Probing the Higgs Yukawa couplings at the Large Hadron Collider

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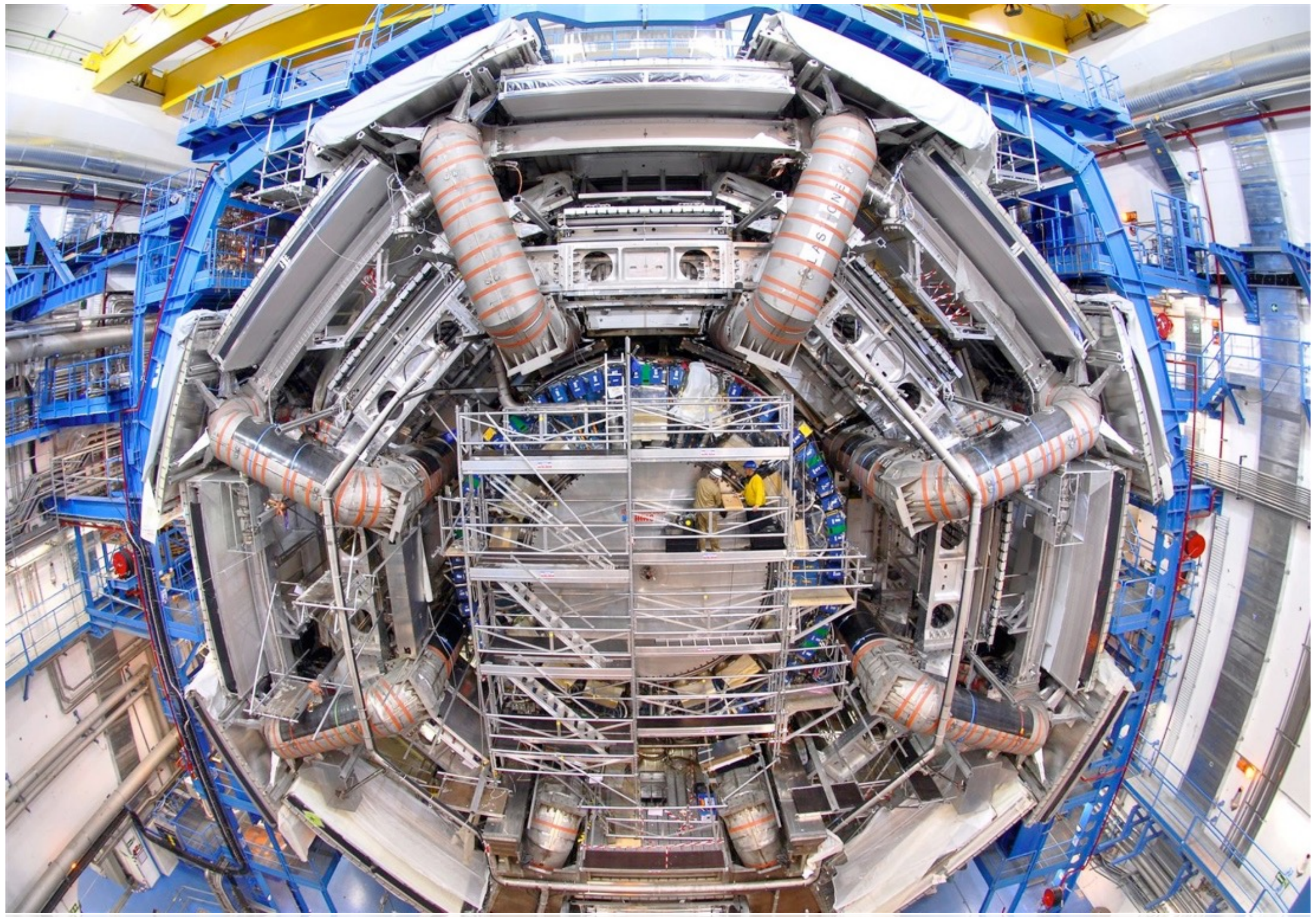
ATLAS experiment at CERN

European Research Council
Established by the European Commission

Particle Physics Seminar
September 13, 2018,
Brookhaven National Laboratory, Upton, USA

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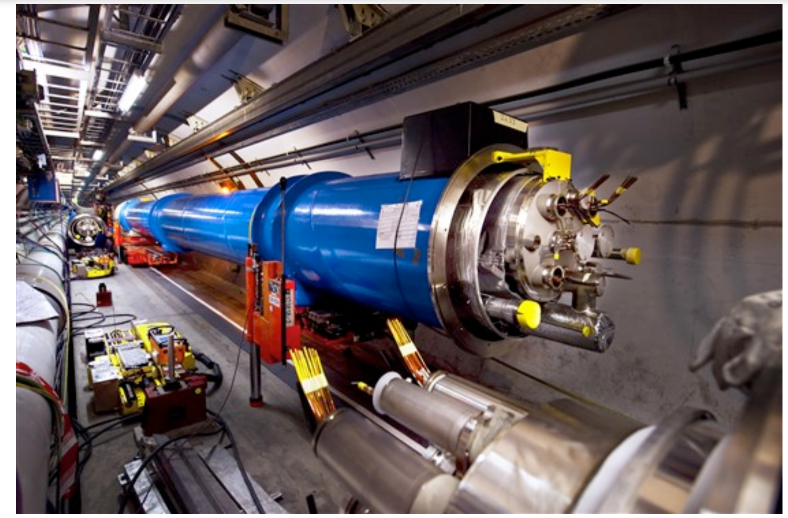
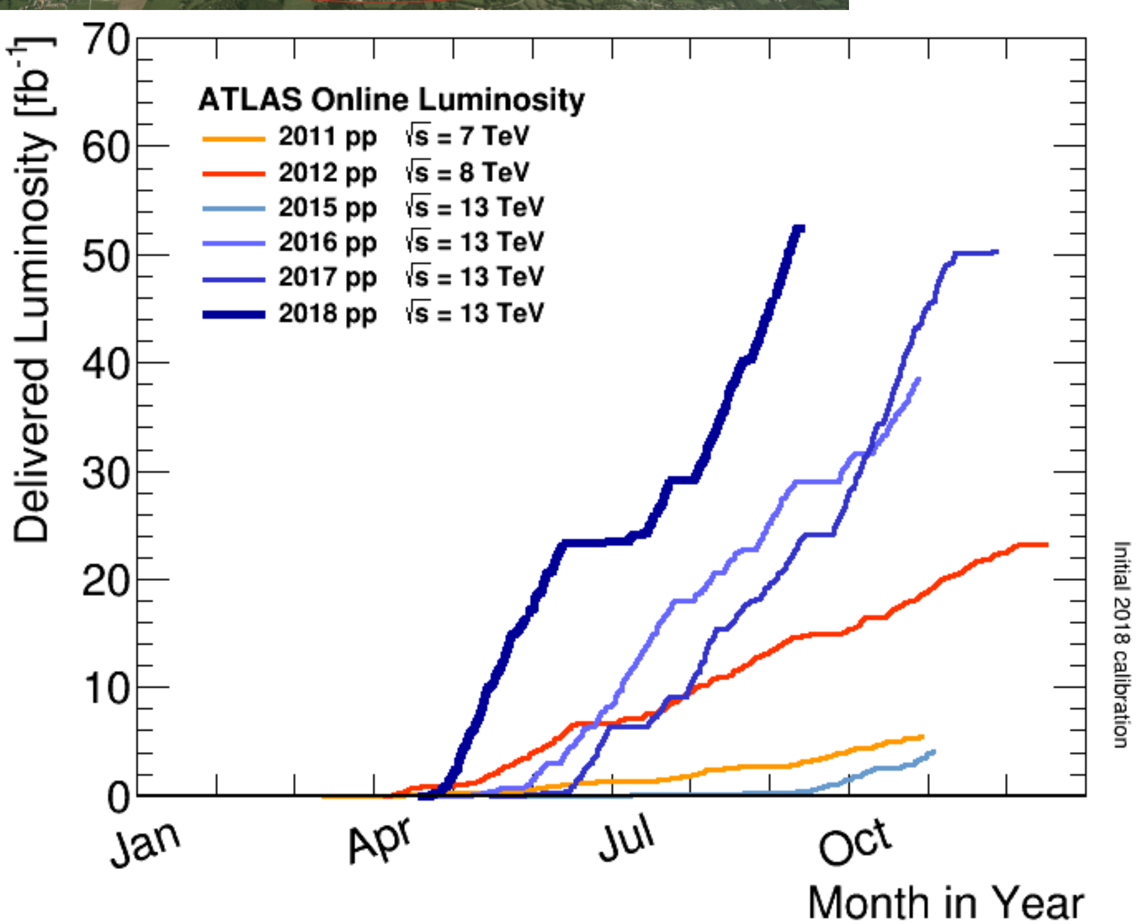
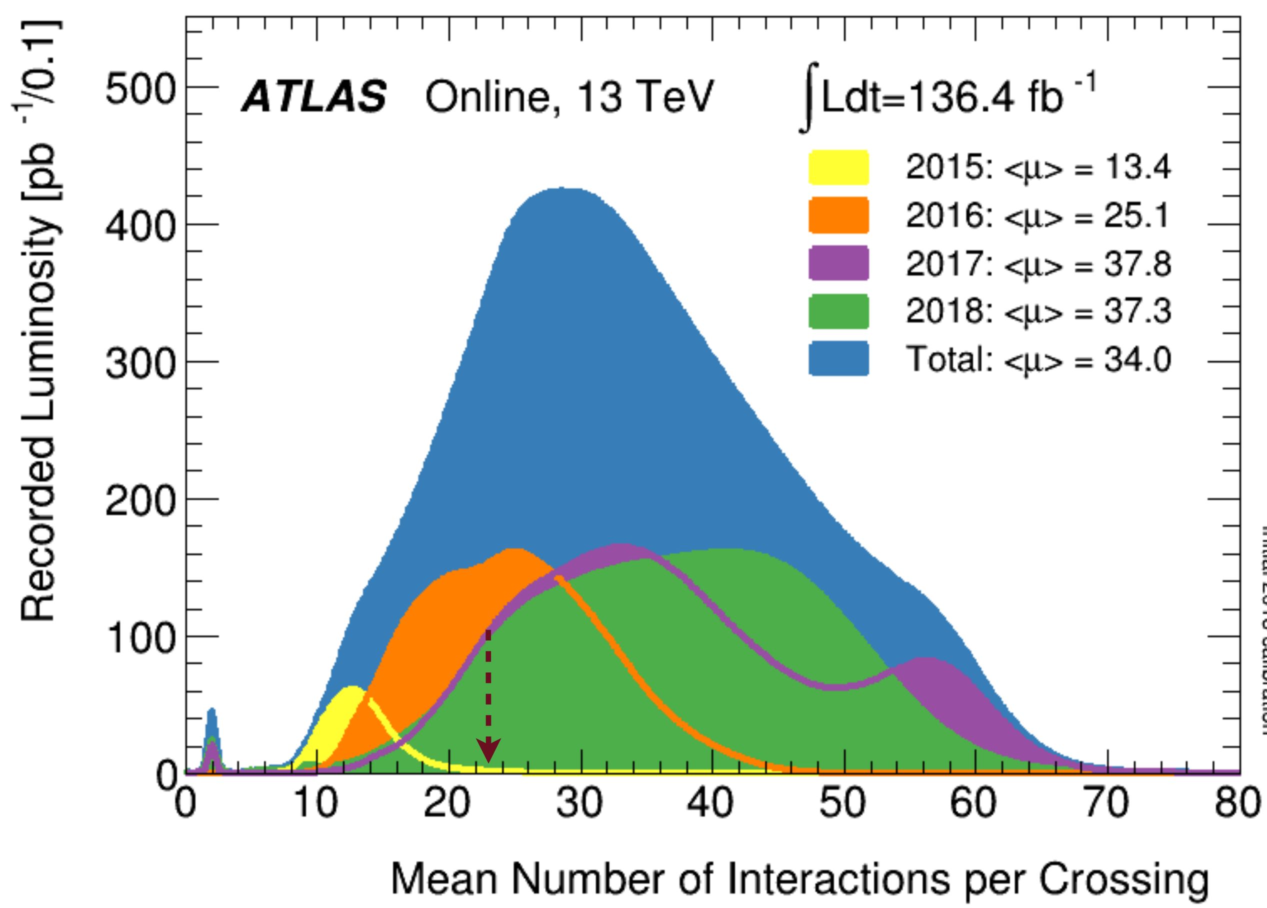
The Large Hadron Collider

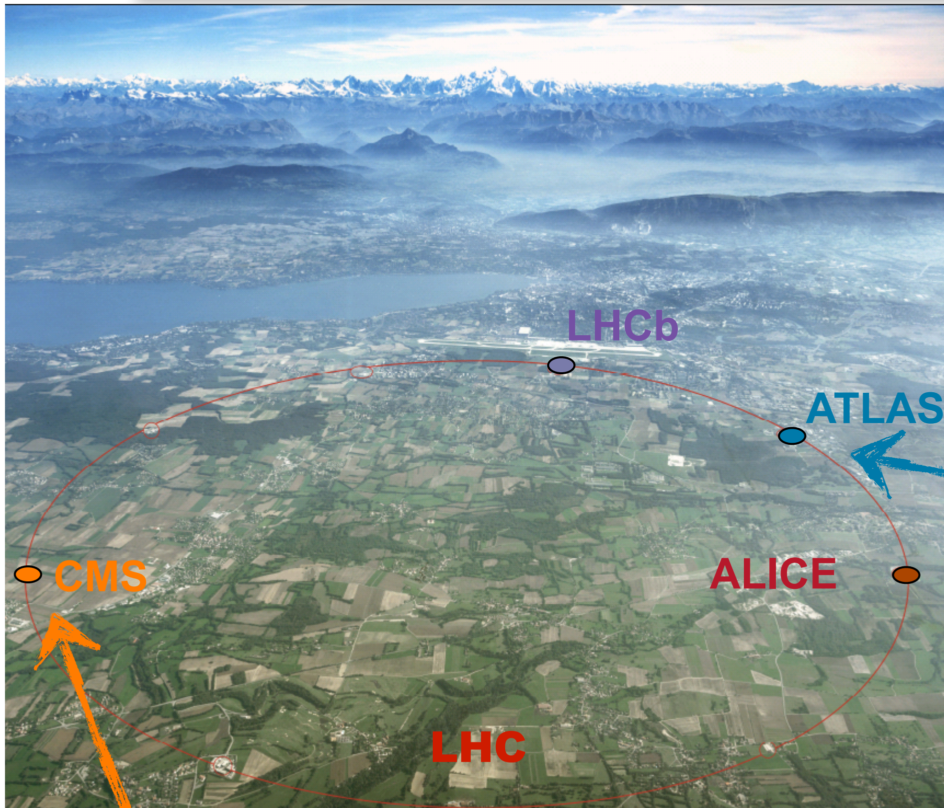


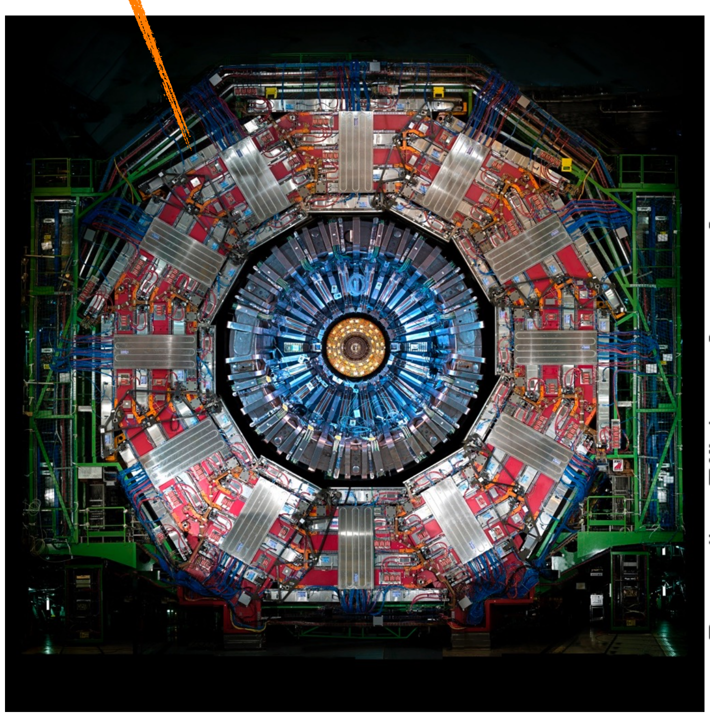
- Run 2 pp dataset at 13 TeV exceeds 130 fb^{-1}
- Inst. Luminosity “levelled” at 2×10^{34} $cm^{-2}s^{-1}$
- Operations and physics in high pile-up now routine

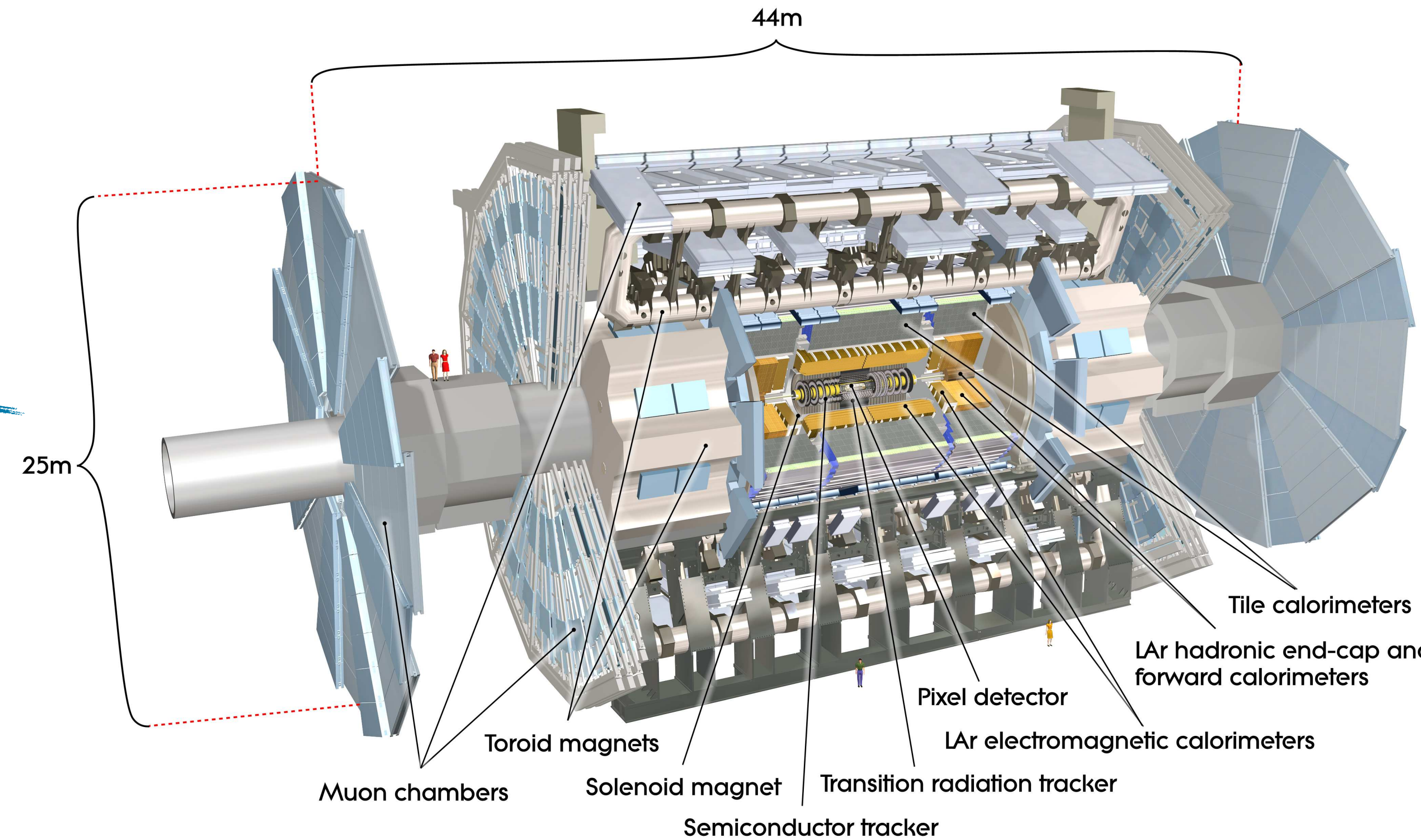


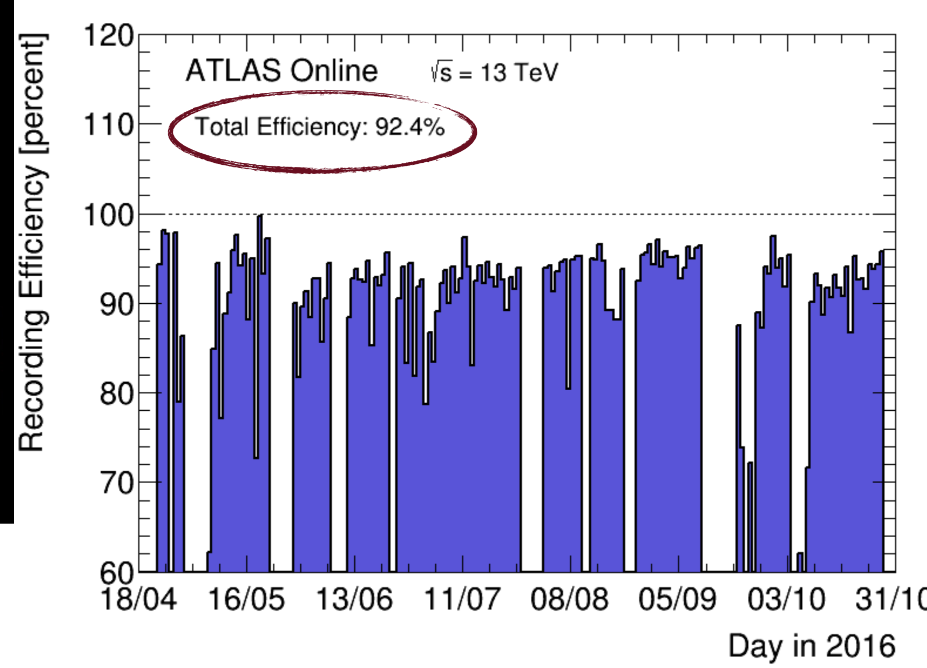


The LHC detectors







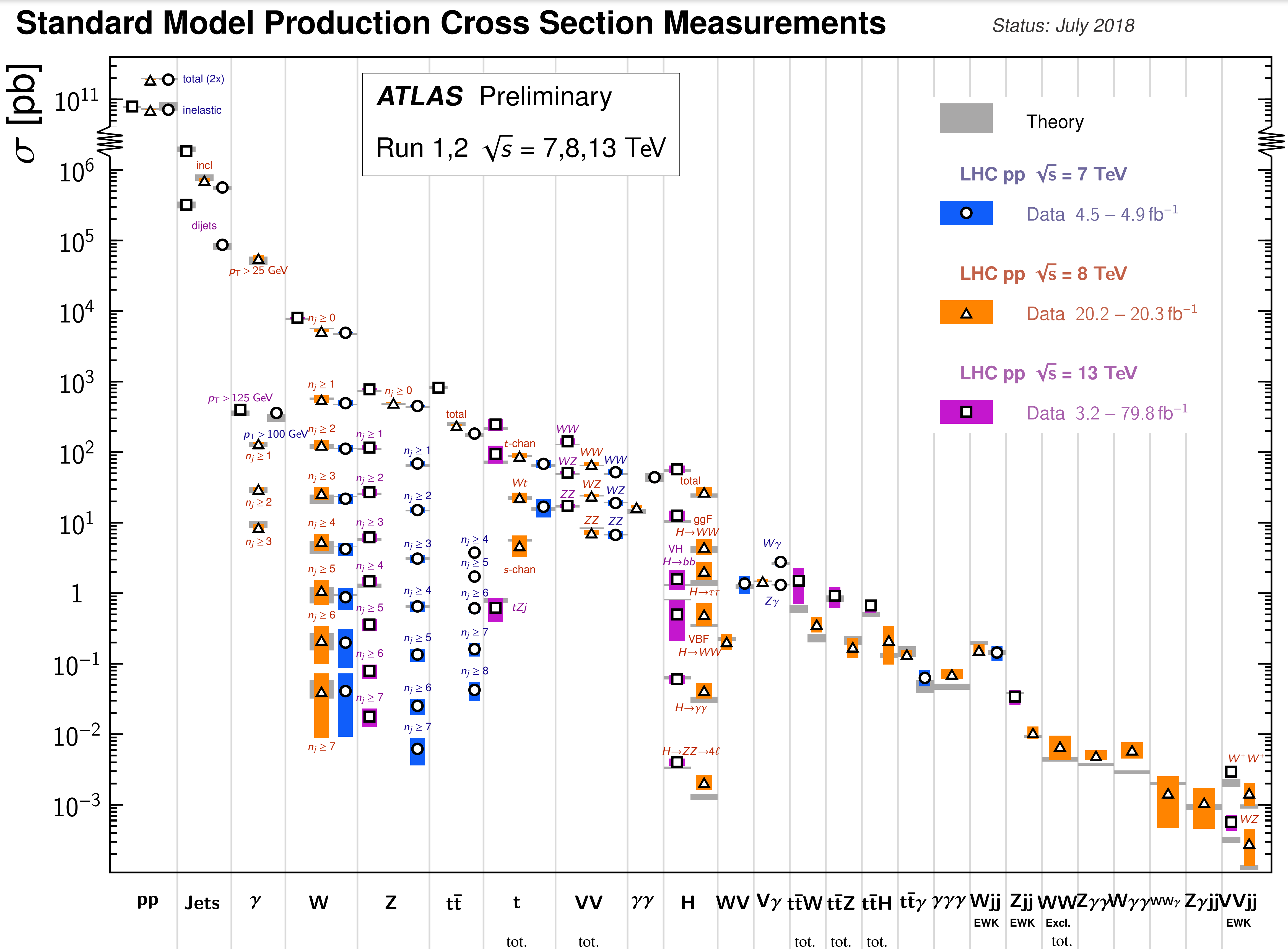


ATLAS pp 25ns run: April-October 2016

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})											

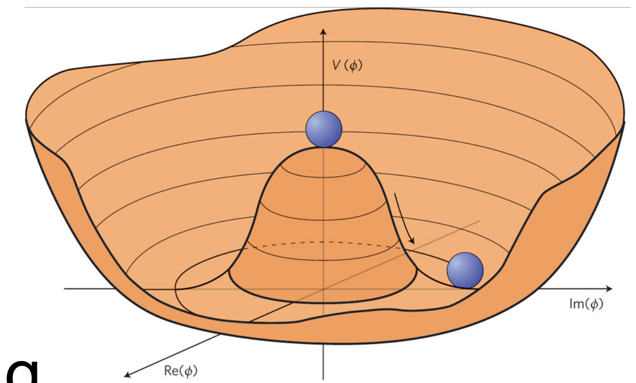
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between April-October 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The toroid magnet was off for some runs, leading to a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

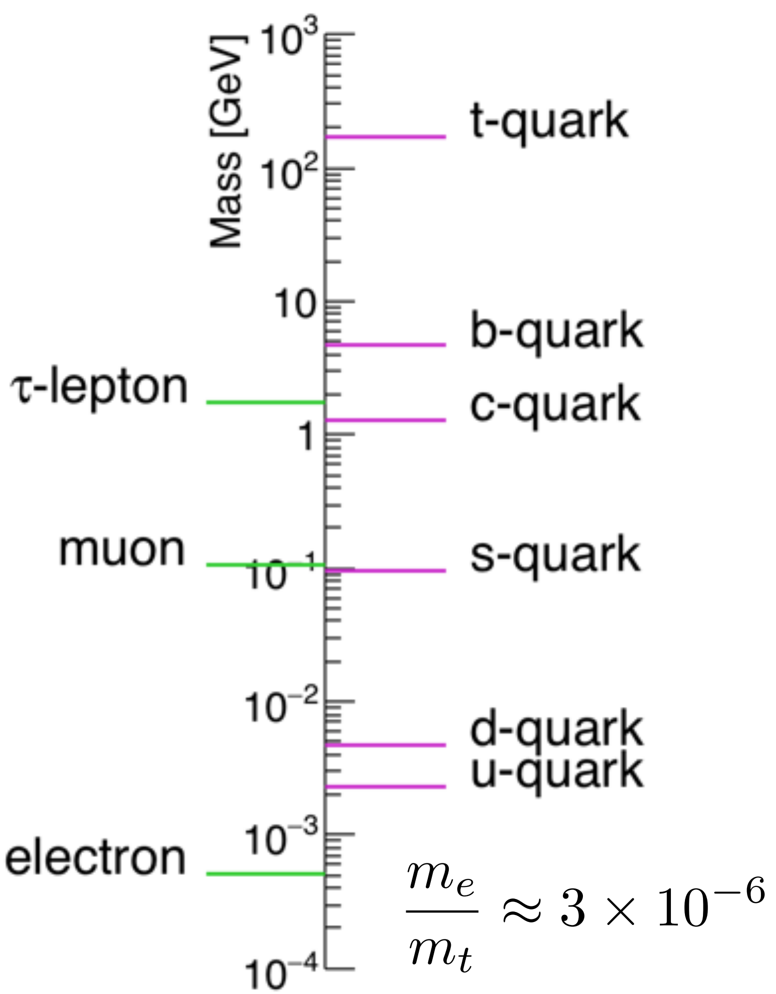
Snapshot of measurements

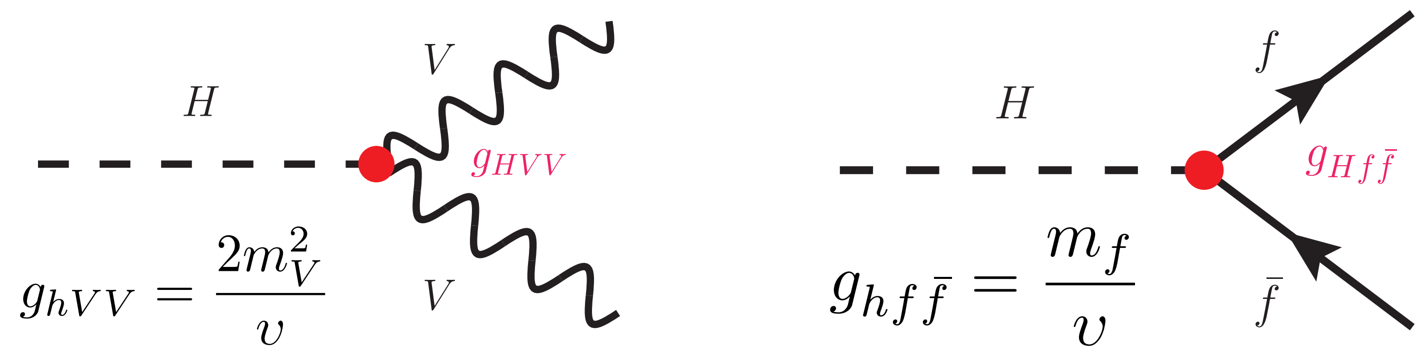


BEH mechanism and fermion masses

- $SU(2)_L \otimes U(1)_Y$ local gauge symmetry;
  EW unification; massless carriers
- Symmetry spontaneously broken; Higgs field acquires vev
  - 3 Higgs d.o.f become longitudinal polarisations of $W^{\pm}/Z$ bosons
  - 1 Higgs d.o.f becomes physical Higgs boson
- **Higgs interactions to vector boson:** defined by symmetry breaking
- **Higgs interactions to fermions:** ad-hoc hierarchical Yukawa couplings $\propto m_f$







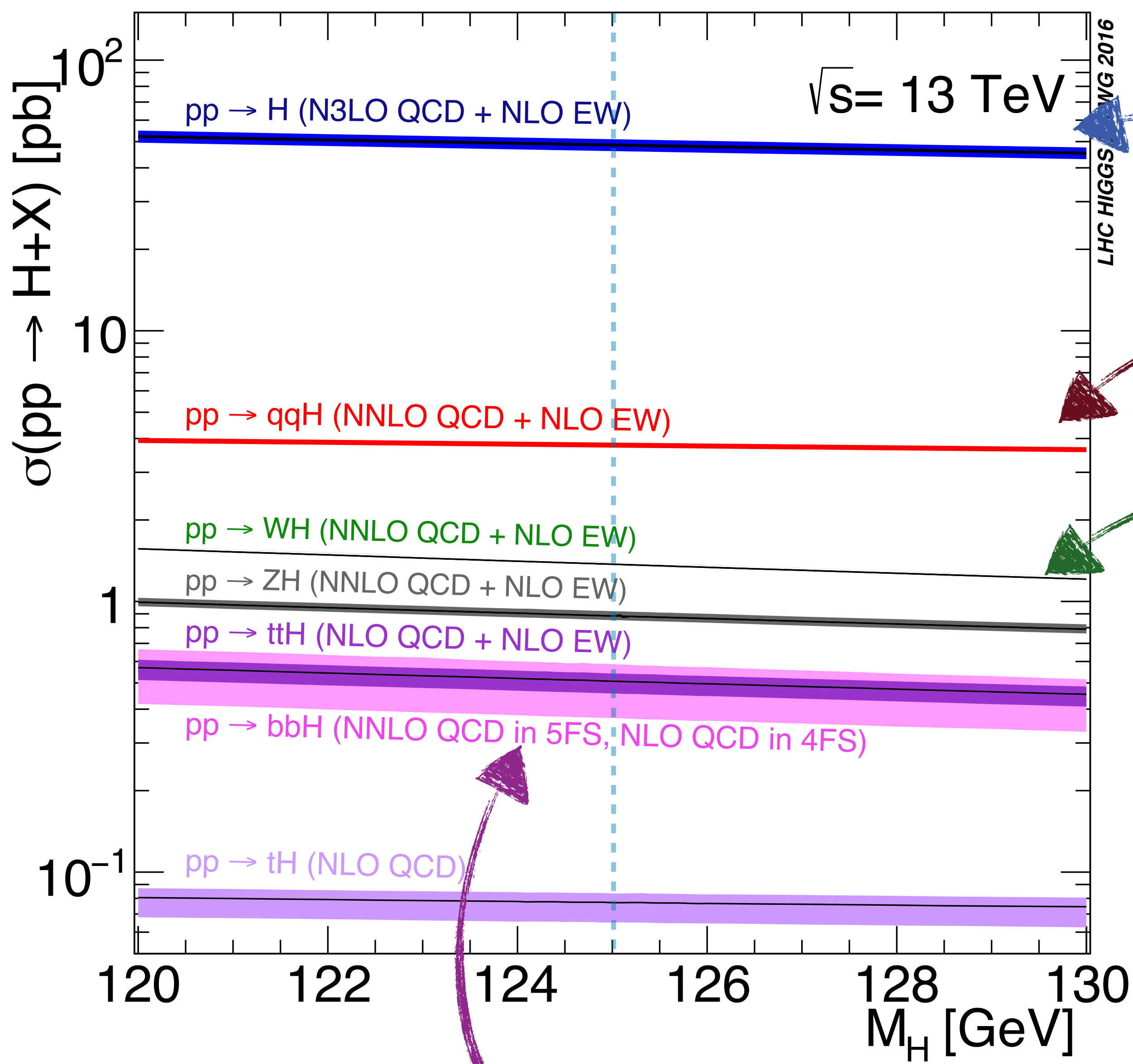
- Yukawa couplings **not** imposed by fundamental principle
- Probing fermion mass generation scale→**independent task**
- Fermion mass generation scale from **unitarity bounds**:

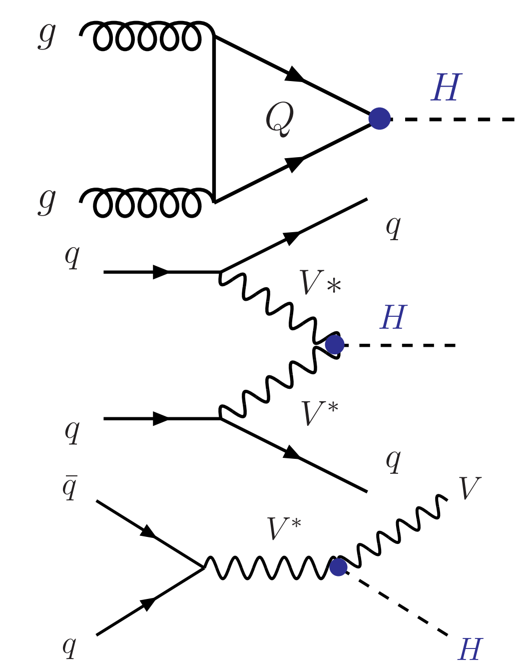
$$\Lambda \approx 23, 31, 52, 77, 84 \text{ TeV} \quad \text{(b,c,s,d,u)}$$

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

SM Higgs boson production and decay

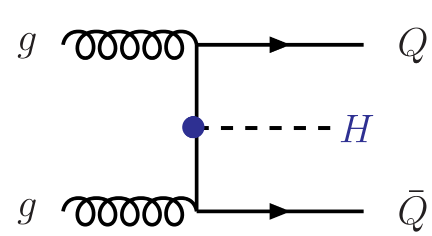




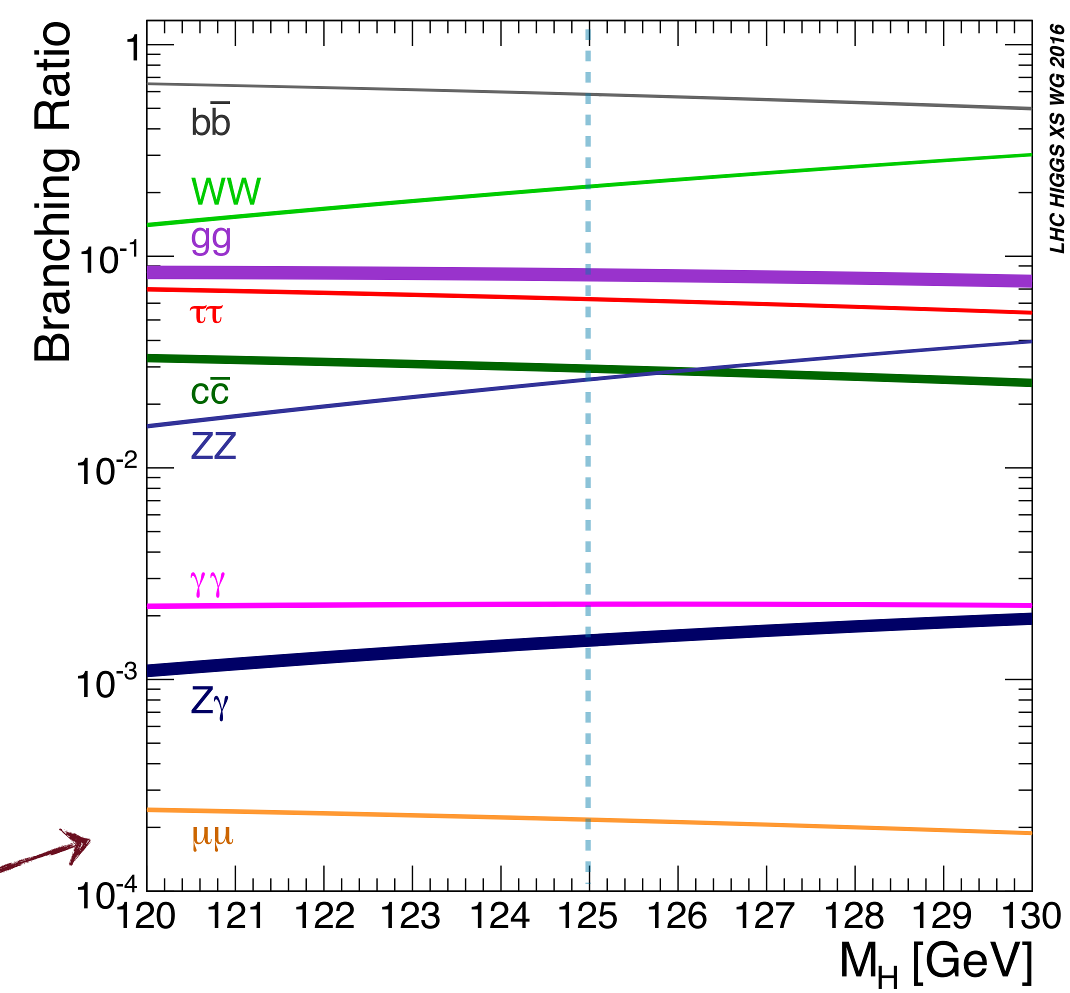
87%
m_h = 125 GeV

7%
m_h = 125 GeV

4%
m_h = 125 GeV

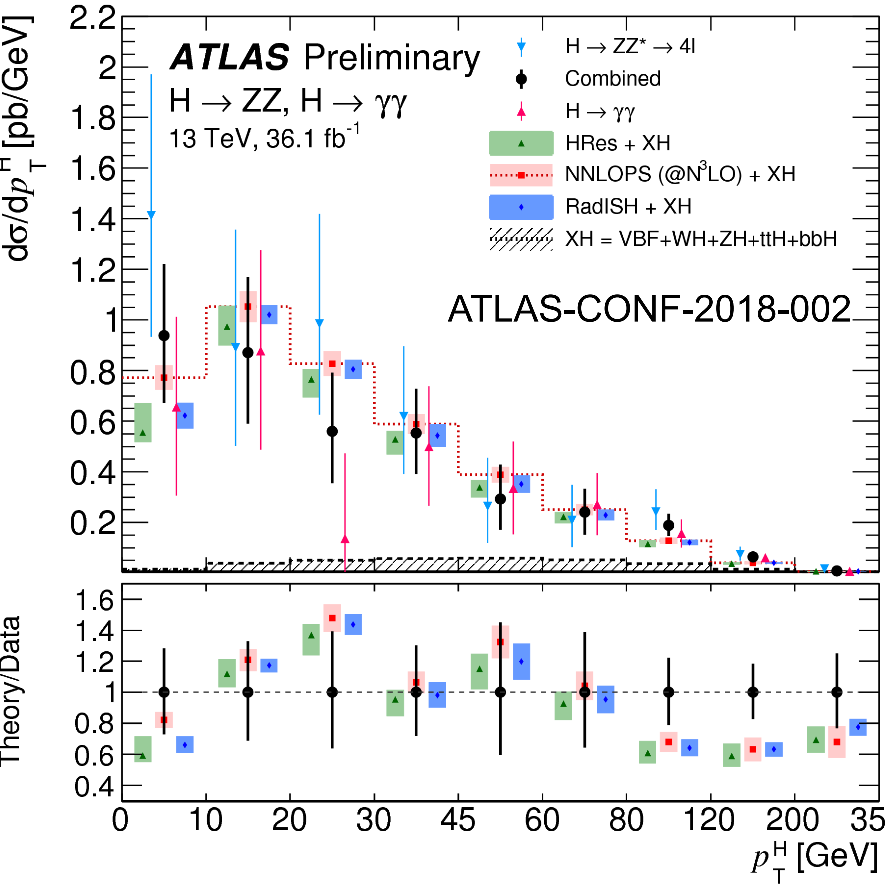


2%
m_h = 125 GeV

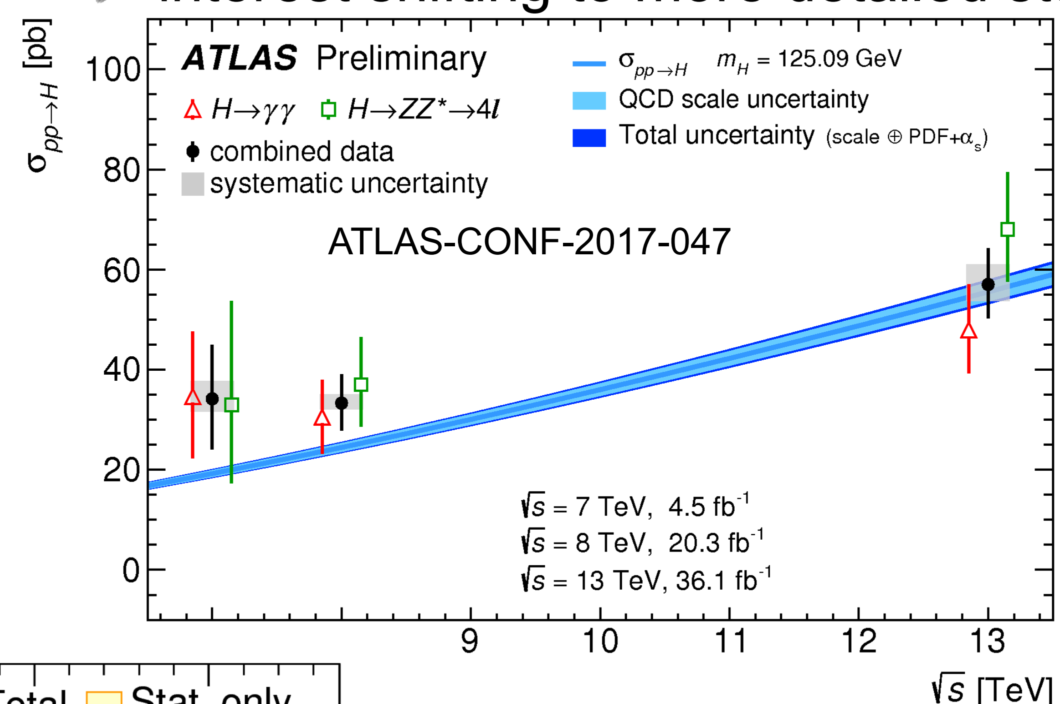


m_h~125 GeV gives access to several decay channels

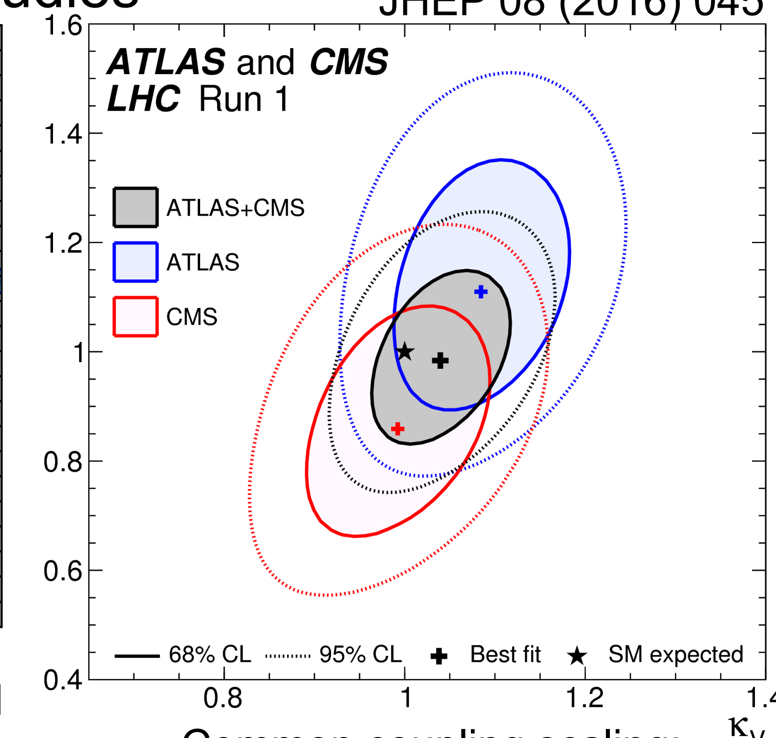
Higgs boson properties



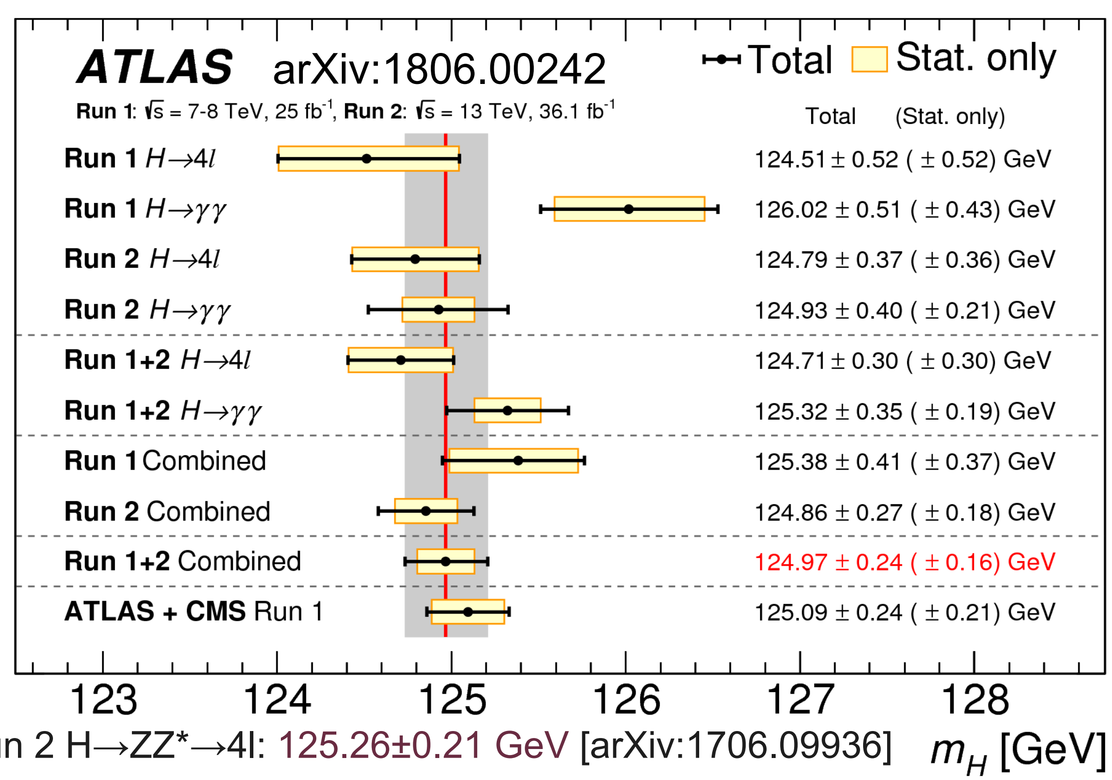
- Discovery channels: h→ZZ/γγ/WW.
- Significant progress in **Higgs boson property** measurements:
  - **mass** precision <0.2% and **bosonic decays** known to ~10%
  - main production mechanisms observed
  - interest shifting to more detailed studies



JHEP 08 (2016) 045



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

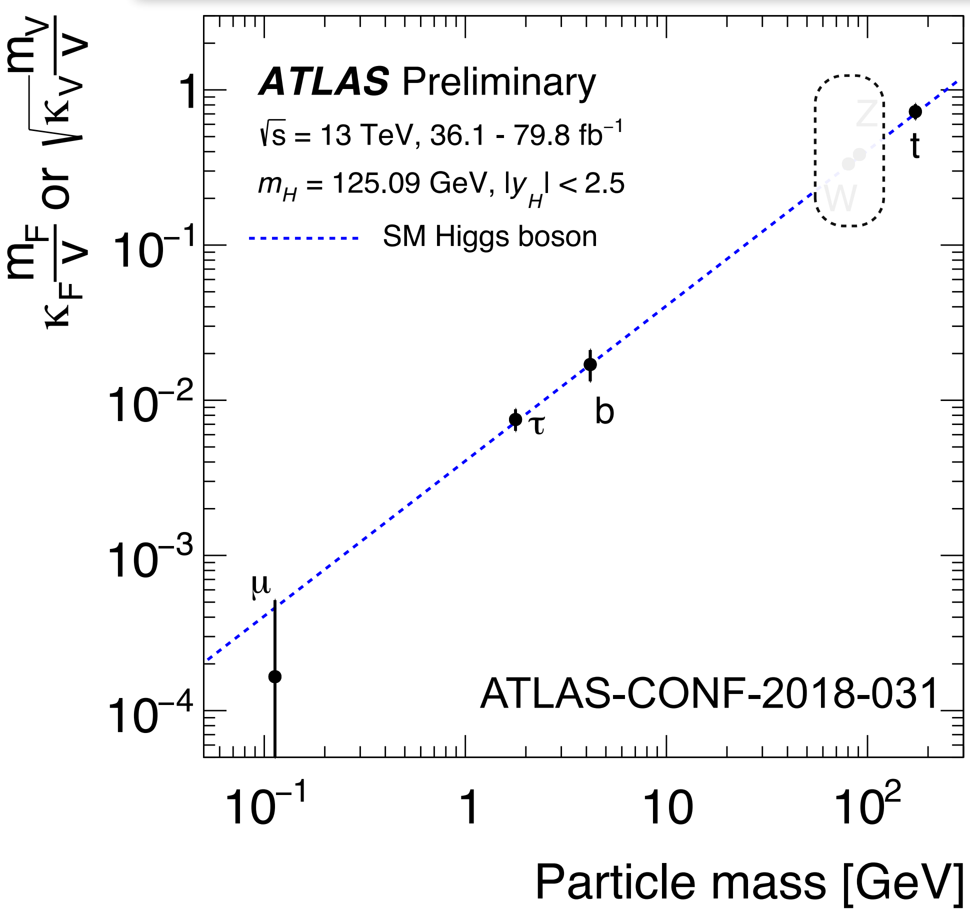


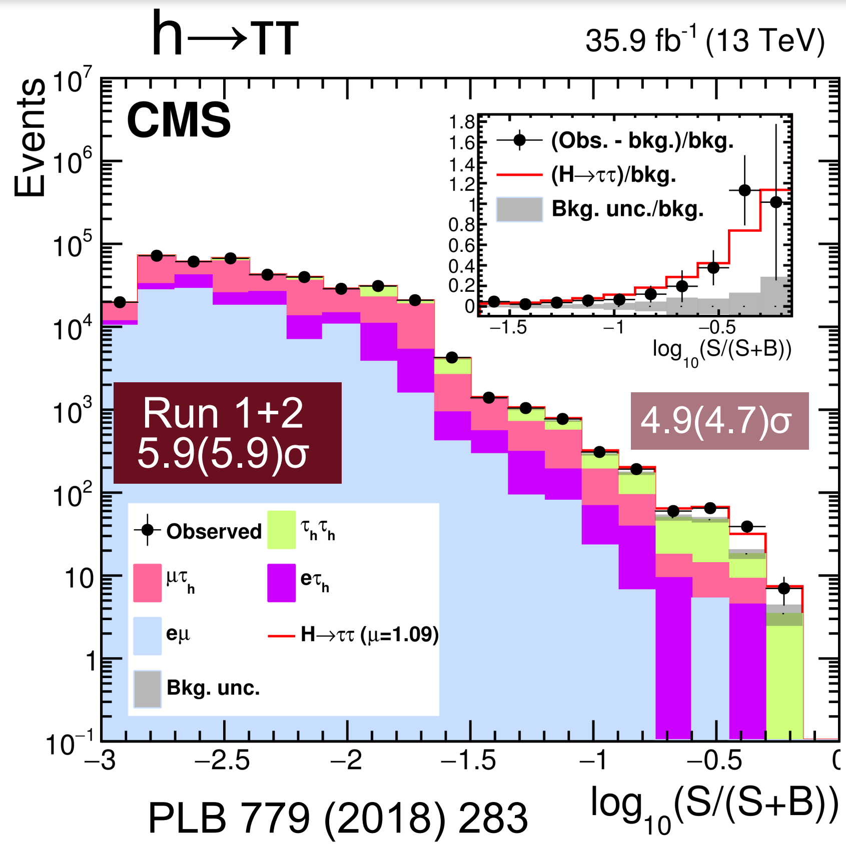
CMS Run 2 H→ZZ*→4l: 125.26±0.21 GeV [arXiv:1706.09936]

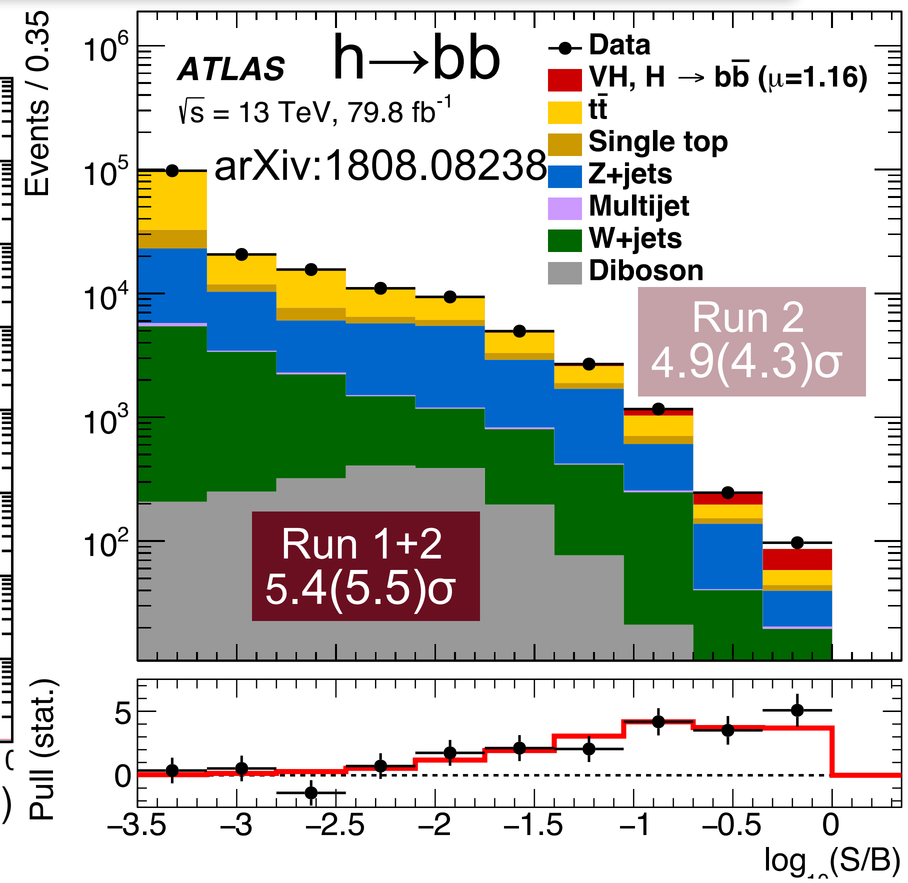
Experimental information on Yukawa couplings essential to fully characterise the observed Higgs boson!

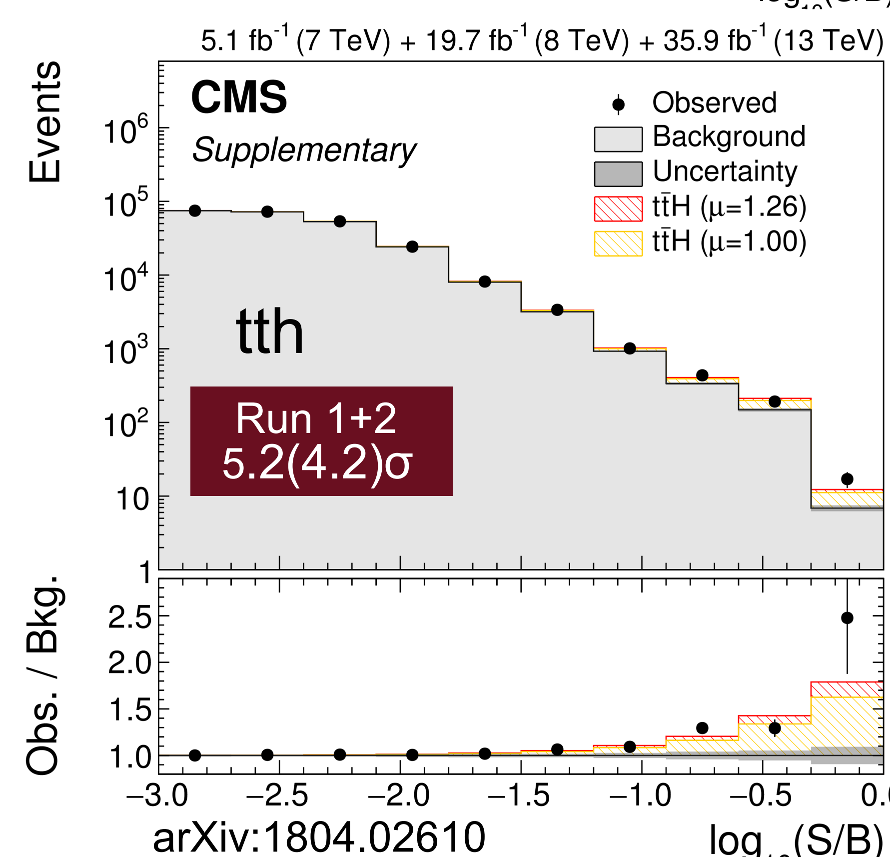
Higgs-fermion interactions: The story so far

[in a nutshell]







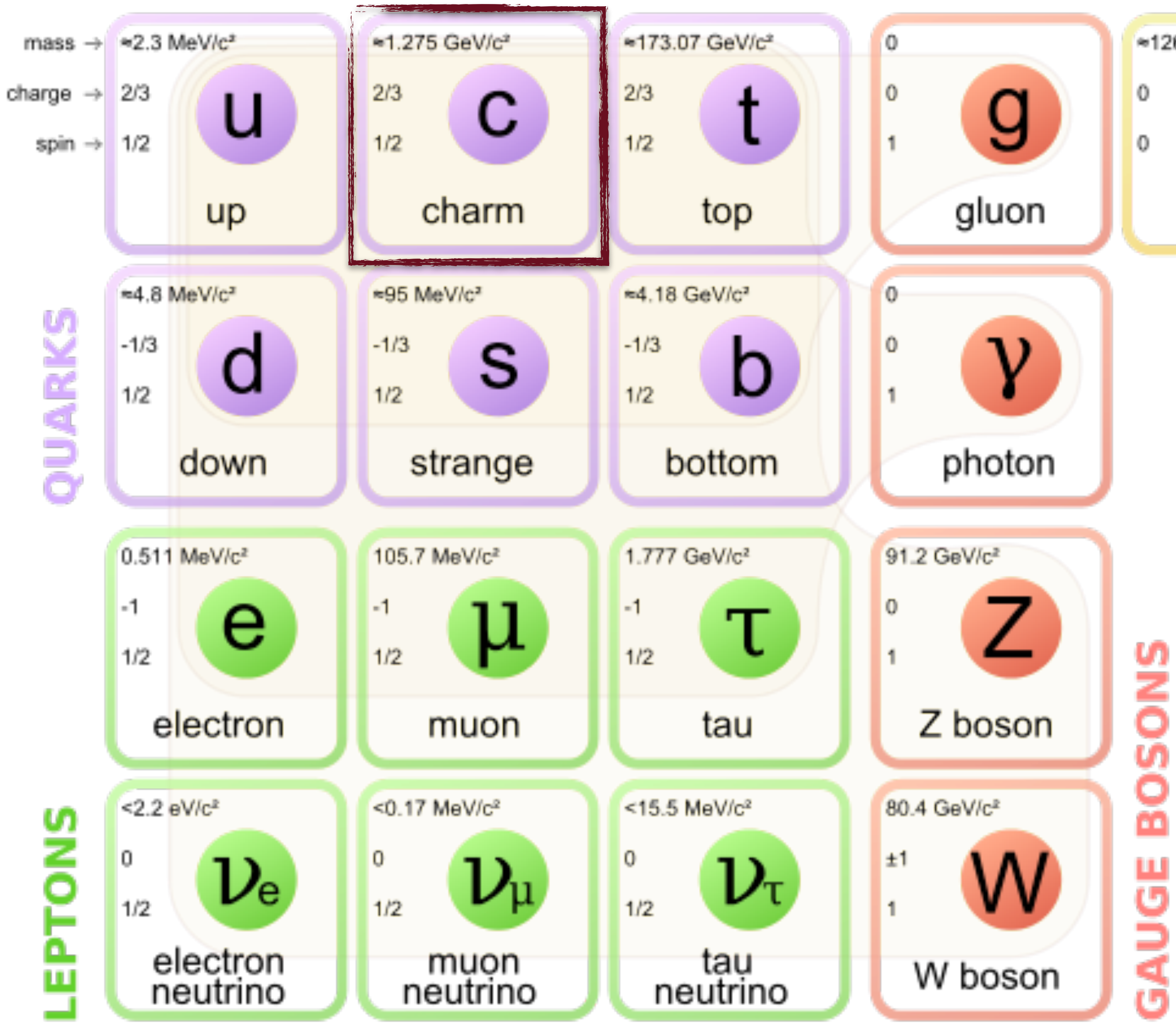


3rd generation fermions:

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

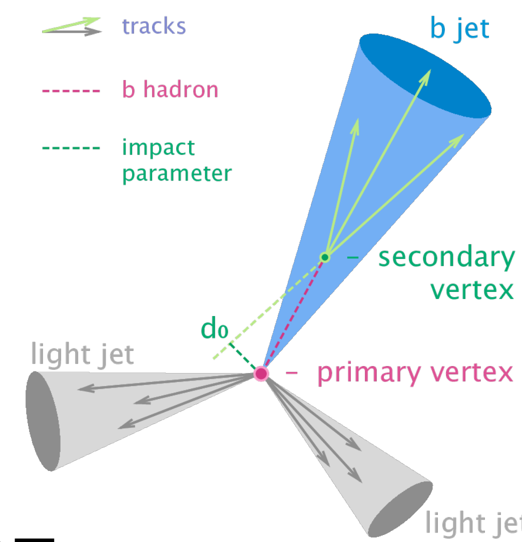
1st/2nd generation fermions, different picture:

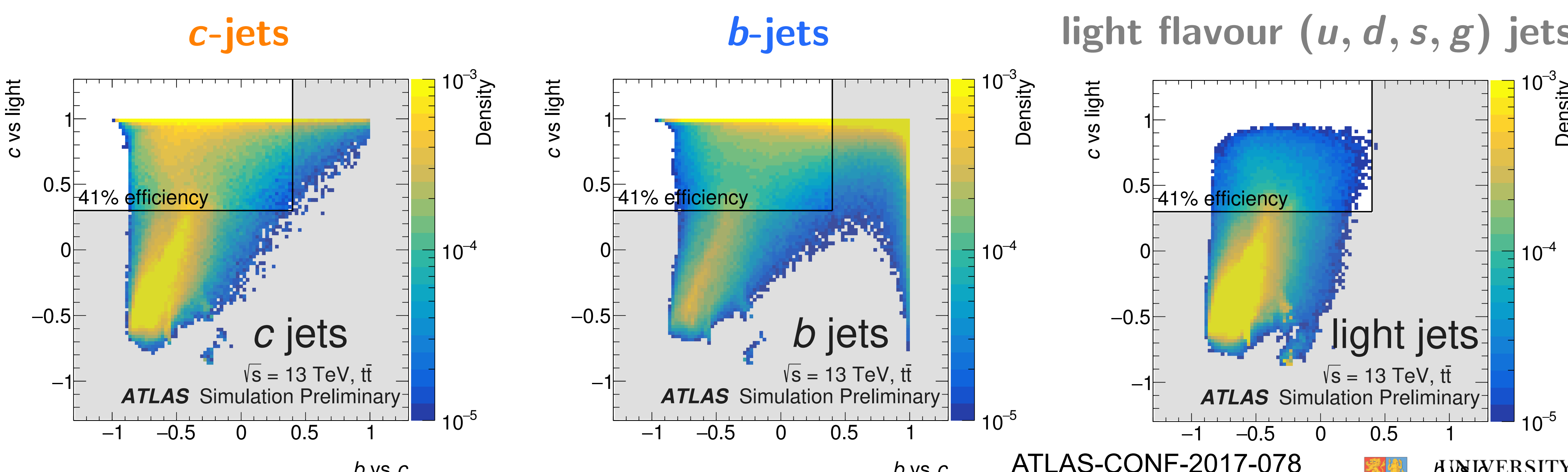
- ☐ **e/μ:** no evidence yet → established non-universality
  - **h→μμ:** feasible in LHC (possibly in Run III)...
- ☐ **c-quark:** no direct evidence, loose bounds from h→bb
- ☐ **u/d/s-quarks:** no inclusive searches available
- Higgs couplings: margin for undetected/unobserved decays


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

- Search for **inclusive** h→cc decays, similar to h→bb
  - associated production with W/Z boson
  - SM BR(h→ccbar)/BR(h→bbbar) ~ 5.1%
- Need a **c-tagging** algorithm
  - Displacements for c-jets ×3.5 less than for b-jets
  - First used **Run 1** for search for s-charm [Phys.Rev.Lett. 114 (2015) 161801]
- **Run 2** new "inclusive" c-tagging
  - Combining "low level" taggers into "high level" tagger using a BDT
    - Track Impact Parameter
    - Reconstruction of Secondary Vertices
    - JetFitter: Fit the decay chain of a b/c-jet
  - Optimal working point: 41% c-jet efficiency for 4× b-jet & 20× light flavour jet rejection





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

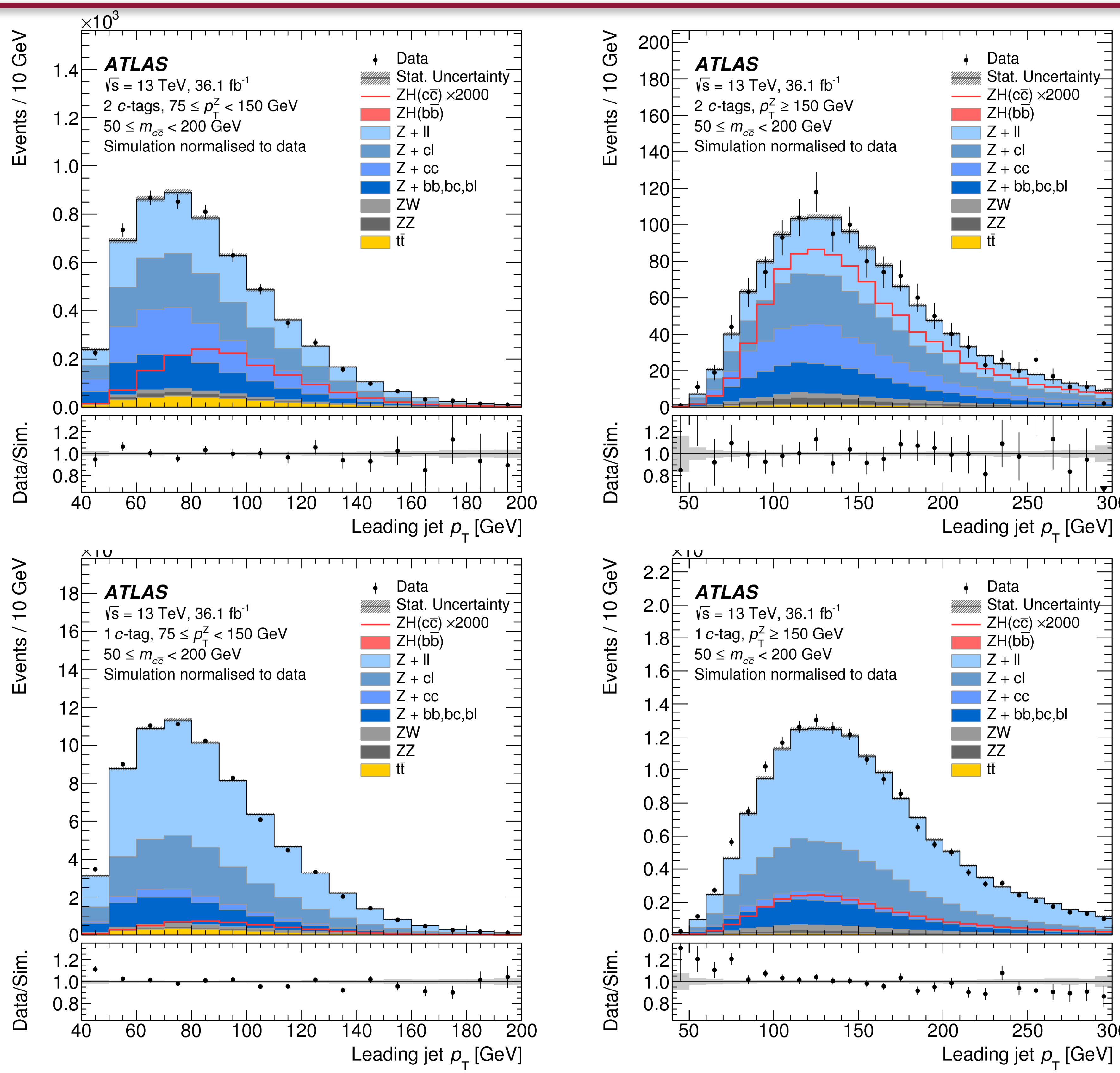
- Split events into 4 categories
  - h→cc candidates with 1 or 2 c-tags
  - p_{TZ} above/below 150 GeV
- Background modelling/uncertainties validated with Z(Z/W) production measurement
  - Observed (expected) ZV production with significance of 1.4σ (2.2σ)
  - Measure ZV signal strength of $0.6^{+0.5}_{-0.4}$,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

Zh(→cc):Background Composition

PRL120 (2018) 211802

2 c-tags

1 c-tag



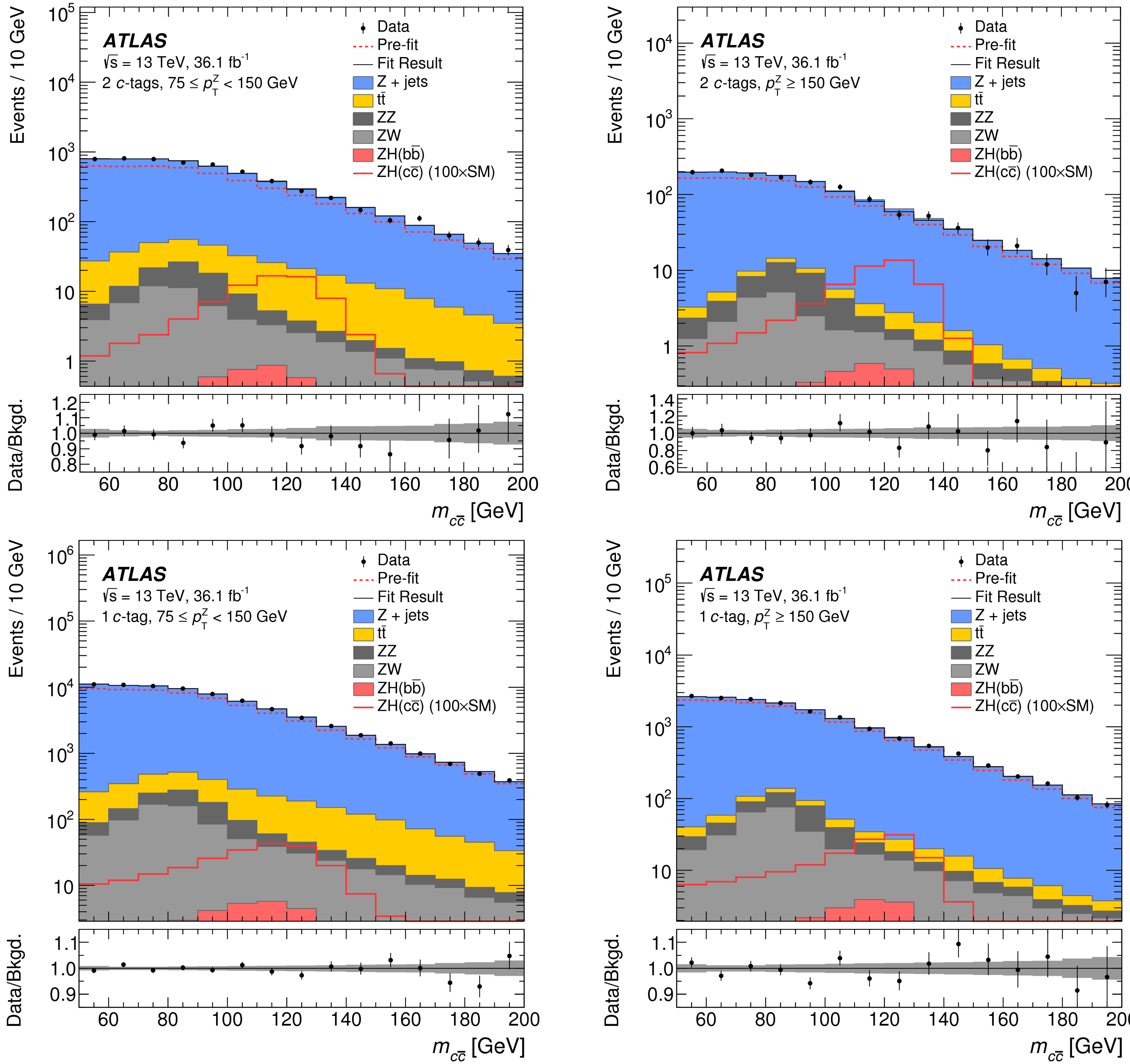
75< p_TZ < 150 GeV **p_TZ > 150 GeV**

Zh(→cc):Fit Results

PRL120 (2018) 211802

2 c-tags

1 c-tag



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

Zh(→cc):Results

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

PRL120 (2018) 211802

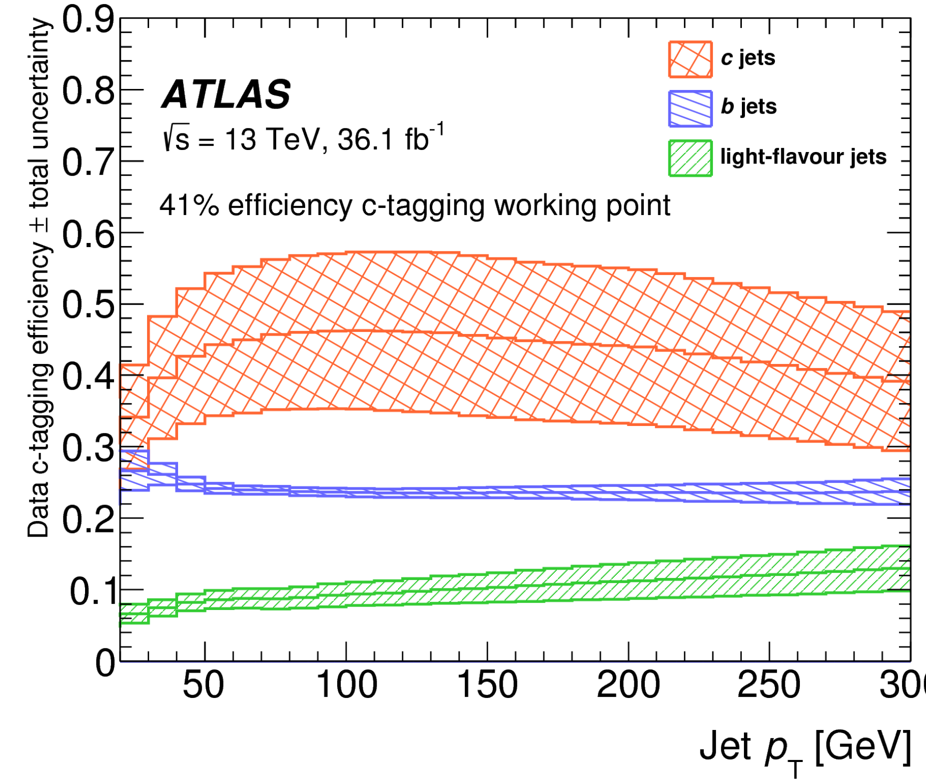
- SM: 2.55×10^{-2} pb
  - 110×SM (150^{+80}_{-40})

Limits on ZH(→ $c\bar{c}$) production

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

Source	σ/σ_{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.

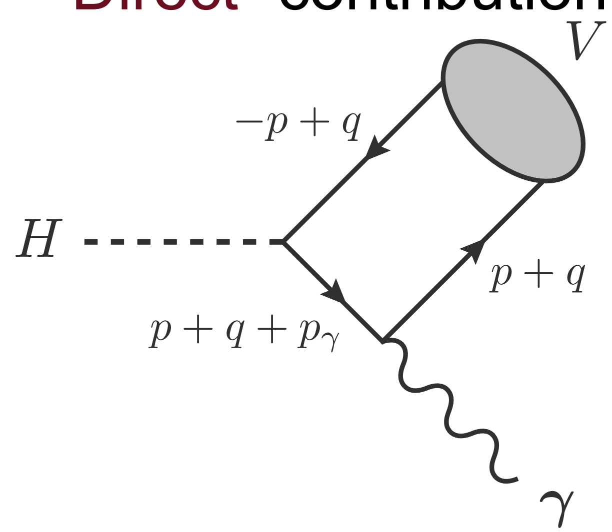


- A tagging working point constrains linear combination of h→cc/h→bb
  - Analysis in conjunction with h→bb; account for cross-contamination
- For future key is the controlling of systematic uncertainties
  - Phenomenological analysis indicates $|\kappa_c| \lesssim 2.5$-5.5 at 95%CL
  - 2×3000 fb^{-1} depending on the c-tagging scenario [Phys.Rev. D93 (2016) 013001]
  - ATLAS HL-HLC projection for Z(ll)H(cc) alone μ<6.3 [ATL-PHYS-PUB-2018-016)]

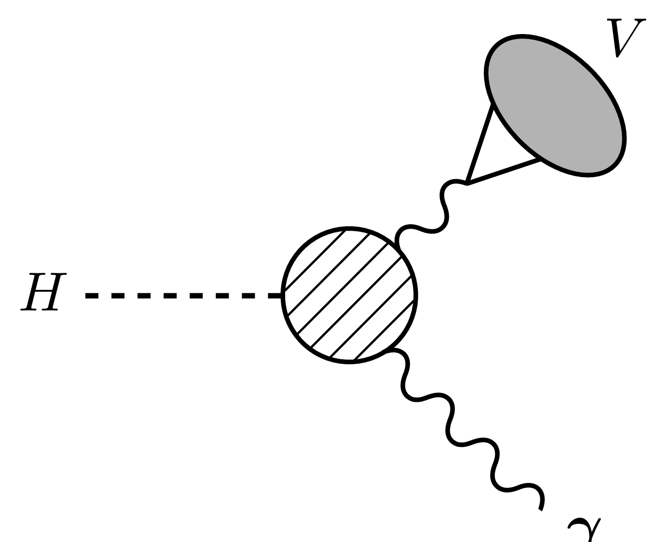
Exclusive Decays h→Qγ

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

- **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 / Method	NRQCD [1487]	LCDA LO [1486]	LCDA NLO [1489]
	Branching Fraction $[10^{-6}]$		
$\mathrm{Br}(h \to \rho\gamma)$	–	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
$Z^0 \to \pi^0\gamma$	$(9.80\,^{+0.09}_{-0.14}\,{}_\mu \pm 0.03_f \pm 0.61_{a_2} \pm 0.82_{a_4}) \cdot 10^{-12}$
$Z^0 \to \rho^0\gamma$	$(4.19\,^{+0.04}_{-0.06}\,{}_\mu \pm 0.16_f \pm 0.24_{a_2} \pm 0.37_{a_4}) \cdot 10^{-9}$
$Z^0 \to \omega\gamma$	$(2.89\,^{+0.03}_{-0.05}\,{}_\mu \pm 0.15_f \pm 0.29_{a_2} \pm 0.25_{a_4}) \cdot 10^{-8}$
$Z^0 \to \phi\gamma$	$(8.63\,^{+0.08}_{-0.13}\,{}_\mu \pm 0.41_f \pm 0.55_{a_2} \pm 0.74_{a_4}) \cdot 10^{-9}$
$Z^0 \to J/\psi\,\gamma$	$(8.02\,^{+0.14}_{-0.15}\,{}_\mu \pm 0.20_f\,^{+0.39}_{-0.36}\,{}_\sigma) \cdot 10^{-8}$
$Z^0 \to \Upsilon(1S)\,\gamma$	$(5.39\,^{+0.10}_{-0.10}\,{}_\mu \pm 0.08_f\,^{+0.11}_{-0.08}\,{}_\sigma) \cdot 10^{-8}$
$Z^0 \to \Upsilon(4S)\,\gamma$	$(1.22\,^{+0.02}_{-0.02}\,{}_\mu \pm 0.13_f\,^{+0.02}_{-0.02}\,{}_\sigma) \cdot 10^{-8}$
$Z^0 \to \Upsilon(nS)\,\gamma$	$(9.96\,^{+0.18}_{-0.19}\,{}_\mu \pm 0.09_f\,^{+0.20}_{-0.15}\,{}_\sigma) \cdot 10^{-8}$

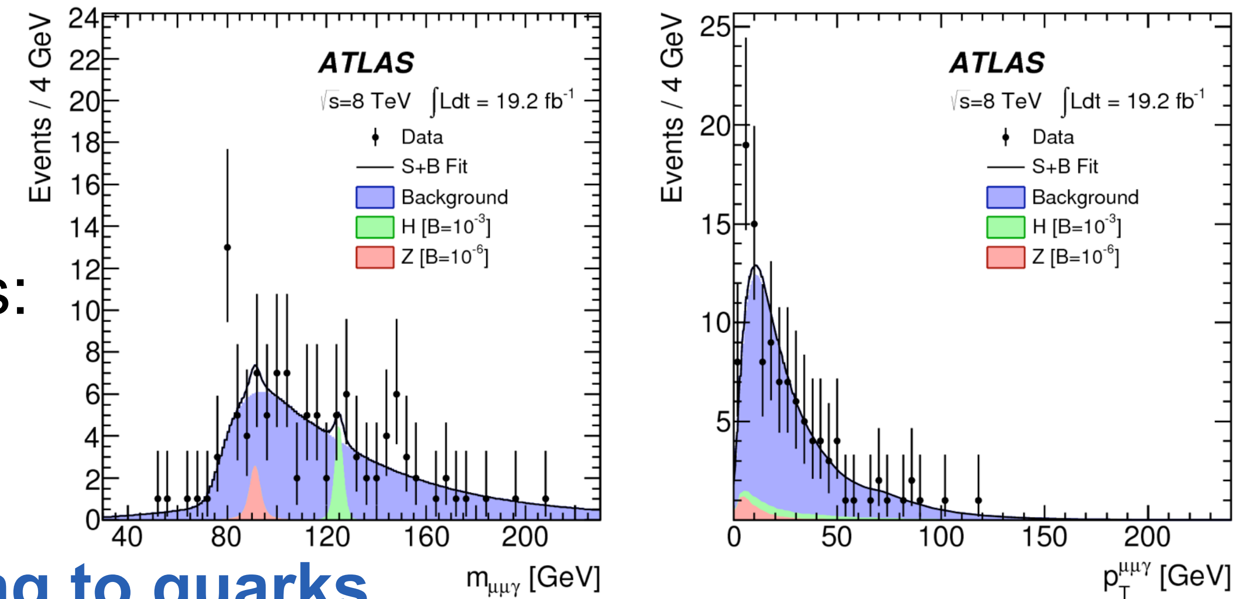
Not exhaustive; accurate at the time of YR4

JHEP 1504 (2015) 101

h/Z→J/ψγ and h/Z→Y(nS)γ (n=1,2,3)

- **First search** for exclusive h/Z→Qγ decays in Run 1
  - Q = J/ψ or Y(nS), n=1,2,3 decaying to $\mu^+\mu^-$
  - ATLAS 19.2 - 20.3 fb^{-1}
  - CMS 19.7 fb^{-1}
- 95% CL upper limits on decay Branching Ratios:
  - $\mathcal{O}(10^{-3})$ for Higgs boson (SM production)
  - $\mathcal{O}(10^{-6})$ for Z boson

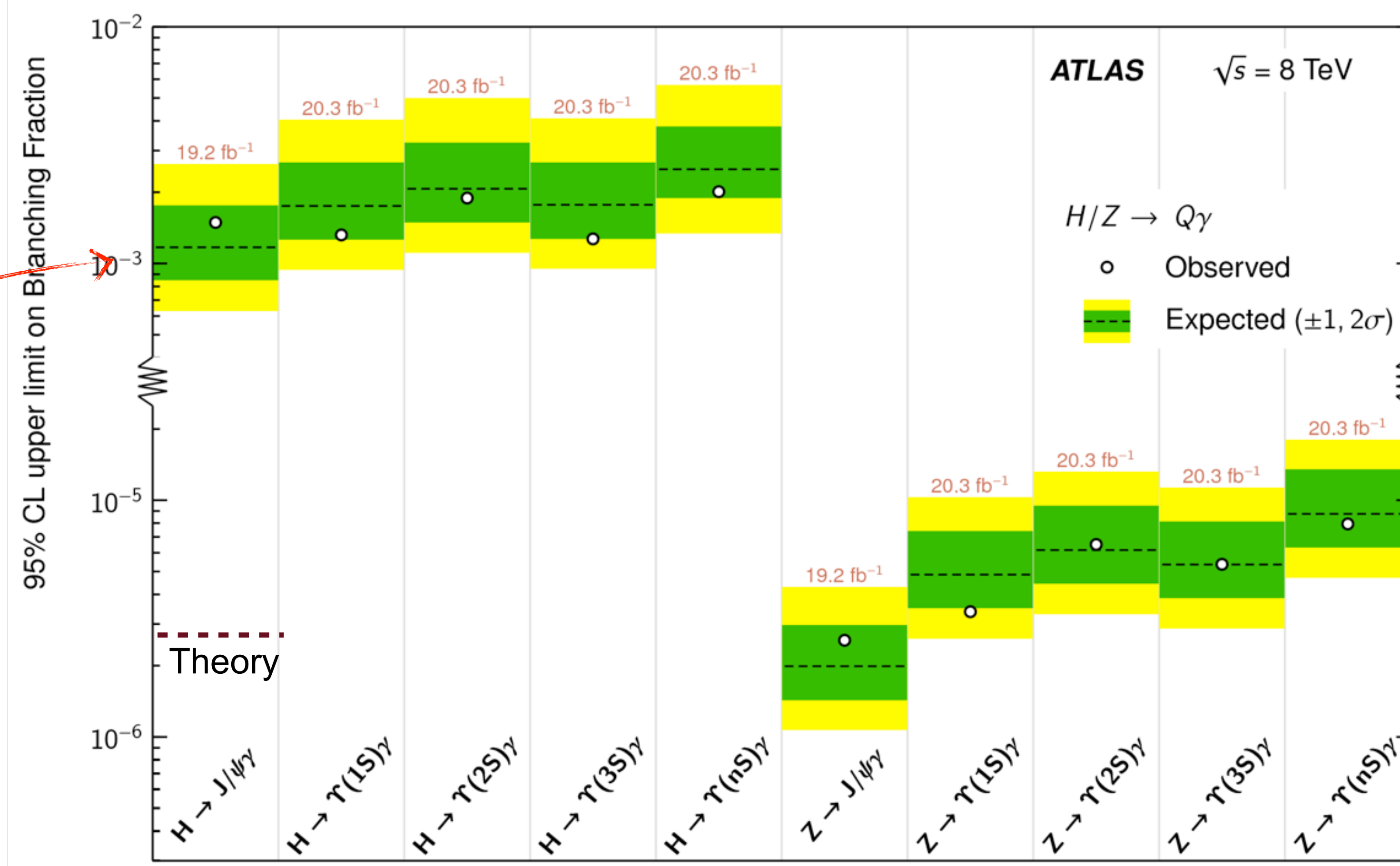
Phys.Rev.Lett. 114 (2015) 12, 121801



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

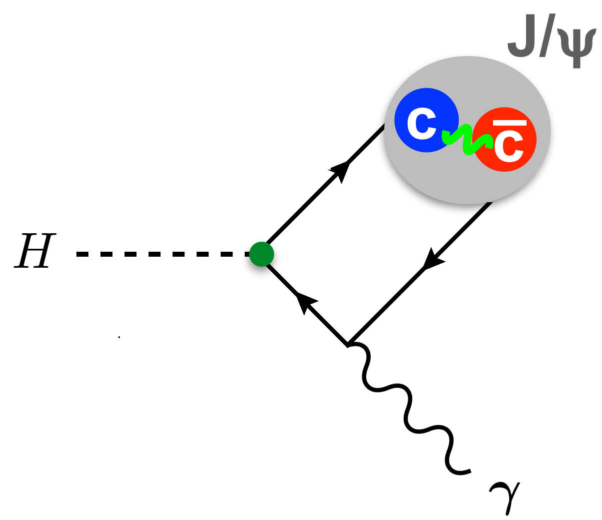
[Phys.Rev. D92 (2015) 033016, JHEP 1508 (2015) 012]

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



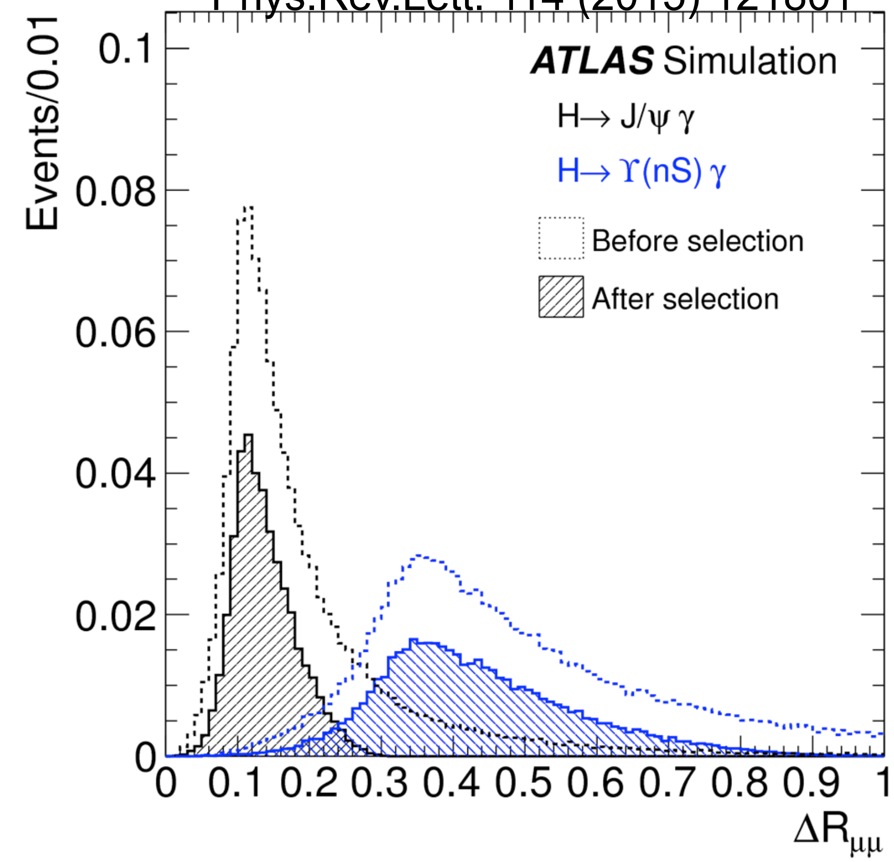
Phys.Rev.Lett. 114 (2015) 12, 121801

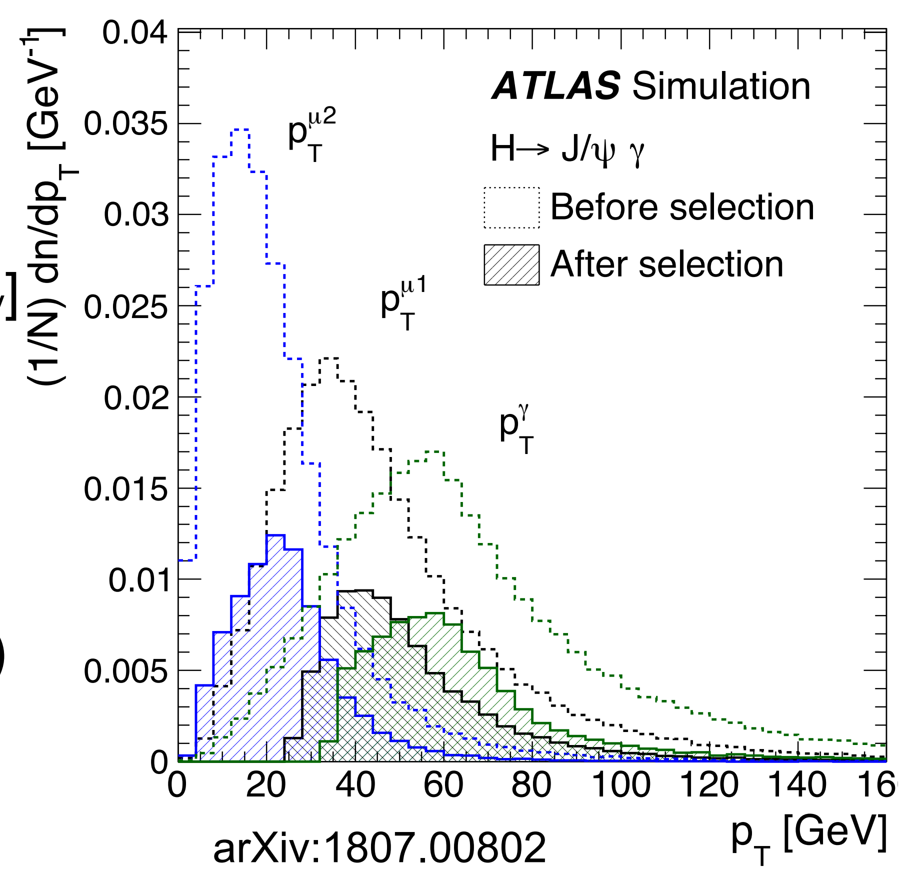
h/Z→ψ(mS)γ (m=1,2) and h/Z→Υ(nS)γ (n=1,2,3)



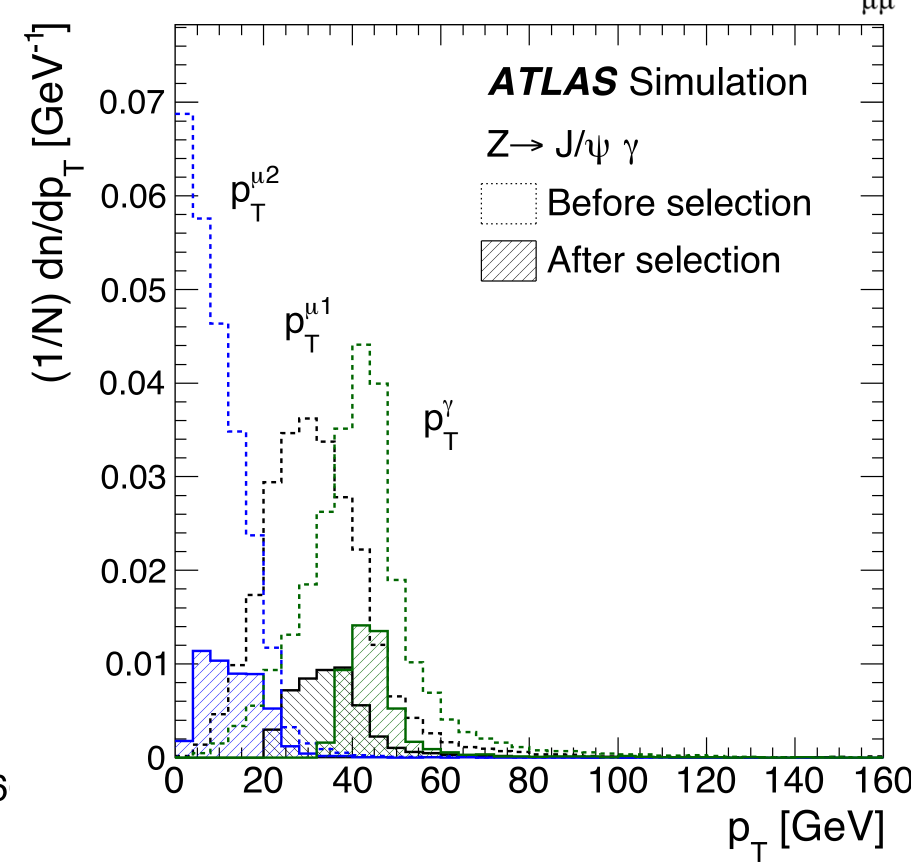
- **New results** on exclusive h/Z→Qγ decays with Run 2 data!
  - Q = ψ(mS) [m=1,2] or Υ(nS) [n=1,2,3] decaying to $\mu^+\mu^-$
- Event Selection (ATLAS example)
  - dedicated photon + muon trigger
  - $|\eta_\mu|<2.5$, $p_{T\mu}>18,3$ GeV
  - $|\eta_\gamma|<2.47$, $p_{T\gamma}>35$ GeV
    - excluding $1.37<|\eta_\gamma|<1.52$
  - $p_{T\mu\mu}$ >34-54.4 GeV [function of $m_{\mu\mu\gamma}$]
  - μμ and γ isolation
  - loose $m_{\mu\mu}$ requirements
  - $|L_{xy}|/\sigma_{Lxy}<3$
- Total efficiency
  - h/Z→J/ψ(→μμ)γ~19% (11%)
  - h/Z→Υ(→μμ)γ~ 23% (16%)

Phys.Rev.Lett. 114 (2015) 121801

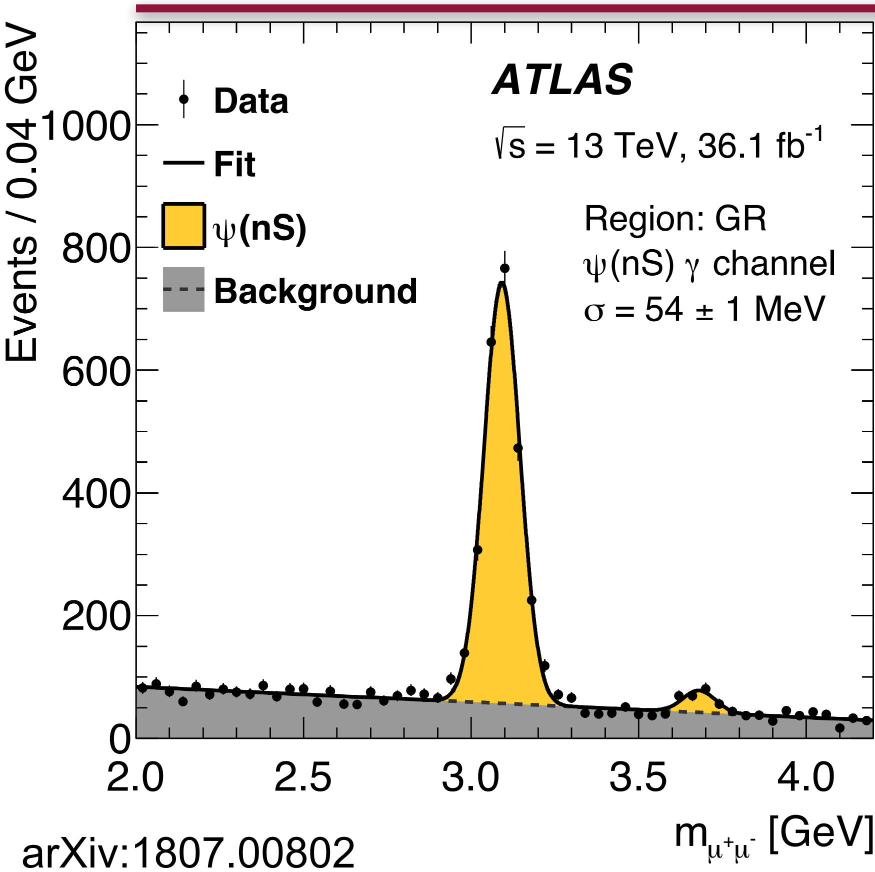


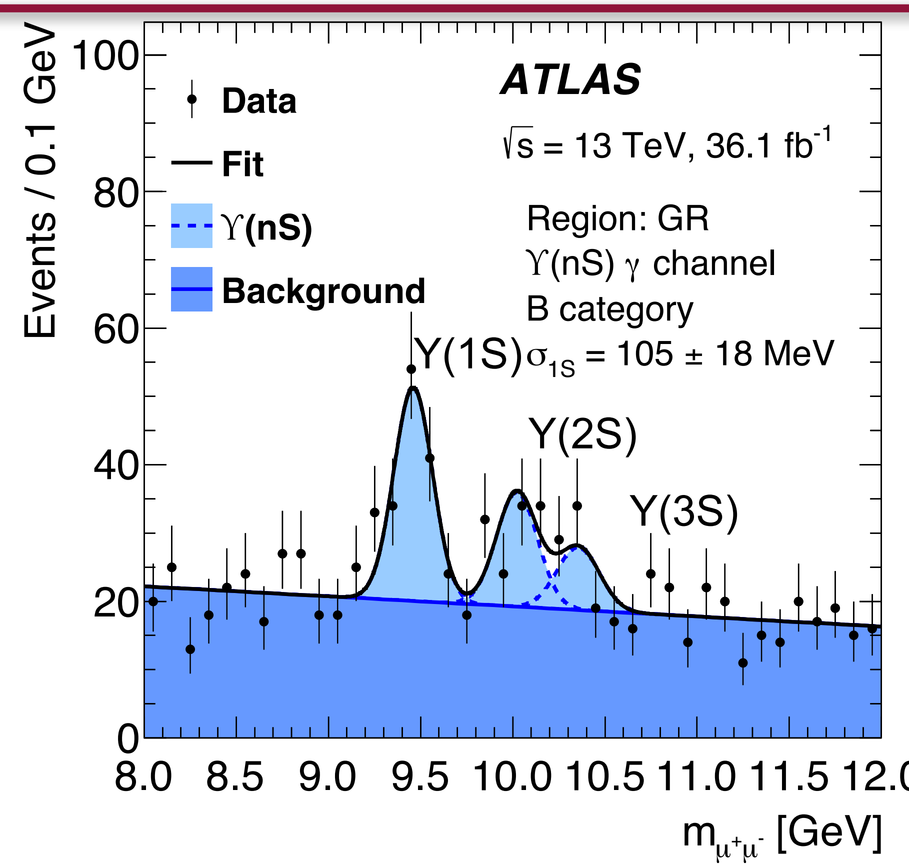


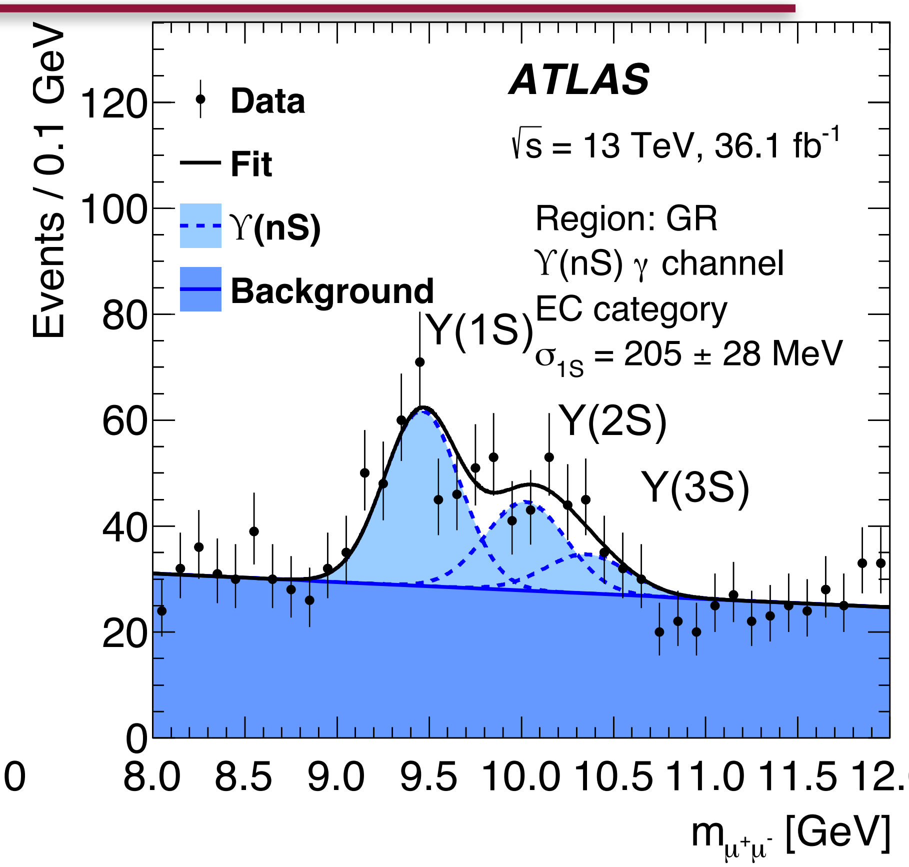
arXiv:1807.00802



h/Z→ψ(mS)γ (m=1,2) and h/Z→Υ(nS)γ (n=1,2,3)







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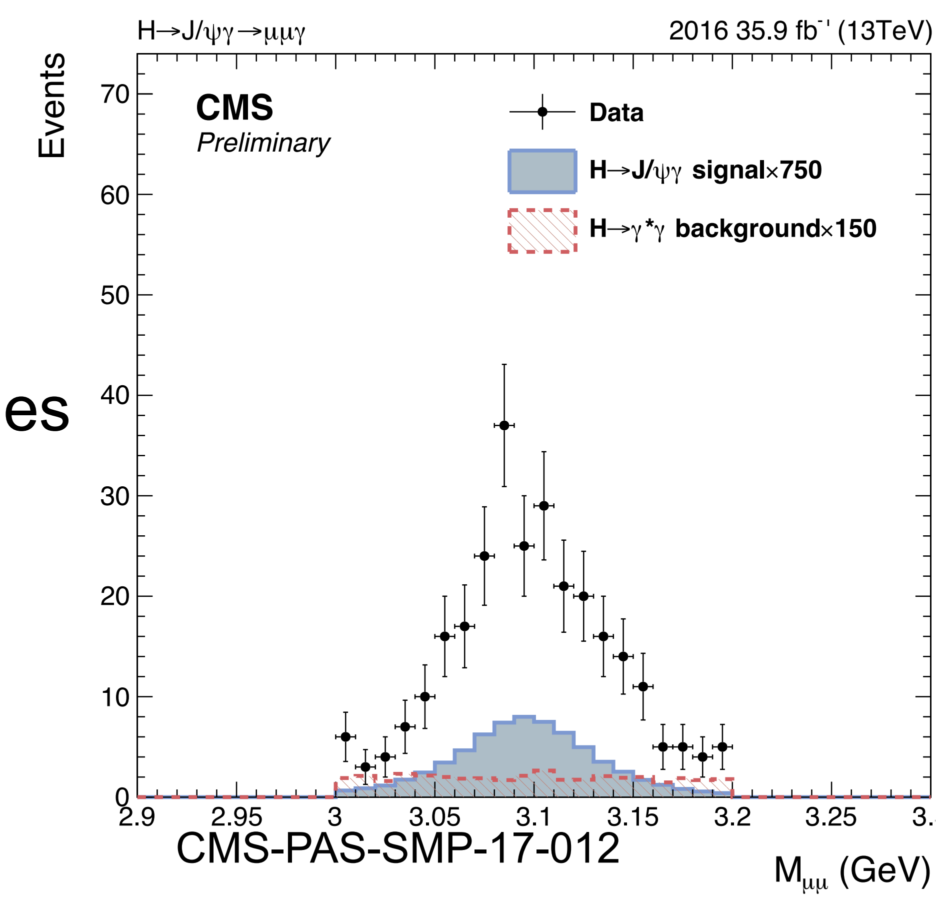
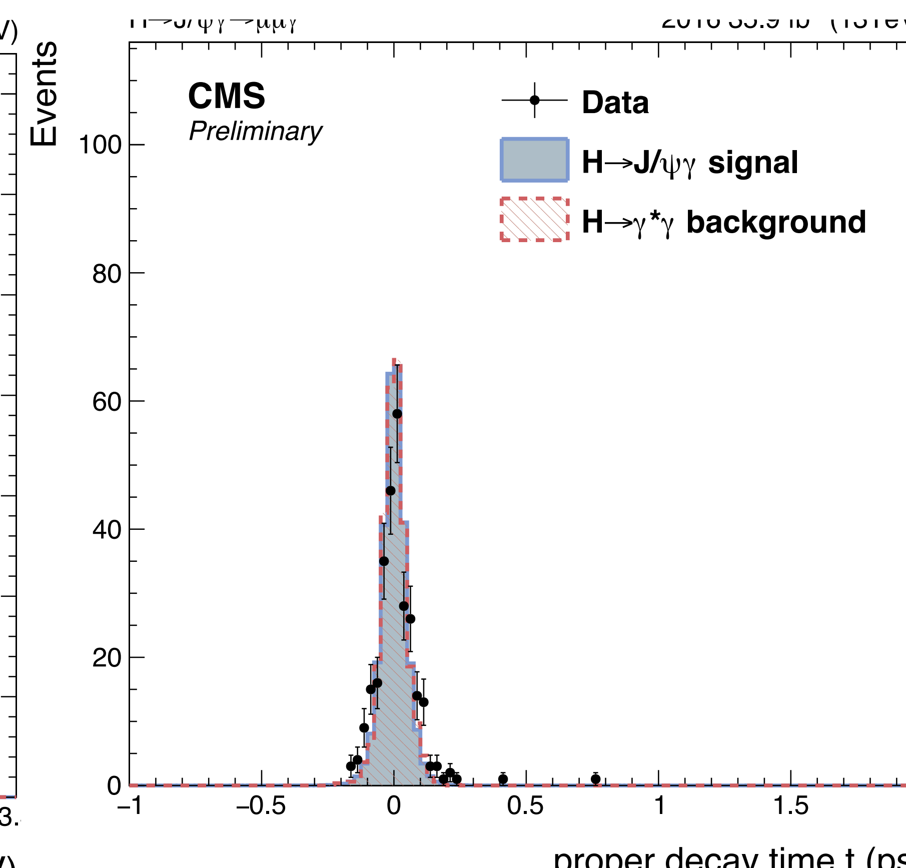


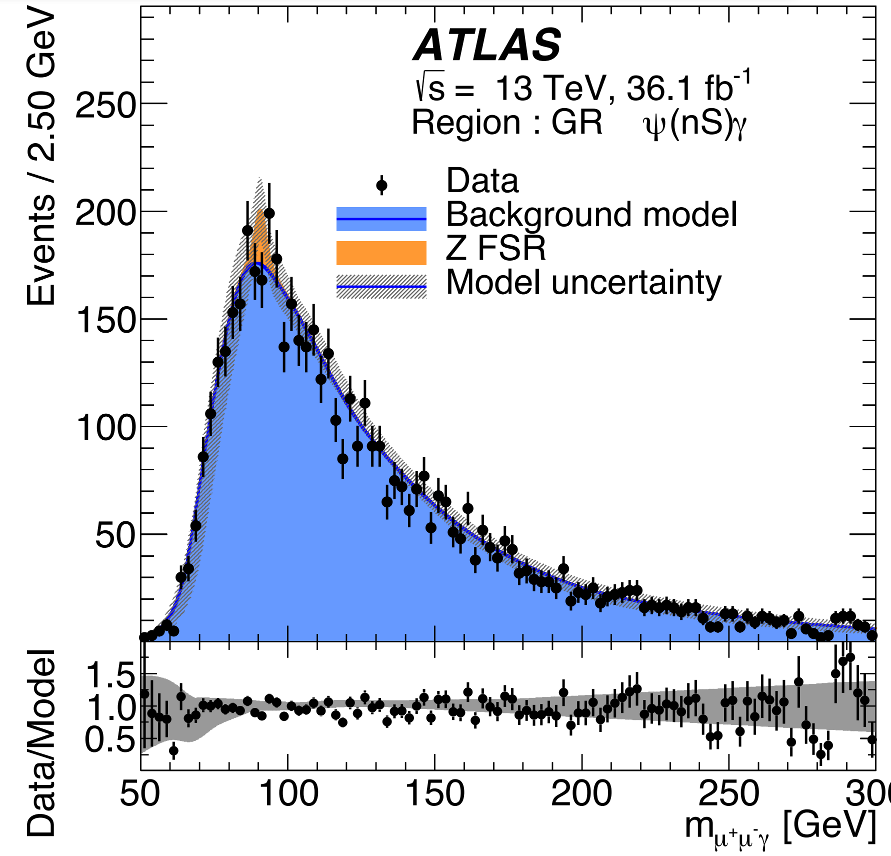
CMS-PAS-SMP-17-012

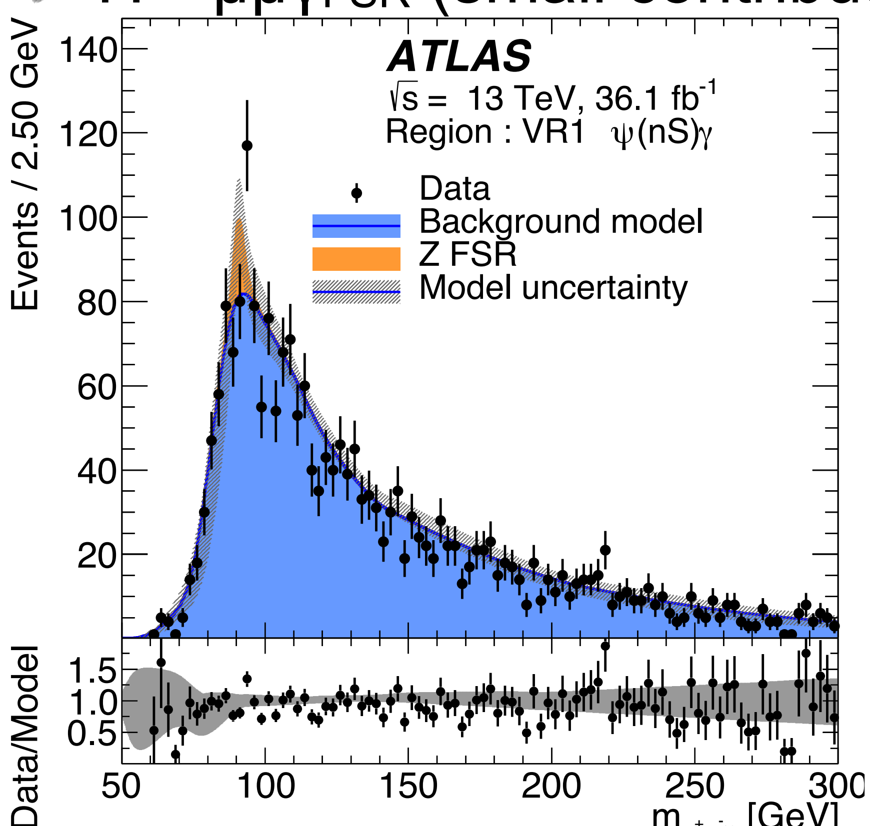


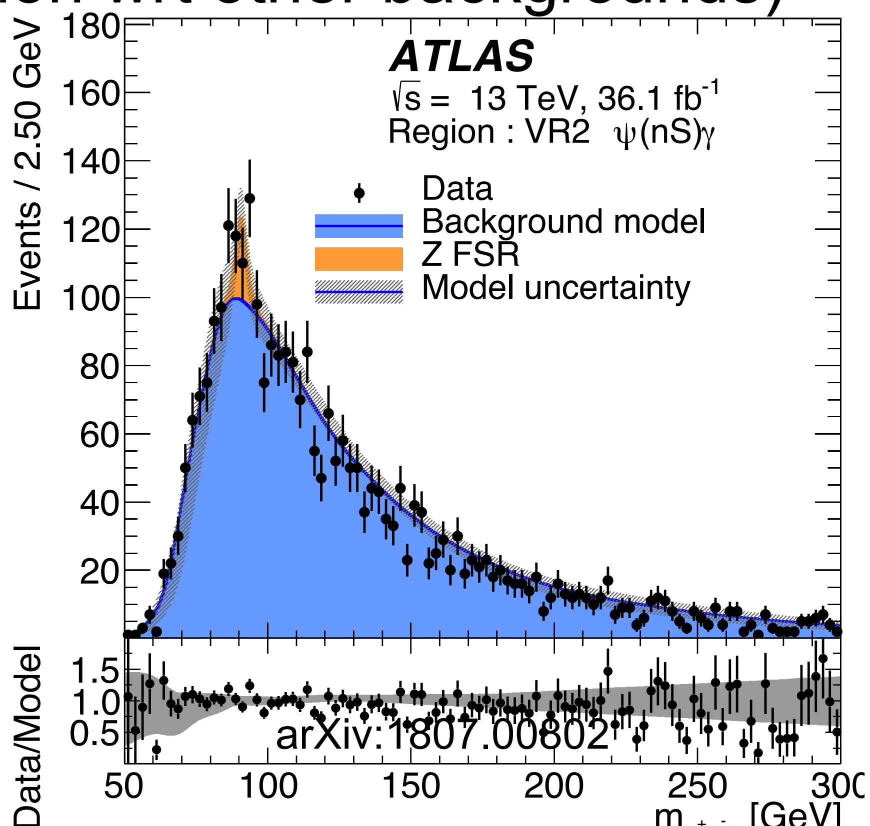
- Mostly no categorisation
  - ATLAS Υ(nS): 2 μ categories
  - CMS ZJ/ψ: 3 γ categories
- Mass resolution ~1.6-1.8%

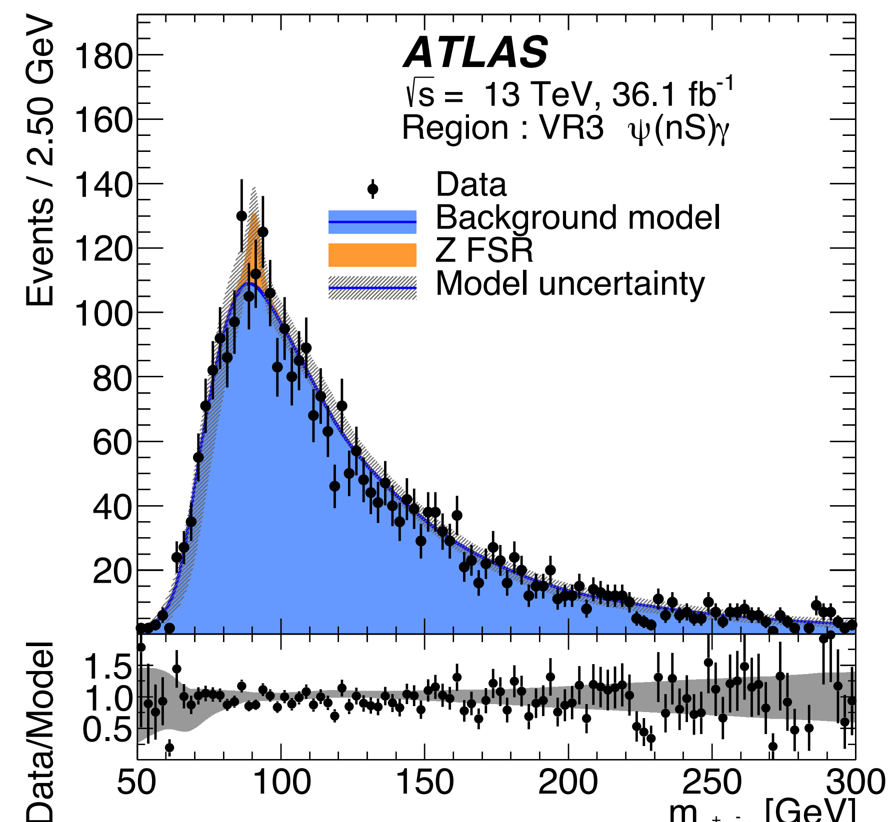
h/Z→Qγ: Background

- **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
- **CMS:** polynomials for background model
- **Peaking backgrounds**
  - $Z \to \mu\mu\gamma_{FSR}$ from side-band fit
  - $H \to \mu\mu\gamma_{FSR}$ (small contribution wrt other backgrounds)









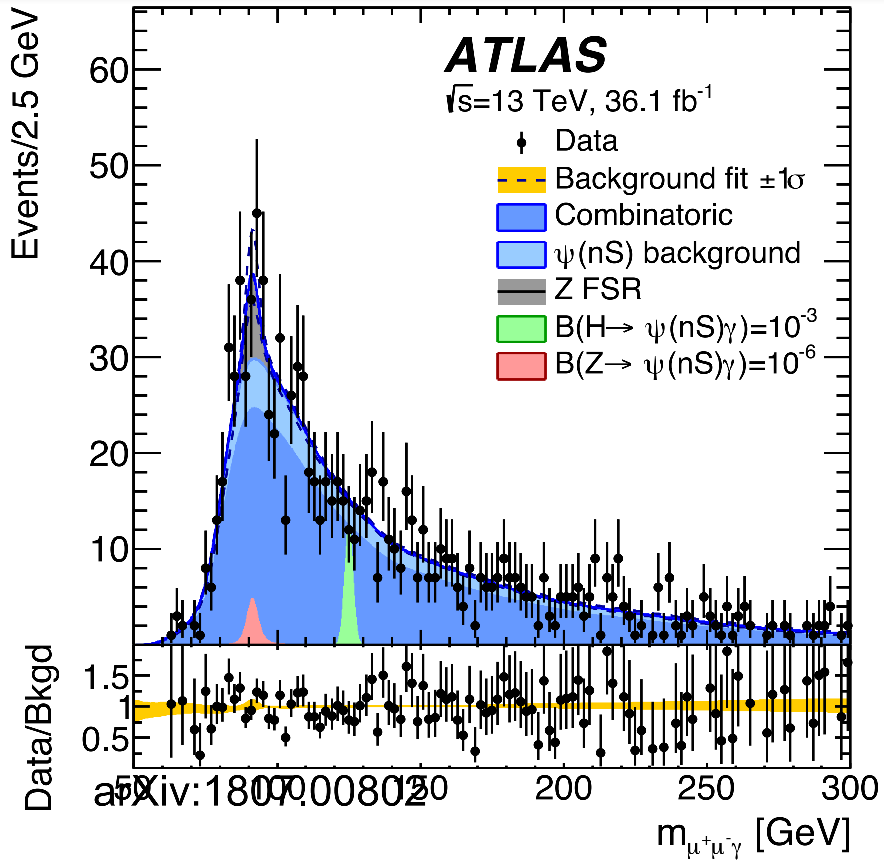
h/Z→Qγ: Systematics

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

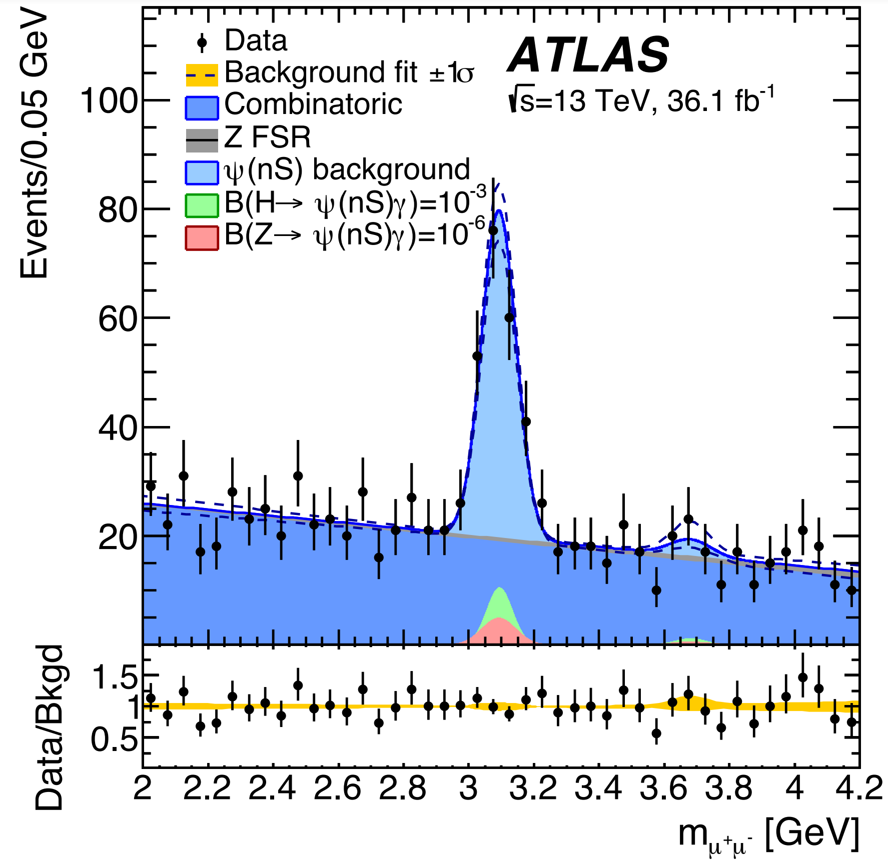
Source	Signal Yield Uncertainty	Estimated From
H Signal Modelling	7.2%	QCD Scale Variations and PDF uncertainties
Z Signal Modelling	5.7%	
Integrated Luminosity	2.1%	Calibration observables and vdM scan uncertainties
Trigger Efficiency	2.0%	Data Driven Techniques with $Z \to \ell\ell$, $Z \to \ell\ell\gamma$, and $J/\psi \to \mu\mu$ events
Photon ID Efficiency	1.4%	
Muon ID Efficiency	2.8%	

- **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

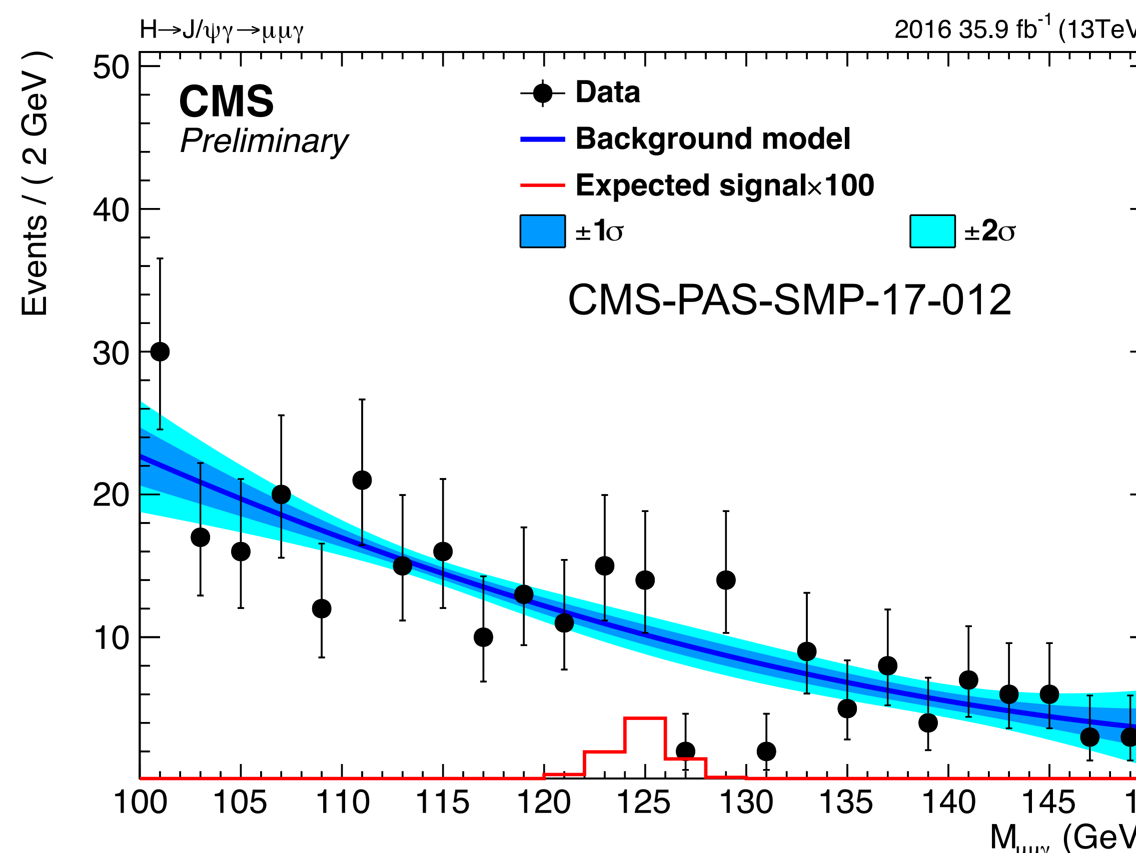
h/Z→Qγ: Results



arXiv:1807.00802

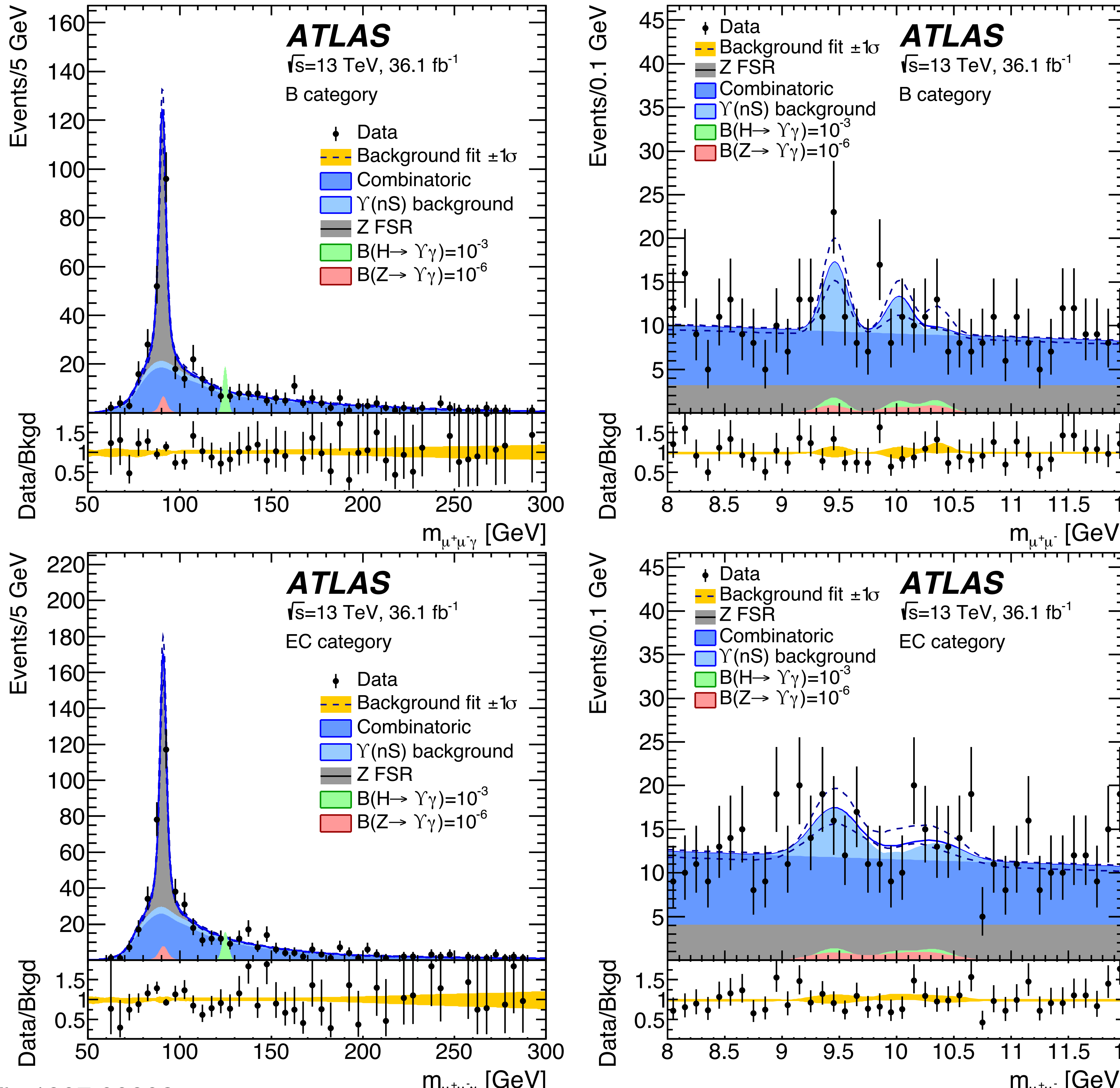


- **ATLAS Two-observable fit**
  - $m_{\mu\mu\gamma}$, $m_{\mu\mu}$
- **CMS Single-observable fit**
  - $m_{\mu\mu\gamma}$
- **No significant excess** above background observed



h/Z→Qγ: Results

- **Two-observable fit**
  - $m_{\mu\mu\gamma}$, $p_{T\mu\mu\gamma}$
- **No significant excess** above background observed



arXiv:1807.00802

h/Z→Qγ: Results

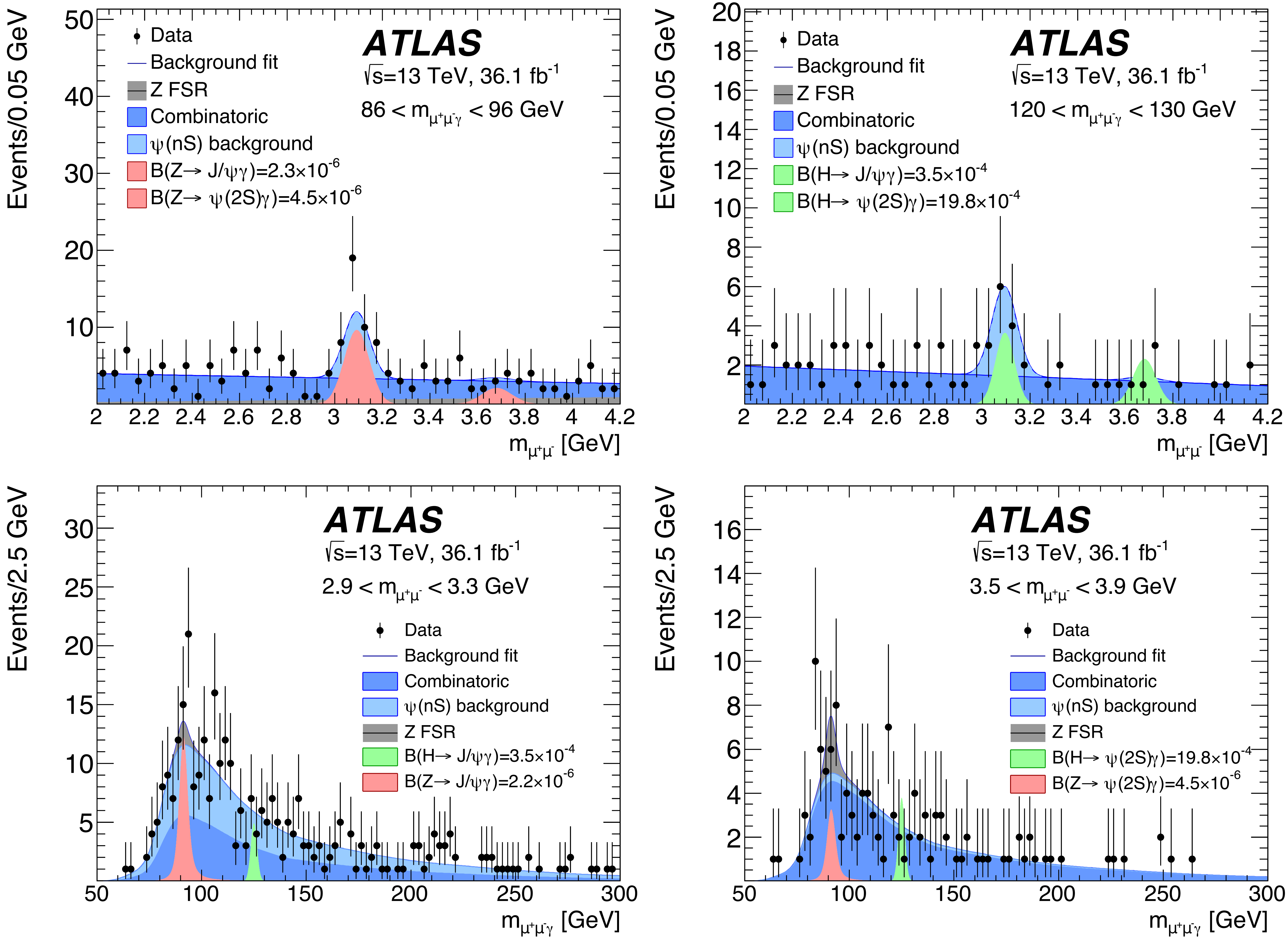
	ATLAS		CMS	
Branching fraction limit (95% CL)	Observed	Expected	Observed	Expected
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	3.5	$3.0^{+1.4}_{-0.8}$	7.6	$5.2^{+2.4}_{-1.6}$
$\mathcal{B}(H \to \psi\,(2S)\,\gamma)\,[\,10^{-4}\,]$	19.8	$15.6^{+7.7}_{-4.4}$	-	-
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	2.3	$1.1^{+0.5}_{-0.3}$	1.4	$1.6^{+0.7}_{-0.5}$
$\mathcal{B}(Z \to \psi\,(2S)\,\gamma)\,[\,10^{-6}\,]$	4.5	$6.0^{+2.7}_{-1.7}$	-	-

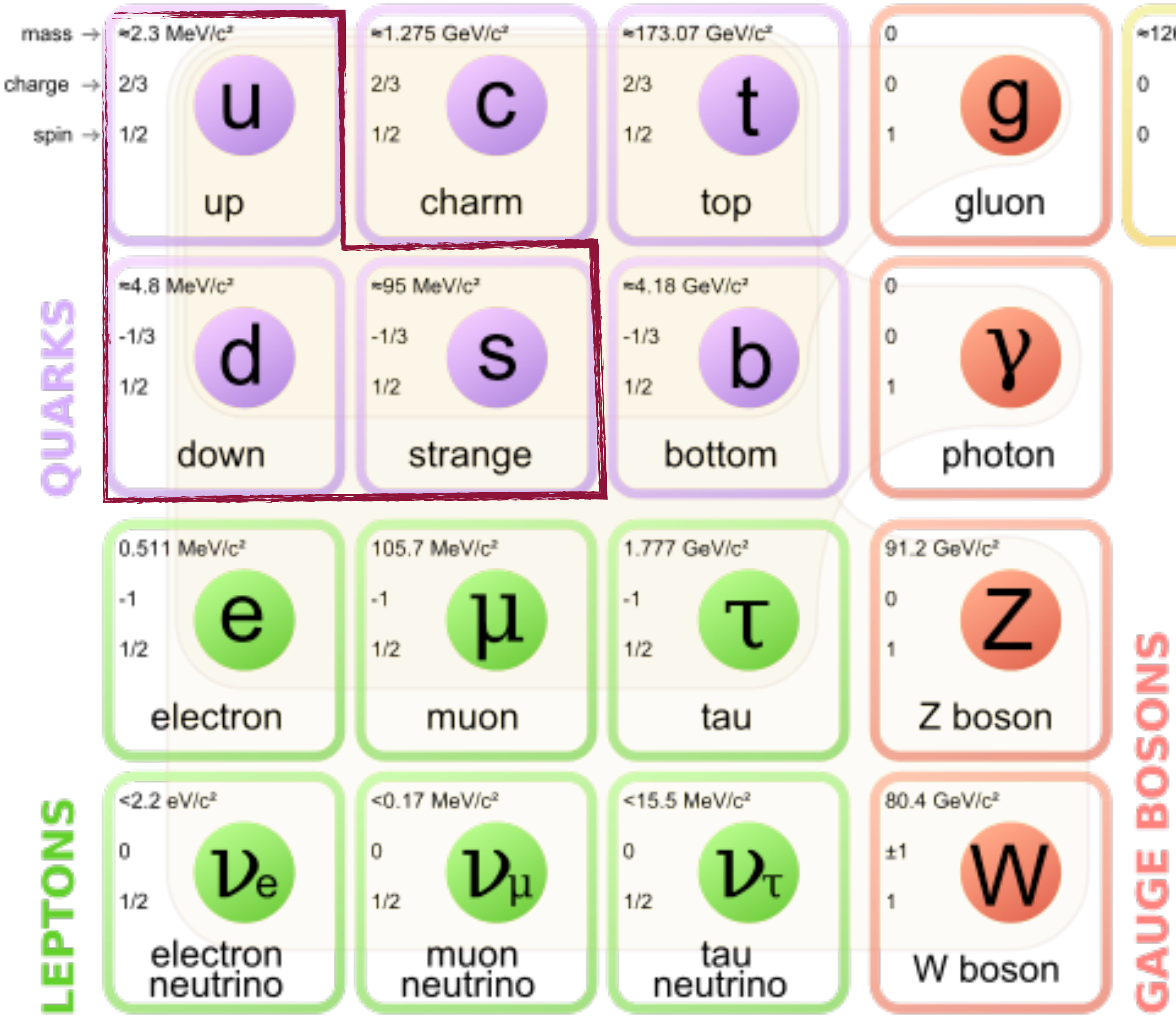
Branching fraction limit (95% CL)	Observed	Expected
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	4.9	$5.0^{+2.4}_{-1.4}$
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	5.9	$6.2^{+3.0}_{-1.7}$
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	5.7	$5.0^{+2.5}_{-1.4}$
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	2.8	$2.8^{+1.2}_{-0.8}$
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	1.7	$3.8^{+1.6}_{-1.1}$
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	4.8	$3.0^{+1.3}_{-0.8}$

- Substantial improvement with respect to Run 1 results
  - Expected limit improved by factor 3-4 for Higgs and by 60-80% for Z
- Current limits imply: $-165<\kappa_c<200$
  - Predictions on the direct amplitude have been revised downwards as a function of time

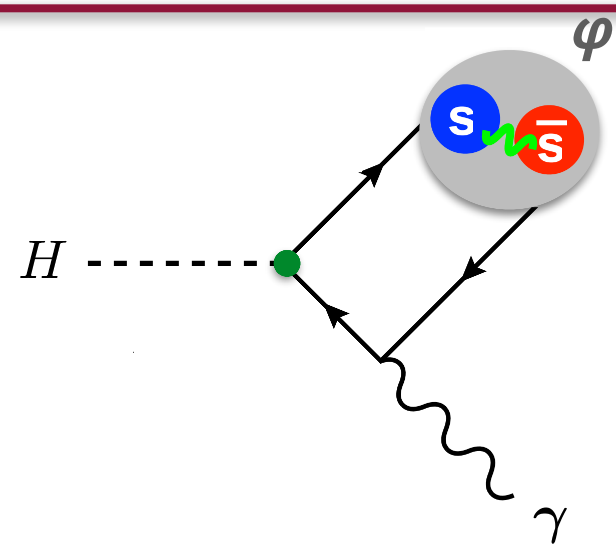
c.f Phys.Rev. D96 (2017) 116014 to PRD90 (2014) 113010

h/Z→J/ψγ and h/Z→Υ(nS)γ: Results




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

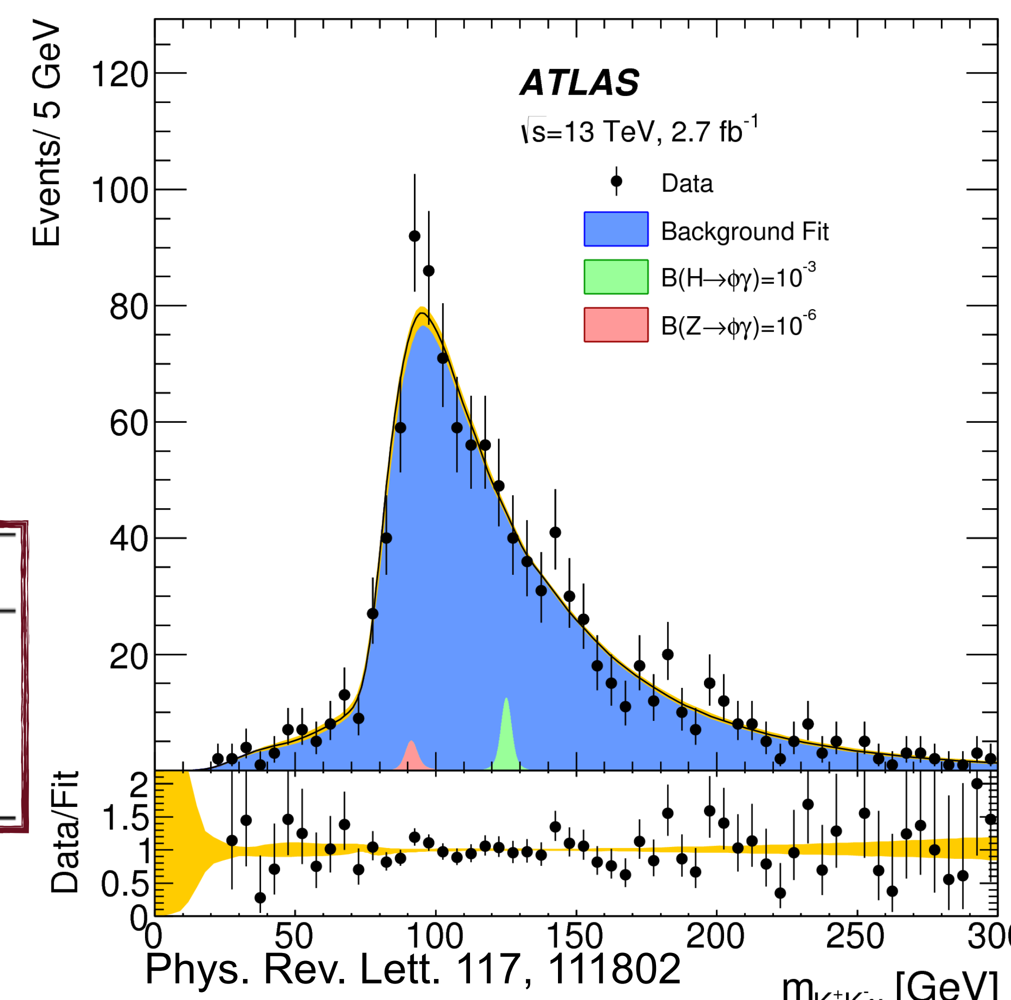
M. Aaboud *et al.*[*]
(ATLAS Collaboration)
(Received 14 July 2016; published 9 September 2016)

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



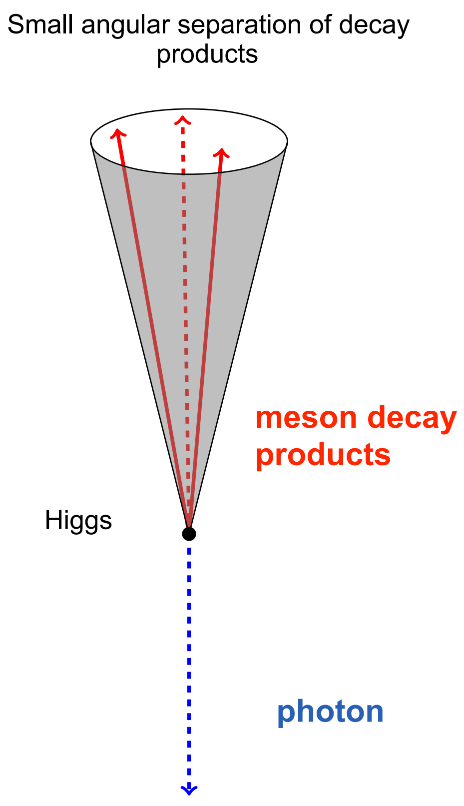
Phys. Rev. Lett. 117, 111802

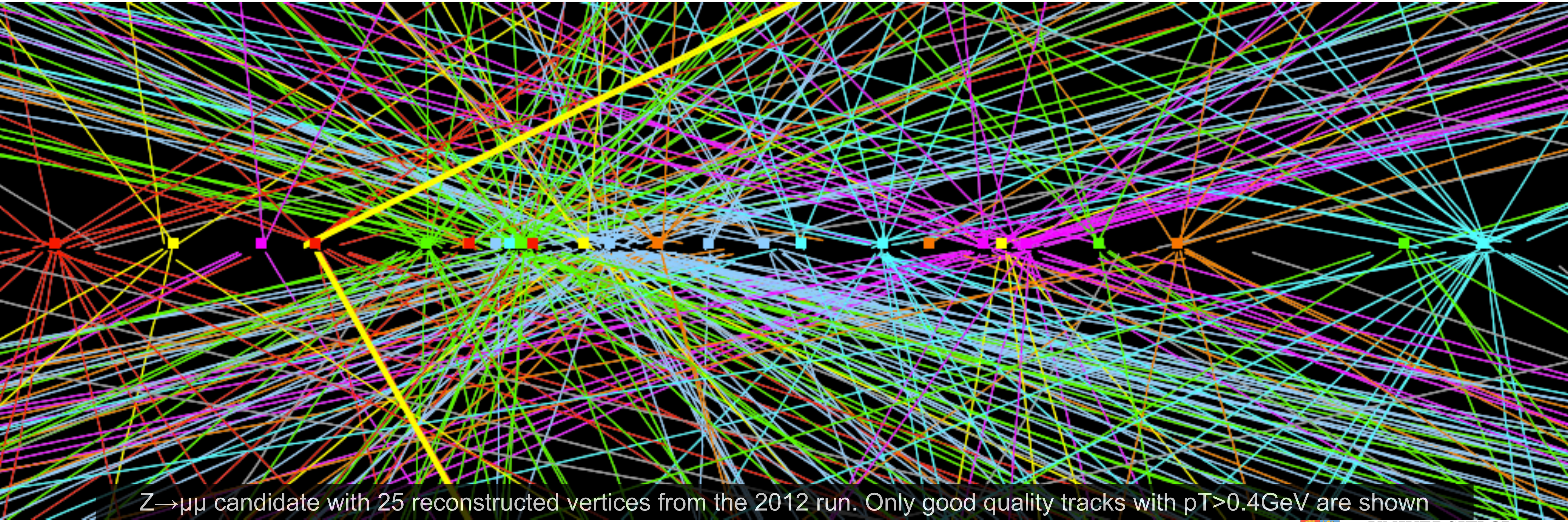
- **New results** with up to 35.6/fb
  - updated h/Z→φγ
  - added h/Z→ργ probing up- and -down quark couplings to Higgs boson

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:**
  - $\varphi \to K^+K^-$, BR=49%
  - $\rho \to \pi^+\pi^-$, BR~100%
- **Small opening angles between decay products**
  - Particularly for $\varphi \to K^+K^-$
  - Tracking in dense environments





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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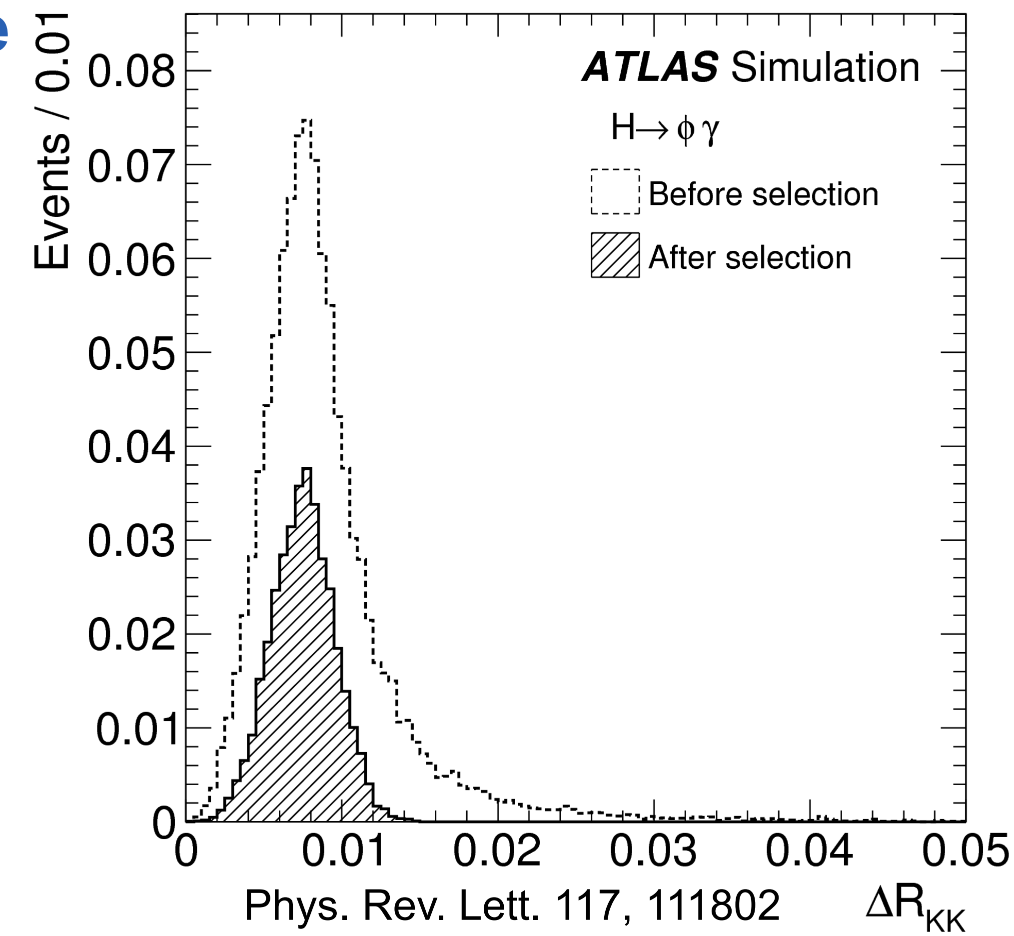
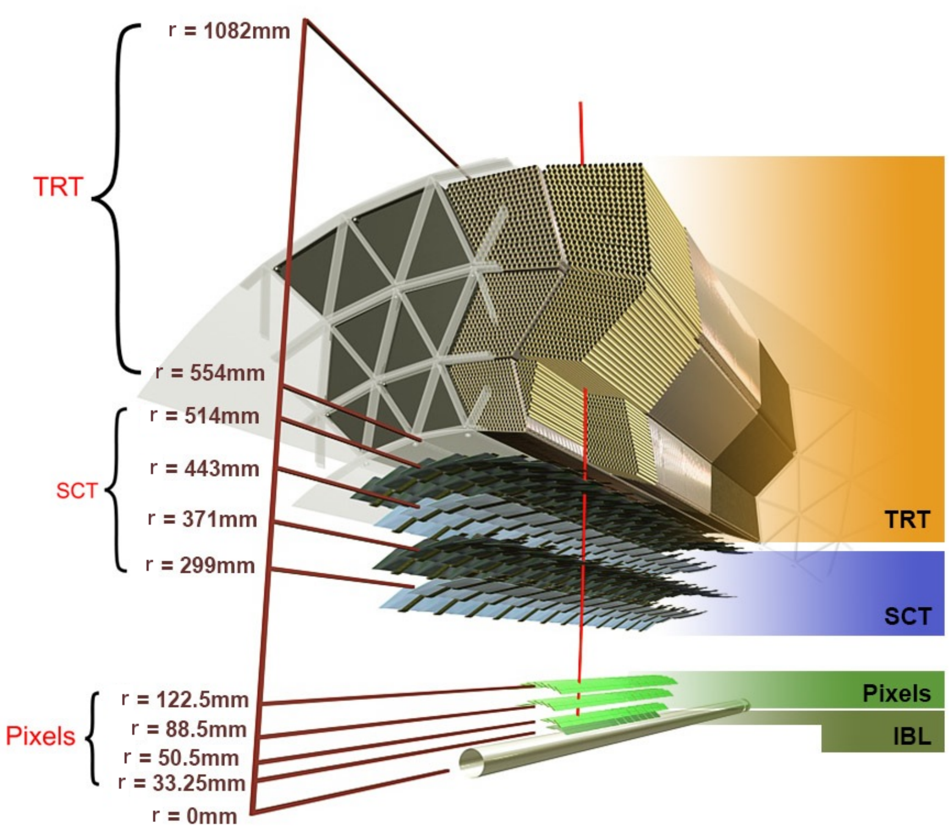
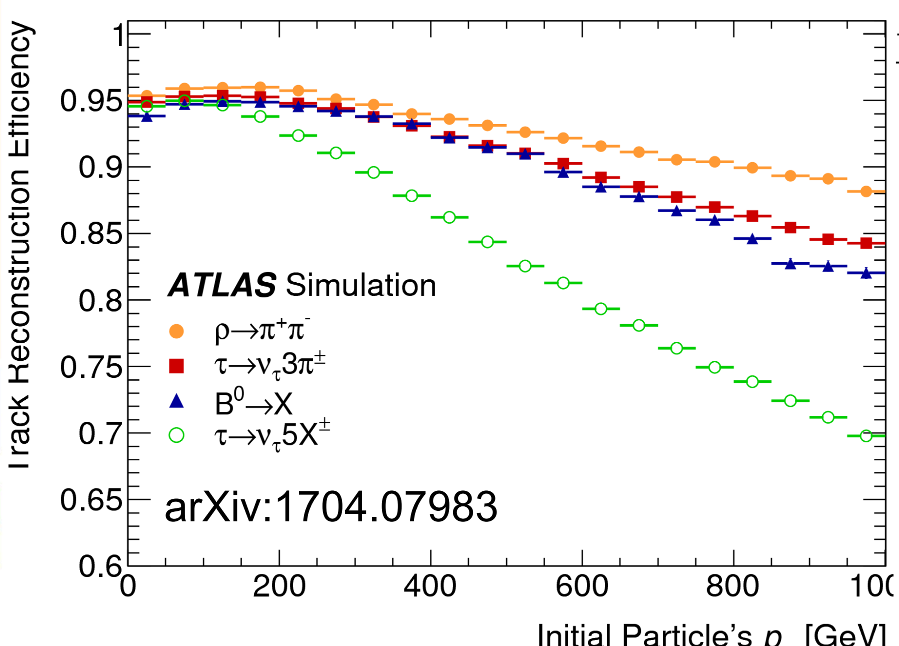
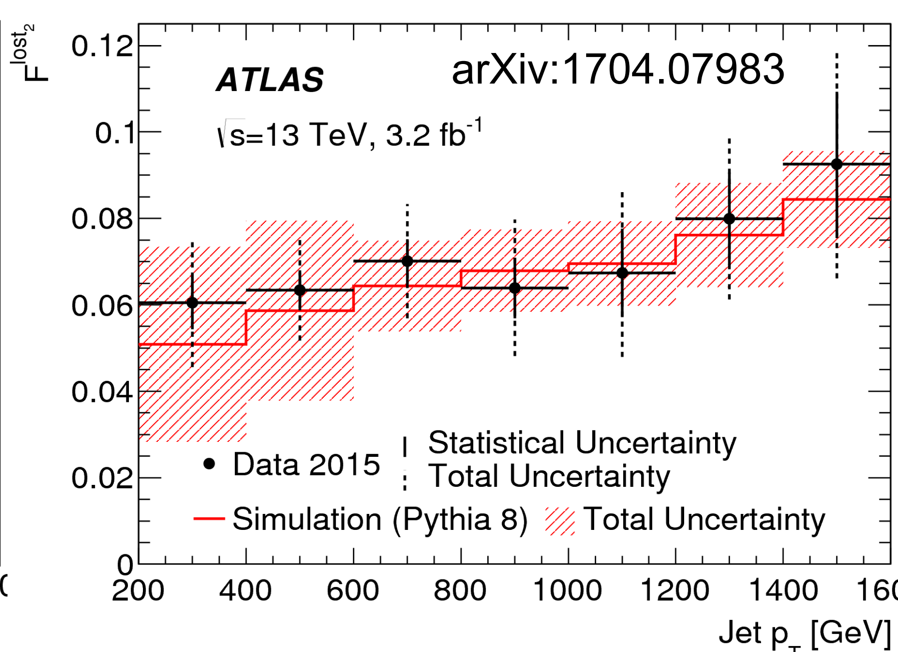


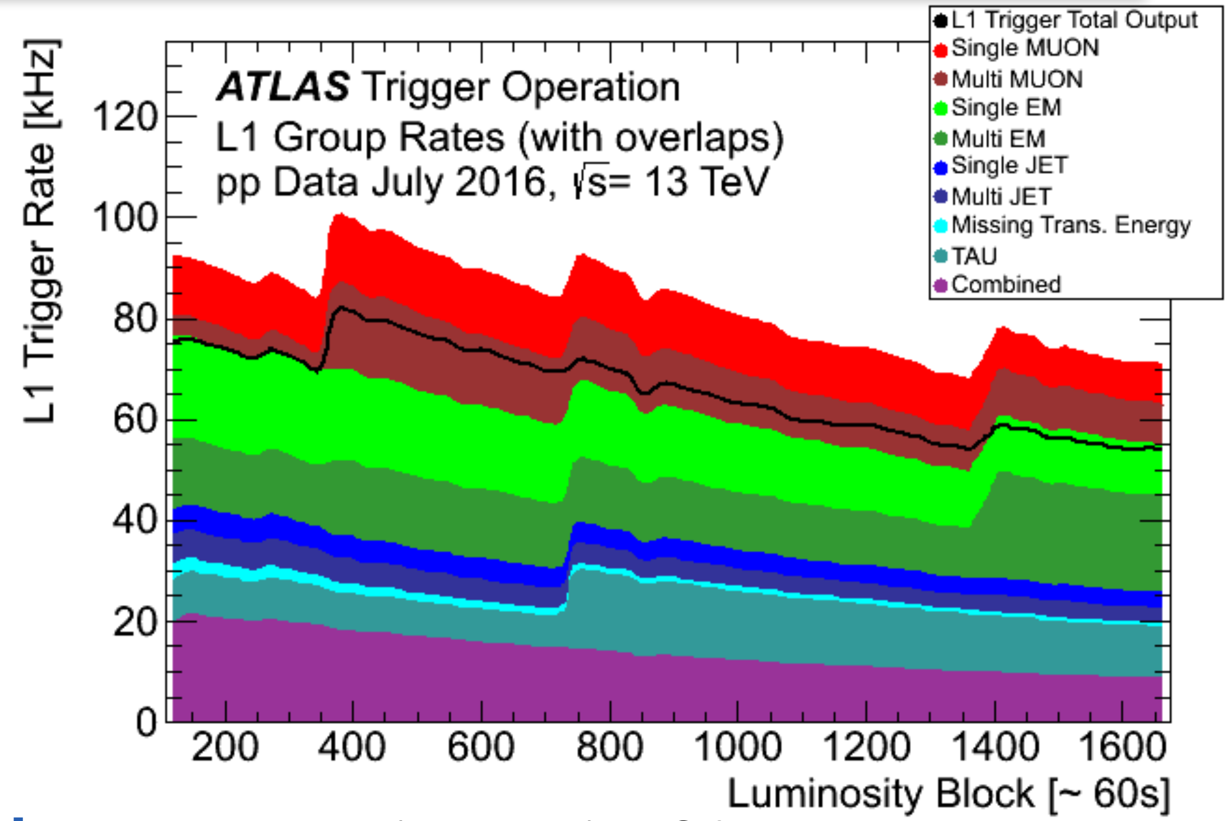




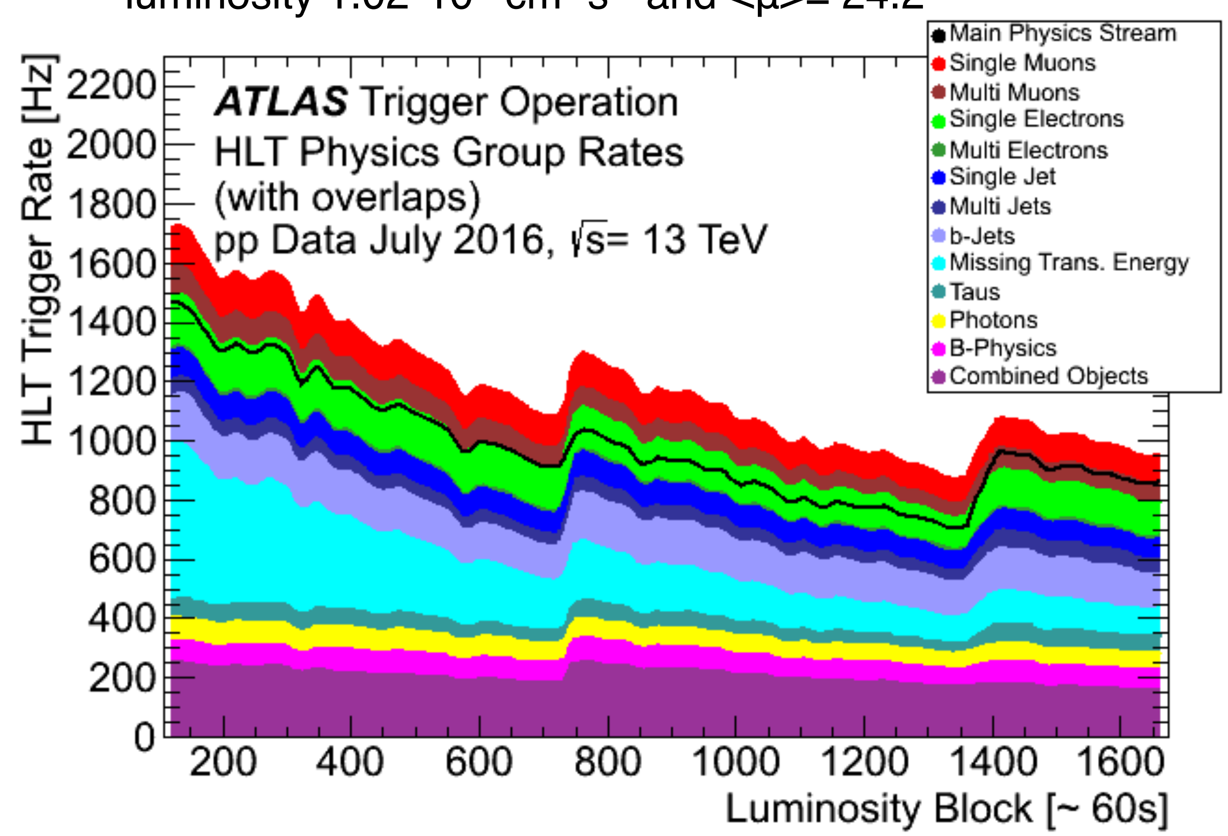


Trigger Strategy

- ATLAS features a **two-level trigger system**
  - 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**
  - Dedicated analysis-specific trigger only allowed a small fraction
    - typically well below 10 Hz
  - Highly selective trigger design required

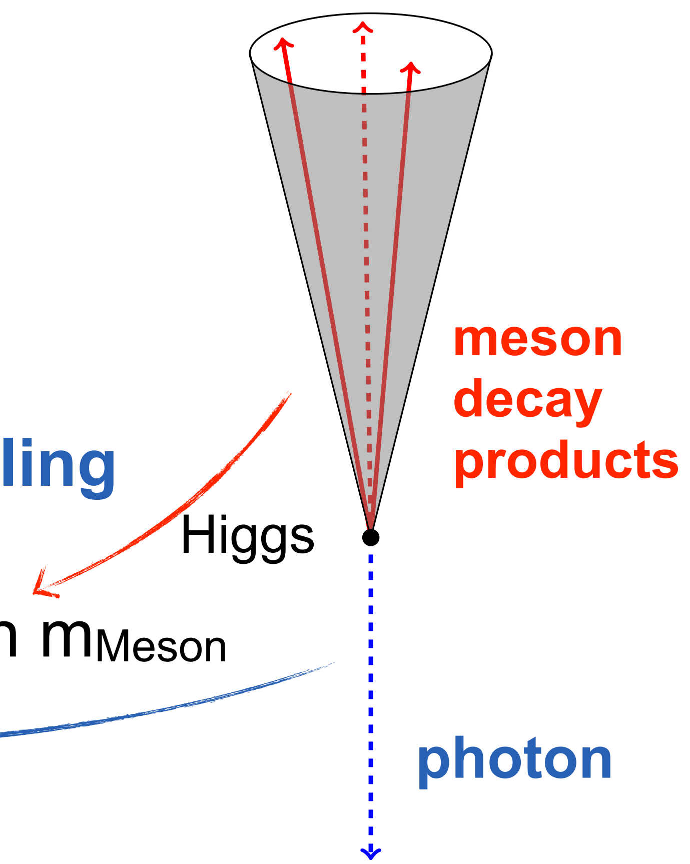


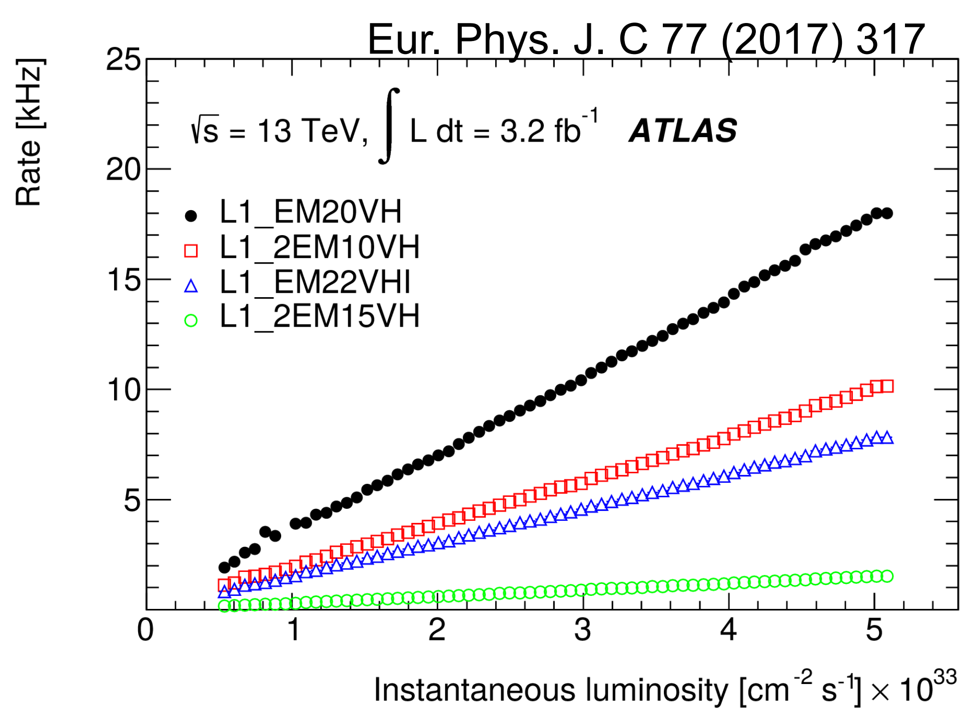
Trigger rates (July 2016) LHC fill with peak luminosity $1.02 \times 10^{34} cm^{-2}s^{-1}$ and $\langle\mu\rangle = 24.2$

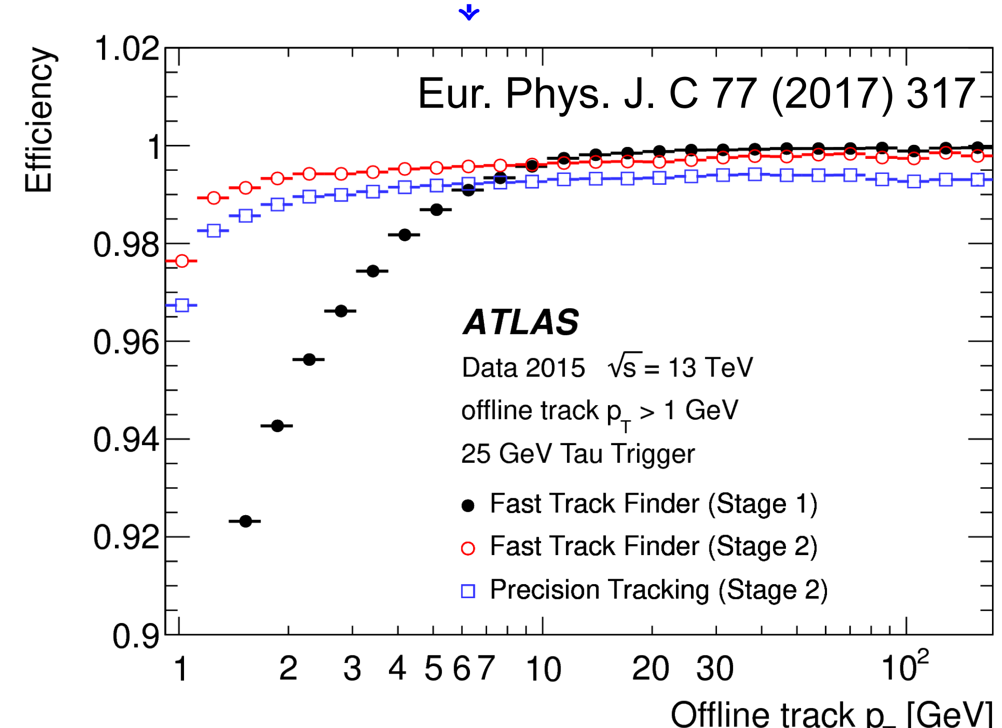


Trigger Strategy

- **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)





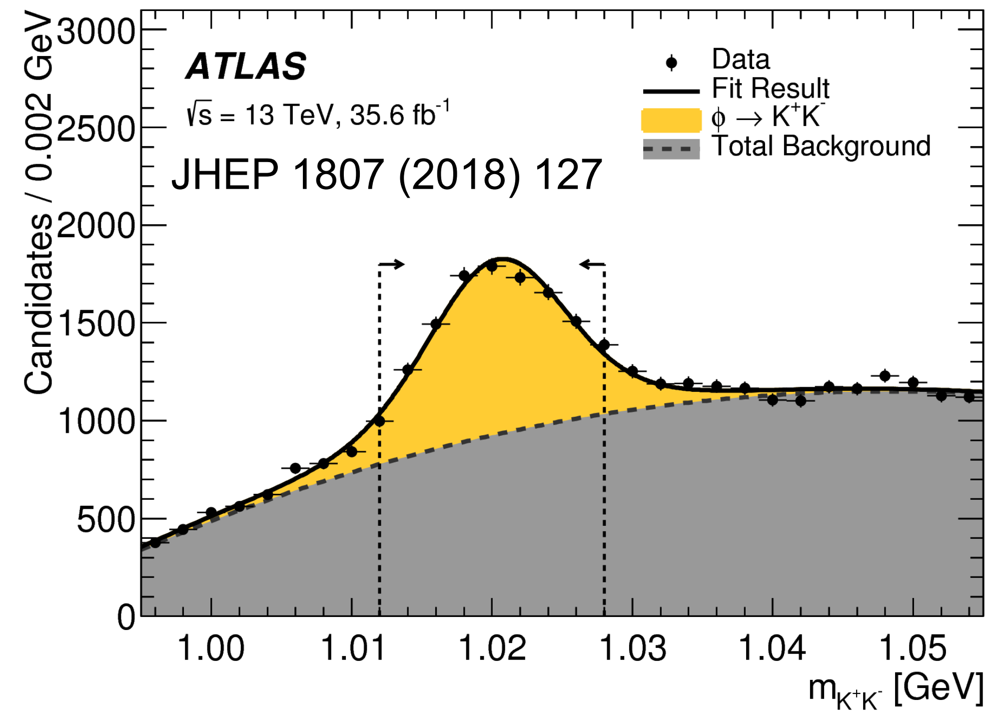


Event Selection

Tracks

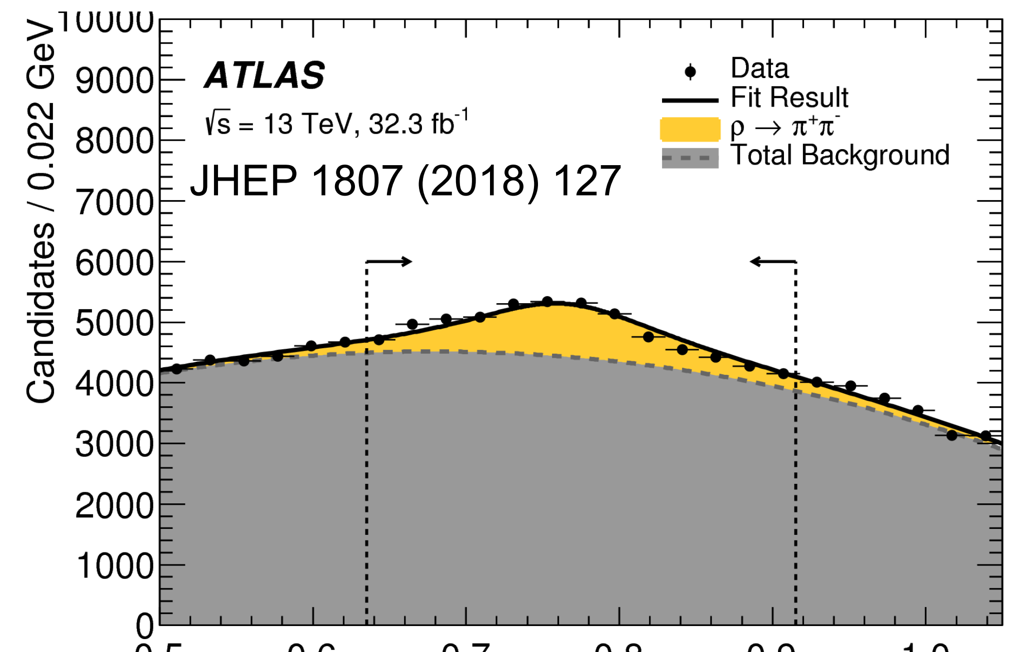
- No particle identification available at pT range of interest, all tracks considered K/π
- Two opposite charged tracks
  - Leading pT>20GeV, sub-leading pT>15 GeV
- di-track consistent to m_{φ}±8 MeV or m_{ρ}±140 MeV
- track-based isolation
- di-track system must satisfy:

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



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



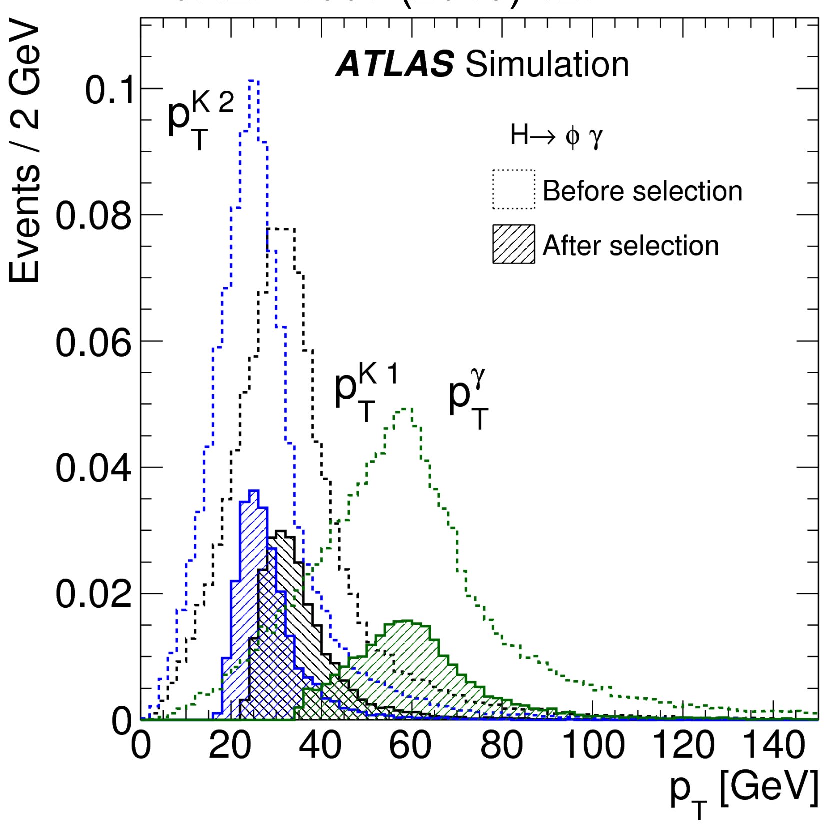
Full event selection w/o m_{KK} requirement

Total signal acceptance/efficiency

- h(Z)→φγ→K^+K^-γ ~ 17% (8%)
- h(Z)→ργ→$\pi^+\pi^-$γ ~ 10% (0.4%)

Efficiency and Resolution

JHEP 1807 (2018) 127



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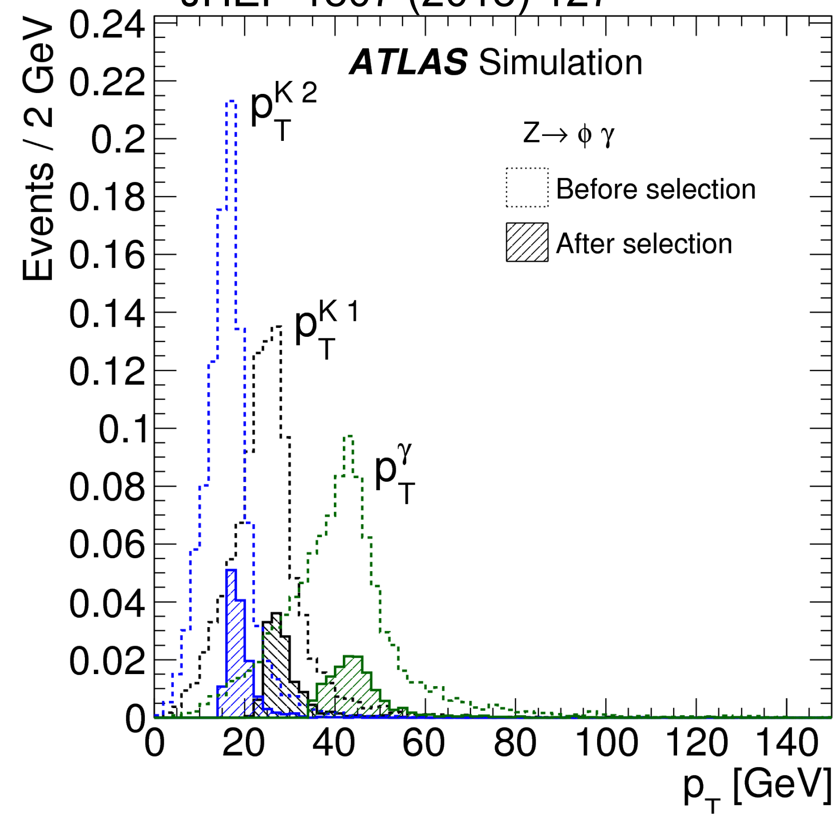

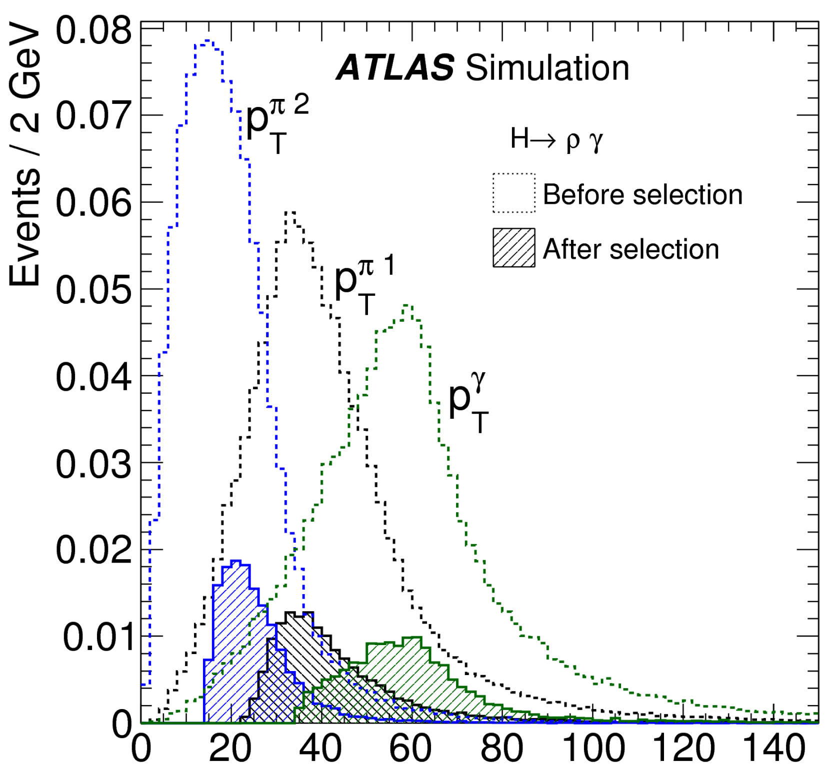

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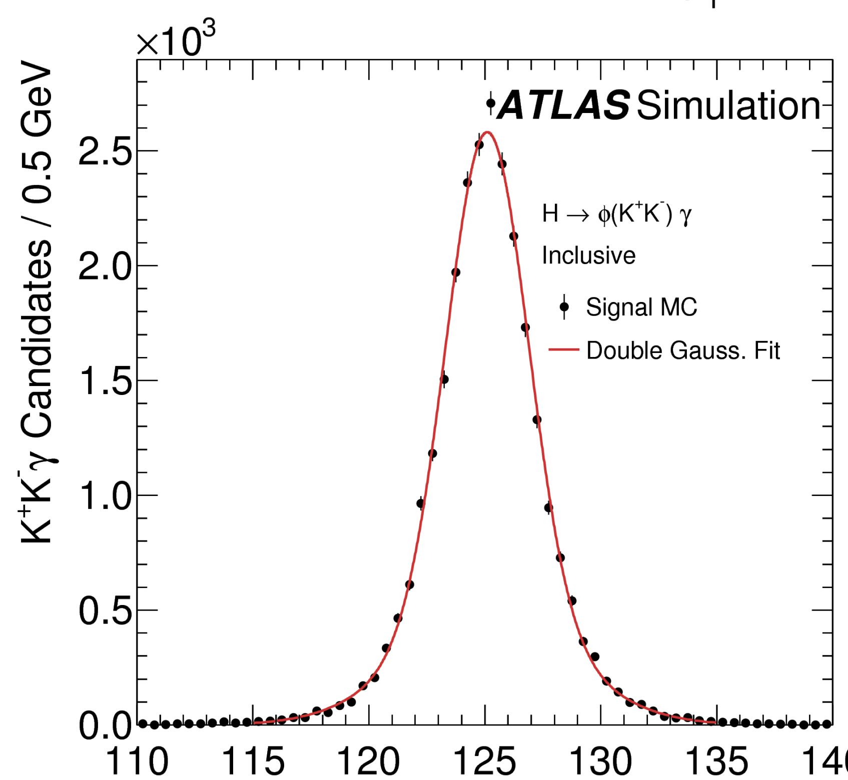

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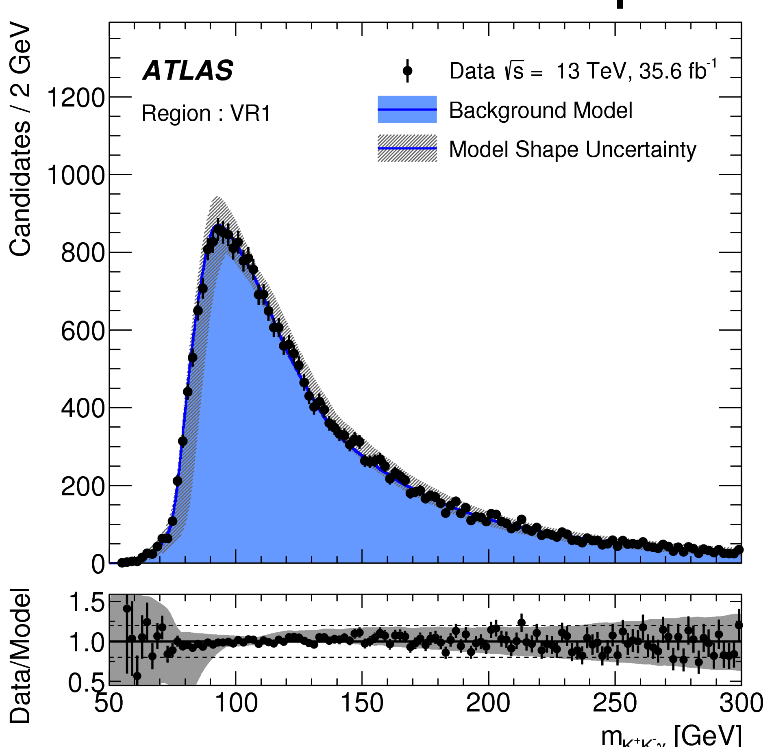
- **No categorisation**
- **Mass resolution ~1.8%**
- **Signal Model**
  - Higgs: double Gauss
  - Z: double Voigt with eff. corr.
- **Signal Systematic Uncertainty**

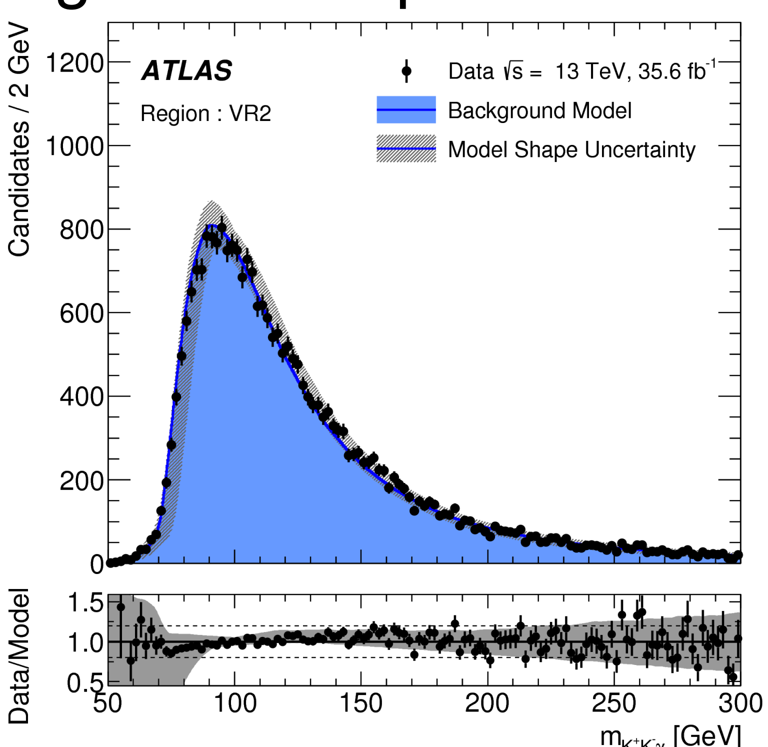
Source of systematic uncertainty	Yield uncertainty
Total H cross section	6.3%
Total Z cross section	2.9%
Integrated luminosity	3.4%
Photon ID efficiency	2.5%
Trigger efficiency	2%
Tracking efficiency	6%

Background Modelling

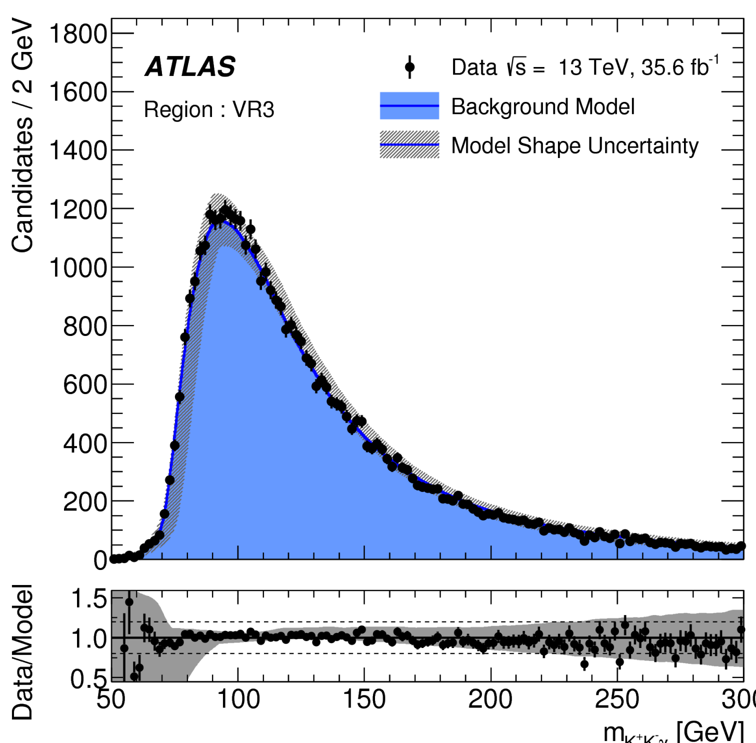
- **Dominated by QCD production** γ+jet and multi-jet events
- **Exclusive "peaking" backgrounds** (e.g. $h/Z \rightarrow \mu\mu\gamma_{FSR}$) **estimated to be negligible**
- **Non-parametric data-driven background model;** common for ATLAS Qγ searches
  - Begin with loose sample of candidates
  - Model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



pT_{Meson}



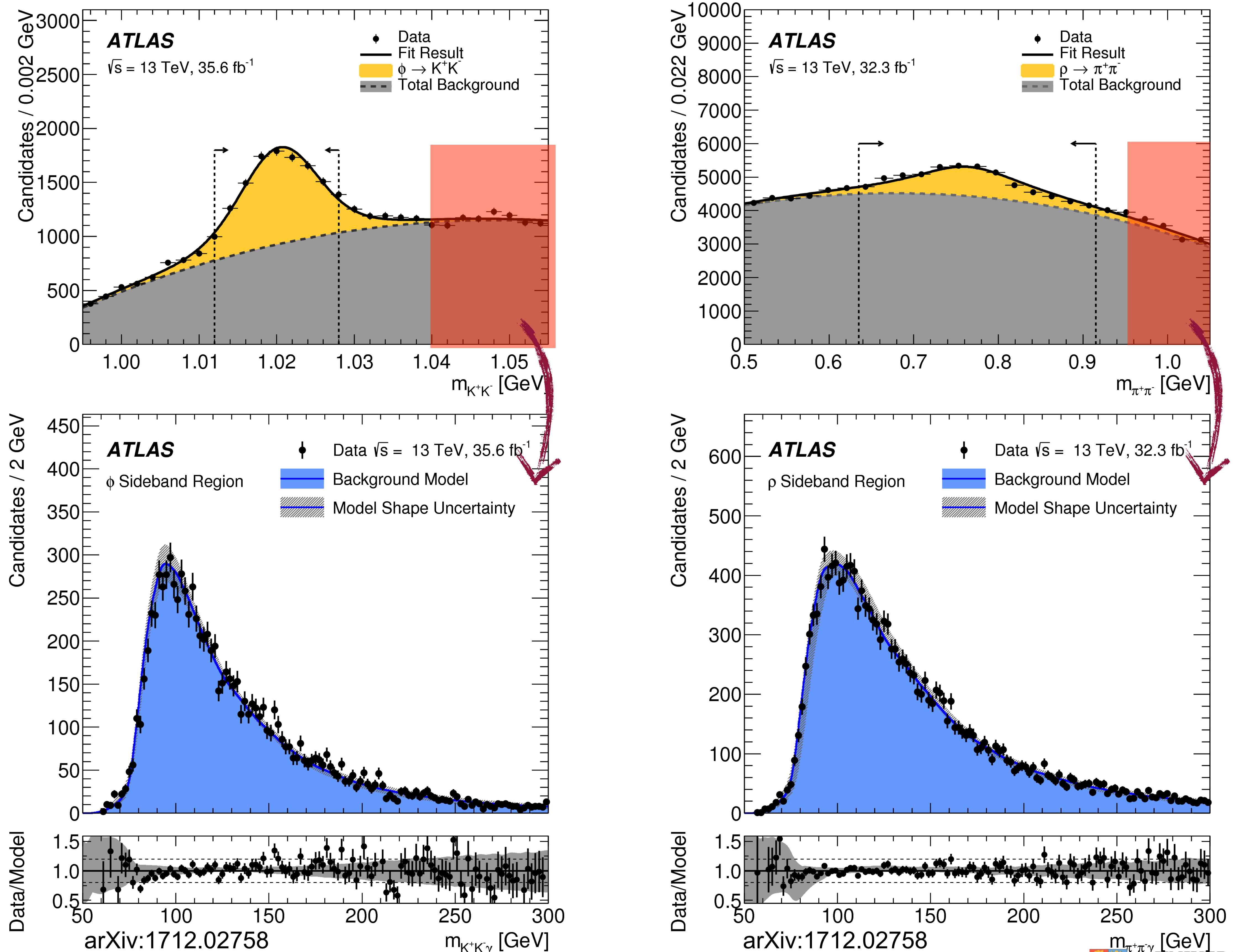
γ-isolation



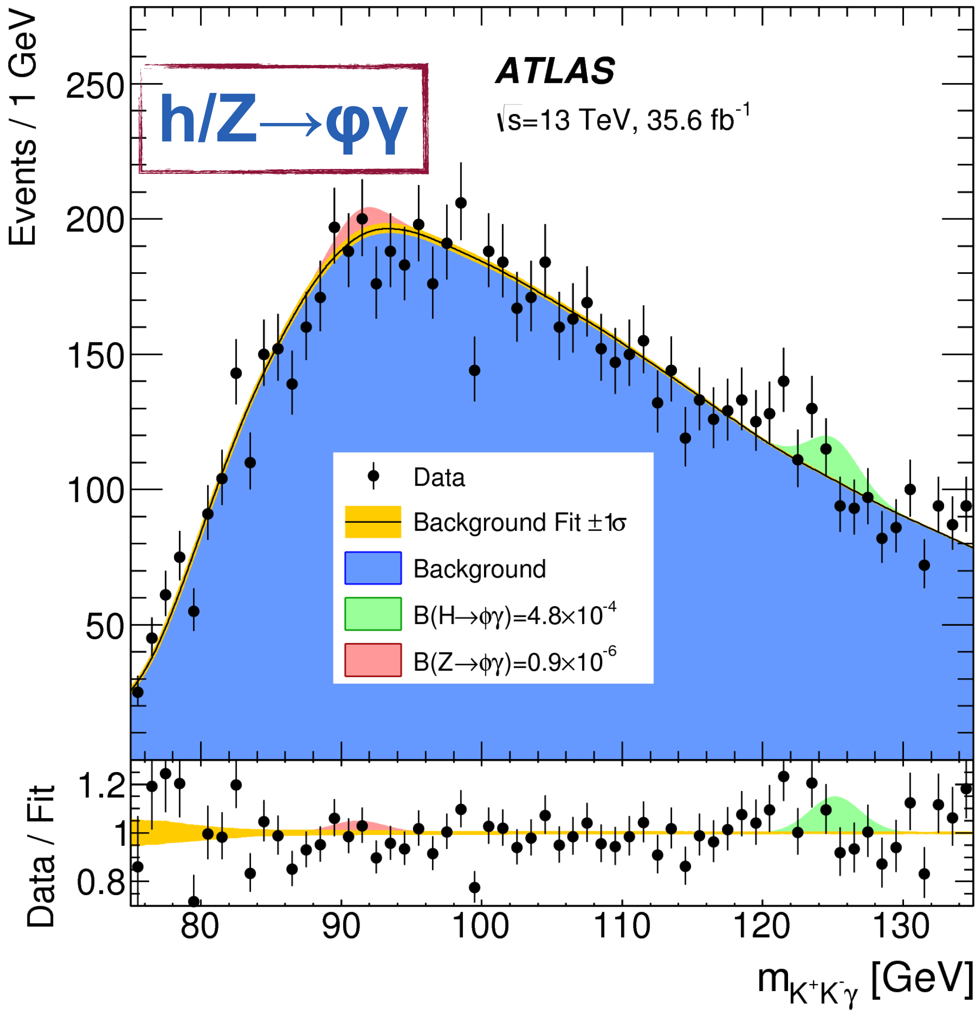
Meson-isolation

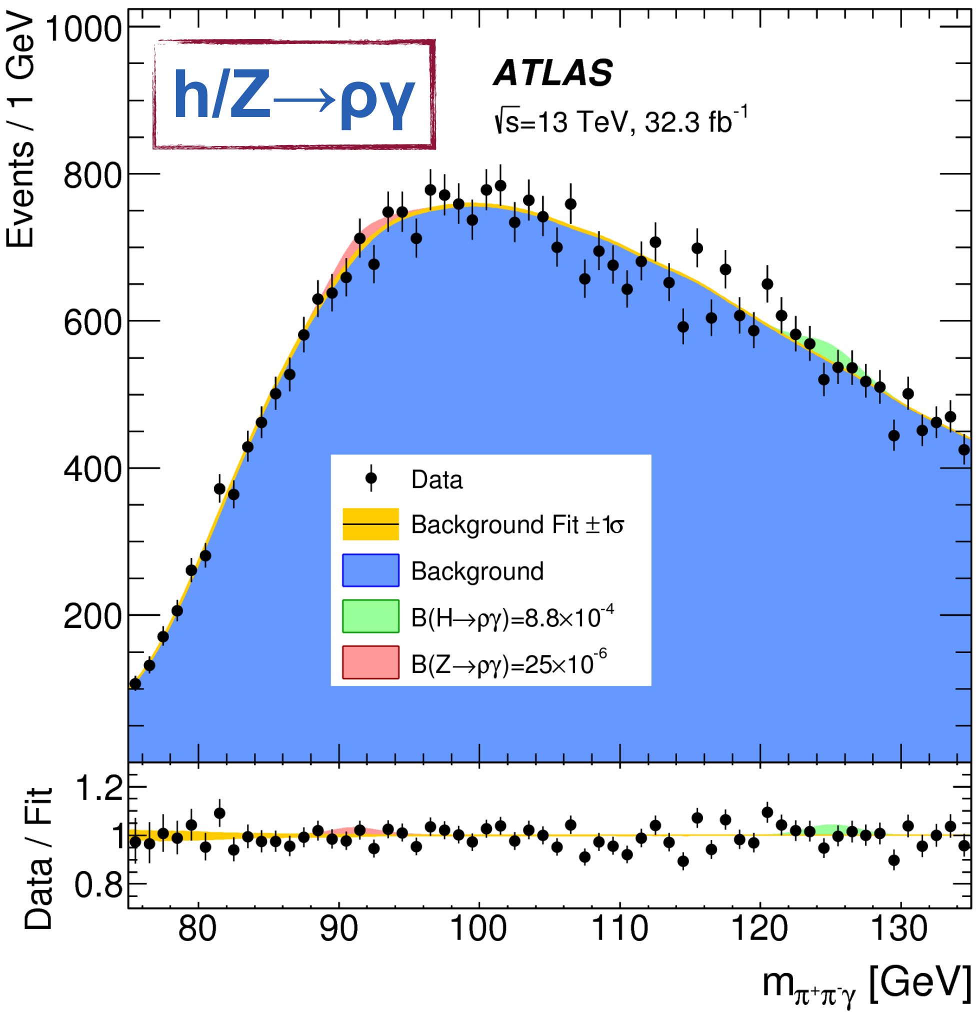
arXiv:1712.02758

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
    - $h \to \phi\gamma < 25.3$ 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

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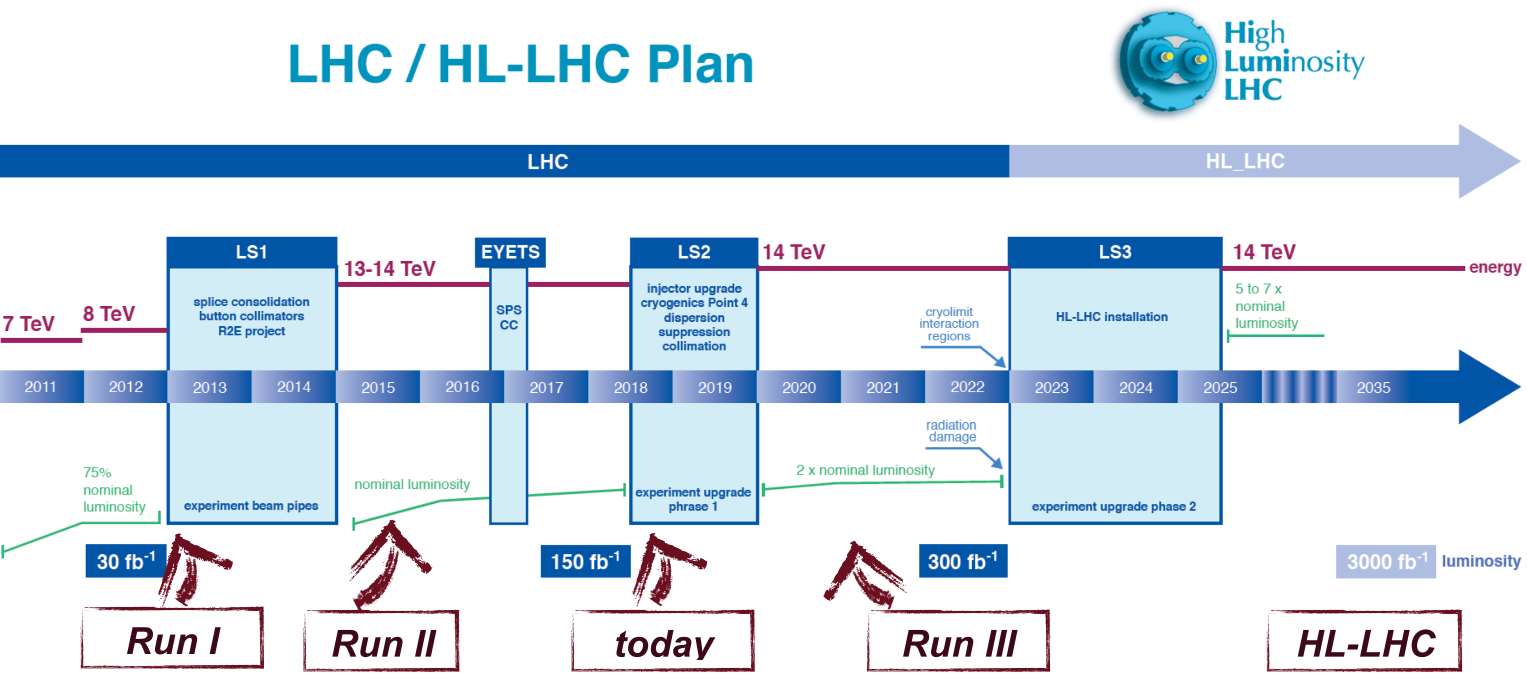
x3 improvement in expected limits with respect to 2.7/fb result [PRL 117, 111802]

HL-LHC and beyond



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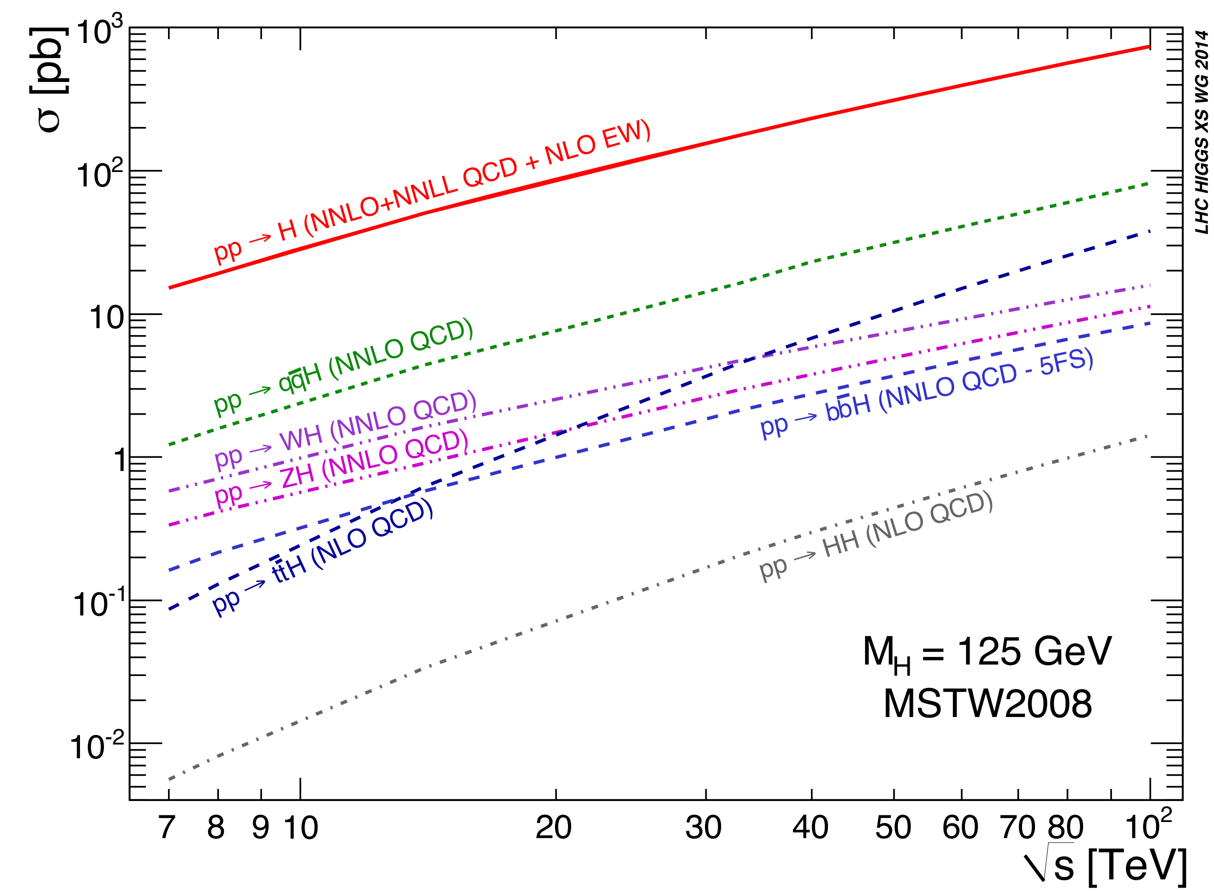
	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)\,[10^{-6}]$		$\mathcal{B}(Z \to J/\psi\gamma)\,[10^{-7}]$
	Cut Based	Multivariate Analysis	Cut Based
$300\ \mathrm{fb}^{-1}$	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
$3000\ \mathrm{fb}^{-1}$	55^{+24}_{-15}	44^{+19}_{-12}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

	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

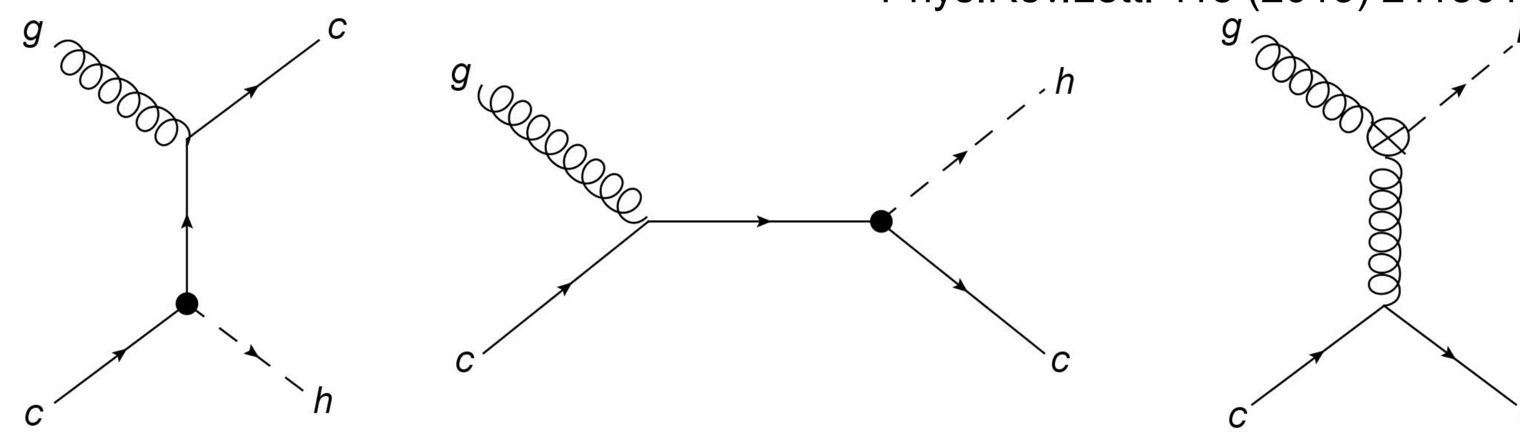
- HL-LHC is a Higgs boson factory
  - $\mathcal{O}$(200M) Higgs bosons produced
- HL-LHC projections for h/Z→J/ψγ
  - Simple and, relatively, clean final state
  - Small branching ratio, few events expected
  - At SM sensitivity $h\to\mu\mu\gamma_{FSR}$ contribution ~3×h→J/ψγ and ($Z\to\mu\mu\gamma_{FSR}$ 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

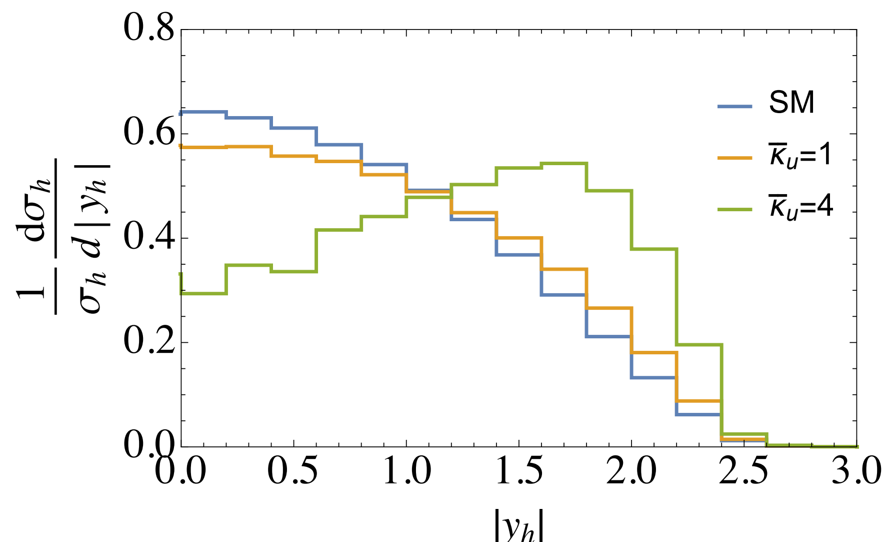


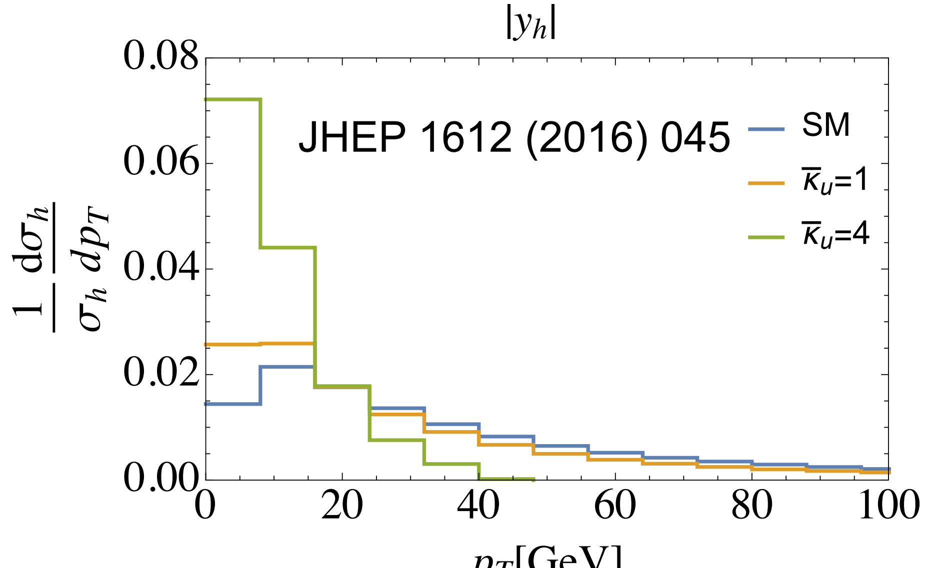
pp→ch(→γγ) 3000 fb^{-1}

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%]

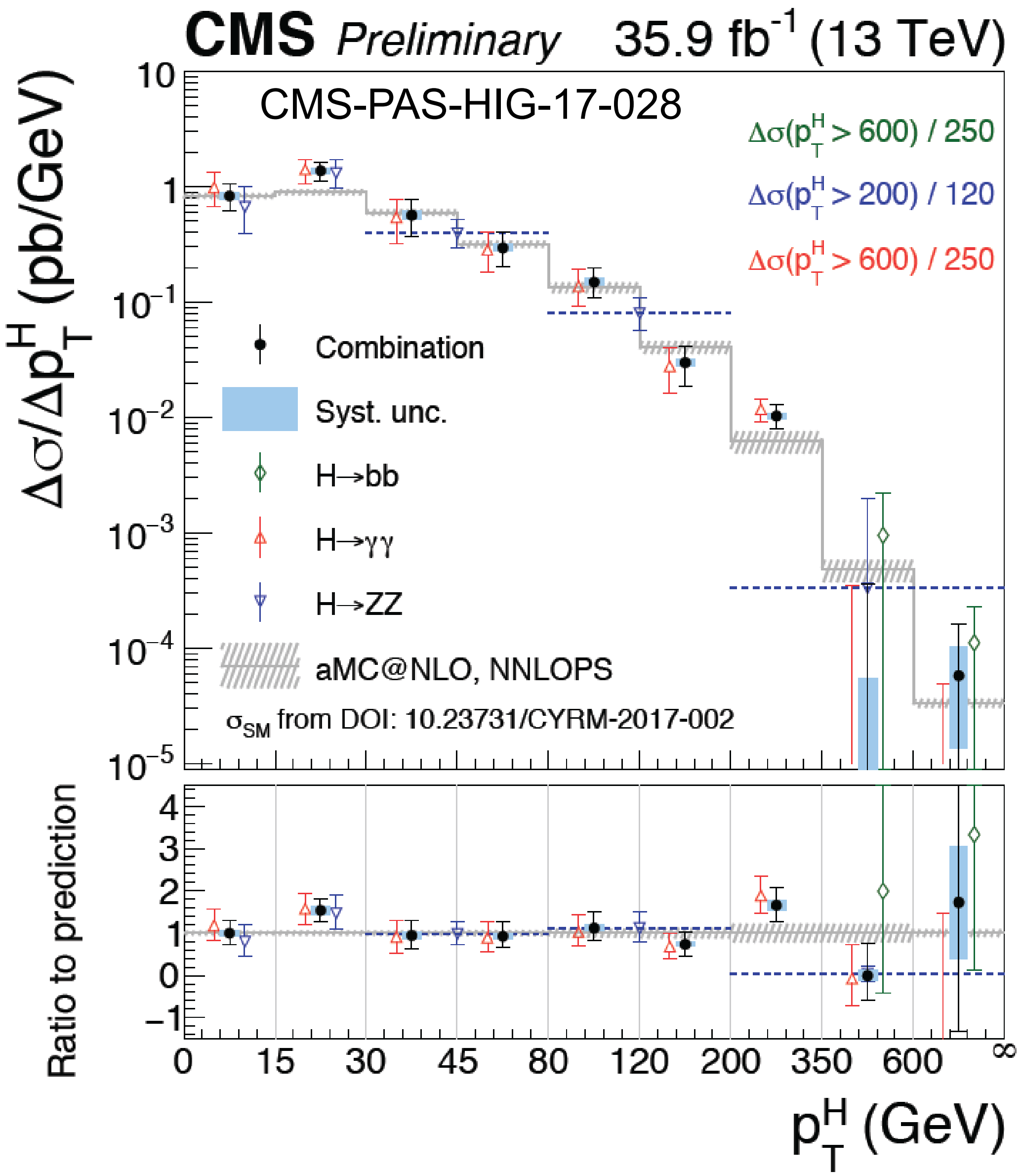




- Derive constraints on Higgs boson-quark couplings through the **Higgs boson kinematic distributions**
  - For example pT_h or y_h
- Phenomenological study suggests that couplings to up- and down-quarks could be constrained to <0.4 of the b-quark Yukawa at HL-LHC.

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

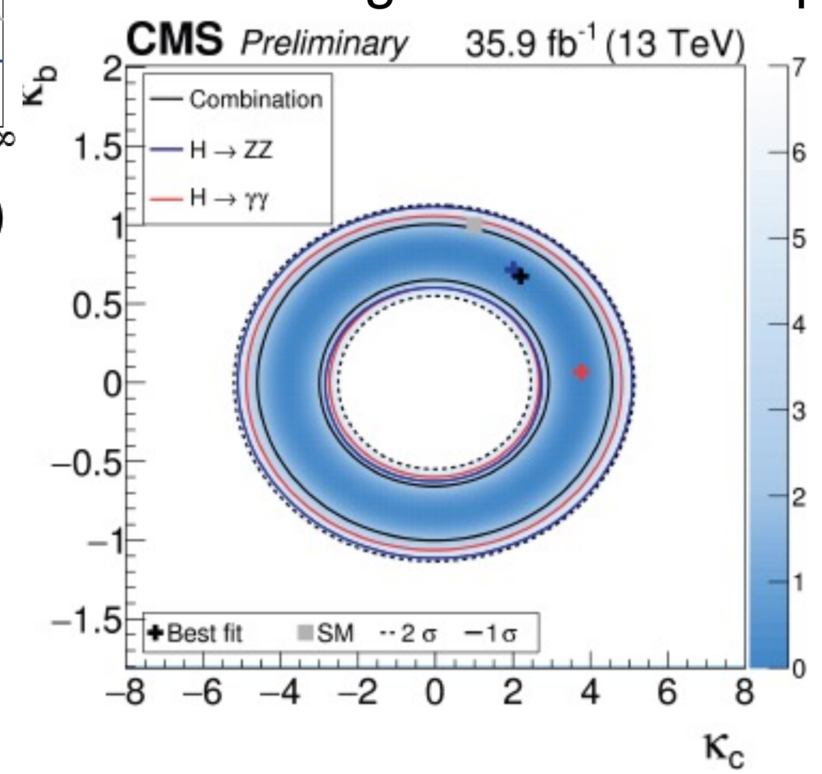
The future is now: kinematic distributions



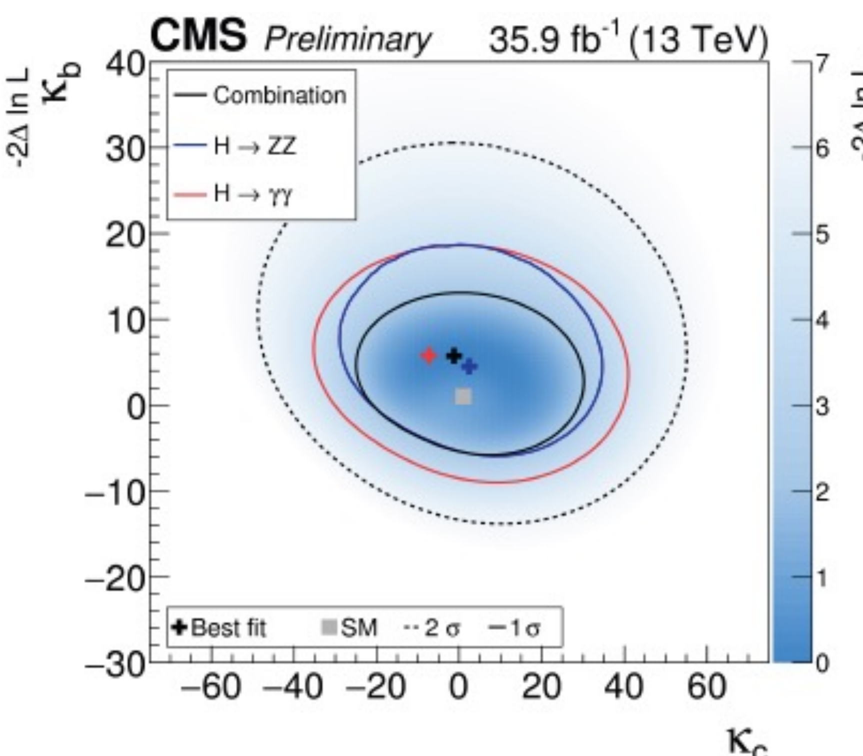
- Inputs: h→γγ, h→ZZ→4l
  - 13 TeV and 35.9 fb^{-1}
  - boosted h→bb sensitive pTH>350 GeV not used
- MADGRAPH5 aMC@NLO
  - ggF reweighted to NNLOPS
- Pt spectrum including light quark effects
  - Calculations from PRL 118 (2017) 121801

- Limits on κ_c at 68% CL:
  - Observed: (-18.0,22.9)
  - Expected: (- 15.7,19.3)

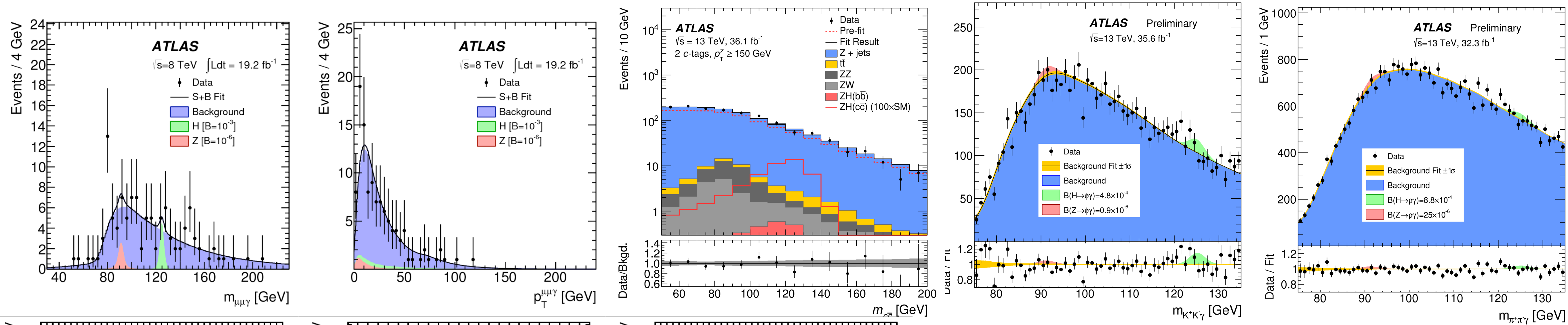
BR scaling with couplings
Assumes full knowledge of Higgs decays, no BR_{BSM}, full understanding of resolved loop

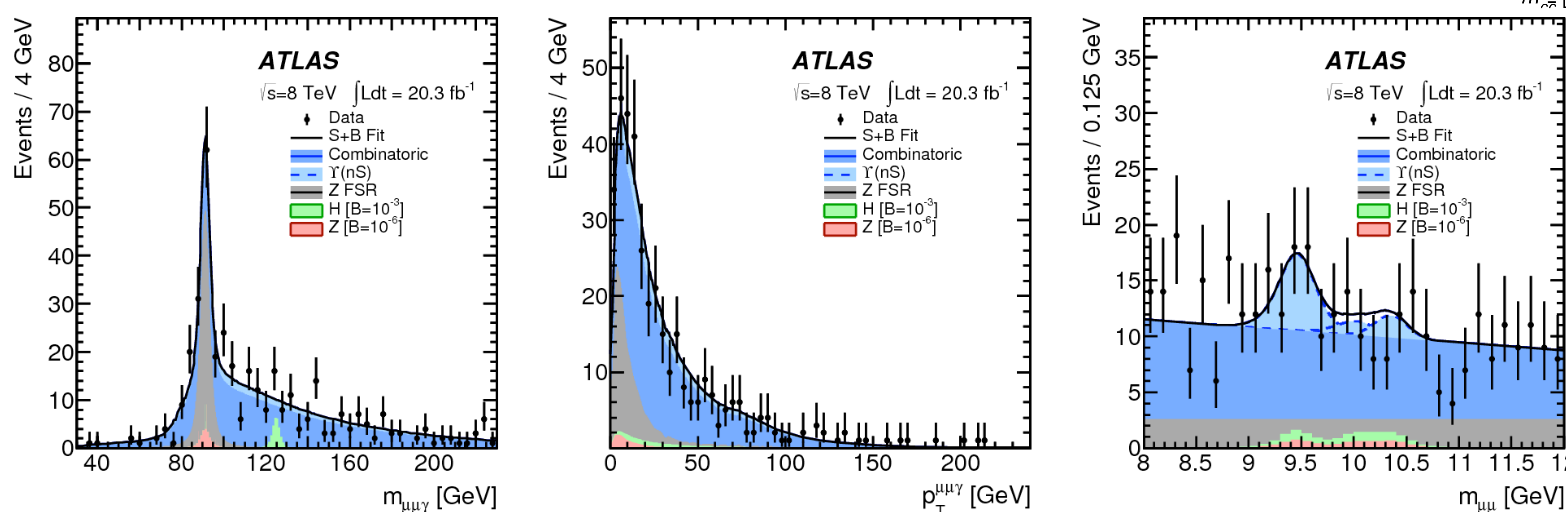


BR freely floating
Constraints only from shape normalisation profiled

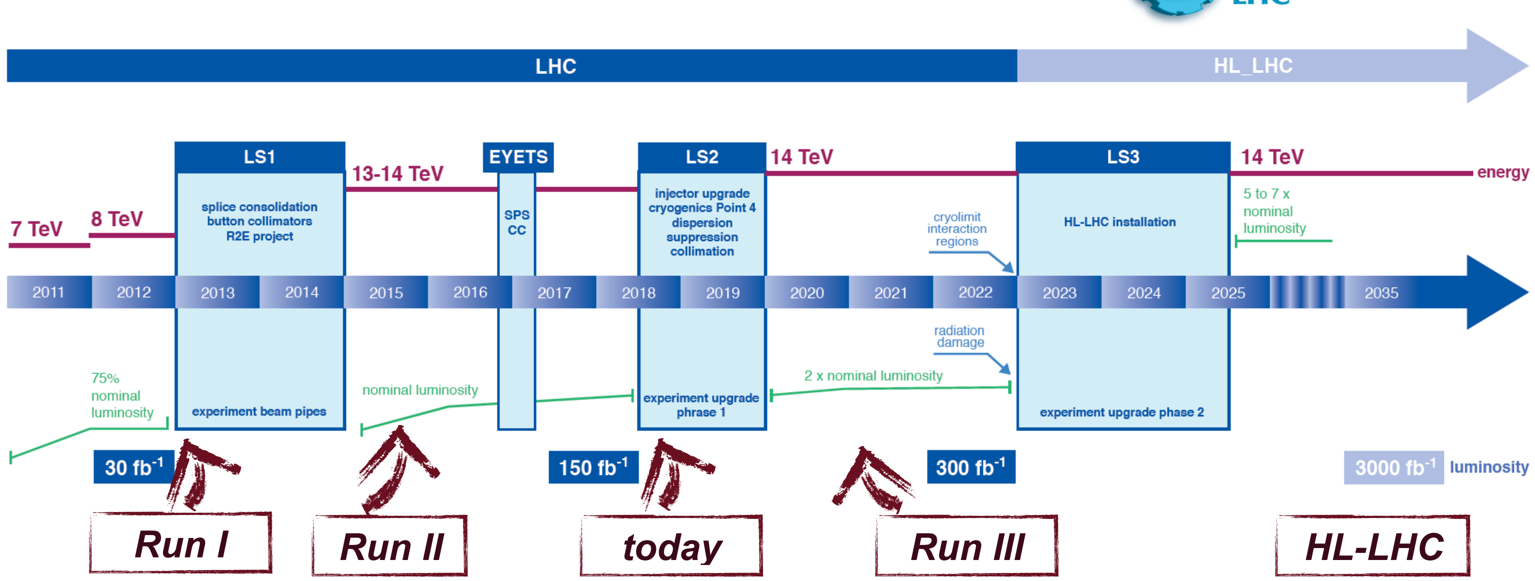


Summary





LHC / HL-LHC Plan



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!