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Probing the Higgs Yukawa couplings at the Large Hadron Collider

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University of Birmingham

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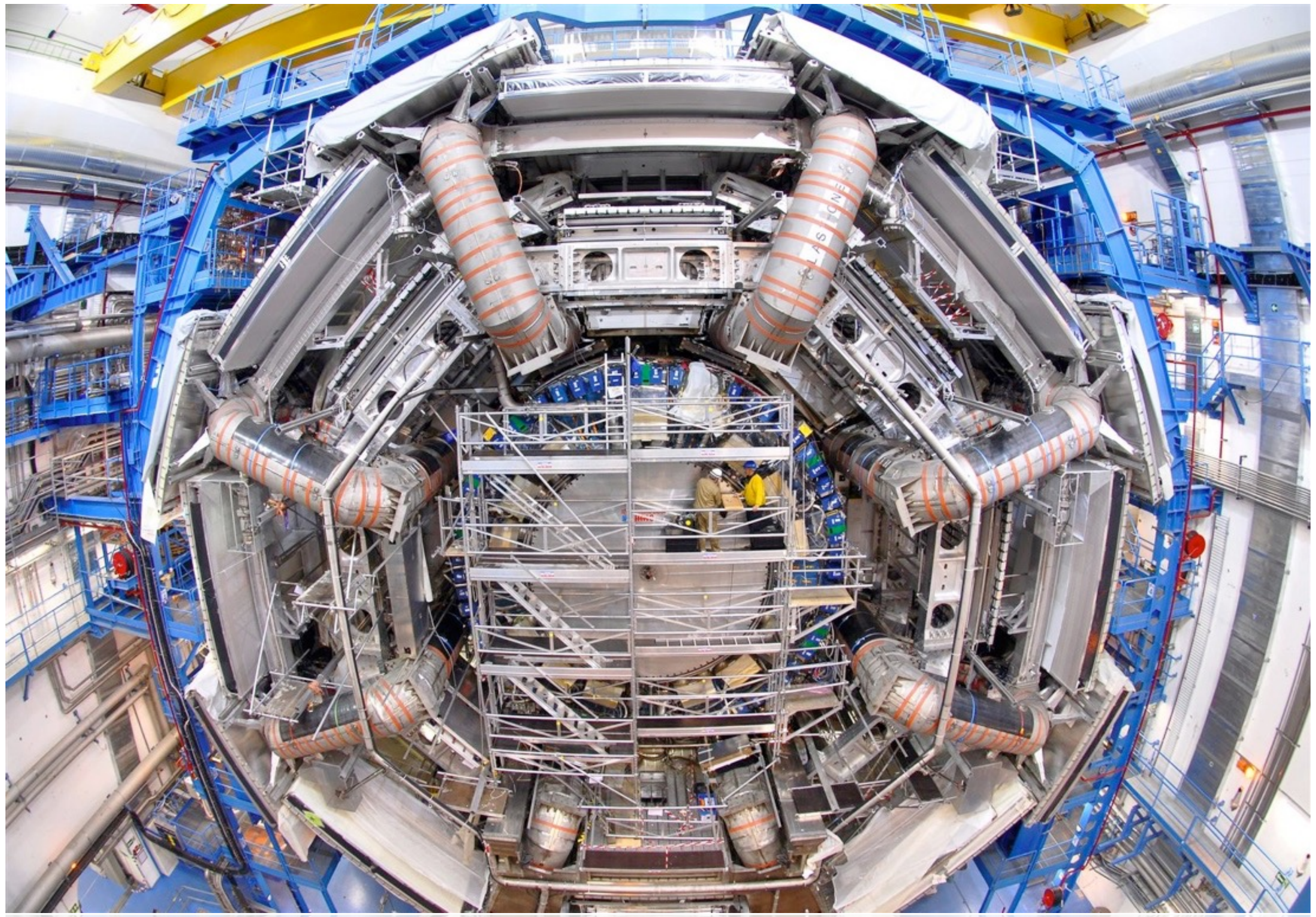


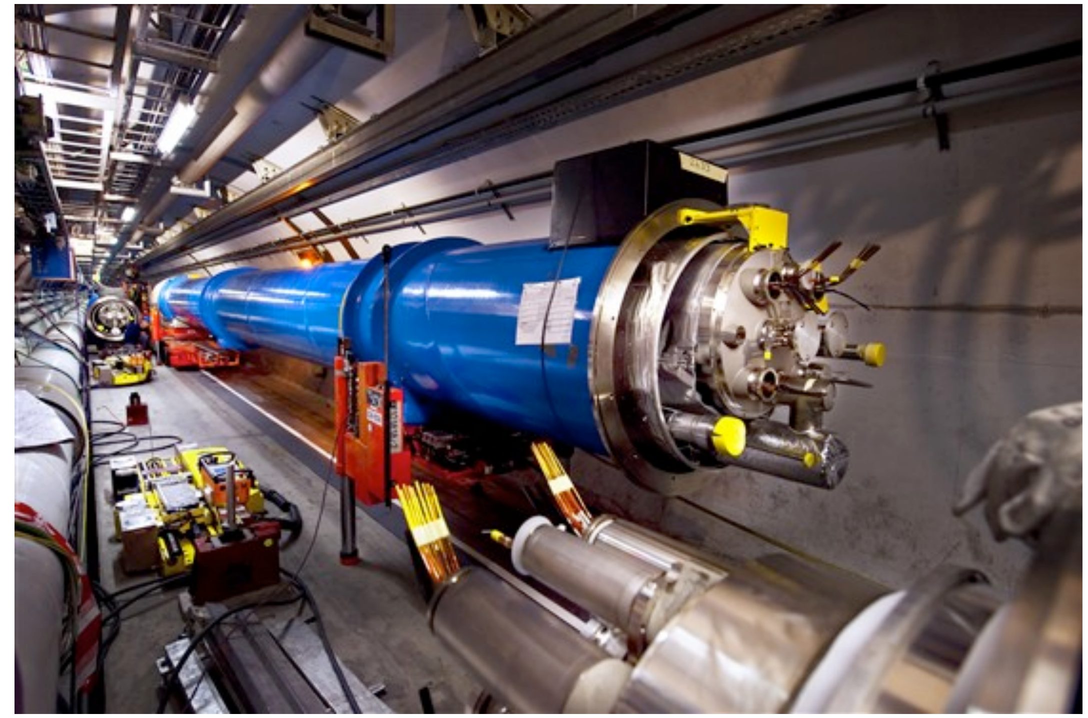
ATLAS experiment at CERN

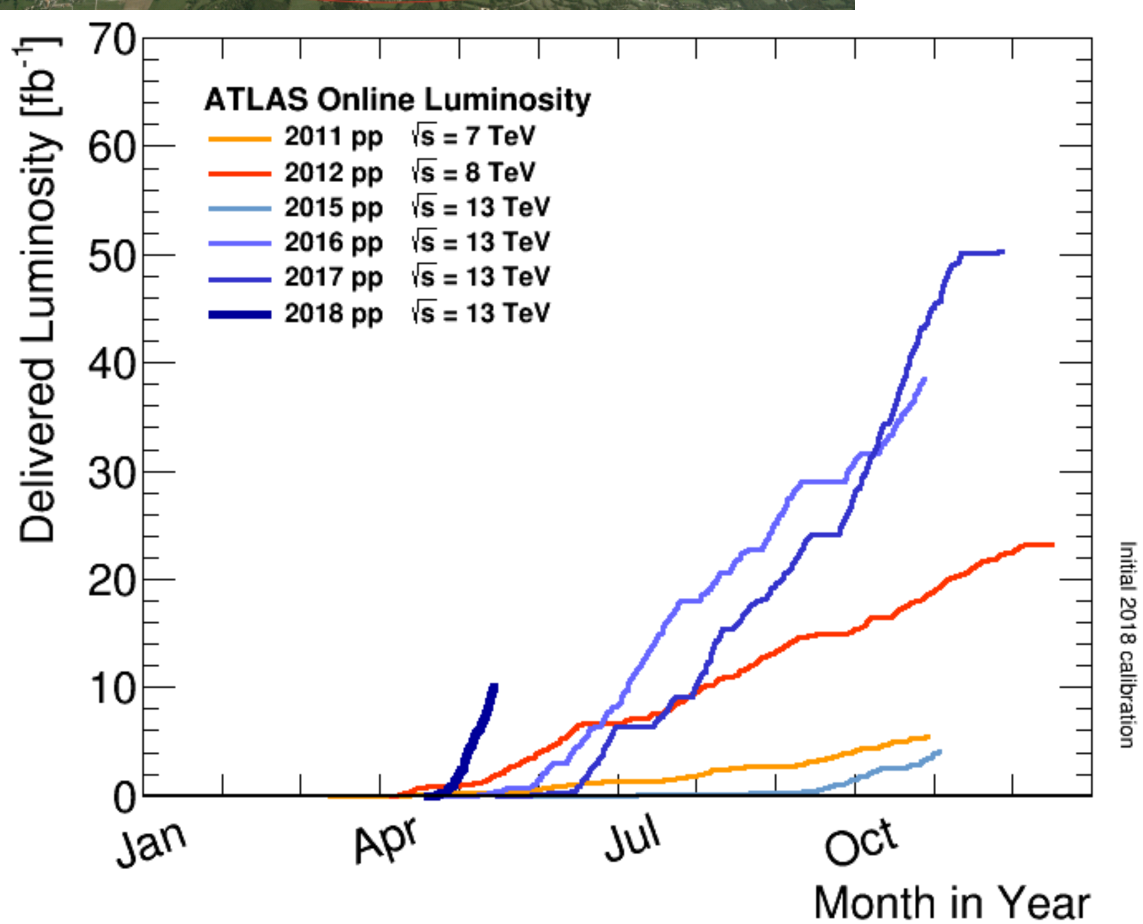
Particle Physics Seminar
May 16, 2018,
University of Liverpool, Liverpool, UK

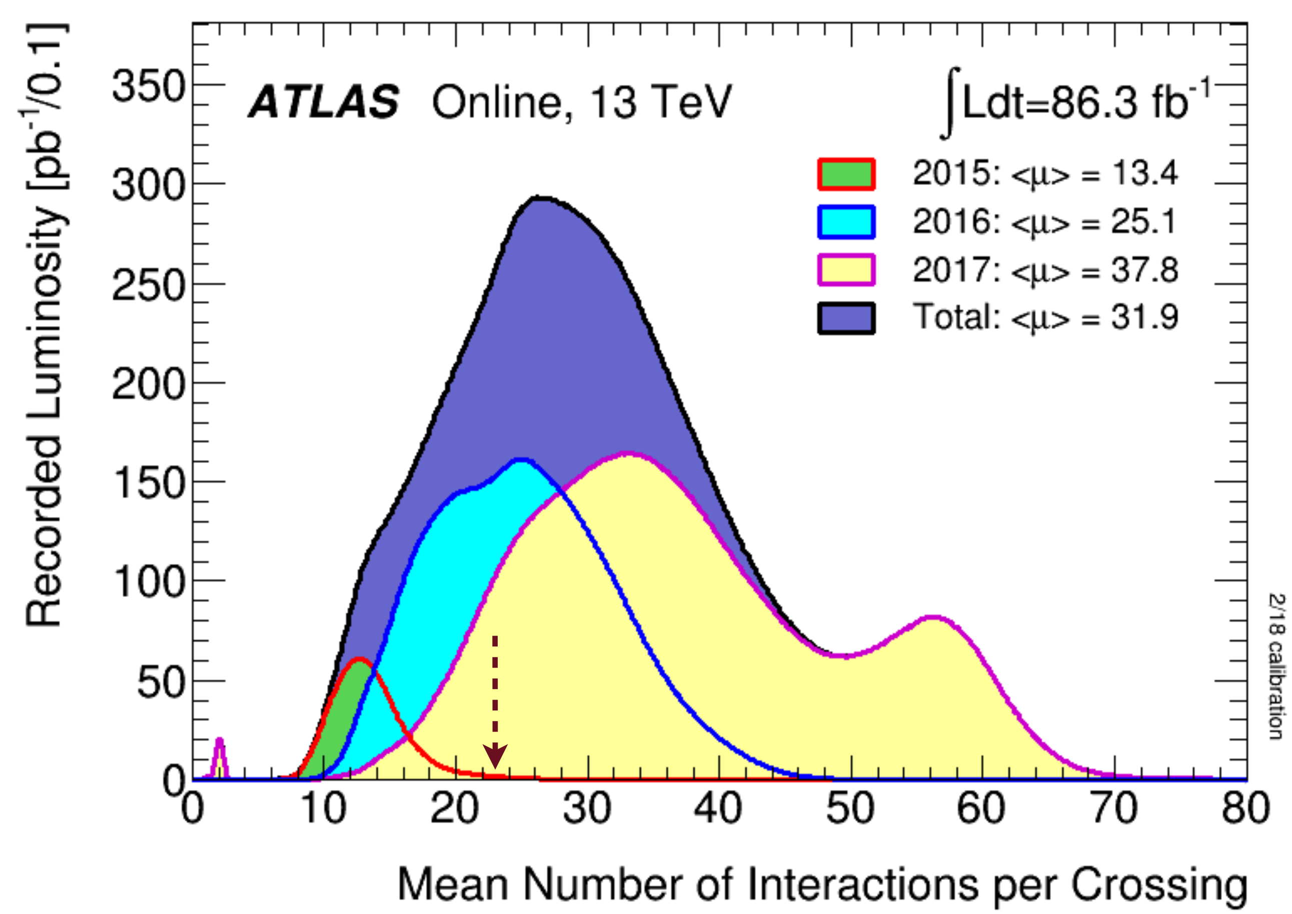
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement no 714893 (ExclusiveHiggs)

The Large Hadron Collider

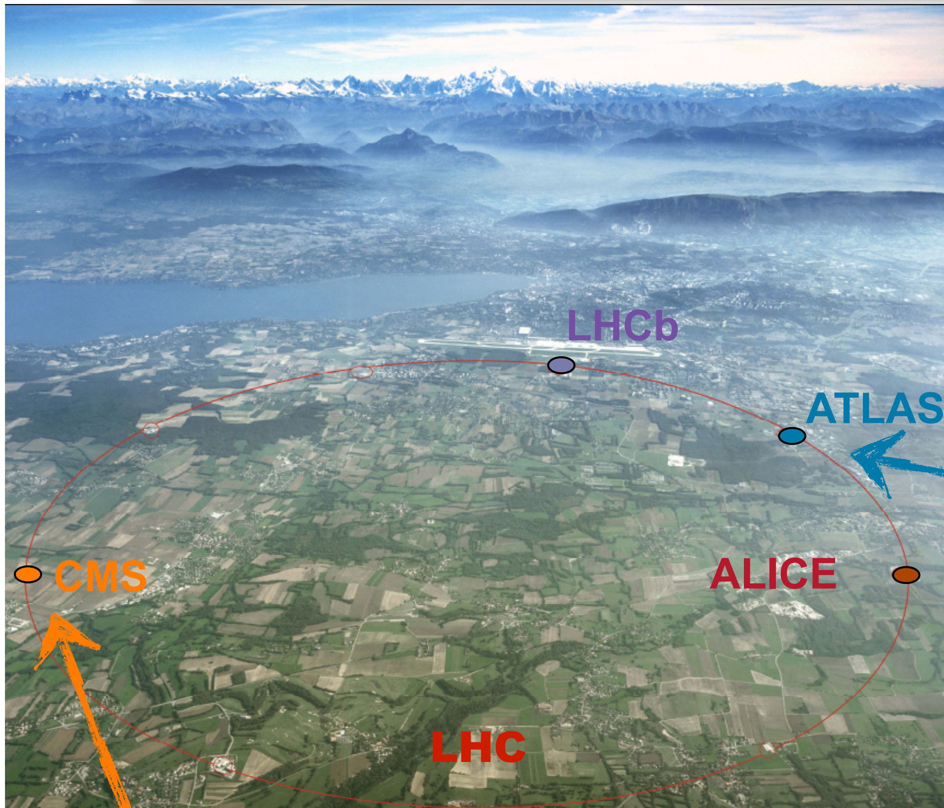
One of the 1232 superconducting dipoles, B field up to 8.3T

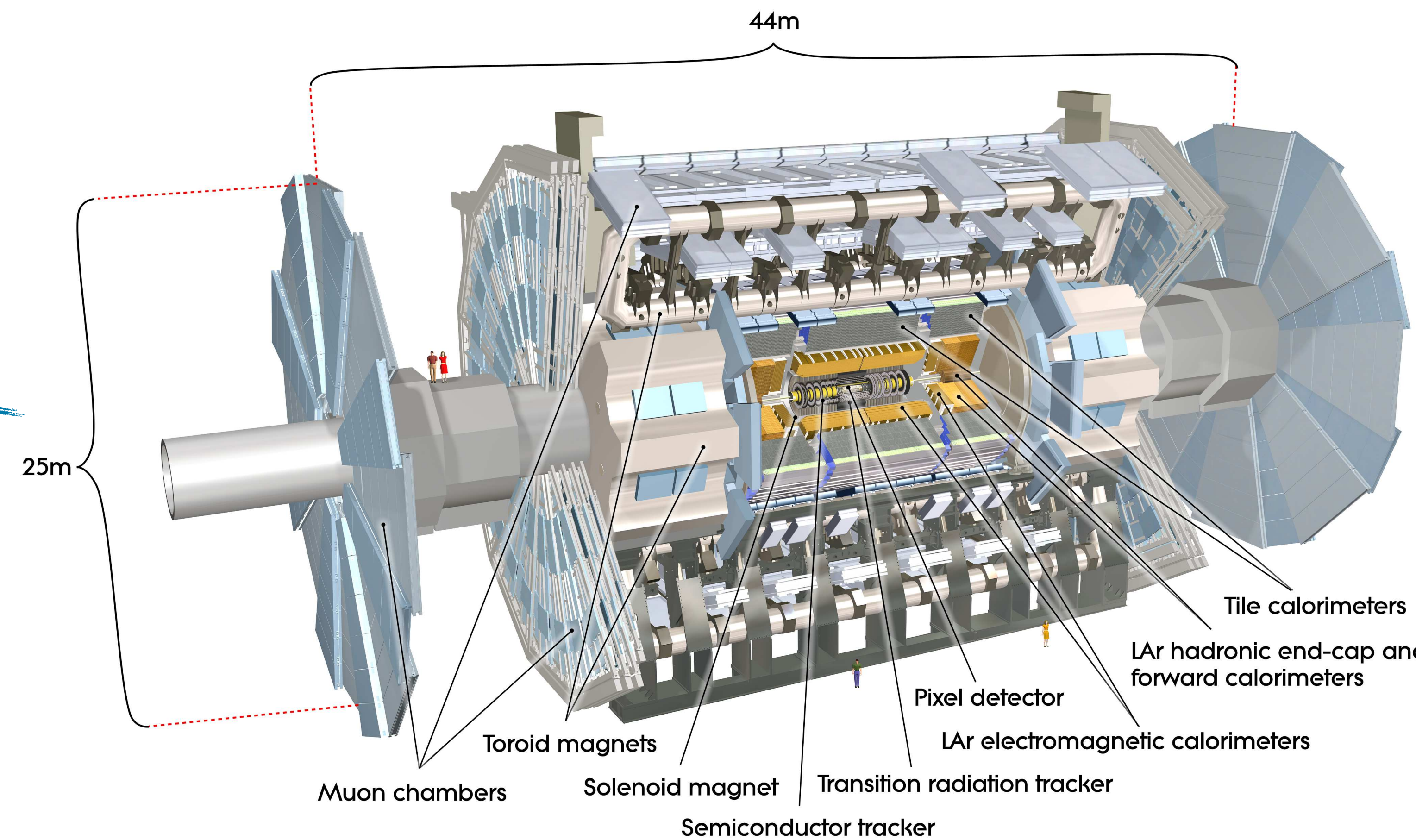


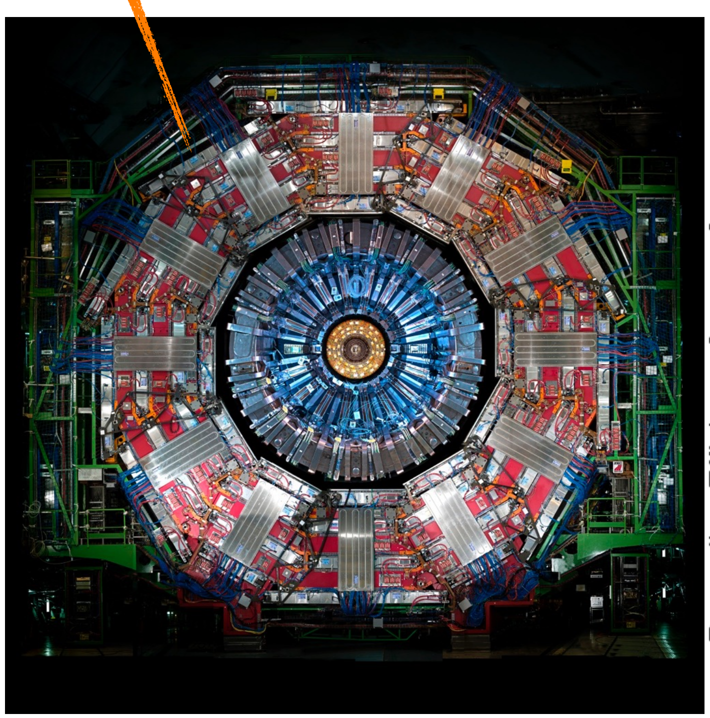


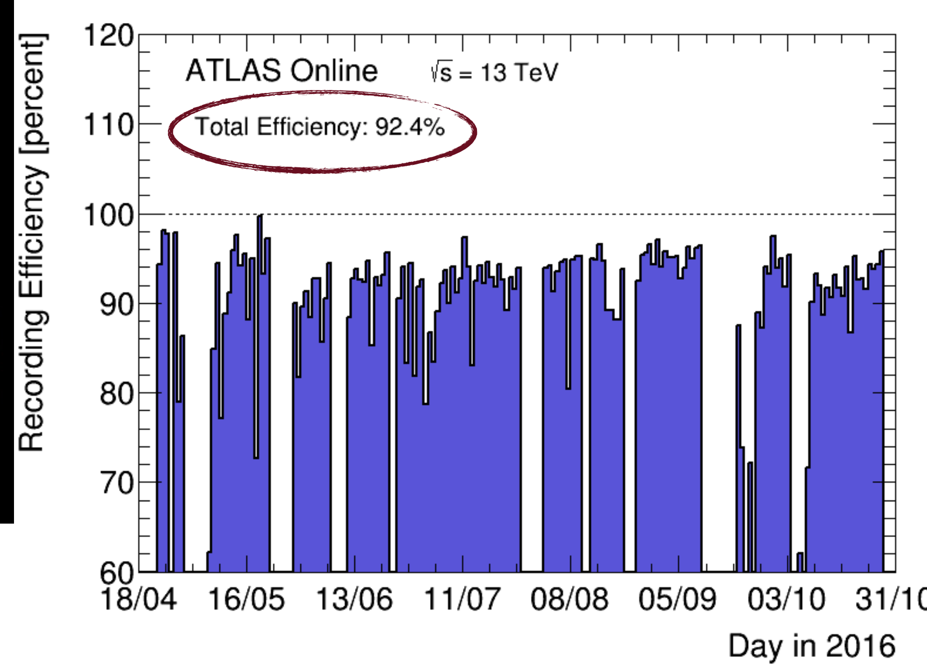


The LHC detectors









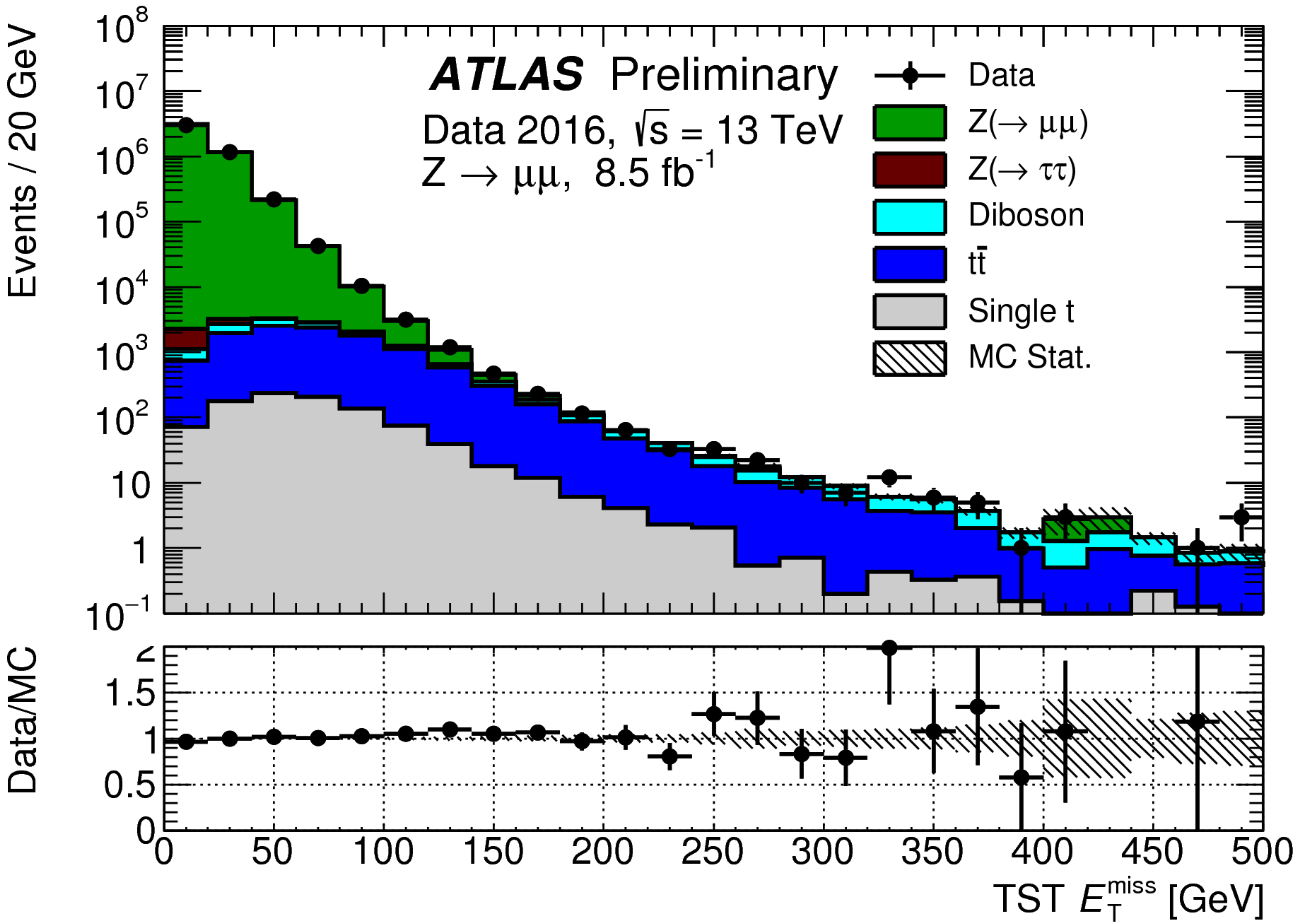
ATLAS pp 25ns run: April-October 2016

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets		Trigger
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid	L1
98.9	99.9	99.7	99.3	98.9	99.8	99.8	99.9	99.9	99.1	97.2	98.3

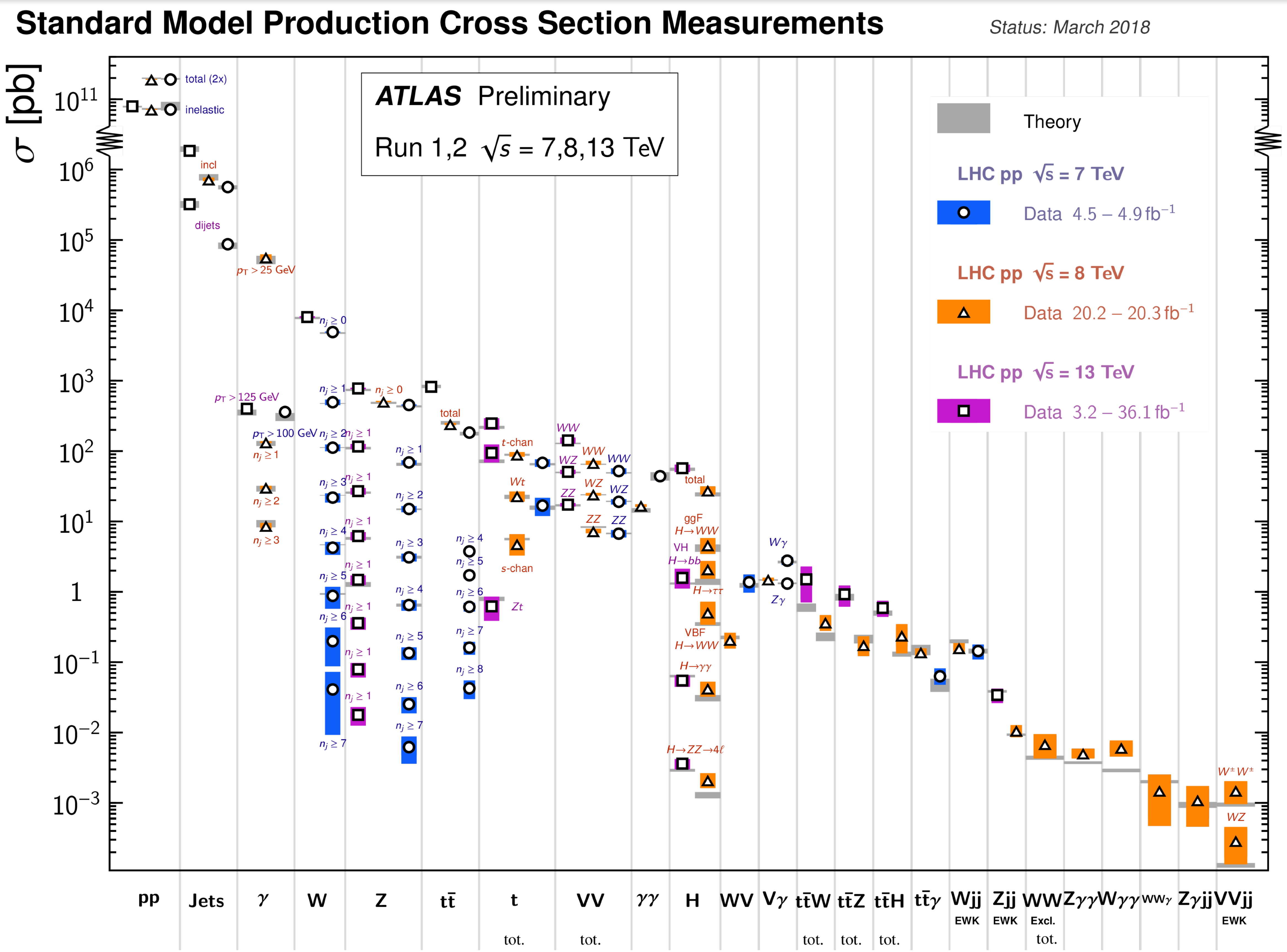
Good for physics: 93-95% (33.3-33.9 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}$=13 TeV between April-October 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.

ATLAS performance overview



Snapshot of measurements



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Higgs mechanism and the Higgs boson

- $SU(2)_L \otimes U(1)_Y$ local gauge symmetry; electro-weak unification: massless carriers
- Symmetry spontaneously broken; Higgs field obtains non-zero vacuum expectation value
  - 3 d.o.f of Higgs field become longitudinal polarisations of $W^{\pm}/Z$ bosons
  - 1 d.o.f of Higgs field becomes the physical Higgs boson
- **Higgs interactions to vector bosons:** defined by symmetry breaking

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

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

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

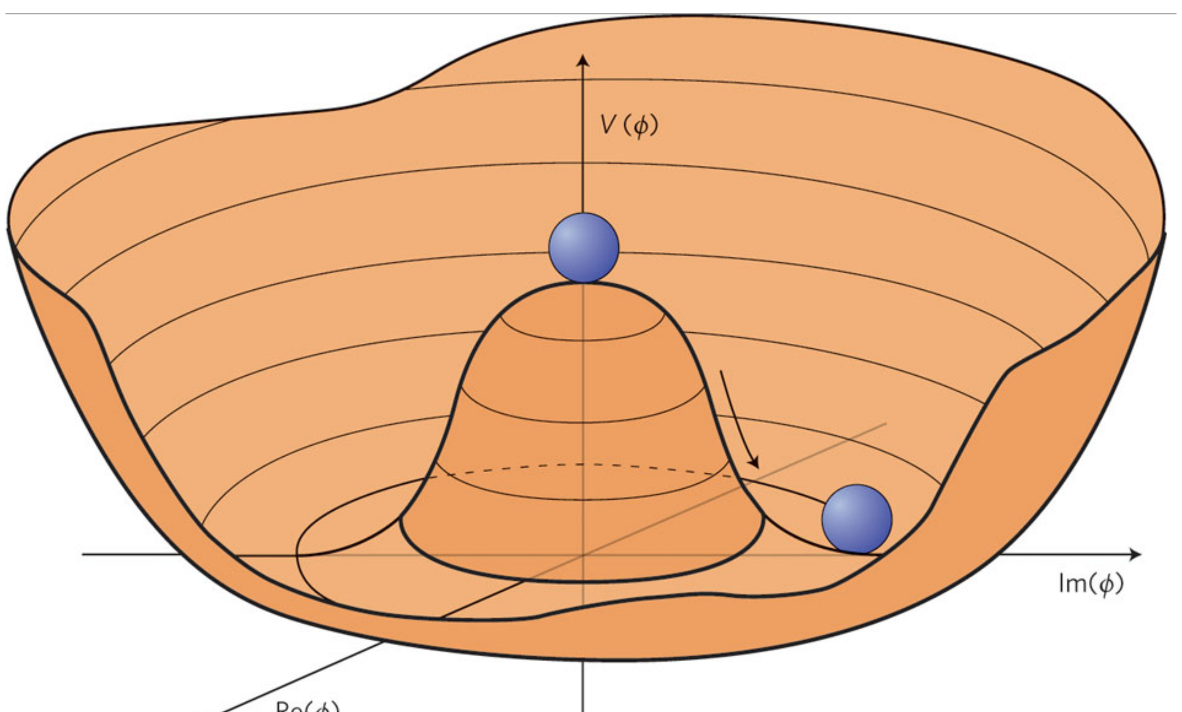
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

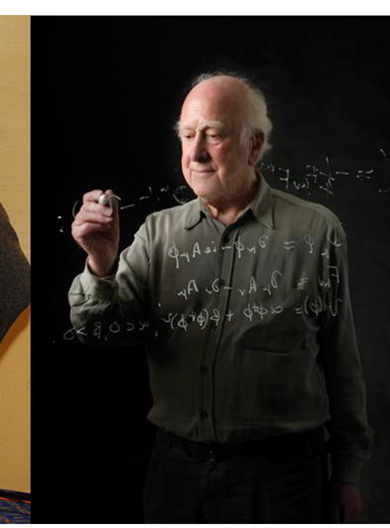
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

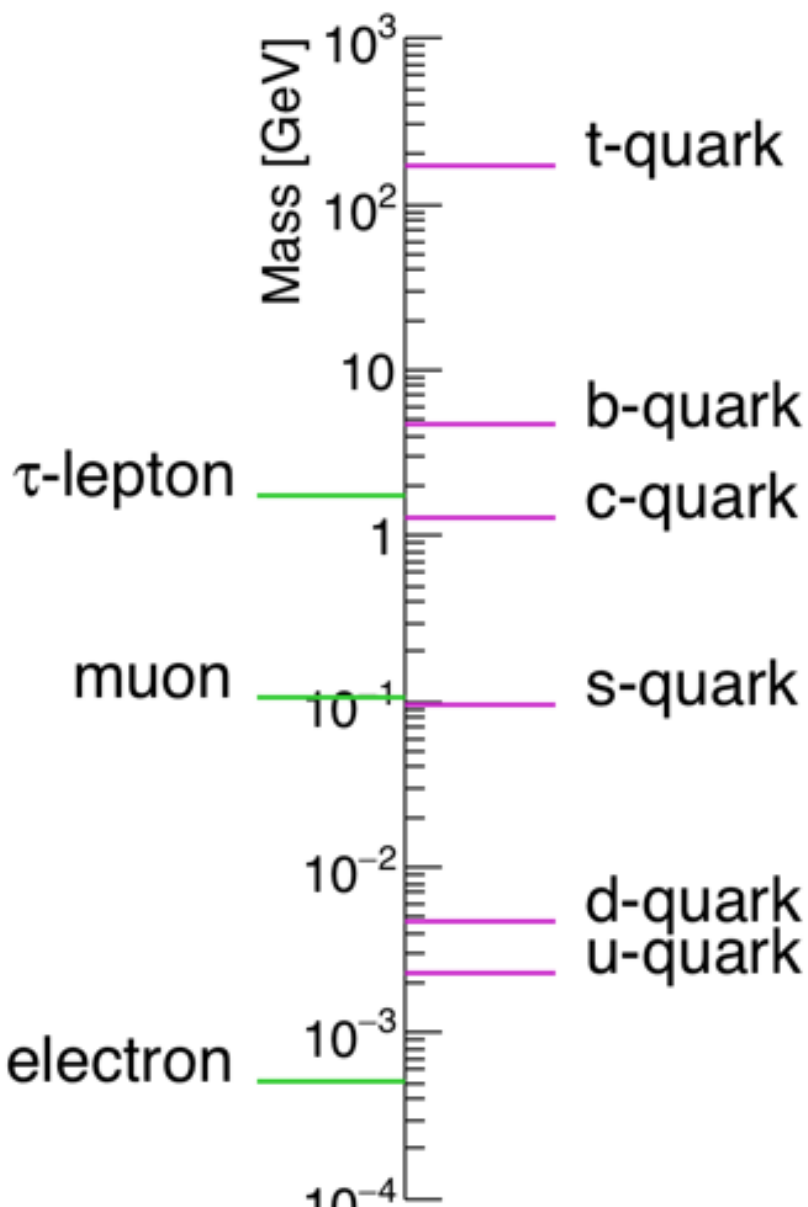
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



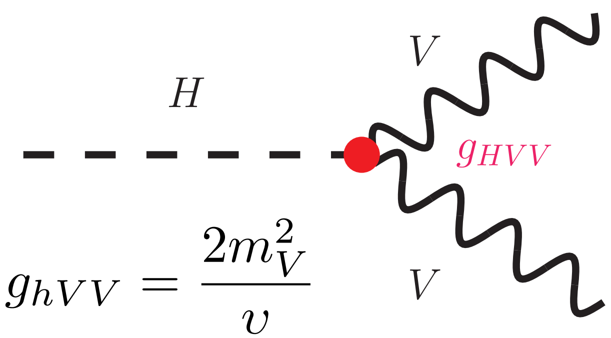


Higgs-fermion interactions: Yukawa couplings

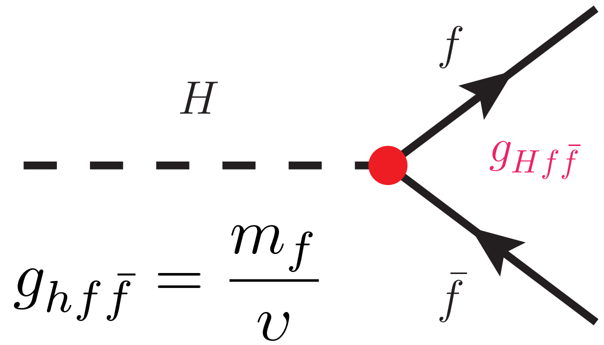
- **Higgs interactions to vector bosons:** defined by electroweak symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$



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



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



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

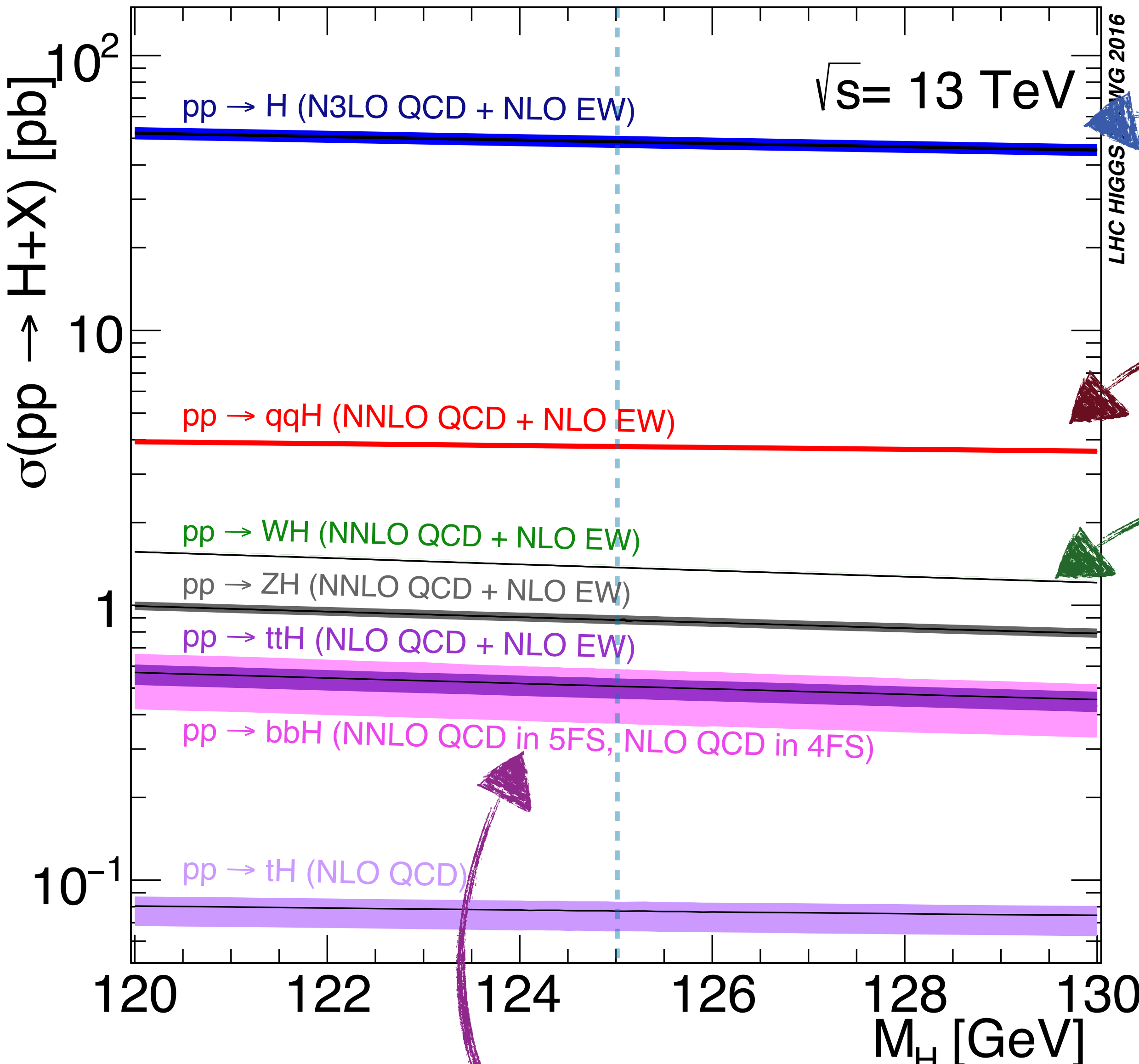
- Yukawa couplings **not** imposed by fundamental principle
- Probing fermion mass generation scale→independent task
- Fermion mass generation scale from **unitarity bounds**:

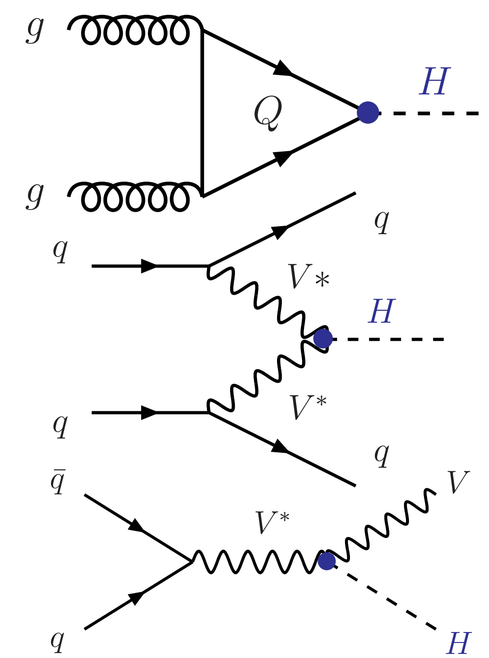
$$\Lambda \approx 23, 31, 52, 77, 84 \text{ TeV}_{(b,c,s,d,u)}$$

[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 ~$1/\Lambda^2$ or ~ to mixing angles with extra scalars

SM Higgs boson production and decay

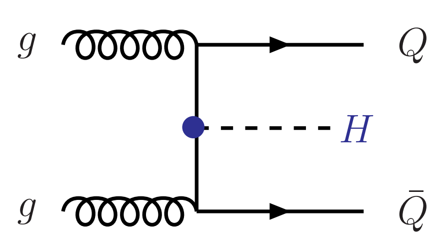




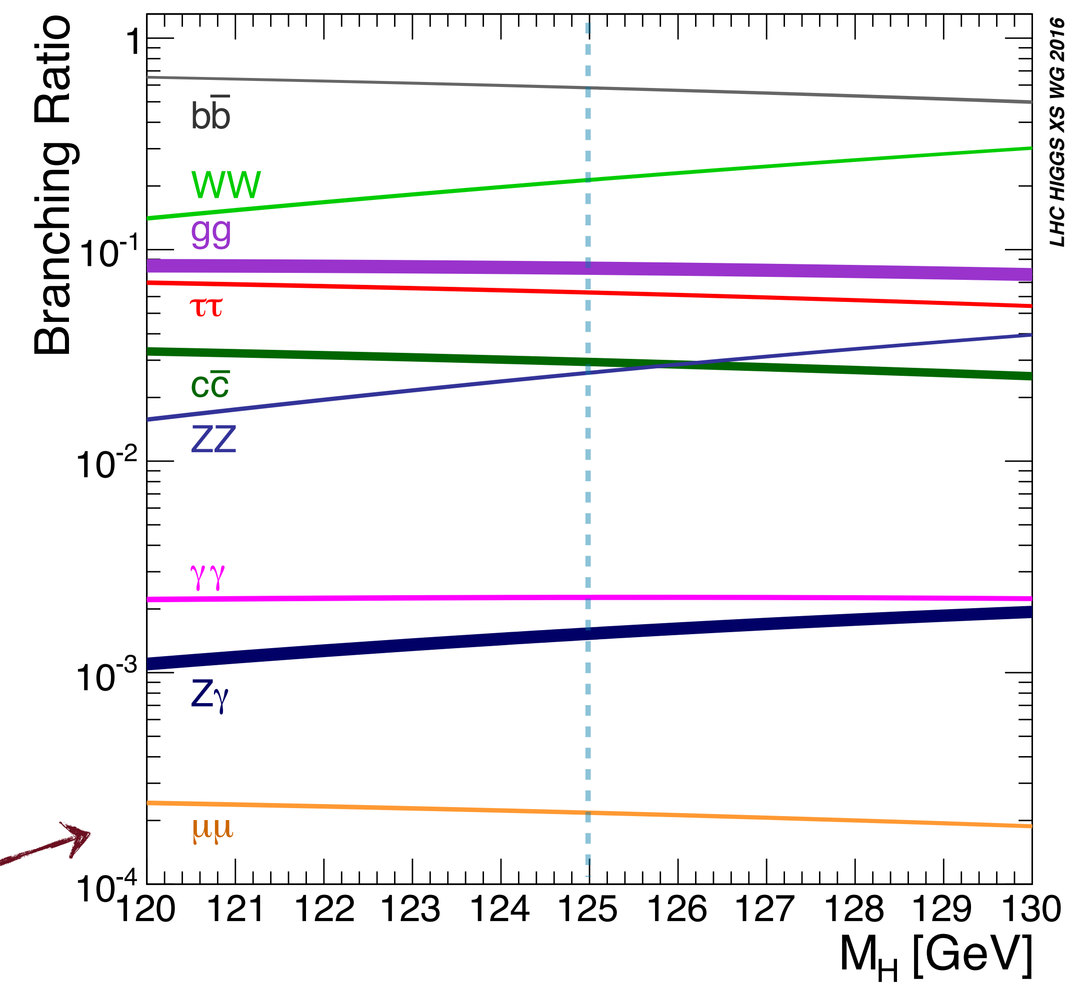
87%
m_h = 125 GeV

7%
m_h = 125 GeV

4%
m_h = 125 GeV

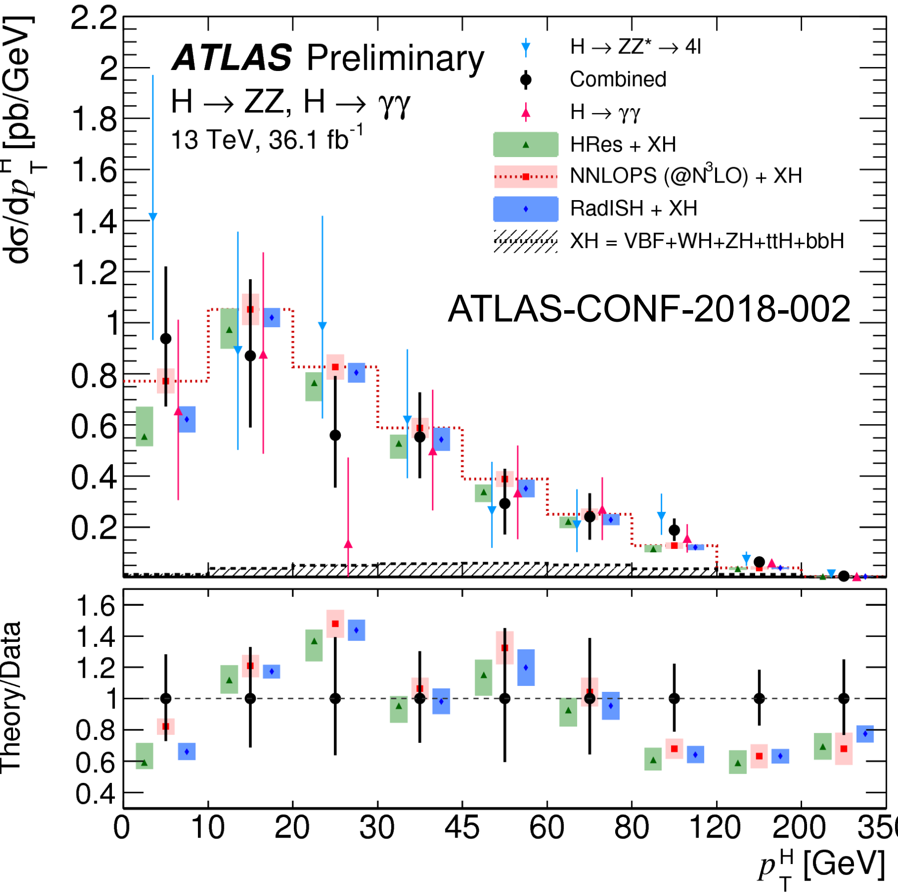


2%
m_h = 125 GeV



m_h~125 GeV gives access to several decay channels

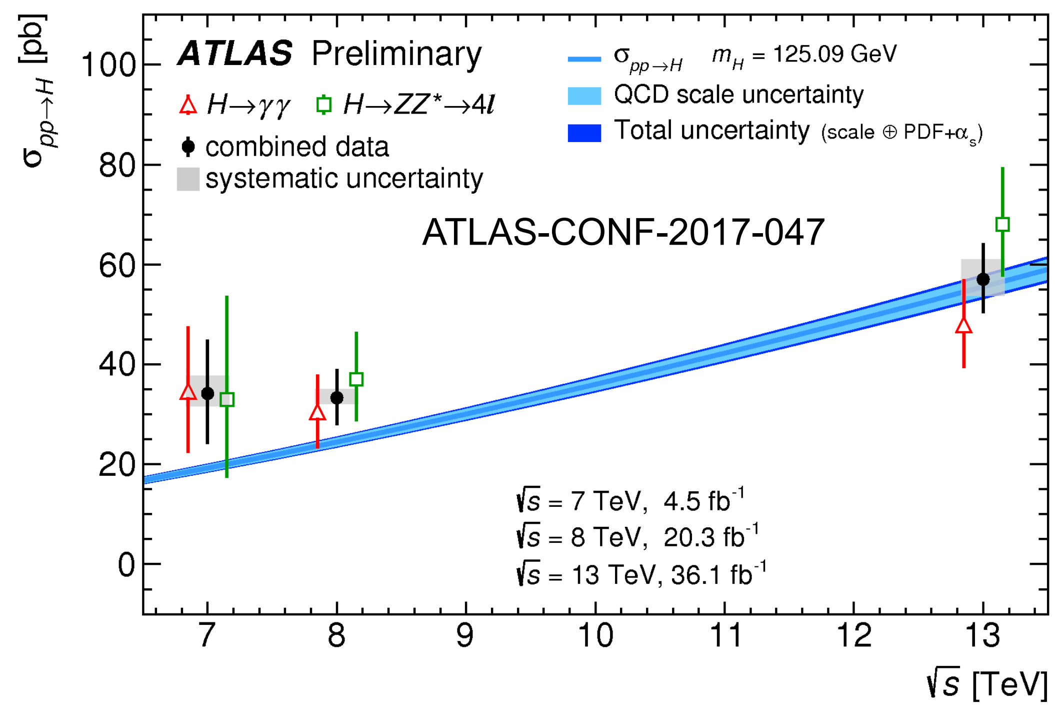
The Higgs boson properties



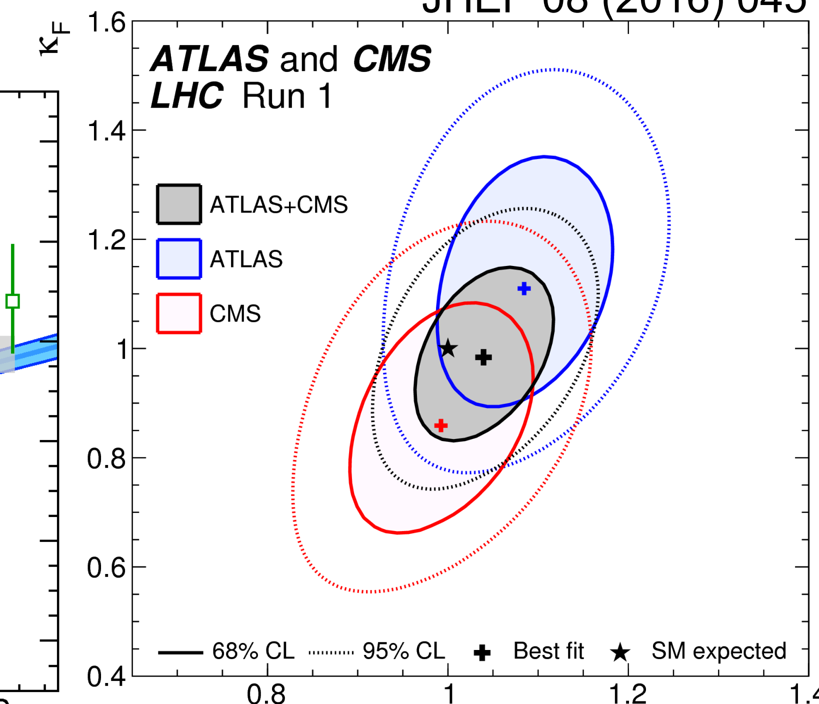
Higgs boson discovery through the h→ZZ/WW/γγ channels

Significant progress in **Higgs boson property** measurements:

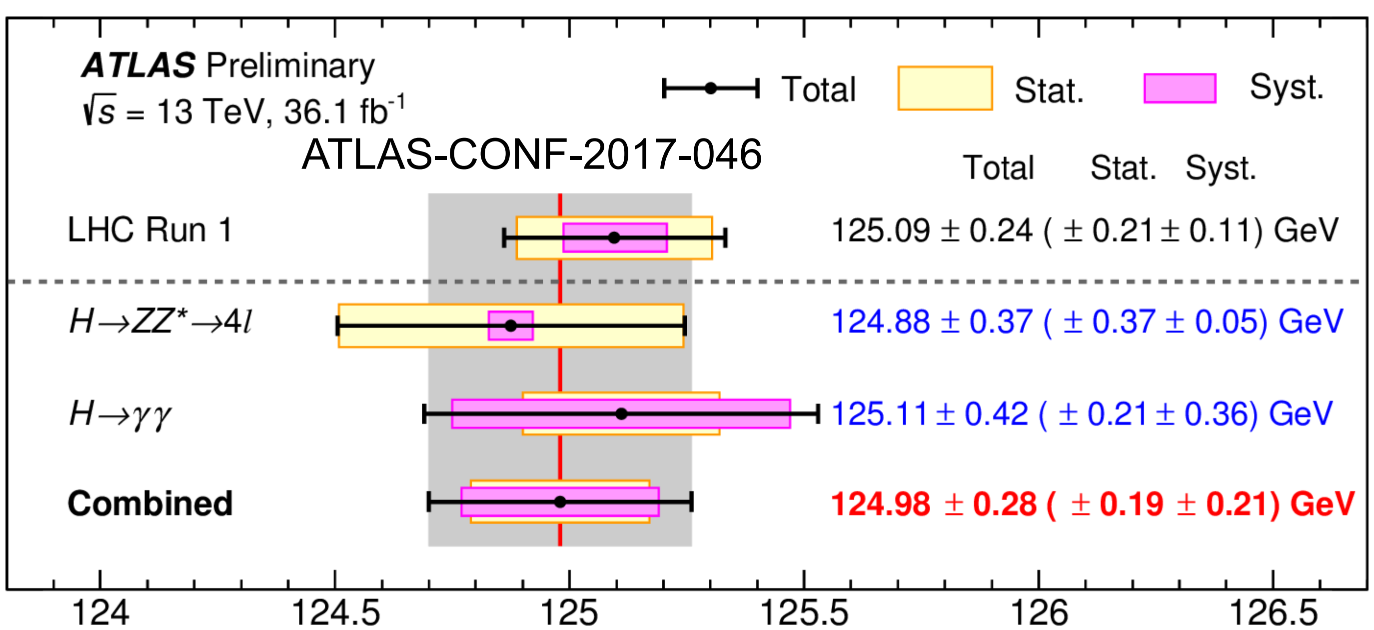
- **mass** known to better than 0.2%
- **bosonic decays** measured to ~10-20%



JHEP 08 (2016) 045



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

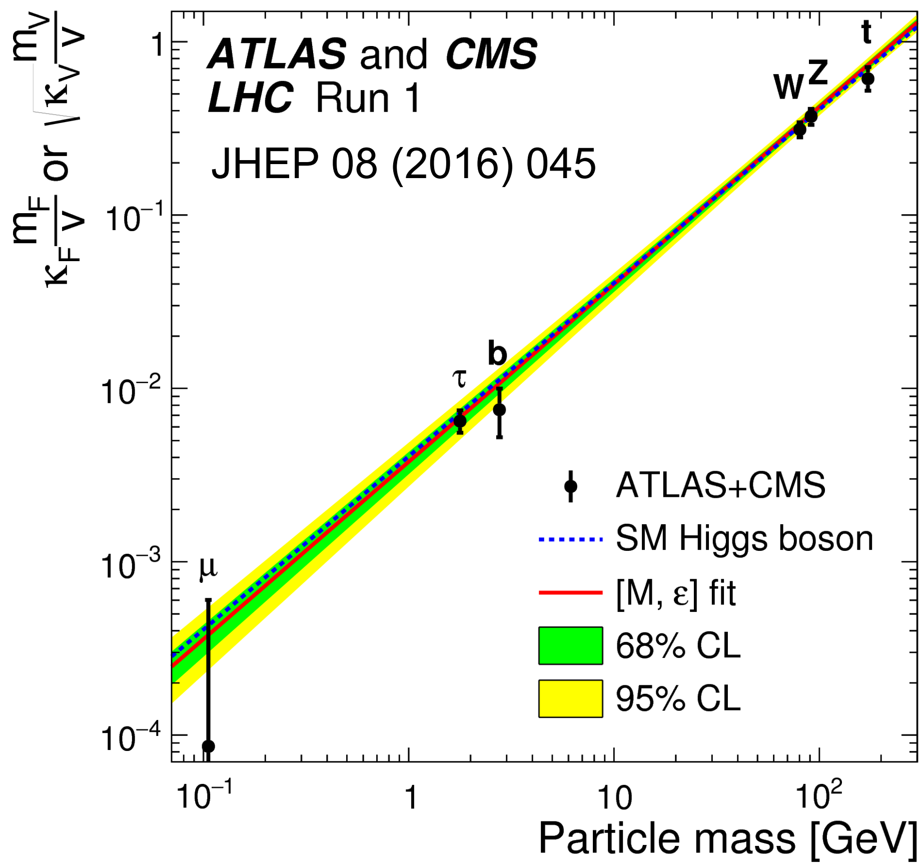


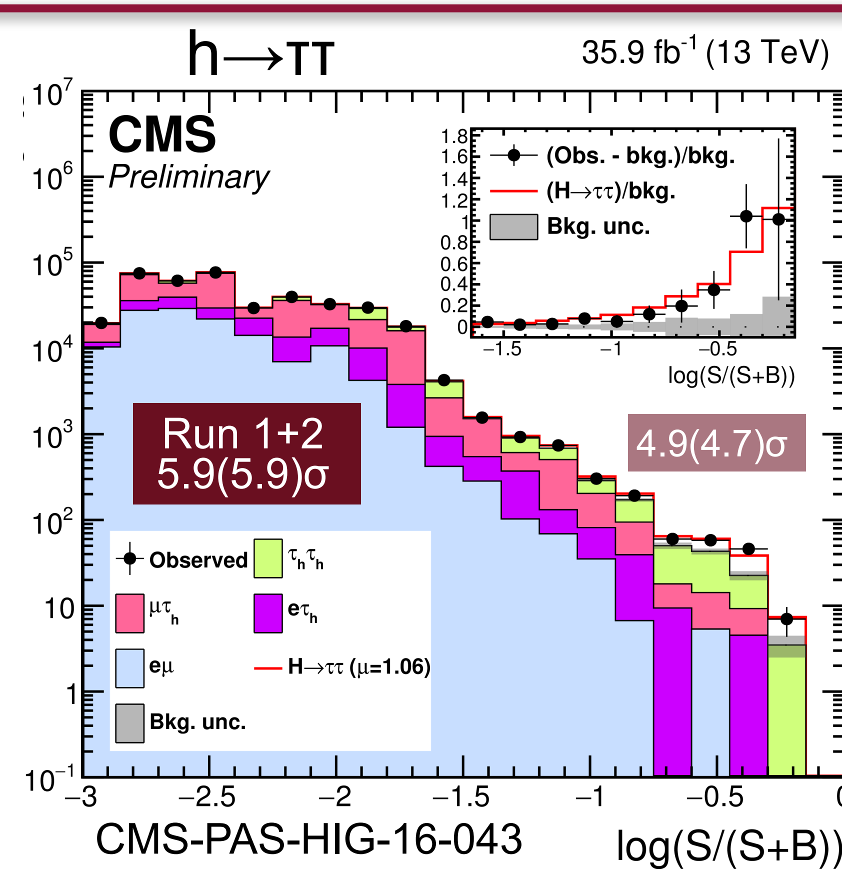
CMS Run 2 H→ZZ*→4l measurement: 125.26±0.21 GeV [arXiv:1706.09936]

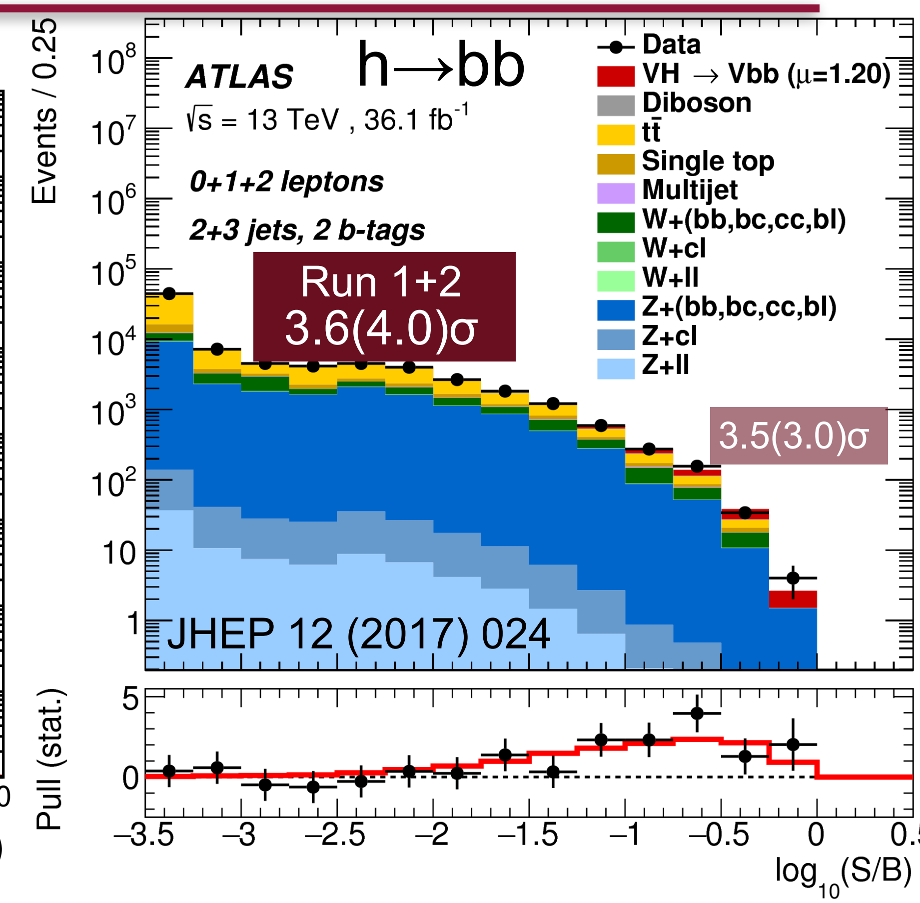
Experimental information on Yukawa couplings essential to fully characterise the observed Higgs boson!

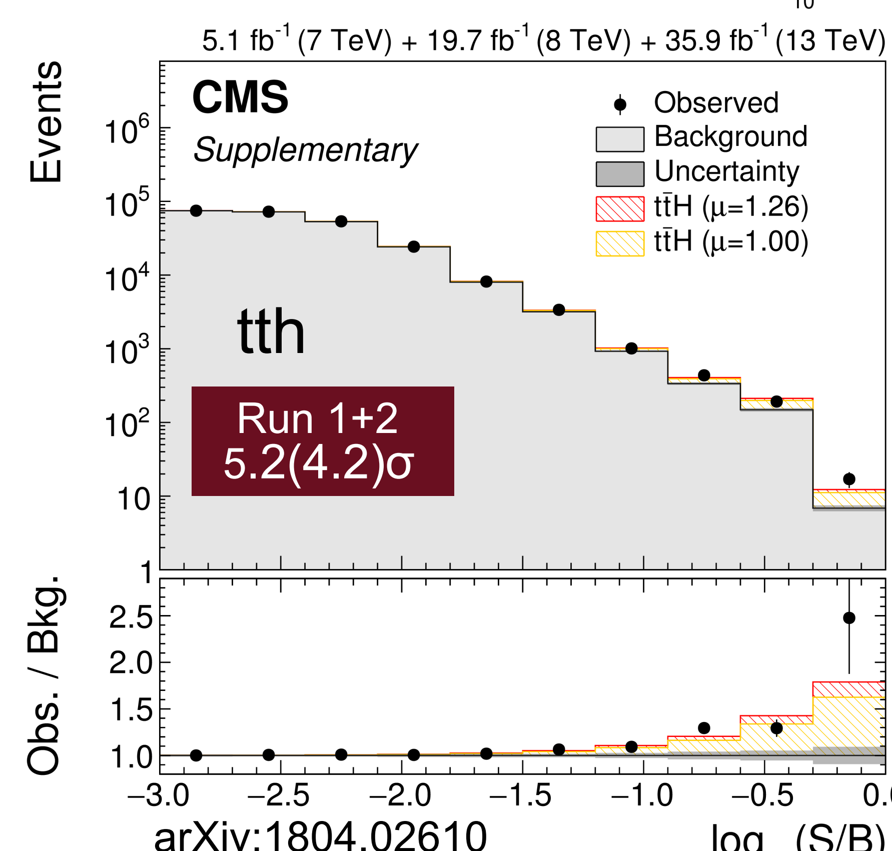
[in a nutshell]

Higgs-fermion interactions: The story so far









For 3rd generation fermions:

☑ **top-quark, bottom-quark, τ-lepton:** tth observed, h→bb established, h→ττ observed

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

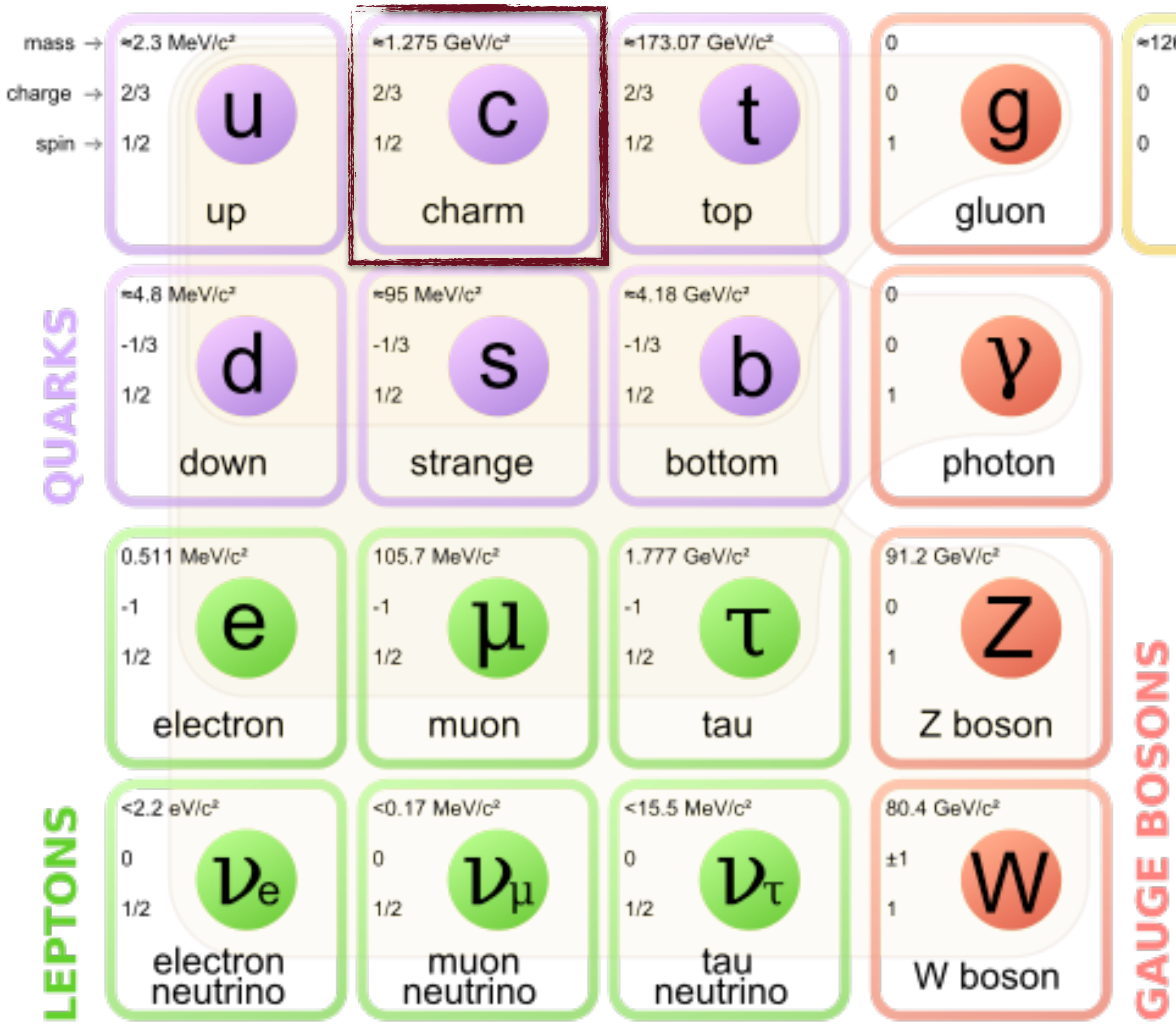
☐ **e/μ:** no evidence yet → established non-universality

- **h→μμ:** feasible in LHC (possibly in Run II/III)...

☐ **c-quark:** no direct evidence, loose bounds from h→bb

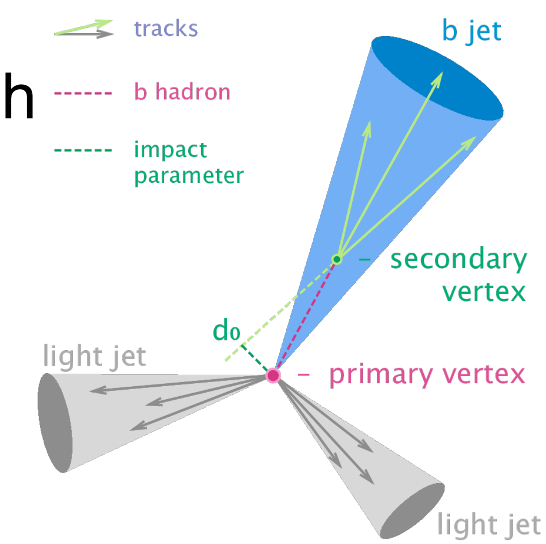
☐ **u/d/s-quarks:** no inclusive searches available

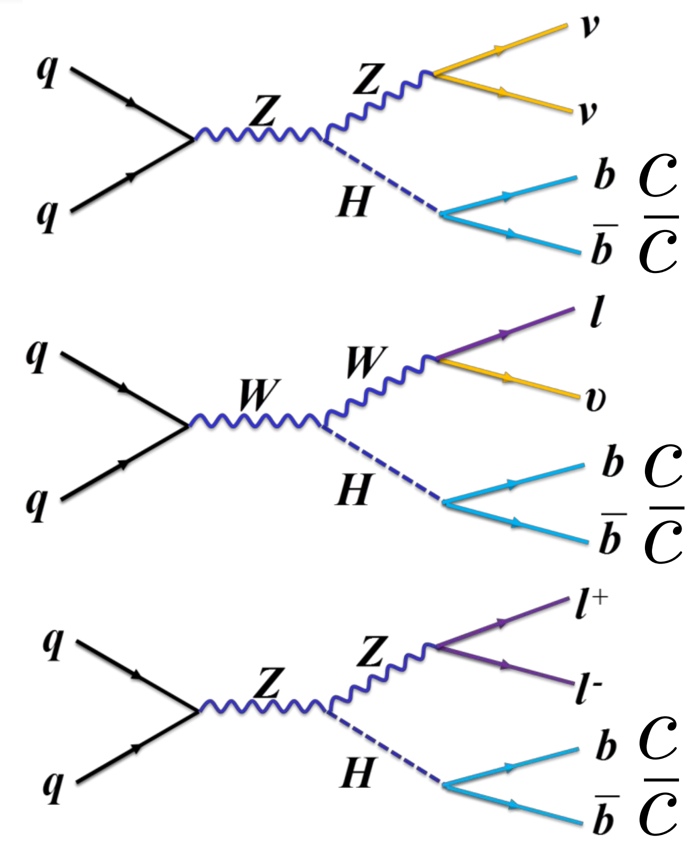
- Higgs couplings: margin for undetected/unobserved decays

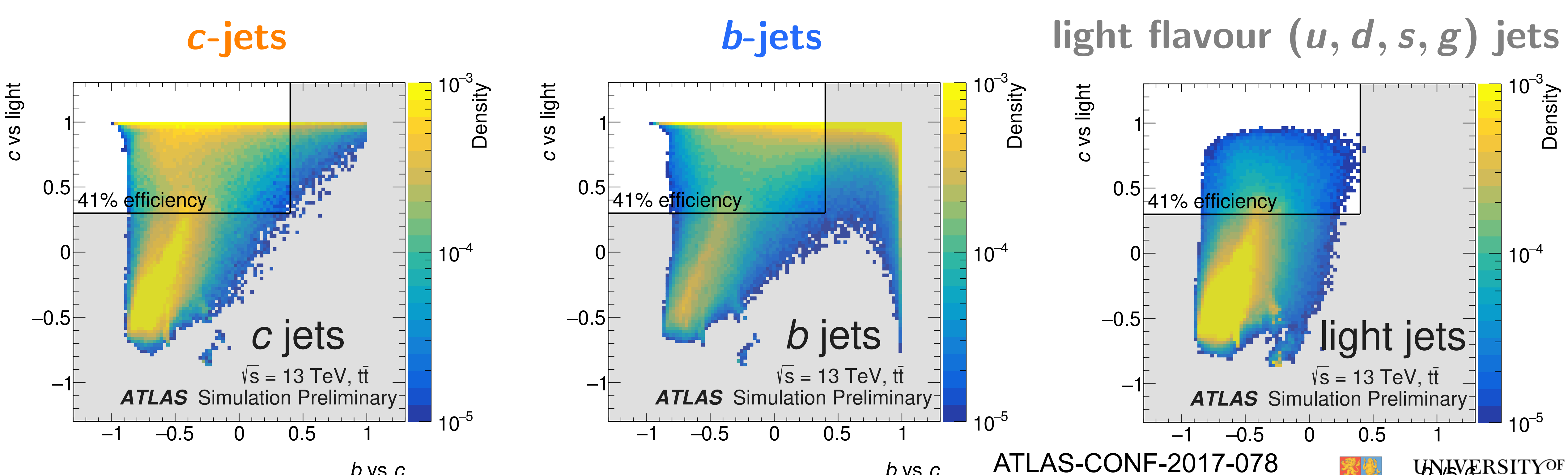

mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

Higgs boson-charm quark coupling

- **Inclusive** search for h→cc, similar to h→bb
  - In SM BR(h→ccbar)/BR(h→bbbar) ~ 5.1%
- Need an algorithm aimed at **c-tagging**
  - Displacements for c-jets ×3.5 less than for b-jets
  - First used for search for scharm [Phys.Rev.Lett. 114 (2015) 161801]
  - New Run2 "inclusive" c-tagging based on several "low level" taggers combined into a "high level" tagger using ML techniques
    - Track Impact Parameter
    - Reconstruction of Secondary Vertices
    - JetFitter: Fit the decay chain of a b/c-jet







ATLAS-CONF-2017-078

Zh(→cc):Event Selection

- **First search** for exclusive Zh→llcc decays, l=e, μ
  - Small experimental uncertainties
  - Main backgrounds: Z+jets, Z(W/Z), ttbar

$Z \to \ell^+\ell^-$ Selection

- Trigger with lowest available p_T single electron or muon triggers
- Exactly two same flavour reconstructed leptons (e or μ)
- Both leptons $p_T > 7$ GeV and at least one with $p_T > 27$ GeV
- Require opposite charges (dimuons only)
- $81 < m_{\ell\ell} < 101$ GeV
- $p_T^Z > 75$ GeV

$H \to c\bar{c}$ Selection

- Consider anti-k_T $R = 0.4$ calorimeter jets with $|\eta| < 2.5$ and $p_T > 20$ GeV
- At least two jets with leading jet $p_T > 45$ GeV
- Form $H \to c\bar{c}$ candidate from the two highest p_T jets in an event
- At least one c-tagged jet from $H \to c\bar{c}$ candidate
- Dijet angular separation ΔR_{jj} requirement which varies with p_T^Z

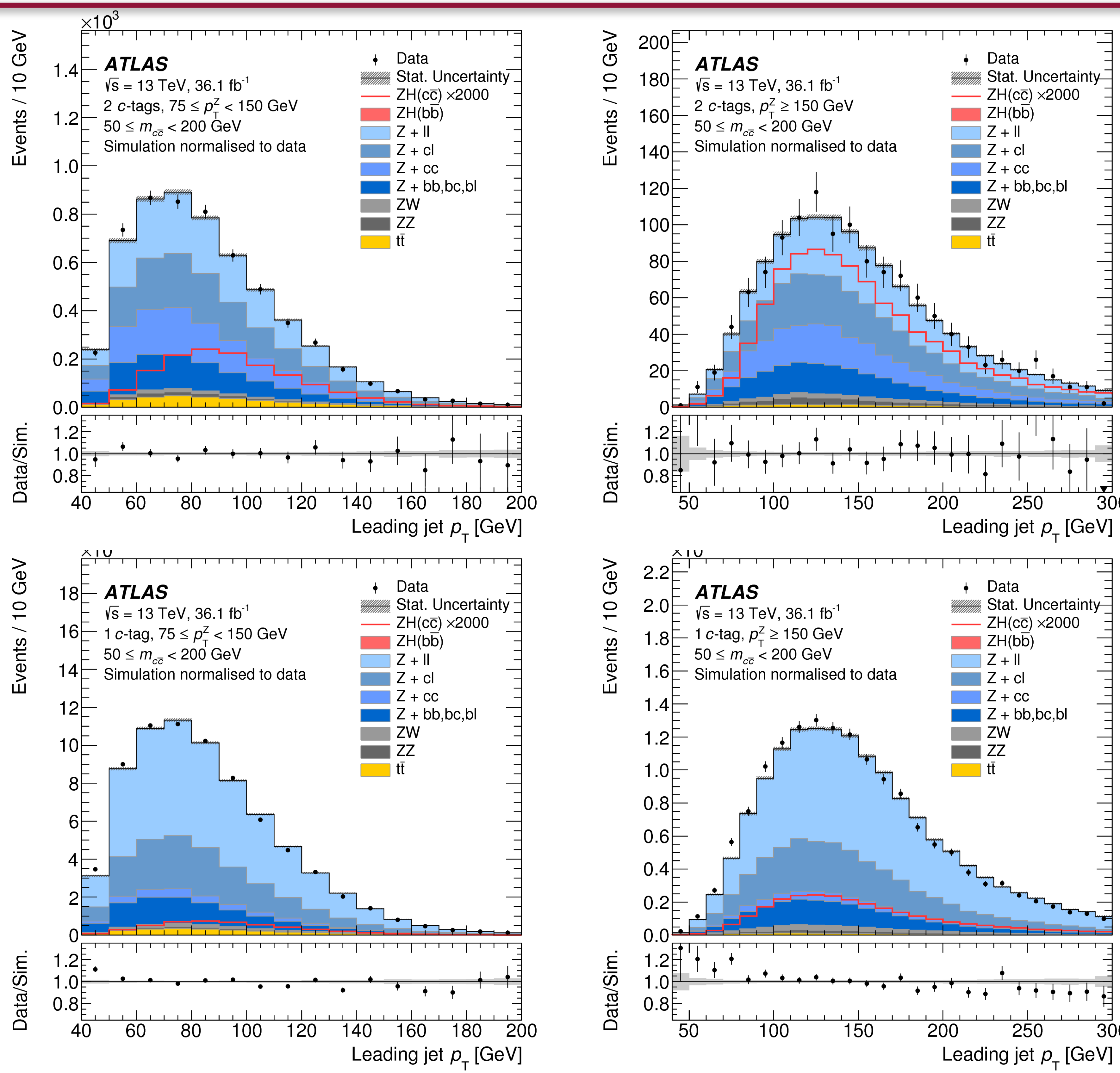
- Split events into 4 categories
  - h→cc candidates with 1 or 2 c-tags
  - p_{TZ} above/below 150 GeV
- Background modelling and uncertainties validated with Z(Z/W) production measurement
  - Observed (expected) ZV production with significance of 1.4σ (2.2σ)
  - Measure ZV signal strength of $0.6^{+0.5}_{-0.4}$, consistent with SM expectation

Zh(→cc):Background Composition

arXiv:1802.04329

2 c-tags

1 c-tag



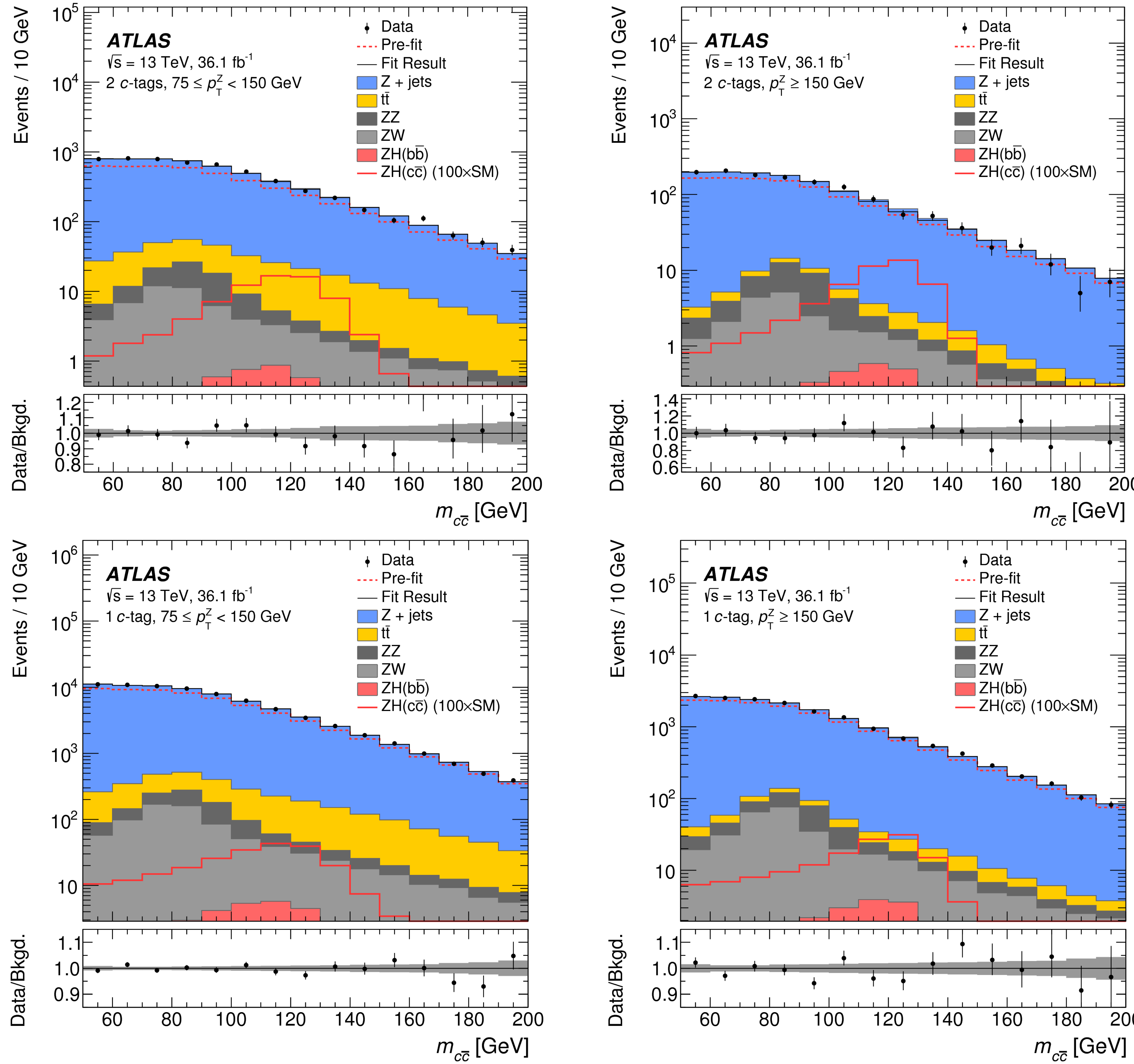
75< p_TZ < 150 GeV **p_TZ > 150 GeV**

Zh(→cc):Fit Results

arXiv:1802.04329

2 c-tags

1 c-tag



75< $p_T Z$ < 150 GeV **$p_T Z$ > 150 GeV**

Zh(→cc):Results

arXiv:1802.04329

- No evidence for Zh(cc) production with current dataset

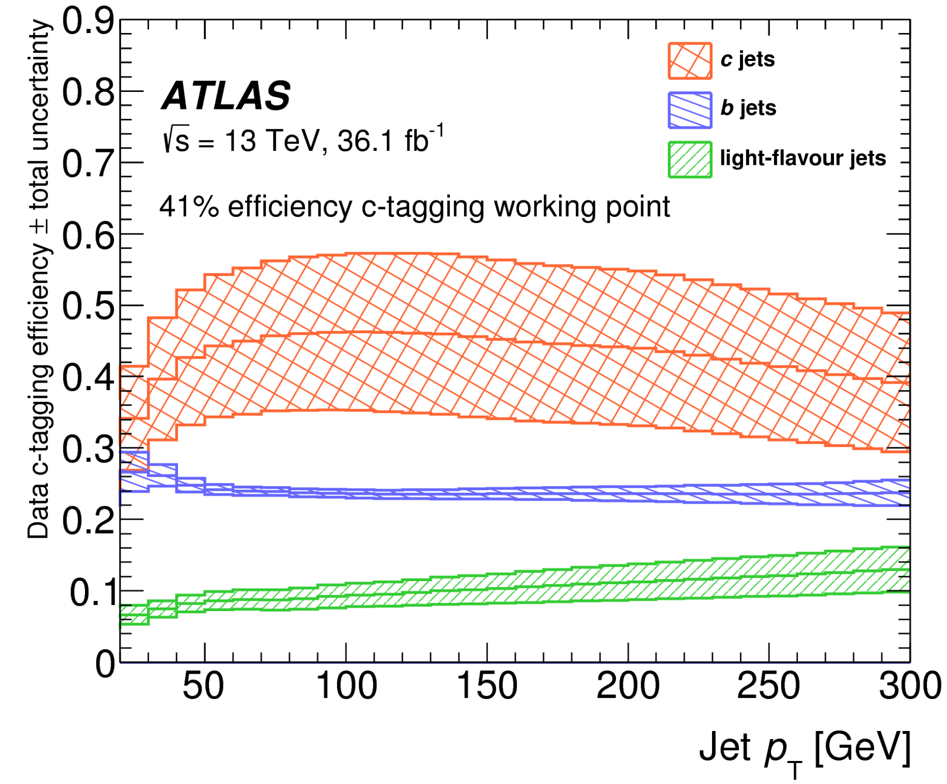
Limits on $ZH(c\bar{c})$ production

95% CL CL_s upper limit on $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ [pb]			
Observed	Median Expected	Expected $+1\sigma$	Expected -1σ
2.7	3.9	6.0	2.8

- SM: 2.55×10^{-2} pb
  - 110×SM (150^{+80}_{-40})

Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating Z + jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

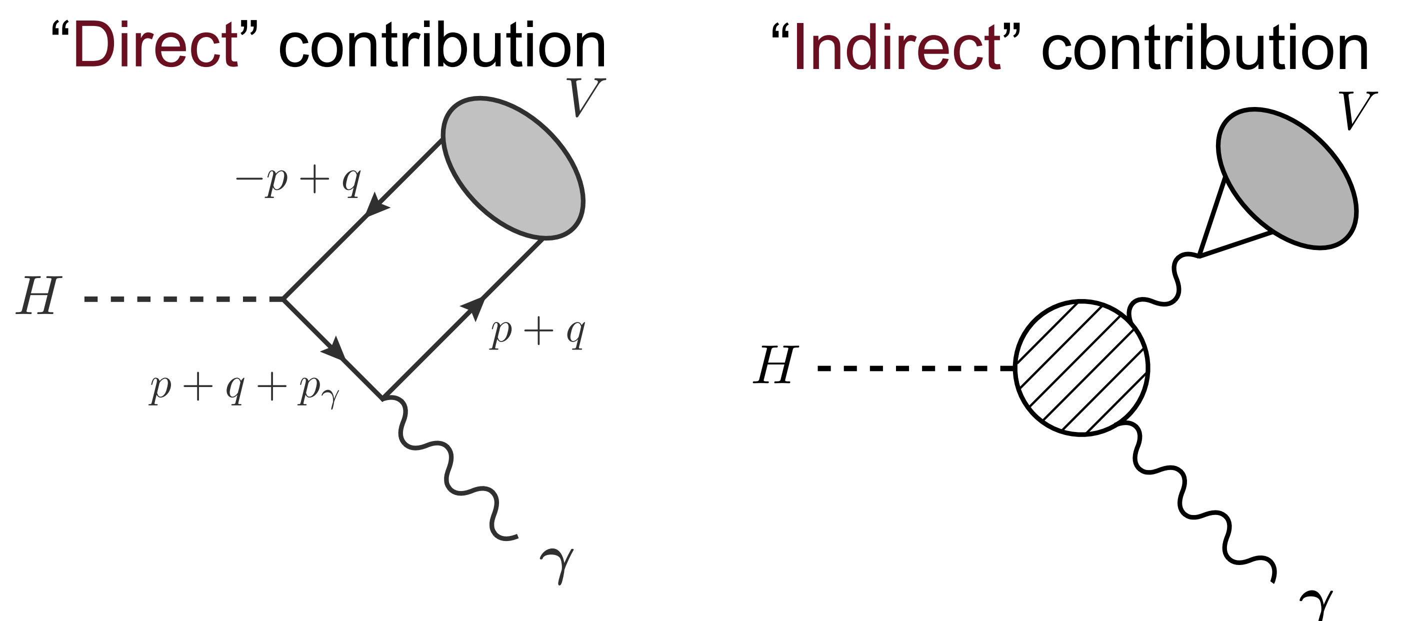
The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the components.



- A tagging working point constrains linear combination of h→cc/h→bb
  - Analysis in conjunction with h→bb; account for cross-contamination
- For future key is the controlling of systematic uncertainties
  - Phenomenological analysis indicates $|\kappa_c|\lesssim2.5$-5.5 at 95%CL
  - 2×3000 fb^{-1} depending on the c-tagging scenario [Phys.Rev. D93 (2016) 013001]

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 boson-quark couplings
  - **Indirect amplitude:** insensitive to Higgs boson-quark couplings; larger than direct amplitude
  - **Destructive interference**



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

Phys.Rev. D90 (2014) 11, 113010

- **Similar decays of W± and Z bosons: also rich physics programme**
  - **Novel** precision studies of quantum chromo-dynamics
  - **W±/Z boson interactions with light quarks** not well covered at earlier facilities
  - **Discovery potential** for new physics processes

Exclusive Decays h→Qγ

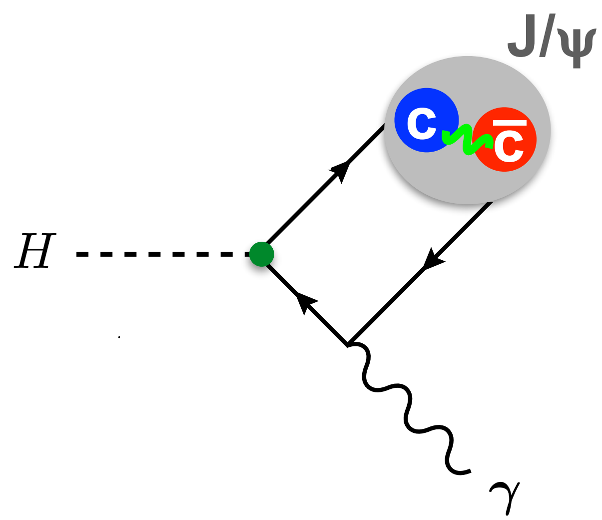
- Substantial interest from theory community on branching ratio estimates and feasibility

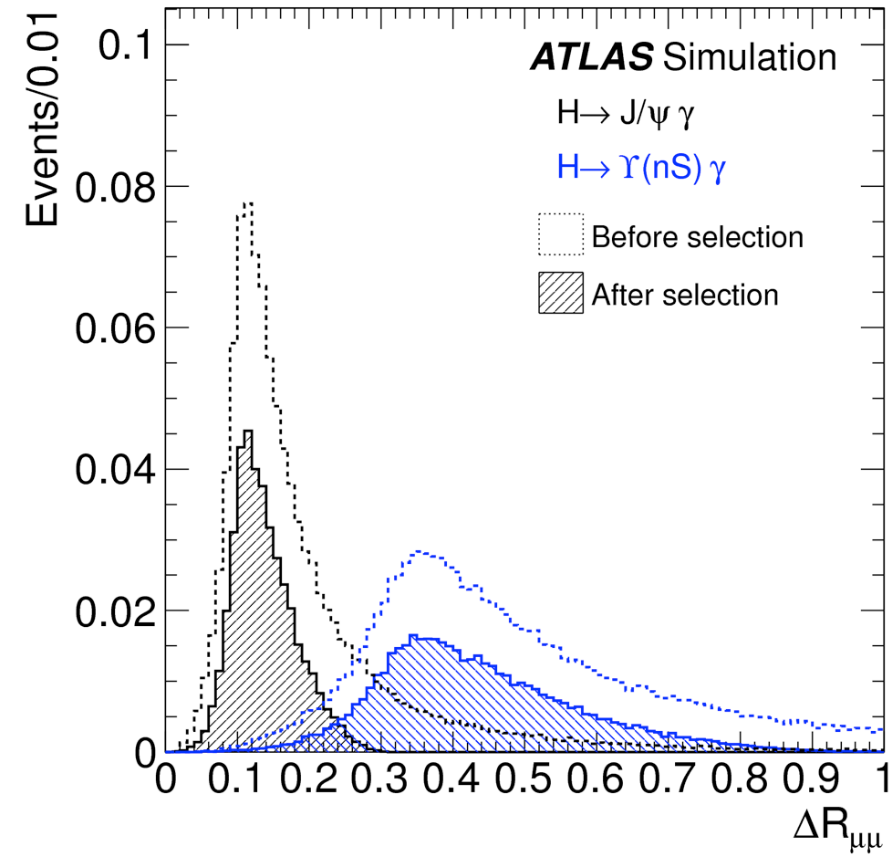
Mode	Branching Fraction [10^{-6}]		
Method	NRQCD [1487]	LCDA LO [1486]	LCDA NLO [1489]
$\mathrm{Br}(h \to \rho\gamma)$	–	19.0 ± 1.5	16.8 ± 0.8
$\mathrm{Br}(h \to \omega\gamma)$	–	1.60 ± 0.17	1.48 ± 0.08
$\mathrm{Br}(h \to \phi\gamma)$	–	3.00 ± 0.13	2.31 ± 0.11
$\mathrm{Br}(h \to J/\psi\,\gamma)$	–	$2.79\,^{+0.16}_{-0.15}$	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

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

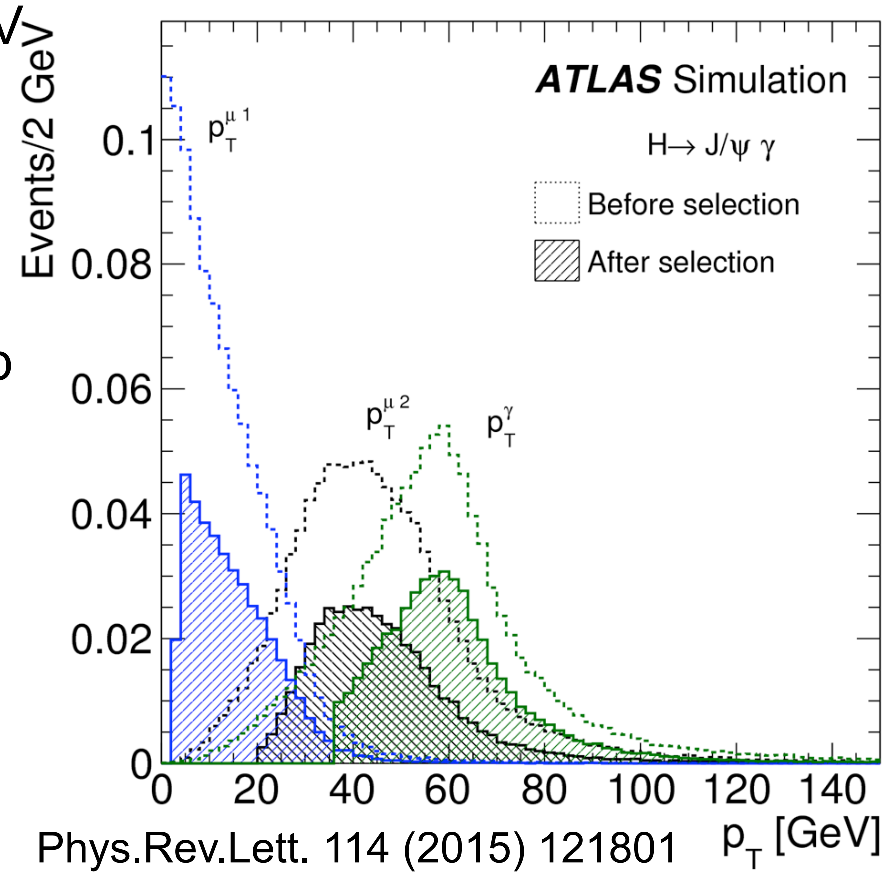
JHEP 1504 (2015) 101

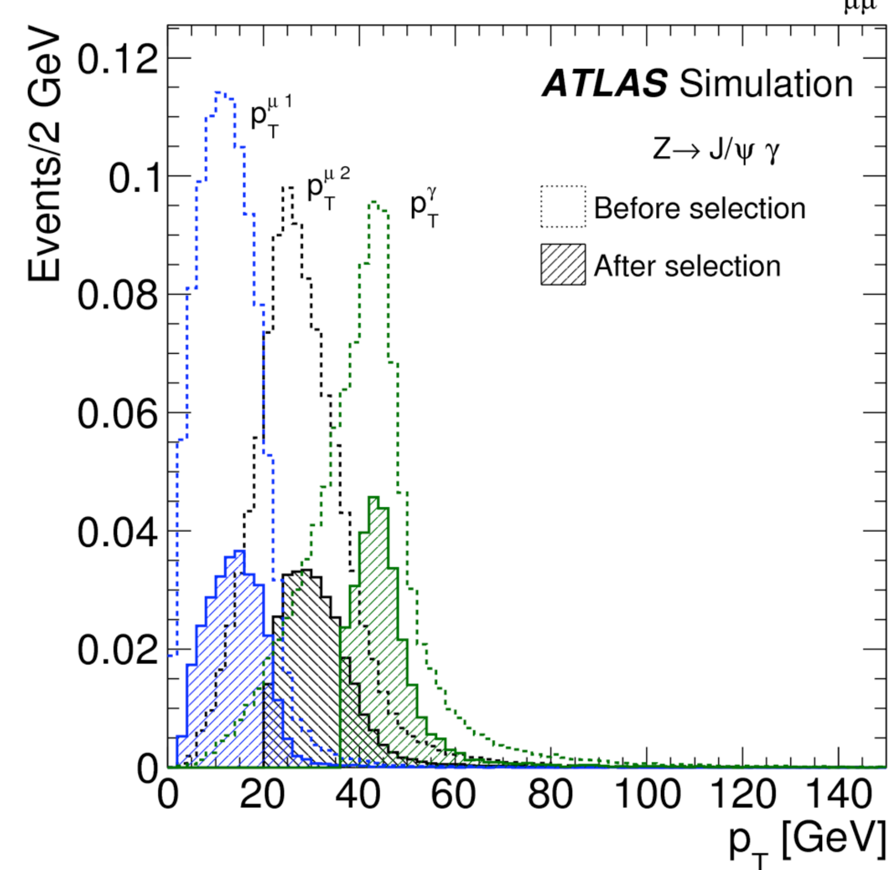
h/Z→J/ψγ and h/Z→Υ(nS)γ (n=1,2,3)





- **First search** for exclusive h/Z→Qγ decays
  - Q = J/ψ or Υ(nS), n=1,2,3 decaying to $\mu^+\mu^-$
- Event Selection
  - single muon and dimuon trigger
  - $|\eta_\mu|<2.5$, $p_{T\mu}>20,3$ GeV, $p_{T\mu\mu}>36$ GeV
  - $|\eta_\gamma|<2.47$, $p_{T\gamma}>36$ GeV
    - excluding $1.37<|\eta_\gamma|<1.52$
  - μμ and γ isolation
  - $m_{\mu\mu}$ requirements
    - $m_{J/\psi}\pm0.15/0.20$ GeV barrel/endcap
    - $8<m_{\mu\mu}<12$ GeV
  - $|L_{xy}/\sigma_{Lxy}|<3$
  - $\Delta\phi(\mu\mu,\gamma)>0.5$
- Total efficiency
  - h/Z→J/ψ(→μμ)γ~22% (12%)
  - h/Z→Υ(→μμ)γ~ 28% (15%)

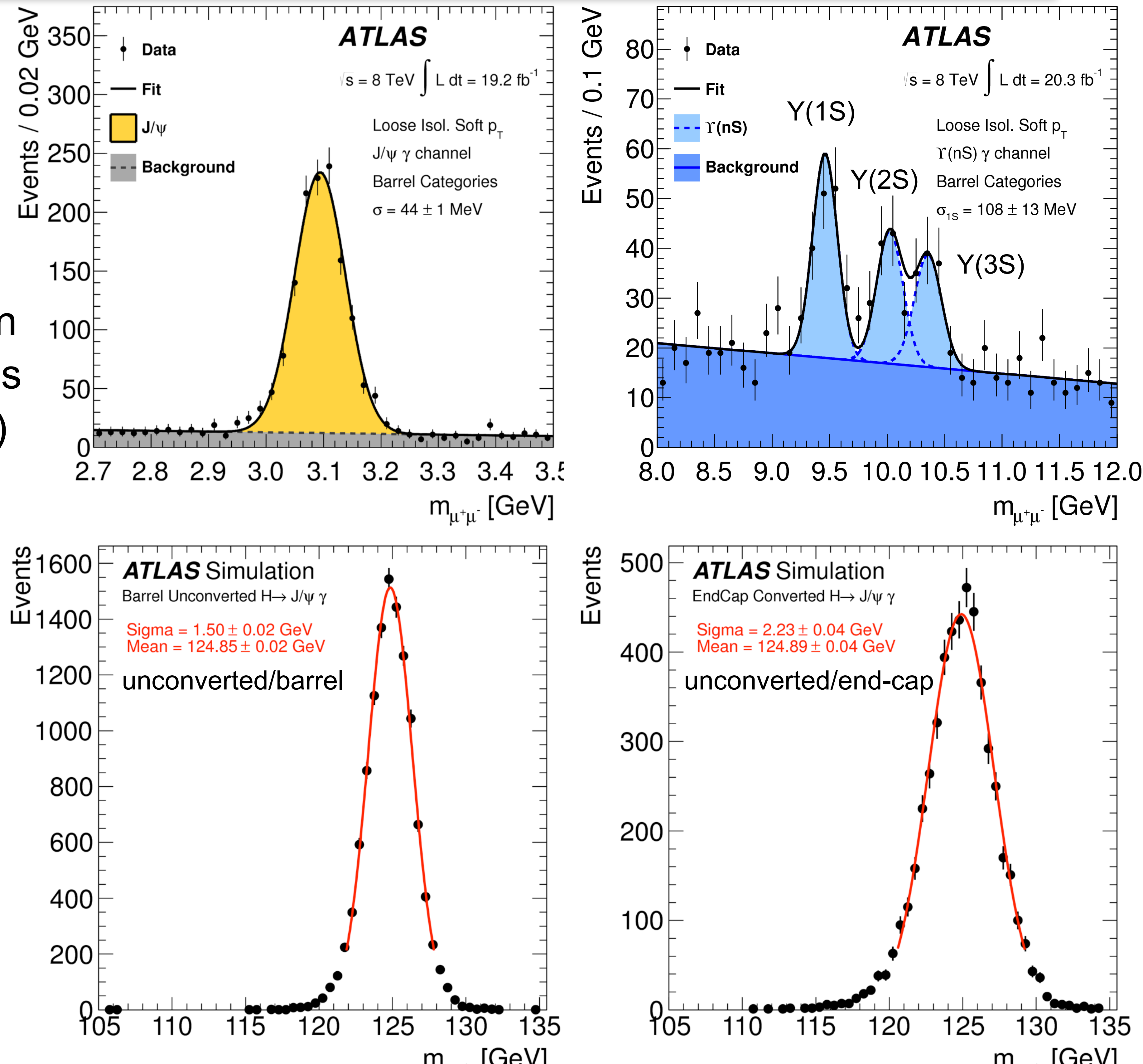




Phys.Rev.Lett. 114 (2015) 121801

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%

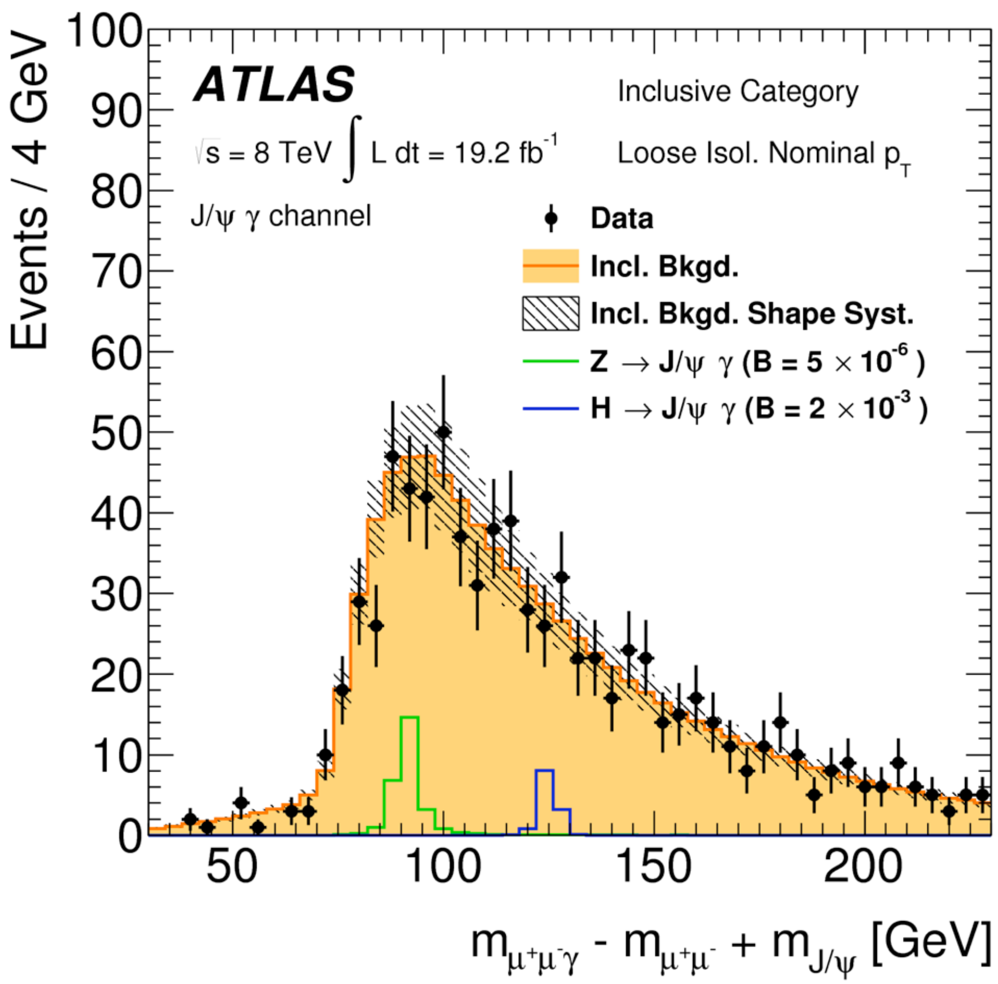


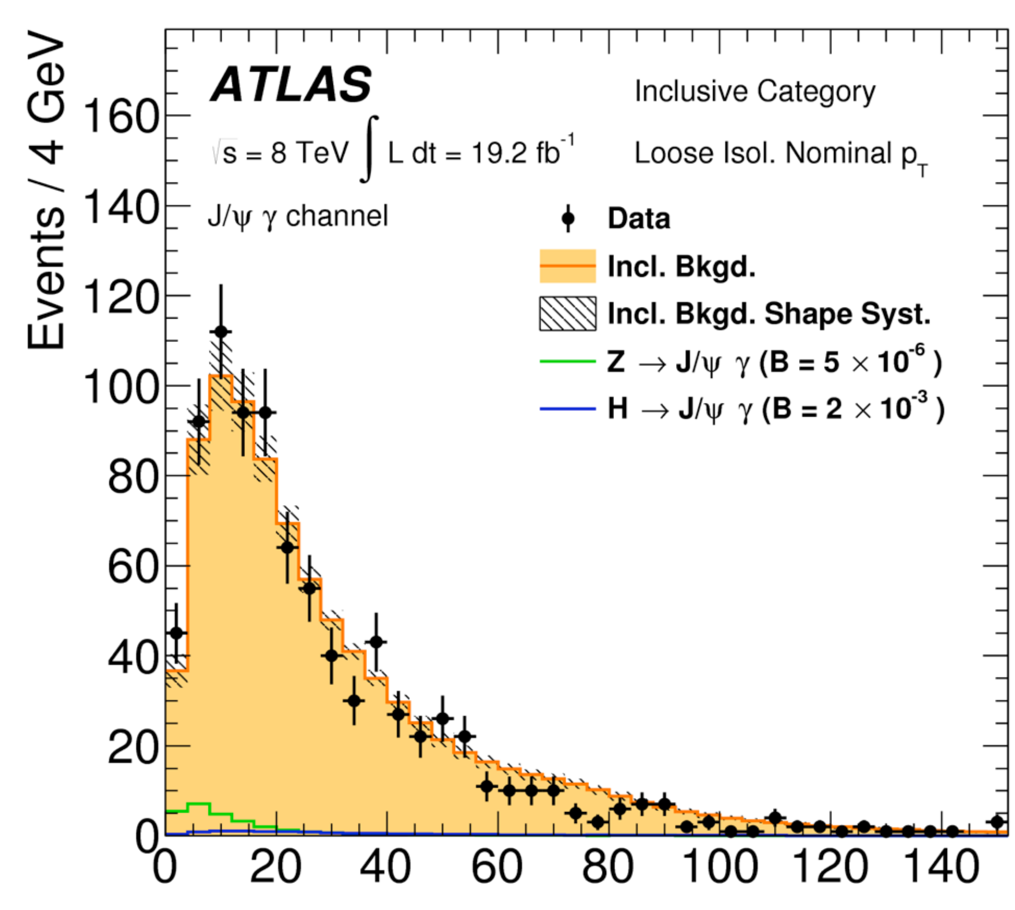
Phys.Rev.Lett. 114 (2015) 121801

h/Z→J/ψγ and h/Z→Υ(nS)γ: Background

- **Inclusive quarkonium** with jet "seen" as γ
  - combinatoric background: small contribution
  - contribution from Q+γ production
- **Non-parametric 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





Phys.Rev.Lett. 114 (2015) 121801

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

$h/Z \to J/\psi\gamma$ and $h/Z \to \Upsilon(nS)\gamma$: Results

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

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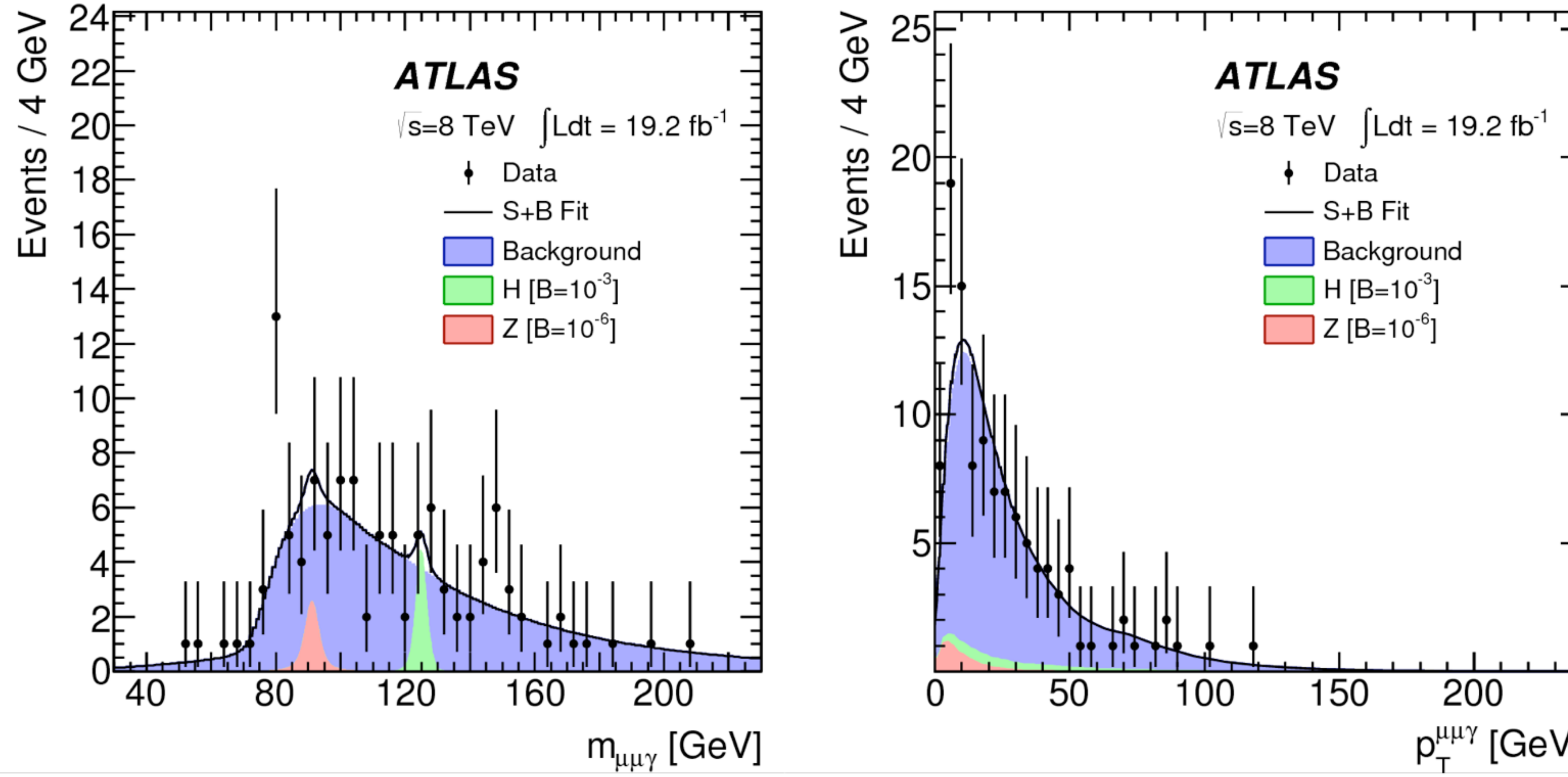
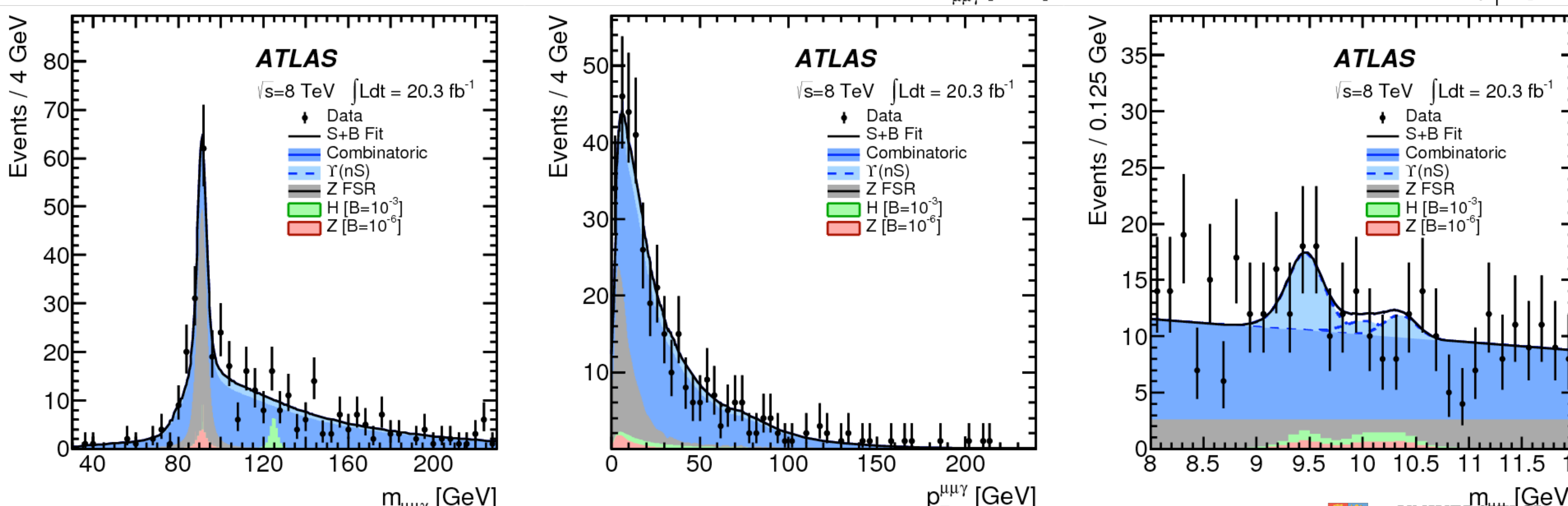
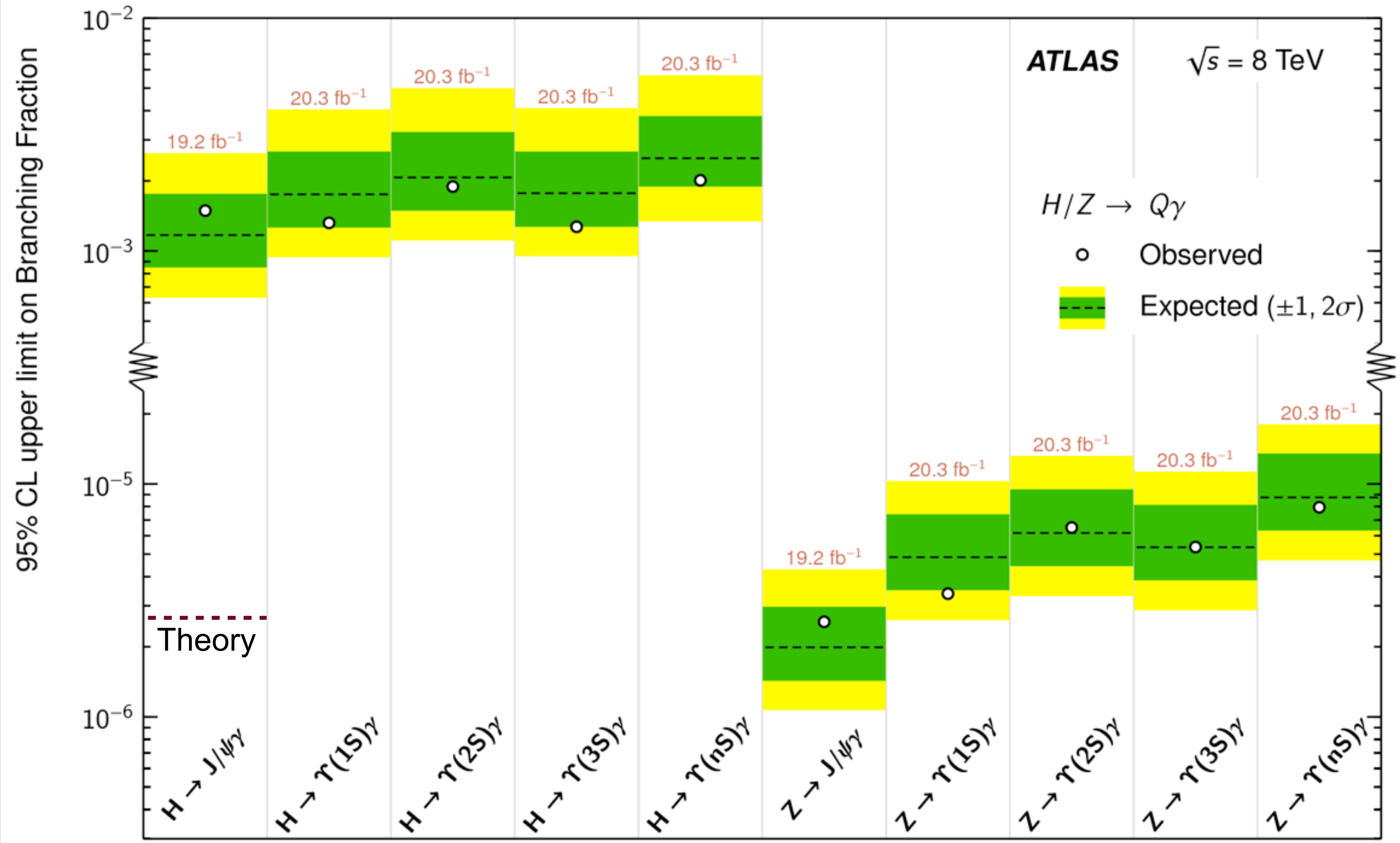




h/Z→J/ψγ and h/Z→Υ(nS)γ: Results



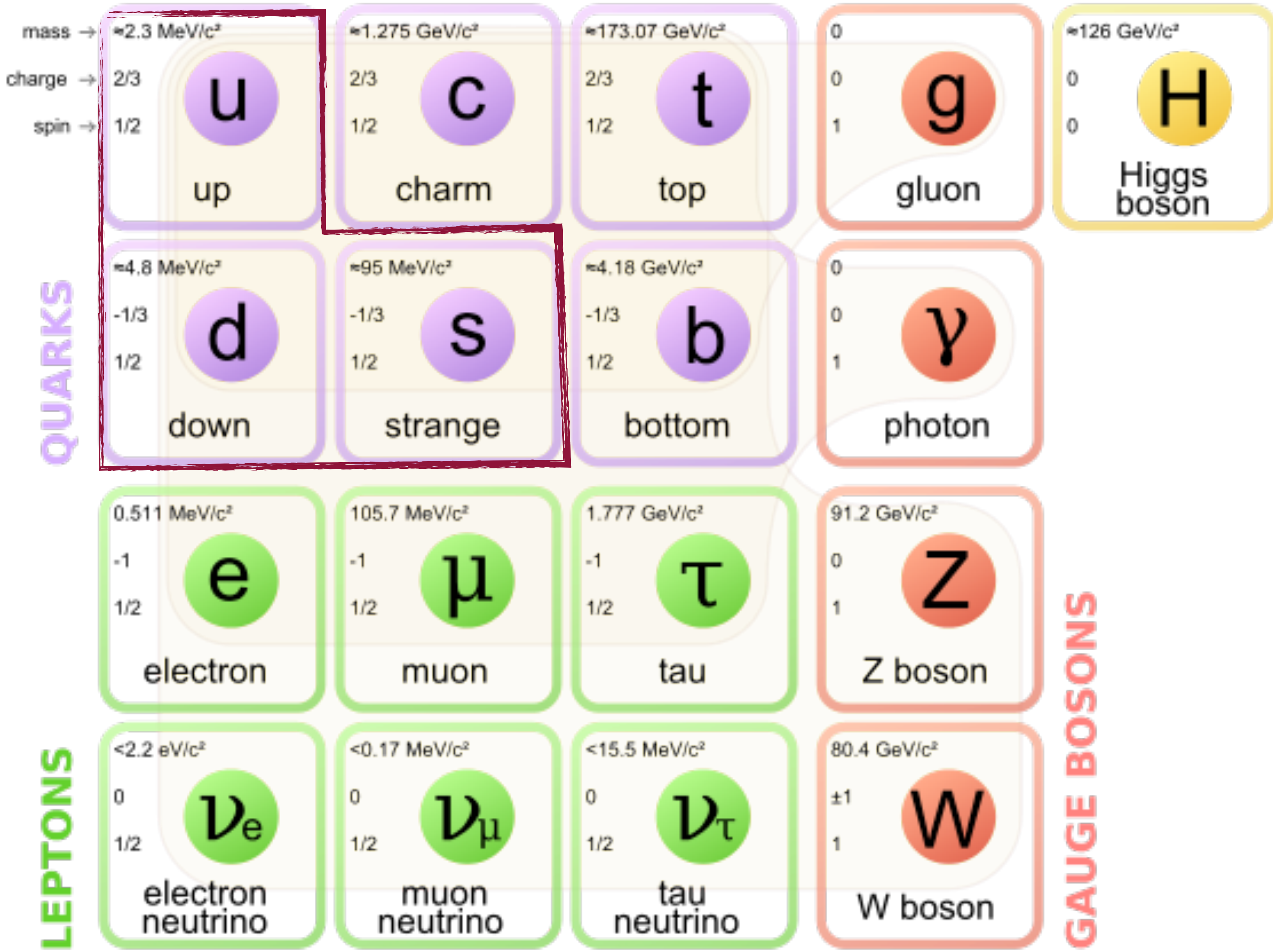
Phys.Rev.Lett. 114 (2015) 12, 121801

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

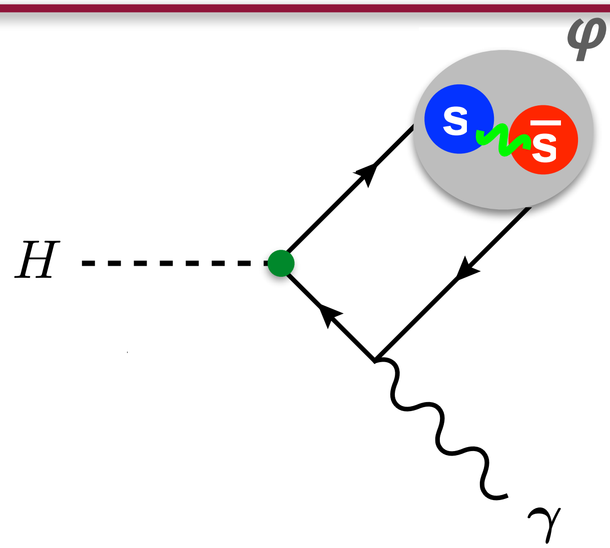
☑ **Indicate non-universal Higgs boson coupling to quarks**

[Phys.Rev. D92 (2015) 033016, JHEP 1508 (2015) 012]

- CMS obtained the same 95% CL upper limit: BR[H→(J/ψ)γ] < 1.5×10^{-3} [Phys.Lett. B753 (2016) 341]


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

Search for h/Z→φγ and ργ



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

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

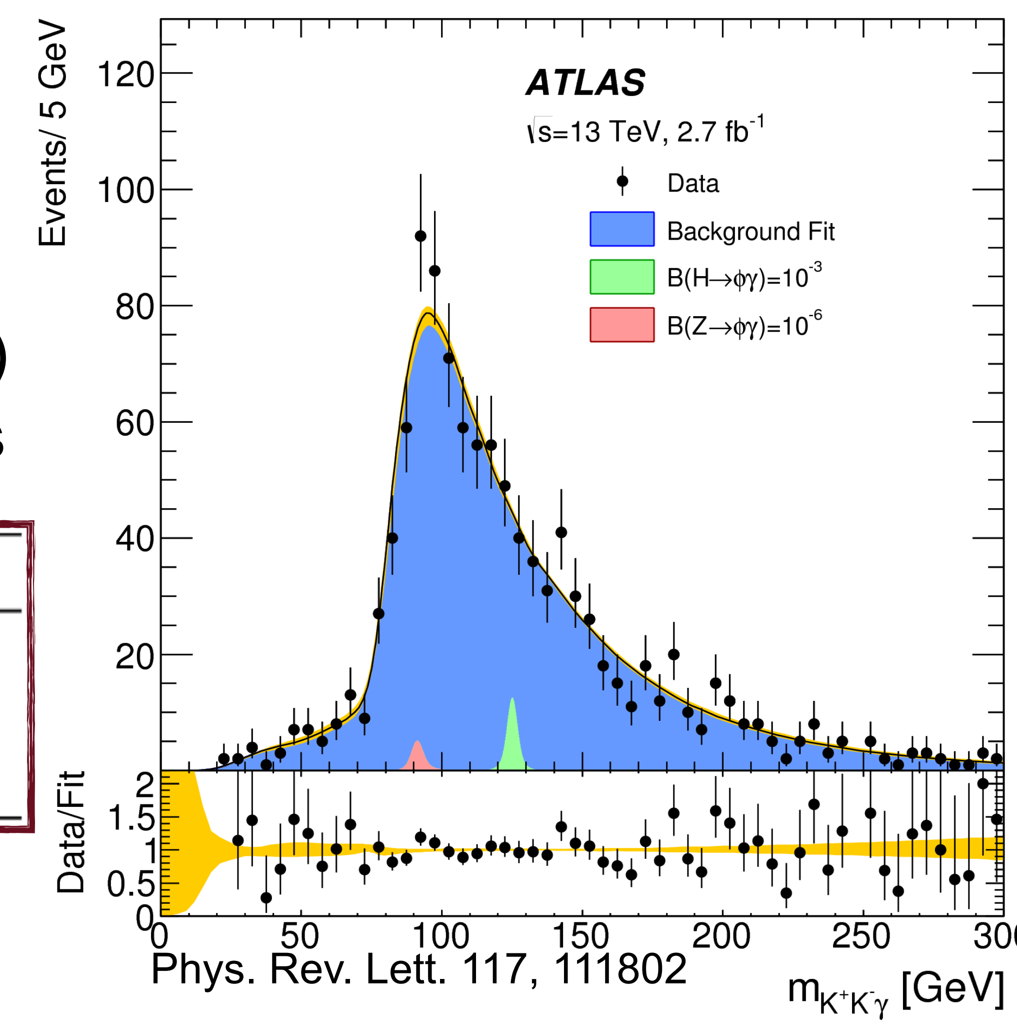
Search for Higgs and *Z* Boson Decays to $\phi\gamma$ with the ATLAS Detector

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



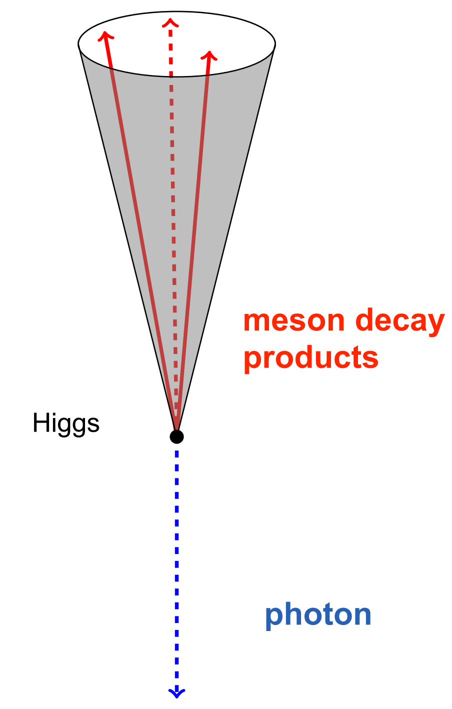
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-3}\,]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$4.4^{+2.0}_{-1.2}$	8.3

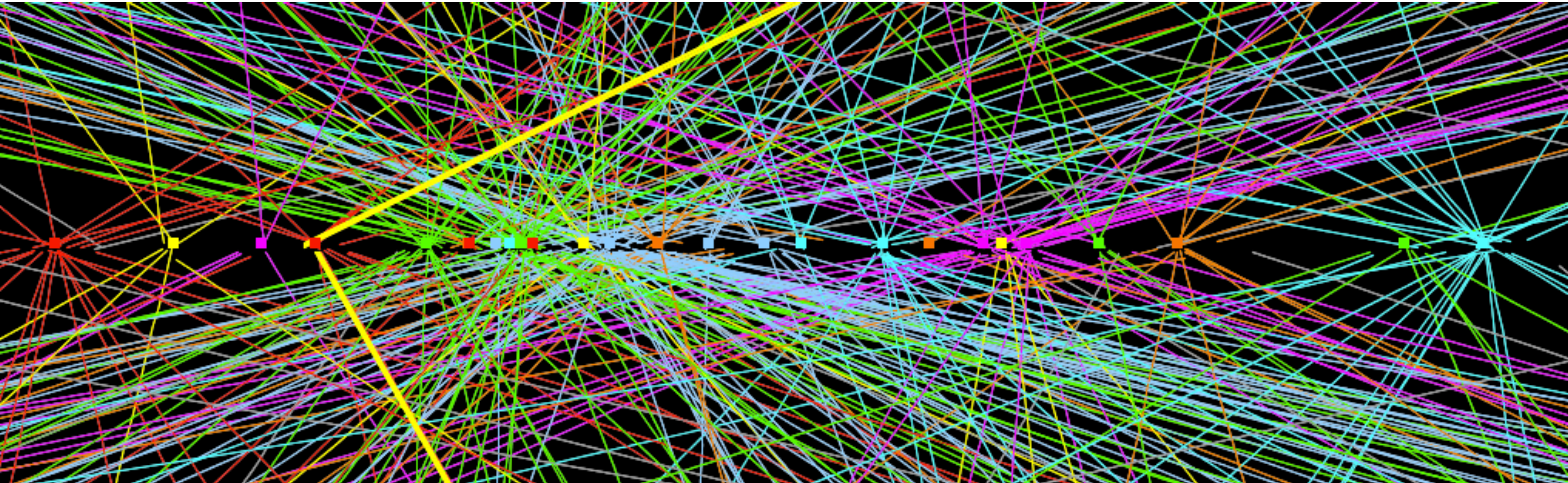
- **New results** with up to 35.6/fb
  - updated h/Z→φγ
  - added h/Z→ργ probing up- and -down quark couplings to Higgs boson

arXiv:1712.02758

Analysis Strategy

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





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

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%
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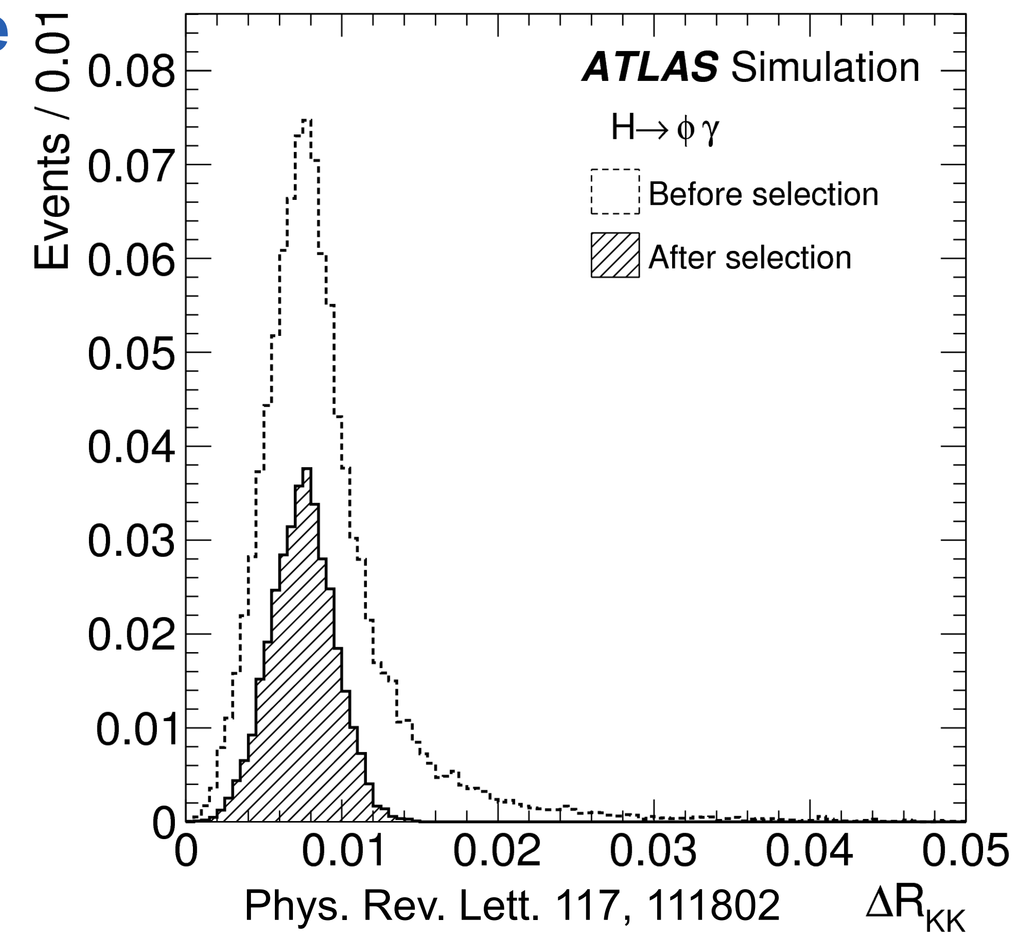
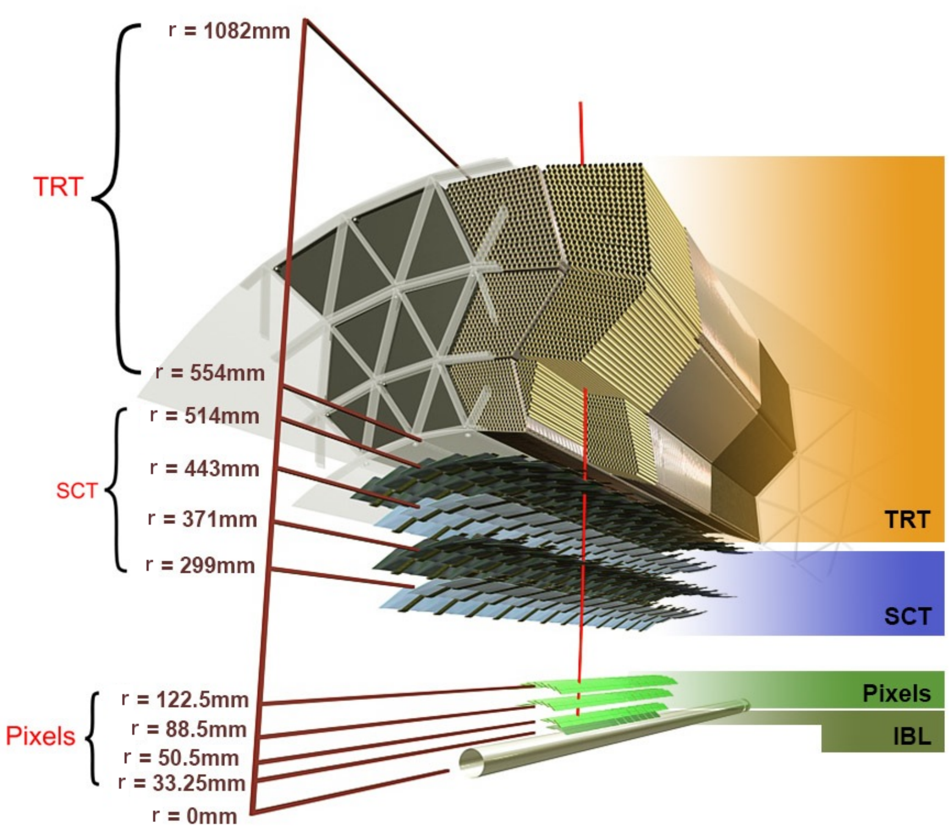
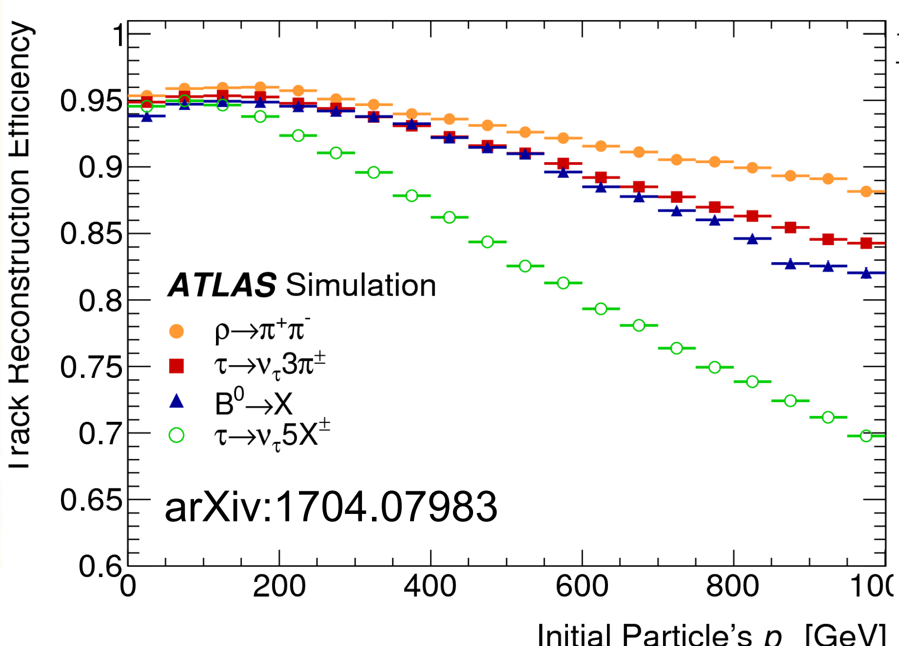
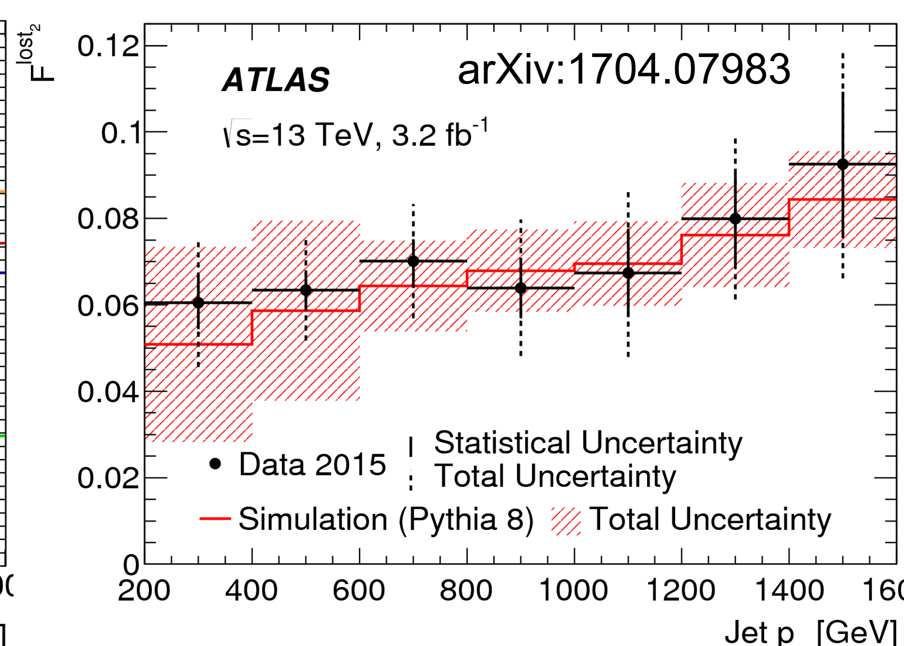


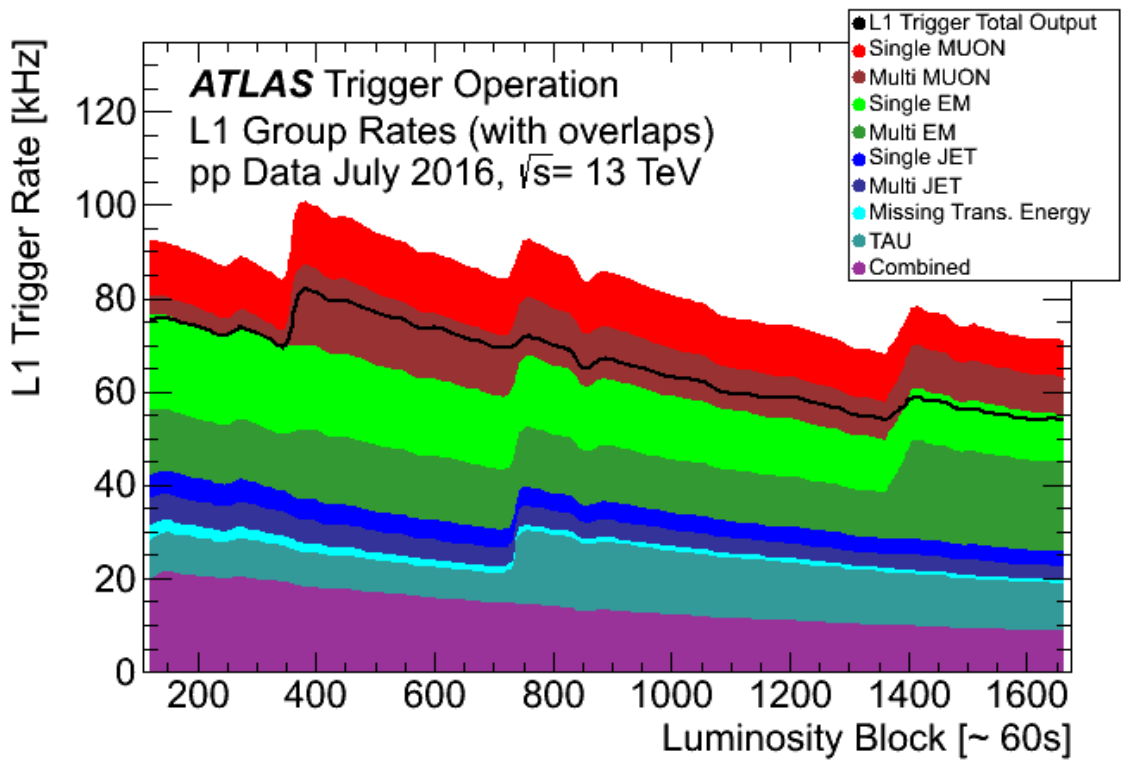
Phys. Rev. Lett. 117, 111802

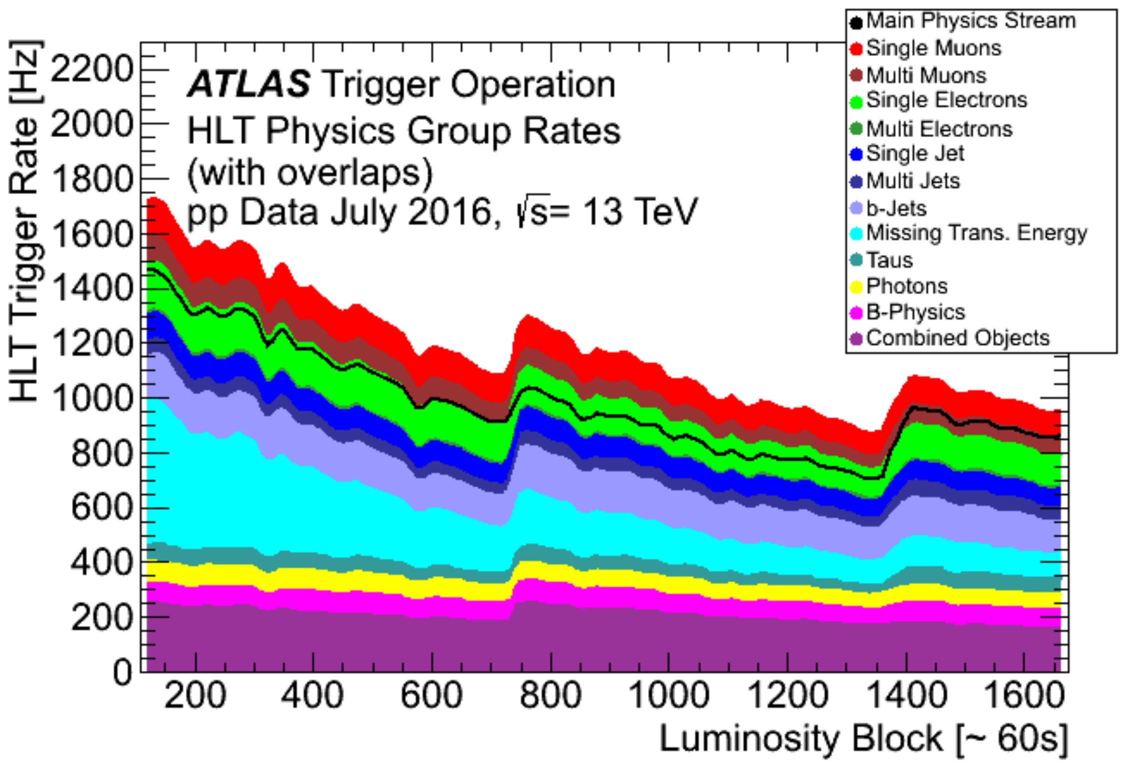






Trigger Strategy



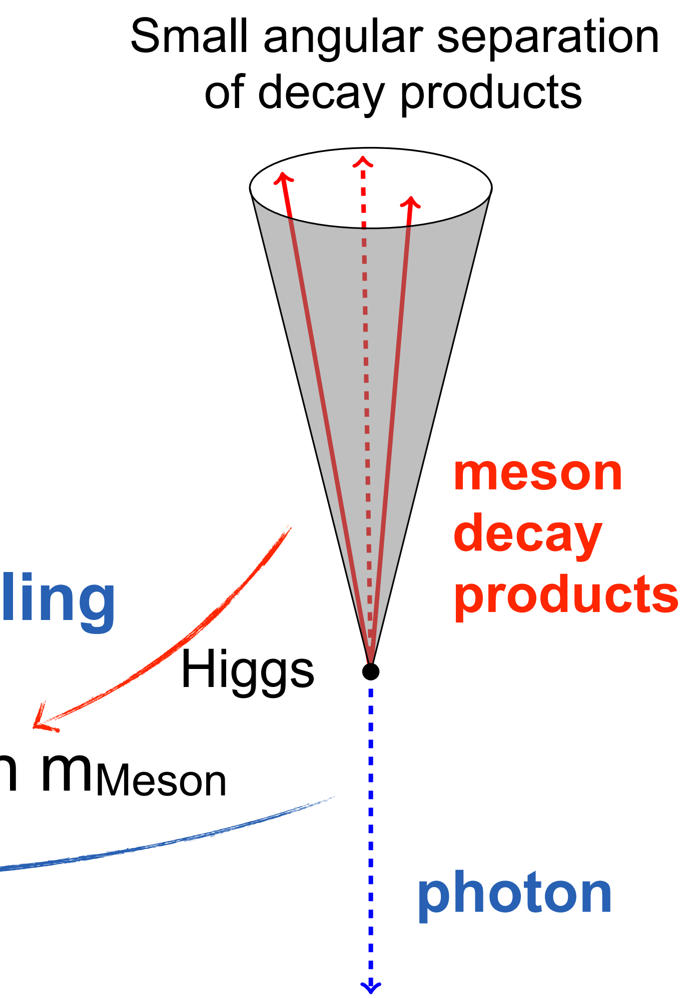


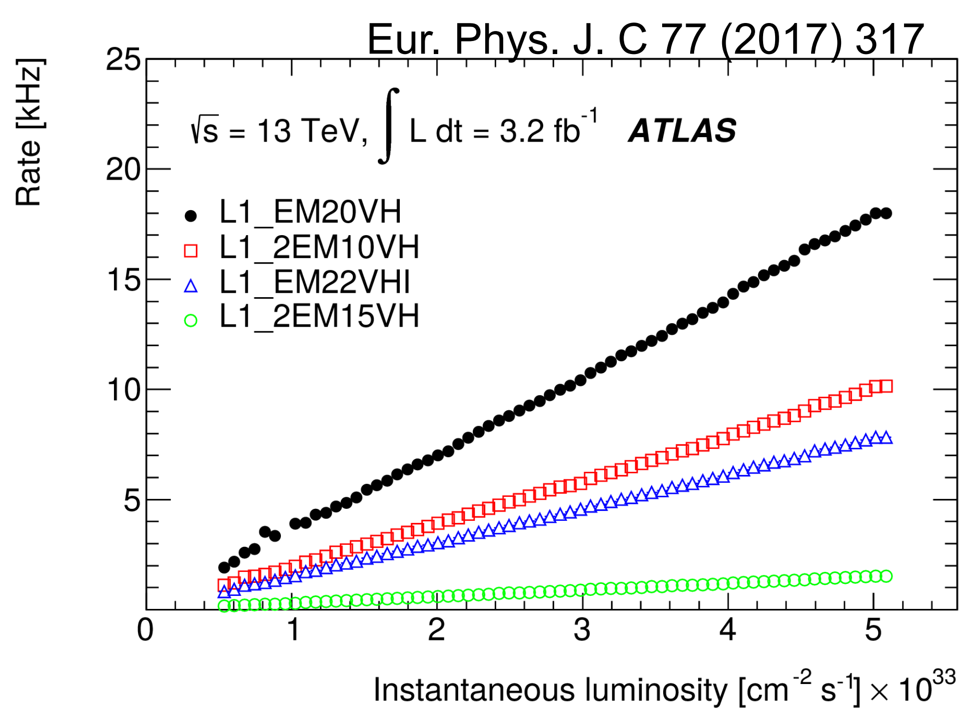
Trigger rates (July 2016) LHC fill with peak luminosity $1.02*10^{34}cm^{-2}s^{-1}$ and <μ>= 24.2

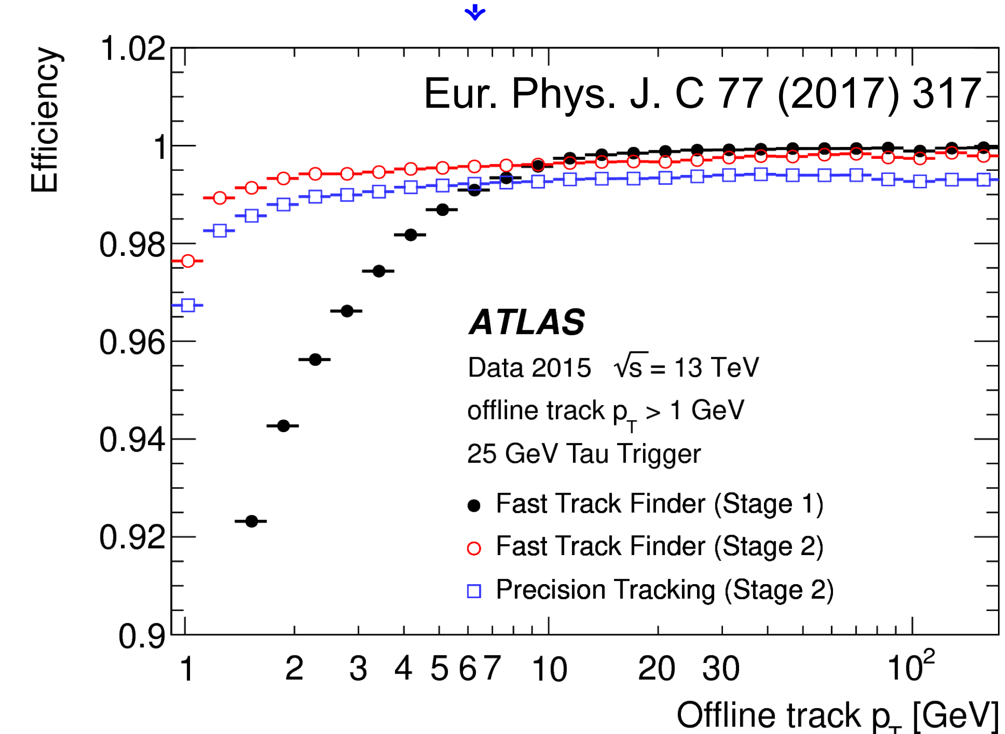
- ATLAS features a **two-level trigger system** to reduce the data rate from 40 MHz to the 1kHz that can be stored for further processing and analysis
  - Level-1: Hardware-based
    - 40 MHz → 100 kHz
  - High Level Trigger: Software-based
    - 100kHz → 1 kHz
- **This is the total data rate ATLAS can record**
  - A dedicated analysis-specific trigger will only allowed a small fraction of this rate
    - typically well below 10 Hz
  - Highly selective trigger design is needed

Trigger Strategy

- **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)





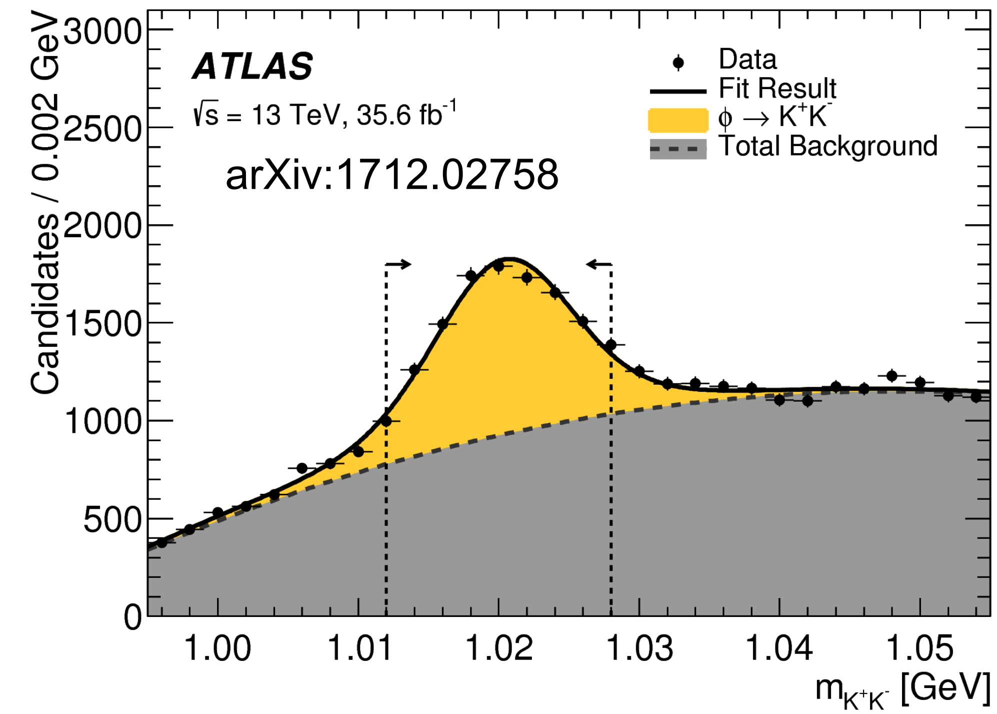


Event Selection

Tracks

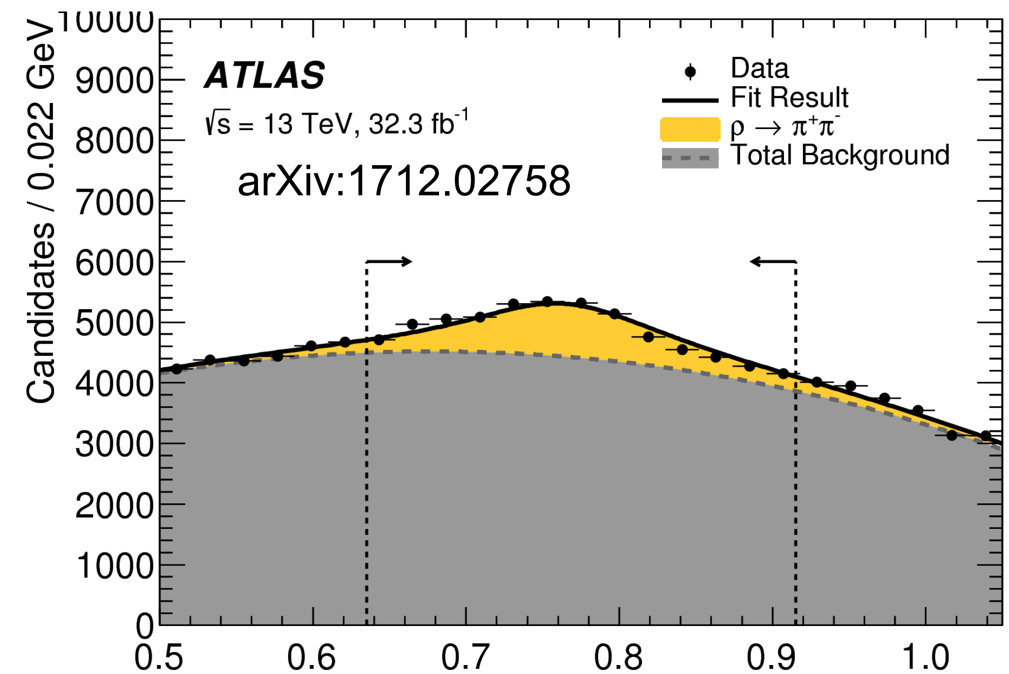
- No particle identification available at pT range of interest, all tracks considered K/π
- Two opposite charged tracks
  - Leading pT>20GeV, sub-leading pT>15 GeV
- di-track consistent to $m_\phi \pm 8$ MeV or $m_\rho \pm 140$ MeV
- track-based isolation
- di-track system must satisfy:

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



Photons

- "Tight" identification criteria
- $p_{T\gamma}$>35 GeV
- $|\eta_\gamma|$<2.47 and not in 1.37<$|\eta_\gamma|$<1.52
- Isolated (calorimeter- and track-based)
- $\Delta\phi(M,\gamma)>\pi/2$



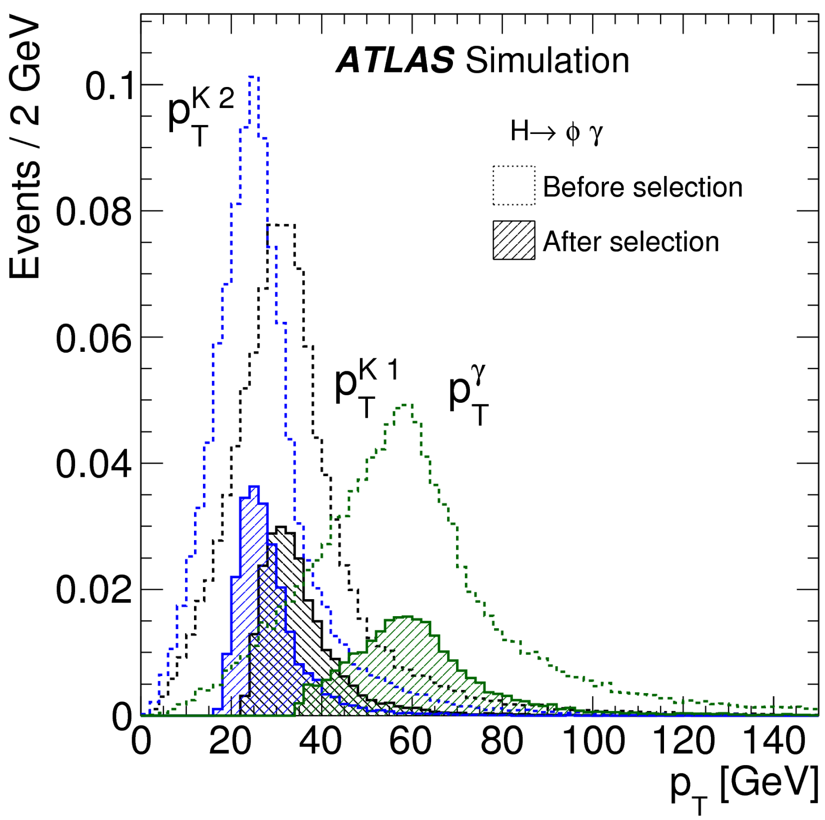
Full event selection w/o m_{KK} requirement

Total signal acceptance/efficiency

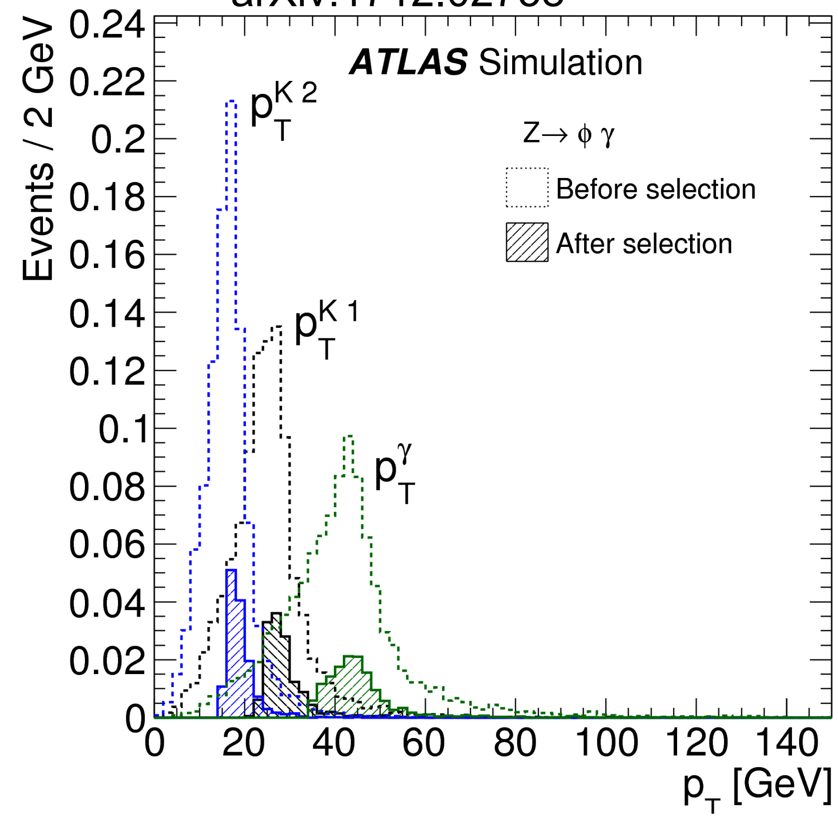
- $h(Z)\rightarrow\phi\gamma\rightarrow K^+K^-\gamma$ ~ 17% (8%)
- $h(Z)\rightarrow\rho\gamma\rightarrow\pi^+\pi^-\gamma$ ~ 10% (0.4%)

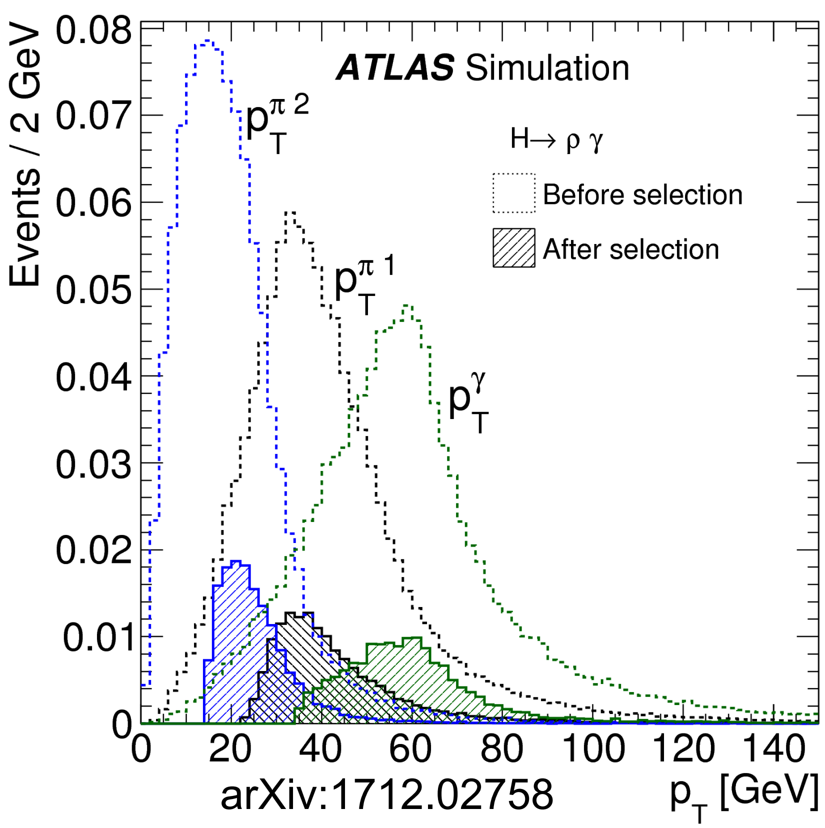
Efficiency and Resolution

arXiv:1712.02758

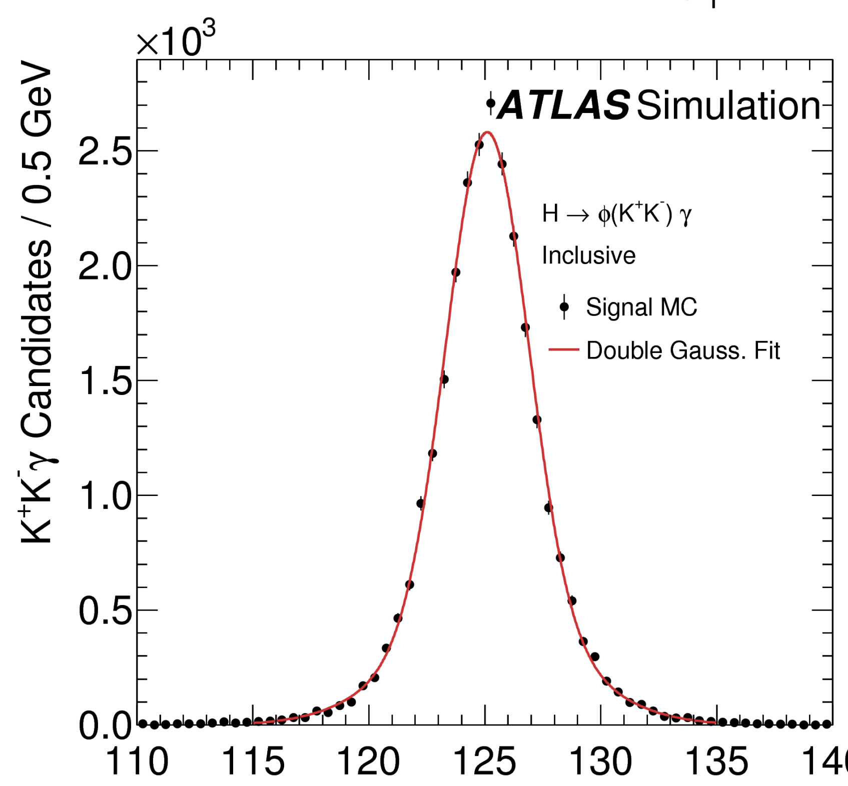


arXiv:1712.02758





arXiv:1712.02758



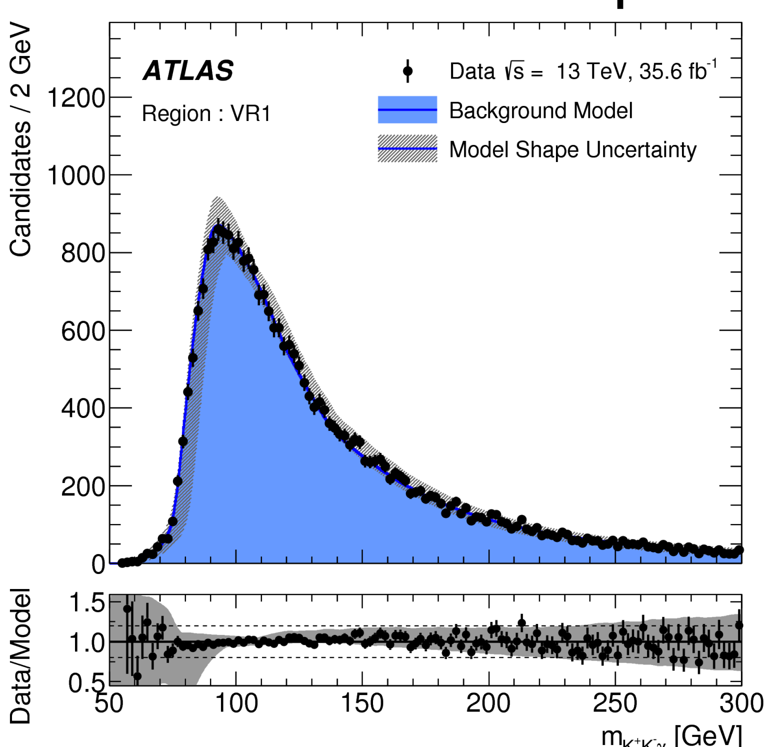
Phys. Rev. Lett. 117, 111802

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

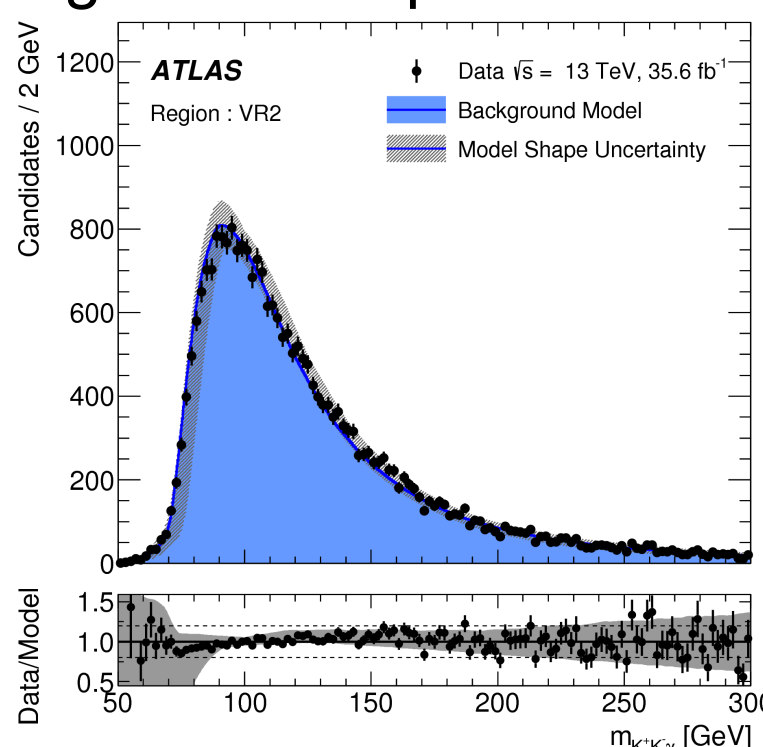
Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2%
Tracking efficiency	6%

Background Modelling

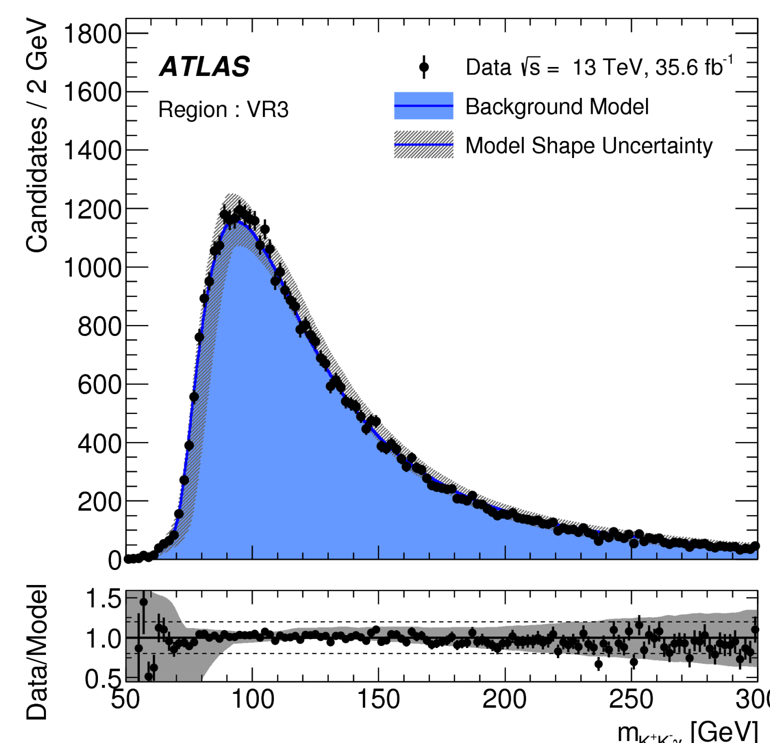
- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. $h/Z \rightarrow \mu\mu\gamma_{FSR}$) **estimated to be negligible**
- **Non-parametric data-driven background model;** common for ATLAS Qγ searches
  - Begin with loose sample of candidates
  - Model 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



$p_{T \text{Meson}}$



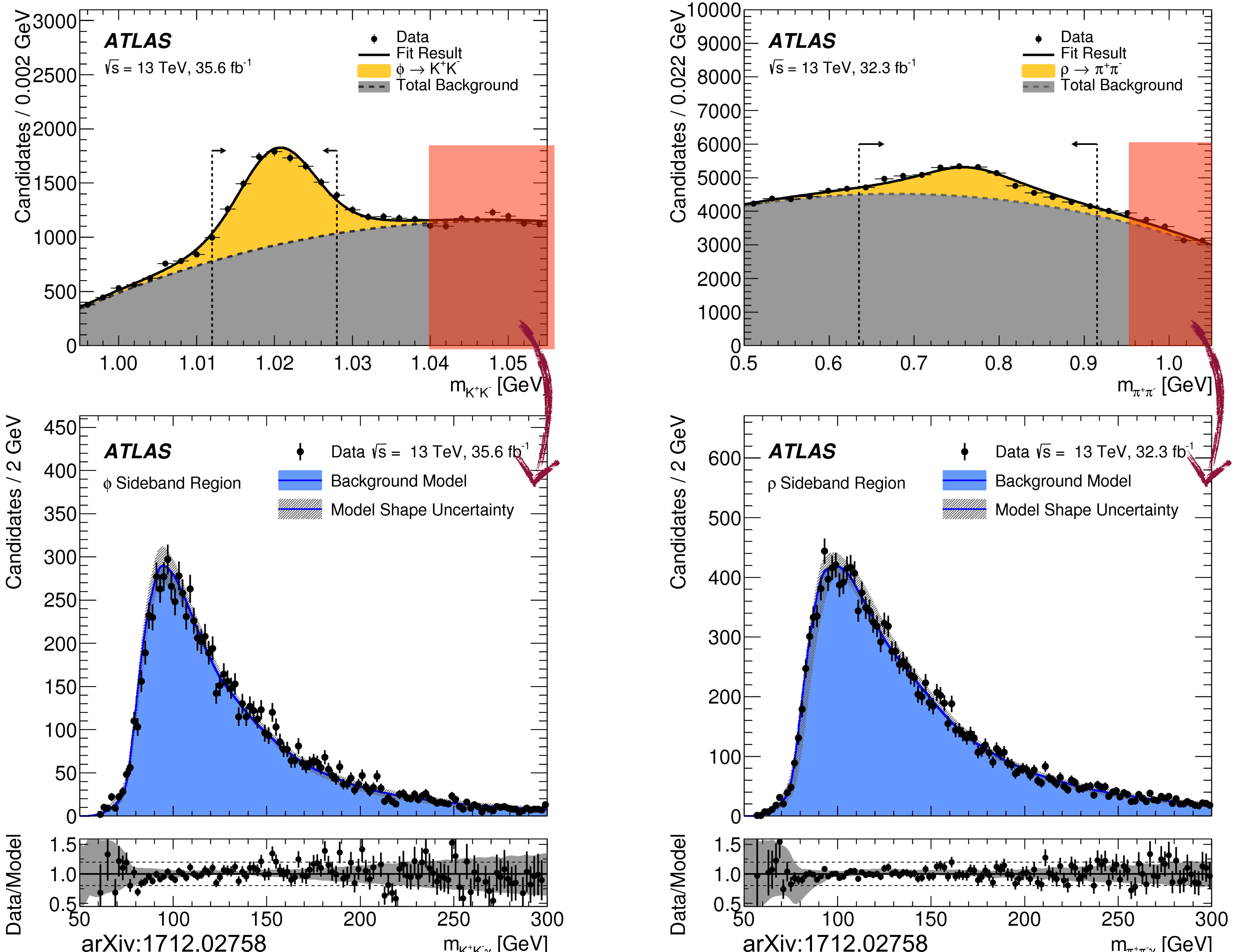
γ-isolation



Meson-isolation

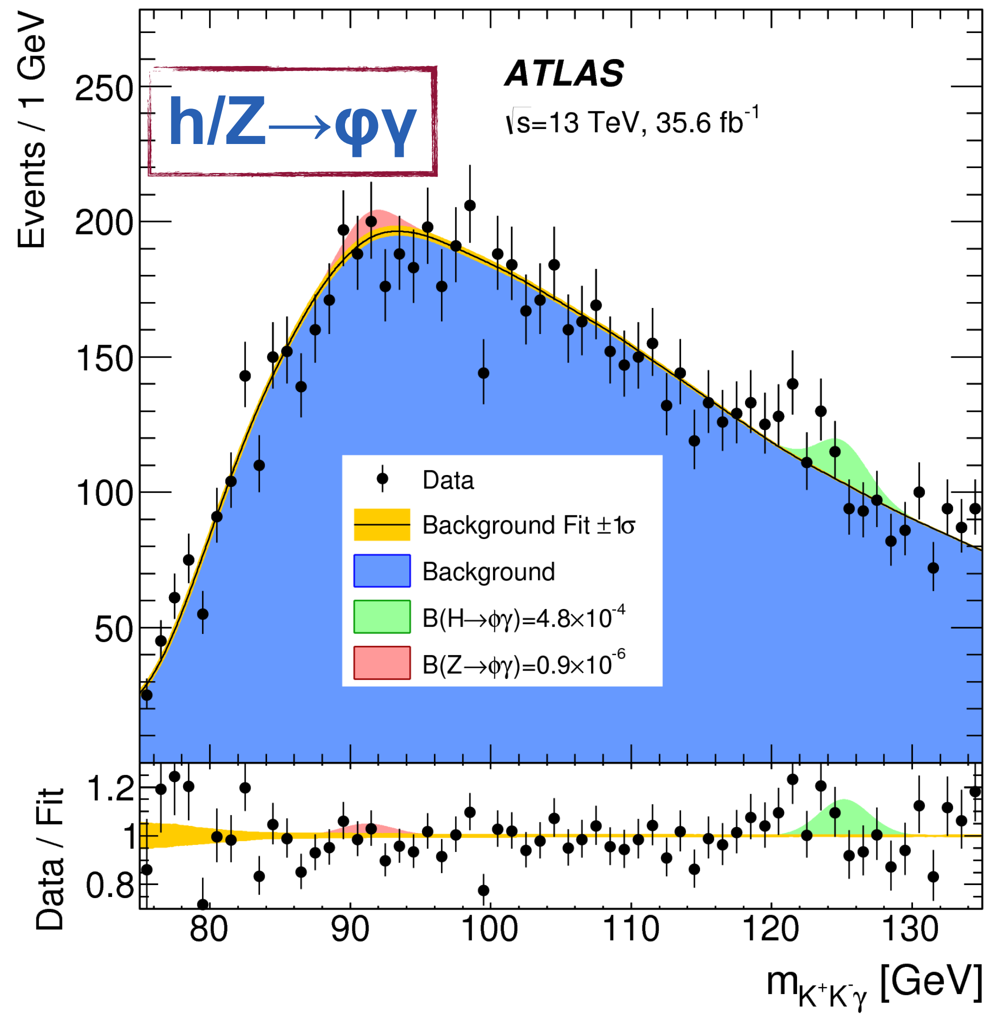
arXiv:1712.02758

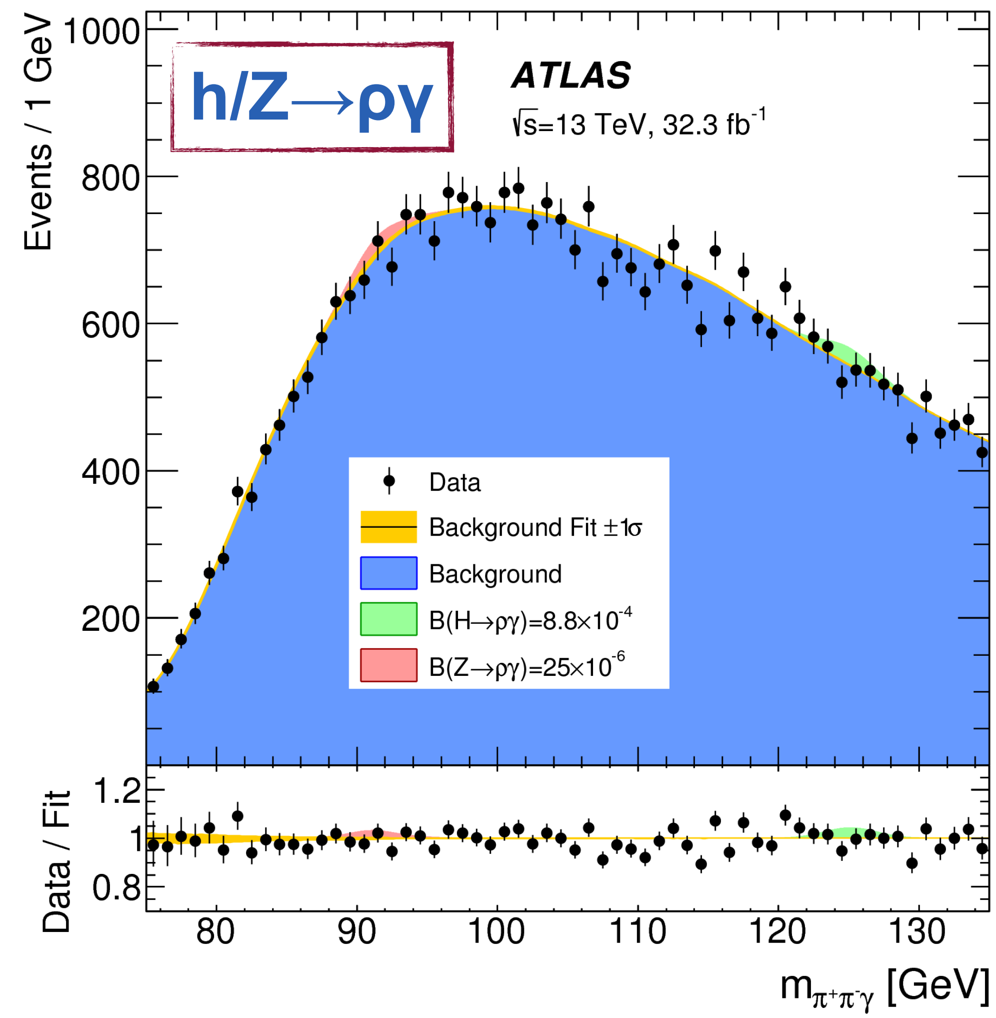
Background validation in side-bands



arXiv:1712.02758 arXiv:1712.02758

Results





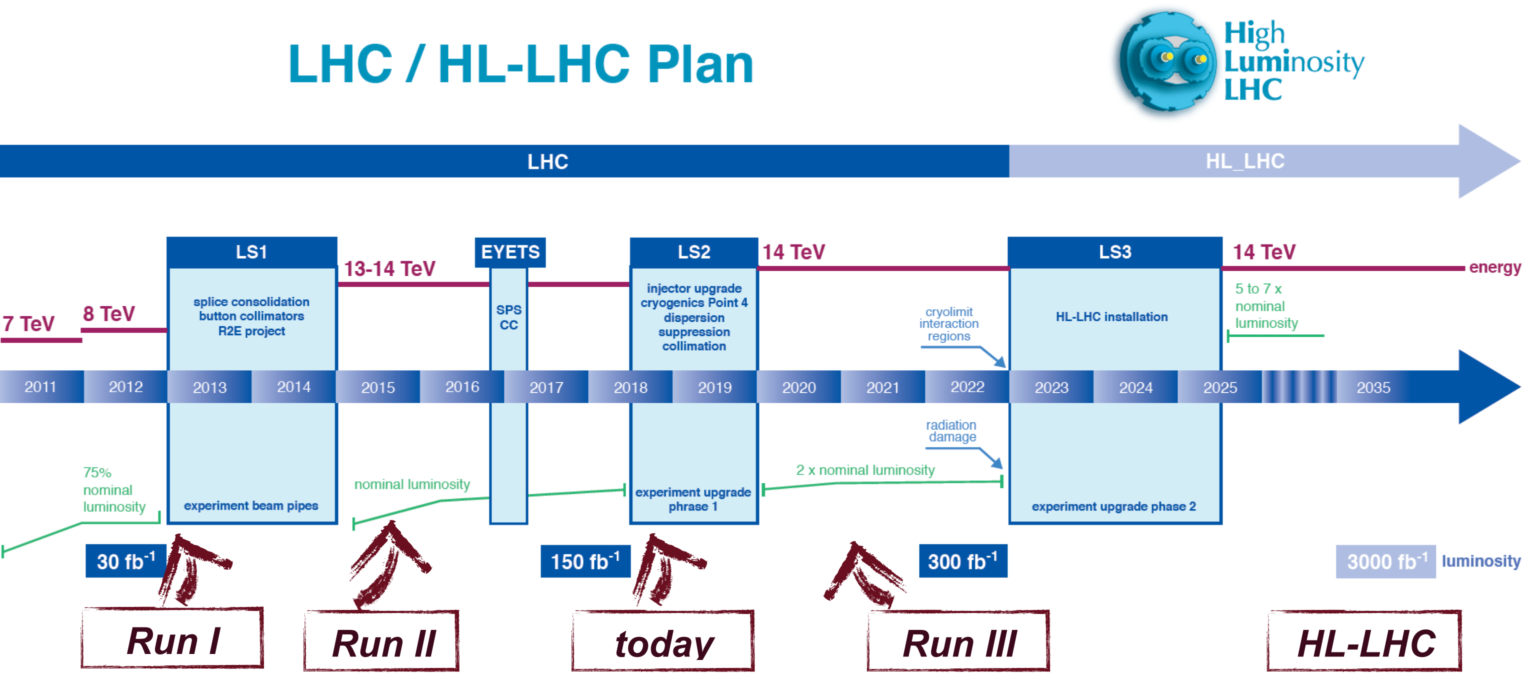
- **Final discriminant** is $m_{KK\gamma}$ and $m_{\pi\pi\gamma}$
- **No significant signal observed**
- 95% confidence level **upper limit**
  - CLs with profile likelihood test statistic
  - Limit on production cross-section times branching ratio
    - h→φγ < 25.3 fb
    - h→ργ < 45.5 fb

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

arXiv:1712.02758

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

HL-LHC and beyond

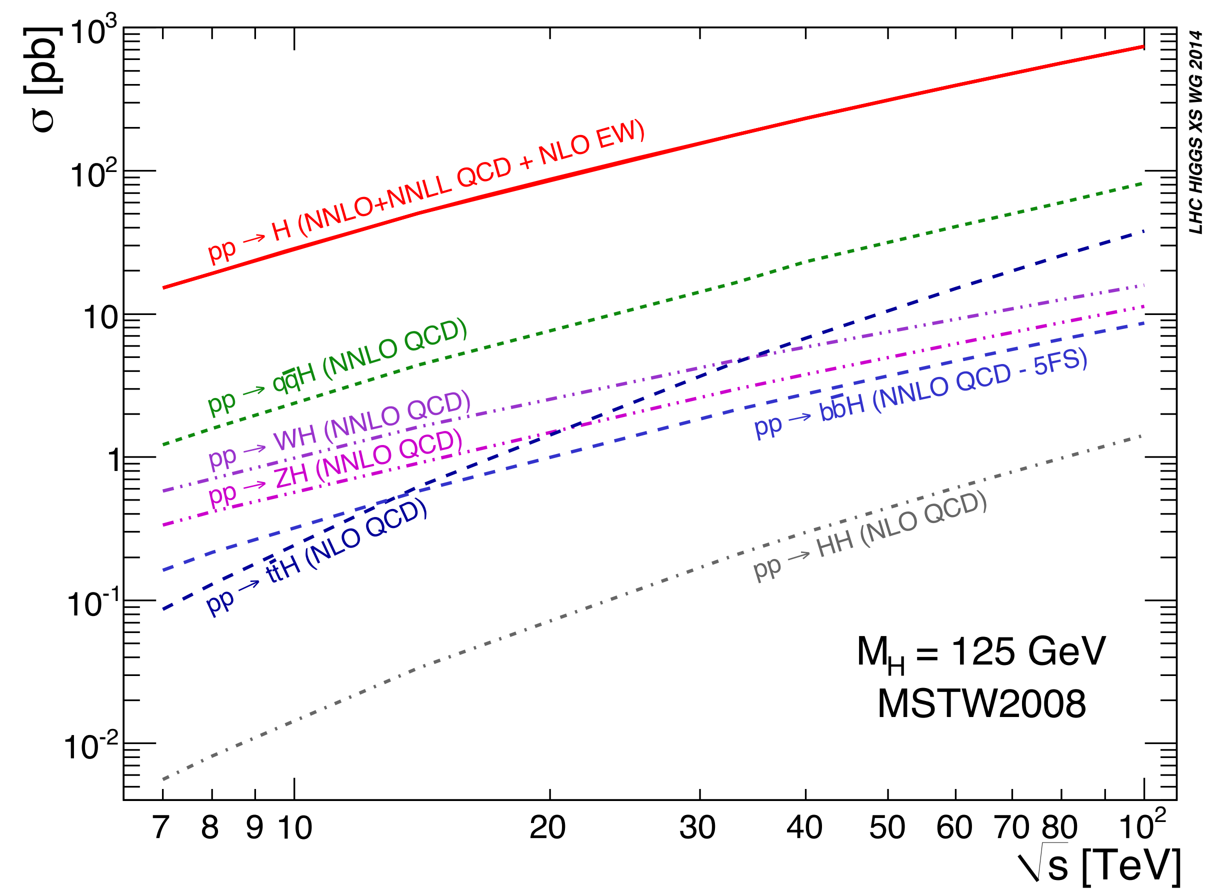


ATLAS-PHYS-PUB-2015-043

	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
$300\ \text{fb}^{-1}$	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
$3000\ \text{fb}^{-1}$	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

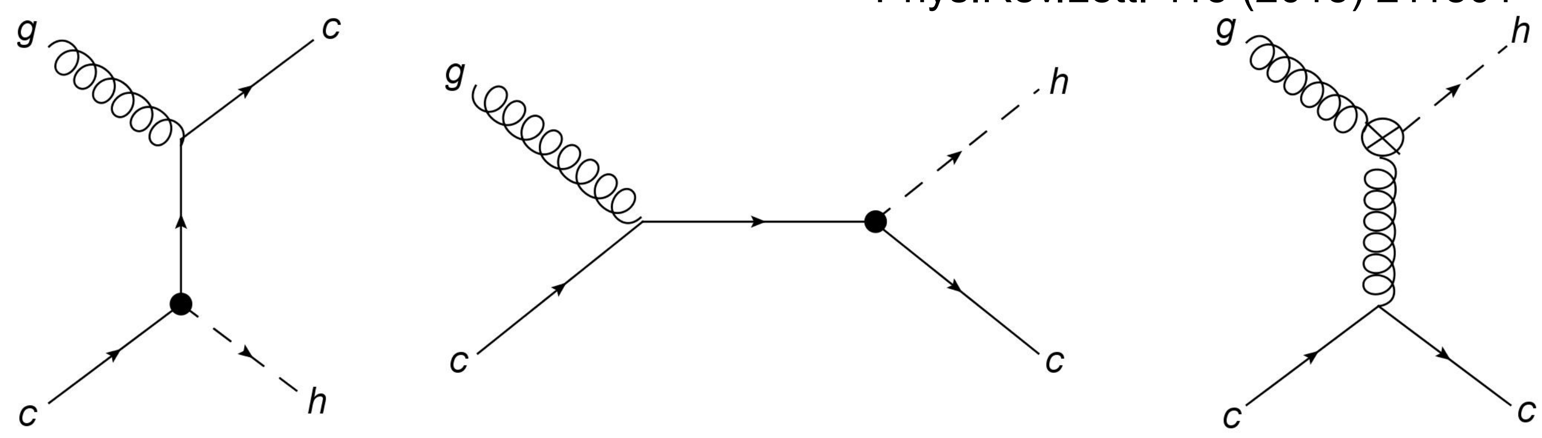
- HL-LHC is a Higgs boson factory
  - $\mathcal{O}$(200M) Higgs bosons produced
- HL-LHC projections for h/Z→J/ψγ
  - Simple and, relatively, clean final state
  - Small branching ratio, few events expected
  - At SM sensitivity $h\to\mu\mu\gamma_{FSR}$ contribution ~3×h→J/ψγ and ($Z\to\mu\mu\gamma_{FSR}$ for Z)
  - Sensitive to "anomalous" h→γγ; use ratio
- Future colliders: leap in Higgs production rate
  - FCC-hh 100 TeV 20/ab: $\mathcal{O}$(15G) Higgs bosons



HL-LHC and beyond

Phys.Rev.Lett. 115 (2015) 211801

- For HL-LHC **pp→hc** could be used
  - with high purity Higgs boson decays
  - SM cross section σ(pp→hc)~166 fb
- Main backgrounds are
  - pp→hg (σ~12pb), pp→hcc (~55fb),
  - pp→hb (σ~200fb)
- Phenomenological study suggests:
  - 2×3000 fb^{-1} $|\kappa_c|\lesssim 2$ at 95%CL

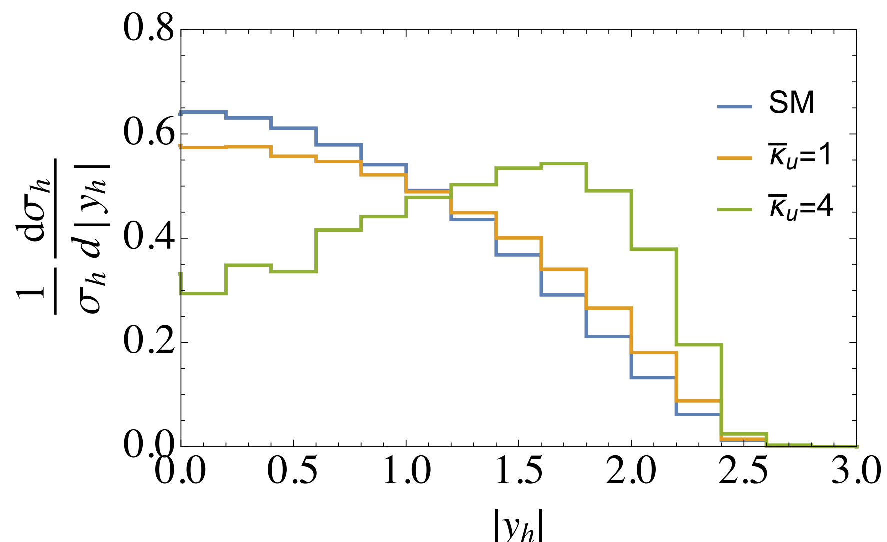


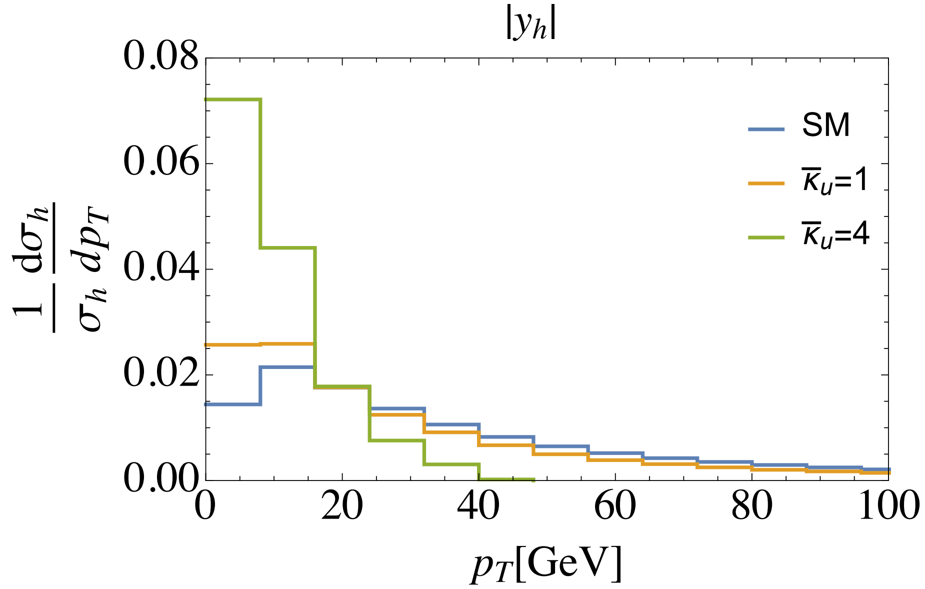
pp→ch(→γγ) 3000 fb^{-1}

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

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

[pT_j>20 GeV, $|\eta_j|$<5, DR(j_1,j_2)>0.4, ε_c=0.4, $\varepsilon_{g\to c}$=1%, $\varepsilon_{b\to c}$=30%]

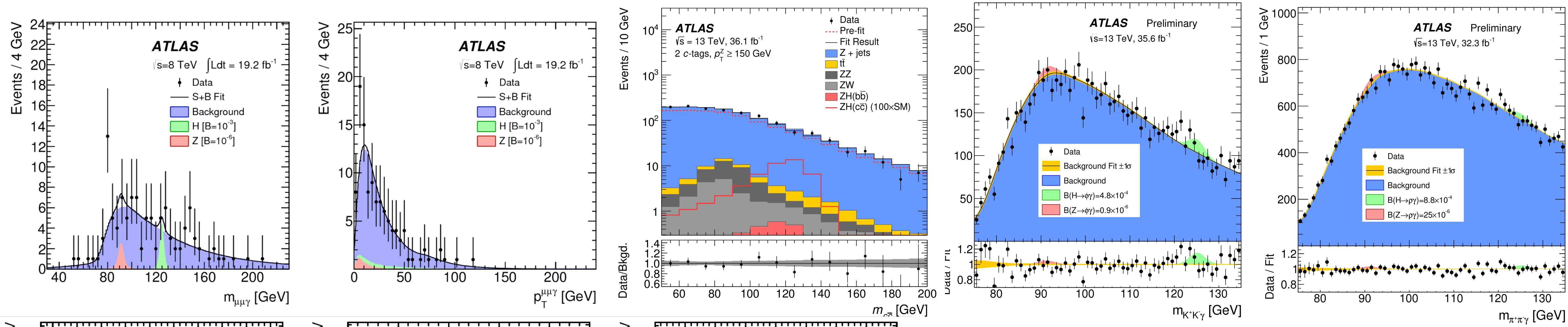


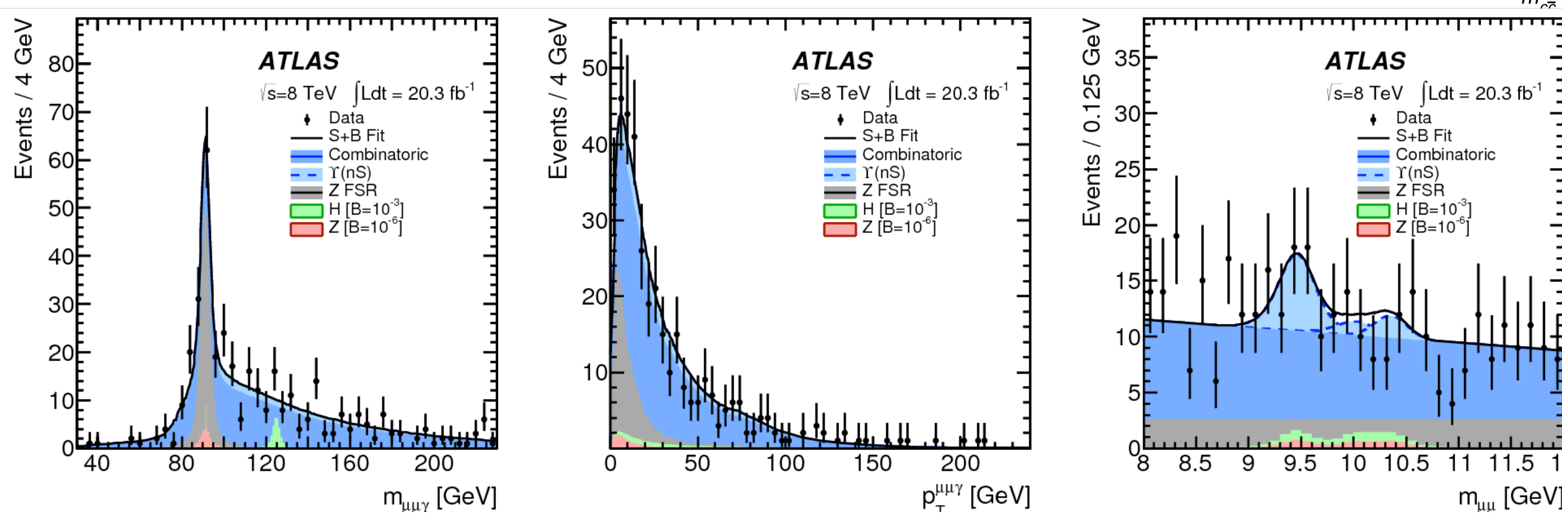


- Derive constraints on Higgs boson-quark couplings through the **Higgs boson kinematic distributions**
  - For example pT_h or y_h
- Phenomenological study suggests that couplings to up- and down-quarks could be constrained to <0.4 of the b-quark Yukawa at HL-LHC.

PRL 118 (2017) 121801, JHEP 1612 (2016) 045, arXiv:1608.04376

Summary





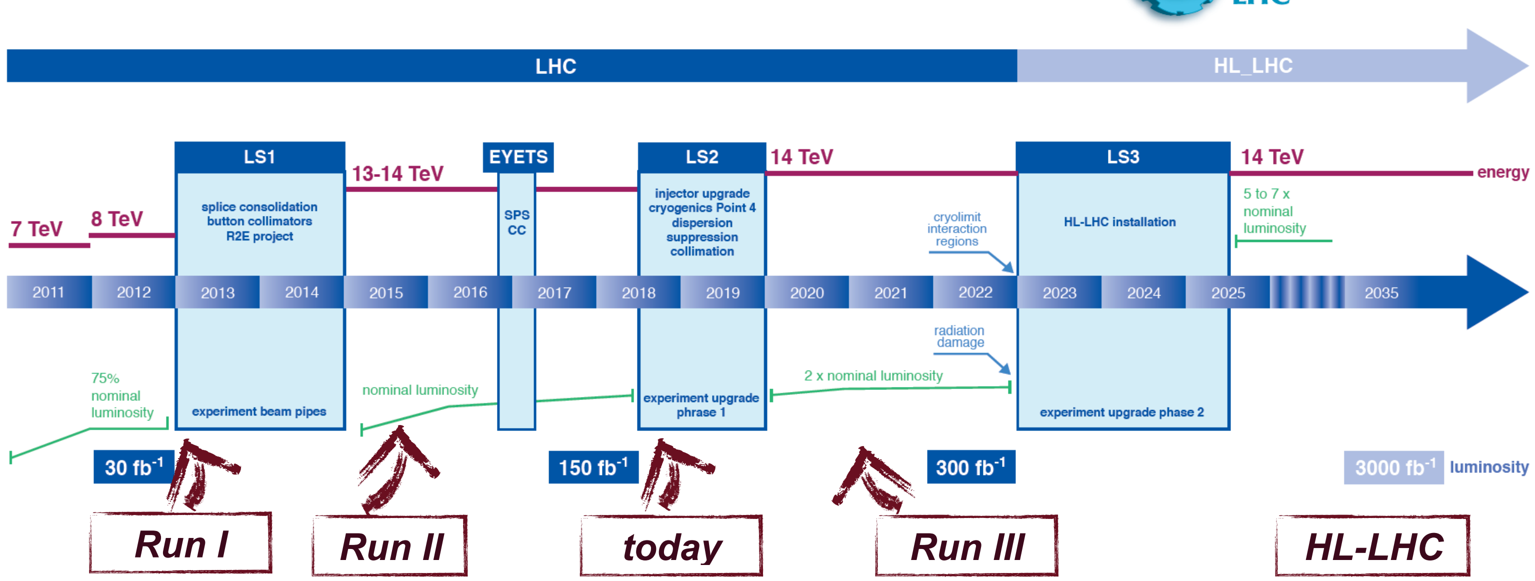
Higgs boson-fermion interactions is the least directly explored part of the SM → particularly first/second generation

New Physics could be hiding here!

Several new and complementary approaches appearing: 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



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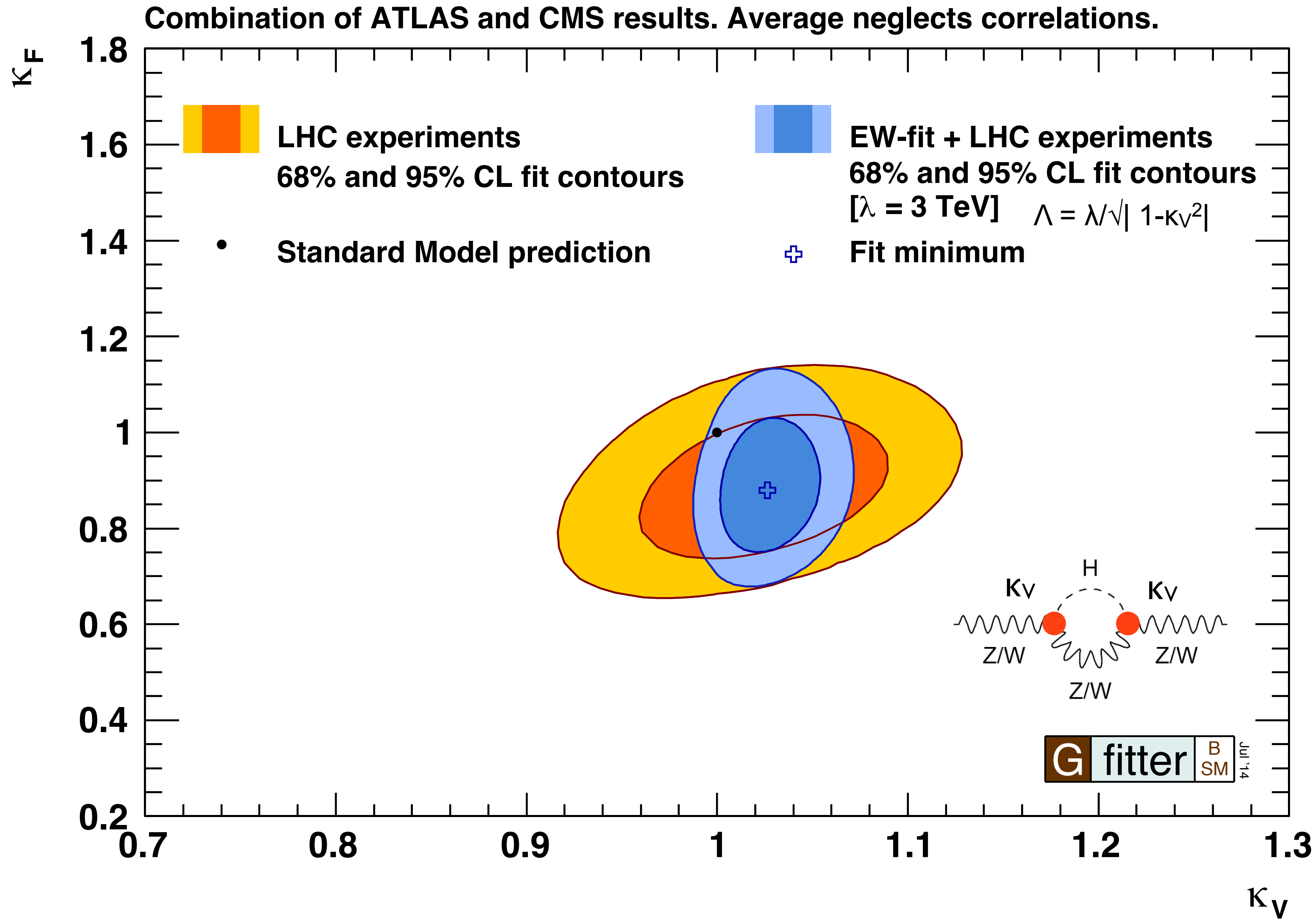
Additional Slides

Higgs boson and precision electroweak physics

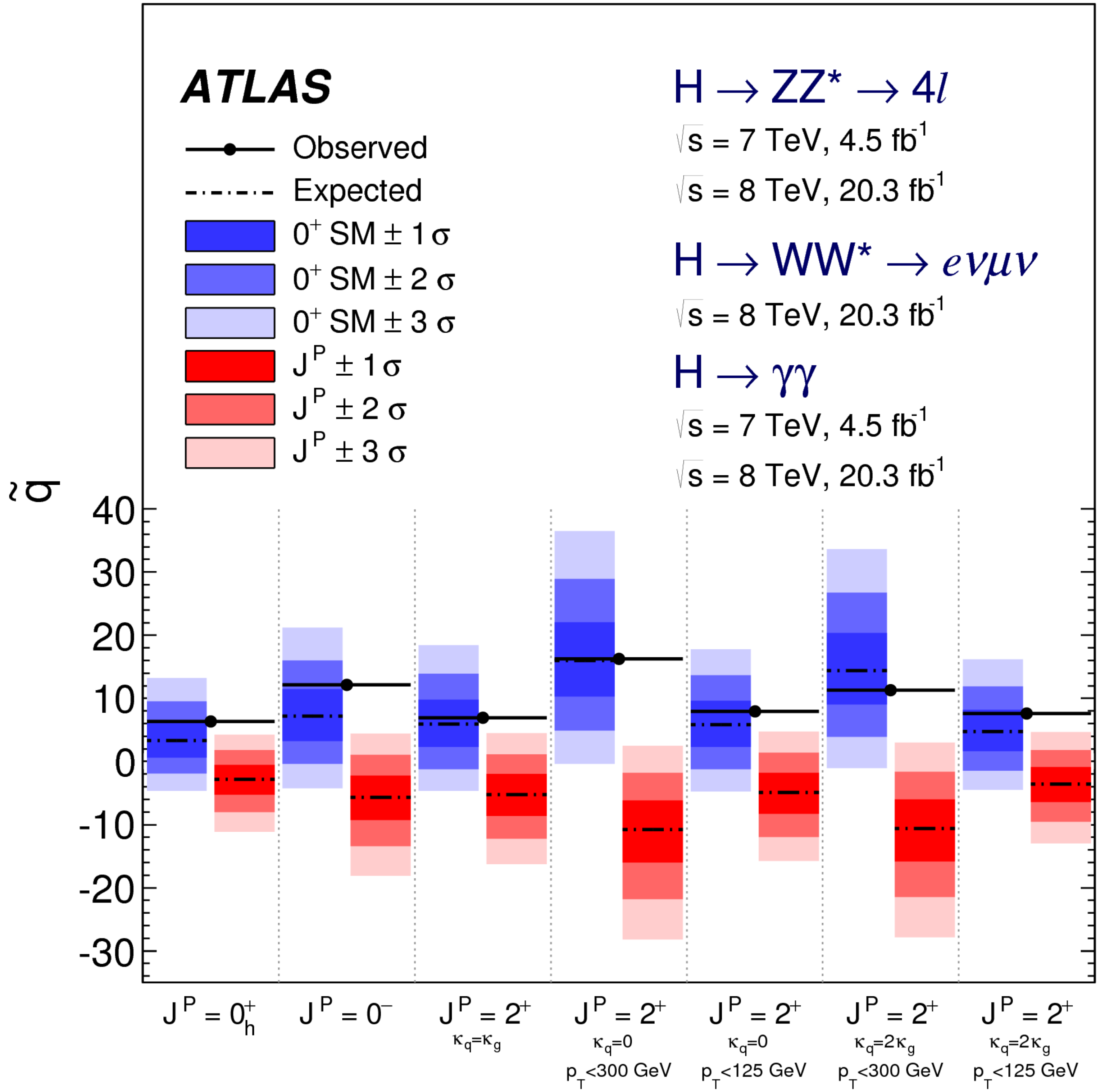
Common coupling scaling for all Fermions (κ_F) and for all Bosons (κ_V); no BSM contributions



Global EW fit more precise for κ_V than Higgs boson measurements
κ_V>1 preferred (many BSM scenarios require κ_V<1)
Global EW fit has ~ no effect on determination of κ_F

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

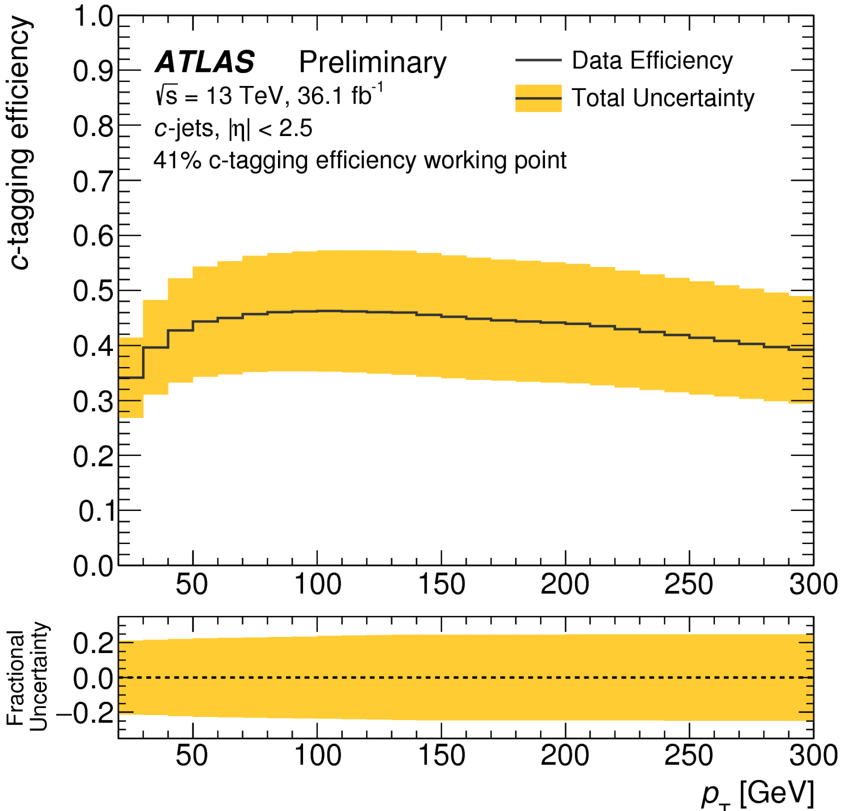
Spin/CP properties

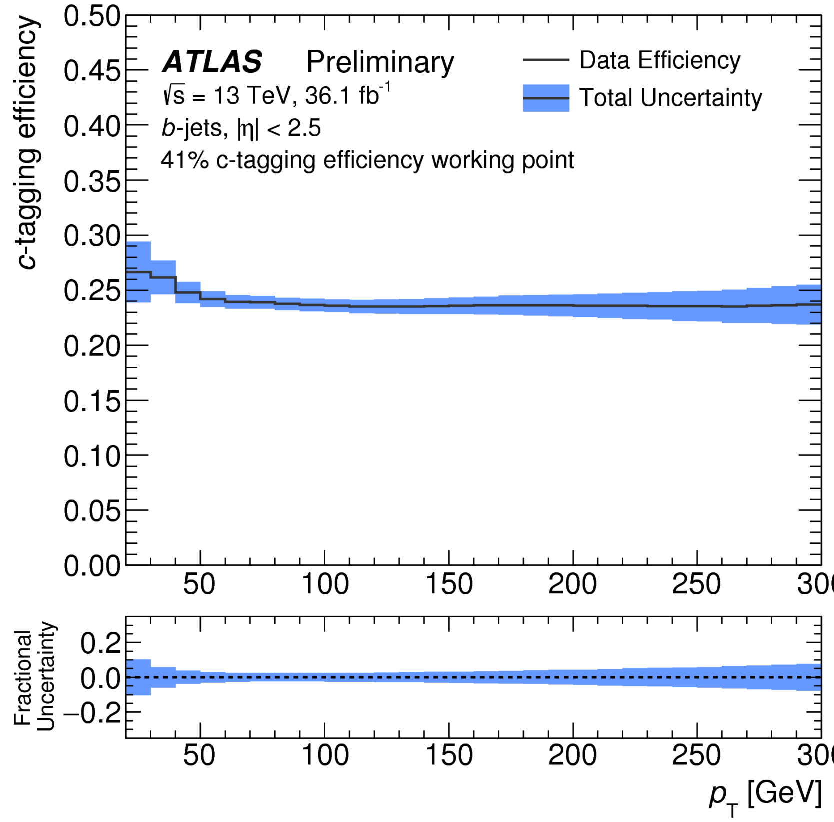


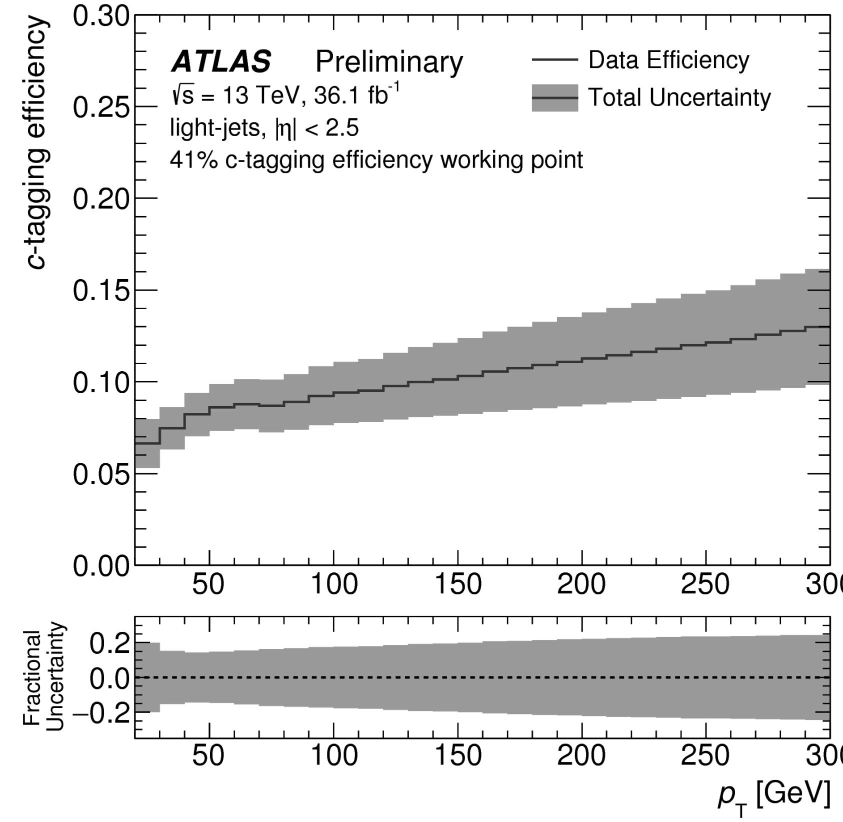
Eur. Phys. J. C75 (2015) 476

Performance of the ATLAS c-tagger

ATLAS-CONF-2017-078

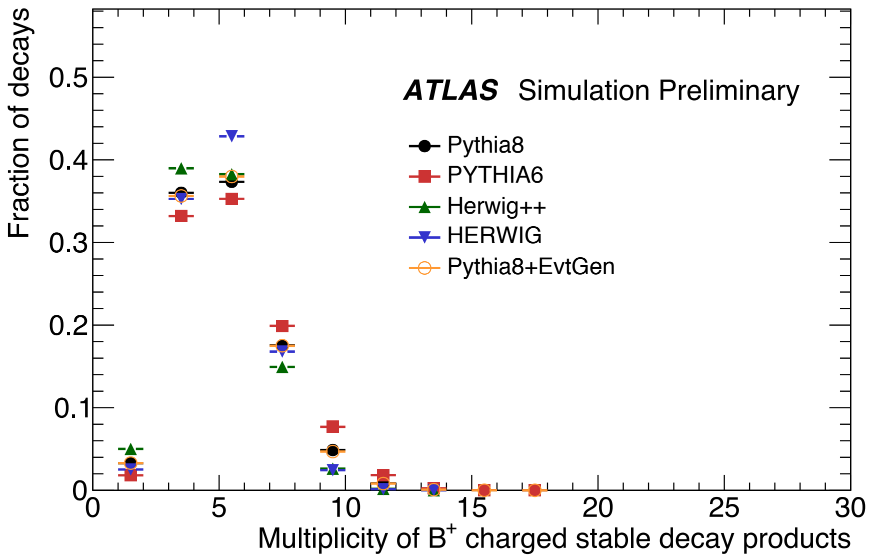


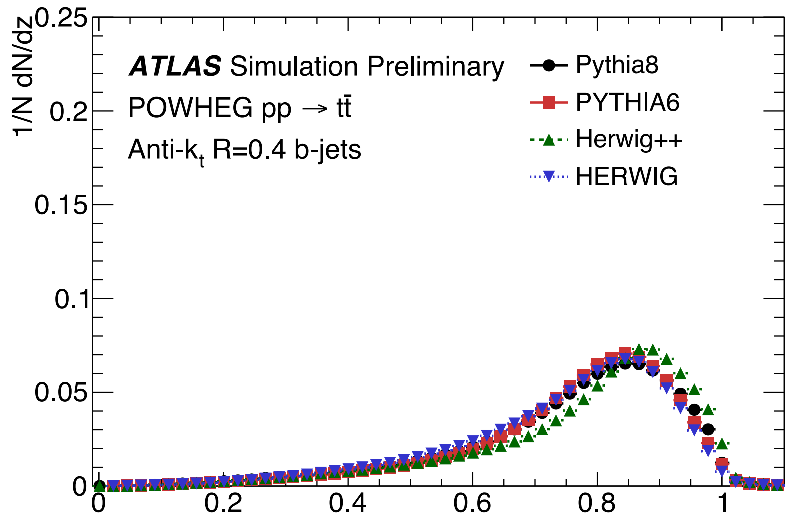




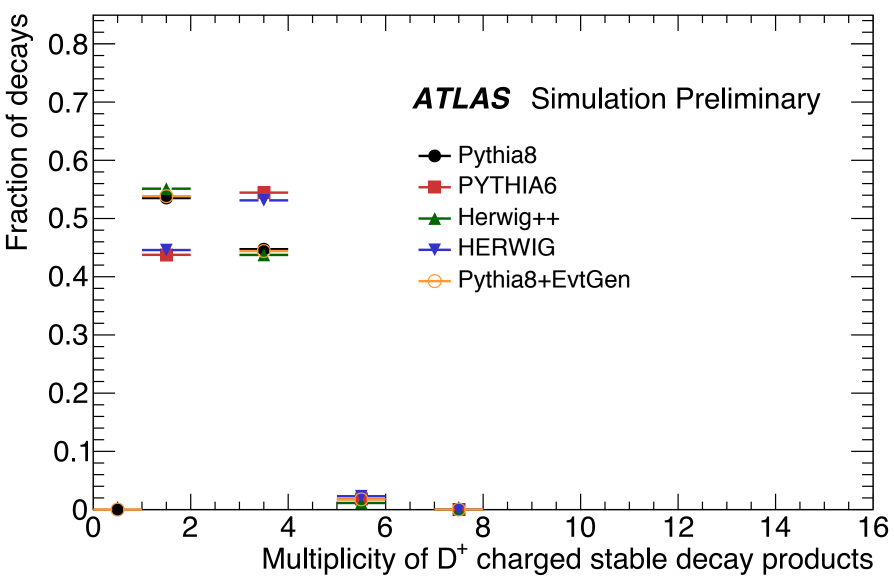
- Efficiency calibrated in data
  - b-jets from t →Wb decays
  - c-jets from W → cs, cd decays (in ttbar events)
- Typical total relative uncertainties of around 25%, 5% and 20% for c-, b- and light jets, respectively

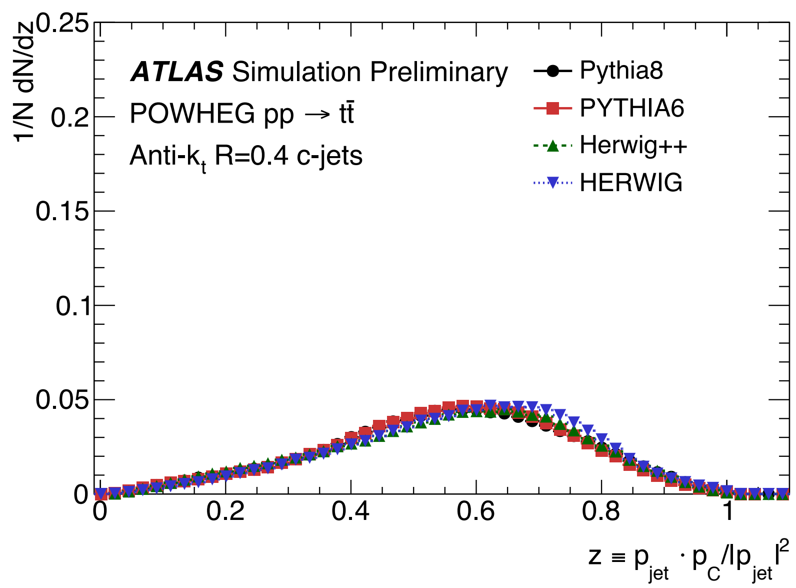
c-tagging

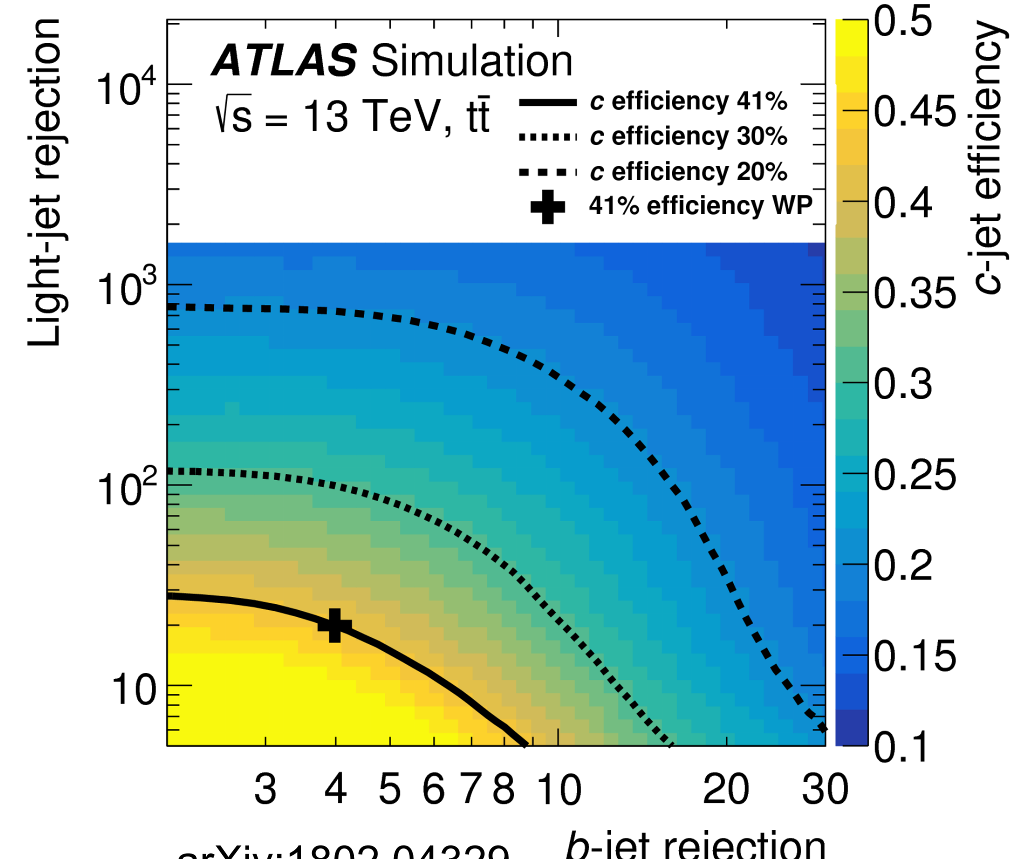




ATL-PHYS-PUB-2014-008

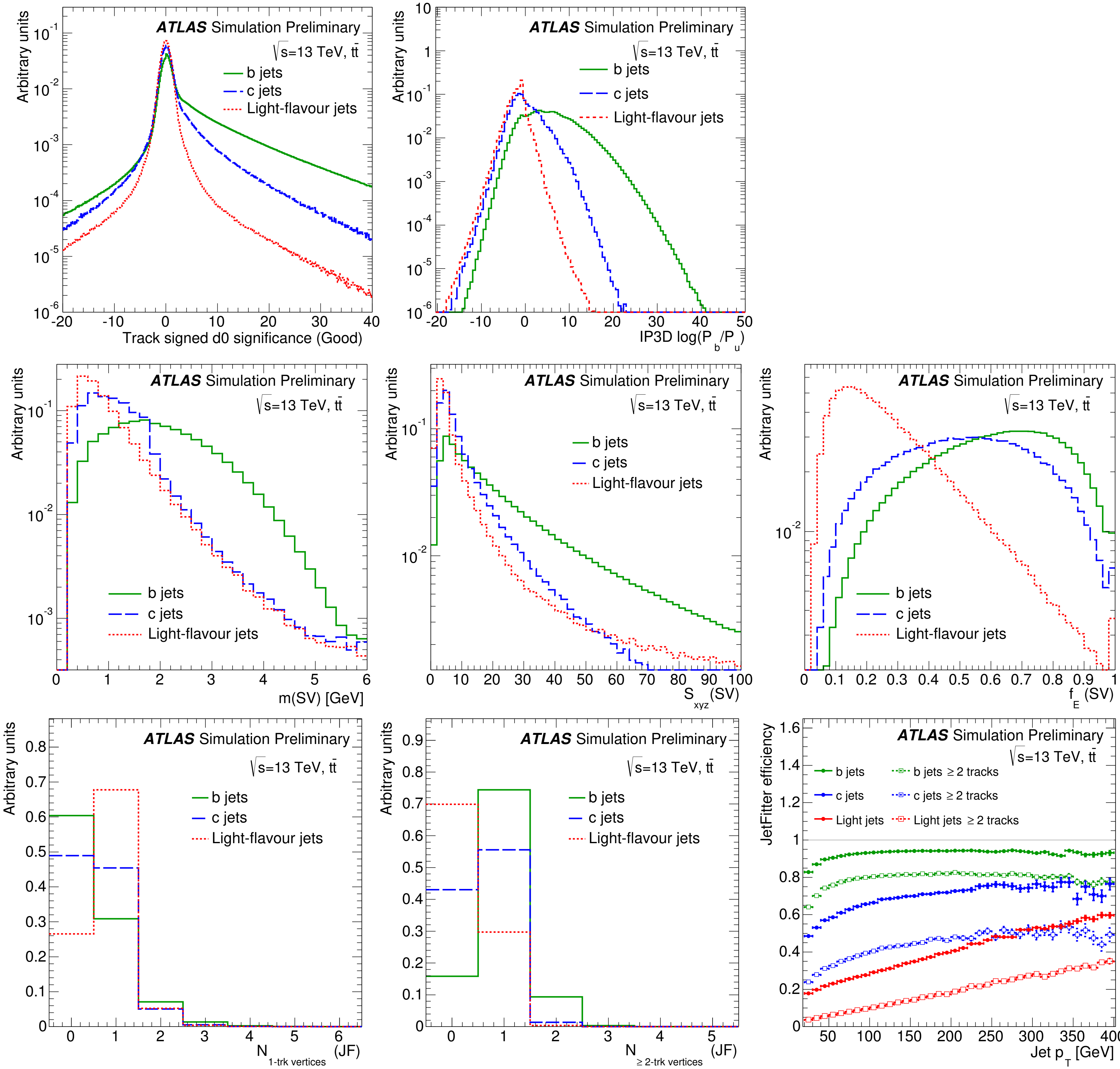






arXiv:1802.04329

c-tagging


ATLAS Simulation Preliminary
√s=13 TeV, tt̄
b jets
c jets
Light-flavour jets
Arbitrary units
Track signed d0 significance (Good)
IP3D log(P_b/P_u)
m(SV) [GeV]
S_xyz(SV)
f_E(SV)
N_1-trk vertices (JF)
N_≥2-trk vertices (JF)
JetFitter efficiency
b jets ≥ 2 tracks
c jets ≥ 2 tracks
Light jets
Light jets ≥ 2 tracks
Jet p_T [GeV]

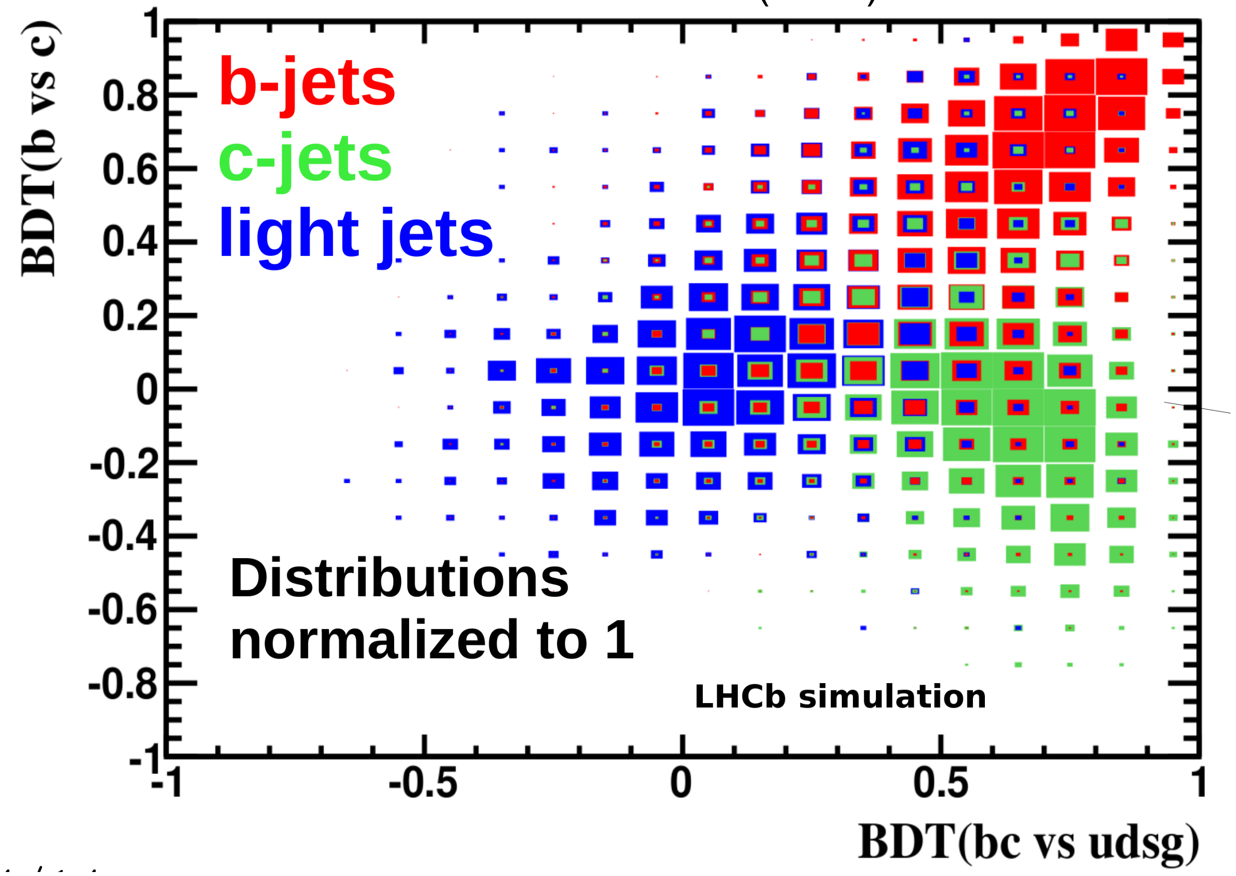
Zh→cc:Yields

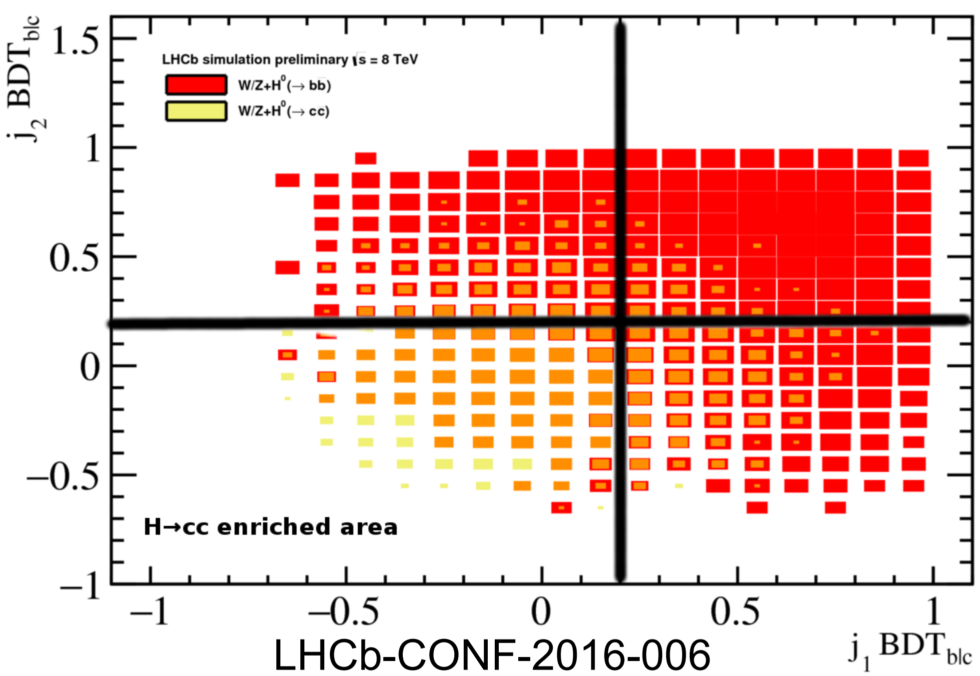
arXiv:1802.04329

Sample	Yield, 50 GeV $< m_{c\bar{c}} <$ 200 GeV			
	1 c-tag		2 c-tags	
	$75 \leq p_{\mathrm{T}}^{Z} < 150$ GeV	$p_{\mathrm{T}}^{Z} \geq 150$ GeV	$75 \leq p_{\mathrm{T}}^{Z} < 150$ GeV	$p_{\mathrm{T}}^{Z} \geq 150$ GeV
Z + jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

- Lower luminosity, ~ $3fb^{-1}$ in Run 1
- Complementary η coverage (2 < η < 5)
- Excellent vertexing (IP resolution of 13-20 μm), momentum resolution (0.4%-0.6%), particle ID
- b/c-tagging
  - efficiency b-tag: ~65%
  - efficiency c-tag: ~25%
  - light mistag prob: ~0.3%
- Additional requirement on the BDT b|c tagging variable: Separation of b jets from c jets is applied
- It removes about 90% of W/Z + H(bb) events while retaining 62% of the W/Z + H(cc)

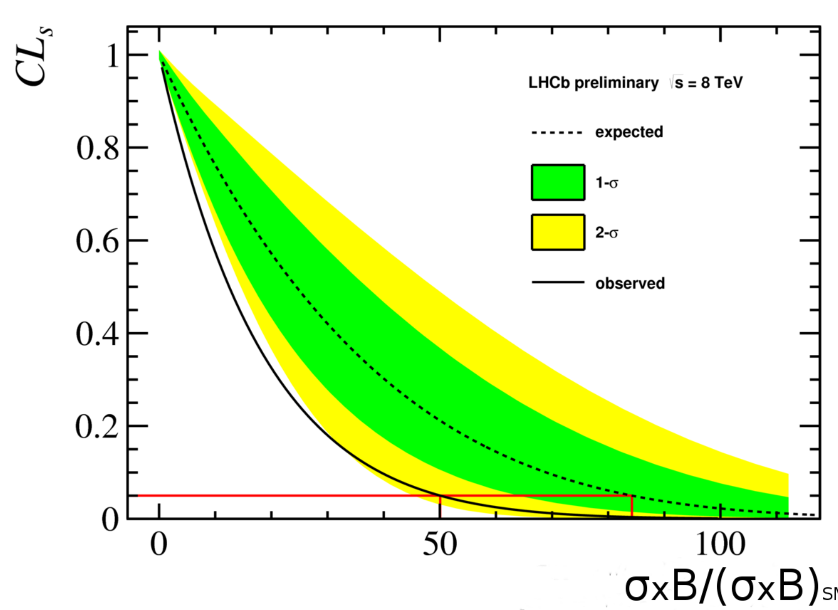
JINST 10 (2015) P06013





LHCb-CONF-2016-006

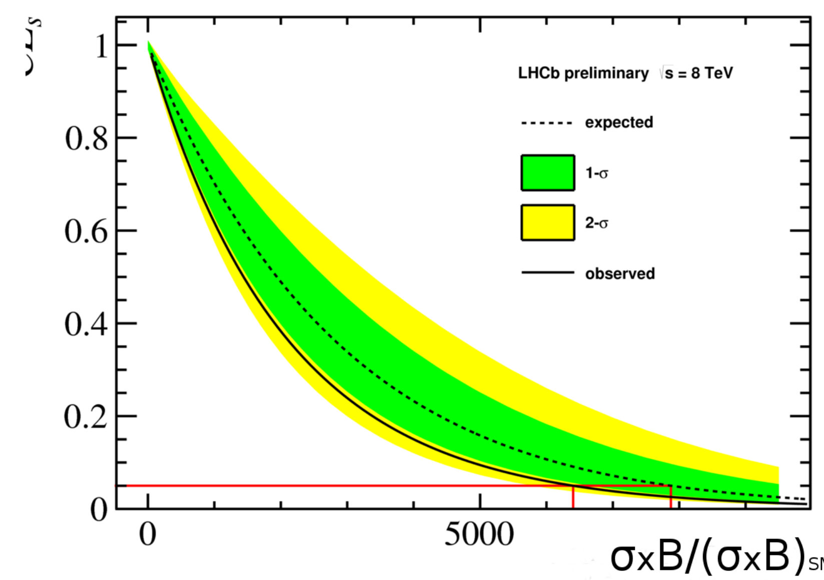
$H \to b\bar{b}$



Limit: < 1.6 pb (50 times SM)

LHCb-CONF-2016-006

$H \to c\bar{c}$

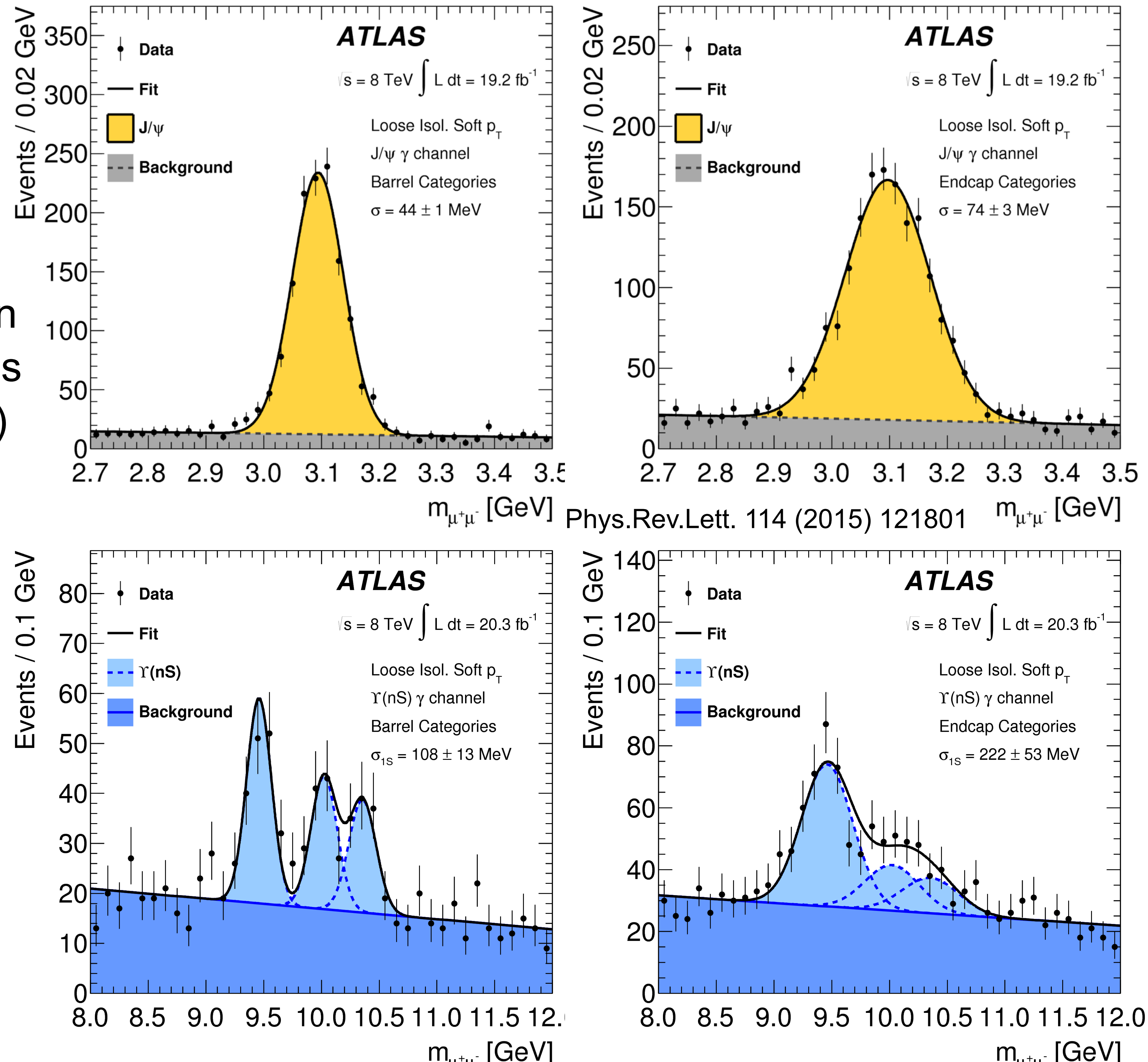


Limit: < 9.4 pb (6400 times SM)

LHCb-CONF-2016-006

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%



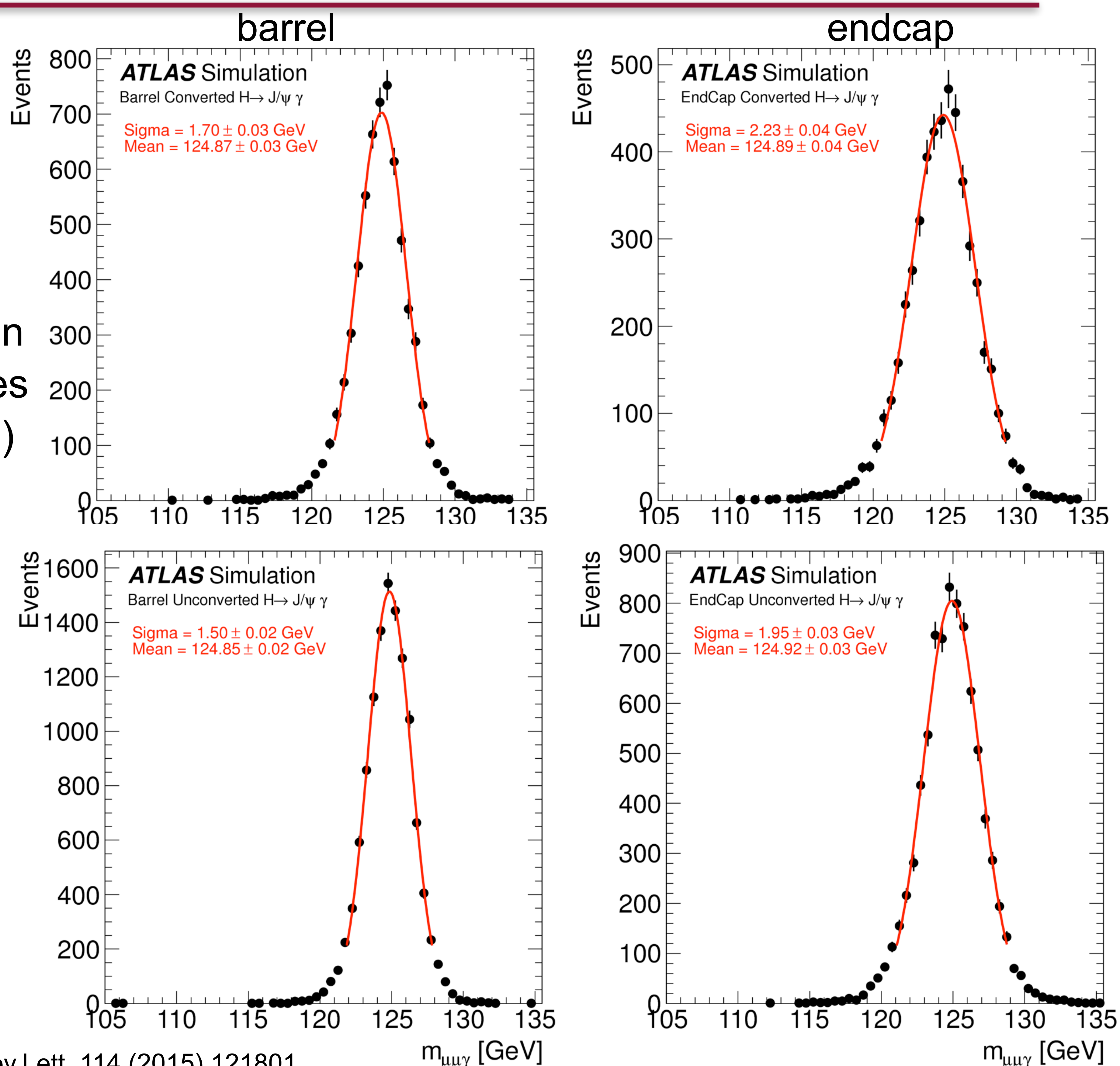
Phys.Rev.Lett. 114 (2015) 121801

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

converted γ

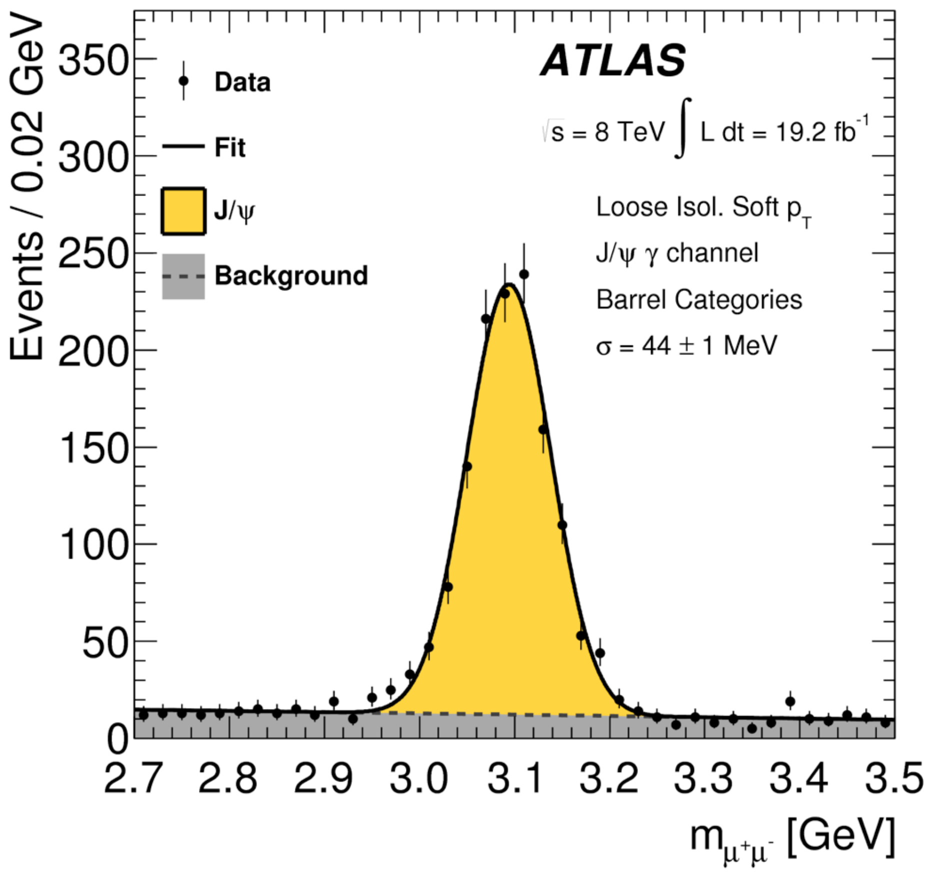
- Simple event categorisation
- 4 detector-driven categories
  - Muon pseudorapidity (×2)
  - Photon conversion (×2)
- Mass resolution: 1.2-1.8%

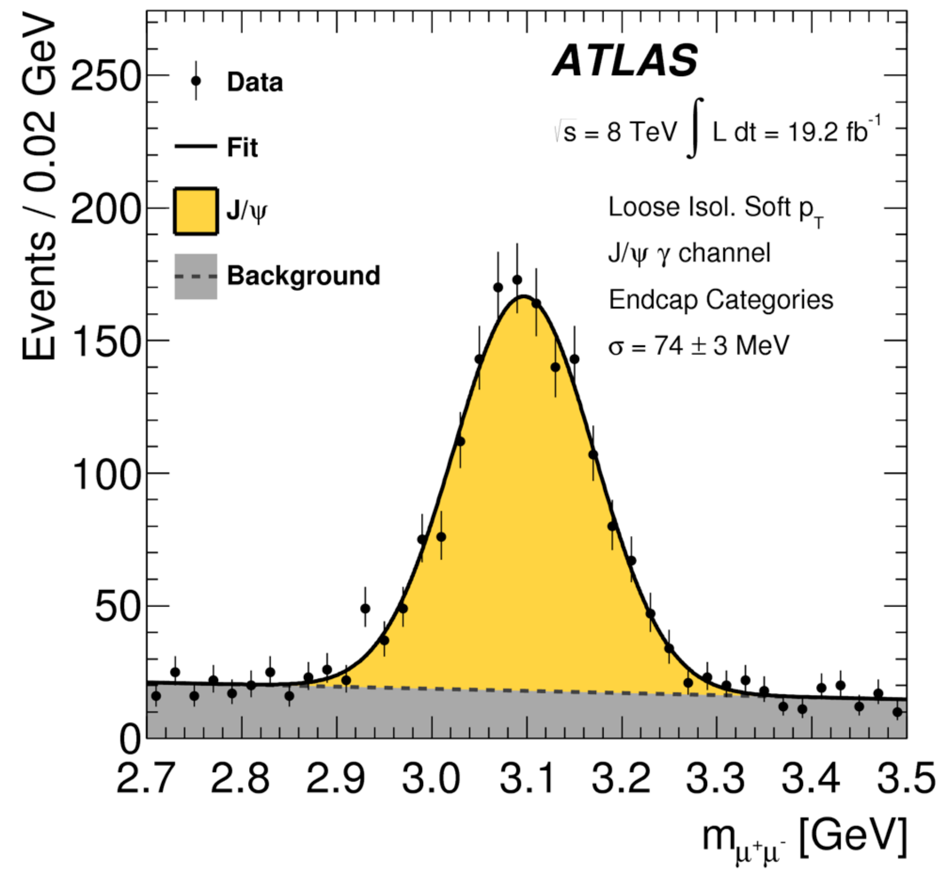
unconverted γ

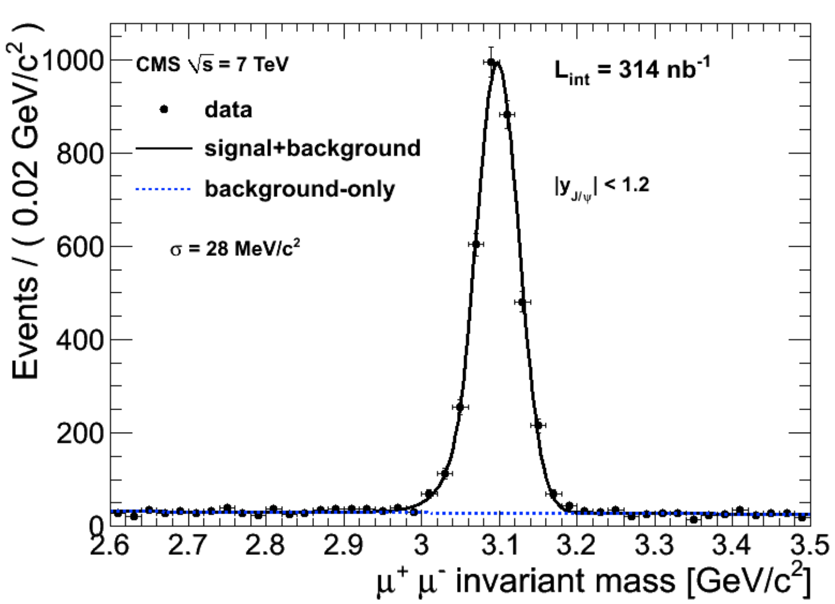


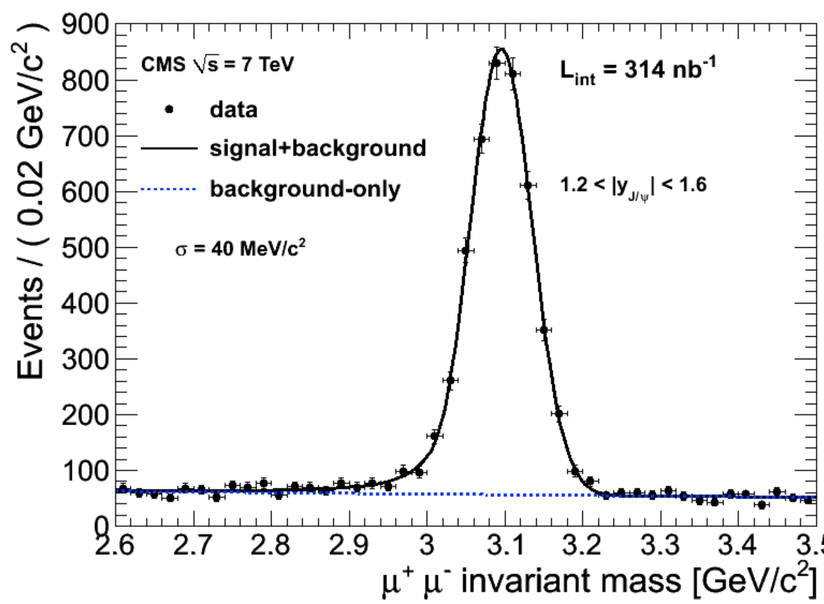
Phys.Rev.Lett. 114 (2015) 121801

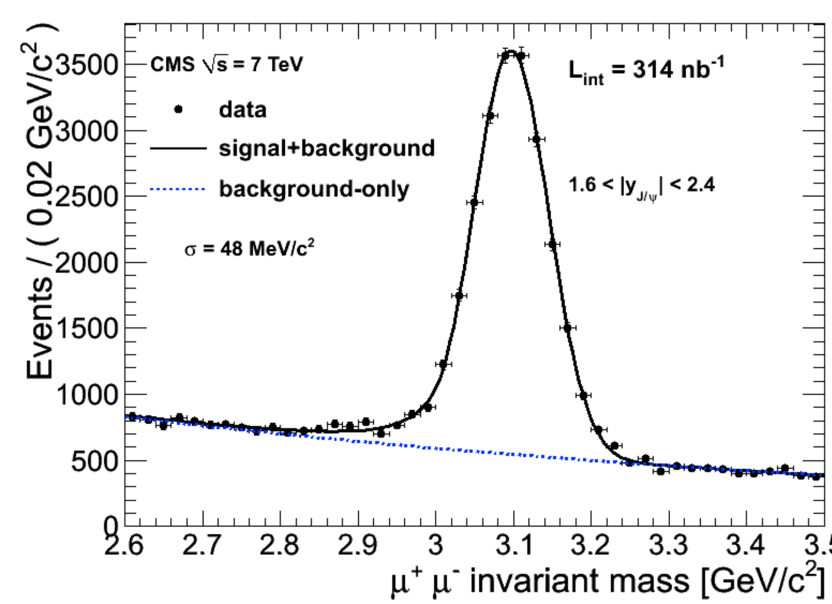
h/Z→J/ψγ and h/Z→Υ(ns)γ





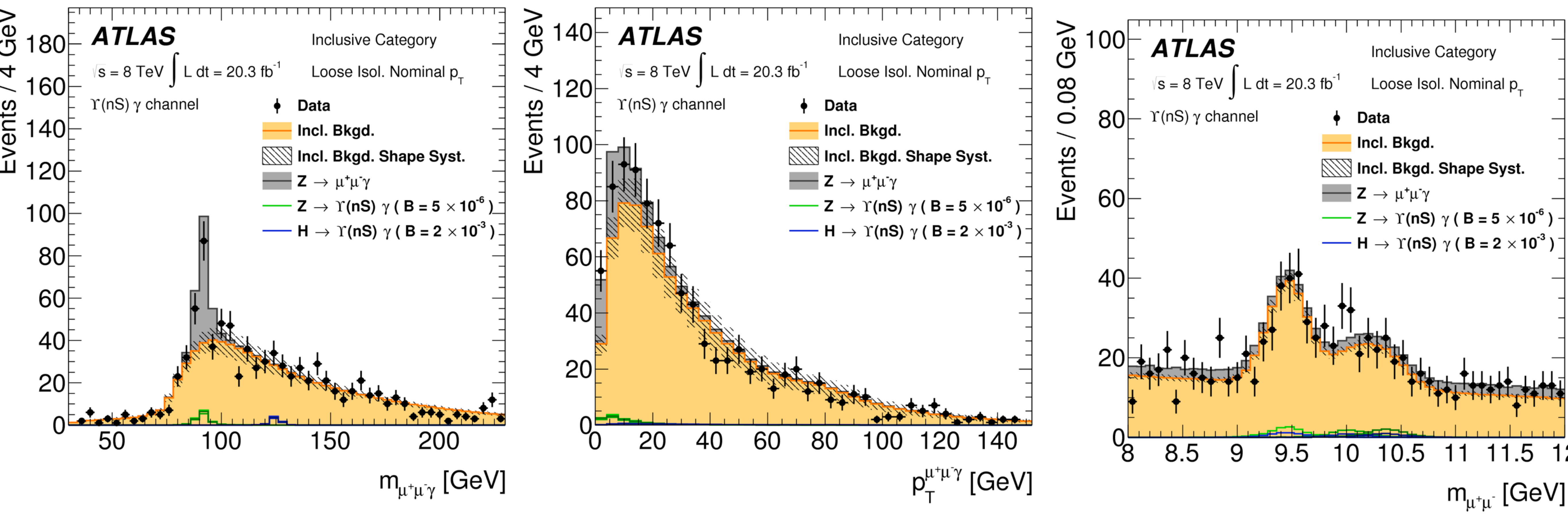




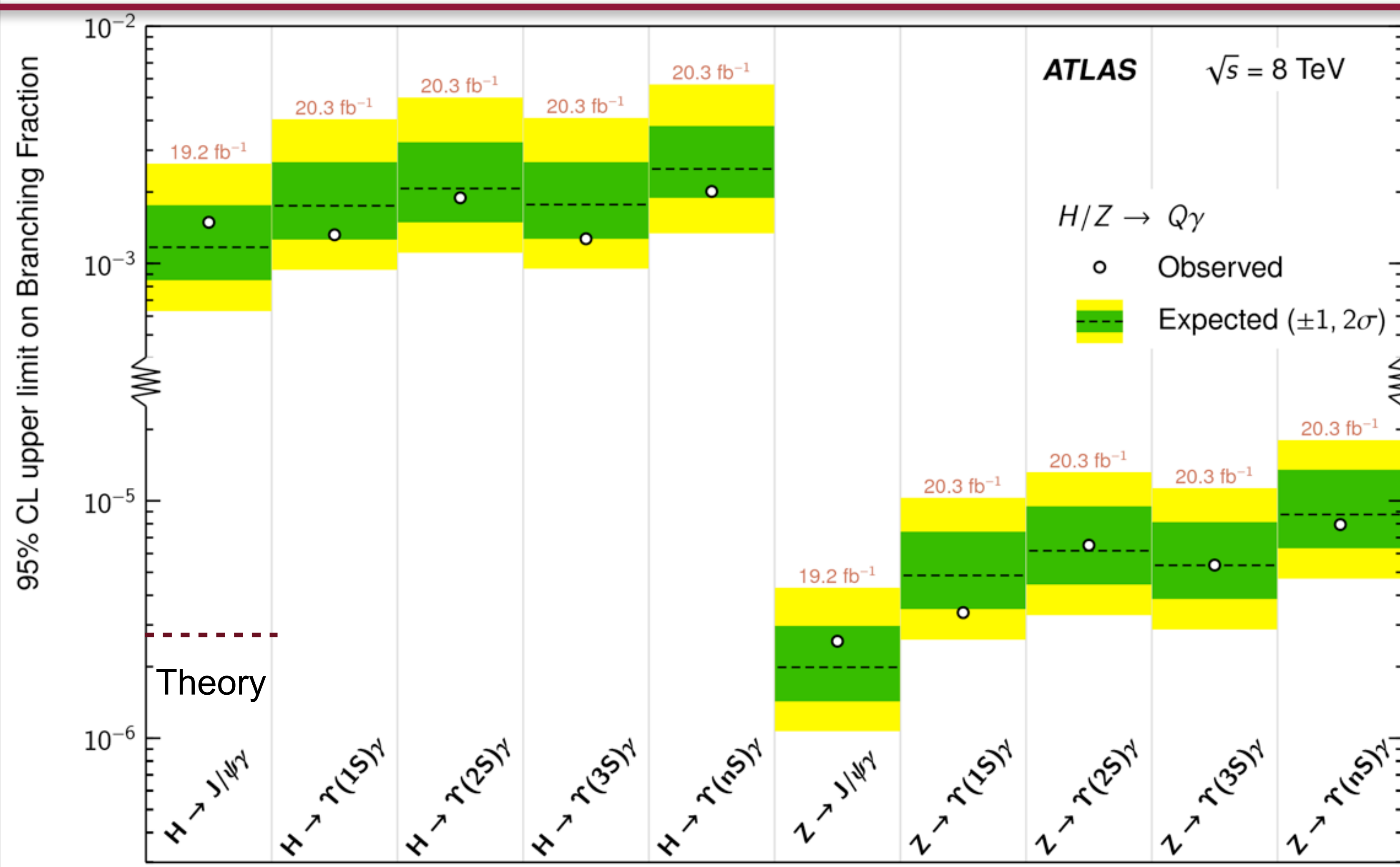


h/Z→J/ψγ and h/Z→Υ(ns)γ

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



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

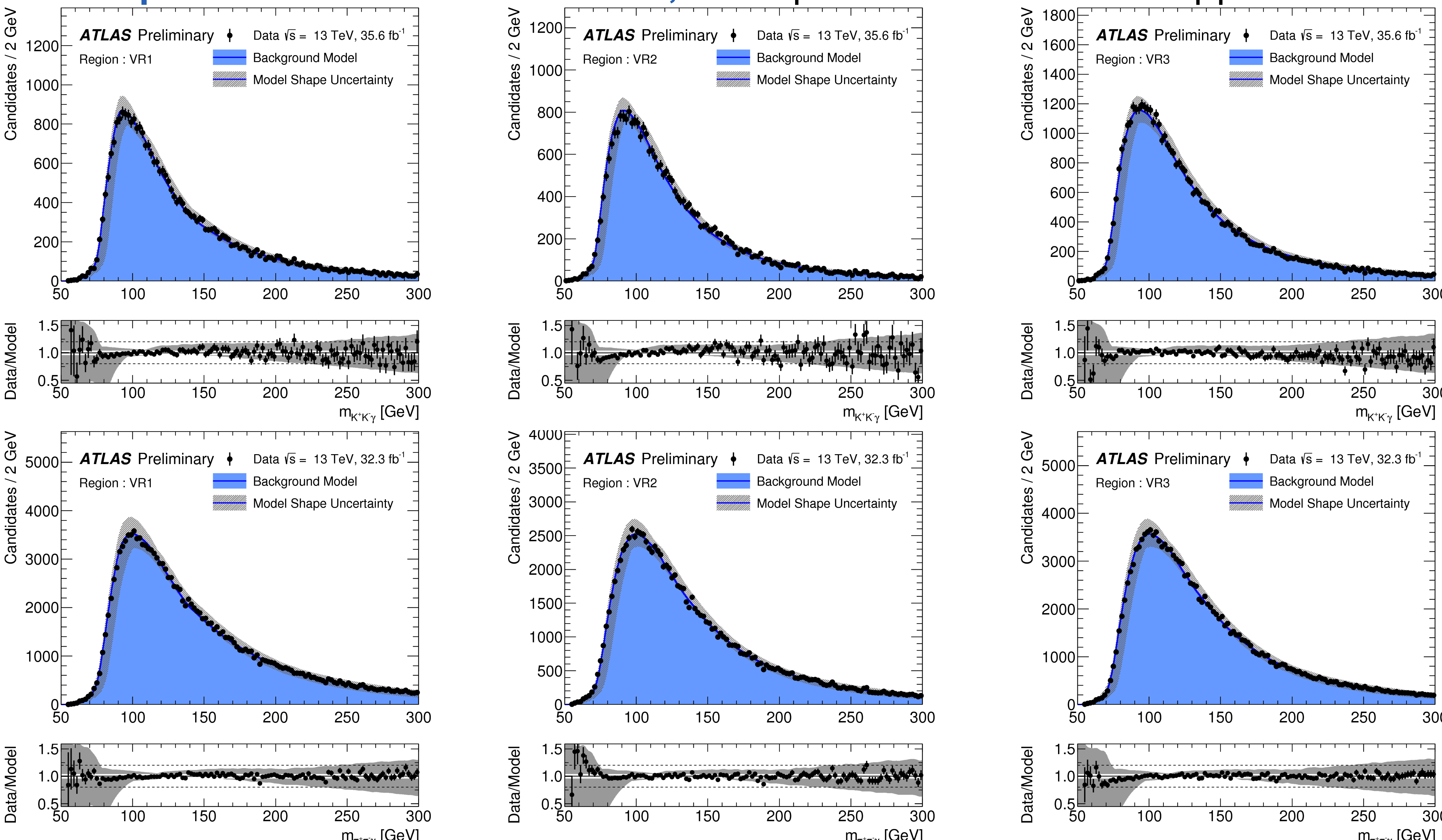
☑ **Indicate non-universal Higgs boson coupling to quarks**

[Phys.Rev. D92 (2015) 033016, JHEP 1508 (2015) 012]

- CMS obtained the same 95% CL upper limit: BR[H→(J/ψ)γ] < 1.5×10^{-3} [Phys.Lett. B753 (2016) 341]

Background

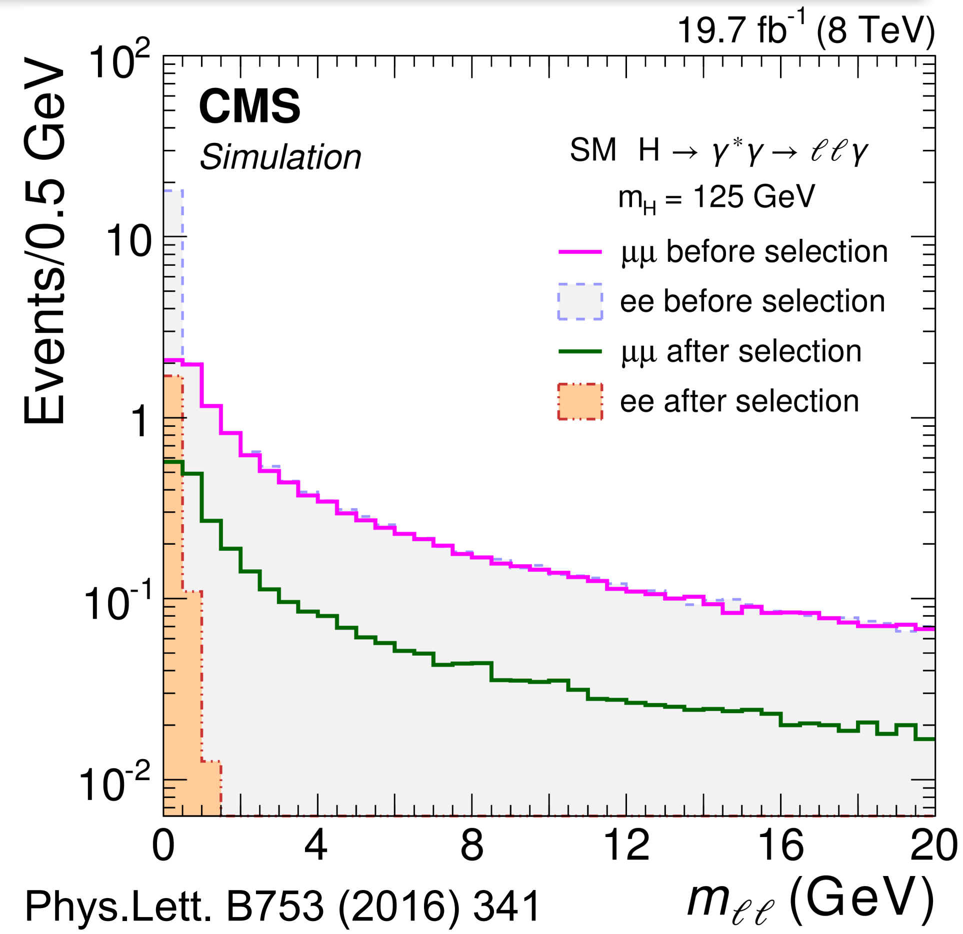
- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. $h/Z \rightarrow \mu\mu\gamma_{FSR}$) **estimated to be negligible**
- **Nonparametric data-driven model;** same procedure as in $h/Z \rightarrow J/\psi\gamma$



ATLAS-CONF-2017-057

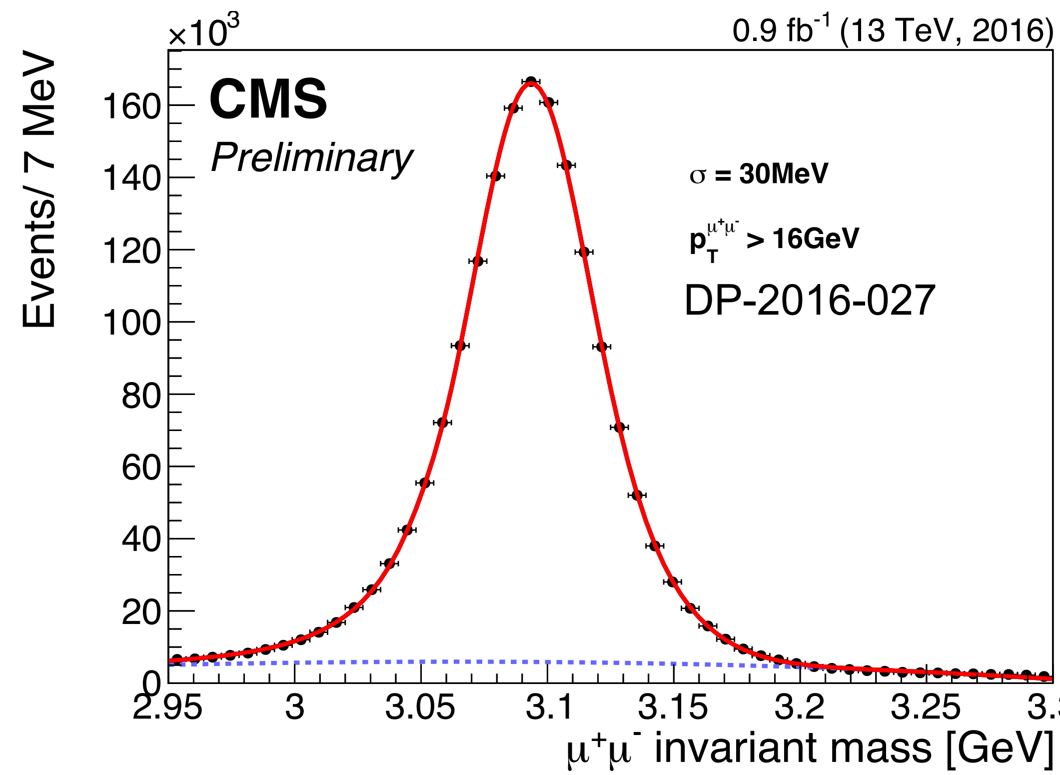
h→γ*γ→llγ and h→J/ψγ

- **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

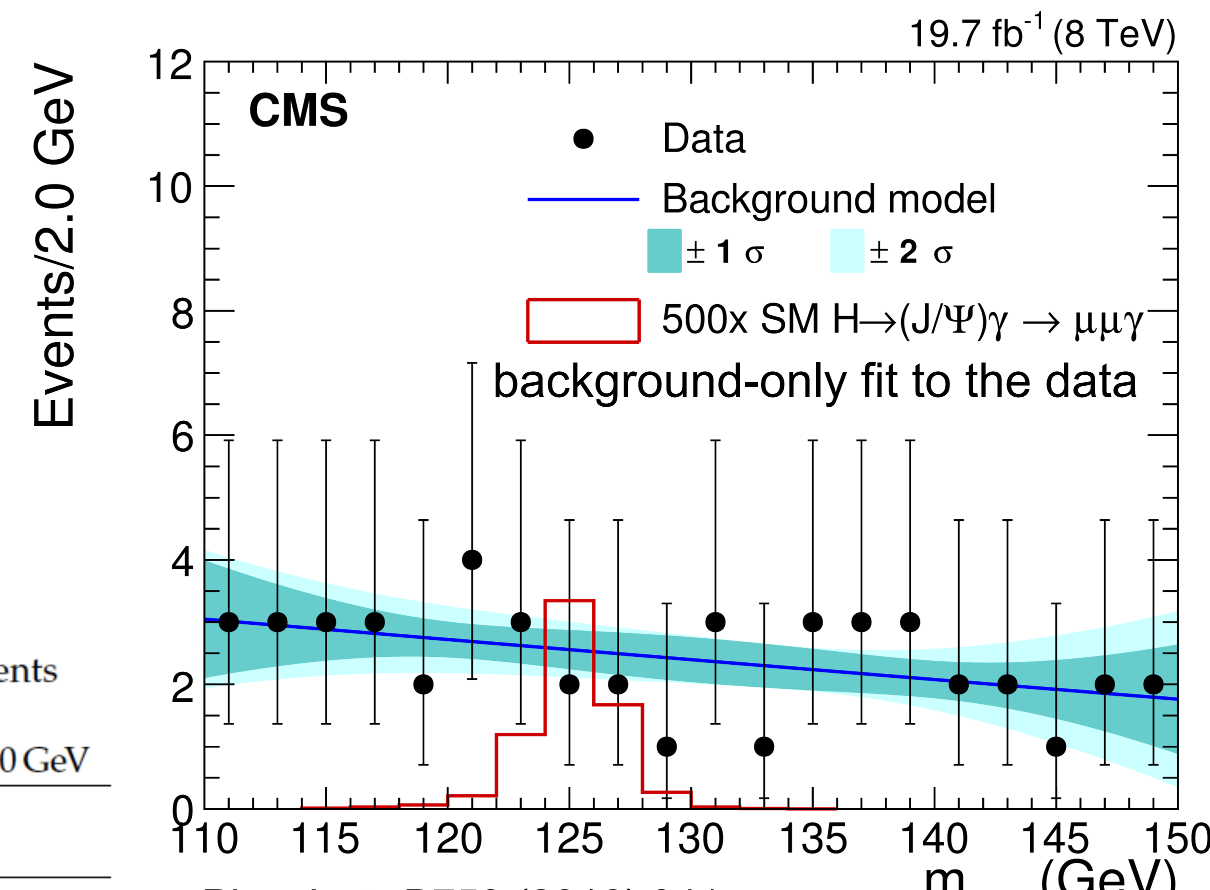
Source	Uncertainty
Integrated luminosity (ref. [37])	2.6%
Theoretical uncertainties:	
PDF	2.6–7.5%
Scale	0.2–7.9%
$H \to \gamma^*\gamma \to \ell\ell\gamma$ branching fraction	10%
Experimental uncertainties:	
Pileup reweighting	0.8%
Trigger efficiency, μ (e) channel	4 (2)%
Muon reconstruction efficiency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



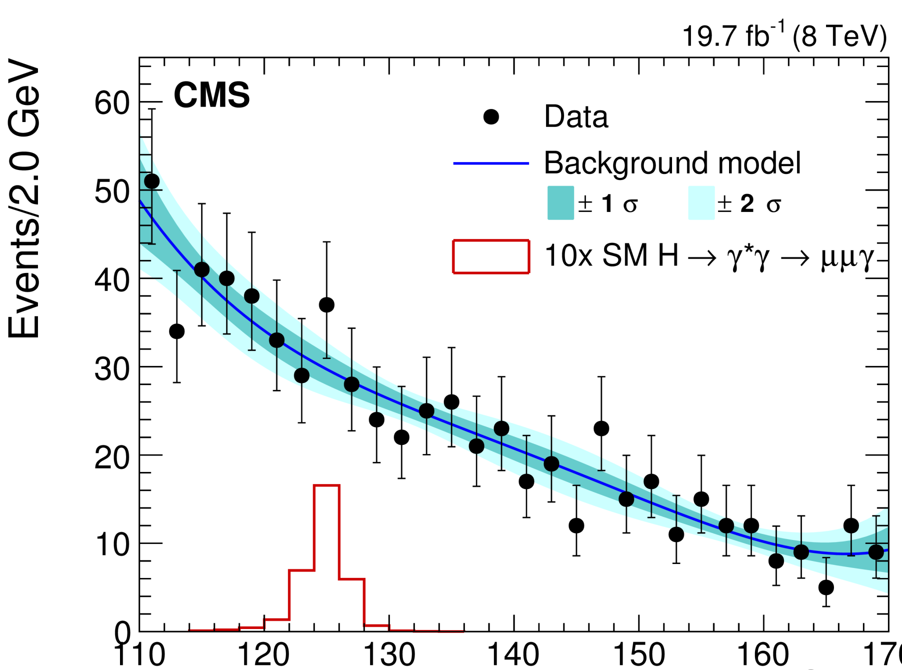
h→γ*γ→llγ and h→J/ψγ

- h→J/ψγ: fit over the 110-150 GeV mass range
  - Background: 2[nd] 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

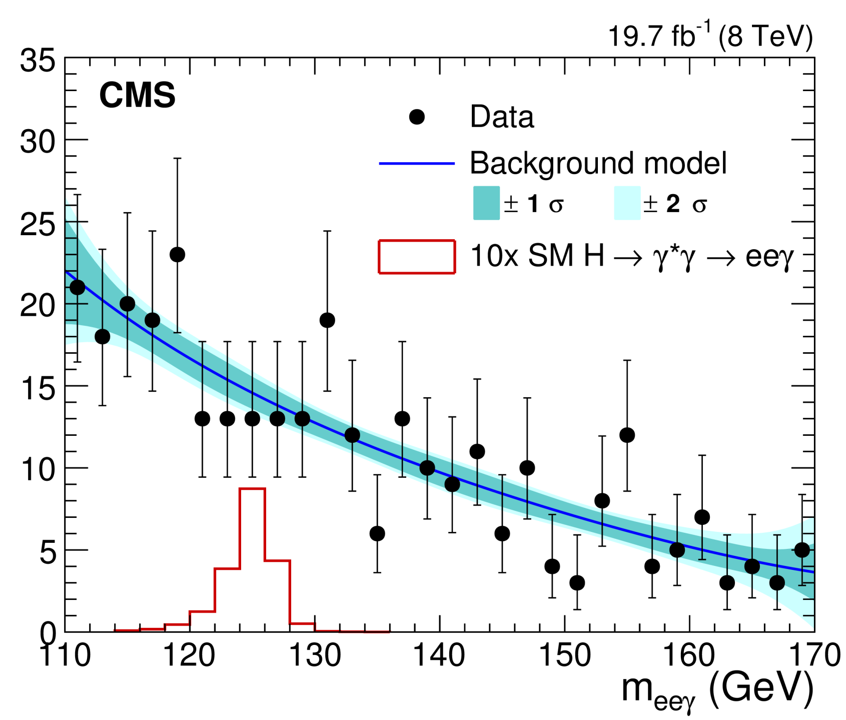
Sample	Signal events before selection $m_H = 125$ GeV	Signal events after selection $m_H = 125$ GeV	Number of events in data $120 < m_{\ell\ell\gamma} < 130$ GeV
$\mu\mu\gamma$	13.9	3.3	151
$ee\gamma$	25.8	1.9	65
$(J/\psi \to \mu\mu)\gamma$	$0.065(J/\psi) + 0.32$ (non-res.)	$0.014(J/\psi) + 0.078$ (non-res.)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

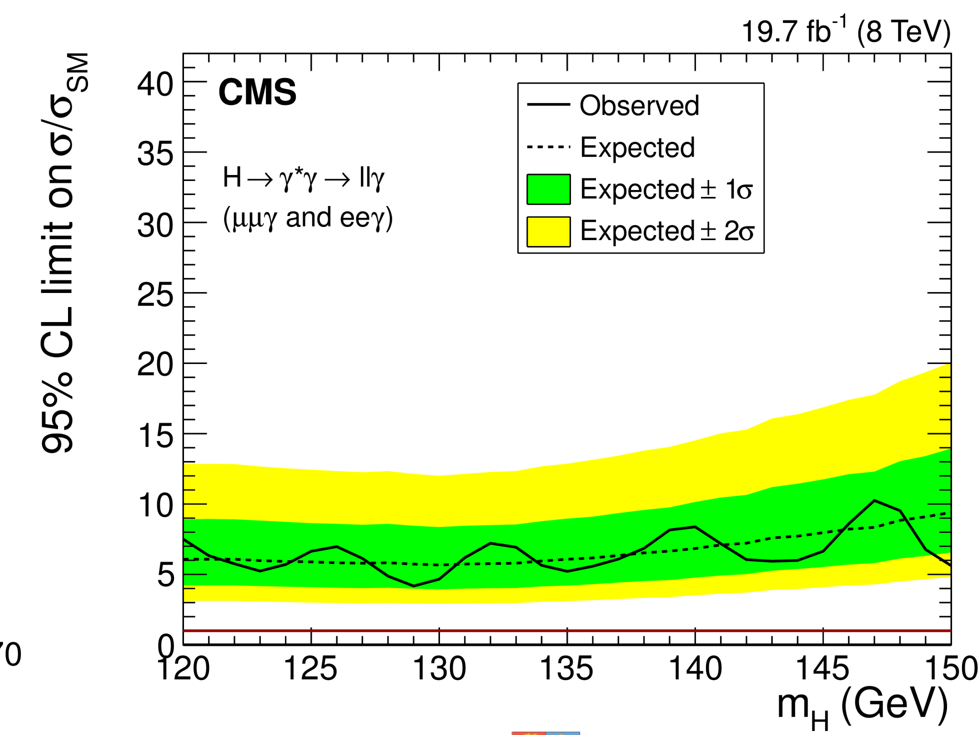


Phys.Lett. B753 (2016) 341



Phys.Lett. B753 (2016) 341





Charm Tagging

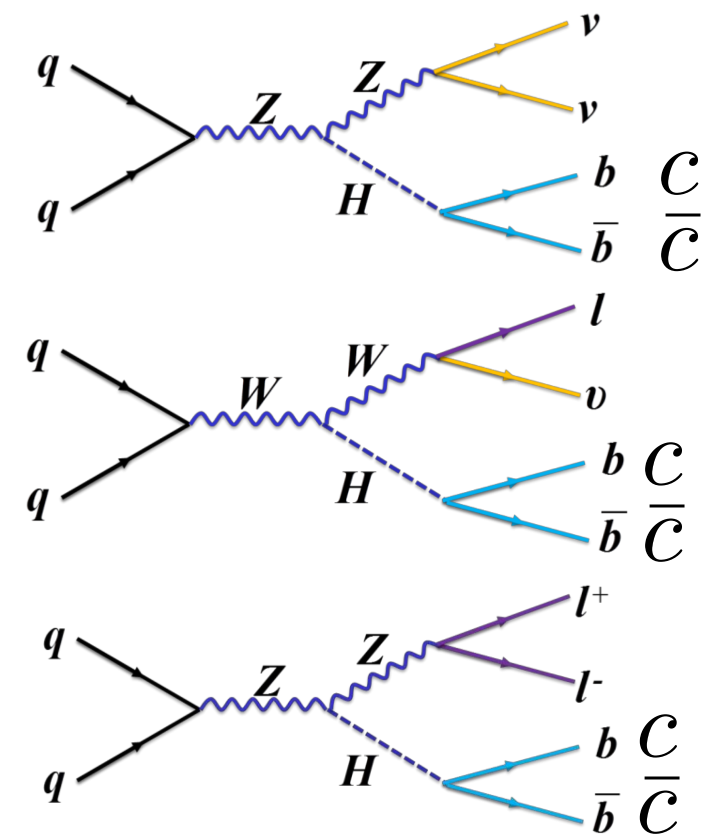
One may “re-interpret” the h→bbbar search for anomalous h→ccbar production

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

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

→ Constrains only a linear combination of μ_b and μ_c

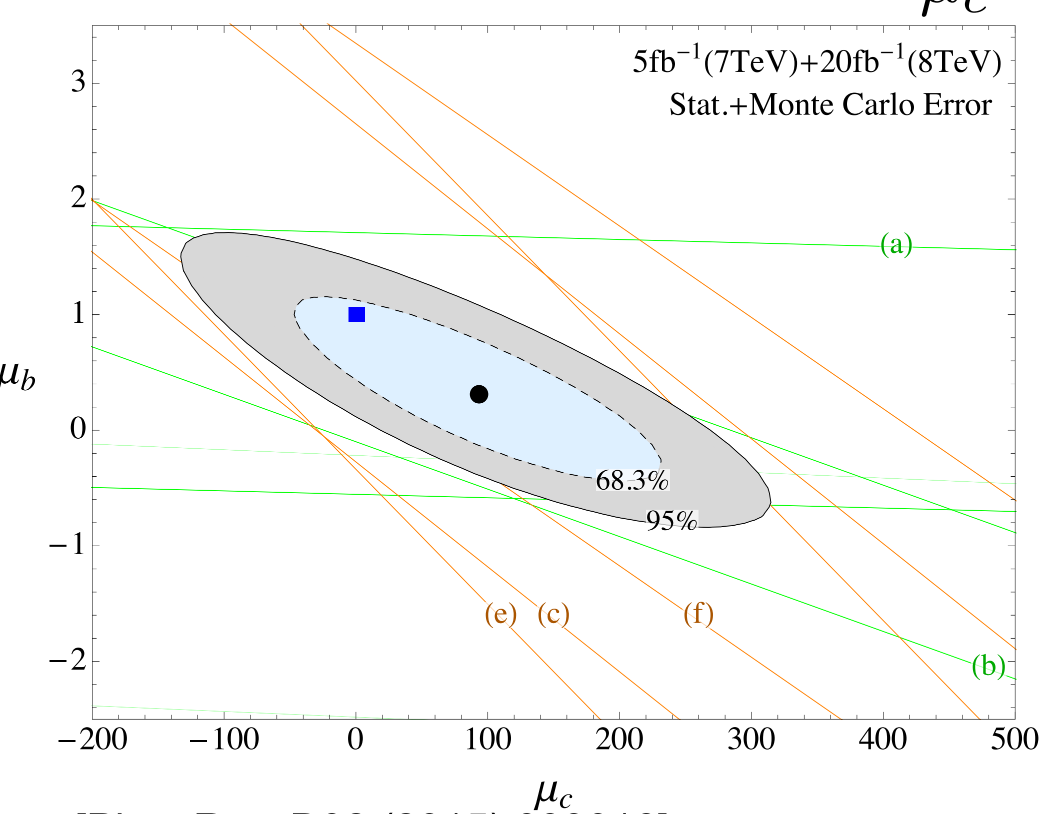
→ Need multiple b-tagging points



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

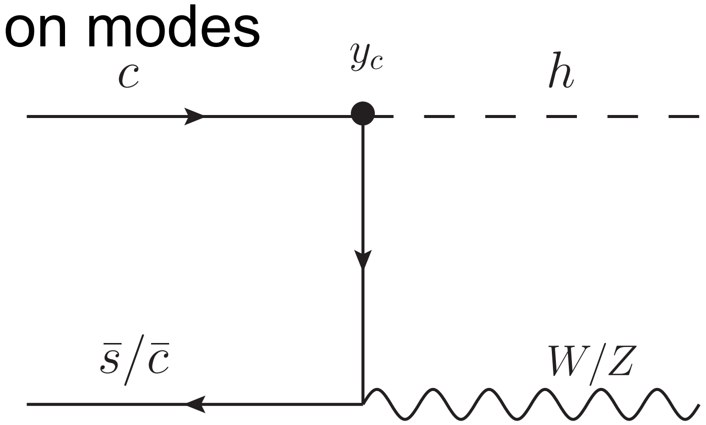
$$= \mu_b + \frac{\mathrm{BR}^{\mathrm{SM}}_{c\bar c}}{\mathrm{BR}^{\mathrm{SM}}_{b\bar b}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\;\mu_c\,,$$

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



[Phys.Rev. D92 (2015) 033016]

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



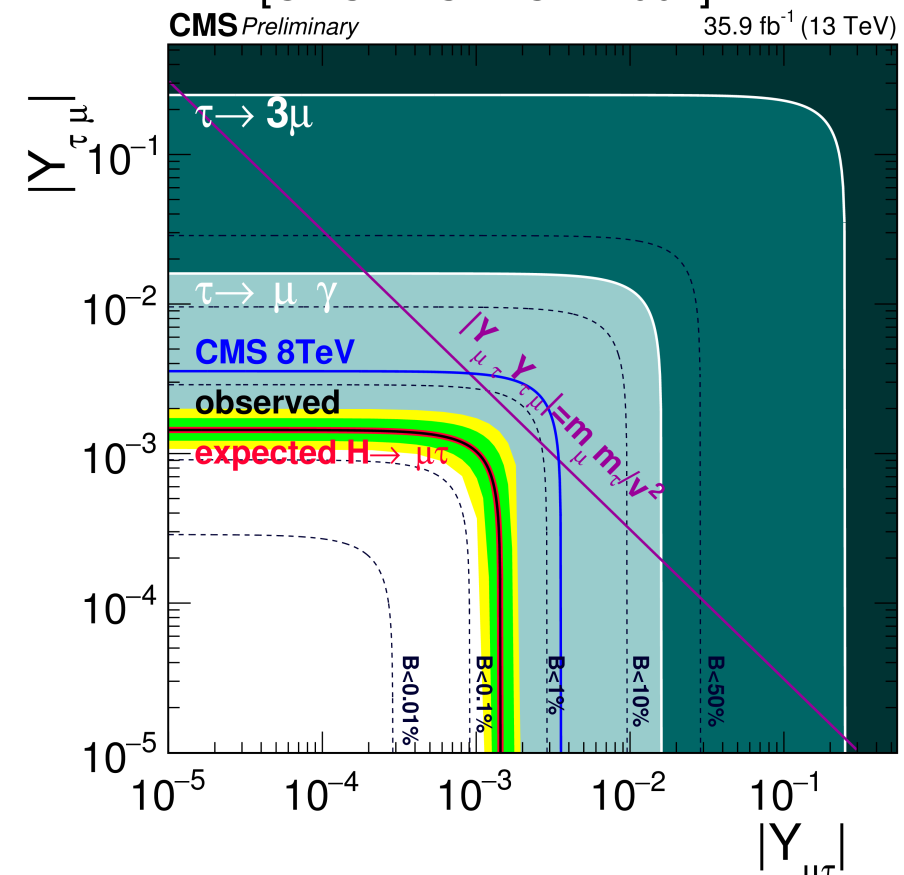
$$\kappa_c \lesssim 234 \text{ at } 95\% \text{ CL}\,,$$

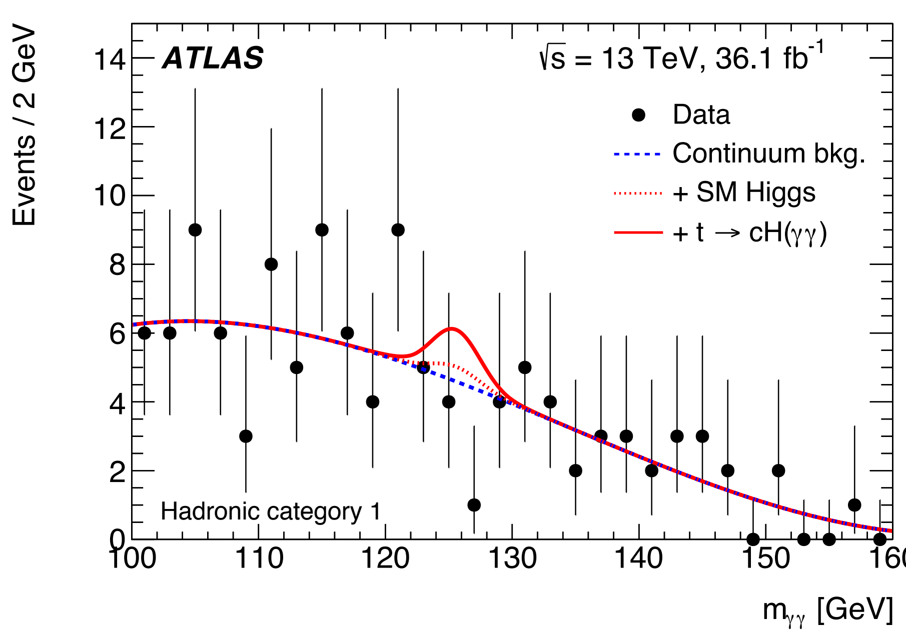
→ No detailed experimental analysis performed yet!

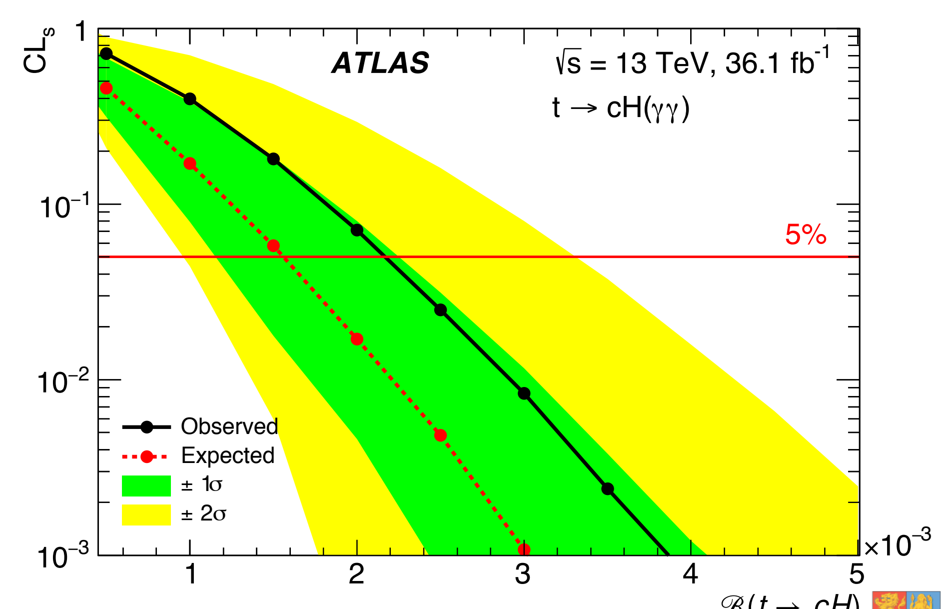
Quark/Lepton Flavour Violation

- Indirect constraints from low-energy data; certain transitions still loosely constrained[JHEP 03 (2013) 026; Phys.Lett. B712 (2012) 386]
- QFV: constraints from flavour physics
- LFV: constraints from μ→eγ, τ→μ/eγ, μ/e g-2, EDM
  - BR(H→eμ)<10^{-8}; BR(H→eτ)≲10%; BR(H→μτ)≲10%
- LFV CMS Run 2 95% CL upper limit with 35.9 fb^{-1}
  - BR(h→μτ)<0.25% (0.25%)
  - BR(h→eτ)<0.61% (0.37%)
- QFV ATLAS Run 2 95% CL upper limit with 36.1 fb^{-1}
  - in ttbar events looking for t→qh
  - hadronic and leptonic decays of the W boson used
  - BR(h→ch)<0.22% (0.16%)
  - BR(h→uh)<0.24% (0.17%)
  - t→uh acceptance ~8% lower than t→ch due to additional b-tagging efficiency provided by the c-quark versus the u-quark

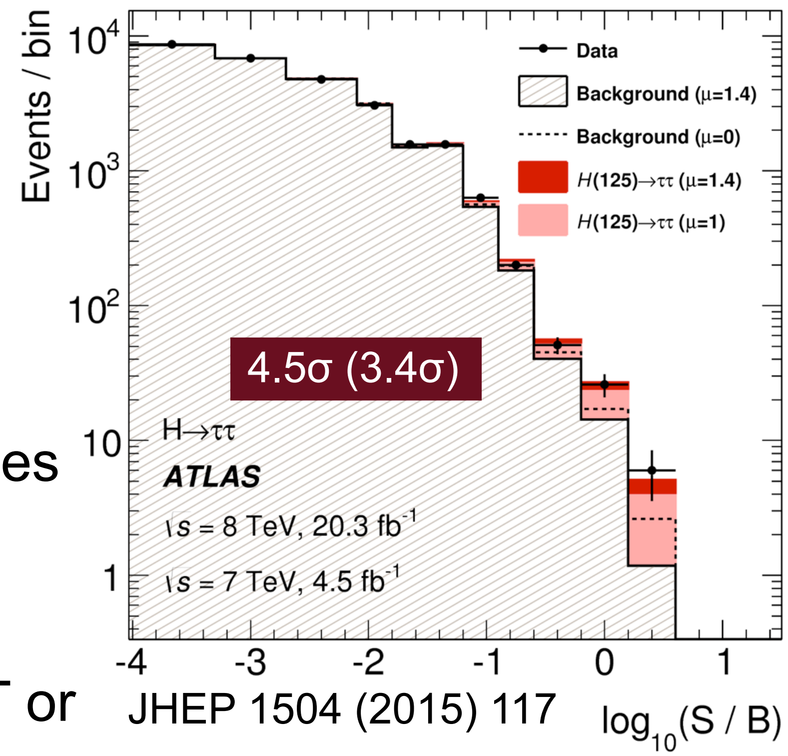
[CMS-PAS-HIG-17-001]



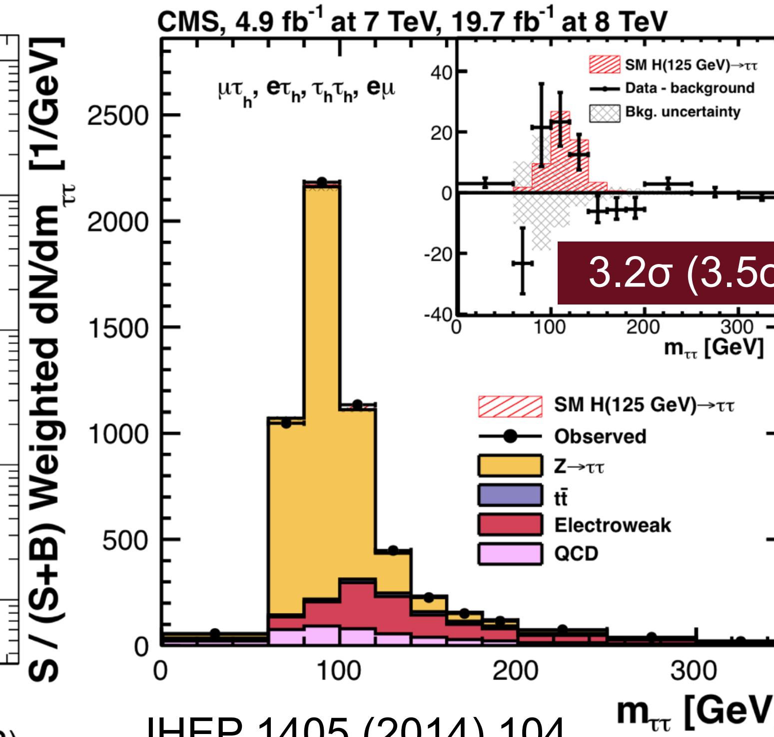




- Higgs boson-fermion coupling
  - first direct evidence
- Backgrounds
  - Z → ττ dominant [embedding]
  - “Fakes”: Multijet, W+jets, top [data-driven]
  - “Other”: Dibosons/H->WW* [MC]
- Sensitivity mostly VBF and boosted topologies
  - Sub-channels: τlepτlep, τlepτhad, τhadτhad
  - Catergories based on event topology
  - Multivariate techniques used either as BDT or multi-dimensional fits

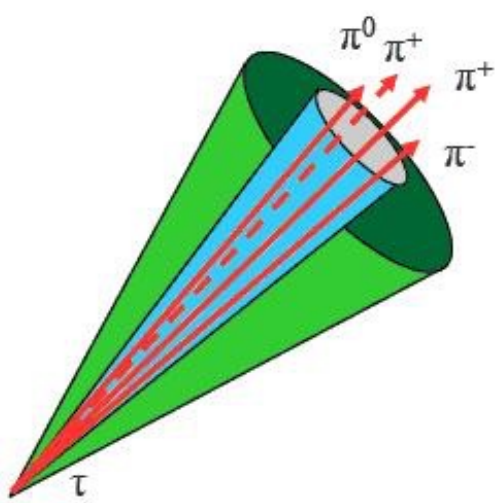


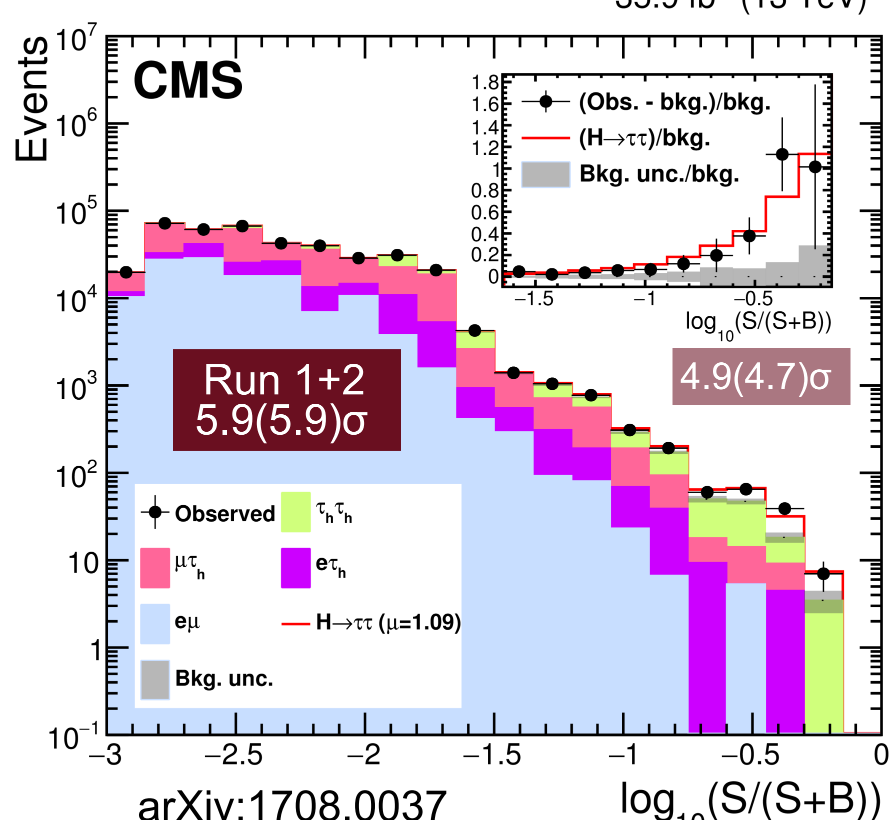
JHEP 1504 (2015) 117



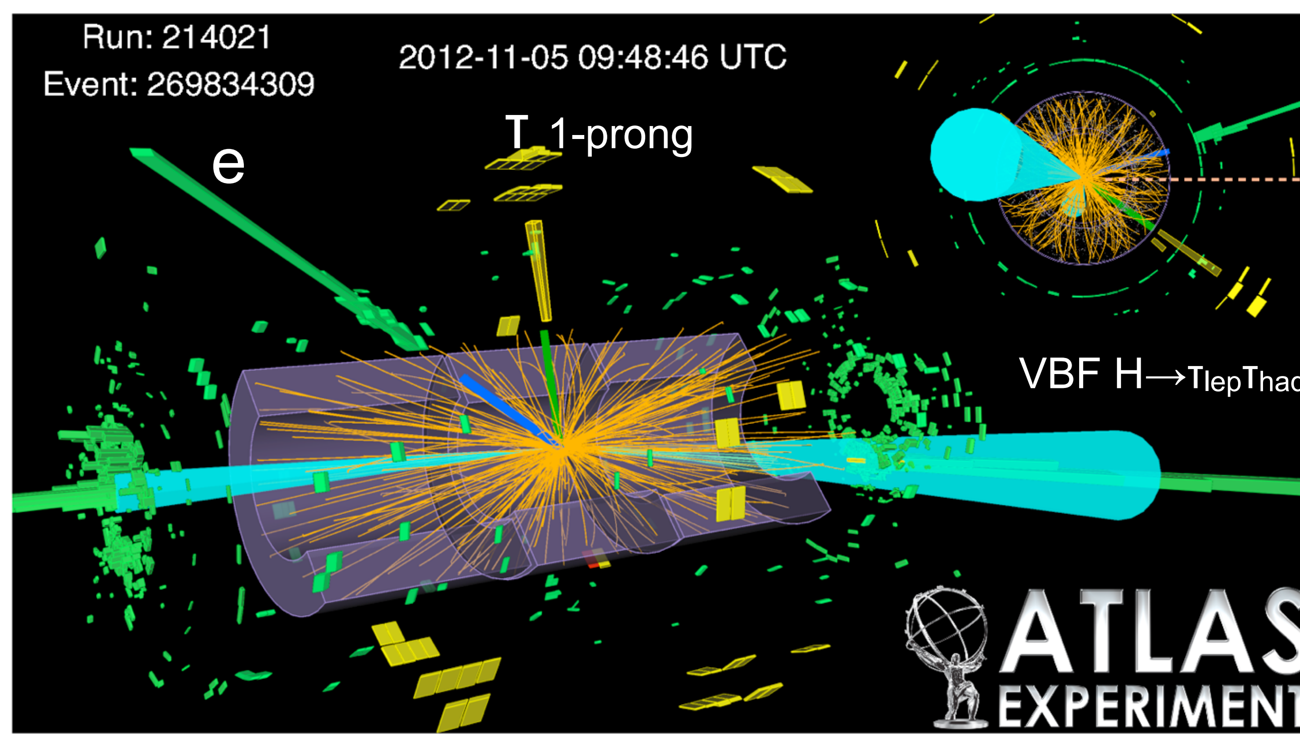
JHEP 1405 (2014) 104

- Run 1 ATLAS+CMS Combination: 5.5σ (5.0σ exp)





arXiv:1708.0037

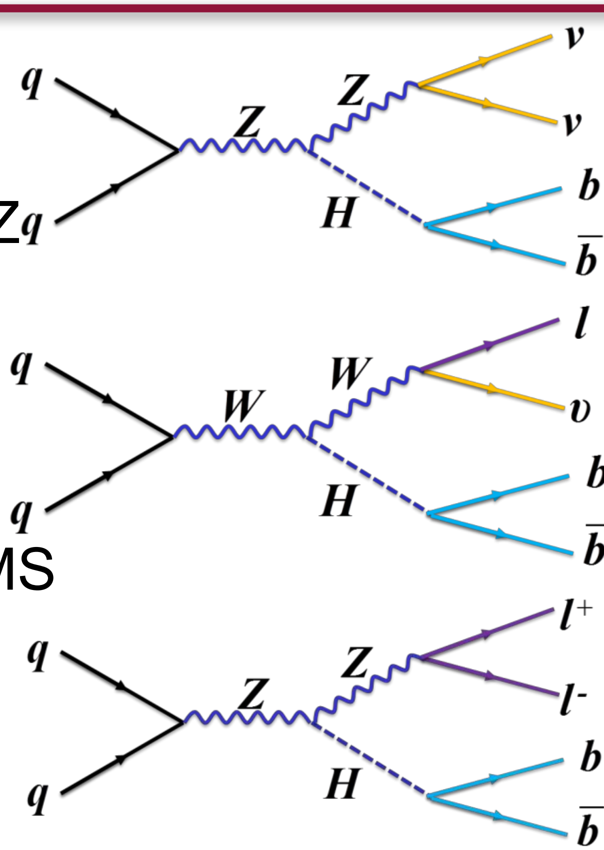


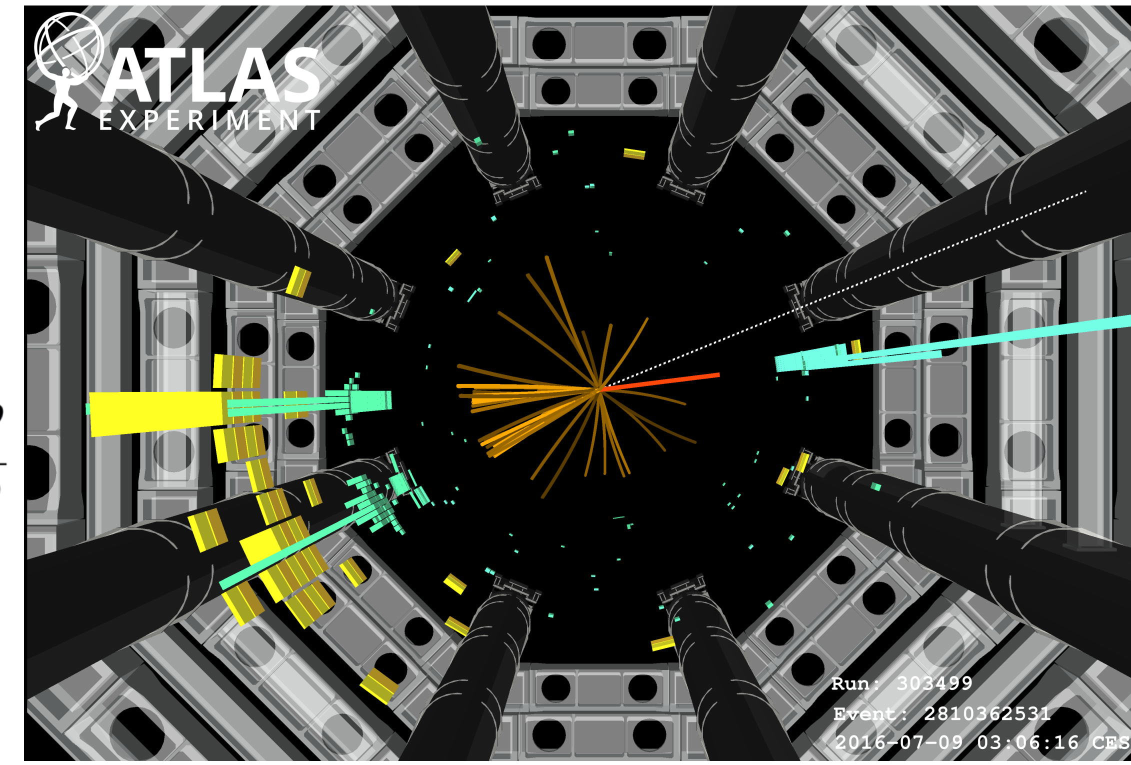
epT = 56 GeV, τhad pT = 27 GeV, MET=113 GeV, mj1,j2=1.53 TeV, mττ^{MMC}=129 GeV, BDT score = 0.99. S/B ratio of this bin 1.0

h→bb

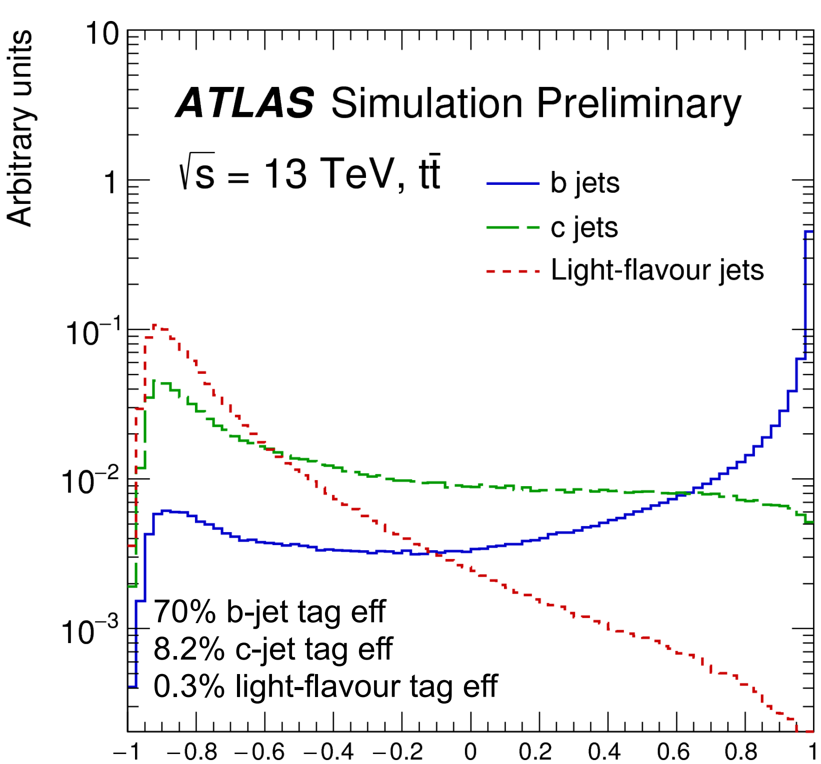
- Largest BR (58%@m_H=125 GeV)
  - large QCD background
- Use associated production with W/Z
  - complex final states
  - b-tagging crucial
- Backgrounds: W/Z+jets and top
- Final discriminant: BDT_{VH}
- Evidence from both ATLAS and CMS

m_H= 125 GeV	Significance	$\mu=\sigma/\sigma_{SM}$
ATLAS	3.6σ (4.0σ)	$0.90^{+0.28}_{-0.26}$
CMS	3.8σ (3.8σ)	$1.06^{+0.31}_{-0.29}$

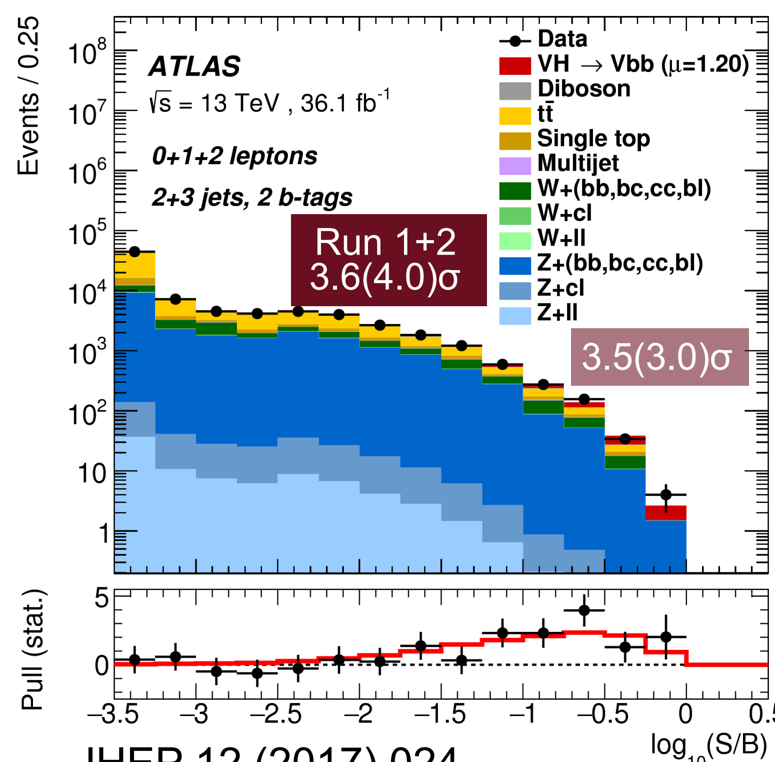




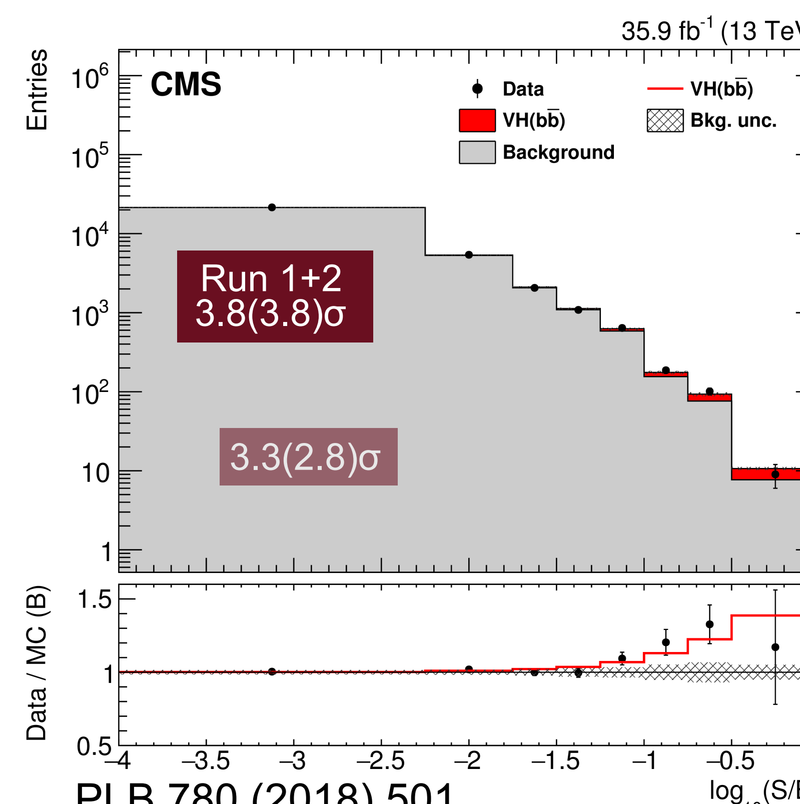
2b-tags, MET=320GeV, P_{Te}=151GeV, p_{TV}=450GeV, m_{bb}=124GeV



ATL-PHYS-PUB-2016-012

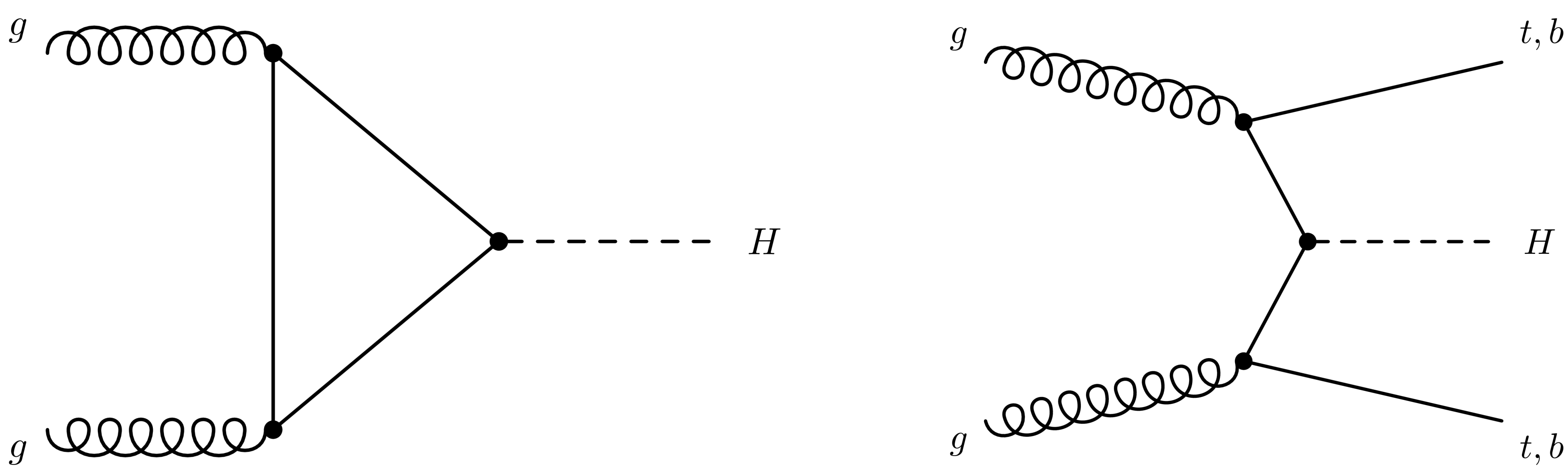


JHEP 12 (2017) 024



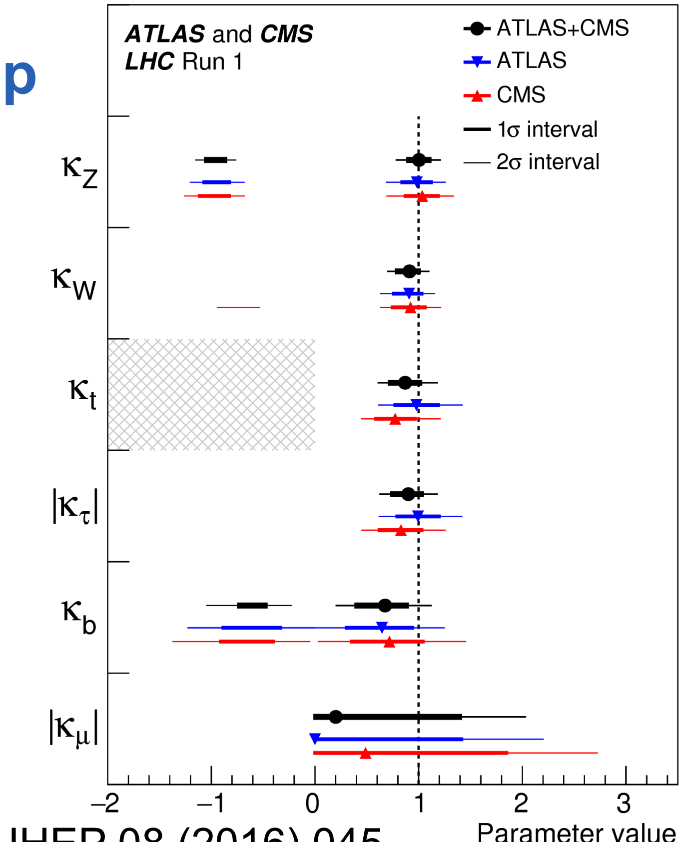
PLB 780 (2018) 501

top quark



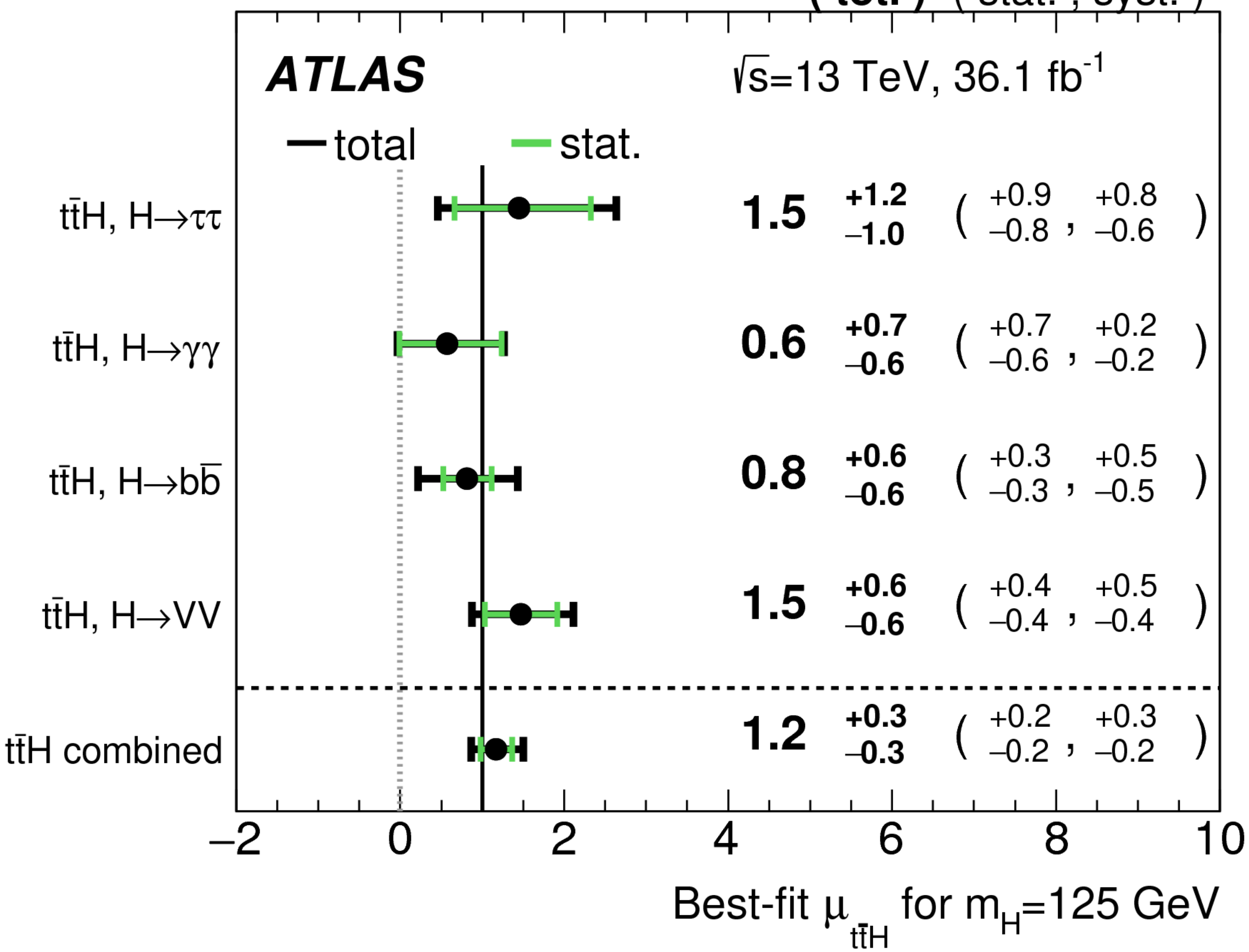
[JHEP 08 (2016) 045]

- **ggF Higgs boson production proceeds mostly through top-quark loop**
  - one can resolve the loops, assuming only SM contributions
  - new physics may appear in the loop
- **ttH production**: direct information on Higgs boson coupling to top-quark
  - Combination of several Higgs boson decay modes
    - h→bb, h→multi-leptons (WW,ττ), h→γγ, h→ZZ→4l
- Complex final states with large number of objects
  - jets, b-jets, light and τ leptons, photons
  - multivariate techniques used extensively
- Run 1 ATLAS+CMS Combination: 4.4σ (2.0σ exp)
- Run 2 evidence for ttH production by ATLAS and CMS

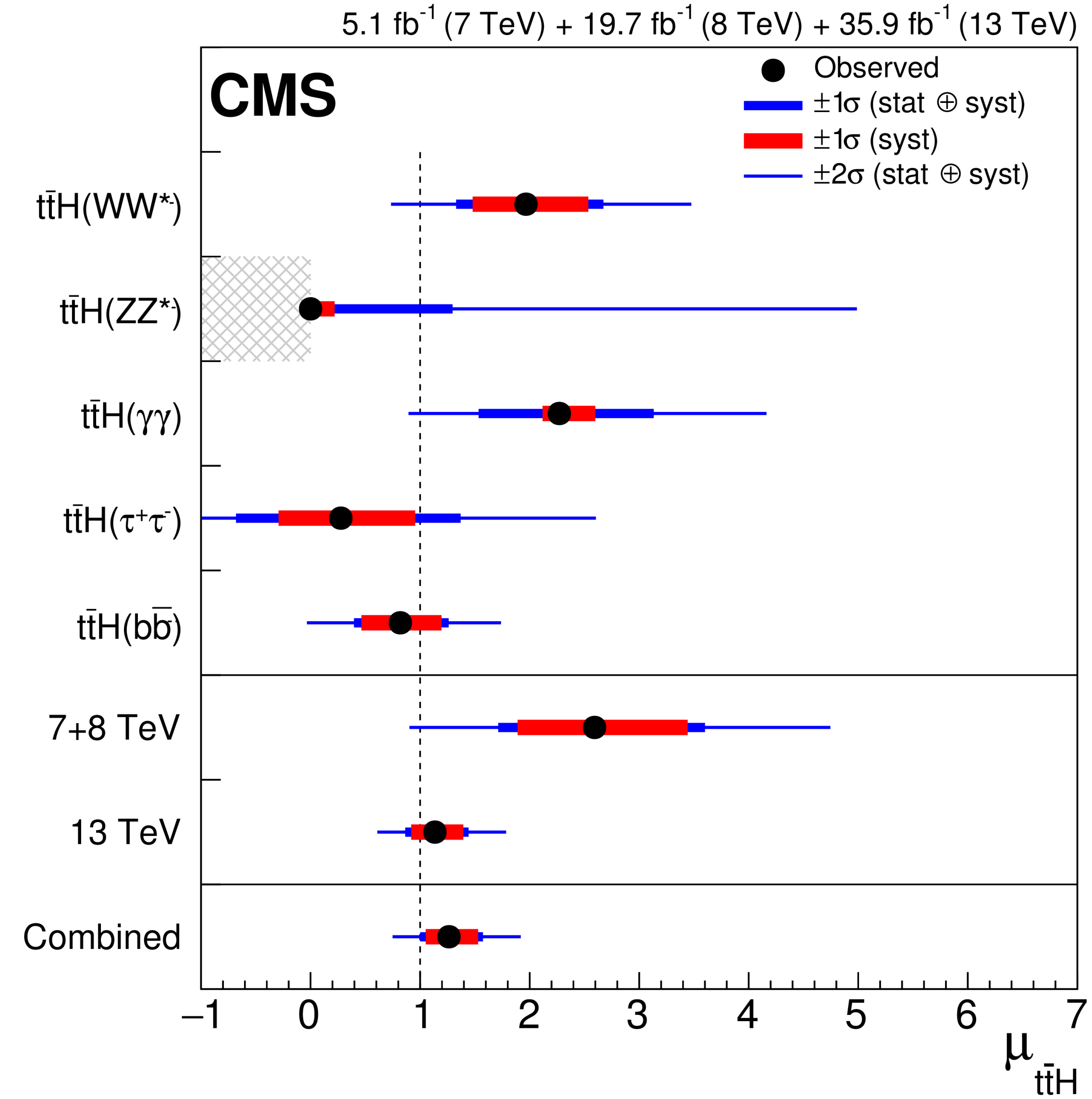


JHEP 08 (2016) 045

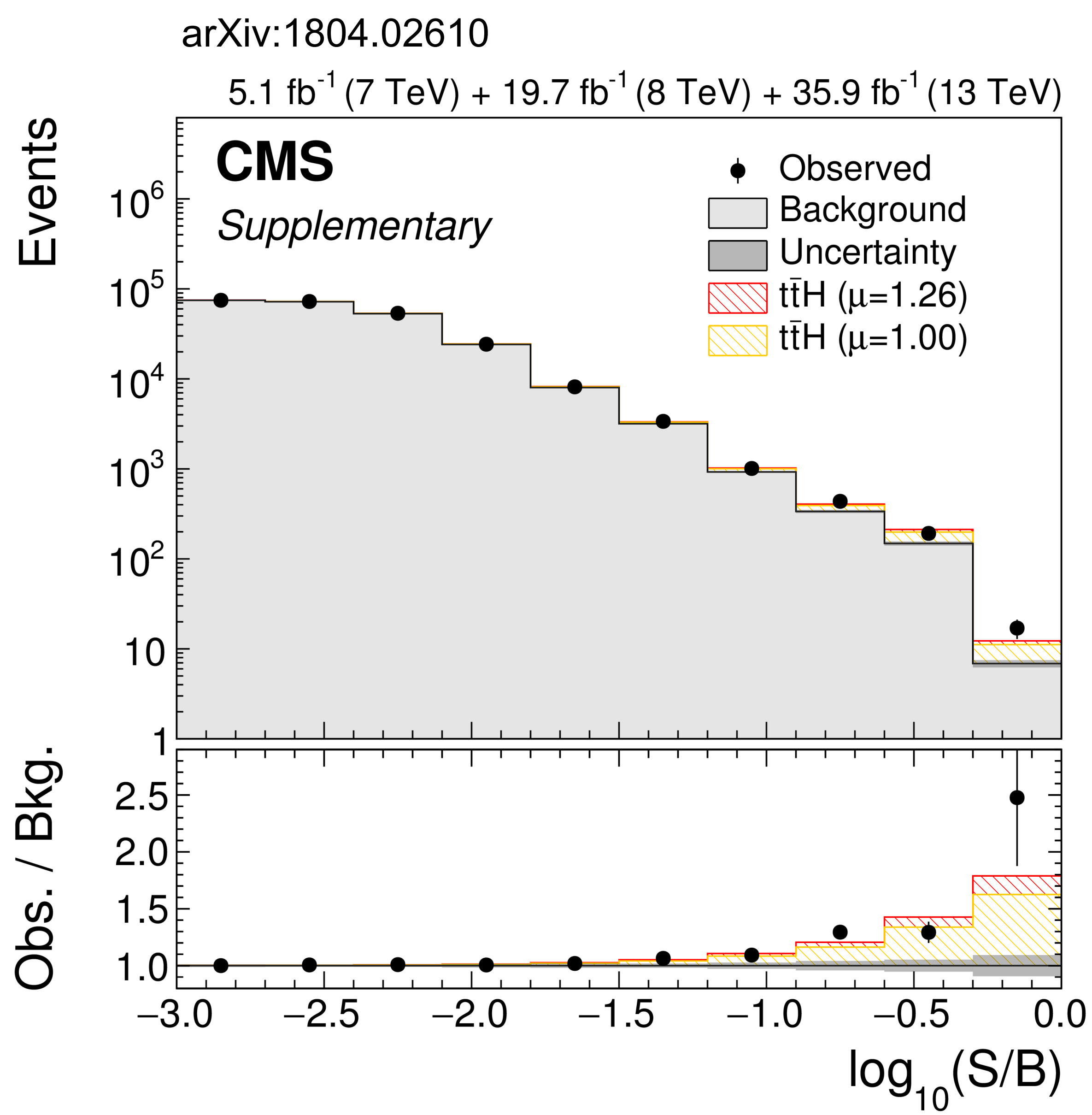
Phys. Rev. D 97 (2018) 072003



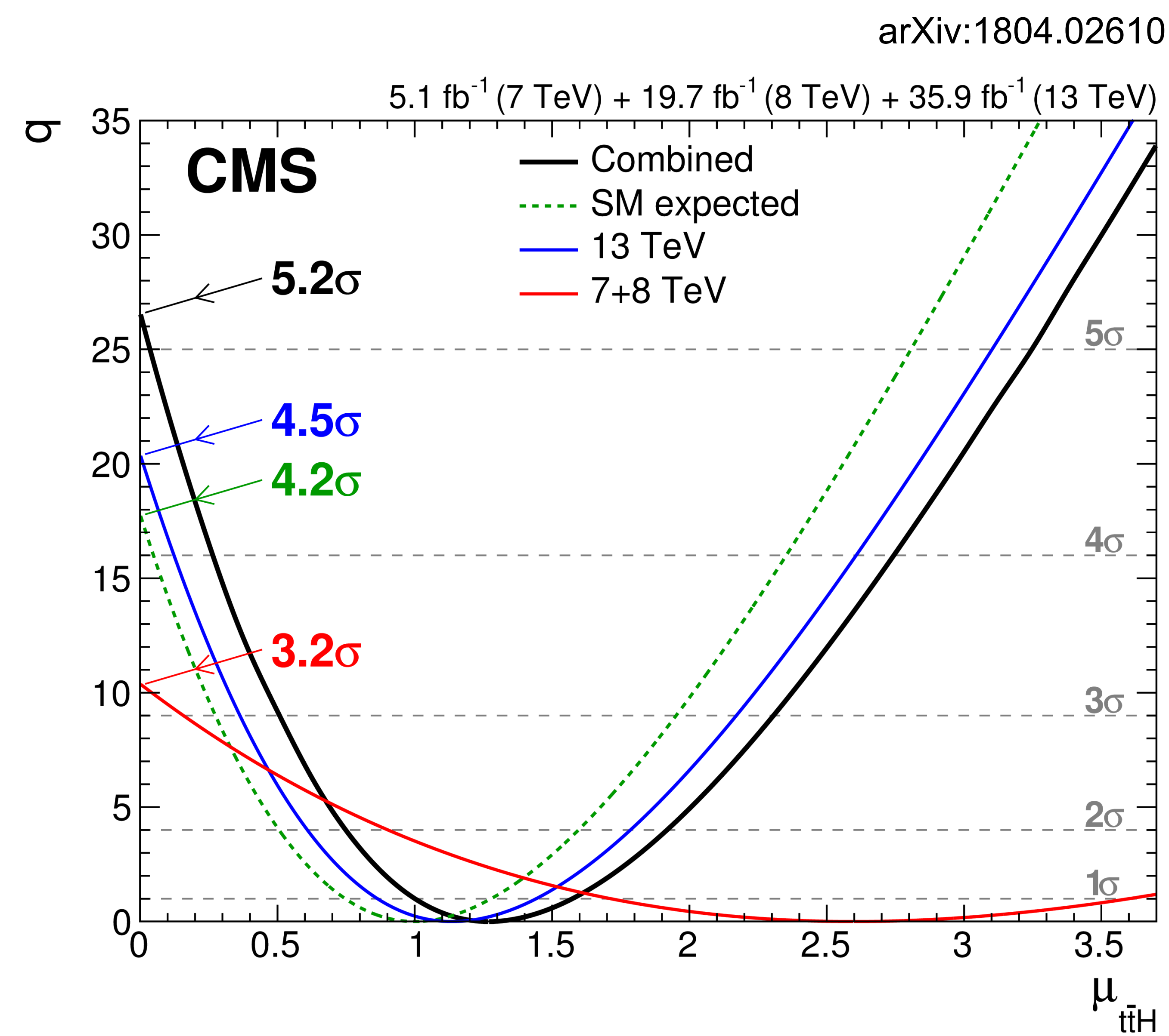
arXiv:1804.02610



top quark



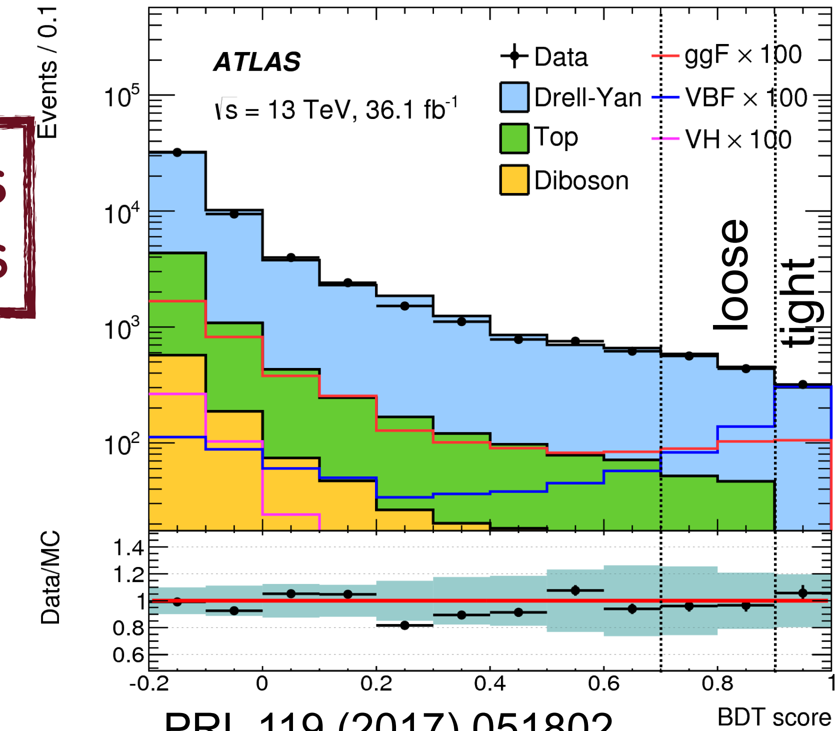
arXiv:1804.02610
5.1 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV) + 35.9 fb-1 (13 TeV)
CMS
Supplementary
Observed
Background
Uncertainty
tt̄H (μ=1.26)
tt̄H (μ=1.00)
Events
Obs. / Bkg.
log10(S/B)



arXiv:1804.02610
5.1 fb-1 (7 TeV) + 19.7 fb-1 (8 TeV) + 35.9 fb-1 (13 TeV)
CMS
Combined
SM expected
13 TeV
7+8 TeV
5.2σ
4.5σ
4.2σ
3.2σ
5σ
4σ
3σ
2σ
1σ
q
μ tt̄H

- h→μμ best available probe for second generation fermions
  - $BR_{SM} \sim 2 \cdot 10^{-4}$(125GeV)
  - simple final state
  - S/B ~0.1-0.4%
- backgrounds: $Z/\gamma^* \to \mu\mu$, top, dibosons
- categorisation
  - 2x VBF (≥2jets+MVA)
    - main variables: m_{jj}, $pT_{\mu\mu}$, $\Delta\eta_{jj}$, ΔR_{jj}, …
  - 6x ggF categories based on pT and η
- Parametric background Model: BW⊗Gaus+Exp/m^3
- 95% CL upper limit @m_H=125 GeV:
  - ATLAS: 2.8 (2.9)xSM [Run 1+2]
  - CMS: 7.4 (6.5)xSM [Run 1]

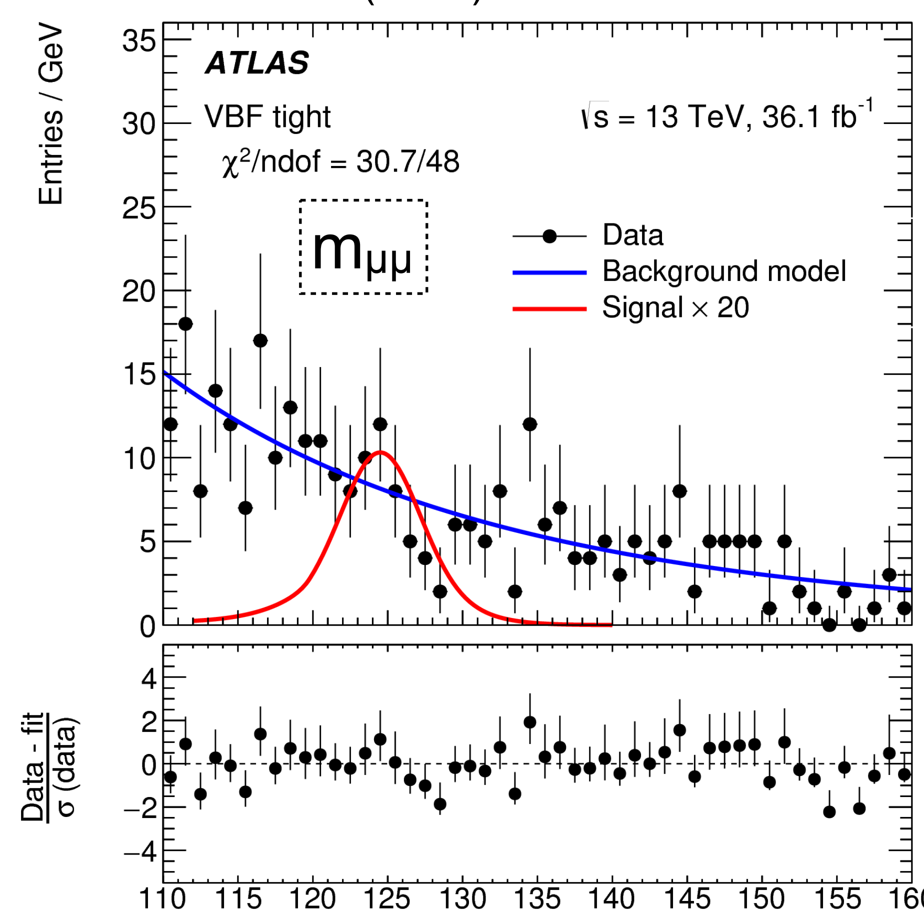
Run 1: non-universal Higgs boson coupling to fermions



PRL 119 (2017) 051802

	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

$pT_{\mu\mu}$<15 GeV, 15<$pT_{\mu\mu}$<50 GeV, $pT_{\mu\mu}$>50 GeV   PRL 119 (2017) 051802



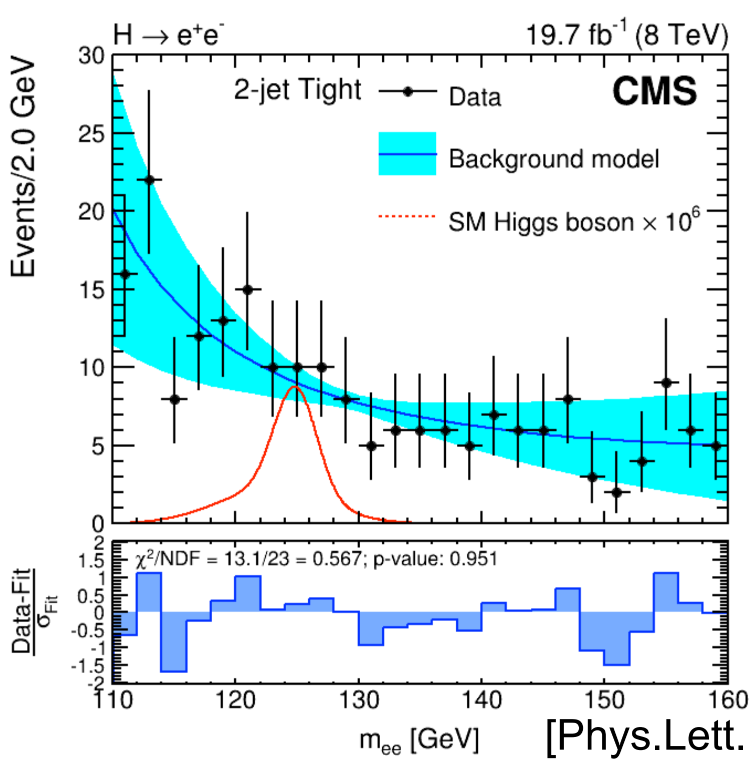
PRL 119 (2017) 051802

- **Closing in on h→μμ!**
  - Expected significance for Run 3 and HL-LHC
    - 2.3σ for 300 fb^{-1} and 7.0σ for 3000 fb^{-1}
    - Conservative extrapolation (no IBL, Run 1 analysis)
- Run 2 result shows improved sensitivity wrt extrapolation
- Evidence for h→μμ possible with Run 3
  - Even earlier with further improvements?
- HL-LHC will be needed for detailed studies

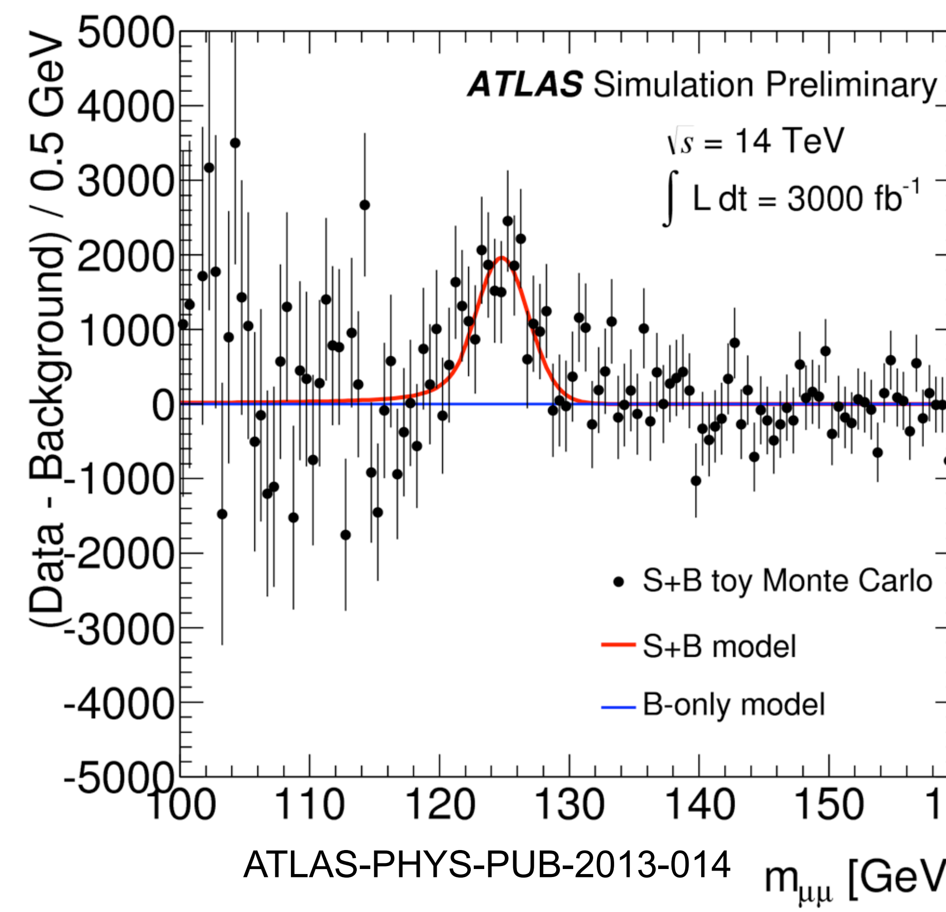
$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

ATLAS-PHYS-PUB-2013-014

- **h→ee**: extremely rare decay in SM
  - $BR_{SM}(h\to\mu\mu)/BR_{SM}(h\to ee) \sim 4\times10^4$
- CMS performed a search for h→μμ/ee with Run 1
  - 95% CL upper limit BR(h→ee)<$1.9\cdot10^{-3}$



[Phys.Lett. B744 (2015) 184]



ATLAS-PHYS-PUB-2013-014