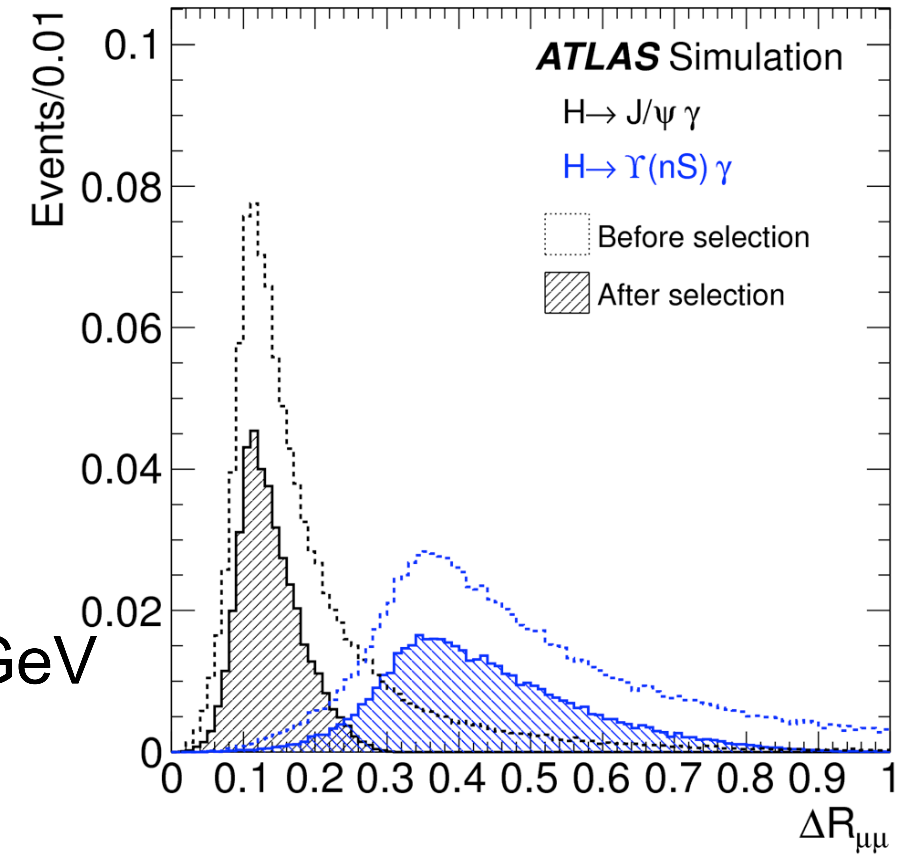


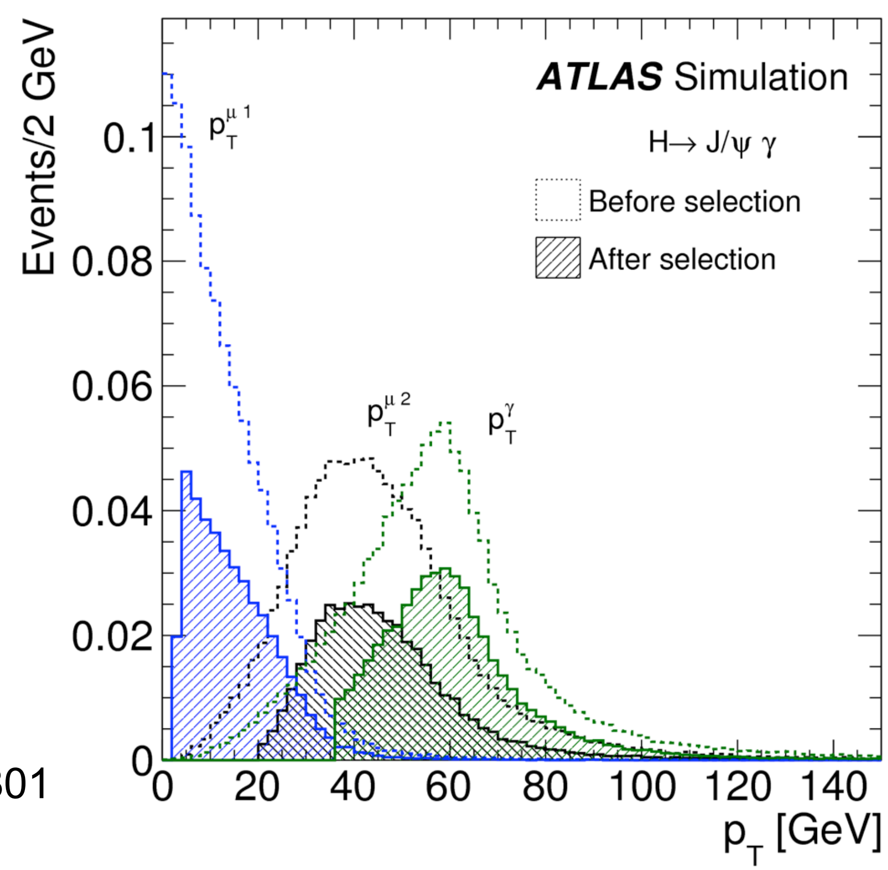


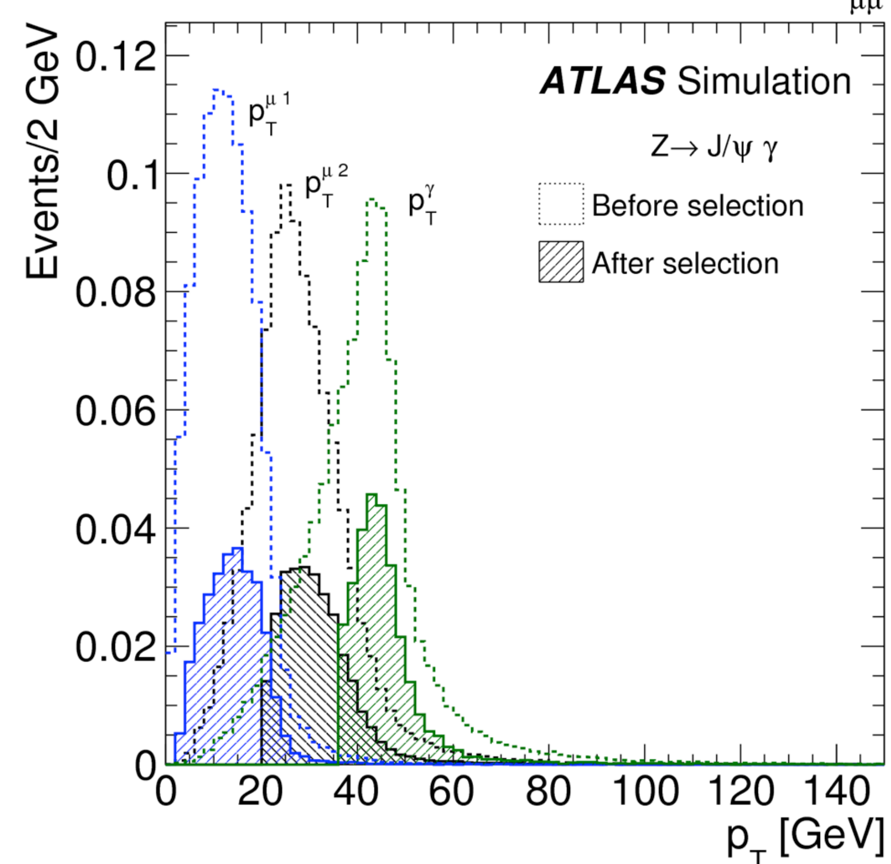
High Quality data collected!

$h/Z \to J/\psi\gamma$ and $h/Z \to \Upsilon(nS)\gamma$ (n=1,2,3)

- **ATLAS first search** for exclusive $h/Z \to Q\gamma$ decays
  - $Q = J/\psi$ or $\Upsilon(nS)$, n=1,2,3
- Event Selection
  - single muon and dimuon trigger
  - $|\eta_\mu|<2.5$, $p_{T\mu}>20,3$ GeV, $p_{T\mu\mu}>36$ GeV
  - $|\eta_\gamma|<2.47$ (excluding $1.37<|\eta_\gamma|<1.52$), $p_{T\gamma}>36$ GeV
  - $\mu\mu$ and γ isolation,
  - $|m_{\mu\mu} - m_{J/\psi}|<0.15$ (0.20) GeV barrel (endcap) $8<m_{\mu\mu}<12$ GeV
  - $|L_{xy}/\sigma_{Lxy}|<3$
  - $\Delta\varphi(\mu\mu,\gamma)>0.5$
- Total efficiency
  - $h \to J/\psi(\to\mu\mu)\gamma \sim 22\%$
  - $h \to \Upsilon(\to\mu\mu)\gamma \sim 28\%$
  - $Z \to J/\psi(\to\mu\mu)\gamma \sim 12\%$
  - $Z \to \Upsilon(\to\mu\mu)\gamma \sim 15\%$







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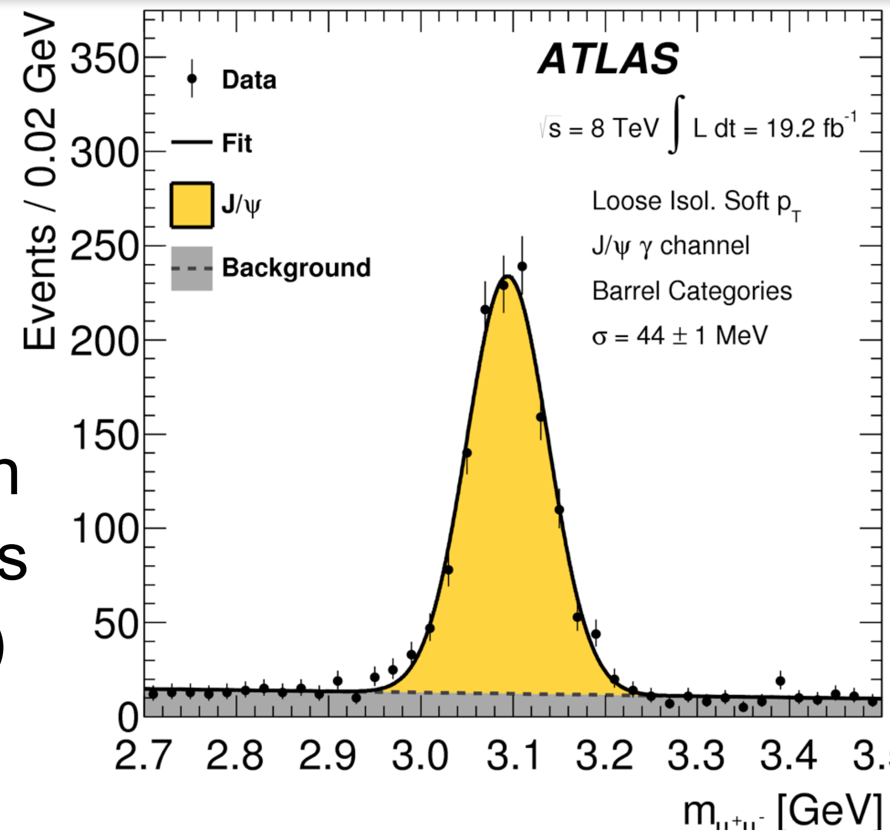
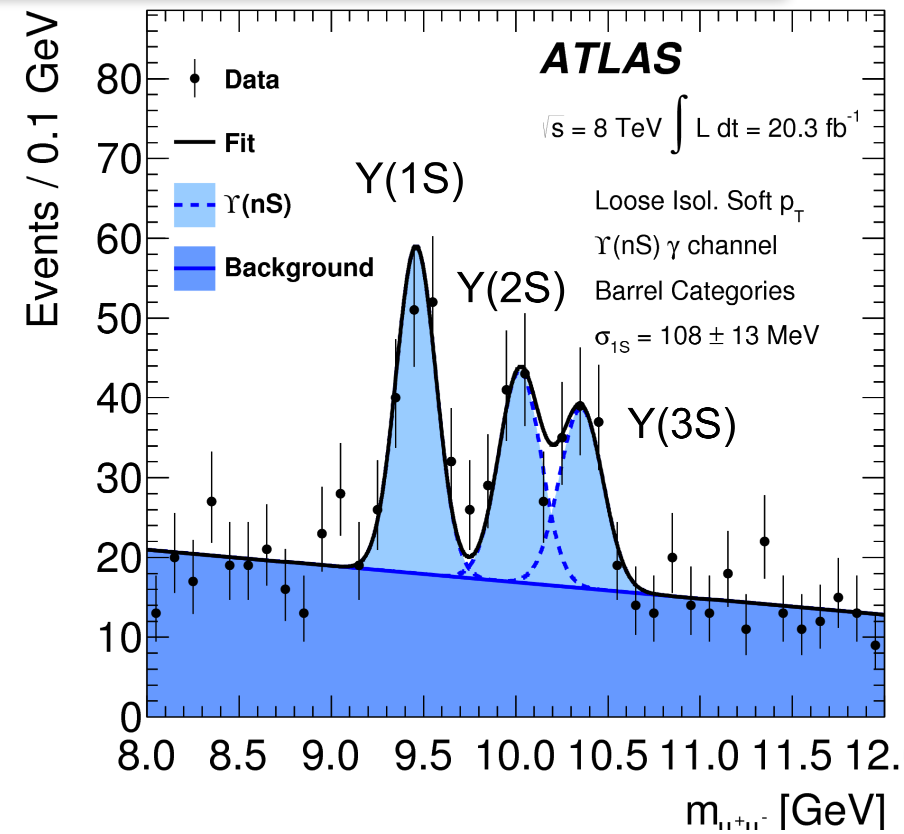
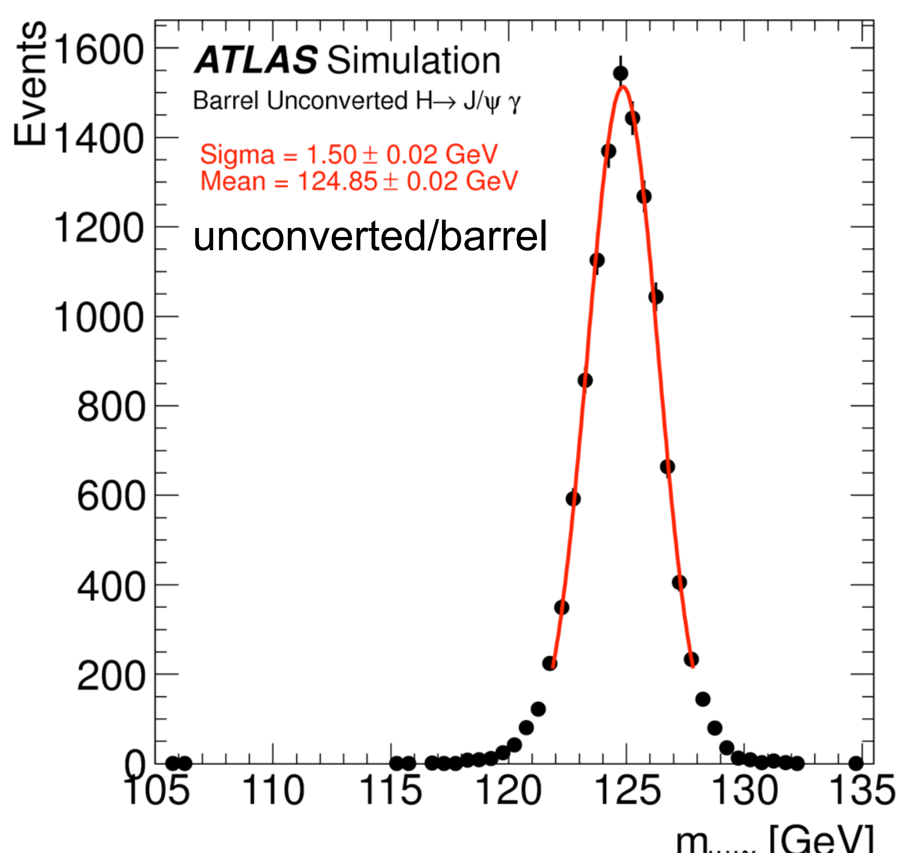
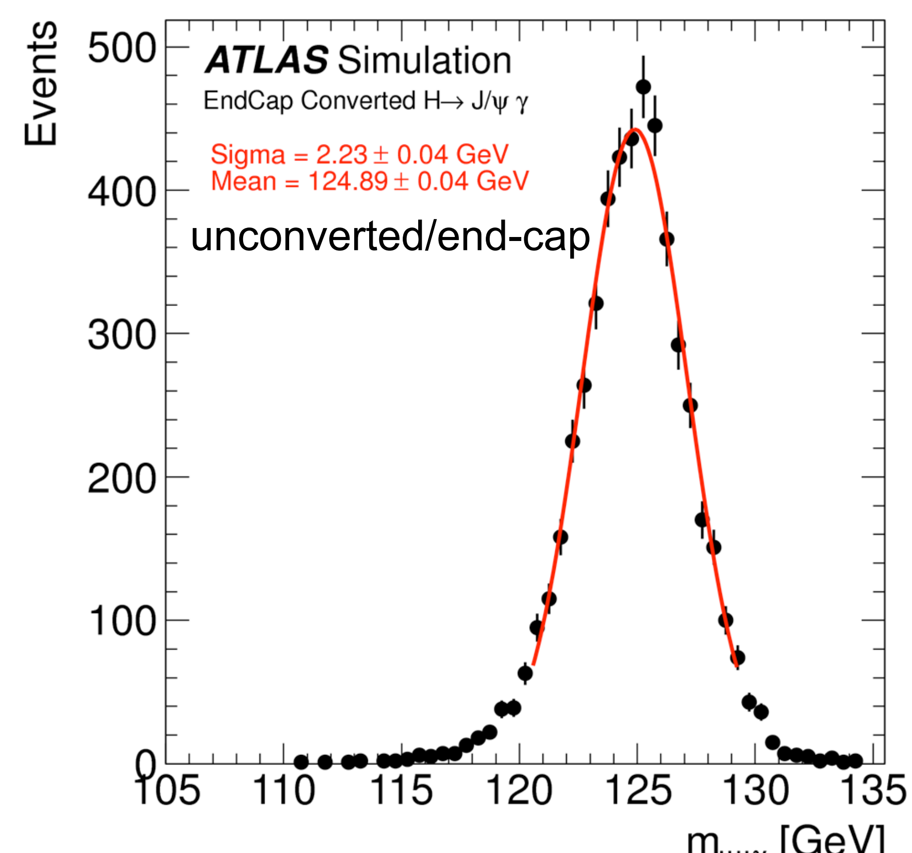
h/Z→J/ψγ and h/Z→Υ(nS)γ: Mass Resolution

- Simple event categorisation
- 4 detector-driven categories
  - Muon pseudorapidity (×2)
  - Photon conversion (×2)
- Mass resolution ~1.2-1.8%









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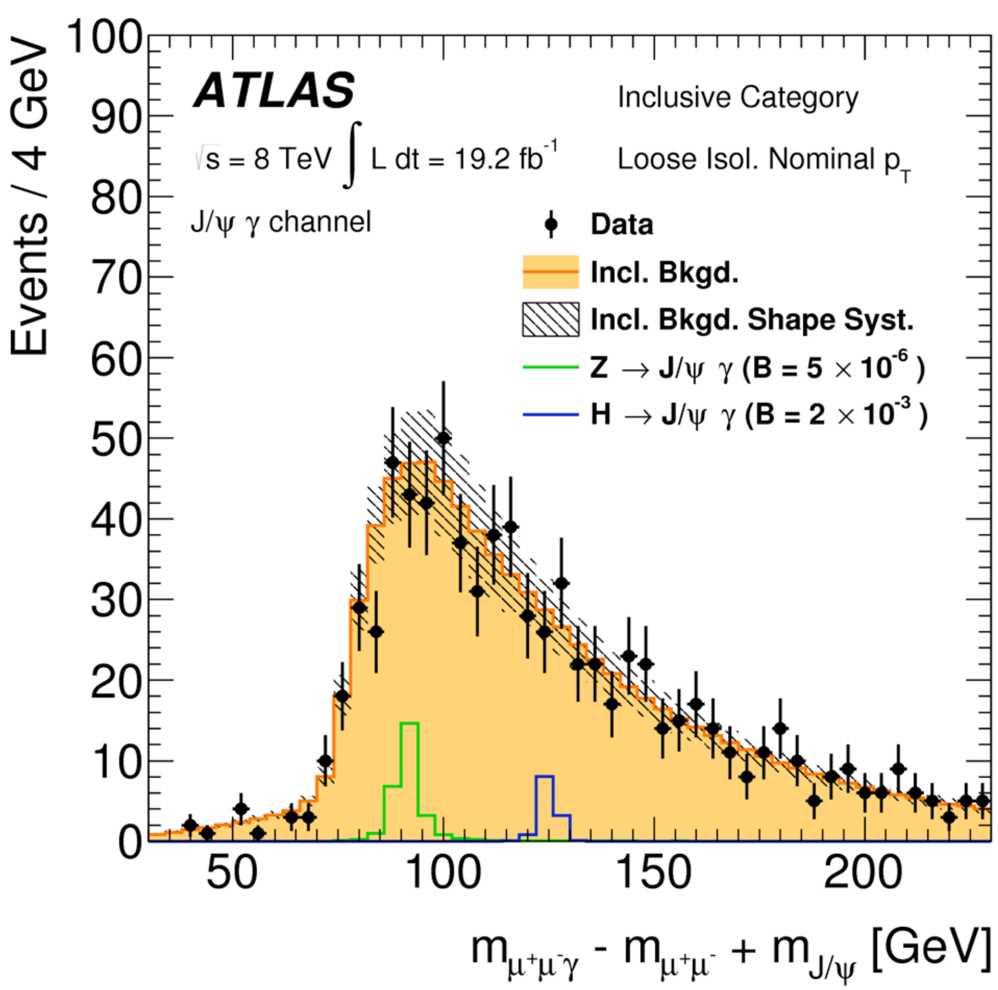
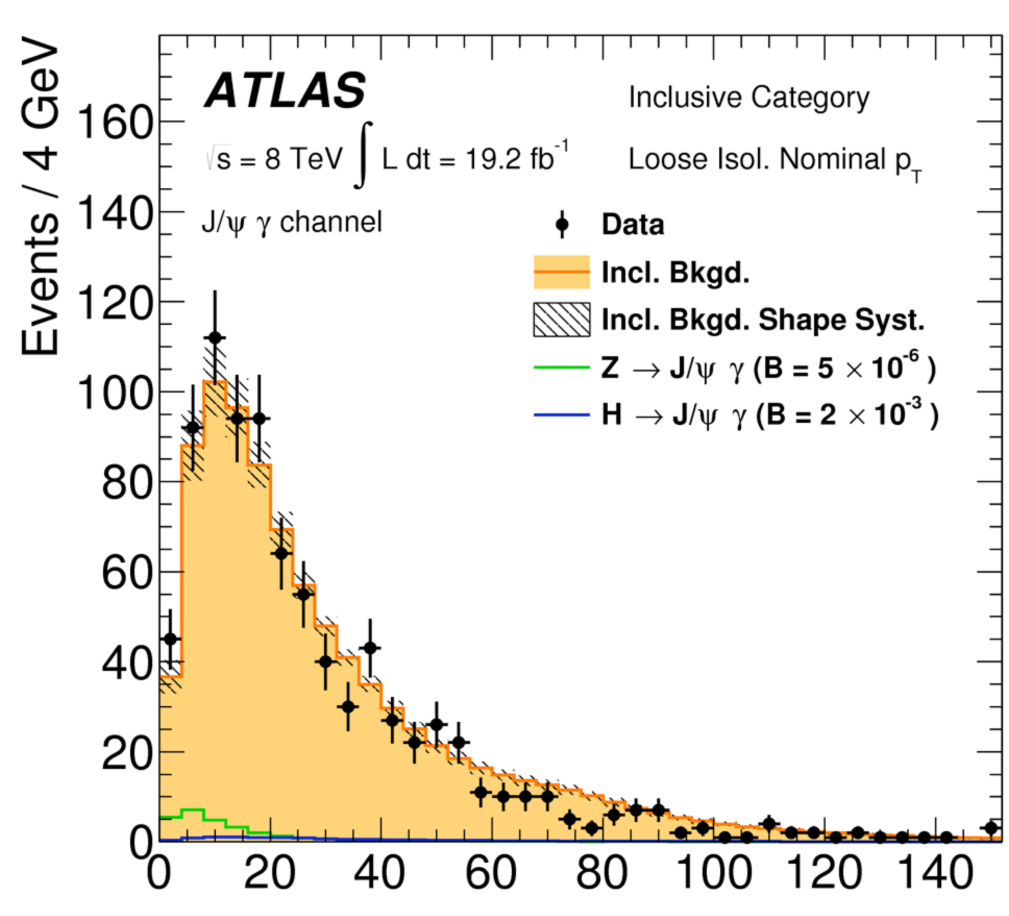
h/Z→J/ψγ and h/Z→Υ(nS)γ: Background

- **Inclusive quarkonium** with jet "seen" as γ
  - combinatoric background: small contribution
  - contribution from Q+γ production
- **Nonparametric data-driven** background model
  - Begin with loose sample of candidates
  - Model kinematic and isolation distributions
  - Generate "pseudo"-background events
  - Apply selection to "pseudo"-candidates
- **Υ(nS)γ:** also $Z \to \mu\mu\gamma_{FSR}$ 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





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h/Z→J/ψγ and h/Z→Υ(nS)γ: Systematics

- **Signal Yield Uncertainty:** Several sources of systematic uncertainty on the h and Z signal yields are considered, all modelled by nuisance parameters in likelihood:

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	

- **Background Shape Uncertainty:** Estimated from modifications to modeling procedure (e.g. shifting/warping input distributions), shape uncertainty included in likelihood as a shape morphing nuisance parameter

h/Z→J/ψγ and h/Z→Υ(nS)γ: Results

- **Multi-observable fit**
  - $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$ for J/ψγ
  - $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$, $m_{\mu\mu}$ for Υ(nS)γ
- **No significant excess** above background observed

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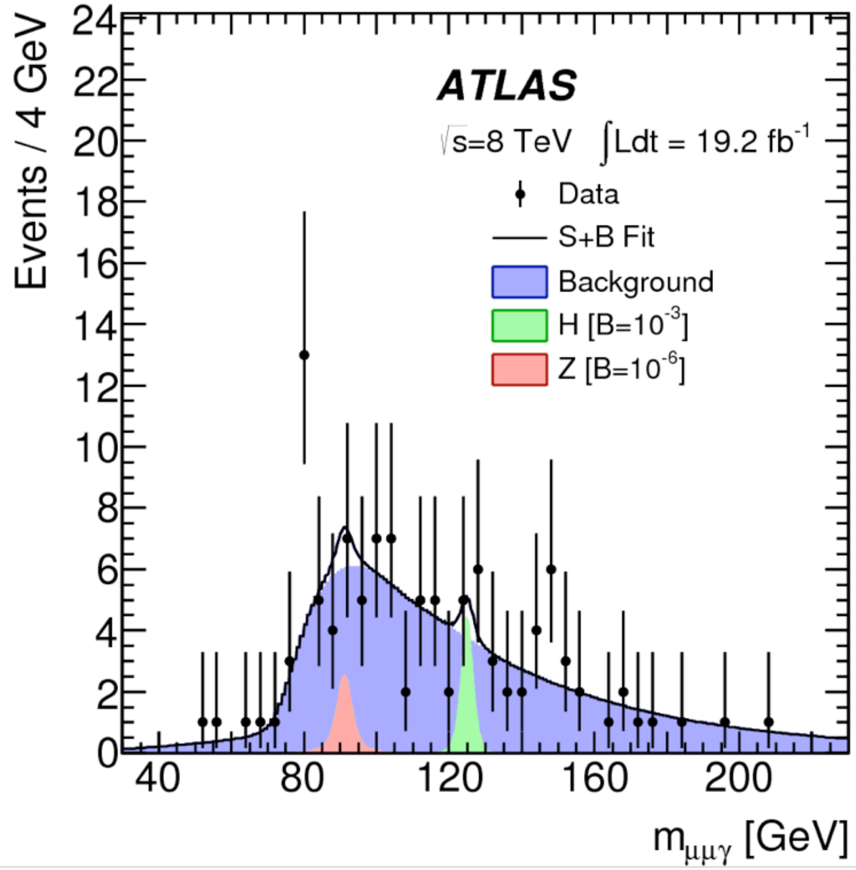
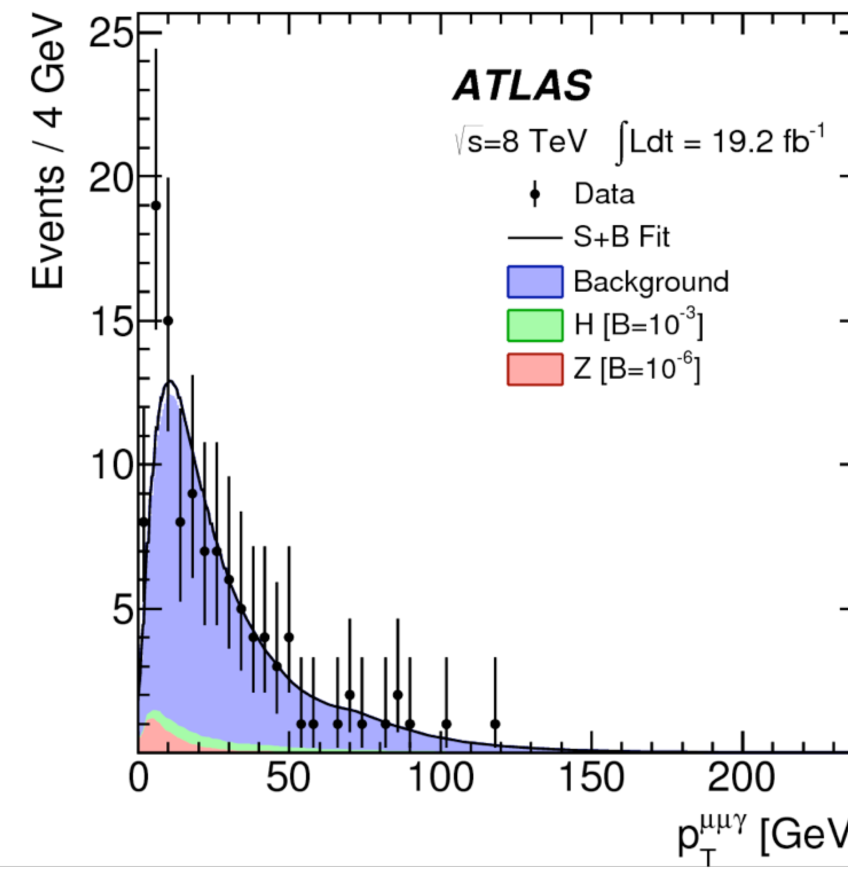
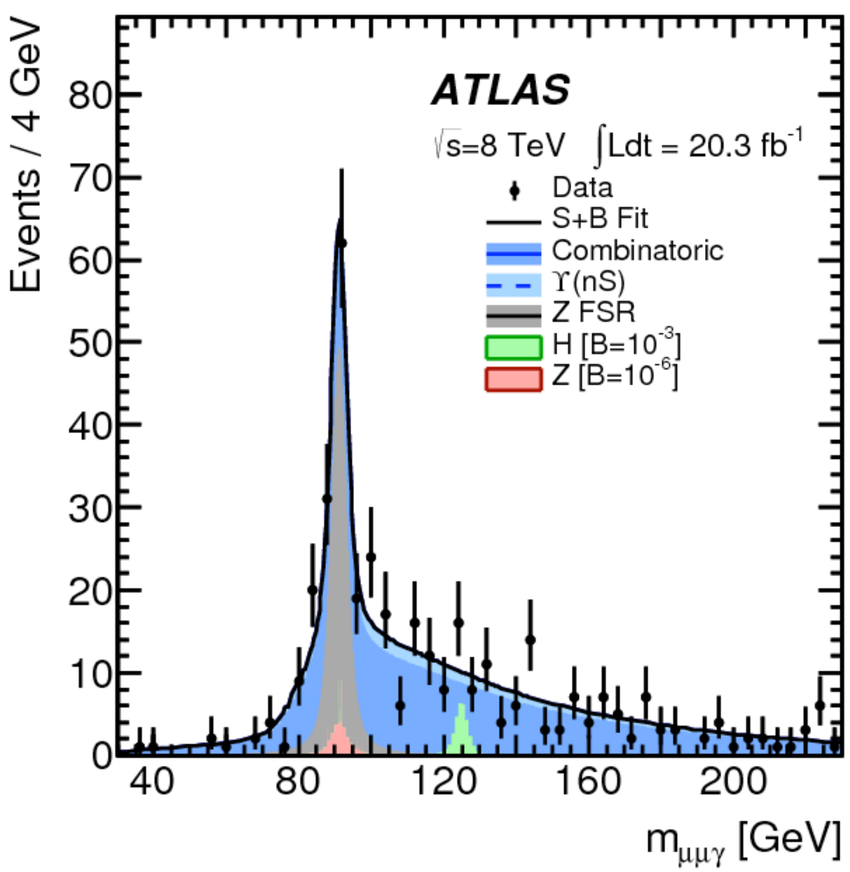
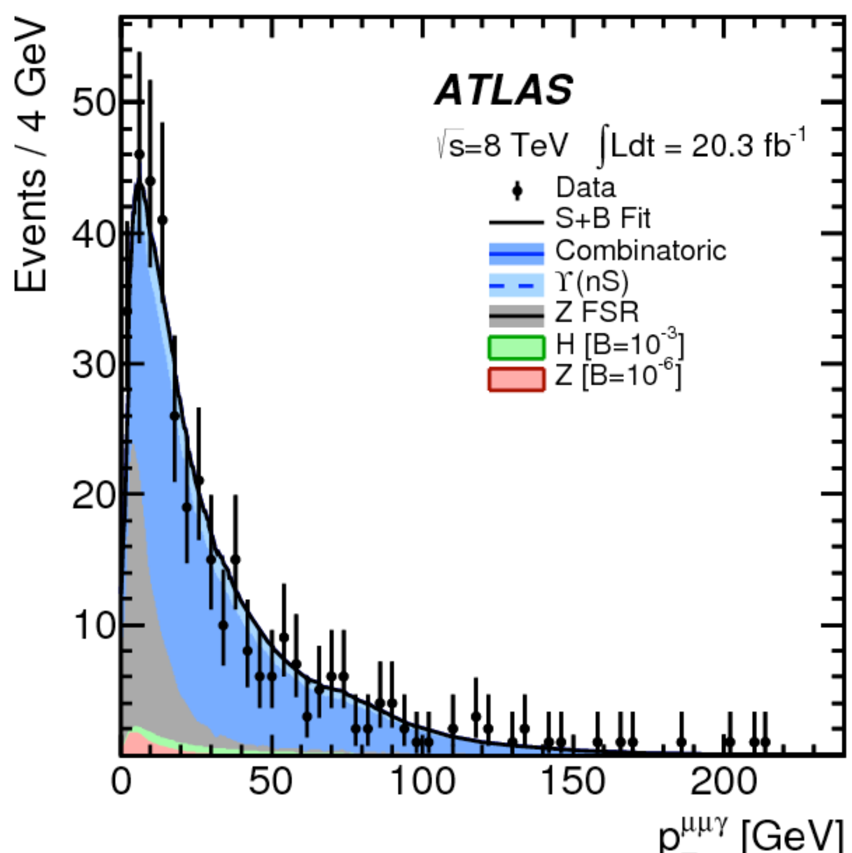
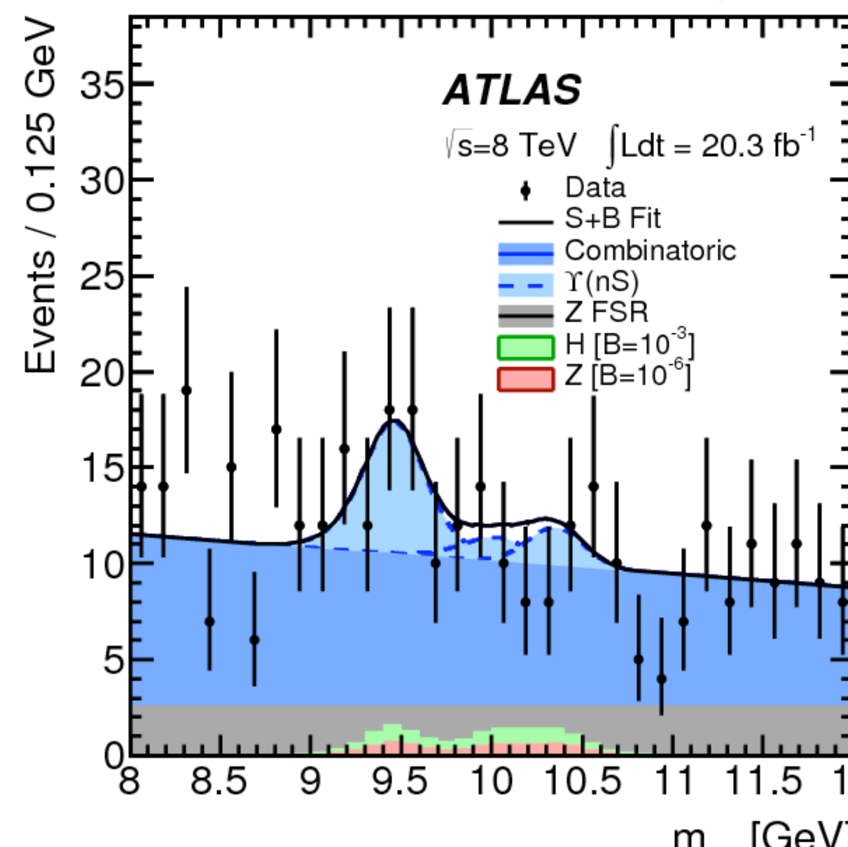


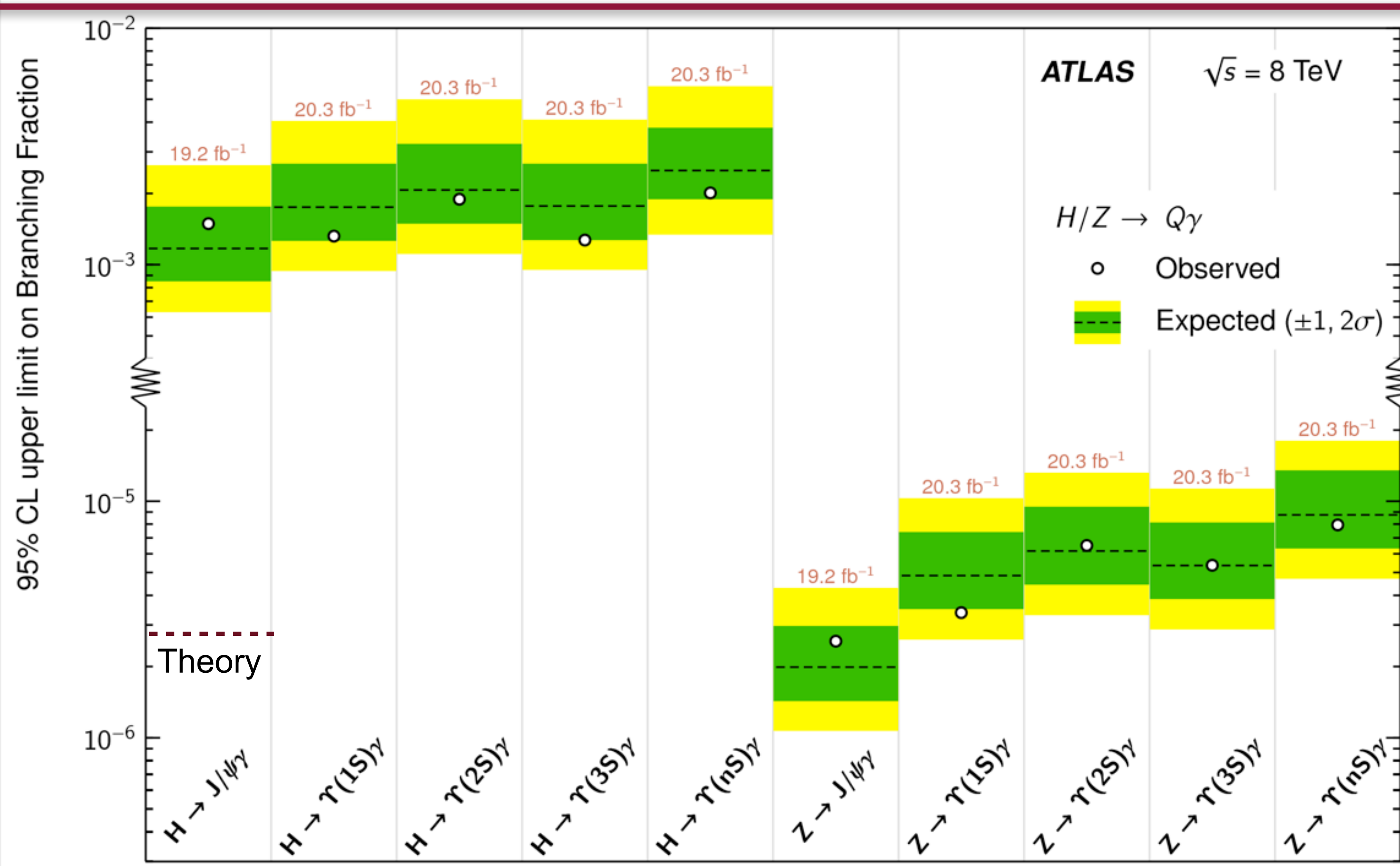








h/Z→J/ψγ and h/Z→Υ(nS)γ: Results



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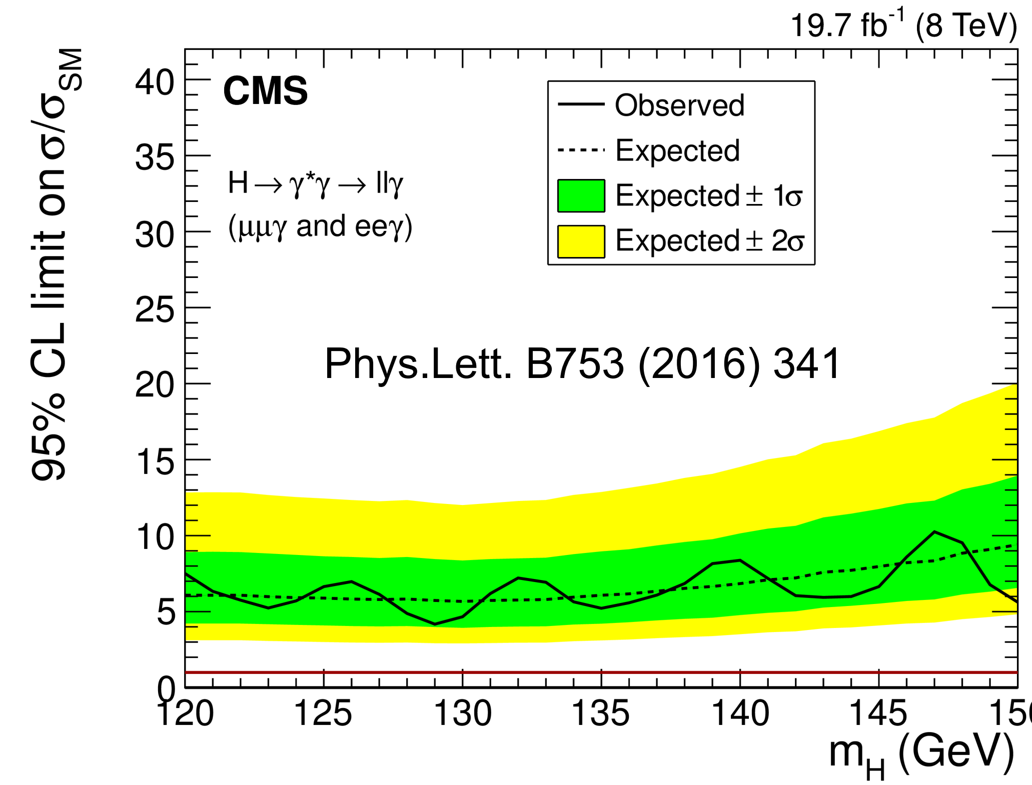
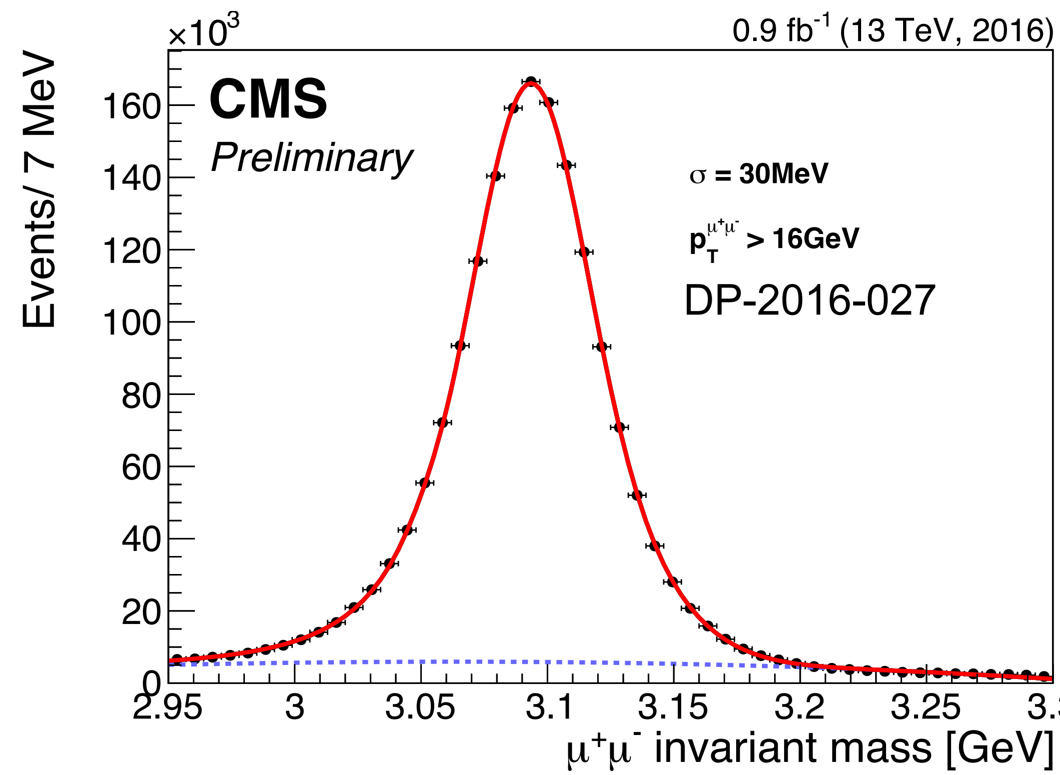
	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H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

- 95% CL upper limits on decay Branching Ratios:
  - $\mathcal{O}(10^{-3})$ for Higgs boson (SM production)
  - $\mathcal{O}(10^{-6})$ for Z boson
- ☑ **Indicate non-universal Higgs boson coupling to quarks** [Phys.Rev. D92 (2015) 033016, JHEP 1508 (2015) 012]

CMS $h \to J/\psi\gamma$

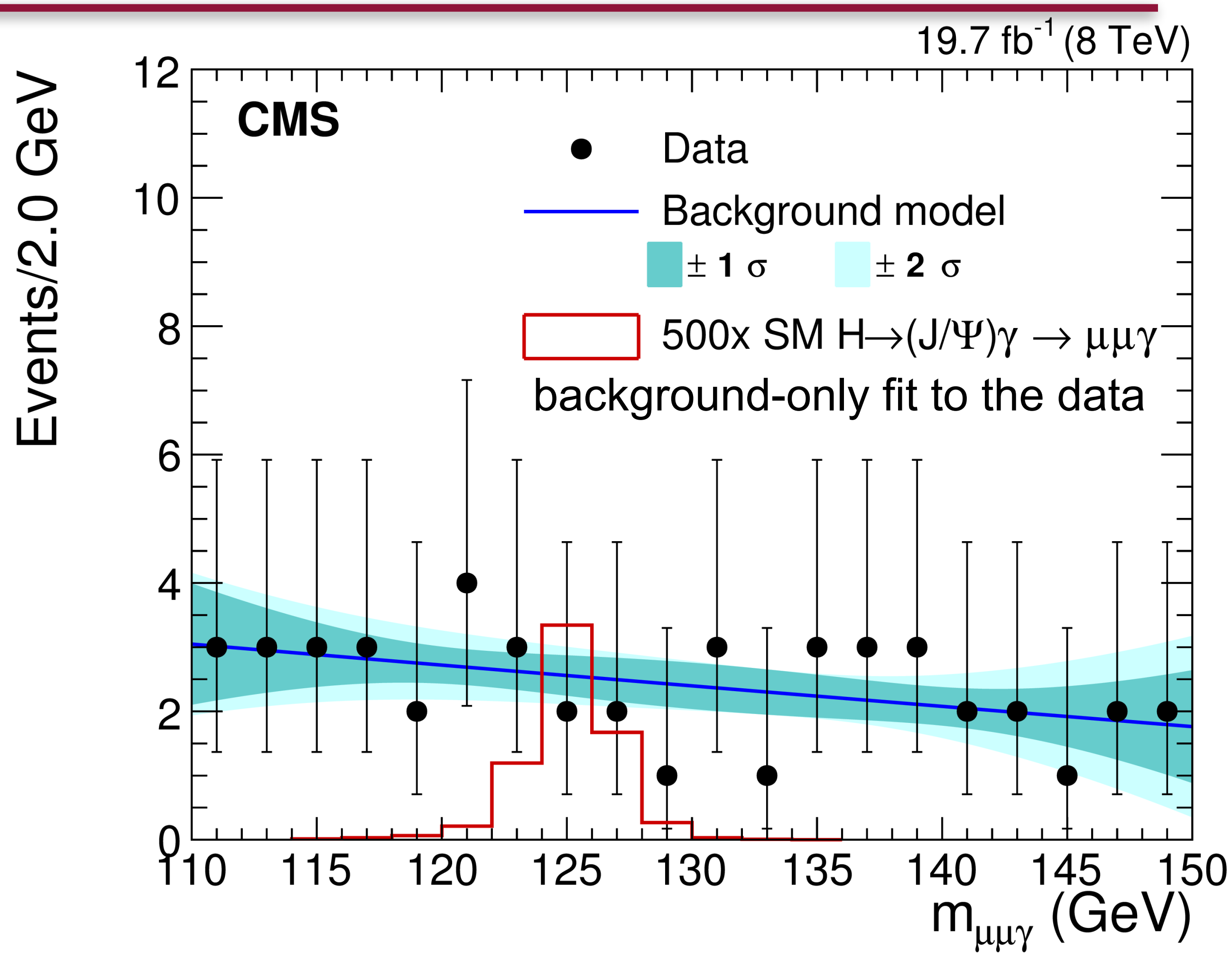
- **CMS search** for $h \to J/\psi\gamma$
  - extending the $h \to ll\gamma$ studies
  - used 19.7 fb^{-1} at 8 TeV
- **Event Selection**
  - single muon and a photon, both $p_T > 22$ GeV
  - $|\eta_\mu| < 2.4$, $p_{T\mu} > 23,4$ GeV, $p_{T\mu\mu} > 40$ GeV
  - $|\eta_\gamma| < 1.44$, $p_{T\gamma} > 40$ GeV
  - $\mu\mu$ and γ isolation,
  - $2.9 < m_{\mu\mu} < 3.3$ GeV
  - $\Delta R(\mu,\gamma) > 1$ for each muon
  - muon impact parameter requirements
    - transverse <2mm
    - longitudinal <5mm





CMS $h\to J/\psi\gamma$

Source	Uncertainty
Integrated luminosity (ref. [37])	2.6%
Theoretical uncertainties:	
PDF	2.6–7.5%
Scale	0.2–7.9%
$H \to \gamma^*\gamma \to \ell\ell\gamma$ branching fraction	10%
Experimental uncertainties:	
Pileup reweighting	0.8%
Trigger efficiency, μ (e) channel	4 (2)%
Muon reconstruction efficiency	11%
Electron reconstruction efficiency	3.5%
Photon reconstruction efficiency	0.6%
$m_{\ell\ell\gamma}$ scale, μ (e) channel	0.1 (0.5)%
$m_{\ell\ell\gamma}$ resolution, μ (e) channel	10 (10)%



- Fit over the 110-150 GeV mass range.
  - Background: 2nd degree polynomial
  - Signal: Crystal Ball + Gaussian
- **No excess** above background observed
- 95% CL upper limit BR($H\to J/\psi\gamma$) < 1.5×10^{-3} → 540 times the SM prediction

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Sample	Signal events before selection $m_H = 125$ GeV	Signal events after selection $m_H = 125$ GeV	Number of events in data $120 < m_{\ell\ell\gamma} < 130$ GeV
$\mu\mu\gamma$	13.9	3.3	151
eeγ	25.8	1.9	65
$(J/\psi \to \mu\mu)\gamma$	$0.065(J/\psi) + 0.32$ (non-res.)	$0.014(J/\psi) + 0.078$ (non-res.)	12

Search for h/Z→φγ

- ☑ **New ATLAS analysis** based on 2.7 fb^{-1} at 13 TeV collected in 2015
- ☑ **Higgs decay h→φγ sensitive to strange quark Yukawa coupling**
  - probing light quark Yukawa coupling was **considered impossible** at the LHC
  - very challenging to access with inclusive H→ss decays!
- ☑ **Looking for new physics** through anomalous H→ss couplings
  - possible in various BSM scenarios, would modify BR(h→φγ)
- Z→φγ not directly constrained by existing measurements

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Supplementary Information: http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-05/

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

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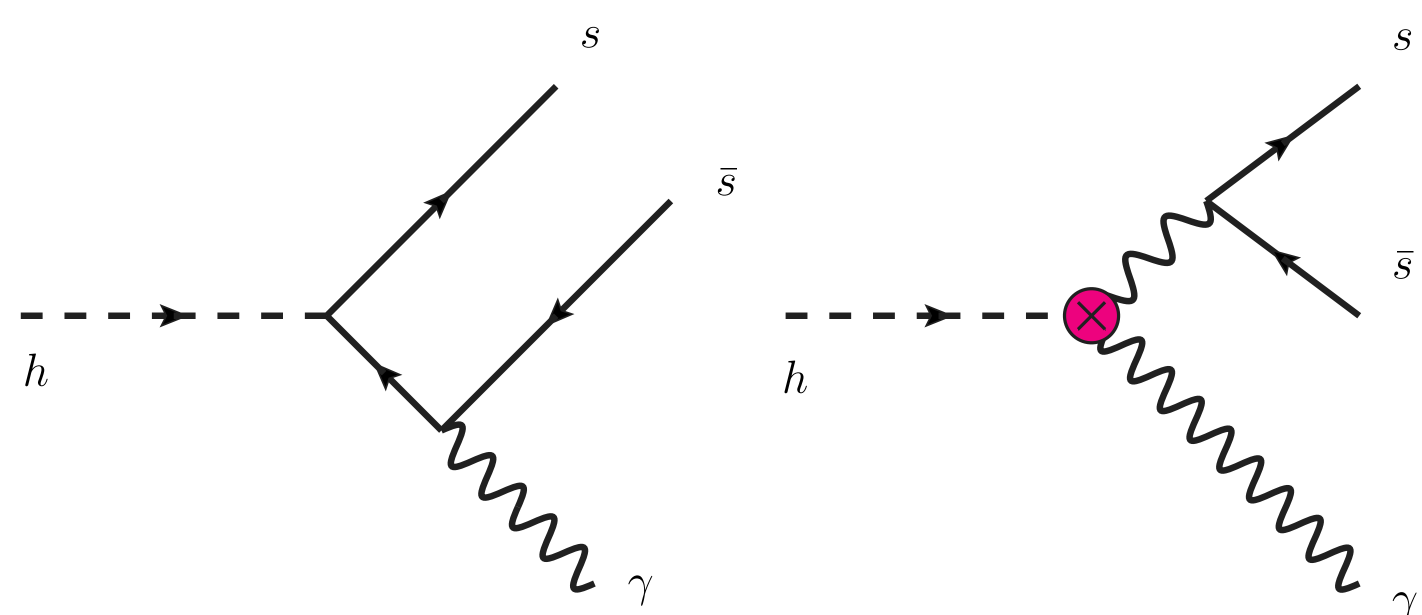
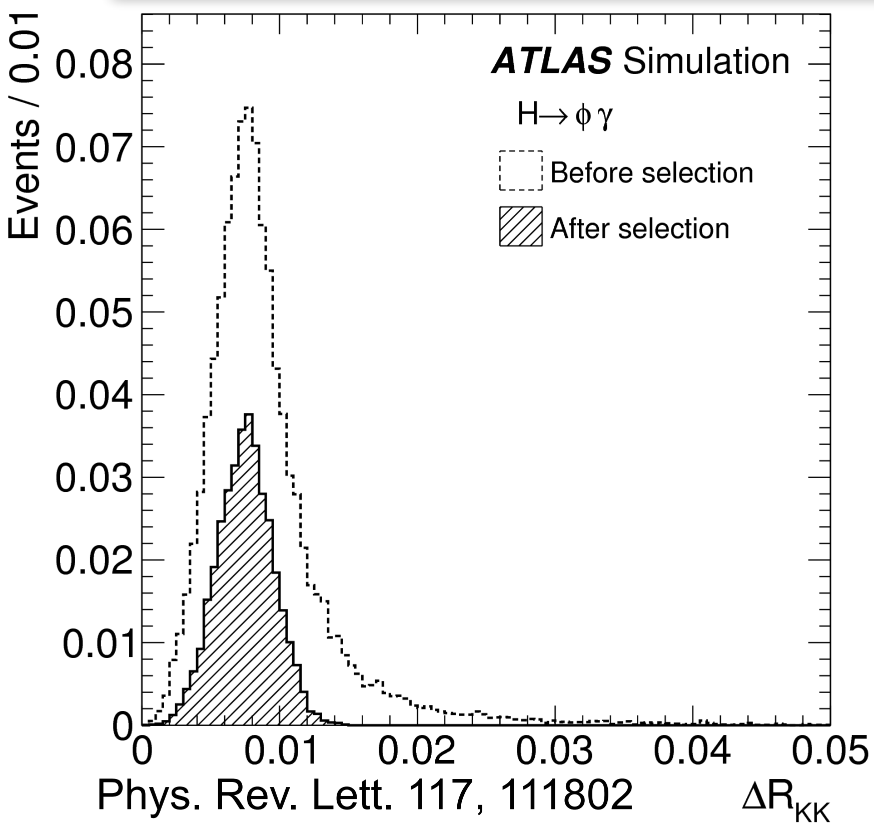


$$BR(h \to \phi\gamma) = (2.31 \pm 0.03_{f_\phi} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}$$

JHEP 1508 (2015) 012

h/Z→φγ: Analysis Strategy



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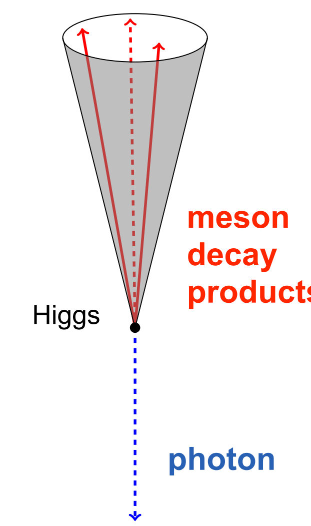
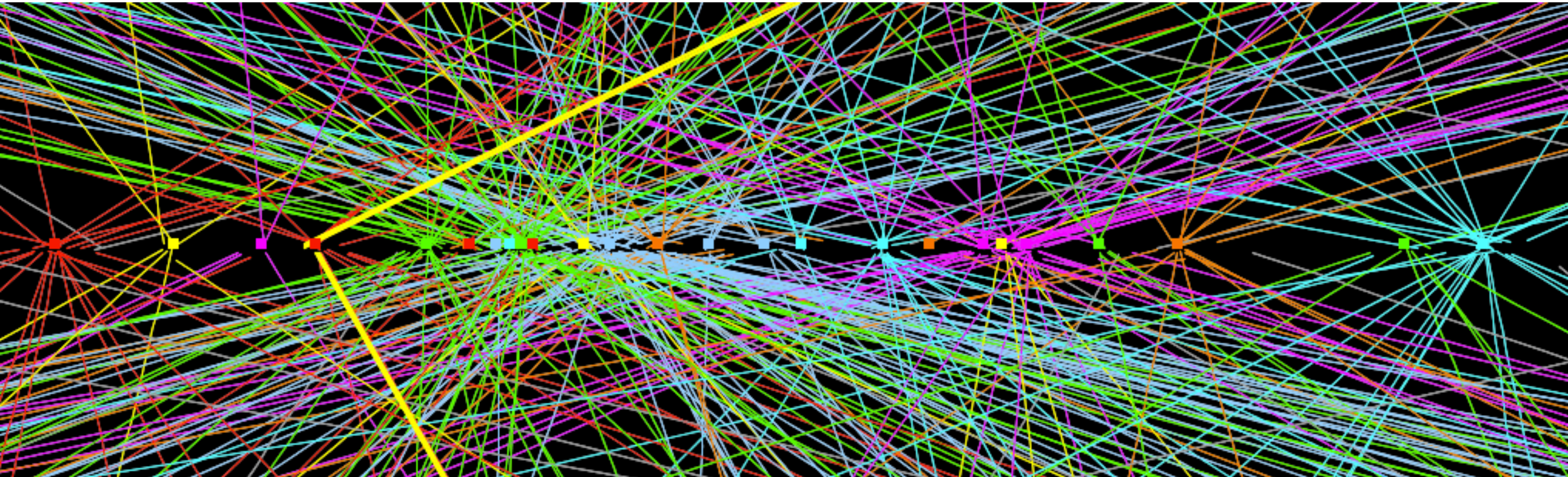
- **Exploit $\varphi \to K^+K^-$ decays**, BR=49%
- **Distinctive topology**
  - Pair of collimated high-pT isolated tracks recoils against high-pT isolated photon
- **Enabled by dedicated trigger** (Sep 2015)
  - Photon ($p_{T\gamma}$>35 GeV) and isolated di-track (at least one p_T>15 GeV) consistent with m_φ
  - Efficiency ~80% w.r.t offline selection





Z→μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown

h/Z→φγ: Event Selection

Tracks

- No particle-ID available at momentum range, all tracks considered Kaons
- looking for two opposite charged tracks; leading pT>20GeV, sub-leading pT>15 GeV
- di-track consistent with φ-meson mass within 20 MeV
- track-based isolation applied
- di-track system must satisfy:

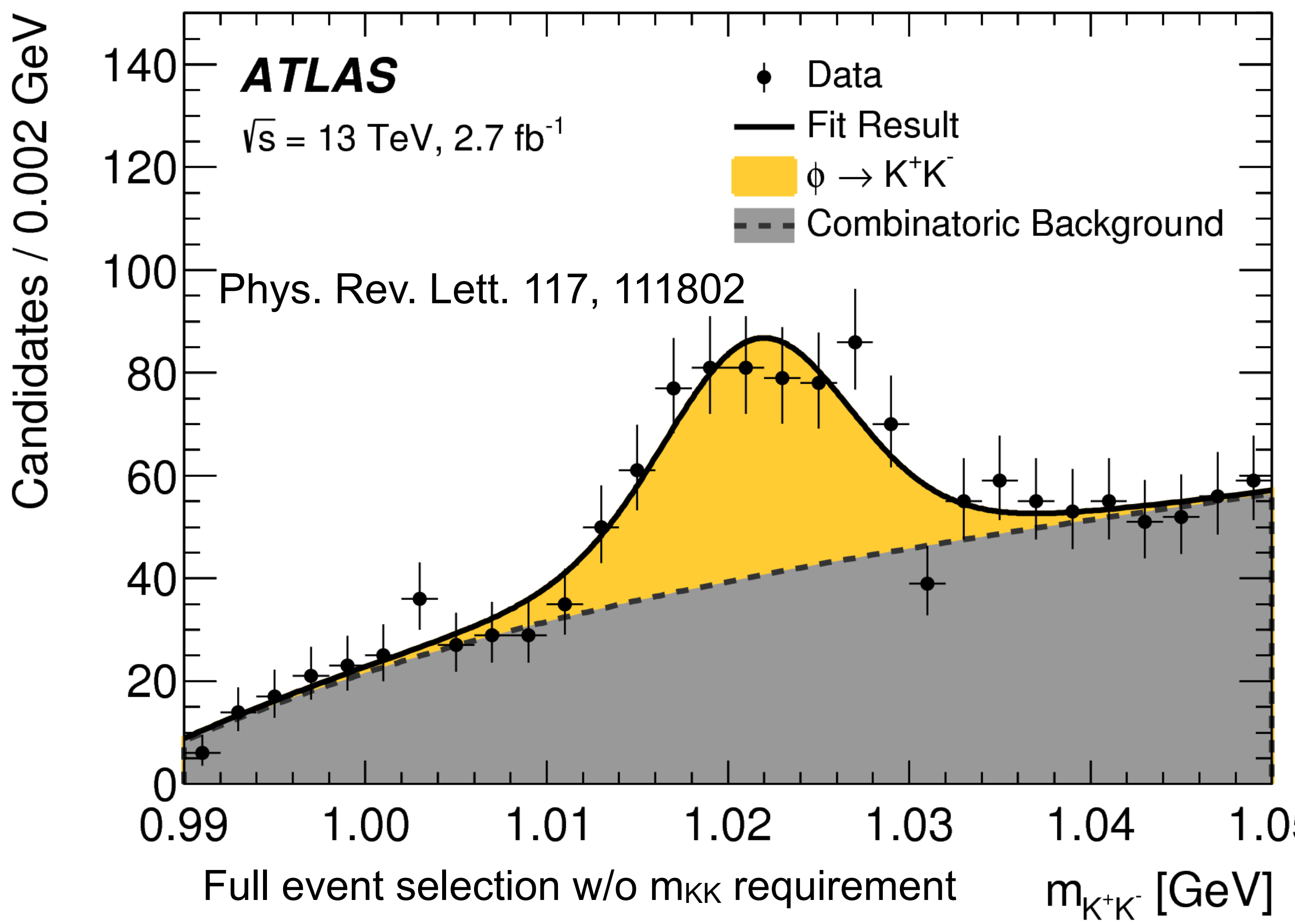
$$p_T^{KK} > \begin{cases} 40\ \text{GeV}, & \text{for } m_{KK\gamma} \leq 91\ \text{GeV} \\ 40 + 5/34 \times (m_{KK\gamma} - 91)\ \text{GeV}, & \text{for } 91\ \text{GeV} < m_{KK\gamma} < 125\ \text{GeV} \\ 45\ \text{GeV}, & \text{for } m_{KK\gamma} \geq 125\ \text{GeV} \end{cases}$$

Photons

- "Tight" identification criteria
- pT_γ>35 GeV
- $|\eta_\gamma|$<2.47 and not in 1.37<$|\eta_\gamma|$<1.52
- Isolated (calorimeter- and track-based)
- $\Delta\varphi(K^+K^-,\gamma)$>0.5

Total signal acceptance/efficiency

- h→φγ→KKγ ~ 18%
- Z→φγ→KKγ ~ 8%



Full event selection w/o mKK requirement

h/Z→φγ: Efficiency and Resolution

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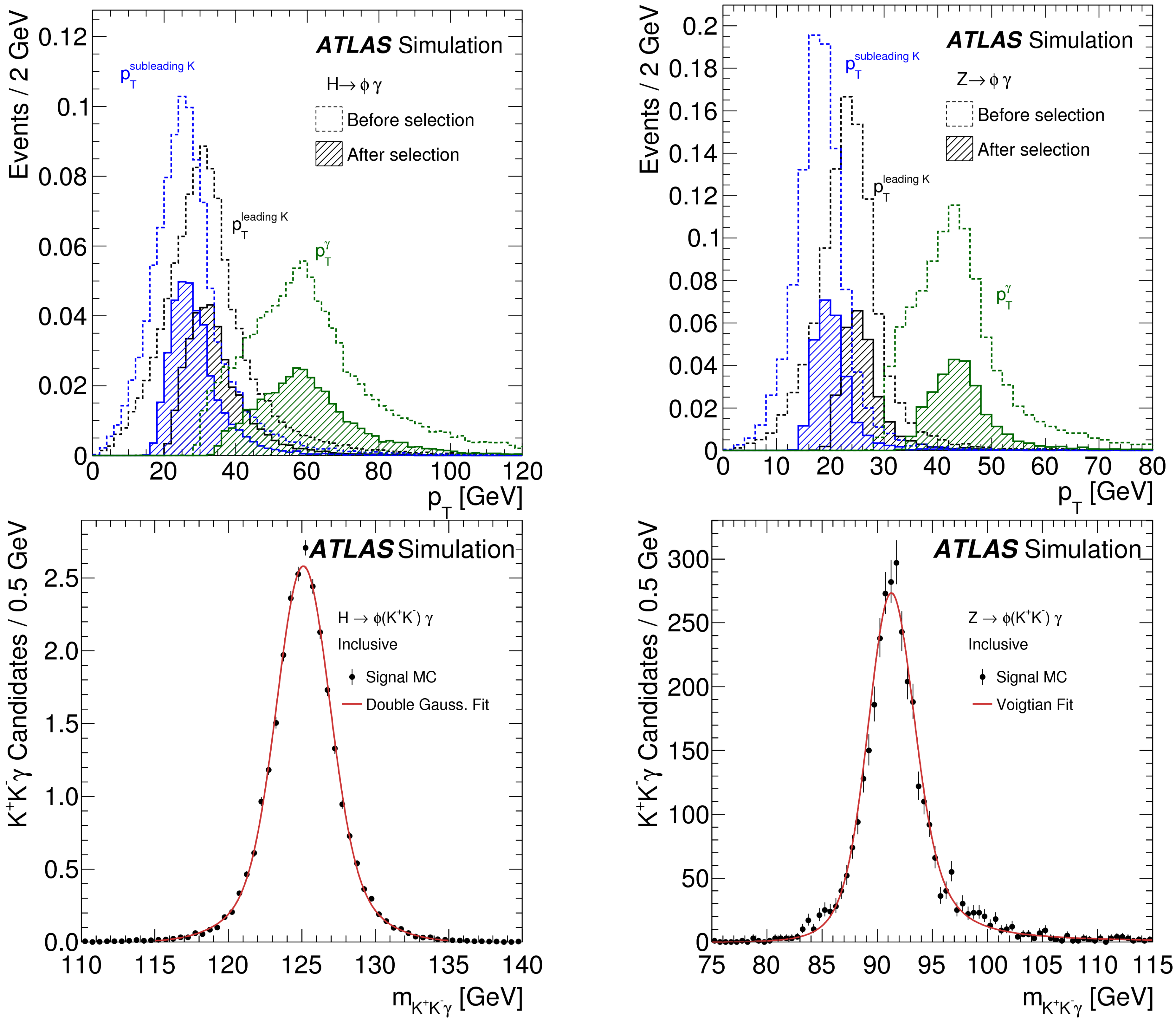
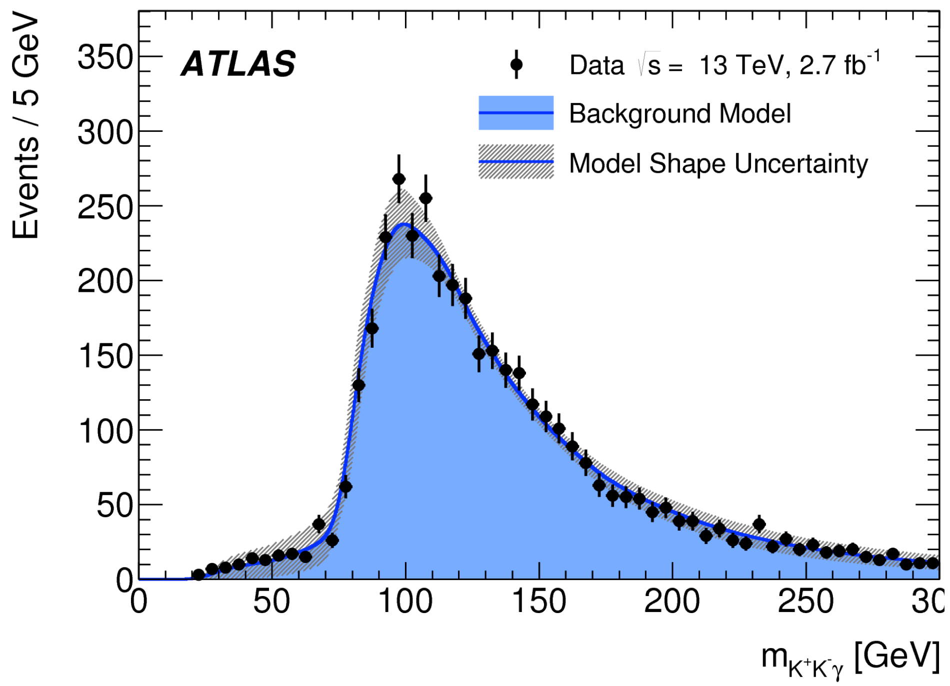


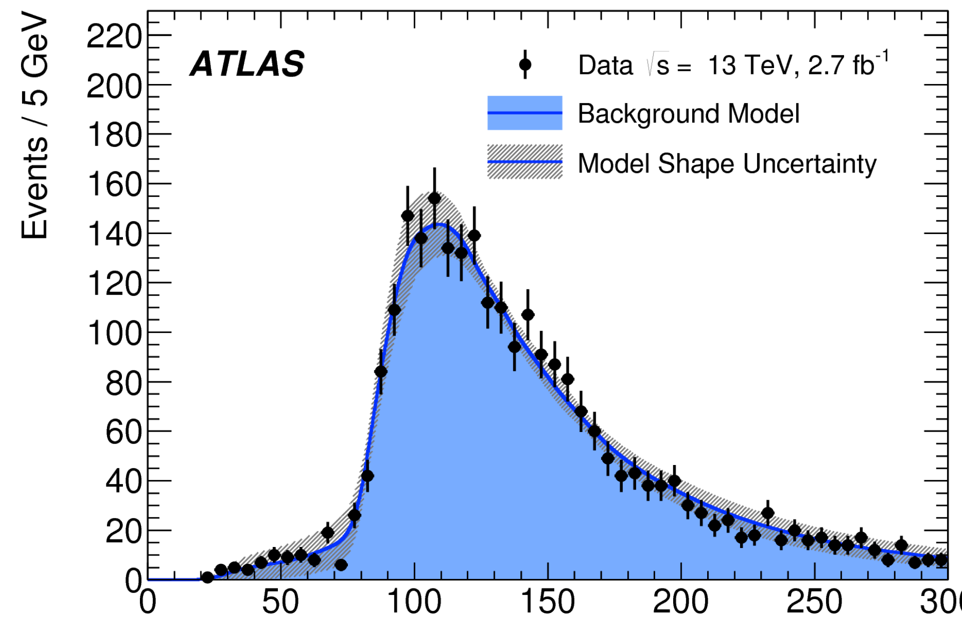
- **Inclusive analysis**
- **Total signal efficiency:**
  - 18% for Higgs boson
  - 8% for Z boson Muon
- **Mass resolution ~1.8%**

h/Z→φγ: Background

- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. h/Z→μμγ_{FSR}) **estimated to be negligible**
- **Nonparametric data-driven model;** same procedure as in h/Z→J/ψγ

Background Region (loose selection)





loose selection +P_{TKK}>45 GeV

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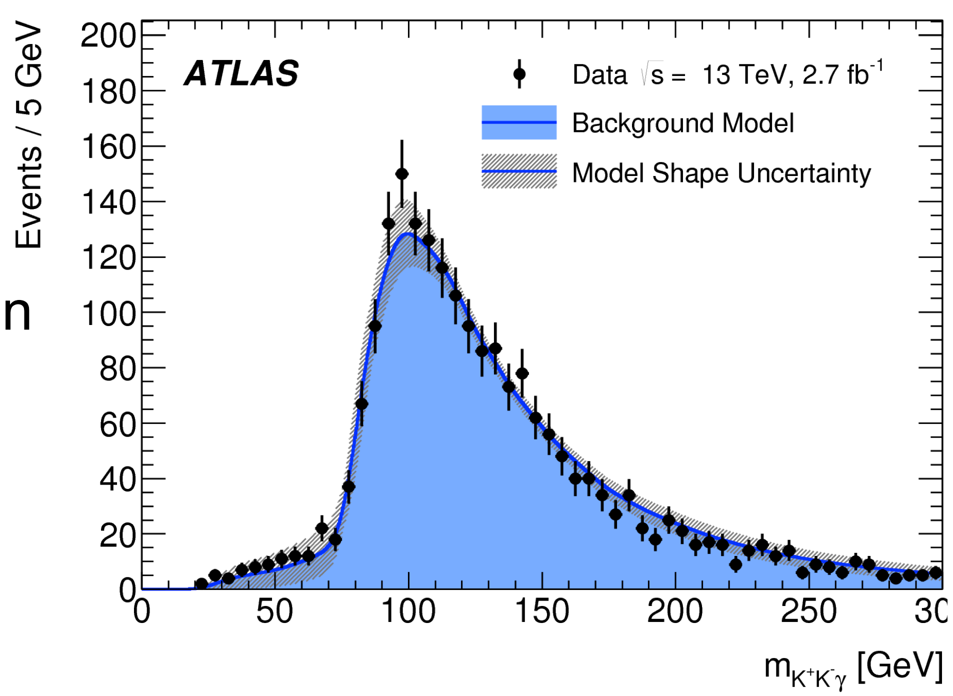
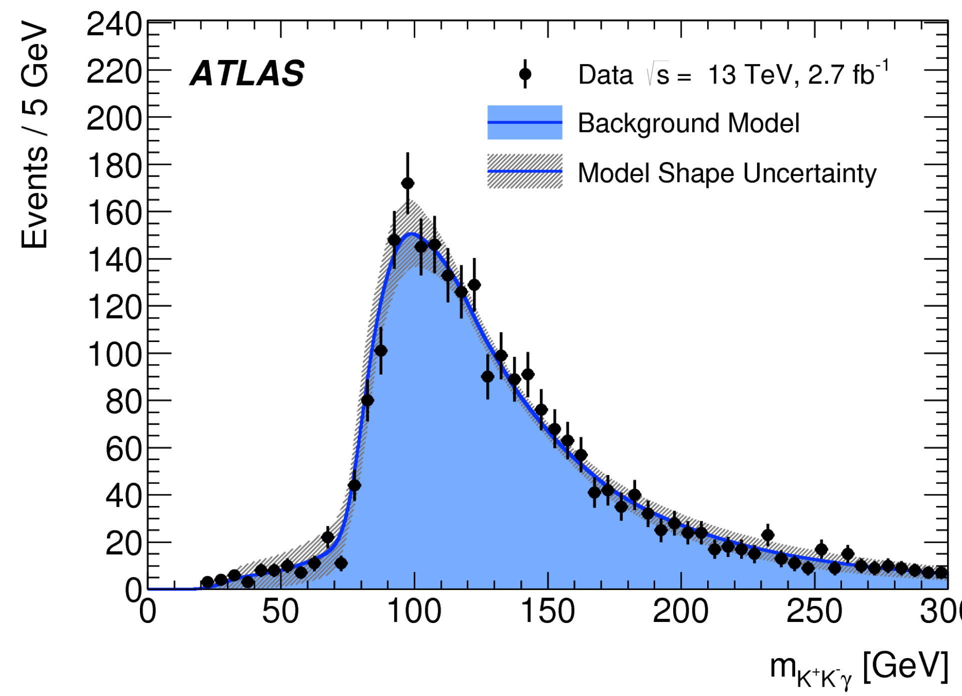
loose selection +γ-isolation





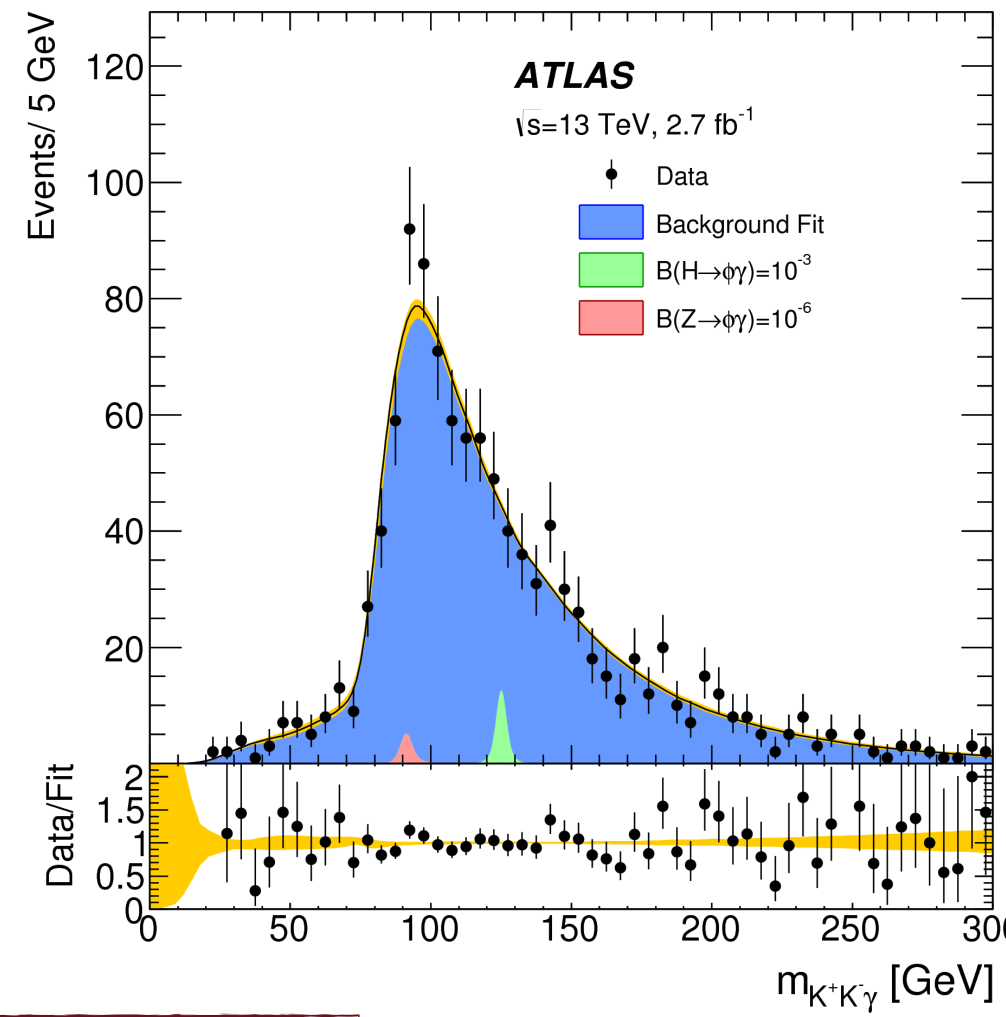
loose selection +KK-isolation

h/Z→φγ: Results

Source	H/Z Yield Uncertainty	Estimated From
Total H cross section	12%	QCD scale variation and PDF uncertainties
Total Z cross section	5.5%	ATLAS Measurement
Integrated Luminosity	5%	Calibration observable and vdM scan uncertainties
Photon ID Efficiency	2.5%	Data driven techniques with $Z \to \ell^+\ell^-$ and $Z \to \ell^+\ell^-\gamma$
Photon Energy Scale	0.3%	
Trigger Efficiency	2%	
Tracking Efficiency	6%	Tracking studies within dense jets

Observed (Expected) Background			Expected Signal	
Mass Range [GeV]			Z	H
All	81–101	120–130	$\mathcal{B}[10^{-6}]$	$\mathcal{B}[10^{-3}]$
1065	288 (266 ± 9)	89 (87 ± 3)	6.7 ± 0.7	13.5 ± 1.5

- **Final discriminant** is $m_{KK\gamma}$
- 95% confidence level **upper limit** using CLs with profile likelihood test statistic
- **Largest observed excess** at ~100GeV; 2σ effect
- **No significant H or Z signal observed,** Branching ratio limits at the level of 10^{-3} (10^{-6}) for Higgs (Z) boson decays



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

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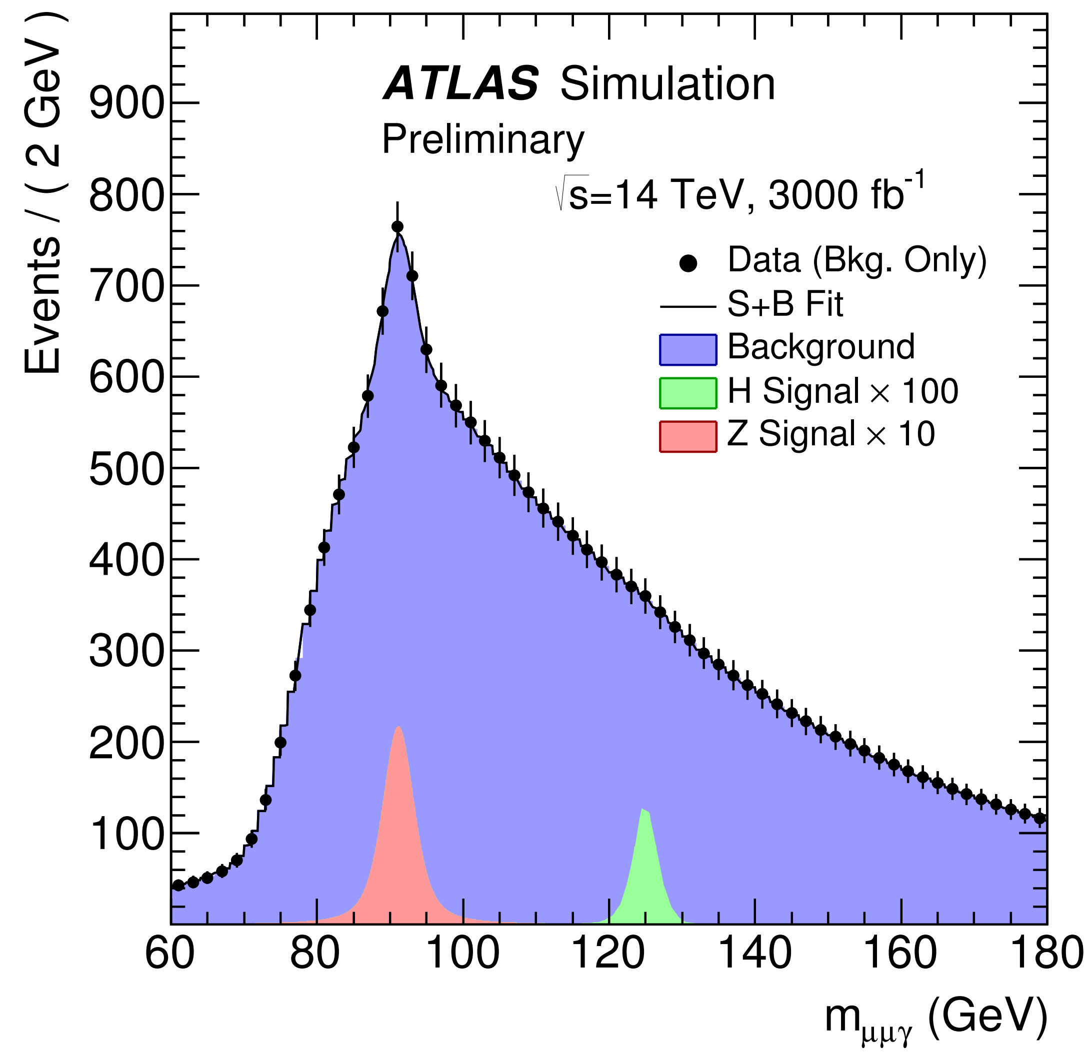
h/Z→Qγ: in the future

- ☑ HL-LHC is a Higgs boson factory
  - $\mathcal{O}$(200M) Higgs bosons
- ☑ ATLAS HL-LHC projections for h/Z→J/ψγ
  - ☑ Nice and, relatively, clean final state
  - ☐ Small branching ratio, few events expected
  - ☐ At SM sensitivity large contribution from $h \to \mu\mu\gamma_{FSR} \sim 3 \times h \to J/\psi\gamma$ and ($Z \to \mu\mu\gamma_{FSR}$ for Z)
  - ☐ Sensitive to "anomalous" h→γγ loop; use ratio to h→γγ

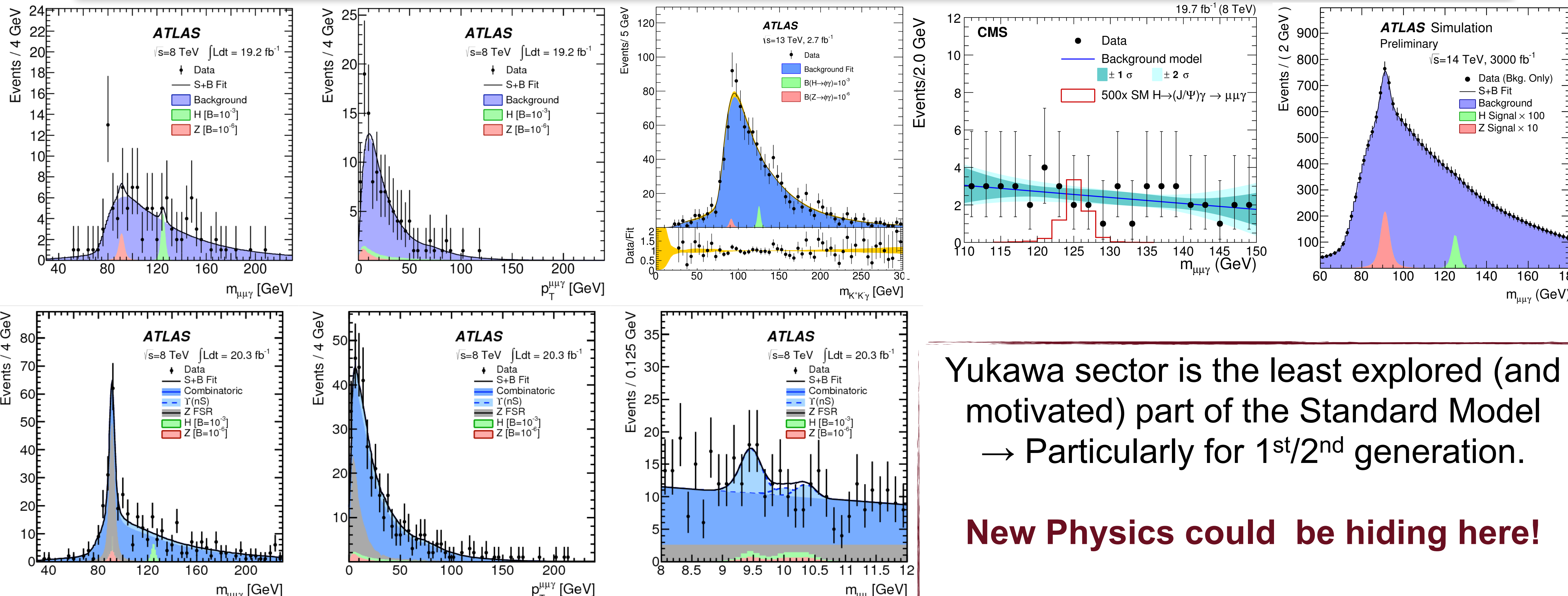
ATLAS-PHYS-PUB-2015-043

	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}	$4.4^{+1.9}_{-1.1}$

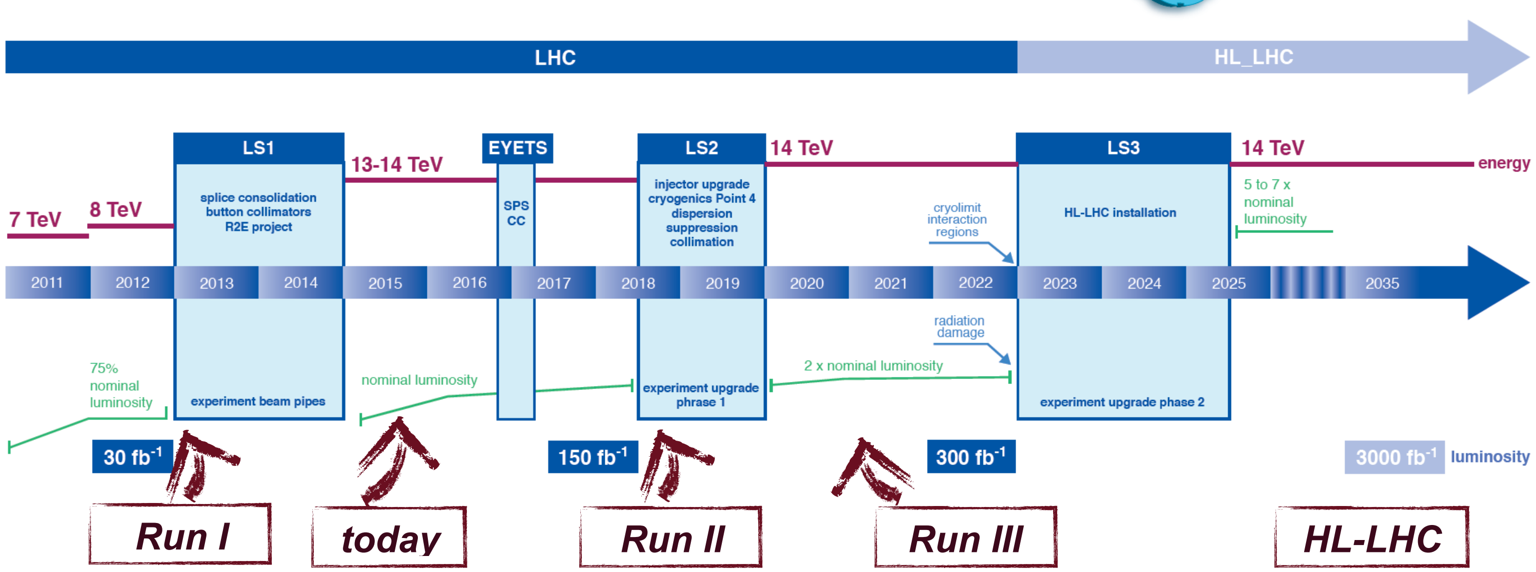
	Standard Model expectation	
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$	$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	2.9 ± 0.2	0.80 ± 0.05



Summary



LHC / HL-LHC Plan



Yukawa sector is the least explored (and motivated) part of the Standard Model → Particularly for 1st/2nd generation.

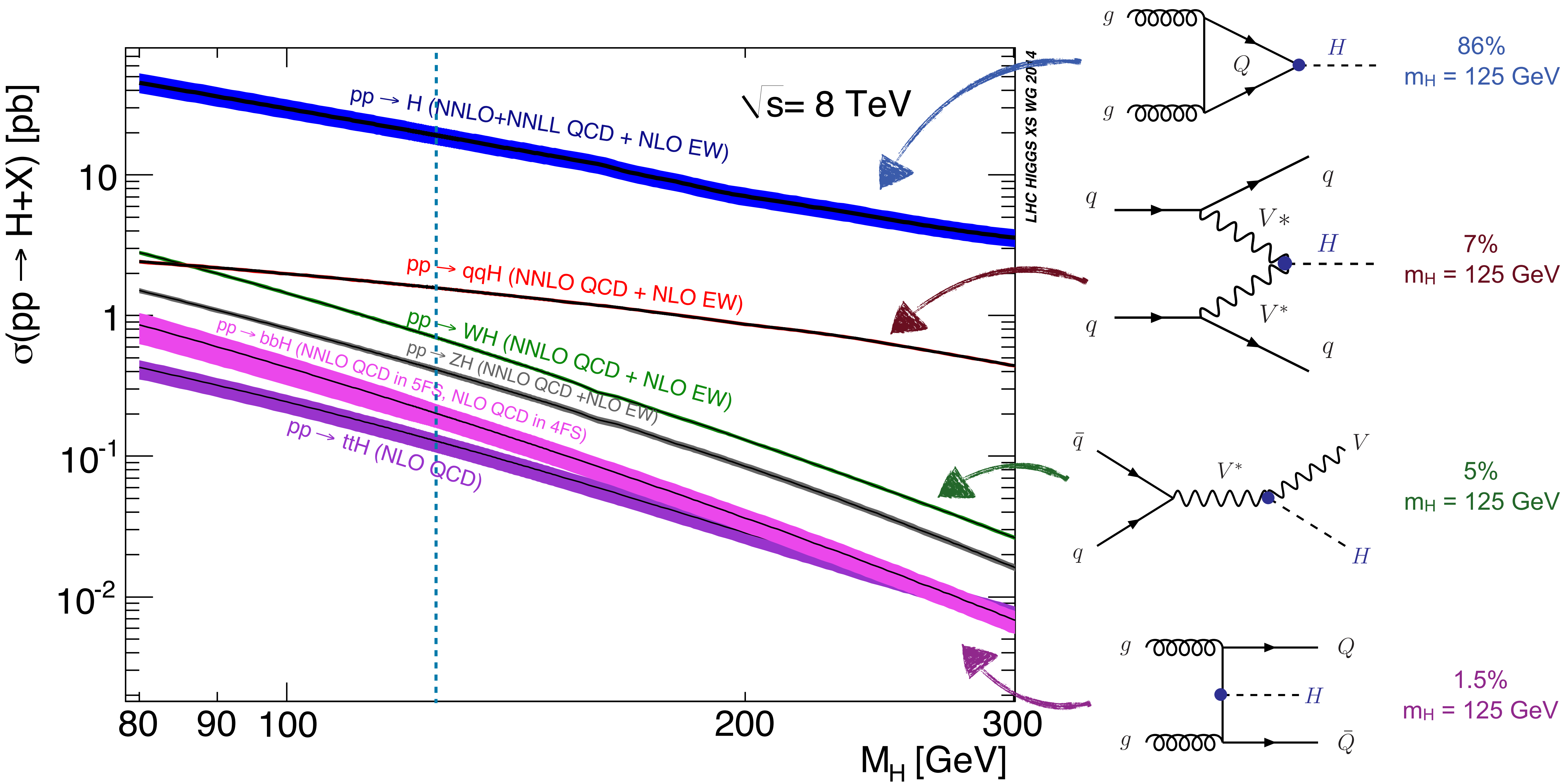
New Physics could be hiding here!

A number of suggestions appearing in literature currently: exclusive decays, charm tagging, Higgs boson kinematic properties, etc.

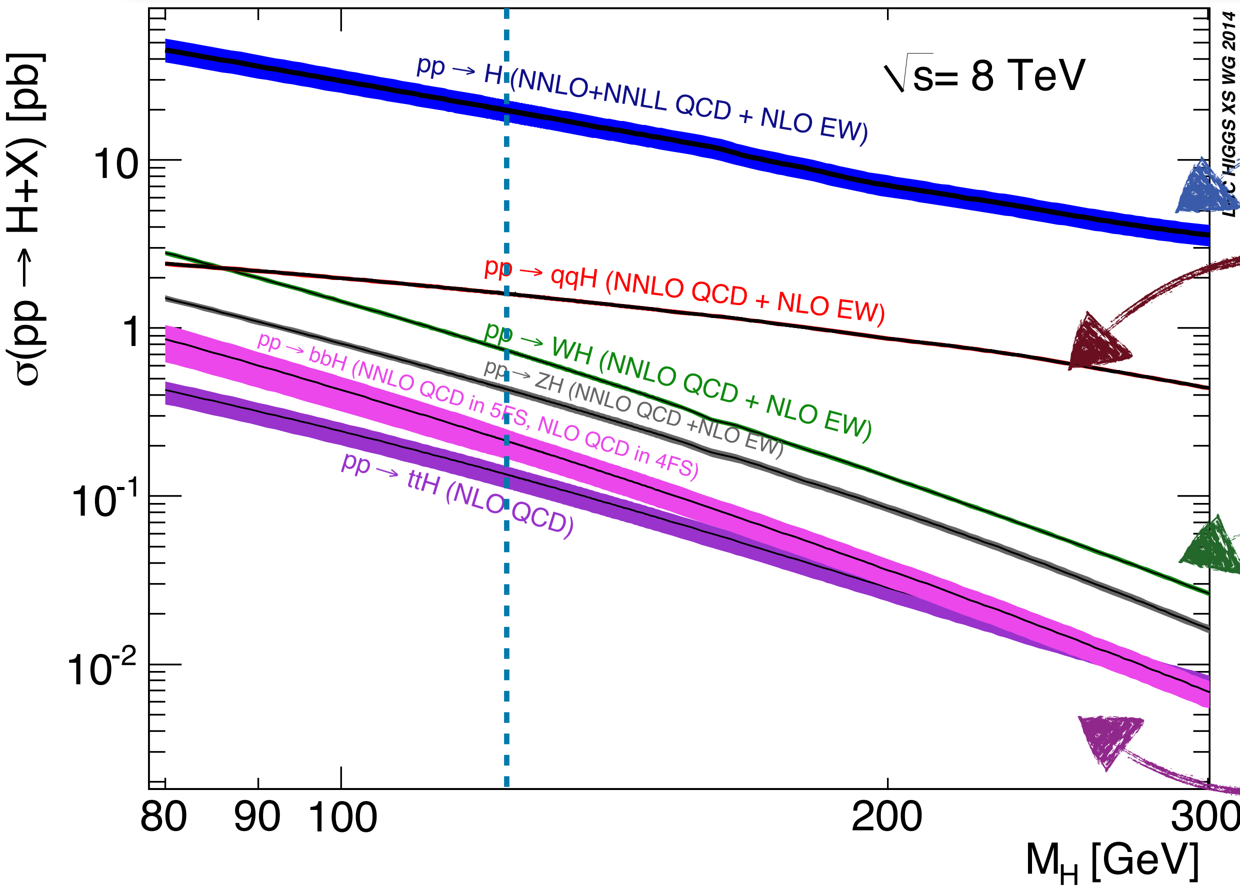
New field of study in Higgs sector; experimental and theoretical ingenuity required to elucidate this corner of the SM!

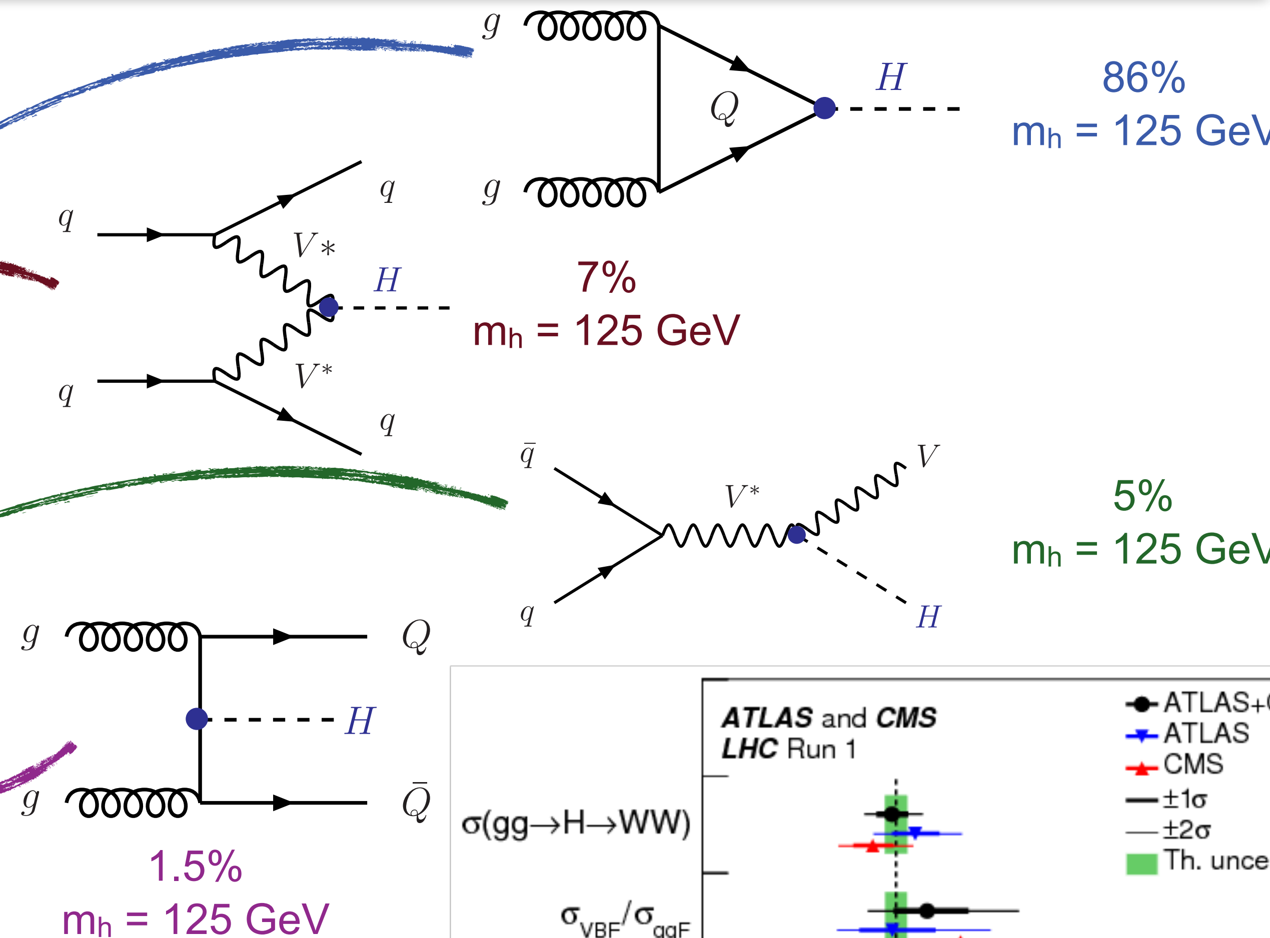
Additional Slides

SM Higgs boson production at the LHC



Higgs boson at the LHC





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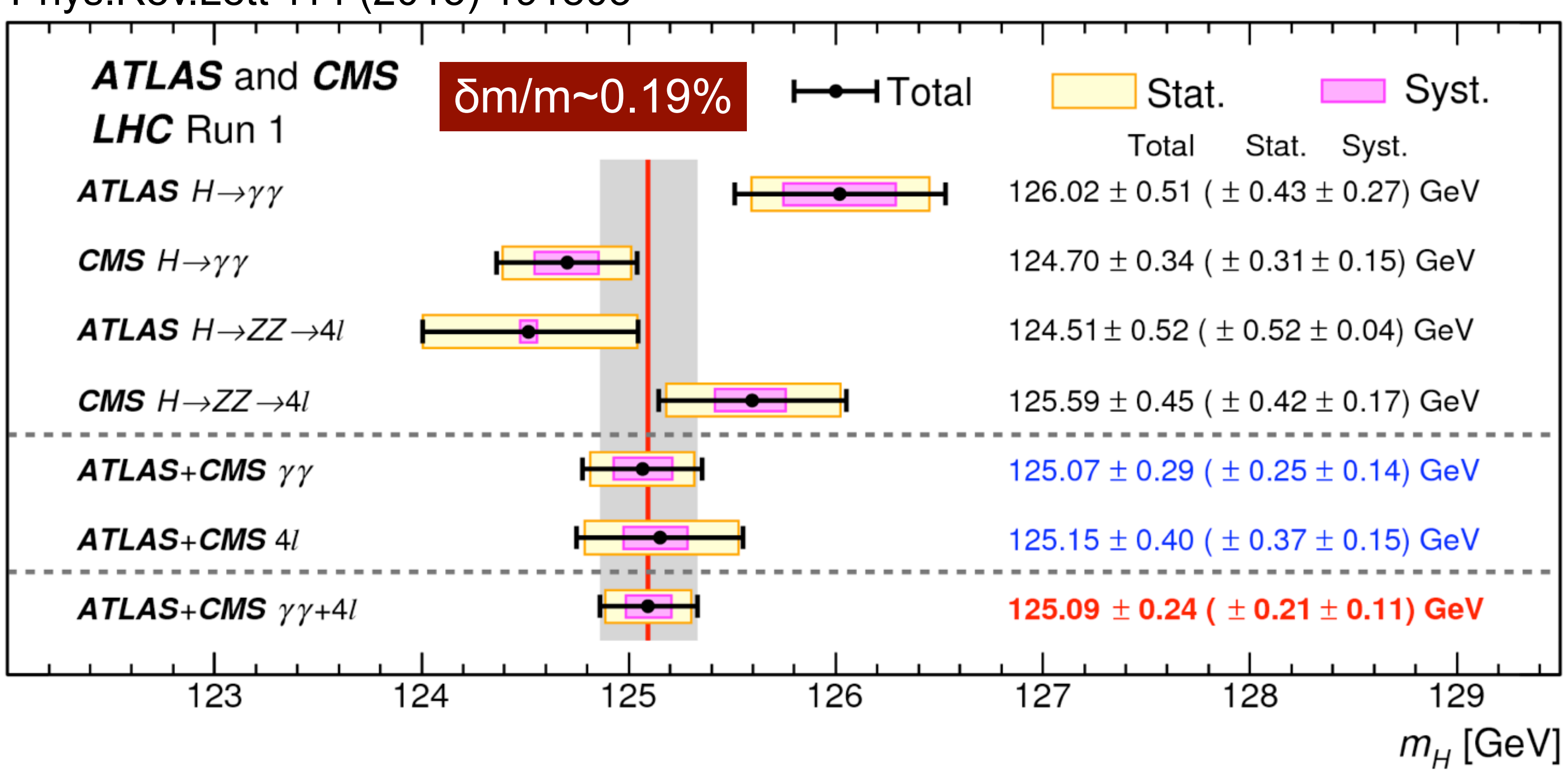
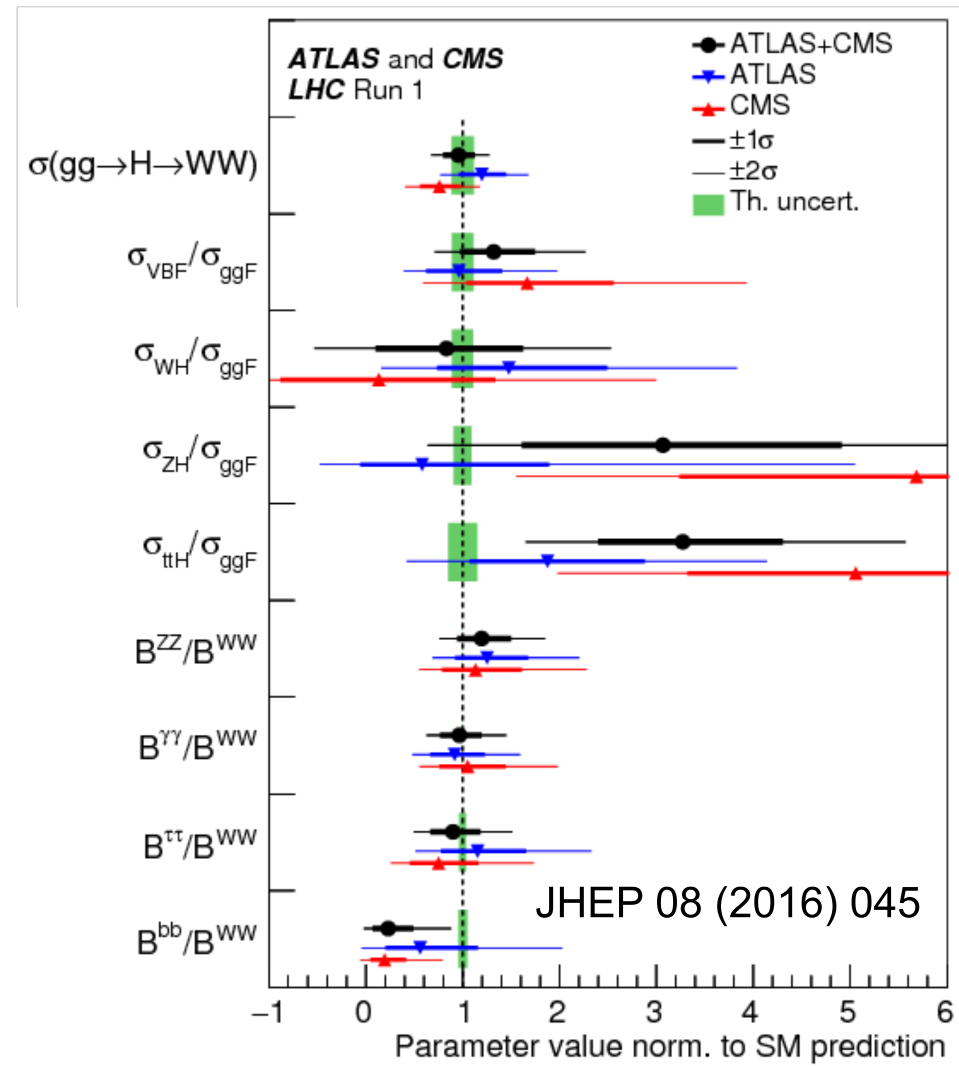
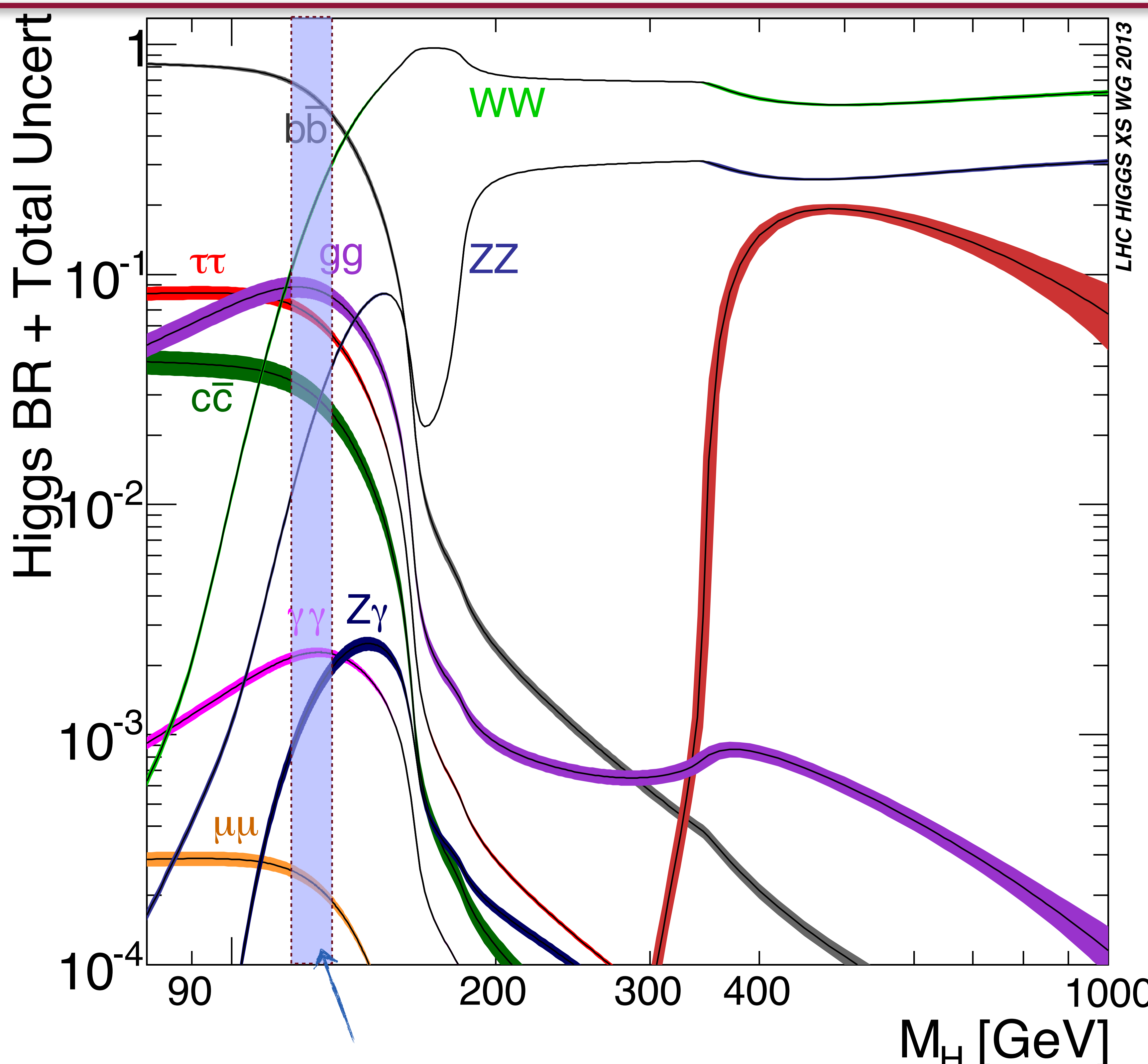




SM Higgs boson decays



m_H~125 GeV gives access to several decay channels

Gauge bosons: γγ, ZZ*, WW*, Zγ

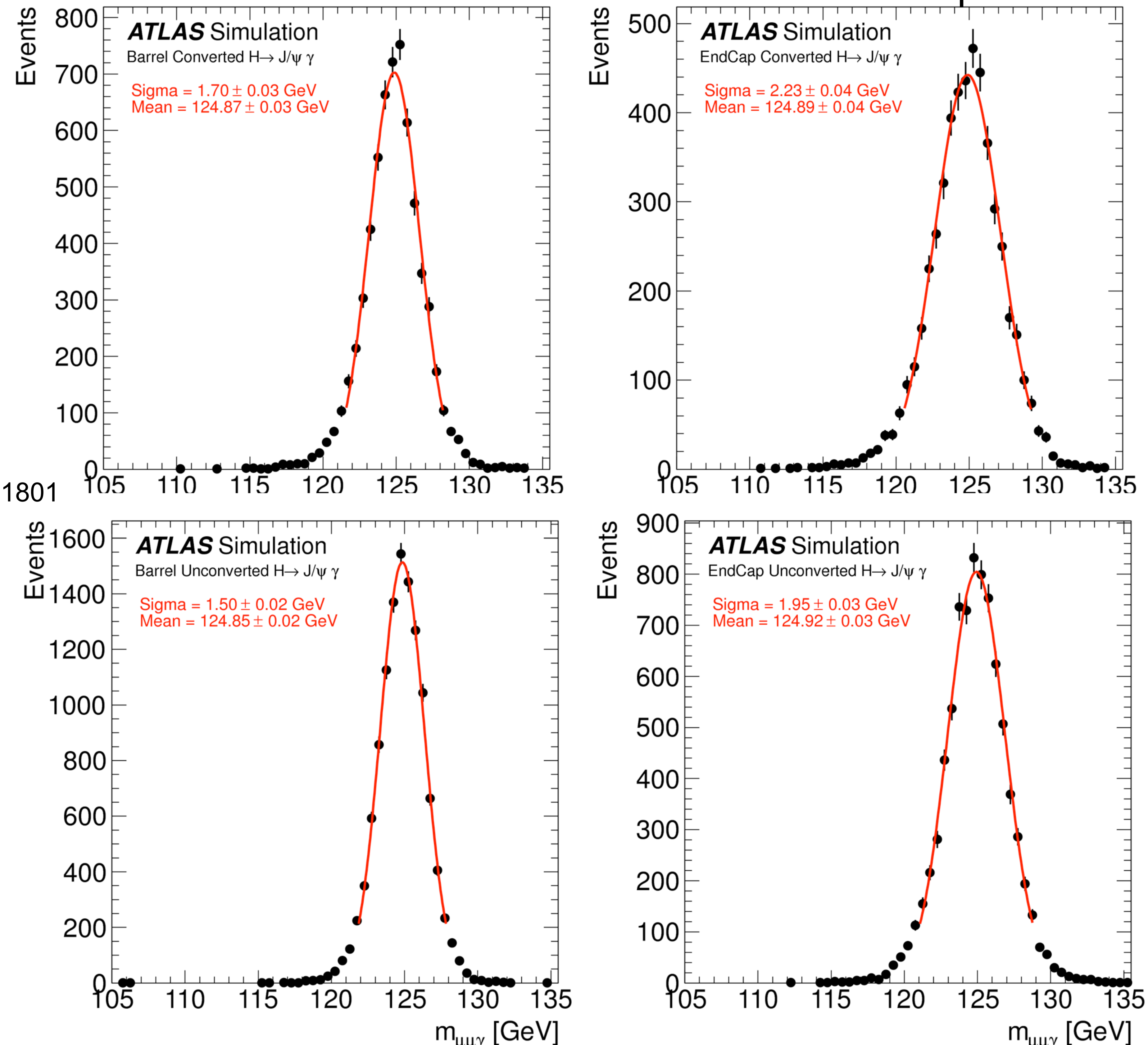
Fermions: bb, ττ, μμ

h/Z→J/ψγ and h/Z→Υ(nS)γ: Mass Resolution

barrel | endcap

converted photon

unconverted photon



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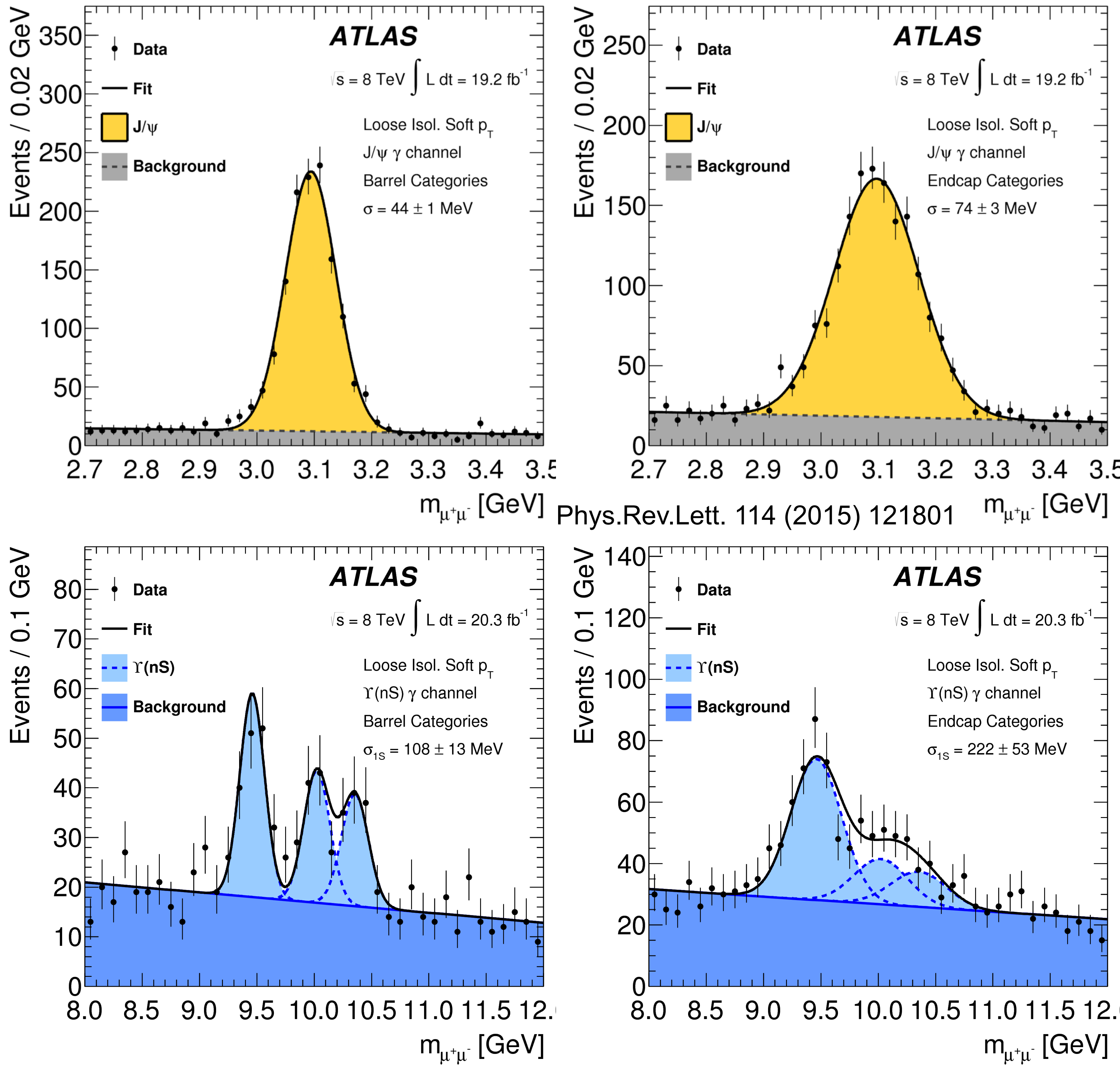
mass resolution ~1.2-1.8%

h/Z→J/ψγ and h/Z→Υ(nS)γ: Mass Resolution



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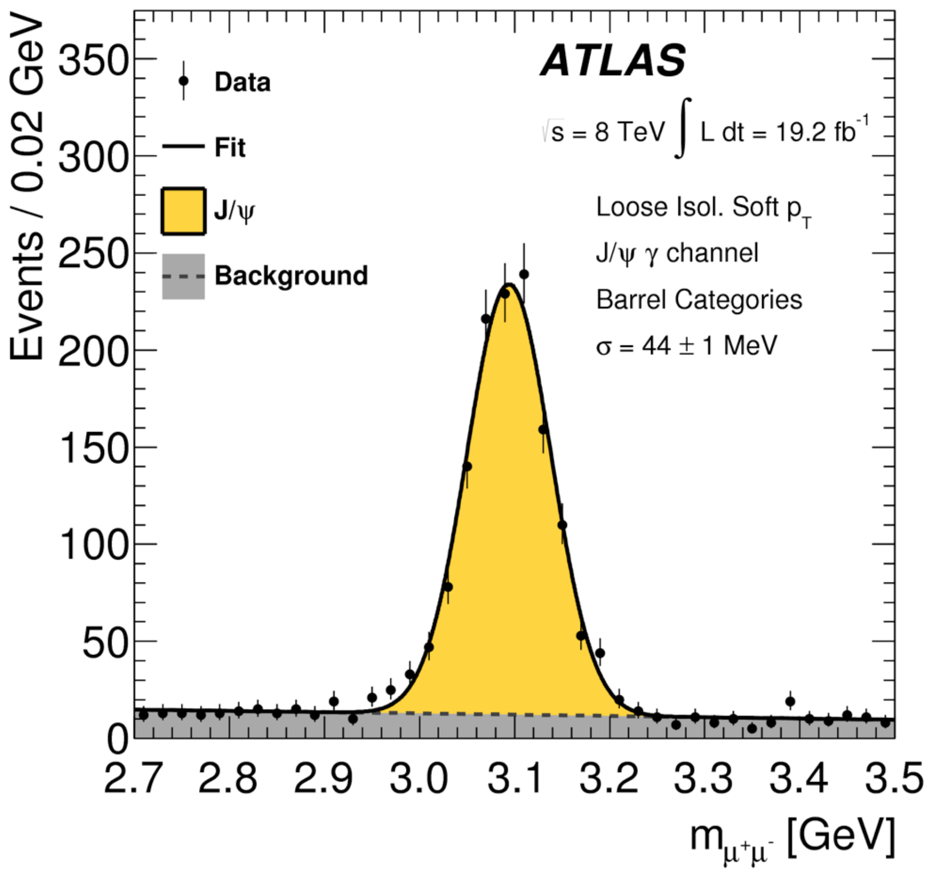
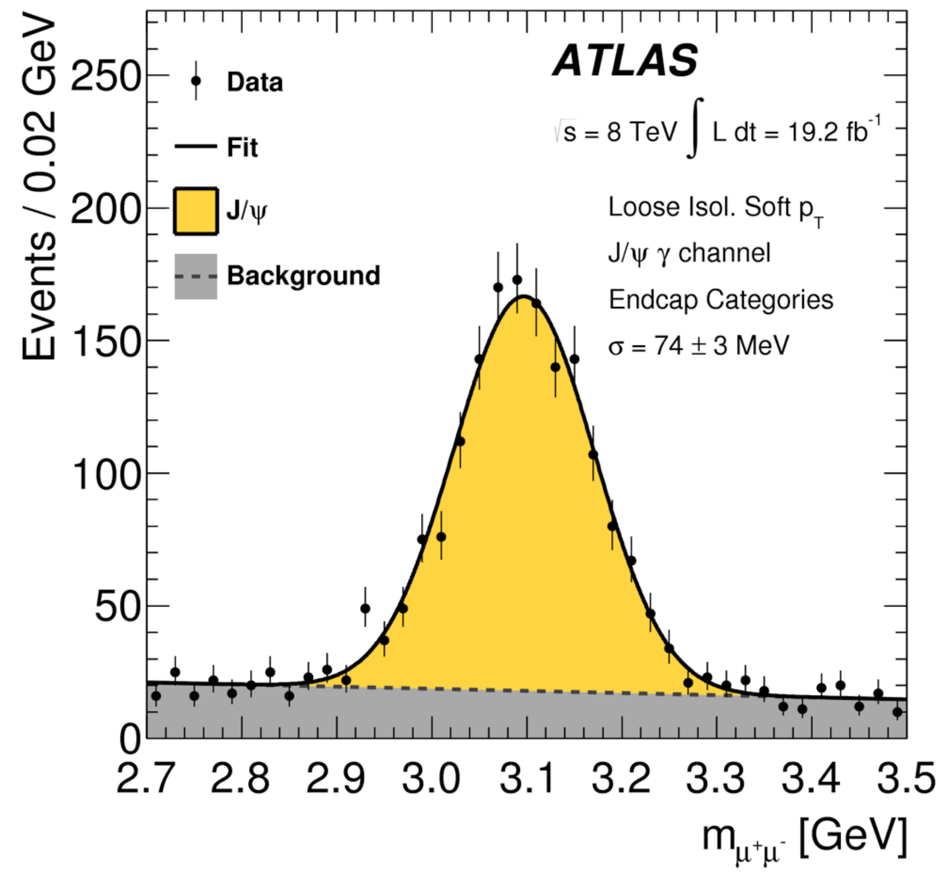
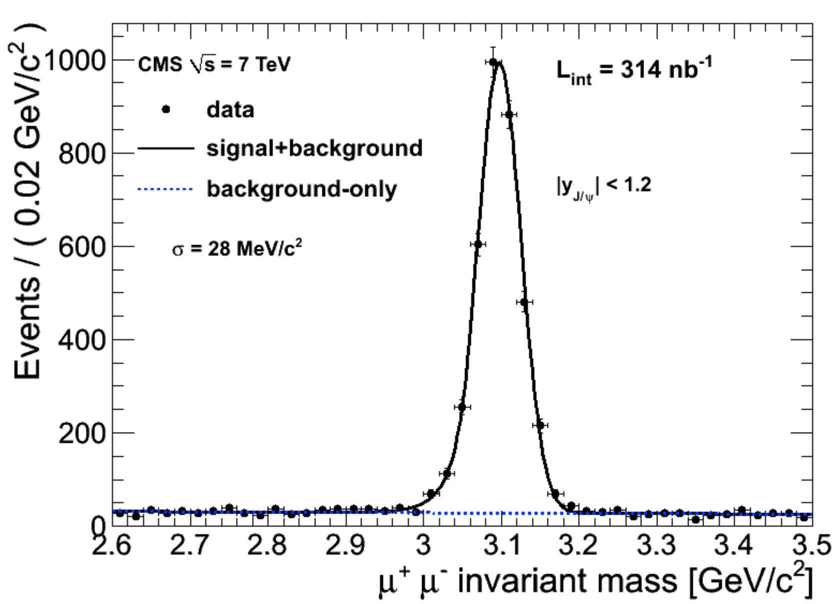
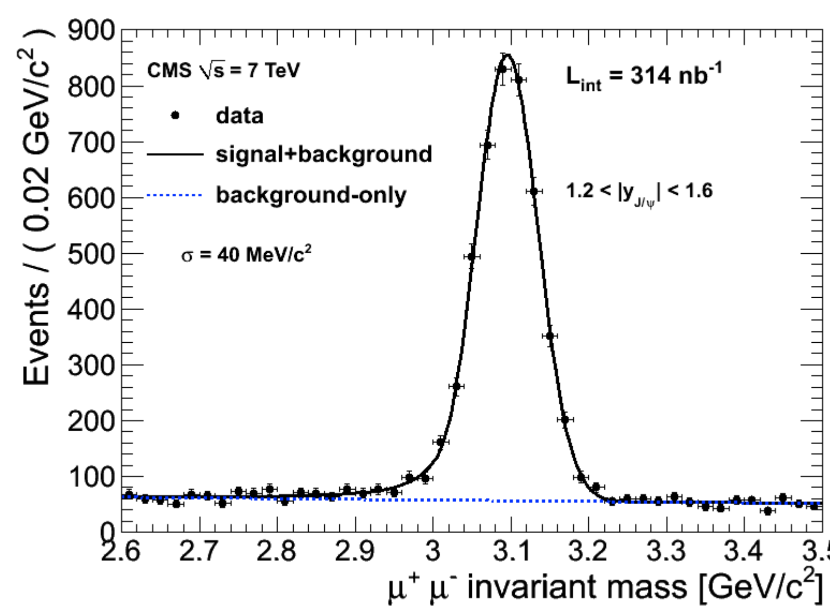
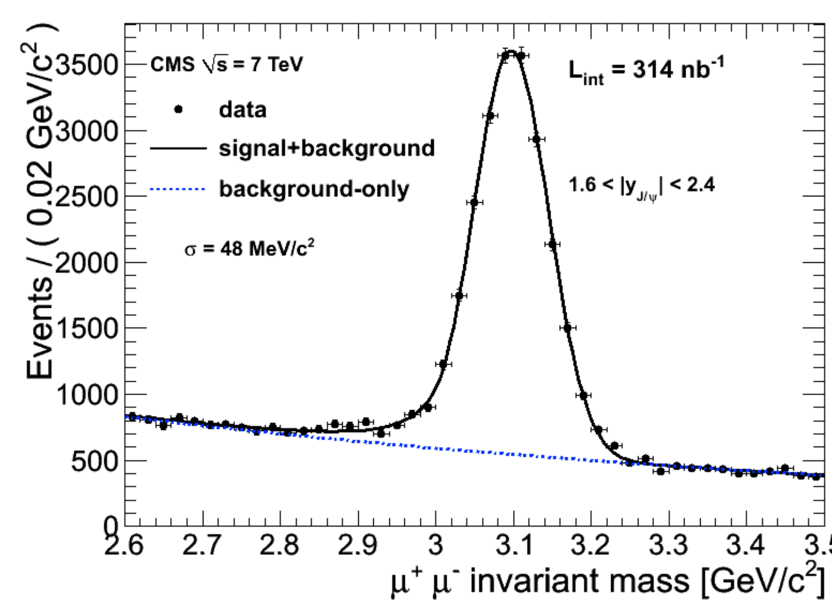
h/Z→J/ψγ and h/Z→Υ(ns)γ











h/Z→J/ψγ and h/Z→Υ(ns)γ

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