Combined measurements of the Higgs boson production and decay rates using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS experiment

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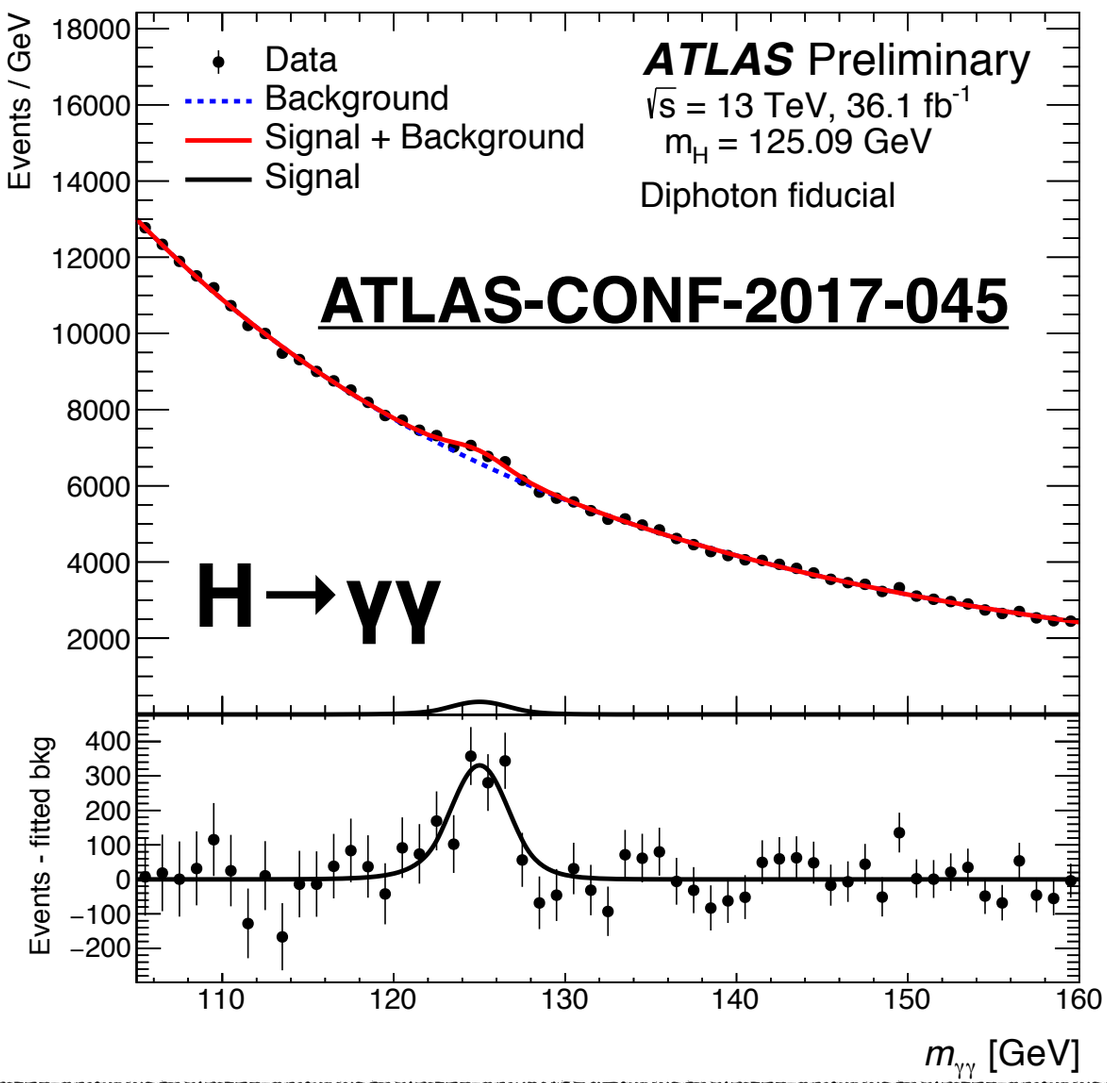
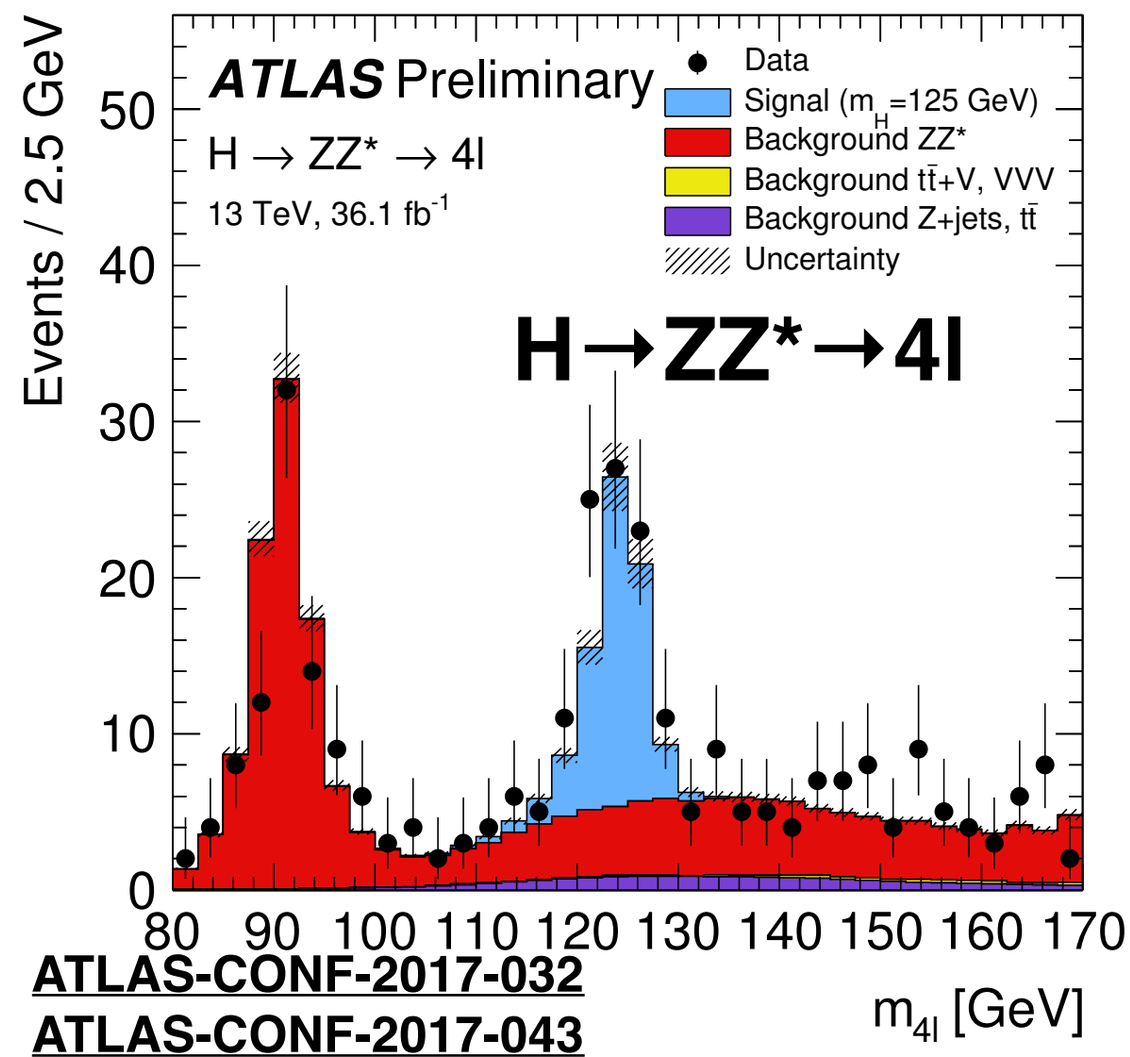
Introduction

- Higgs boson has a unique role in the SM. Need to understand how Higgs boson couples with other particles through measuring production and decay rates
- This talk: latest combined Higgs coupling measurement results using **H→γγ** and **H→ZZ*→4l** channels based on **36.1 fb^{-1} of 13 TeV data**





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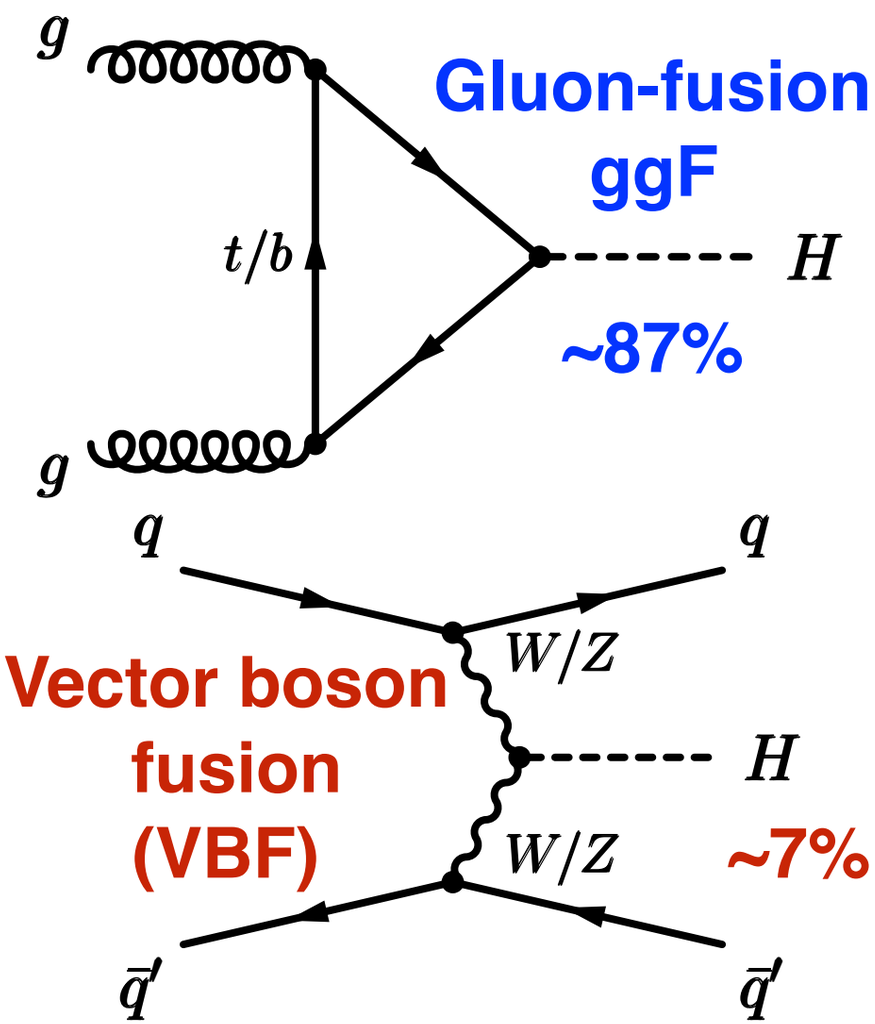
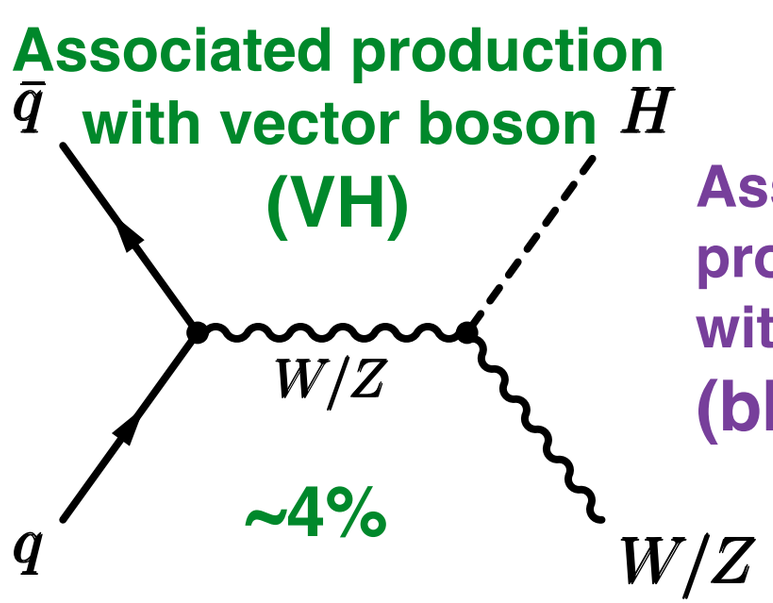
SM Higgs boson production modes at LHC

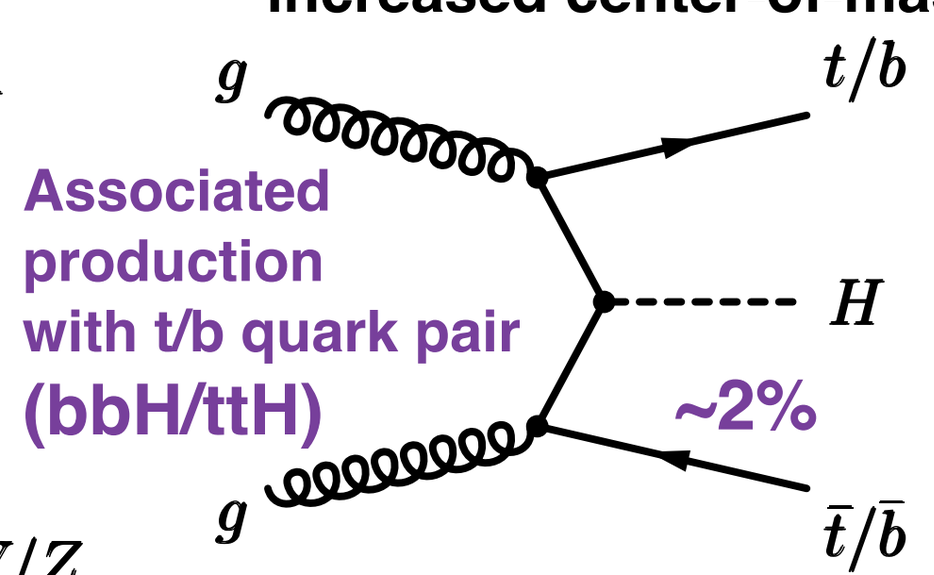


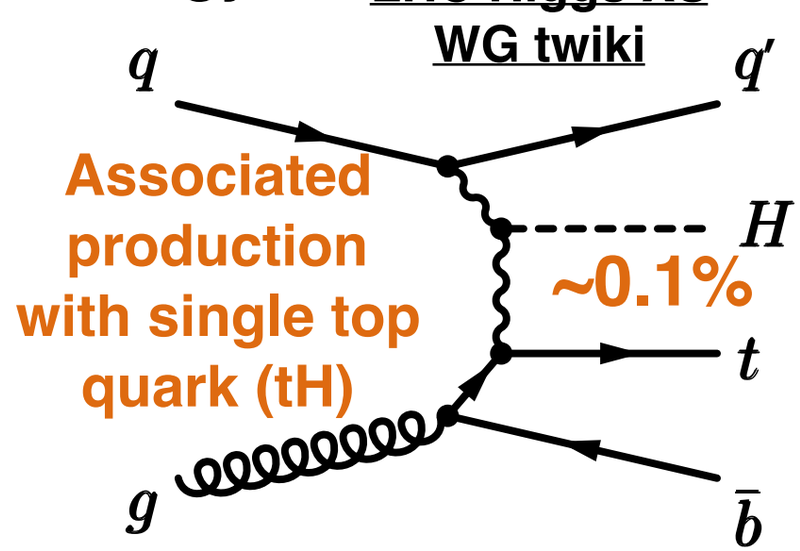
XS in pb	13 TeV	8 TeV	$\sigma_{13\ TeV}/\sigma_{8\ TeV}$
ggF	48.52	21.39	2.3
VBF	3.78	1.60	2.4
WH	1.37	0.70	2.0
ZH	0.88	0.42	2.1
bbH	0.49	0.20	2.4
ttH	0.51	0.13	3.8
tH	0.092	0.023	3.9

Significant boost in production cross sections from increased center-of-mass energy

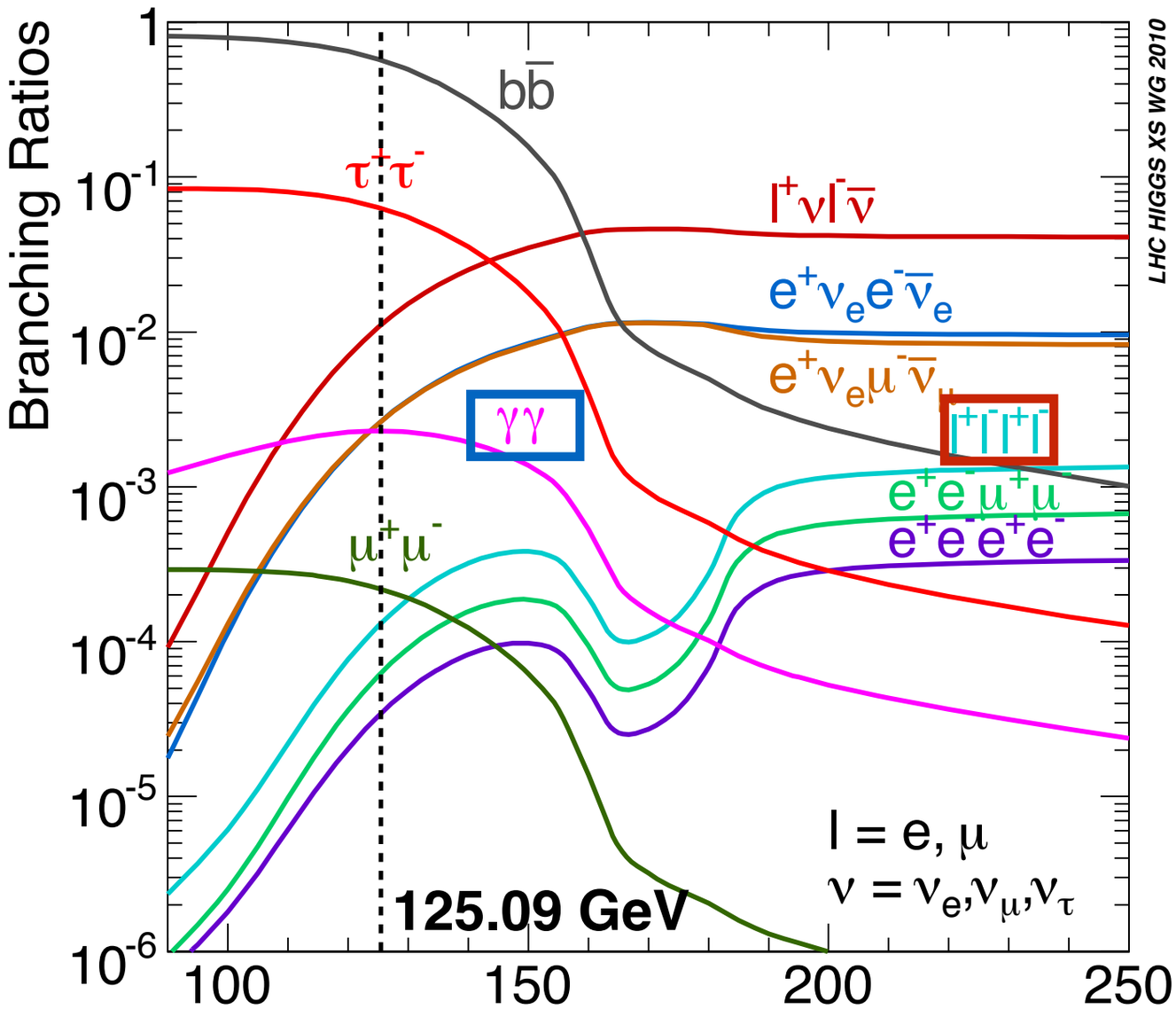
LHC Higgs XS WG twiki







SM Higgs boson decays



LHC Higgs XS WG twiki

Decay channel	Branching ratio [%]
H→bb	58.09
H→WW	21.52
H→gg	8.18
H→ττ	6.26
H→cc	2.88
H→ZZ	2.64
(H→ZZ*→4l)	(0.013)
H→γγ	0.23
H→Zγ	0.15
H→μμ	0.022

- Both diphoton and four-lepton channels have small BR
  - Nonetheless, they are very important for Higgs property measurements due to excellent sensitivity and mass resolution

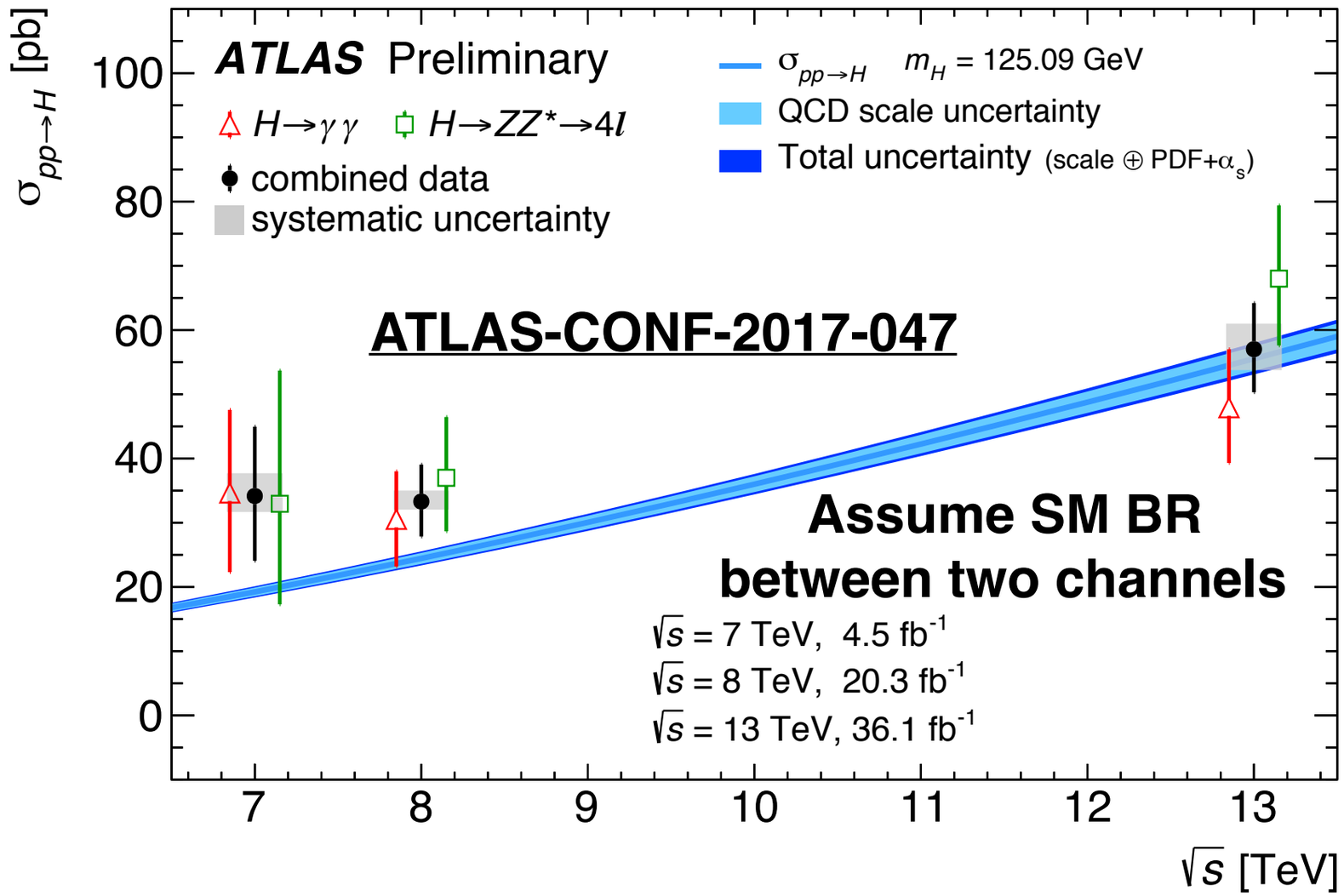
Dataset used for analysis

$\sqrt{s}$	Integrated luminosity (fb^{-1})	Number of H produced	Decayed to diphoton	Decayed to four-lepton
7 TeV	4.5	~90,000	~200	~10
8 TeV	20.3	~500,000	~1,100	~60
13 TeV	36.1	~2,000,000	~4,600	~250

Assuming SM prediction @m_H=125.09 GeV
(from LHC Run 1 Higgs mass measurement)

- Statistics from 13 TeV data has increased by ~4 compared with Run 1 (7 TeV / 8 TeV)
- Signal selection efficiency: ~40% in diphoton channel, ~20% in four-lepton channel

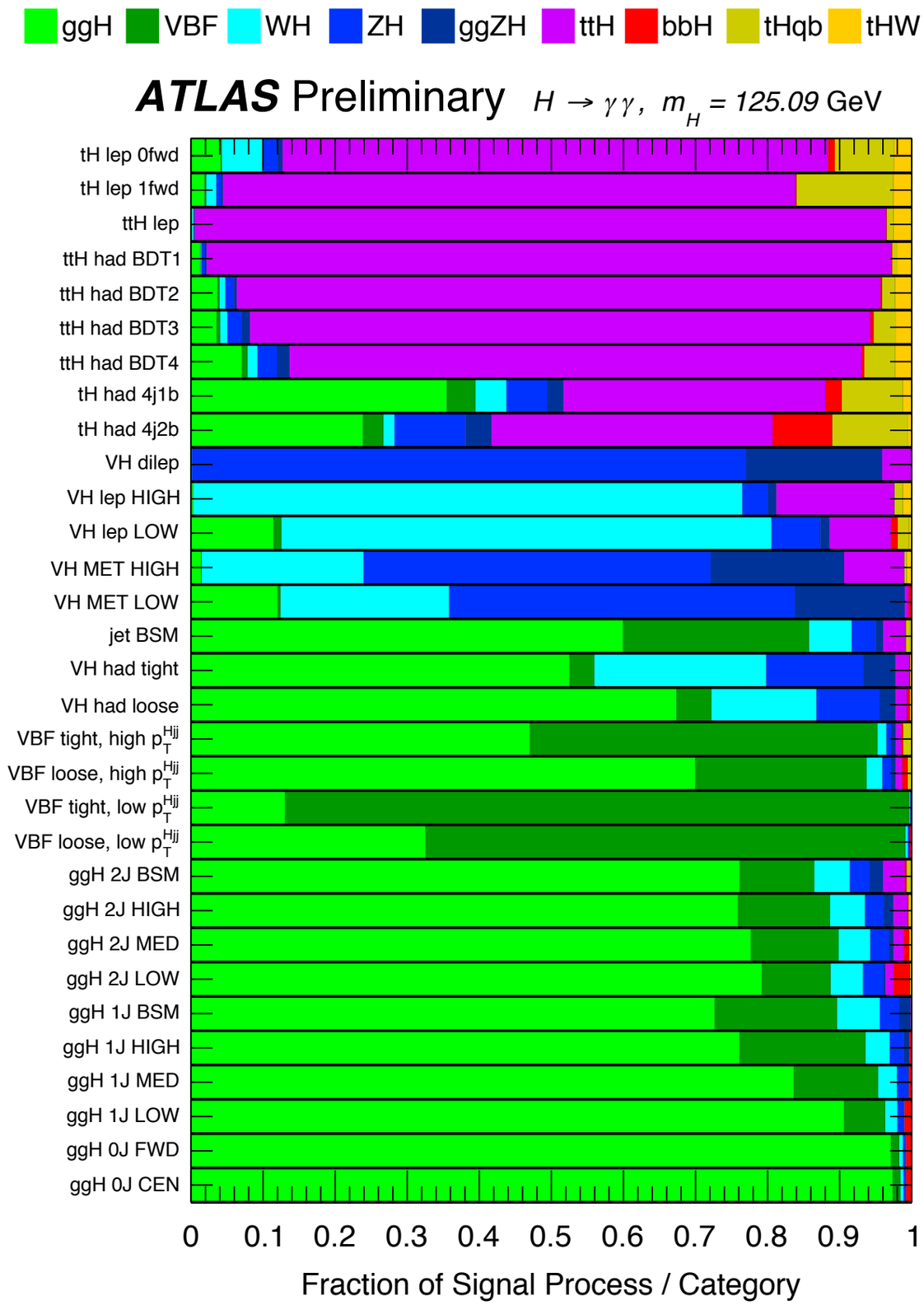
Total cross section measurement



- Cross section extracted from inclusive spectra: agnostic about production modes
- Extrapolate to full phase-space
- Good compatibility with SM (p-value = 84%)
- Compatibility between two channels: 1σ

XS in pb	7 TeV	8 TeV	13 TeV
H→γγ	35^{+13}_{-12}	$30.5^{+7.5}_{-7.4}$	$47.9^{+9.1}_{-8.6}$
H→ZZ*→4l	33^{+21}_{-16}	37^{+9}_{-8}	$68.0^{+11.4}_{-10.4}$
Combination	$34 \pm 10(\text{stat.})^{+4}_{-2}(\text{syst.})$	$33.3^{+5.5}_{-5.3}(\text{stat.})^{+1.7}_{-1.3}(\text{syst.})$	$57.0^{+6.0}_{-5.9}(\text{stat.})^{+4.0}_{-3.3}(\text{syst.})$
SM prediction	19.2 ± 0.9	24.5 ± 1.1	$55.6^{+2.4}_{-3.4}$

Analysis categorizations



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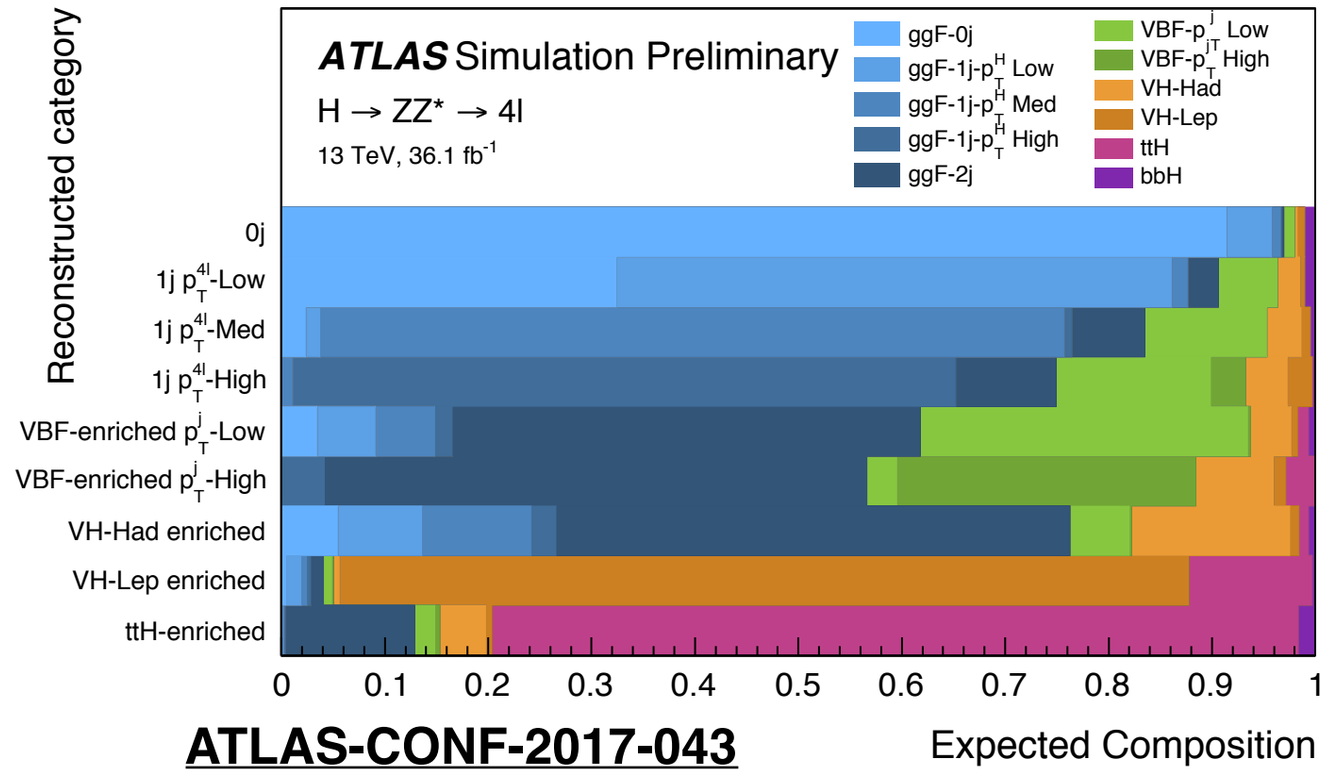

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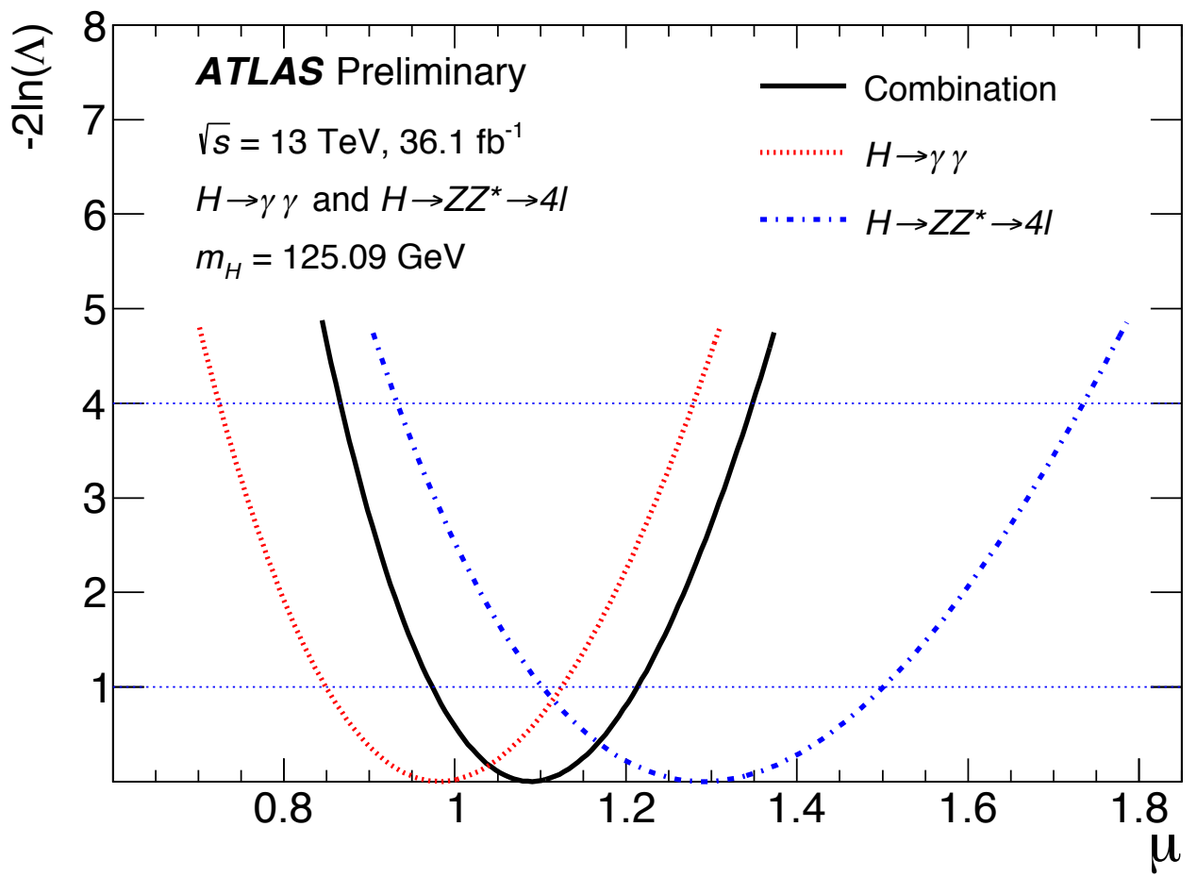
- Introduce categories to distinguish different **production modes** and a variety of **kinematic regions**

✳ *Results presented from this point on are all based on categorized analyses!*

Signal strength measurement



Source	Up	Down
Theoretical		
$\sigma_{\mathrm{ggF}}^{\mathrm{SM}}$ (perturbative)	-0.045	$+0.044$
PDFs	± 0.018	
Branching fractions	± 0.014	
α_S	-0.011	$+0.012$
Experimental		
Luminosity	-0.037	$+0.038$
Electron and photon resolution	$+0.021$	-0.019
Pileup	$+0.014$	-0.015

Signal strength=$n_{sig.}^{obs.}/n_{sig.}^{exp.}$

- $\mu = 1.09 \pm 0.12$

  $= 1.09 \pm 0.09(\mathrm{stat.})^{+0.06}_{-0.05}(\mathrm{exp.})^{+0.06}_{-0.05}(\mathrm{th.})$
- Very good compatibility with SM (p-value=45%)
- Stat. uncertainty dominates. Experimental and theory uncertainty are comparable

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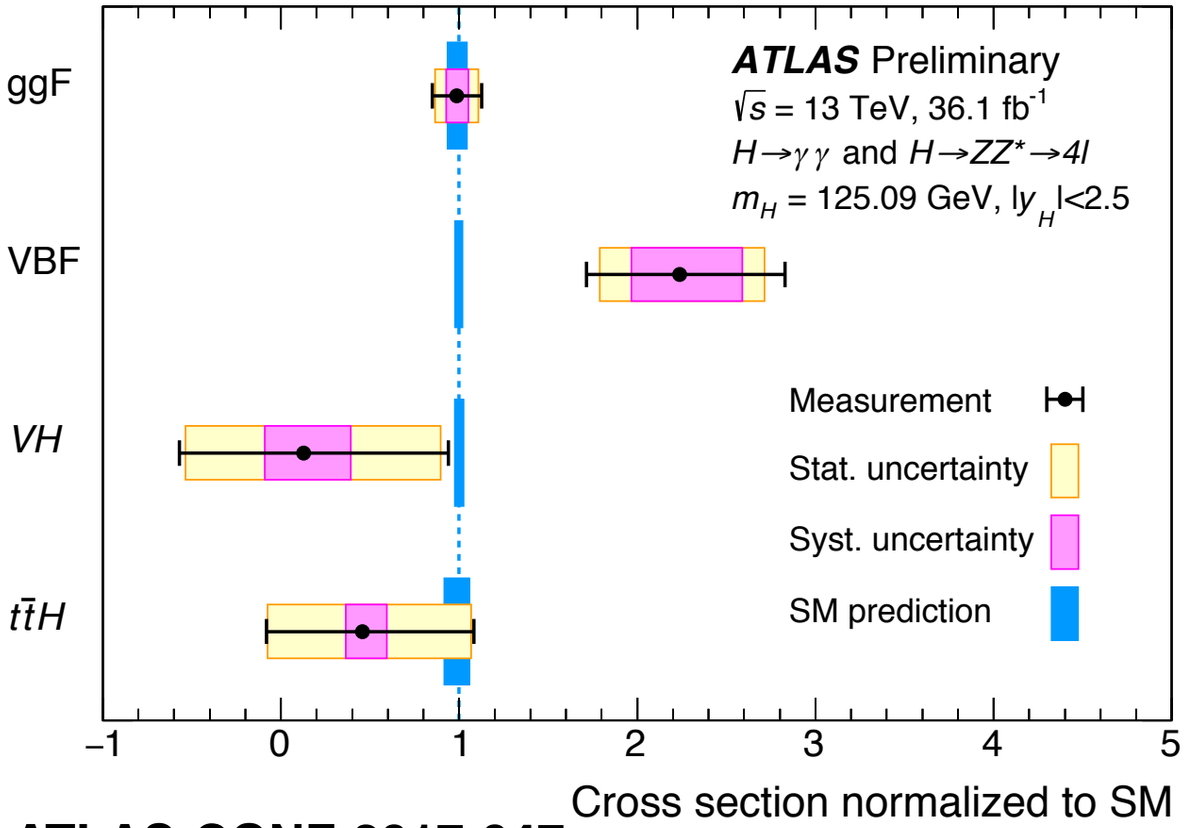
Measurement of production mode cross sections



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- Cross sections measured for ggF(+bbH), VBF, VH and ttH(+tH), assuming SM BRs
  - Measurement performed for **$|y_H| < 2.5$**: no sensitivity beyond
- All measurements dominated by statistical uncertainties
- 4D compatibility with SM: 5%

Process ($\lvert y_H\rvert < 2.5$)	Result [pb]	Uncertainty [pb] Total	Stat.	Exp.	Th.	SM prediction [pb]
ggF	43.9	$^{+6.2}_{-6.0}$	$^{+5.5}_{-5.4}$	$^{+2.7}_{-2.3}$	± 1.2	$44.5^{+2.0}_{-3.0}$
VBF	7.9	$^{+2.1}_{-1.8}$	$^{+1.7}_{-1.6}$	$^{+0.8}_{-0.6}$	$^{+1.0}_{-0.7}$	$3.52^{+0.08}_{-0.07}$
VH	0.3	$^{+1.6}_{-1.4}$	$^{+1.5}_{-1.3}$	± 0.4	$^{+0.3}_{-0.2}$	$1.99^{+0.06}_{-0.05}$
$t\bar{t}H$	0.27	$^{+0.37}_{-0.32}$	$^{+0.36}_{-0.31}$	$^{+0.06}_{-0.05}$	$^{+0.05}_{-0.02}$	$0.59^{+0.03}_{-0.05}$

ggF vs. VBF contour & correlation matrix

- Correlation between production modes comes from crosstalk
  - E.g. ggF contamination in VBF categories

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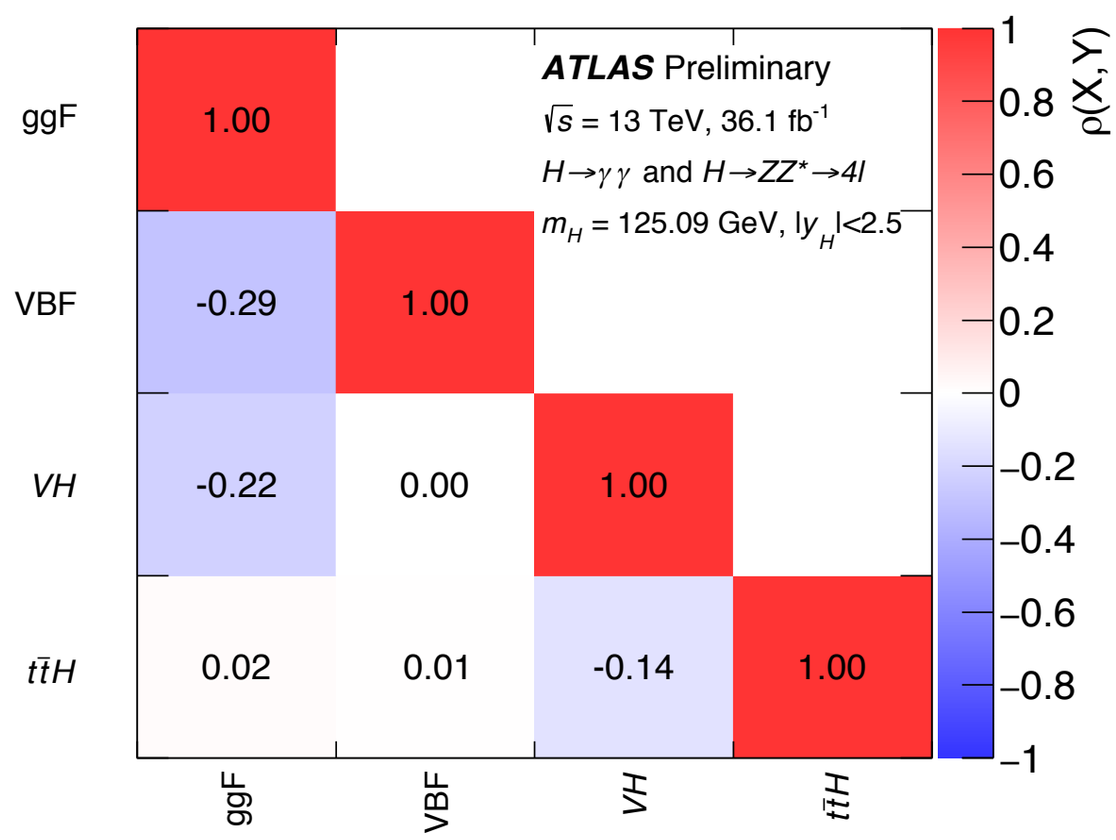

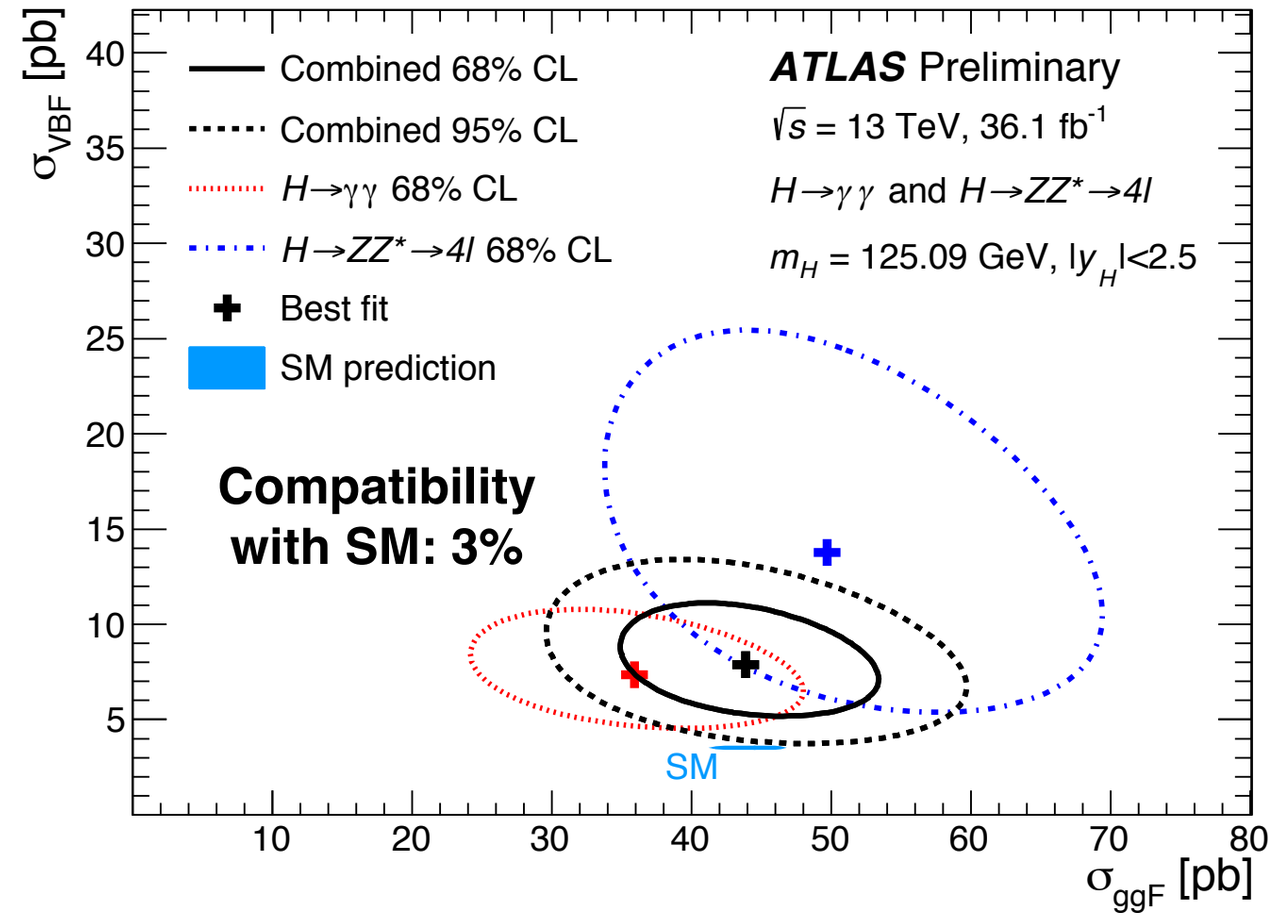

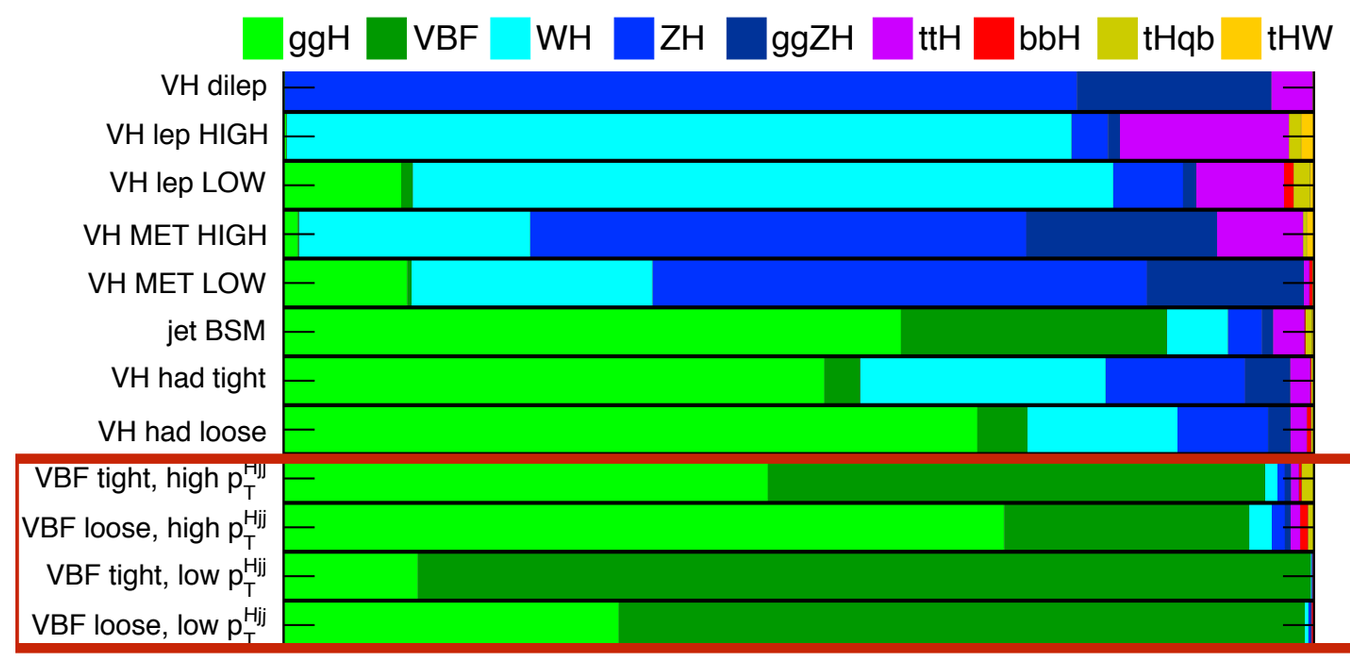

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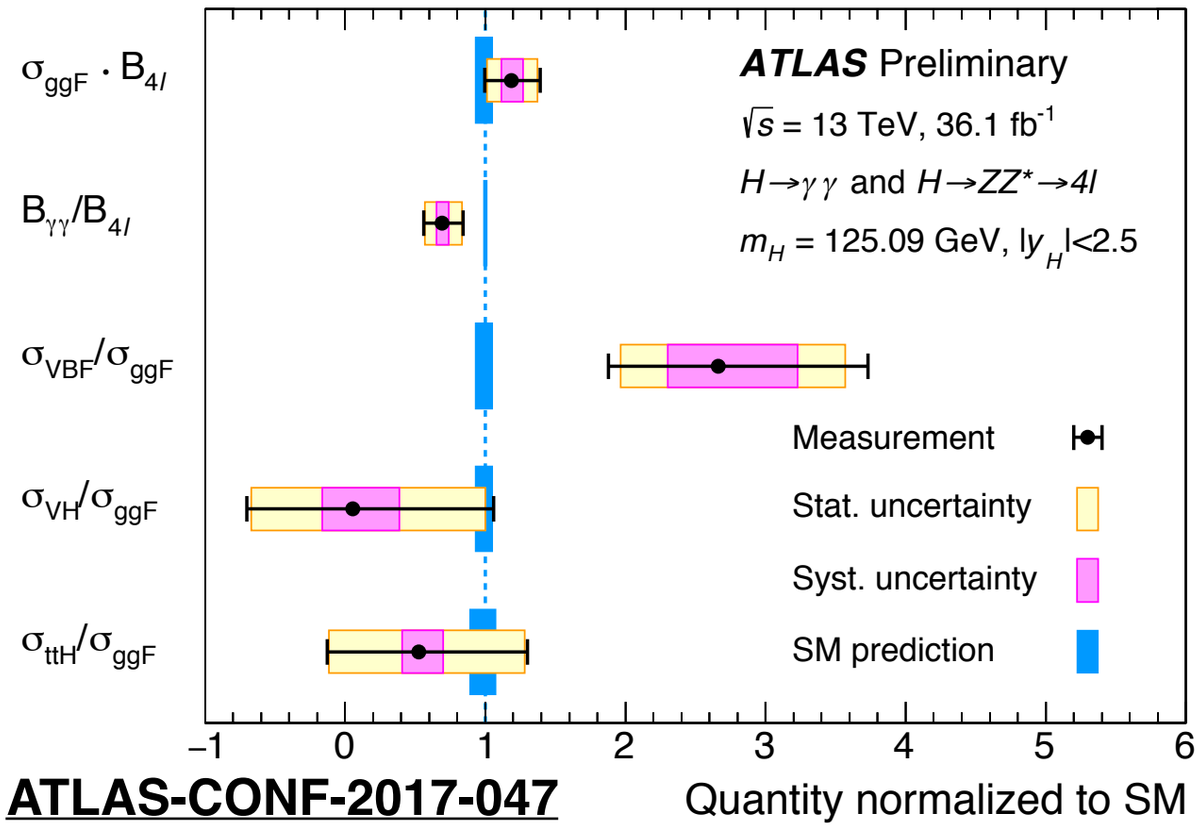
Ratio of production cross-sections and BRs



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- No assumptions on BR: $B_{\gamma\gamma}/B_{4l}$ floating in the fit
- Ratios allow cancellation of common systematic uncertainties
- 5D compatibility with SM 3%

Quantity		Result	Uncertainty Total	Stat.	Exp.	Th.	SM prediction
$\sigma_{\mathrm{ggF}}\cdot \mathrm{B}_{4\ell}$	[fb]	6.6	$^{+1.2}_{-1.0}$	$^{+1.1}_{-1.0}$	± 0.4	± 0.2	$5.6^{+0.3}_{-0.4}$
$\mathrm{B}_{\gamma\gamma}/\mathrm{B}_{4\ell}$		12.5	$^{+2.8}_{-2.3}$	$^{+2.6}_{-2.2}$	$^{+0.9}_{-0.7}$	± 0.2	18.1 ± 0.2
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{ggF}}$	$[10^{-2}]$	21.5	$^{+8.5}_{-6.3}$	$^{+7.3}_{-5.6}$	$^{+2.8}_{-1.7}$	$^{+3.6}_{-2.2}$	$7.9^{+0.4}_{-0.6}$
$\sigma_{VH}/\sigma_{\mathrm{ggF}}$	$[10^{-2}]$	0.2	$^{+4.5}_{-3.4}$	$^{+4.2}_{-3.2}$	$^{+1.2}_{-0.9}$	$^{+0.9}_{-0.4}$	$4.5^{+0.2}_{-0.3}$
$\sigma_{t\bar{t}H}/\sigma_{\mathrm{ggF}}$	$[10^{-2}]$	0.7	$^{+1.0}_{-0.9}$	$^{+1.0}_{-0.9}$	$^{+0.2}_{-0.1}$	± 0.1	1.3 ± 0.1

Simplified Template Cross Section (STXS) framework

- In Run 1 LHC Higgs boson coupling measurements, the production processes are accessed inclusively assuming SM predicted kinematic distributions
- In Run 2, we have started exploring different kinematic regions using the **STXS framework**
  - Regroup production processes according to final states
  - Divide cross sections into kinematic regions (“bins”) and thus **reduces dependence on theory predictions**
    - Division granularity will increase in “stages” as data statistics grow
      - “**Stage 0**”: essentially Run-1 style inclusive measurements
      - “**Stage 1**”: start introducing splitting in kinematic regions
    - Rely on SM predictions in each production bin (“template”)

STXS Stage 1 definition & merging scheme

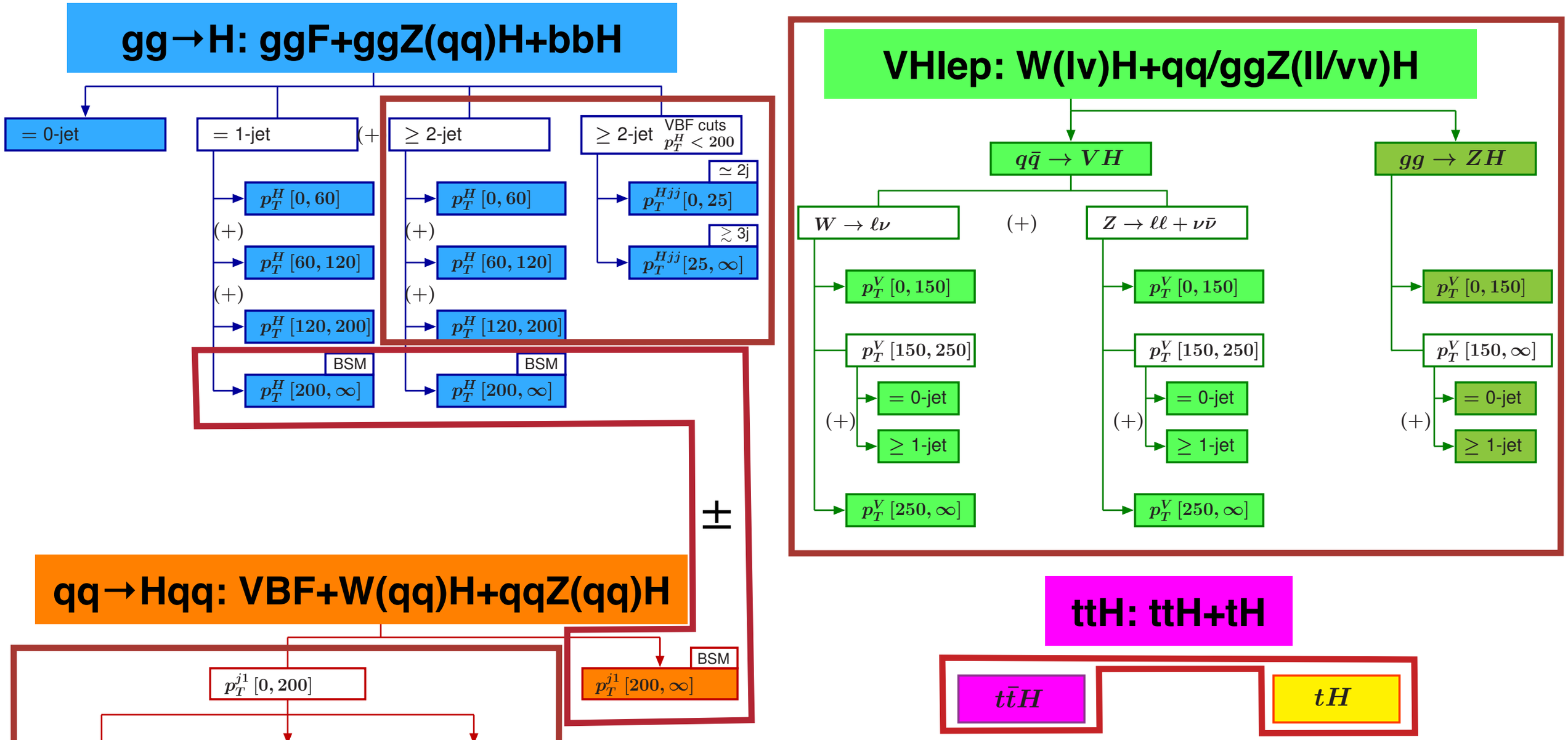
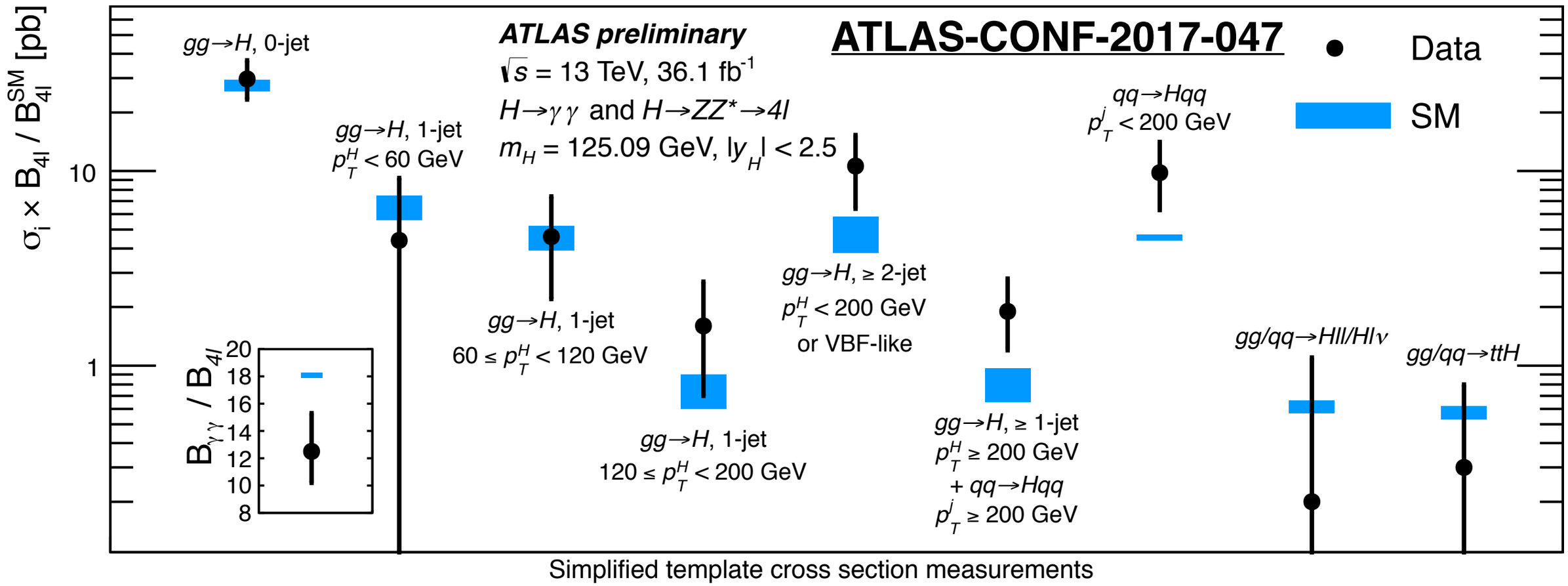


Diagram slightly modified from Les Houches 2015 proceeding

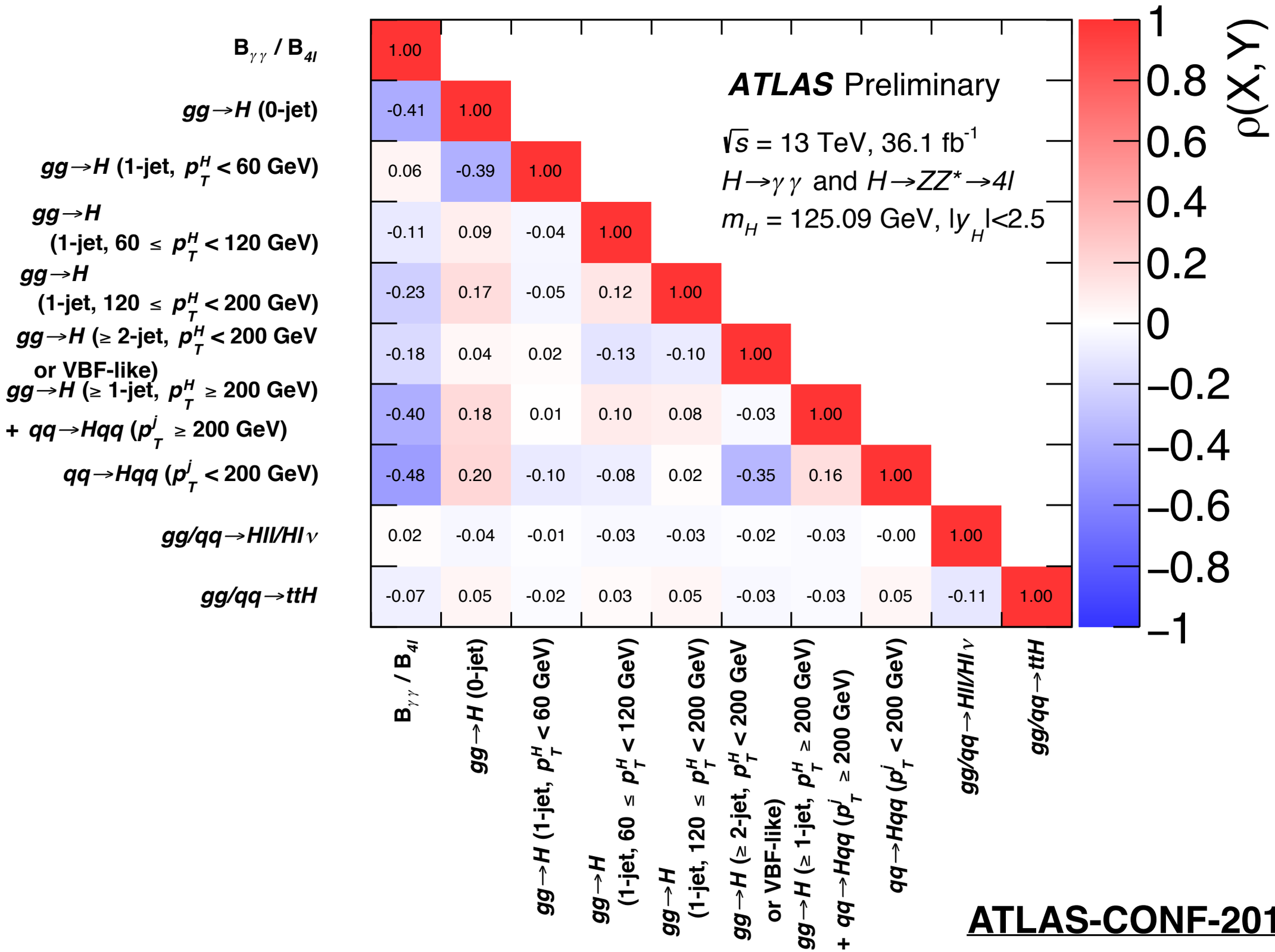
- Develop merging scheme which
  - Keeps interesting BSM bins
  - <100% expected uncertainty in the rest of the bins
  - Minimizes correlations between bins

STXS results



- Besides cross section of production bins, $\mathbf{B_{\gamma\gamma}/B_{4l}}$ is also a free parameter measured from data
  - Therefore, the reported cross sections are actually corresponding to $\boldsymbol{\sigma_i \times B_{4l}}$. $\mathbf{B_{4l}^{SM}}$ is divided out in above plot
- 10D compatibility with SM: 9%
- σ(gg→H+≥2j, p^H_T>200 GeV – qq2Hqq, p^j_T>200 GeV) is floating in the fit. The best fit result is $1.7^{+1.7}_{-1.5}$ pb

Correlation matrix for STXS results



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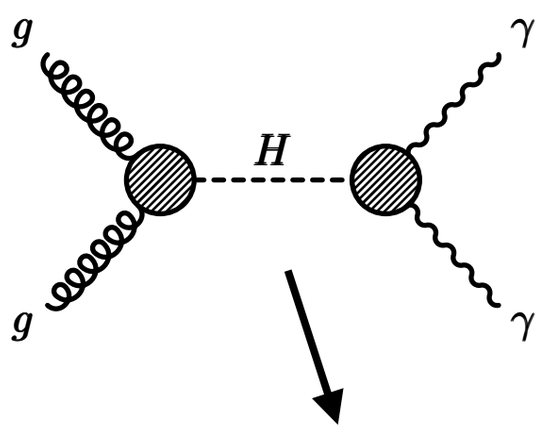
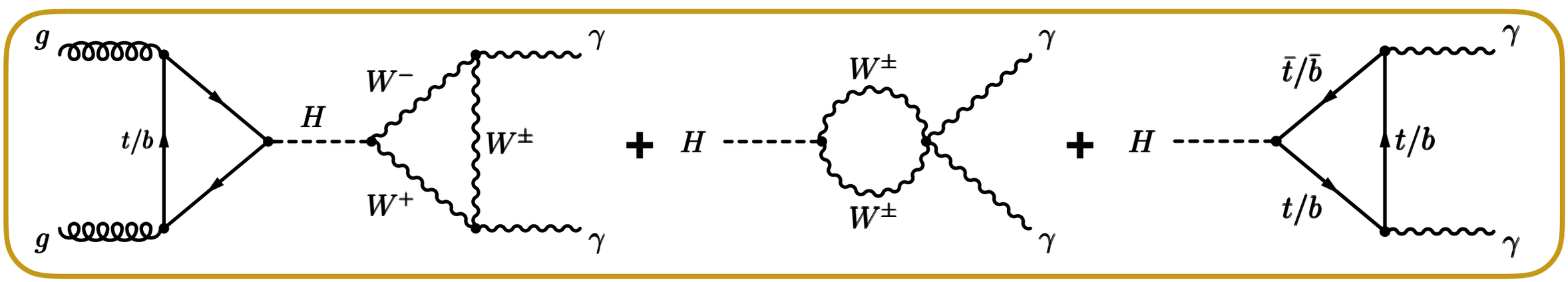
Kappa framework for deriving coupling info

Leading-order tree-level motivated framework:
kappa framework

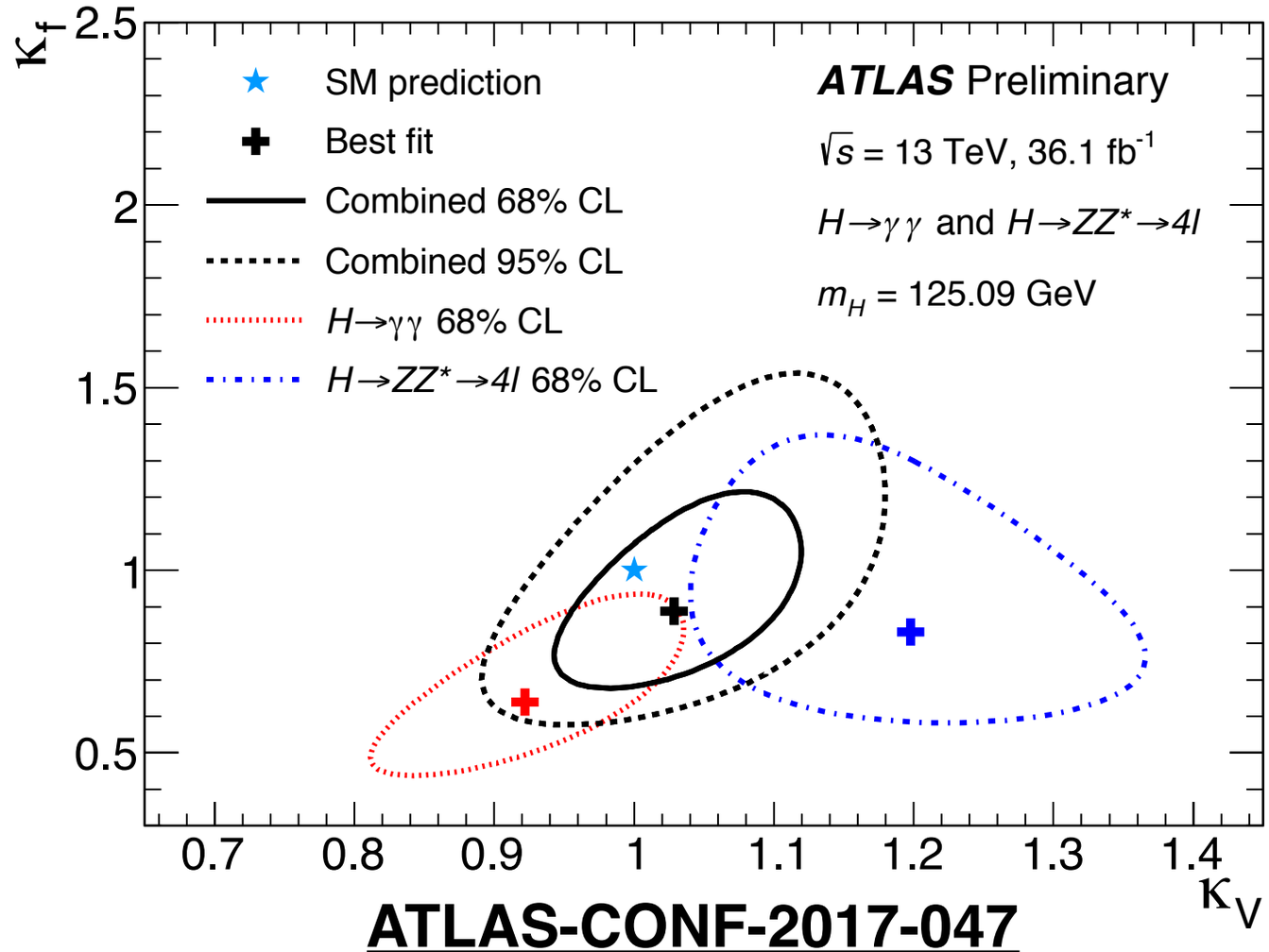


$$(\sigma \times \mathbf{BR})(\mathbf{gg} \to \mathbf{H} \to \gamma\gamma) \sim \frac{\kappa_{\mathbf{g}}^{\mathbf{2}}(\kappa_{\mathbf{t}}, \kappa_{\mathbf{b}}, \ldots)\kappa_{\gamma}^{\mathbf{2}}(\kappa_{\mathbf{W}}, \kappa_{\mathbf{t}}, \ldots)}{\kappa_{\mathbf{H}}^{\mathbf{2}}(\kappa_{\mathbf{b}}, \kappa_{\mathbf{W}}, \kappa_{\mathbf{Z}}, \kappa_{\tau}, \kappa_{\mathbf{t}}, \ldots)}$$



- Can handle other production and decay vertices in a similar way (much simpler in most cases)

Kappa model: κ_V vs. κ_f



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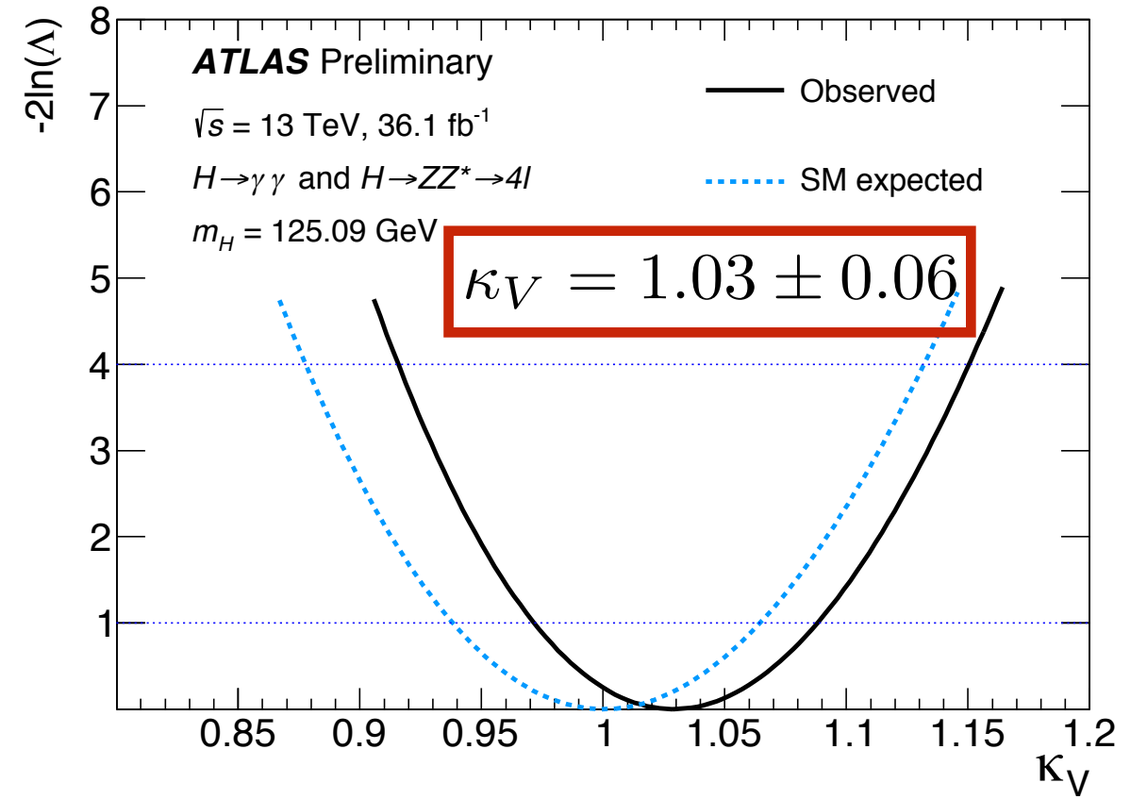
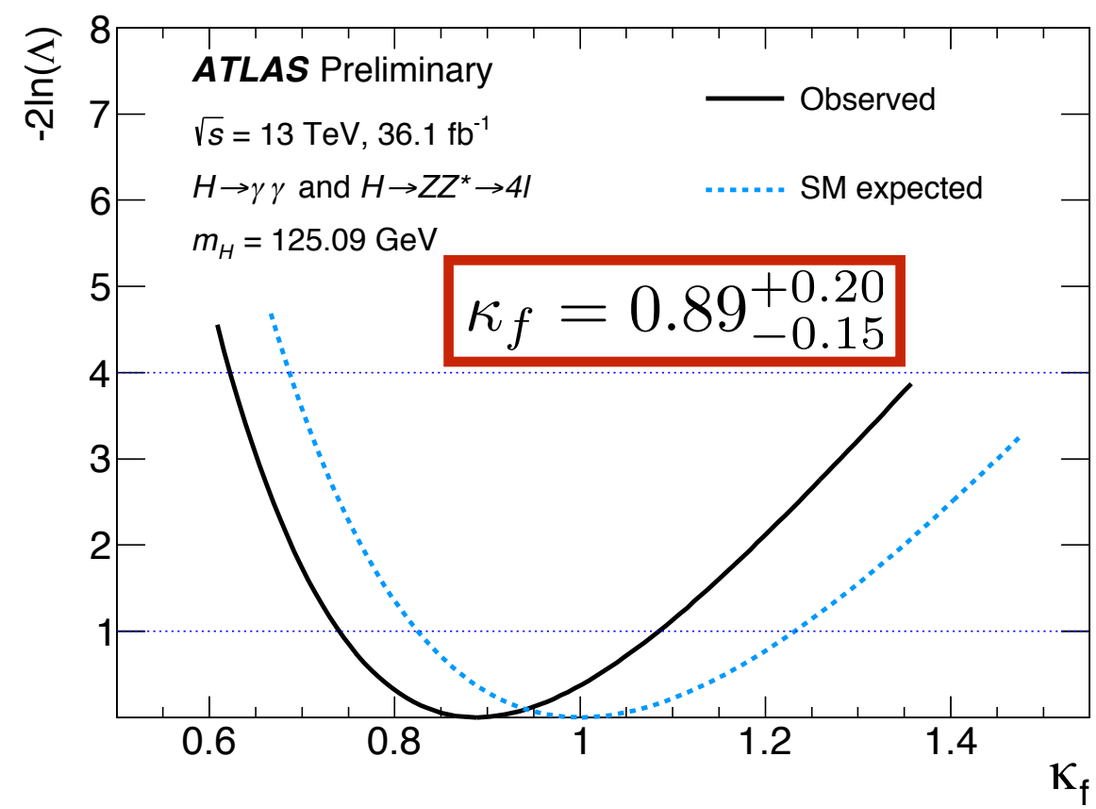
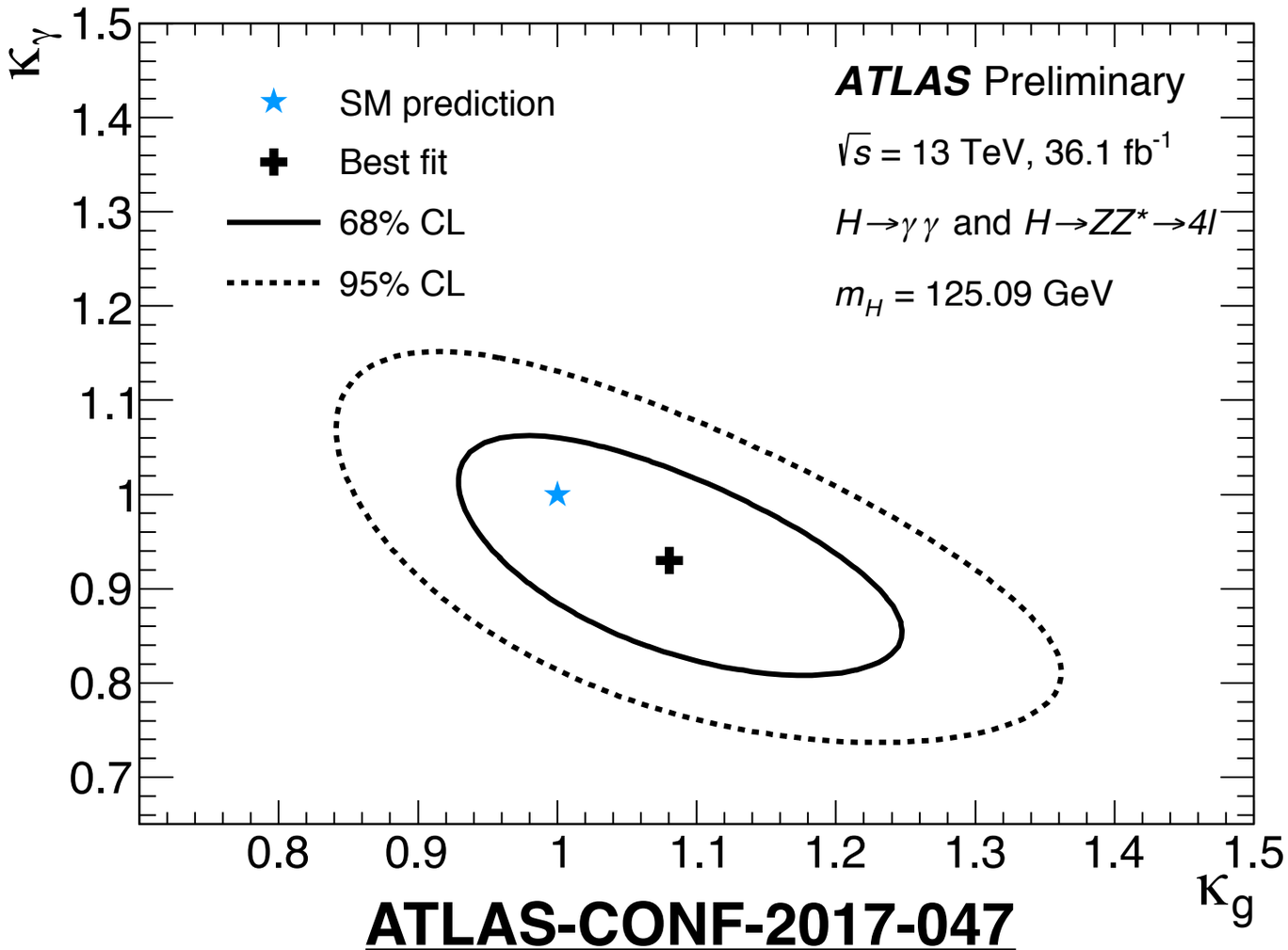




- Assume uniform coupling modifiers for all weak vector bosons (κ_V) and all fermions (κ_f), including those in the loops. In addition, no BSM contribution to loop vertices or total width
- 2D compatibility with SM: 52%

Kappa model: κ_g vs. κ_γ



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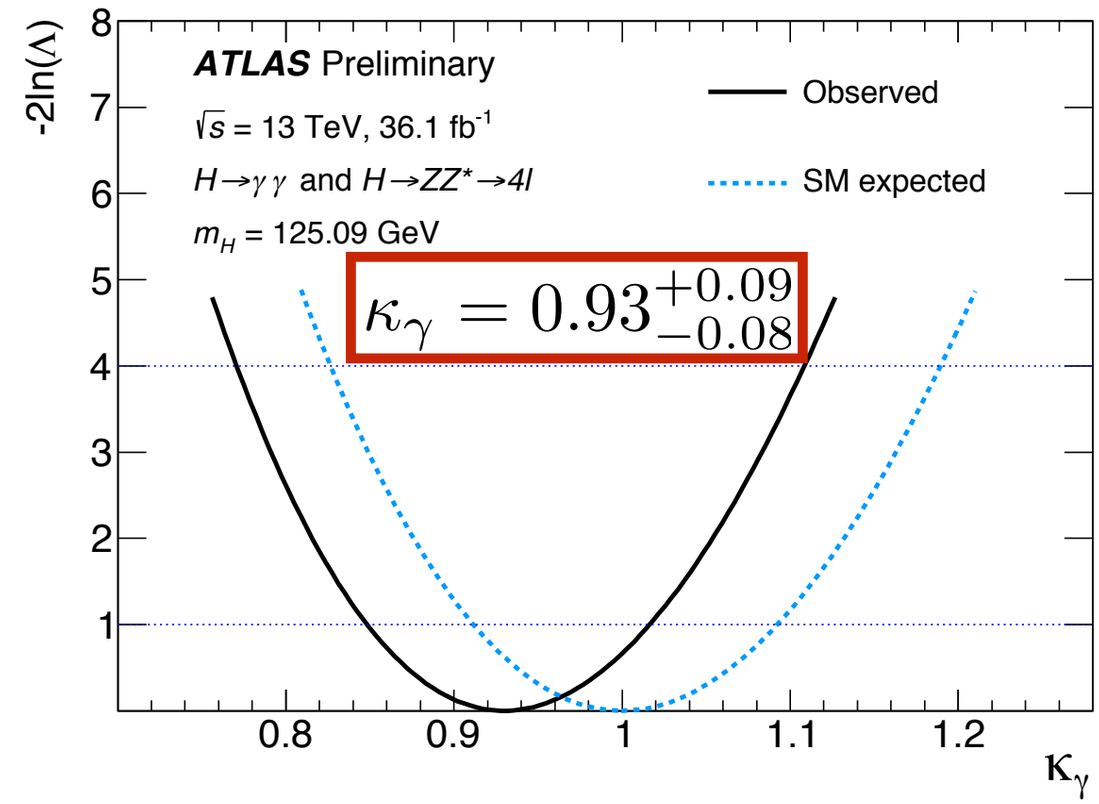
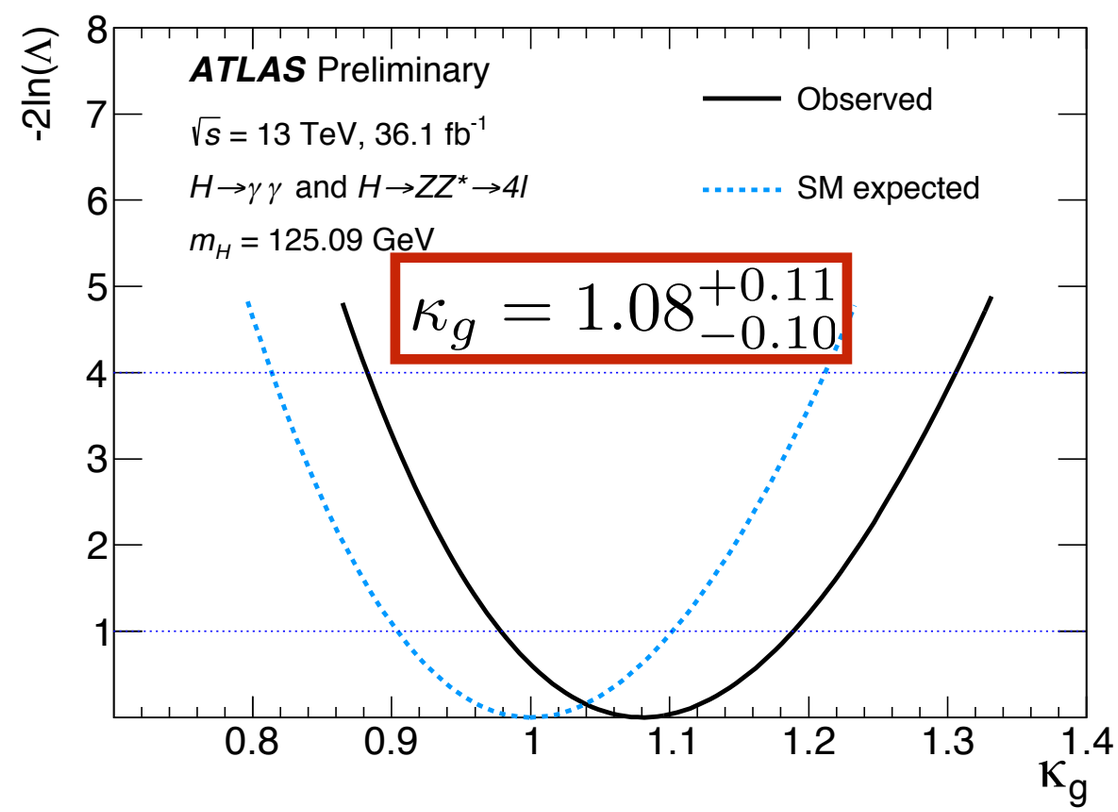
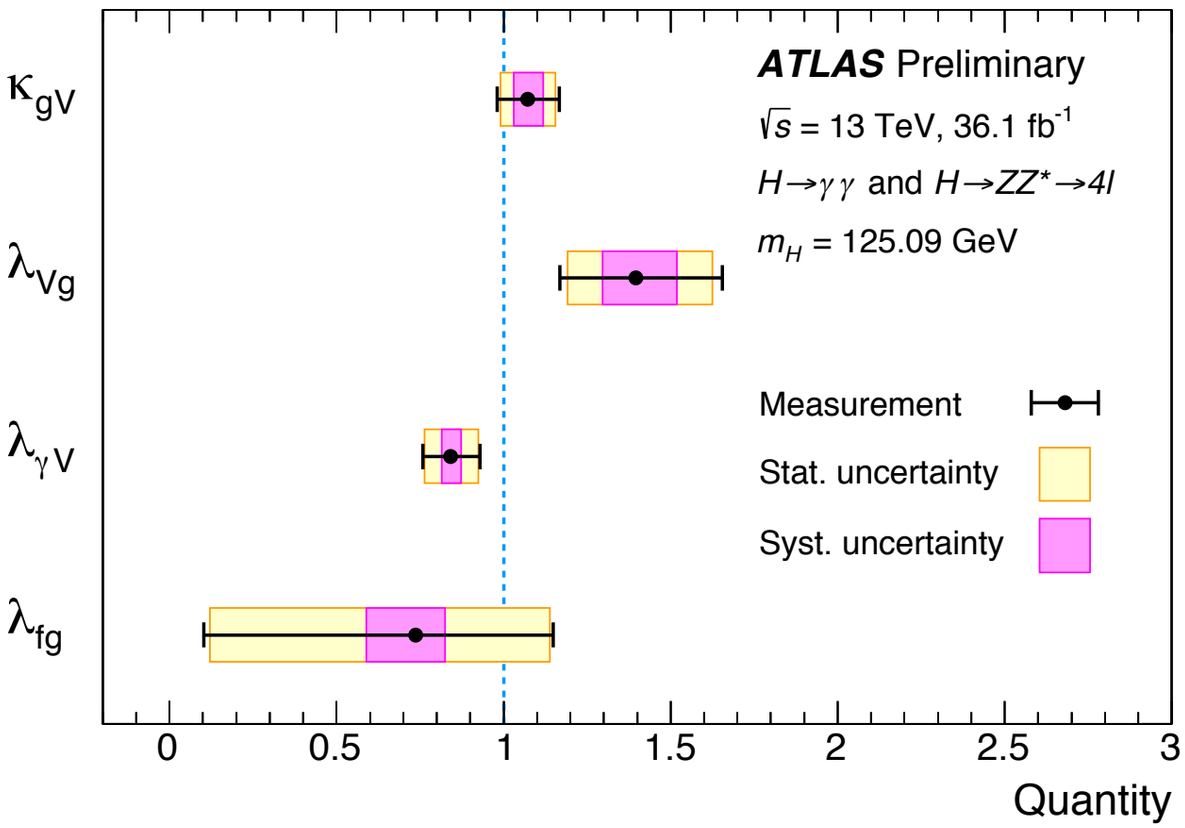
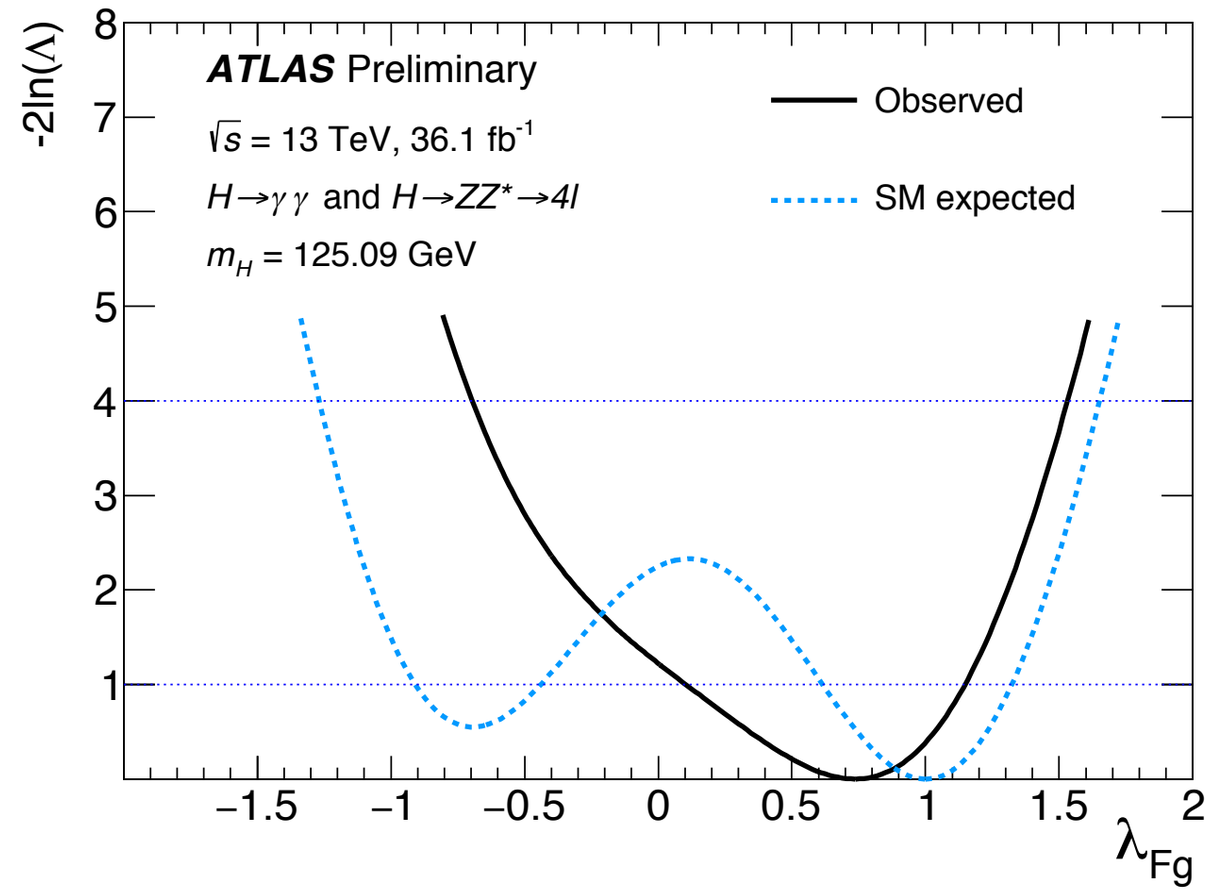




- Assign coupling modifier to gg→H/H→gg (**κ_g**) and H→γγ (**κ_γ**). All the other couplings fixed to SM. In addition, no BSM decays contributing to total width
- 2D compatibility with SM: 68%

Kappa model: generic model





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- No assumptions on loop vertices or total width: define $\boldsymbol{\kappa_{gV}}=\kappa_g\kappa_V/\kappa_H$, $\boldsymbol{\lambda_{Vg}}=\kappa_V/\kappa_g$, $\boldsymbol{\lambda_{\gamma V}}=\kappa_\gamma/\kappa_V$, $\boldsymbol{\lambda_{fg}}=\kappa_f/\kappa_g$
- Allow λ_{fg} to be negative. Other parameters assume to be positive without losing generality
- 4D compatibility with SM: 15%

Conclusion

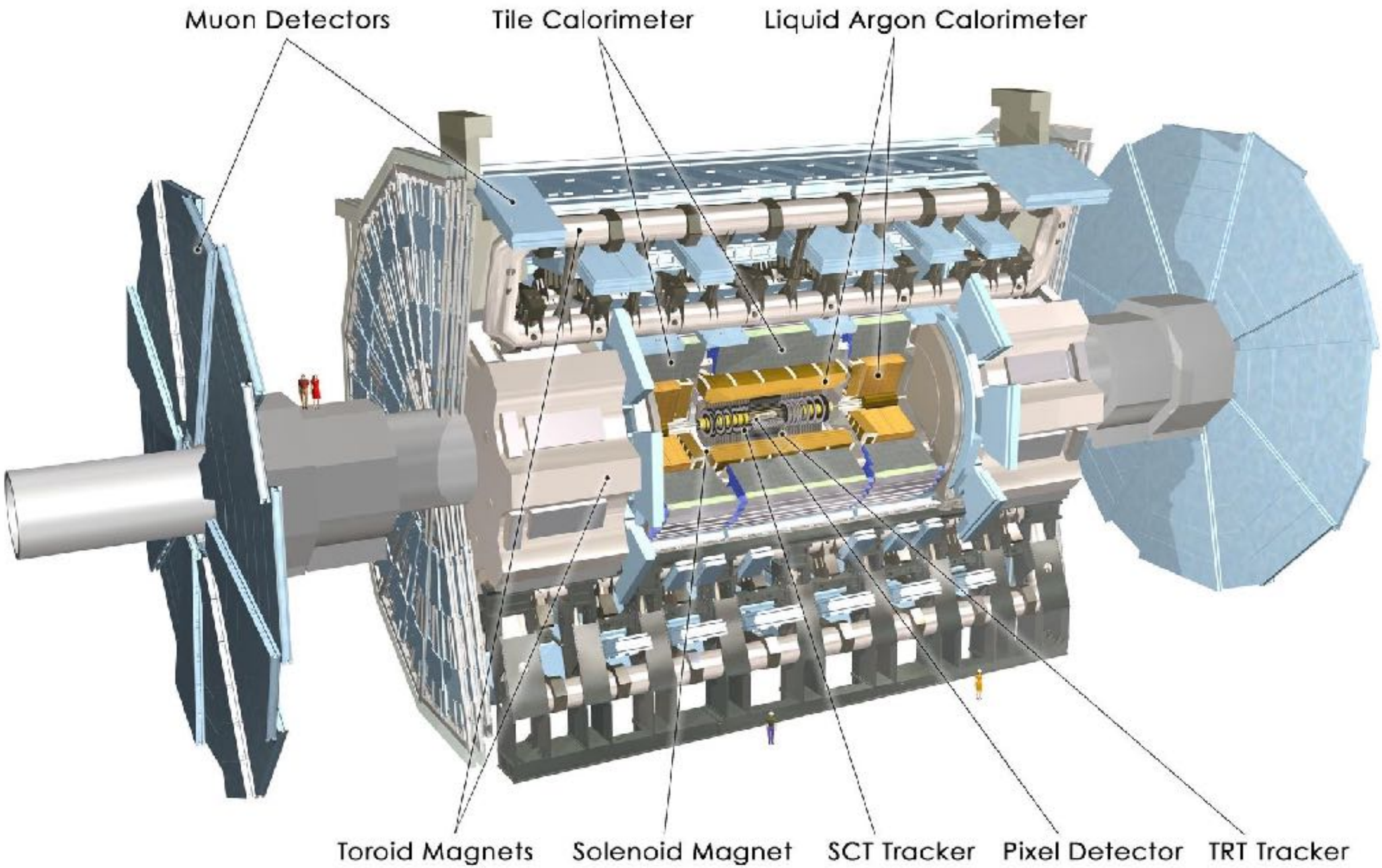
- Measurement of Higgs boson production and decay performed based on 36.1 fb^{-1} of 13 TeV data, combining info from $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$
- Total XS @13 TeV: $57.0^{+6.0}_{-5.9}(\mathrm{stat.})^{+4.0}_{-3.3}(\mathrm{syst.})$ pb
- Signal strength: $1.09 \pm 0.09(\mathrm{stat.})^{+0.06}_{-0.05}(\mathrm{exp.})^{+0.06}_{-0.05}(\mathrm{th.})$
- Production mode cross sections, ratios of production mode cross sections and BRs, and merged Stage 1 STXS are measured. Data also interpreted using kappa framework
- Measurements are still dominated by statistical uncertainty!
- In all cases, compatibility between data and SM is at 2σ level or better
- More channels and more interpretations to be added later this year. Stay tuned!

References

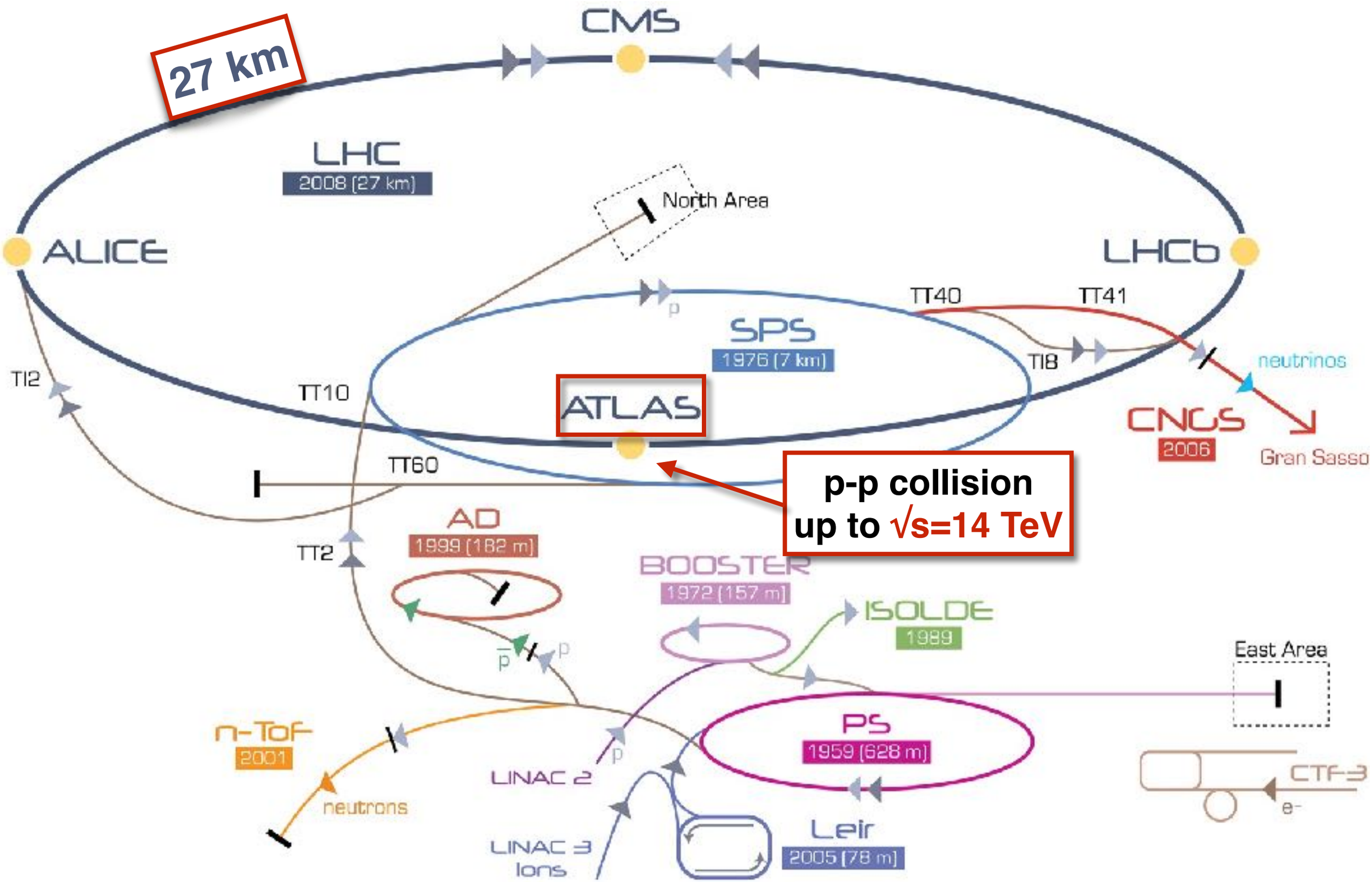
- LHC Higgs XS WG twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
- arXiv:1605.04692: Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report
- ATLAS-CONF-2017-045: Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb^{-1} pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector
- ATLAS-CONF-2017-032: Measurement of inclusive and differential fiducial cross sections in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel at 13 TeV with the ATLAS detector
- ATLAS-CONF-2017-043: Measurement of the Higgs boson coupling properties in the $H \rightarrow ZZ \rightarrow 4\ell$ decay channel at $\sqrt{s}$ = 13 TeV with the ATLAS detector
- ATLAS-CONF-2017-047: Combined measurements of Higgs boson production and decay in the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels using $\sqrt{s}$ = 13 TeV proton-proton collision data collected with the ATLAS experiment

Backup

ATLAS detector



Large Hadron Collider at CERN



Understanding uncertainty components

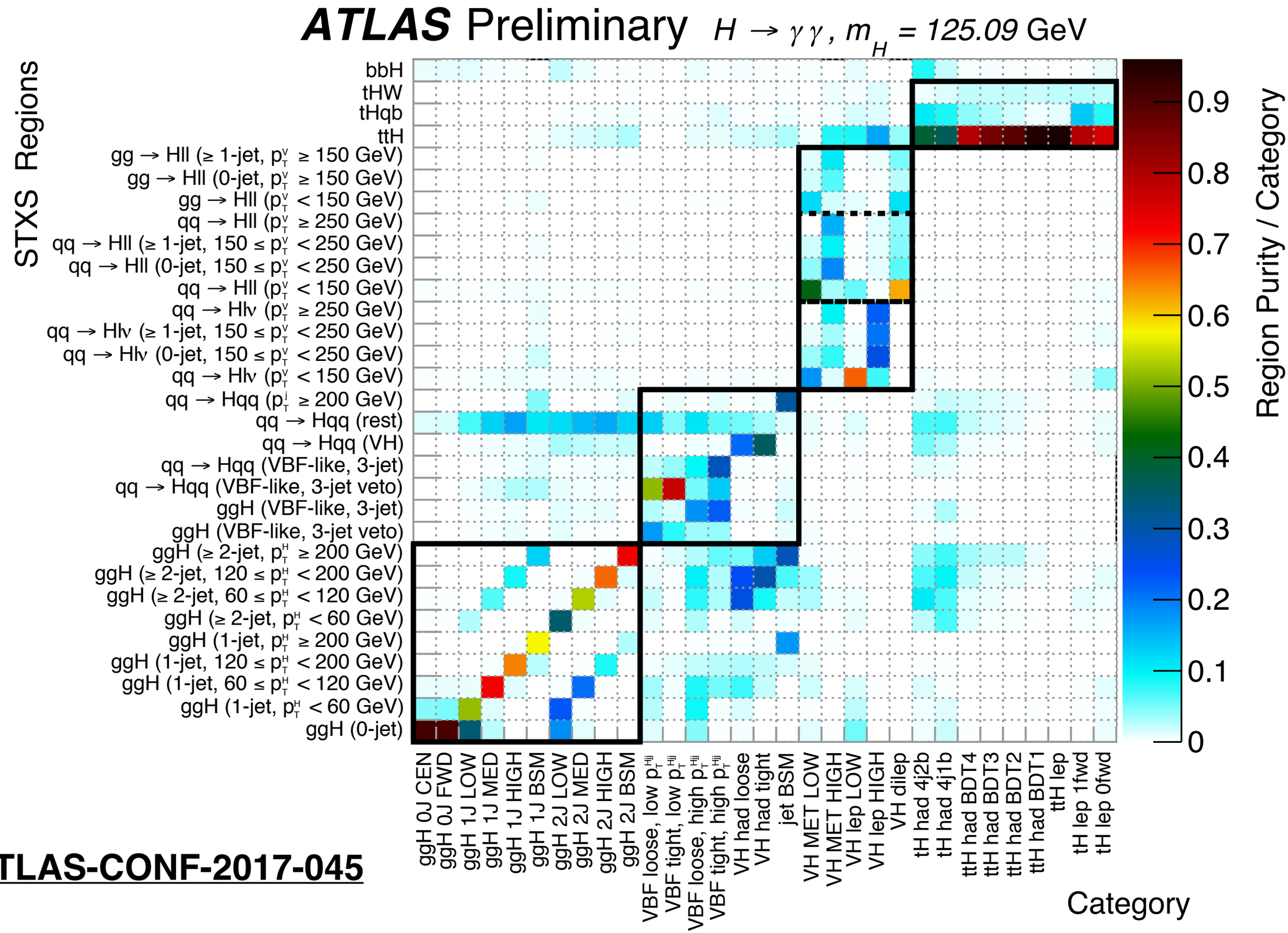
- "**Theory**" uncertainty only include those on **signal**
  - When measuring cross sections, only **theory uncertainties on signal acceptance** are considered. The uncertainties on the inclusive xs are indicated on SM predictions
  - When measuring signal strength and coupling modifiers, **full theory uncertainties** are considered
  - BR uncertainty will be considered when the SM BR is assumed (otherwise not)
- All the other systematics, including theory uncertainties on background (in four-lepton channel), are classified as "**Experimental**".
- "Systematic" = "Experimental" $\oplus$ "Theory"

Summary of analysis categorizations

$H \to \gamma\gamma$
$t\bar{t}H$+tH leptonic (two tHX and one $t\bar{t}H$ categories)
$t\bar{t}H$+tH hadronic (two tHX and four BDT $t\bar{t}H$ categories)
VH dilepton
VH one-lepton, $p_{\mathrm{T}}^{\ell+\mathrm{MET}} \geq 150$ GeV
VH one-lepton, $p_{\mathrm{T}}^{\ell+\mathrm{MET}}$ <150 GeV
VH $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}} \geq 150$ GeV
VH $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV
VH+VBF $p_{\mathrm{T}}^{j1} \geq 200$ GeV
VH hadronic (BDT tight and loose categories)
VBF, $p_{\mathrm{T}}^{\gamma\gamma jj} \geq 25$ GeV (BDT tight and loose categories)
VBF, $p_{\mathrm{T}}^{\gamma\gamma jj} < 25$ GeV (BDT tight and loose categories)
ggF 2-jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV
ggF 2-jet, 120 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma} < 200$ GeV
ggF 2-jet, 60 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma} < 120$ GeV
ggF 2-jet, $p_{\mathrm{T}}^{\gamma\gamma} < 60$ GeV
ggF 1-jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV
ggF 1-jet, 120 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma} < 200$ GeV
ggF 1-jet, 60 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma} < 120$ GeV
ggF 1-jet, $p_{\mathrm{T}}^{\gamma\gamma} < 60$ GeV
ggF 0-jet (central and forward categories)

$H \to ZZ^* \to 4\ell$
$t\bar{t}H$
VH leptonic
2-jet VH
2-jet VBF, $p_{\mathrm{T}}^{j1} \geq 200$ GeV
2-jet VBF, $p_{\mathrm{T}}^{j1} < 200$ GeV
1-jet ggF, $p_{\mathrm{T}}^{4\ell} \geq 120$ GeV
1-jet ggF, 60 GeV $< p_{\mathrm{T}}^{4\ell} < 120$ GeV
1-jet ggF, $p_{\mathrm{T}}^{4\ell} < 60$ GeV
0-jet ggF

Signal composition in H→γγ categories expressed in STXS bins



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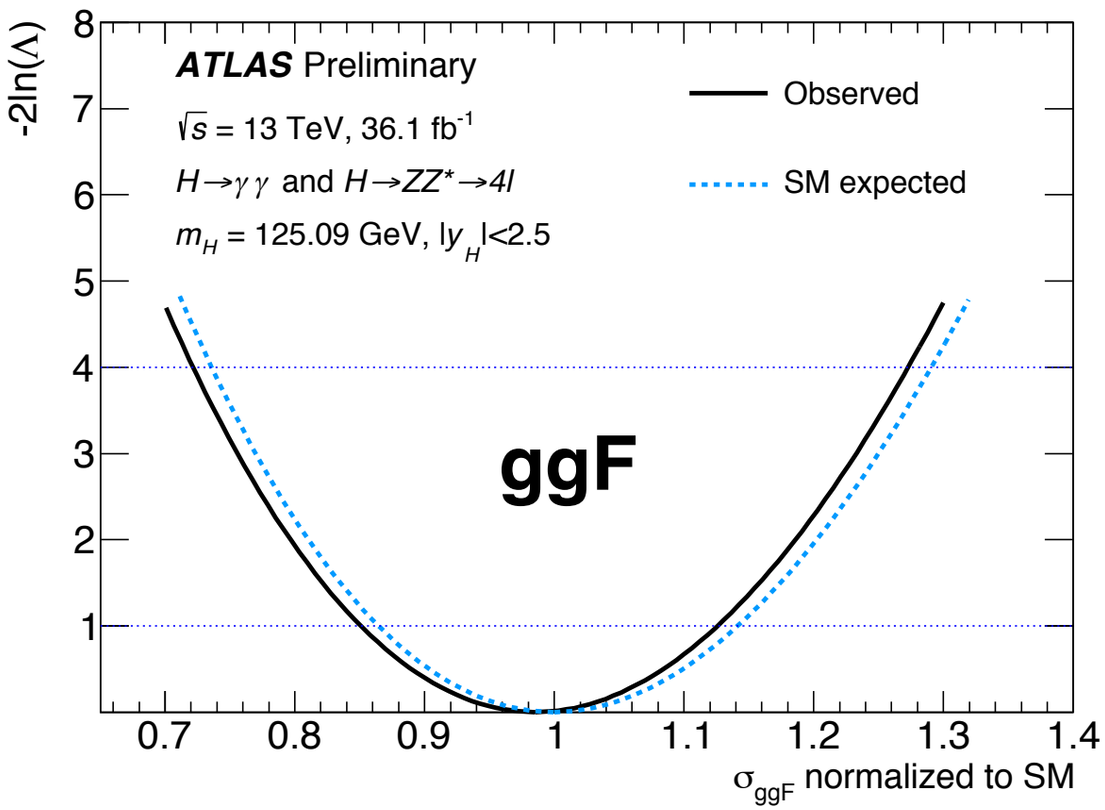
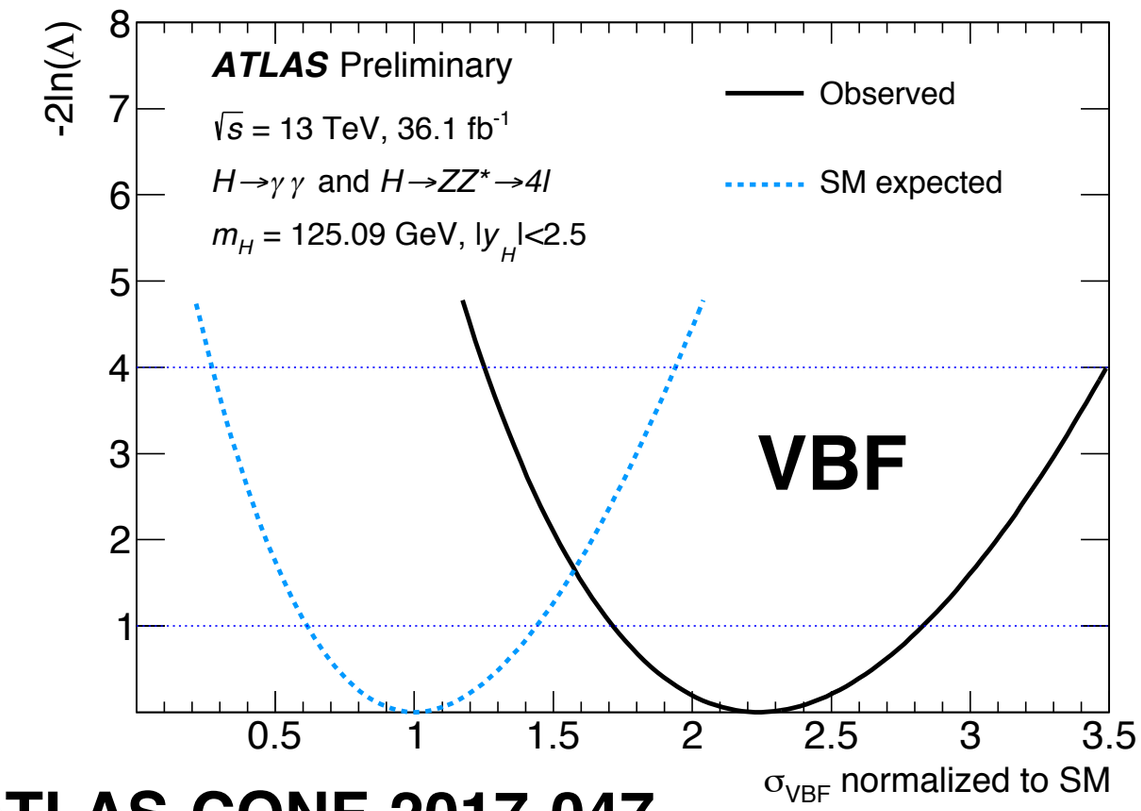
Likelihood scans for production mode cross sections





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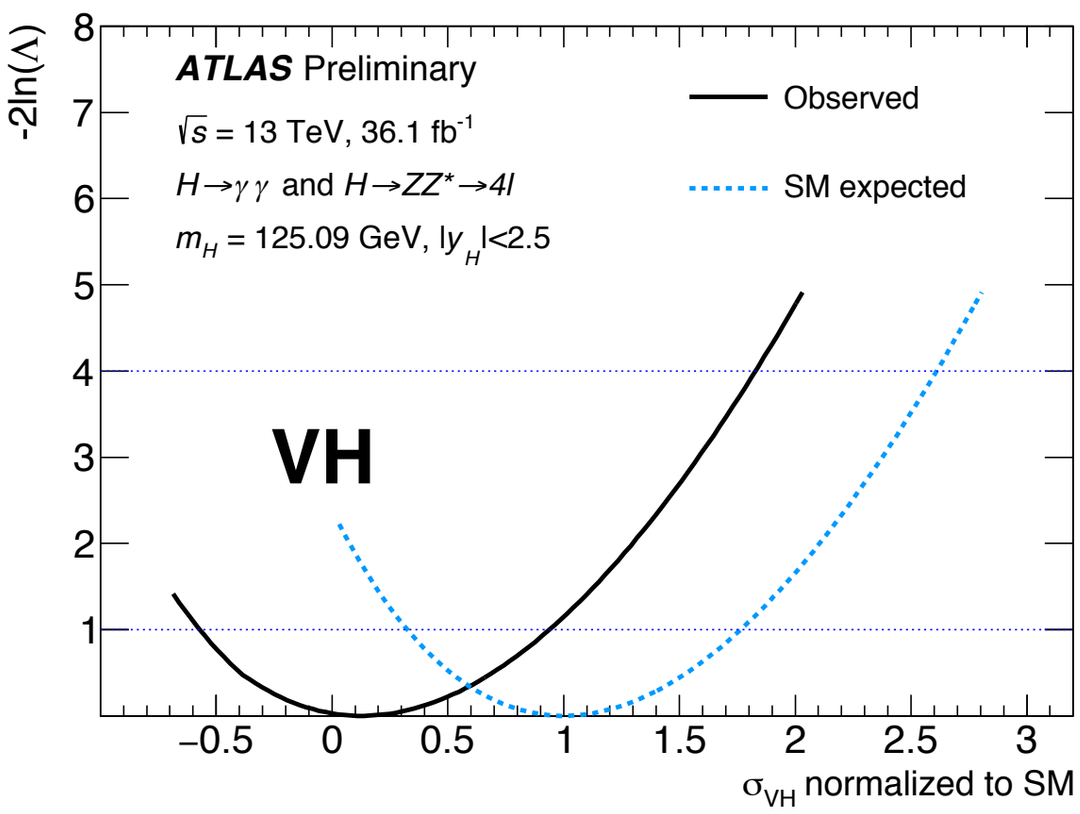
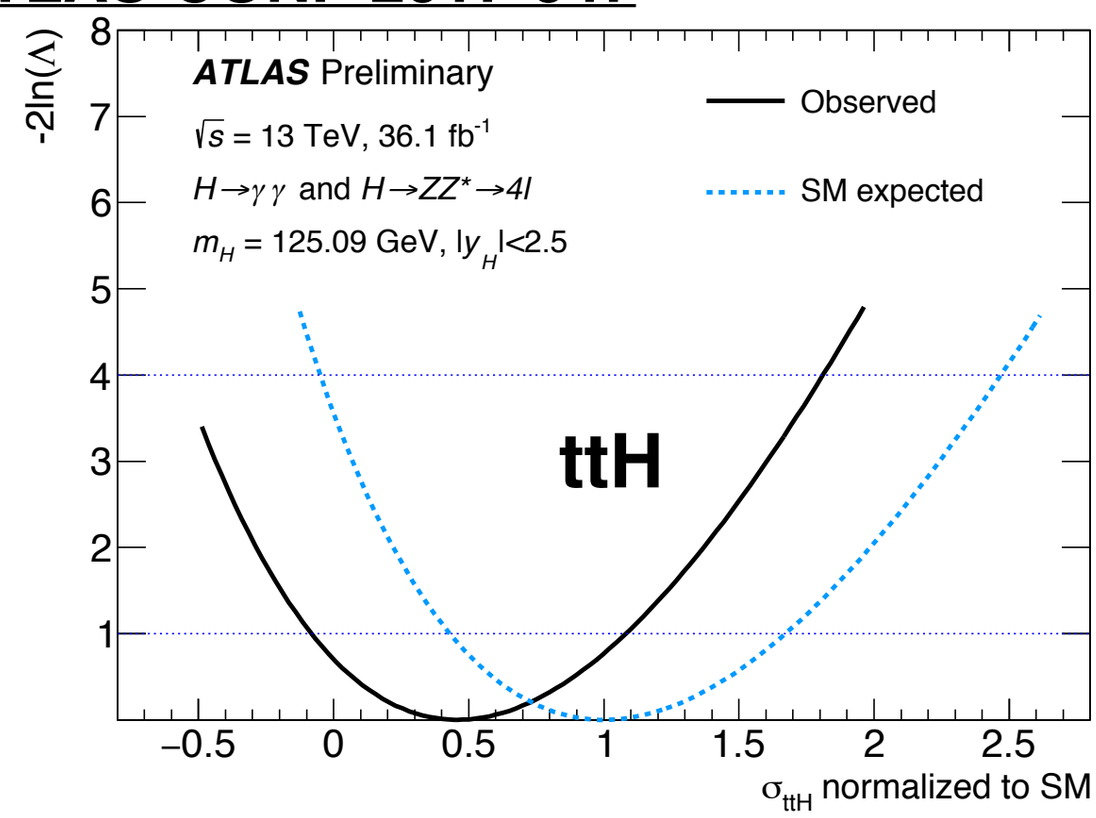
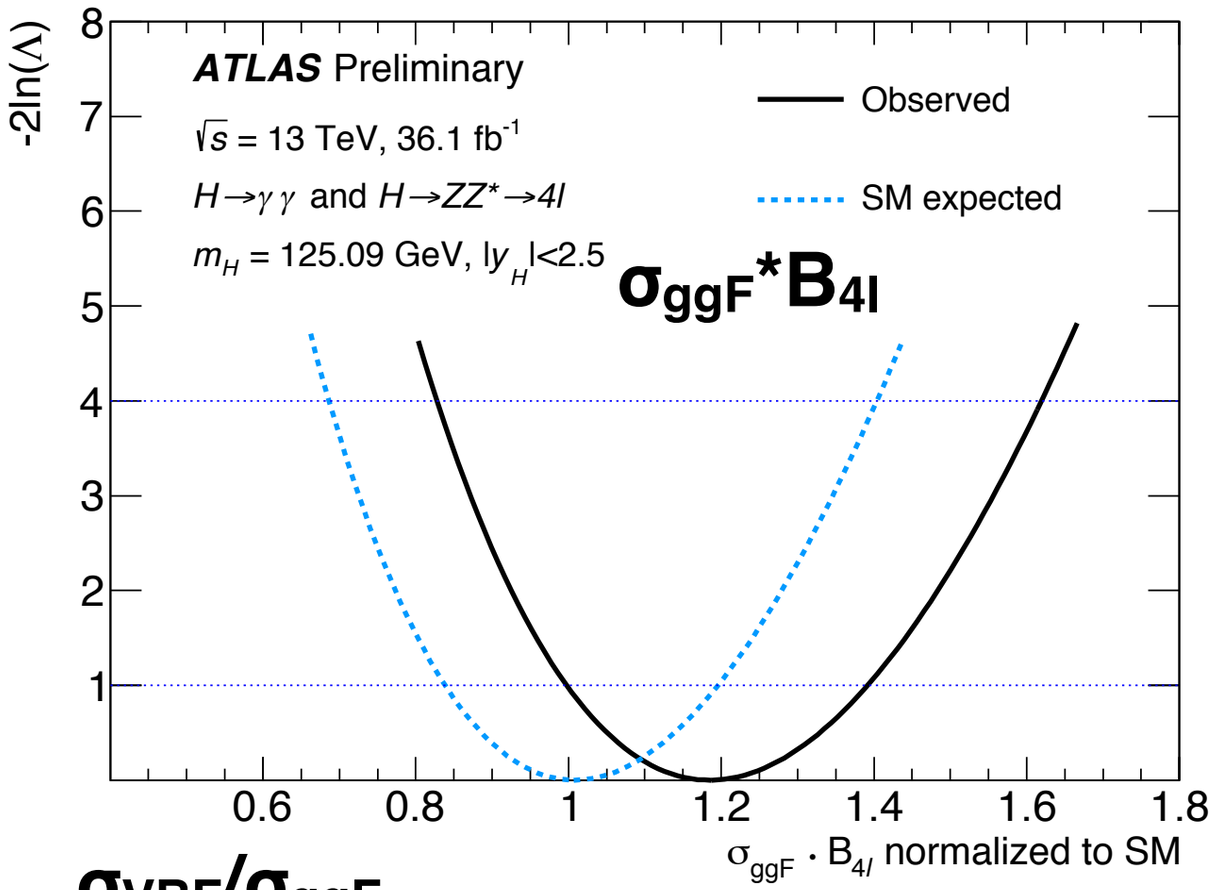
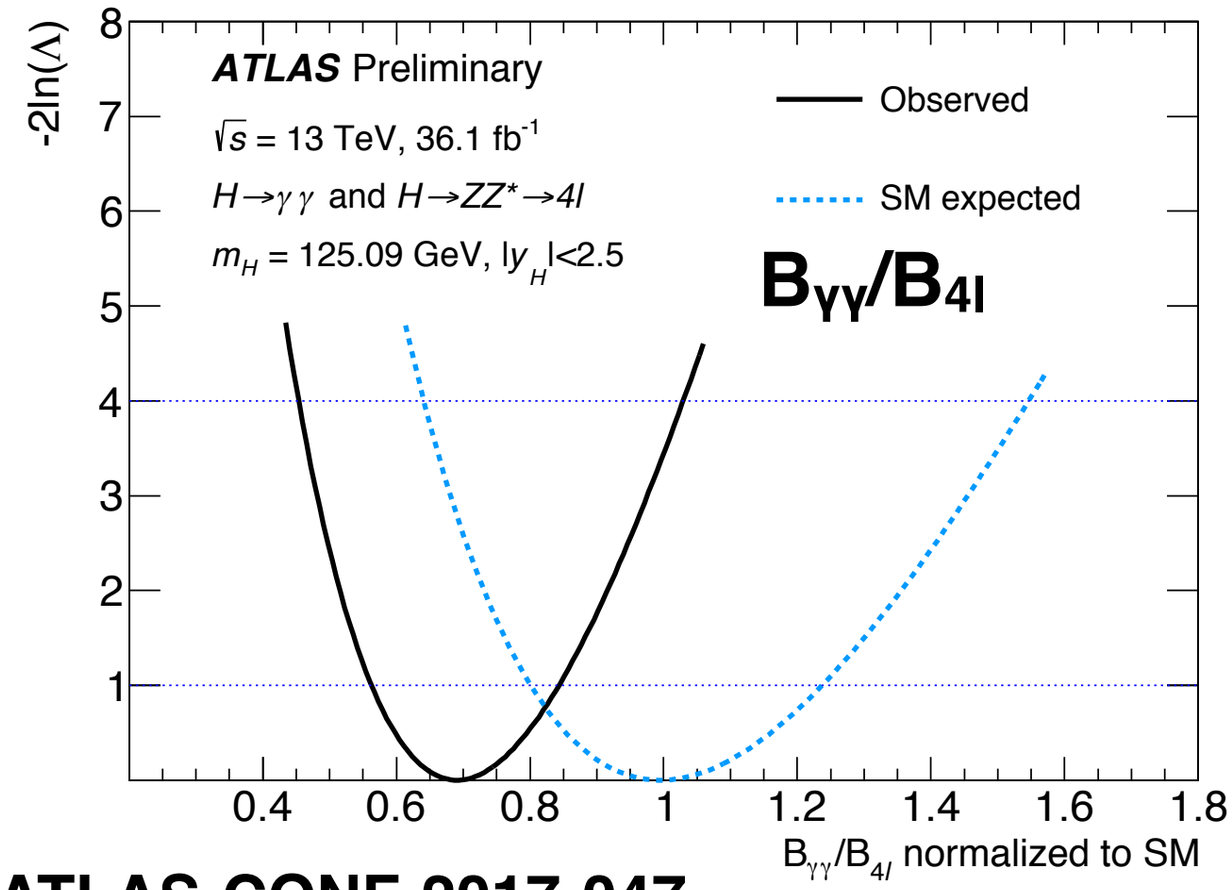




Likelihood scans for ratios of production x-sections and BRs





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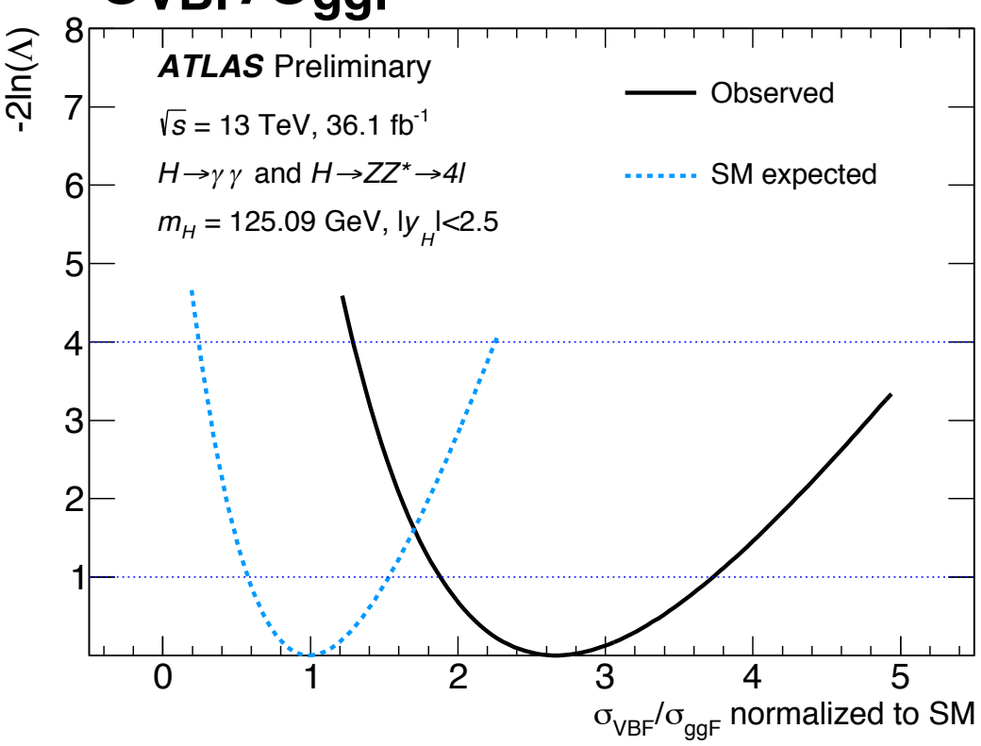
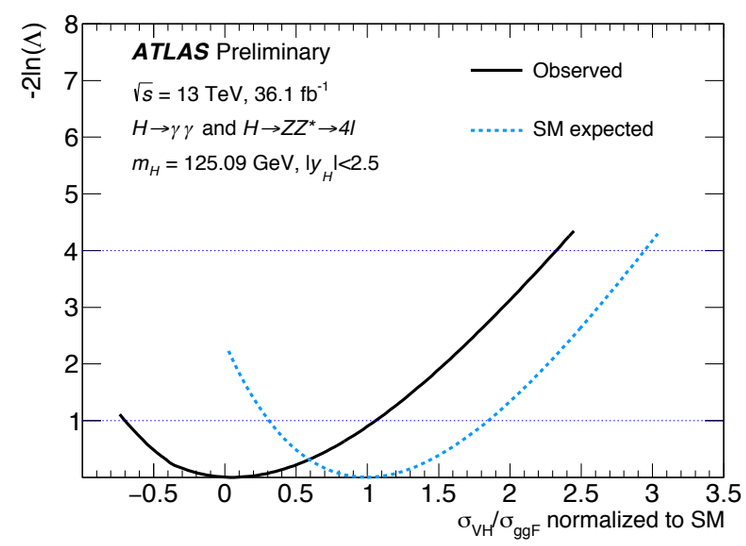
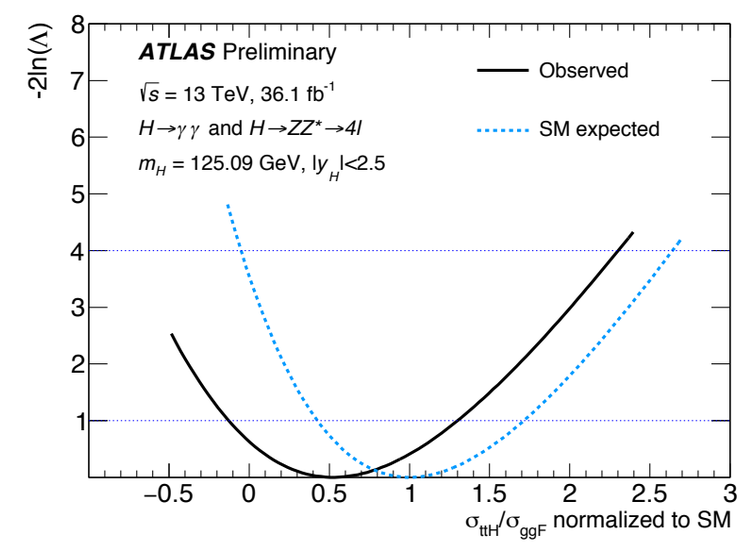
$\sigma_{VBF}/\sigma_{ggF}$



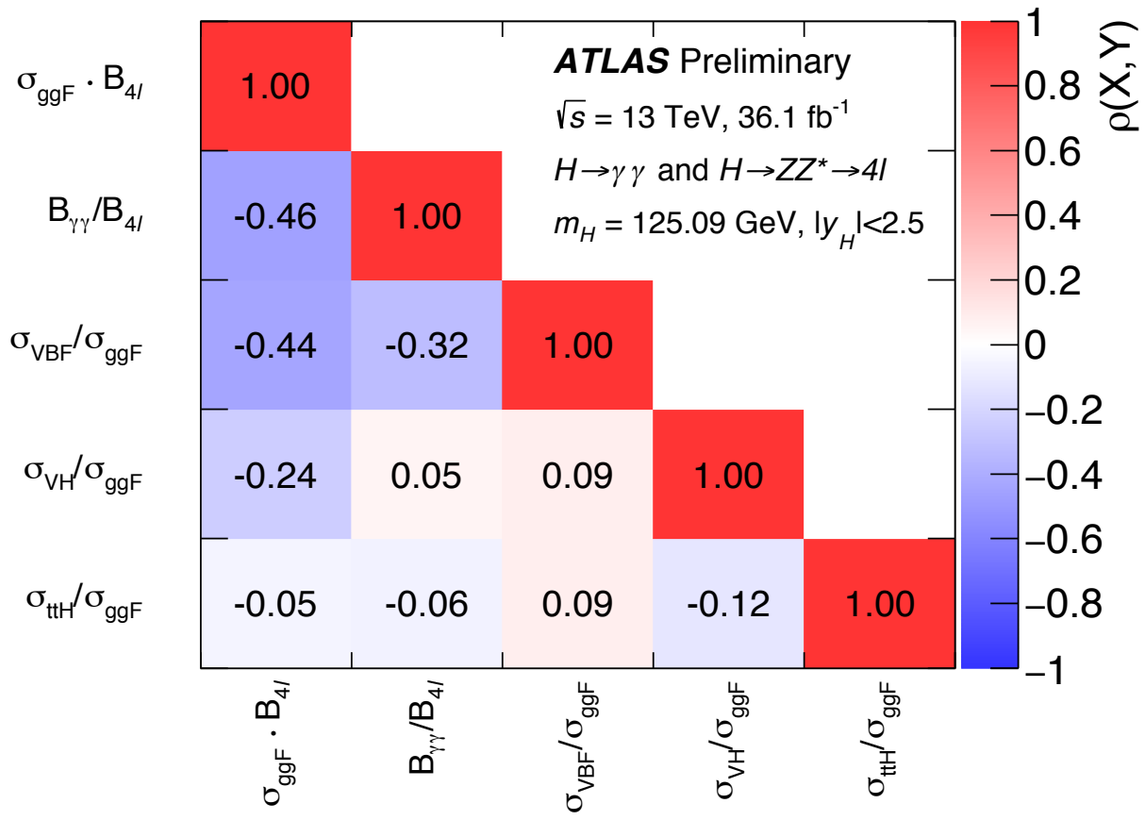
σ_{VH}/σ_{ggF}



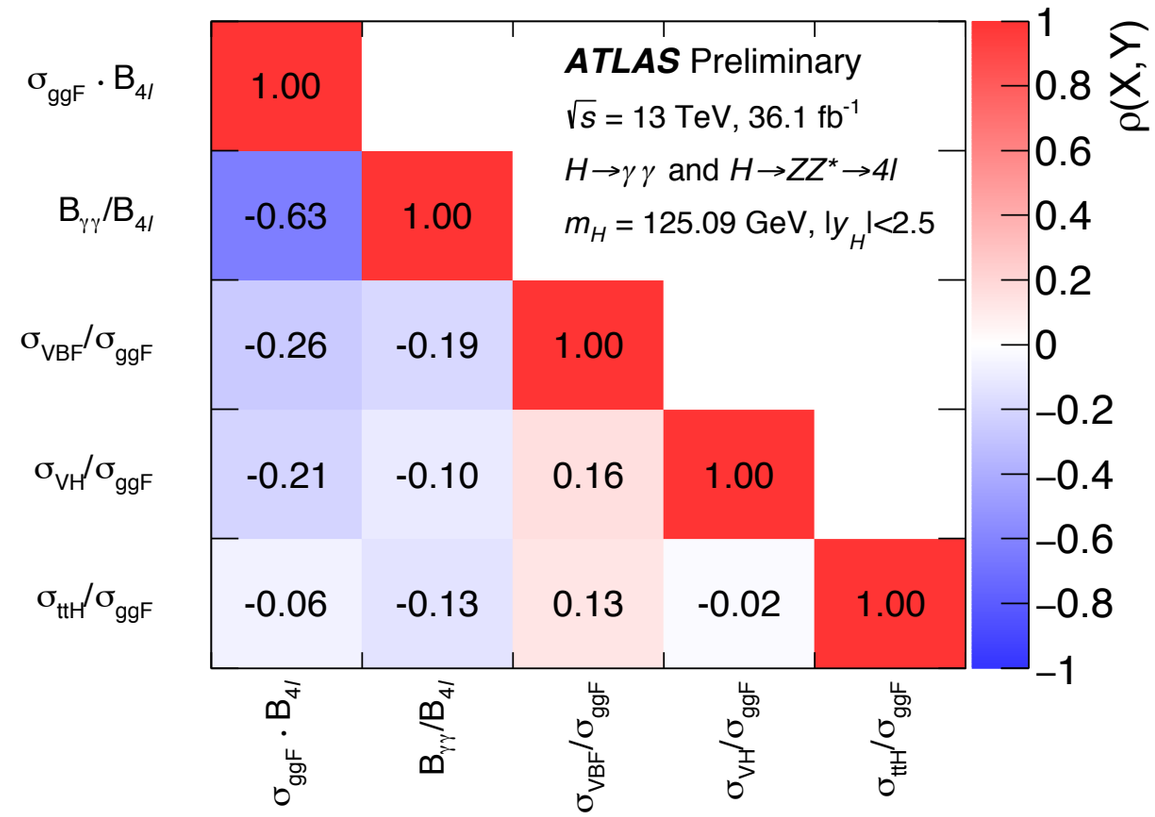
$\sigma_{ttH}/\sigma_{ggF}$



Correlation matrices for the ratio model



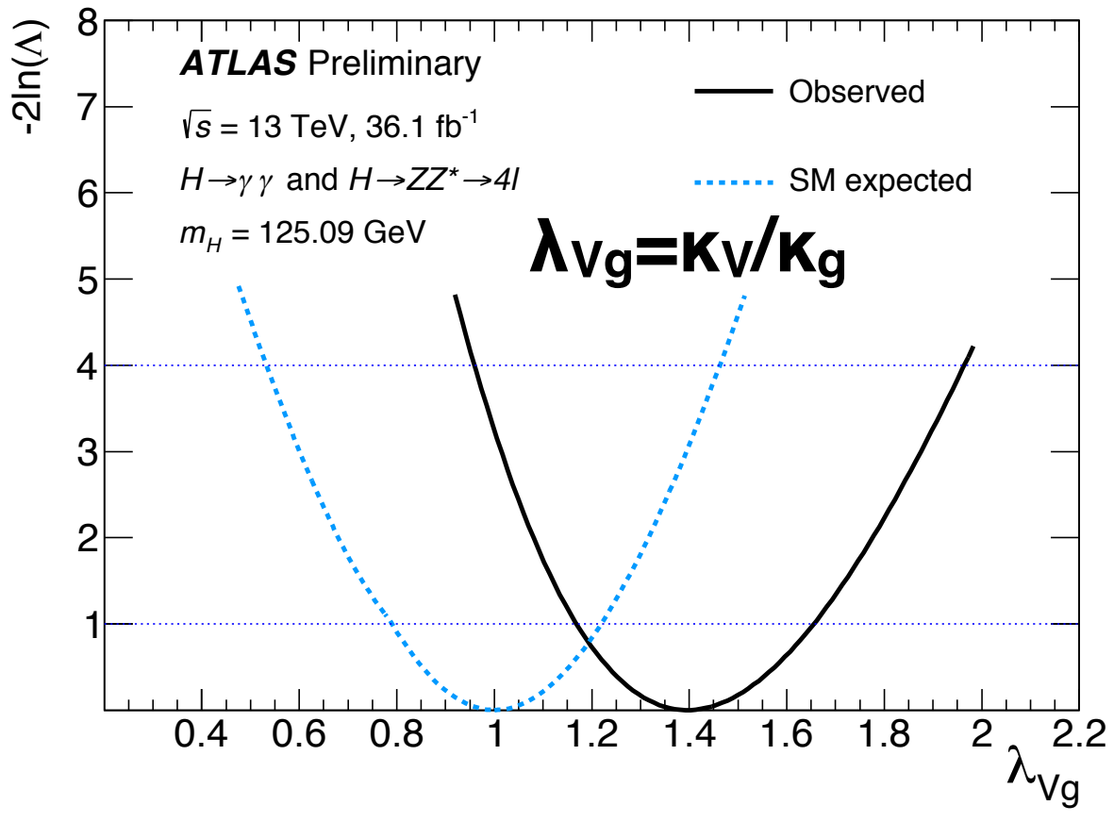
Data

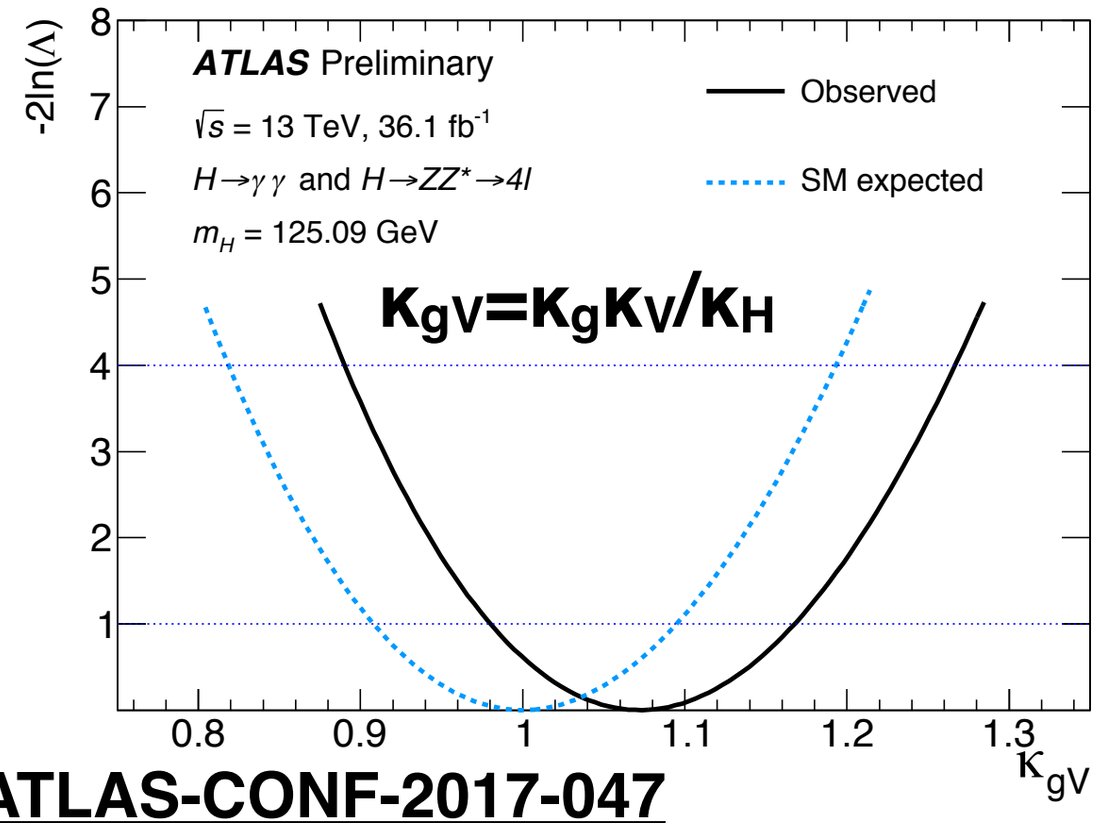


SM

- Strong correlation between parameters
  - σ_{ggF} or B_{4l} shared among parameters
  - $\sigma_{ggF} \cdot B_{4l}$ and $B_{\gamma\gamma}/B_{4l}$ anti-correlate in $H \rightarrow \gamma\gamma$ channel

Likelihood scans for kappa generic model





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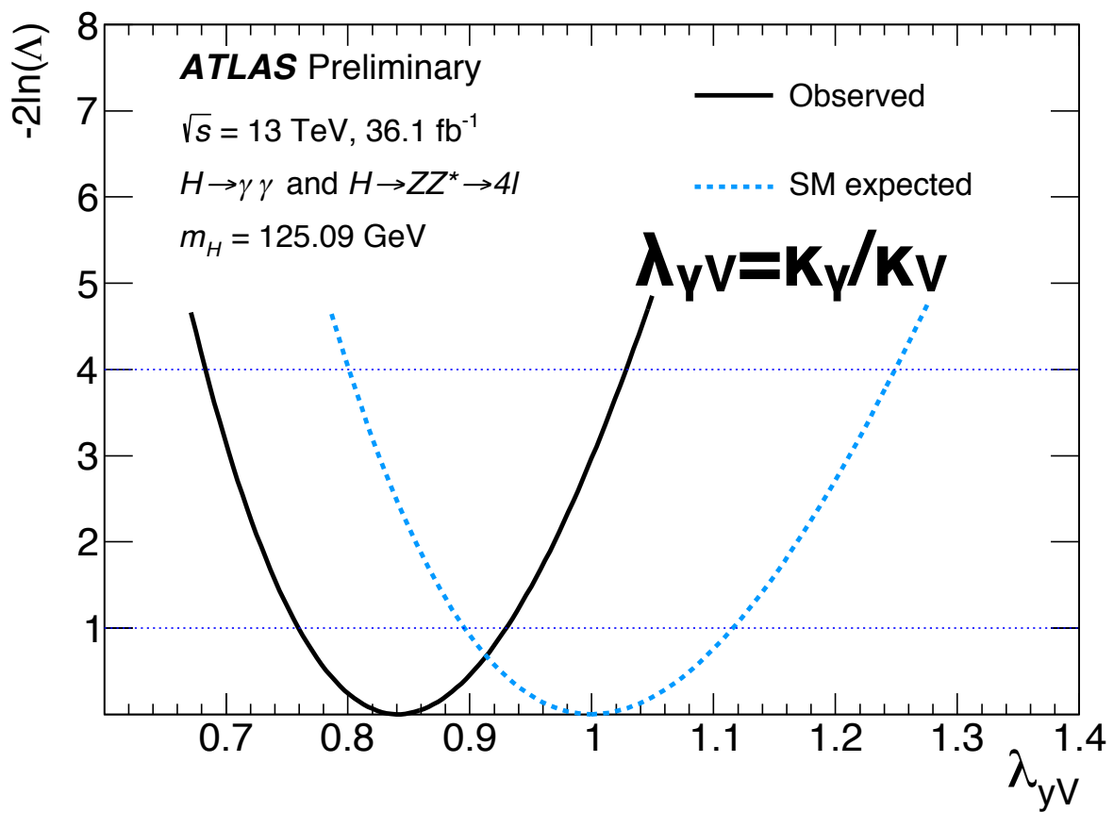
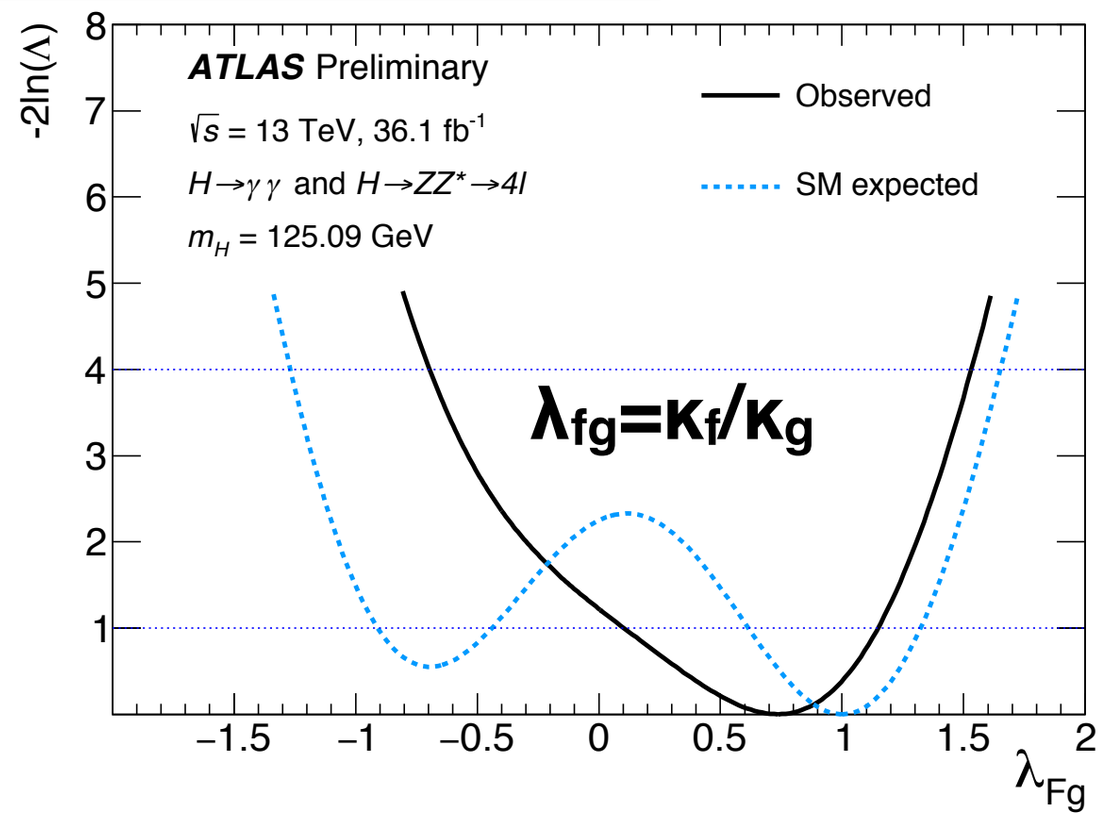
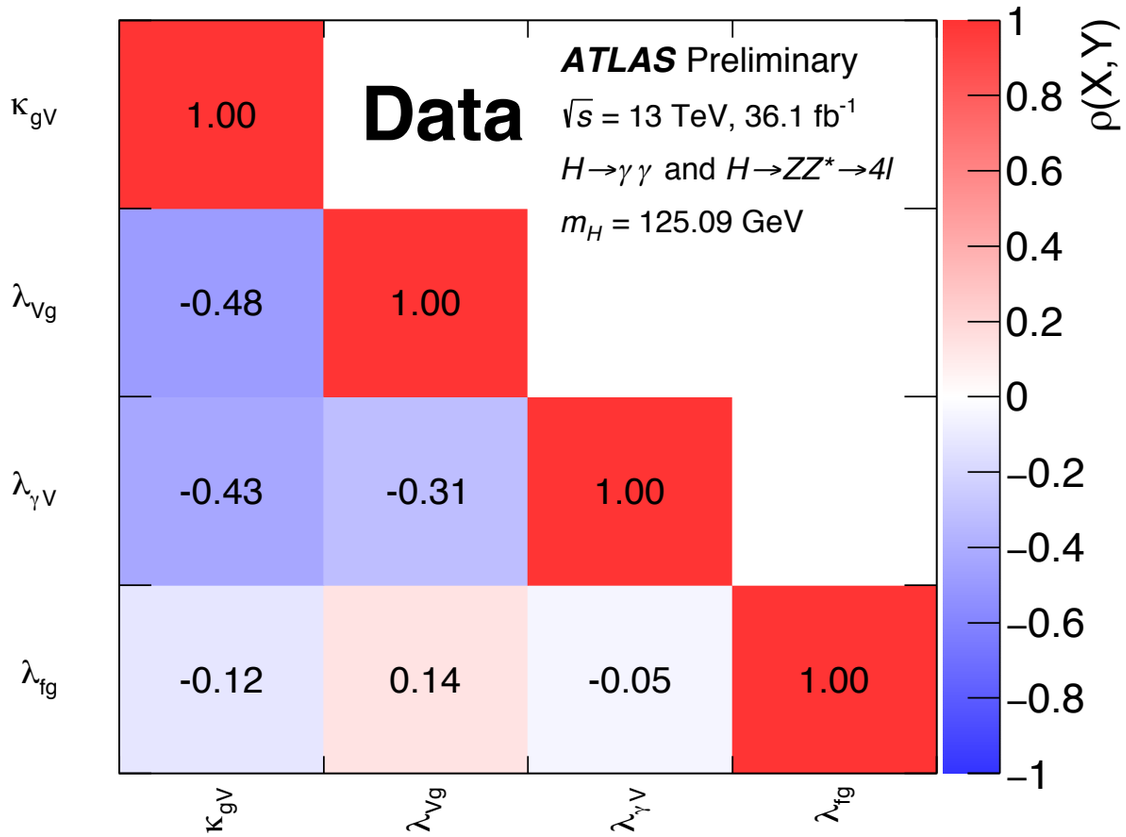
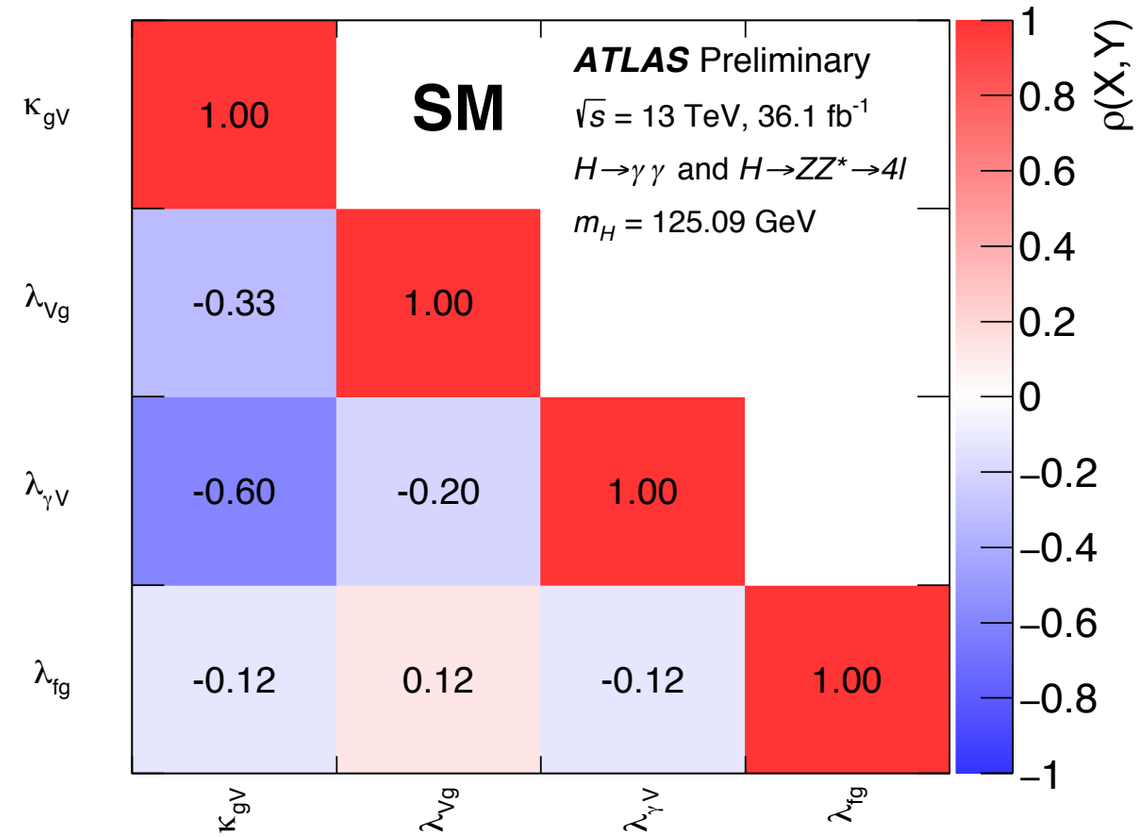




Correlation matrices and numerical results for kappa generic model





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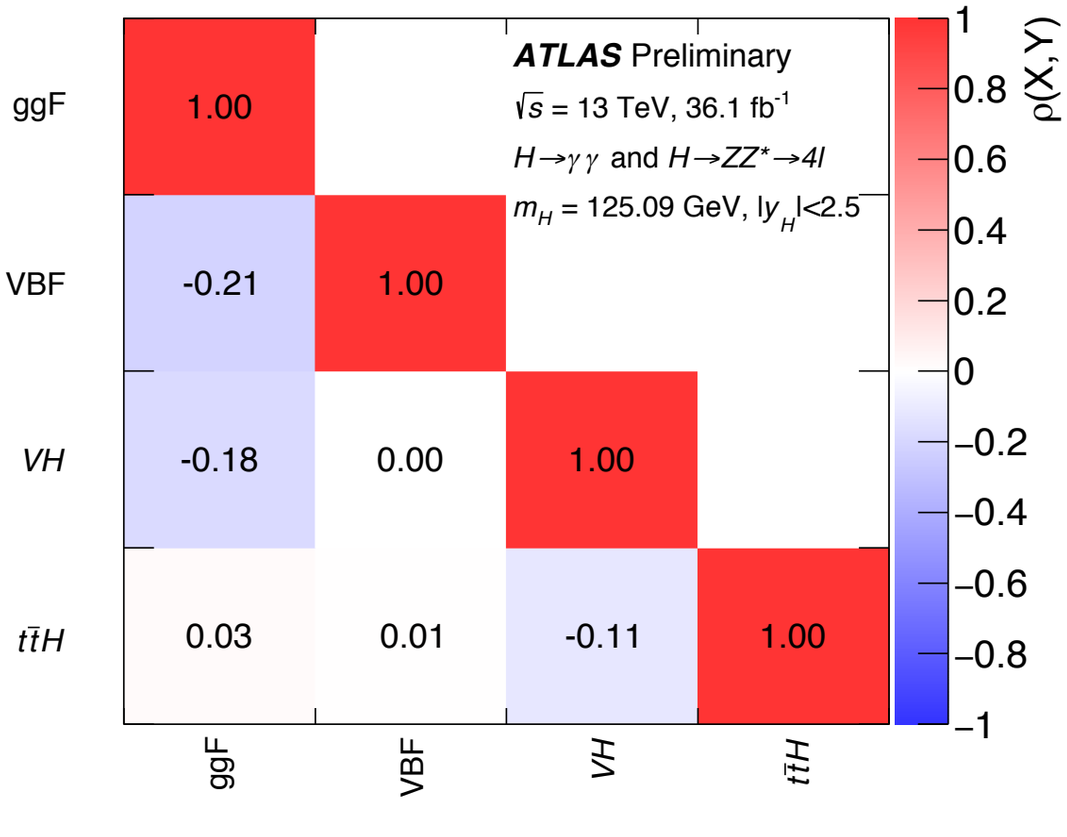
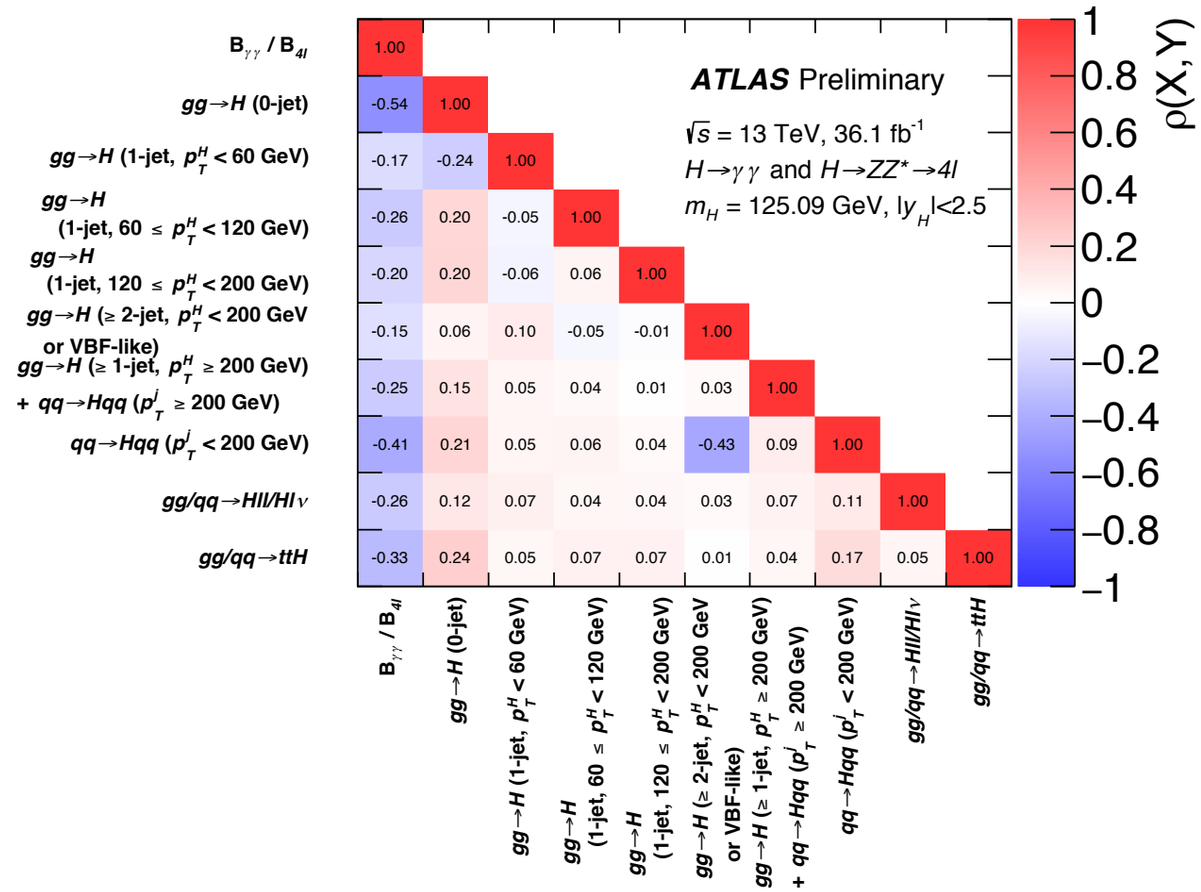
Parameter	Result	Uncertainty			
		Total	Stat.	Exp.	Th.
κ_{gV}	1.07	± 0.09	± 0.08	± 0.03	$^{+0.04}_{-0.03}$
λ_{Vg}	1.41	$^{+0.26}_{-0.23}$	$^{+0.23}_{-0.20}$	$^{+0.08}_{-0.06}$	$^{+0.09}_{-0.08}$
$\lambda_{\gamma V}$	0.84	$^{+0.09}_{-0.08}$	± 0.08	$^{+0.03}_{-0.02}$	± 0.01
λ_{fg}	0.74	$^{+0.41}_{-0.63}$	$^{+0.40}_{-0.62}$	$^{+0.06}_{-0.14}$	$^{+0.07}_{-0.05}$

SM correlation matrices for production mode x-section and STXS measurements



Production mode x-section



STXS

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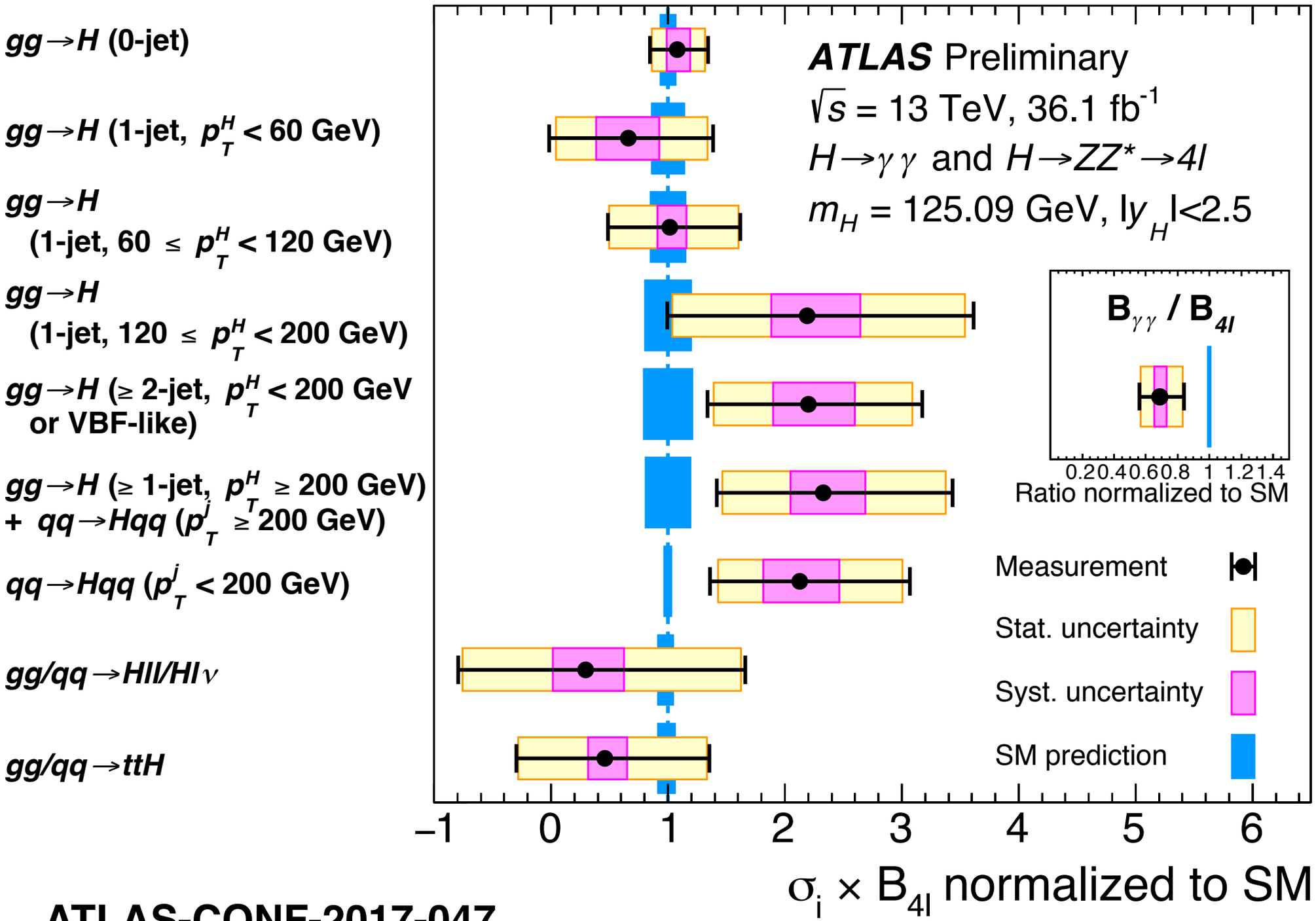
- Good agreement between data and SM prediction

Normalized STXS summary plot



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Stage 1 STXS production bin definitions

STXS process	Production modes	Stage 1 STXS measurement region	
gg→H	ggF+ ggZ(qq)H+ bbH	0-jet	
		1-jet, pTH<60 GeV	≥2-jet, pTH<60 GeV
		1-jet 60 GeV<pTH<120 GeV	≥2-jet 60 GeV<pTH<120 GeV
		1-jet 120 GeV<pTH<200 GeV	≥2-jet 120 GeV<pTH<200 GeV
		VBF-like, pTHjj<25 GeV	VBF-like, pTHjj>25 GeV
		1-jet pTH>200 GeV	≥2-jet pTH>200 GeV
qq→Hqq	VBF+ W(qq)H+ qqZ(qq)H	pTj1>200 GeV	
		VBF-like, pTHjj<25 GeV	VBF-like, pTHjj>25 GeV
		pTj1<200 GeV, VH-like	pTj1<200 GeV, Rest
VHlep	W(lv)H+ qq/ggZ(ll/ vv)H	pTV<150 GeV	150 GeV<pTV<250 GeV, 0-jet
		150 GeV<pTV<250 GeV, ≥1-jet	pTV>250 GeV
ttH	ttH+tH	—	

- Stage 1 STXS framework has too fine granularity given current data statistics, and introduces large anti-correlation between bins
- Red background means merging the bins under same process into 1 bin. Blue background means reporting the sum and difference between two processes

Summary of kappa parameterizations

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($\mathrm{B_{BSM}} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$