# Searches for Higgs boson decays to a meson and a photon

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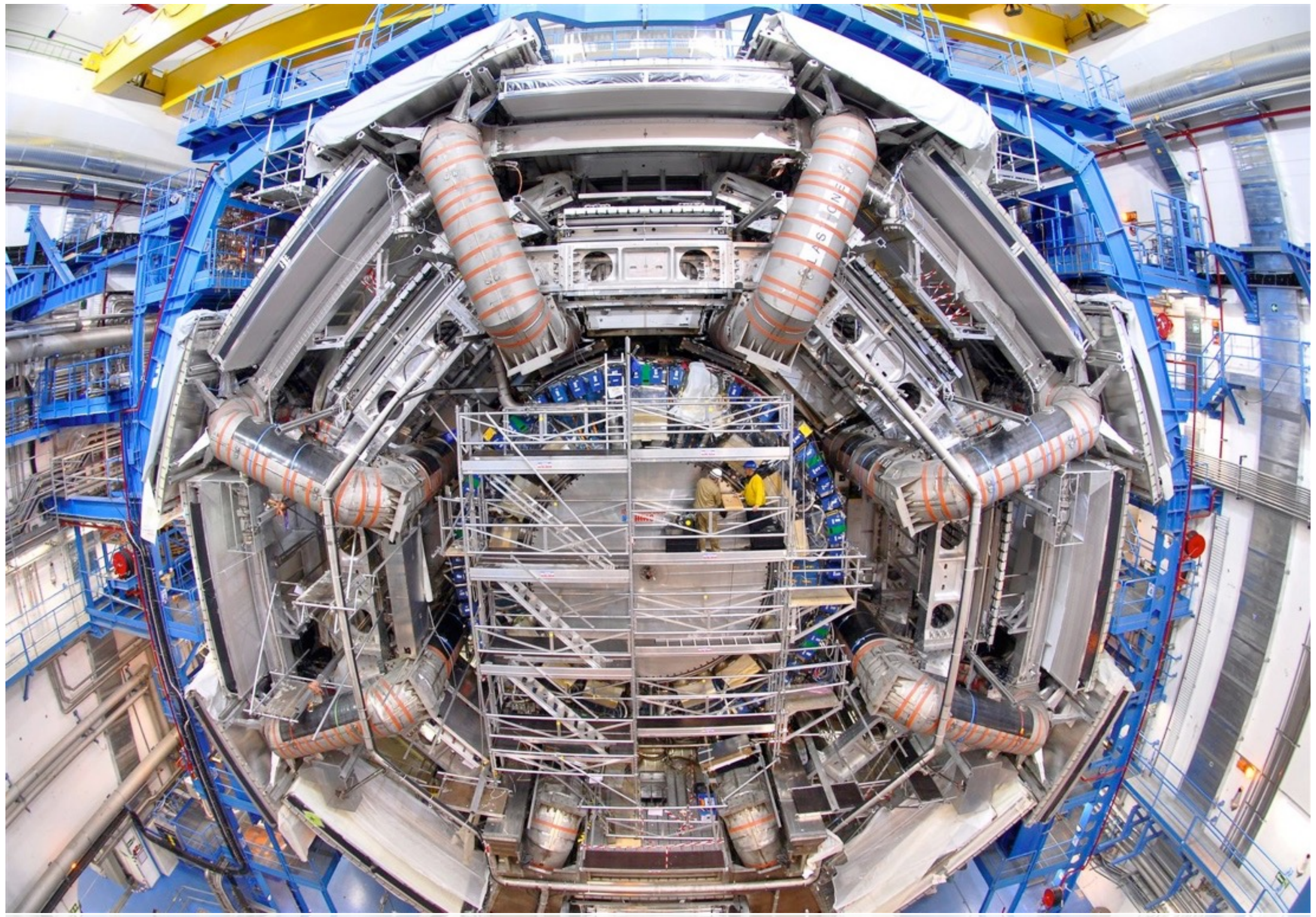

ATLAS experiment at CERN

Exotic Higgs Decays Meeting - SLAC
8 November 2016, Melno Park, U.S.A.

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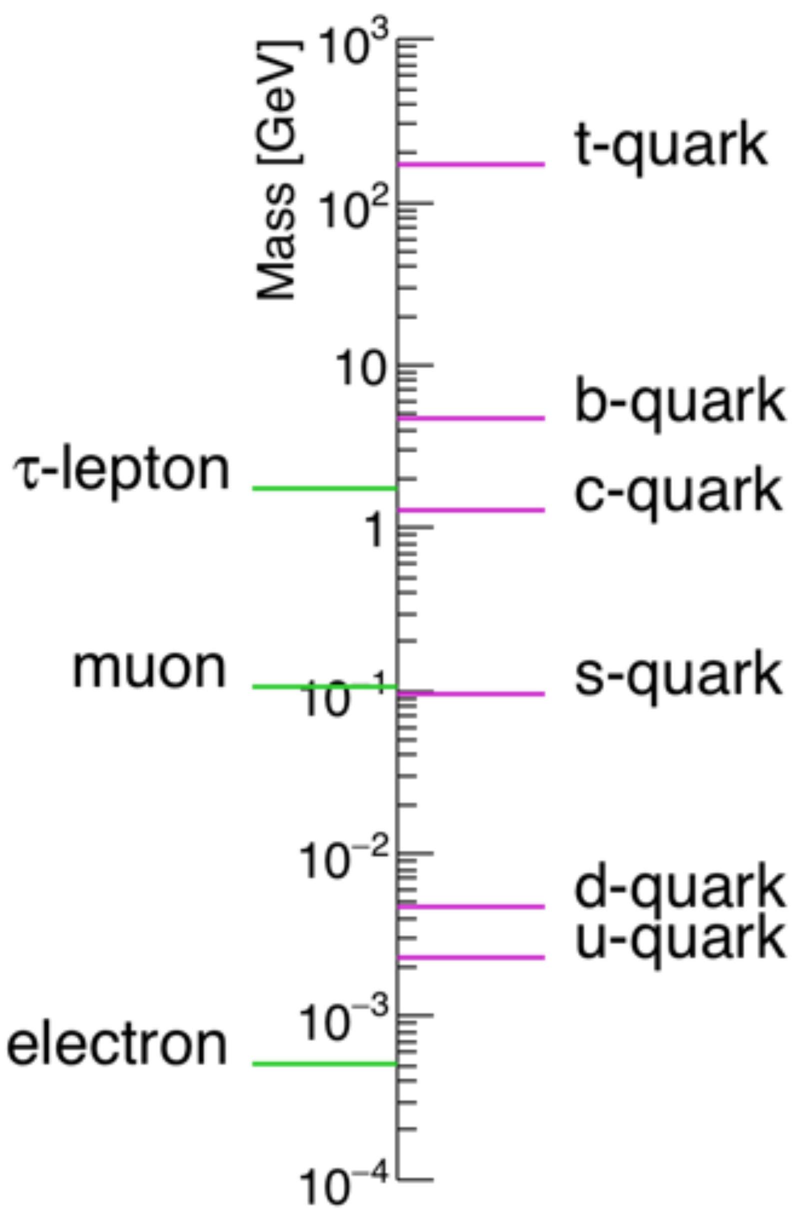
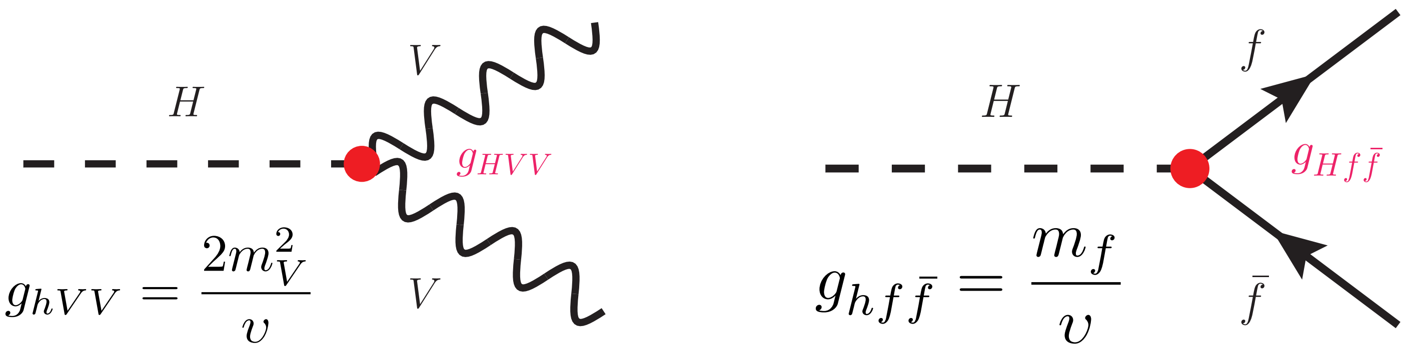
# Higgs-fermion interactions: Yukawa couplings

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



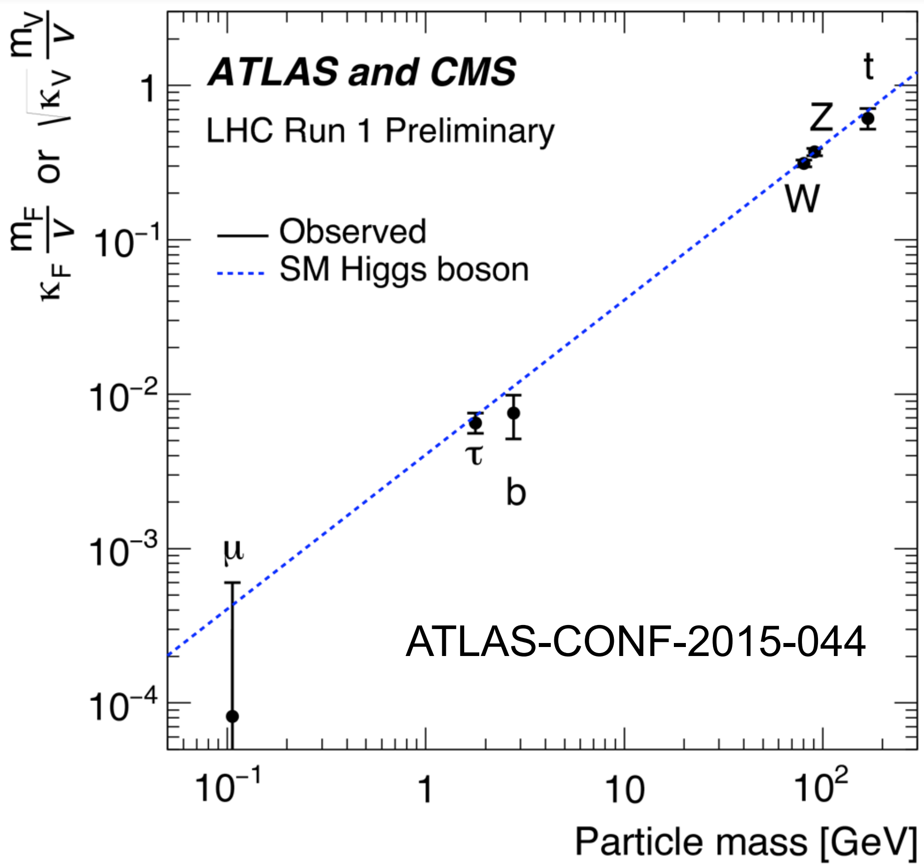

$$g_{hVV} = \frac{2m_V^2}{v} \qquad g_{hf\bar{f}} = \frac{m_f}{v}$$

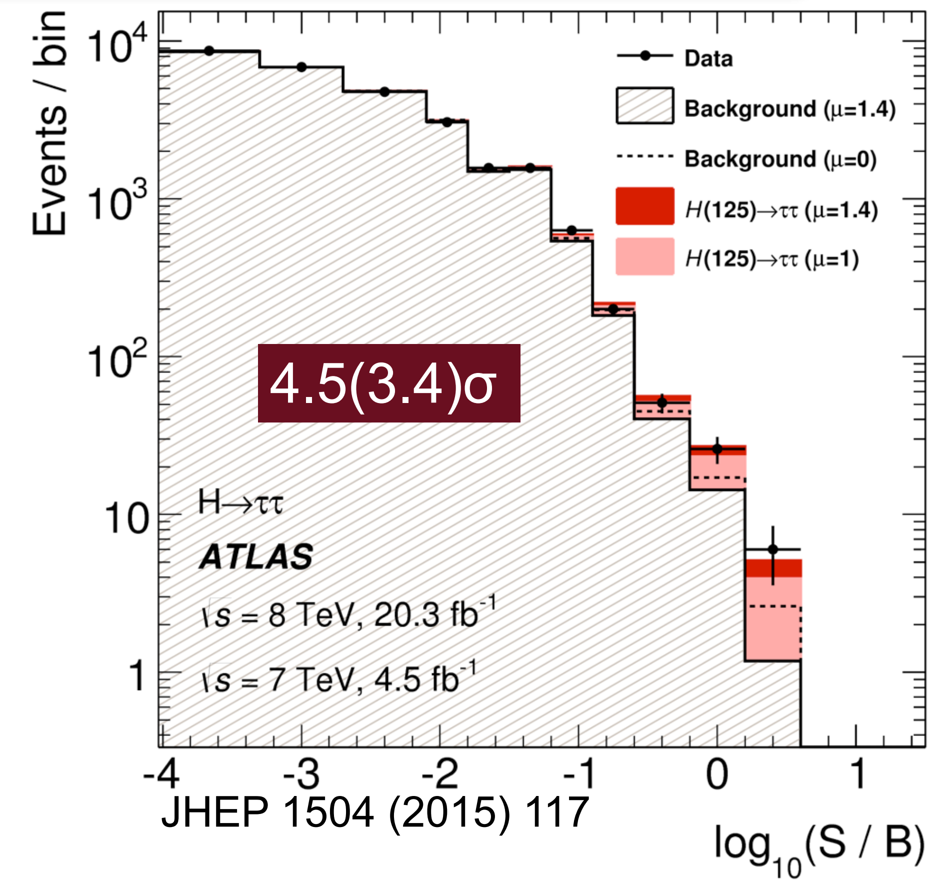
- ❑ Yukawa couplings **not** imposed by fundamental principle
- ☑ **Enhanced Yukawa couplings in BSM scenarios**
  [Phys. Rev. D80, 076002, Phys. Lett. B665 (2008) 79, Phys.Rev. D90 (2014) 115022,…]
- ❑ **Unitarity bounds** (through EFT) for fermion mass generation scale (1st/2nd generation)

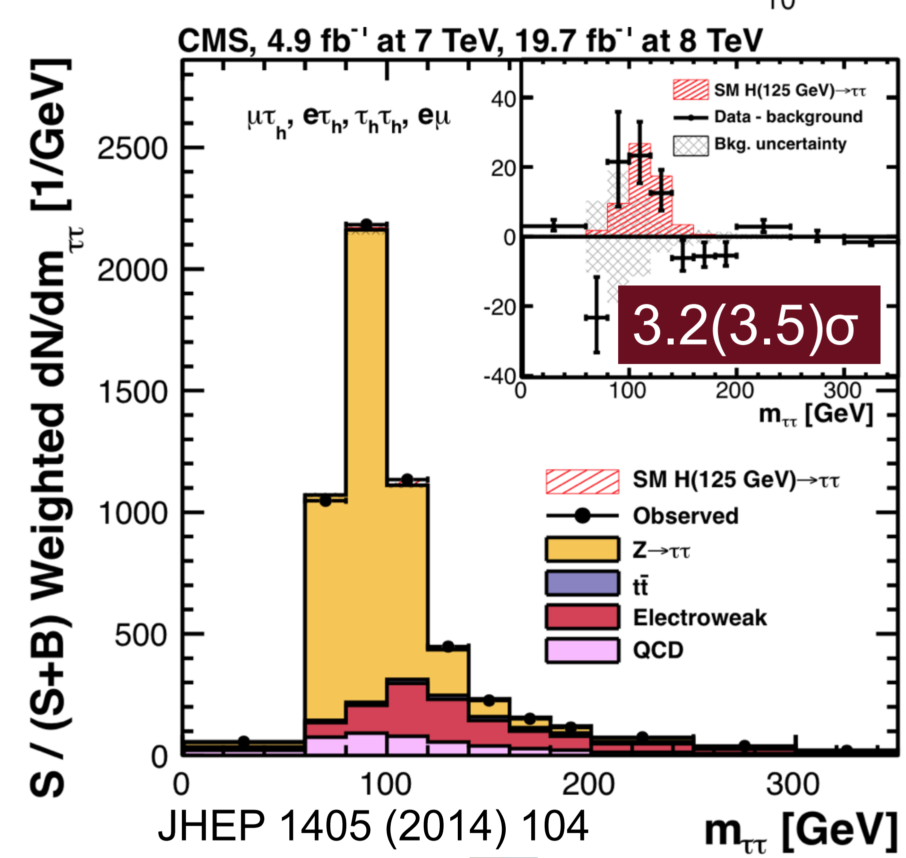
$$\Lambda \sim \sqrt{\frac{v^3}{m_f}} \text{ <20 TeV}$$

[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%

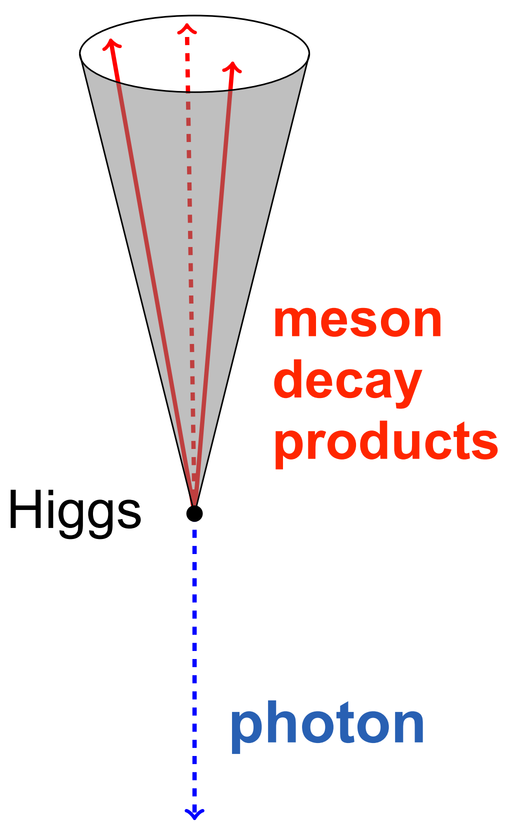
In **fermion sector**, different picture:

- ☑ **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

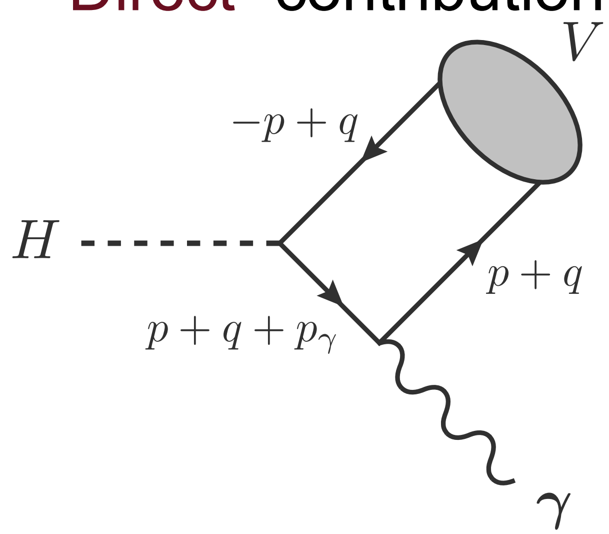
# Exclusive Decays h→Qγ

- **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**

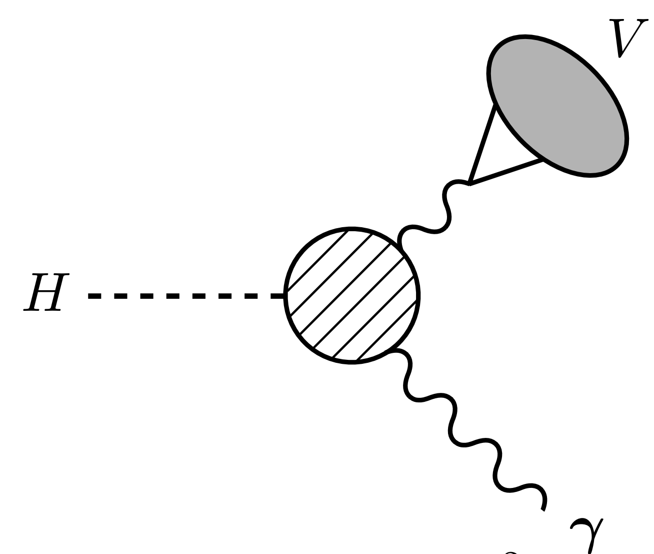
Small angular separation of decay products




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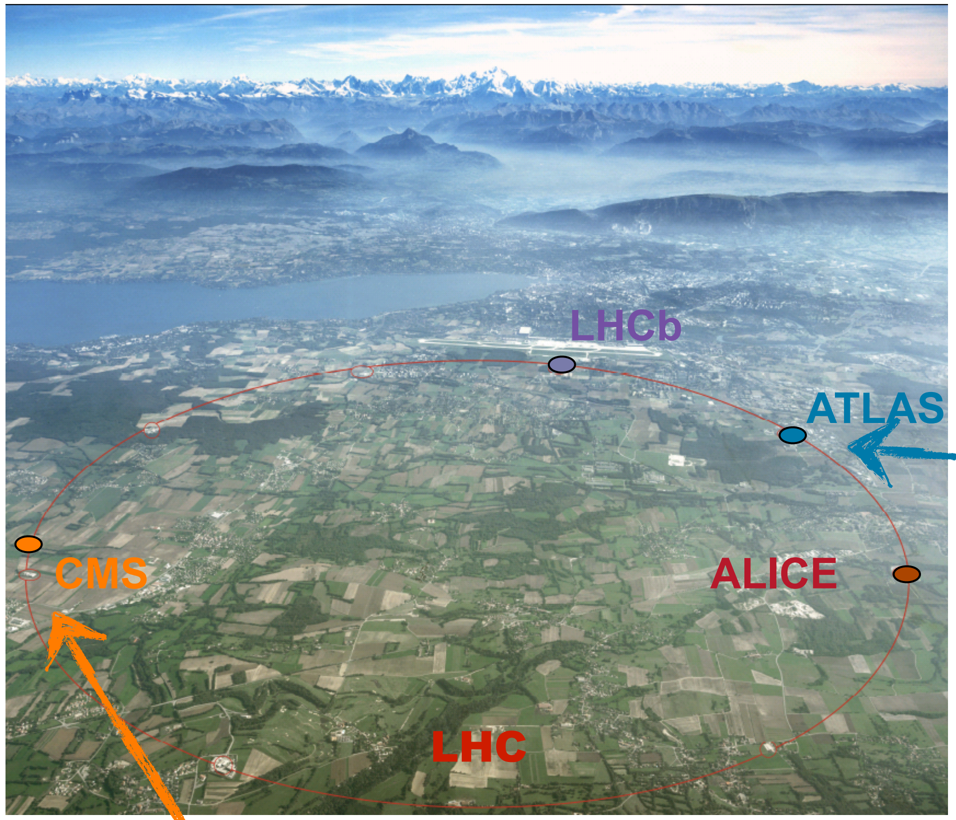
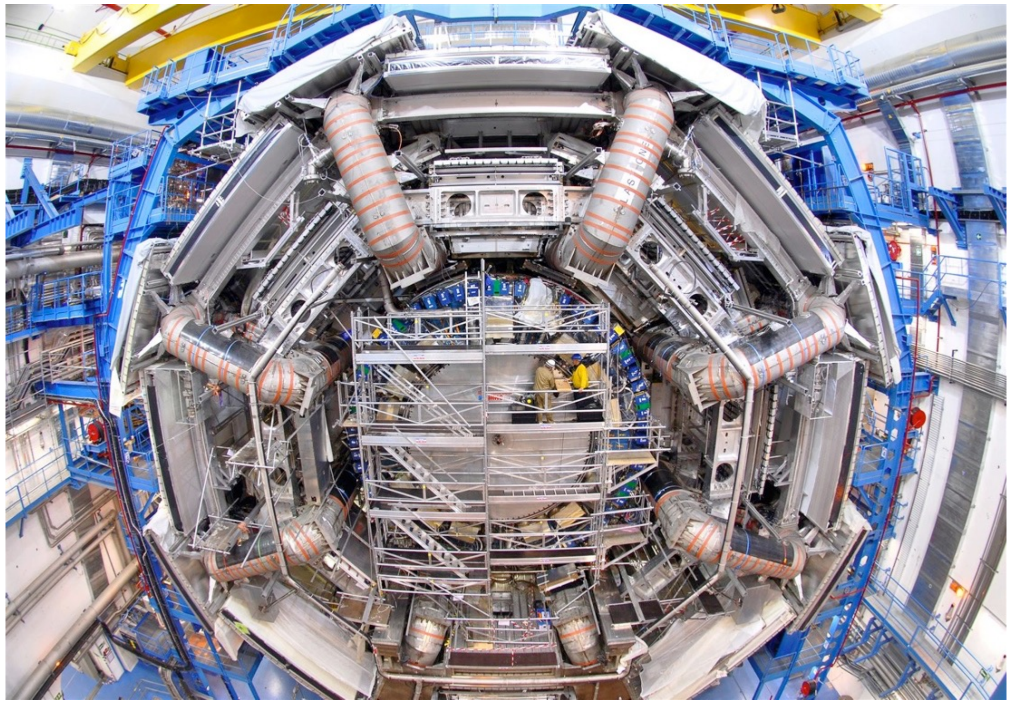
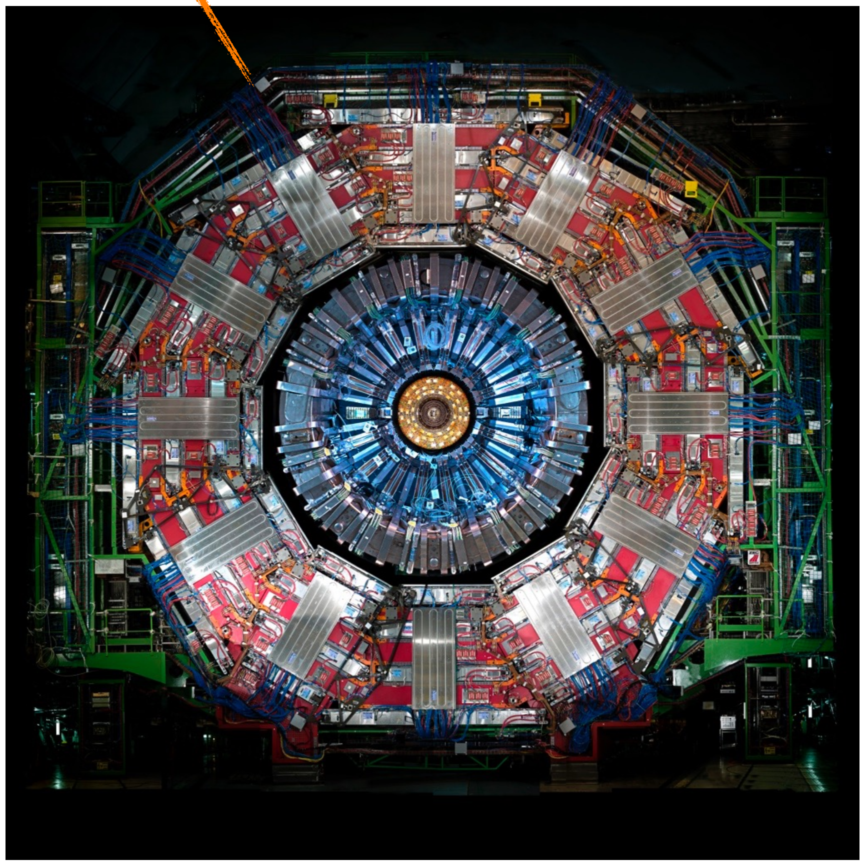
| Decay mode | Branching ratio |
|---|---|
| $Z^0 \to \pi^0\gamma$ | $(9.80\,{}^{+\,0.09}_{-\,0.14}\,{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$ |
| $Z^0 \to \rho^0\gamma$ | $(4.19\,{}^{+\,0.04}_{-\,0.06}\,{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$ |
| $Z^0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

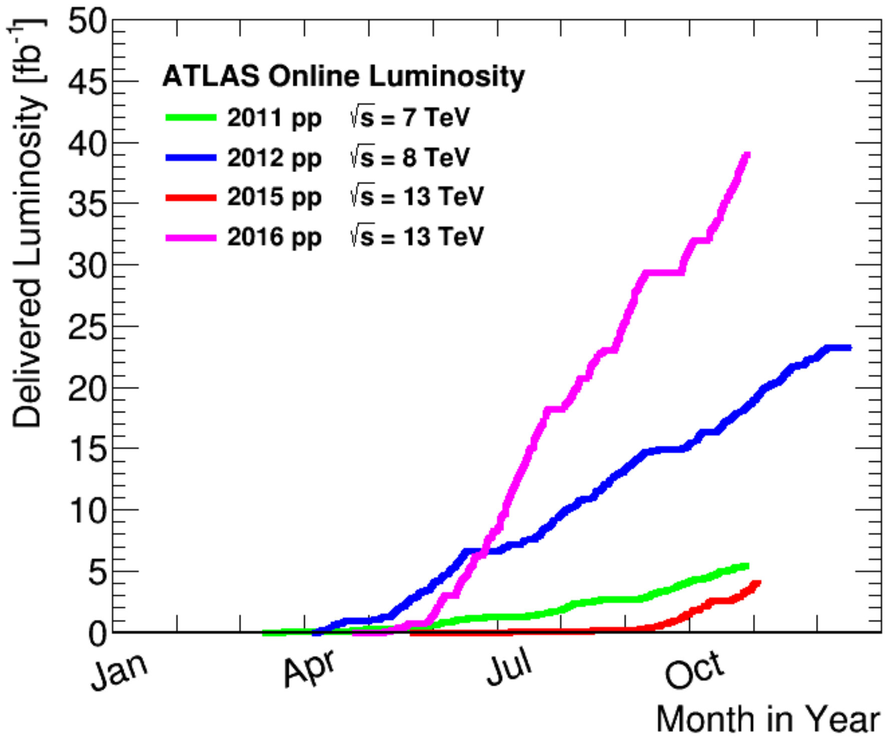
- Z→Qγ decays also interesting
- Experimentally unconstrained
  - LEP accurately measured b-/c-quark couplings (~1%)
  - light quark couplings less constrained
- Sensitive to BSM contributions

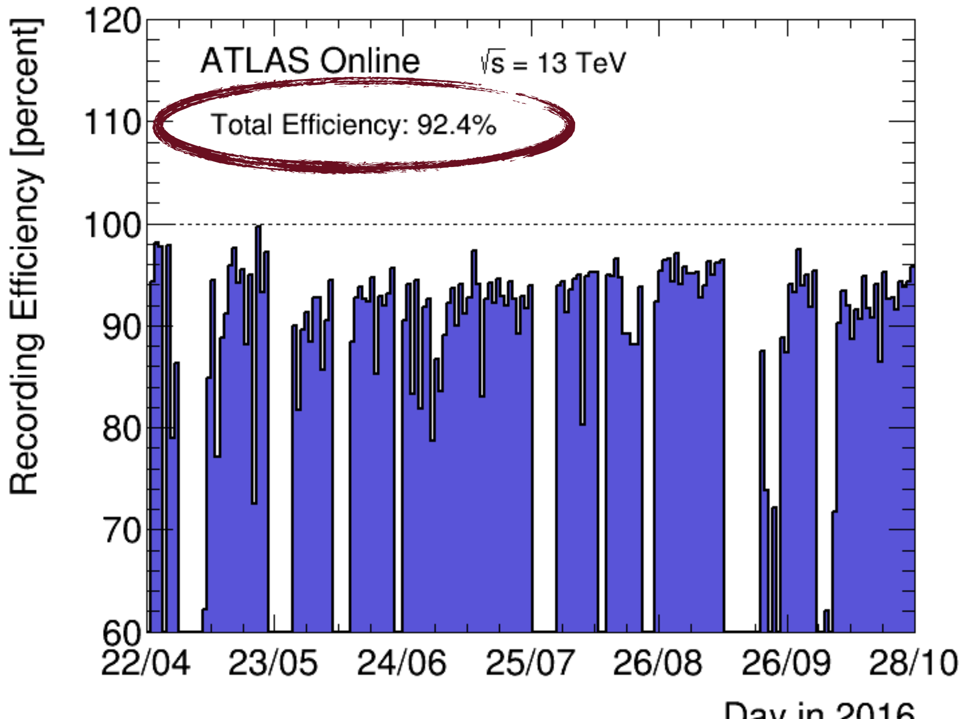
# The LHC, ATLAS, and CMS





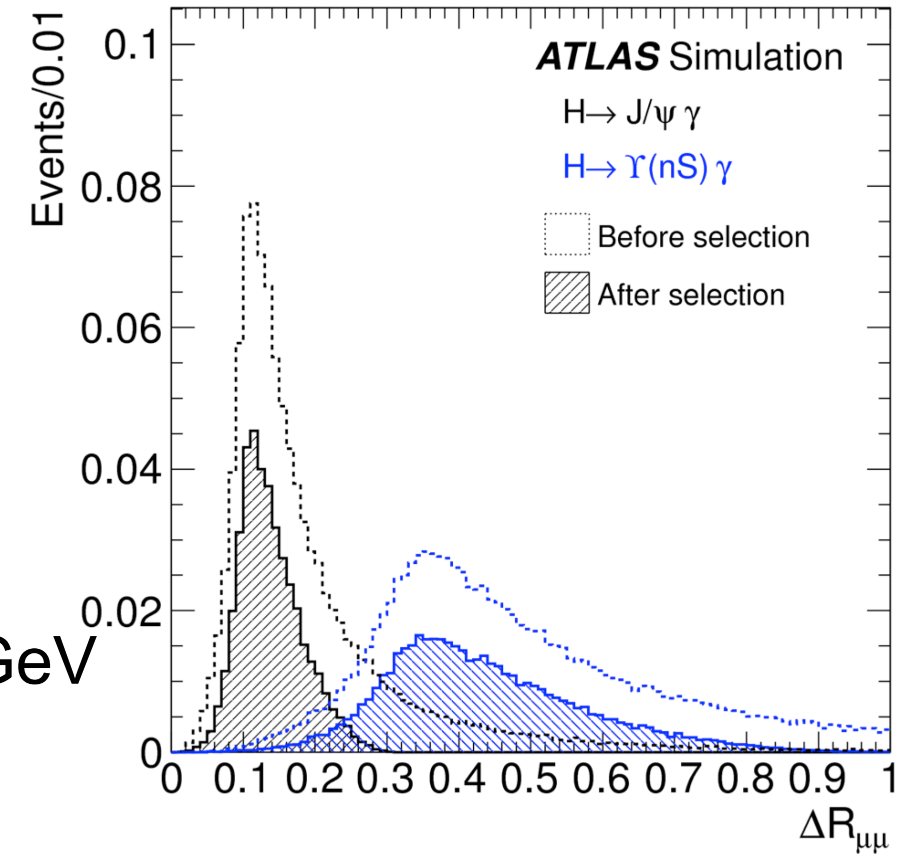


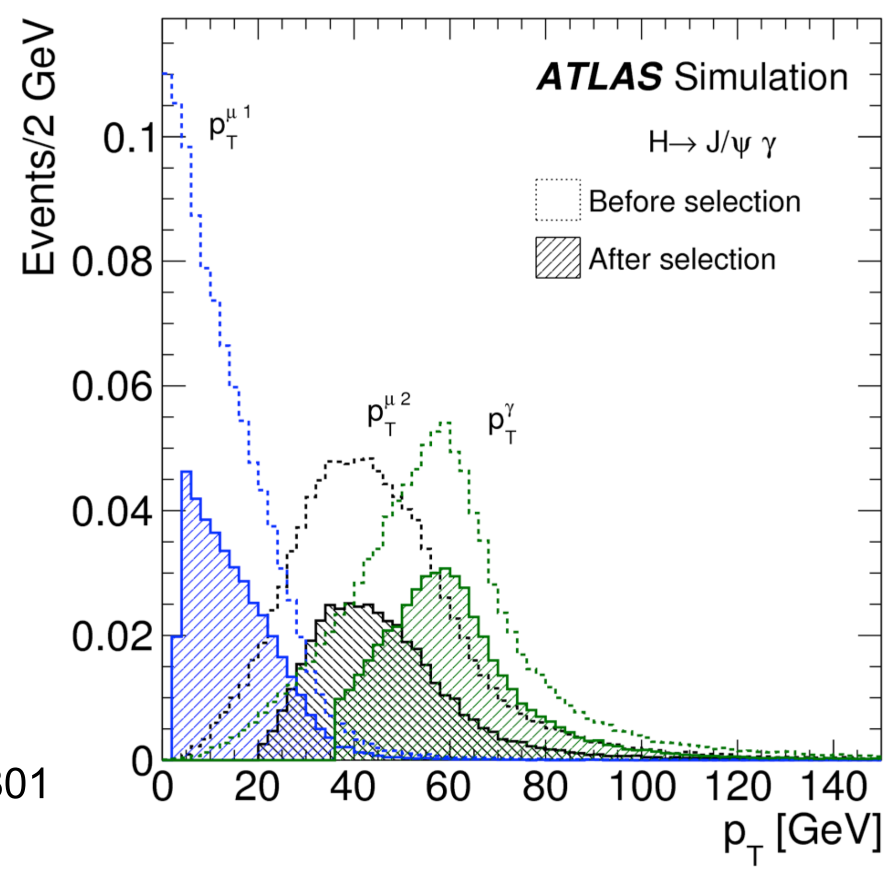



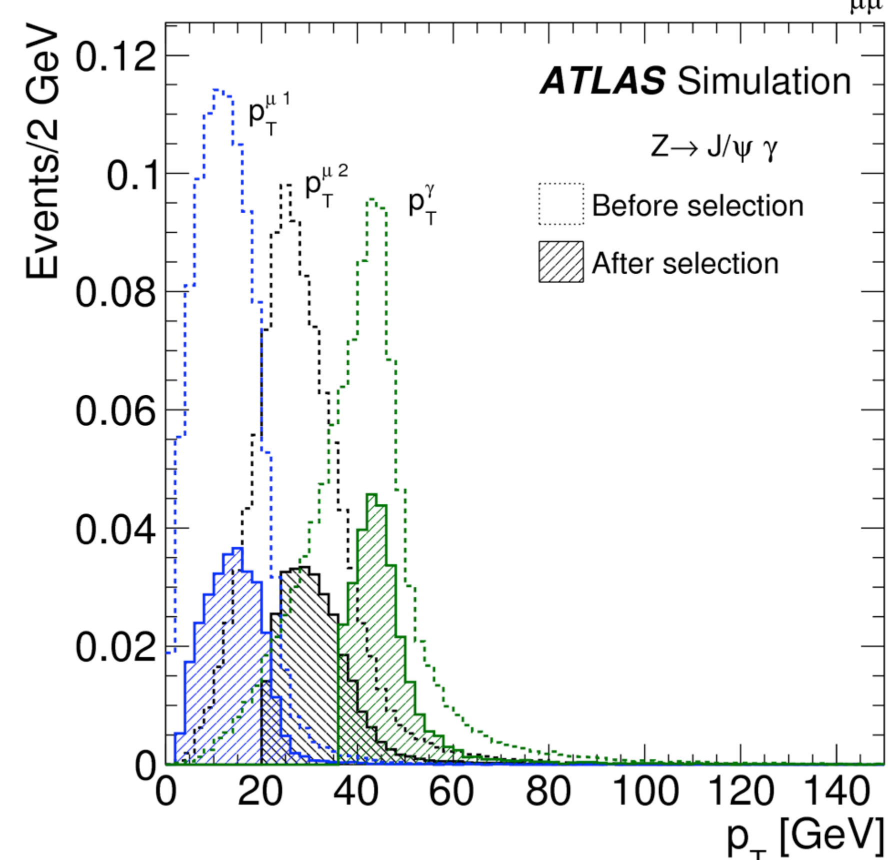

High Quality data collected!

# h/Z→J/ψγ and h/Z→Υ(nS)γ (n=1,2,3)

- **ATLAS first search** for exclusive h/Z→Qγ decays
  - Q = J/ψ or Υ(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
  - μμ and γ isolation,
  - $|m_{\mu\mu} - m_{J/\psi}|<0.15$ (0.20) GeV barrel (endcap) $8<m_{\mu\mu}<12$ GeV
  - $|L_{xy}/\sigma_{L_{xy}}|<3$
  - $\Delta\phi(\mu\mu,\gamma)>0.5$
- Total efficiency
  - h→J/ψ(→μμ)γ~22%
  - h→Υ(→μμ)γ~ 28%
  - Z→J/ψ(→μμ)γ~12%
  - Z→Υ(→μμ)γ~15%

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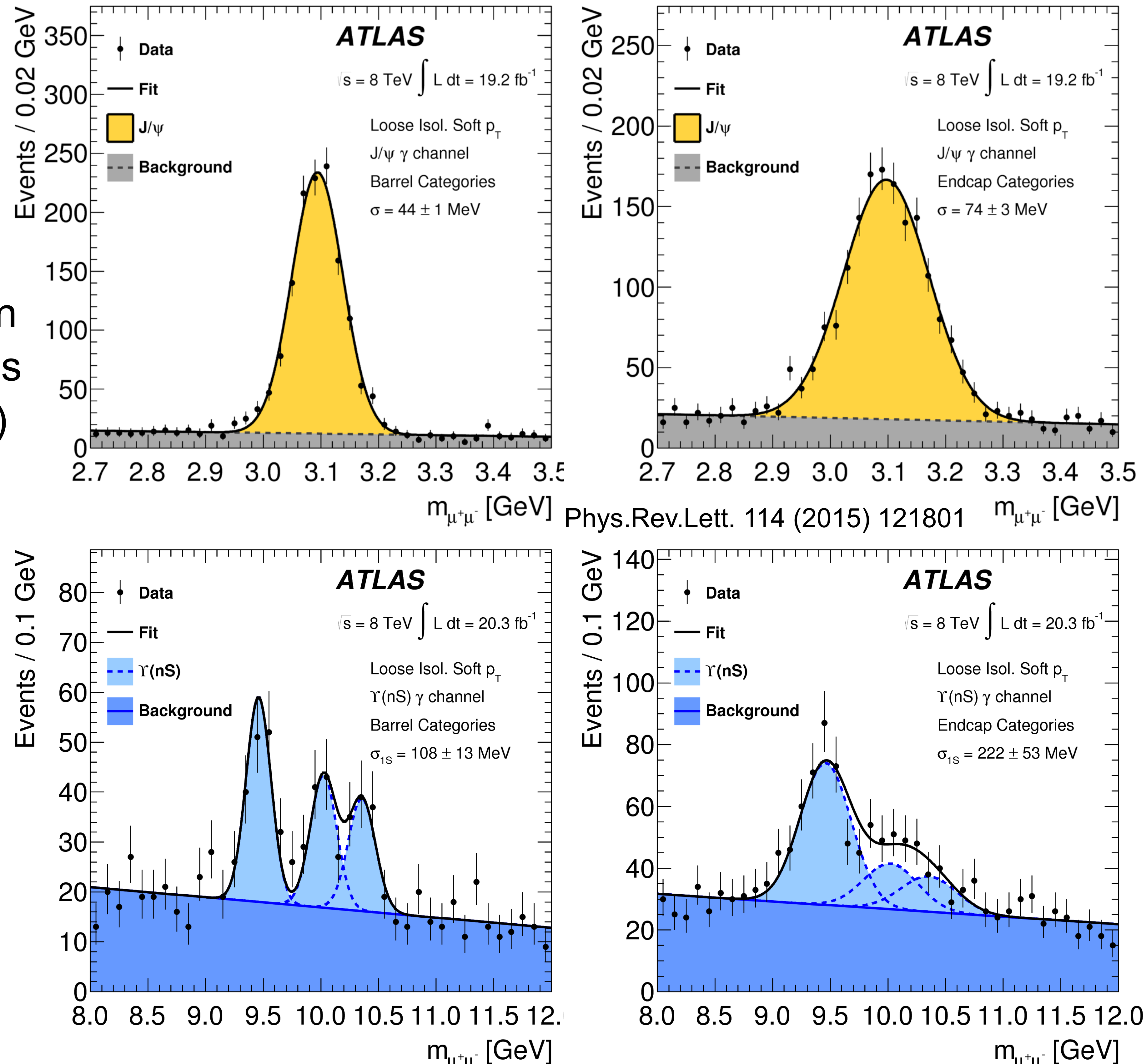
# h/Z→J/ψγ and h/Z→Υ(nS)γ: Mass Resolution

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



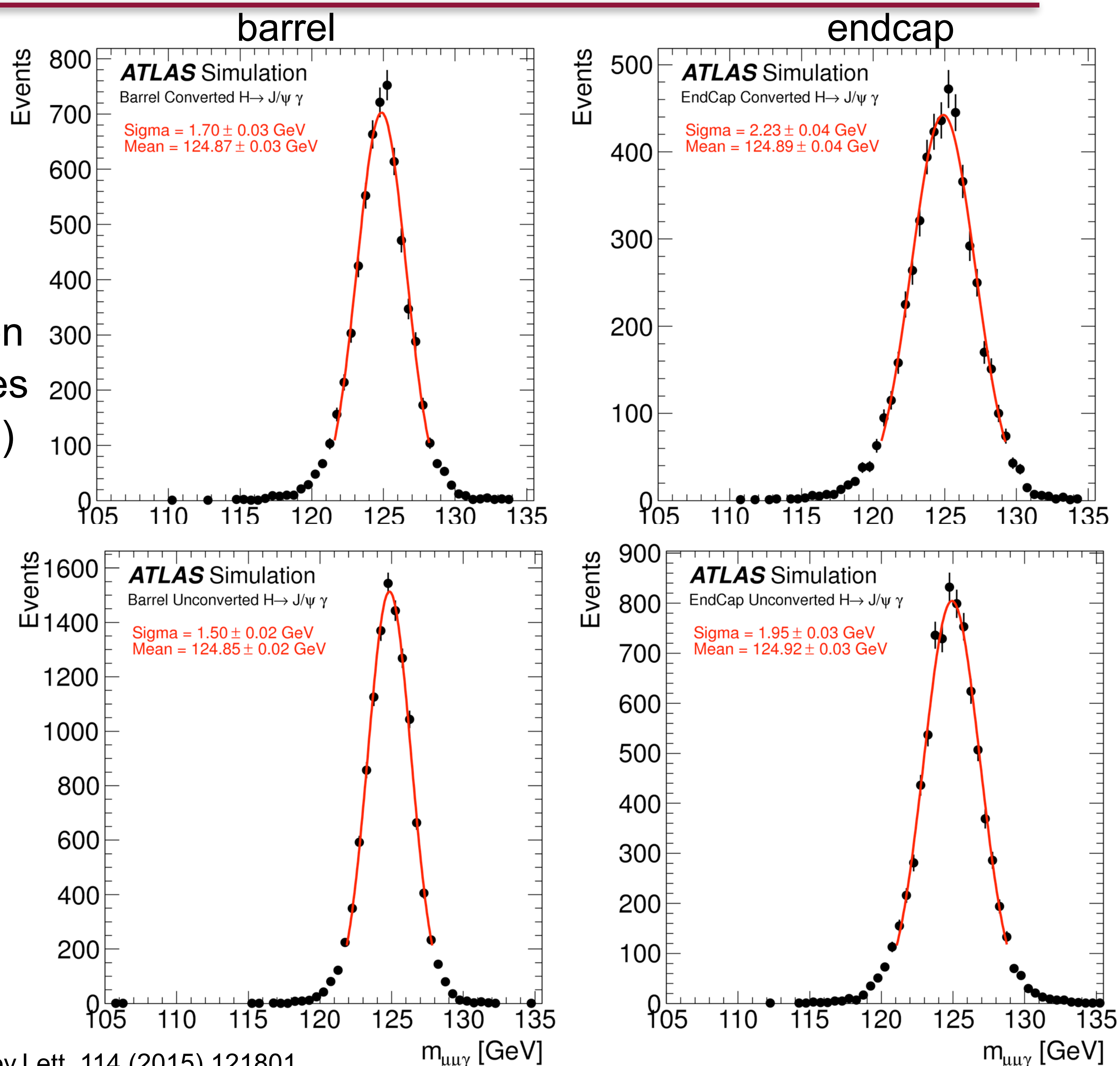

Phys.Rev.Lett. 114 (2015) 121801

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

converted γ

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

unconverted γ

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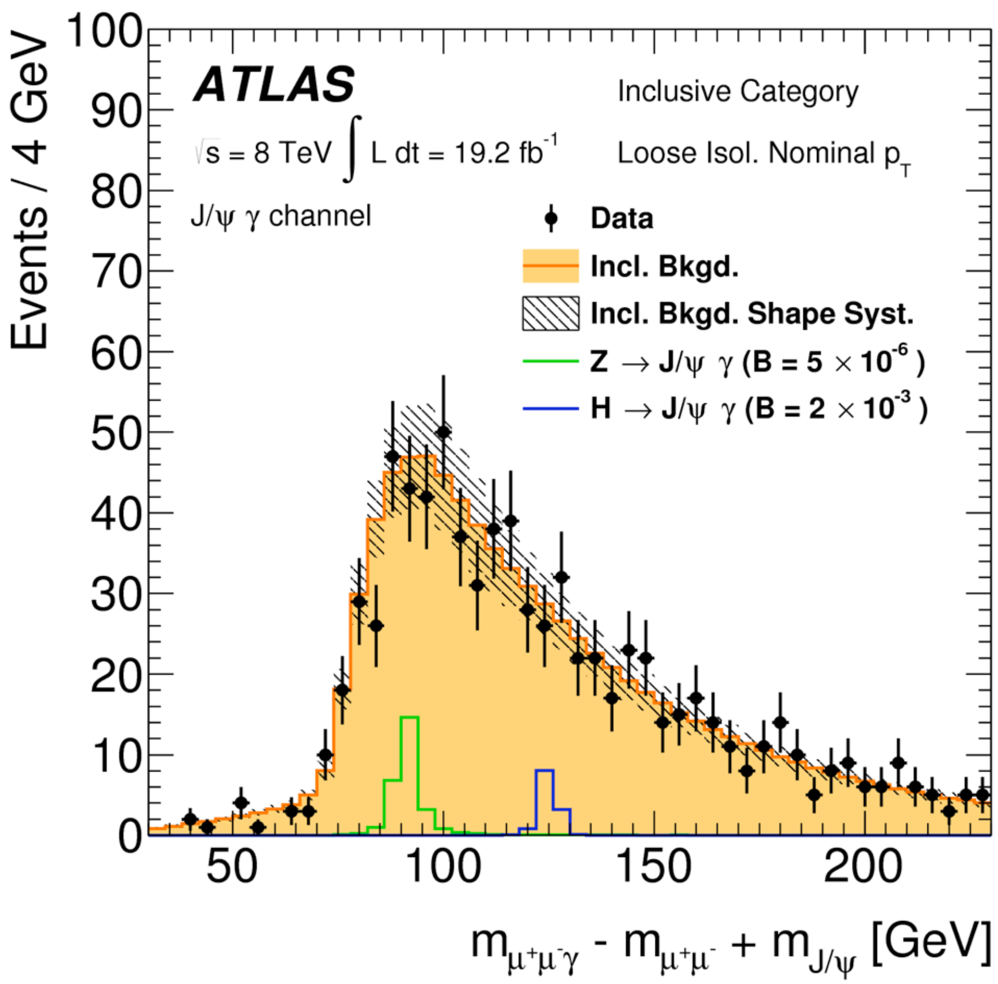
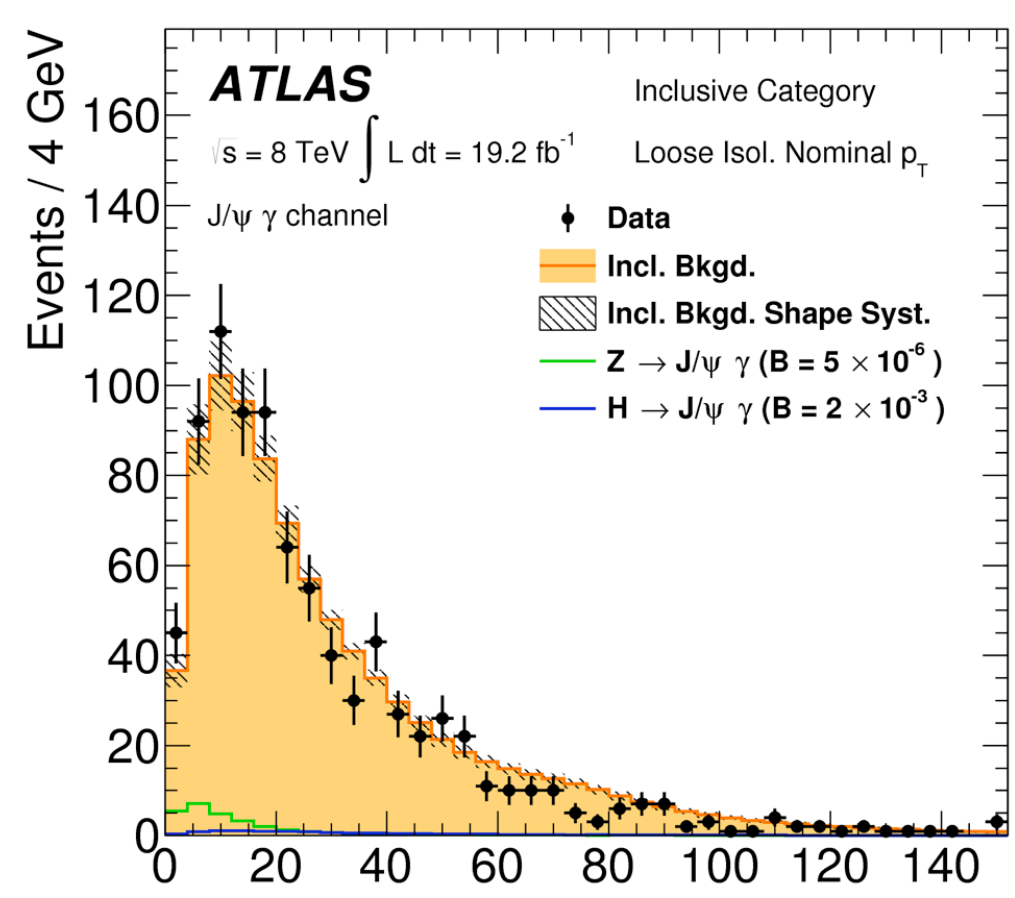
# h/Z→J/ψγ and h/Z→Υ(nS)γ: Background

- **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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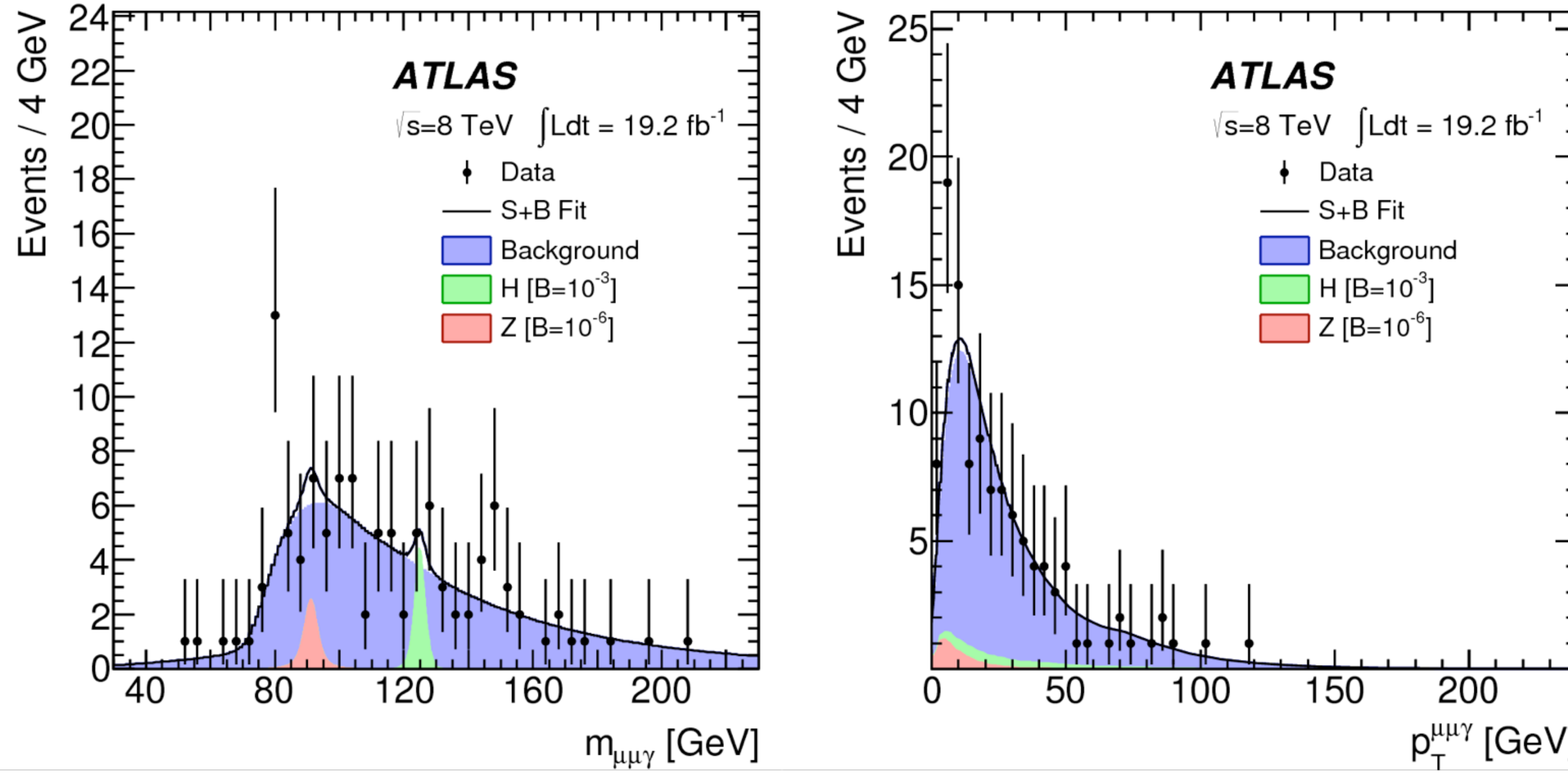
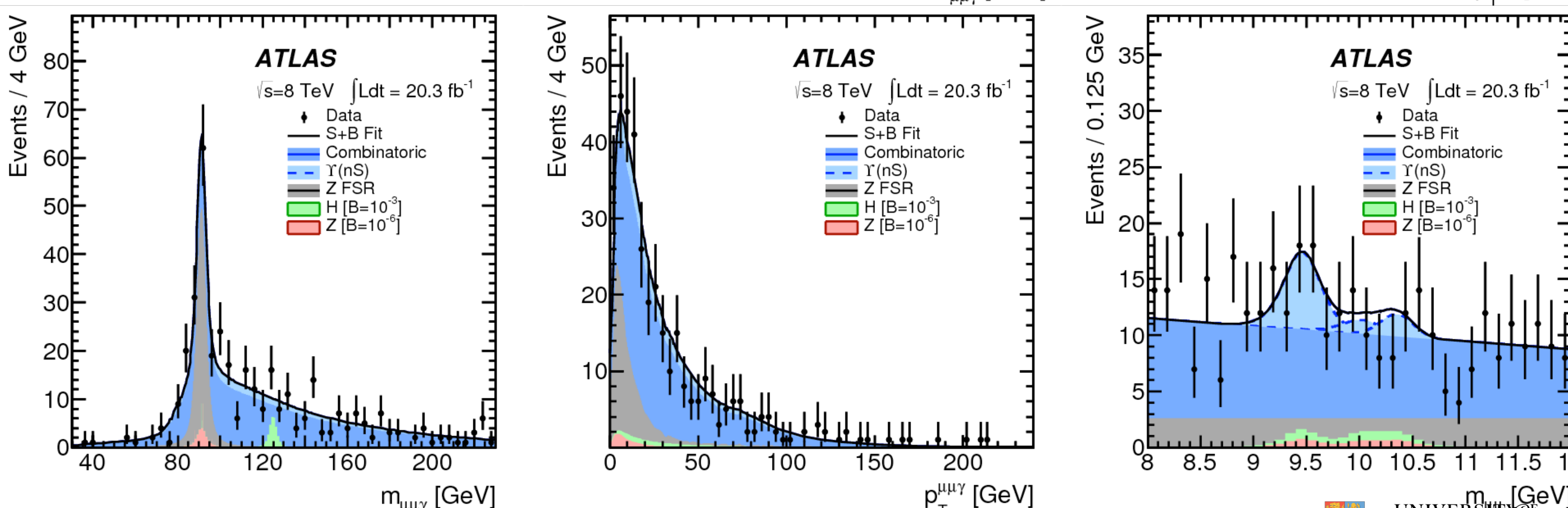
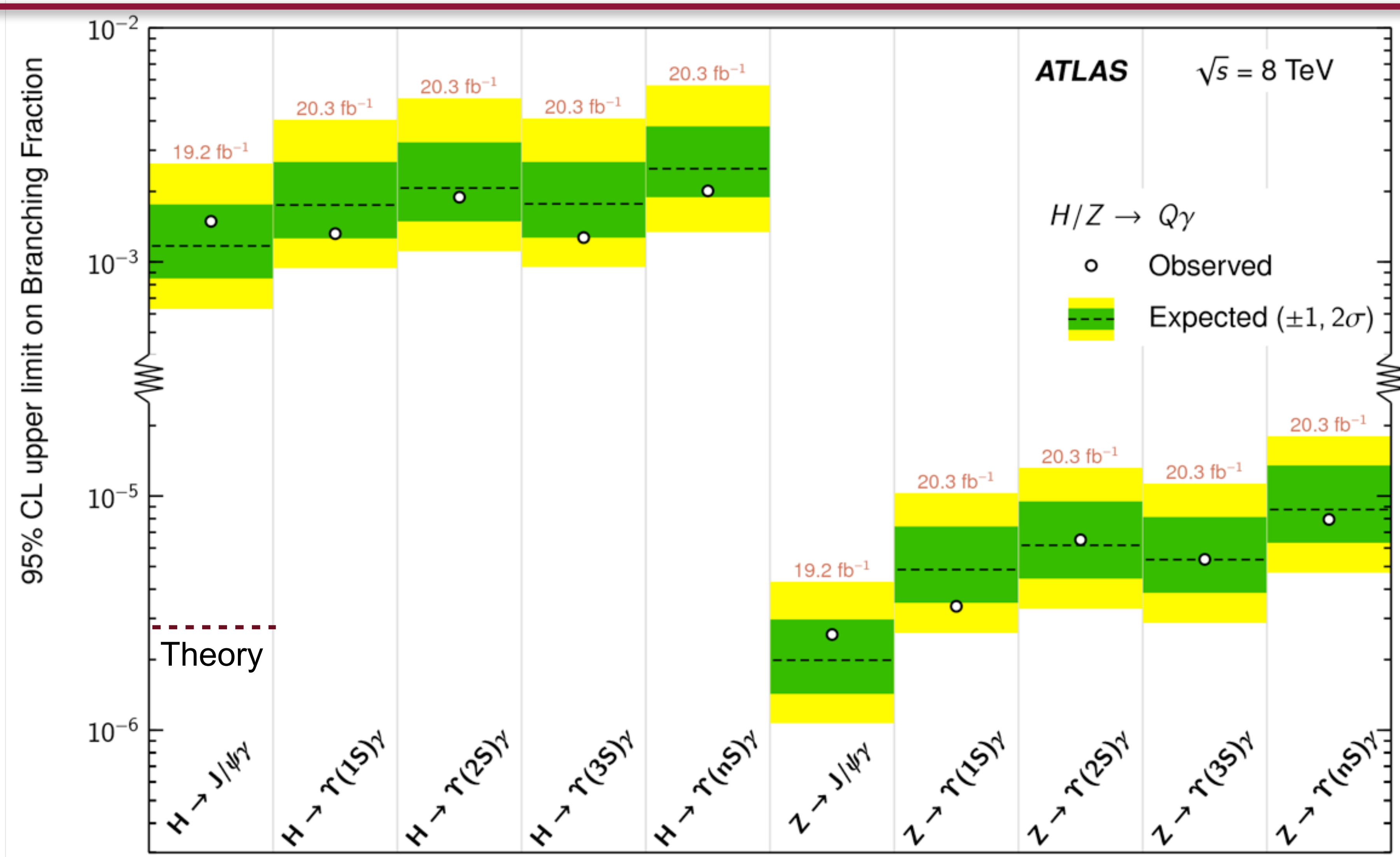


# h/Z→J/ψγ and h/Z→Υ(nS)γ: Results

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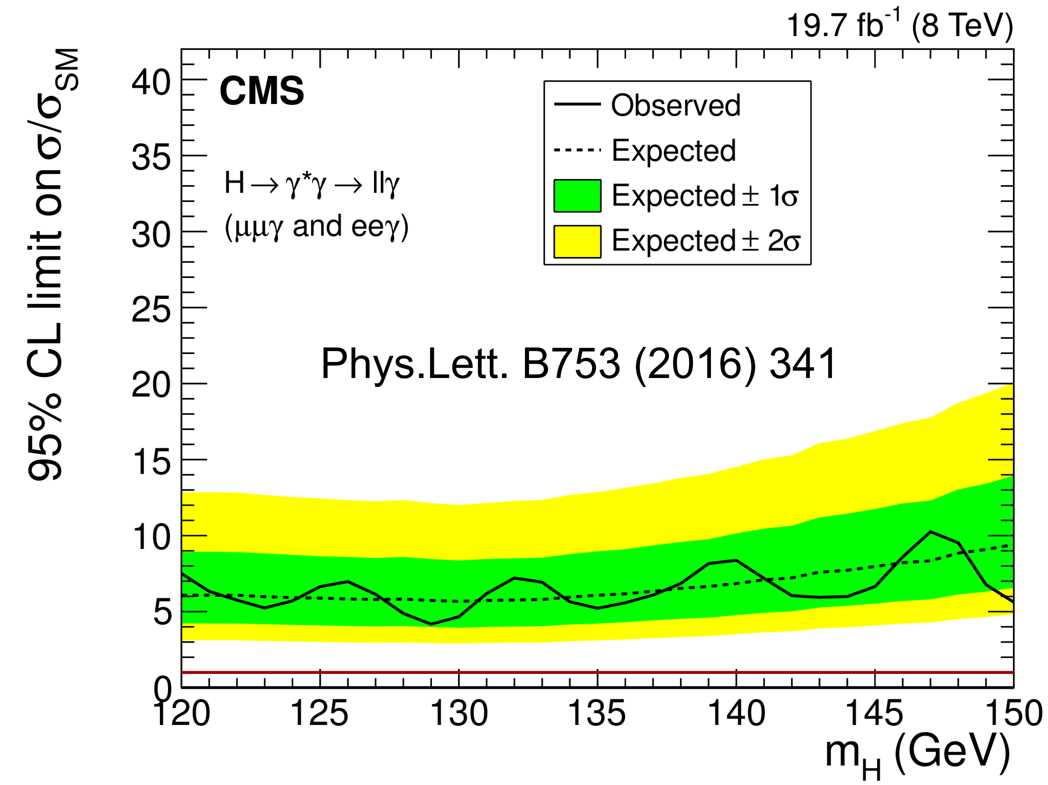
| | 95% $CL_s$ Upper Limits | | | | |
|---|---|---|---|---|---|
| | $J/\psi$ | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ | $\sum^n \Upsilon(nS)$ |
| | $\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [ $10^{-6}$ ] | | | | |
| Expected | $2.0^{+1.0}_{-0.6}$ | $4.9^{+2.5}_{-1.4}$ | $6.2^{+3.2}_{-1.8}$ | $5.4^{+2.7}_{-1.5}$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

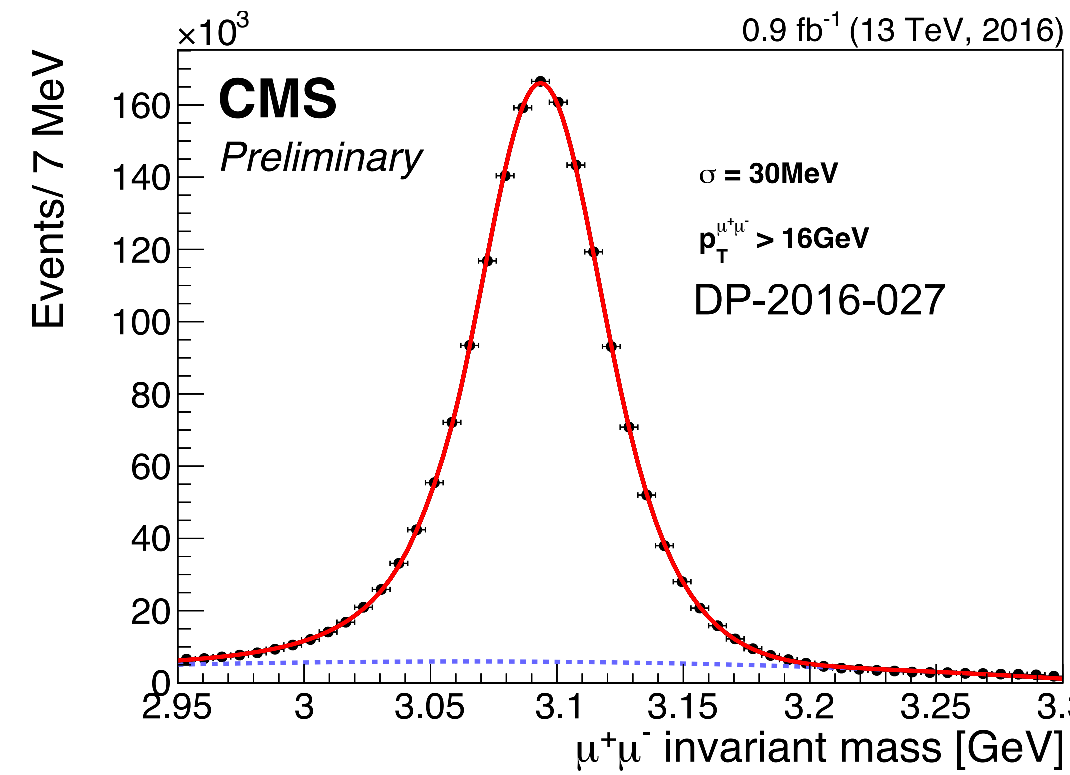
- 95% CL upper limits on decay Branching Ratios:
  - $\mathcal{O}(10^{-3})$ for Higgs boson (SM production)
  - $\mathcal{O}(10^{-6})$ for Z boson

☑ **Indicate non-universal Higgs boson coupling to quarks** [Phys.Rev. D92 (2015) 033016, JHEP 1508 (2015) 012]

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

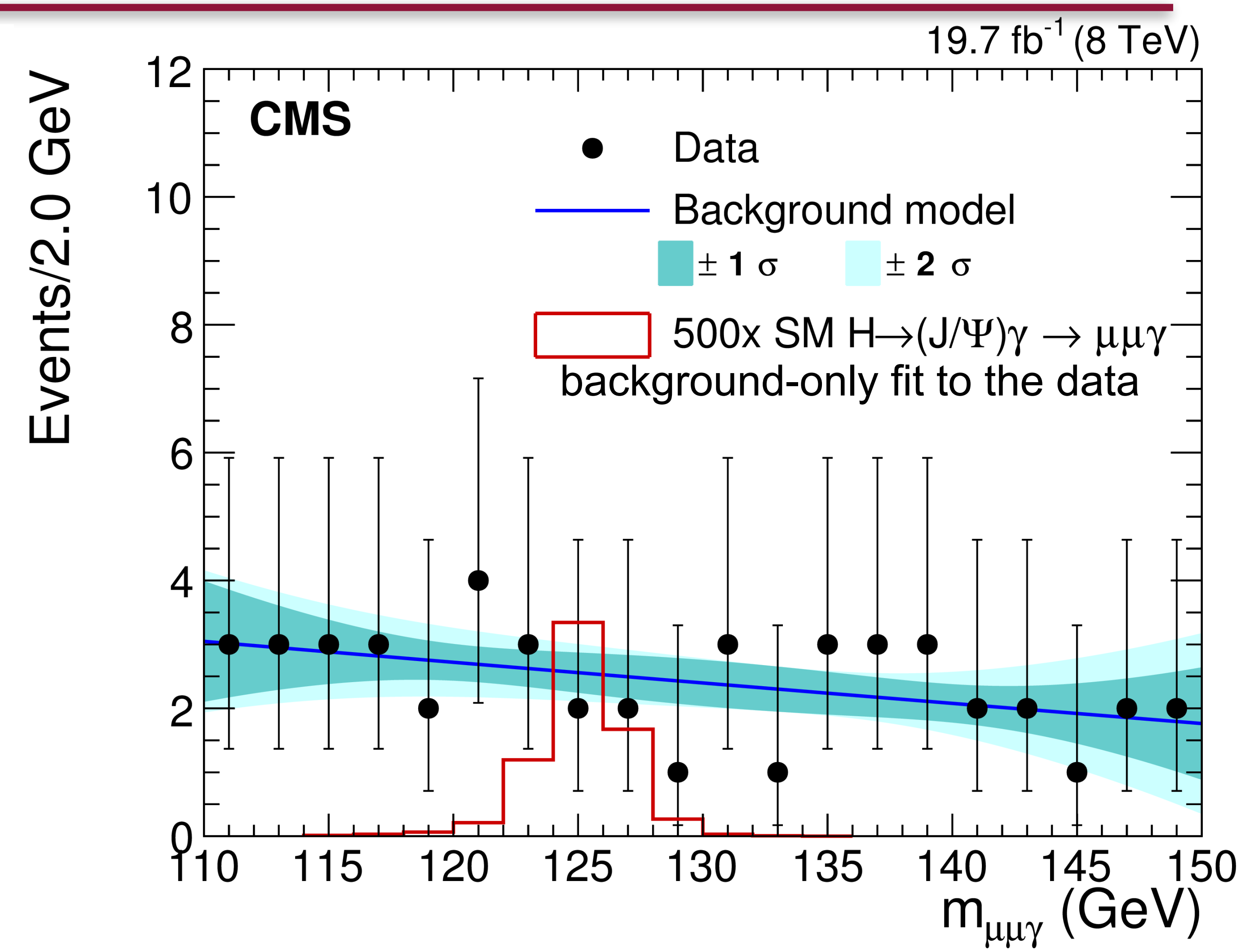
- ☑ **CMS search** for $h \to J/\psi\gamma$
  - extending the $h \to ll\gamma$ studies
  - used 19.7 $fb^{-1}$ at 8 TeV
- ☑ **Event Selection**
  - single muon and a photon, both $p_T$>22 GeV
  - $|\eta_\mu|$<2.4, $p_{T\mu}$>23,4 GeV, $p_{T\mu\mu}$>40 GeV
  - $|\eta_\gamma|$<1.44, $p_{T\gamma}$>40 GeV
  - $\mu\mu$ and $\gamma$ 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→J/ψγ

| 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, $\mu$ (e) channel | 4 (2)% |
| Muon reconstruction efficiency | 11% |
| Electron reconstruction efficiency | 3.5% |
| Photon reconstruction efficiency | 0.6% |
| $m_{\ell\ell\gamma}$ scale, $\mu$ (e) channel | 0.1 (0.5)% |
| $m_{\ell\ell\gamma}$ resolution, $\mu$ (e) channel | 10 (10)% |

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- 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→J/ψγ) < 1.5x10$^{-3}$ → 540 times the SM prediction

| 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 |
| ee$\gamma$ | 25.8 | 1.9 | 65 |
| $(J/\psi \to \mu\mu)\gamma$ | 0.065(J/ψ) + 0.32 (non-res.) | 0.014(J/ψ) + 0.078 (non-res.) | 12 |

# Search for h/Z→φγ

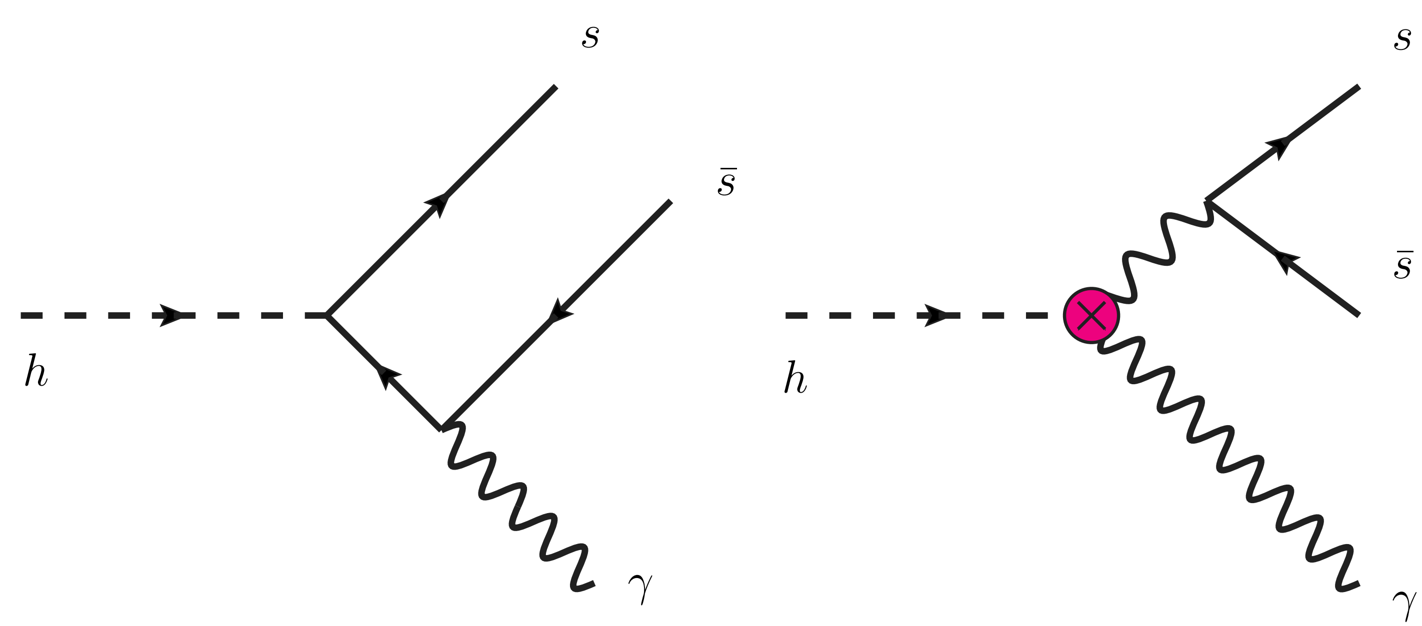
- **New ATLAS analysis** based on 2.7 $fb^{-1}$ at 13 TeV collected in 2015
- **Higgs decay h→φγ sensitive to strange quark Yukawa coupling**
  - probing light quark Yukawa coupling was **considered impossible** at the LHC
  - very challenging to access with inclusive H→ss decays!
- **Looking for new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

Phys. Rev. Lett. 117, 111802

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!

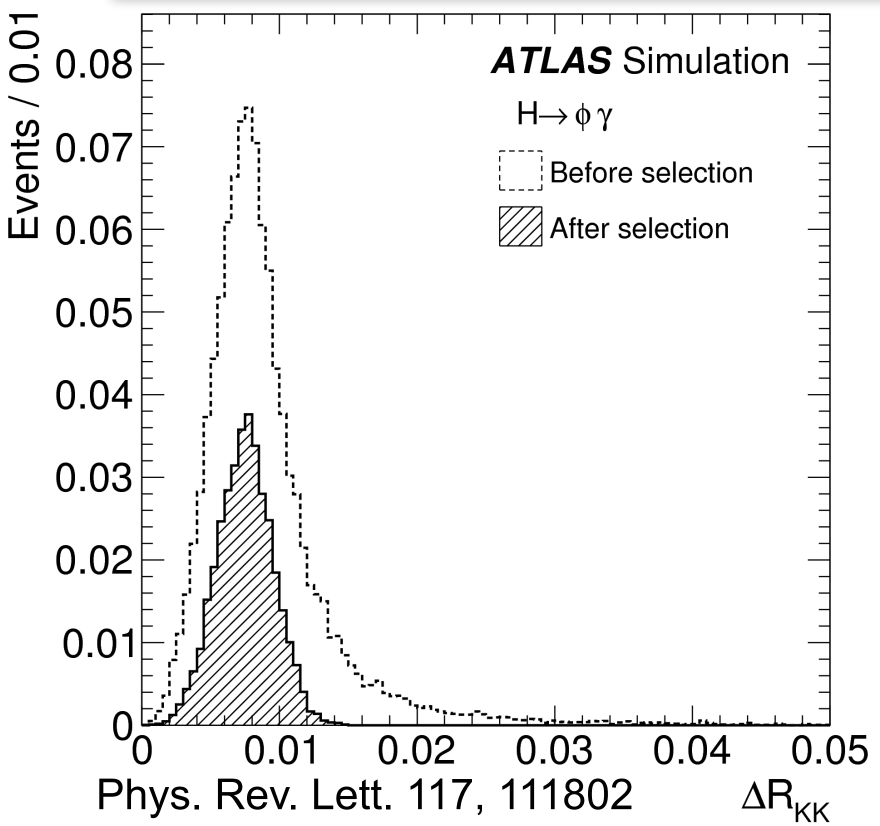
Phys.Rev.Lett. 114 (2015) 101802




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

JHEP 1508 (2015) 012

# h/Z→φγ: Analysis Strategy



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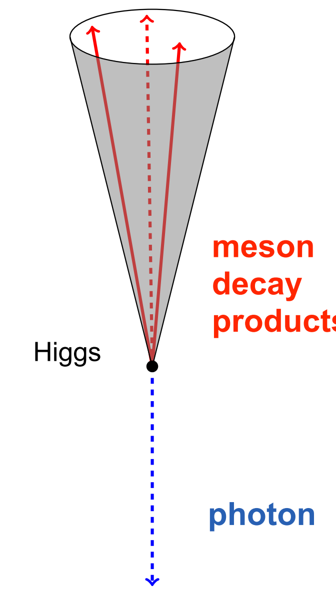
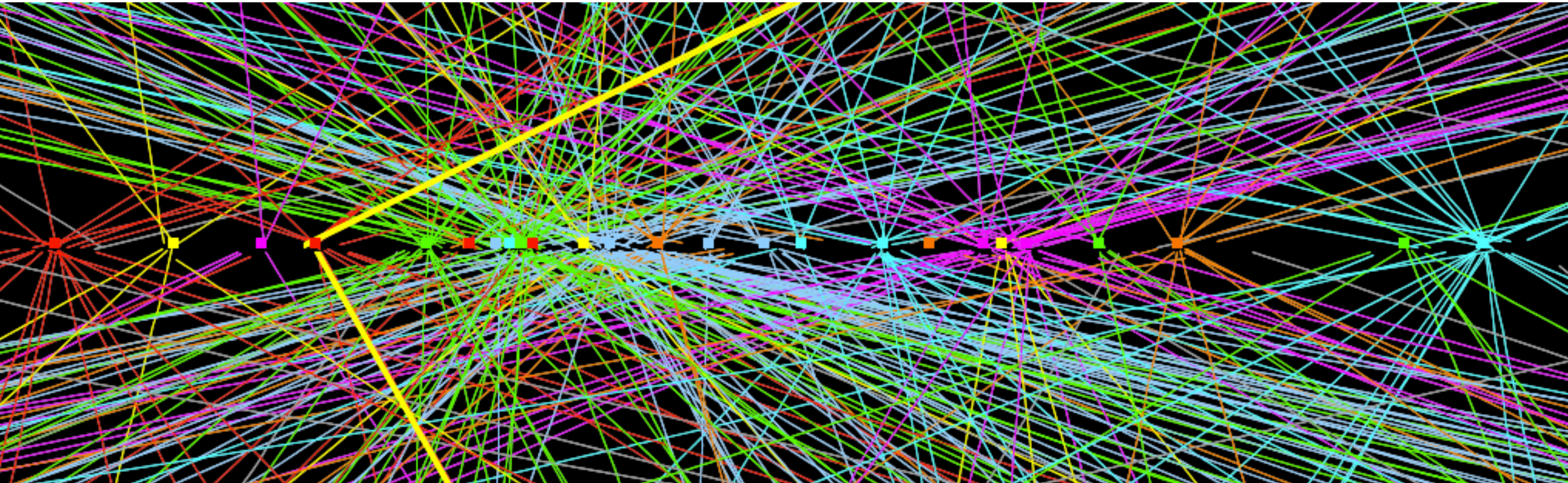
- **Exploit $\varphi \to K^+K^-$ decays**, BR=49%
- **Distinctive topology**
  - Pair of collimated high-pT isolated tracks recoils against high-pT isolated photon
- **Enabled by dedicated trigger** (Sep 2015)
  - Photon ($p_{T\gamma}$>35 GeV) and isolated di-track (at least one $p_T$>15 GeV) consistent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



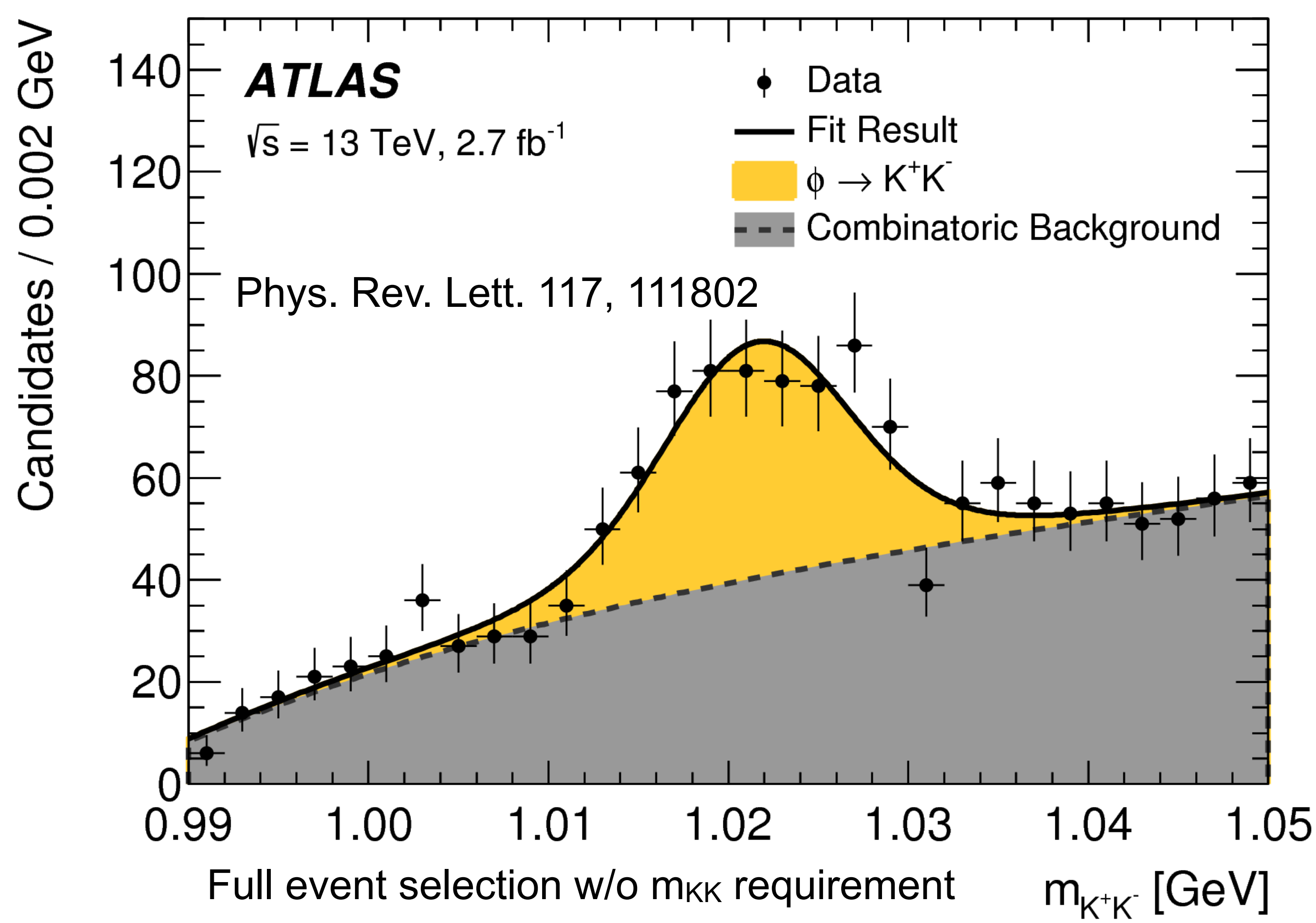
Z→μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown

# 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
  - $pT_\gamma$>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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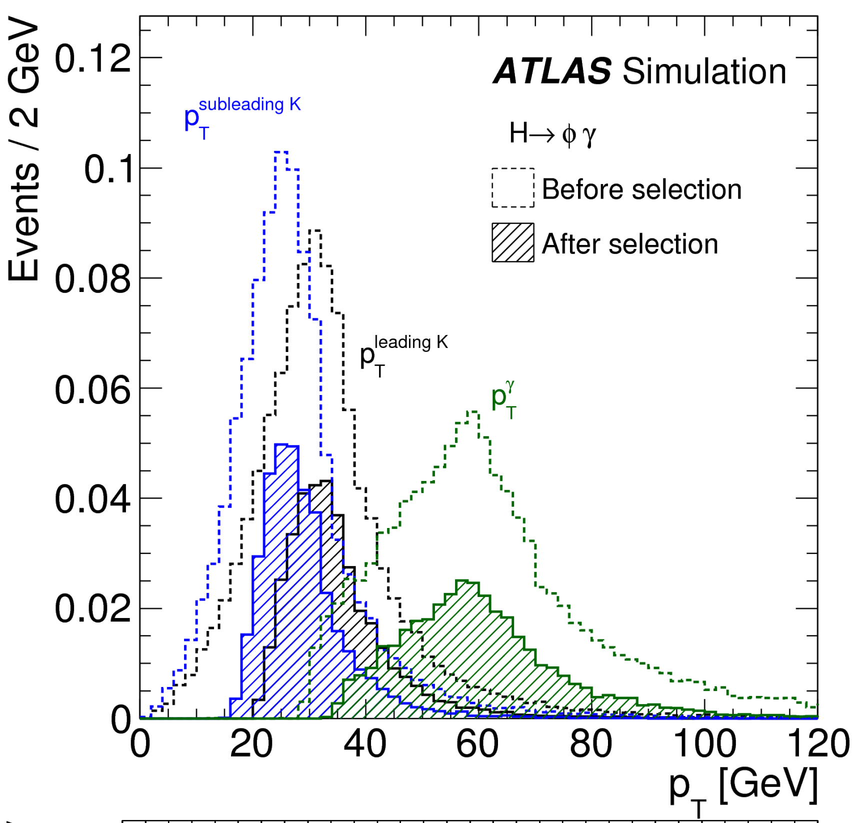
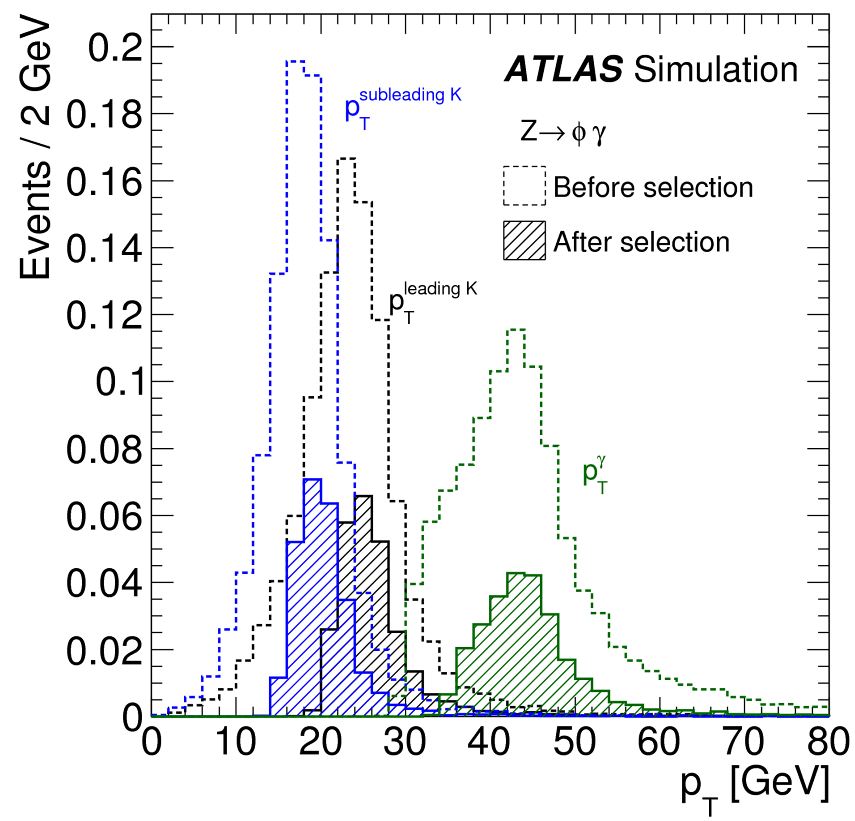
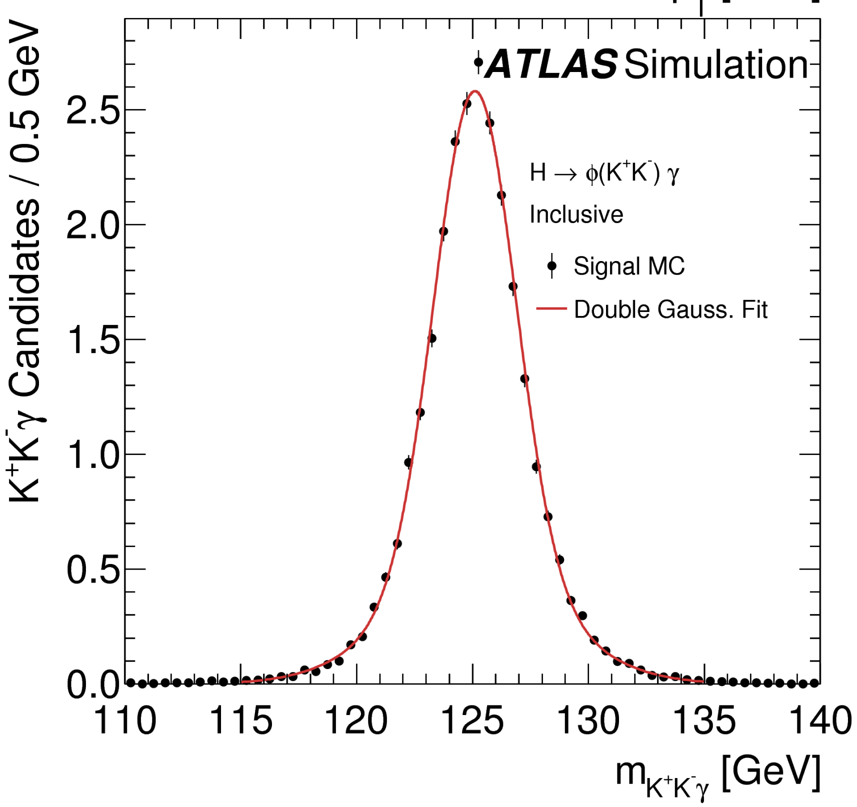
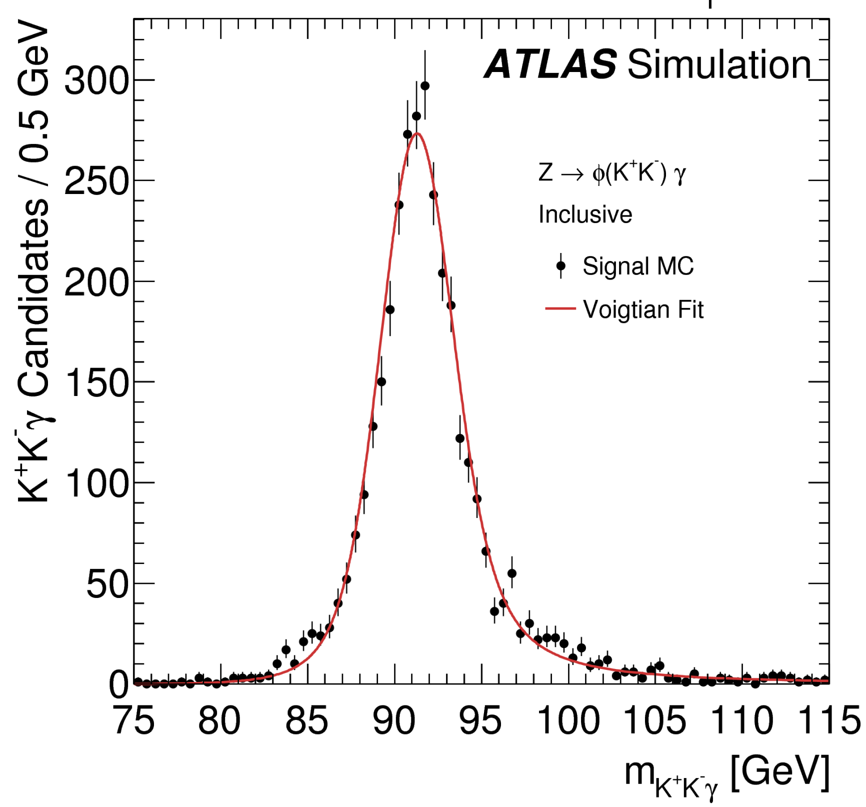


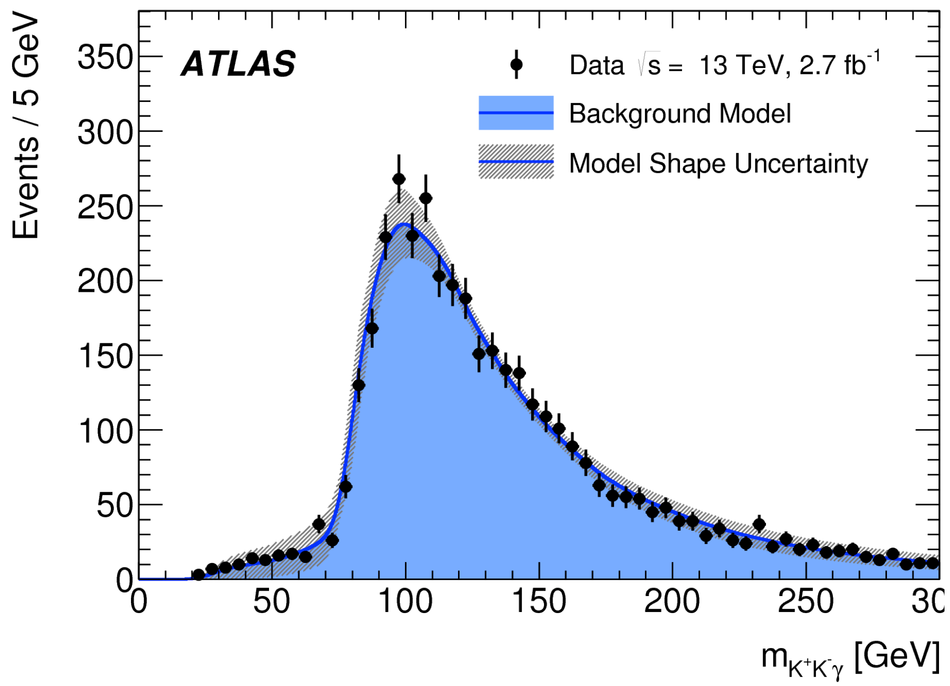



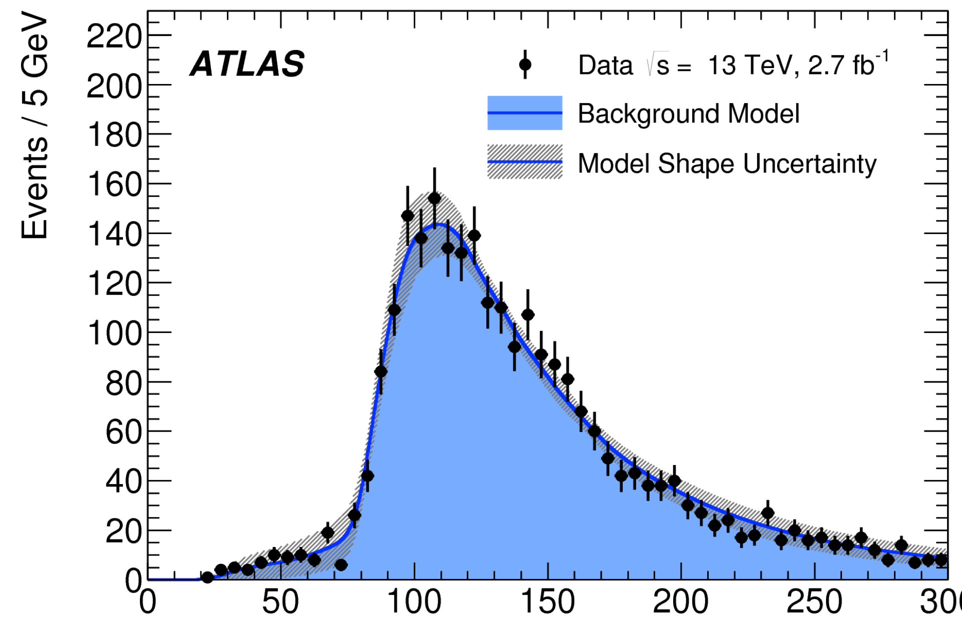

- **Inclusive analysis**
- **Total signal efficiency:**
  - 18% for Higgs boson
  - 8% for Z boson Muon
- **Mass resolution ~1.8%**

# h/Z→φγ: Background

- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. h/Z→$\mu\mu\gamma_{FSR}$) **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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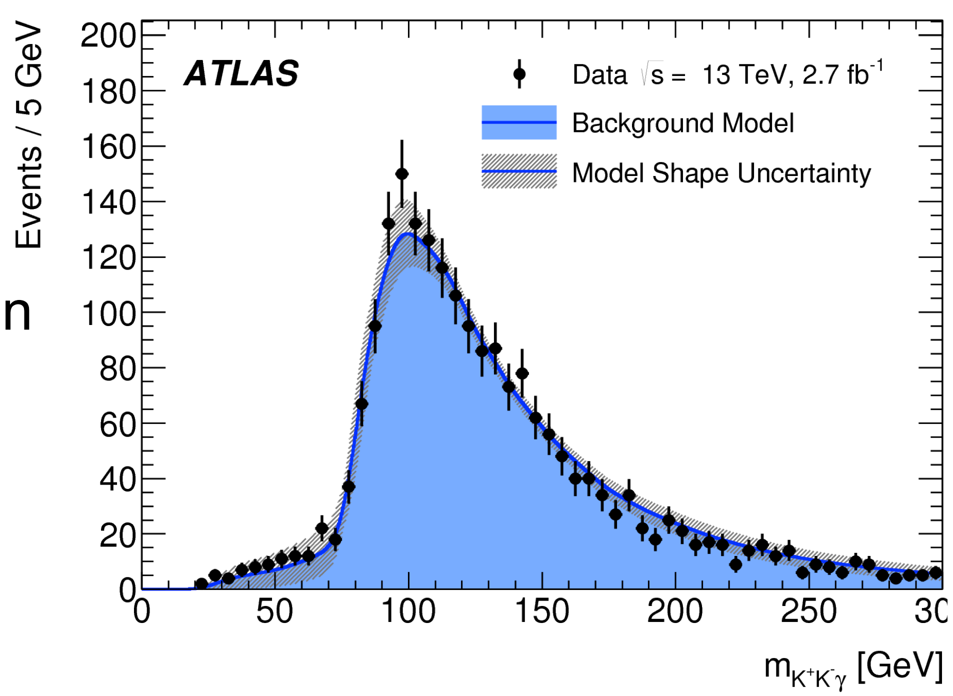
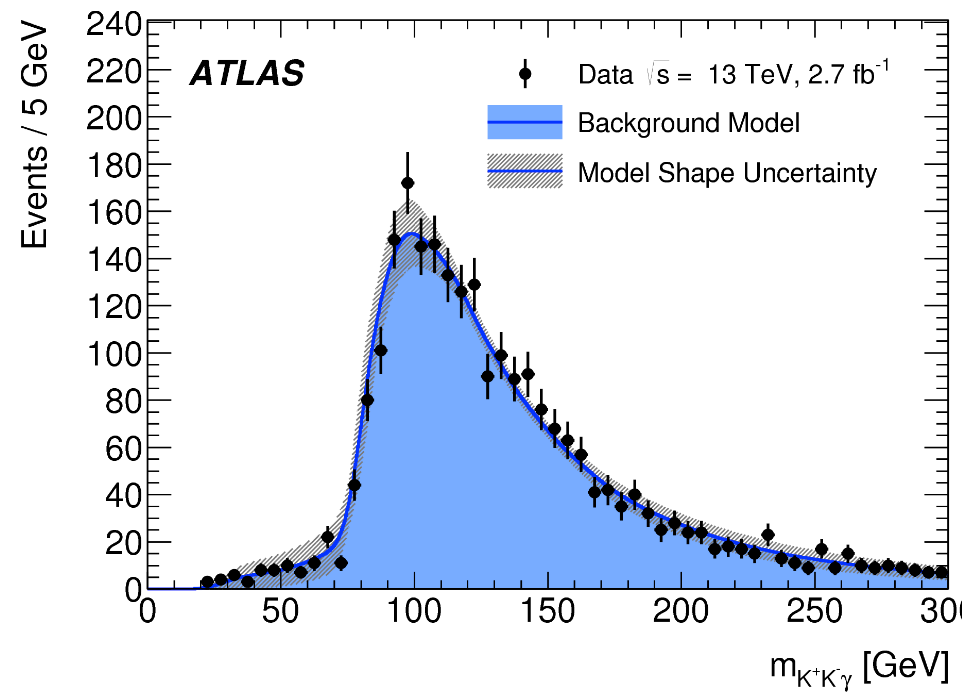
loose selection +γ-isolation



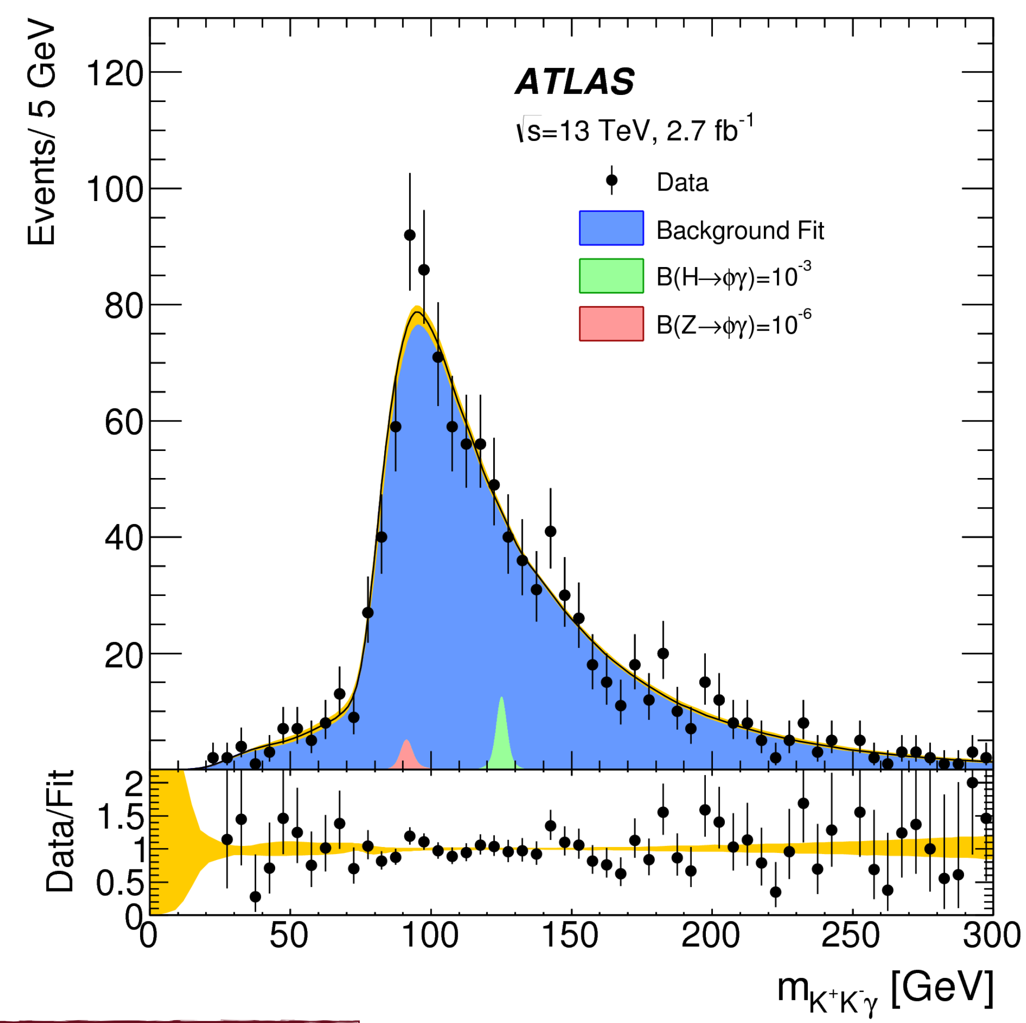

loose selection +KK-isolation

# 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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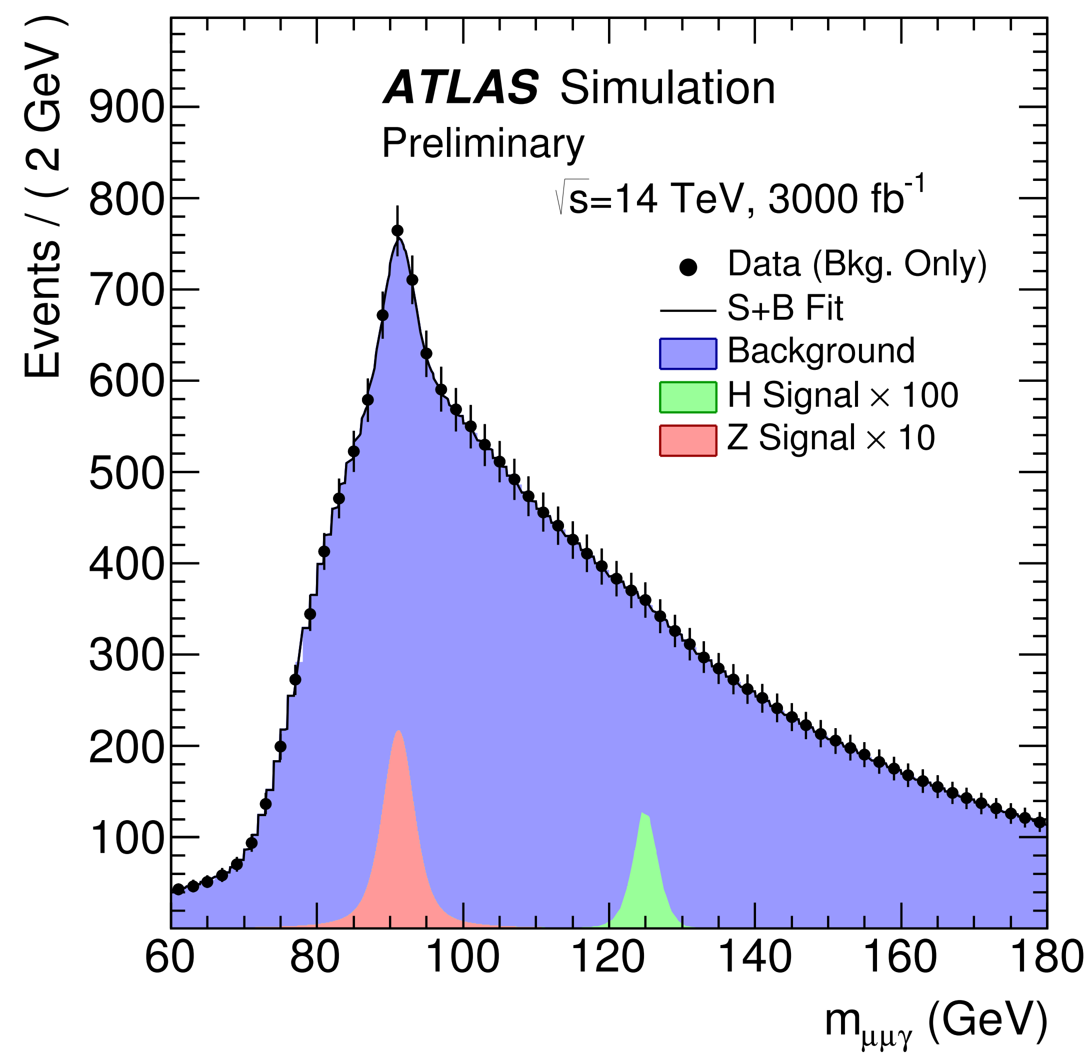
# h/Z→Qγ: in the future

- ☑ 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→μμγ$_{FSR}$~3×h→J/ψγ and (Z→μμγ$_{FSR}$ for Z)
  - ☐ Sensitive to "anomalous" h→γγ loop; use ratio to h→γγ

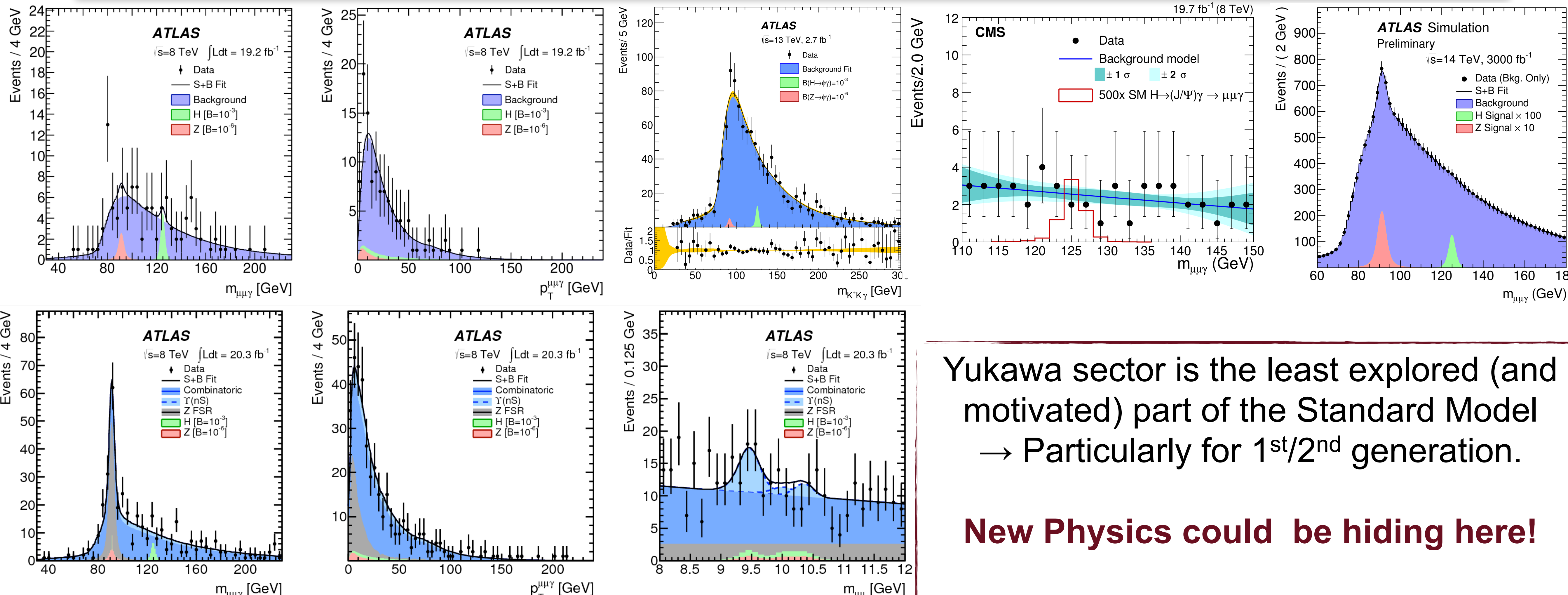
ATLAS-PHYS-PUB-2015-043

| | 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$^{-1}$ | $55^{+24}_{-15}$ | $44^{+19}_{-12}$ | $4.4^{+1.9}_{-1.1}$ |

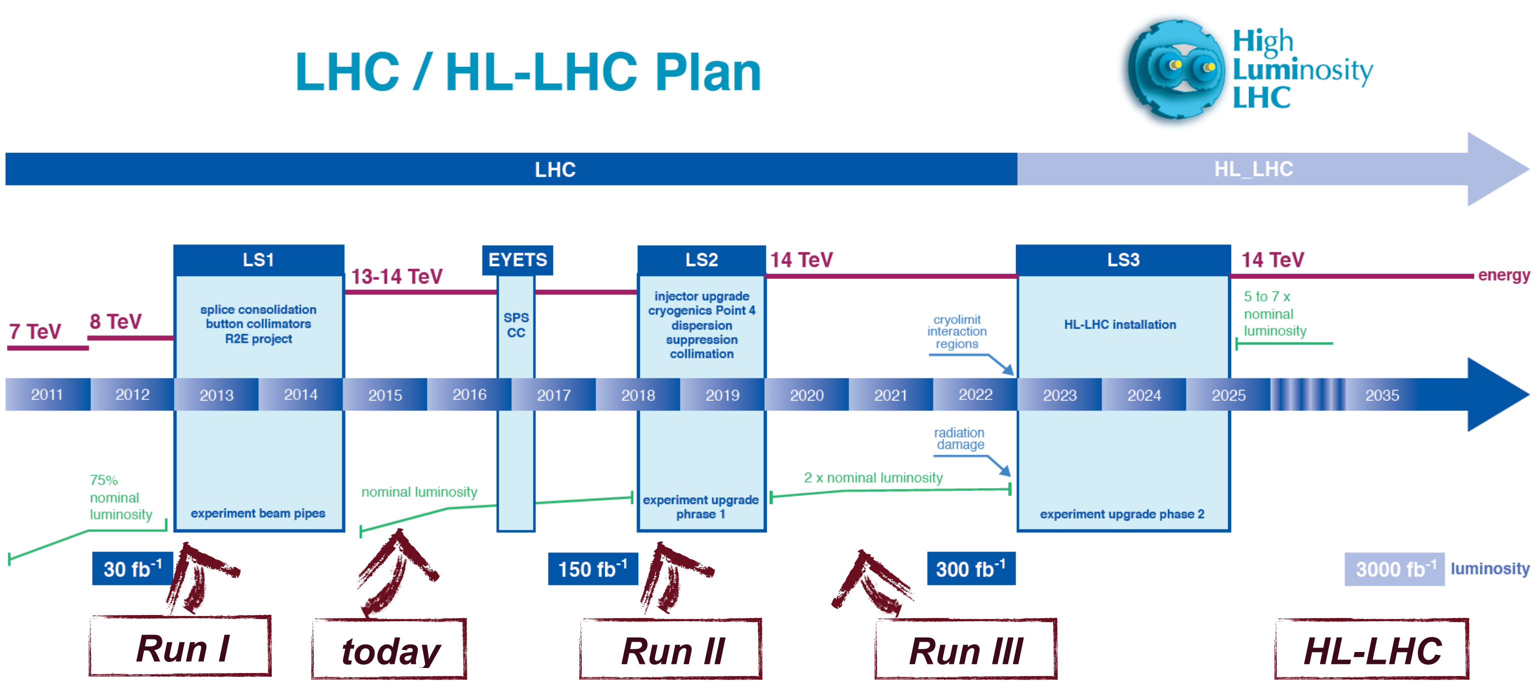
| | Standard Model expectation | |
|---|---|---|
| | $\mathcal{B}(H \to J/\psi\gamma)\,[\,10^{-6}\,]$ | $\mathcal{B}(Z \to J/\psi\gamma)\,[\,10^{-7}\,]$ |
| | 2.9 ± 0.2 | 0.80 ± 0.05 |



# Summary




## LHC / HL-LHC Plan




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

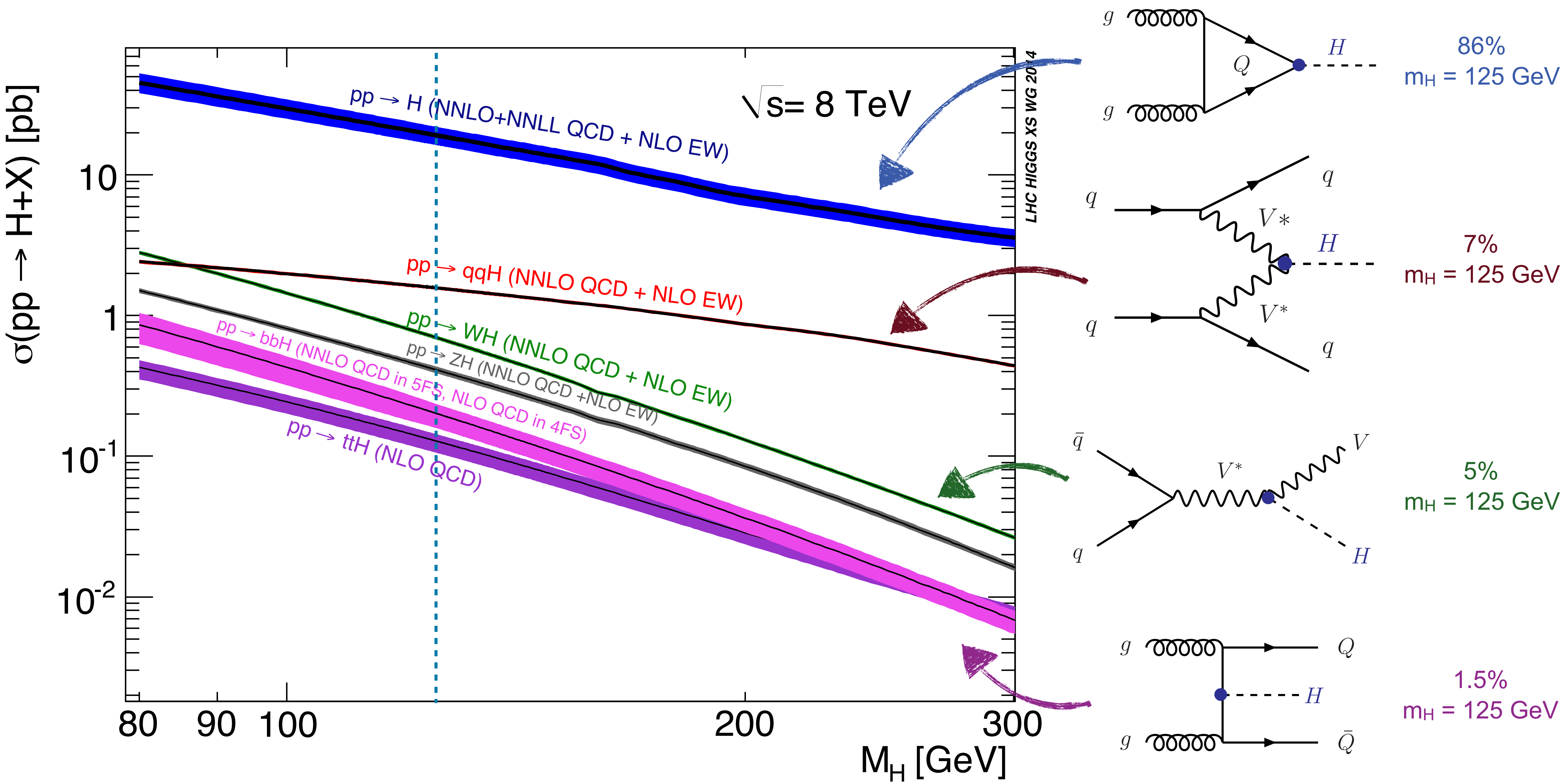
**New Physics could be hiding here!**

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

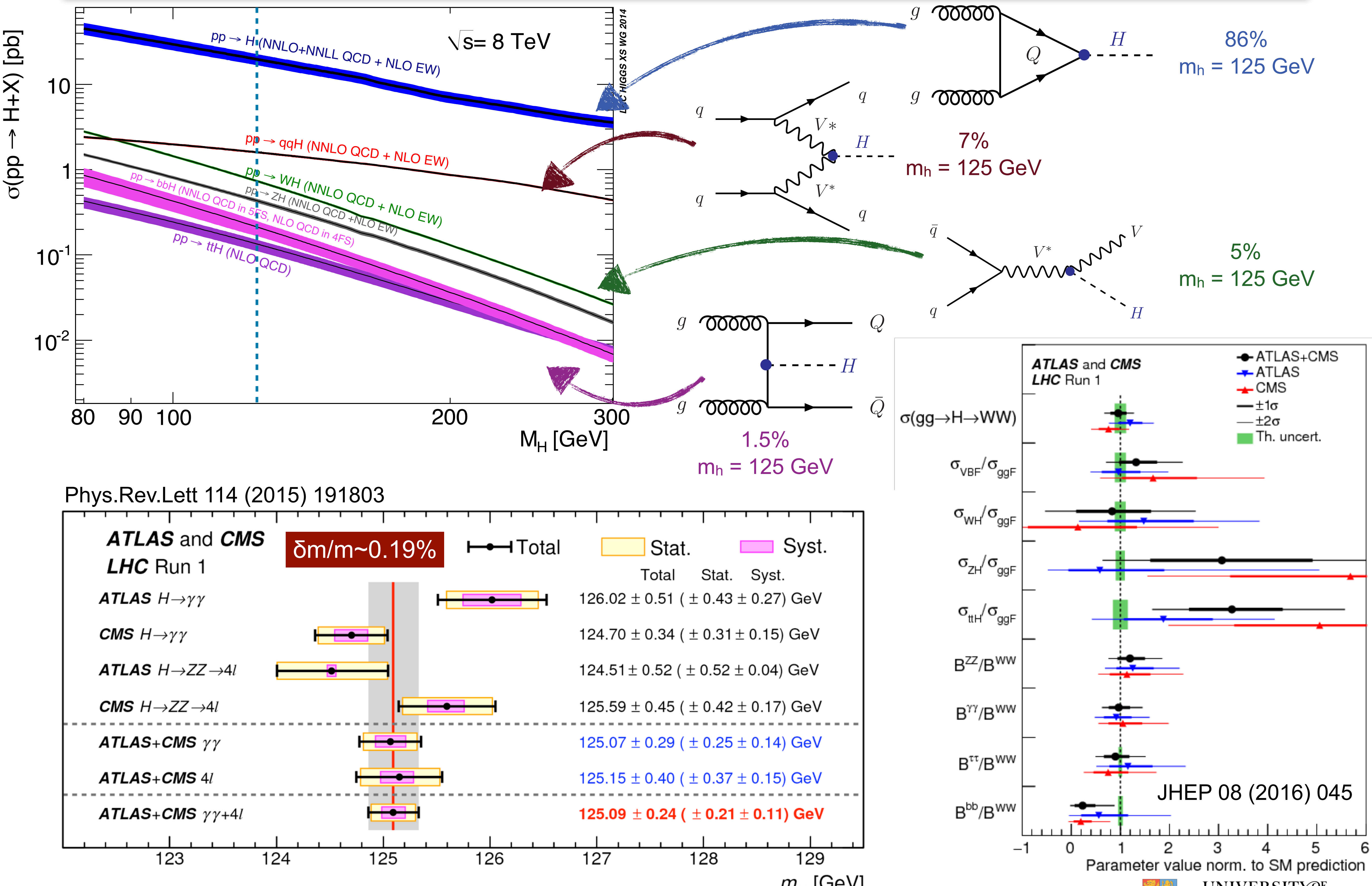
New field of study in Higgs sector; experimental and theoretical ingenuity required to elucidate this corner of the SM!

# Additional Slides

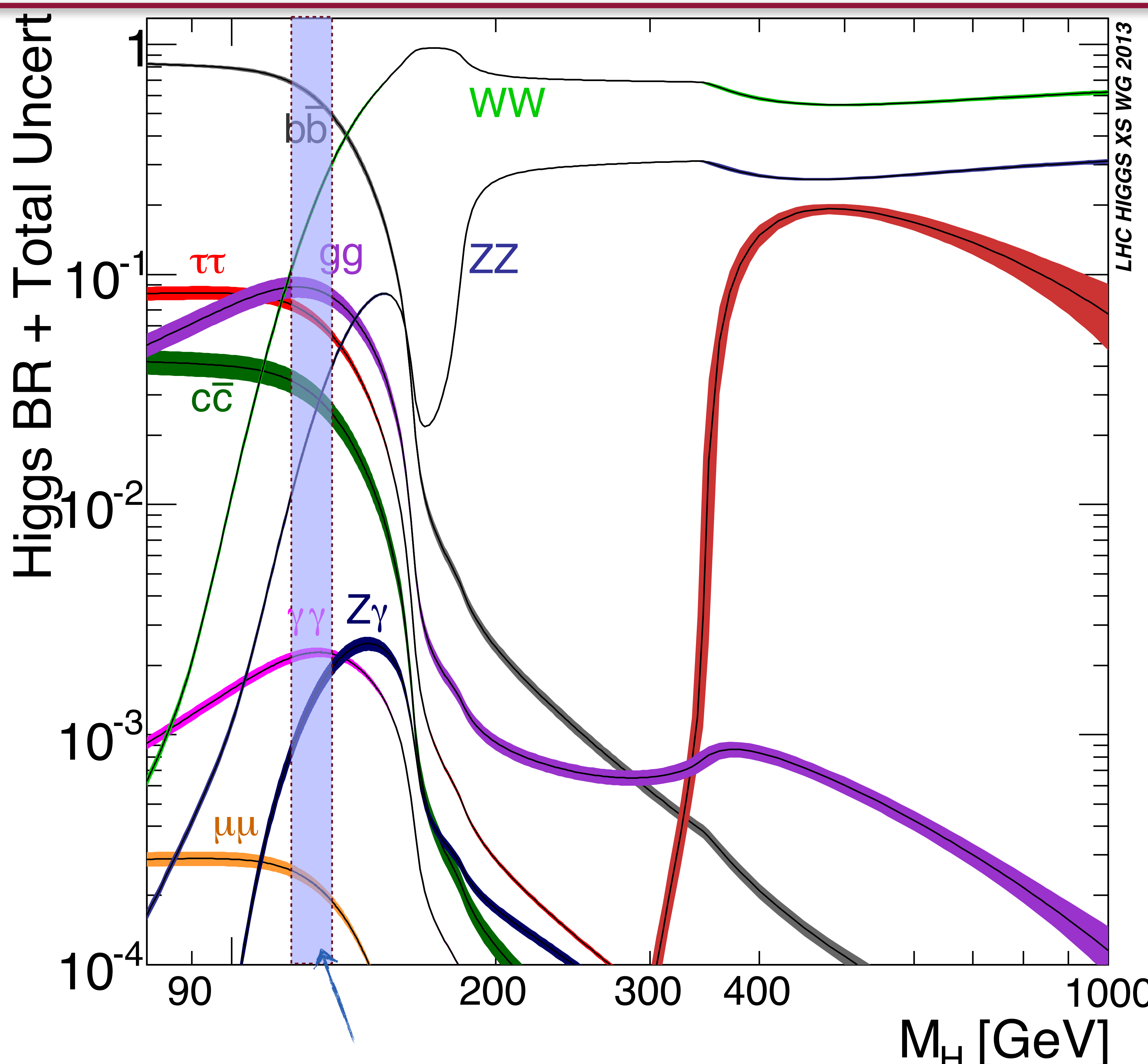
# SM Higgs boson production at the LHC



# Higgs boson at the LHC

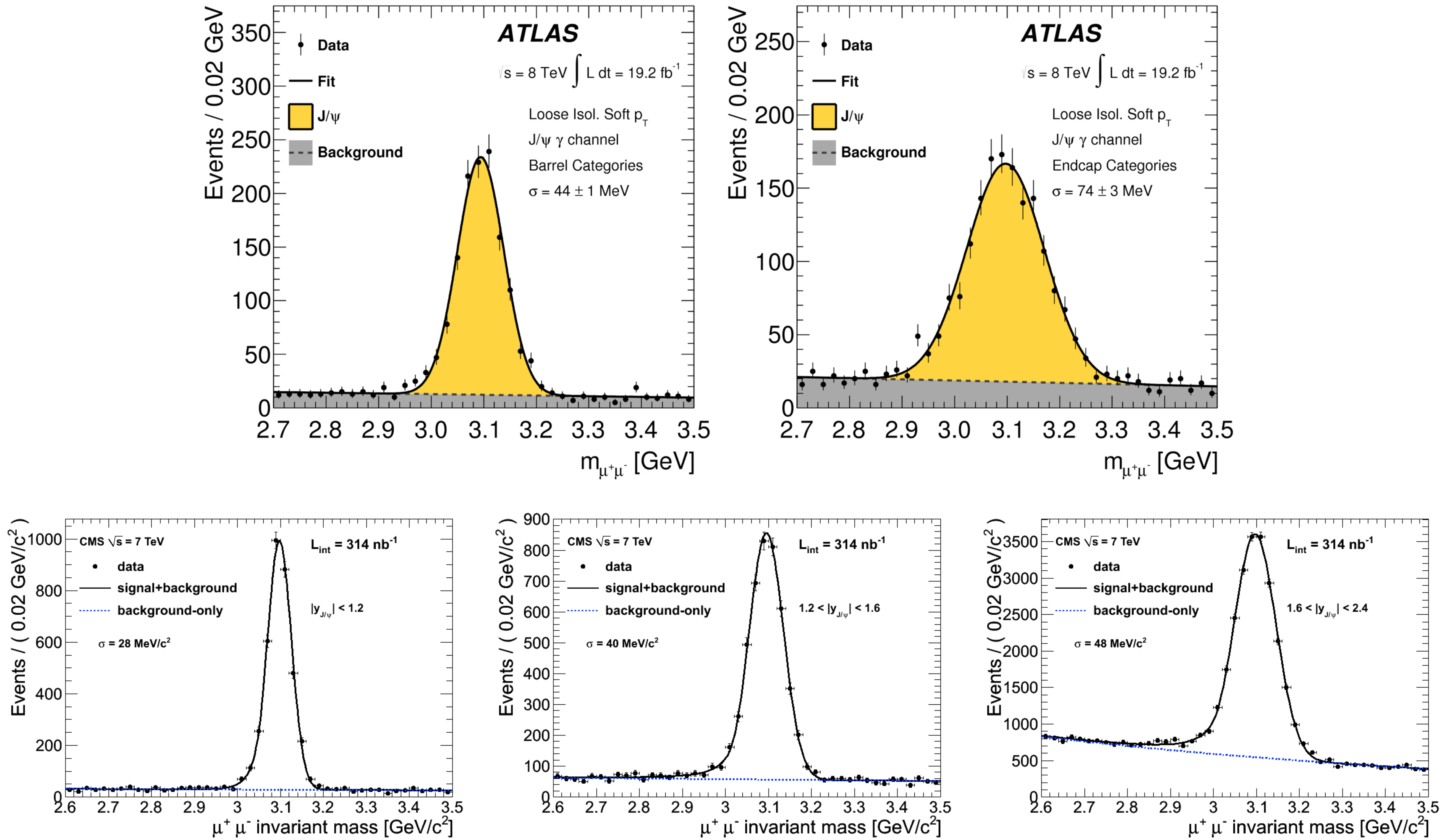


# SM Higgs boson decays




**$m_H$~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



# h/Z→J/ψγ and h/Z→Υ(ns)γ

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