Measurements of the Higgs boson

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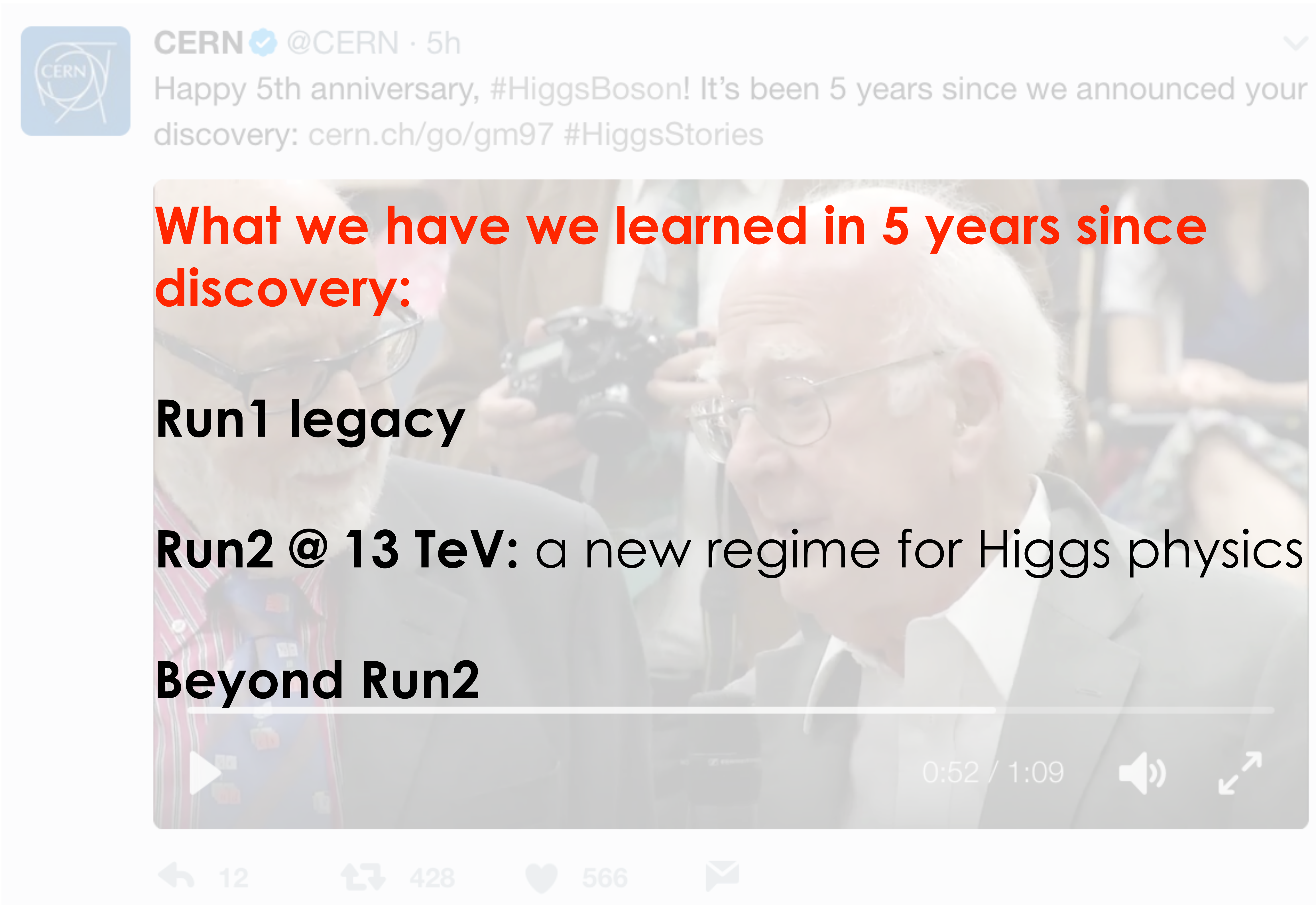
Only 5 Years Ago…

CERN @CERN · 5h

Happy 5th anniversary, #HiggsBoson! It’s been 5 years since we announced your discovery: cern.ch/go/gm97 #HiggsStories

12 428 566

Outline



What we have we learned in 5 years since discovery:

Run1 legacy

Run2 @ 13 TeV: a new regime for Higgs physics

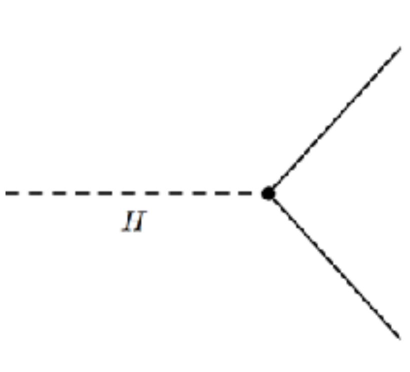
Beyond Run2

A FUNDAMENTAL SCALAR PARTICLE

Higgs in the Standard Model: "one scalar to rule them all"

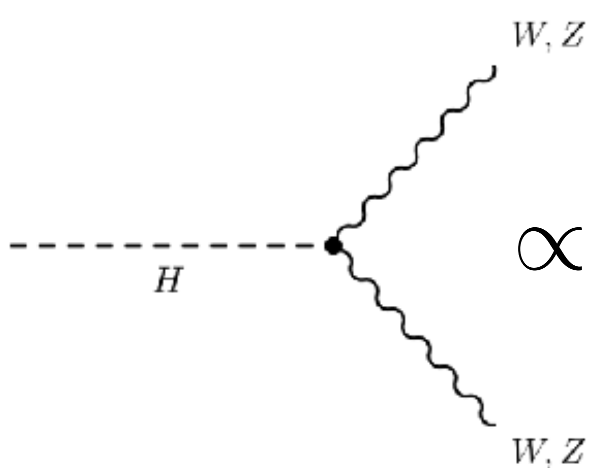
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Yukawa: coupling to fermions



$\propto m_F$

Gauge: coupling to vector bosons

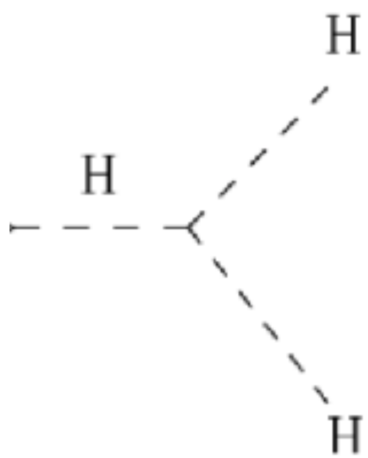


$\propto m_V$

Higgs potential

$$V(\phi) = \mu^2|\phi|^2 + \frac{1}{2}\lambda|\phi|^4$$

Higgs mass is a free parameter in the SM



Self-coupling: Higgs is the only particle coupling to itself in the SM

WHY MEASURE HIGGS PROPERTIES?

Is it really a **fundamental scalar boson**?

Are there **additional scalar bosons**?

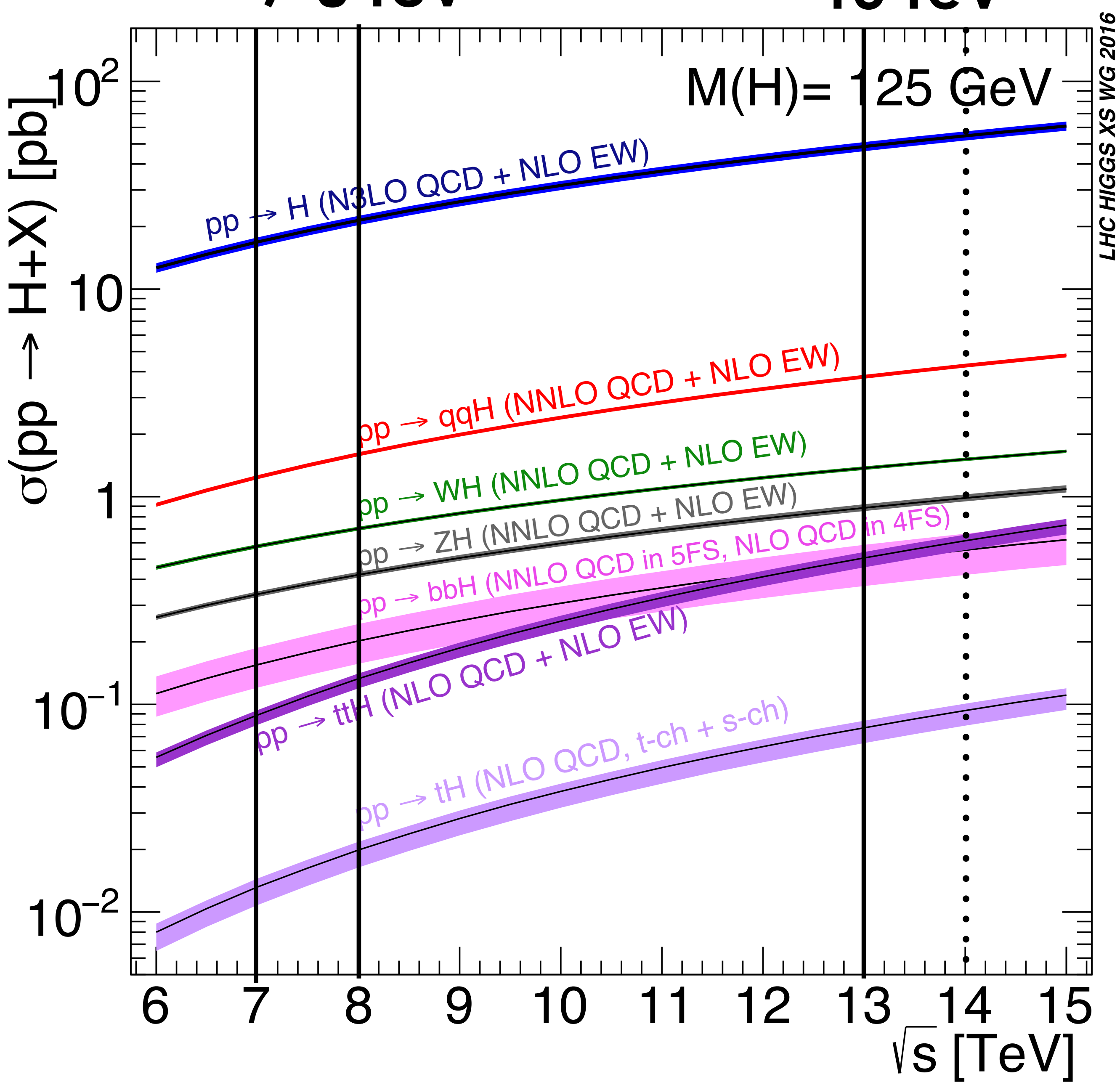
Is it **directly coupled to BSM particles**?

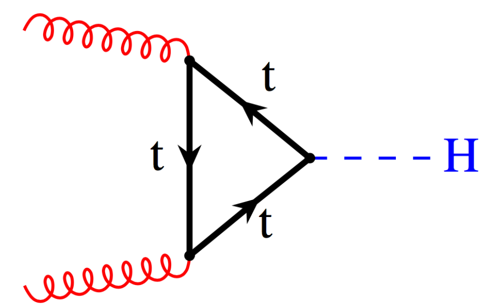
No direct sign of new physics @ LHC from searches
Higgs couplings can provide indirect BSM indication:

- SUSY (tanβ=5): $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$
- Composite Higgs: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

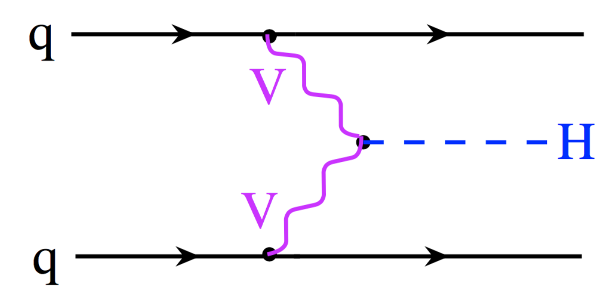
Higgs Production @ LHC

Run1
7-8 TeV ⇒ **Run2**
13 TeV

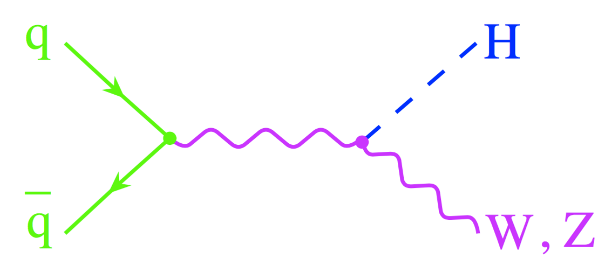




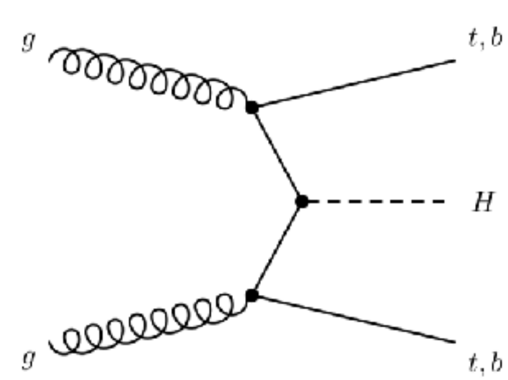
Gluon fusion
87%



VBF
7.1%

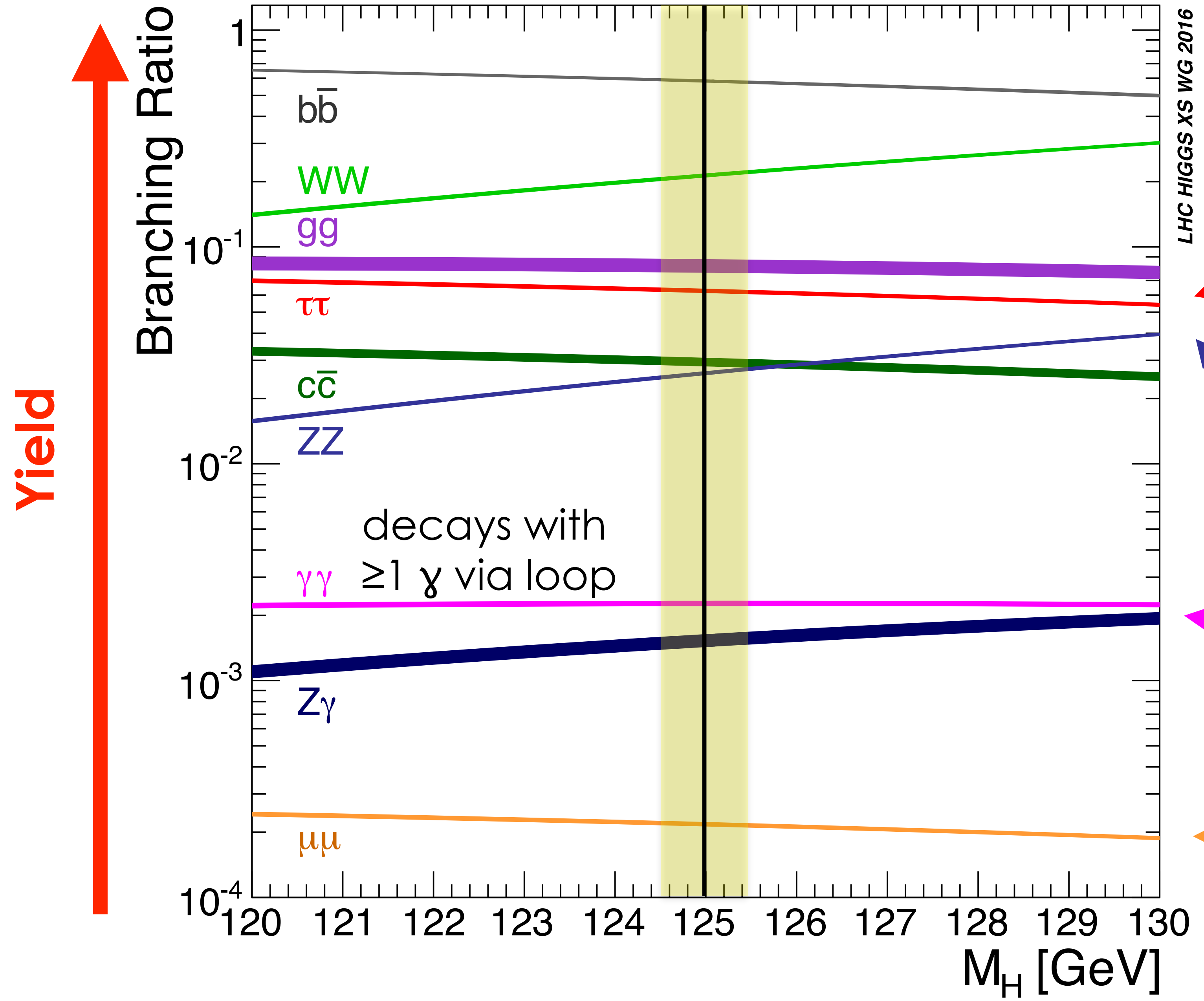


WH, ZH
4.9%



ttH, bbH
0.6%

Higgs Decay



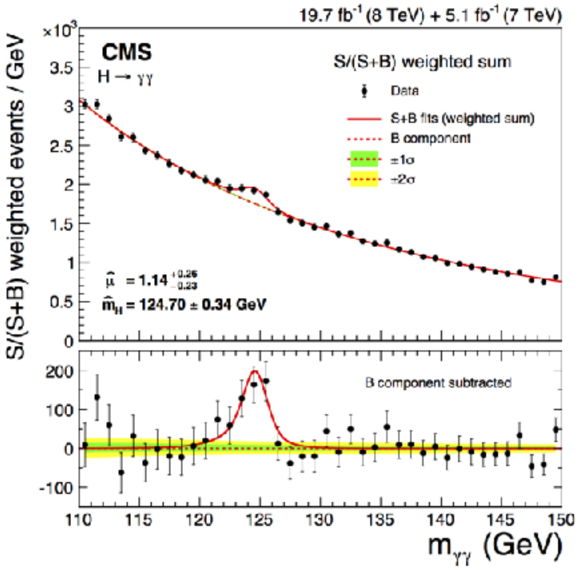
bb, $\tau\tau$: 3rd gen fermion coupling
High yield but low S/B

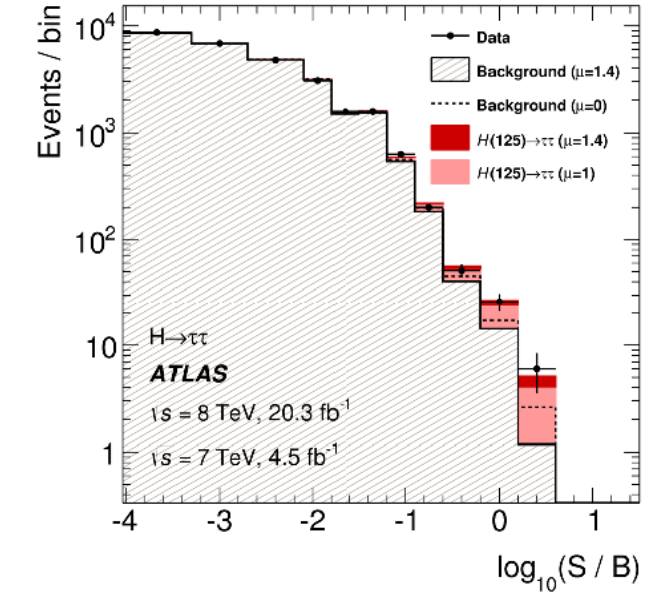
ZZ(4l), γγ: High mass resolution channels (full decay reconstruction)

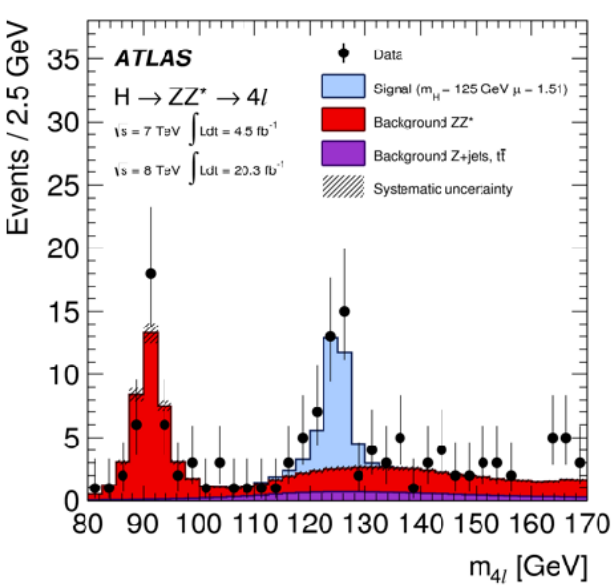
μμ: 2nd gen fermion coupling

Most of the H(125) decays accessible at the LHC

THE RUN-I LEGACY







$\boxed{H^0}$ $\quad J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

Full width $\Gamma < 1.7$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11

$WW^* = 1.08^{+0.18}_{-0.16}$

$ZZ^* = 1.29^{+0.26}_{-0.23}$

$\gamma\gamma = 1.16 \pm 0.18$

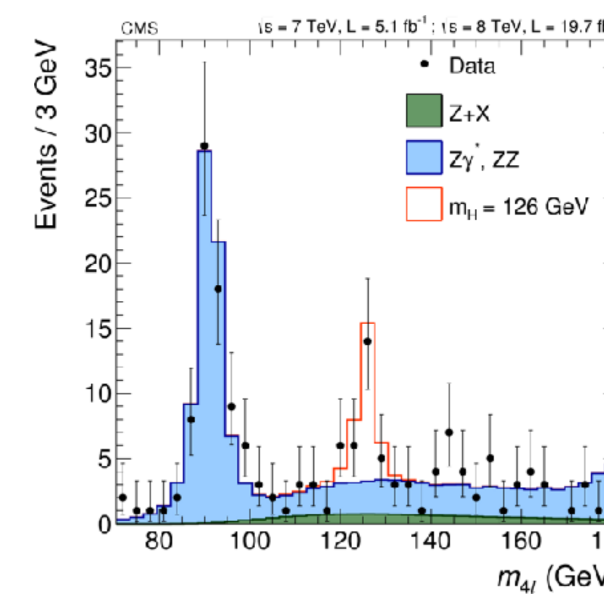
$b\overline{b} = 0.82 \pm 0.30$ (S = 1.1)

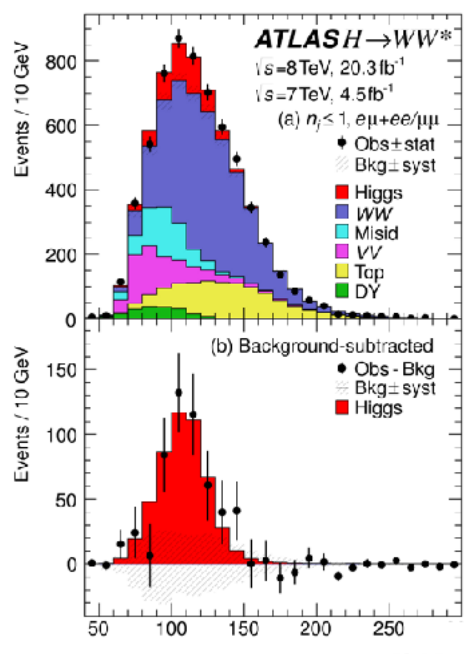
$\mu^+\mu^- < 7.0$, CL = 95%

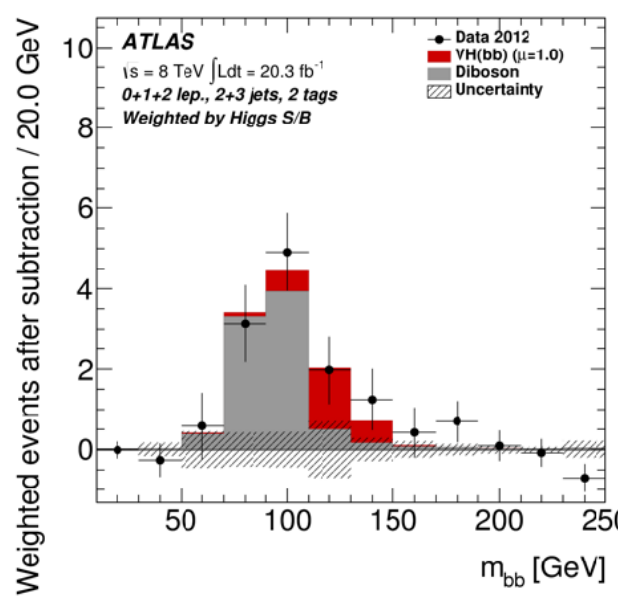
$\tau^+\tau^- = 1.12 \pm 0.23$

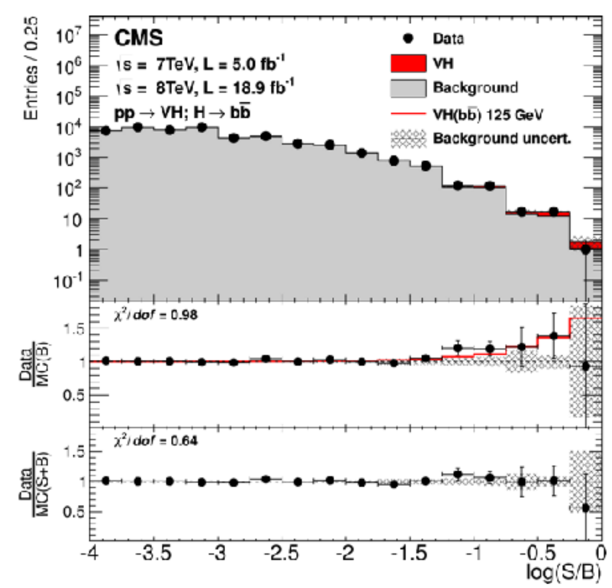
$Z\gamma < 9.5$, CL = 95%

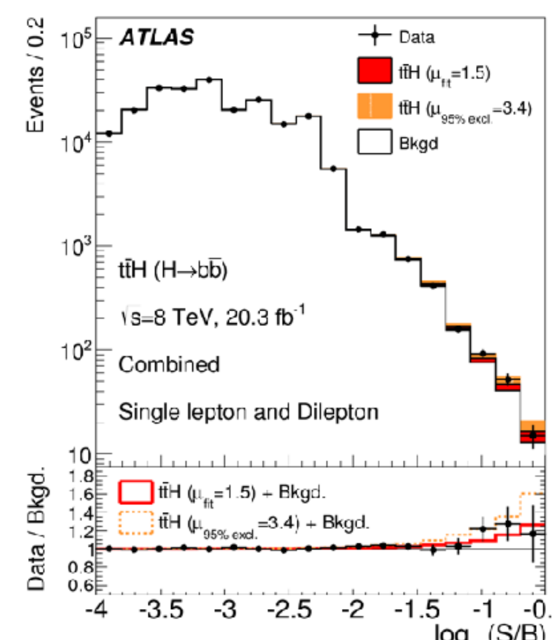
$t\overline{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$





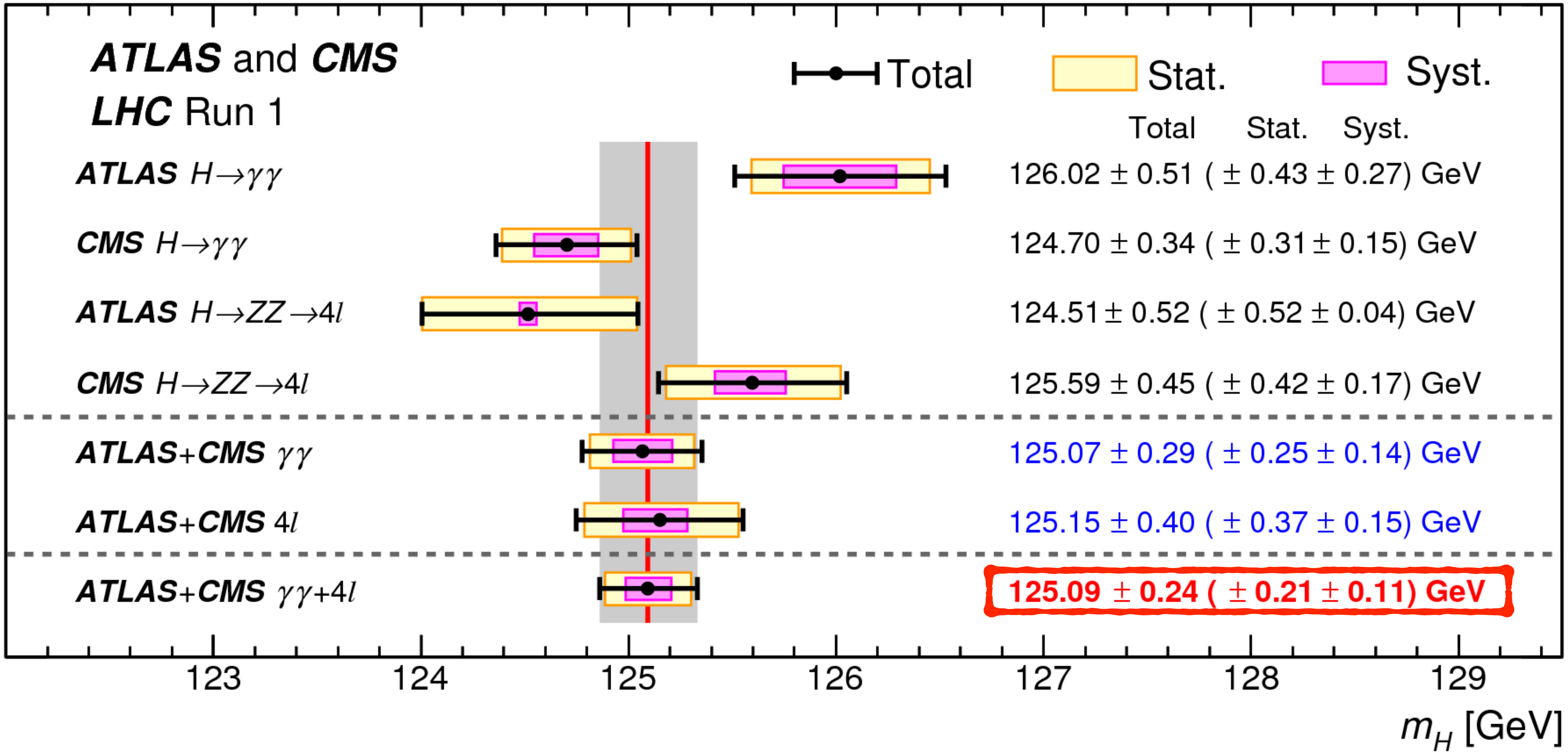






Run1: Mass

ATLAS+CMS PRL 114 (2015) 191803

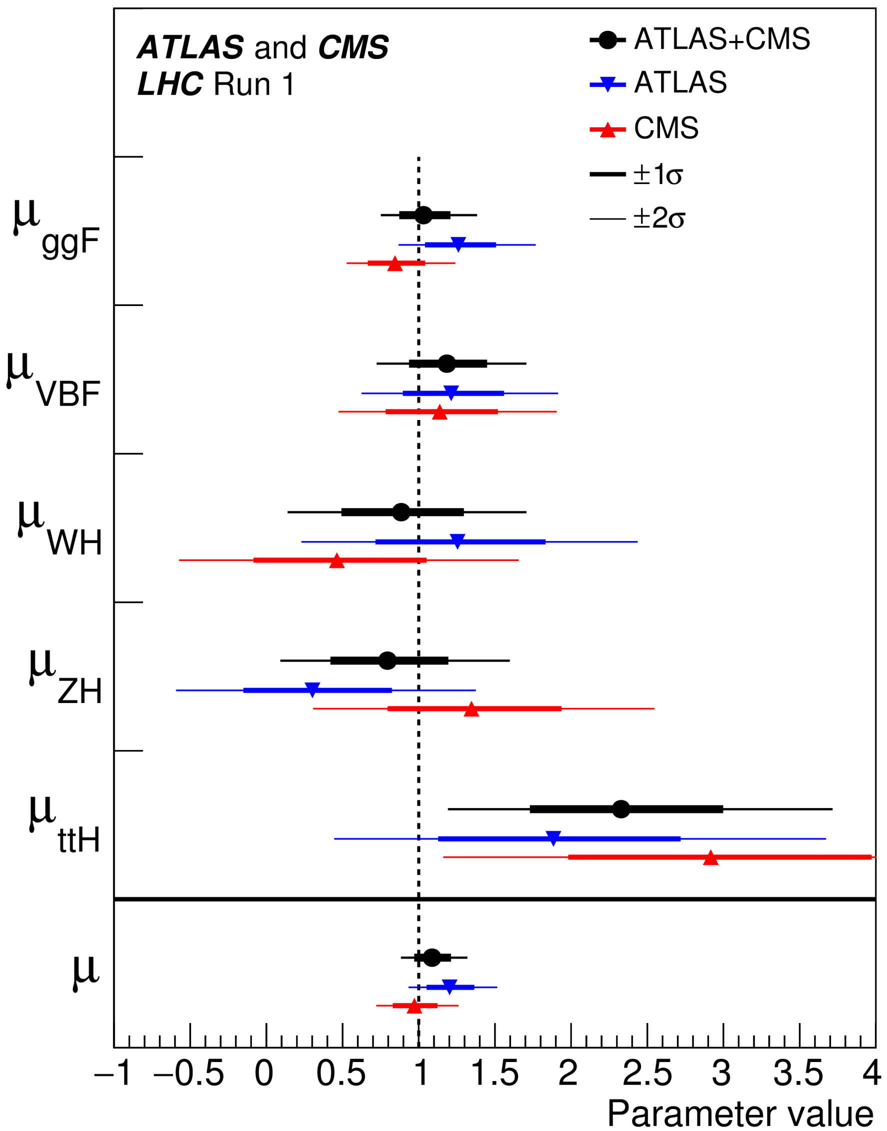


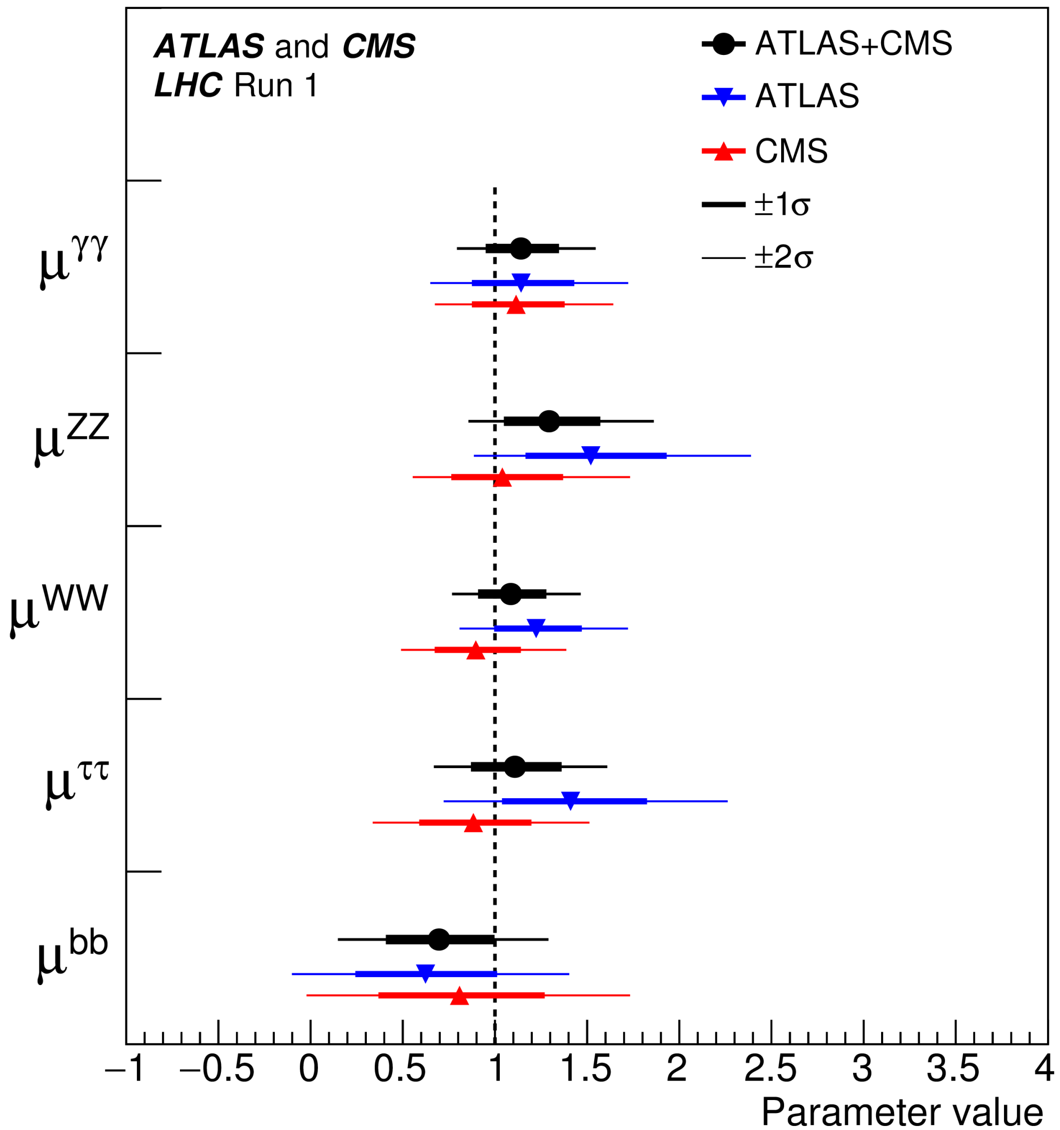
~0.2% precision (statistically limited)

Run1: Production & Decay

signal strength $\mu=\sigma/\sigma_{SM}$

ATLAS+CMS JHEP 08 (2016) 045





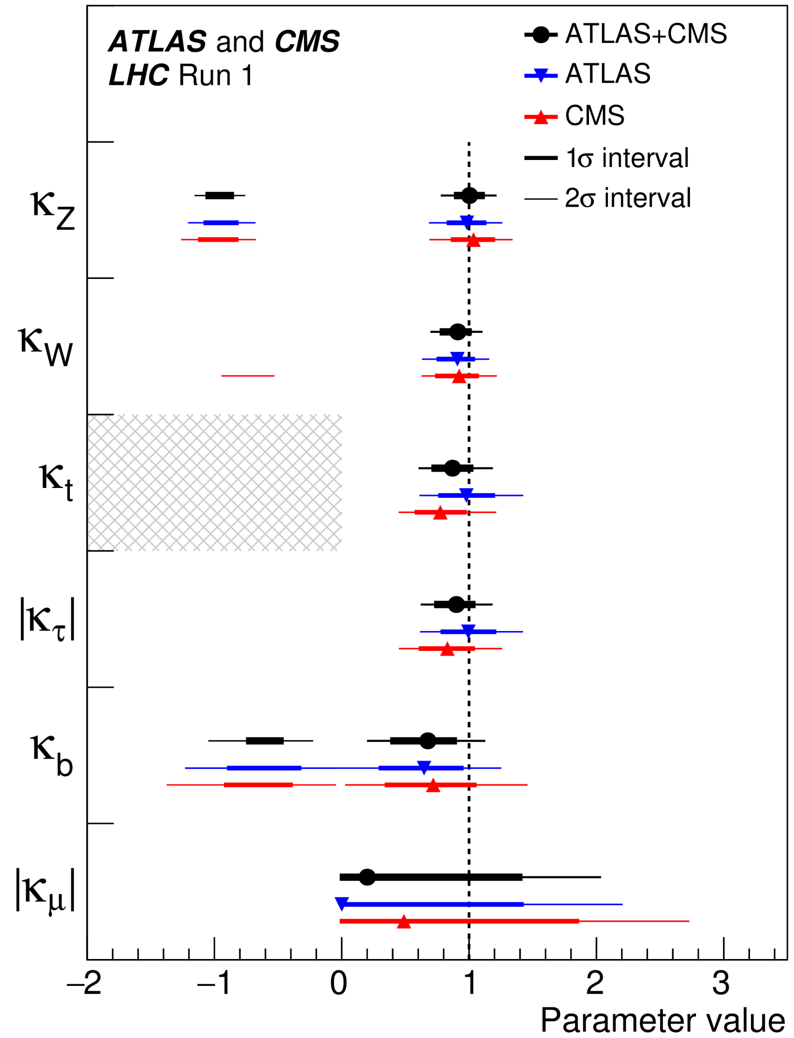
Production & decay measured to be compatible with SM Higgs

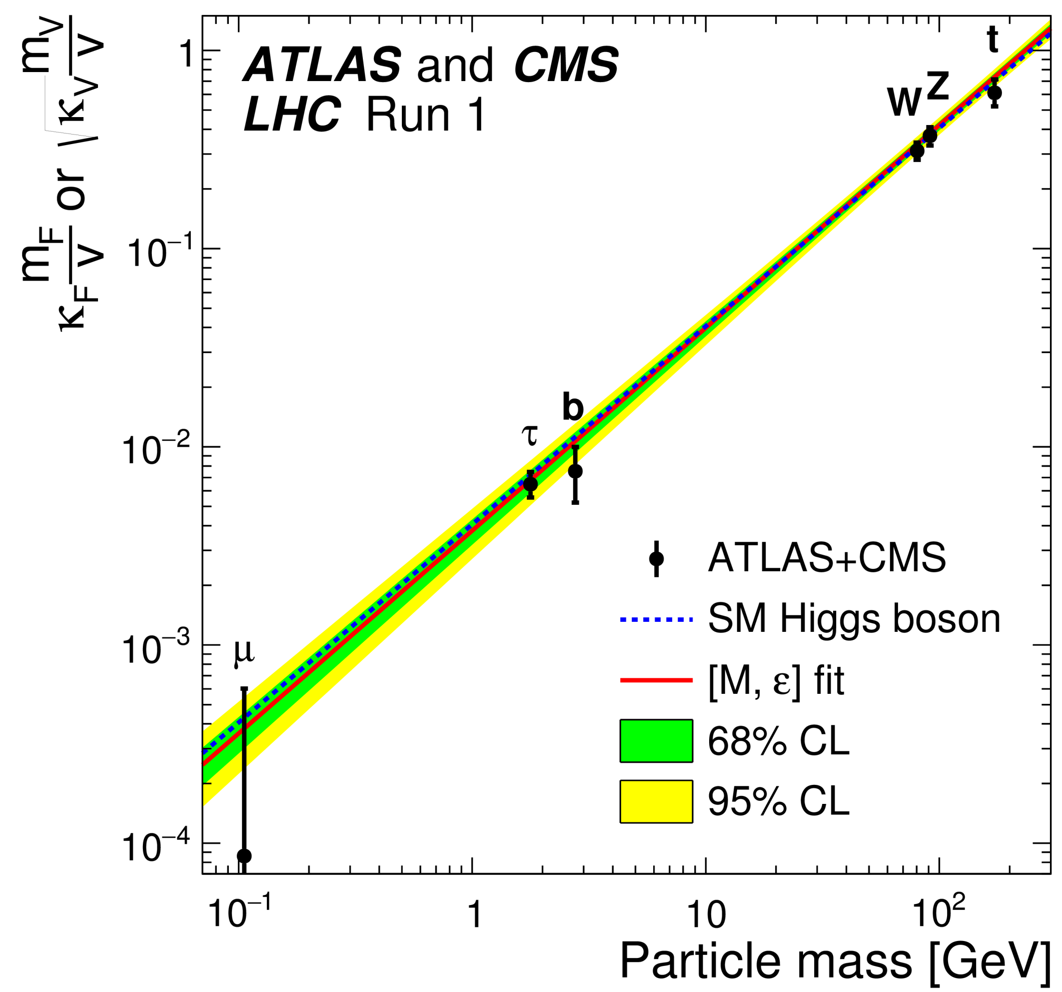
Observation of boson decay modes: $\gamma\gamma$, WW, ZZ

Direct coupling to fermions not fully established: $H\rightarrow\tau\tau$ 5.5σ (exp 5σ), H→bb 2.6σ (exp 3.7σ)

RUN1: COUPLINGS

ATLAS+CMS JHEP 08 (2016) 045





"k-framework" used for couplings in Run1:

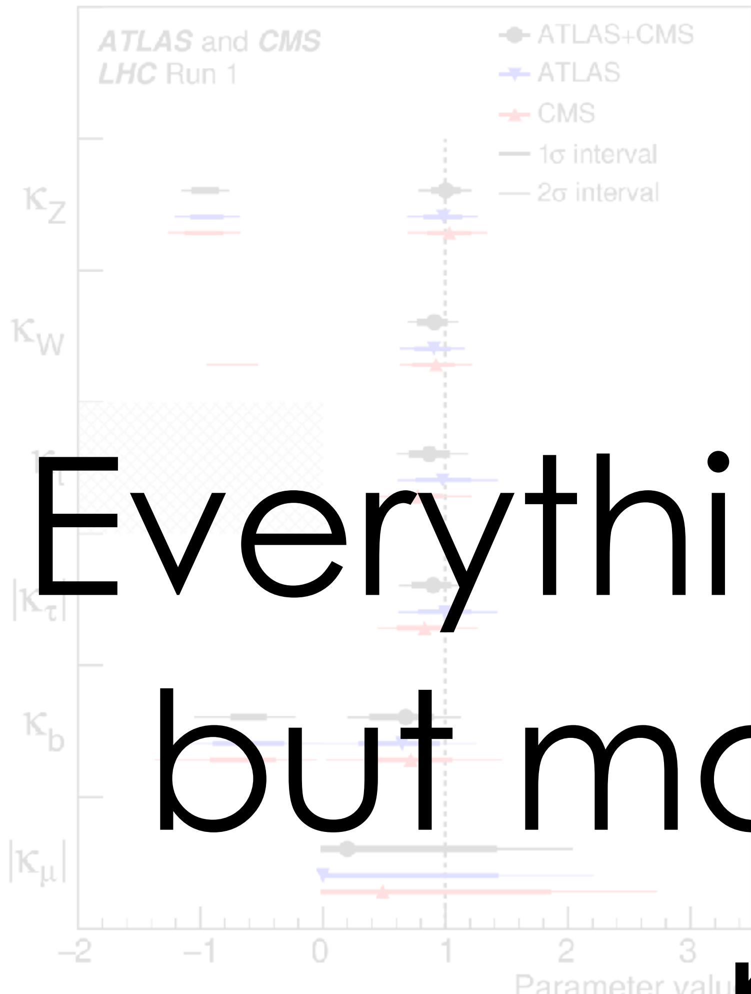
express cross-sections and decay widths in terms of simple coupling modifiers **k** (k=1 means SM)

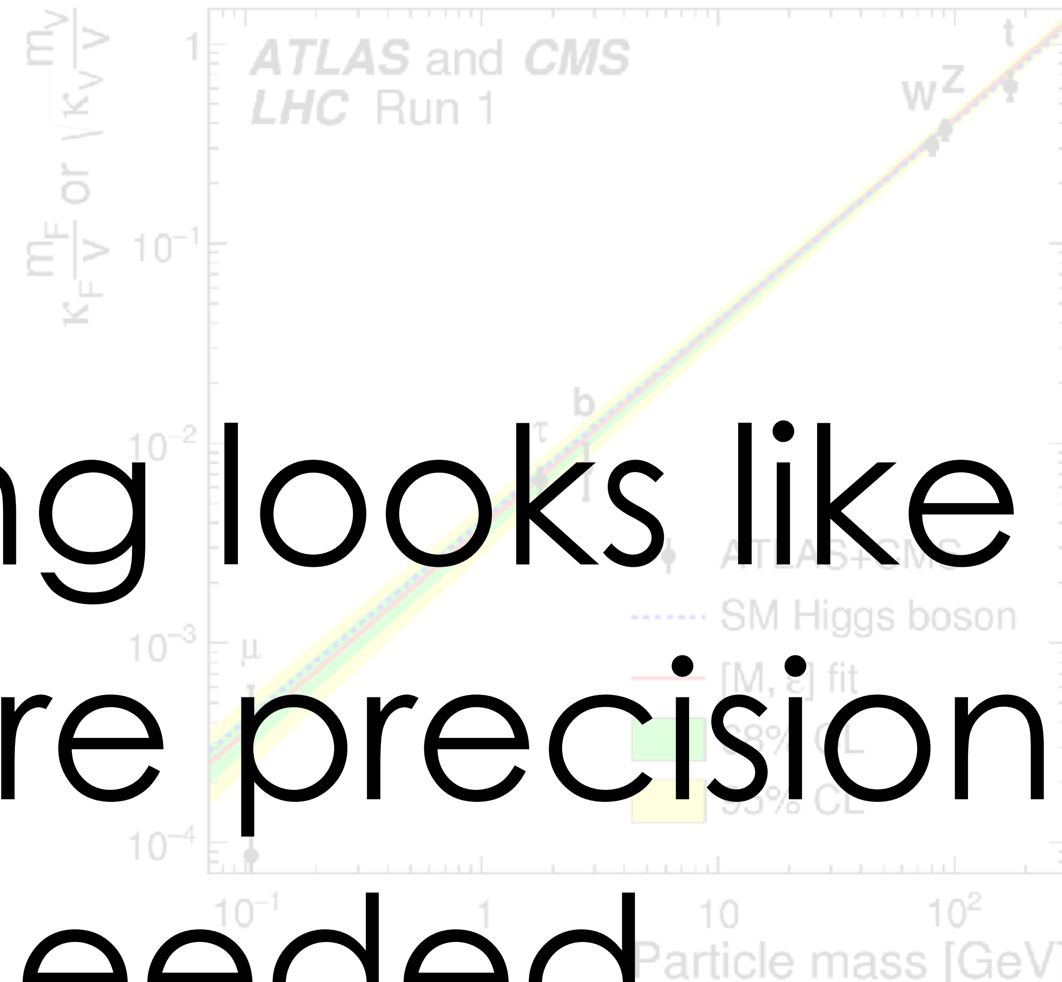
Couplings compatible with SM < 2σ

No hints of BSM particles in loops (gluon-fusion, γγ). BR_{BSM}<0.34 @ 95% CL

In Other Words

ATLAS+CMS JHEP 08 (2016) 045





Everything looks like SM but more precision is needed

"k-framework" used for couplings interpretation in Run1:

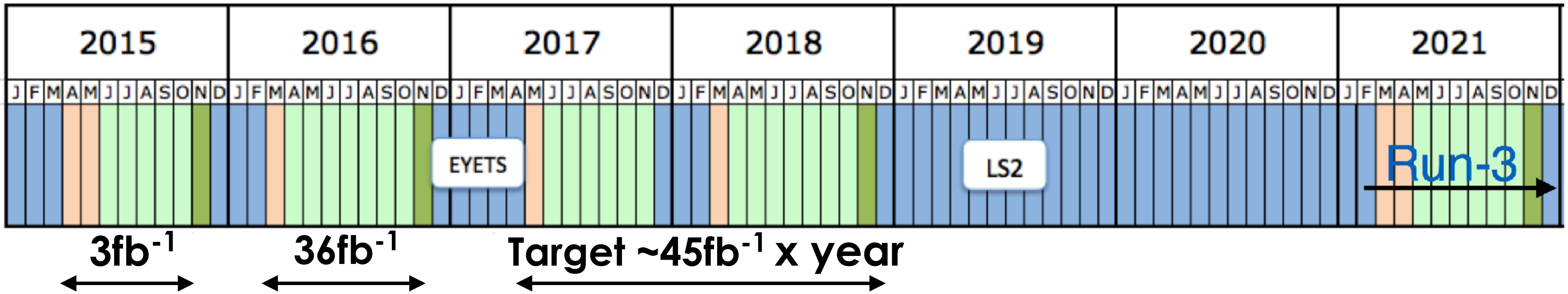
express cross-sections and decay widths in terms of simple coupling modifiers **k** (k=1 means SM)

Couplings compatible with SM < 2σ

No hints of BSM particles in loops (gluon-fusion, γγ). BR_{BSM}<0.34 @ 95% CL

Run 2: Towards The Higgs Precision Physics Era

LHC RUN 2

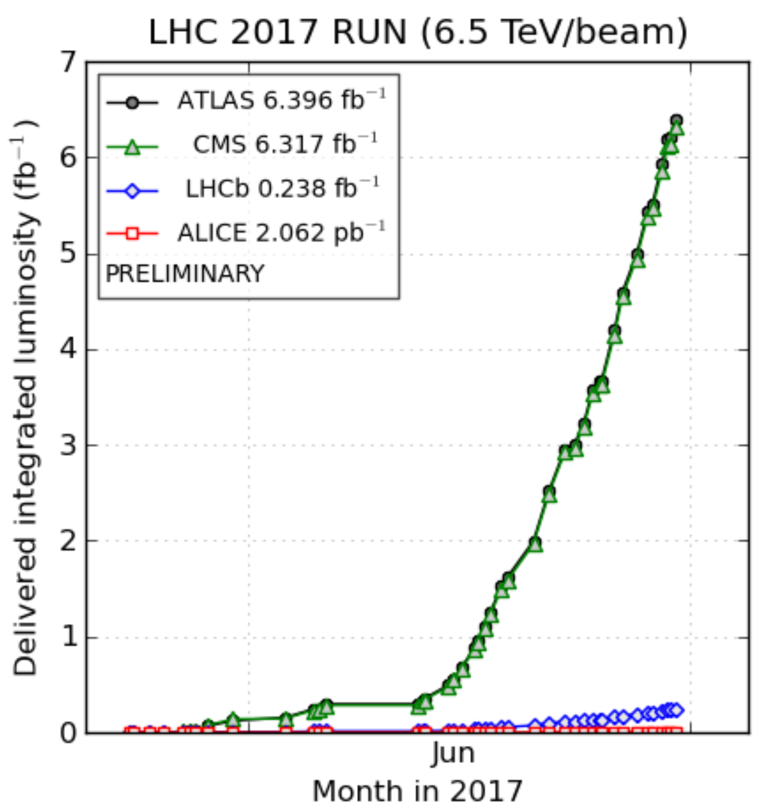


>100fb^{-1} by the end of Run 2. 3000 fb^{-1} expected by the end of HL-LHC

Most of the results presented today done with **full 2016 dataset**:

36 fb^{-1} @ 13 TeV ⇒ #Higgs produced ~ x4 wrt Run1

2017 run in full swing: already 6fb^{-1} delivered. **Record peak lumi: 1.6E34 cm^{-2}s^{-1}**



Challenge: precision physics with high pile-up

2017 >50 pile-up

Roadmap For Higgs In Run2

see M. D'Onofrio's talk

Precision
Cross-sections
Couplings
Mass

Discovery
Couplings to fermions

Other scalars
Charged/neutral
Heavy/light

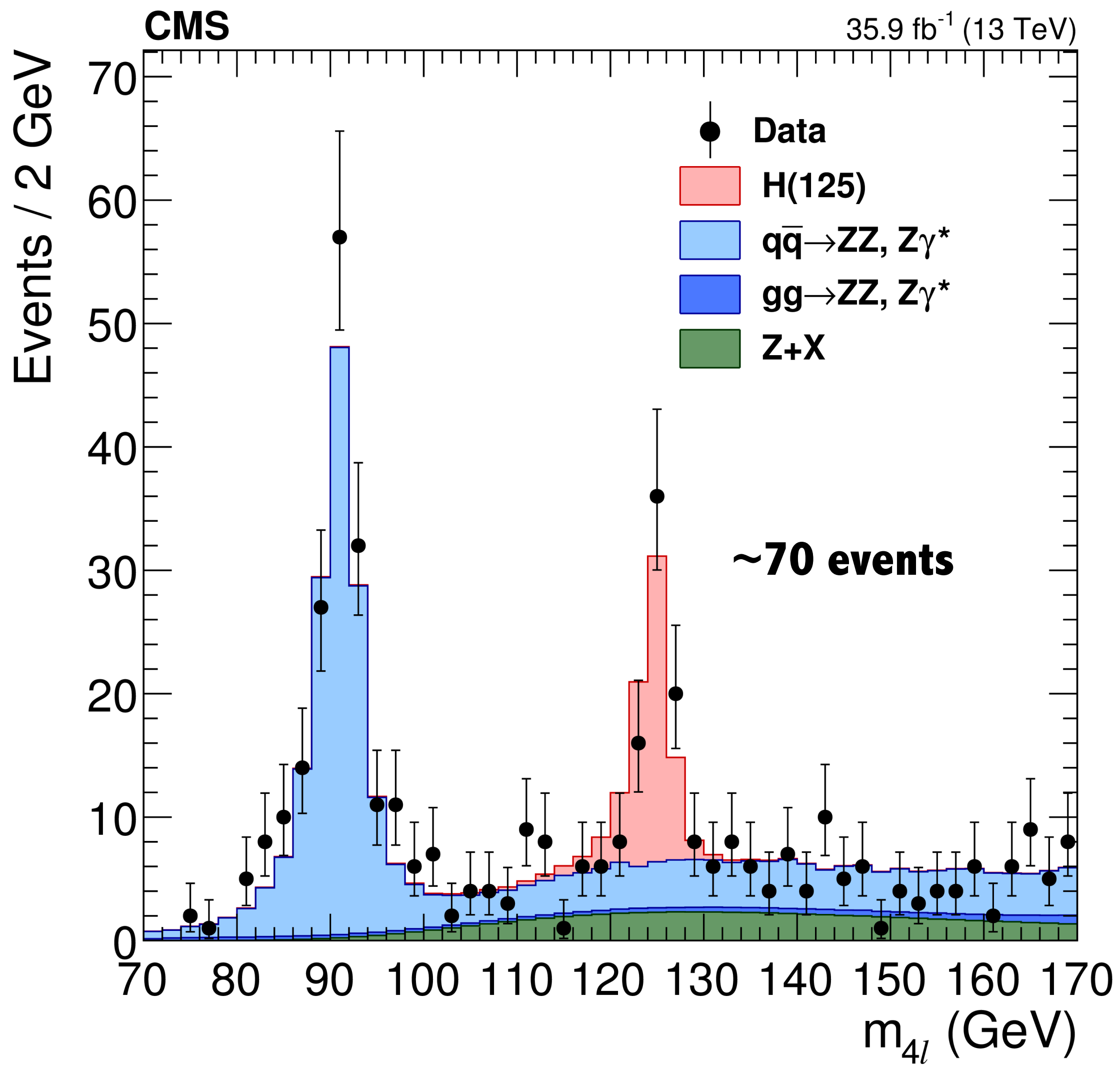
Known unknowns
Rare decays
Self-couplings

Unknown unknowns
BSM couplings
BSM decays

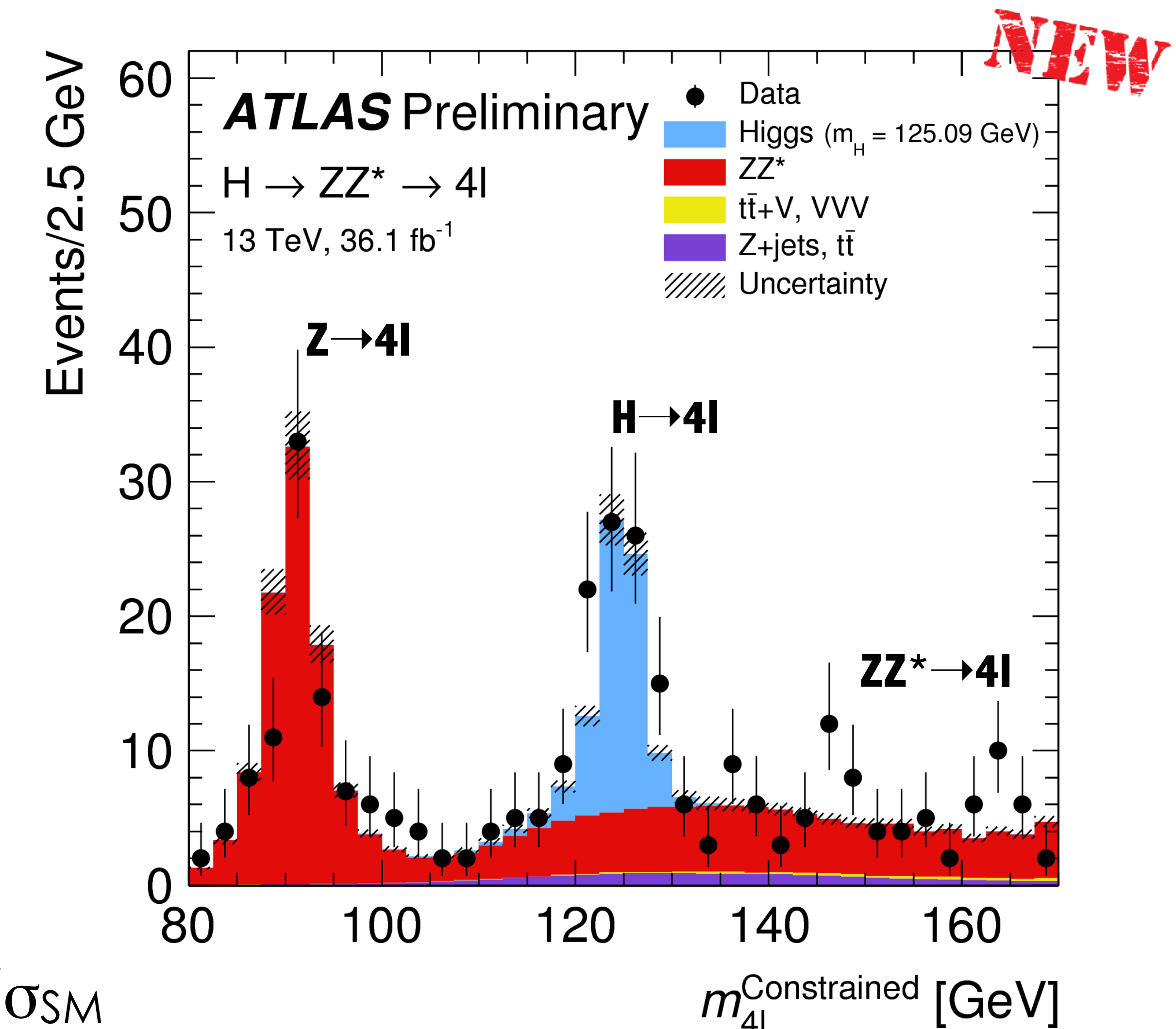
$H \rightarrow ZZ$ & $H \rightarrow \gamma\gamma$ The Quest For High Precision

H→ZZ→4ℓ (4μ, 2e2μ, 4e)

CMS arXiv:1706.09936 Submitted to JHEP



ATLAS-CONF-2017-043



$\mu = \sigma/\sigma_{SM}$

$$\mu = 1.05^{+0.15}_{-0.14}(\mathrm{stat})^{+0.11}_{-0.09}(\mathrm{syst})$$

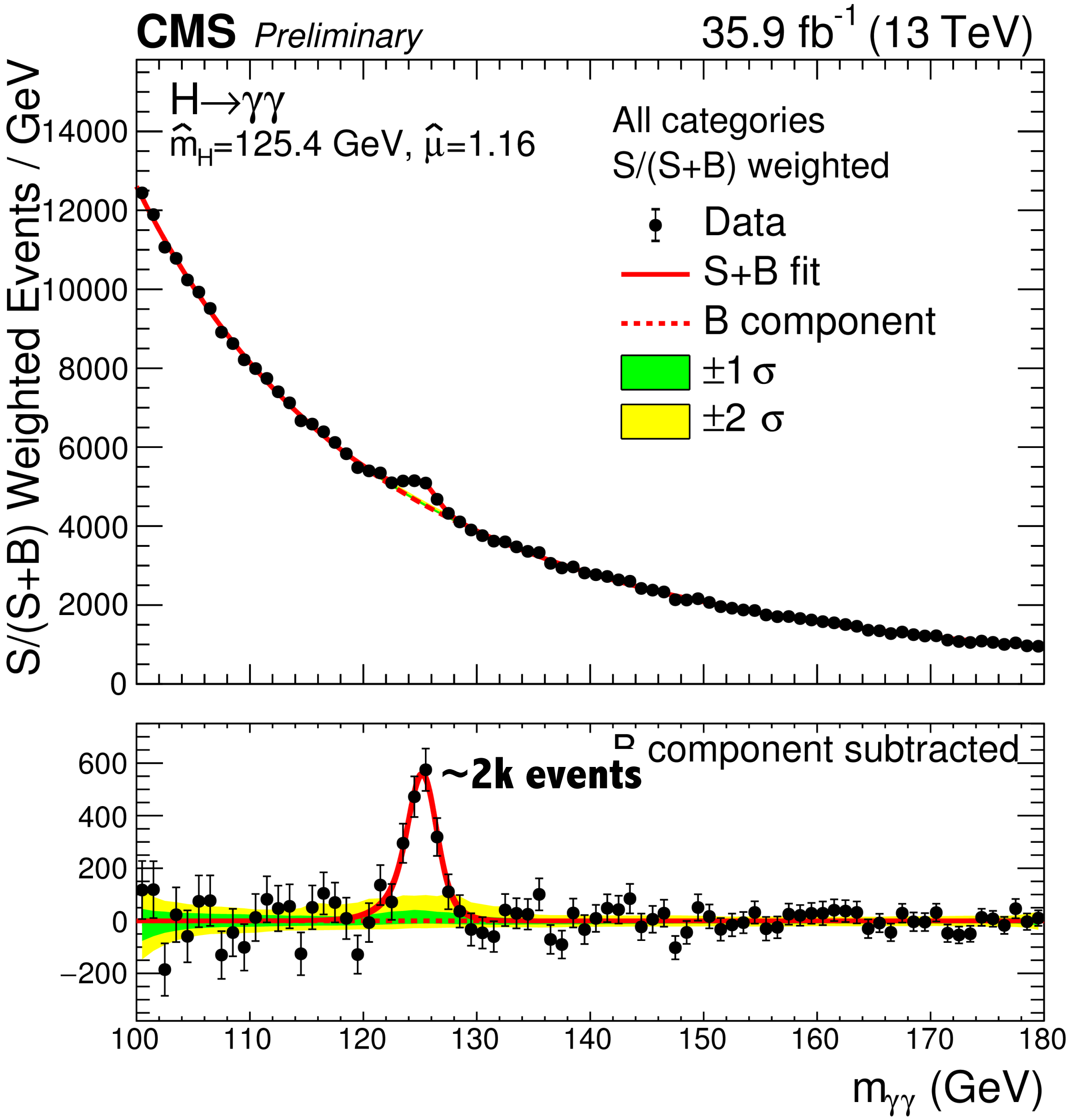
$$\mu = 1.28^{+0.18}_{-0.17}(\mathrm{stat})^{+0.08}_{-0.06}(\mathrm{exp})^{+0.08}_{-0.06}(\mathrm{theo})$$

Improvements on overall precision ~ x2 wrt Run1

Starting to approach SM theory uncertainty

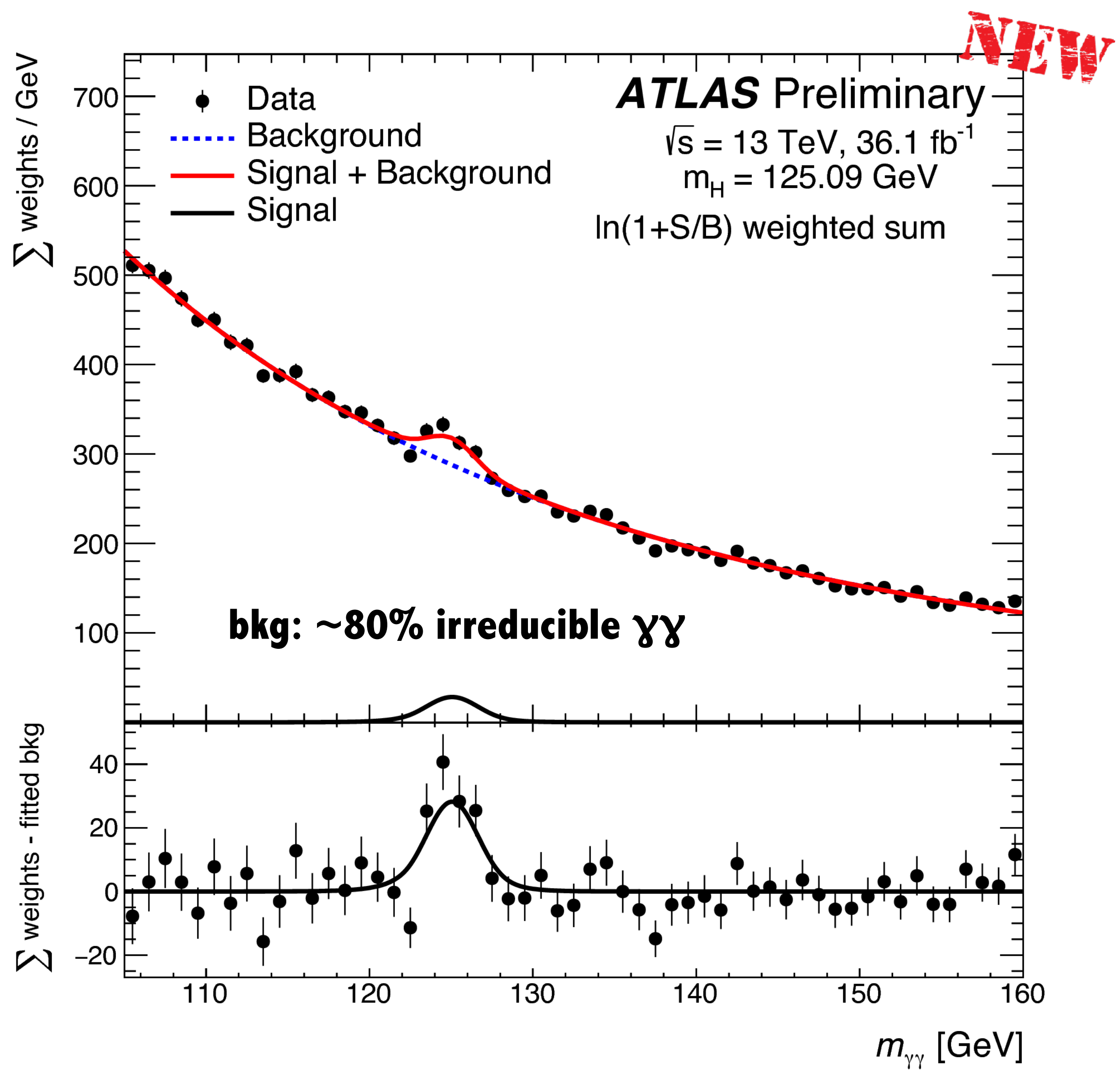
H→γγ

CMS HIG-16-040



$$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\text{stat})^{+0.09}_{-0.08}(\text{exp})^{+0.06}_{-0.05}(\text{theo})$$

ATLAS-CONF-2017-045



$$\mu = 0.99\ ^{+0.14}_{-0.14} = 0.99\ ^{+0.12}_{-0.11}\,(\text{stat.})\ ^{+0.06}_{-0.05}\,(\text{exp.})\ ^{+0.06}_{-0.05}\,(\text{theory})$$

MASS PEAKS: MASS MEASUREMENTS

ATLAS

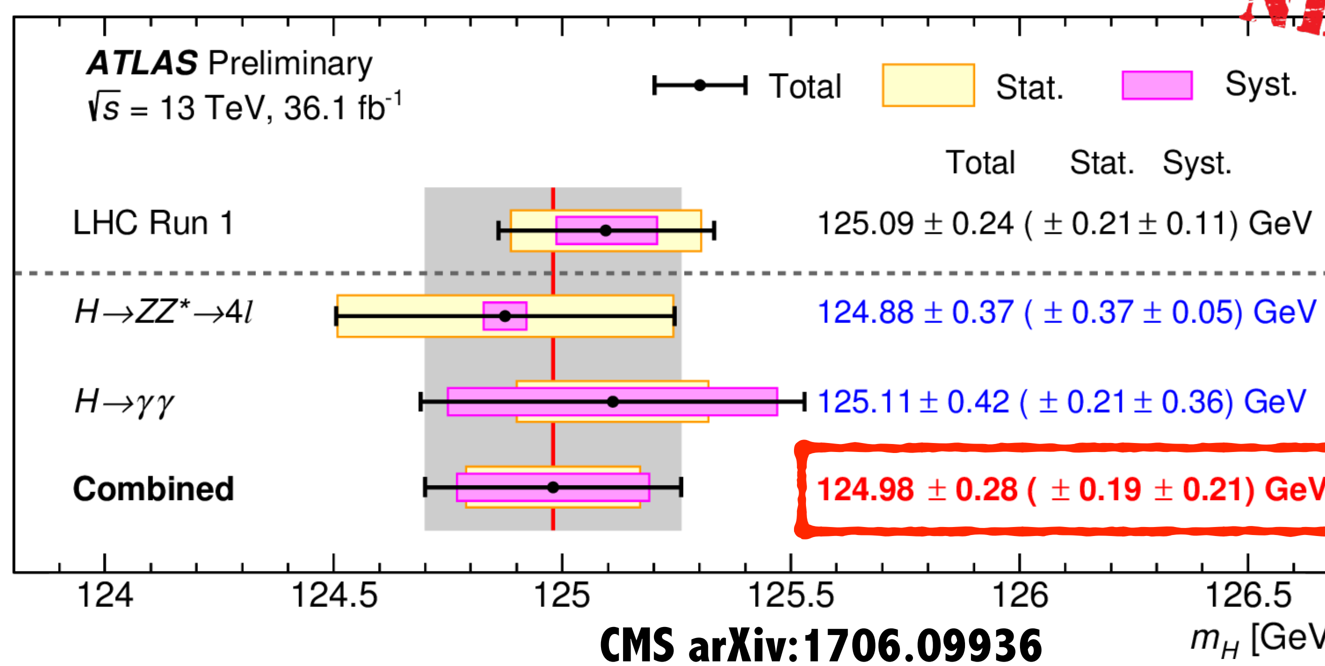
Combination of H→ZZ→4l & H→γγ

H→ZZ→4l: stat limited

H→γγ: systematics dominated

ATLAS-CONF-2017-046

NEW



CMS arXiv:1706.09936

CMS

H→ZZ→4l:

3D likelihood fit: (m_{4l}, mass uncertainty, ZZ bkg discriminator)

Kinematic fit on higher mass lepton pair

21% better then 1D(m_{4l}) fit

$$m_H = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})\ \text{GeV}$$

INCLUSIVE CROSS SECTIONS

H→ZZ	ATLAS	CMS
$\sigma_{fid}[fb]$	$3.62^{+0.53}_{-0.50}(\text{stat})^{+0.25}_{-0.20}(\text{syst})$	$2.92^{+0.48}_{-0.44}(\text{stat})^{+0.28}_{-0.24}(\text{syst})$
$\sigma^{theory}_{fid}[fb]$	2.91 ± 0.13	2.76 ± 0.14

Δσ/σ [15-16]%

H→γγ	ATLAS	CMS
$\sigma_{fid}[fb]$	$54.7 \pm 9.1(\text{stat}) \pm 4.5(\text{syst})$	$84 \pm 11(\text{stat}) \pm 7(\text{syst})$
$\sigma^{theory}_{fid}[fb]$	63.5 ± 2.4	75 ± 4

Different fiducial volumes definitions for ATLAS & CMS

Fiducial cross sections. Unfolding at particle level in fiducial volume

e.g. CMS H→γγ

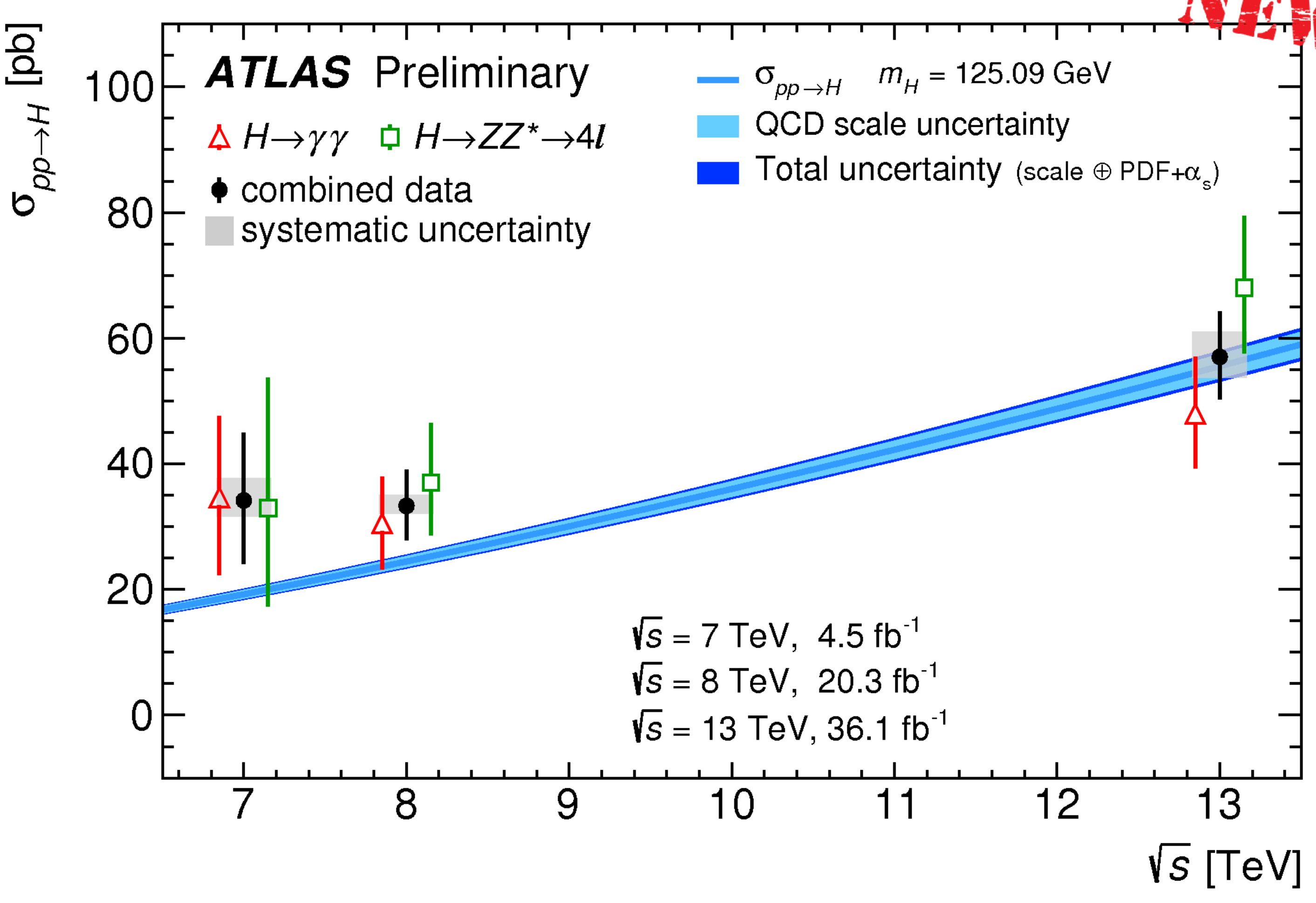
$p_T^{1(2)}/m_{\gamma\gamma} > 1/3\ (1/4)$

$|\eta_\gamma^{1(2)}| < 2.5$

$E_{iso} < 10$ GeV ΔR=0.3

ATLAS-CONF-2017-047

NEW



Good agreement with SM prediction

Run1 ⇒ Run2: theory precision improved x2

ggH @ N3LO QCD + PDF4LHC [arXiv:1610.07922]

CROSS SECTIONS BY PRODUCTION MODES

H→γγ, H→ZZ split events into several categories

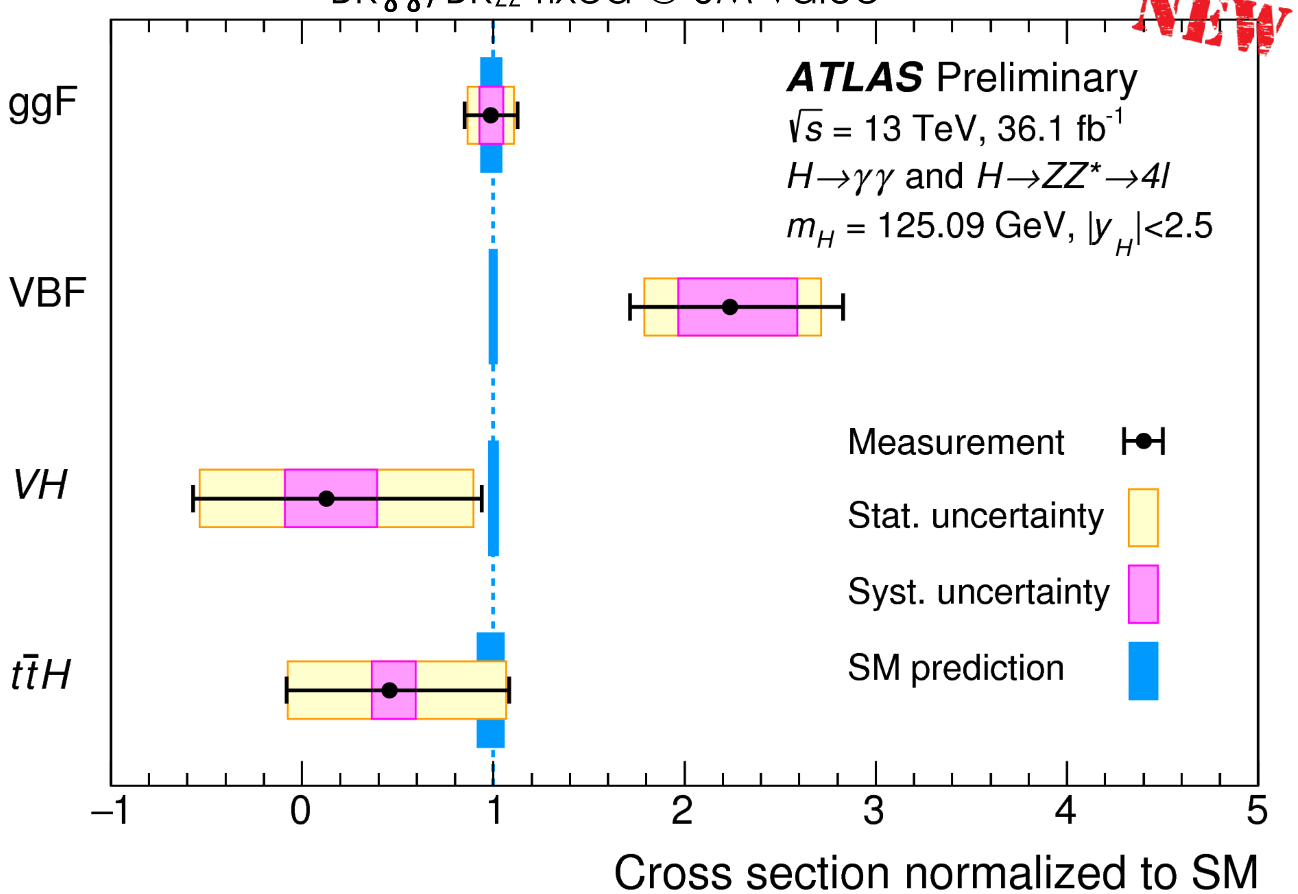
associated production modes (additional jets, leptons)

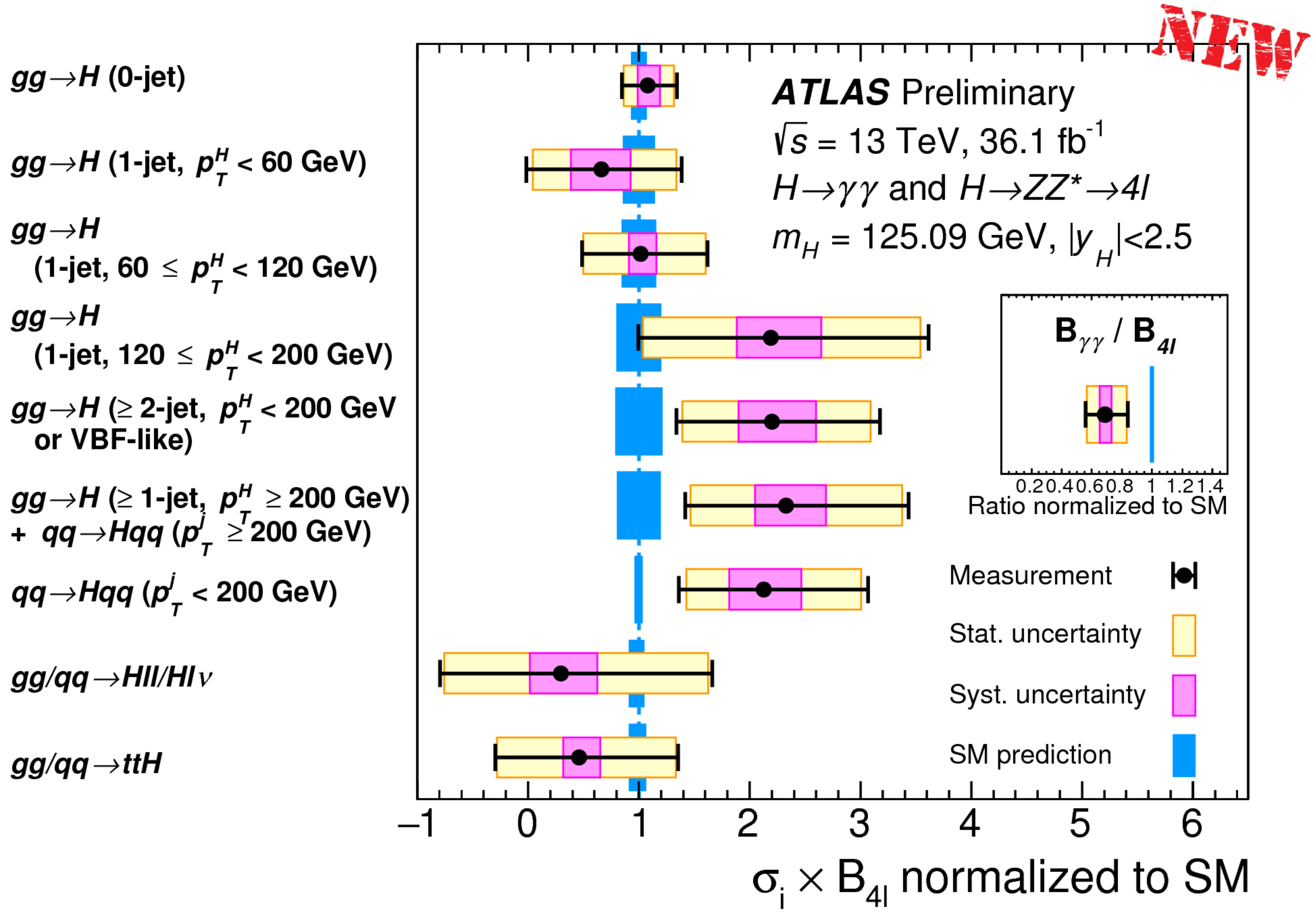
different kinematics region (vs p_T(H), p_T(jet))

ATLAS-CONF-2017-047

$$\mu = 1.09 \pm 0.12 = 1.09 \pm 0.09\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{syst.})\,^{+0.06}_{-0.05}\,(\text{th.})$$

BRγγ/BRZZ fixed @ SM value





Excess in VBF (both H→4l & γγ)

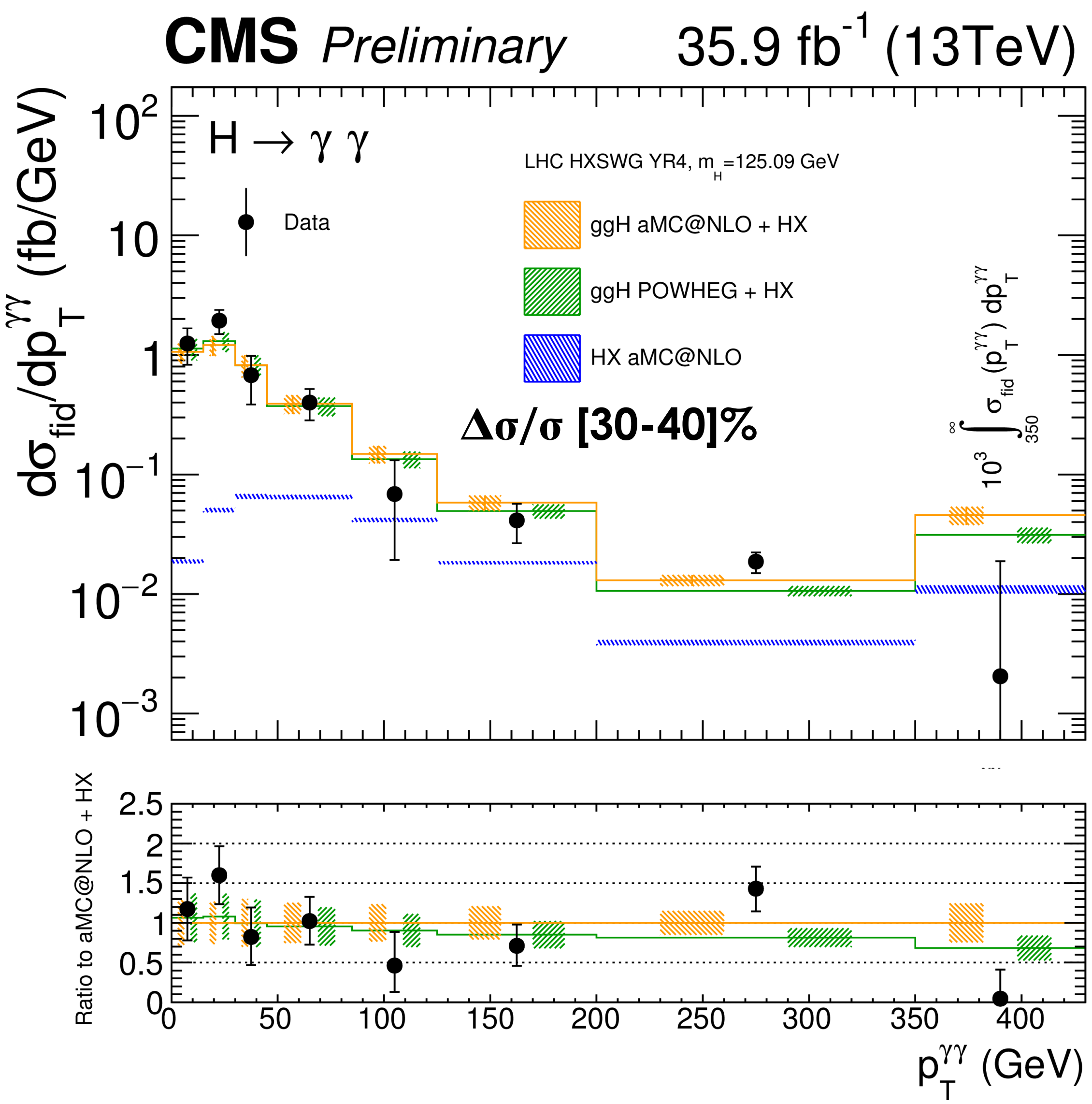
SM compatibility p-value 5%

Production modes binned in kinematic regions

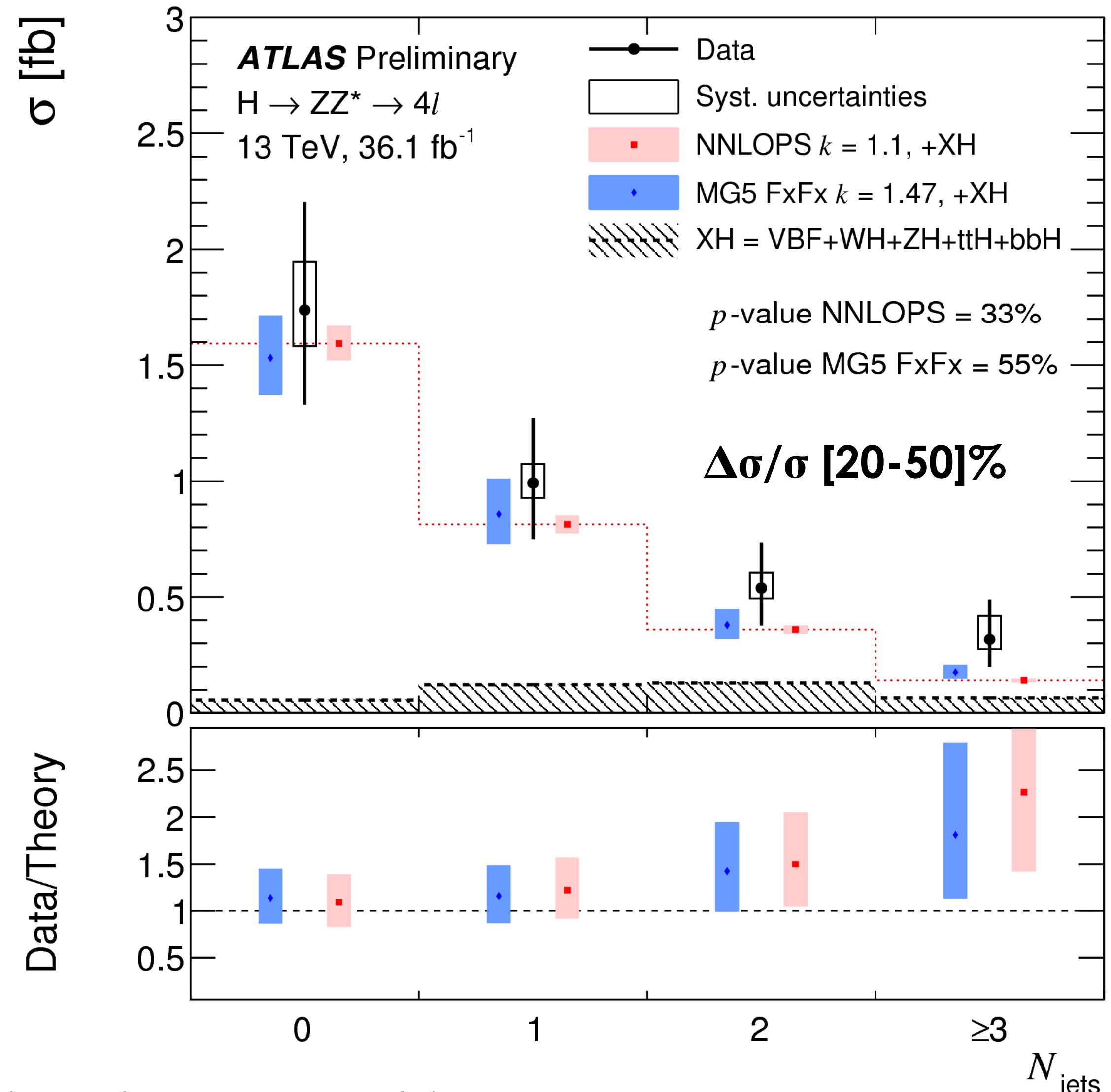
SM compatibility p-value 9%

DIFFERENTIAL CROSS SECTIONS

CMS HIG-17-015



ATLAS-CONF-2017-032

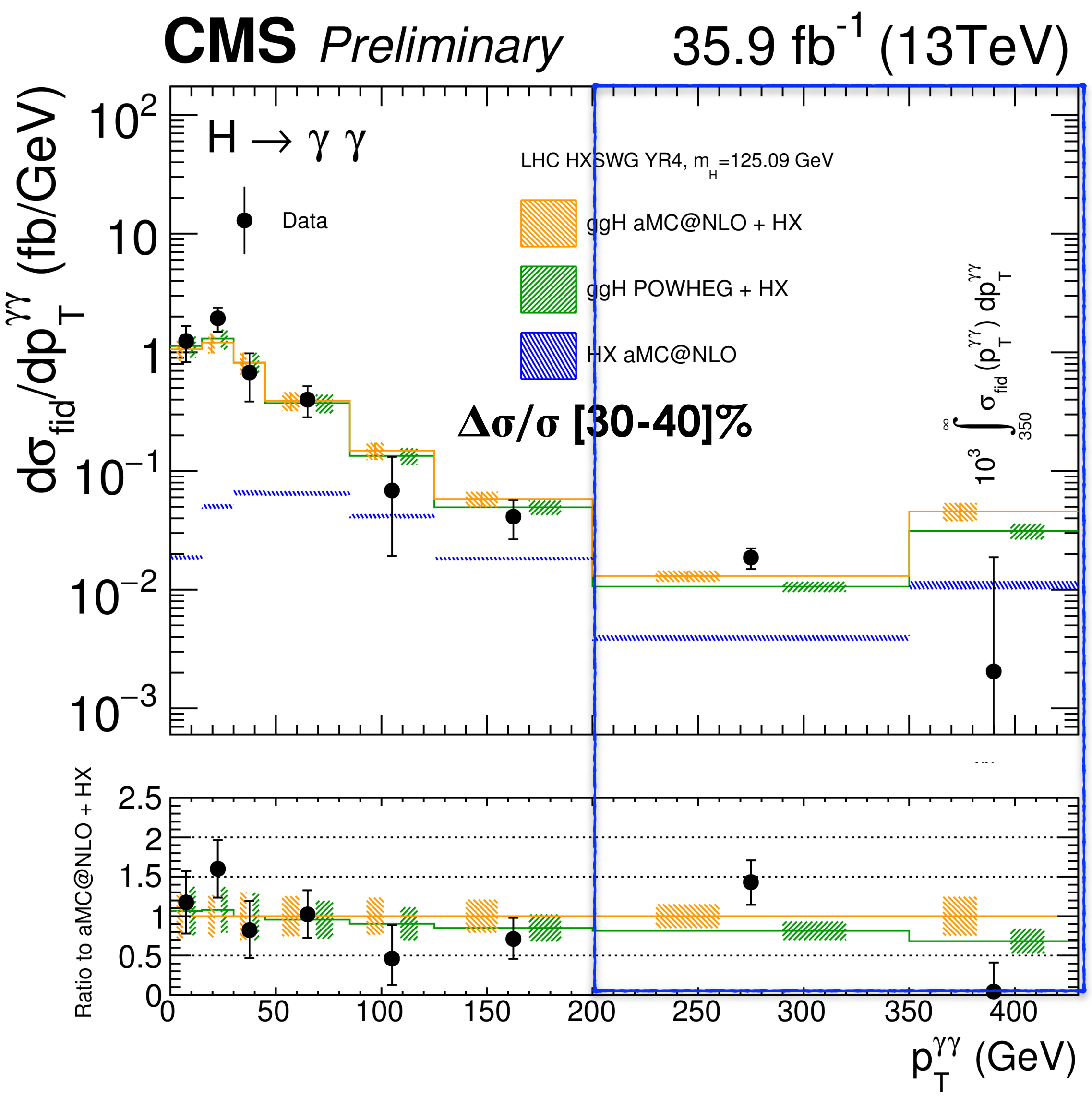


Unfolding: ~ no smearing for p_T, 10% in N_{jet}

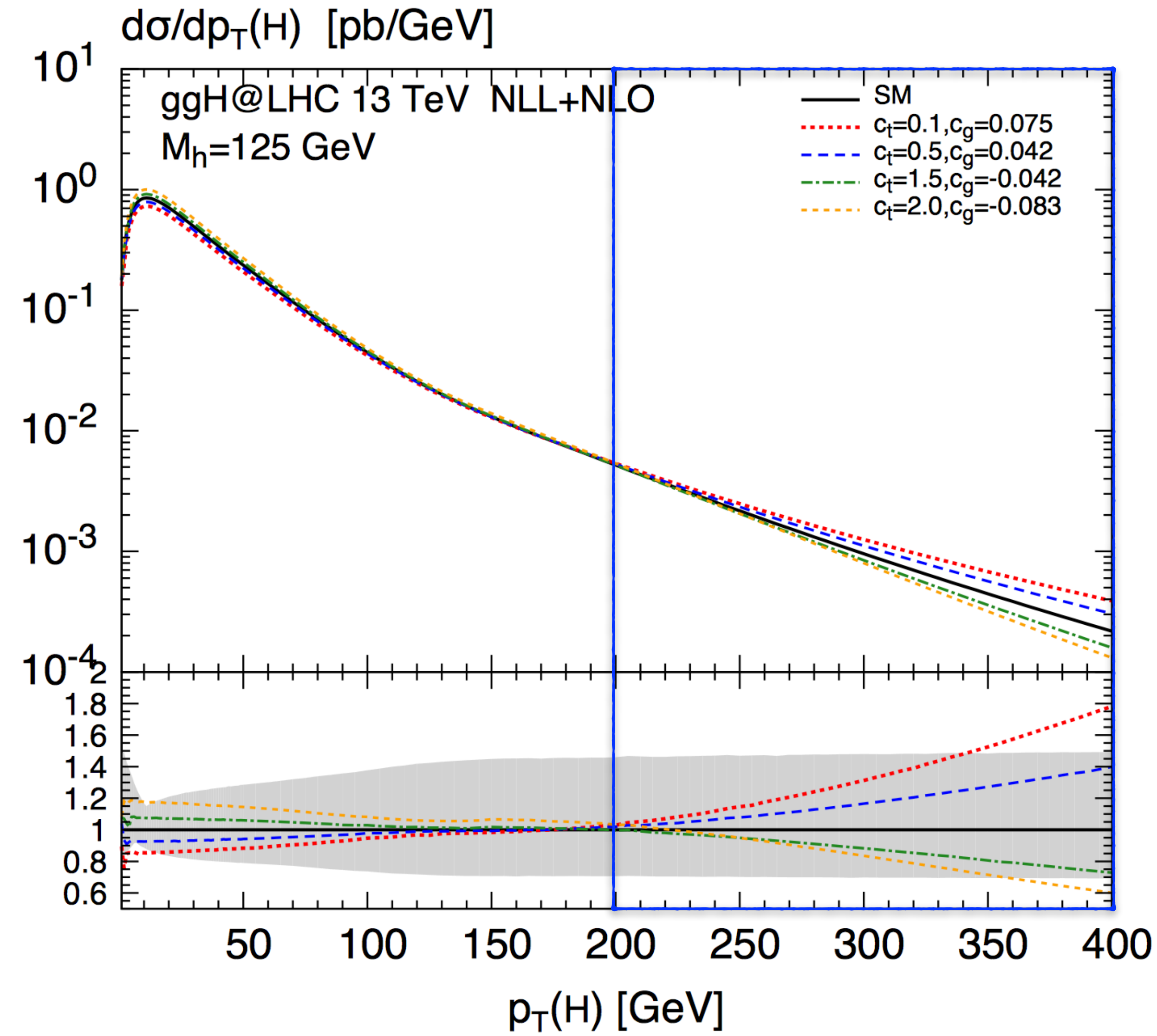
Measurements ⇄ Theory

Differential Cross Sections

CMS HIG-17-015



JHEP(2017) 2017:115



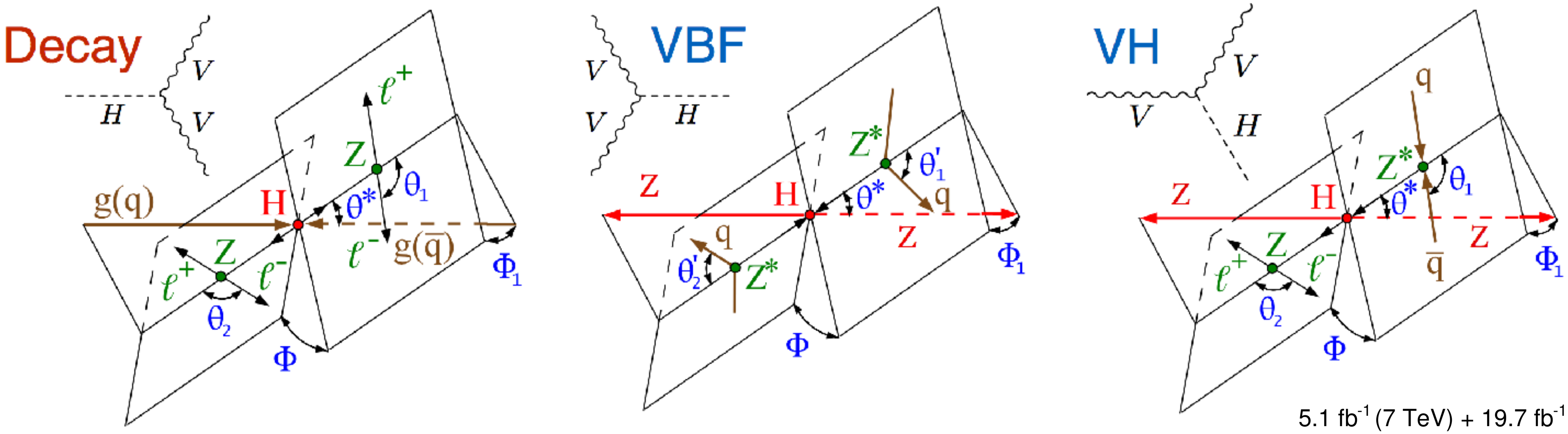
Model independent way to probe BSM effects

HVV: ANOMALOUS COUPLINGS

CMS arXiv:1707.00541 Submitted to PLB

Anomalous HVV couplings from angular information in H→ZZ→4l

NEW: production (VBF and VH tagged events) used together with **decay** informations



HVV amplitude parametrisation

SM — BSM CP-even — BSM CP-odd

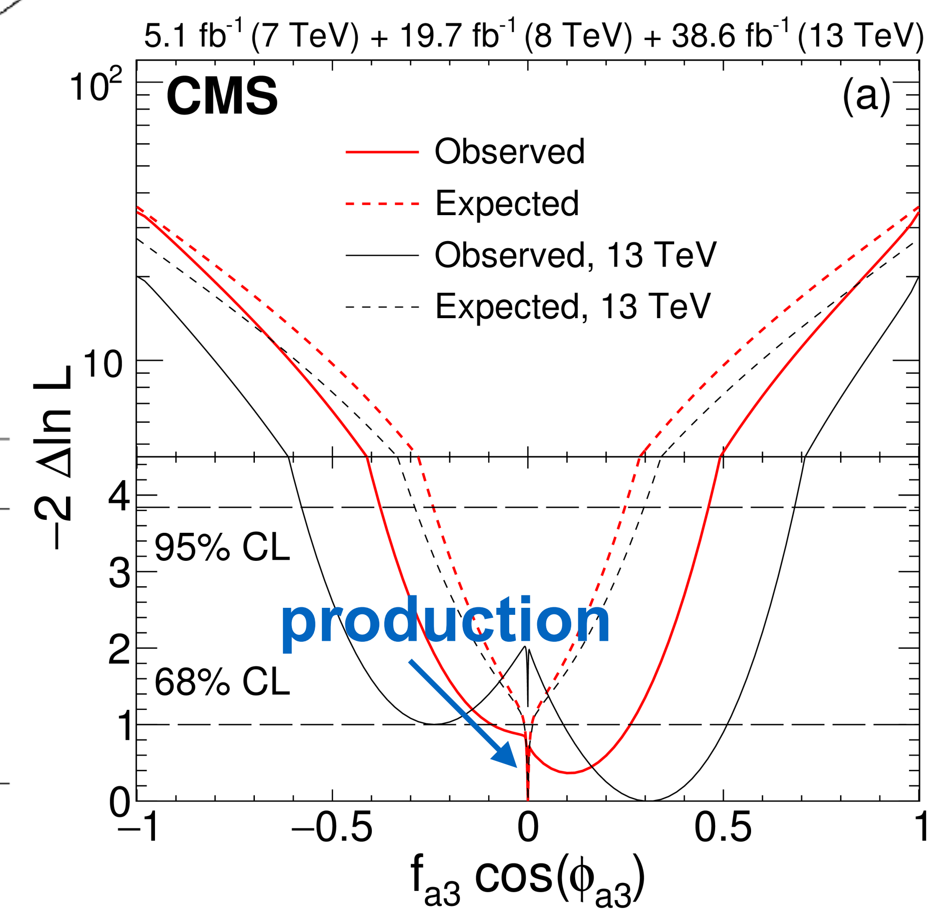
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$$f_{ai} = |a_i|^2\sigma_i \Big/ \sum |a_j|^2\sigma_j$$

effective fractions of anomalous cross-sections

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$

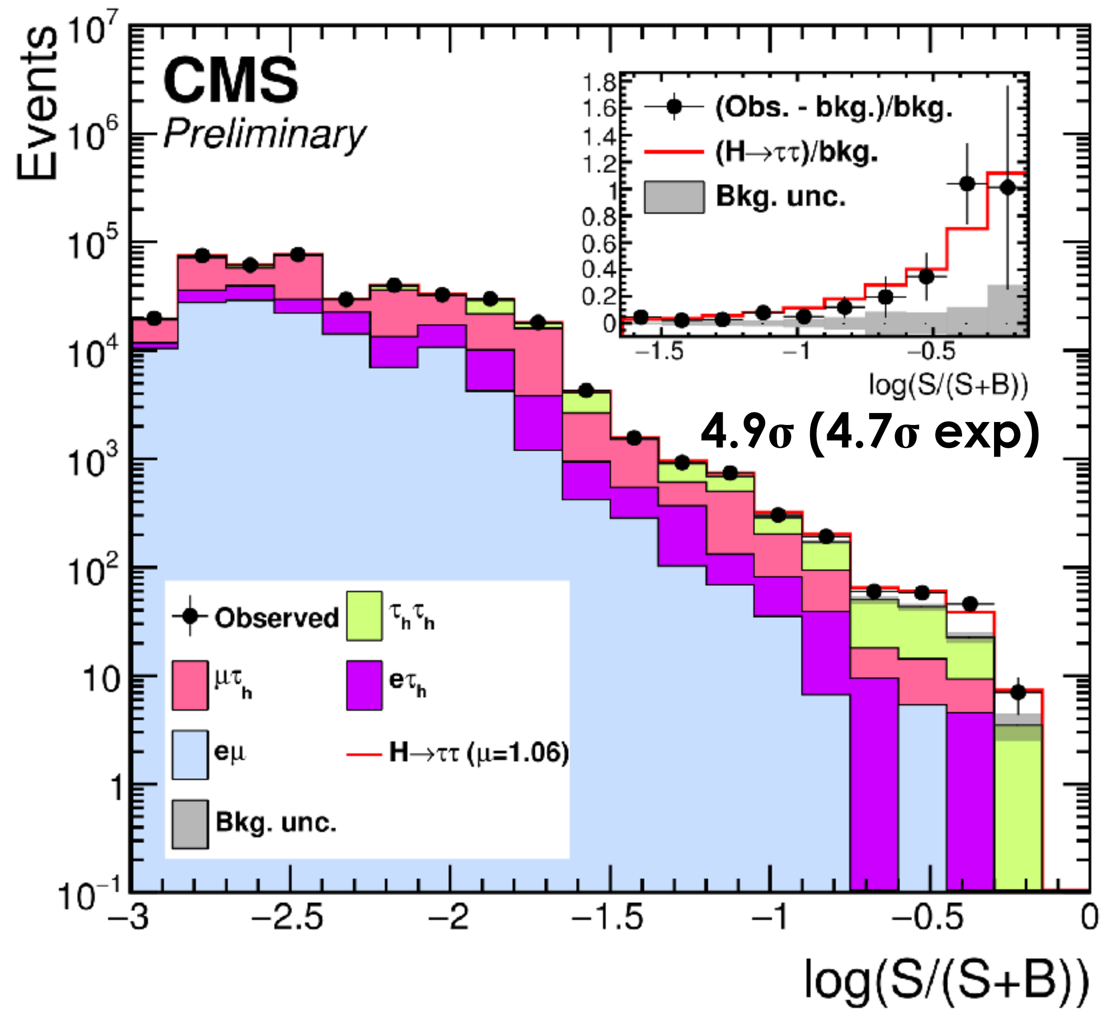
[95% CL intervals]

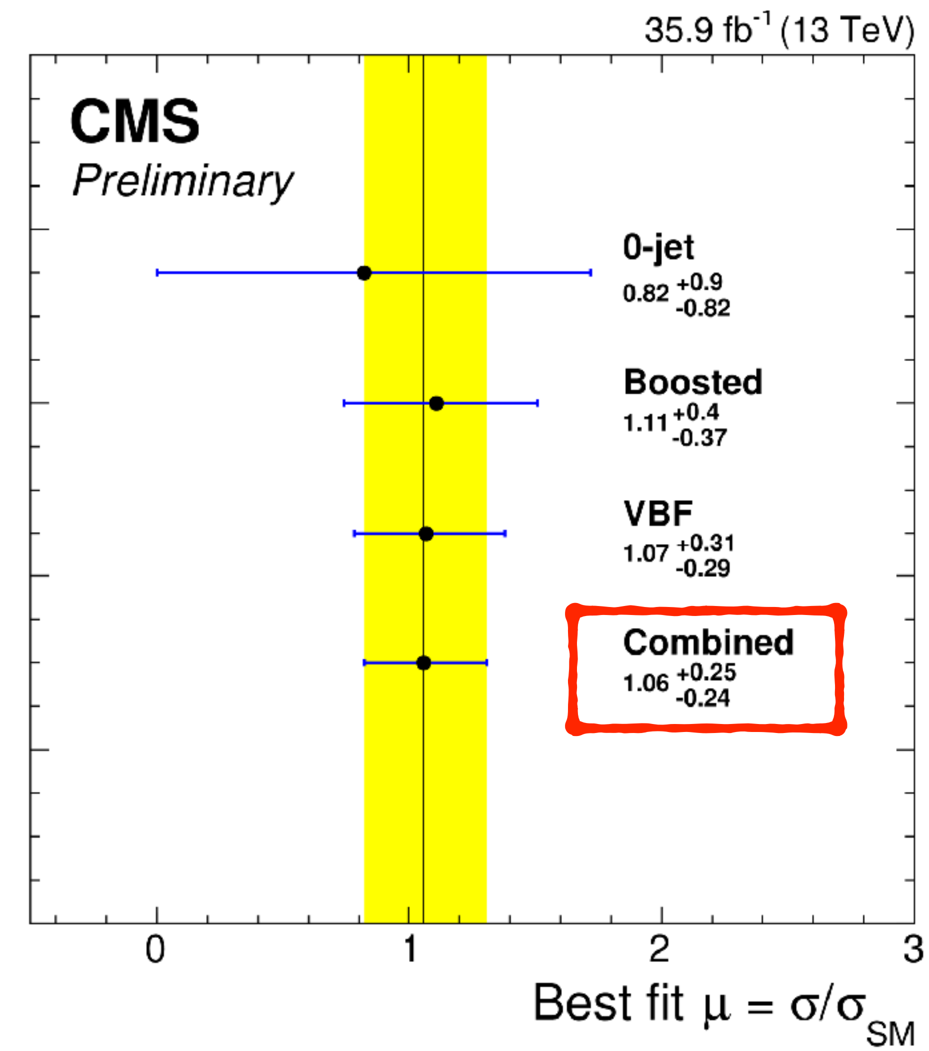


Coupling To Fermions

Observation of H→ττ

CMS HIG-16-043





sensitivity driven by VBF & boosted category

4τ decay channels ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$) x 3 categories (0-jet, boosted, VBF)

2D fit signal extraction: $m_{\tau\tau}$ vs (τ decay mode, p_T, di-jet mass)

Observation of $\tau\tau$ decay mode from a single experiment: 4.9σ (4.7σ exp), 5.9σ when combined with CMS Run1

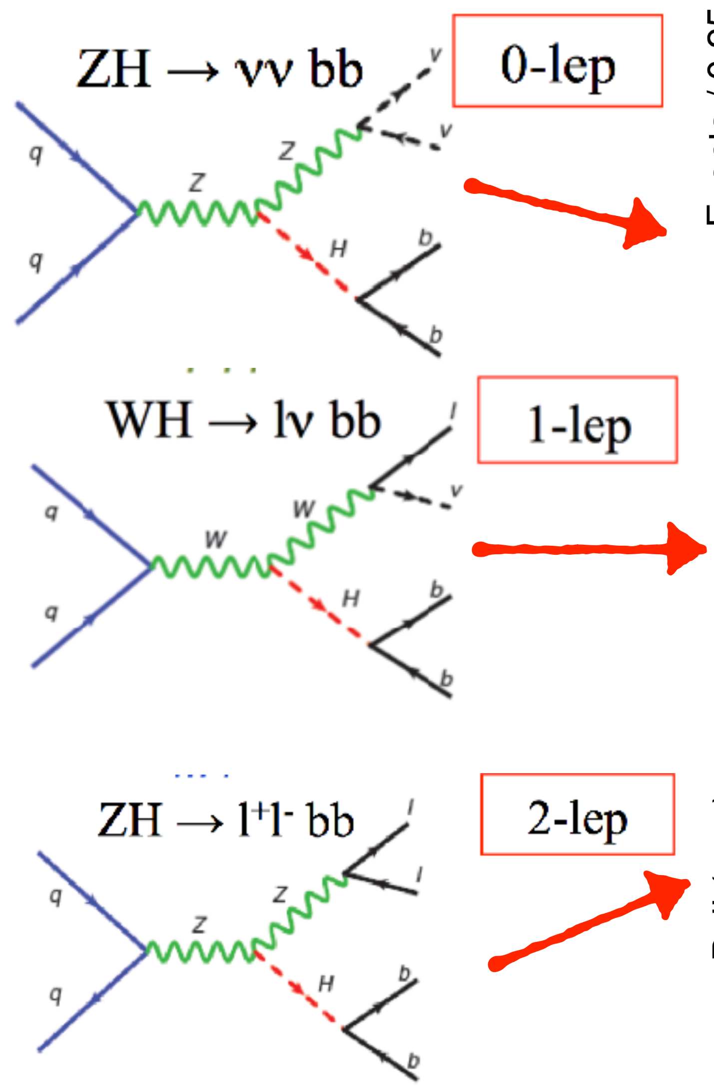
EVIDENCE FOR H→bb

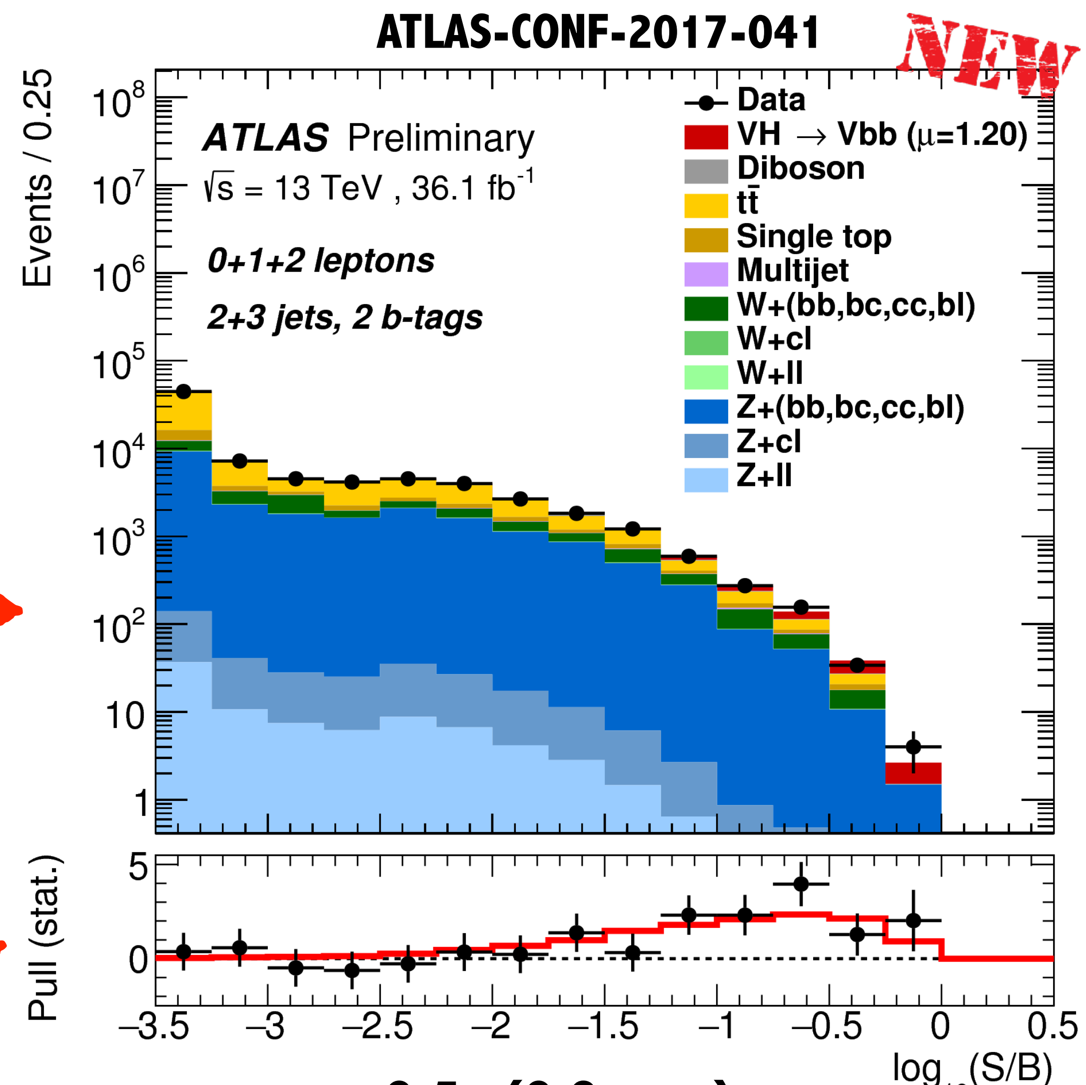
H→bb: Run1 ATLAS+CMS 2.6σ (3.7 exp)

VH(→bb) production: overcome large QCD background

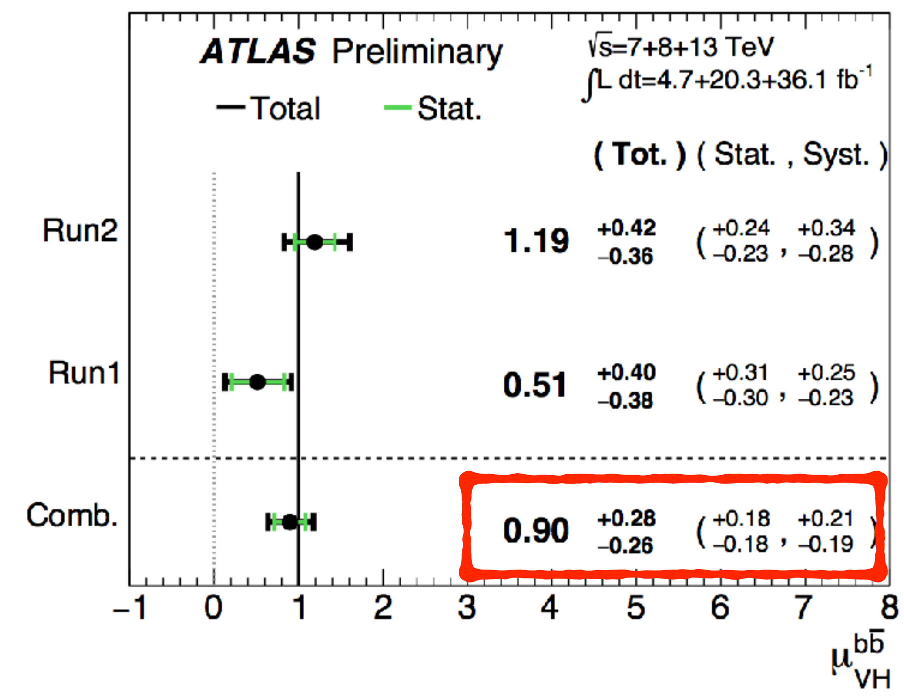
Backgrounds: W/Z+jets, tt

Observable: BDT including m_{bb}





3.5σ (3.0 exp)

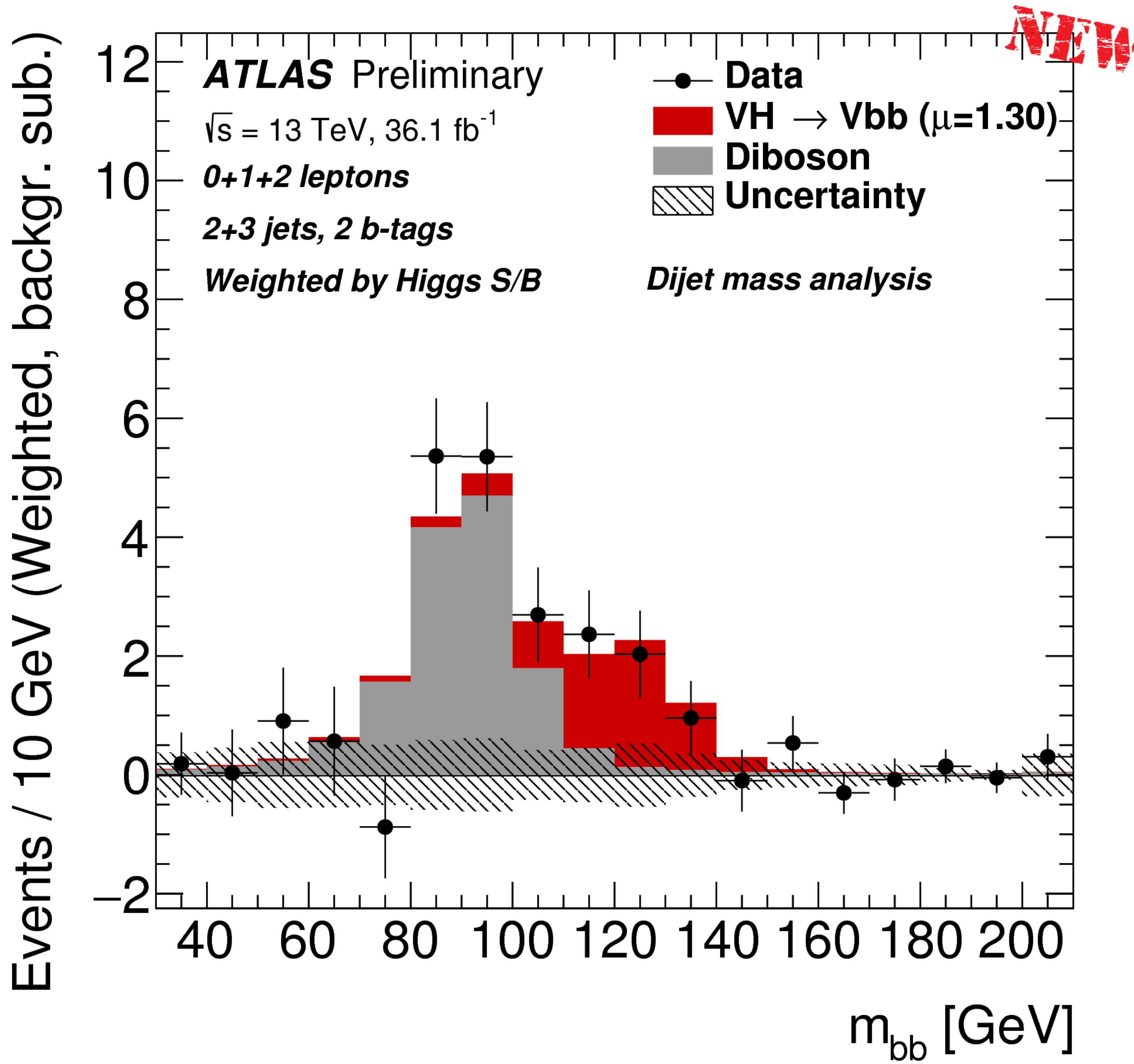


Evidence for VH(bb): 3.6σ when combined with ATLAS Run1

EVIDENCE FOR H→bb

ATLAS-CONF-2017-041

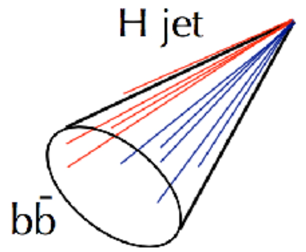
Di-jet mass cross-check analysis (~10% less sensitive): nice peak on VZ(→bb) shoulder



INCLUSIVE H→bb

CMS HIG-17-010

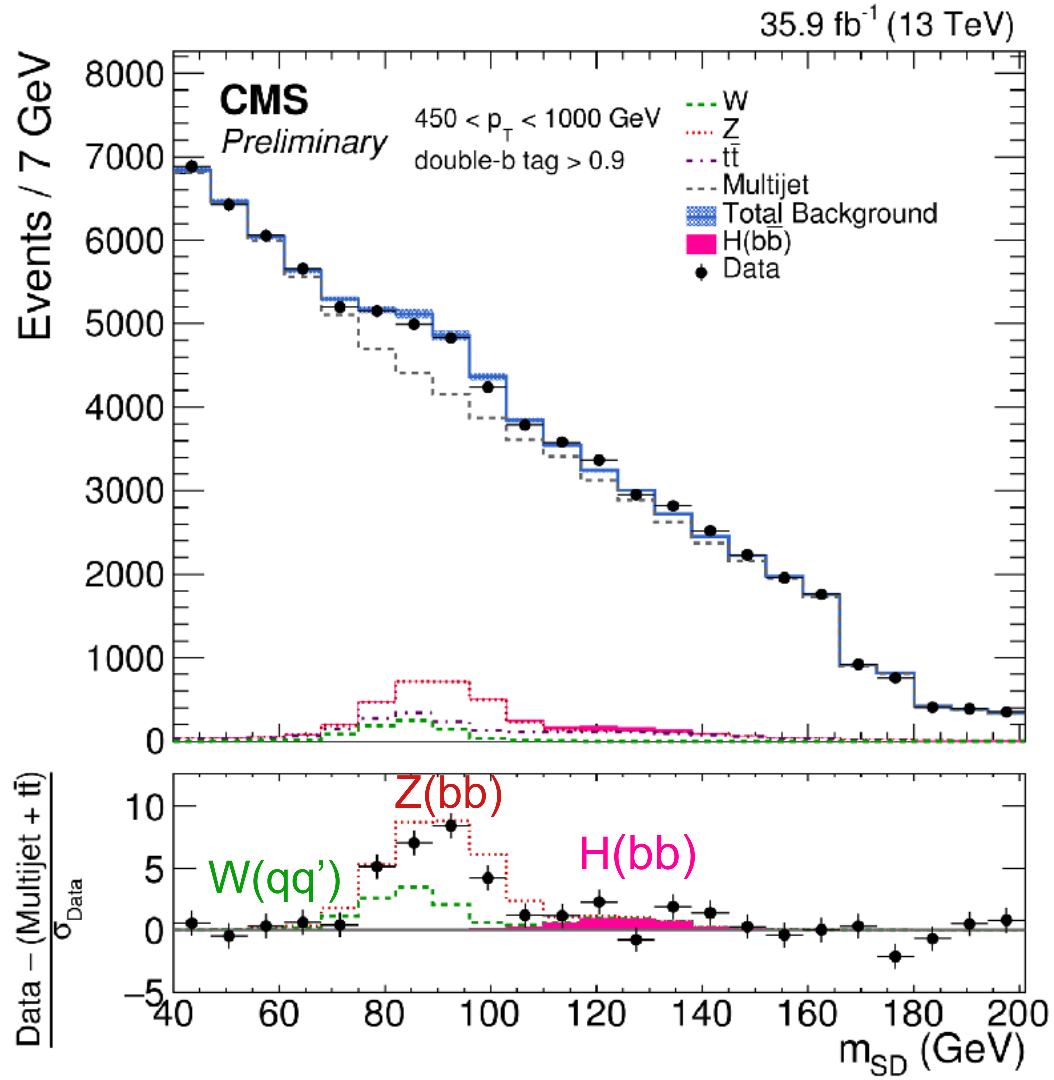
p_T>450 GeV

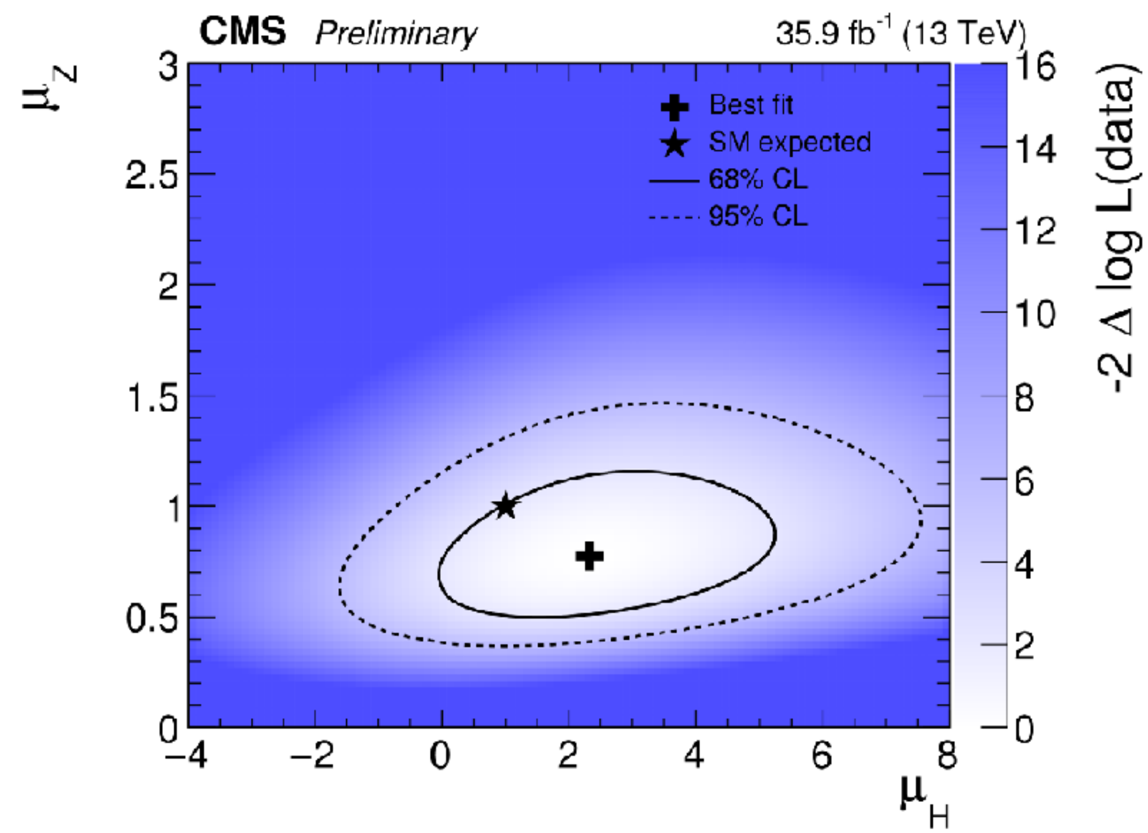


Single large cone fat jet (R=0.8) p_T>450 GeV

double b-tagging on sub-jets

Jet mass: main observable



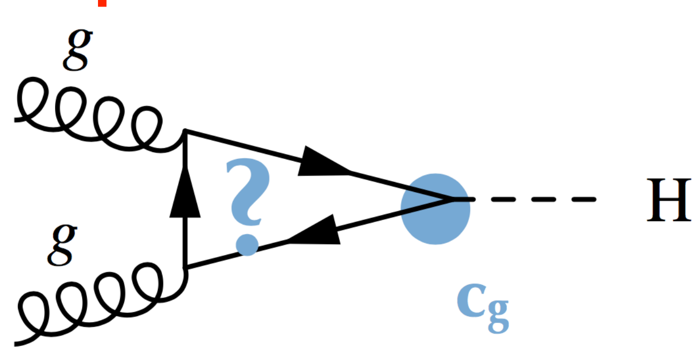


	H	Z
Observed best fit	$\mu H = 2.3^{+1.8}_{-1.6}$	$\mu Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ ($\mu H = 1$)	5.8σ ($\mu_Z = 1$)
Observed significance	1.5σ	5.1σ

Observation of boosted Z→bb

First search for gg→H→bb in boosted topology

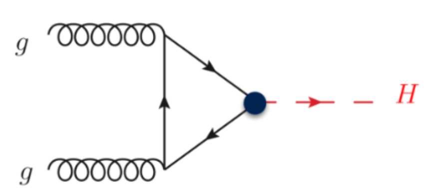
boosted jet techniques: searches ⇒ measurements



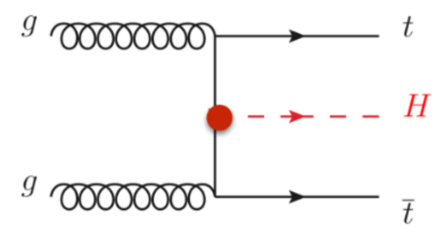
Explore a brand new regime
ggF p_T>450 GeV

TOWARDS *ttH* OBSERVATION

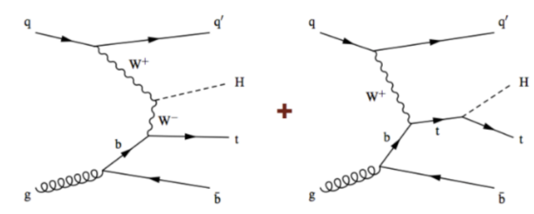
Indirect (loop)
ggH: 44 pb

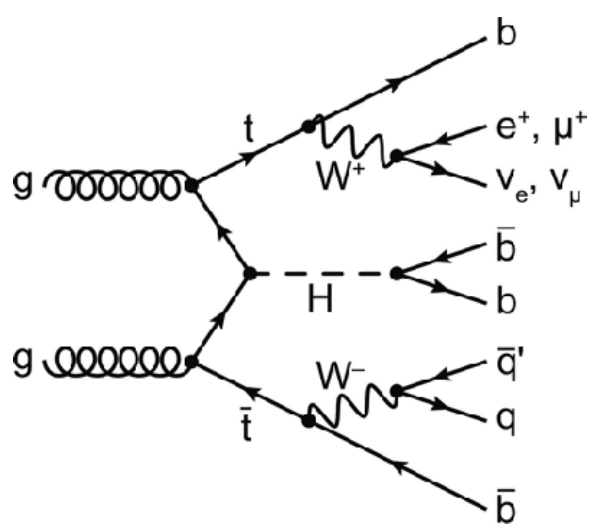


Direct
ttH: 0.5 pb



Interference
tH: 0.08 pb





Final state with additional leptons, jets, b-jets

Different strategy depending on Higgs decay

$H \to b\bar{b}$	$H \to (WW, \tau\tau)$ multileptons	$H \to (4l, \gamma\gamma)$
tt+HF background prediction	tt+V, tt+jets background	Clean bump hunt

- Theory systematics → Simple background
- High yield ← Low yield
- Low signal/background → Clear peak

ttH Summary

Run1 (yellow)
Run2: 13 fb^{-1} (green), 36 fb^{-1} (red)

$\mu_{ttH}=\sigma_{ttH}/\sigma_{SM}$

	ATLAS	CMS	
Run1 comb.	$2.3^{+0.7}_{-0.6}$		← **4.4σ (2.0σ exp)**
bb	$2.1^{+1.0}_{-0.9}$	-0.2 ± 0.8	
multilepton	$2.5^{+1.3}_{-1.1}$	1.5 ± 0.5	← **3.3σ (2.5σ exp)**
τ_h+X		$0.7^{+0.6}_{-0.5}$	
γγ	$0.5^{+0.6}_{-0.6}$	$2.2^{+0.9}_{-0.8}$	← **3.3σ (1.5σ exp)**
ZZ	<7.5 @ 95%CL	$0.0^{(*)+1.2}_{-0.0}$	

(*): 68% CL interval with μ≥0

Evidence for ttH? Statistically a combination would be largely incompatible with $\mu_{ttH}=0$, but not yet a single unambiguous signal

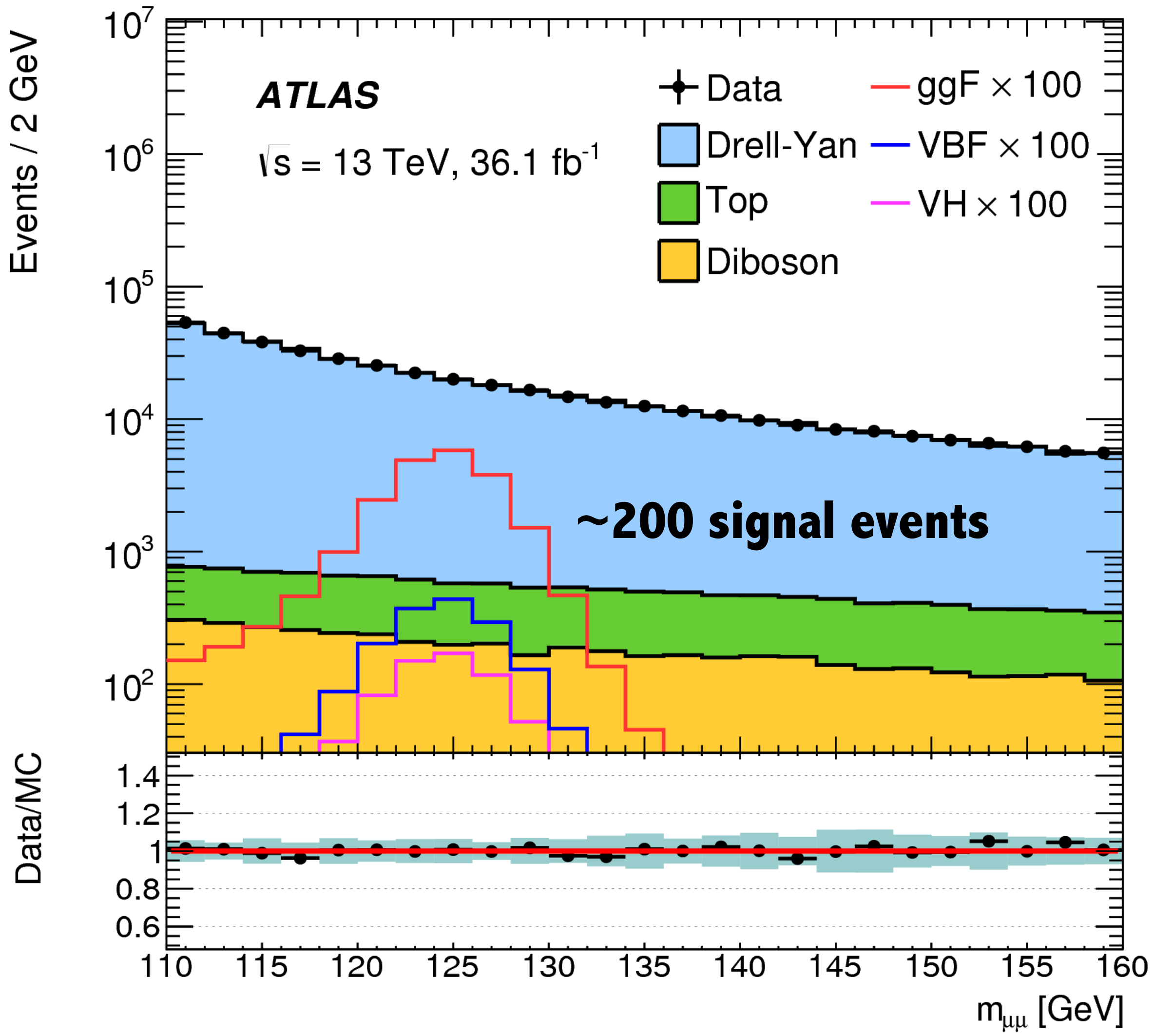
2ND GENERATION COUPLING

H→μμ: probing 2nd generation Yukawa coupling (BR 2.18E-4)

ATLAS Run1 + 36fb^{-1} @ 13 TeV:
σ/σ_{SM}<2.7 @ 95%CL (2.8 exp)

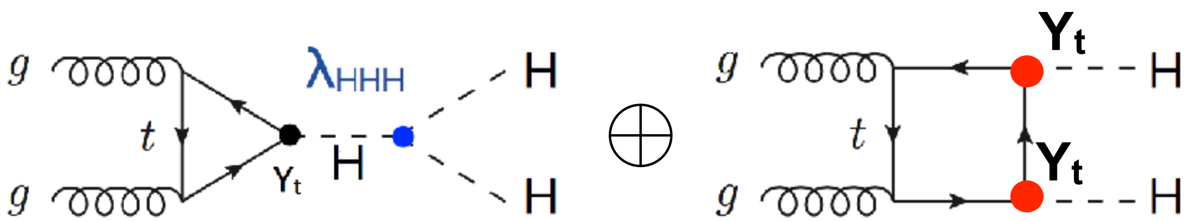
ATLAS+CMS combination sensitivity ~2σ by the end of Run2

ATLAS arXiv:1705.04582



Rare Processes

DOUBLE HIGGS PRODUCTION

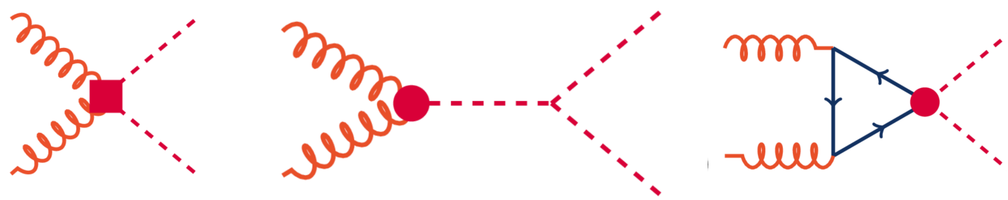


$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

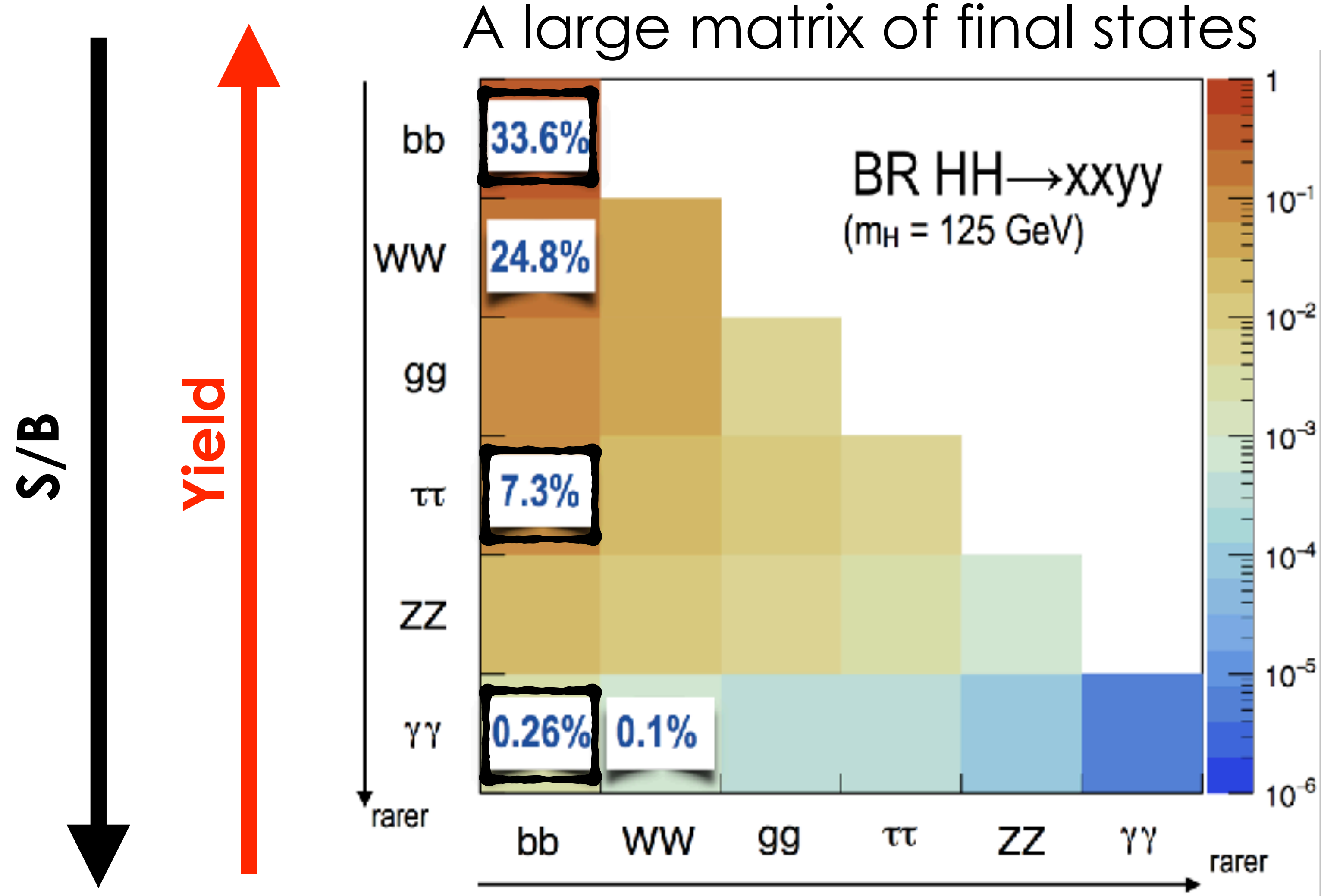
[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]

Main probe for trilinear Higgs coupling λ_{HHH}. Diagrams interfere destructively in SM

sensitive to possible BSM contributions



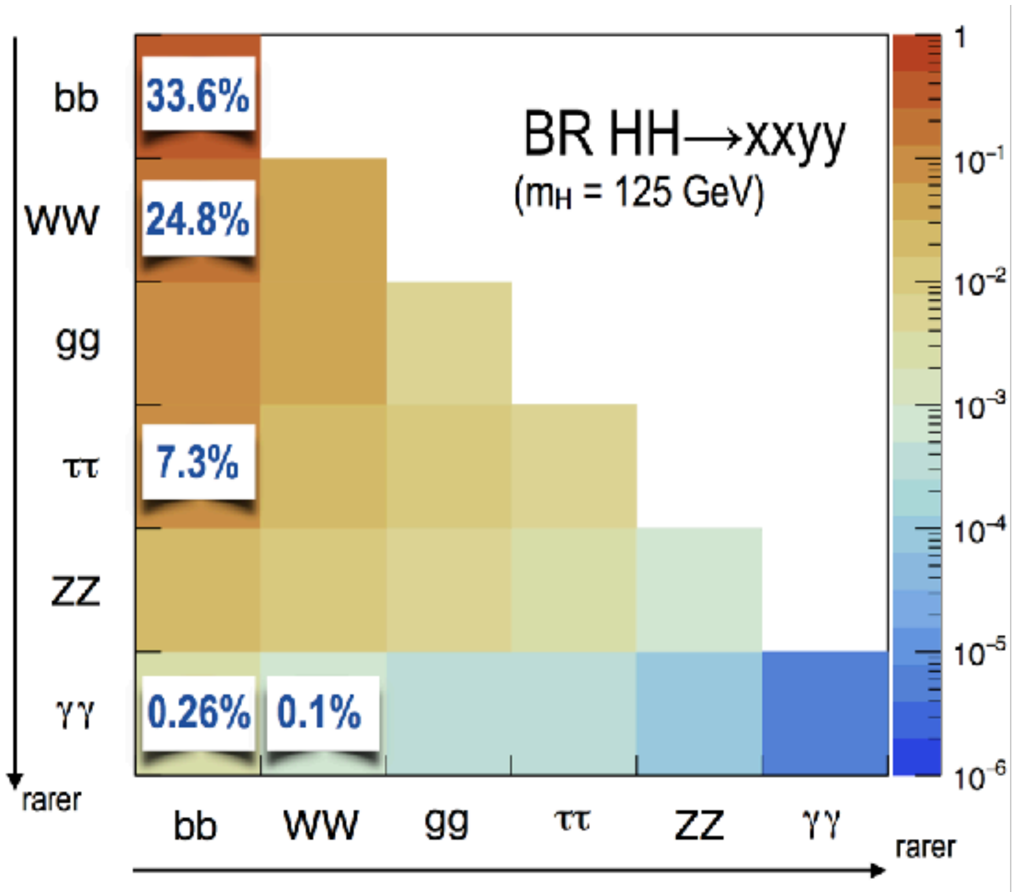
A large matrix of final states



bbbb largest statistics

bb(γγ,ττ) good compromise between statistics and S/B

HH: RESULTS



σ/σ_{SM} 95% CL (exp)

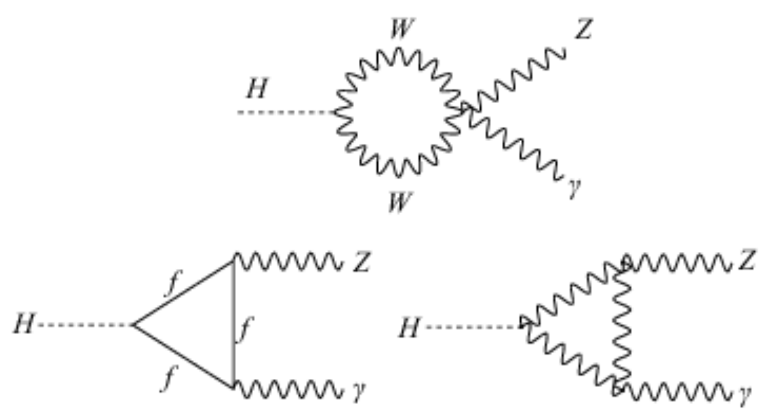
	ATLAS	**CMS**
bbbb	<29 (38)	<342 (308)
bbWW		<79 (89)
bbττ		<28 (25)
bbγγ	<117 (161)	<19 (17) NEW
WWγγ	<747 (386)	

Run2 | **3 fb^{-1}** | **13 fb^{-1}** | **36 fb^{-1}**

Rare Decay Status

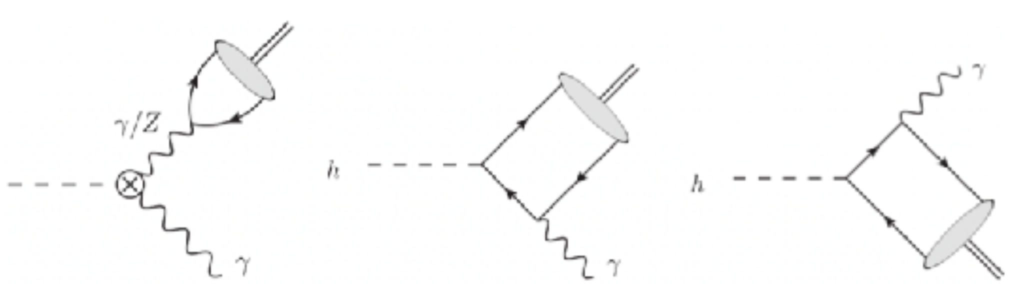
Searches for rare decays: observation would imply BSM physics

$H\to Z\gamma$, $H\to\gamma^*\gamma$: access BSM in loops



$H\to J/\Psi\gamma$: coupling to charm

$H\to\rho\gamma$ & $H\to\phi\gamma$: couplings to light quarks

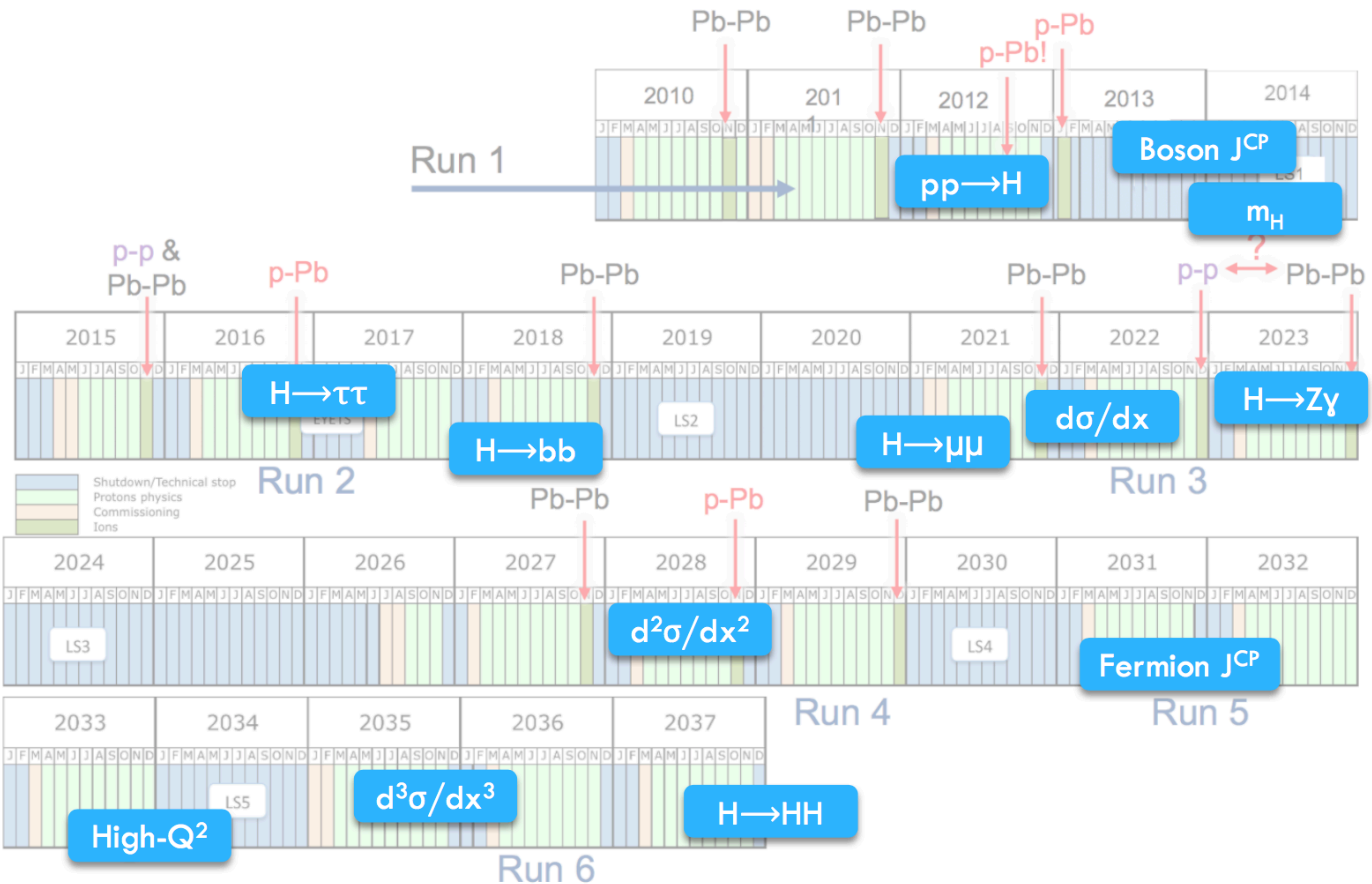


NEW

Process	σ/σ_{SM} (95% CL)
$H\to Z\gamma$ (ATLAS) $36 fb^{-1}$@ 13 TeV	<6.6
$H\to Z\gamma$ (CMS) Run1	<9
$H\to\gamma^*\gamma$ (CMS) Run1	<7.7
$H\to J/\Psi\gamma$ (ATLAS) Run1	<540
$H\to J/\Psi\gamma$ (CMS) Run1	<540
$H\to\rho\gamma$ (ATLAS) 36 fb-1 @ 13 TeV	<52
$H\to\phi\gamma$ (ATLAS) 36 fb-1 @ 13 TeV	<208
$H\to ee$ (CMS) Run1	<~10^5

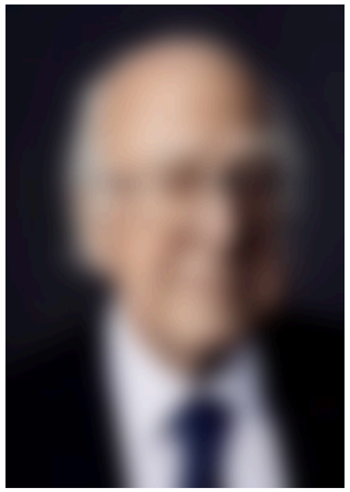
Run1 (yellow)
Run2 (red): $36\ fb^{-1}$

PROSPECTS

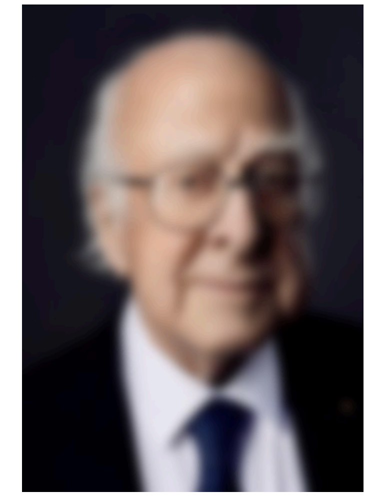


Credits: A. David @ GRC 2017

SUMMARY

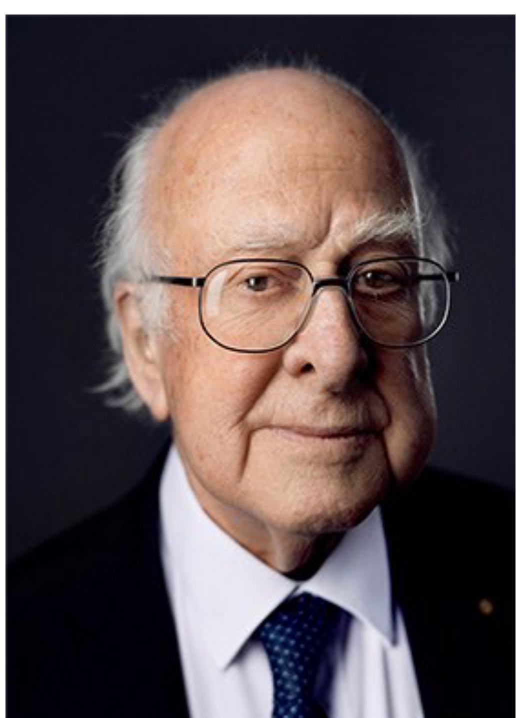


Higgs 5 years after discovery



Still looks like "Standard Model Higgs" with better resolution

- Run2 cross-section measurements improving by a factor ~2 Run1
- 3rd gen Yukawa couplings: **5σ observation of $\tau\tau$ decay mode, >3σ for bb**
- **not only improvements from statistics**: boosted ggH(→bb)



The road is still very long

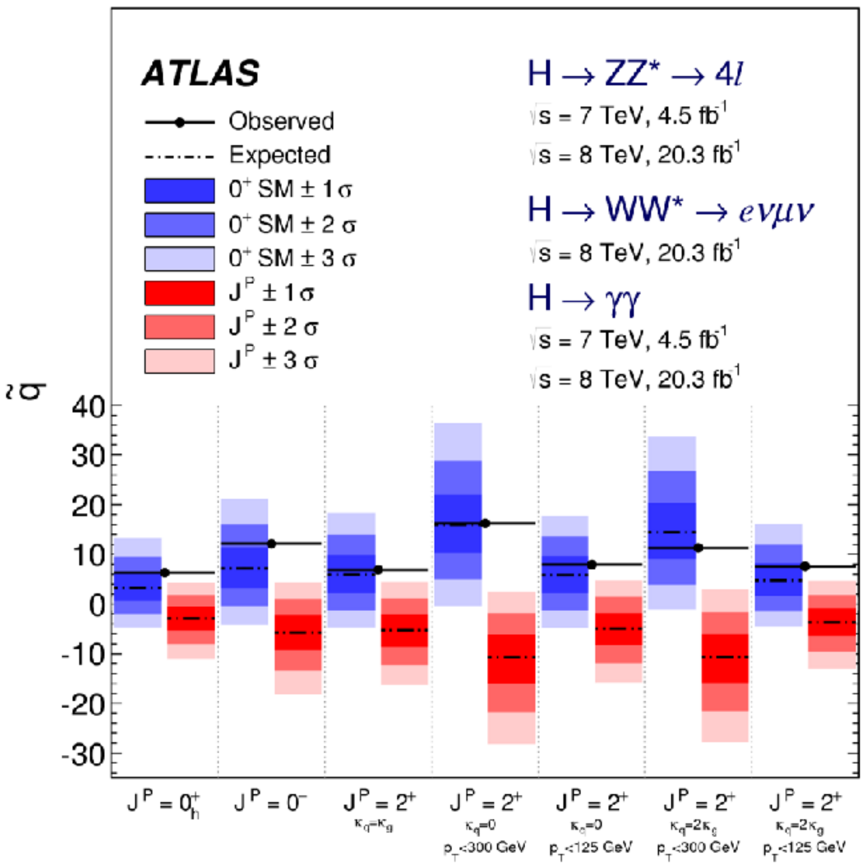
a lot of data to squeeze in front of us (@ very high pile-up)
but obvious roads will soon close up, we will need to look also for other directions

We need **just ONE deviation to point us in the right direction**

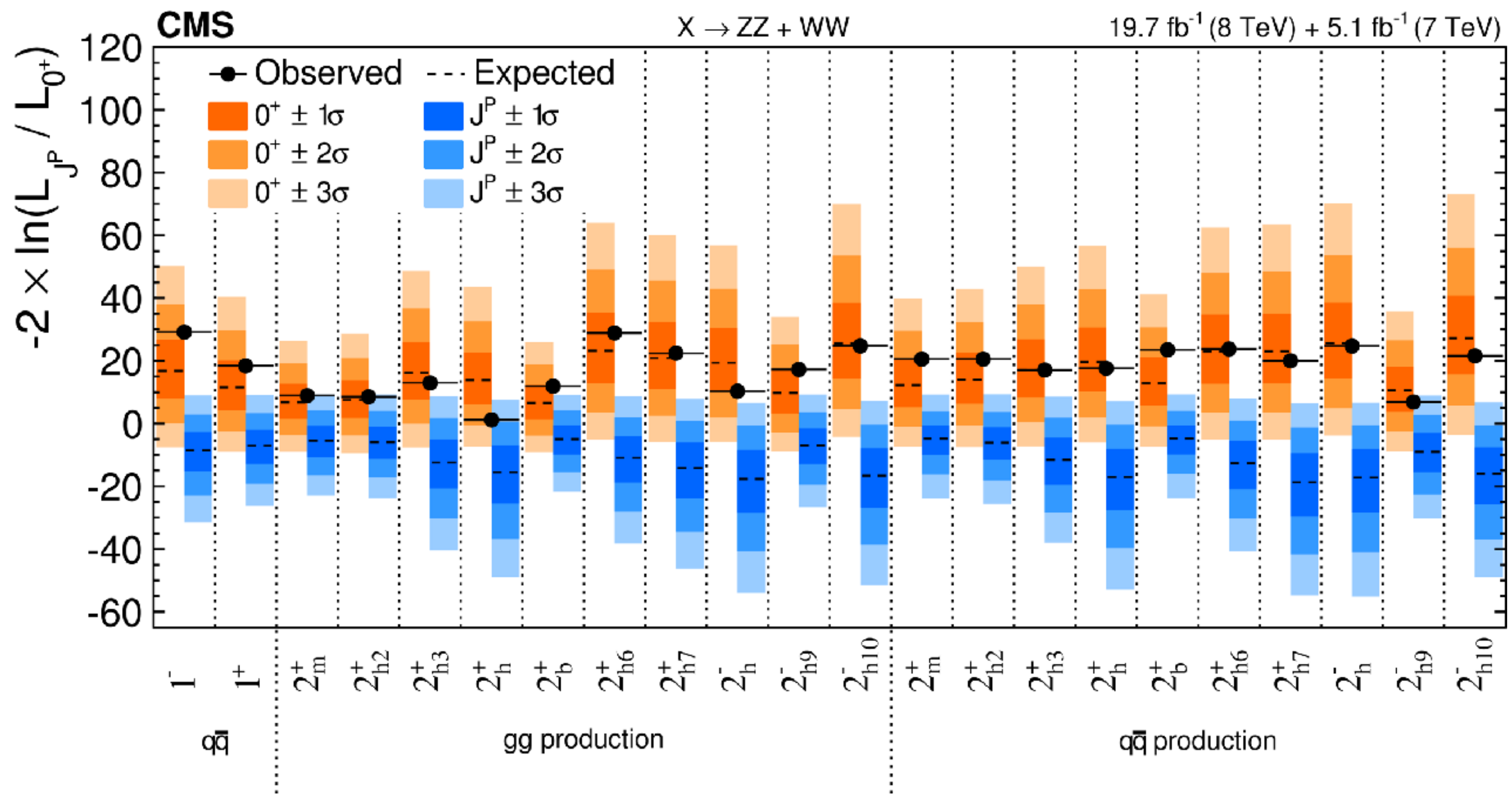
Backup

Run1: Spin-Parity

ATLAS Eur. Phys. J. C 75 (2015) 476



CMS Phys. Rev. D 92 (2015) 012004



Angular analysis in ZZ, WW, γγ final states

All observations consistent with the $J^{PC}=0^{++}$ hypothesis

- pure pseudo-scalar, spin 1 & spin 2 scenarios typically excluded >99.9%
- still room for anomalous interactions or CP violation

Fiducial Volumes

H→ZZ

ATLAS

Leptons and jets	
Muons:	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.47$
Jets:	$p_T > 30$ GeV, $\|y\| < 4.4$
Jet-lepton overlap removal:	$\Delta R(\text{jet}, \ell) > 0.1\,(0.2)$ for muons (electrons)
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per channel)	
Mass requirements:	$50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1\,(0.2)$ for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115\ GeV < m_{4\ell} < 130$ GeV

CMS

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Subleading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7\,(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5\,(2.4)$
Sum p_T of all stable particles within $\Delta R < 0.3$ from lepton	$<0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Invariant mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell'^-} > 4$ GeV
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

H→γγ

ATLAS

Objects	Definition
Photons	$\|\eta\| < 1.37$ OR $1.52 < \|\eta\| < 2.37$, $p_T^{\text{iso},0.2}/p_T^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_T > 30$ GeV, $\|y\| < 4.4$
Leptons, ℓ	e or μ, $p_T > 15$ GeV, $\|\eta\| < 2.47$ (excluding $1.37 < \|\eta\| < 1.52$ for $\ell = e$)

Fiducial region	Definition
Diphoton fiducial	$N_\gamma \geq 2$, $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$, $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$
VBF-enhanced	Diphoton fiducial, $N_j \geq 2$, $m_{jj} > 400$ GeV, $\|\Delta y_{jj}\| > 2.8$, $\|\Delta\phi_{\gamma\gamma,jj}\| > 2.6$
$N_{\text{lepton}} \geq 1$	Diphoton fiducial, $N_\ell \geq 1$
High E_T^{miss}	Diphoton fiducial, $E_T^{\text{miss}} > 80$ GeV, $p_T^{\gamma\gamma} > 80$ GeV
$t\bar{t}H$-enhanced	Diphoton fiducial, $(N_j \geq 4, N_{\text{b-jets}} \geq 1)$ OR $(N_j \geq 3, N_{\text{b-jets}} \geq 1, N_\ell \geq 1)$

CMS

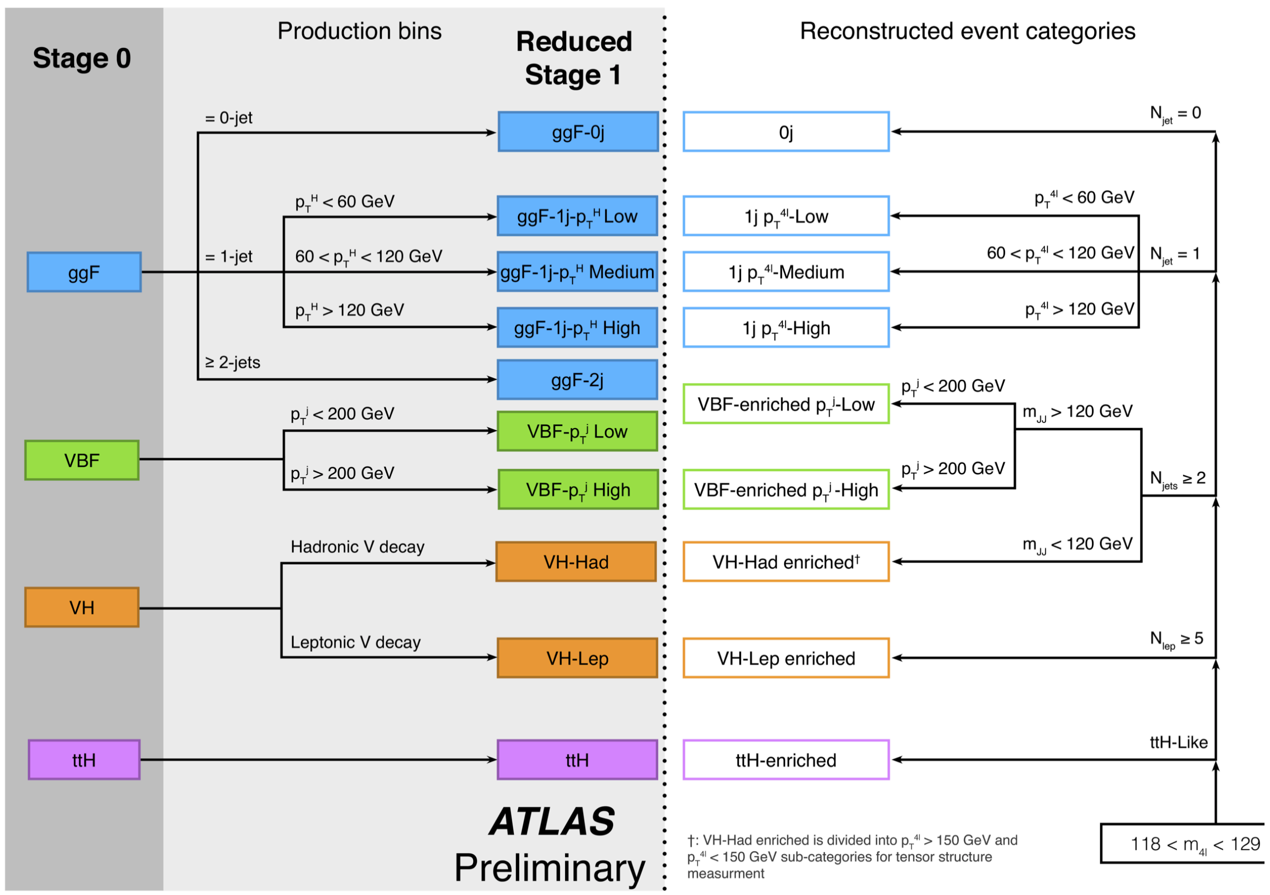
CMS H→γγ

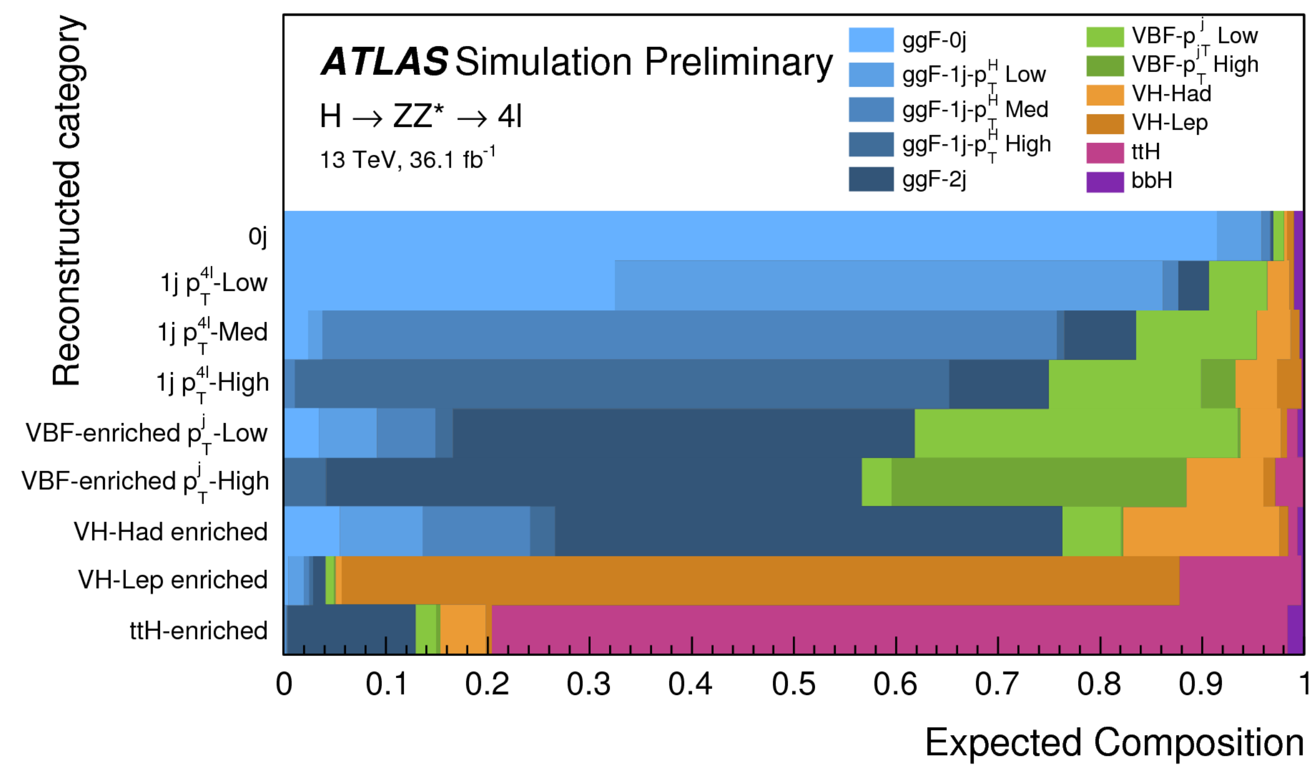
$p_T^{1(2)}/m_{\gamma\gamma} > 1/3\ (1/4)$

$|\eta_\gamma^{1(2)}| < 2.5$

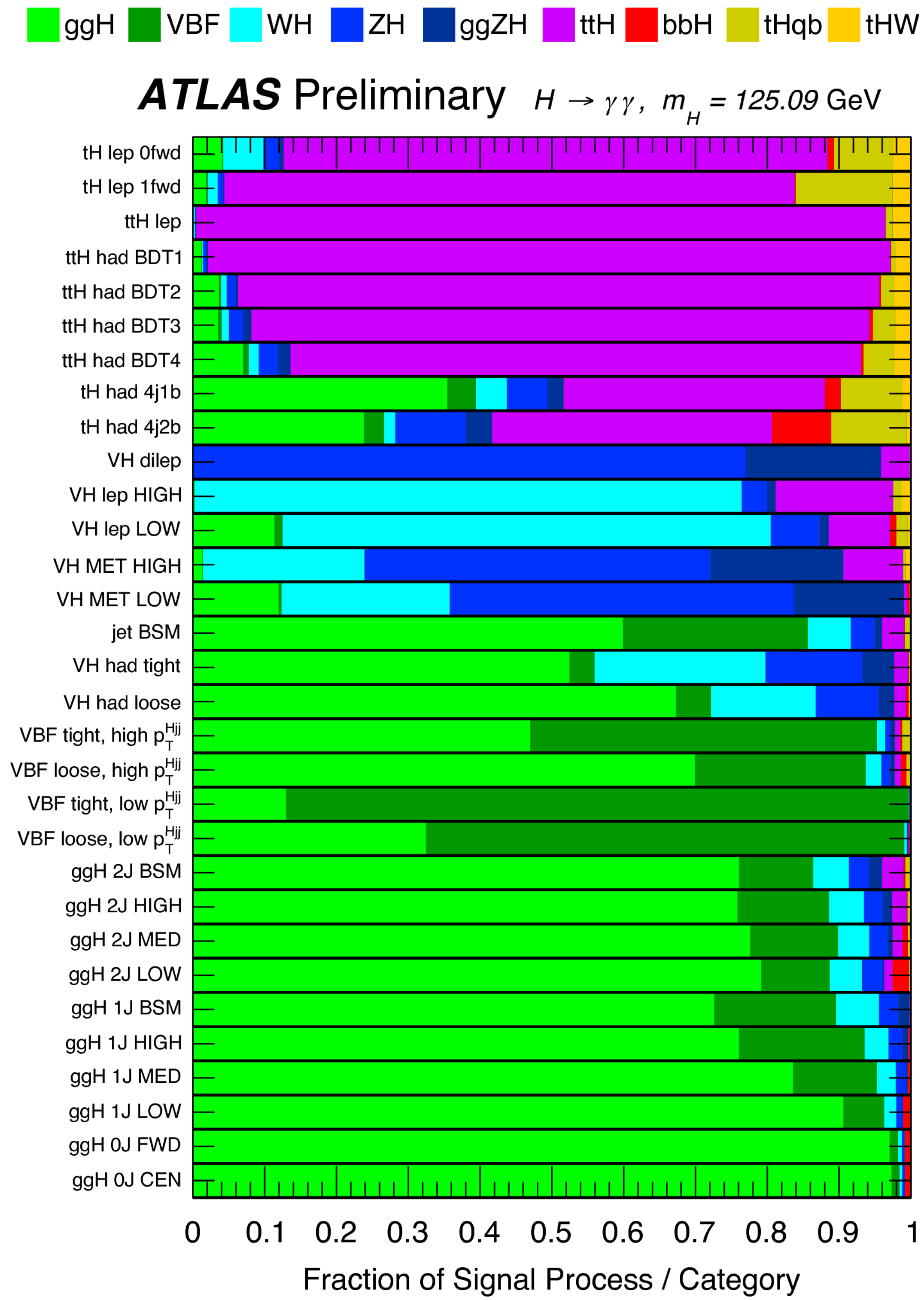
$E_{iso} < 10$ GeV $\Delta R = 0.3$

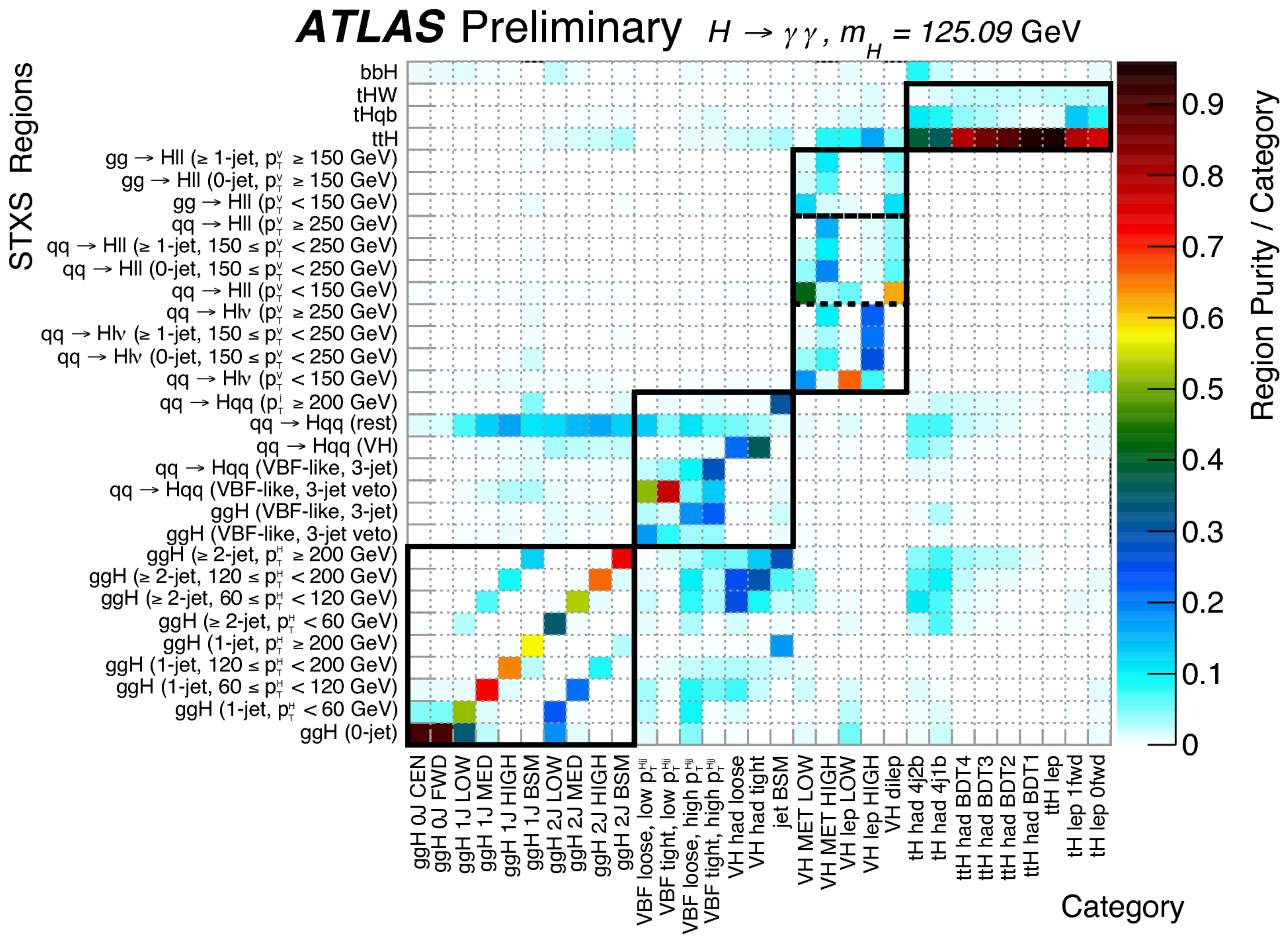
H→ZZ: EVENT CATEGORIES



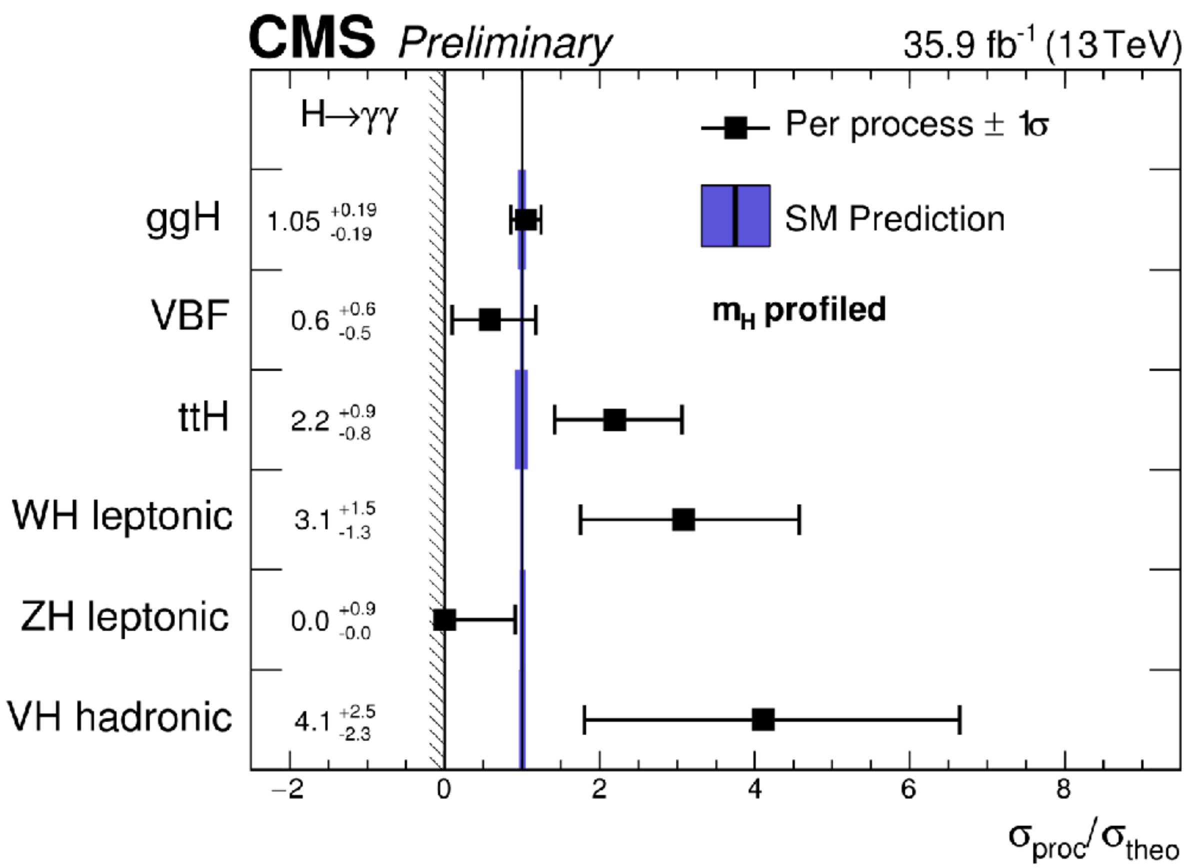


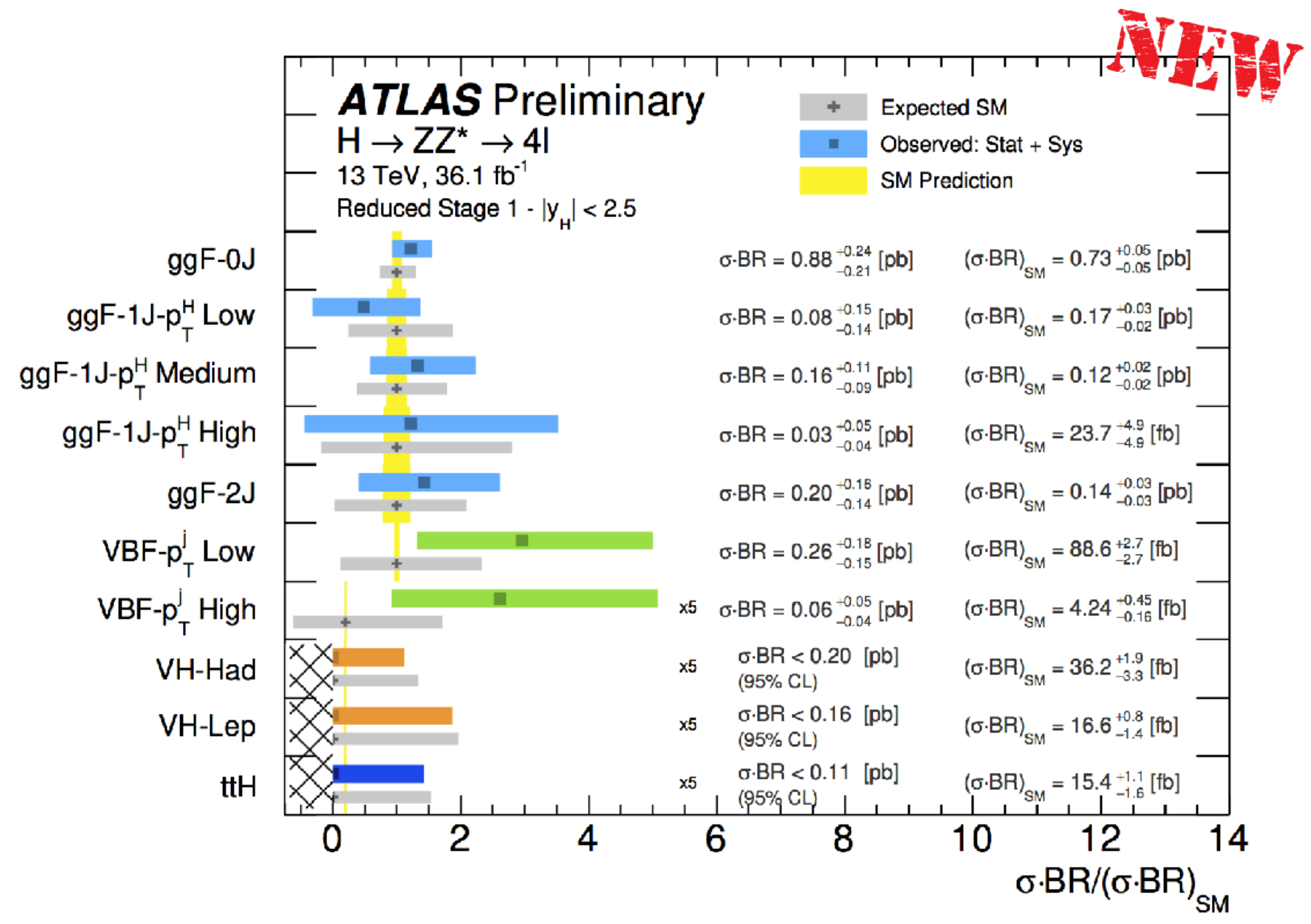
H→γγ: Event Categories





Cross Sections By Production Modes



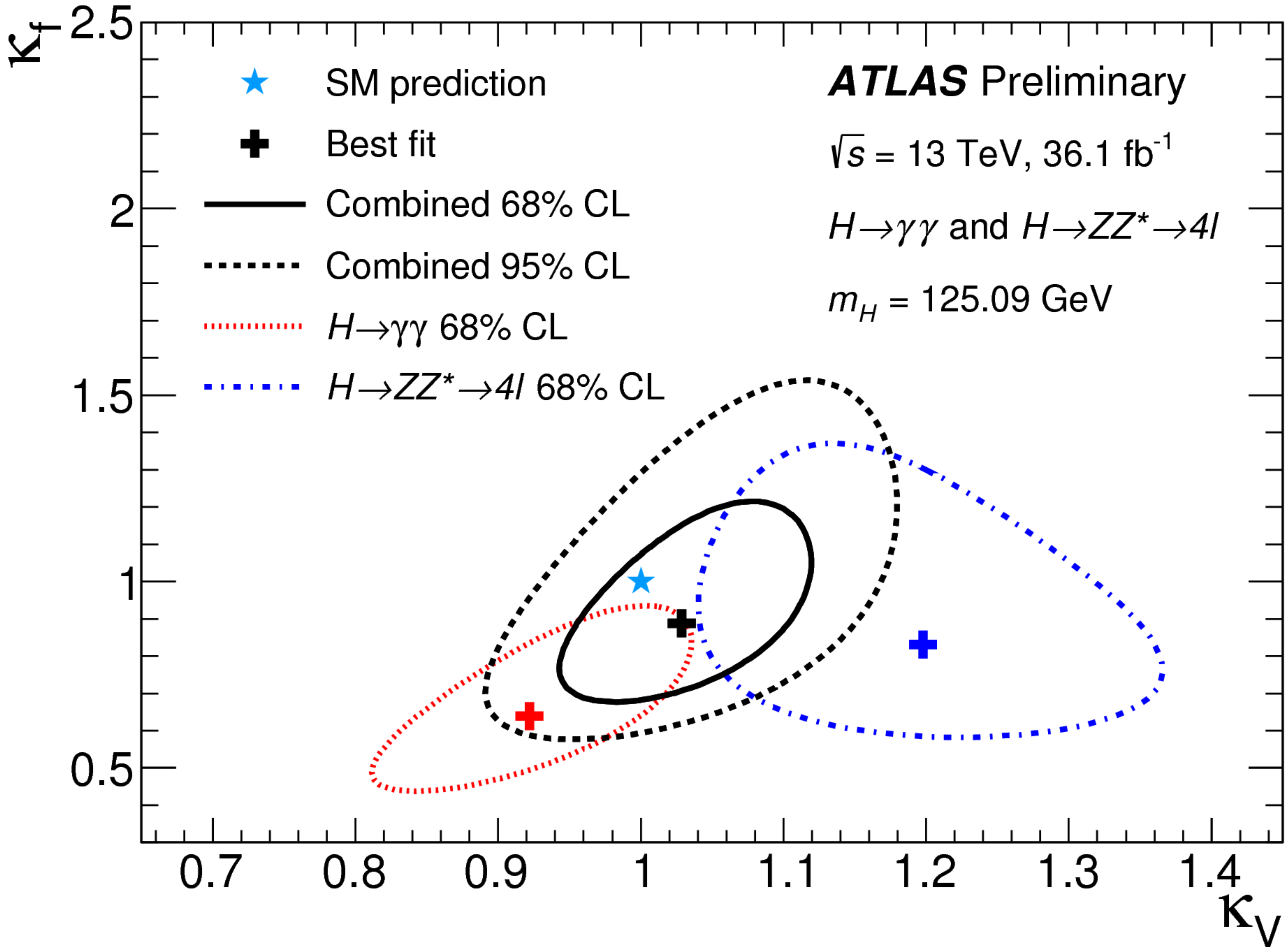


H→γγ, H→ZZ split events into several categories

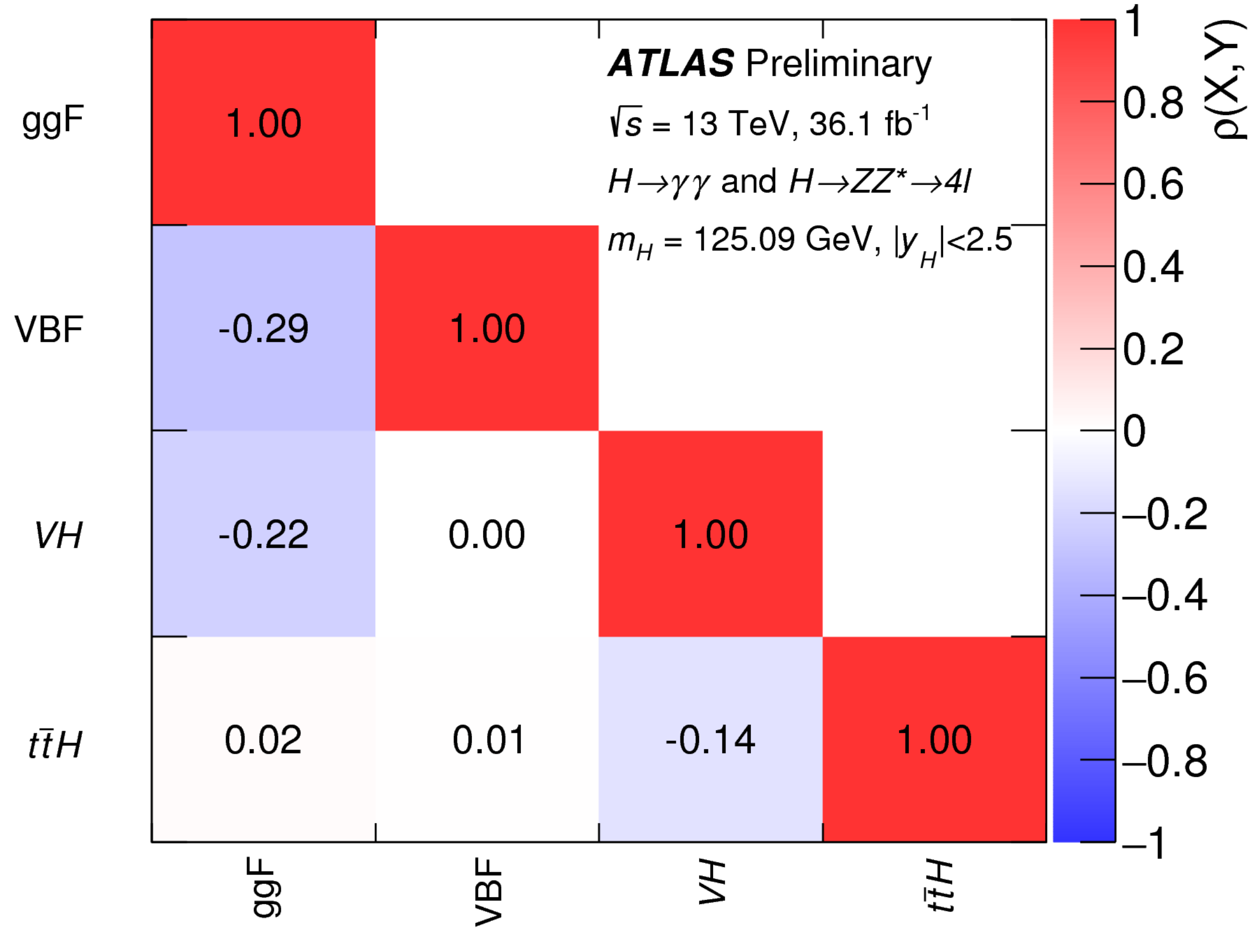
associated production modes (additional jets, leptons)

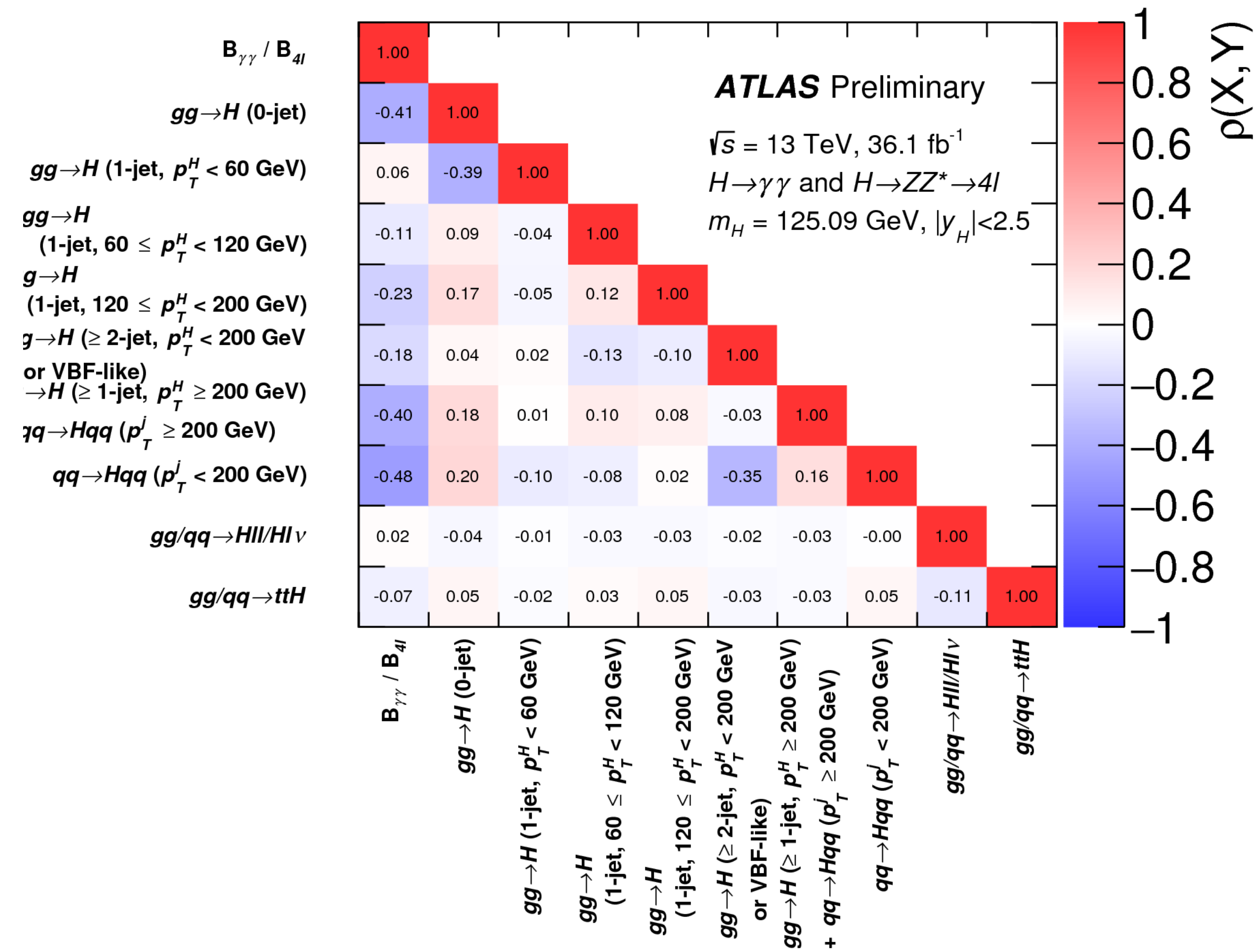
different kinematics region (vs $p_T(H)$, $p_T(jet)$)

H→ZZ + H→γγ: Couplings



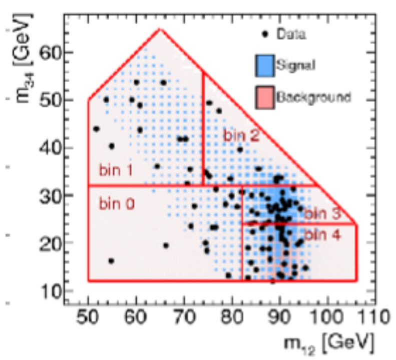
H→ZZ + H→γγ: Correlations

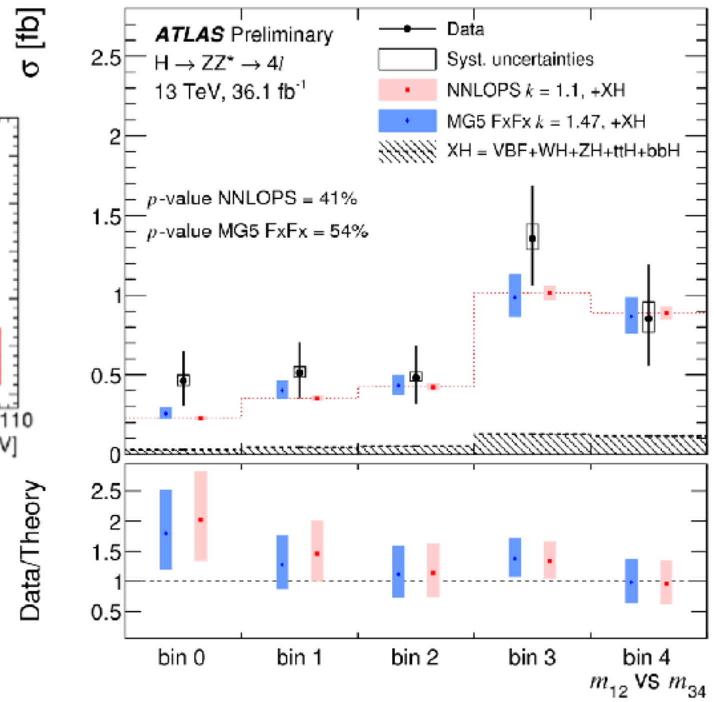




$H \rightarrow ZZ \rightarrow 4L$: Anomalous Couplings

ATLAS-CONF-2017-032



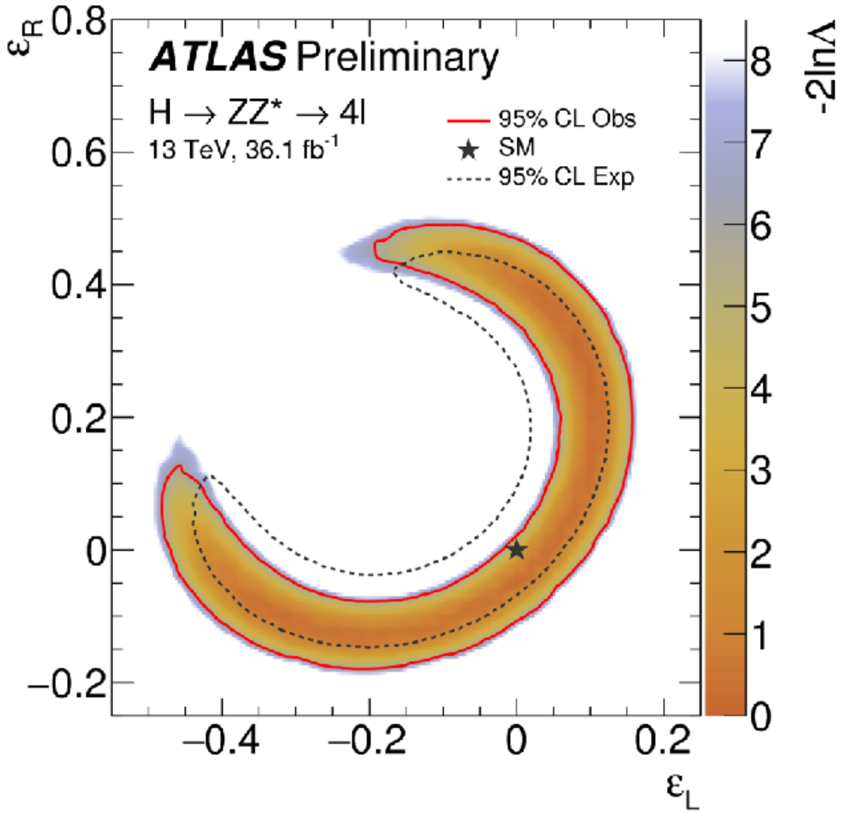


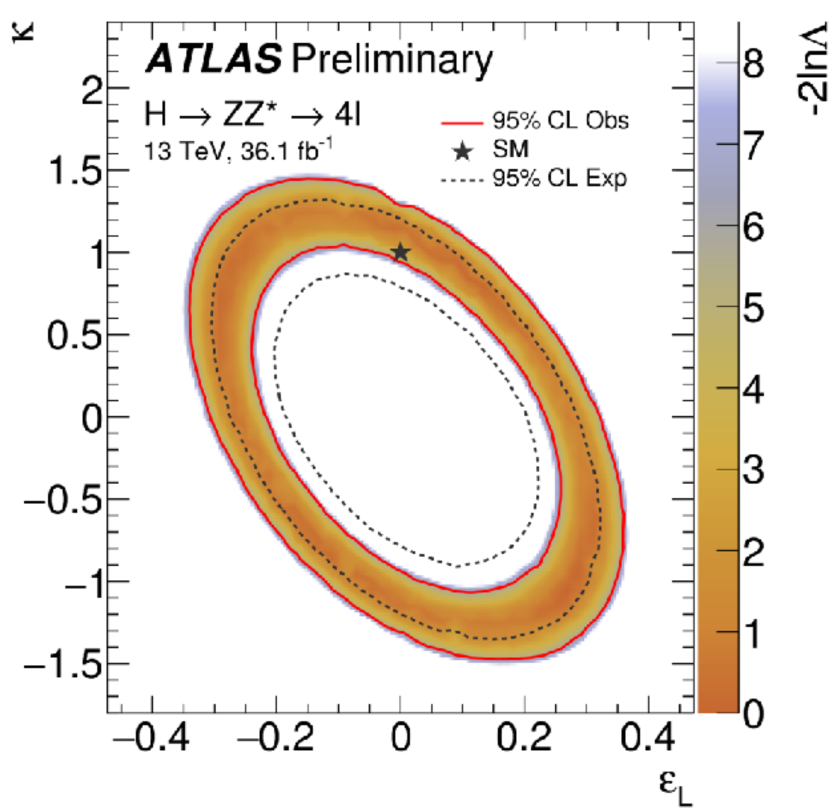
Example: constraints on anomalous couplings in $h \rightarrow 4l$ from differential cross-sections

ε_L, ε_R : regulate contact interactions with left, right-handed leptons (assumed flavour universal) [Eur. Phys. J. C75 (2015) 128]

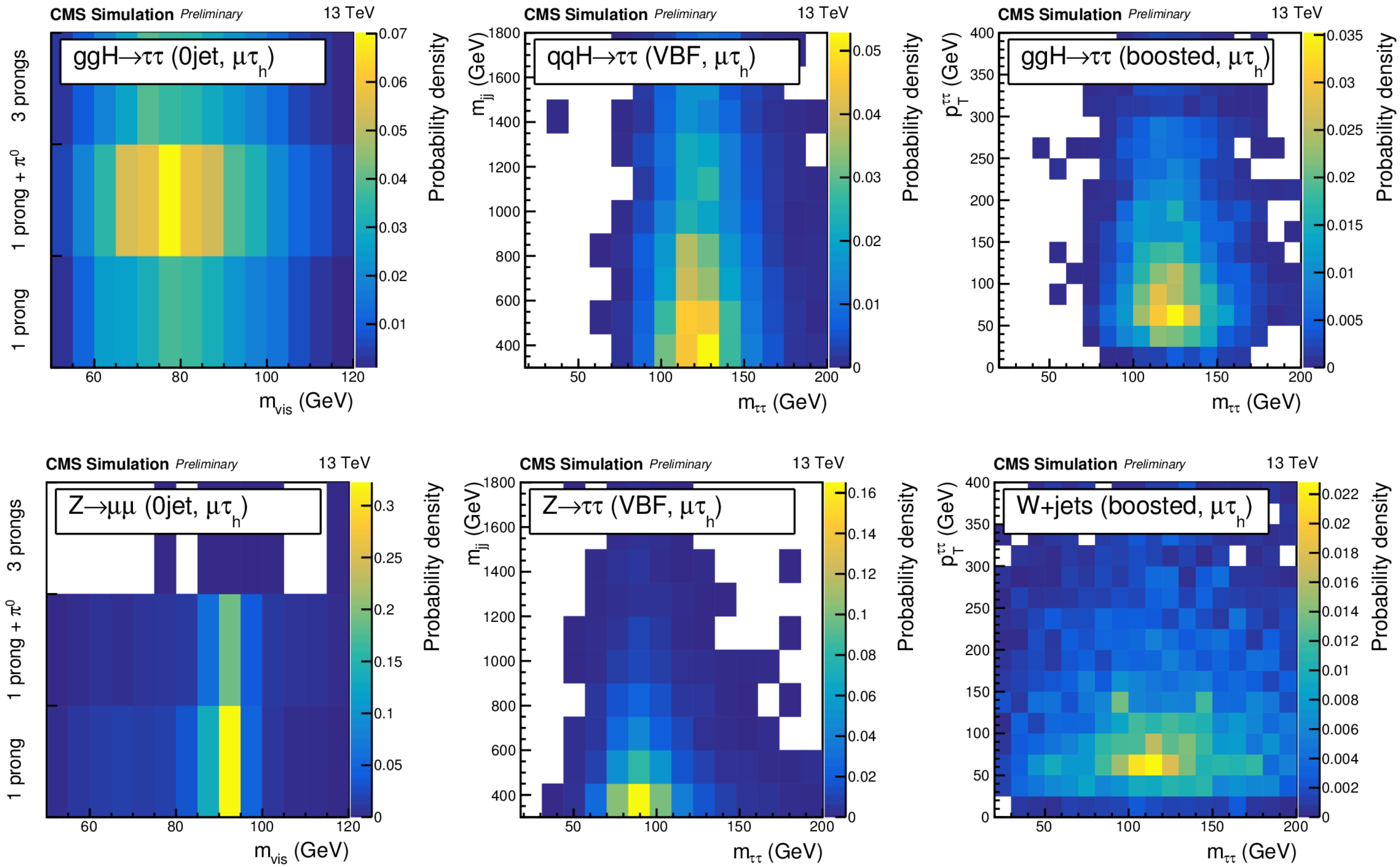
expect changes in overall signal strength + di-lepton invariant mass (m_{12} vs m_{34})

Limits in the plane ε_L vs ε_R and ε_L vs κ_Z

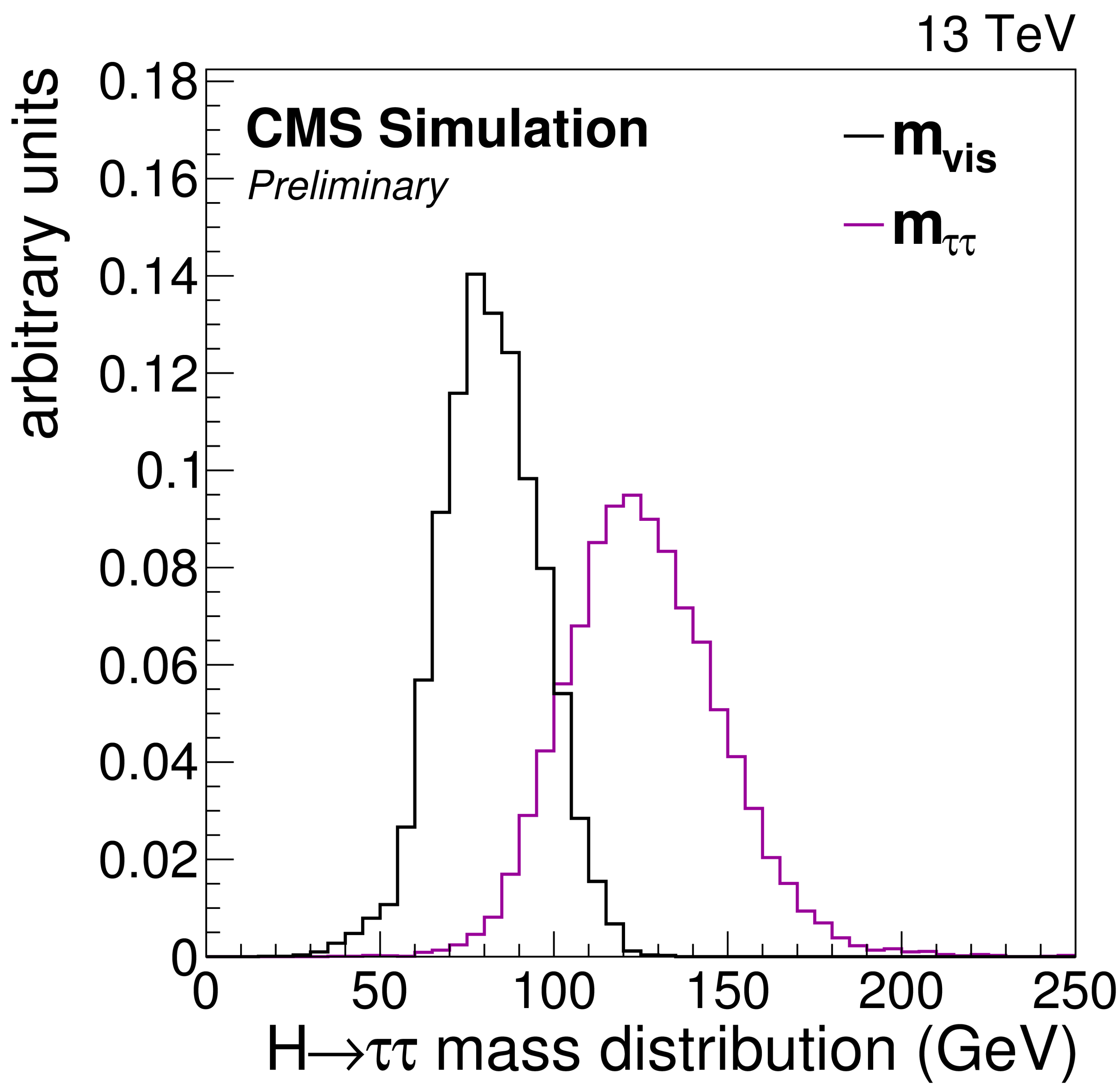




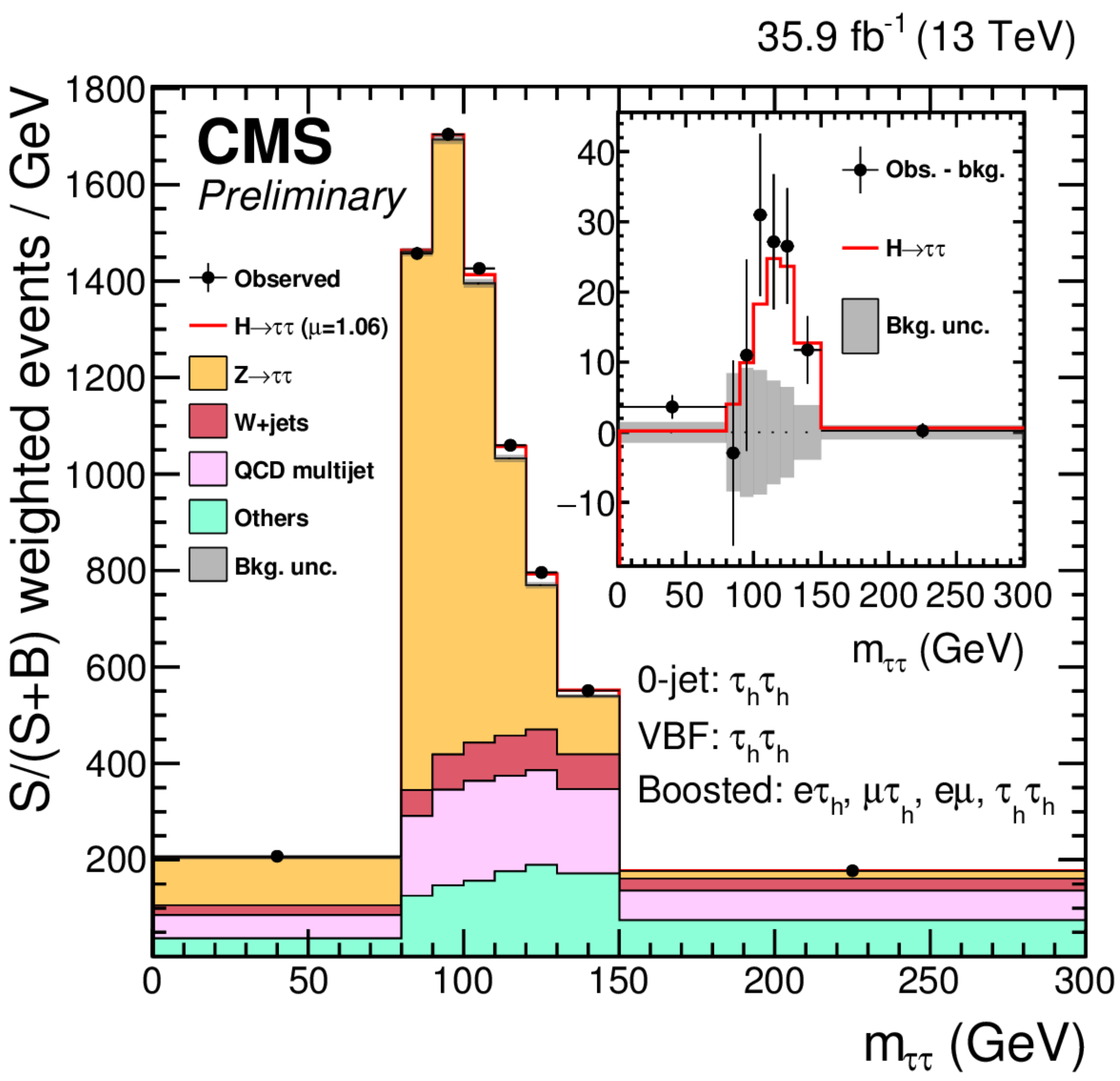
$H \rightarrow \tau\tau$

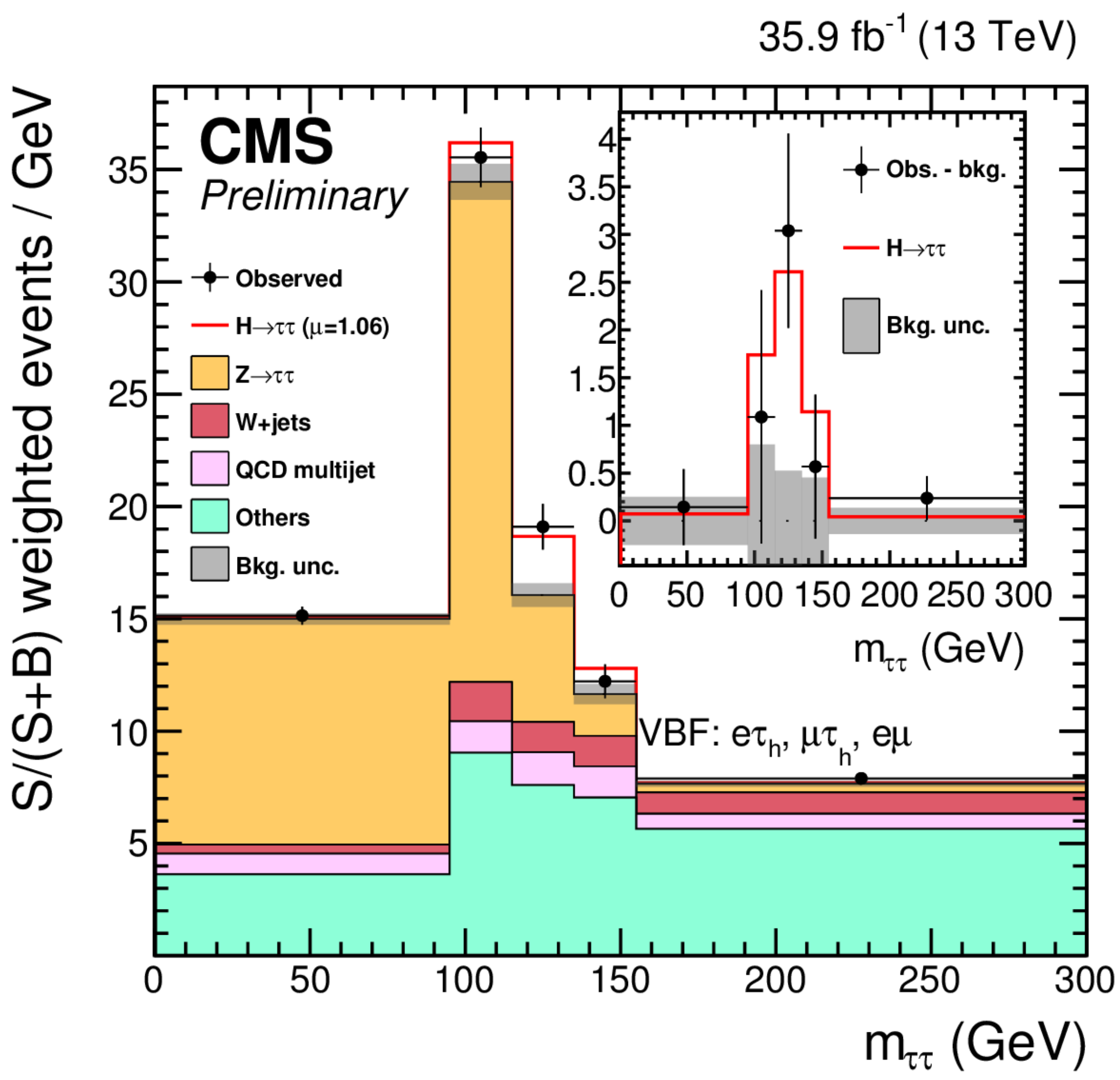


$m\tau\tau$

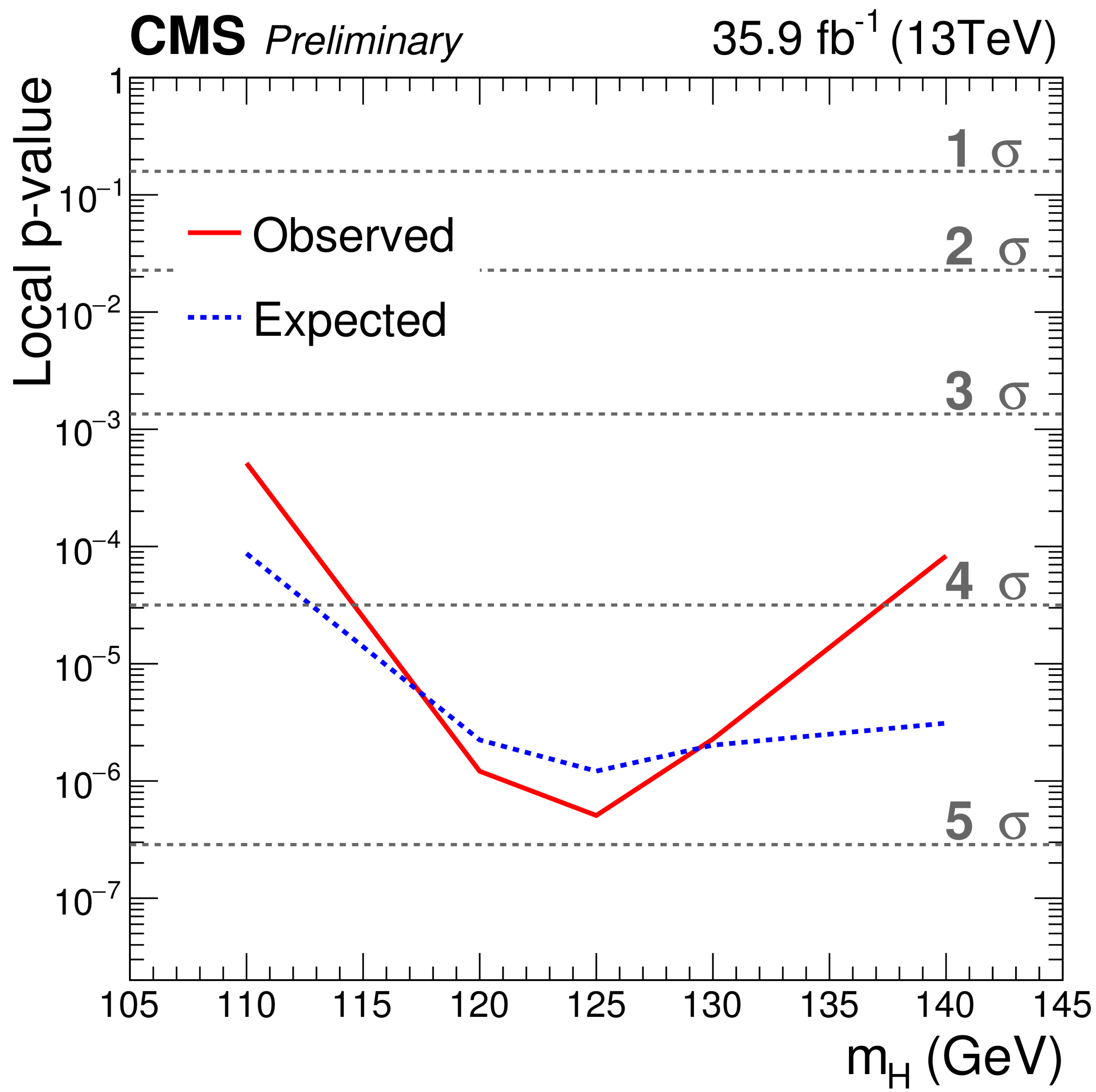

13 TeV
CMS Simulation
Preliminary
m_{vis}
$m_{\tau\tau}$
arbitrary units
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
200
250
H→ττ mass distribution (GeV)

$m_{\tau\tau}$

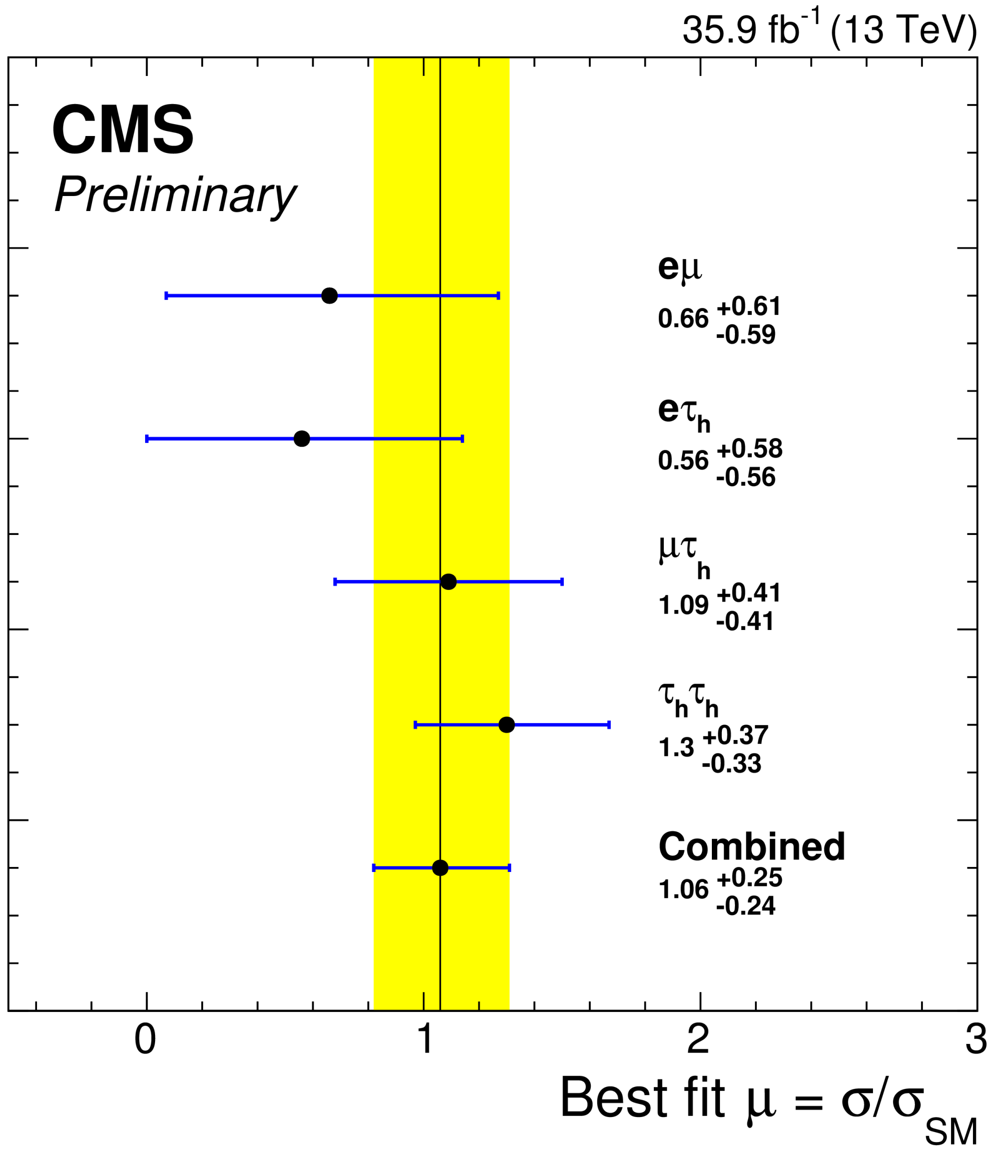

35.9 fb-1 (13 TeV)
CMS
Preliminary
Observed
H→ττ (μ=1.06)
Z→ττ
W+jets
QCD multijet
Others
Bkg. unc.
Obs. - bkg.
H→ττ
Bkg. unc.
0-jet: τhτh
VBF: τhτh
Boosted: eτh, μτh, eμ, τhτh
S/(S+B) weighted events / GeV
mττ (GeV)

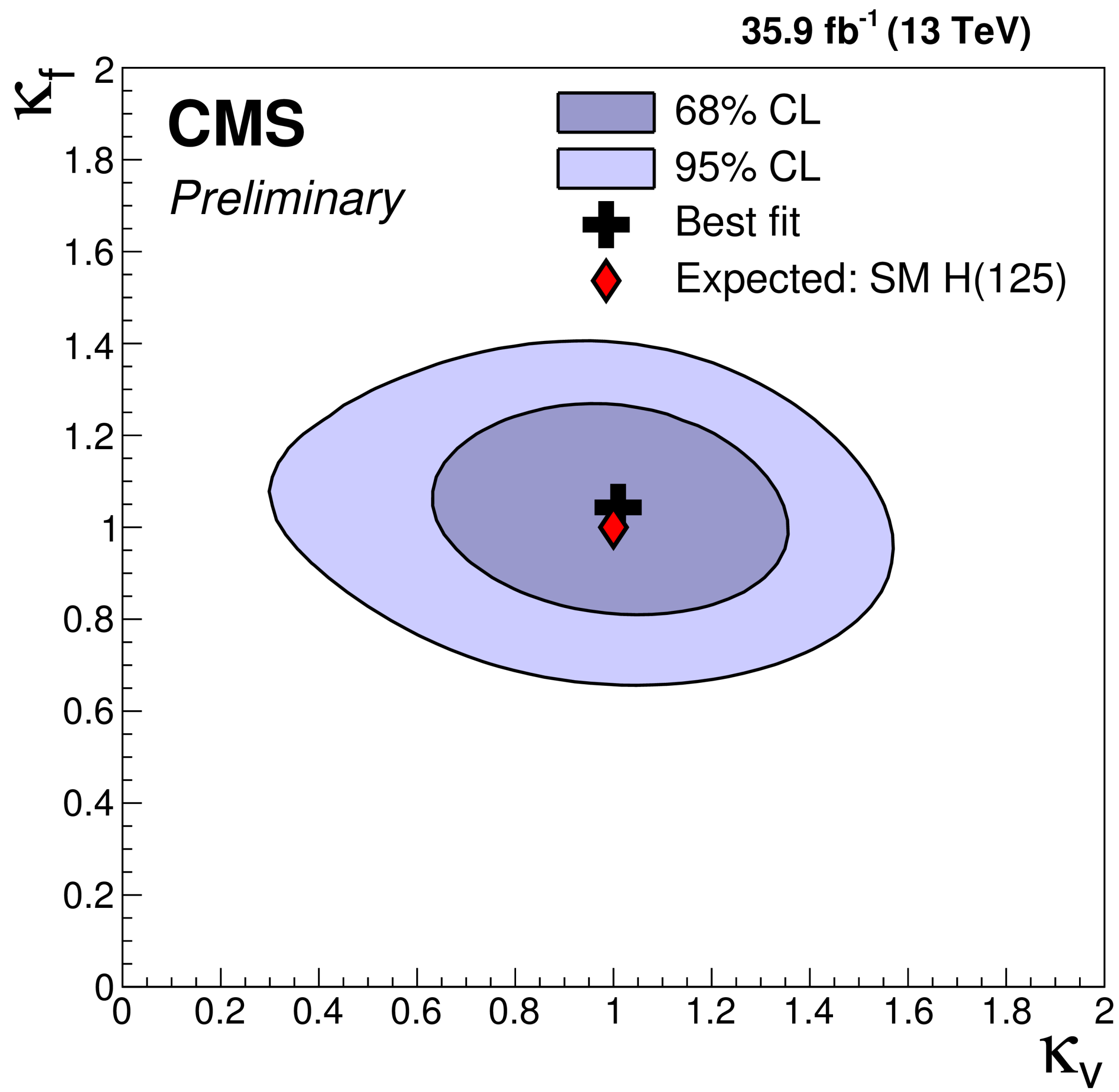

35.9 fb-1 (13 TeV)
CMS
Preliminary
Observed
H→ττ (μ=1.06)
Z→ττ
W+jets
QCD multijet
Others
Bkg. unc.
Obs. - bkg.
H→ττ
Bkg. unc.
VBF: eτh, μτh, eμ
S/(S+B) weighted events / GeV
mττ (GeV)

H→$\tau\tau$: SIGNIFICANCE

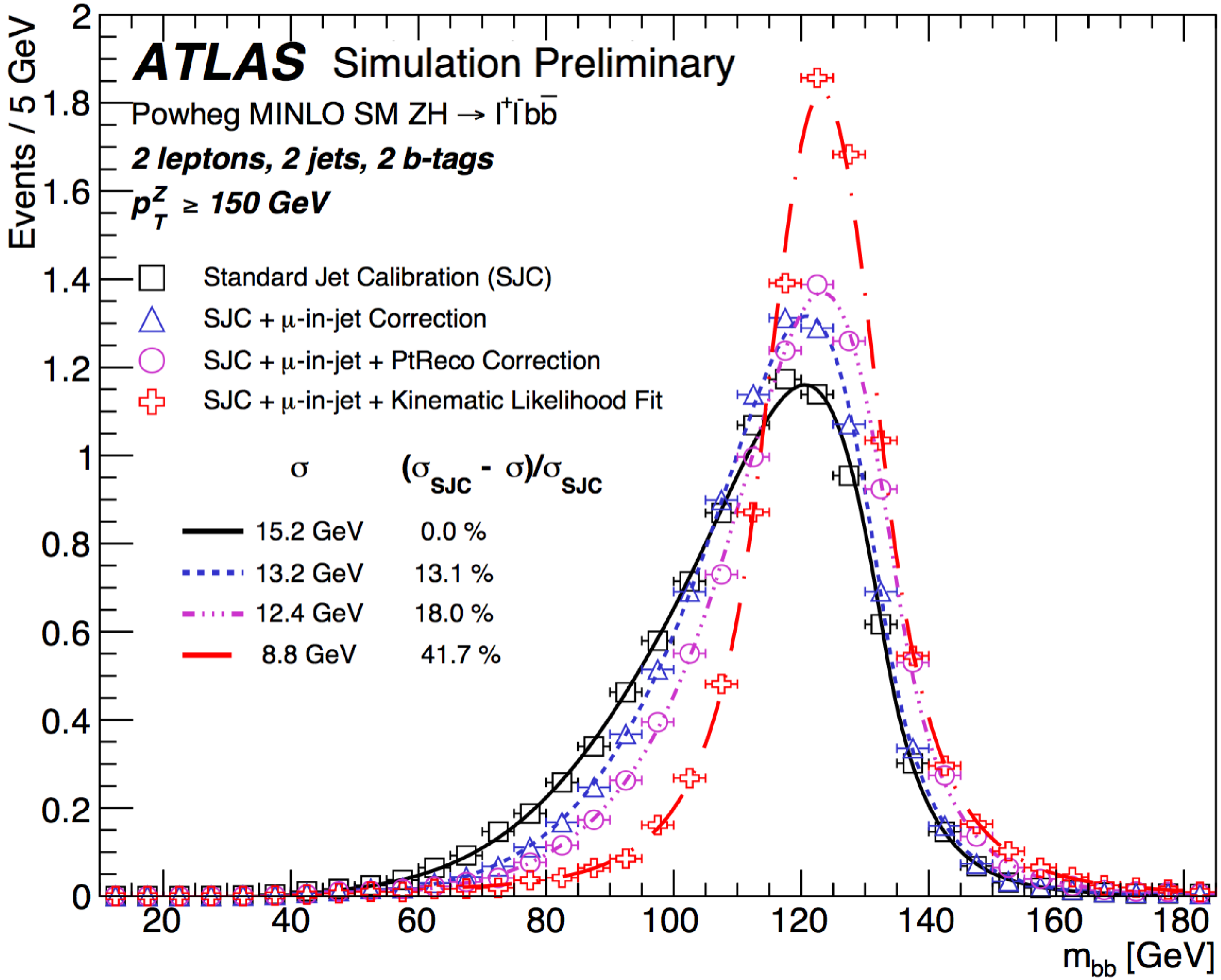


H→ττ: By Channel & κ_V/κ_F

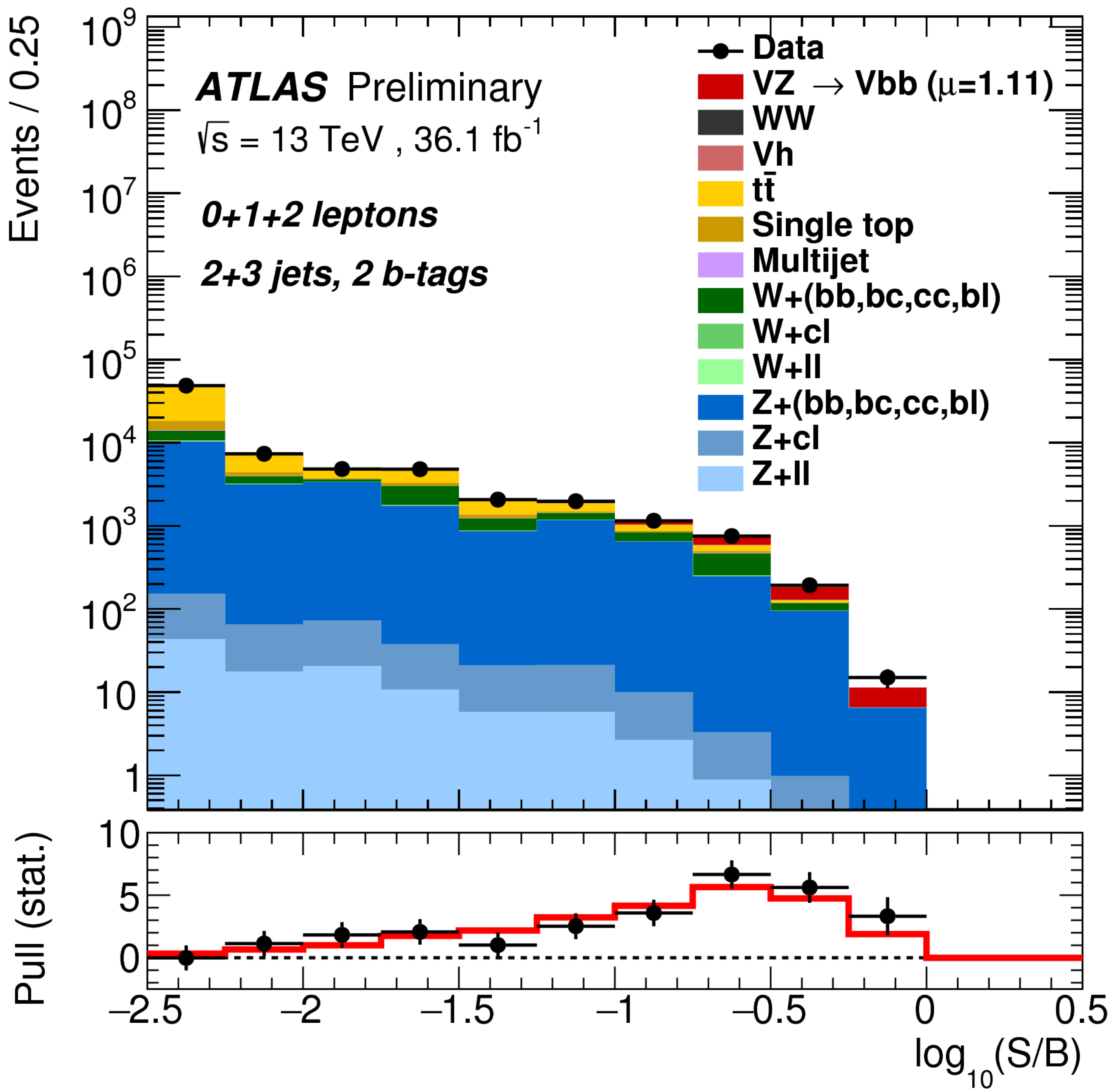


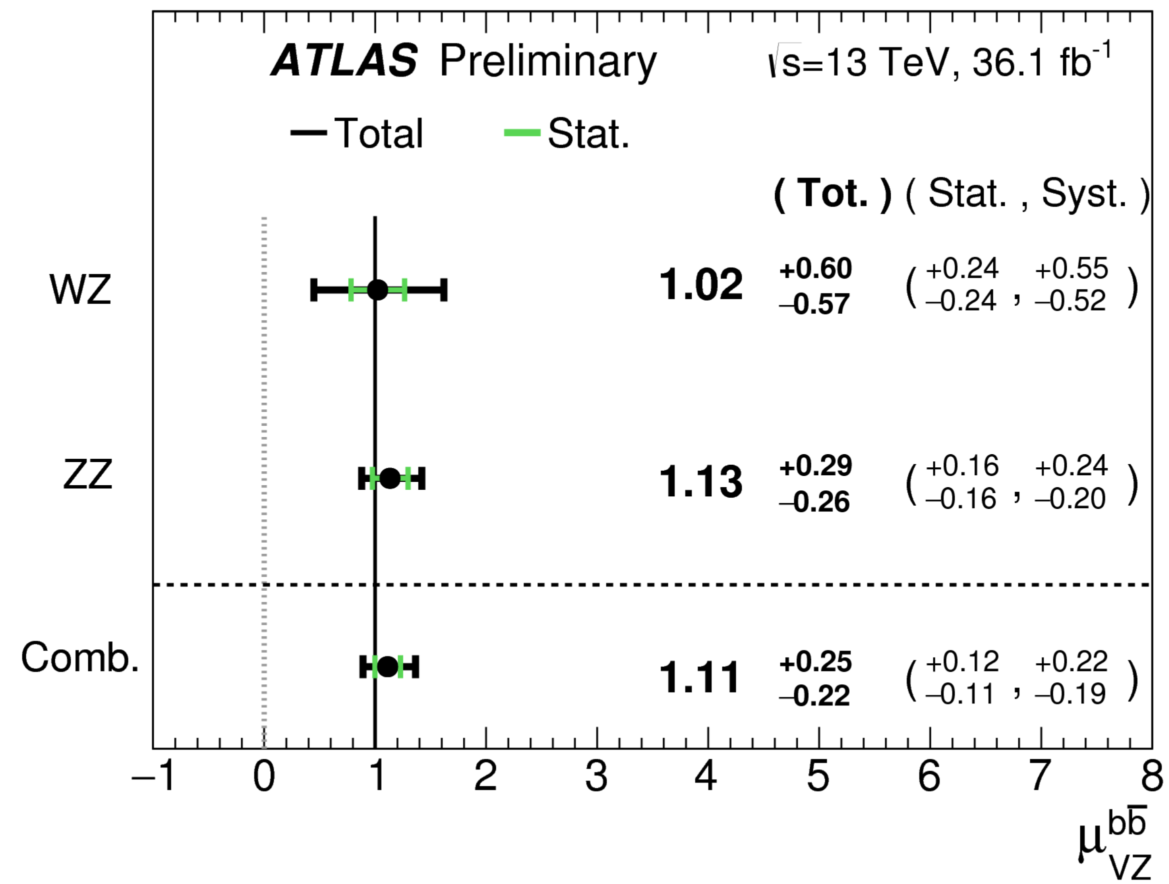


VH(BB): MBB IMPROVEMENTS

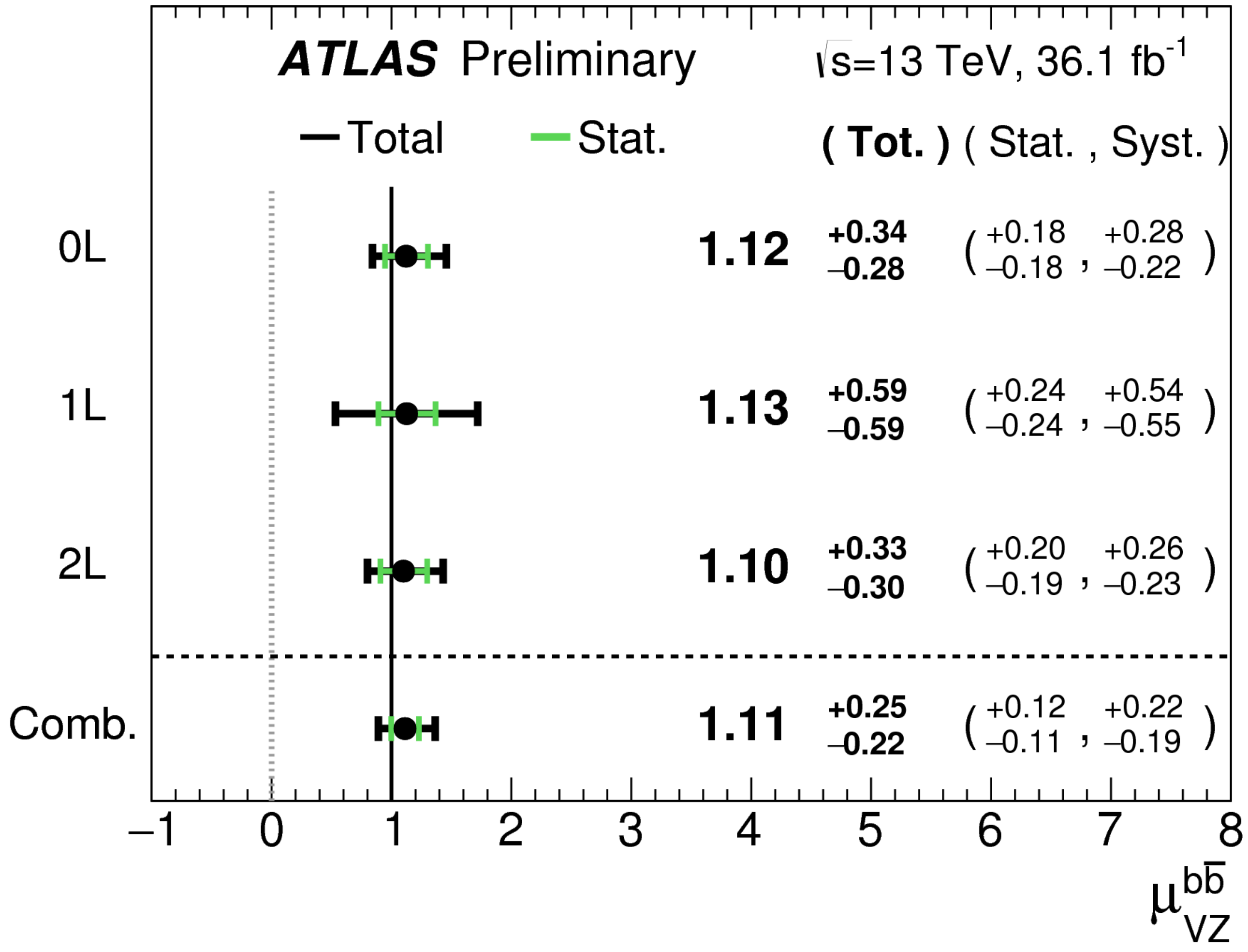


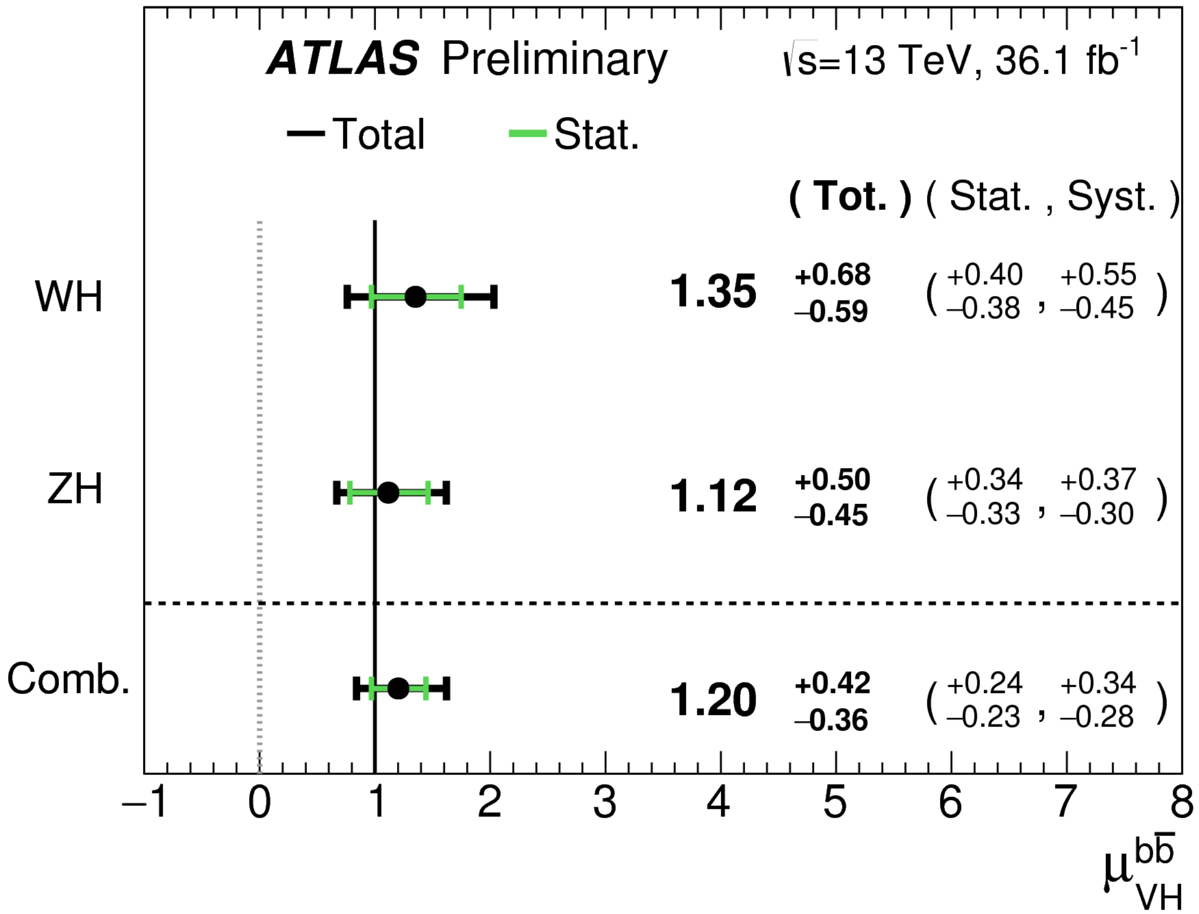
VZ(BB)


ATLAS Preliminary
√s = 13 TeV , 36.1 fb-1
0+1+2 leptons
2+3 jets, 2 b-tags
Data
VZ → Vbb (μ=1.11)
WW
Vh
tt̄
Single top
Multijet
W+(bb,bc,cc,bl)
W+cl
W+ll
Z+(bb,bc,cc,bl)
Z+cl
Z+ll
Events / 0.25
Pull (stat.)
log10(S/B)


ATLAS Preliminary
√s=13 TeV, 36.1 fb-1
Total
Stat.
(Tot.) (Stat. , Syst.)
WZ 1.02 +0.60 −0.57 (+0.24 −0.24 , +0.55 −0.52)
ZZ 1.13 +0.29 −0.26 (+0.16 −0.16 , +0.24 −0.20)
Comb. 1.11 +0.25 −0.22 (+0.12 −0.11 , +0.22 −0.19)
μVZ bb̄

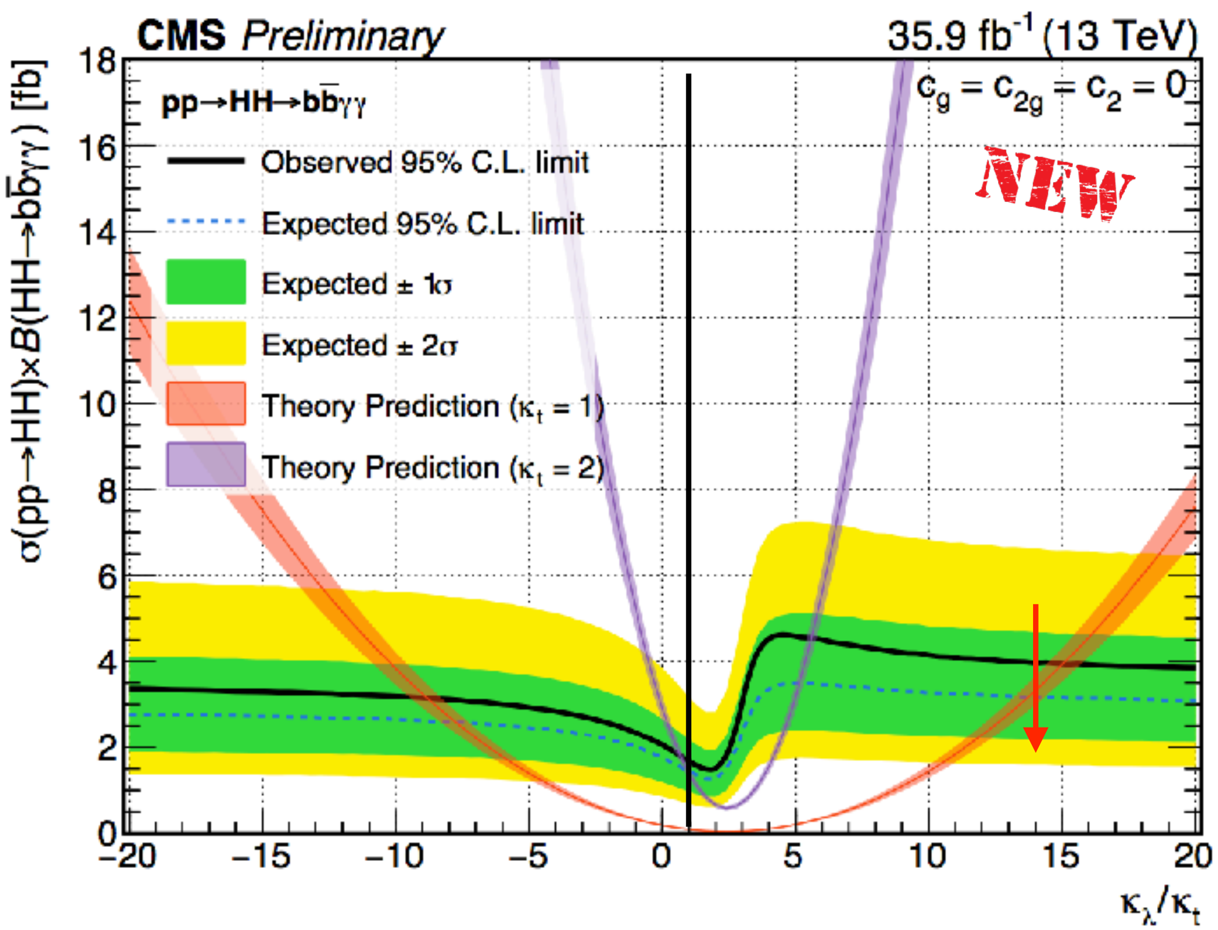
H→BB: CHANNELS





HH→bbγγ

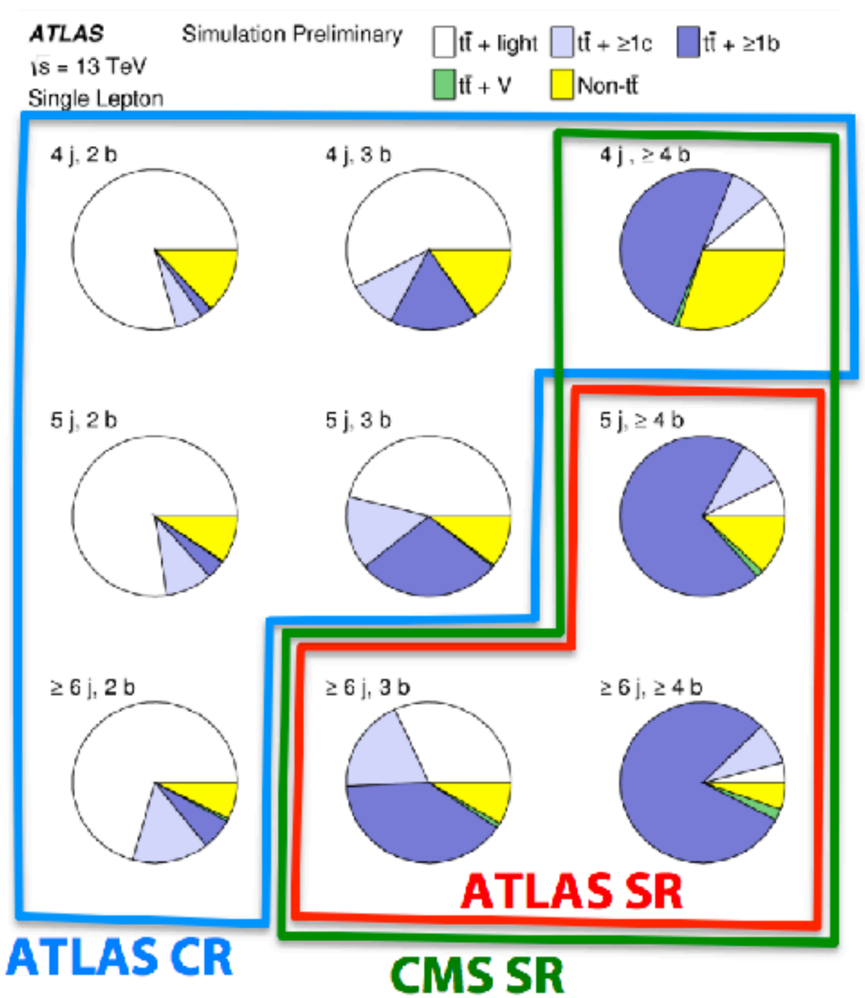
CMS HIG-17-008



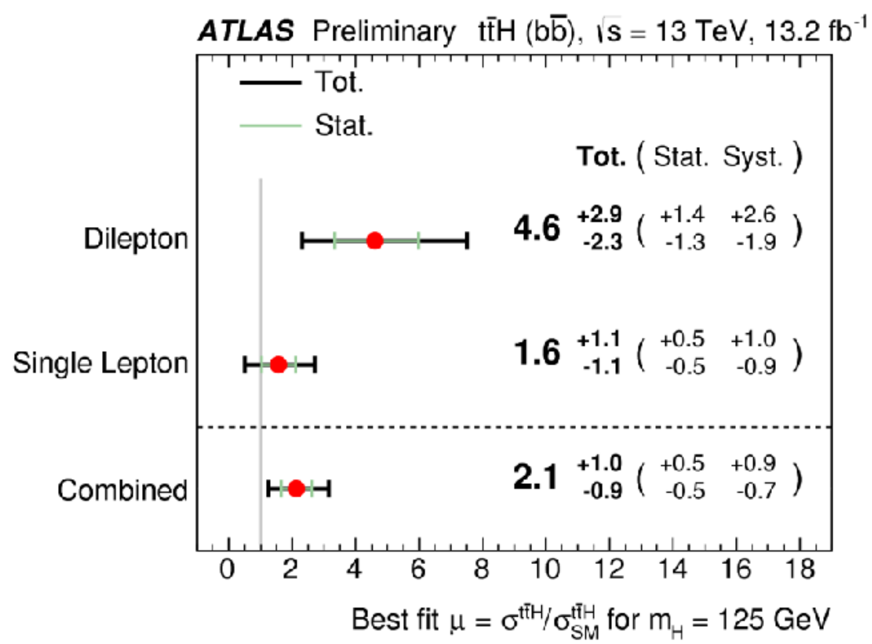
bbγγ most sensitive channel:
limit on σ(HH) <19 σ/σ_{SM} @ 95% CL

self-coupling modifier $k_\lambda(k_{t=1})$ ϵ [-8.8,15]

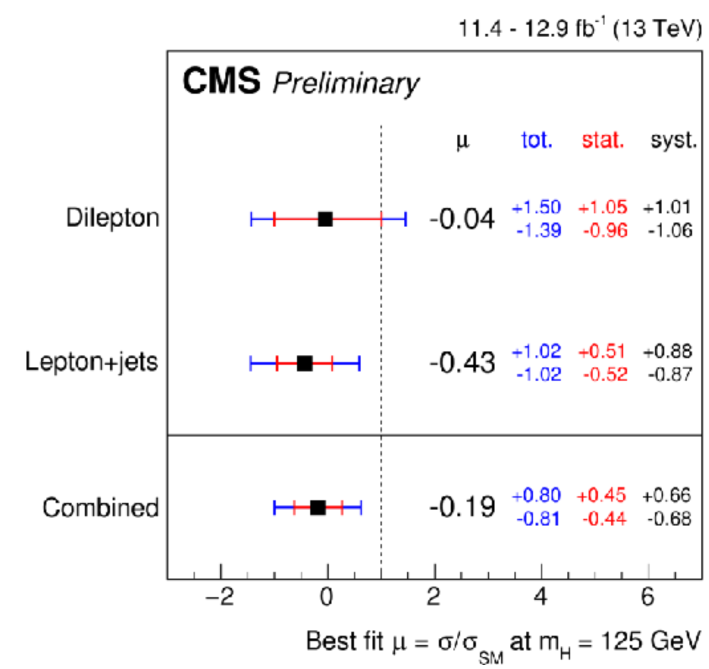
TTH(BB)



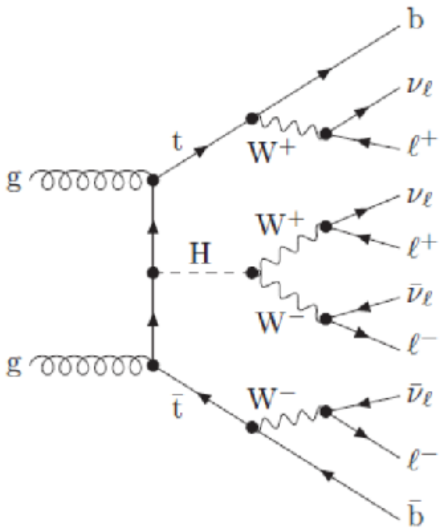
ATLAS-CONF-2016-080



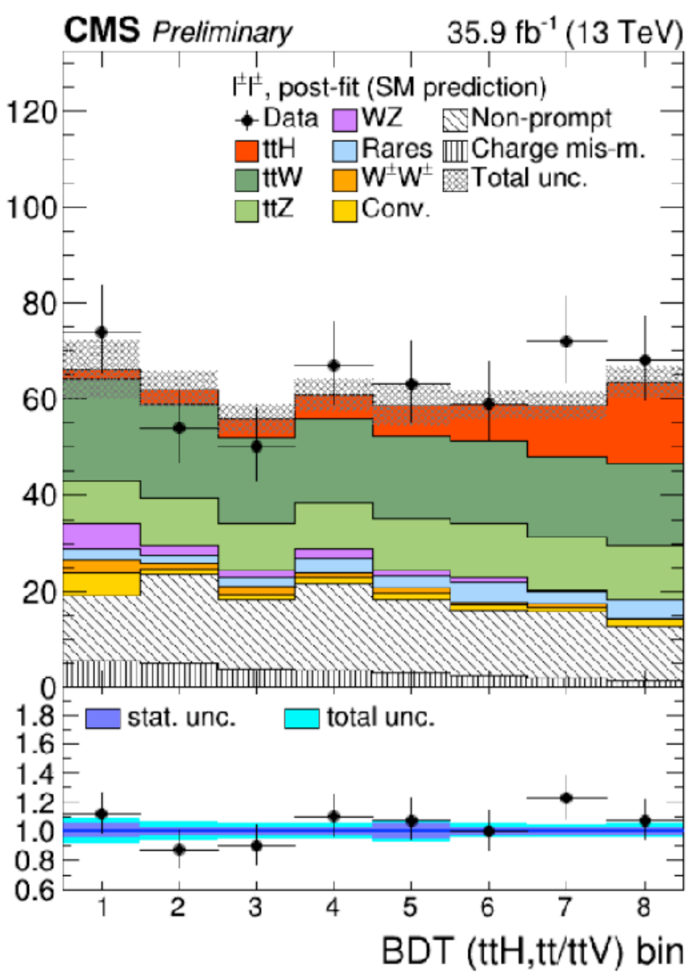
CMS HIG-16-038



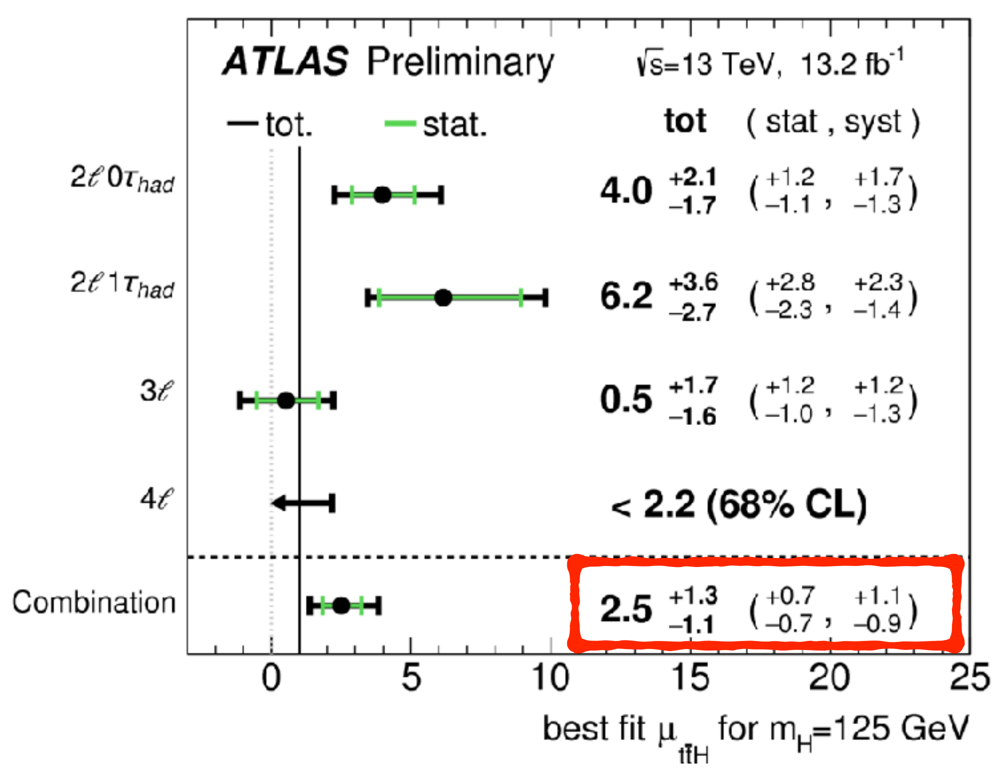
TTH MULTILEPTON



ttH(multilepton): target H→WW,ZZ,$\tau_\ell\tau_\ell$
Select events with $\ell^\pm\ell^\pm$ or ≥3ℓ + additional jets and b-jets
Residual background: tt+(W,Z,γ*) + reducible tt+jets
ATLAS: counting experiment
CMS: 2D BDT to discriminate from tt and tt+V

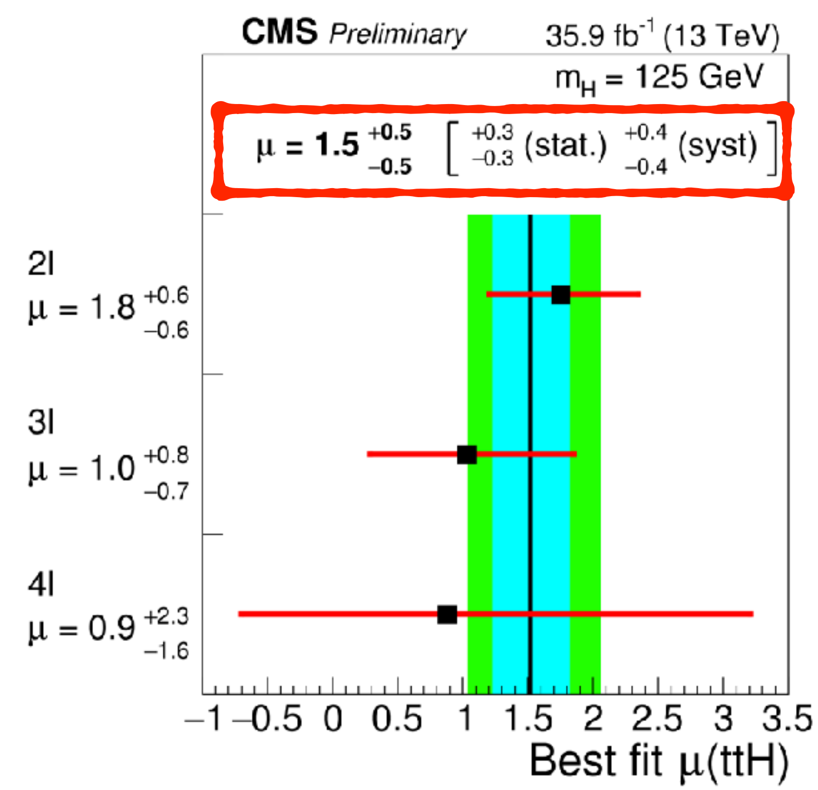


ATLAS-CONF-2016-058



2.2σ (exp. 1σ)

CMS HIG-17-004



3.3σ (exp. 2.5σ)