Prospects of combined measurements of Higgs boson properties

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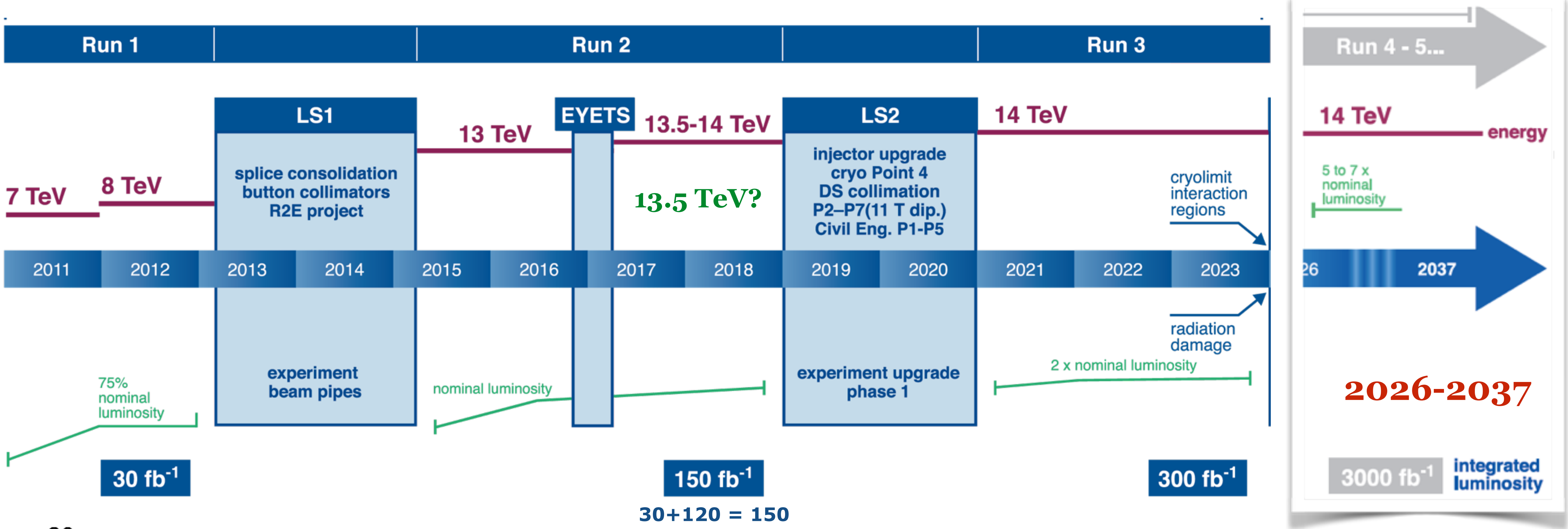
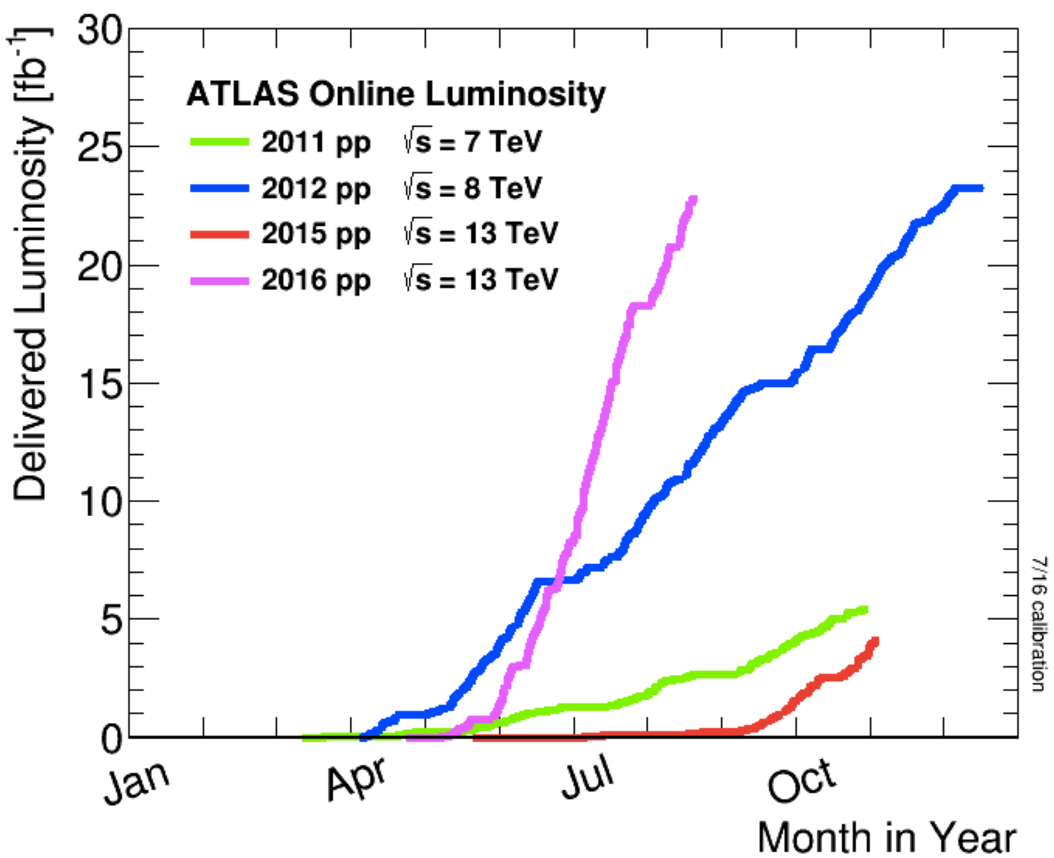
Outline

- Outline
- LHC Schedule
- Run-1 highlights of Higgs boson measurements
- Run-2 first Higgs results
- Projections of Higgs boson results
  - LHC and ATLAS detector upgrades
  - Mass
  - Couplings
  - Rare decays
  - Di-Higgs production

LHC Schedule



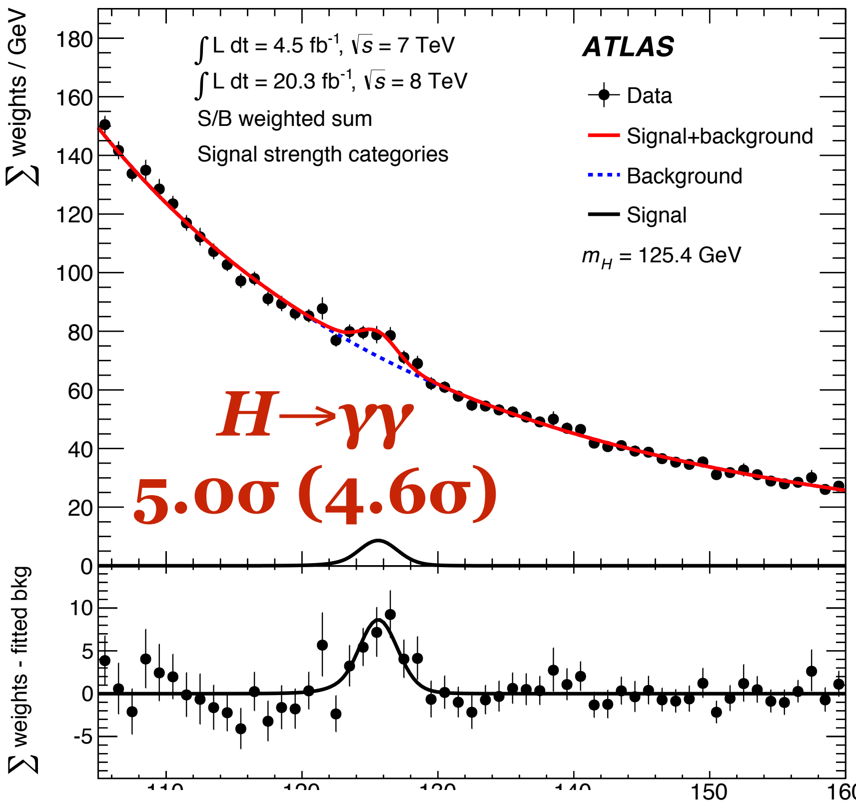


- LHC operates very well:
  current data acquisition exceeds expectation
- Higher centre-of-mass energy means larger cross sections
  ggF, VBF, *VH*: ~ ×**2**, ***ttH*** ×**4** (similar for associated backgrounds)
- Expect
  - **30 fb^{-1} @ 13 TeV** by end of **2016**
  - **120 fb^{-1} @ 13-13.5 TeV** by end or **Run-2, 2018**
  - **~300 fb^{-1} @ 13-14 TeV** by end of **Run-3, 2023**
  - **~3000 fb^{-1} @ 14 TeV**, **HL-LHC, 2026-2037**

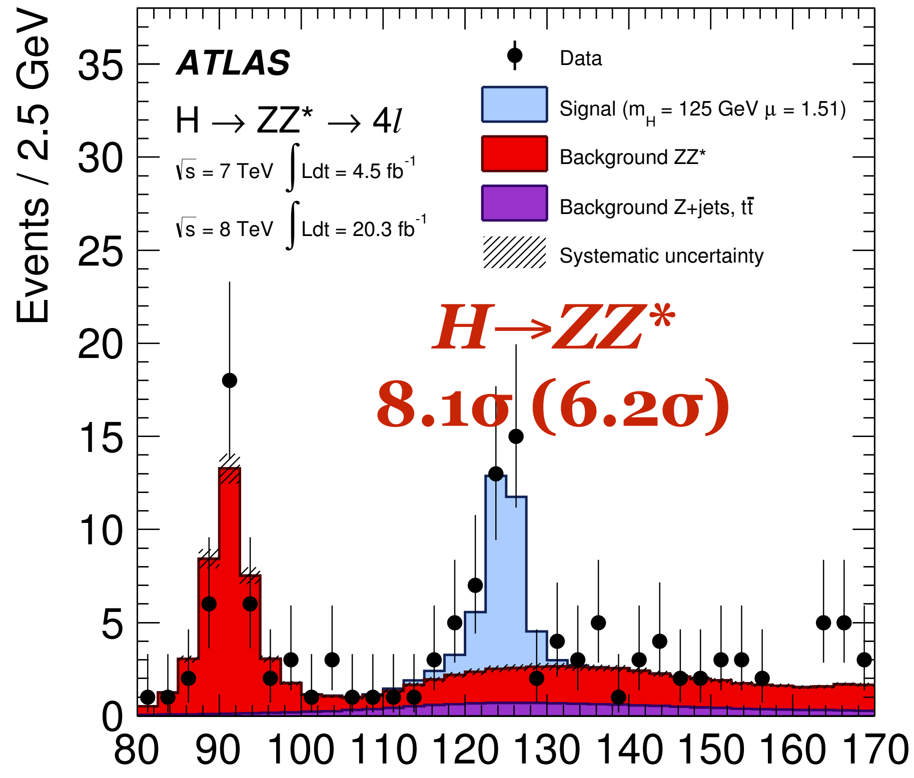
I. Run-1 highlights

based on ~25 fb-1 7-8 TeV data

Run-1 Higgs boson highlights

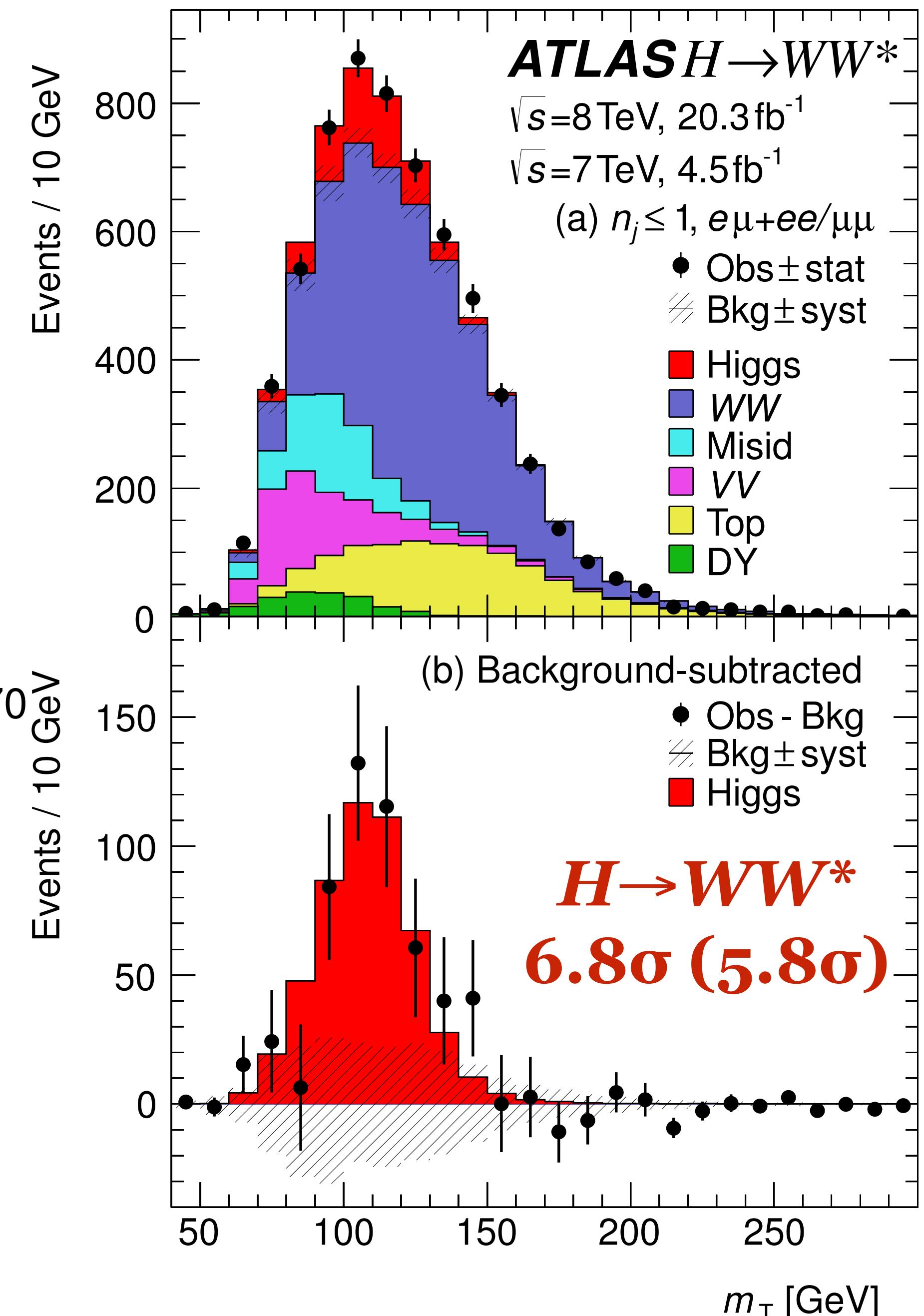


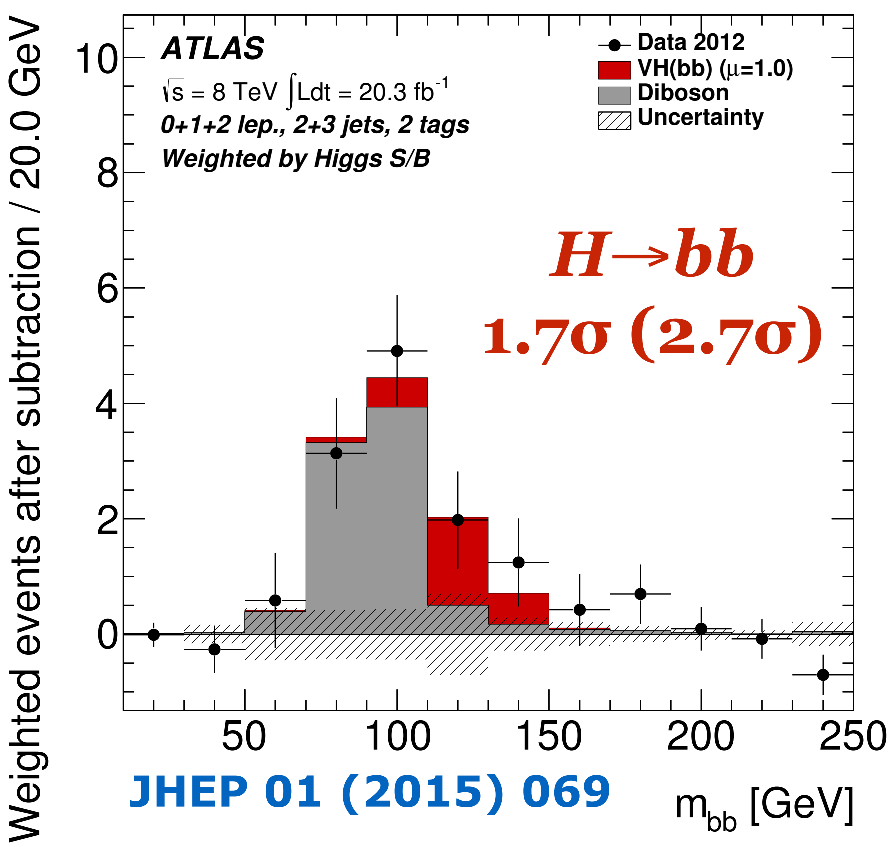
PRD 90 (2014) 902015



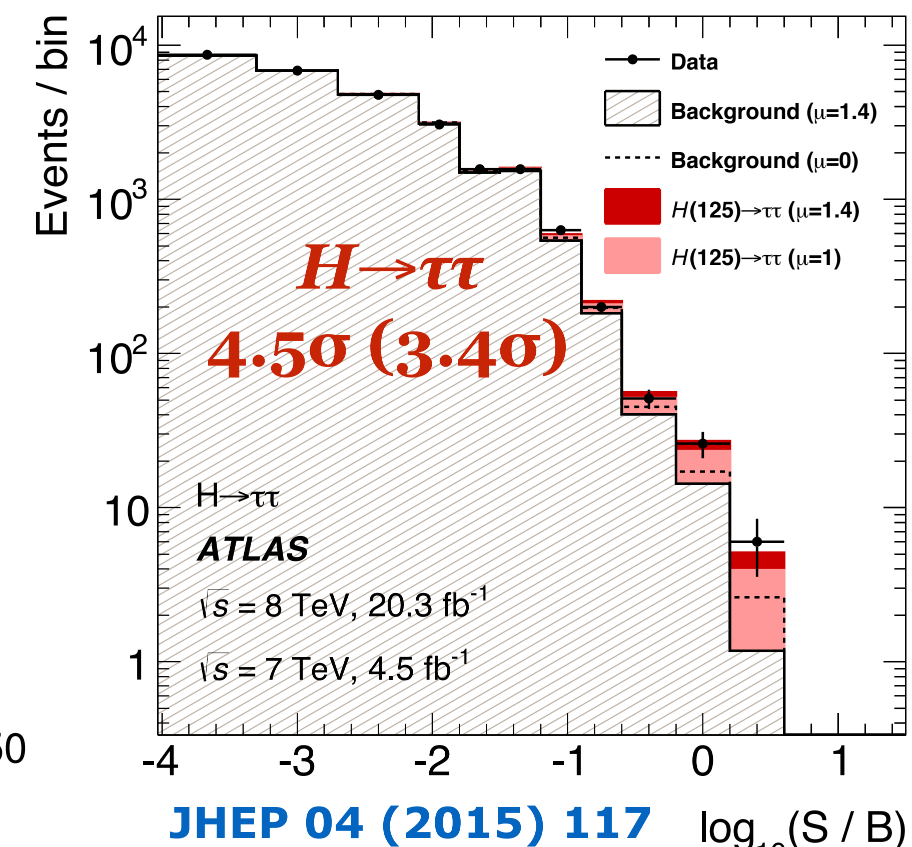
PRD 91 (2015) 012006

PRD 92 (2015) 012006





JHEP 01 (2015) 069



JHEP 04 (2015) 117

$\sigma(H \to Z\gamma) < 11 \times \mathrm{SM}$

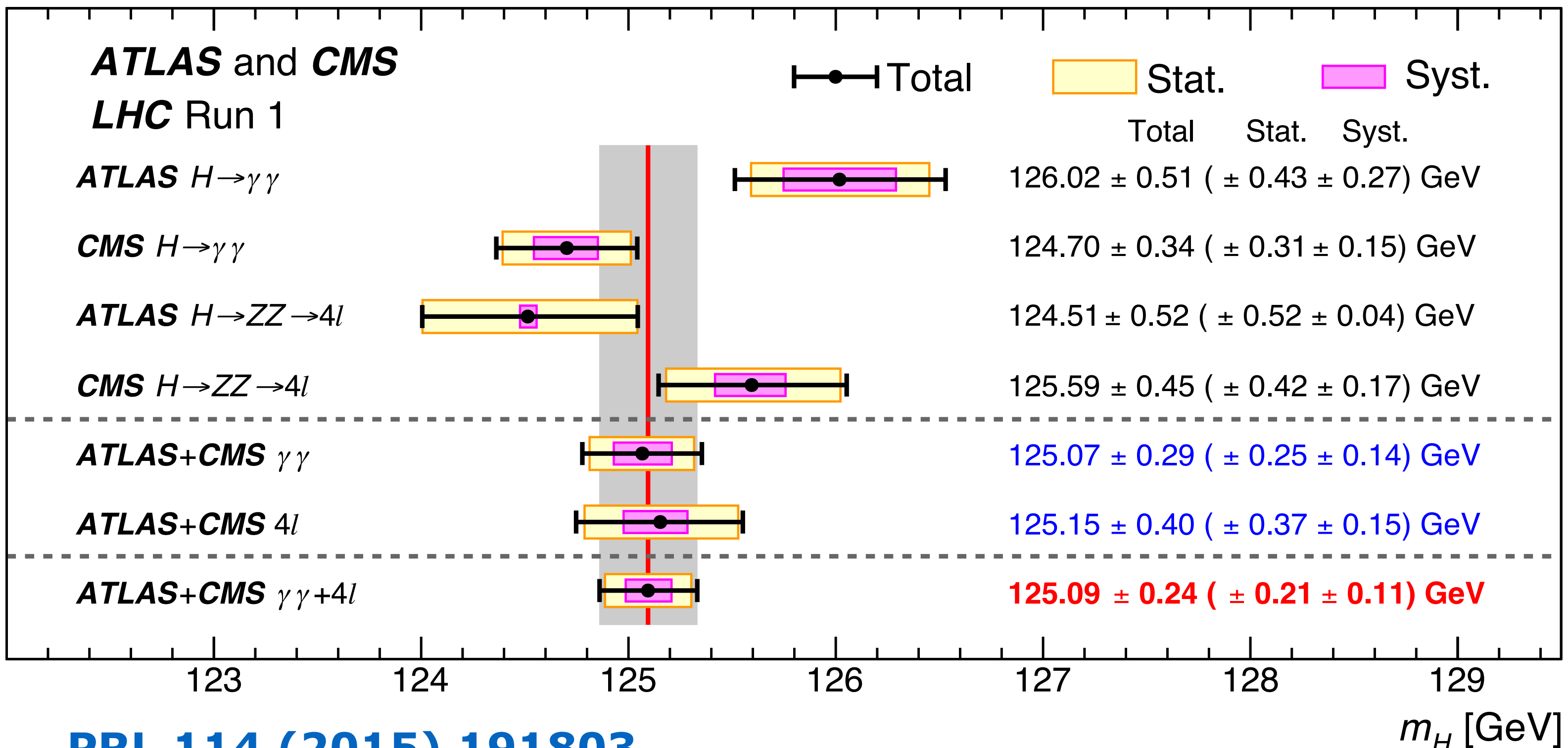
$\sigma(H \to \mu\mu) < 7 \times \mathrm{SM}$

Observed (expected) sign. from

JHEP 08 (2016) 045

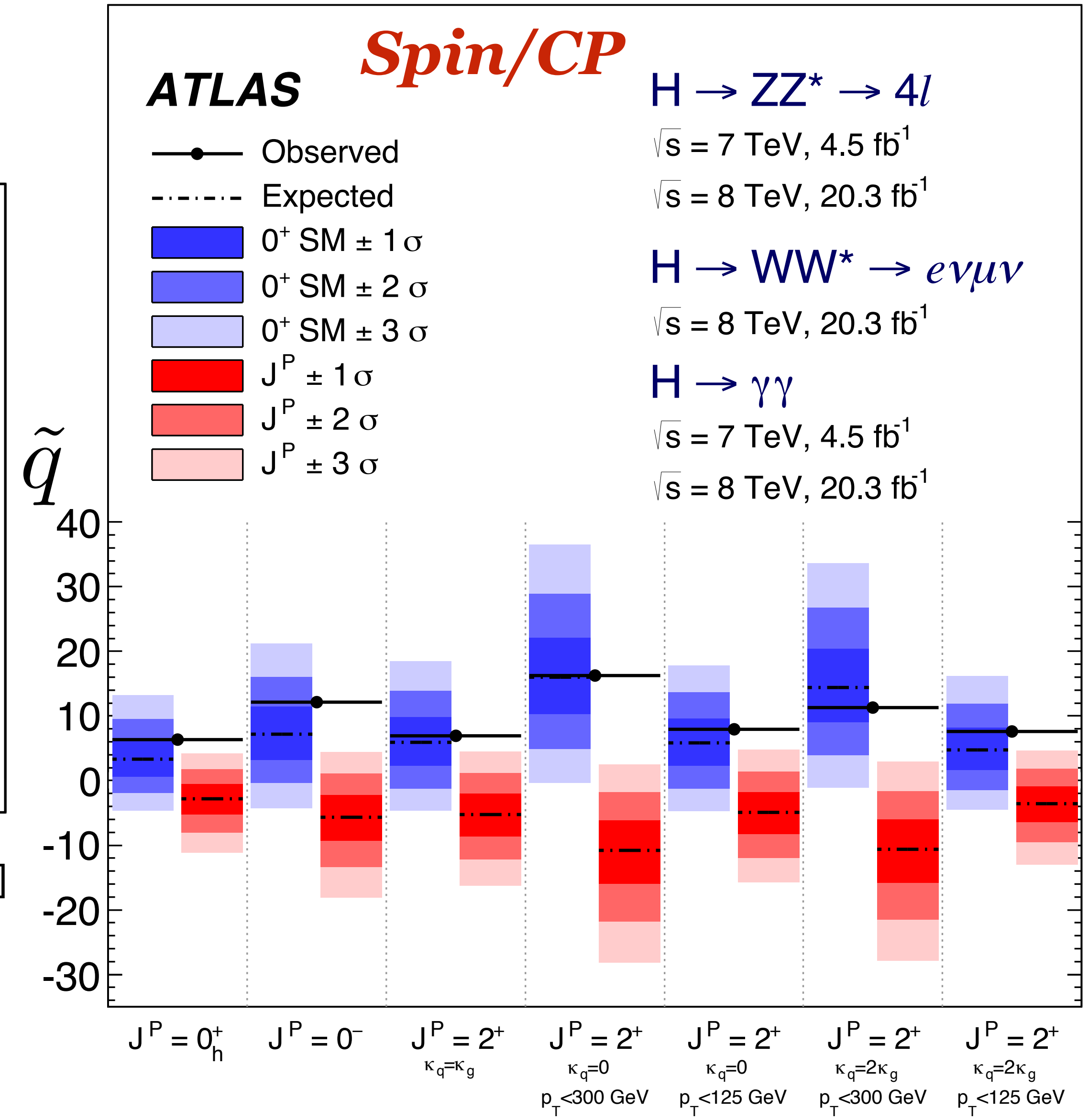
Run-1 Higgs boson results

Higgs boson mass



PRL 114 (2015) 191803

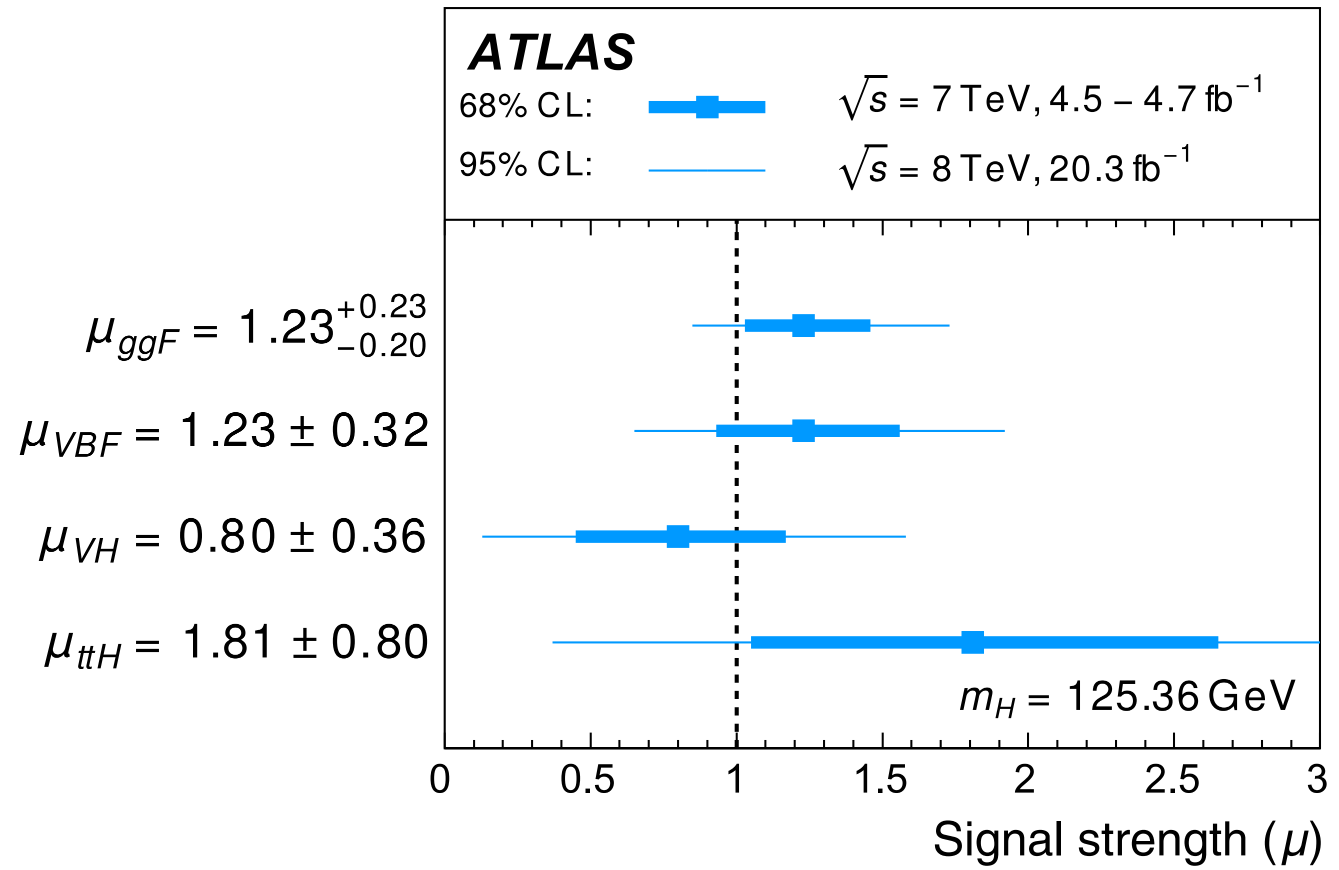
Spin/CP

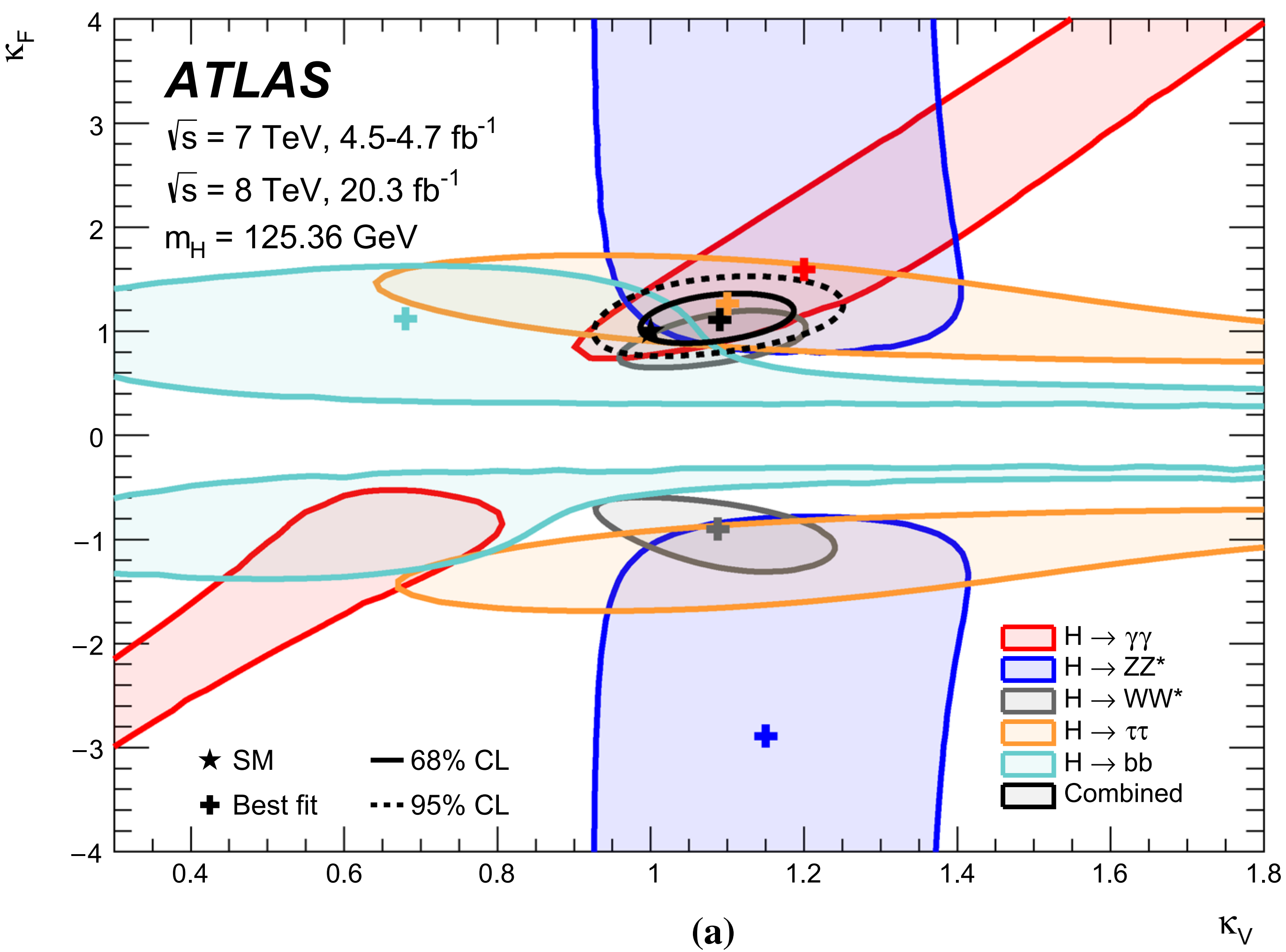


- Precision of mass measurement: **0.2%** 240 MeV
  - **Statistically limited**, especially for $ZZ^*\rightarrow 4l$: stat error ≈ 10 × syst error
- Consistent with SM **spin/CP** expectation **0^+** **EPJC 75 (2015) 476**
  Alternative models (spin 2, negative parity, etc.) excluded at at least 99.9% CL

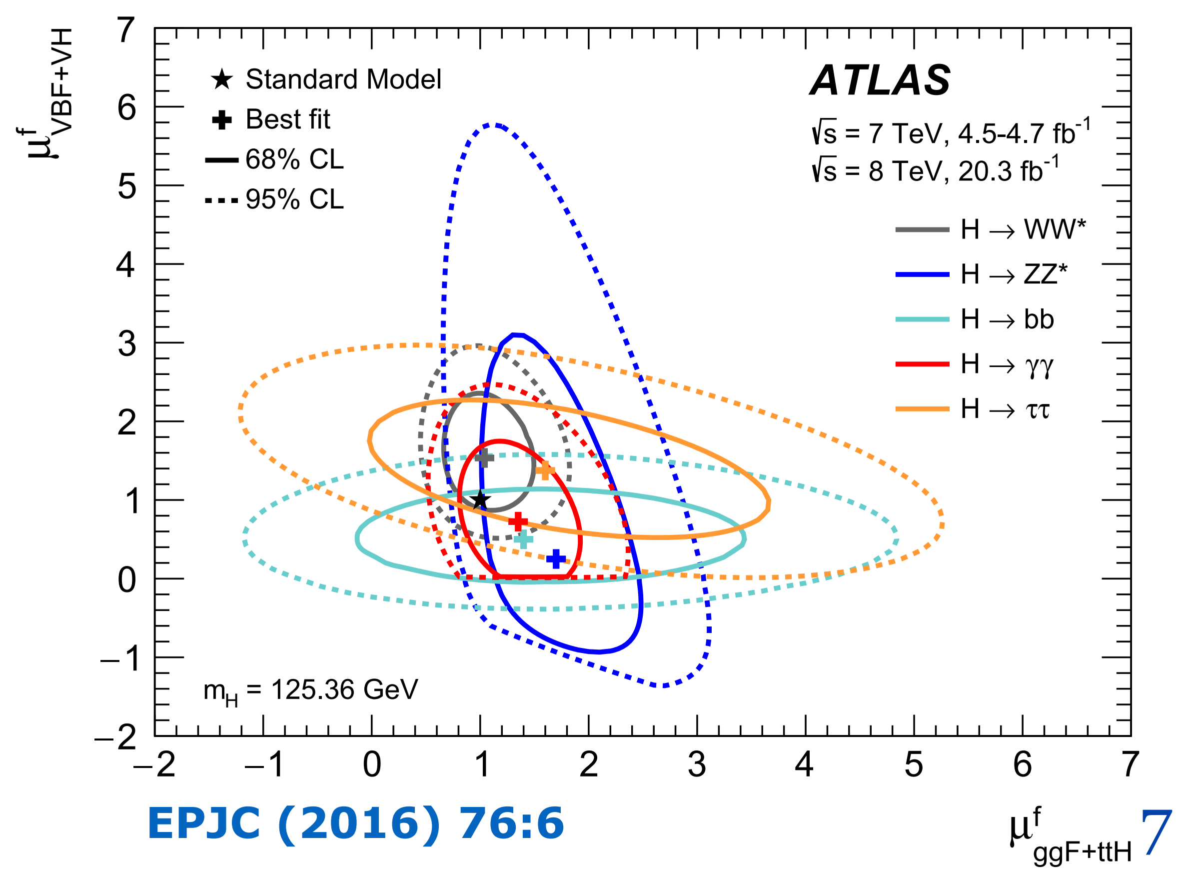
Run-1 Higgs boson results

- The Higgs boson production and decay were studied using
  - Dedicated analyses in **7 different decay modes** (γγ, ZZ*, WW*, bb, ττ, Zγ, μμ)
  - Full Run-1 dataset: ~25 fb^{-1}
- All results are consistent with the Standard Model expectation
- "Micro-anomalies": *H→bb* low by ~2.5σ, *ttH* high by ~2.3σ





(a)

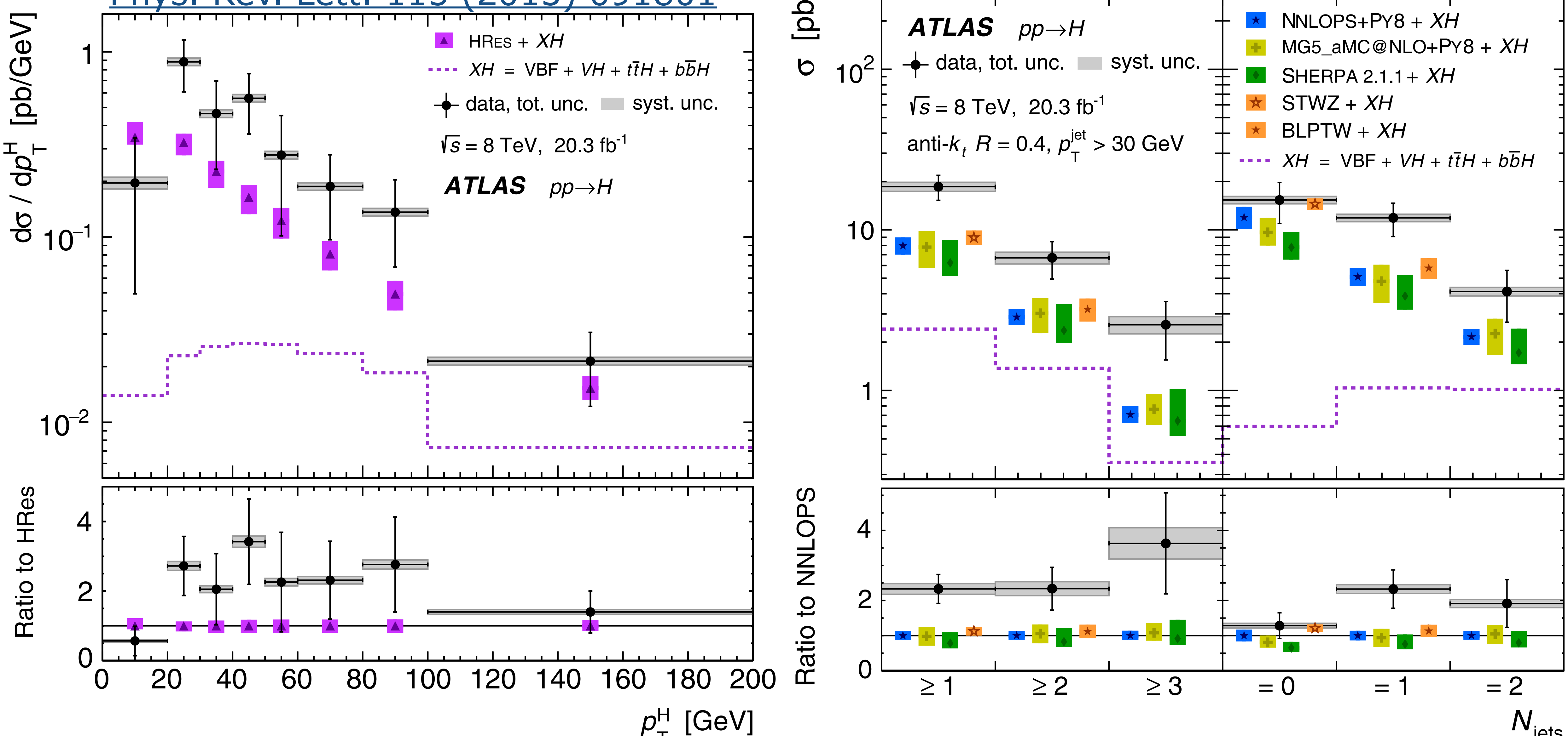


EPJC (2016) 76:6

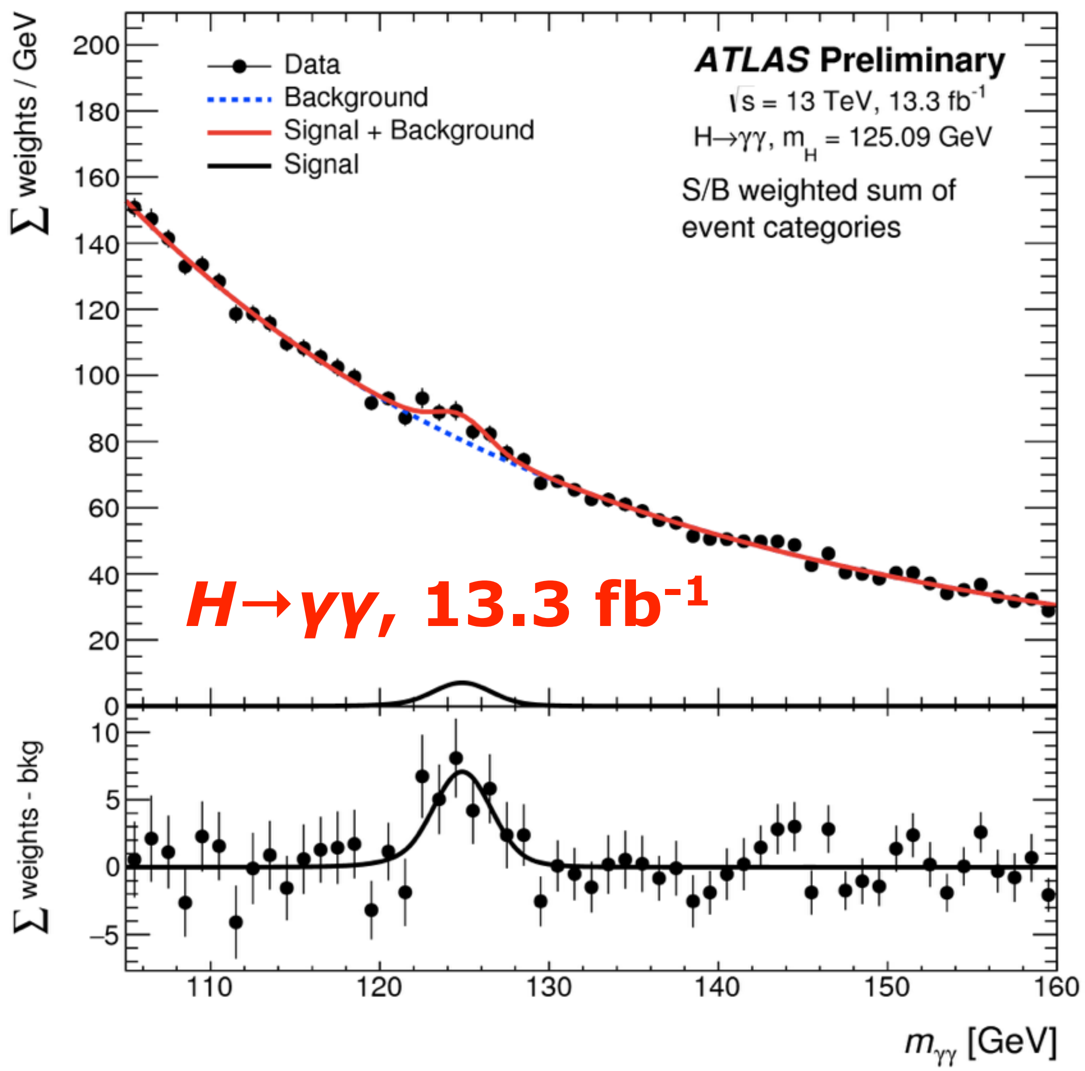
Run-1 Higgs boson results

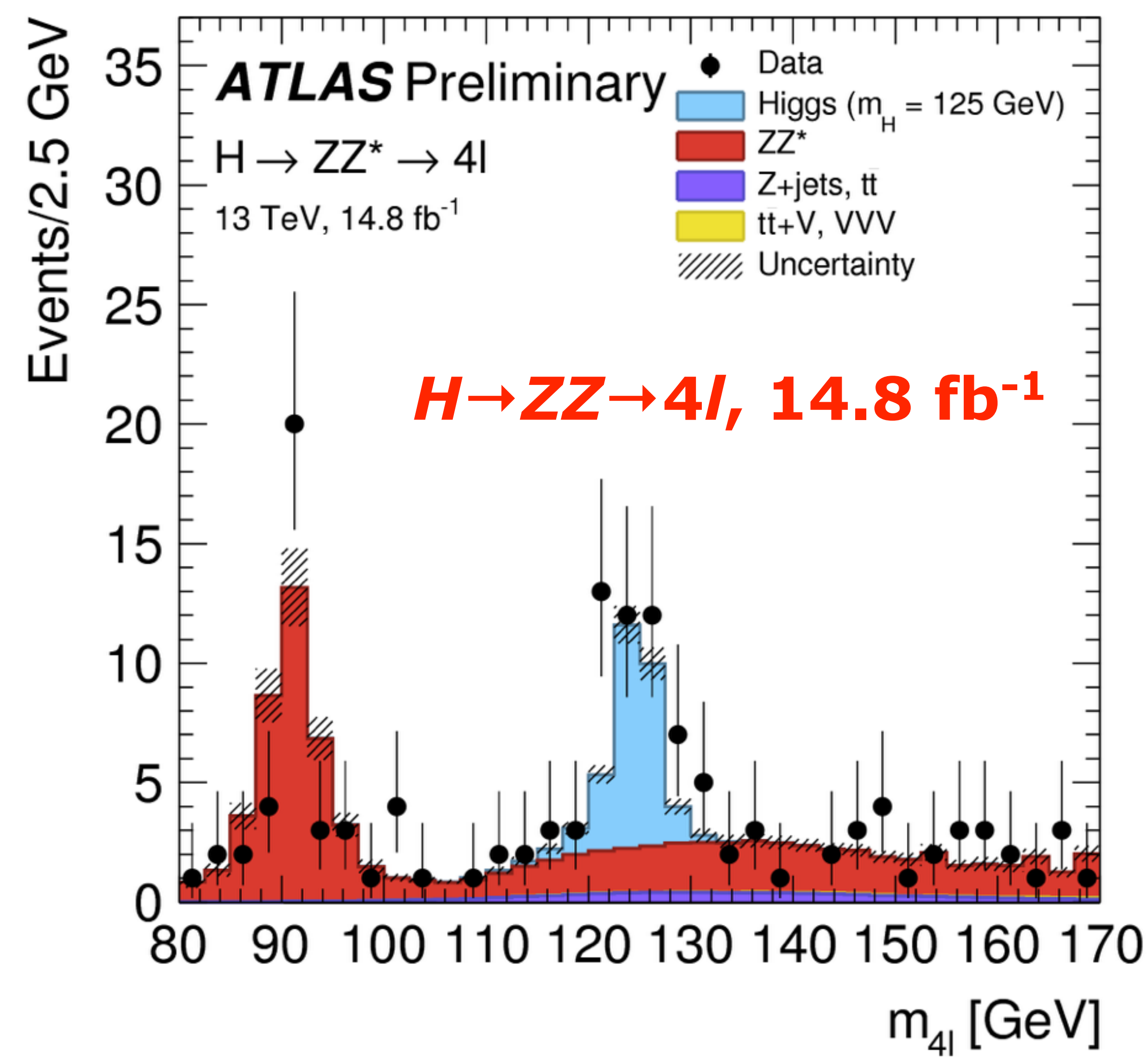
- **Differential cross sections** and normalized **shapes of kinematic distributions** measured both in individual channels (fiducial regions of $\gamma\gamma$, ZZ^*, WW^*) and combined ($\gamma\gamma$+ZZ^*), correcting for acceptances and branching ratio
- Higgs boson p_T, jet multiplicity, m_{jj}, etc.
- "Micro-anomalies": $p_{\mathrm{T},H}$ spectrum harder and more jets (see below)
  p-value for SM-agreement: 4% (8%) or better for norm+shape (shape-only)

Phys. Rev. Lett. 115 (2015) 091801



II. Current Run-2 results





*See talk by **Yusheng Wu** for details on the individual analyses*

$pp \to H$ cross section ($\gamma\gamma$+4l)

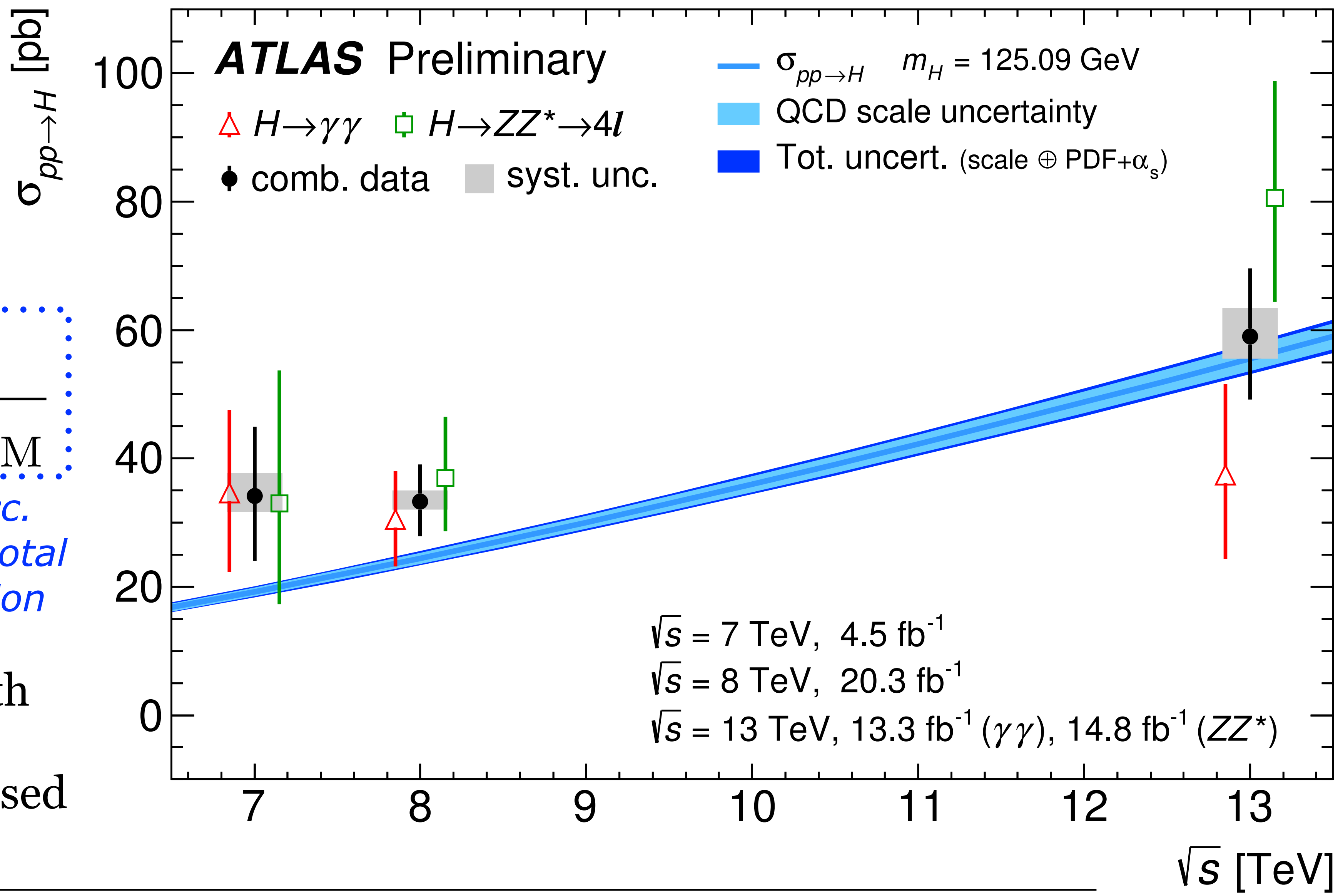
- Extracted event yields after analysis selection (without further categorization) are converted to a production cross section:

$$\sigma_{pp\to H} = \boxed{\frac{n_{\text{data}}}{\varepsilon\,\mathcal{L}}} \times \boxed{\frac{1}{\mathcal{B}_{\text{SM}}\,\mathcal{A}_{\text{SM}}}}$$

Fiducial cross section

BR and acc. Fiducial → total extrapolation

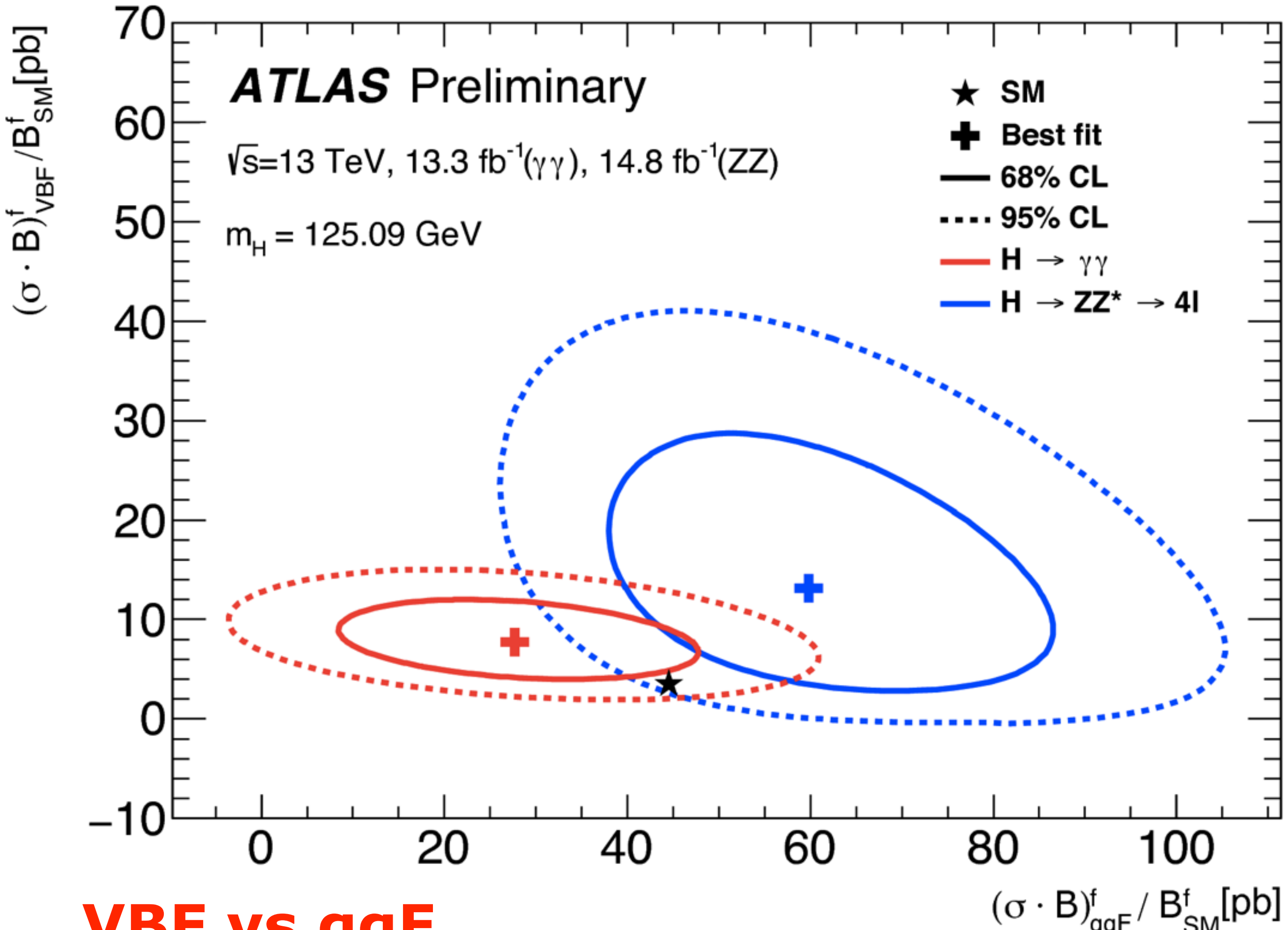
- Profile likelihood ratio fit with systematics implemented as ~200 nuisance parameters used



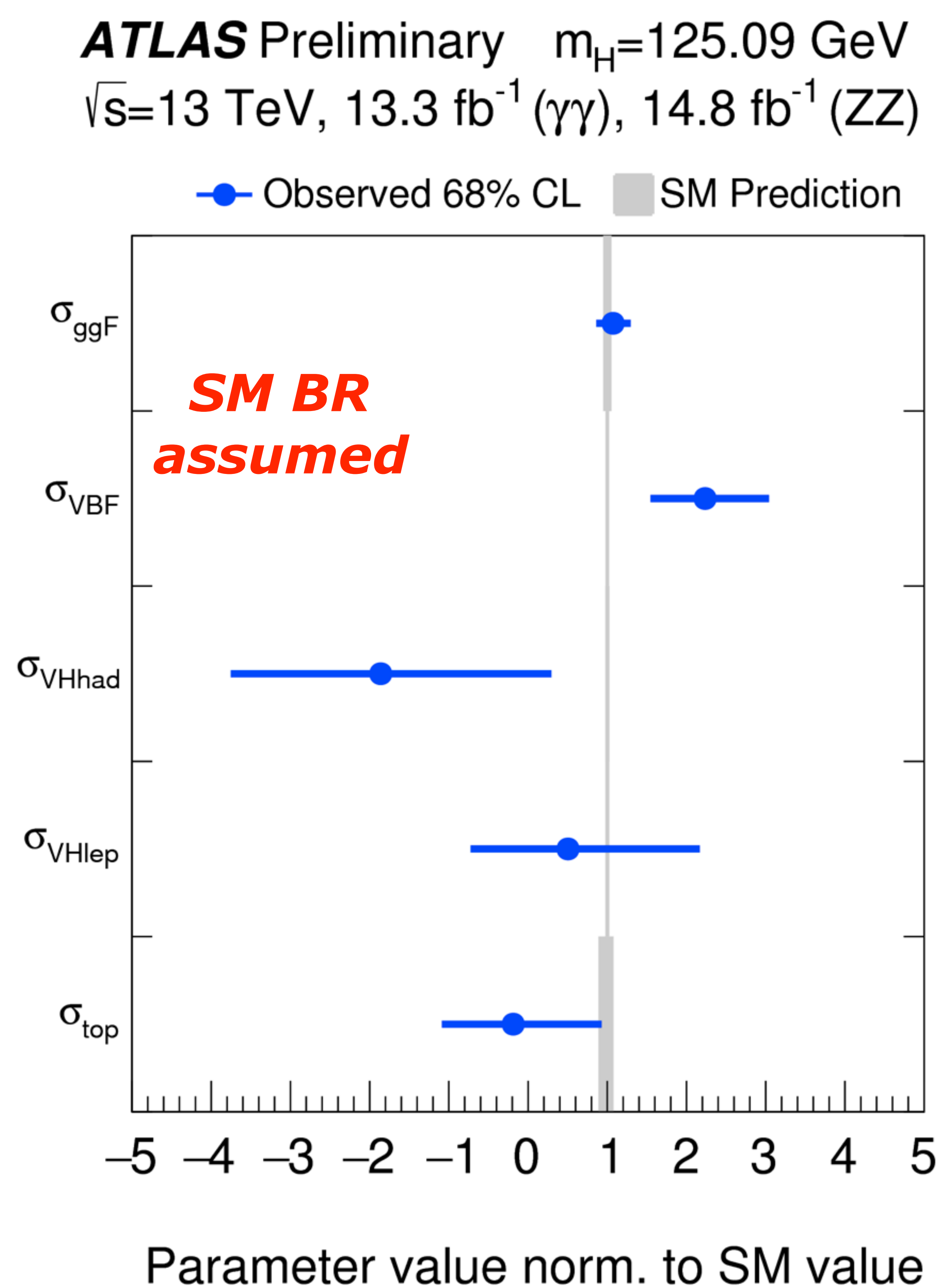
Decay channel	Total cross section ($pp \to H + X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

Run-2 Higgs boson couplings

- Targeting Higgs production mode with dedicated analysis event categories: **13** for ***γγ***, **5** for ***ZZ→4l***.
    - Combined fits for cross sections and coupling parameters performed using these categories
- Global signal strength: ~10σ (8.6σ) significance $\mu = 1.13^{+0.18}_{-0.17}$
- Fitted production mode cross sections (below and right) consistent with SM expectation



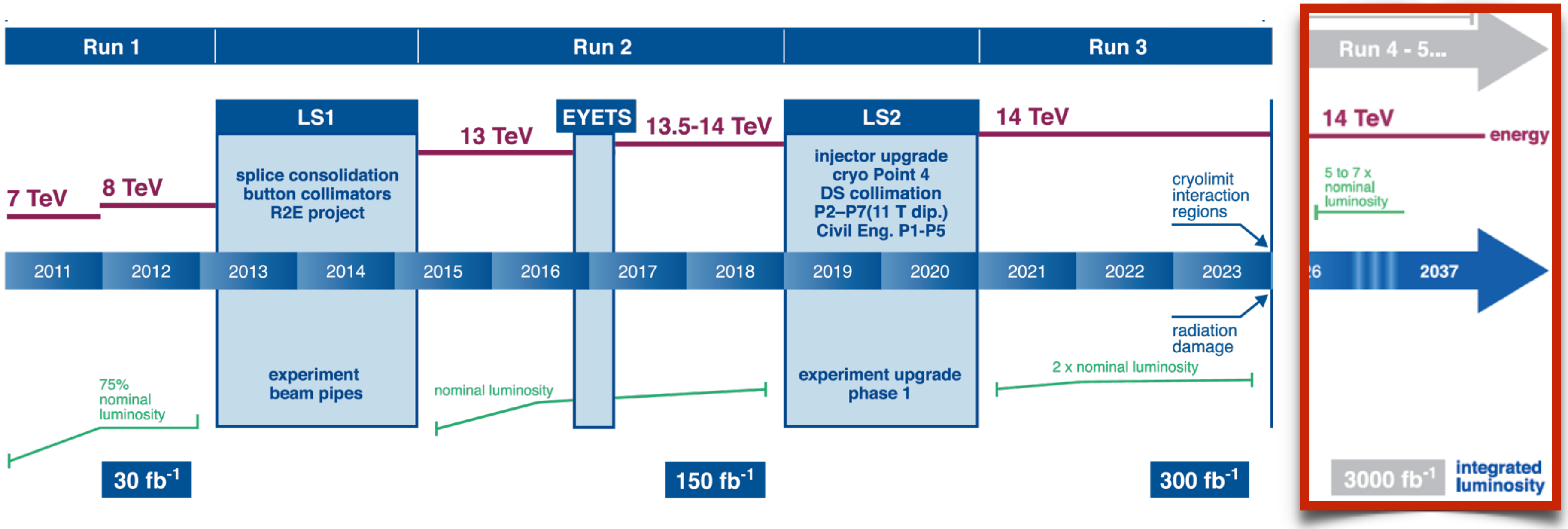
VBF vs ggF



III. Projected results

- **120 fb^{-1} @ 13-13.5 TeV** by end or **Run-2, 2018**
- **~300 fb^{-1} @ 13-14 TeV** by end of **Run-3, 2023**
- **~3000 fb^{-1} @ 14 TeV**, **HL-LHC**, **2026-2037** (Runs 4&5)

Detector upgrades



HL-LHC

- During the HL-LHC beam intensity will increase to ×7.5 the design intensity
- Major detector detector upgrades needed

- Main detector improvements with implications on physics:
  - New **all-silicon tracker** with significantly improved fwd. coverage: $|\eta|<4$ (now 2.5)
  - Improved granularity of forward calorimeter
  - Improved triggering capabilities
  - New high-granularity timing detector in the forward region
- Will improve capabilities to suppress pileup, in particular in the forward region: → enhanced precision to study events with **VBF** topology
- Projections for Run-3 (300 fb^{-1}) and HL-LHC (3000 fb^{-1}) derived using MC hadron-level samples with detector smearing functions derived from full simulation of the expected upgraded detector and the correspond to the expected beam conditions

Projections

Goals for ATLAS Higgs physics program

- Improve precision on Higgs boson coupling and cross section measurements
- Establish rare Higgs decays
- Study Higgs self coupling
- Search for BSM signatures

Higgs boson mass

Run-1 result
γγ: ±0.43 (stat) **±0.27** (sys) GeV
ZZ*: ±0.53 (stat) **±0.04** (sys) GeV
ATLAS comb: ±0.36 GeV

due to smaller systematics, ZZ will drive the mass measurement by the **end of Run-2** (120 fb^{-1}): **~±0.20 GeV**

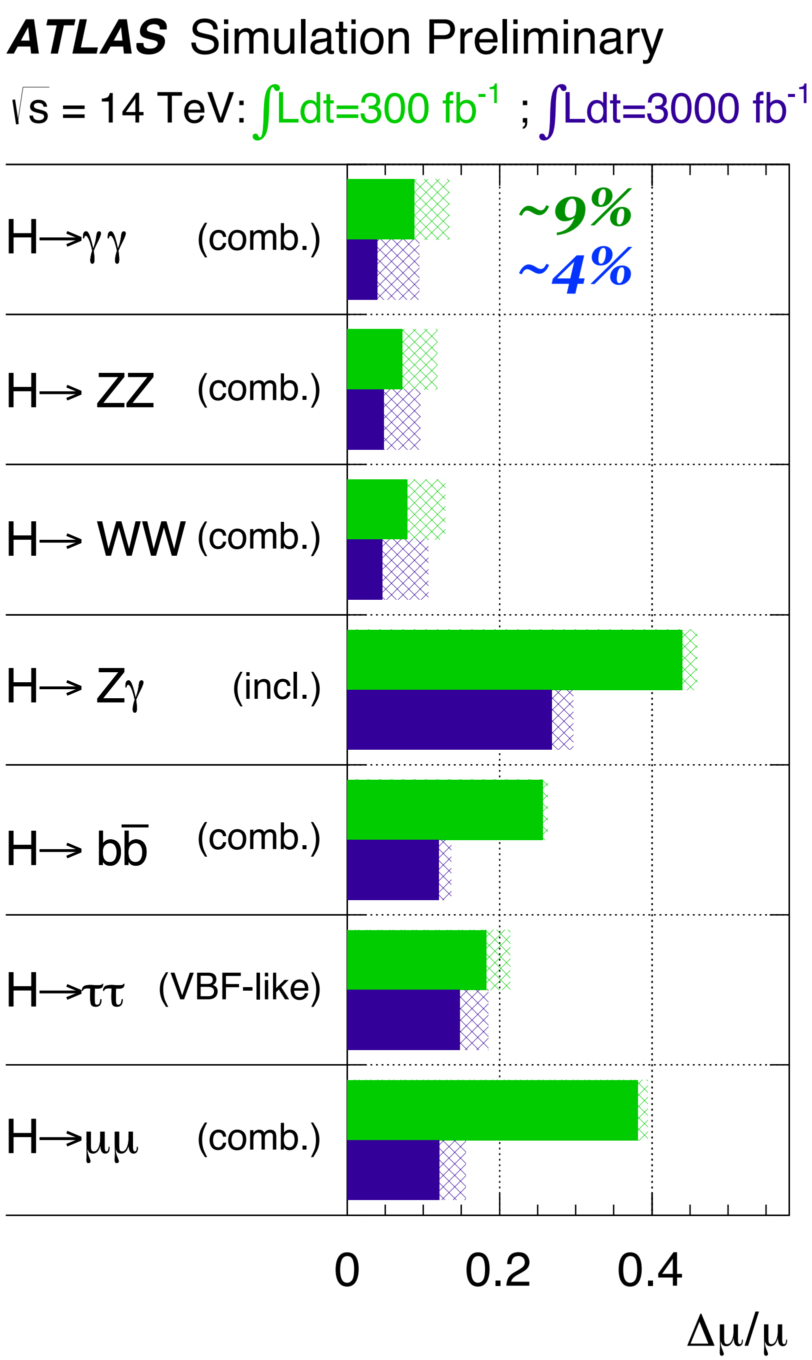
Expected event yields

After full analysis selection
(rough approximation)

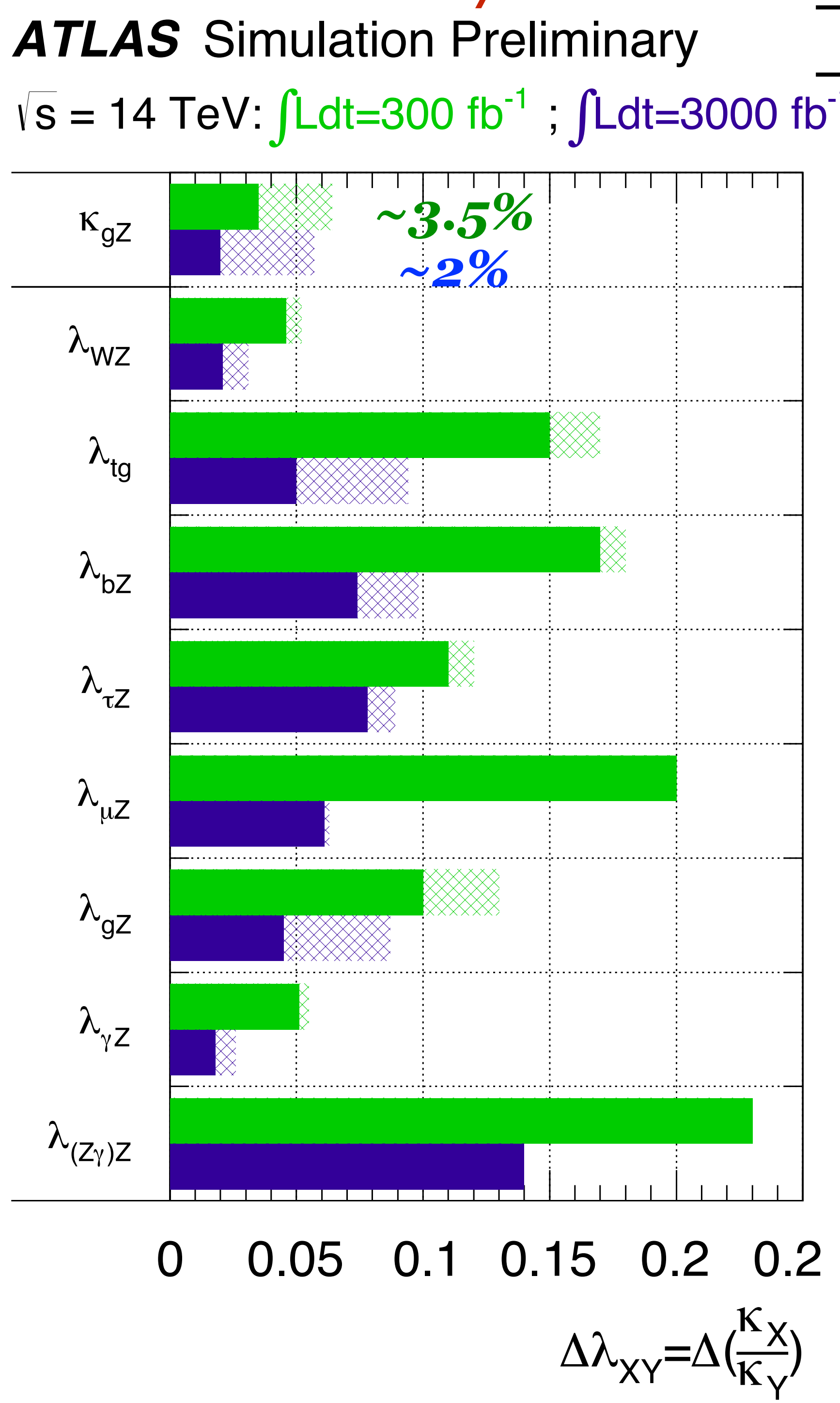
$\mathcal{L}$ [fb^{-1}]	All	$H\to\gamma\gamma$	$H\to ZZ\to 4l$	$H\to WW^*\to l\nu l\nu$
13.3	0.75M	600	20	400
120	7M	6,000	200	4,000
300	17M	14,000	500	10,000
3000	170M	140,000	5,000	100,000

Higgs coupling measurements

Precision on signal strength



Precision on Higgs coupling ratios: $\lambda_{XY} = \kappa_X/\kappa_Y$



Global Higgs boson signal strength/ rate precision (stat+exp. unc. only):

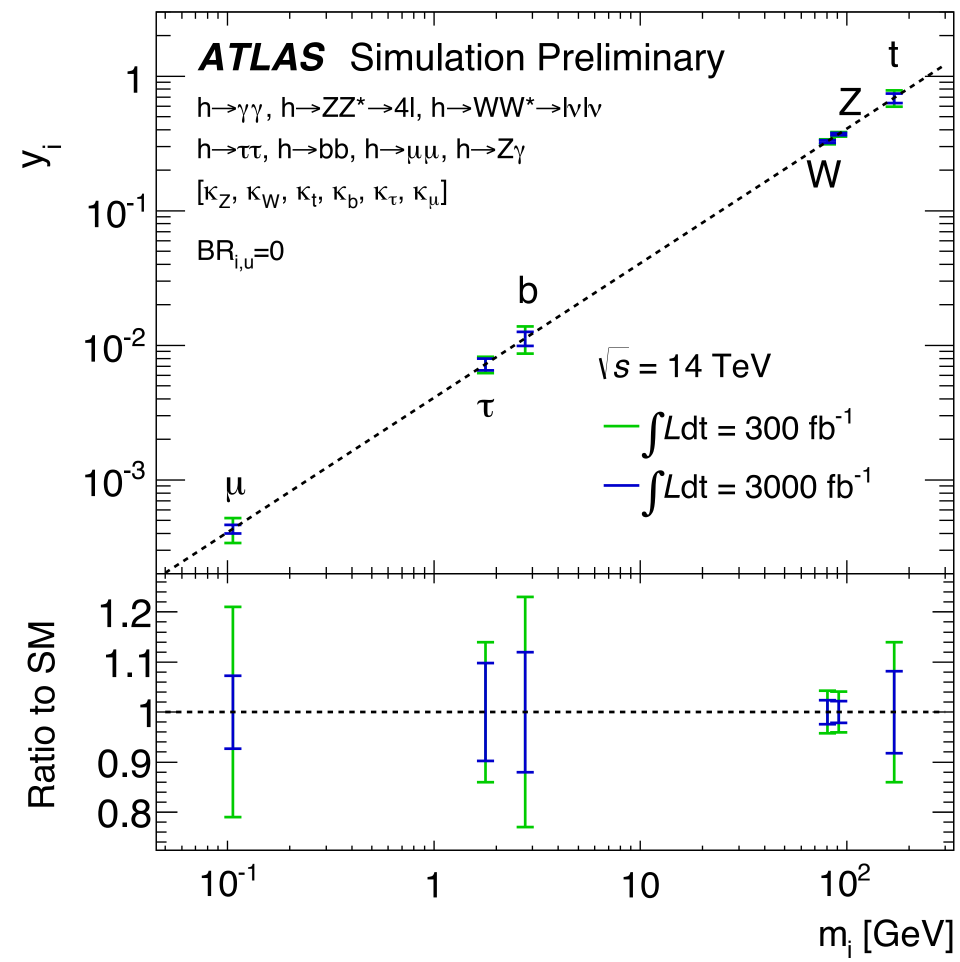
→ ICHEP, 13.3 fb^{-1}, 18% (γγ+ZZ only)

→ Run-2, 120 fb^{-1}, ~7% (γγ+ZZ)

→ Run-3, 300 fb^{-1}, ~5%

→ HL-LHC, 3 ab^{-1}, ~2.5%

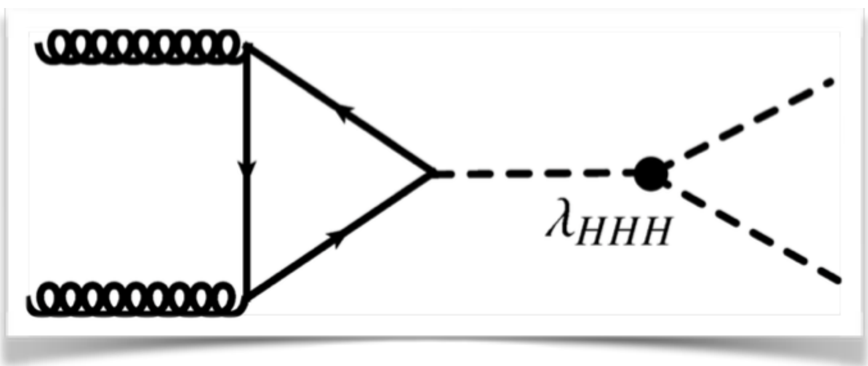
Higgs coupling vs mass
(PR plot)

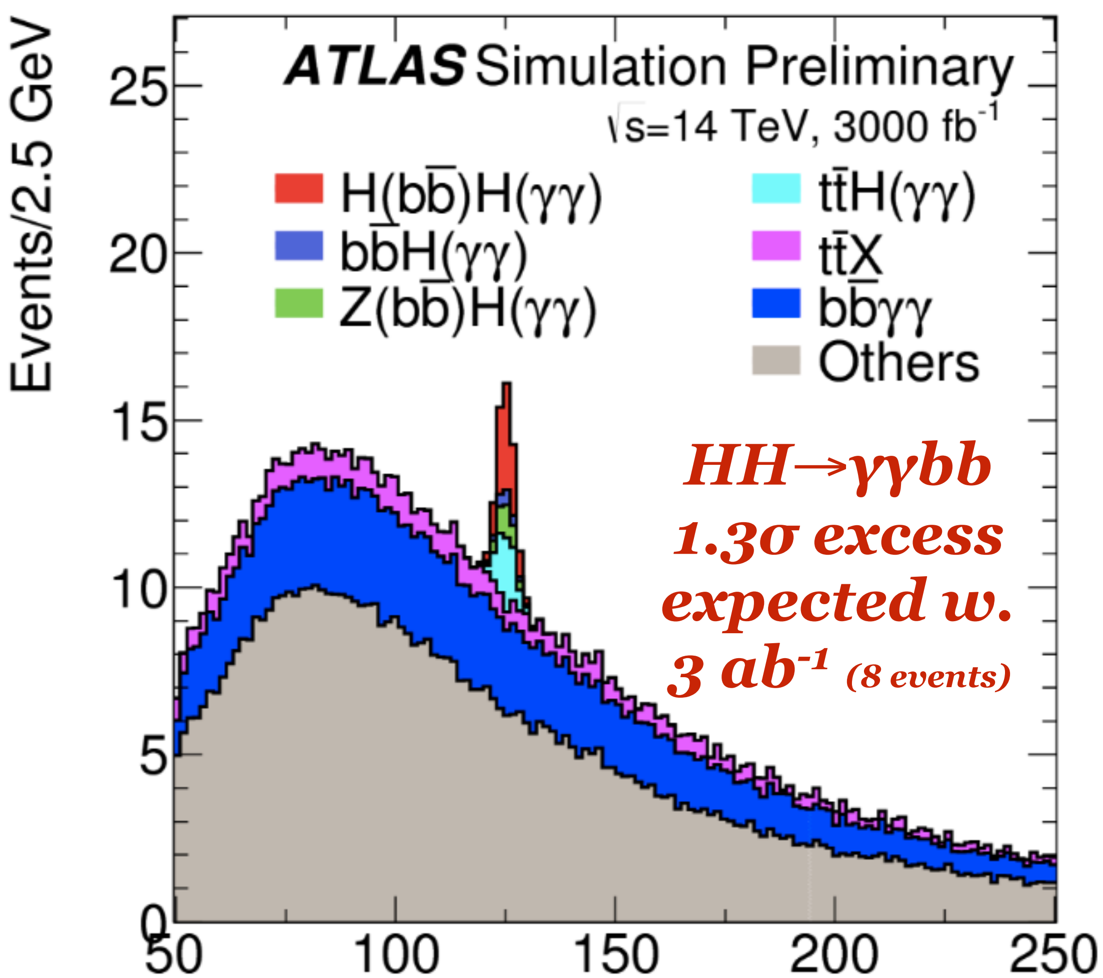


ATL-PUB-2014-016

Di-Higgs and rare decays

The Higgs boson self coupling





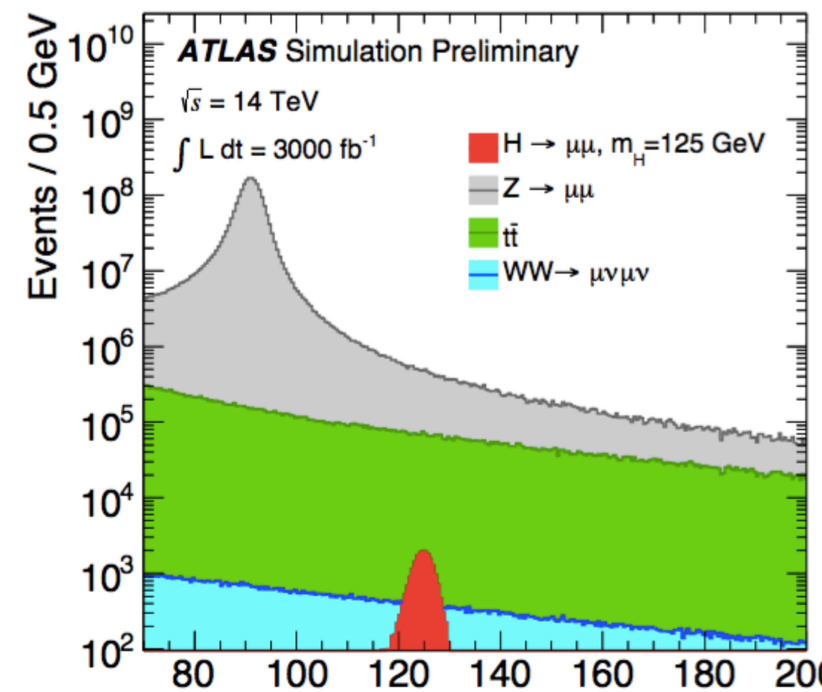
HH→γγbb
1.3σ excess expected w. 3 ab^{-1} ***(8 events)***

Combination with many other decay channels will improve the sensitivity.

ATL-PUB-2014-019

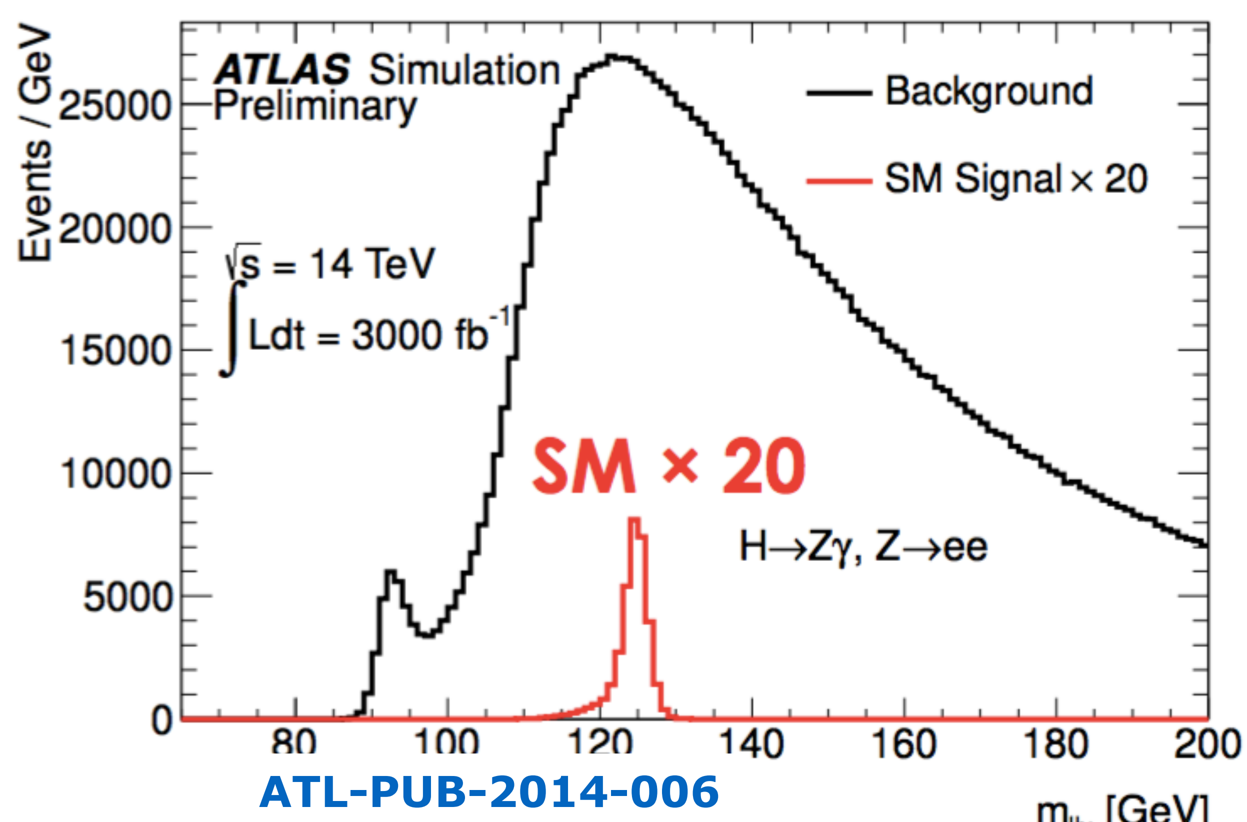
H→μμ, ***7.0σ*** excess expected in 3 ab^{-1}
~21% error on rate

SM sensitivity (1σ) expected with ~70 fb^{-1} (2018)



ATL-PUB-2013-014

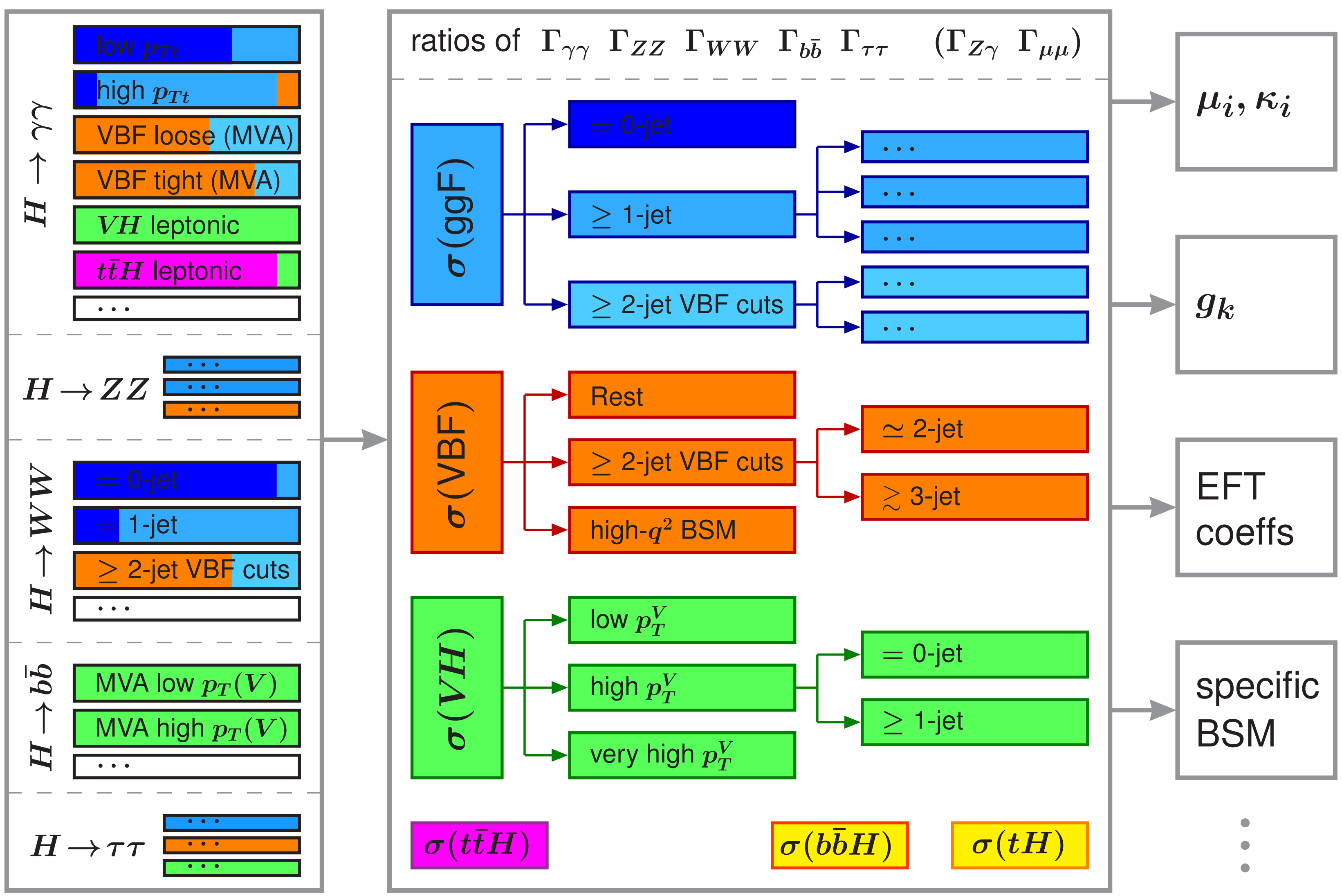
H→Zγ→eeγ, 3.9σ excess expected in 3 ab^{-1}
~25% uncertainty on rate



ATL-PUB-2014-006

Higgs cross sections

- Measurements of fiducial and differential cross sections will be done in individual channels
  - Back-of-the-envelope precision of σ(p_{TH}>100 GeV) for γγ+ZZ combination: ~40%, ~14%, ~5% with 13.3 fb-1, 120 fb-1, 3000 fb^{-1}
- Simplified template cross sections provides natural way to combine different channels → cross sections extracted via global fit
  - "Stage-0" measurements already performed for ICHEP 2016
  - "Stage-1" measurements as outlined in Yellow Report 4 are in progress

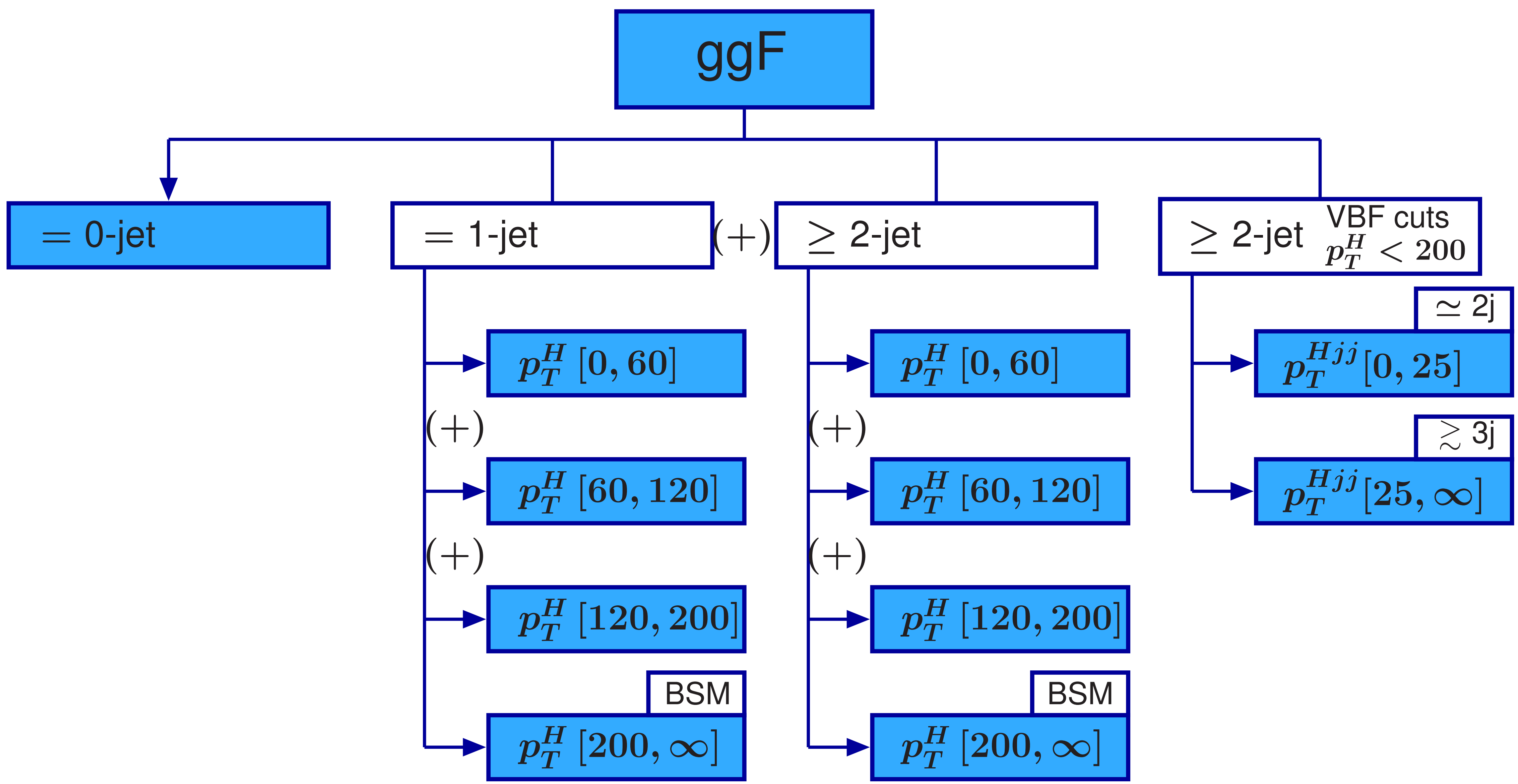


Yellow Report 4

Higgs cross sections

- Measurements of fiducial and differential cross sections will be done in individual channels
  - Back-of-the-envelope precision of $\sigma(p_{TH}>100\ \mathrm{GeV})$ for $\gamma\gamma$+ZZ combination: ~40%, ~14%, ~5% with 13.3 fb-1, 120 fb-1, 3000 fb^{-1}

Higgs simplified template cross section, "Stage-1" ggF categorization



Yellow Report 4

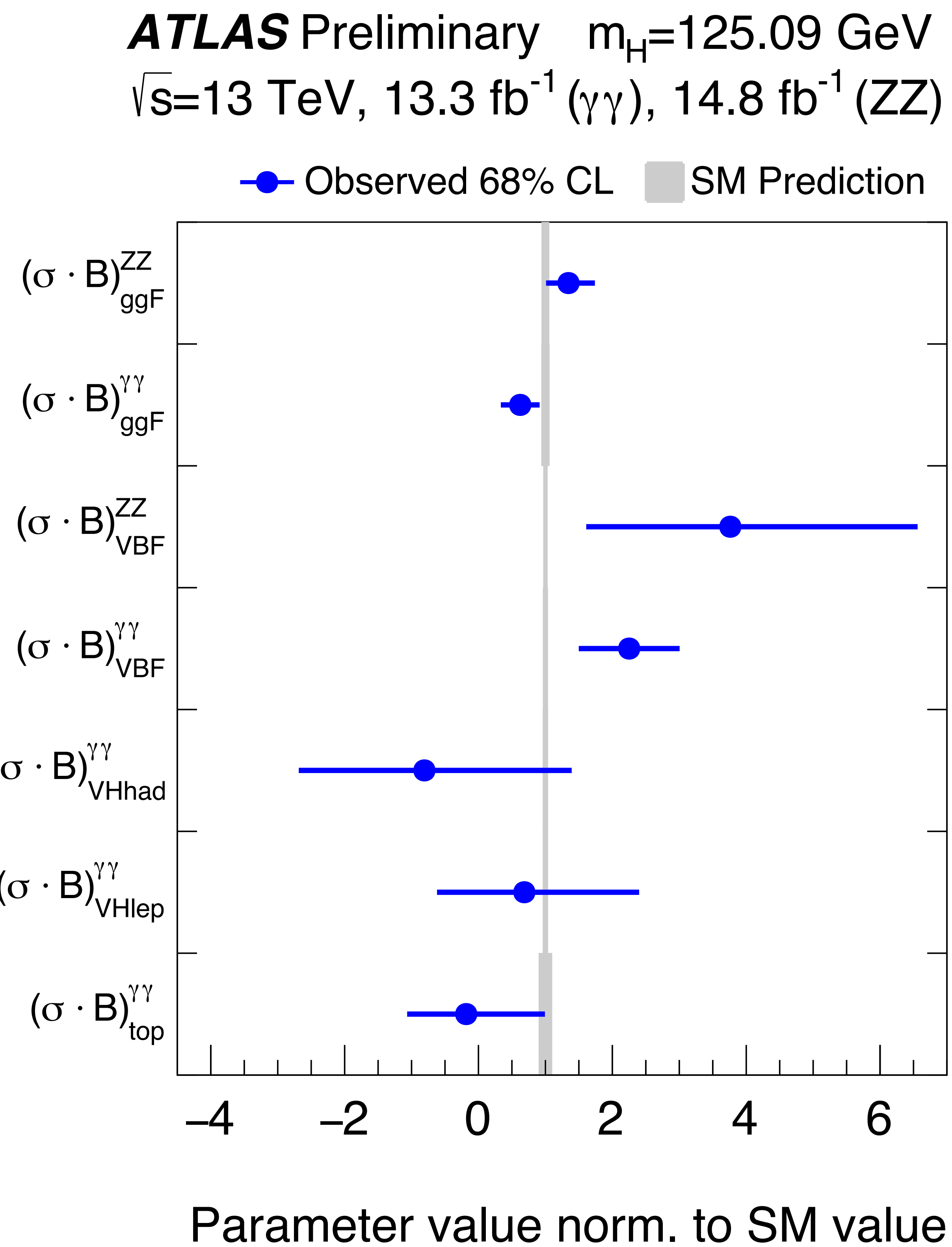
Summary

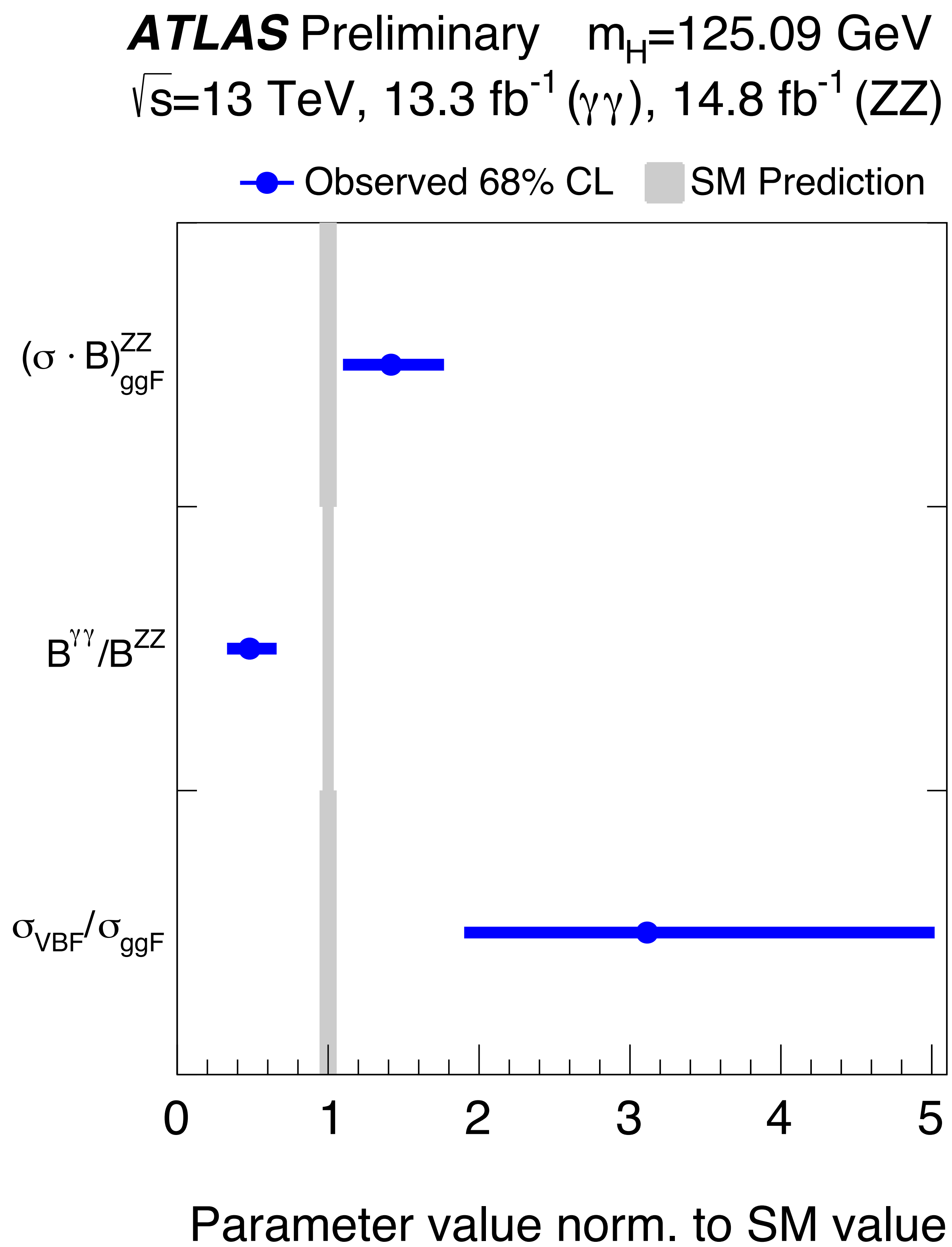
- LHC Run-2 currently delivers data beyond expectation
  - High-quality data being recorded by the ATLAS detector
- In ICHEP dataset, the Higgs boson was observed in the $\gamma\gamma$+ZZ channels with ~10σ (8.6σ) observed (expected) significance
  - Preliminary measurements of the Higgs boson cross section and couplings examined in first Run-2 and are consistent with SM expectations
- Significant detector upgrades and improvements will be installed for HL-LHC phase: 2026-2035, during with we expect to collect 3 ab^{-1} data
  - In particular improvements will be made to the forward region:
    tracking extended to |eta|<4 + improved calorimetry and timing detector
    → increase acceptance for all physics objects
    → improve $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution
    → in particular helpful for VBF topology
- Higgs physics remains a very important part of the LHC physics program
  - Improve precision of cross section and coupling measurements
  - Study Higgs self coupling
  - Search for rare decays and BSM signatures

References

- ATLAS Run-1 papers
  - $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW^*$, $H \rightarrow bb$, $H \rightarrow \tau\tau$
  - Mass (ATLAS+CMS), Spin/CP, couplings, differential, couplings (ATLAS+CMS)
- ATLAS Run-2 conference note for ICHEP 2016
  - ATLAS-CONF-2016-067, $H \rightarrow \gamma\gamma$
  - ATLAS-CONF-2016-079, $H \rightarrow 4l$
  - ATLAS-CONF-2016-081, $\gamma\gamma$+ZZ combination
- ATLAS public projection, 300 and 3000 fb^{-1}
  - ATL-PHYS-PUB-2014-016, Higgs couplings
  - ATL-PHYS-PUB-2014-017, BSM Higgs
  - ATL-PHYS-PUB-2014-006, $H \rightarrow Z\gamma$
  - ATL-PHYS-PUB-2014-019, $HH \rightarrow bb\gamma\gamma$
- Full list: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

More Run-2 coupling results





Projected signal strengths uncertainties

ATL-PUB-2014-016

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
(1j)	0.30	0.18	0.26	0.10
(VBF-like)	0.21	0.20	0.15	0.09
$H \to Z\gamma$ (incl.)	0.46	0.44	0.30	0.27
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
$H \to \mu\mu$ (comb.)	0.39	0.38	0.16	0.12
(incl.)	0.47	0.45	0.18	0.14
(ttH-like)	0.74	0.72	0.27	0.23

Expected precision on Higgs couplings

ATL-PUB-2014-016

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	4.2%	3.0%	2.4%	3.2%	2.2%	1.7%
2	$\kappa_V = \kappa_Z = \kappa_W$	4.3%	3.0%	2.5%	3.3%	2.2%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.8%	7.5%	7.1%	5.1%	3.8%	3.2%
3	κ_Z	4.7%	3.7%	3.3%	3.3%	2.3%	1.9%
	κ_W	4.9%	3.6%	3.1%	3.6%	2.4%	1.8%
	κ_F	9.3%	7.9%	7.3%	5.4%	4.0%	3.4%
4	κ_V	5.9%	5.4%	5.3%	3.7%	3.2%	3.0%
	κ_u	8.9%	7.7%	7.2%	5.4%	4.0%	3.4%
	κ_d	12%	12%	12%	6.7%	6.2%	6.1%
5	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	8.7%	7.8%	6.6%	4.5%	3.6%
	κ_l	10%	9.6%	9.3%	6.0%	5.3%	5.1%
6	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	9.0%	8.1%	6.7%	4.7%	3.8%
	κ_τ	12%	11%	11%	9.2%	8.4%	8.1%
	κ_μ	20%	20%	19%	6.9%	6.3%	6.1%
7	κ_Z	8.1%	7.9%	7.8%	4.3%	3.9%	3.8%
	κ_W	8.5%	8.2%	8.1%	4.8%	4.1%	3.9%
	κ_t	14%	12%	11%	8.2%	6.1%	5.3%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	13%	13%	9.8%	9.0%	8.7%
	κ_μ	21%	21%	21%	7.3%	7.1%	7.0%
8	κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
	κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
	κ_t	22%	21%	20%	11%	8.5%	7.6%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
	κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
	κ_g	14%	12%	11%	9.1%	6.5%	5.3%
	κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
	$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%