Exclusive and rare Higgs boson decays

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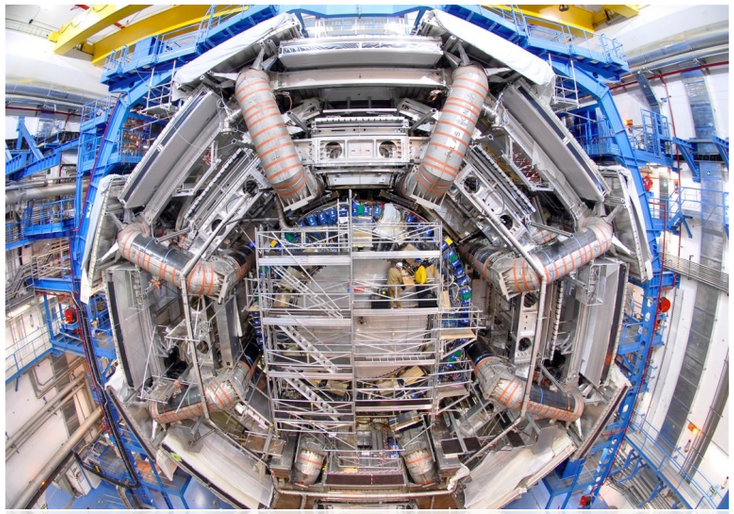
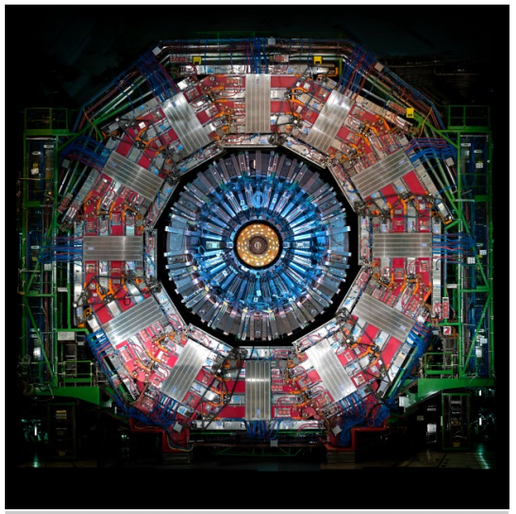
on behalf of
the ATLAS and CMS Collaborations


ATLAS detector


CMS detector

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erc
European Research Council
Established by the European Commission

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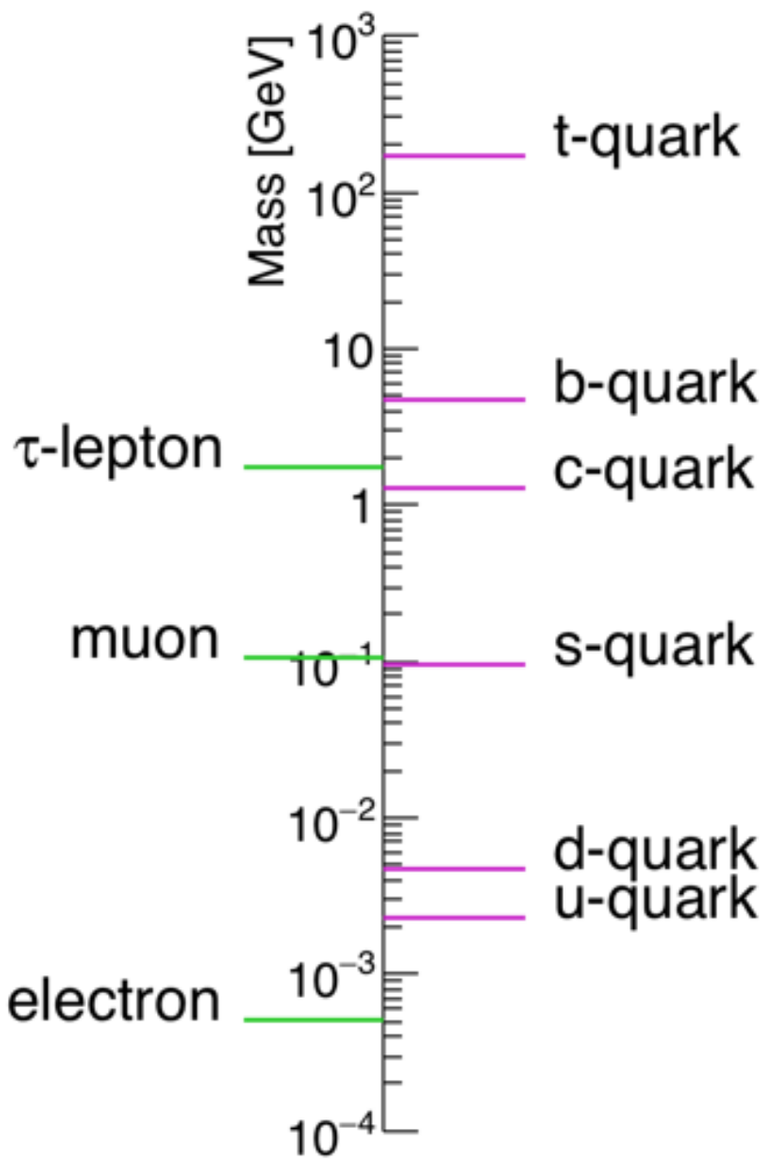
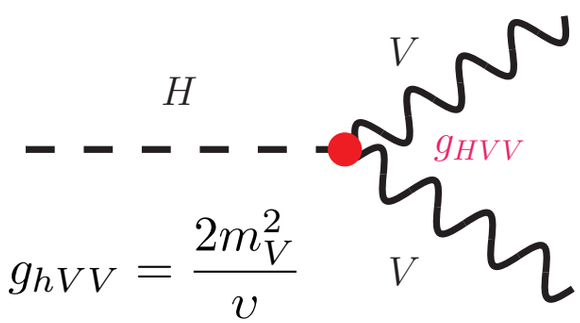
Higgs-fermion interactions: Yukawa couplings

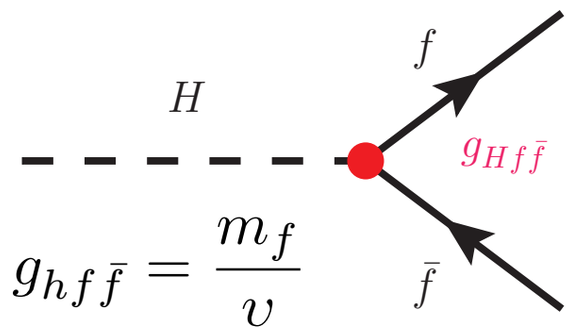
- **Higgs interactions to vector bosons:** defined by electroweak symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$



$$\frac{m_e}{m_t} \approx 3 \times 10^{-6}$$



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



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

- ☐ Yukawa couplings **not** imposed by fundamental principle
- ☐ Probing fermion mass generation scale→independent task
- ☐ Fermion mass generation scale from **unitarity bounds**:

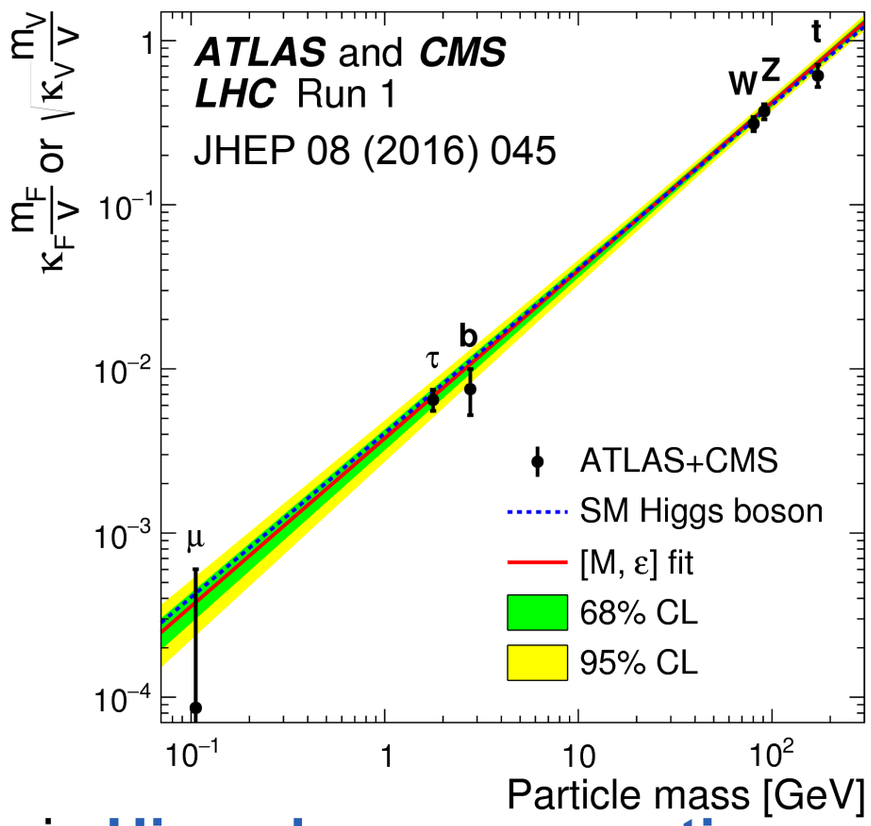
$$\Lambda \approx 23, 31, 52, 77, 84 \text{ TeV}_{\text{(b,c,s,d,u)}}$$

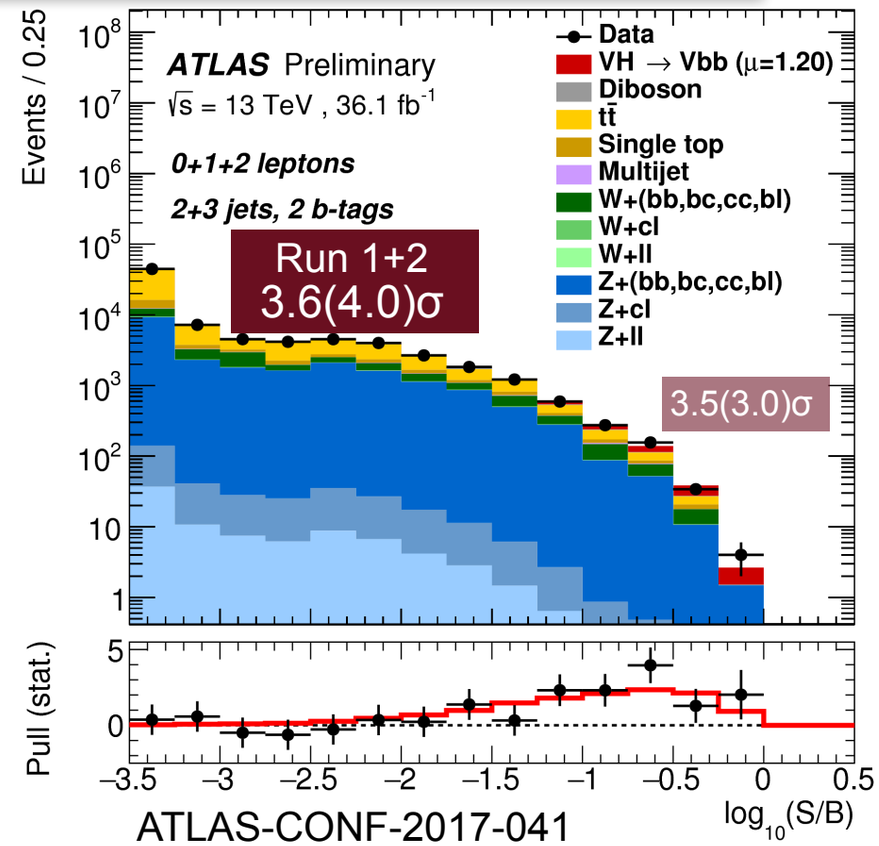
[Phys. Rev. Lett. 59, 2405 (1987); Phys.Rev. D71 (2005) 093009]

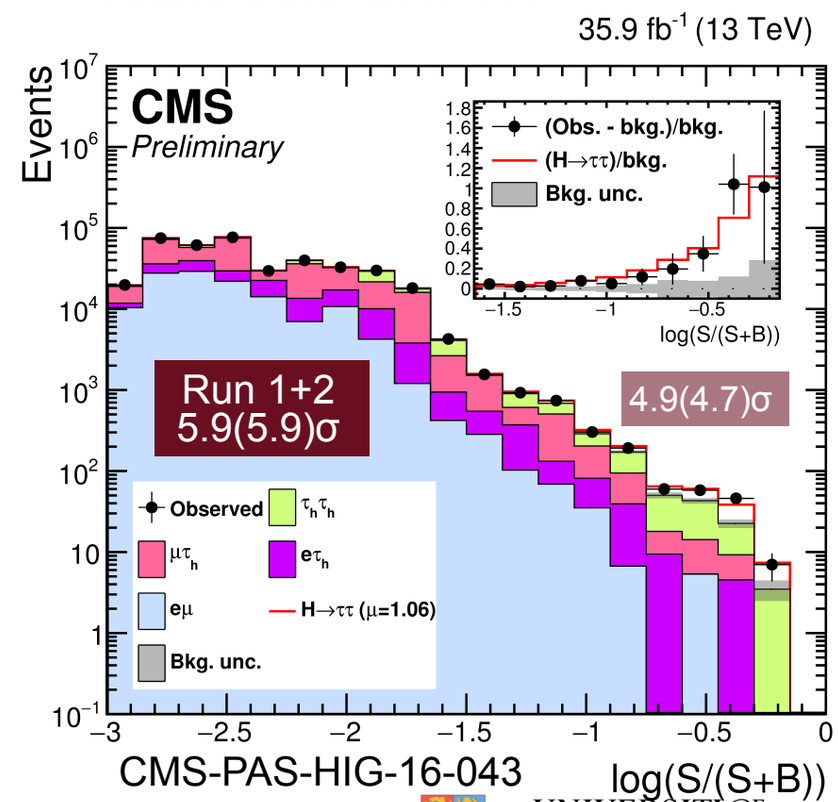
- ☑ Modified Higgs-fermion couplings in BSM scenarios
  - Concise summary in LHC Higgs Cross-section WG YR4 [arxiv:1610.07922]
  - Effects suppressed $1/\Lambda^2$ or proportional to mixing angles with extra scalars.

Higgs-fermion interactions: The story so far

[in a nutshell]







Progress in **Higgs boson properties**:

- ☑ **mass** known to better than 0.19%
- ☑ **bosonic decays** measured to ~10-20%

For **3rd generation fermions**:

- ☑ **t-quark:** several significant ttH excesses; indirect evidence
- ☑ **b-quark:** evidence for h→bb at LHC and Tevatron
- ☑ **τ-lepton:** h→ττ observation established

For **1st/2nd generation fermions**, different picture:

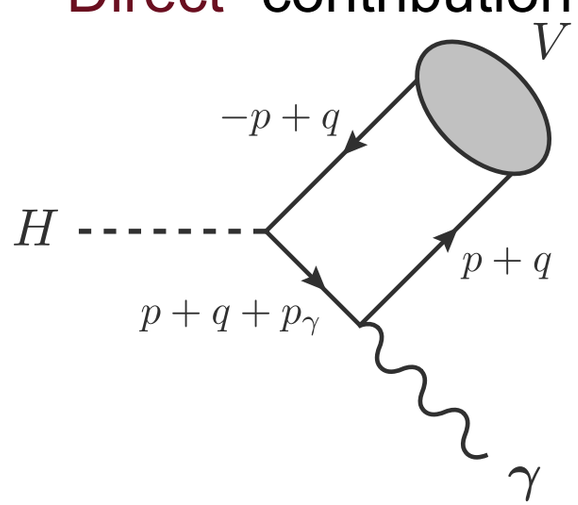
- ☐ **e/μ:** no evidence yet → established non-universality
- ☐ **c-quark:** no direct evidence, loose bounds from h→bb
- ☐ **u/d/s-quarks:** no inclusive searches available

▶ Higgs couplings: margin for undetected/unobserved decays

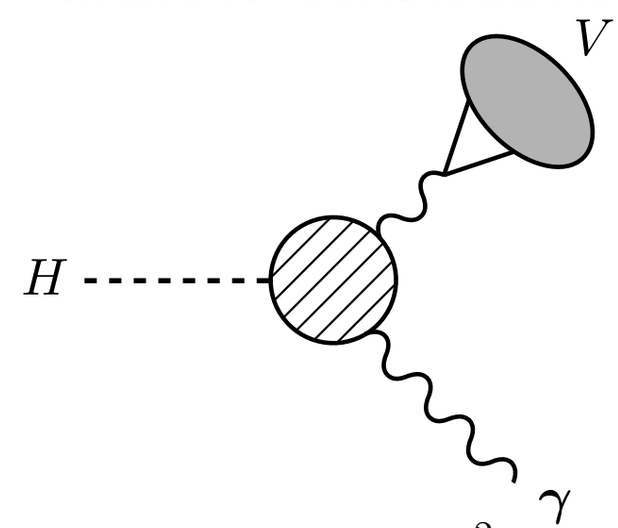
Exclusive Decays h→Qγ

- **h→Qγ decays: clean probe** for Higgs-quark couplings for 1st/2nd generation quarks
  - Q is a vector meson or quarkonium state
- **Two contributions:** direct and indirect amplitude
  - **Direct amplitude:** provides sensitivity to Higgs-quark couplings
  - **Indirect amplitude:** insensitive to Higgs-quark couplings; larger than direct amplitude
  - **Destructive interference**

"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 h→Qγ

- ☑ Substantial interest from theory community on branching ratio estimates and feasibility

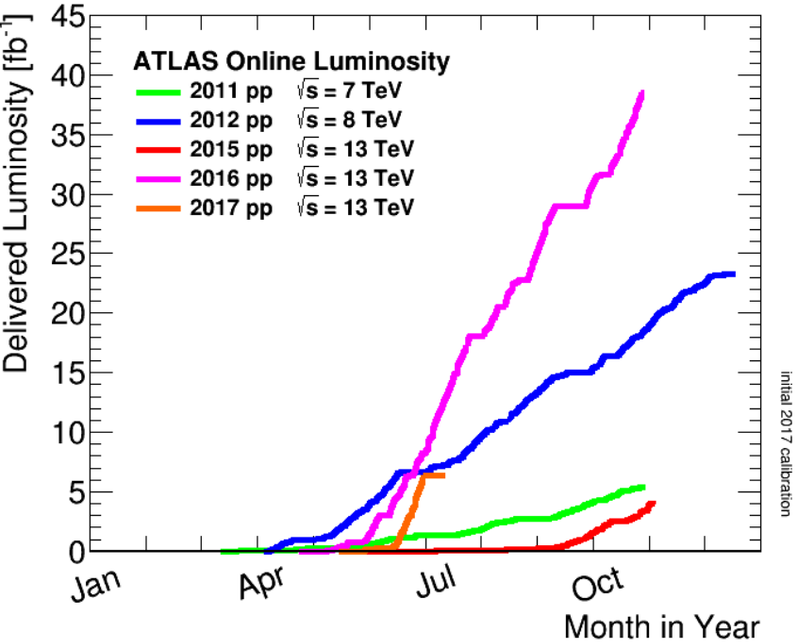
Mode	Branching Fraction $[10^{-6}]$		
Method	NRQCD [1487]	LCDA LO [1486]	LCDA NLO [1489]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	2.95 ± 0.17
$\mathrm{Br}(h \to \Upsilon(1S)\,\gamma)$	$(0.61\,^{+1.74}_{-0.61}) \cdot 10^{-3}$	–	$(4.61\,^{+1.76}_{-1.23}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(2S)\,\gamma)$	$(2.02\,^{+1.86}_{-1.28}) \cdot 10^{-3}$	–	$(2.34\,^{+0.76}_{-1.00}) \cdot 10^{-3}$
$\mathrm{Br}(h \to \Upsilon(3S)\,\gamma)$	$(2.44\,^{+1.75}_{-1.30}) \cdot 10^{-3}$	–	$(2.13\,^{+0.76}_{-1.13}) \cdot 10^{-3}$
	PRD90 (2014) 113010	PRL 114 (2015) 101802	JHEP 1508 (2015) 012

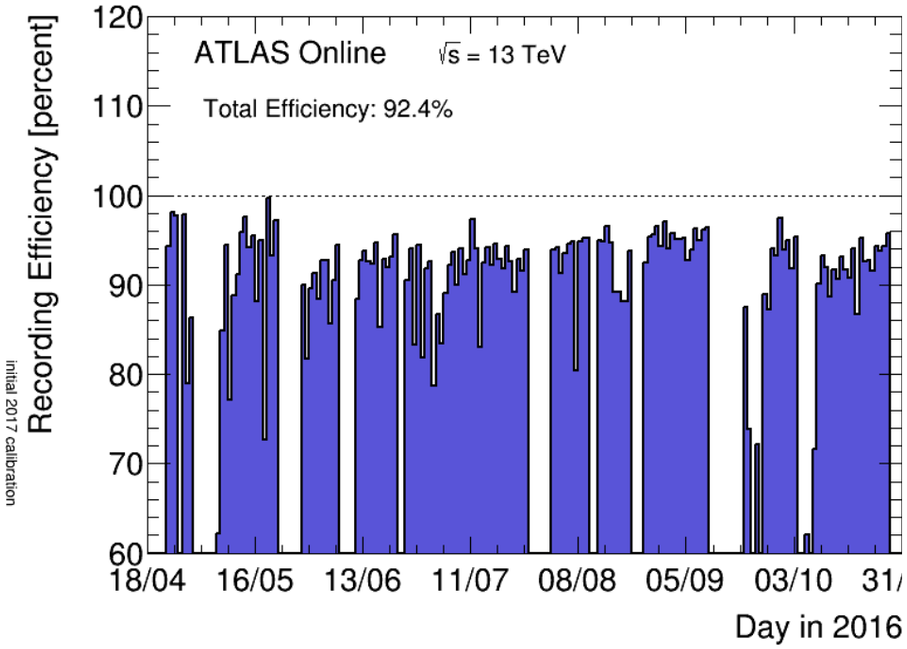
- ☑ Z→Qγ decays also interesting
- ☑ Experimentally unconstrained
  - LEP: accurately measured b-/c-quark couplings (~1%)
  - light quark couplings less constrained
- ☑ Sensitive to BSM contributions

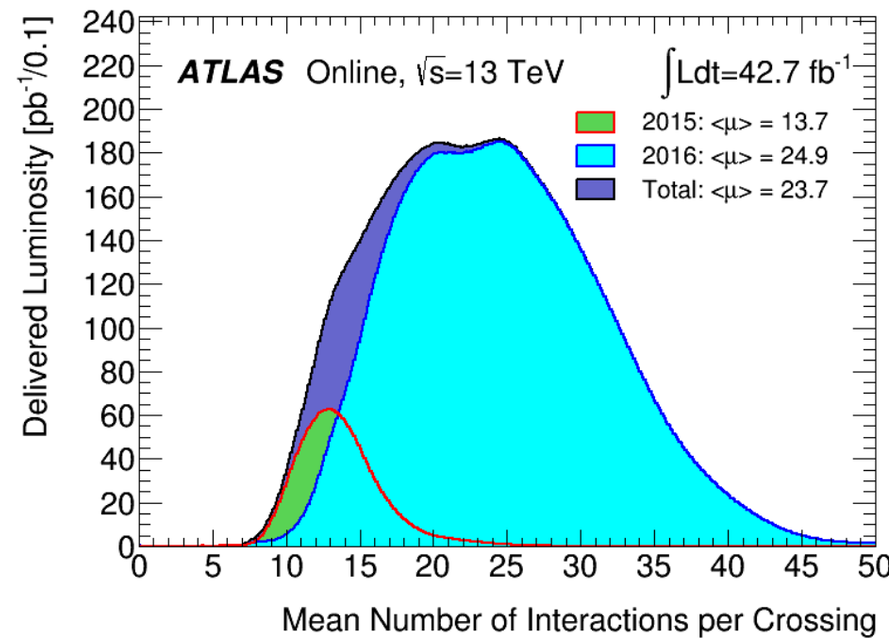
Decay mode	Branching ratio
$Z^0 \to \pi^0\gamma$	$(9.80\,^{+0.09}_{-0.14}{}_{\mu} \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,^{+0.04}_{-0.06}{}_{\mu} \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,^{+0.03}_{-0.05}{}_{\mu}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

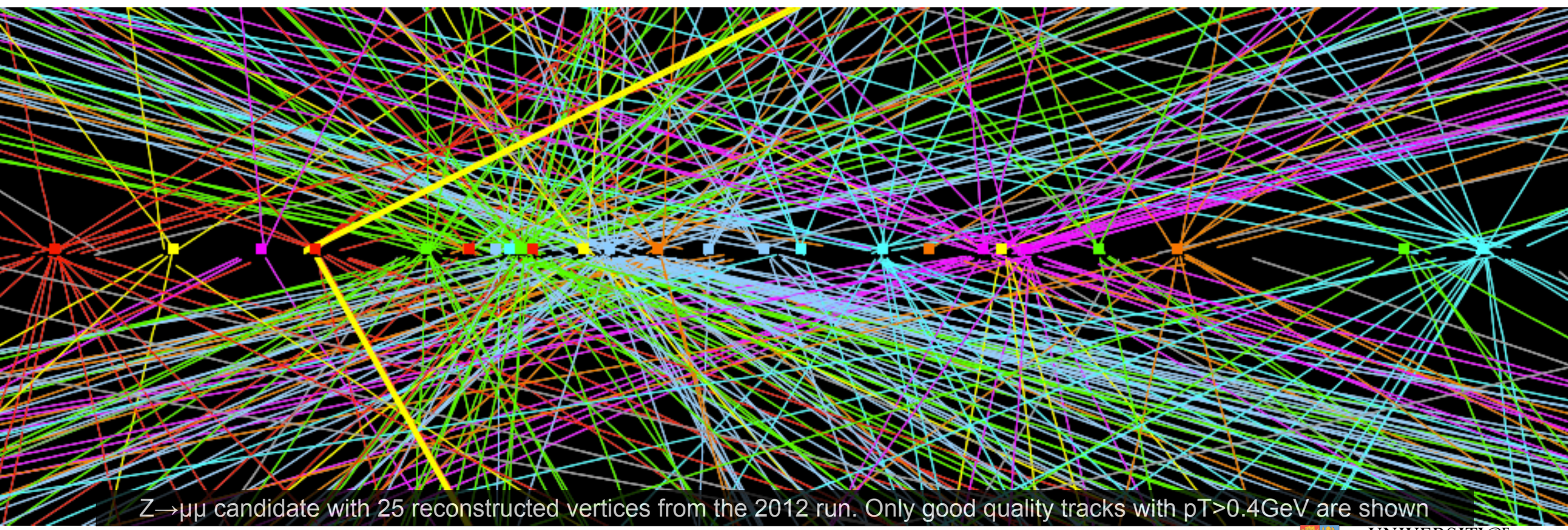
JHEP 1504 (2015) 101

Dataset and pile-up



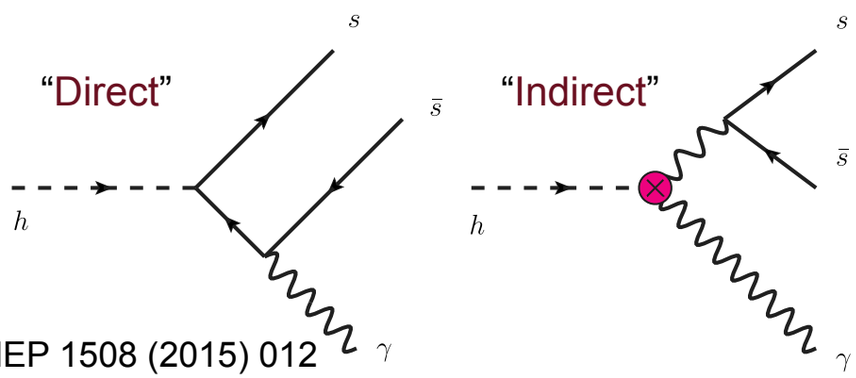






Z→μμ candidate with 25 reconstructed vertices from the 2012 run. Only good quality tracks with pT>0.4GeV are shown

Search for h/Z→φγ and ργ



JHEP 1508 (2015) 012

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

PRL 117, 111802 (2016) PHYSICAL REVIEW LETTERS week ending 9 SEPTEMBER 2016

Search for Higgs and Z Boson Decays to $\phi\gamma$ with the ATLAS Detector

M. Aaboud *et al.*[*]
(ATLAS Collaboration)

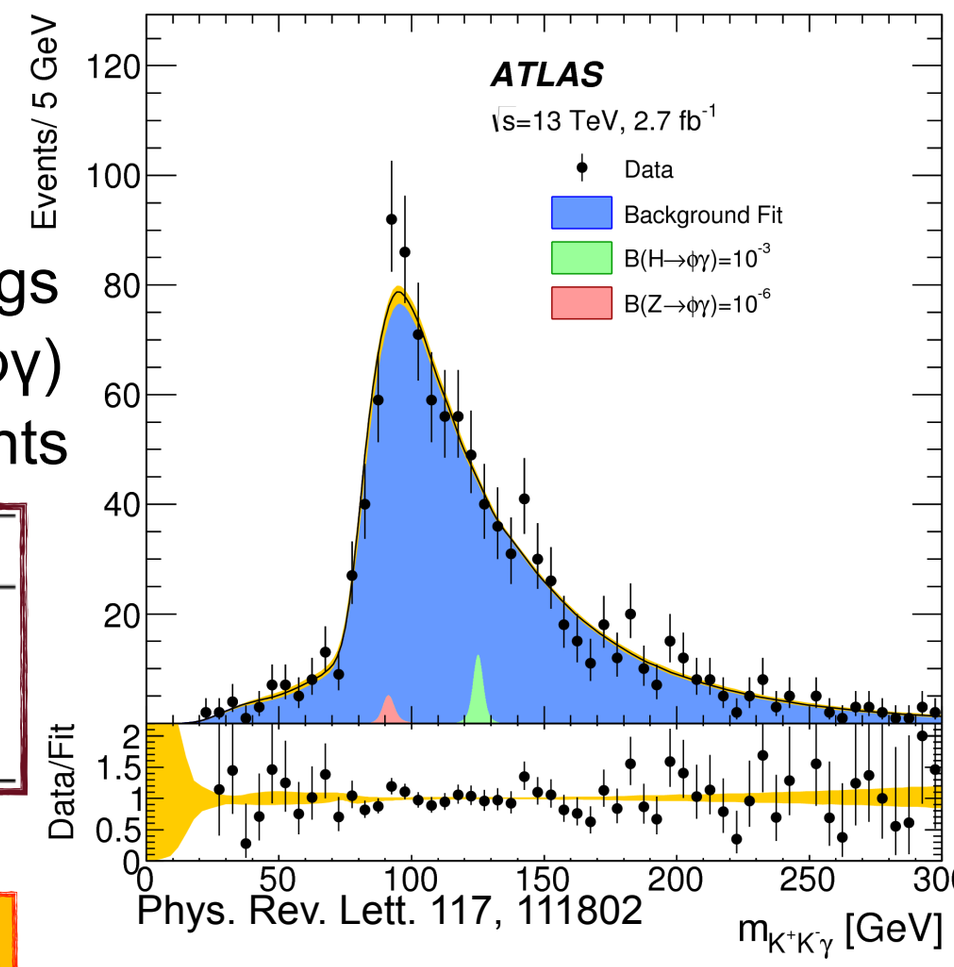
(Received 14 July 2016; published 9 September 2016)

A search for the decays of the Higgs and Z bosons to a ϕ meson and a photon is performed with a pp collision data sample corresponding to an integrated luminosity of 2.7 fb^{-1} collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC. No significant excess of events is observed above the background, and 95% confidence level upper limits on the branching fractions of the Higgs and Z boson decays to $\phi\gamma$ of 1.4×10^{-3} and 8.3×10^{-6}, respectively, are obtained.

DOI: 10.1103/PhysRevLett.117.111802

- ☑ **First search**, with 2.7 fb^{-1} at 13 TeV collected in 2015
- ☑ **h→φγ sensitive to strange quark Yukawa coupling**
  - challenging to access with inclusive h→ss decays!
- ☑ **Looking for new physics** through anomalous couplings
  - possible in various BSM scenarios, modifies BR(h→φγ)
- ☑ Z→φγ not directly constrained by existing measurements

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

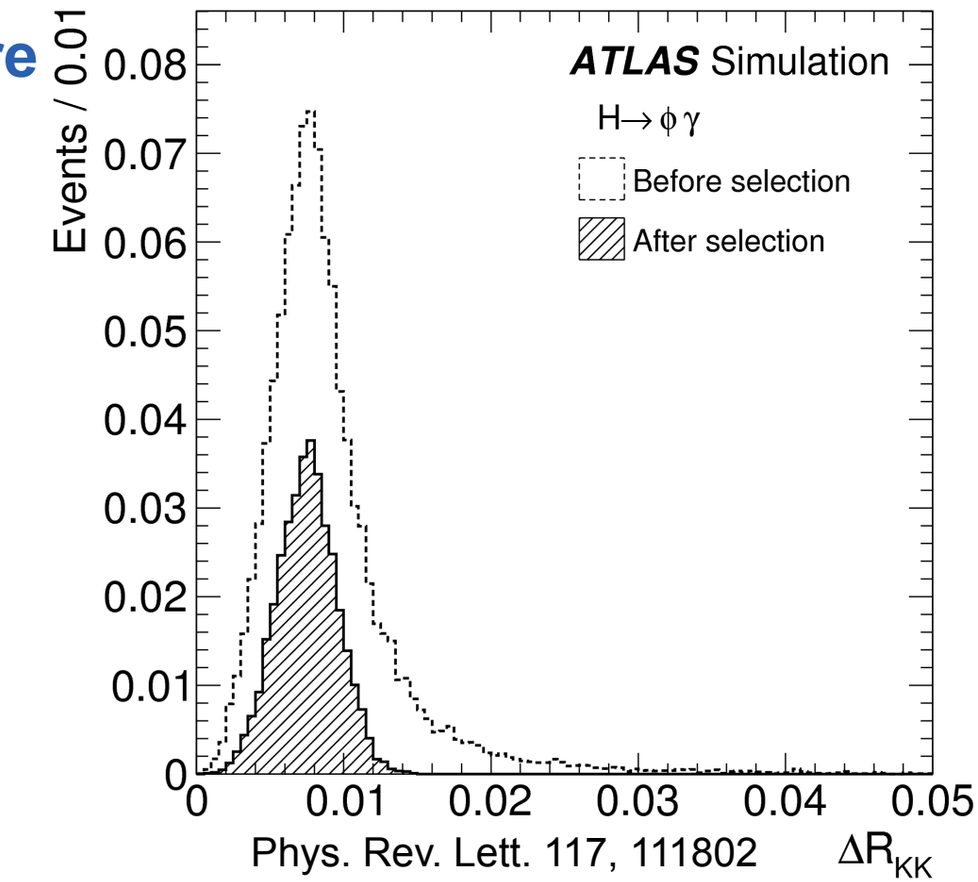


- ☑ **New results for Summer 2017!**
  - updated h/Z→φγ
  - added h/Z→ργ probing up- and -down quark couplings to Higgs boson

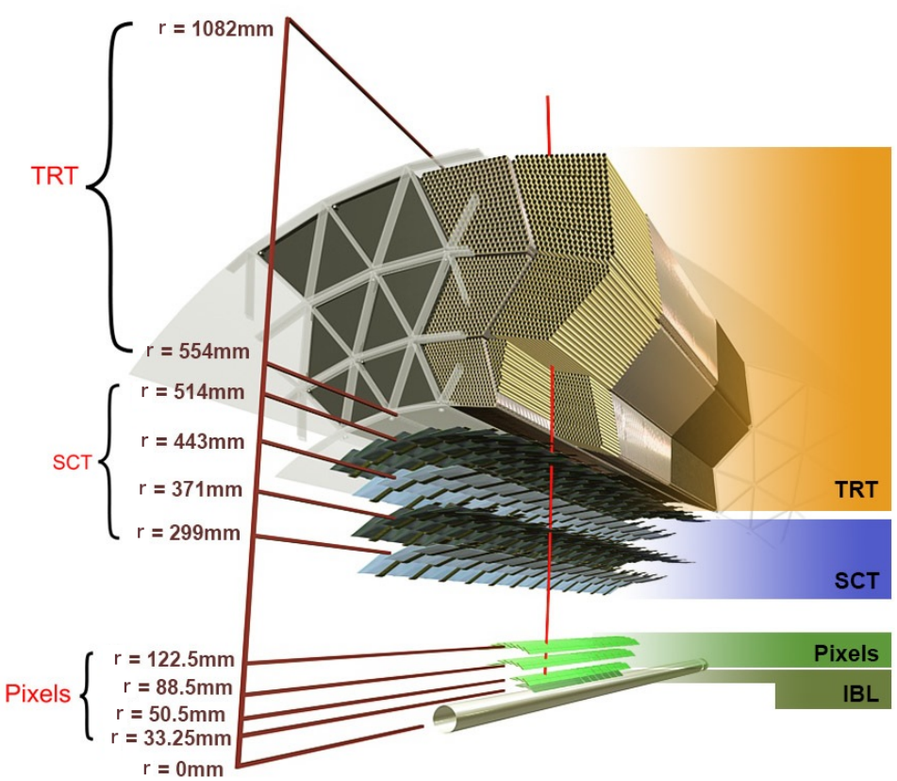
ATLAS-CONF-2017-057

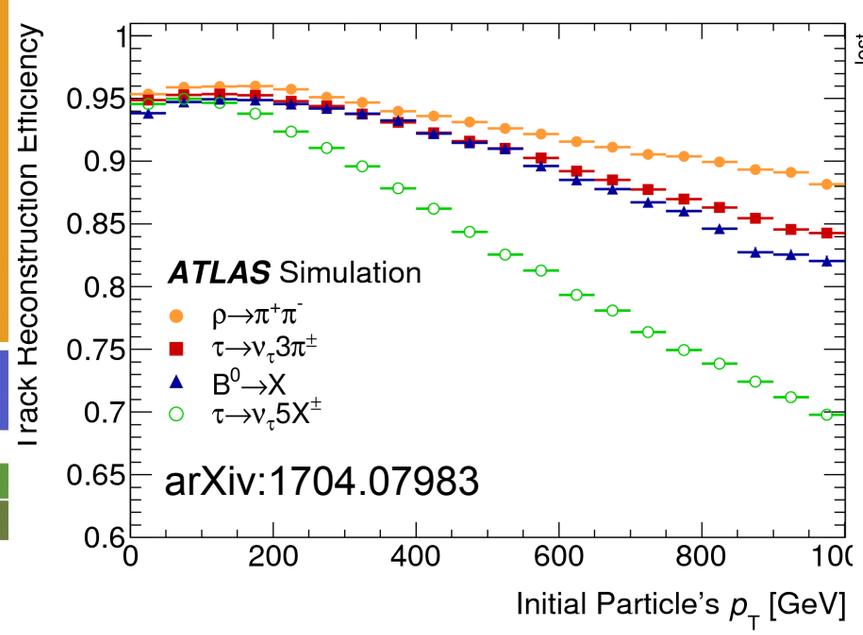
Analysis Strategy

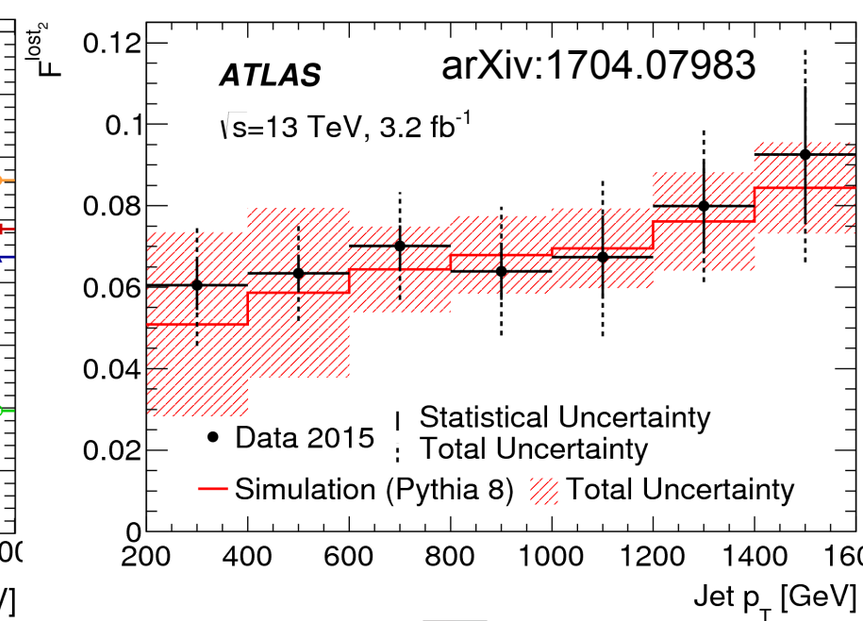
- ☑ **Exclusive decays → distinct experimental signature**
  - Pair of collimated high-pT isolated tracks recoils against high-pT isolated photon
- ☑ **Meson decays:**
  - **$\varphi \to K^+K^-$**, BR=49%
  - **$\rho \to \pi^+\pi^-$**, BR~100%
- ☑ **Small opening angles between decay products**
  - Particularly for $\varphi \to K^+K^-$
  - Tracking in dense environments



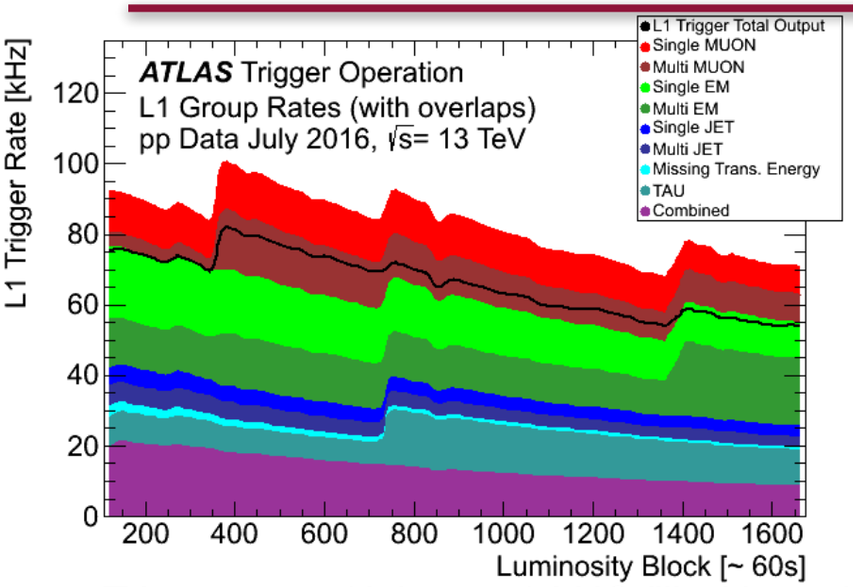
Phys. Rev. Lett. 117, 111802

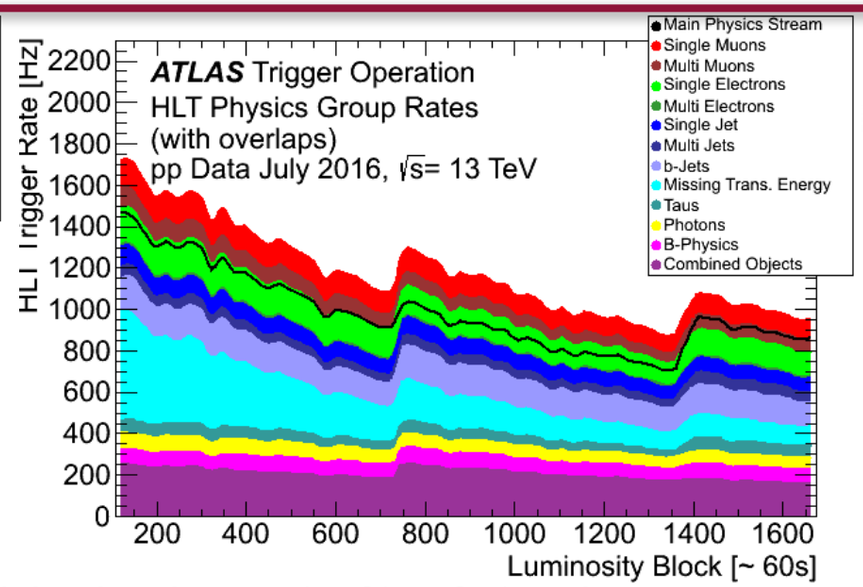






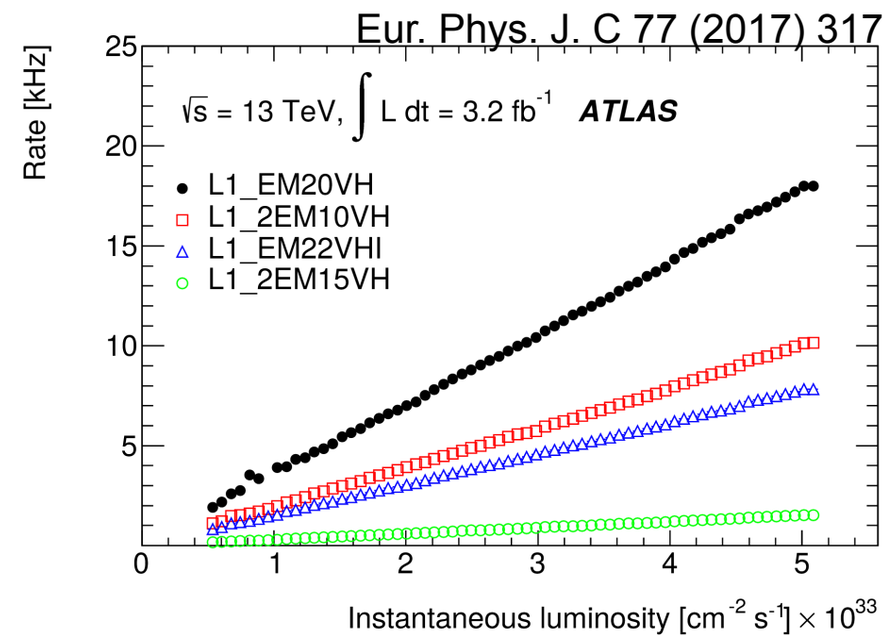
Trigger Strategy



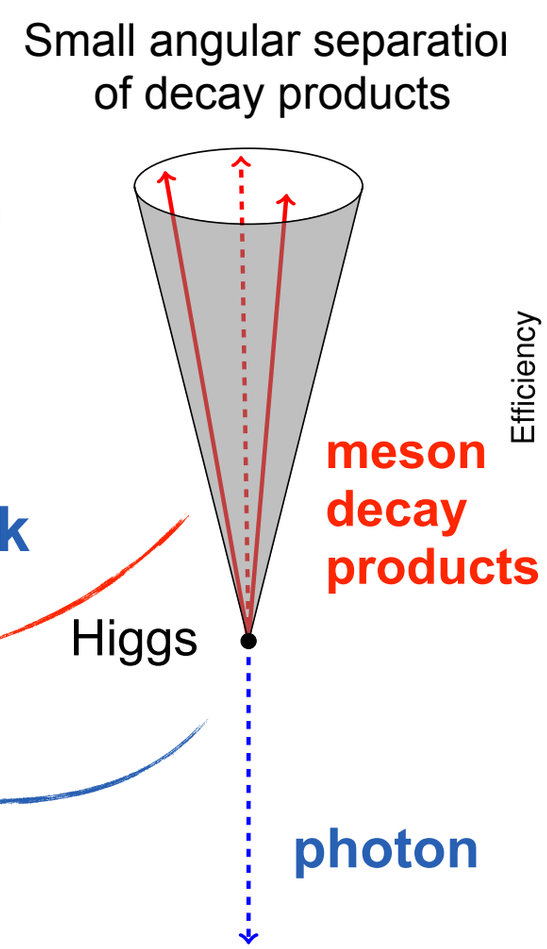


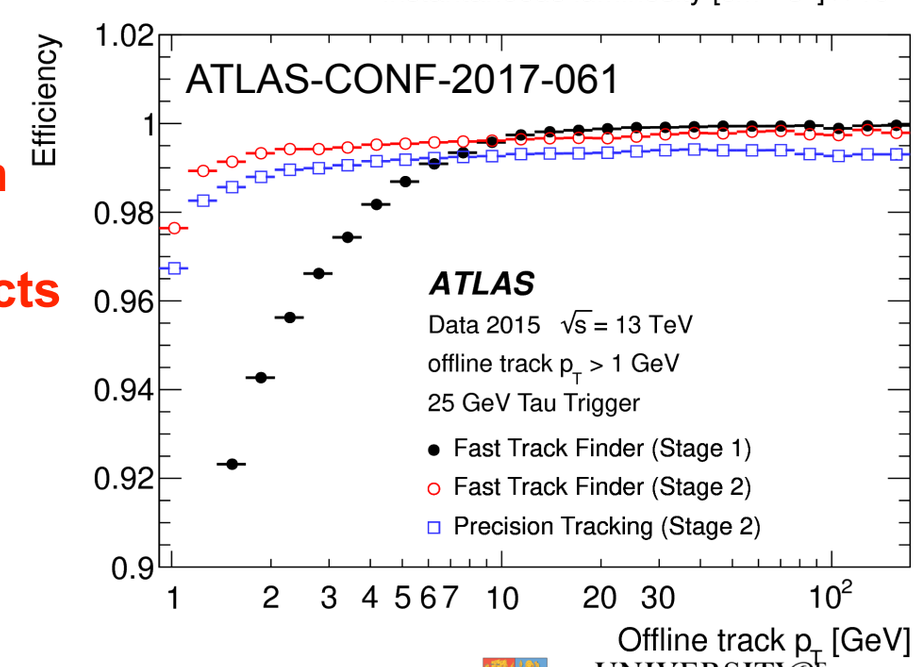
Trigger rates (July 2016) LHC fill with peak luminosity $1.02*10^{34}cm^{-2}s^{-1}$ and <μ>= 24.2

- **Two-level trigger system**
  - Level-1: Hardware-based
  - HLT: Software-based



- **Enabled by dedicated trigger items**
  - Modified τ-lepton algorithms
  - Activated: 9/2015 (φγ) and 5/2016 (ργ)
  - Efficiency ~80% w.r.t offline selection
- **Level-1: Isolated EM object**
  - Lowest pT unprescaled EM object
- **HLT: Collimated/isolated high-pT track pair recoiling against high-pT photon**
  - Isolated di-track (leading p_T>15 GeV) consistent with m_{Meson}
  - Photon ($p_{T\gamma}$>35 GeV)



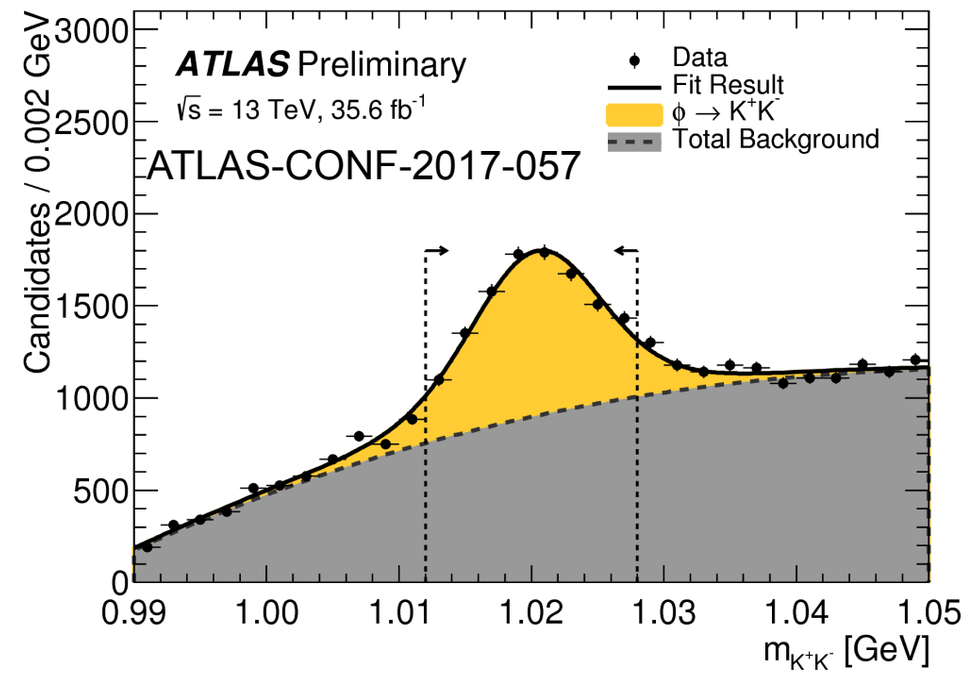


Event Selection

Tracks

- No particle identification available at momentum range, all tracks considered K/π
- Two opposite charged tracks
  - Leading pT>20GeV, sub-leading pT>15 GeV
- di-track consistent to m_φ±8 MeV or m_ρ±140 MeV
- track-based isolation
- di-track system must satisfy:

$$p_{\mathrm{T}}^{M} > \begin{cases} 40\ \mathrm{GeV}, & \text{for } m_{M\gamma} \leq 91\ \mathrm{GeV} \\ 40 + 5/34 \times (m_{M\gamma} - 91)\ \mathrm{GeV}, & \text{for } 91\ \mathrm{GeV} < m_{M\gamma} < 140\ \mathrm{GeV} \\ 47.2\ \mathrm{GeV}, & \text{for } m_{M\gamma} \geq 140\ \mathrm{GeV} \end{cases}$$

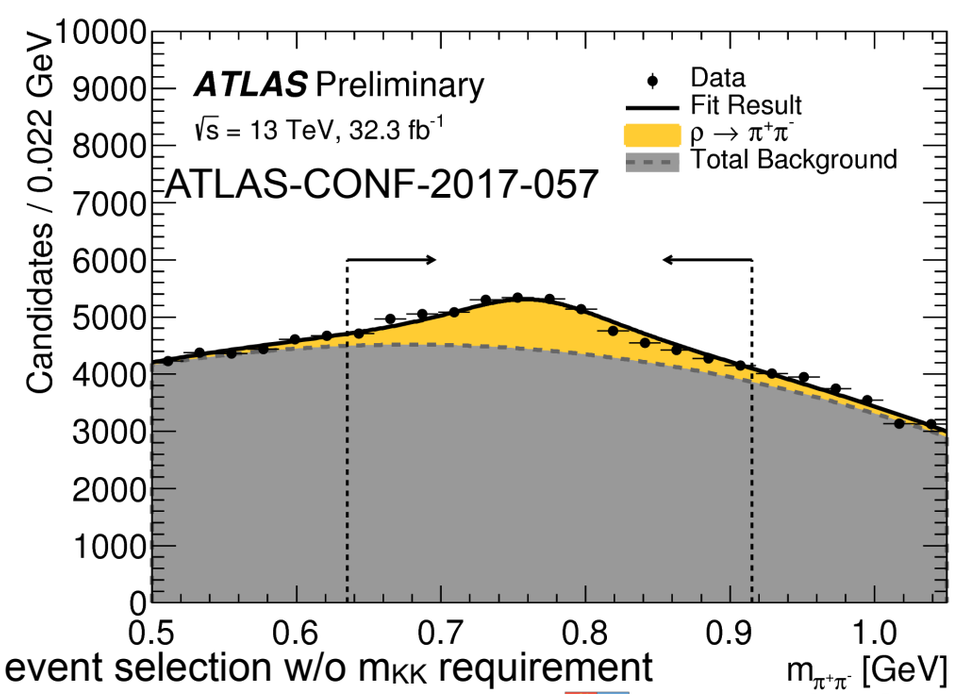


Photons

- "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)
- Δφ(M,γ)>π/2

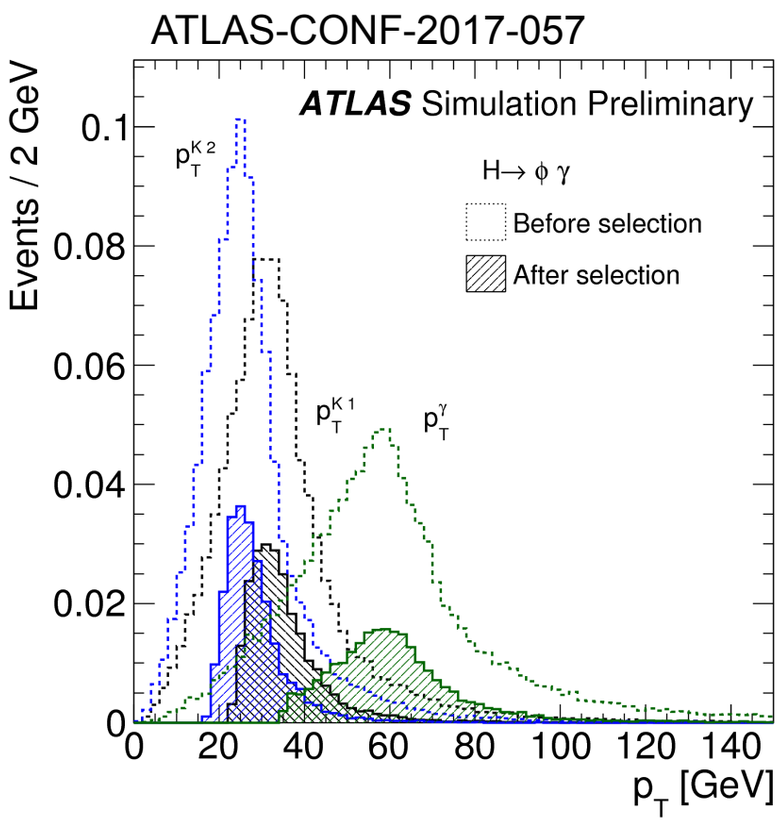
Total signal acceptance/efficiency

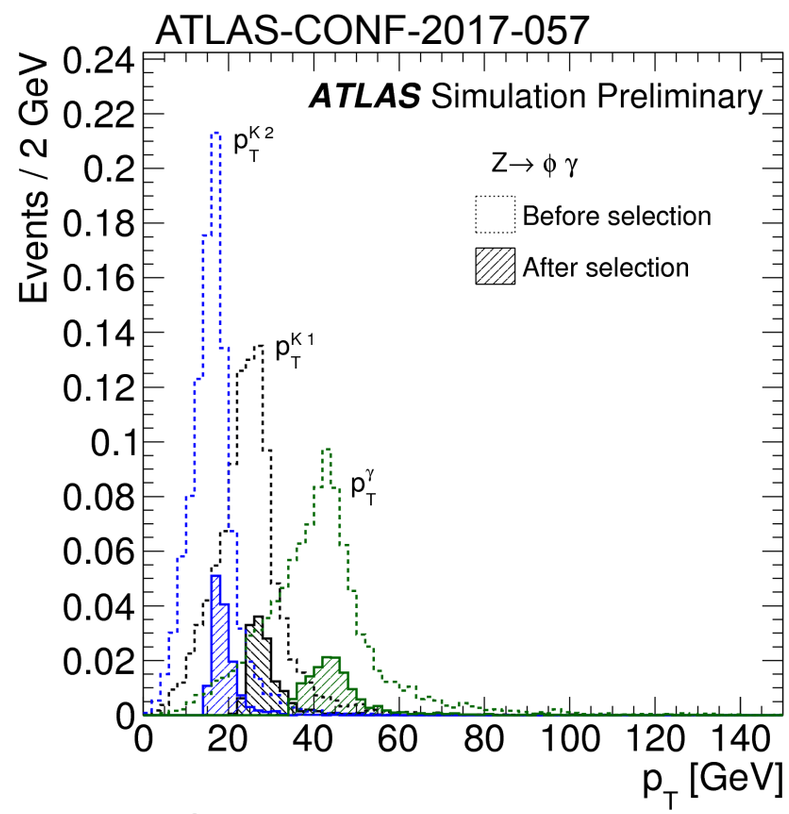
- $h(Z)\rightarrow\varphi\gamma\rightarrow K^+K^-\gamma$ ~ 17% (8%)
- $h(Z)\rightarrow\rho\gamma\rightarrow\pi^+\pi^-\gamma$ ~ 10% (0.4%)

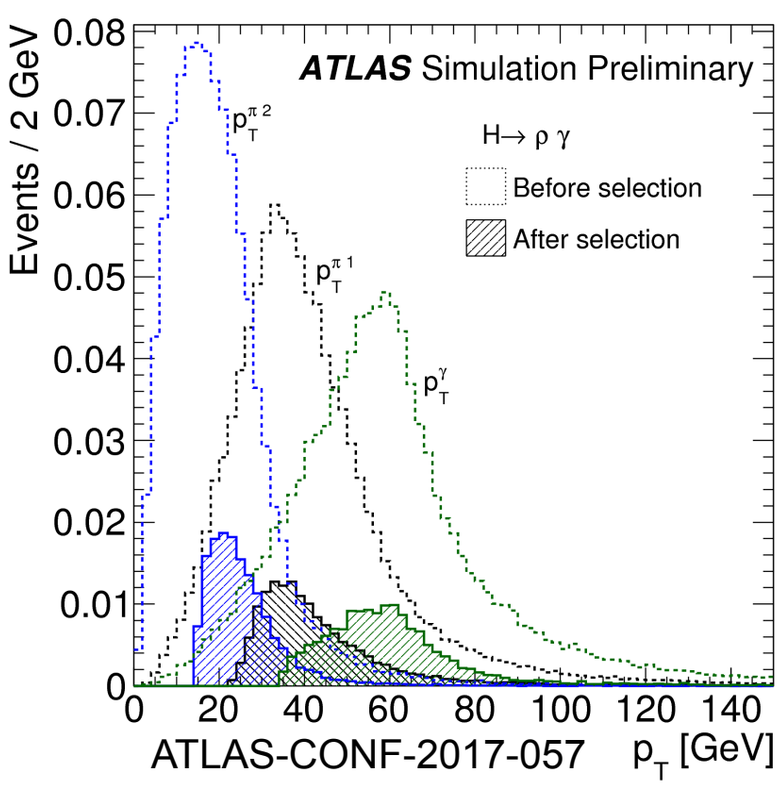


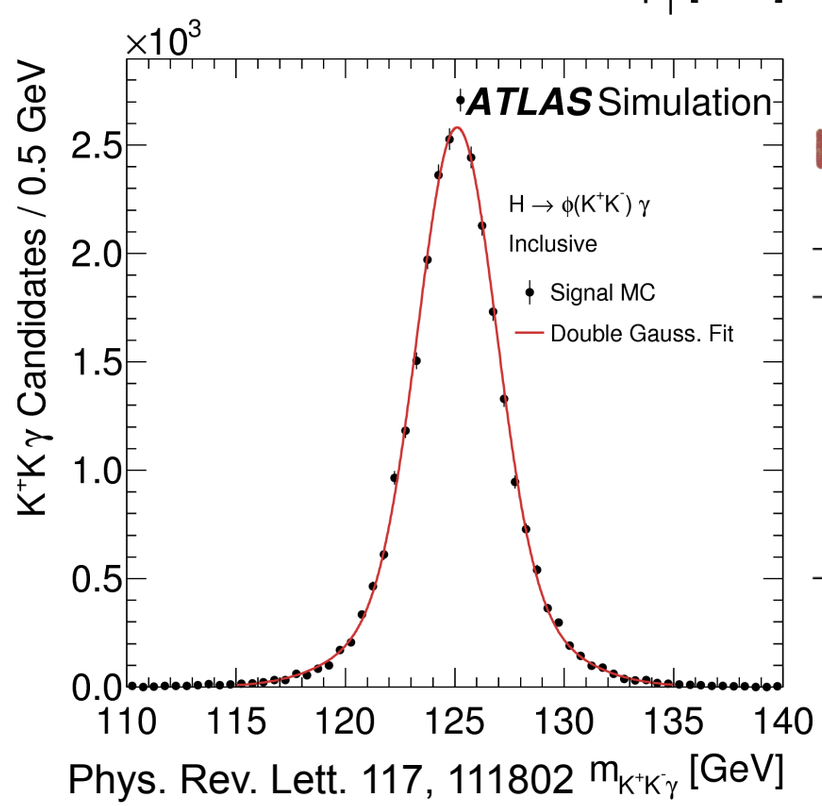
Full event selection w/o m_{KK} requirement

Efficiency and Resolution







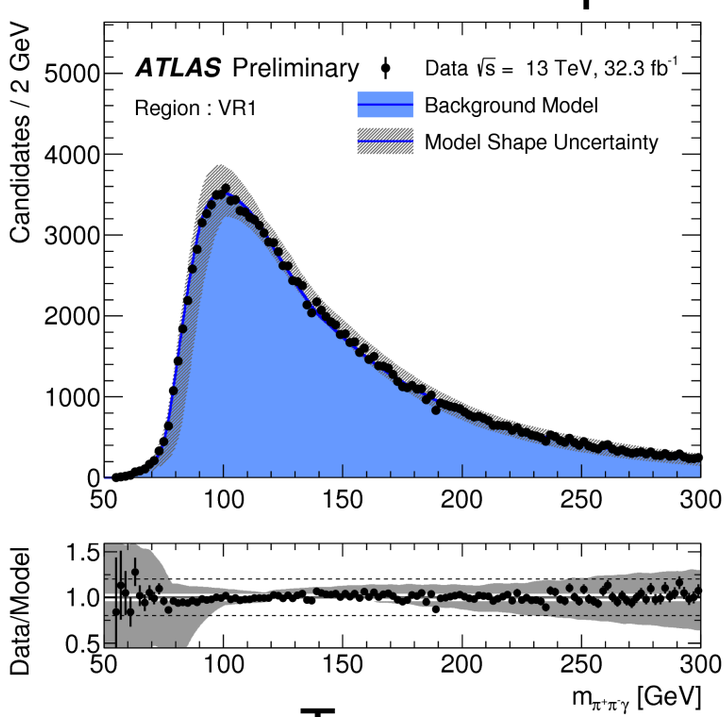


- **No categorisation**
- **Mass resolution ~1.8%**
- **Signal Model**
  - Higgs: double Gauss
  - Z: double Voigt with eff. corr.
- **Signal Systematic Uncertainty**

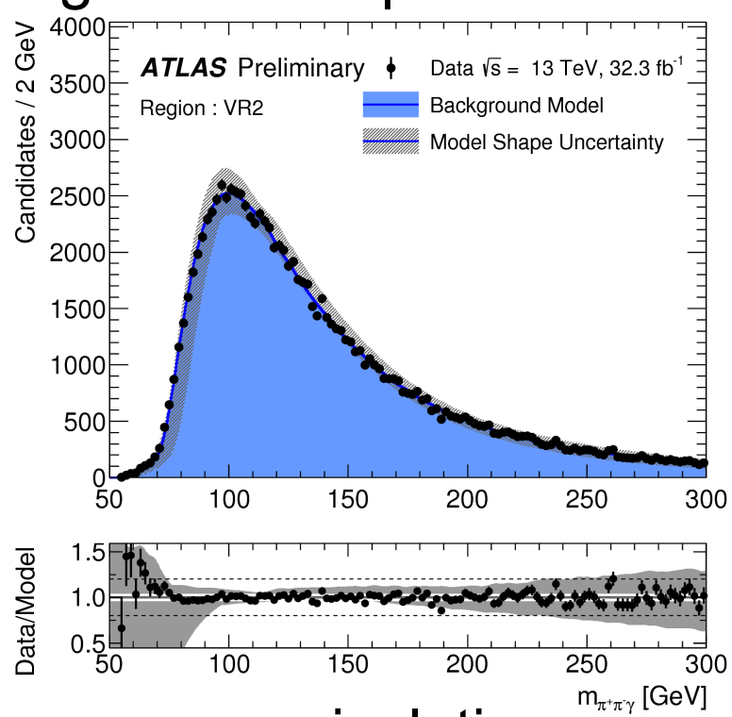
Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2%
Tracking efficiency	6%

Background Modelling

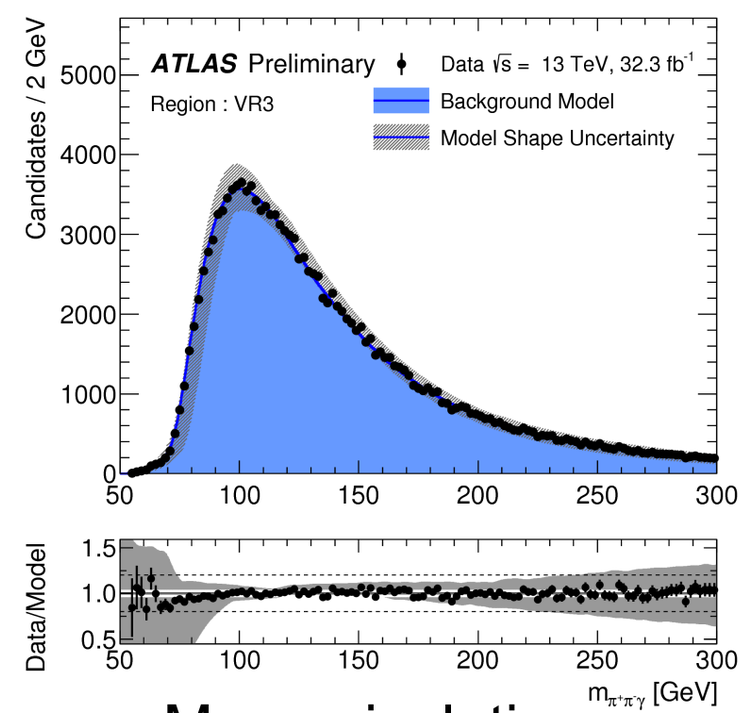
- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. $h/Z \to \mu\mu\gamma_{FSR}$) **estimated to be negligible**
- **Non-parametric data-driven background model;** common for ATLAS Qγ searches
  - Begin with loose sample of candidates
  - Model kinematic and isolation distributions
  - Generate "pseudo"-background events
  - Apply selection to "pseudo"-candidates
- **Background Normalisation:** Directly from the data in the Signal Region
- **Background Shape Uncertainty:** Estimated from modifications to modelling procedure (e.g. shifting/warping input distributions), shape uncertainty included in likelihood as a shape morphing nuisance parameter



pT_{Meson}



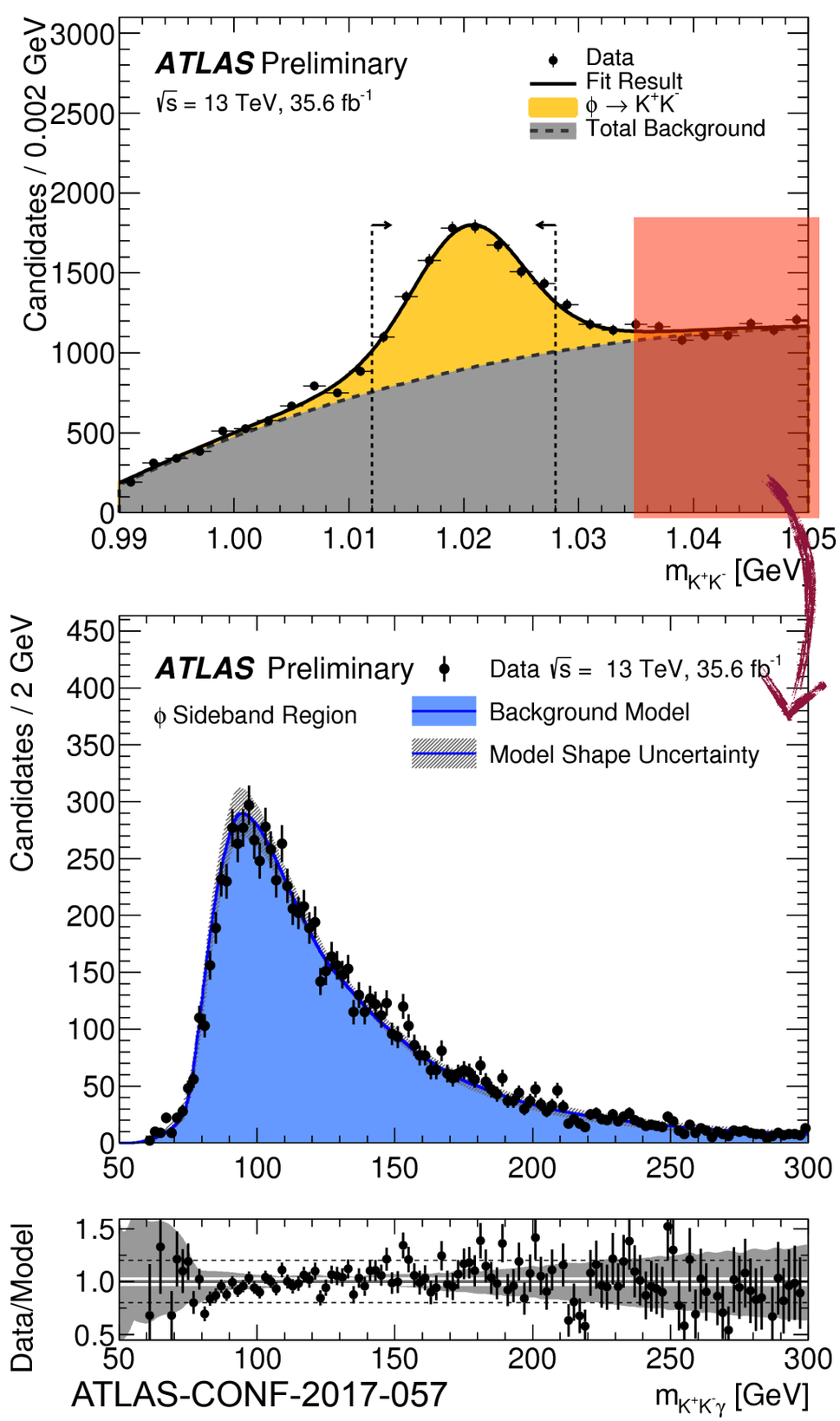
γ-isolation

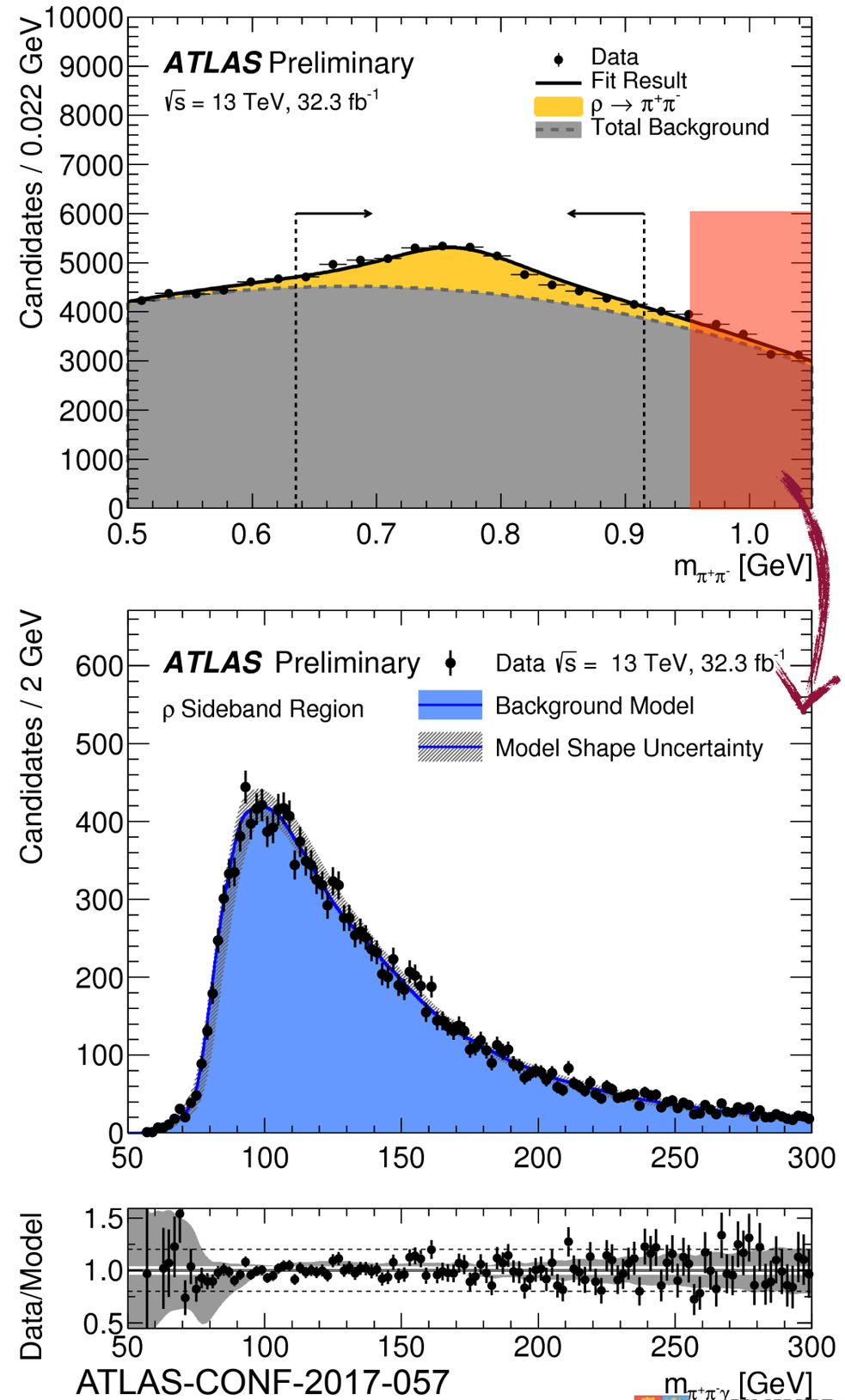


Meson-isolation

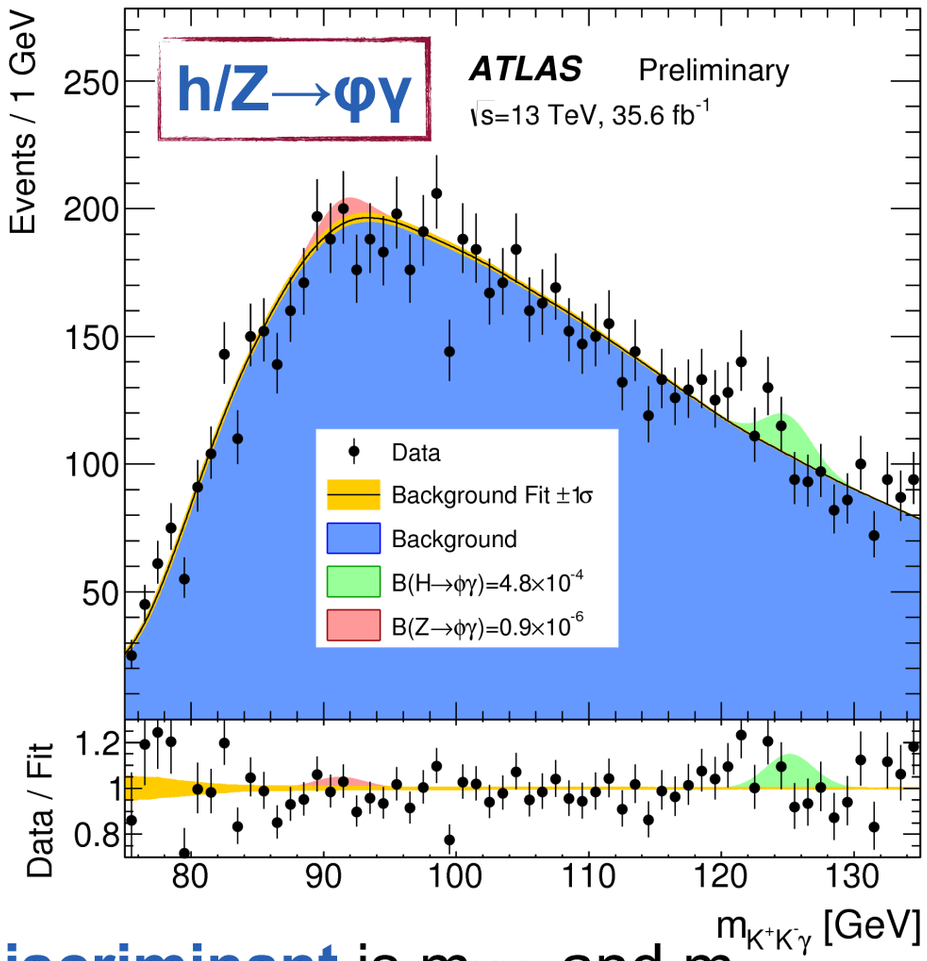
ATLAS-CONF-2017-057

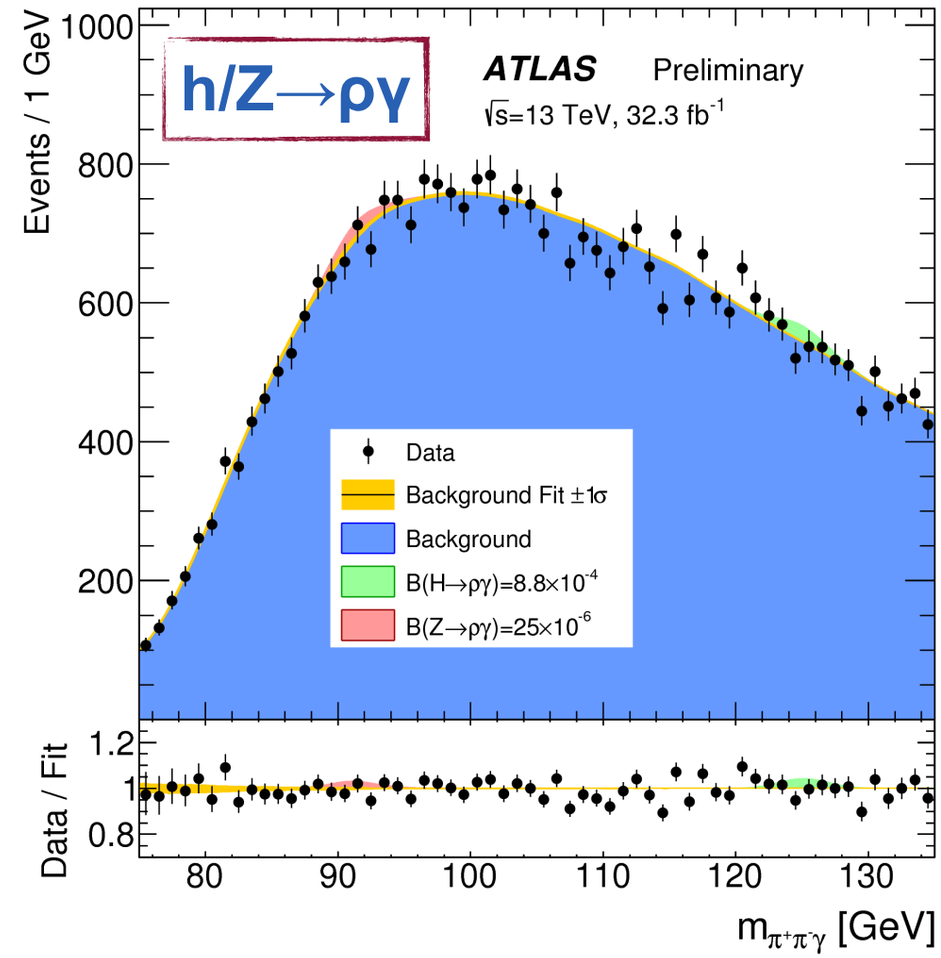
Background validation in side-bands





Results





- **Final discriminant** is $m_{KK\gamma}$ and $m_{\pi\pi\gamma}$
- **No significant signal observed**
- 95% confidence level **upper limit**
  - CLs with profile likelihood test statistic
  - Limit on production cross-section times branching ratio
    - $h \to \varphi\gamma < 25.3$fb
    - $h \to \rho\gamma < 45.5$fb

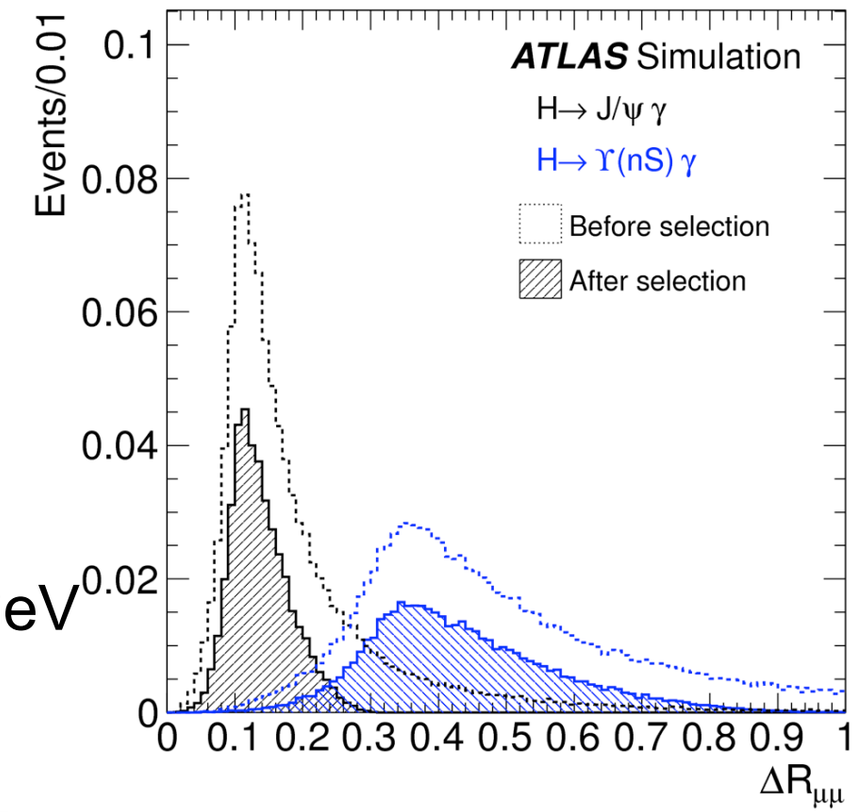
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

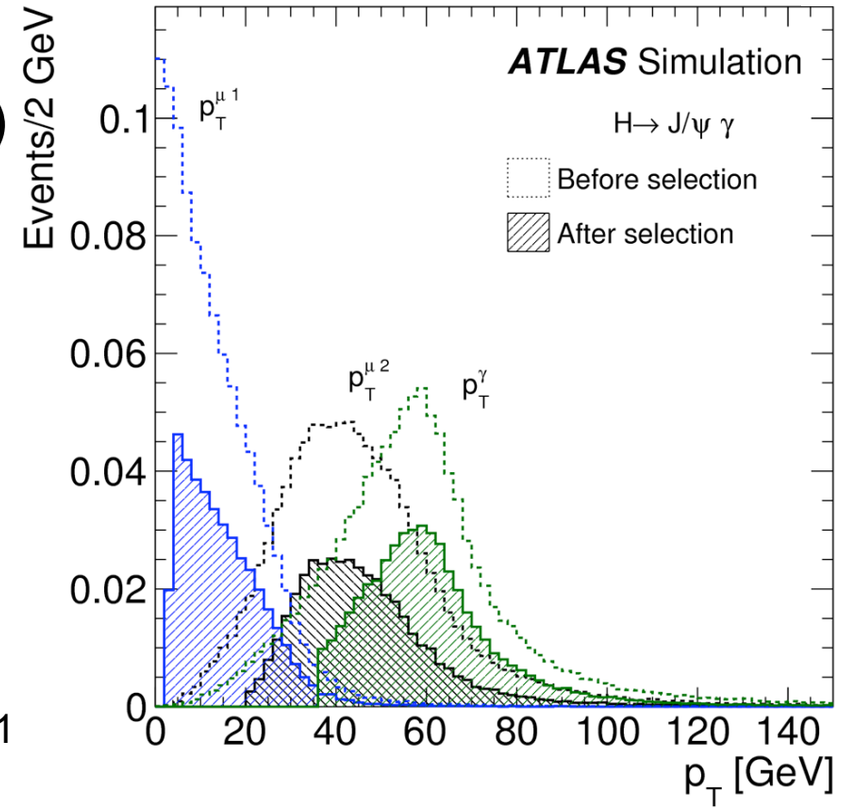
ATLAS-CONF-2017-057

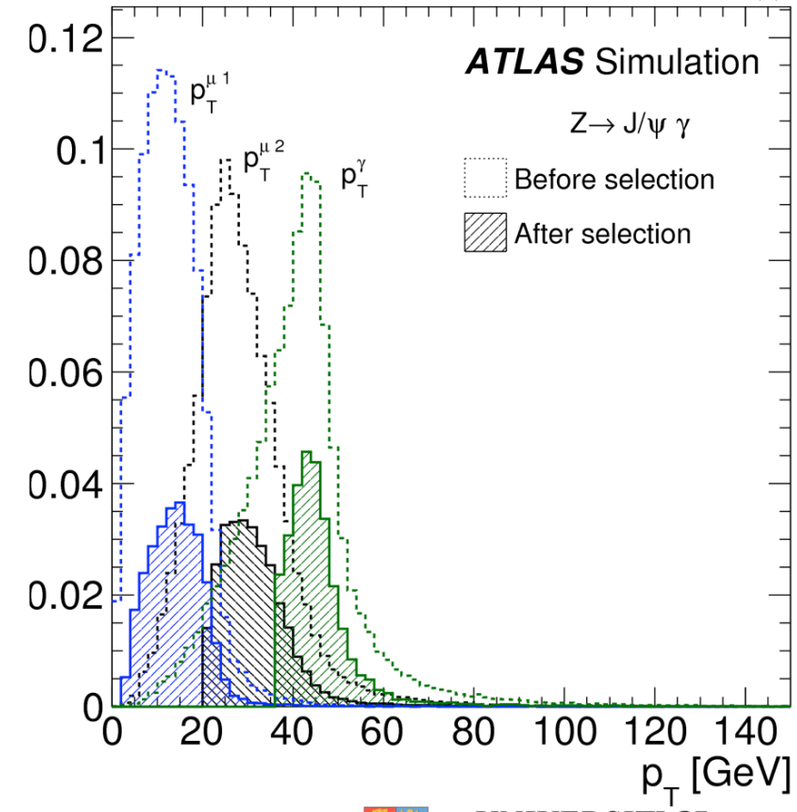
x3 improvement in expected limits with respect to 2.7/fb result [PRL 117, 111802]

h/Z→J/ψγ and h/Z→Υ(nS)γ (n=1,2,3)

- **ATLAS 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
  - $|L_{xy} /\sigma_{Lxy}|<3$
  - $\Delta\varphi(\mu\mu,\gamma)>0.5$
- Total efficiency
  - h(Z)→J/ψγ→μμγ~22%(12%)
  - h(Z)→Υγ→μμγ~28% (15%)



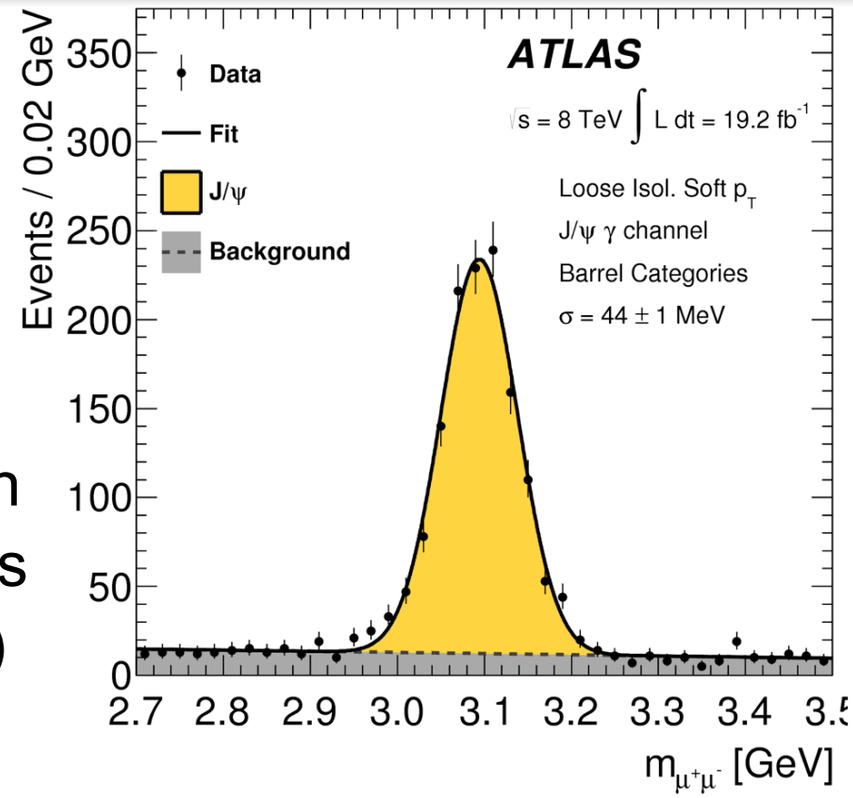


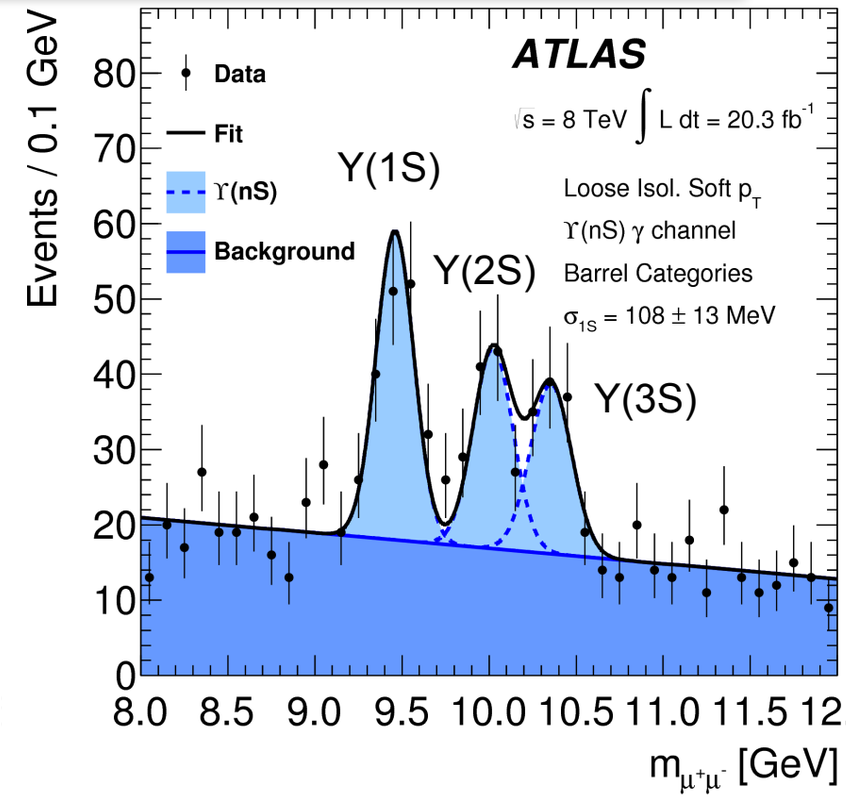


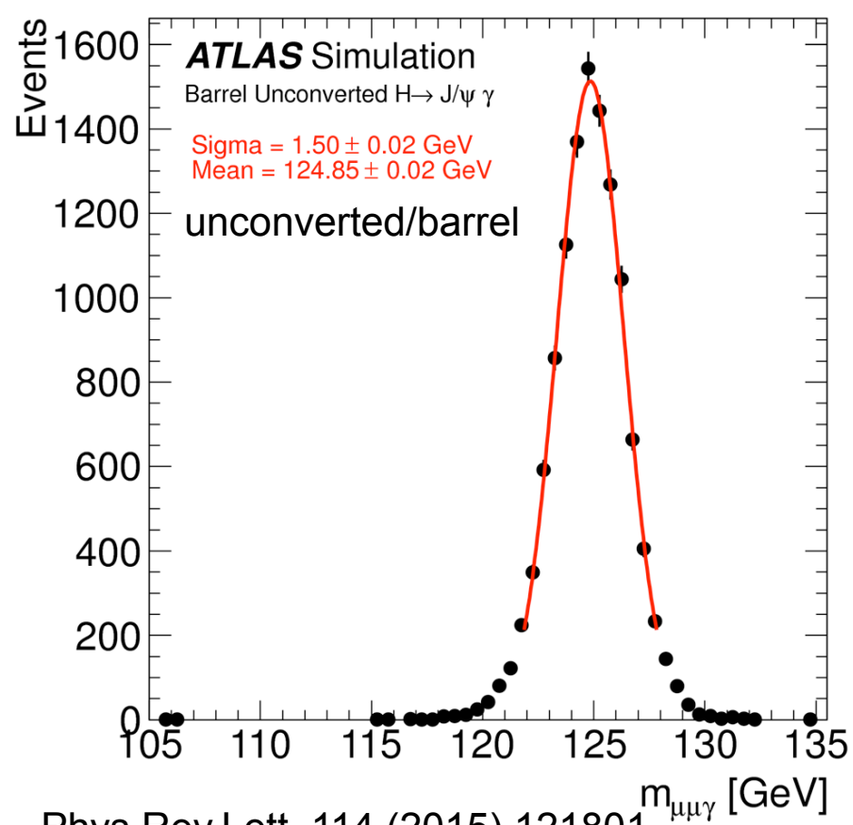
Phys.Rev.Lett. 114 (2015) 121801

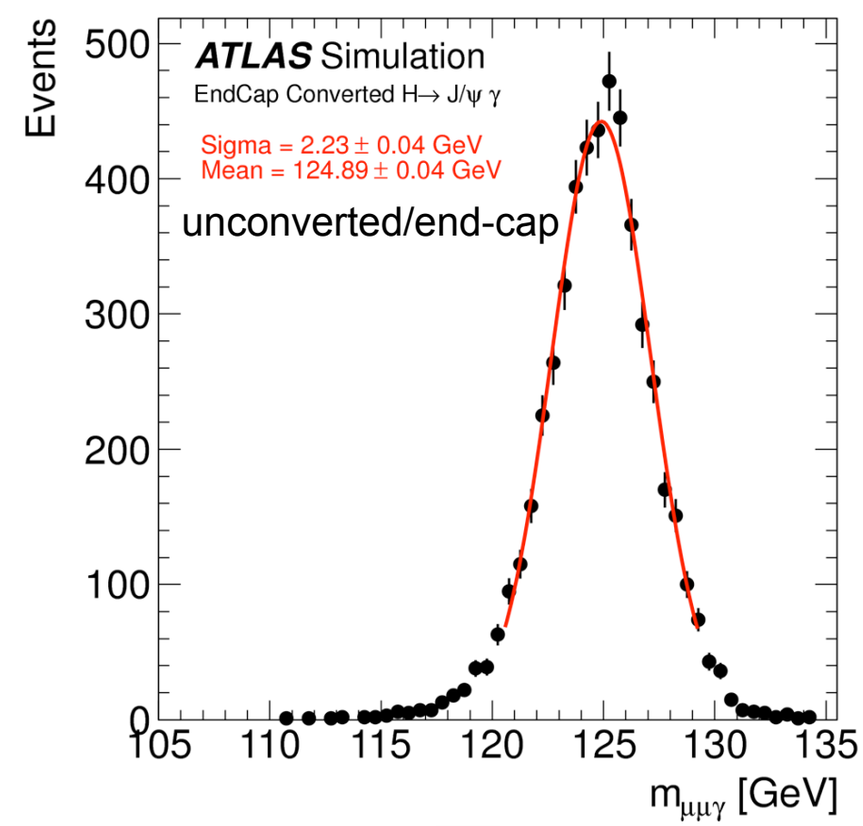
Mass Resolution

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







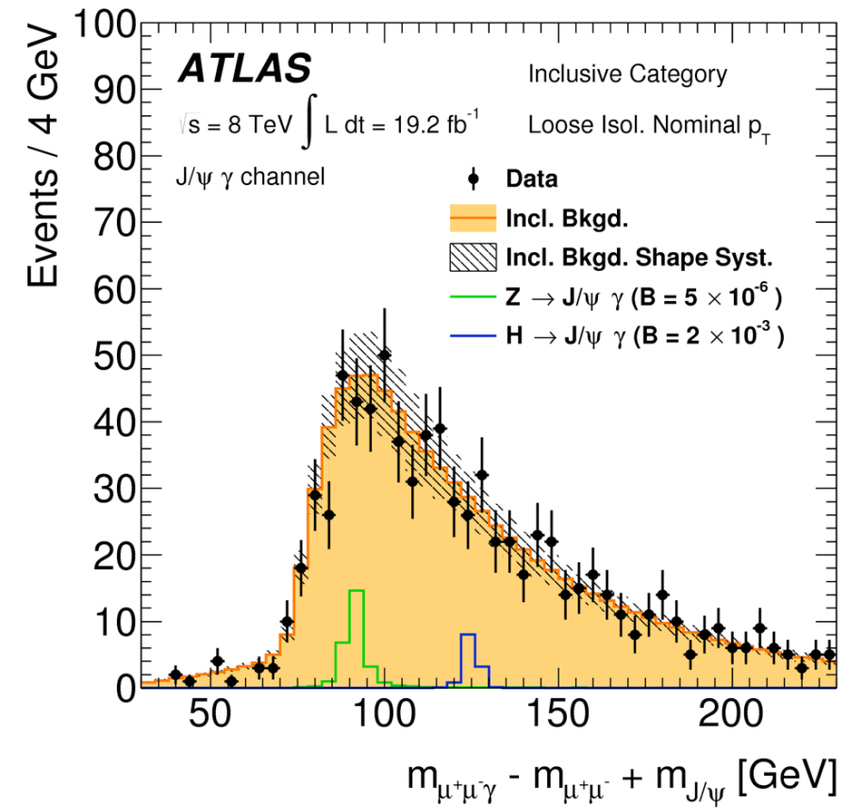


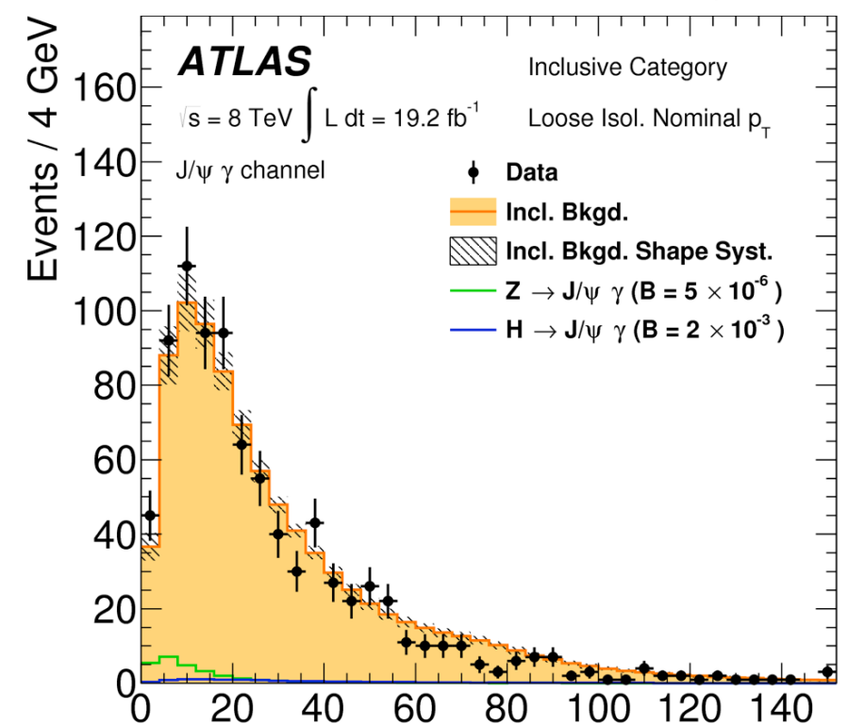
Phys.Rev.Lett. 114 (2015) 121801

Background Modelling

- **Inclusive quarkonium** with jet "seen" as γ
  - combinatoric background: small contribution
  - contribution from Q+γ production
- **Nonparametric data-driven** background model
  - Similar to h/Z→φγ and h/Z→ργ analyses
- **Υ(nS)γ:** also Z→μμγ_{FSR} from side-band fit

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





Phys.Rev.Lett. 114 (2015) 121801

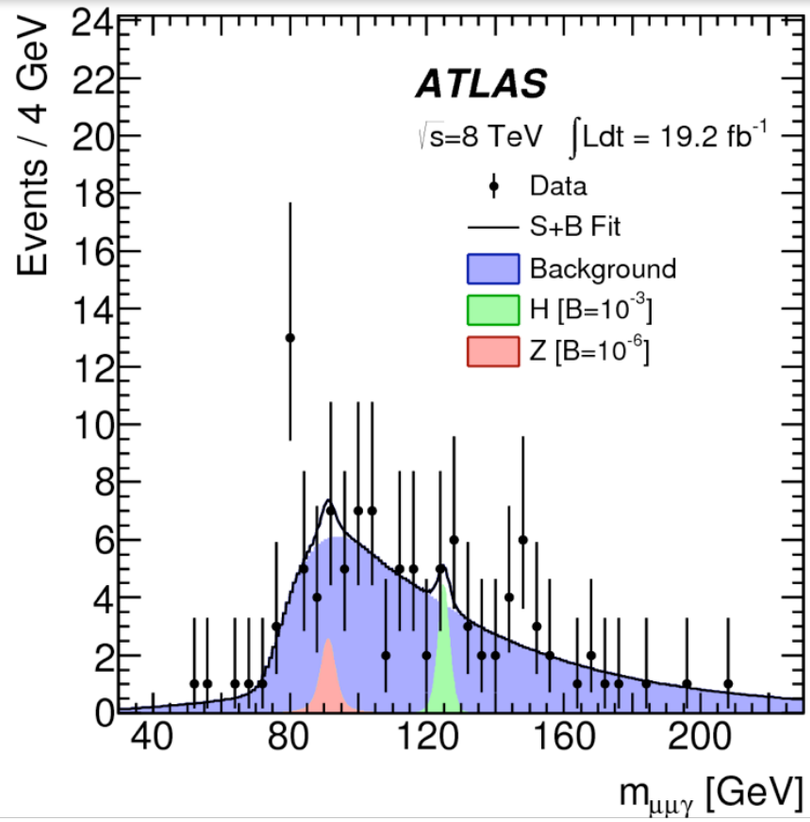
Systematic Uncertainties

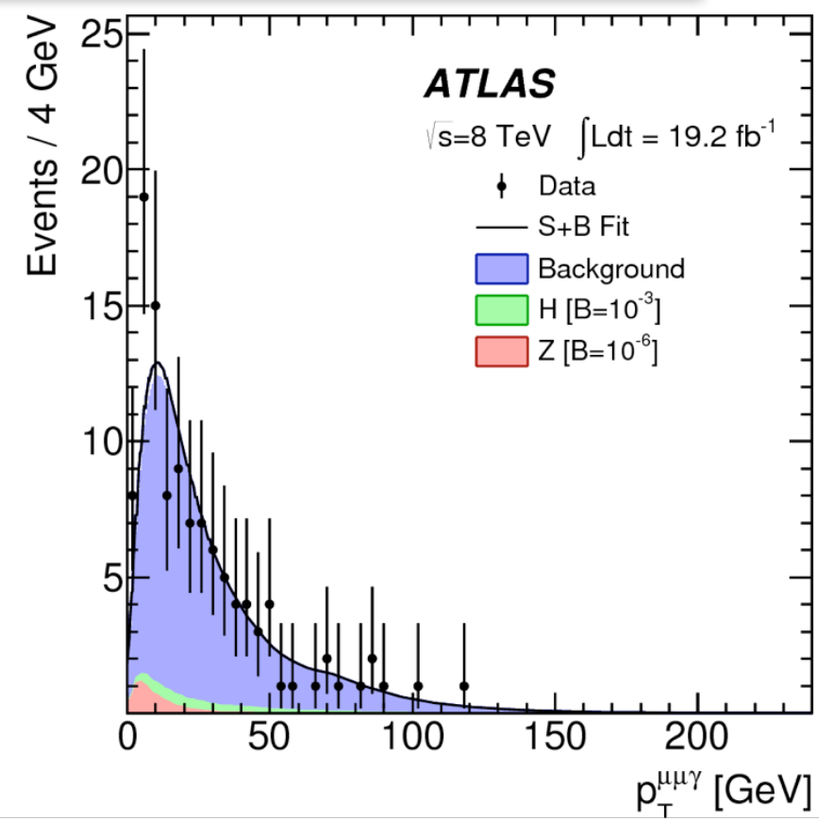
Source	Signal Yield Uncertainty	Estimated From
Total H cross section	12%	QCD scale variation and PDF uncertainties
Total Z cross section	4%	
Integrated Luminosity	2.8%	Calibration observable and vdM scan uncertainties
Trigger Efficiency	1.7%	Data driven techniques with $Z \to \ell^+\ell^-$, $Z \to \ell^+\ell^-\gamma$ 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	

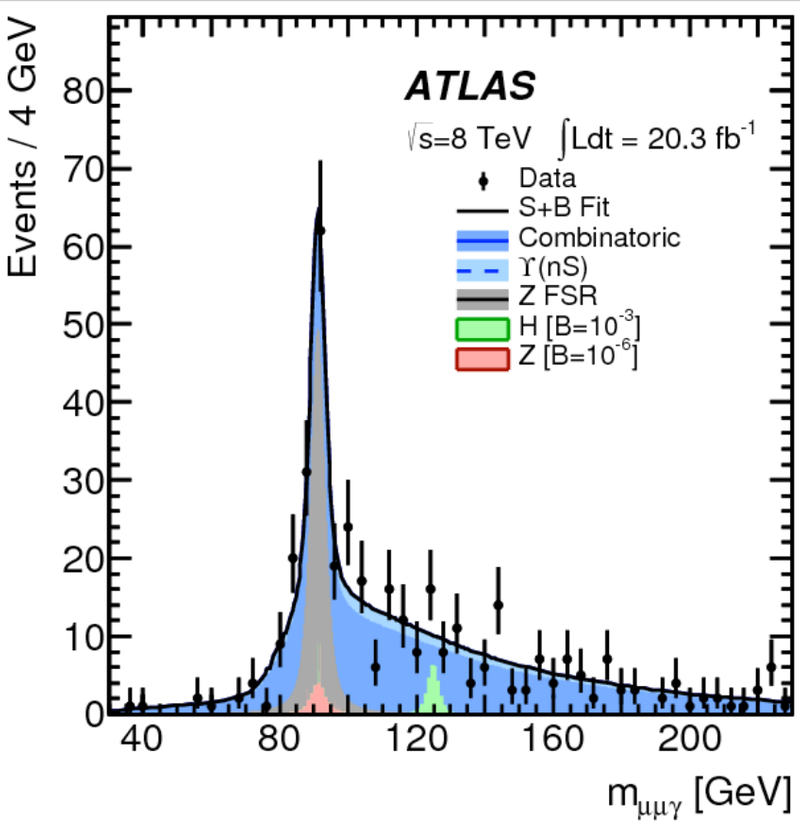
Results

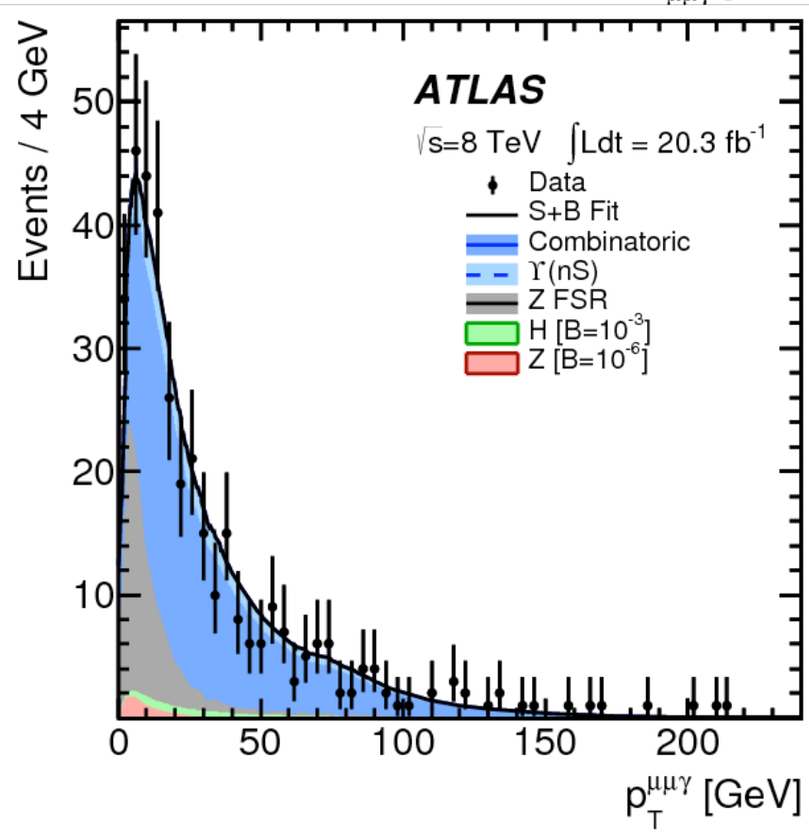
- **Multi-observable fit**
  - $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$ for J/ψγ
  - $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$,$m_{\mu\mu}$ for Υ(nS)γ
- **No significant excess** above background observed

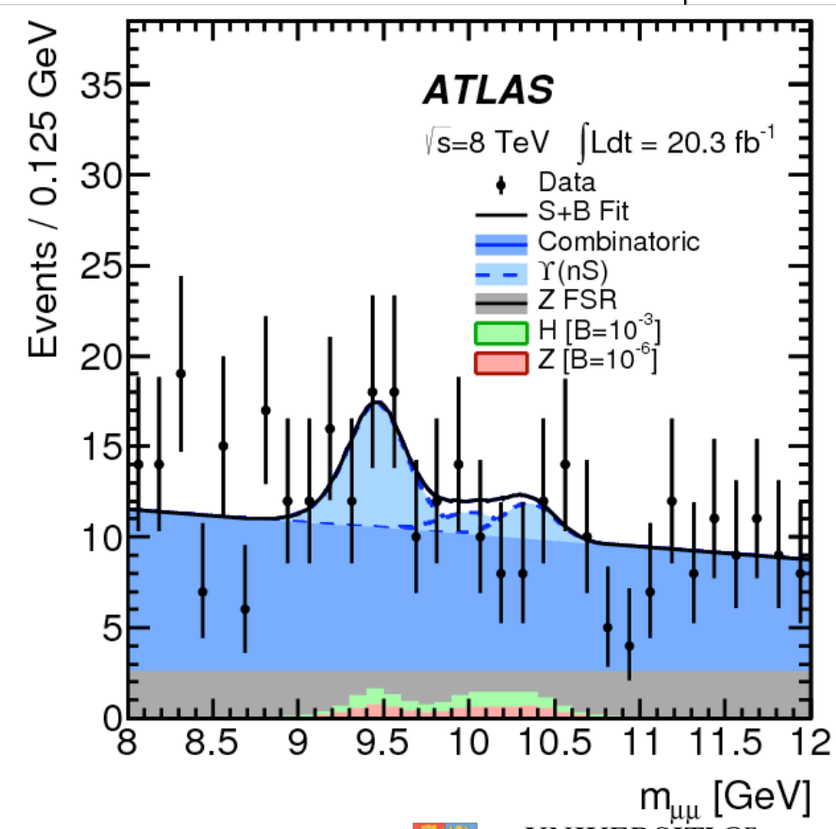
Phys.Rev.Lett. 114 (2015) 1121801



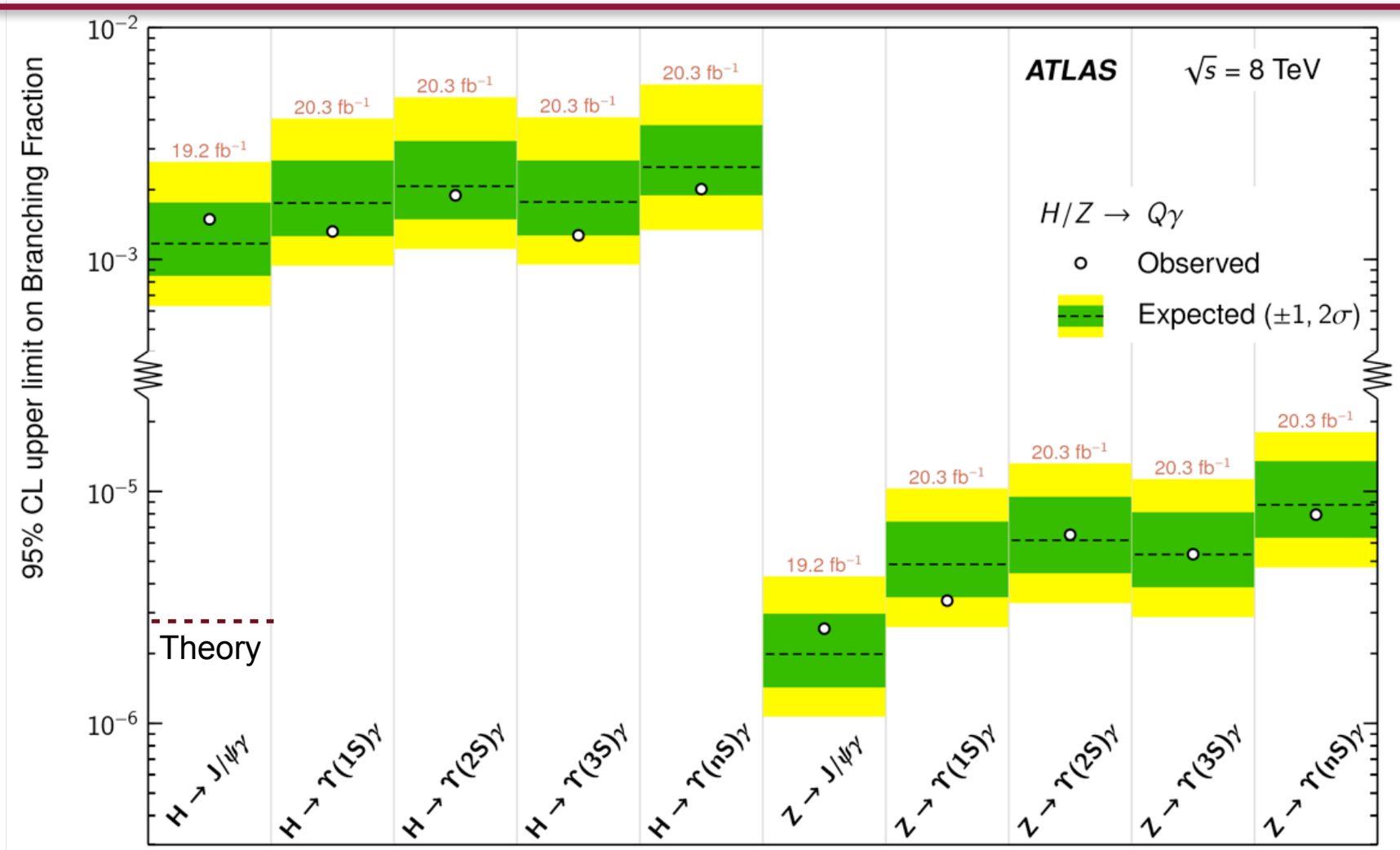








h/Z→J/ψγ and h/Z→Υ(nS)γ: Results



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

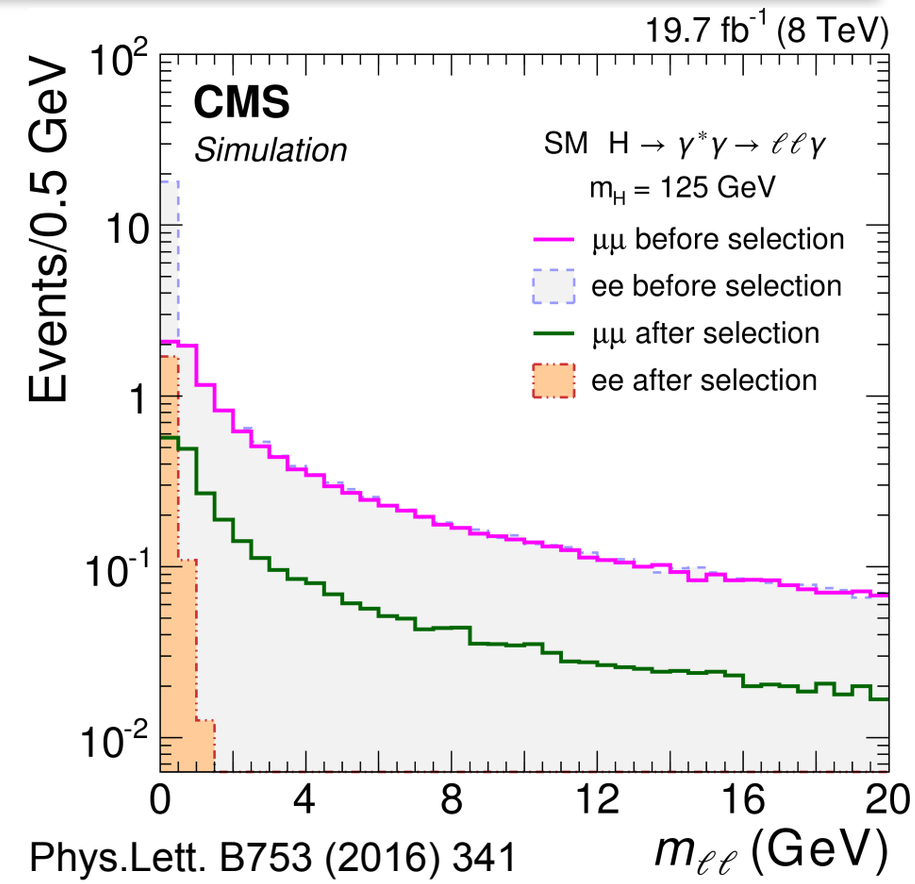
	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H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

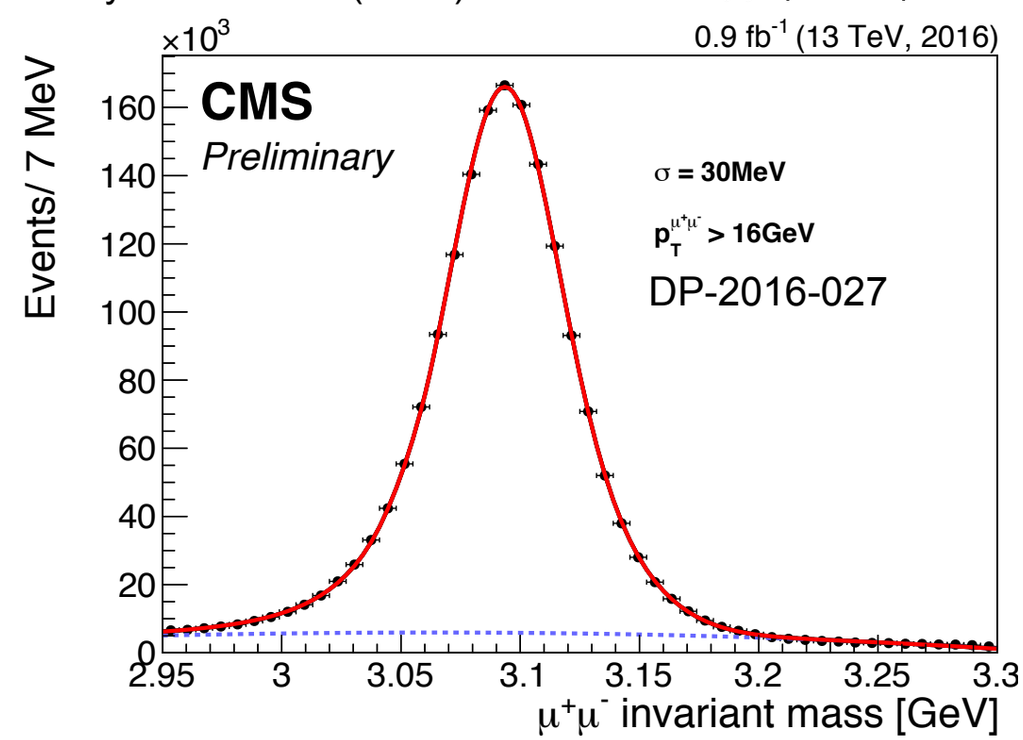
h→γ*γ→llγ and h→J/ψγ

- **CMS search** for h→γ*γ→llγ and h→J/ψγ
  - used 19.7 fb^{-1} at 8 TeV
- **Event Selection** [for h→J/ψγ]
  - 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
  - μμ and γ isolation,
  - $2.9 < m_{\mu\mu} < 3.3$ GeV
  - ΔR(μ,γ)>1 for each muon
  - muon impact parameter requirements



Phys.Lett. B753 (2016) 341

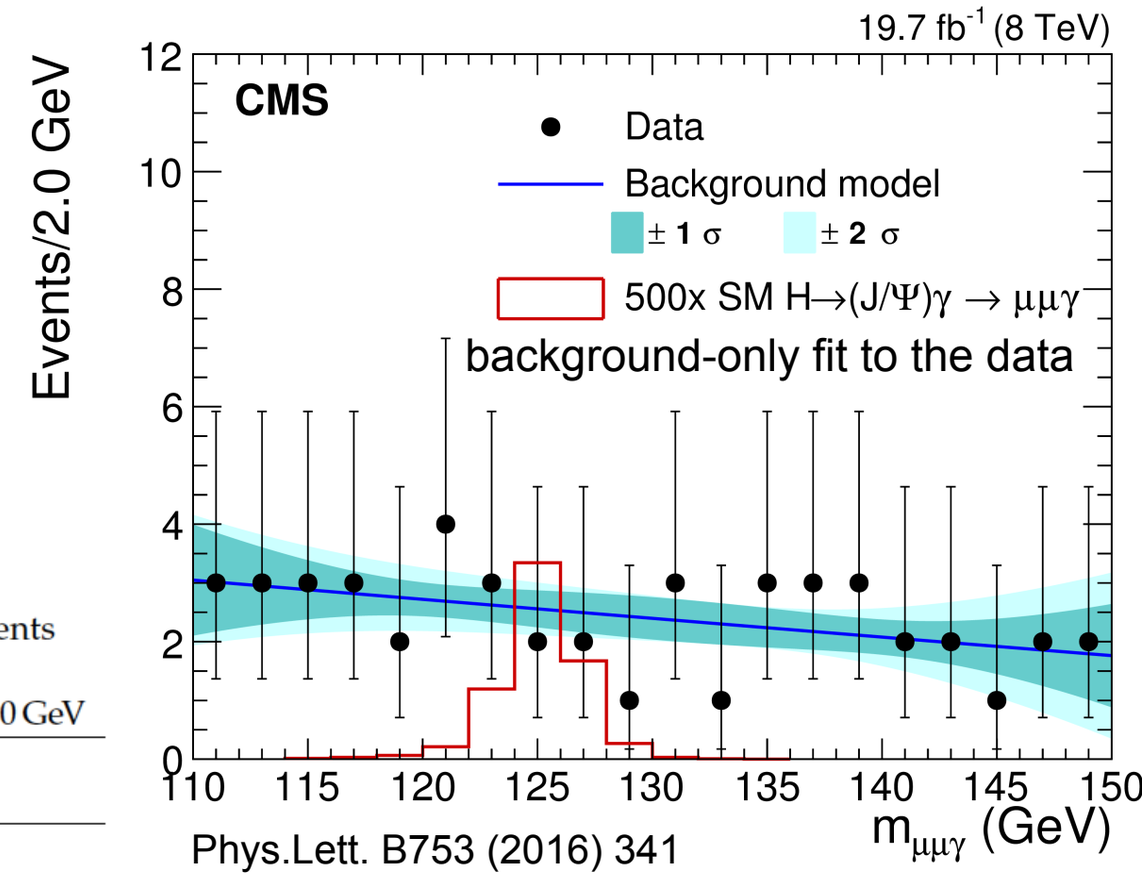
Source	Uncertainty
Integrated luminosity (ref. [37])	2.6%
Theoretical uncertainties:	
PDF	2.6–7.5%
Scale	0.2–7.9%
$H \to \gamma^*\gamma \to \ell\ell\gamma$ branching fraction	10%
Experimental uncertainties:	
Pileup reweighting	0.8%
Trigger efficiency, μ (e) channel	4 (2)%
Muon reconstruction efficiency	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)%



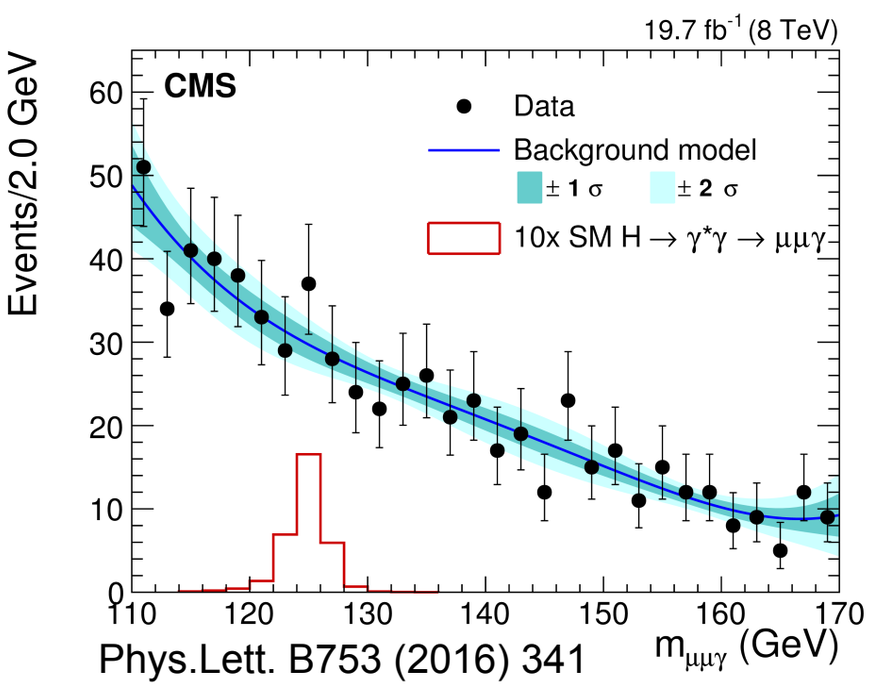
h→γ*γ→llγ and h→J/ψγ

- h→J/ψγ: 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 H→γ*γ→llγ: 6.7(5.9)xSM
- 95% CL upper limit BR(H→J/ψγ) < 1.5×10^{-3}
  - 540 times the SM prediction

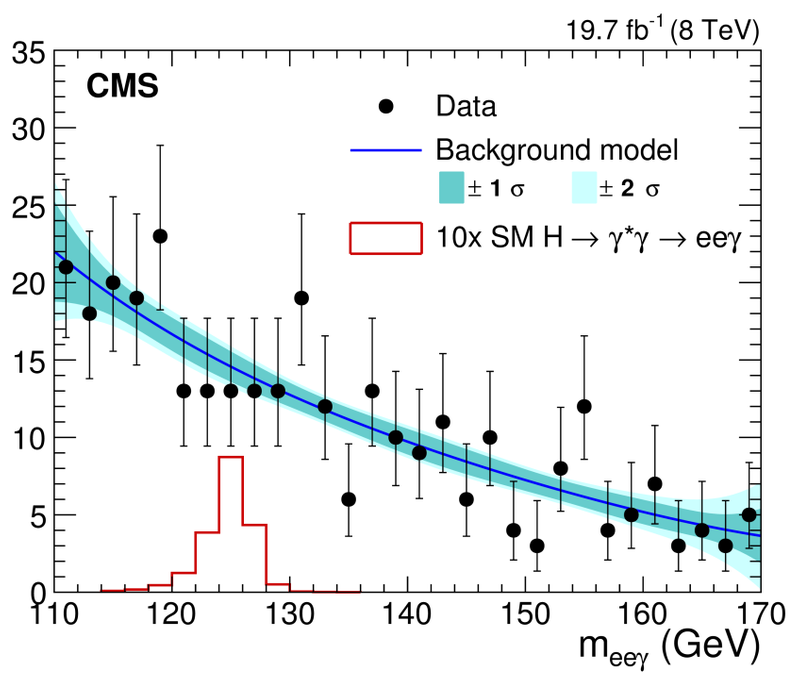
Sample	Signal events before selection $m_H = 125$ GeV	Signal events after selection $m_H = 125$ GeV	Number of events in data $120 < m_{\ell\ell\gamma} < 130$ GeV
$\mu\mu\gamma$	13.9	3.3	151
$ee\gamma$	25.8	1.9	65
$(J/\psi \to \mu\mu)\gamma$	$0.065(J/\psi) + 0.32$ (non-res.)	$0.014(J/\psi) + 0.078$ (non-res.)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

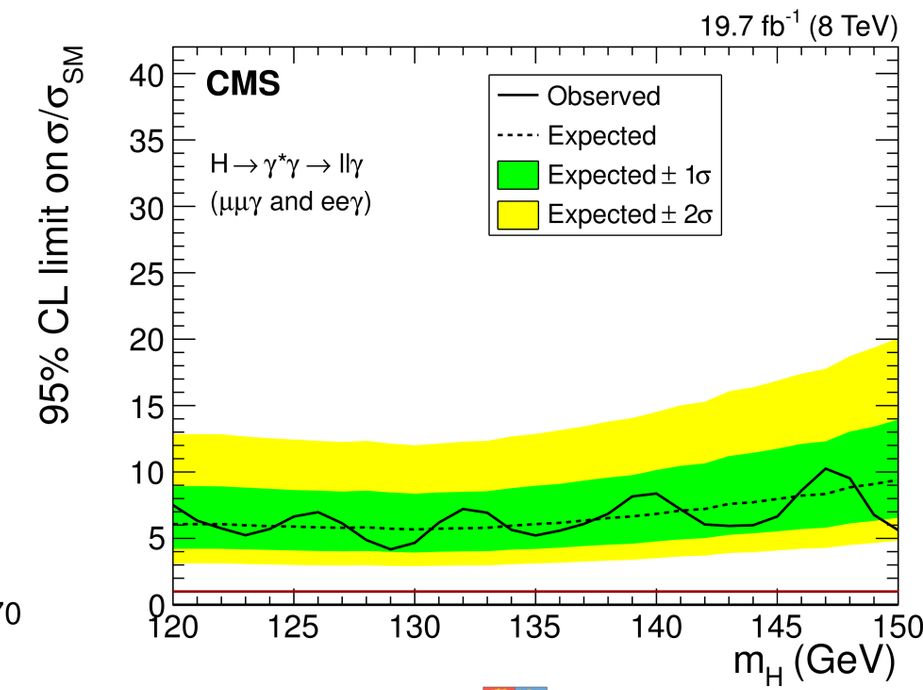


Phys.Lett. B753 (2016) 341



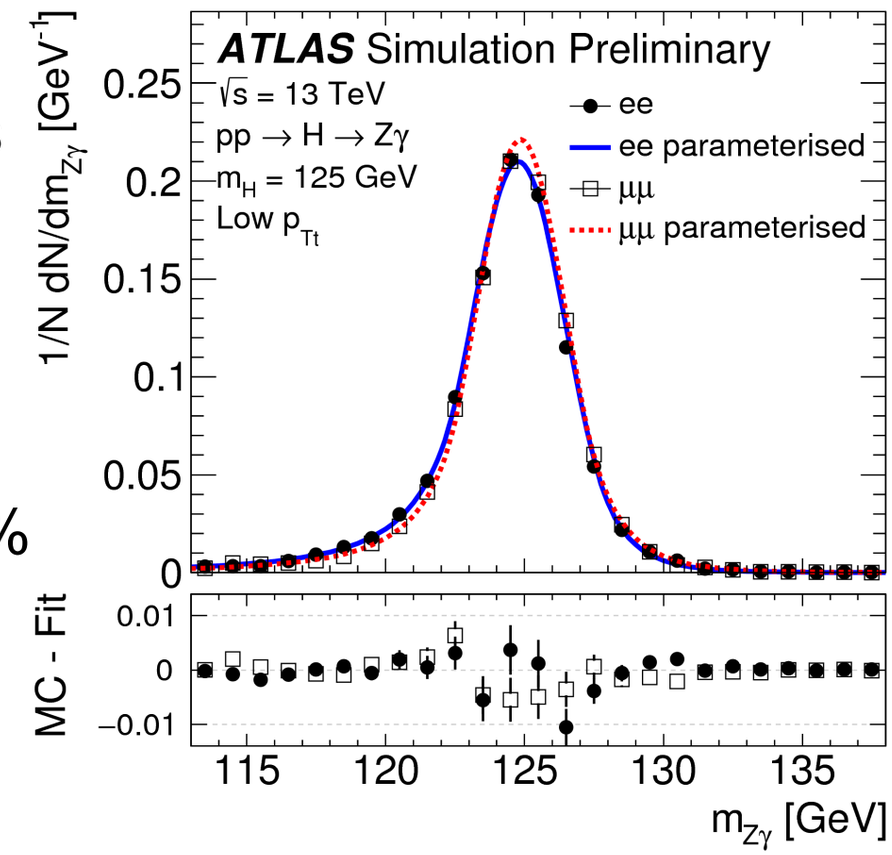
Phys.Lett. B753 (2016) 341

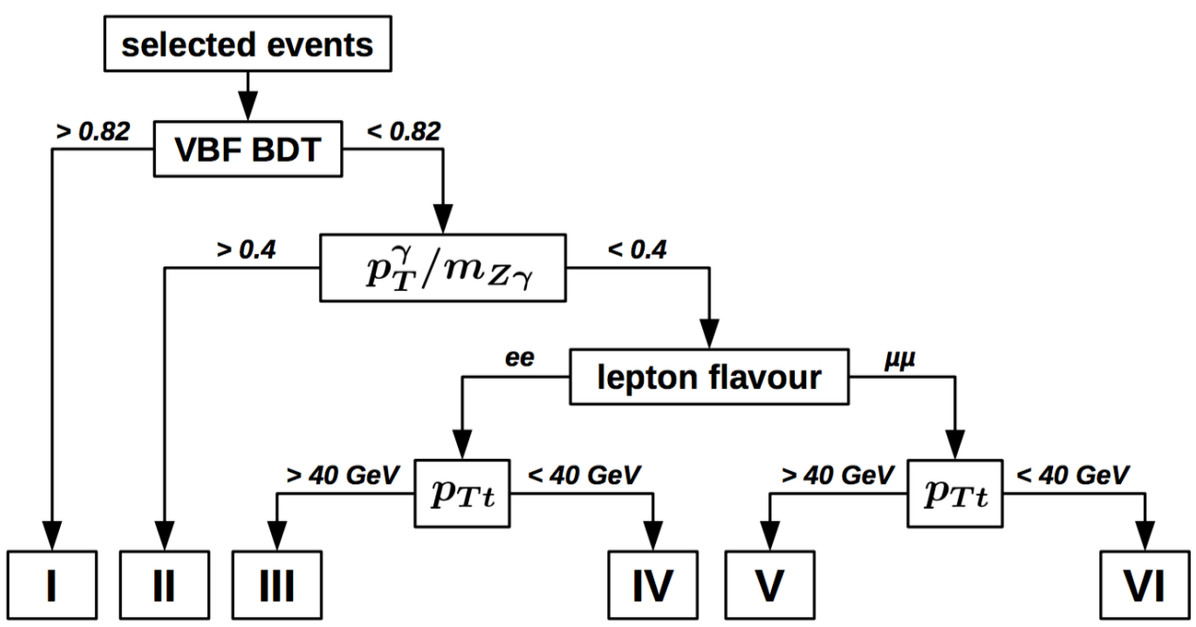


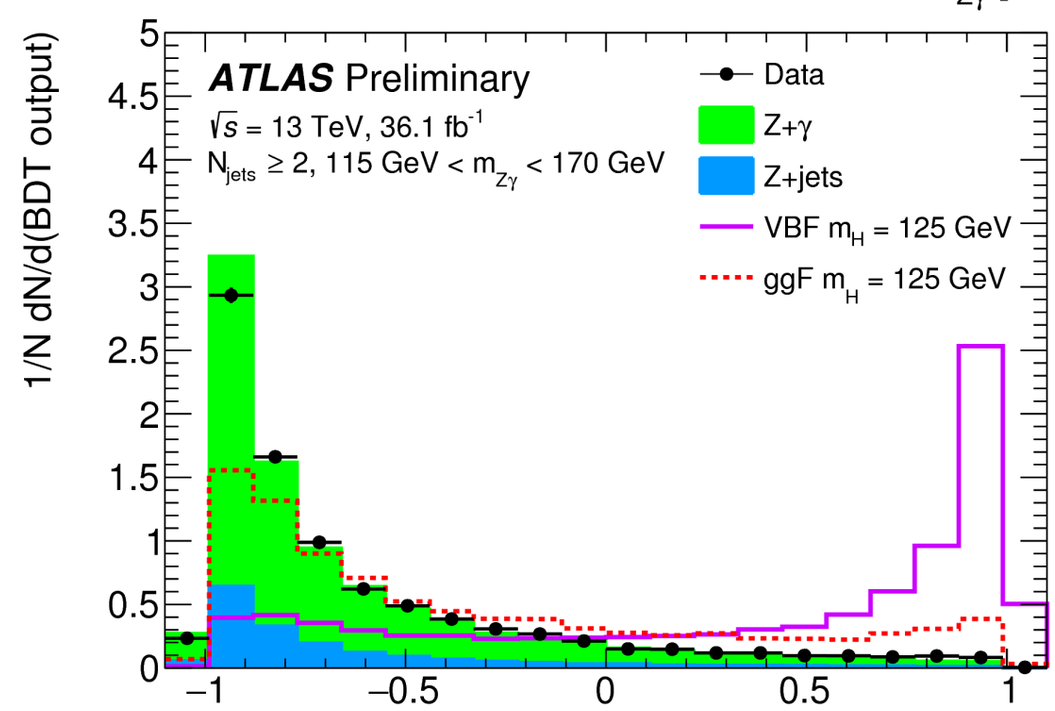


Search for h→Zγ

- Modified BR(H→Zγ) predicted in several BSM scenarios
  - H→Zγ proceeds by loop diagrams similar to H→γγ
  - SM BR~1.5×10^{-3} (m_H=125GeV)
- Signal extracted by signal+background fit to $m_{Z\gamma}$
  - Mass resolution essential
  - M_Z constraint improves $m_{\mu\mu\gamma}$ ($m_{ee\gamma}$) resolution by 7(13)%
  - FSR recovery in μμγ channel 3% improvement
- 6 categories are used to enhance sensitivity

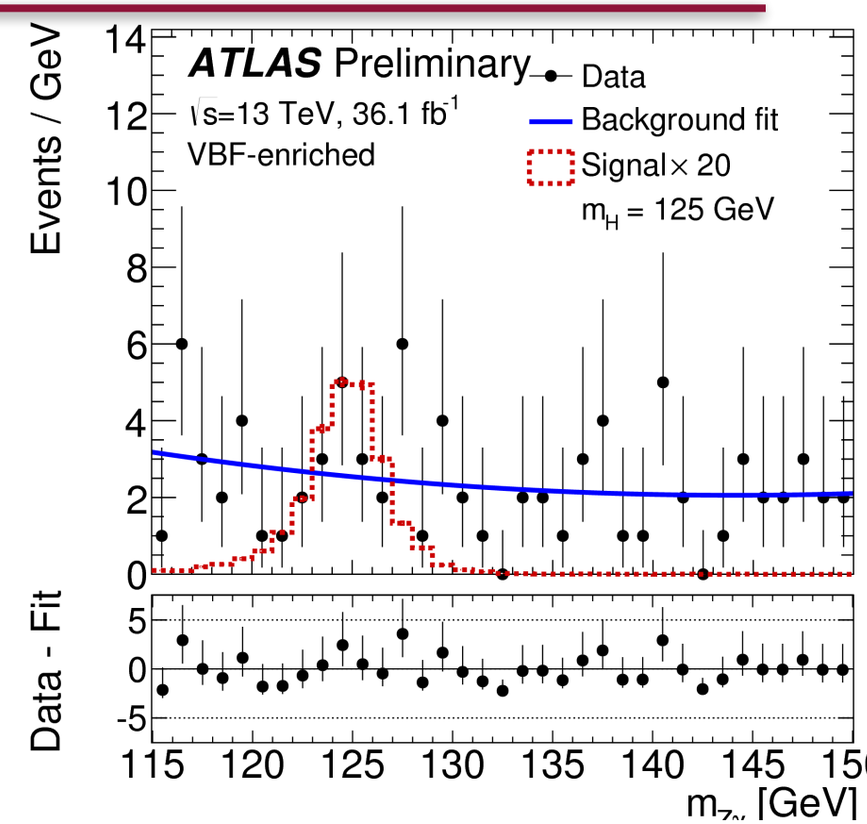


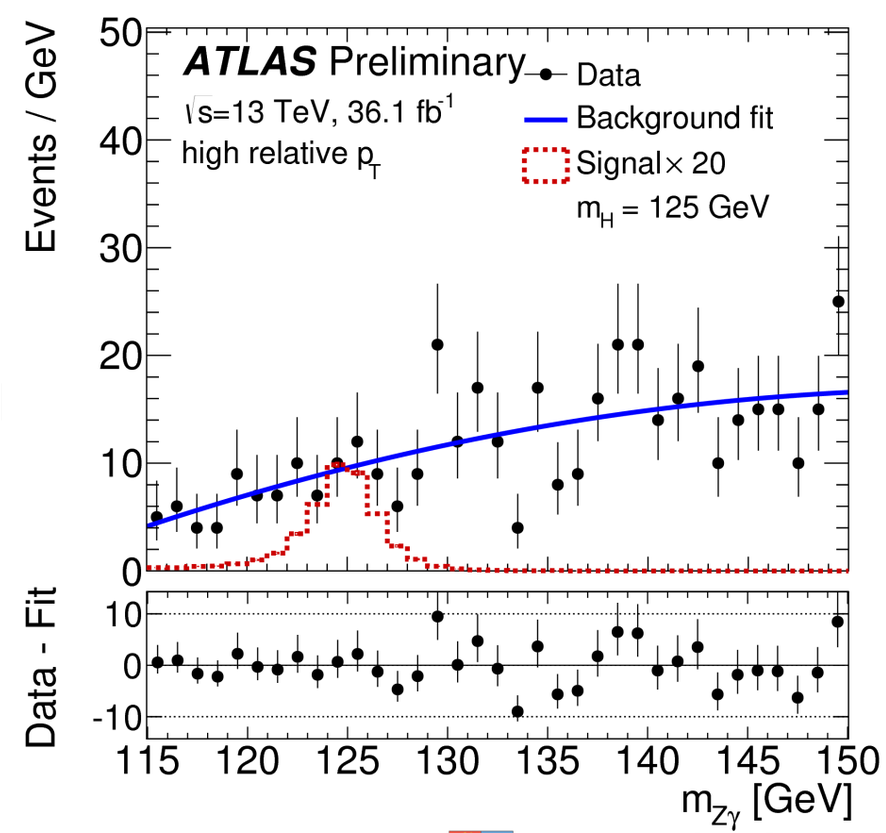




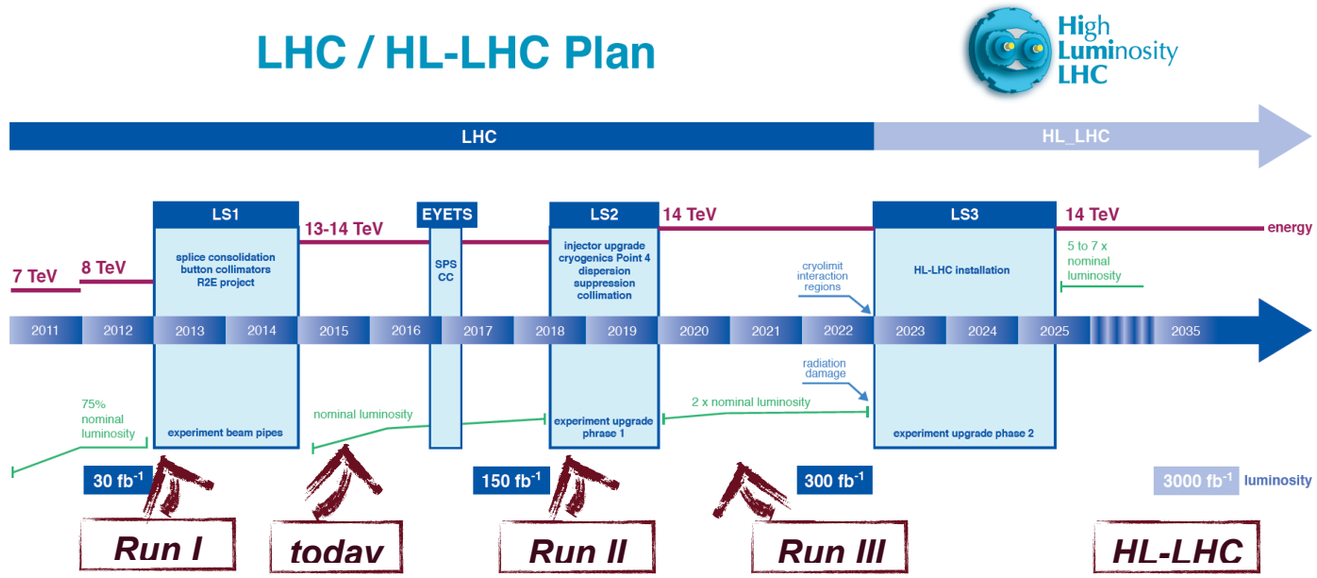
Search for h→Zγ

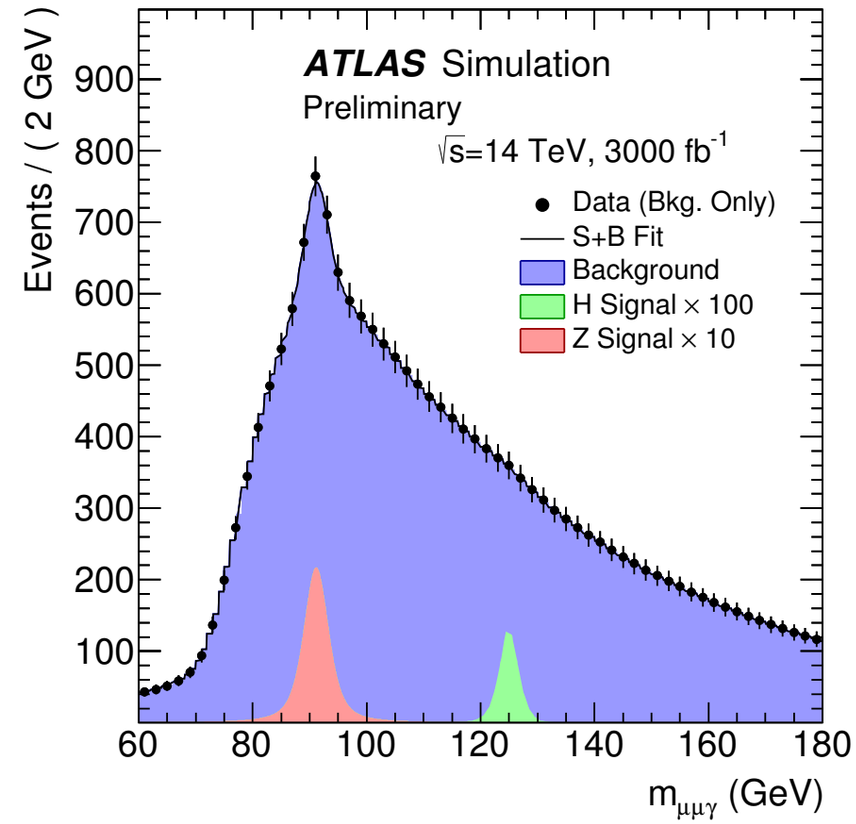
- Fit over the 115-150 GeV mass range.
  - Signal Modelled by double sided Crystal-Ball
  - Background: Bernstein polynomials,
    - Shape studied on Z+γ (fast) simulation
    - Parameters extracted from fit to data
- Background composition (Z+jets, Z+γ) is estimated by data-driven method using looser isolation requirements
  - Z+jets<20% in all categories
- 95% CL upper limit 6.6(4.4)xSM observed(expected)
  - Run 1 results:
    - ATLAS 11(9)xSM (m_H=125.5 GeV) [Phys. Lett. B 732C (2014) 8-27]
    - CMS 9.5(10)xSM (m_H=125 GeV) [Phys. Lett. B 726 (2013) 587-609]





h/Z→Qγ: in the future



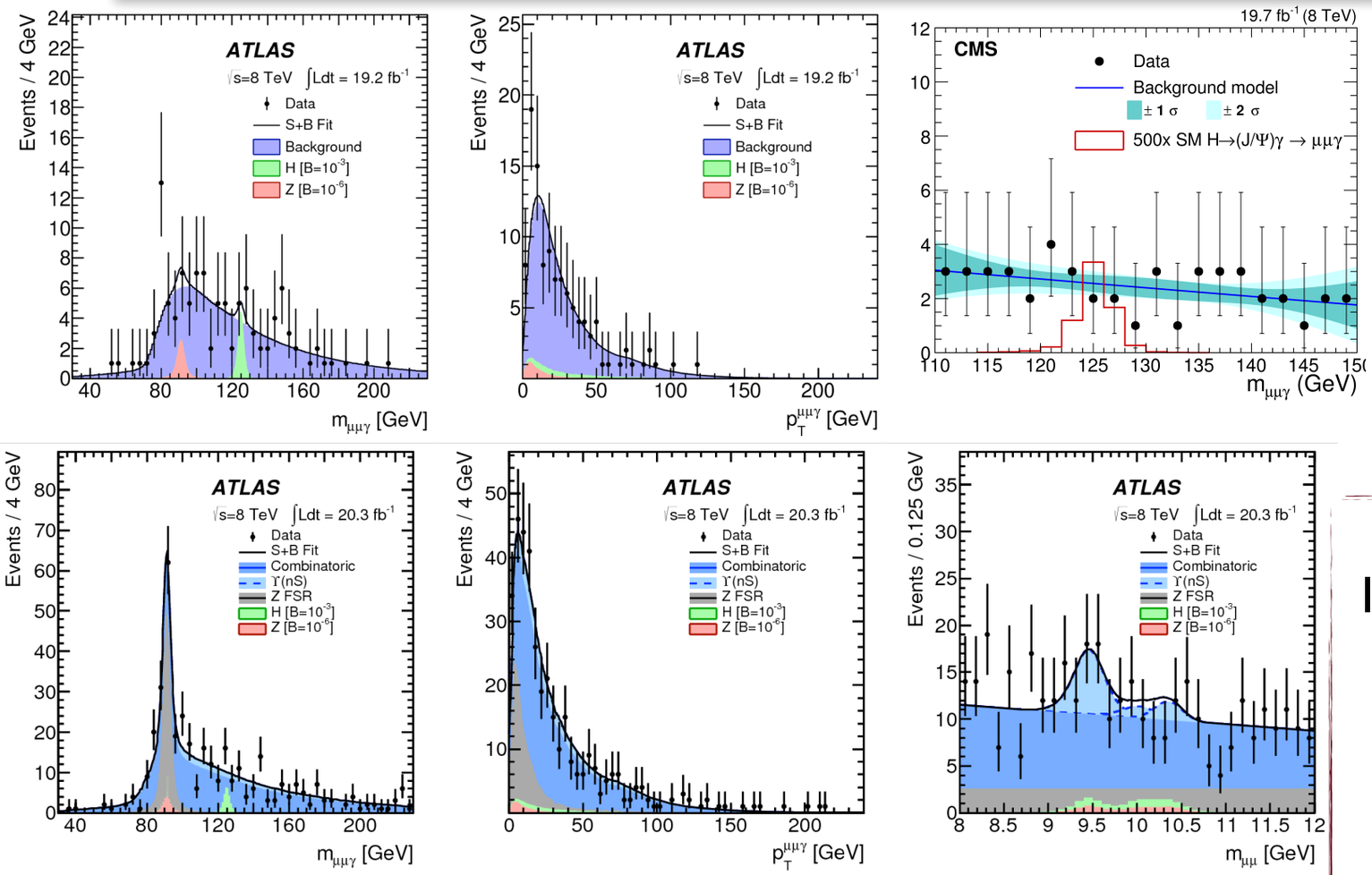


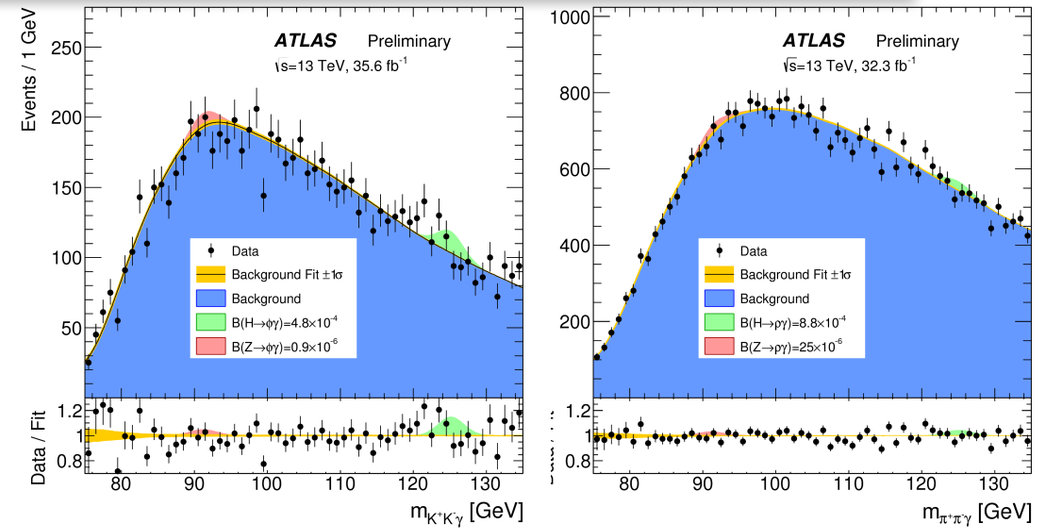
ATLAS-PHYS-PUB-2015-043

- ☑ HL-LHC is a Higgs boson factory
  - $\mathcal{O}$(200M) Higgs bosons produced
- ☑ HL-LHC projections for h→Zγ
  - ☑ Significance 3.9σ δμ/μ ~ 25 (30%)
    [ATL-PHYS-PUB-2014-006]
- ☑ HL-LHC projections for h/Z→J/ψγ
  - ☑ Simple and, relatively, clean final state
  - ☐ Small branching ratio, few events expected
  - ☐ At SM sensitivity h→μμγ_{FSR} contribution~3×h→J/ψγ and (Z→μμγ_{FSR} for Z)
  - ☐ Sensitive to "anomalous" h→γγ; use ratio
- ☑ Future colliders: leap in Higgs production
  - FCC-hh 100 TeV 20/ab: $\mathcal{O}$(15G) Higgs bosons

	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





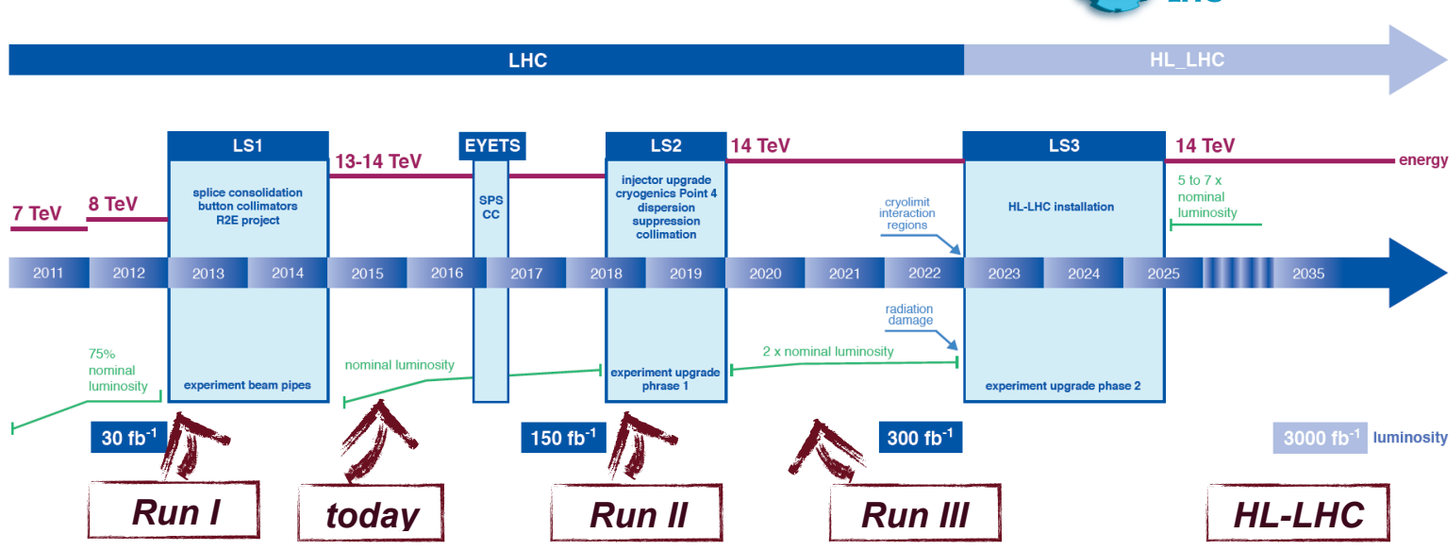
Higgs boson-fermion interactions is the least explored (and motivated) part of the SM → Particularly1st/2nd generation.

New Physics could be hiding here!

A number of complementary approaches appear currently in the literature: exclusive decays, inclusive (e.g. charm tagging), Higgs boson kinematic properties (somewhat less direct), etc.

New field of study in Higgs sector; novel ideas available to elucidate this corner of the SM!

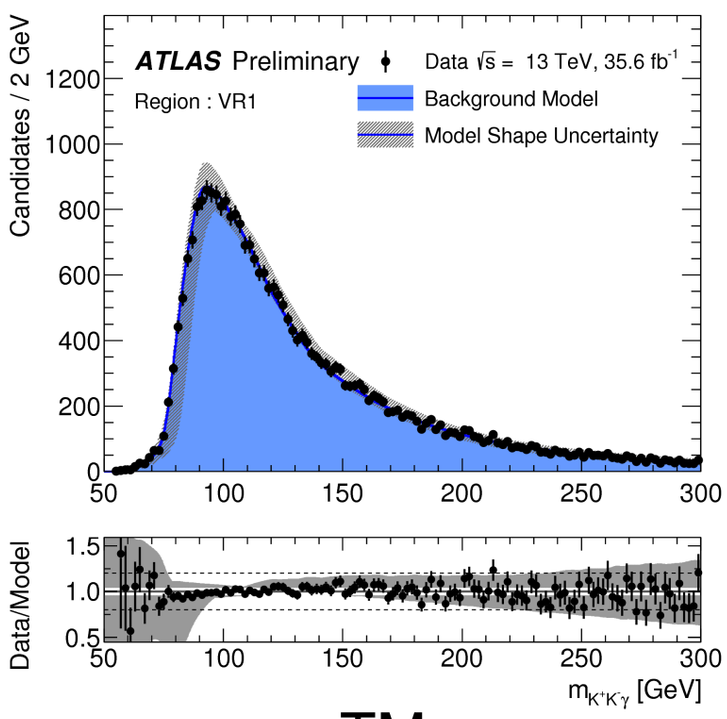
LHC / HL-LHC Plan



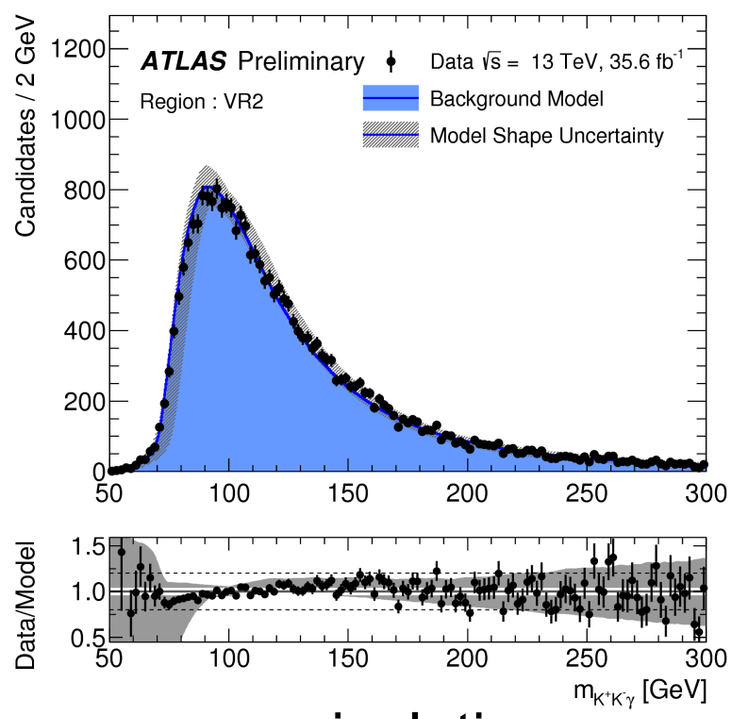
Additional Slides

Background: φγ

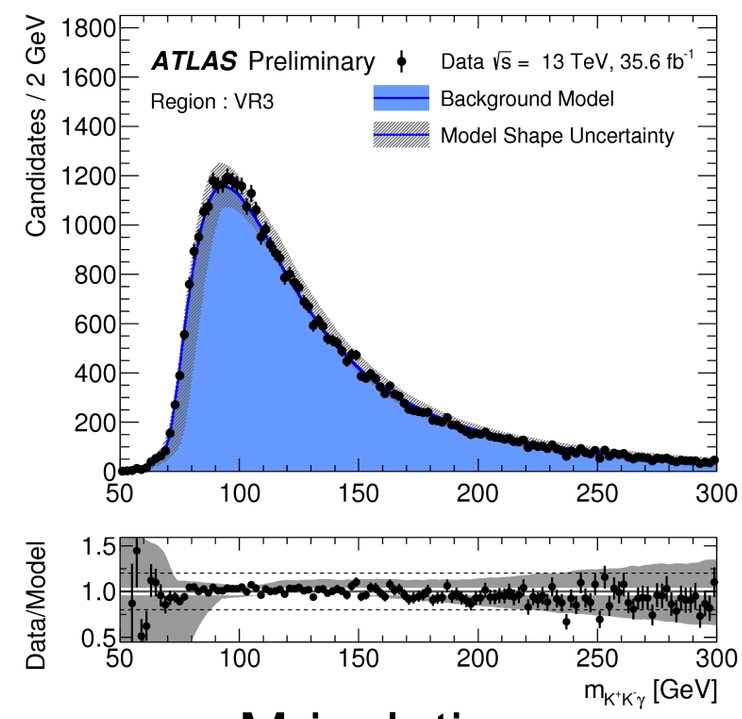
- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. $h/Z \to \mu\mu\gamma_{FSR}$) **estimated to be negligible**
- **Nonparametric data-driven model;** same procedure as in $h/Z \to J/\psi\gamma$



pTM



γ-isolation



M-isolation

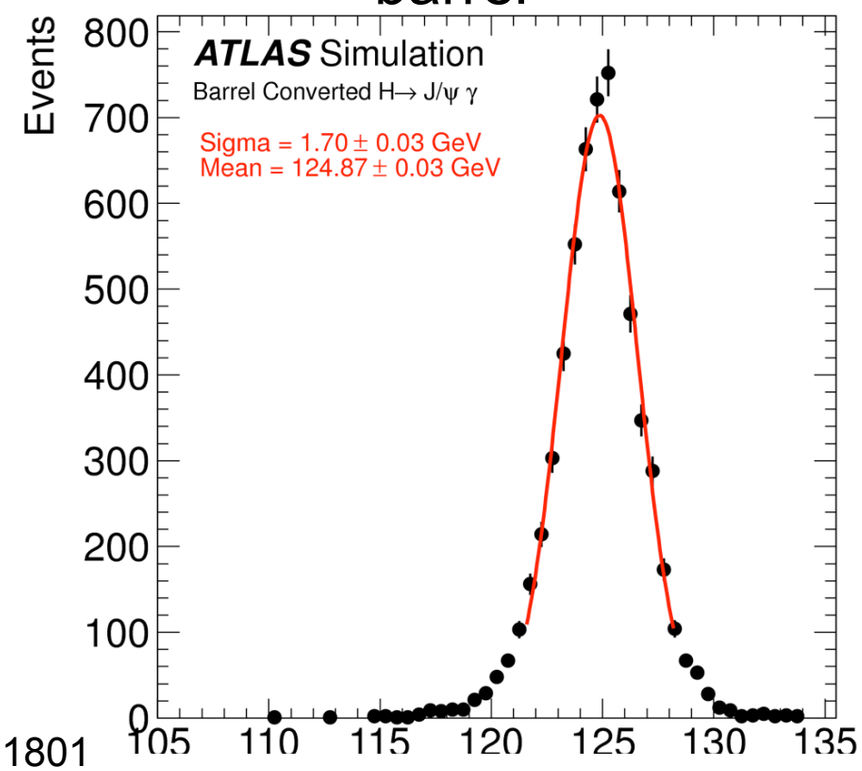
ATLAS-CONF-2017-057

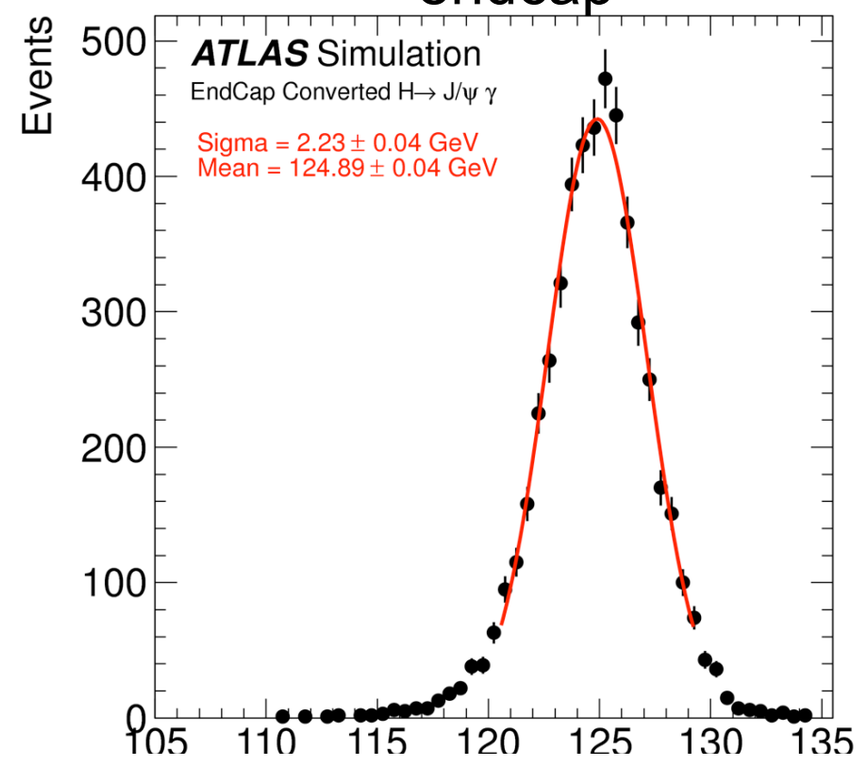
h/Z→J/ψγ and h/Z→Υ(nS)γ: Mass Resolution

barrel

endcap

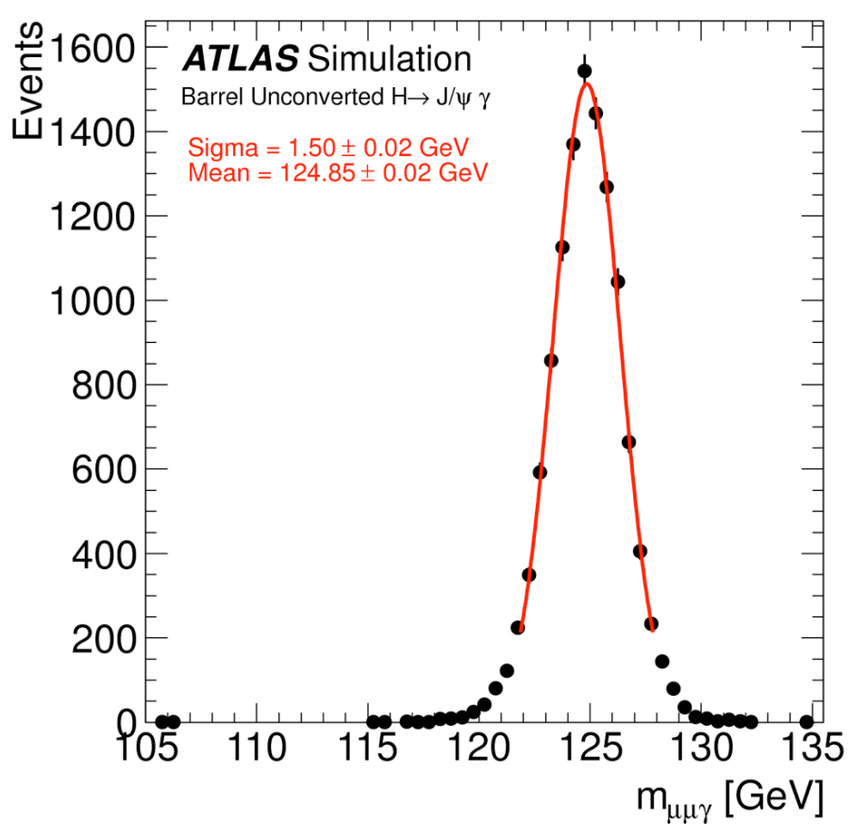
converted photon

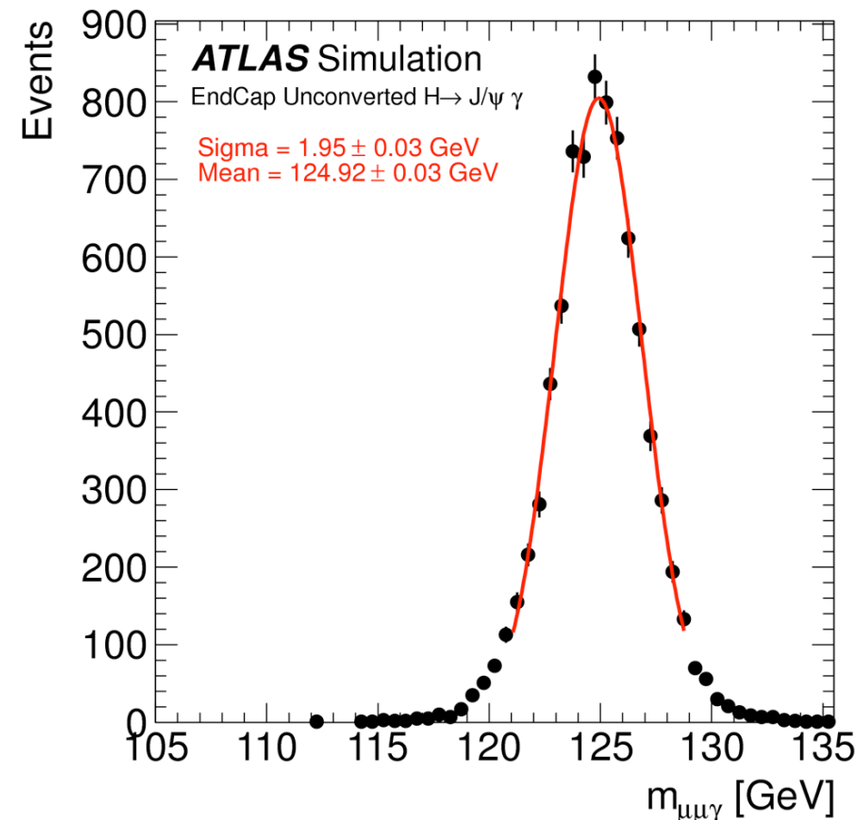




Phys.Rev.Lett. 114 (2015) 121801

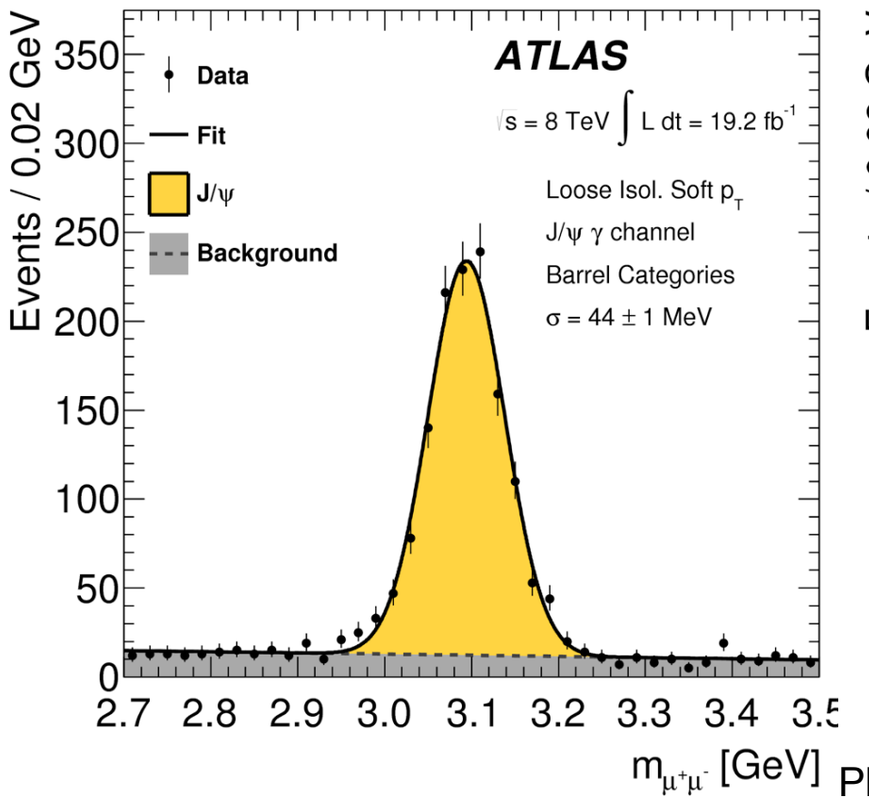
unconverted photon

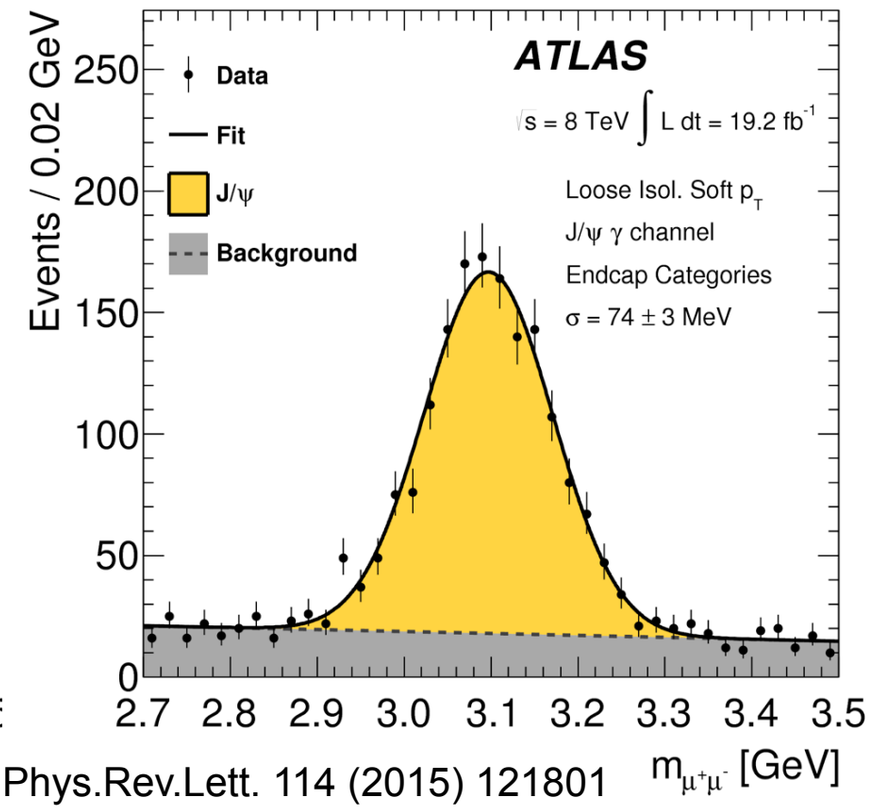




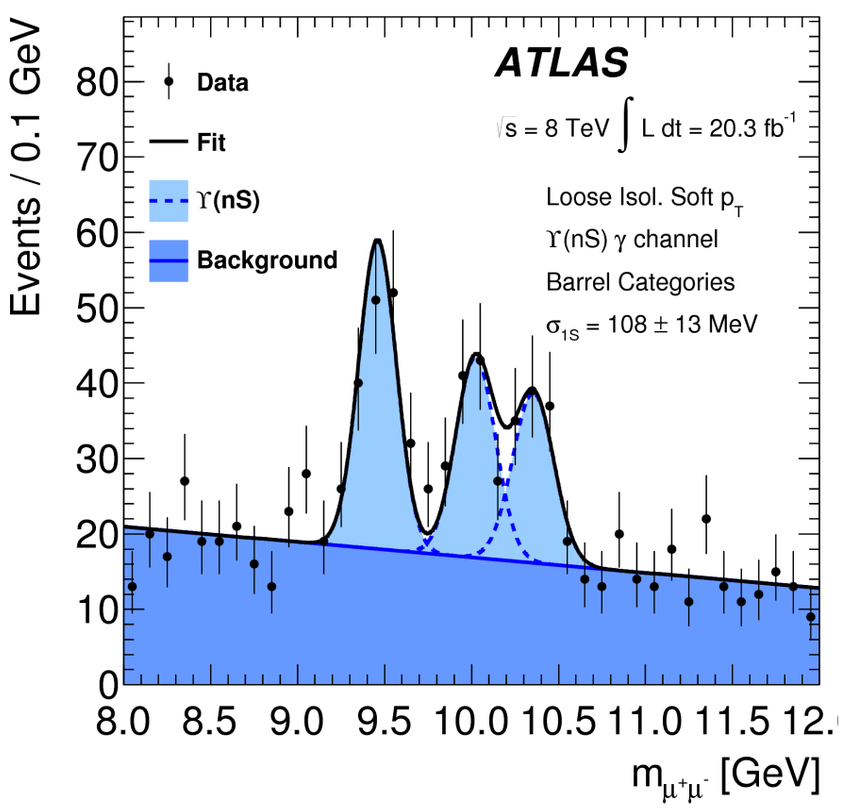
mass resolution
~1.2-1.8%

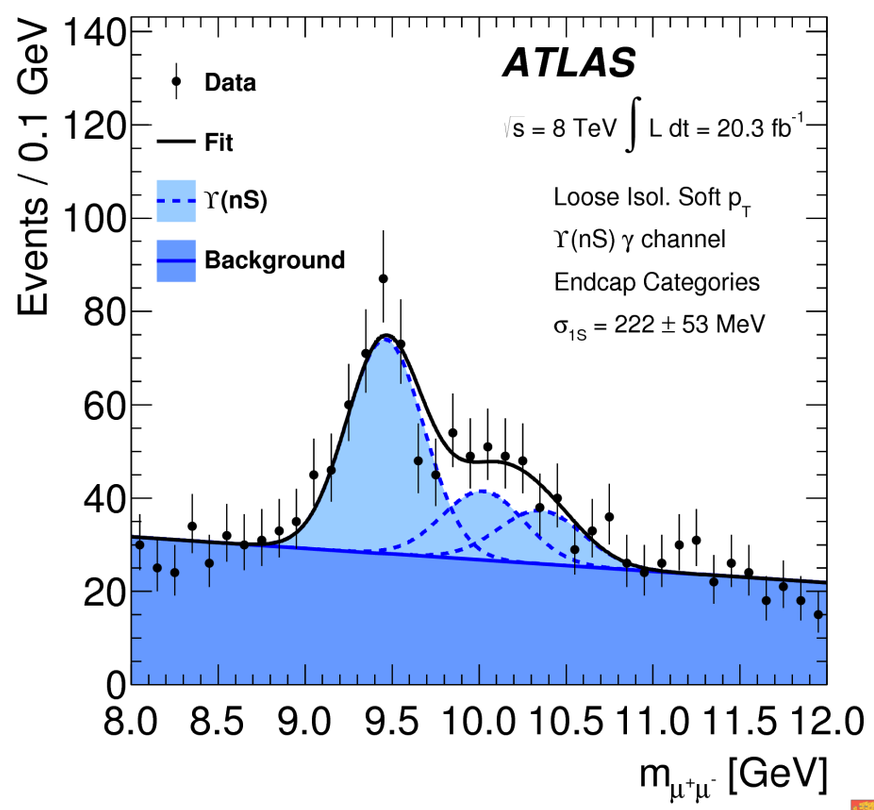
h/Z→J/ψγ and h/Z→Υ(nS)γ: Mass Resolution





Phys.Rev.Lett. 114 (2015) 121801





h/Z→J/ψγ and h/Z→Υ(ns)γ

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