New physics and flavour high-p_T

Markus Cristinziani
Universität Bonn & CERN

CKM 2018, Heidelberg, Sept. 17 – 21, 2018

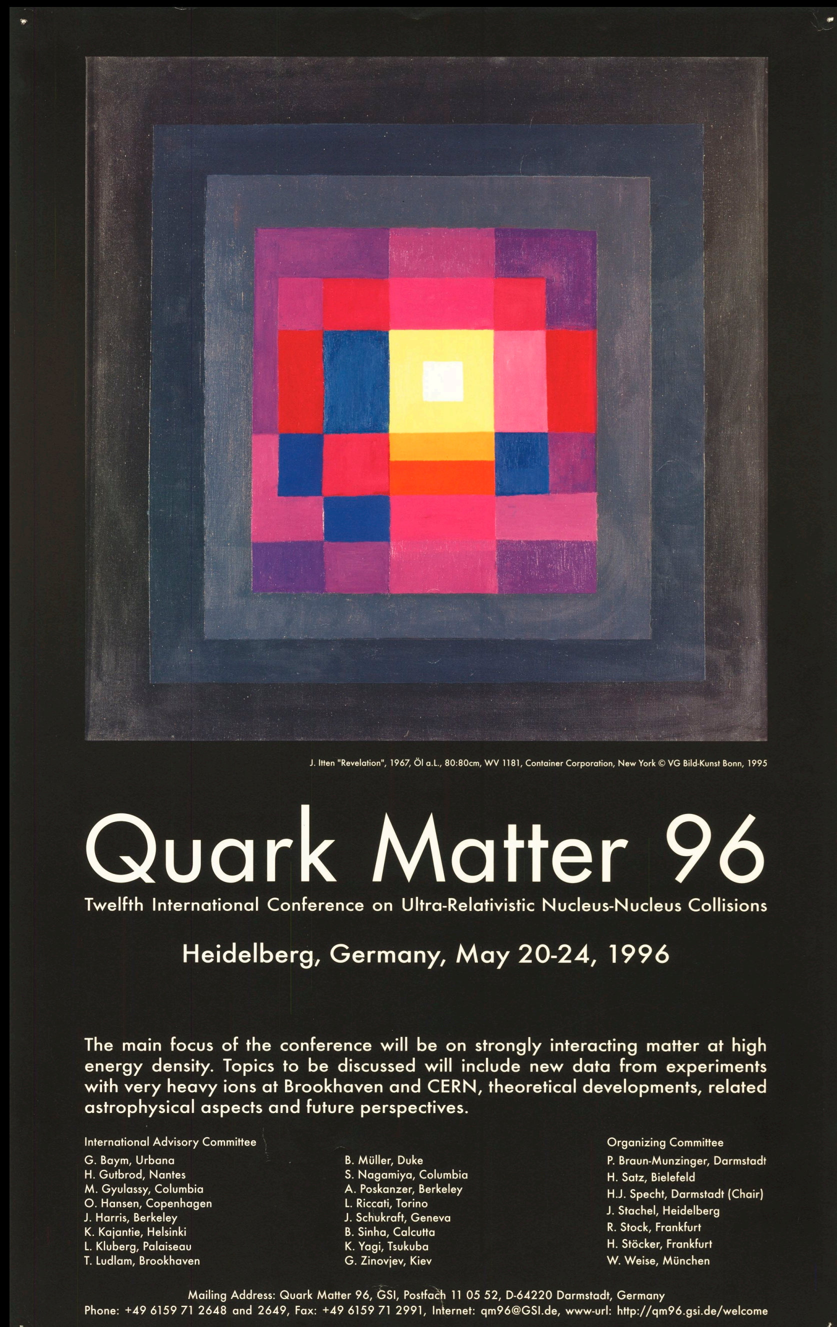
UNIVERSITÄT BONN

European Research Council

CERN

Great to be in Heidelberg !

QM'96: my first conference



Great to be at a CKM workshop !

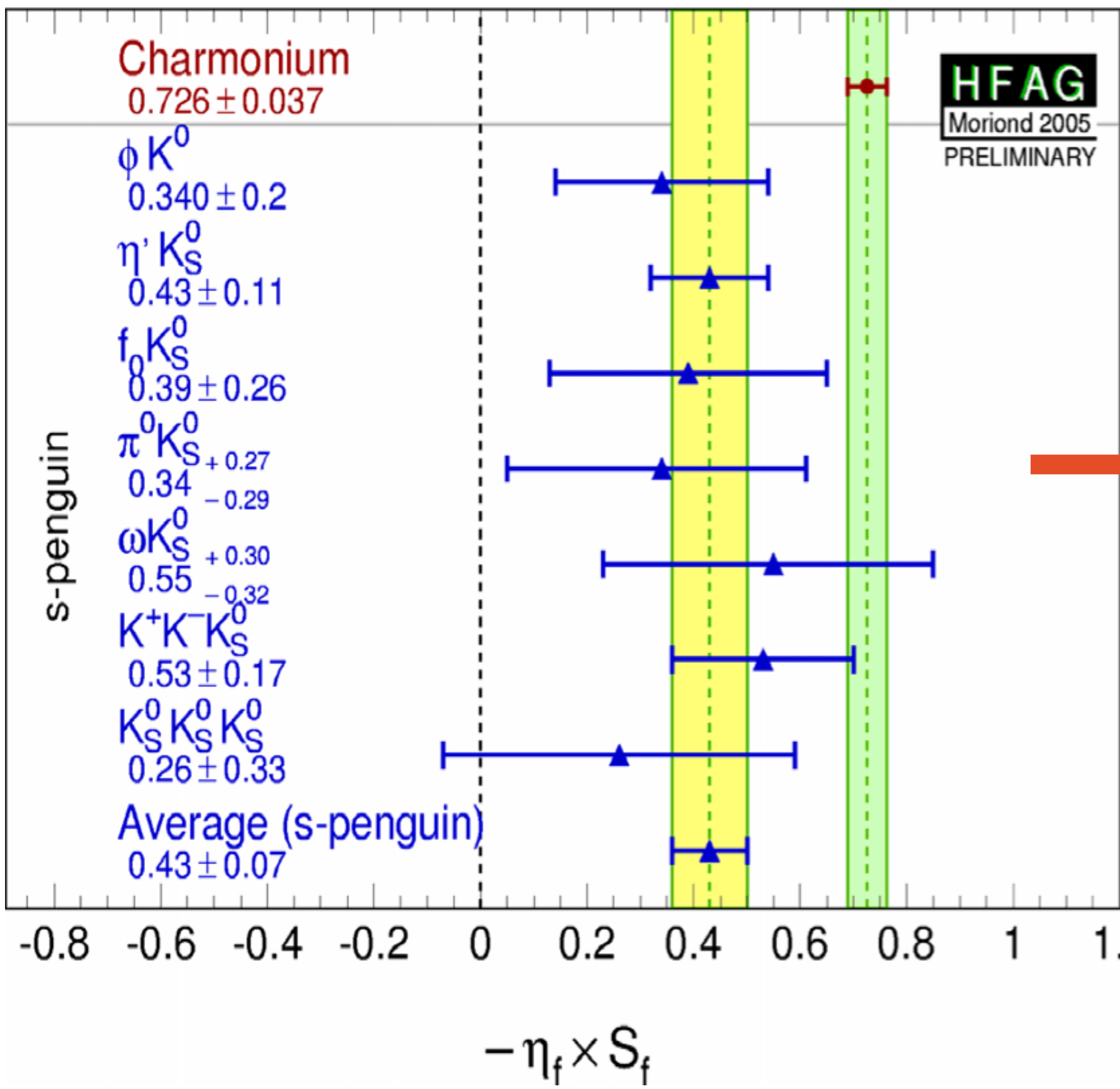
There has never been a more **exciting time** for "high-p_T flavour physics"

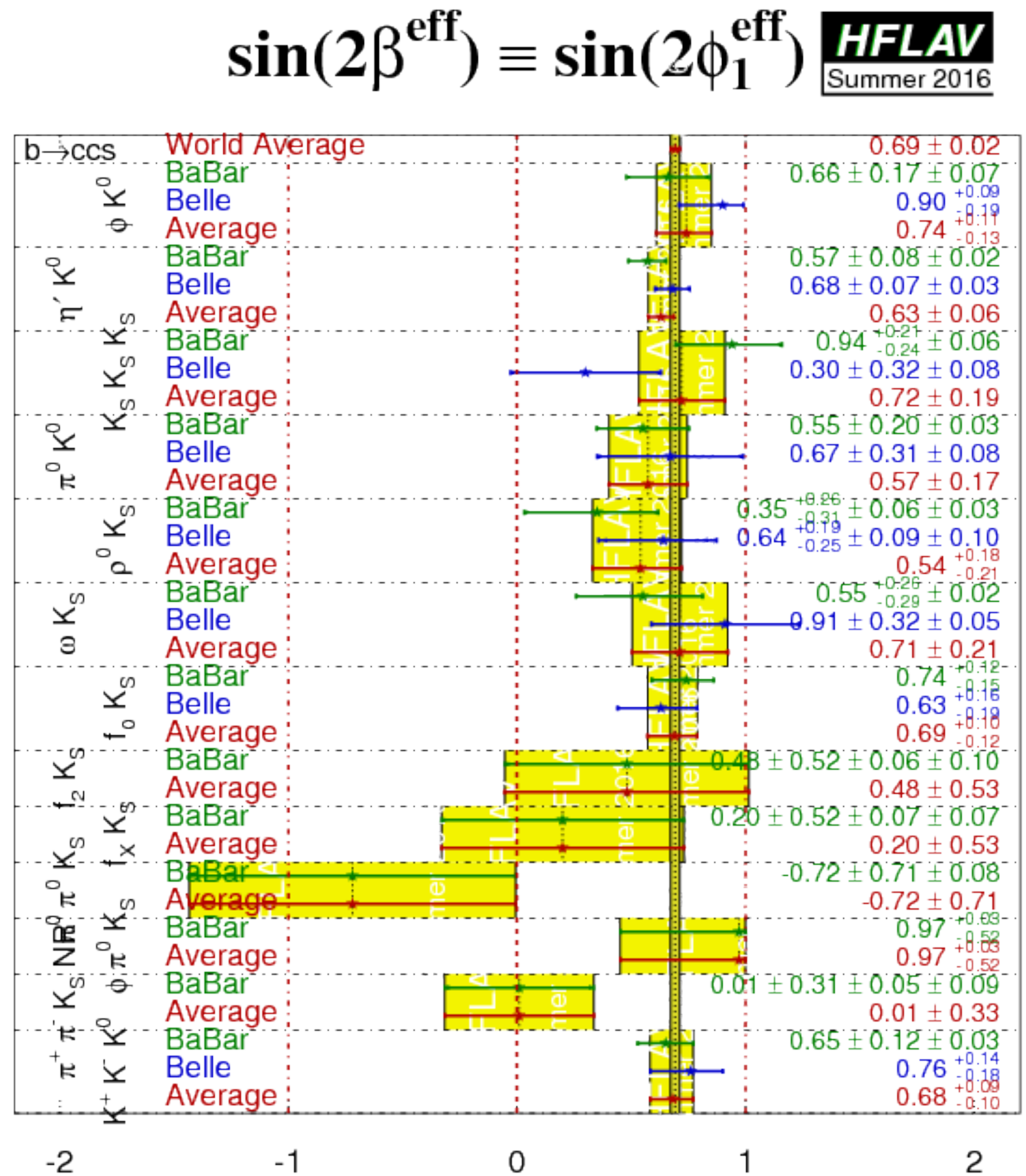
A flood of **first observations** in the last year, months or even weeks

Constraining BSM … but no clear sign, yet

Anomalies come and go (or stay?)

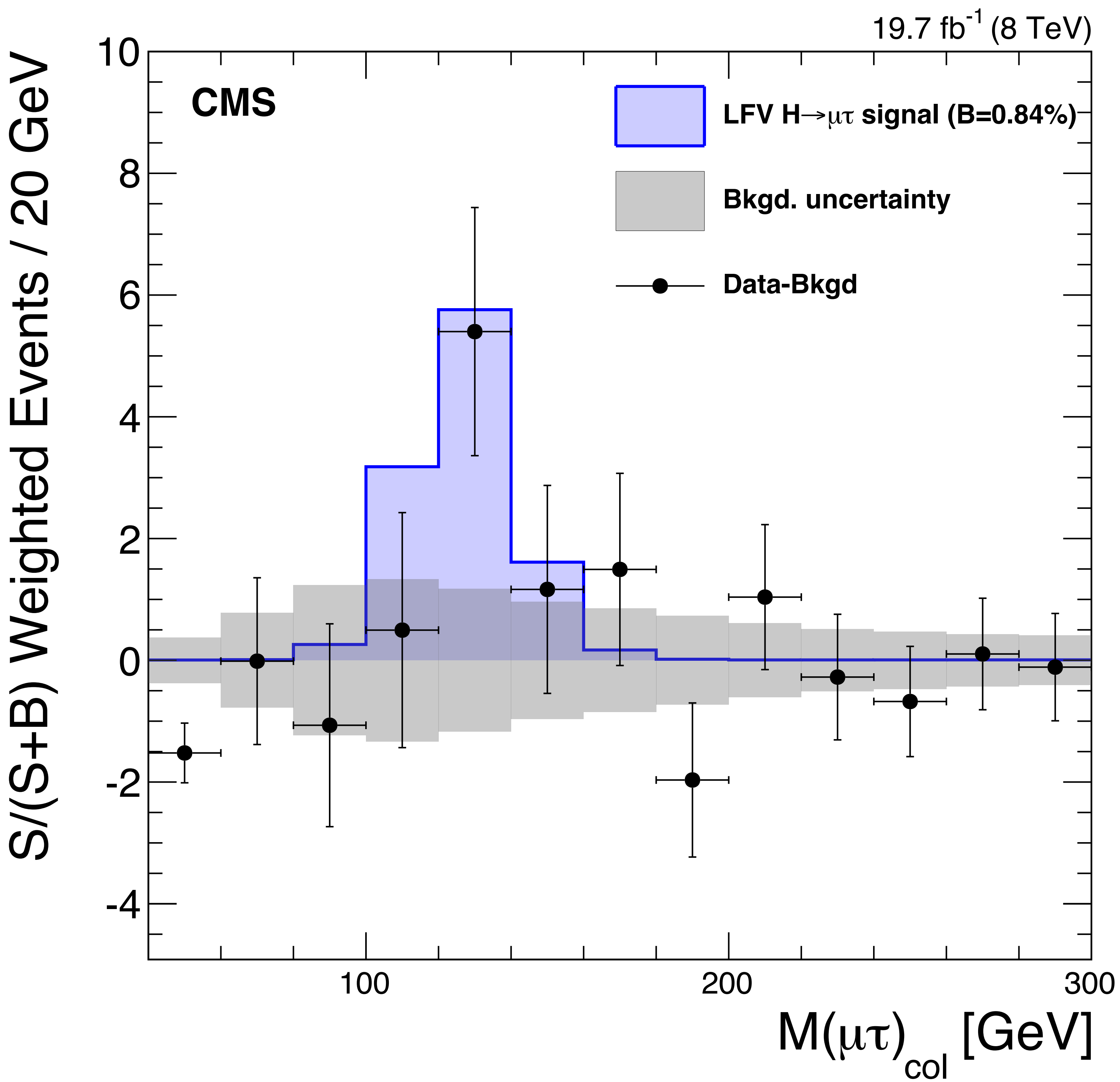
CKM2005 – **3.7σ** between $b \to c\bar{c}s$ and *s*-penguins





Anomalies come and go (or stay?)

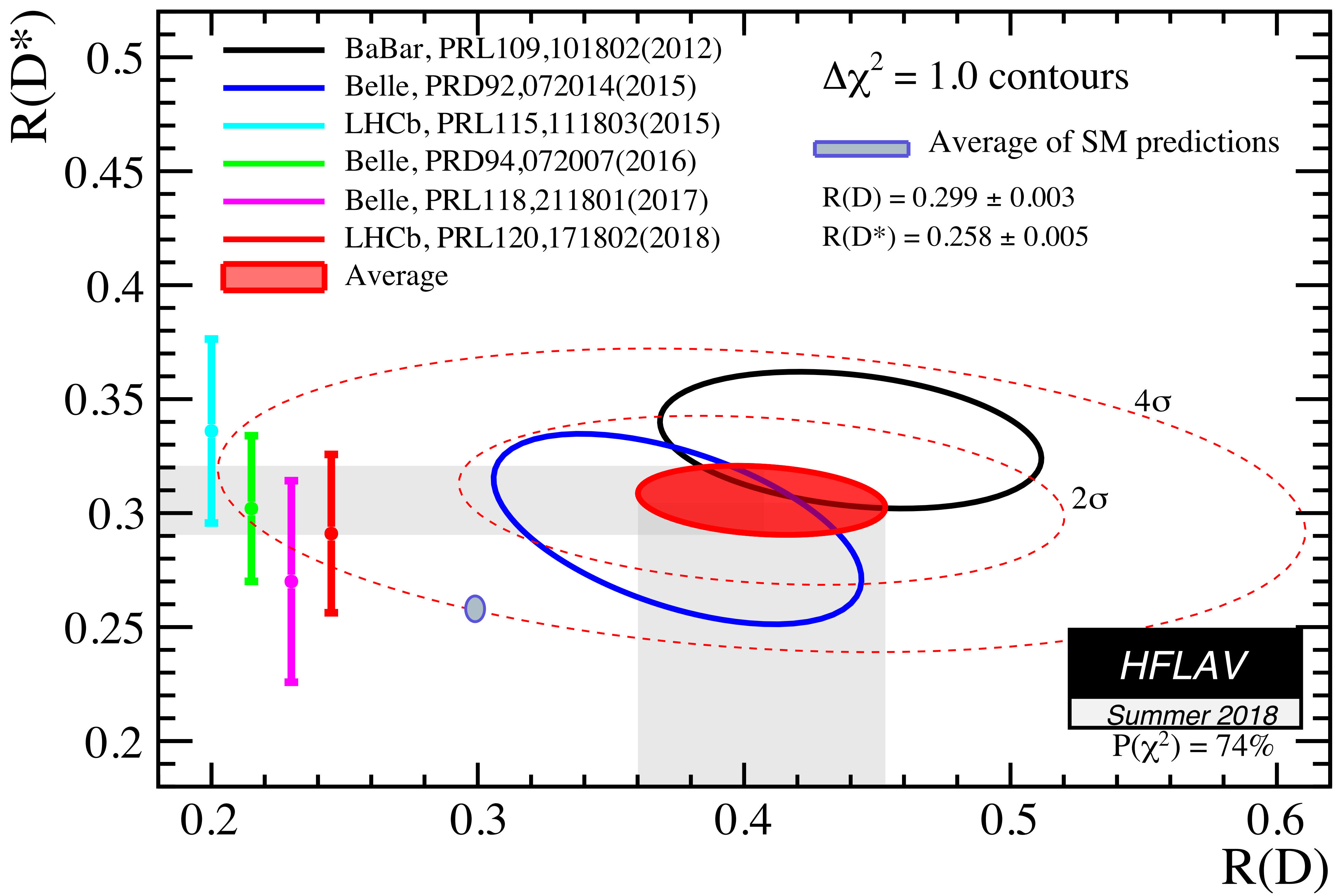
CKM2016 – **2.4σ** excess for LFV $H \to \tau\mu$



… be patient,
it's towards
the end
of the talk

Anomalies come and go (or stay?)

CKM2018 – **~4σ** LFU violation in $B \to D^{(*)}\ell\nu$



How will these look like in 2 or 10 years?

More data will help clarifying !

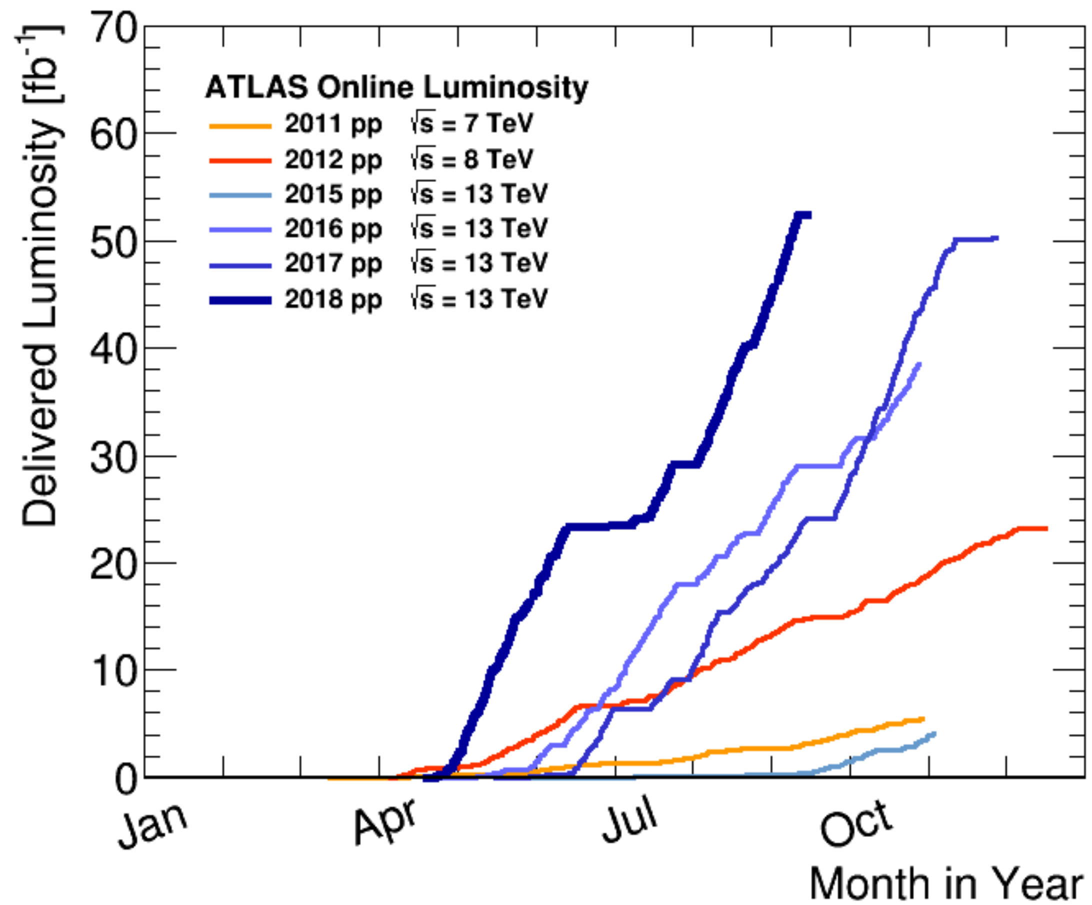
High-p_T dataset at the LHC

Run-1 : 7 and 8 TeV

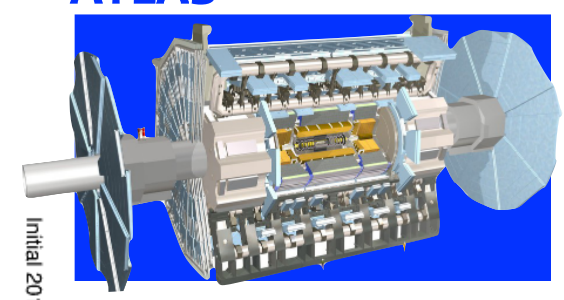
- 2010–2012: 20 fb^{-1}
  - discovery of Higgs boson
  - exploring new physics

Run-2 : 13 TeV

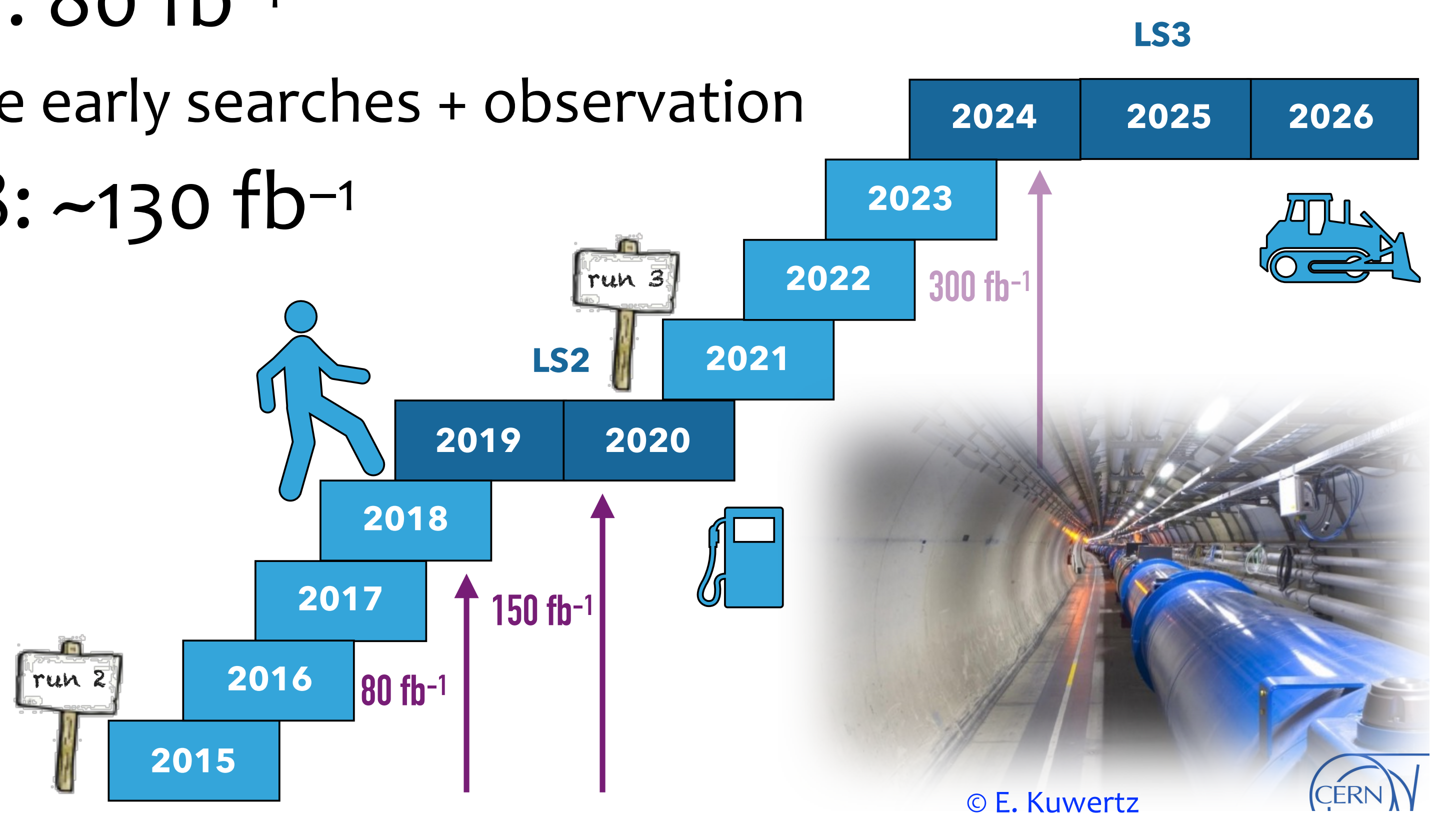
- 2015–2016: 36 fb^{-1}
  - most measurements
- +2017: 80 fb^{-1}
  - some early searches + observation
- +2018: ~130 fb^{-1}

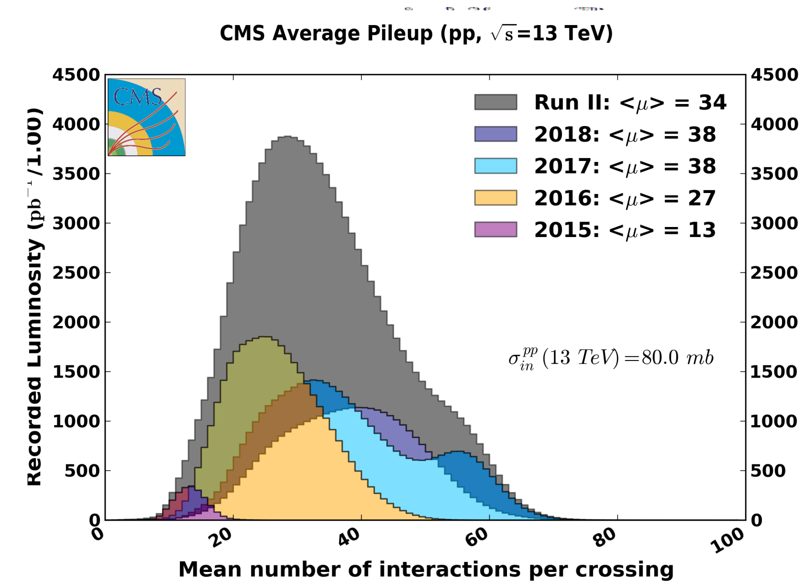


ATLAS



CMS





Closer look at Higgs boson and Yukawa sector

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

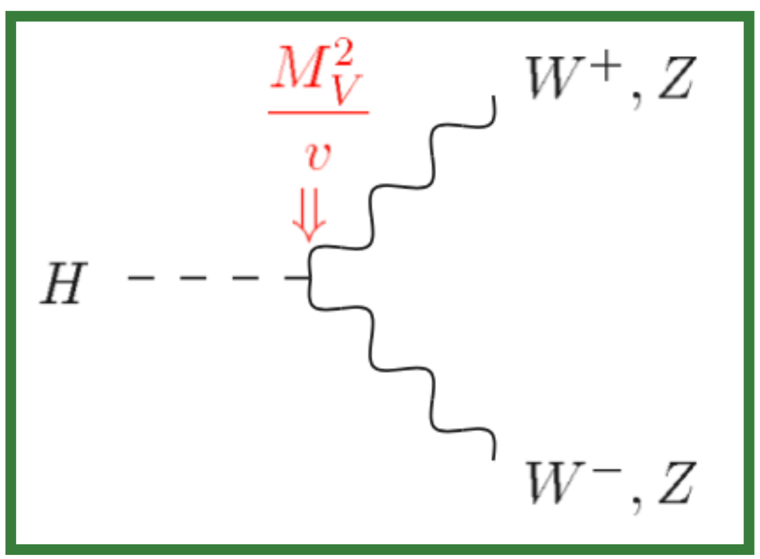
Precision electroweak and QCD

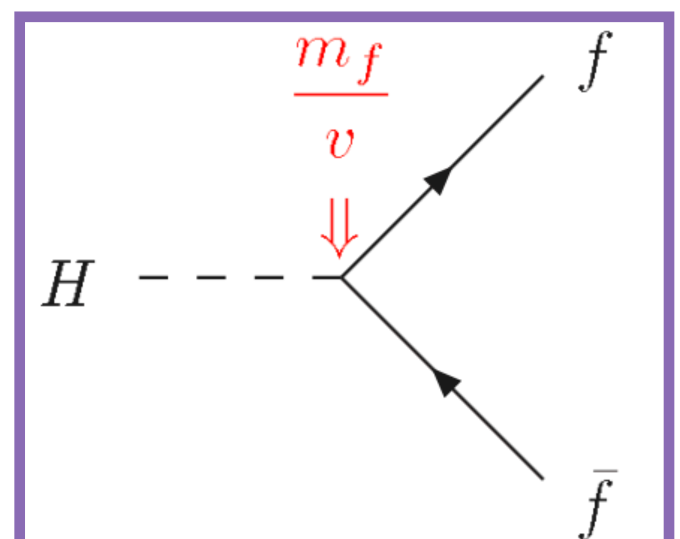
$$+|D_\mu \phi|^2 - V(H)$$

Higgs coupling to bosons
Higgs self interaction

$$+Y_{ij}\psi_i\psi_j\phi + \text{h.c.}$$

Higgs coupling to fermions
CKM matrix and CP violation

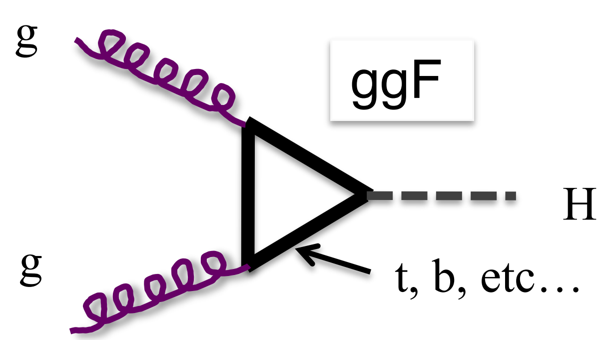


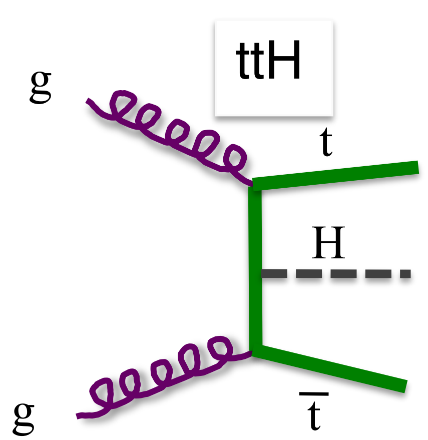


Status after Run-1

Higgs couplings

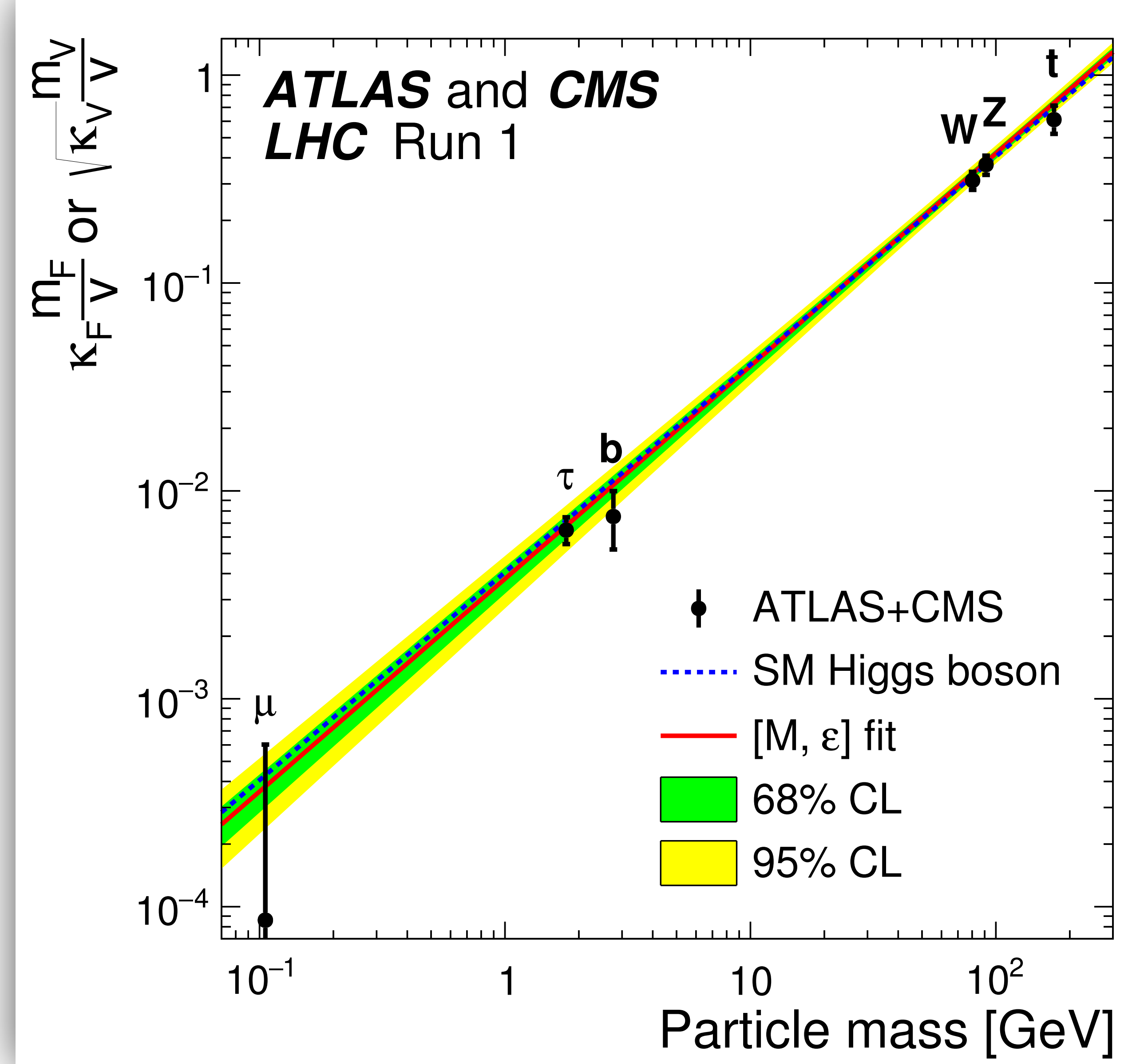
- to bosons: established
- to fermions: indirect





Assuming no new physics in the loops

JHEP 08 (2016) 045



Important to study all possible decay channels

Is it all

Standard Model

like ?

Higgs

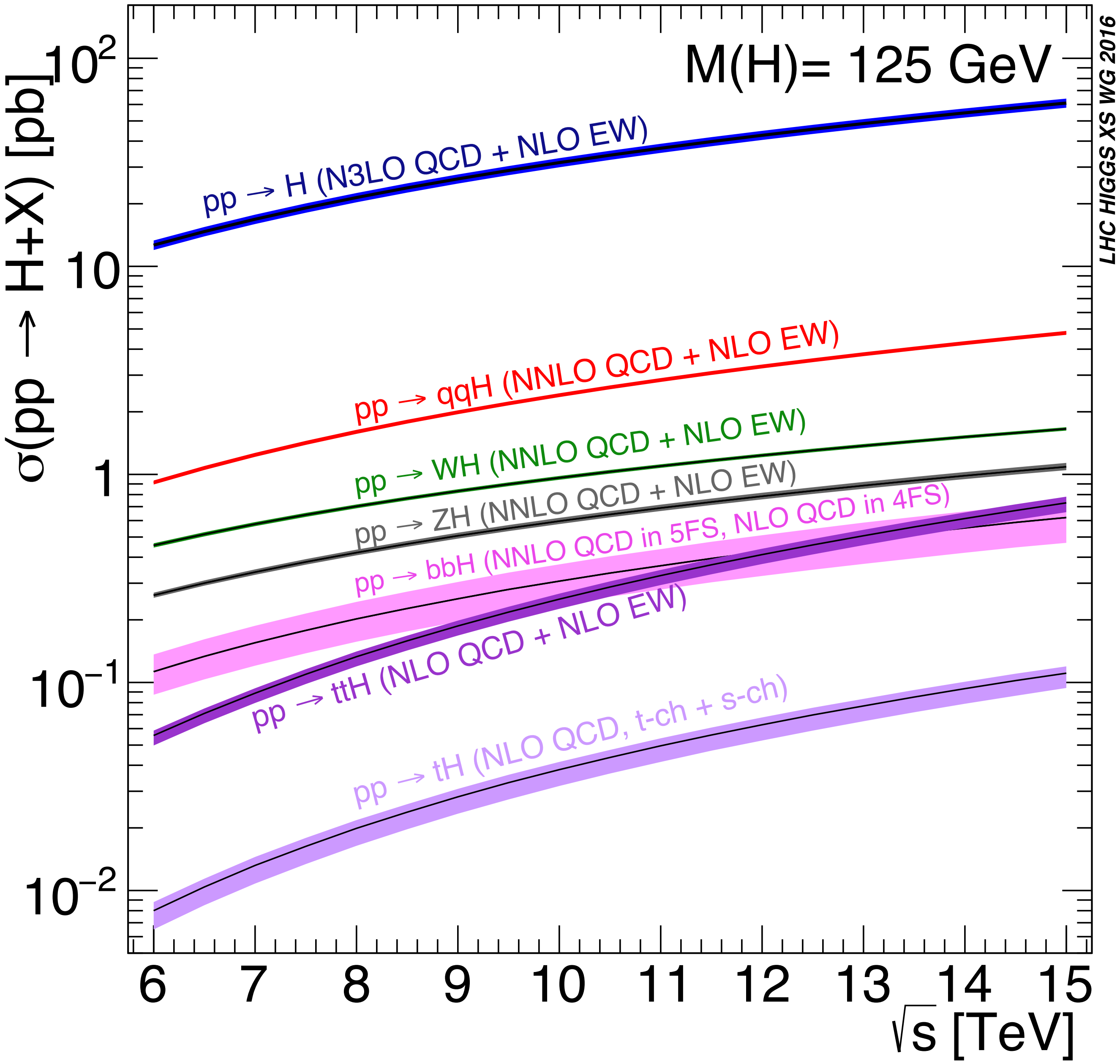
Top

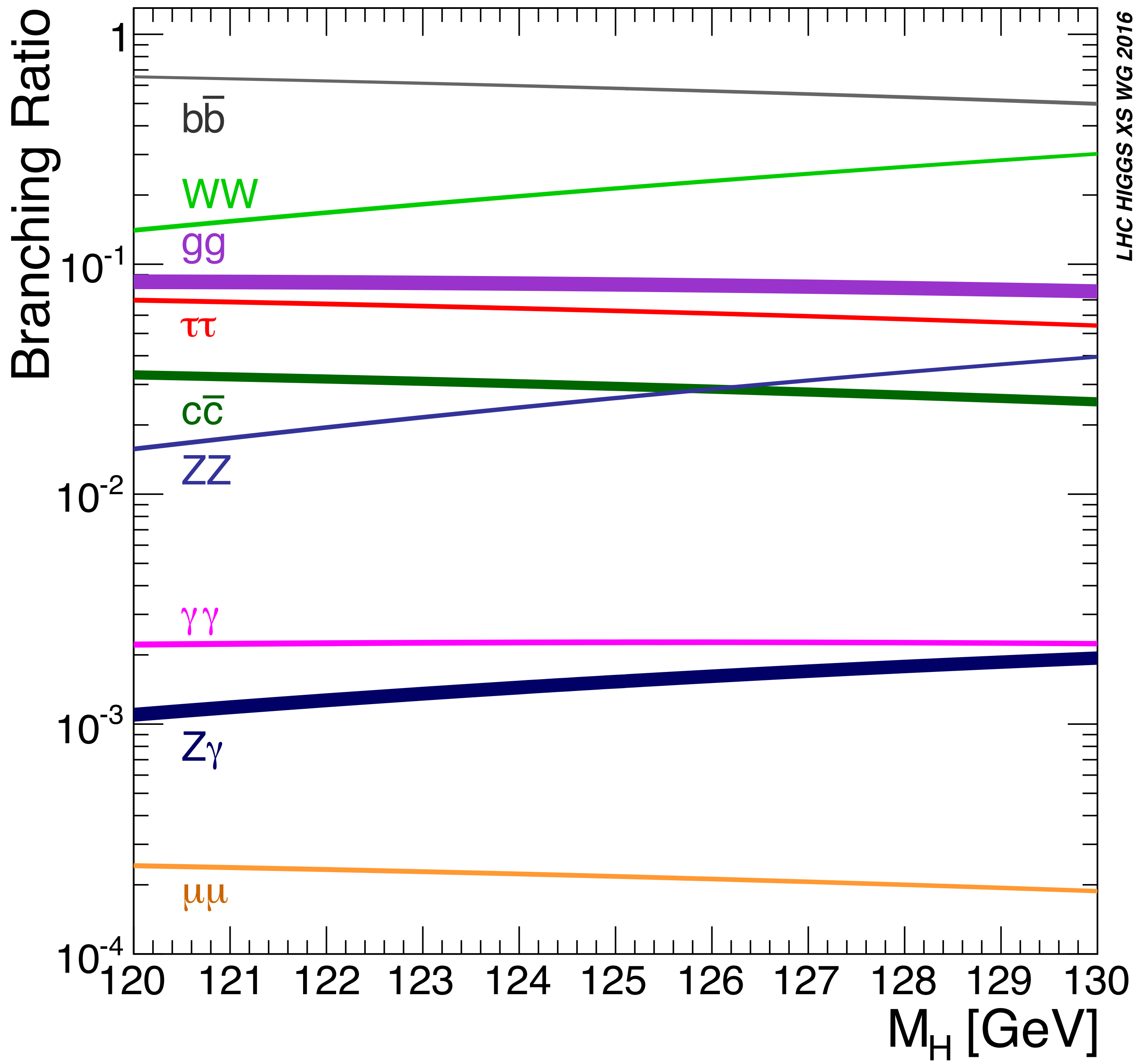
Searches

Interpretation

Higgs boson production and decay

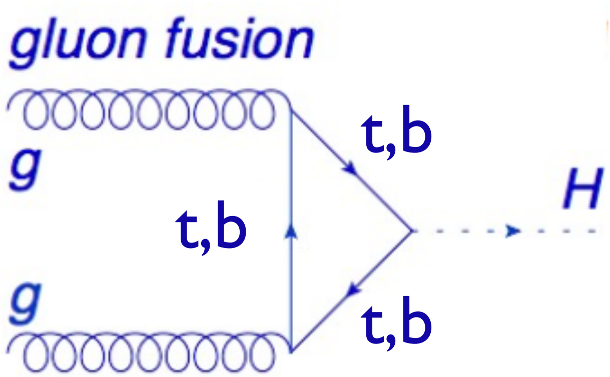
1610.07922



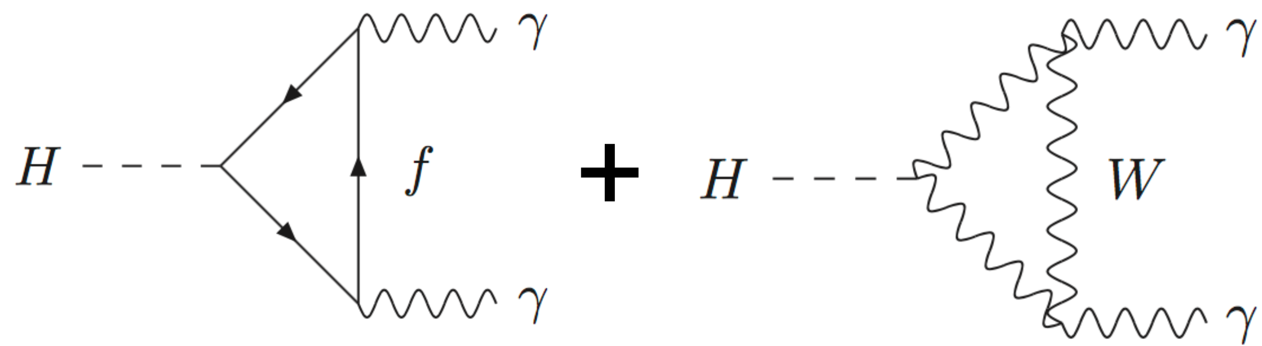


Higgs boson couplings to fermions

Indirect probe (loop diagrams)



$$gg \to H$$

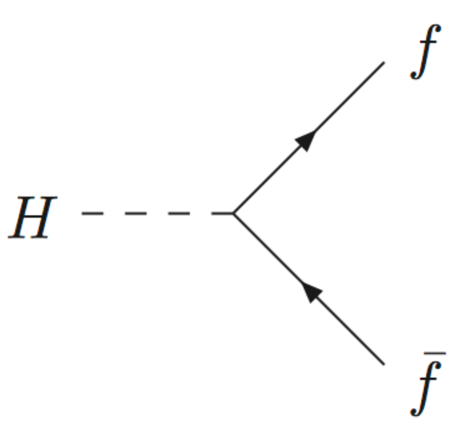


+ ...

$$H \to \gamma\gamma$$

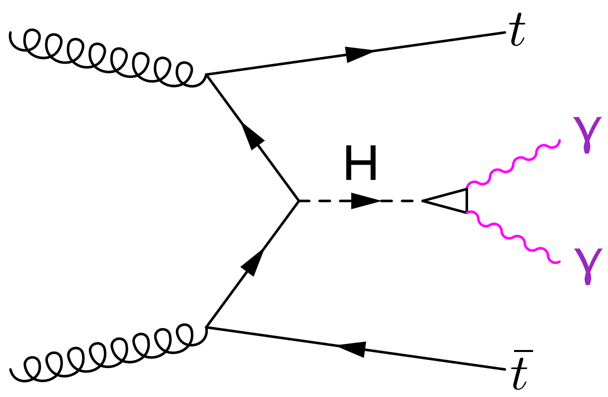
Direct probe (tree-level diagrams)

$$Y_{ij}\psi_i\psi_j\phi + \mathrm{h.c.}$$



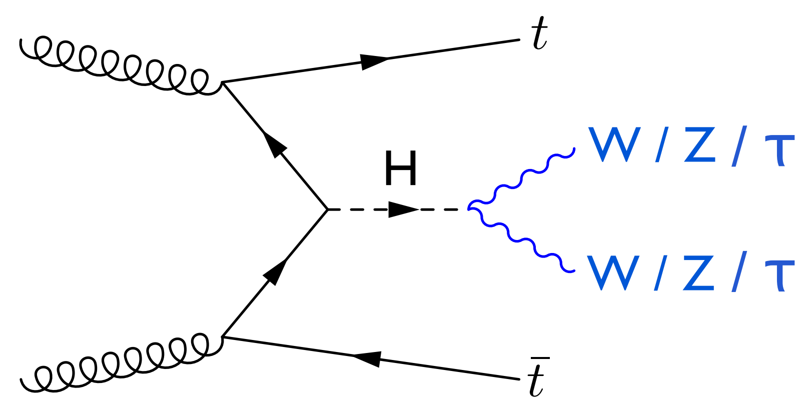
	3rd gen.	*2nd gen.*
Leptons	$H \to \tau\tau$	$H \to \mu\mu$
Down-type quarks	$H \to b\bar{b}$	
Up-type quarks	$t\bar{t}H$	$H \to c\bar{c}$

Higgs and *top* quarks – $t\bar{t}H$



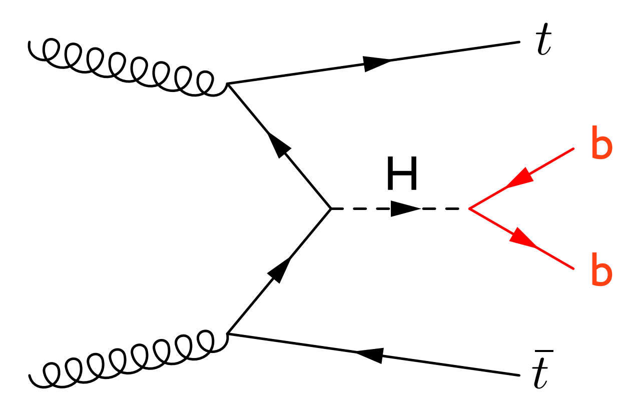
0.2%

narrow peak



22%

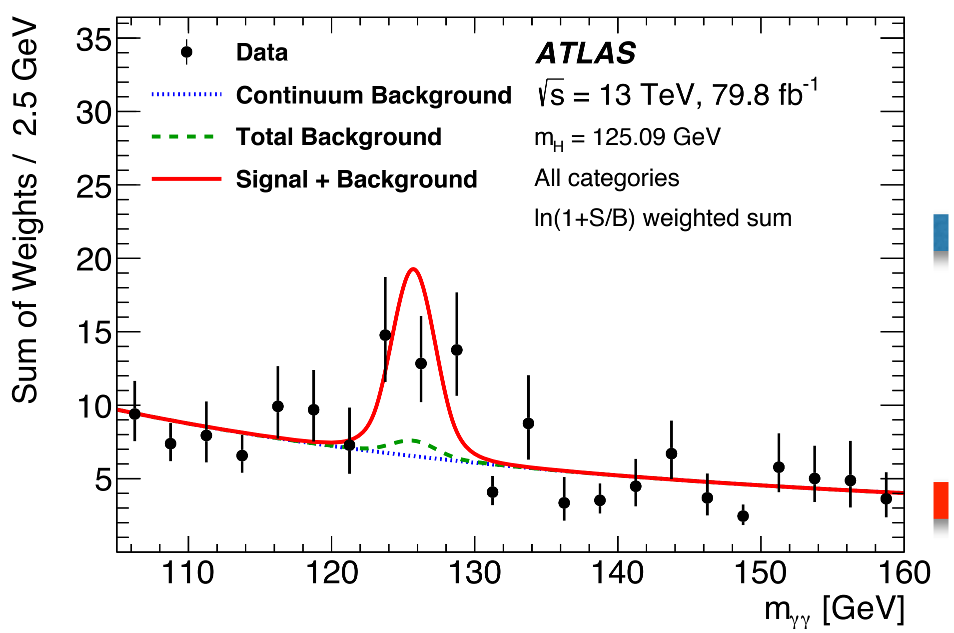
multi-lepton signature



58%

4 b-tags: pairing ambiguities

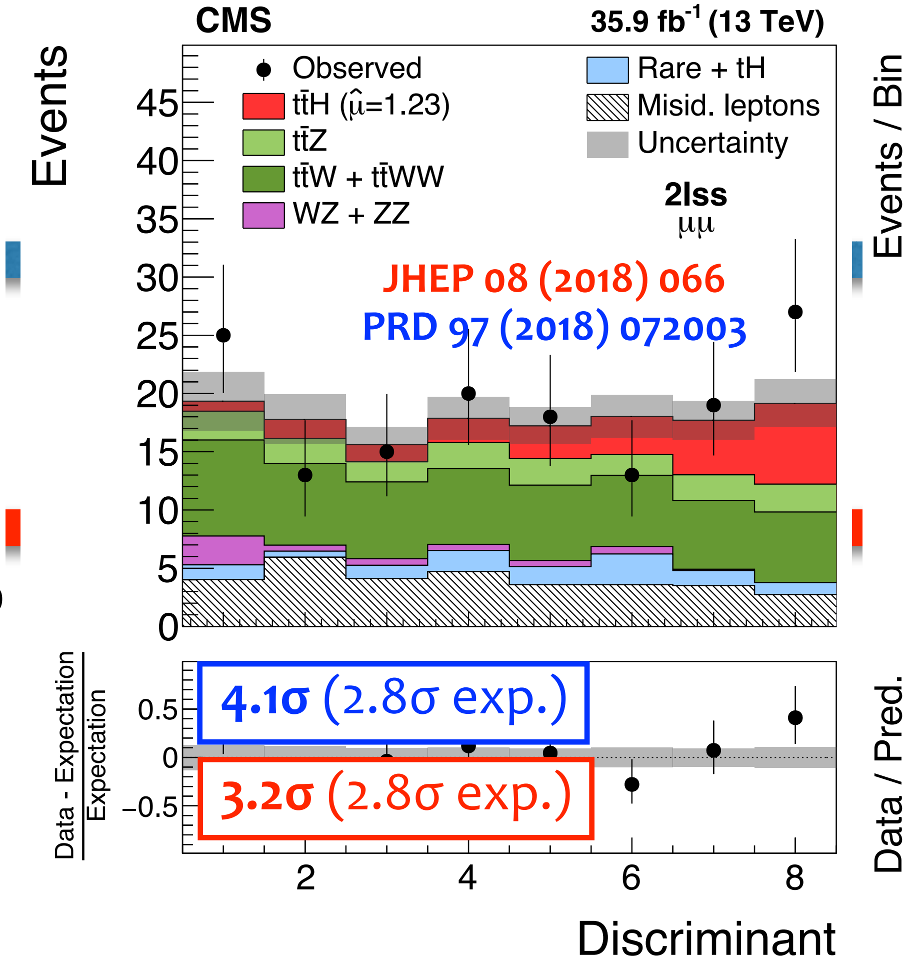
PLB 784 (2018) 173 1804.02716



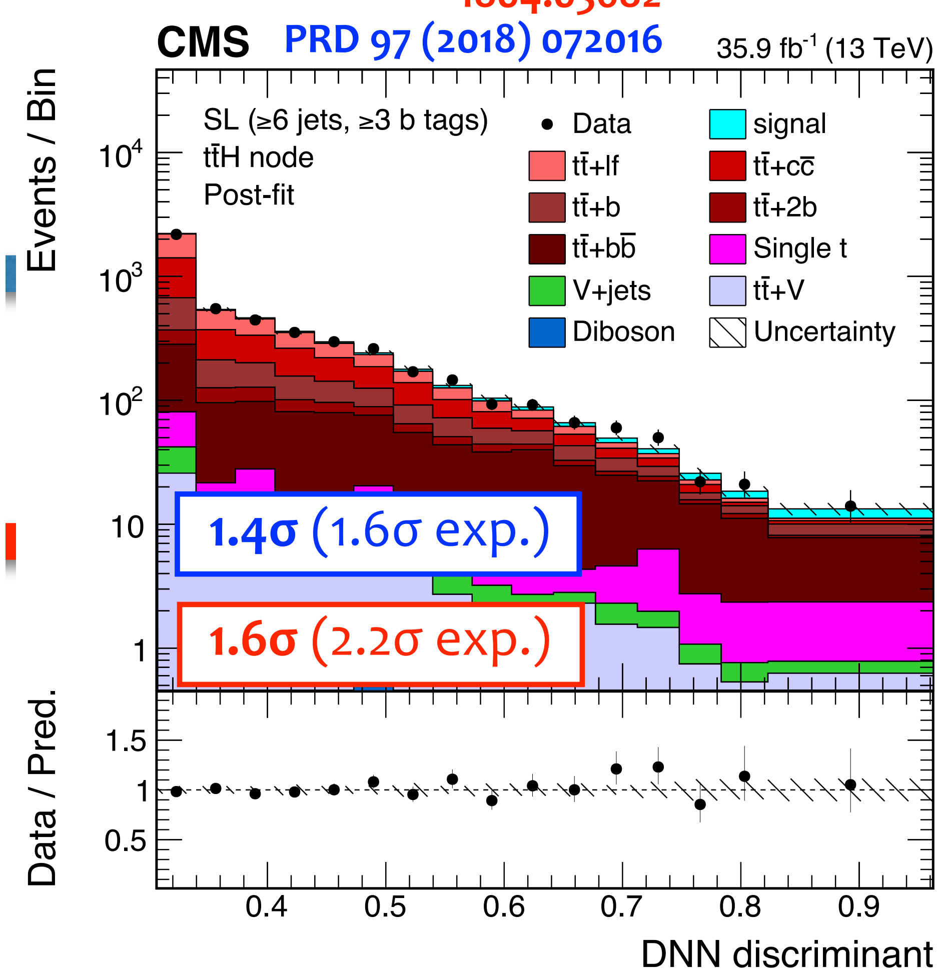
ATLAS **4.1σ** (3.7σ exp.)

CMS **1.4σ** (1.5σ exp.)

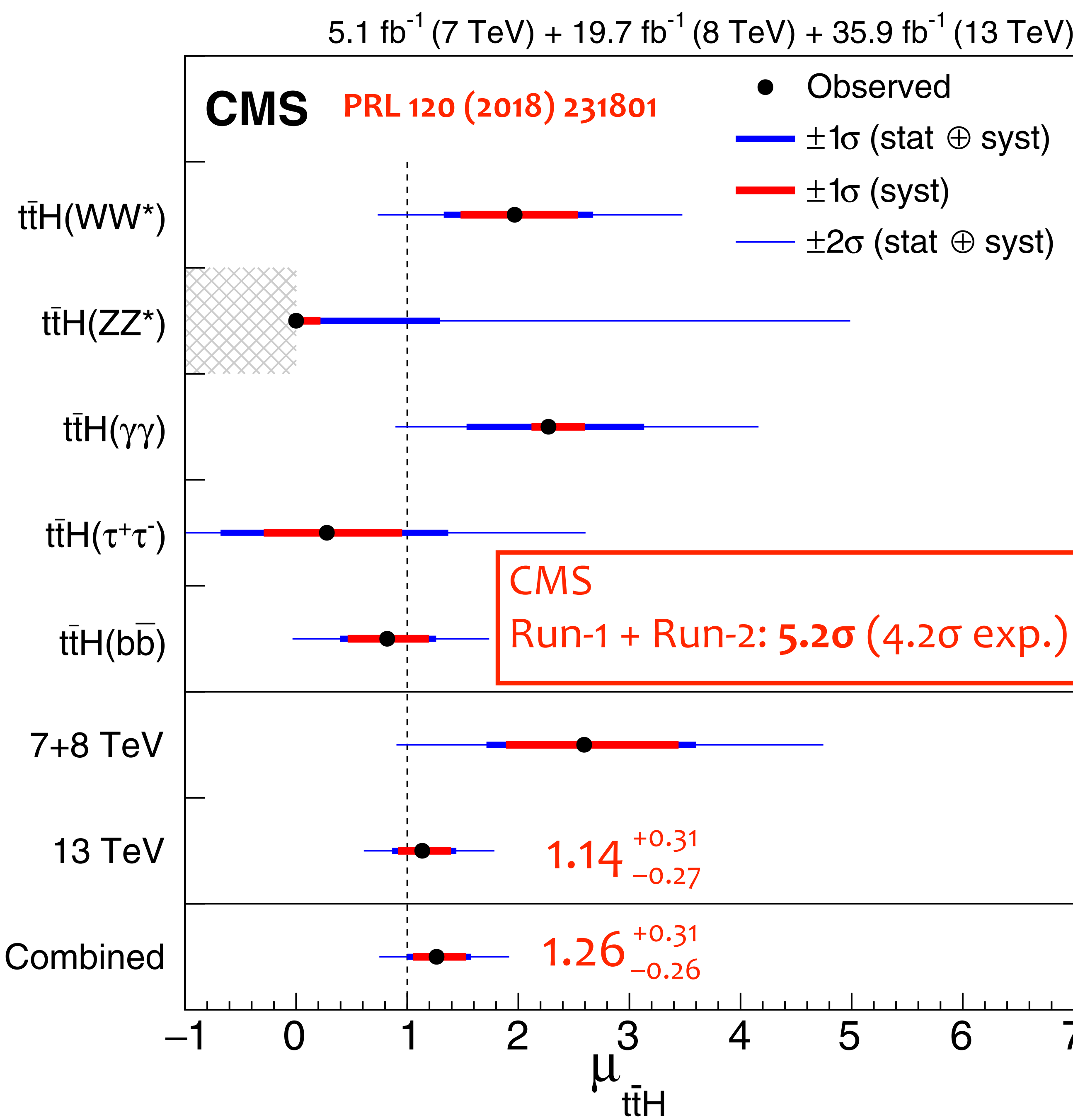
80 fb-1



1804.03682

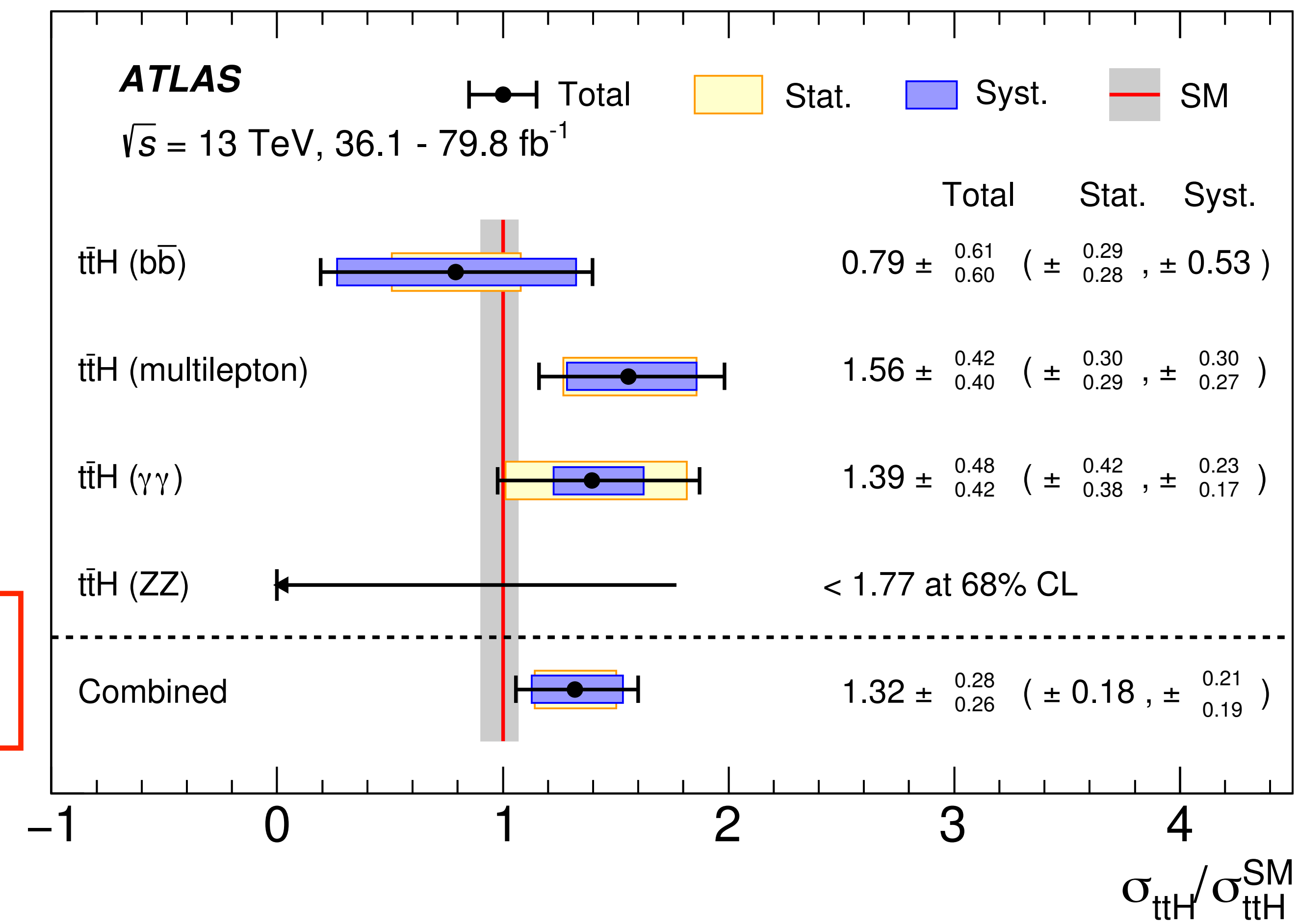


Combination of channels and runs



CMS
Run-1 + Run-2: **5.2σ** (4.2σ exp.)

PLB 784 (2018) 173



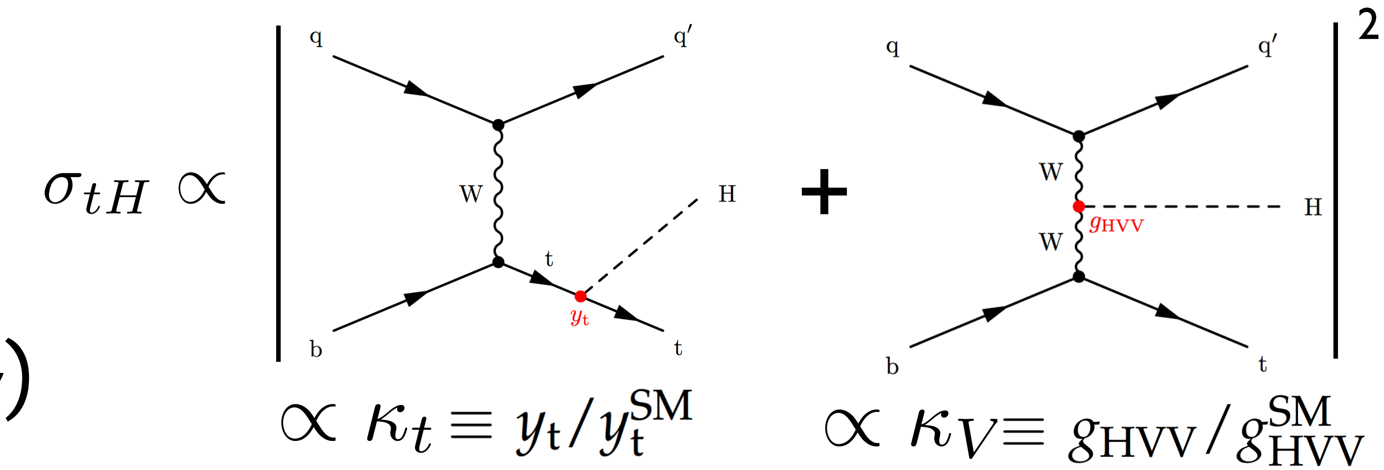
ATLAS (up to 80 fb^{-1})
Run-2: **5.8σ** (4.9σ exp.)
Run-1 + Run-2: **6.3σ** (5.1σ exp.)

Observation of $t\bar{t}H$ production !

CMS PAS HIG-18-009

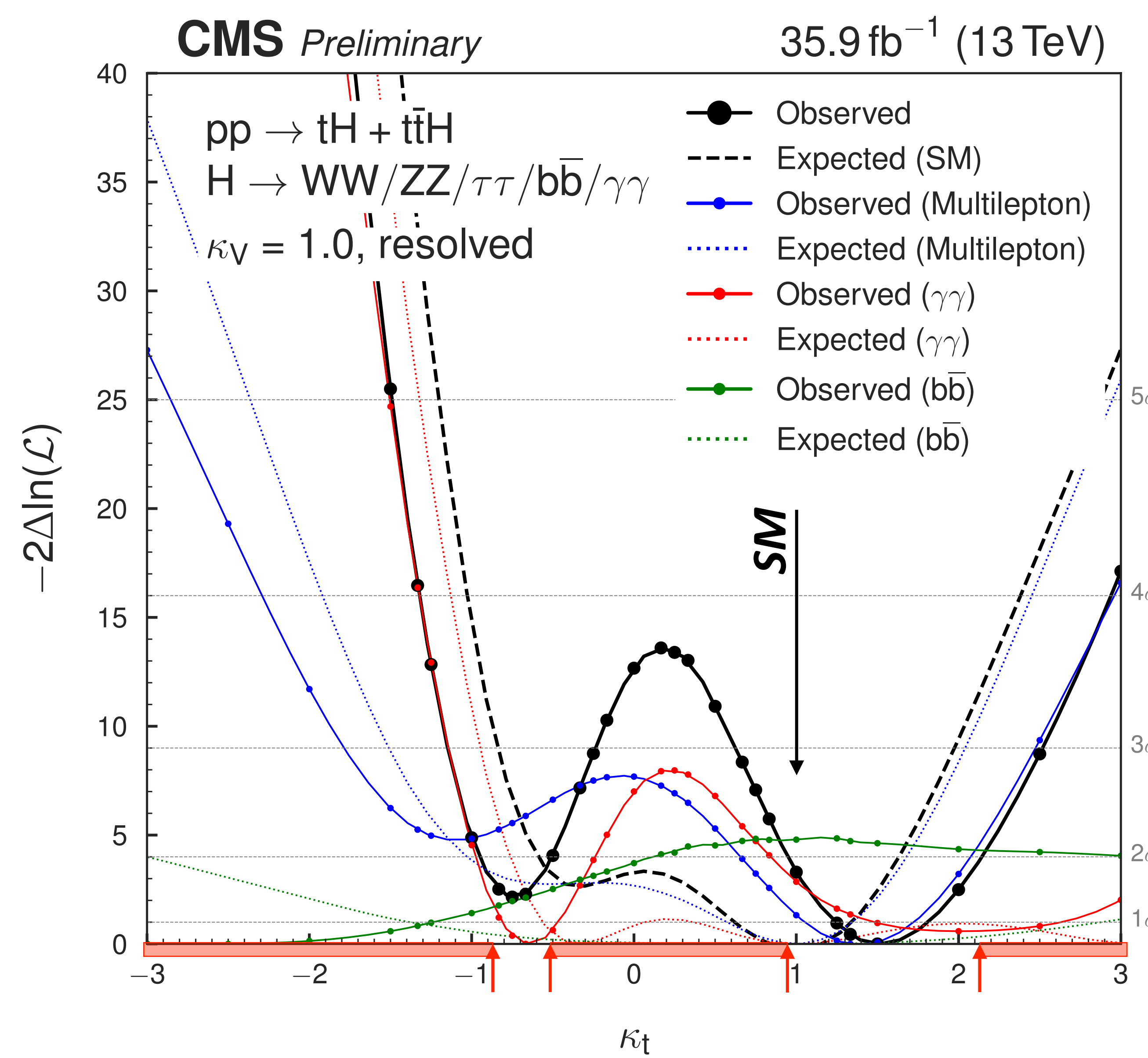
Single top + Higgs

- very small production cross section in SM
- but enhanced ~10x if sign($\varkappa_t/\varkappa_V$) opposite to SM → $\sigma_{tH} > \sigma_{t\bar{t}H}$ possible
- can be used to constrain relative sign of $\varkappa_t$ and $\varkappa_V$



New Run-2 combination

- data favors sign($\varkappa_t/\varkappa_V$)=1 at 1.5σ
- assuming SM $t\bar{t}H$ yield and SM *tH* acceptance
- CMS: μ_{tH} < 26.5 (13.6 expected)



$H \to b\bar{b}$ in earlier searches

- LEP: $m_H > 114.4$ GeV
- Tevatron: $m_H = 125$ GeV @ 2.8σ

ATLAS Insertable B-Layer

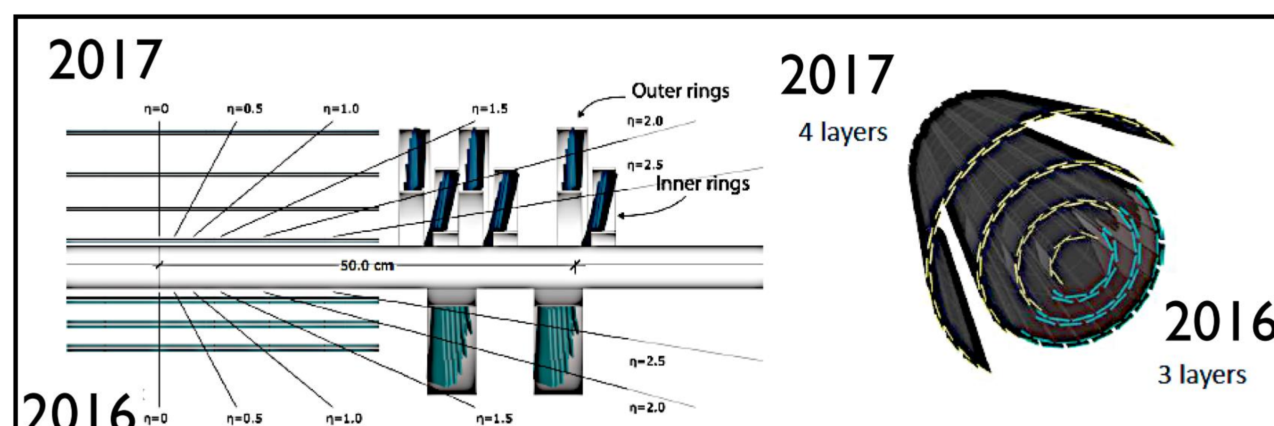
LHC Run-1

- combined 2.6σ (3.7σ expected)

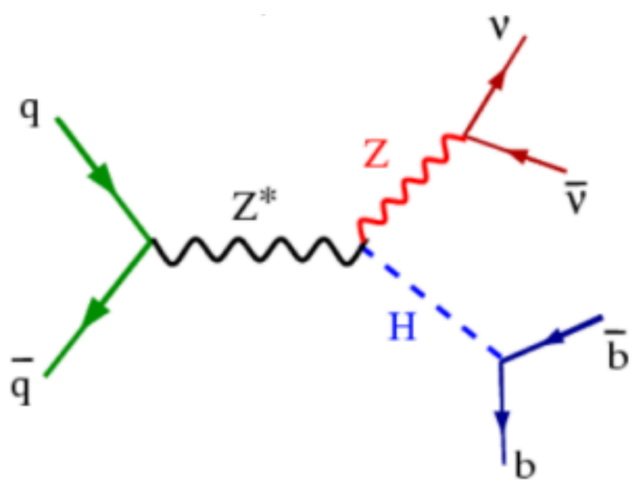
LHC Run-2

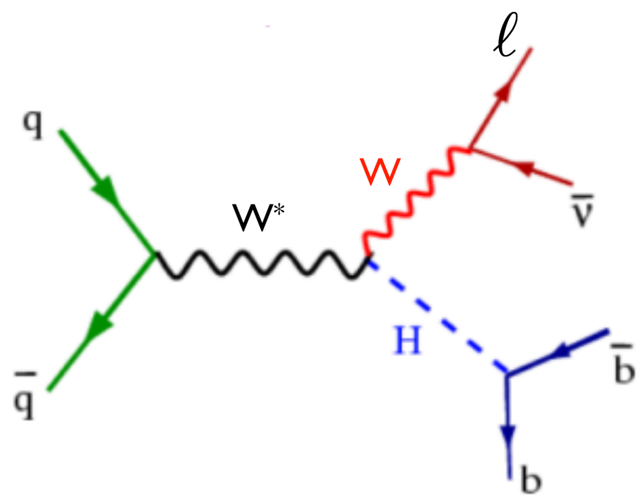
- improved b-tagging
- ATLAS and CMS pixel detector upgrades
- deep learning algorithms

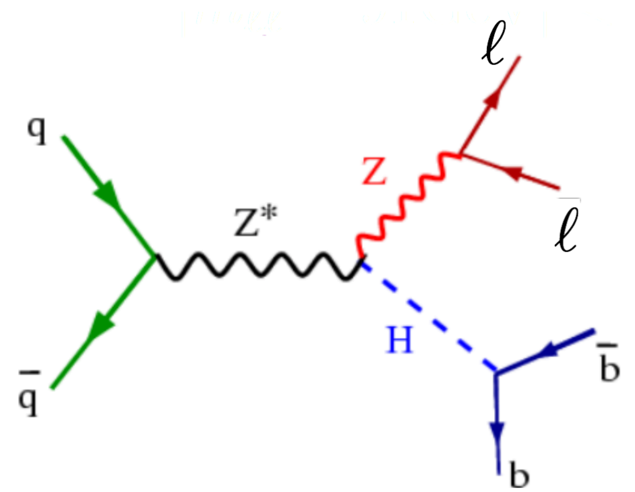
CMS Pixel detector upgrades



Higgs and *beauty* quarks







Observation of $H \to b\bar{b}$

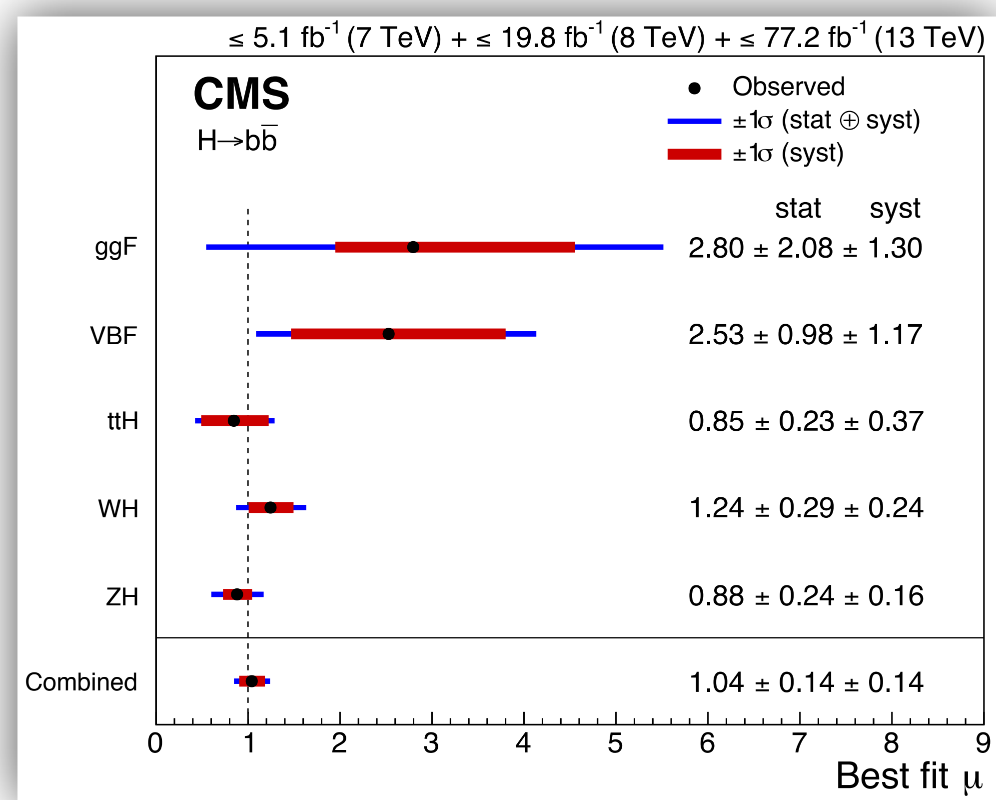
80 fb^{-1}

ATLAS 1808.08238

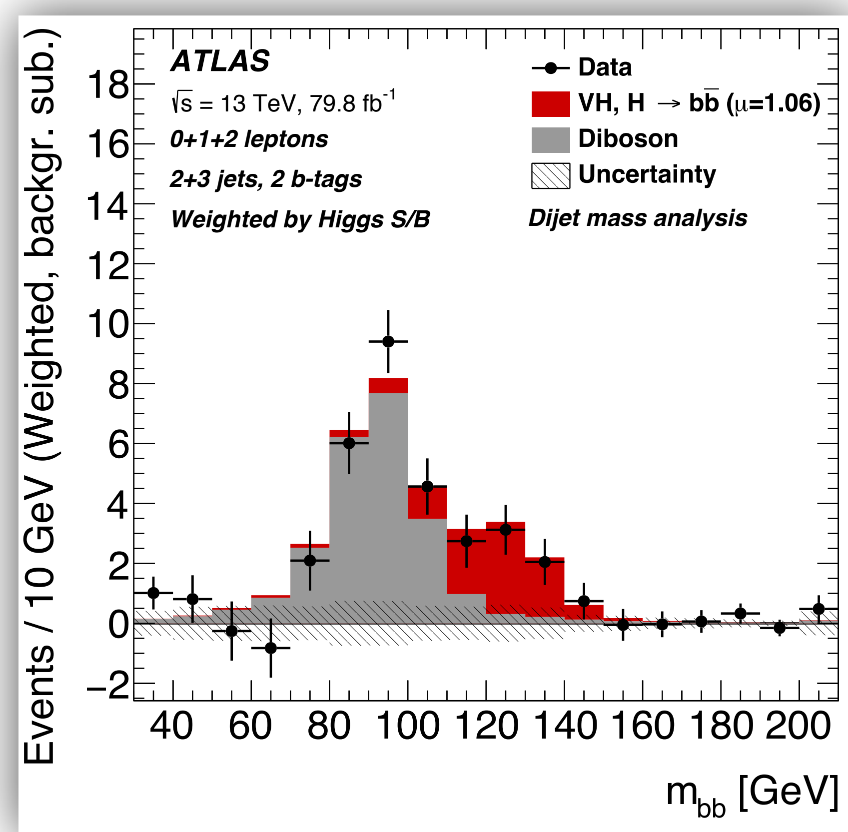
CMS 1808.08242

- mainly in *WH* and *ZH* channels
- can reconstruct the $m_{b\bar{b}}$ peak

5.6σ (5.5σ expected)



5.4σ (5.5σ expected)



Observation of associated production

- *WH* and *ZH* most sensitive channels

Interpretation of p_T (Higgs)

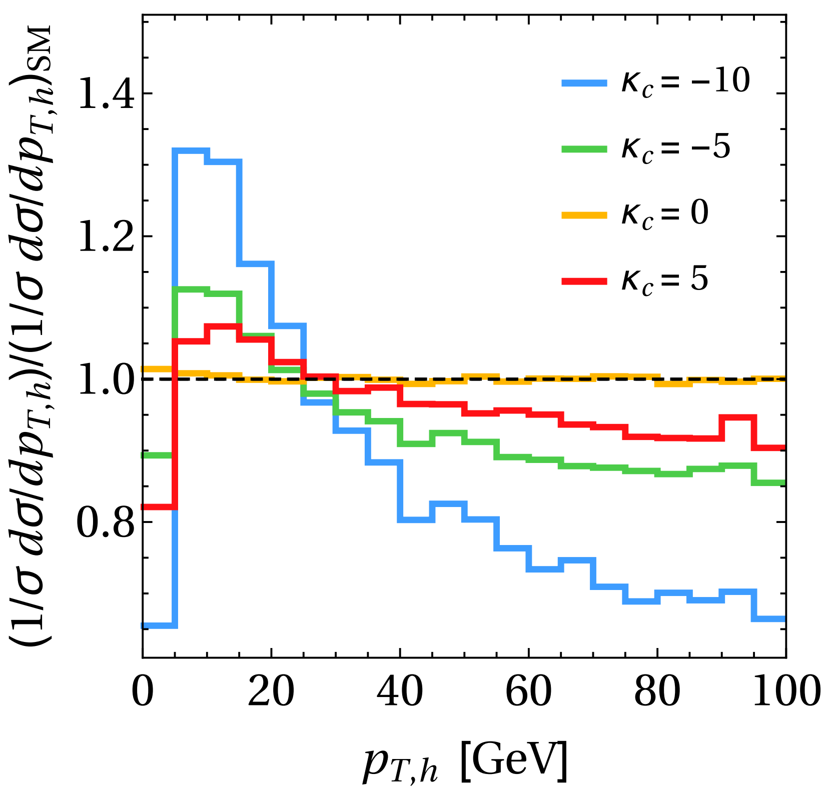
Shape & normalisation of $p_T(H)$

Grazzini et al. ‘17
Grazzini et al. ‘18

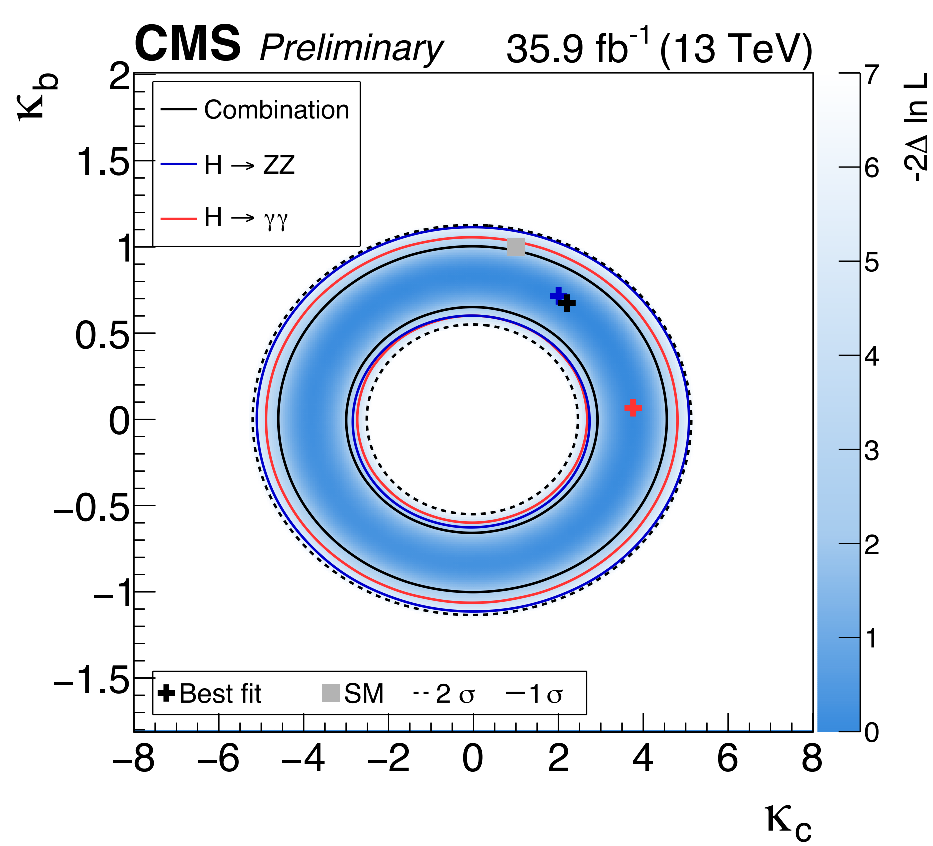
- can give constraints on κ_t, κ_b, κ_c and c_g (eff. ggH coupling)

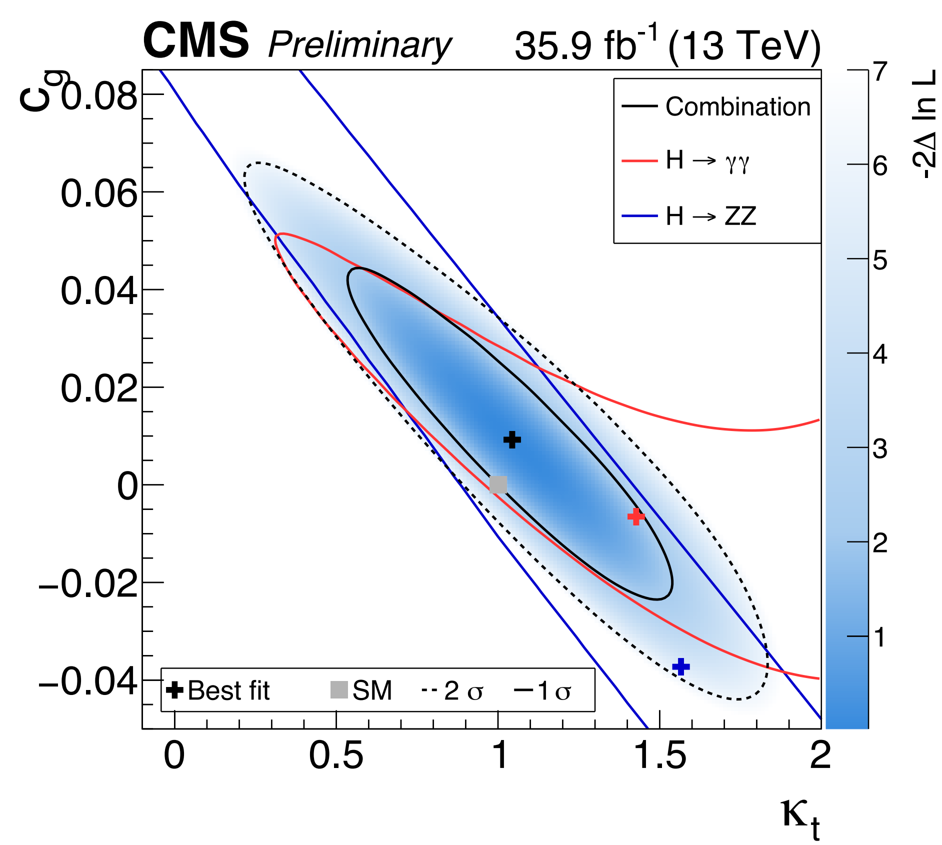
Additional handle to constrain Higgs couplings

Bishara et al. ‘17



CMS-PAS-HIG-17-028

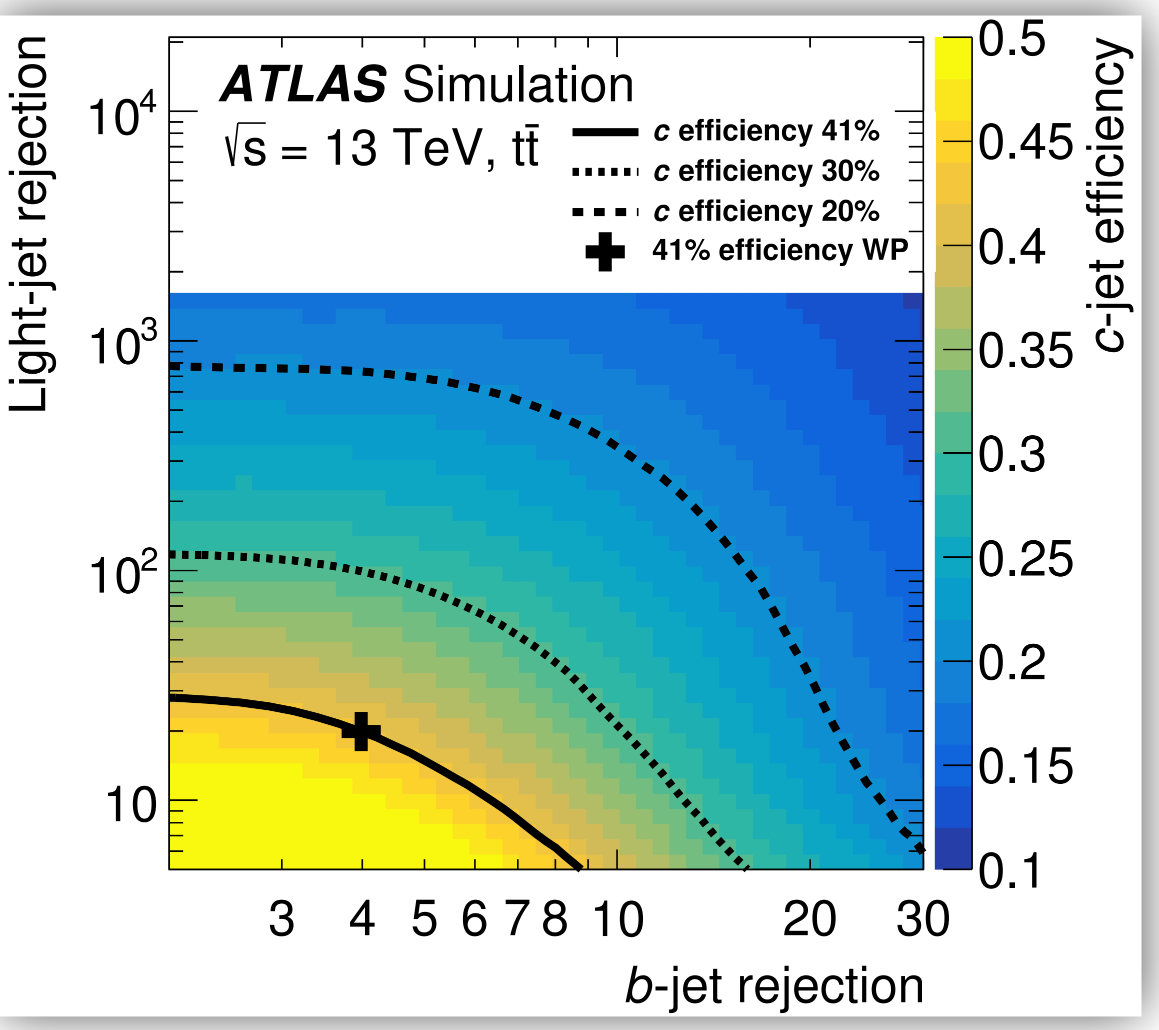


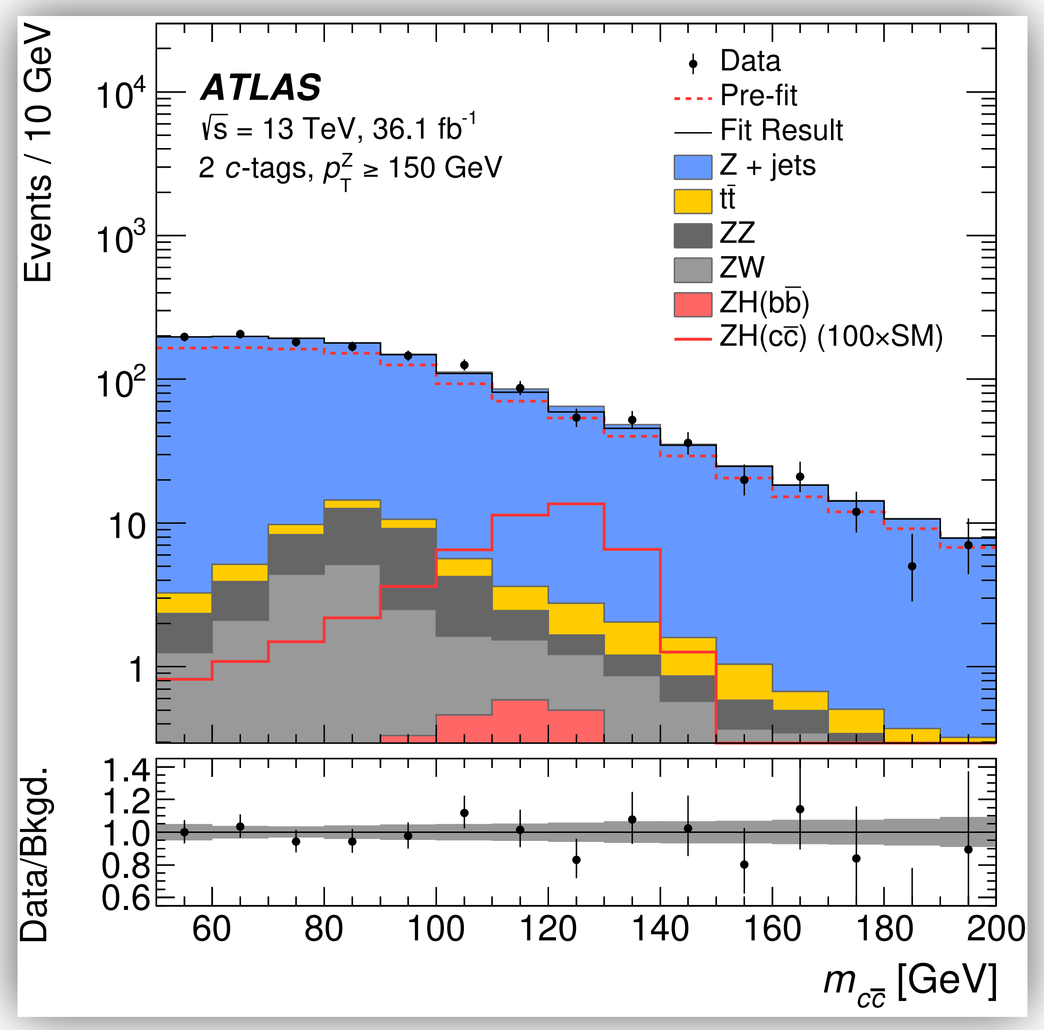


ATLAS PRL 120 (2018) 211802

First direct search of $H \to c\bar{c}$

- use of charm tagging algorithms
- two BDTs, separating *c*- from light and *c*- from *b*-jets
- uncertainties: tagging, jet energy, background modelling
- $\mu < 110$ ($\mu = -69 \pm 101$), tough channel!

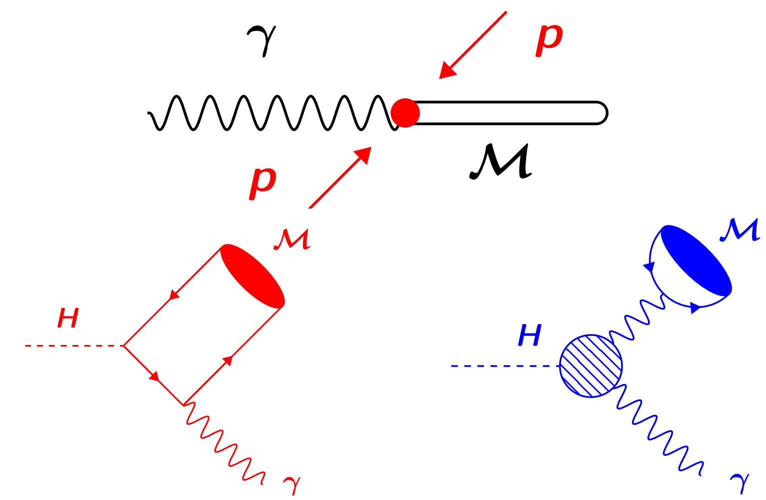


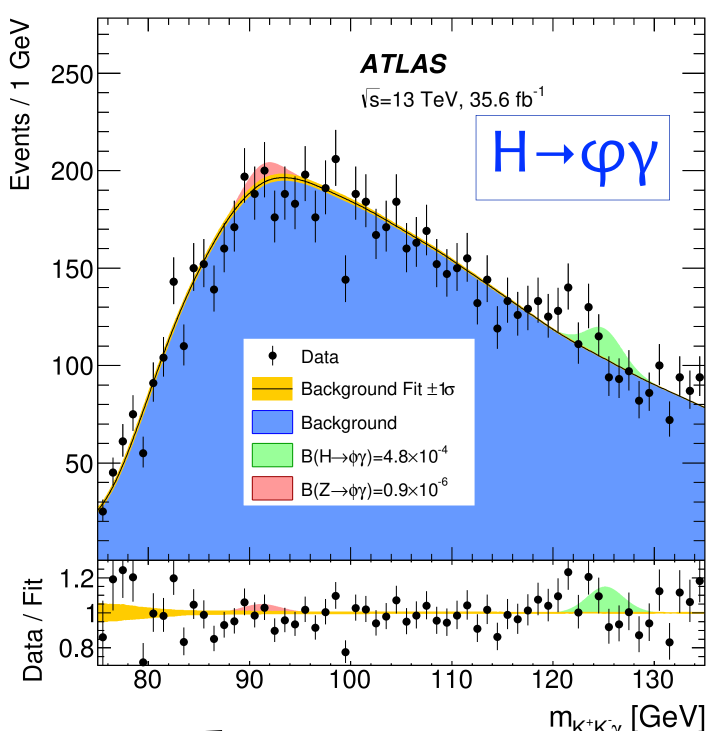


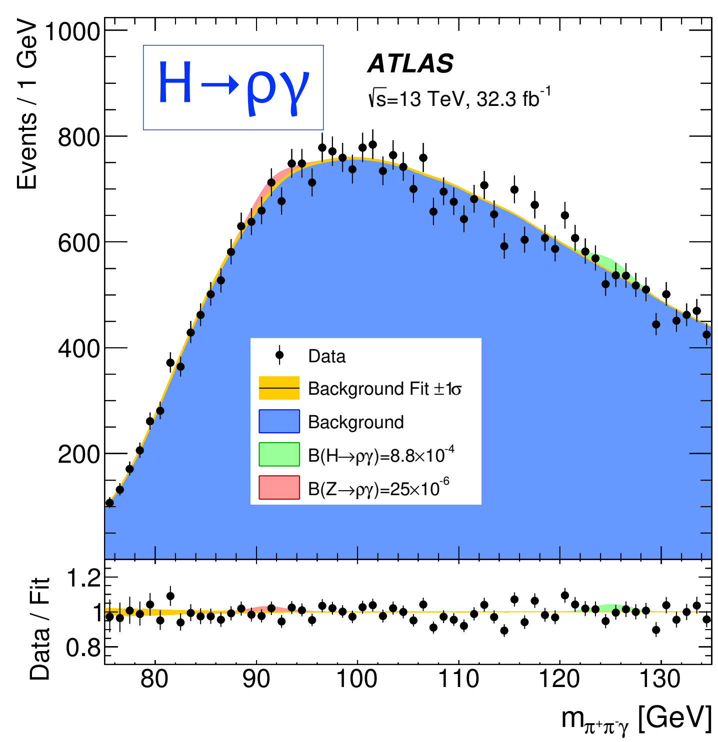
Radiative Higgs decays to mesons

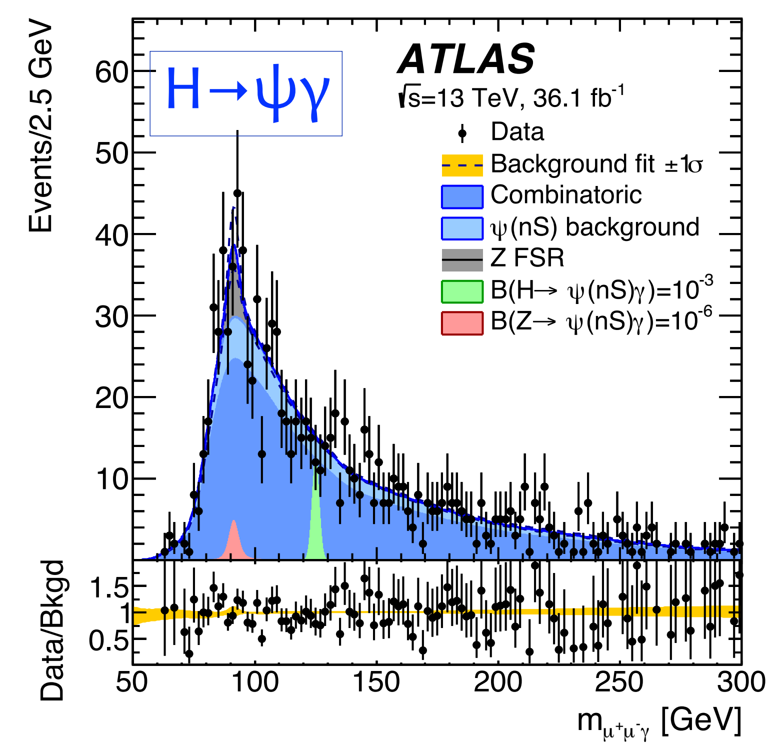
Search for $H \to M+\gamma$

- $M = \rho \to \pi\pi$, $\varphi \to KK$, $\psi(nS) \to \mu\mu$, $\Upsilon(nS) \to \mu\mu$
- $H \to q\bar{q}$ and $H \to \gamma\gamma^*$ amplitudes
- gives direct access to u, d, s, c Yukawa









Results

ATLAS

- first constraint on light-quark Yukawa : $\mu_{H\to\rho\gamma} < 52$ — JHEP 07 (2018) 127
- first limit on $H \to \psi(2S)\gamma$ decays — 1807.00802
- cancellations in $H \to \Upsilon(nS)\gamma$: $y_b / y_b^{SM} < O(10)$ — 1807.00802

Higgs and fermions

The very colorful table of Higgs and fermions

Channel	μ	Significance	Reference	Experiment
$t\bar{t}H$	$1.26\ {+0.31}\ {-0.26}$	5.2 (4.2)	PRL 120 (2018) 231801	CMS
	$1.32\ {+0.28}\ {-0.26}$	6.3 (5.1)	PLB 784 (2018) 173	ATLAS
tH+X	< 26	$\varkappa_t \in (-0.9,-0.5)$ or $(1.0, 2.1)$	CMS PAS HIG-18-009	CMS
$H \to b\bar{b}$	$1.01 + 0.20\ {-0.19}$	5.4 (5.5)	1808.08238	ATLAS
	1.04 ± 0.20	5.6 (5.5)	1808.08242	CMS
$H \to \Upsilon(1,2,3S)$	$(< 94, < 420, <630) \times 10^3$		1807.00802	ATLAS
$H \to c\bar{c}$	< 110 (-69 ± 101)		PRL 120 (2018) 211802	ATLAS
$H \to \psi(nS)\gamma$	< 120 J/ψ < 1900 $\psi(2S)$		1807.00802	ATLAS
$H \to \varphi\gamma$	< 210		JHEP 07 (2018) 127	ATLAS
$H \to \rho\gamma$	<52			
$H \to \tau\tau$	$1.09\ {+0.27}\ {-0.26}$	5.9 (5.9)	PLB 779 (2018) 283	CMS
	$1.09\ {+0.36}\ {-0.30}$	6.4 (5.4)	ATLAS-CONF-2018-021	ATLAS
$H \to \mu\mu$	< 2.92 (1.0 ± 1.0)	0.9 (1.0)	1807.06325	CMS
	< 2.1 $(0.1\ {+1.0}\ {-1.1})$		ATLAS-CONF-2018-026	ATLAS
$H \to \mu\tau$	< 0.25%		JHEP 06 (2018) 001	CMS
$H \to e\tau$	< 0.61%			

t b c uds τ μ

LHC after the Higgs discovery

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\!\!\!/\,\psi$$

Precision electroweak and QCD

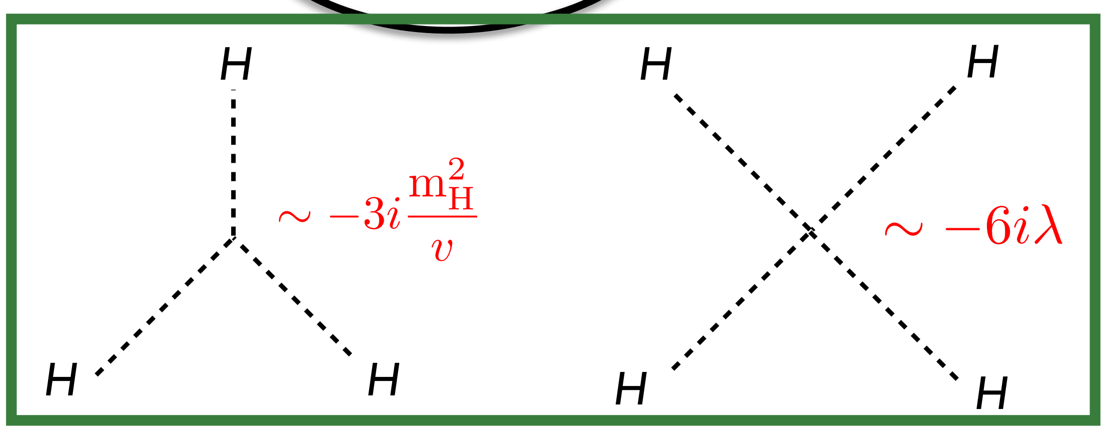
$$+|D_\mu\phi|^2 - V(H)$$

Higgs coupling to bosons
Higgs self interaction

$$+Y_{ij}\psi_i\psi_j\phi + \mathrm{h.c.}$$

Higgs coupling to fermions
CKM matrix and CP violation

$$V(\phi) \sim -\mu^2\left(\phi\phi^\dagger\right) + \lambda\left(\phi\phi^\dagger\right)^2$$



Higgs self interaction can be probed through di-Higgs production

Di-Higgs production

Sensitive to Higgs self-coupling

- $\sigma(gg \to HH) / \sigma(gg \to H) \sim 1/1500$
- and to BSM physics

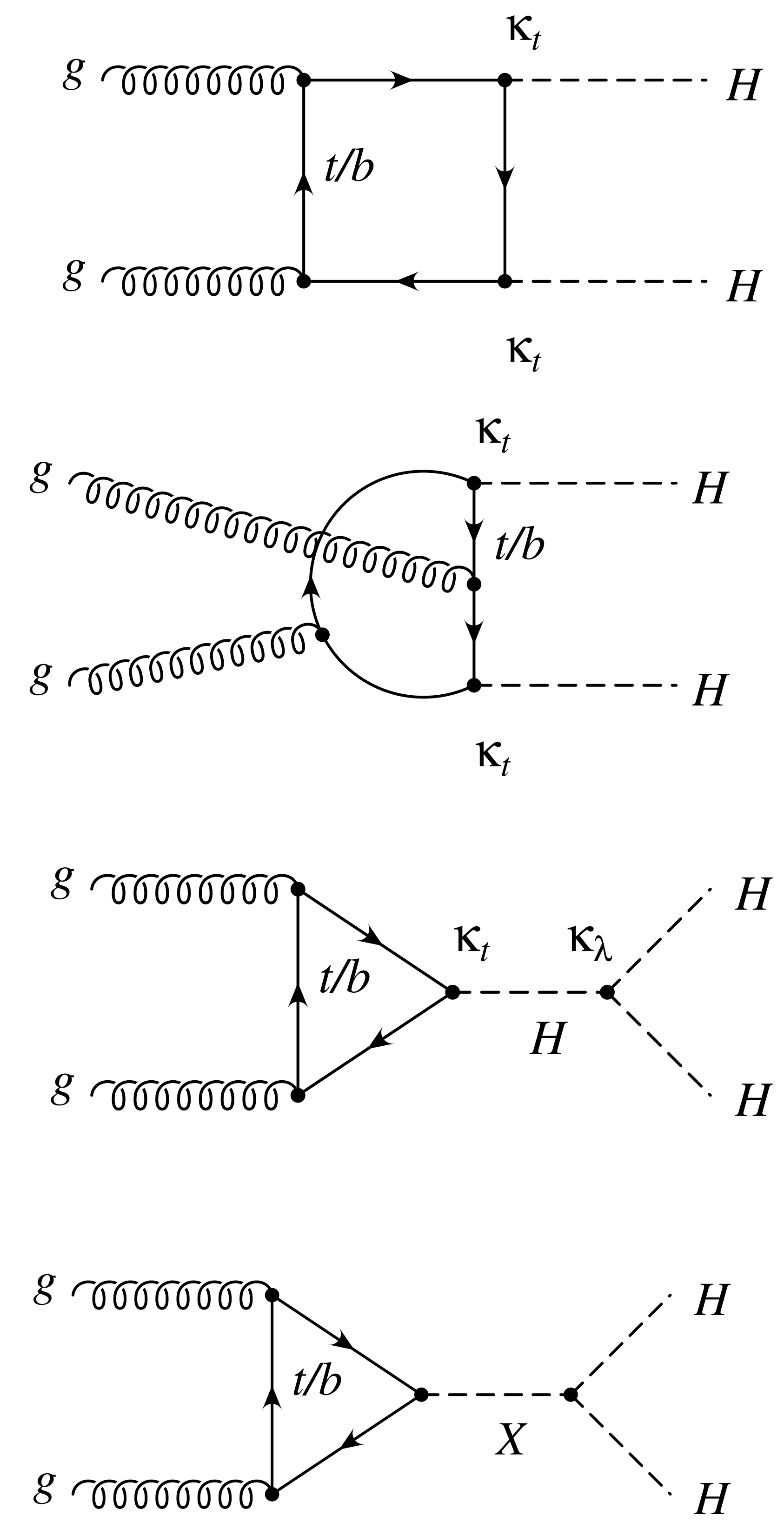
Strategy

- several possible channels

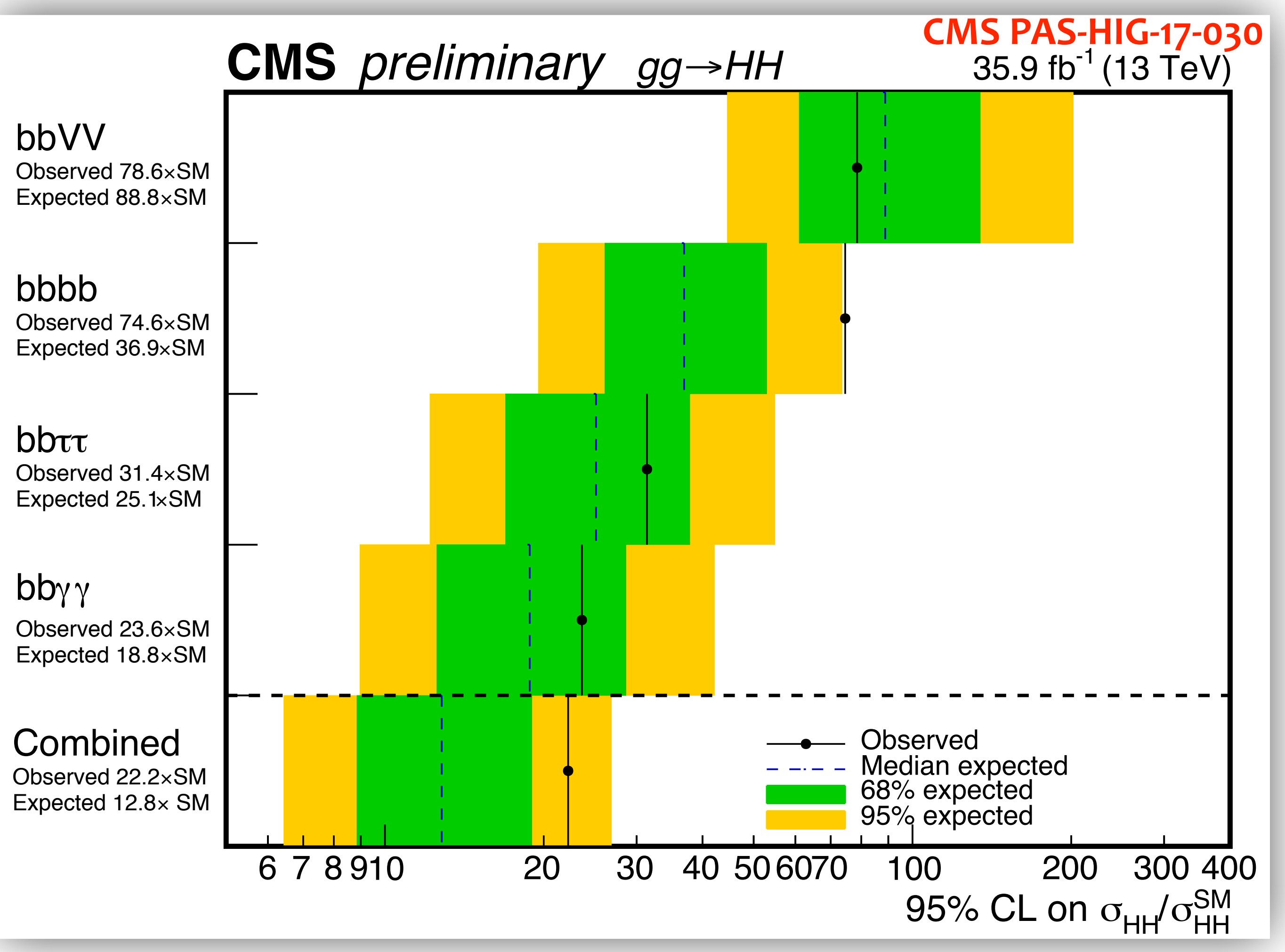
$b\bar{b}b\bar{b}$	$b\bar{b}WW$	$b\bar{b}\tau\tau$	$b\bar{b}\gamma\gamma$	$WW\gamma\gamma$
34%	25%	7%	0.26%	0.1%

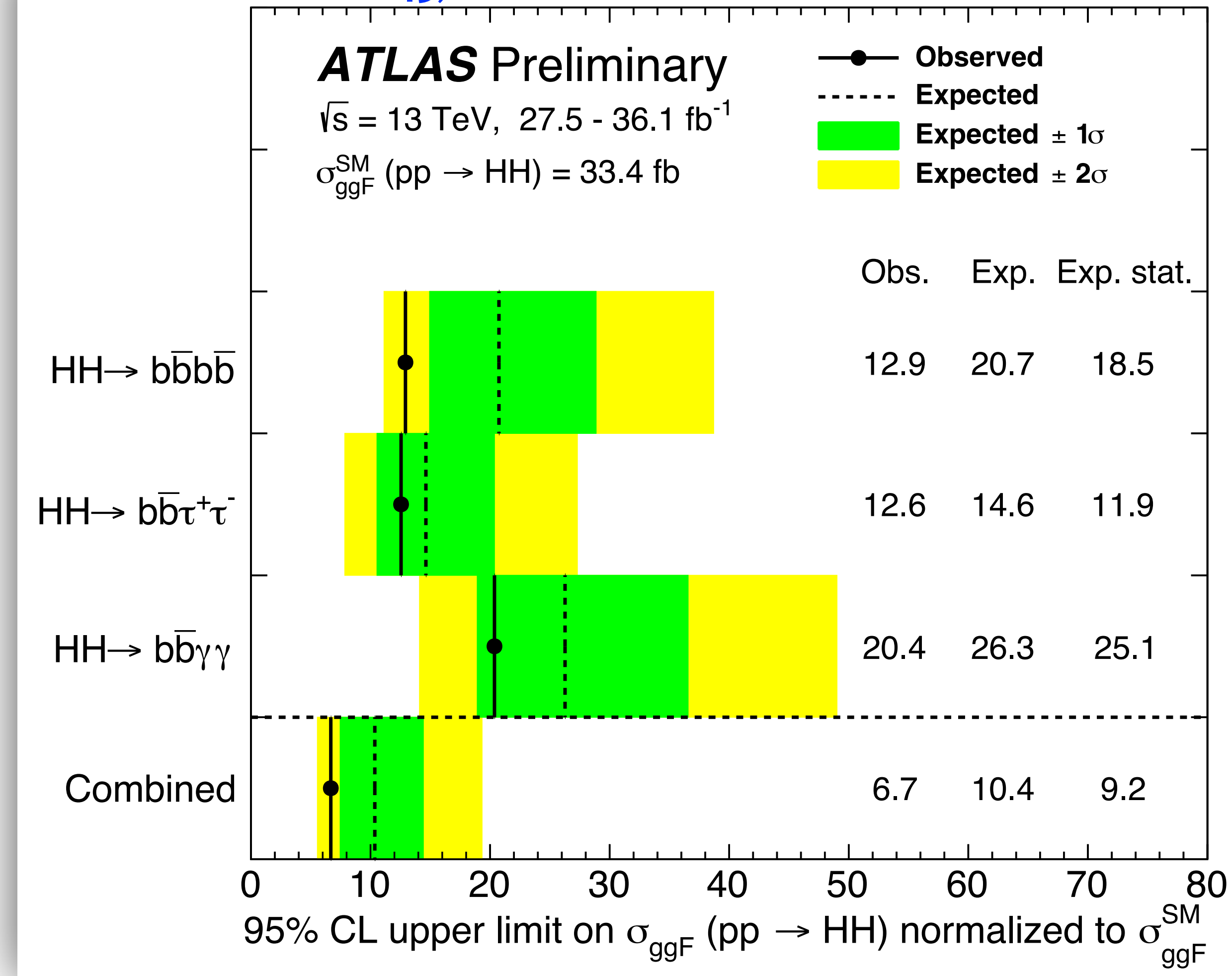
← Higher σ x BR

Higher purity →



Di-Higgs production





- CMS μ_{comb} < 22 (**13** exp.) and ATLAS μ_{comb} < 6.7 (**10.4** exp.)
- already below ~10 x SM
- goal: reach SM sensitivity with HL-LHC (3 ab^{-1})

Extracting constraints on trilinear Higgs coupling

- $-5.0 < \lambda_{HHH}/\lambda^{SM}_{HHH} < 12.1$ @ 95% C.L. ATLAS-CONF-2018-043

Is it all

Standard-Model

like ?

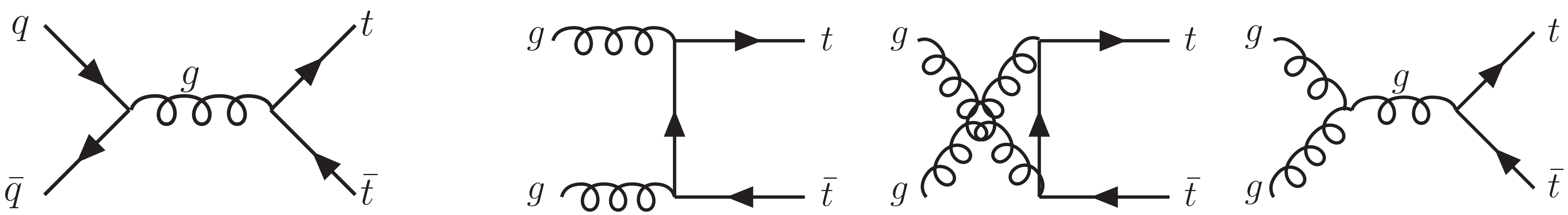
Higgs

Top

Searches

Interpretation

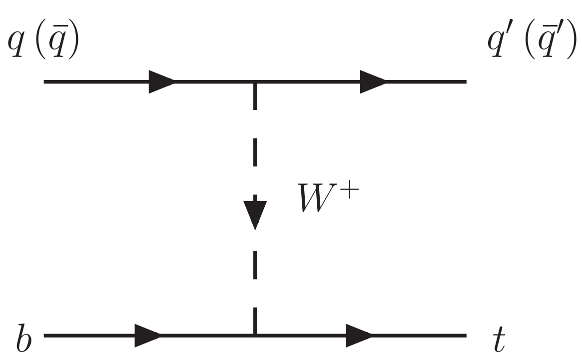
Top-quark pairs via strong interaction



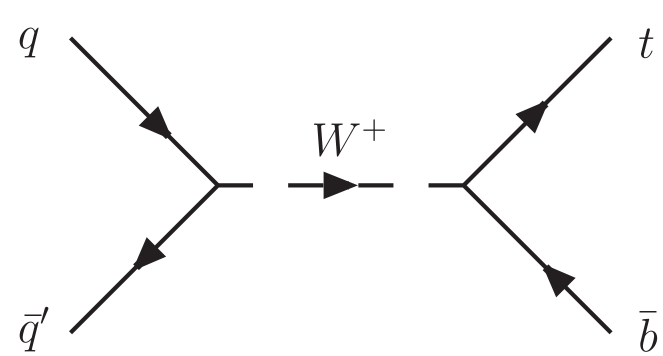
At LHC (13 TeV): $\sigma_{t\bar{t}}^{\mathrm{NNLO}}$ = 830 pb ± 4%

Only 1 in 10^8 collisions produces a top-quark pair
10^8 collisions produced a top-quark pair

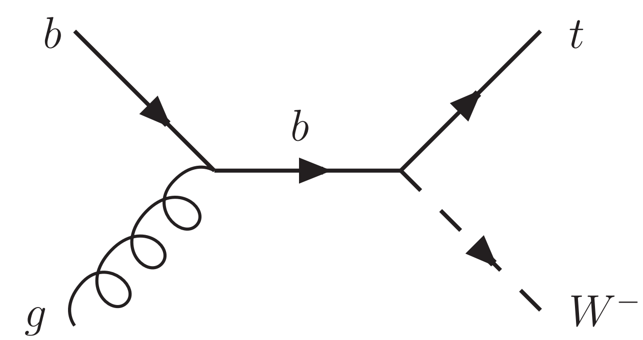
Single-top quarks via weak interaction



σ_t^{NNLO} = 213 pb ± 1%

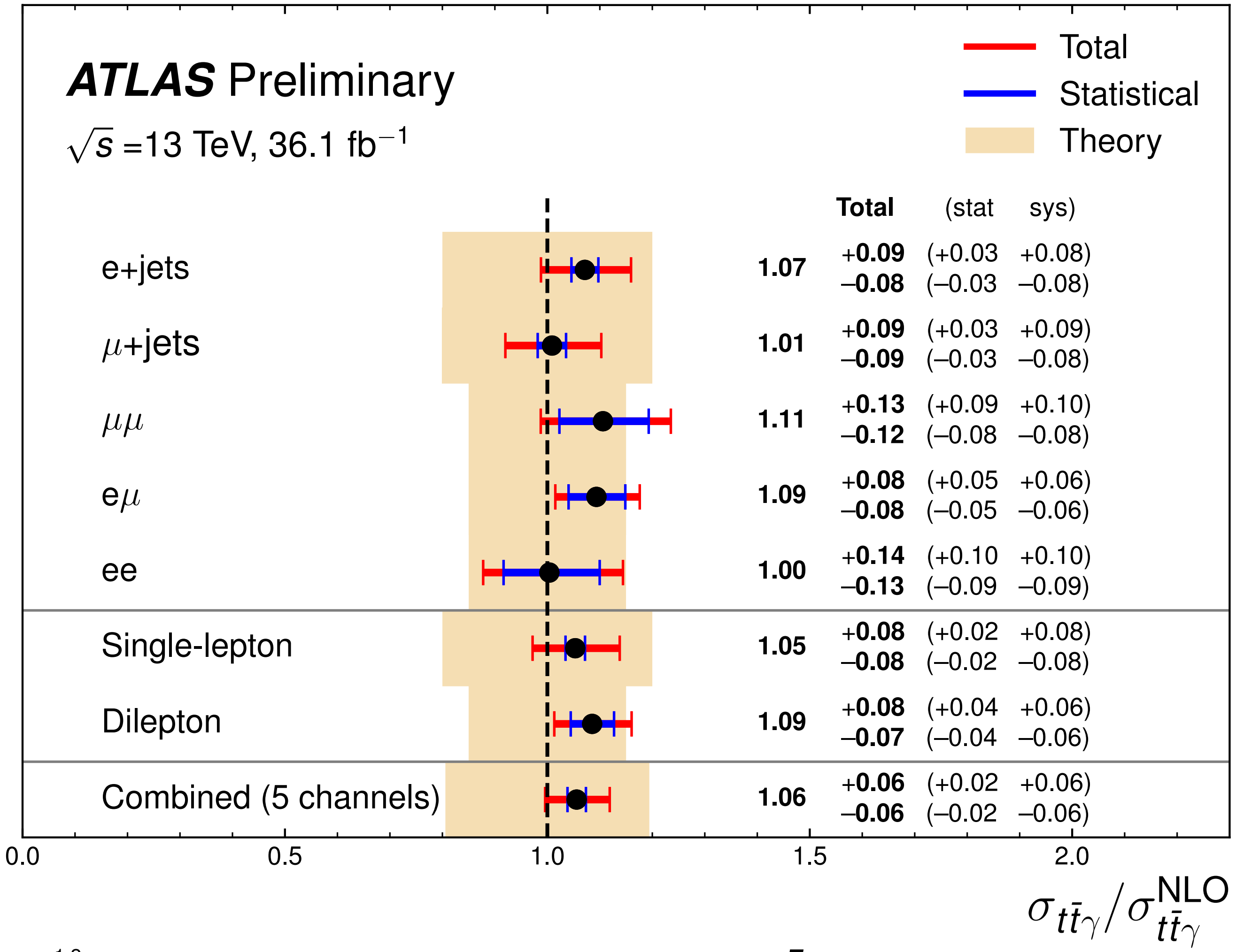


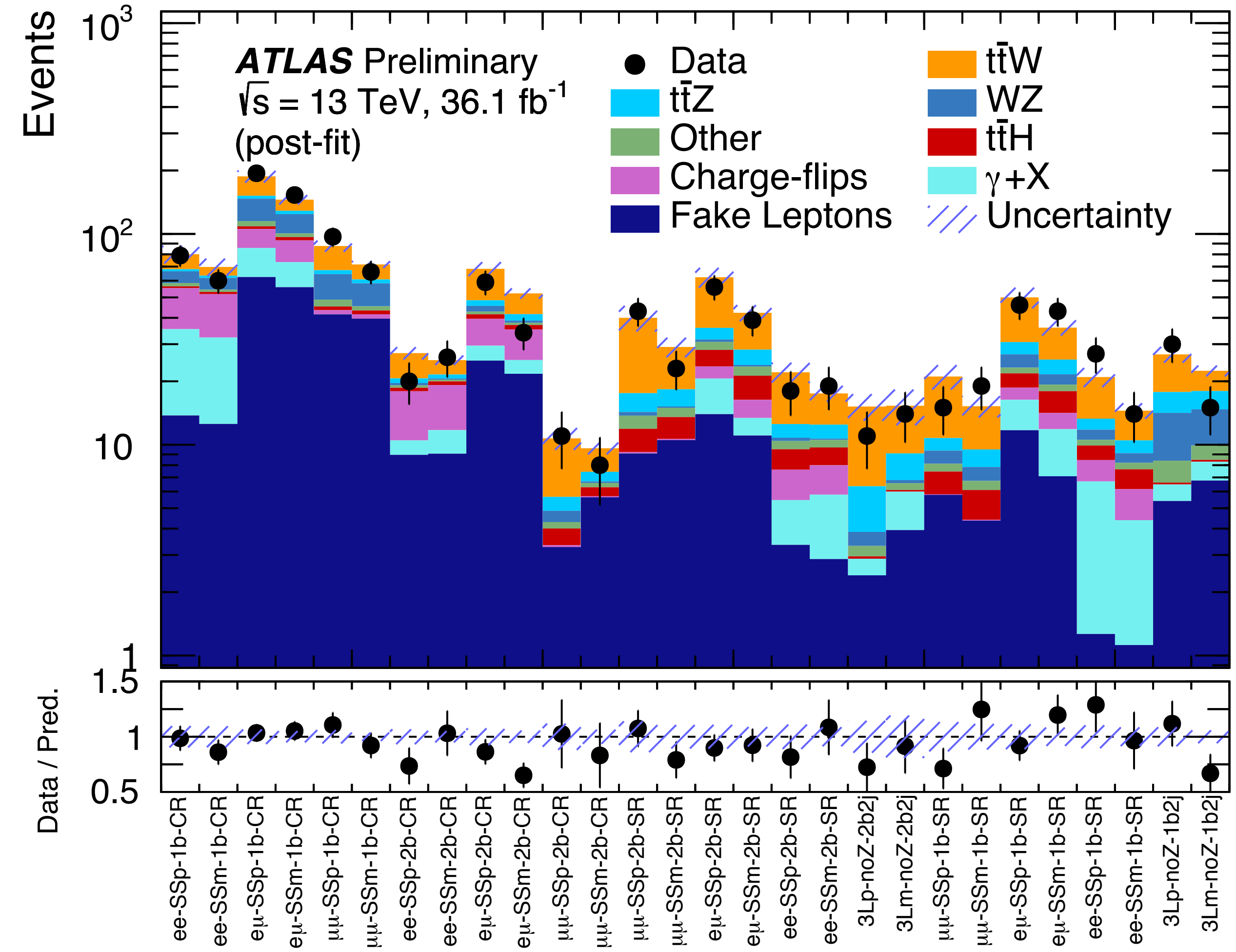
$\sigma_{Wt}^{\mathrm{aNNLO}}$ = 70 pb ± 5%

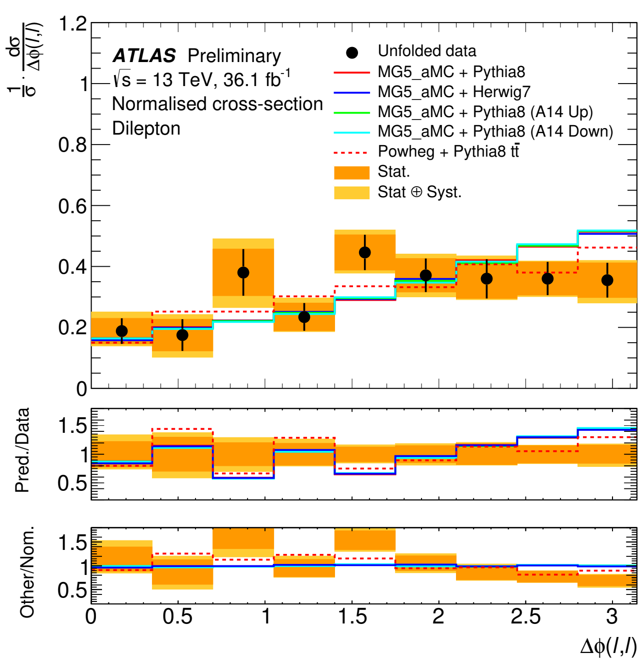


$\sigma_s^{\mathrm{aNNLO}}$ = 11 pb ± 4%

Top electroweak couplings: $t\bar{t}\gamma$, $t\bar{t}Z$







$t\bar{t}\gamma$@13TeV

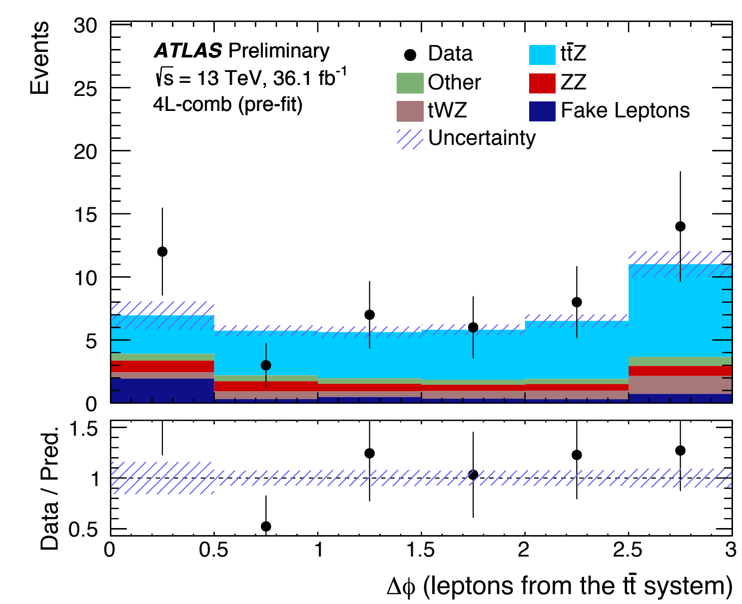
including dilepton differential spectra

ATLAS-CONF-2018-048

$\sigma(t\bar{t}Z$@13TeV) in pb

0.95 ± 0.08 ± 0.10 — 1711.02547

0.91 ± 0.08 ± 0.09 — **ATLAS-CONF-2018-047**

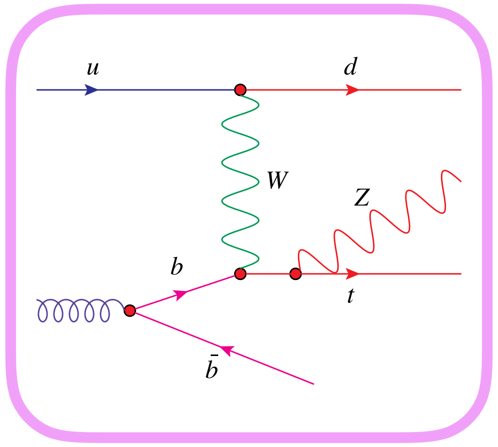


Evidence for tZ

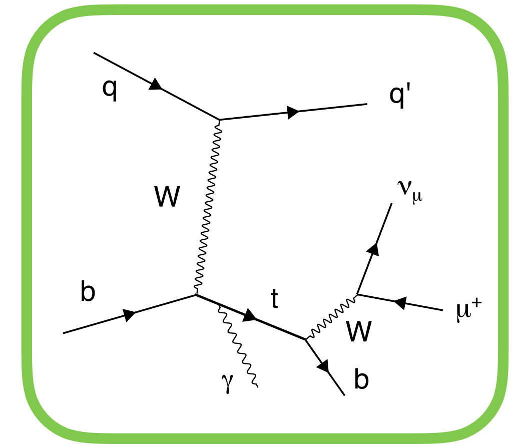
- observed **4.2σ** / **3.7σ** ATLAS PLB 780 (2018) 557 CMS PLB 779 (2018) 358

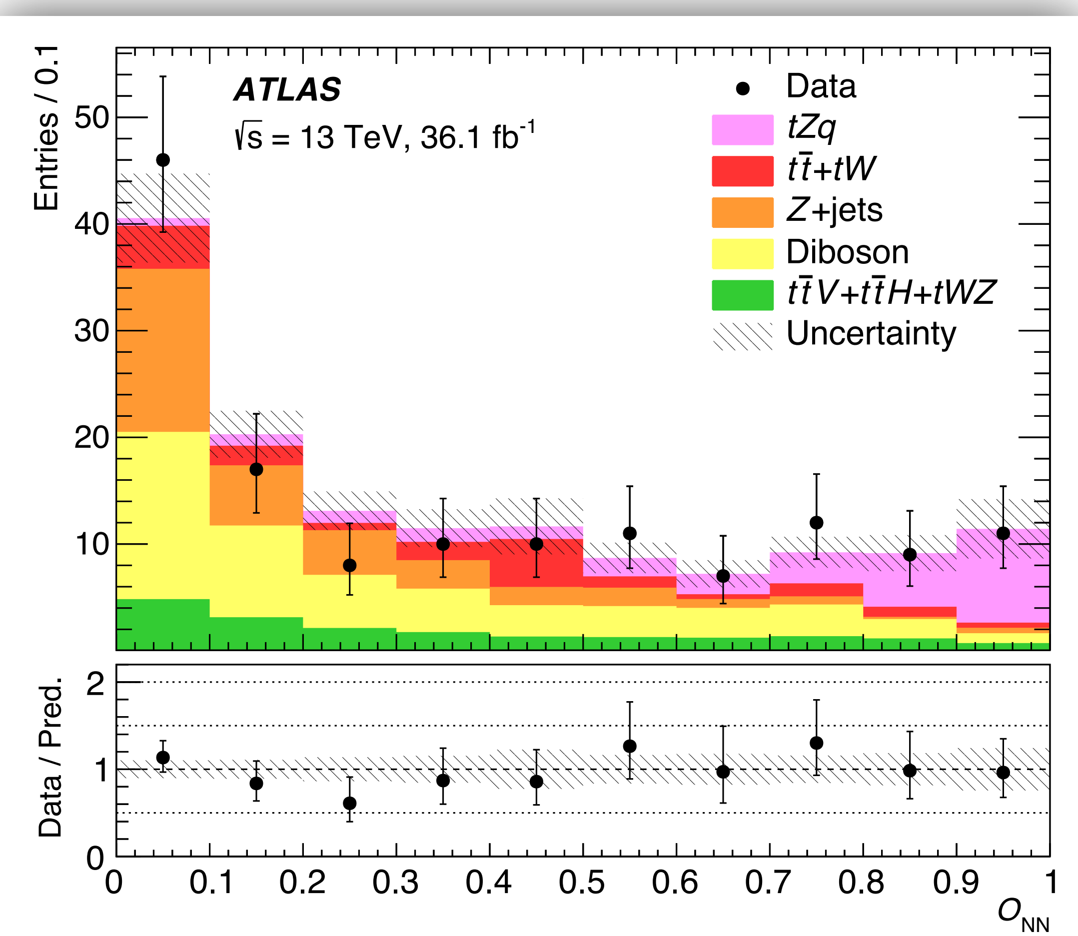
Evidence for tγ

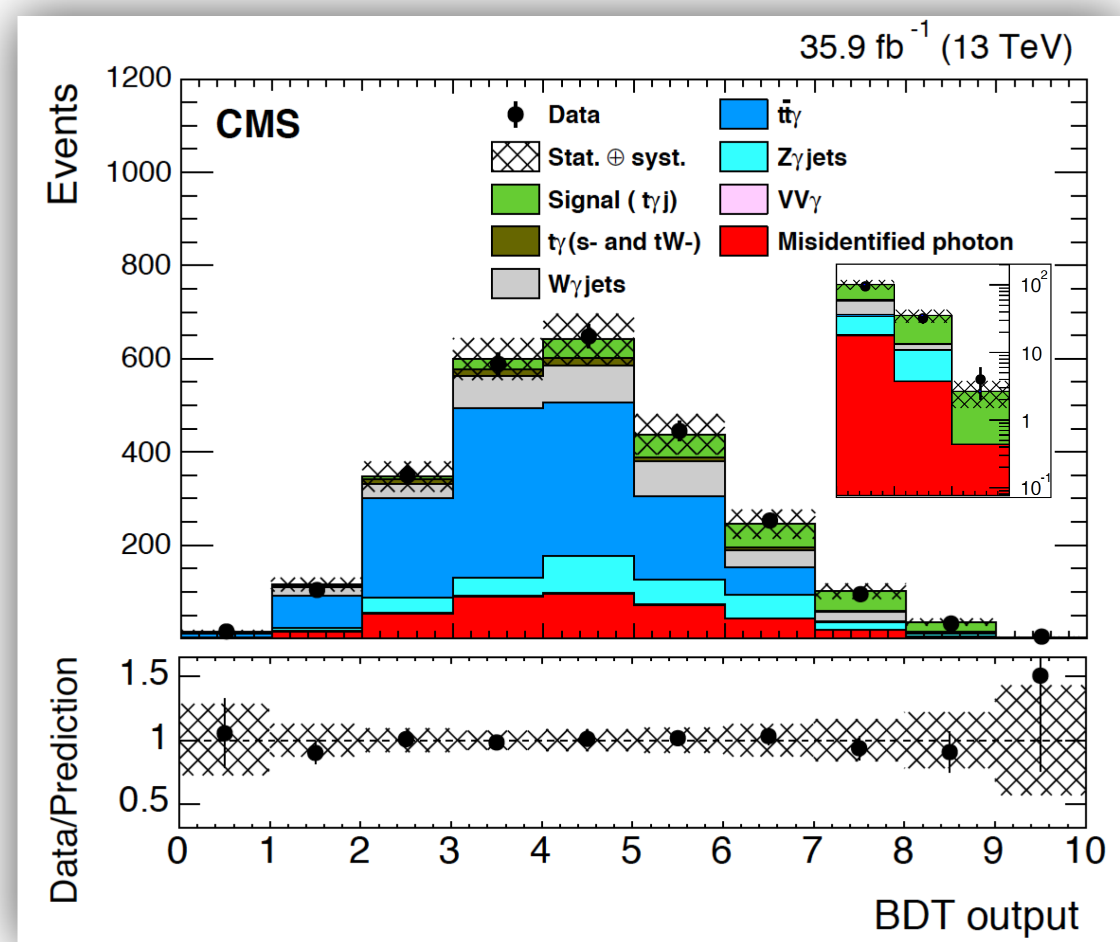
- observed **4.4σ** CMS 1808.02913



Both in good agreement with SM predictions



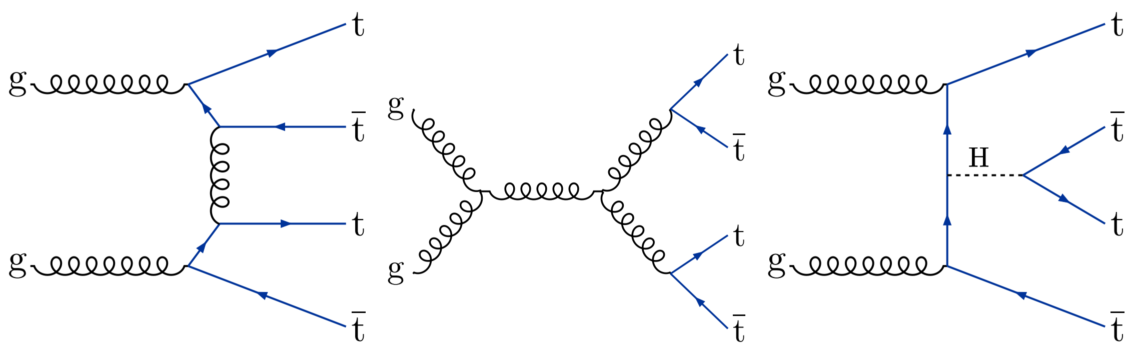




Production of four top quarks

SM $t\bar{t}t\bar{t}$

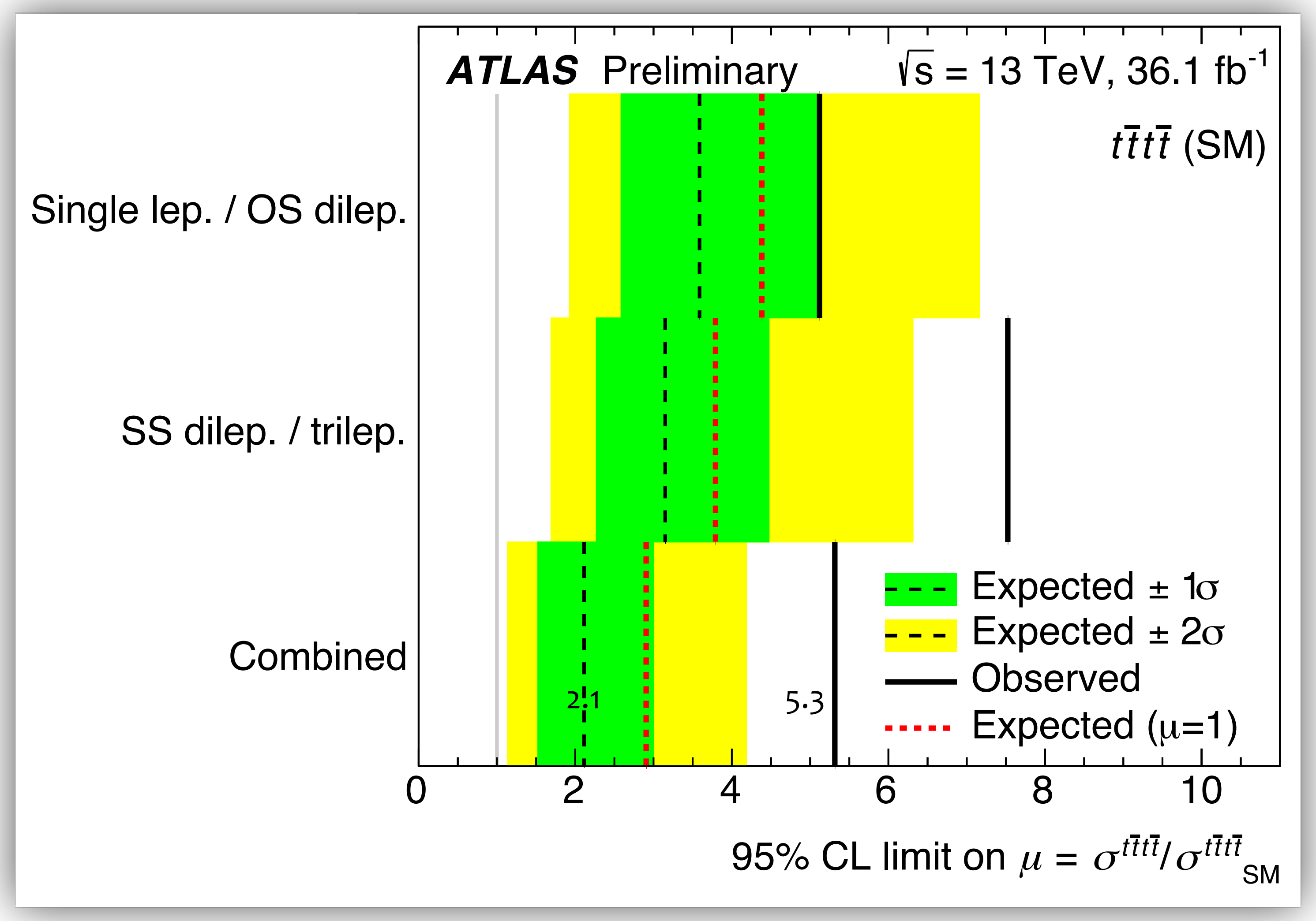
- sensitive to NP and top Yukawa
- $\sigma_{t\bar{t}t\bar{t}}/\sigma_{t\bar{t}} = 10^{-5}$

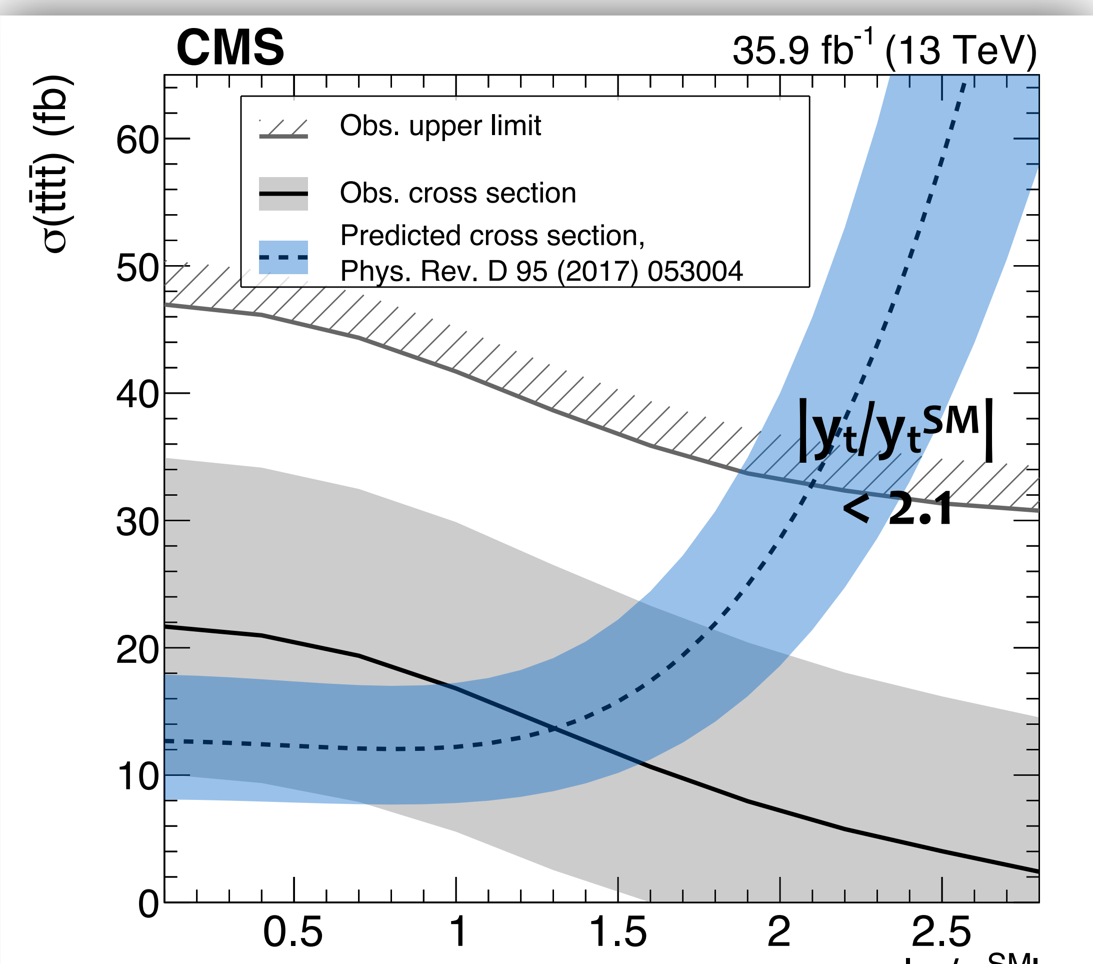


Results

- **2.8σ** (1.0σ exp) SS, 3ℓ, 2ℓ, 1ℓ

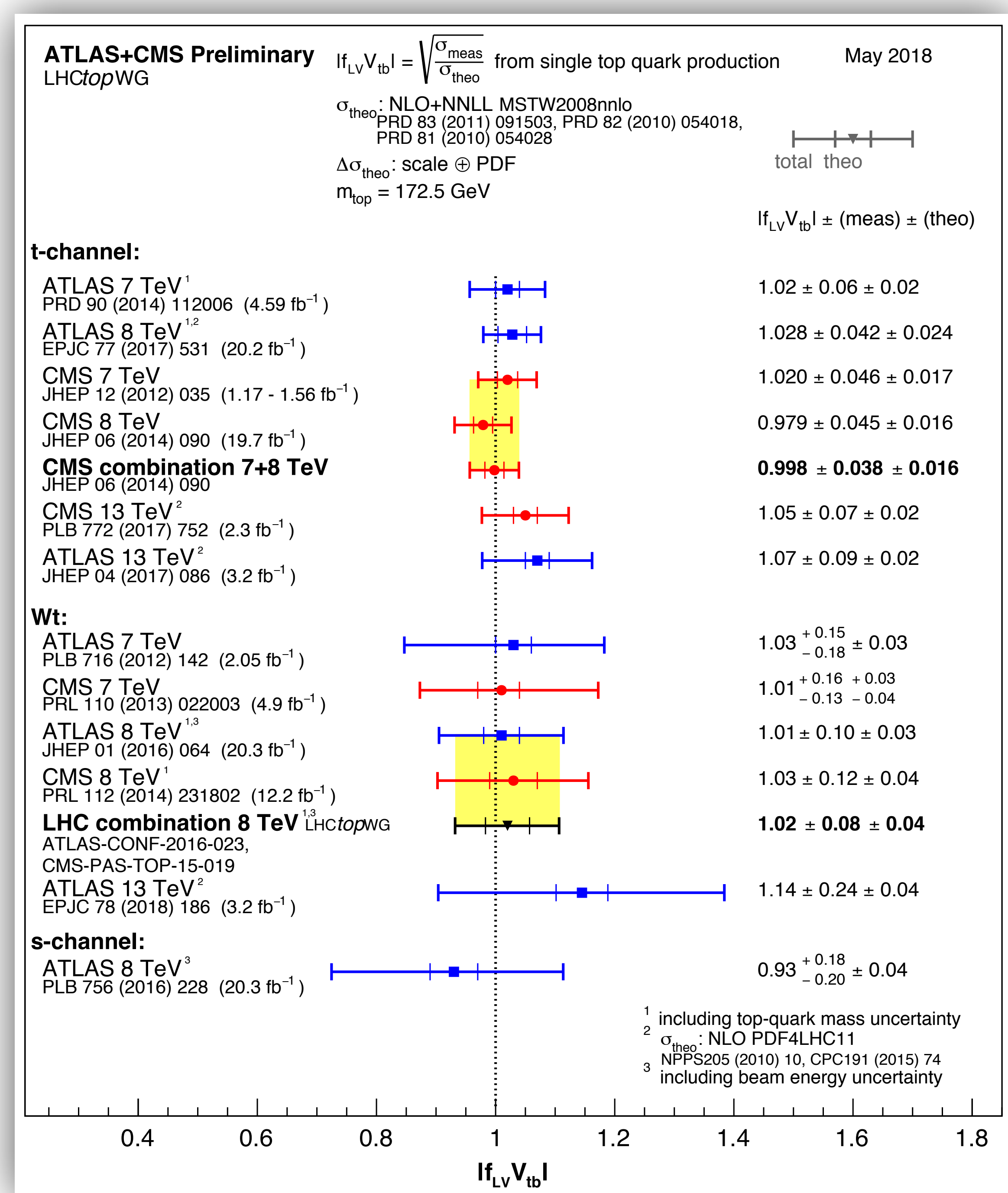
1.6σ (1.0σ exp) SS, 3ℓ





CMS EPJC 78 (2018) 140

CKM V_{tx}



V_{tb} from single top

- *t*-, *Wt*-, *s*-channel @ 7, 8, 13 TeV
- assuming $|V_{tb}| \gg |V_{td}|, |V_{ts}|$

CMS

- $|V_{tb}| = 0.998 \pm 0.038 \pm 0.016$
- 7+8 TeV *t*-channel

LHCtopWG

- $|V_{tb}| = 1.02 \pm 0.08 \pm 0.04$
- 8 TeV *Wt*-channel

PDG ’18

- $|V_{tb}| = 1.019 \pm 0.025$
- assumes correlated error

… there is much more than $|V_{tb}|$ in these measurements

Also:

studies of light-quark tagging and |Vtd| from Wt asymmetry

Alvarez et al. ’17
Faroughy et al. ’18

Is it all

Standard-Model

like ?

Higgs

Top

Searches

Interpretation

Search for LFV Higgs decay τ-channels (τμ, τe)

- decays are forbidden in the SM
- can occur in many NP scenarios
- would allow $\tau \to \ell$ via a virtual Higgs
- arise at tree level from the flavour violating Yukawa $Y_{\ell^\alpha \ell^\beta}$, where the two leptons have different flavours

$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$

$$B(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_{SM}}$$

Previous direct searches

- CMS : **2.4σ** excess in the $H \to \mu\tau$ channel — PLB 749 (2015) 337
- ATLAS : no excess observed — JHEP 11 (2015) 211 — EPJC 77 (2017) 70

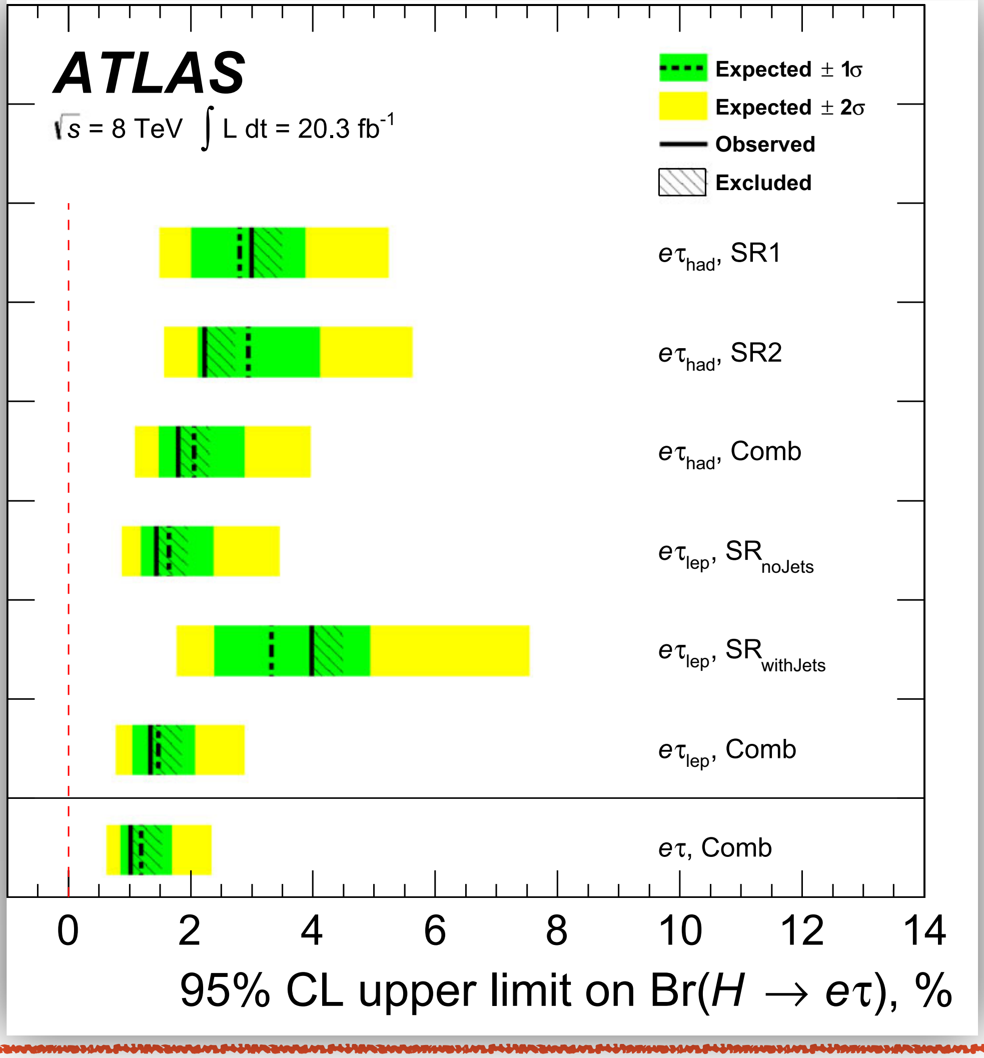
CMS update with 36 fb⁻¹ and BDT discr.

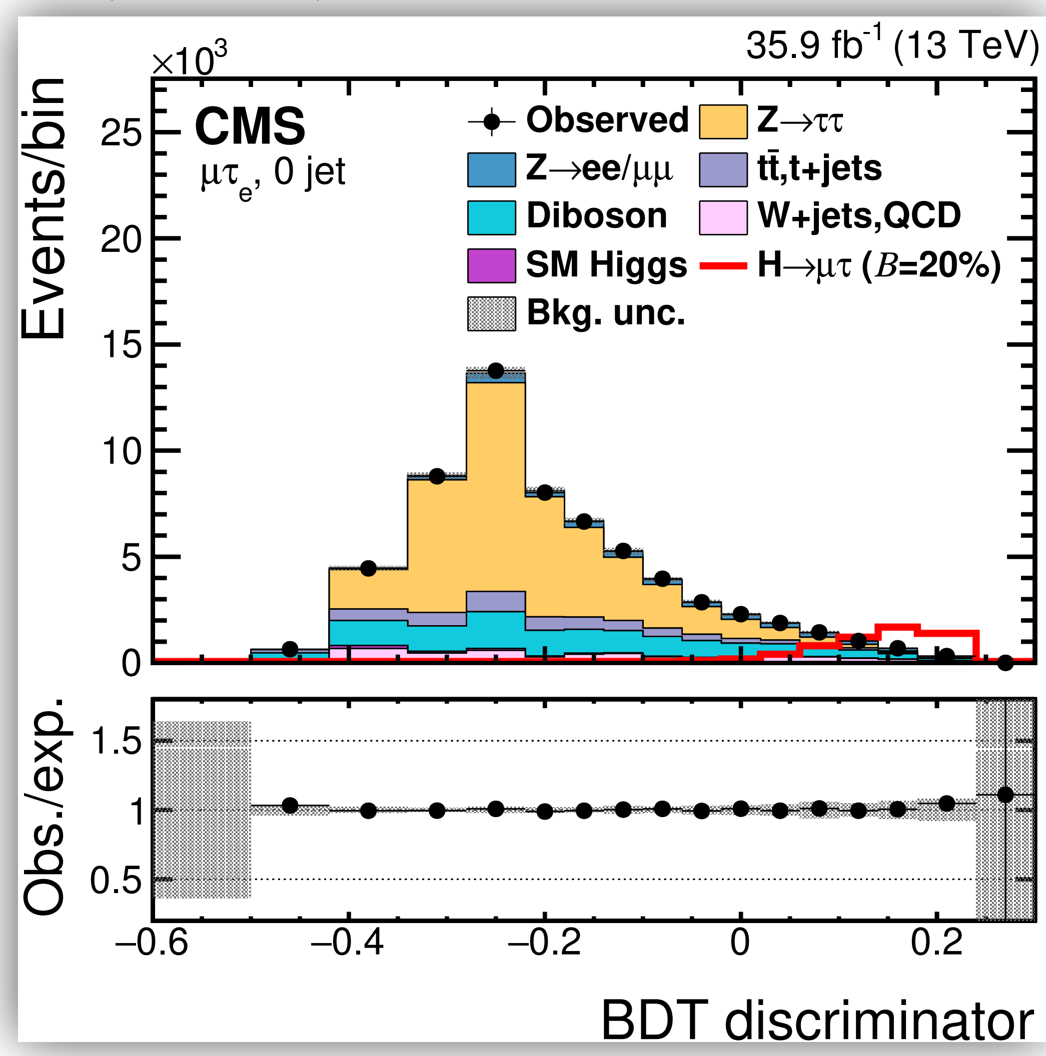
ATLAS EPJC 77 (2017) 70
CMS JHEP 06 (2018) 001

- **excludes** BF of best fit for 2.4σ excess

New limits

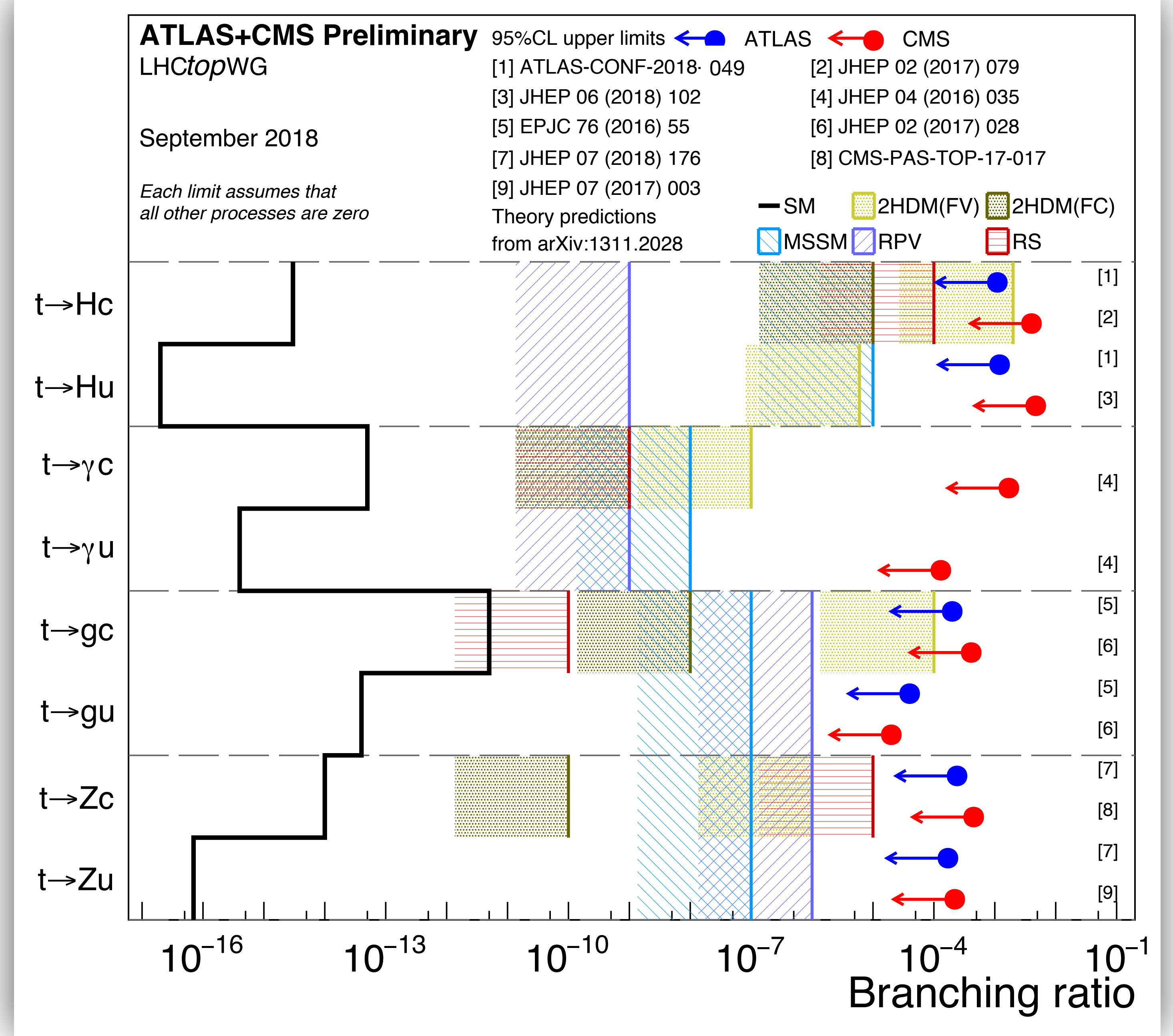
	ATLAS	CMS
$B(H \to \mu\tau) <$	1.43% (1.03%)	0.25% (0.25%)
$B(H \to e\tau) <$	1.04% (1.21%)	0.61% (0.37%)





Flavour changing neutral currents and top quarks

- suppressed in SM, access to BSM physics in the loops
- search for $t \to (\gamma, g, Z, \mathbf{H}) + (u, c)$



ATLAS-CONF-2018-049

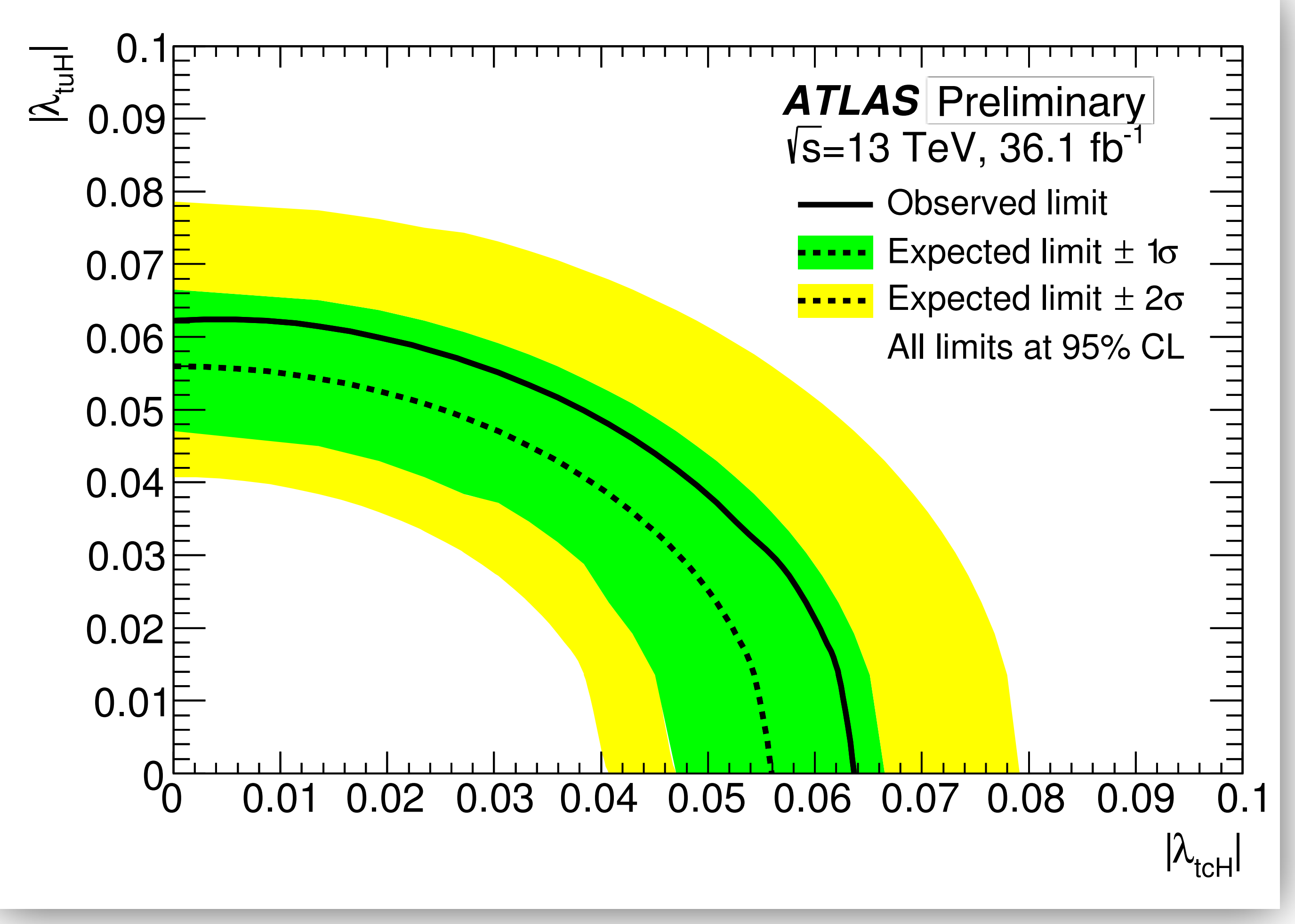
New at CKM 2018

New results for this week

- $t \to H(b\bar{b})q$ or $t \to H(\tau\tau)q$
- full combination of 2015–2016 dataset for $t \to Hq$

Results

- $B(t \to Hc) < 11\ (8.3) \times 10^{-4}$ and $B\,(t \to Hu) < 12\ (8.3) \times 10^{-4}$

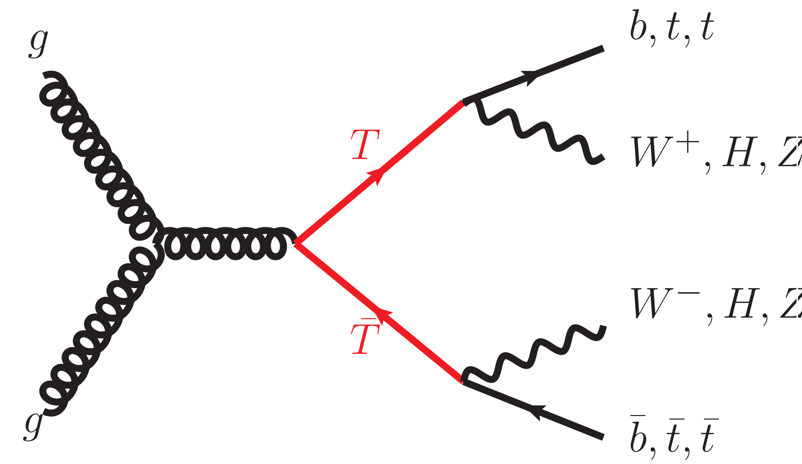


Vector-like quarks

ATLAS 1808.02343

Vector-like partners of 3rd generation quarks

- color-triplet spin-1/2
- couple preferentially to 3rd generation



New combination of all channels

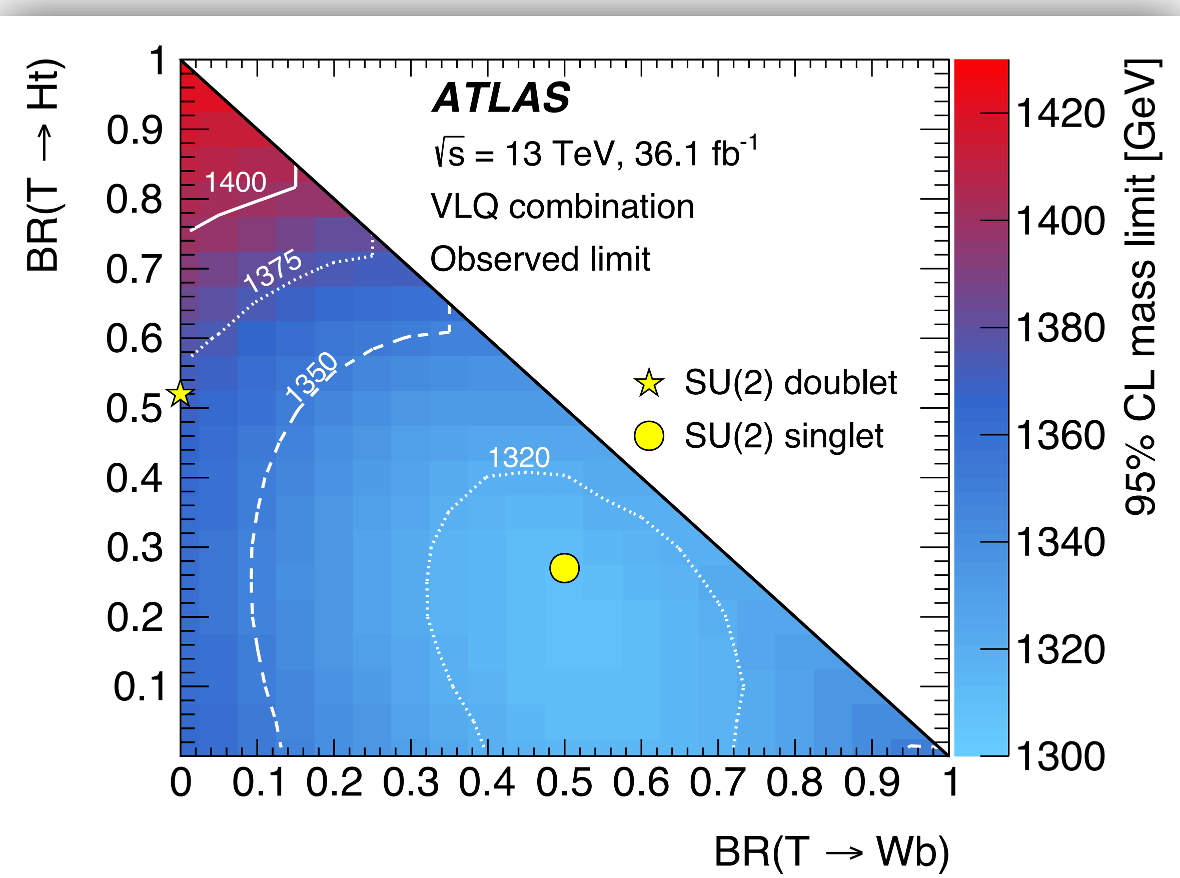
- decays of $T(+2/3)$, $B(-1/3)$ to W, Z, H bosons

Singlet exclusion limits

- $m_T < 1.31$ TeV
- $m_B < 1.22$ TeV

Weak isospin (T, B) doublet

- m_T and $m_B < 1.37$ TeV excluded

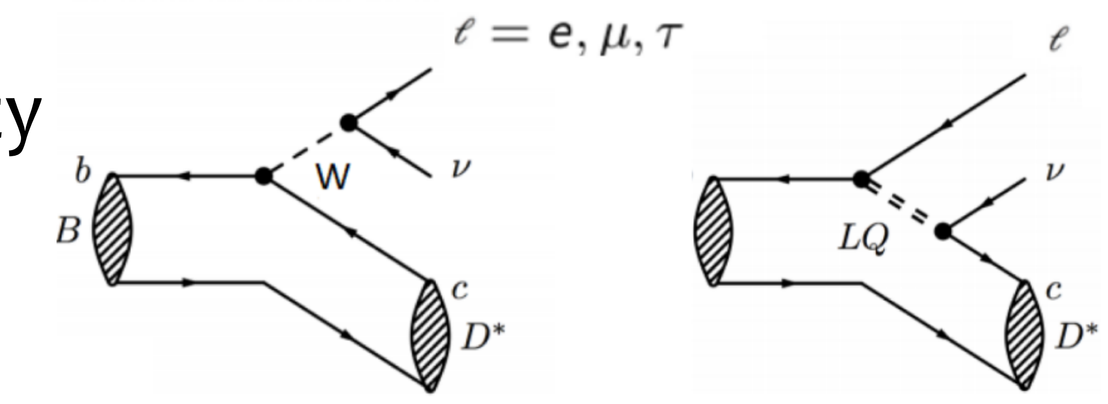


B(T→Ht) + B(T→Zt) + B(T→Wb) = 1

Implications of B-anomalies (I)

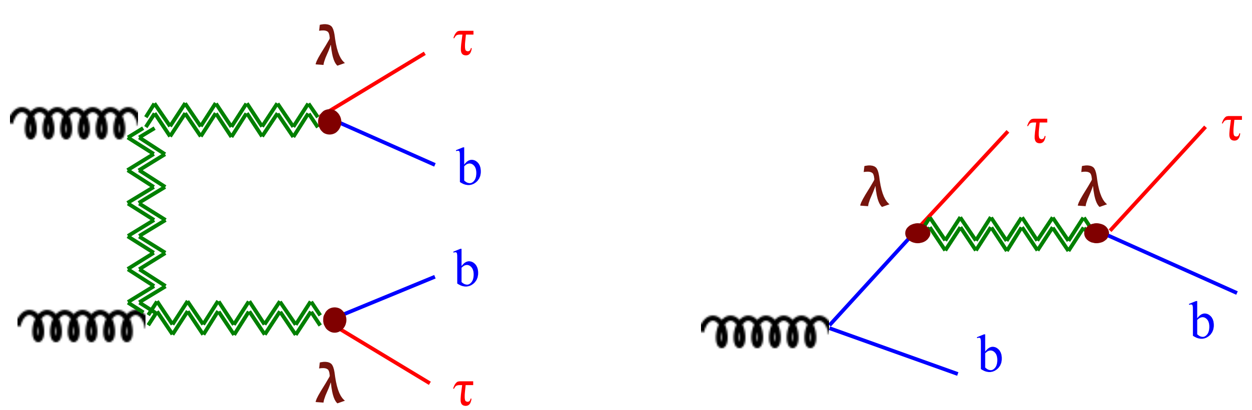
$R_{D(*)}$ and $R_{K(*)}$ anomalies

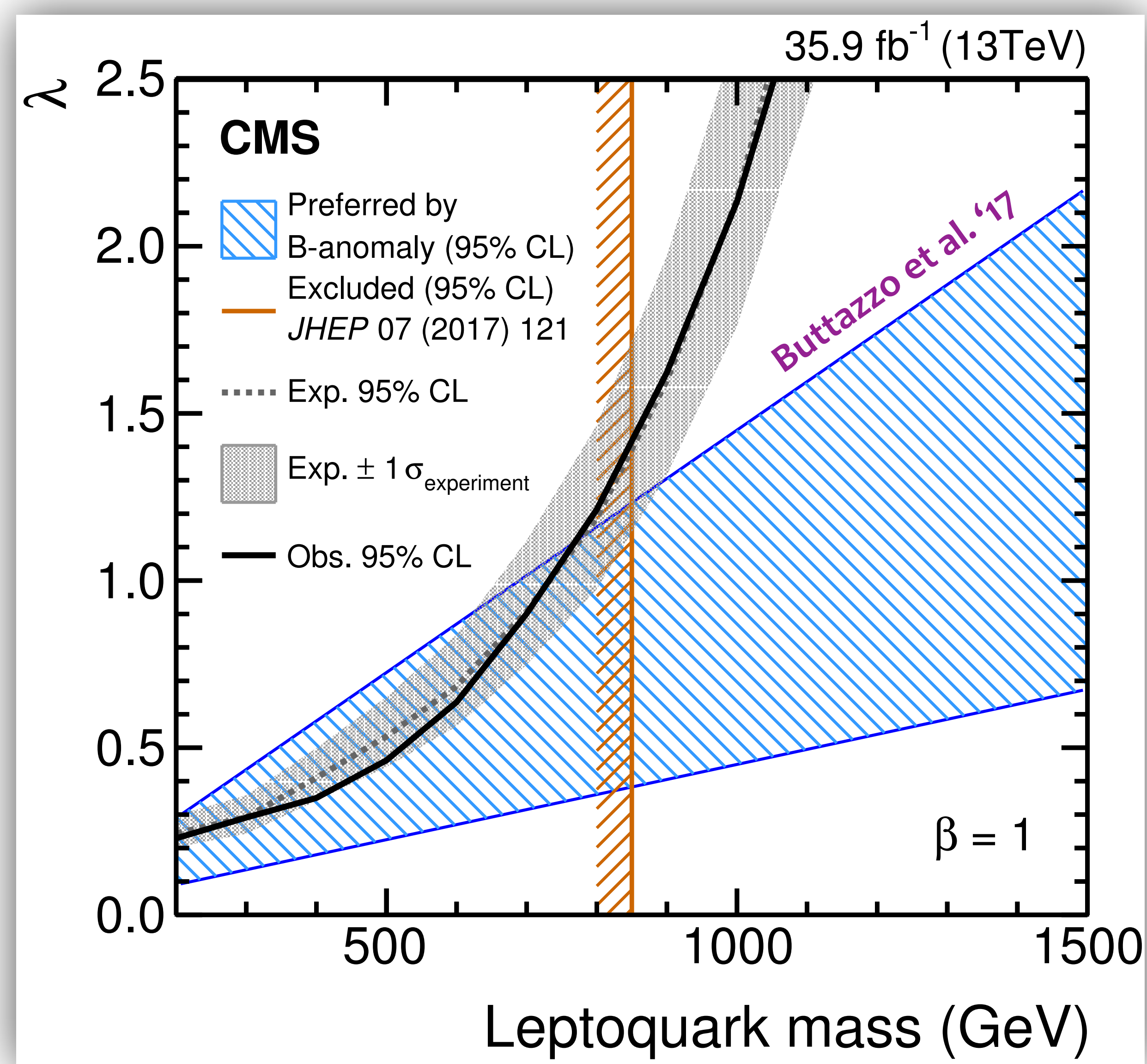
- challenging Lepton Flavour Universality



Rescue of leptoquarks?

- Could preferentially couple to 3rd generation leptons and quarks
- final states with *t, b, τ, ν*





Recent results

- LQ LQ → $\ell\tau jj$ — CMS JHEP 07 (2017) 121
- single LQ → $\ell\tau(\tau)b$ — CMS JHEP 07 (2018) 115

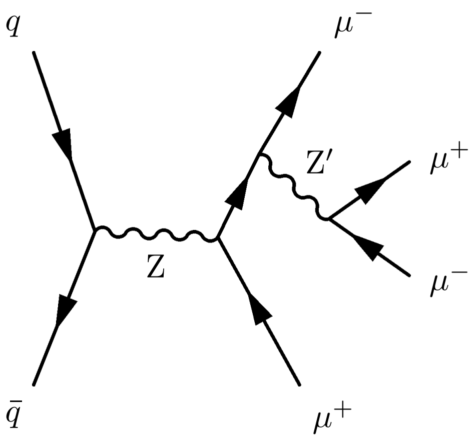
Implications of B-anomalies (II)

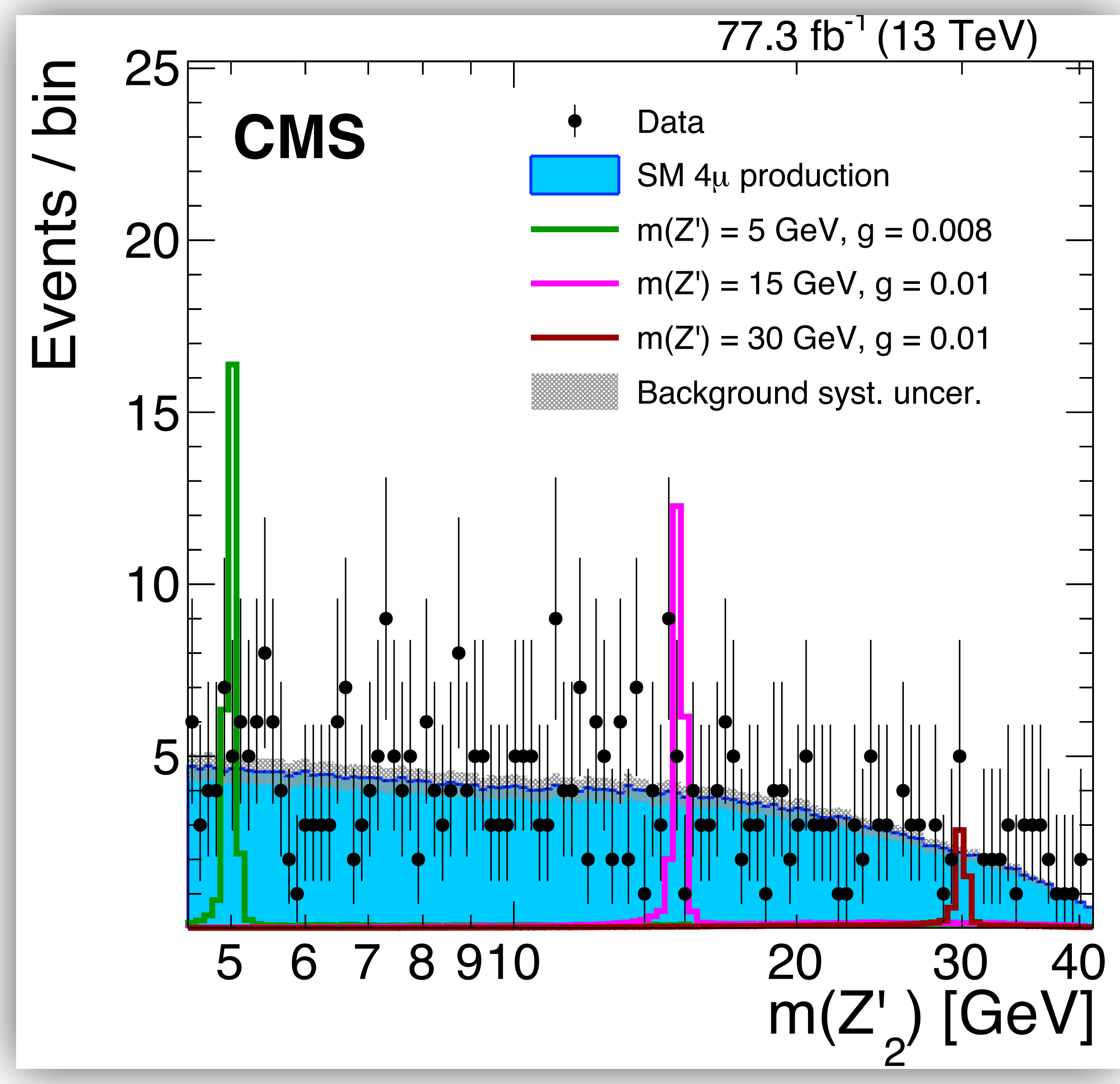
CMS 1808.03684

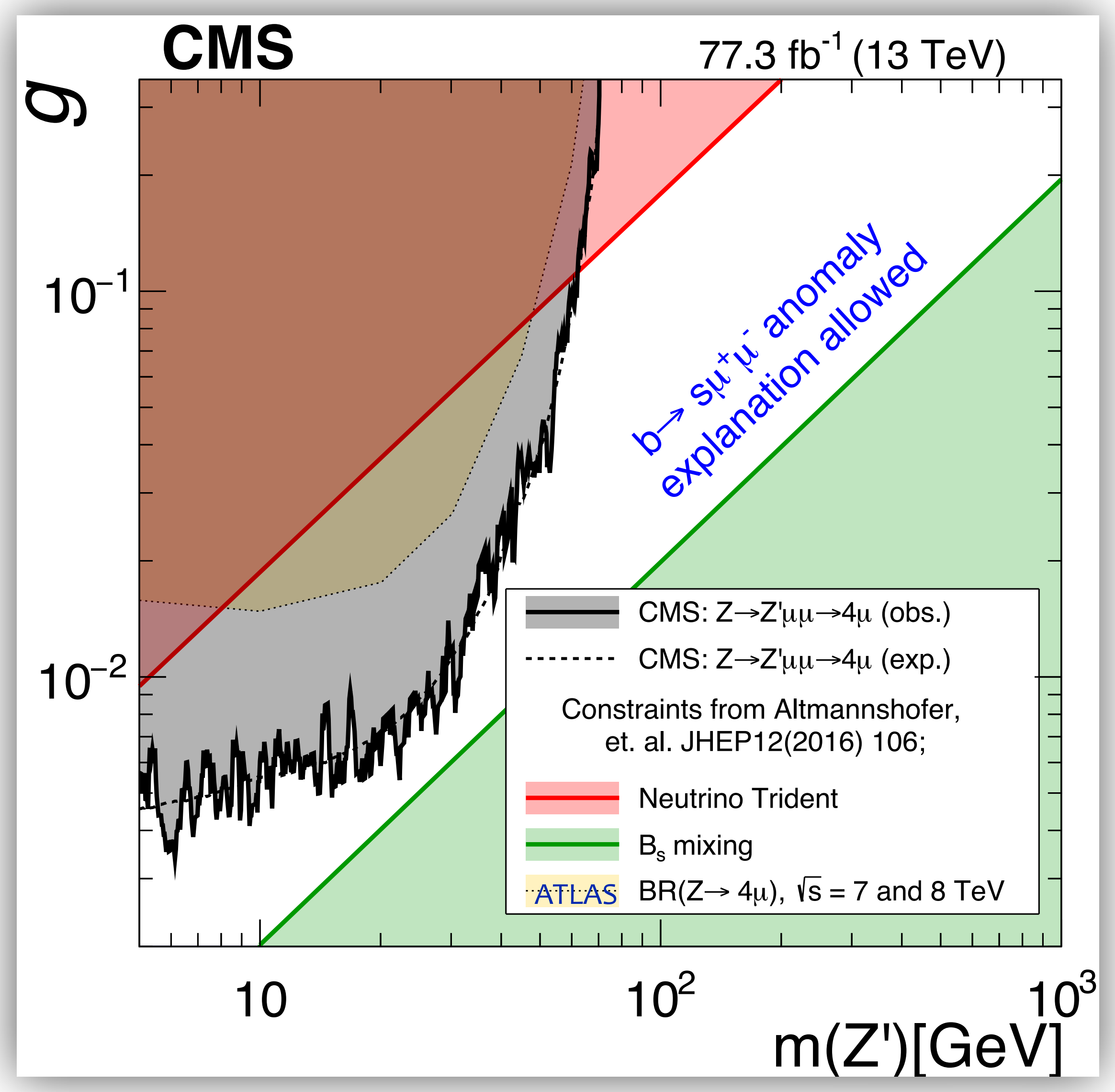
Search for Z' boson below the Z mass

80 fb^{-1}

- can result from additional U(1)' symmetry (here: $L_\mu - L_\tau$)
- search for Z' → $\mu\mu$ within Z → 4μ



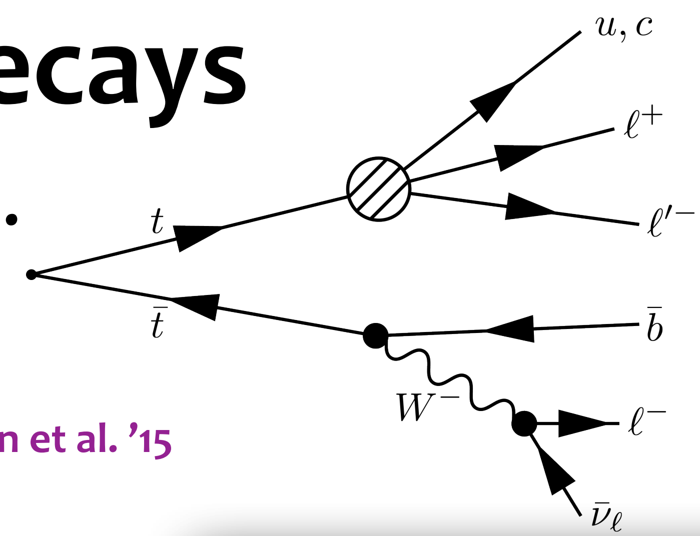




Implications of B-anomalies (III)

ATLAS-CONF-2018-044

Search for LFV in top quark decays



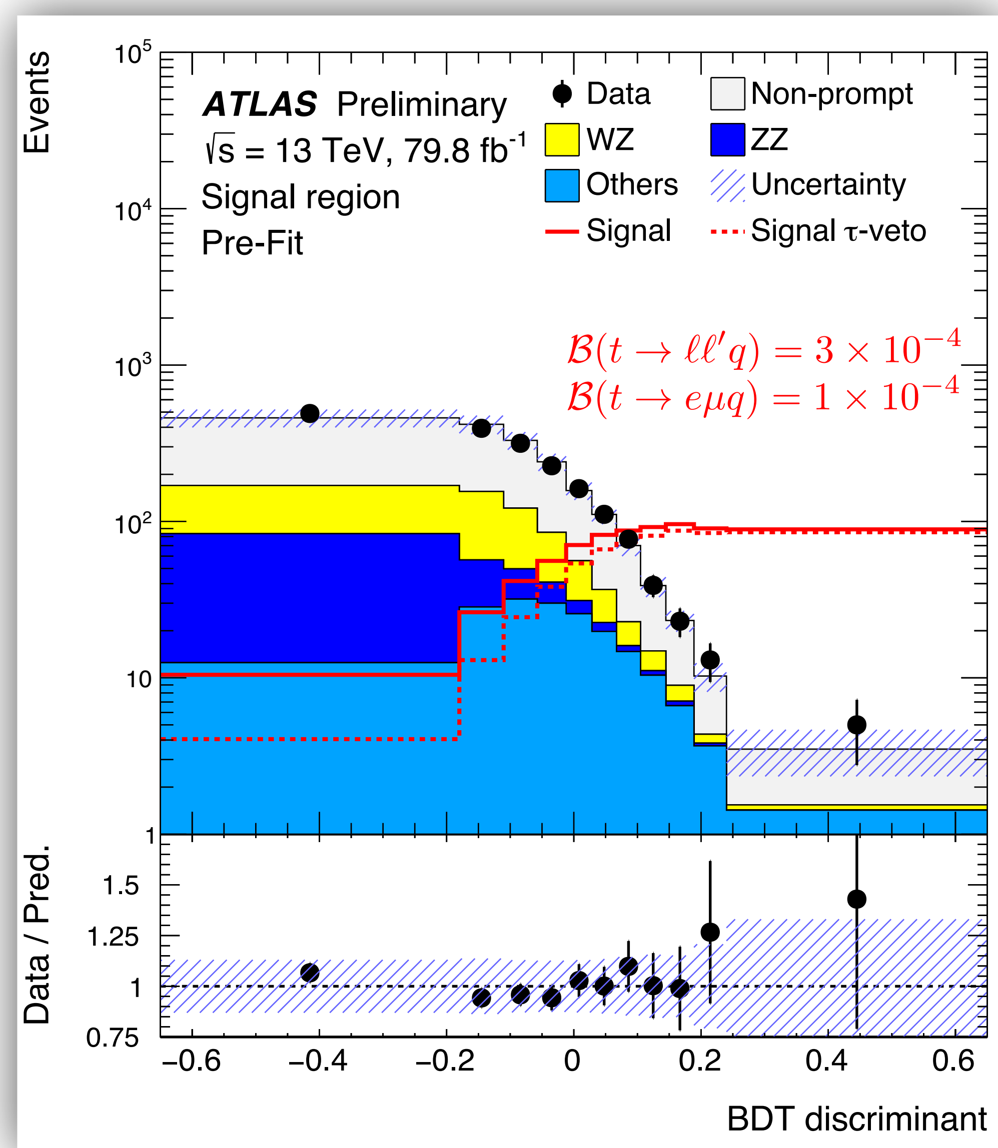
- LFV probed in decays of μ, τ, B, Z, H …
- never searched for in top quarks
- indirect limit $B(t \to e\mu q) < 10^{-3}$ Davidson et al. '15

New search: $t\bar{t} \to (\ell\ell' q)(\ell\nu b)$ 80 fb^{-1}

- $\ell = \{e, \mu\}$, $q = \{u, c\}$
- SR: $ee\mu$, $e\mu\mu$, Z boson veto
- BDT trained → shape fit

First top result with 2017 data

- Data compatible with absence of signal
- $B(t \to \ell\ell' q) < 1.9\ (1.4) \times 10^{-5}$
- $B(t \to e\mu q) < 6.6\ (4.8) \times 10^{-6}$



Is it all

Standard-Model

like ?

Higgs

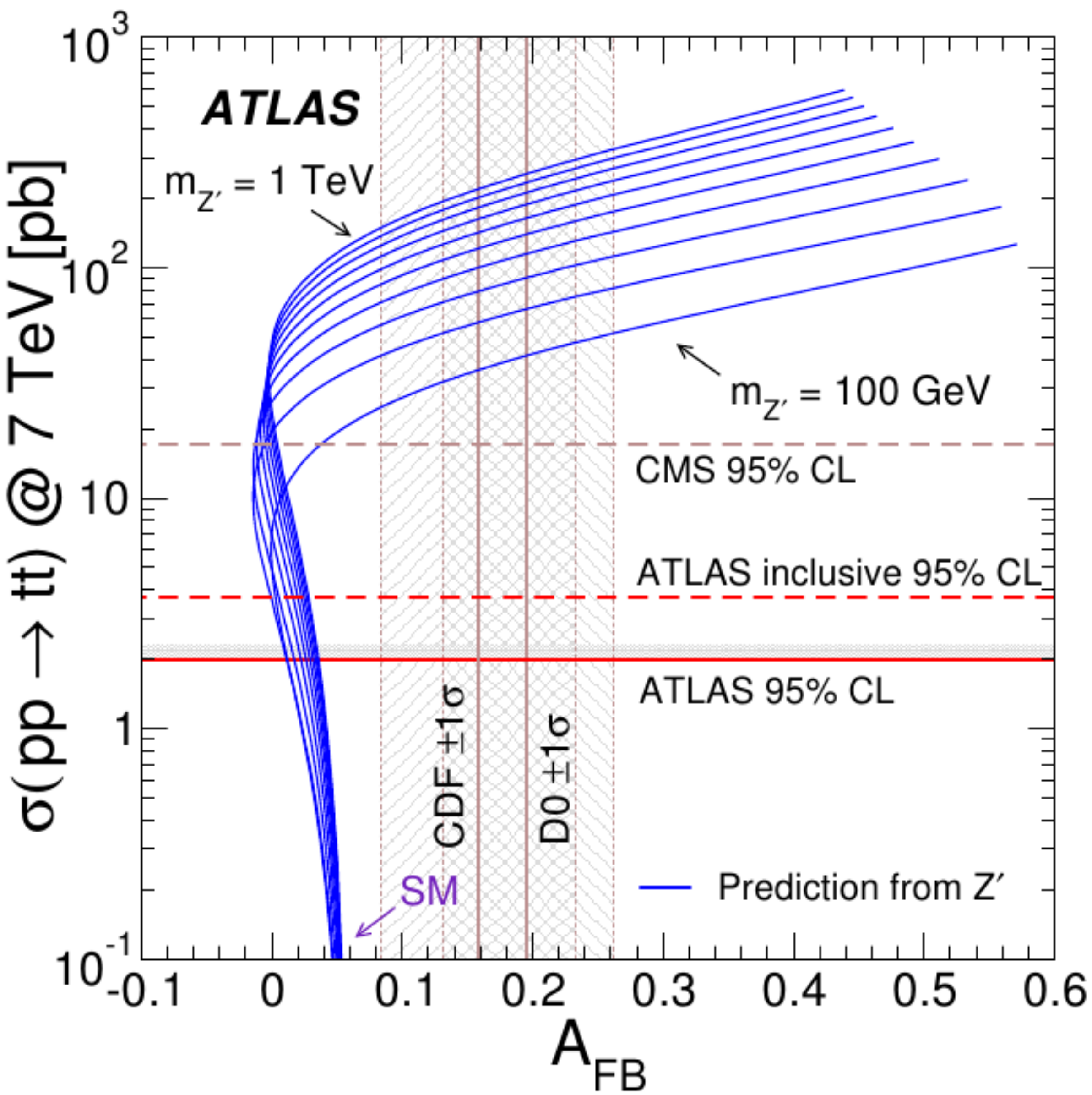
Top

Searches

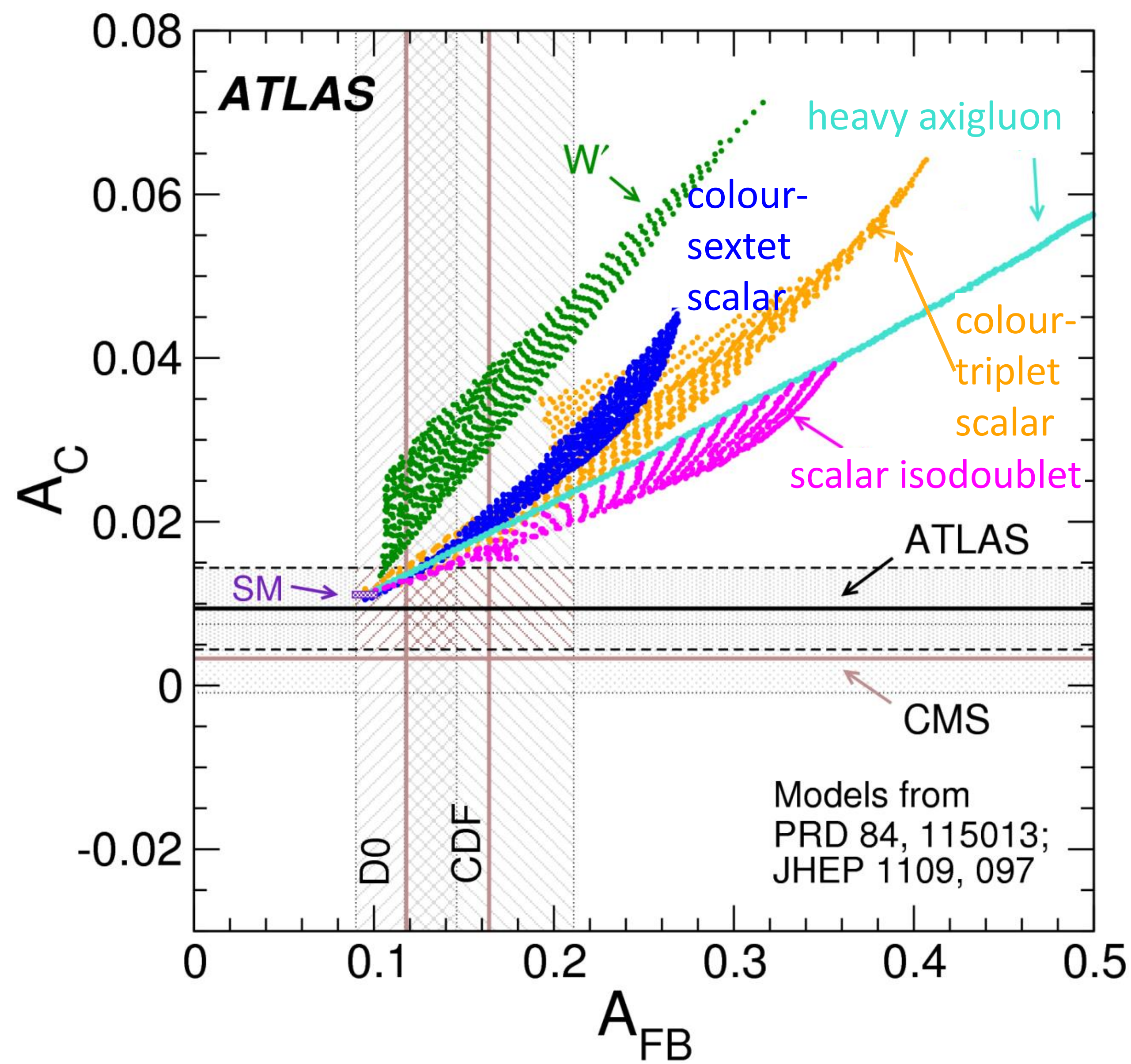
Interpretation

Precision measurements and explicit models

- e.g. asymmetries



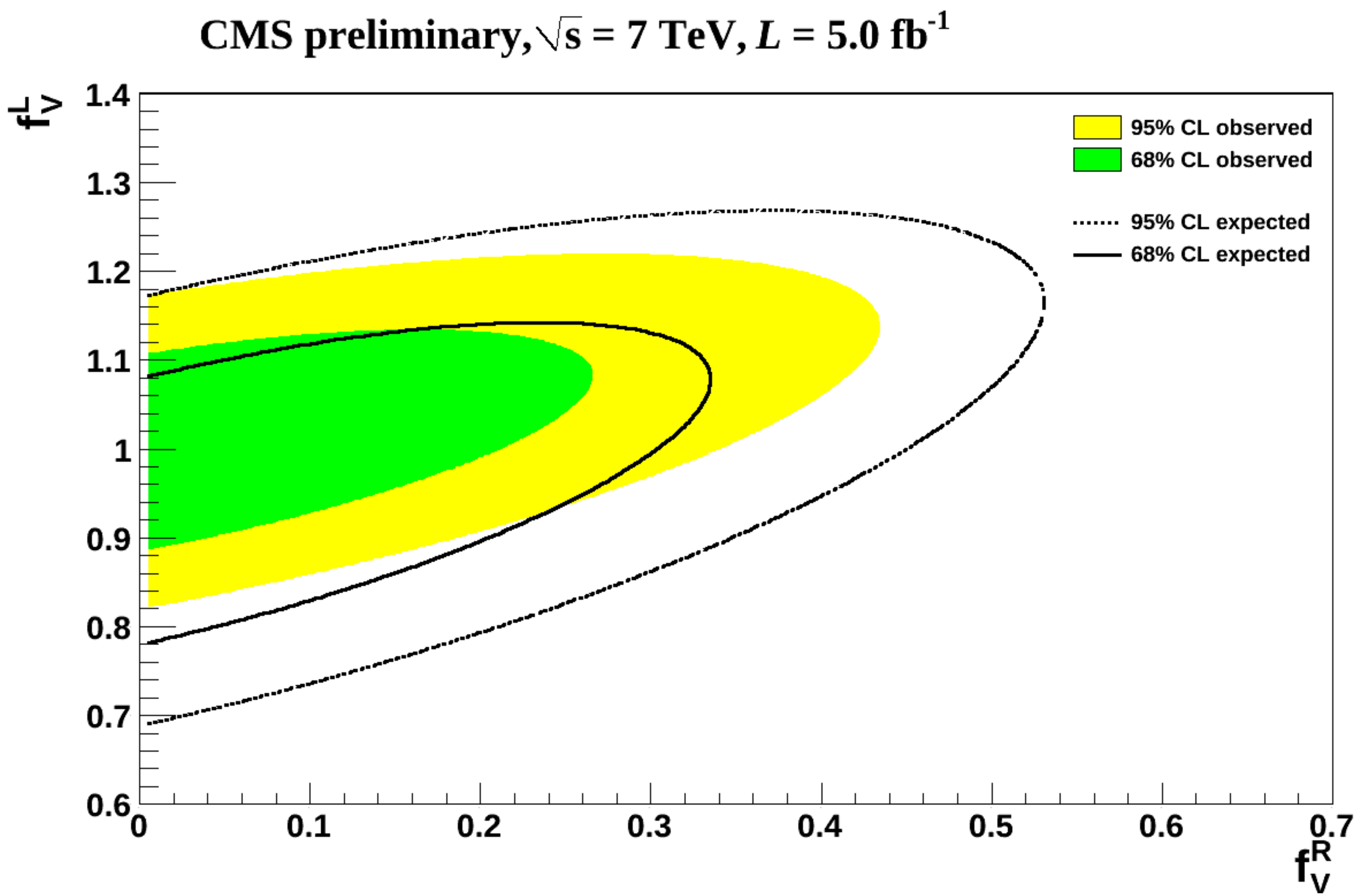
CKM 2012



CKM 2014

Extracting limits on anomalous couplings

- e.g. *Wtb* $\mathfrak{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + h.c.$



CKM 2016

Effective Field Theory interpretation

No direct evidence for NP

- add all "possible" operators to SM Lagrangian
- respect SM symmetries (results in *d* > 4)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_d \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} + h.c.$$

SM Lagrangian

(complex) Wilson coefficient

Dimension

Effective Lagrangian

New-physics scale

Operator

Discussions (LHCtopWG) common standards and best practices

1802.07237

Interpreting top-quark LHC measurements in the standard-model effective field theory

J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3] F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors), D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11] M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16] M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17] T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20] A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

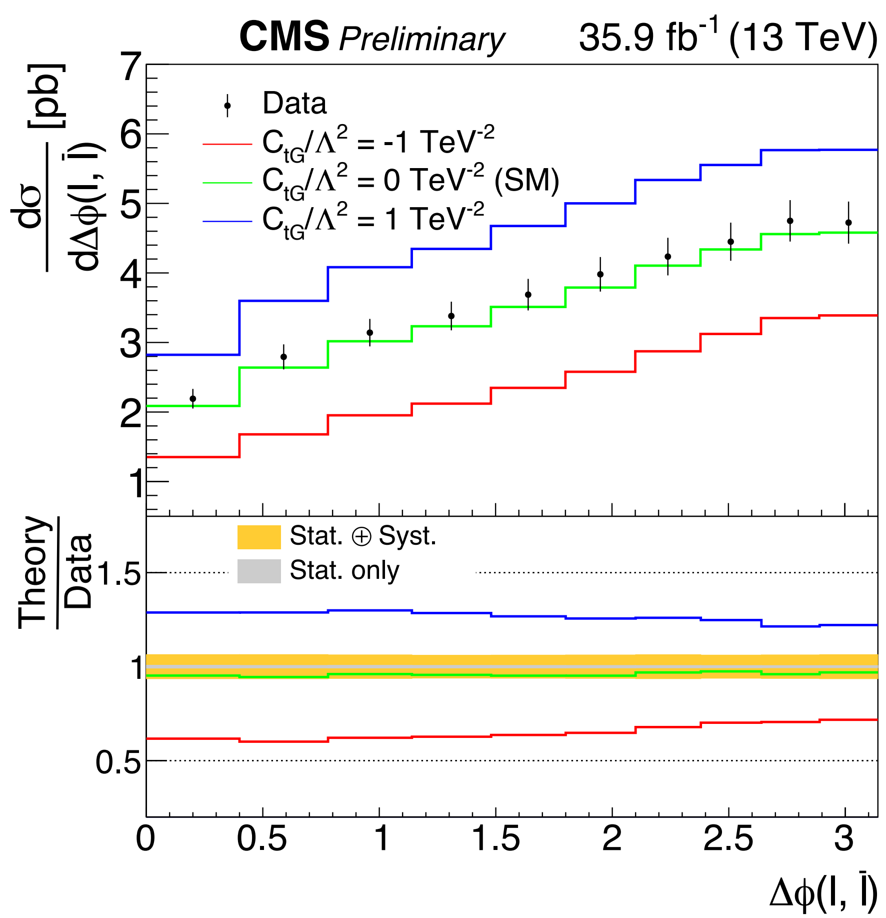
CKM 2018

Constraining new physics with EFT

Example

- dσ/dΔφ
- constrain top chromo-magnetic dipole moment
- $-0.06 < C_{tG}/\Lambda^2 < 0.41$

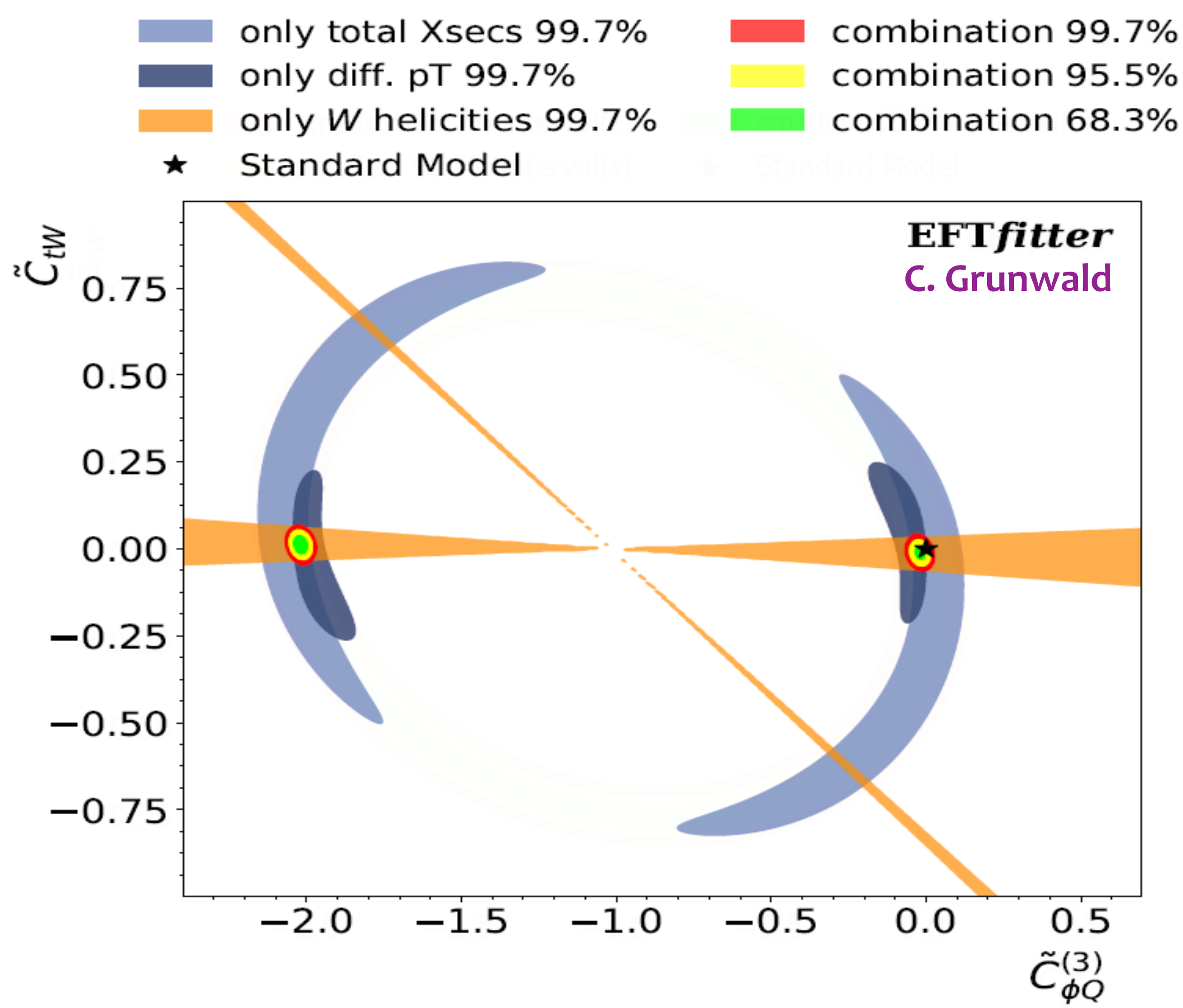
CMS PAS TOP-17-014



Global fits: EFTFitter

Castro et al. '16

- combination
- include correlations
- consistent treatment of backgnd



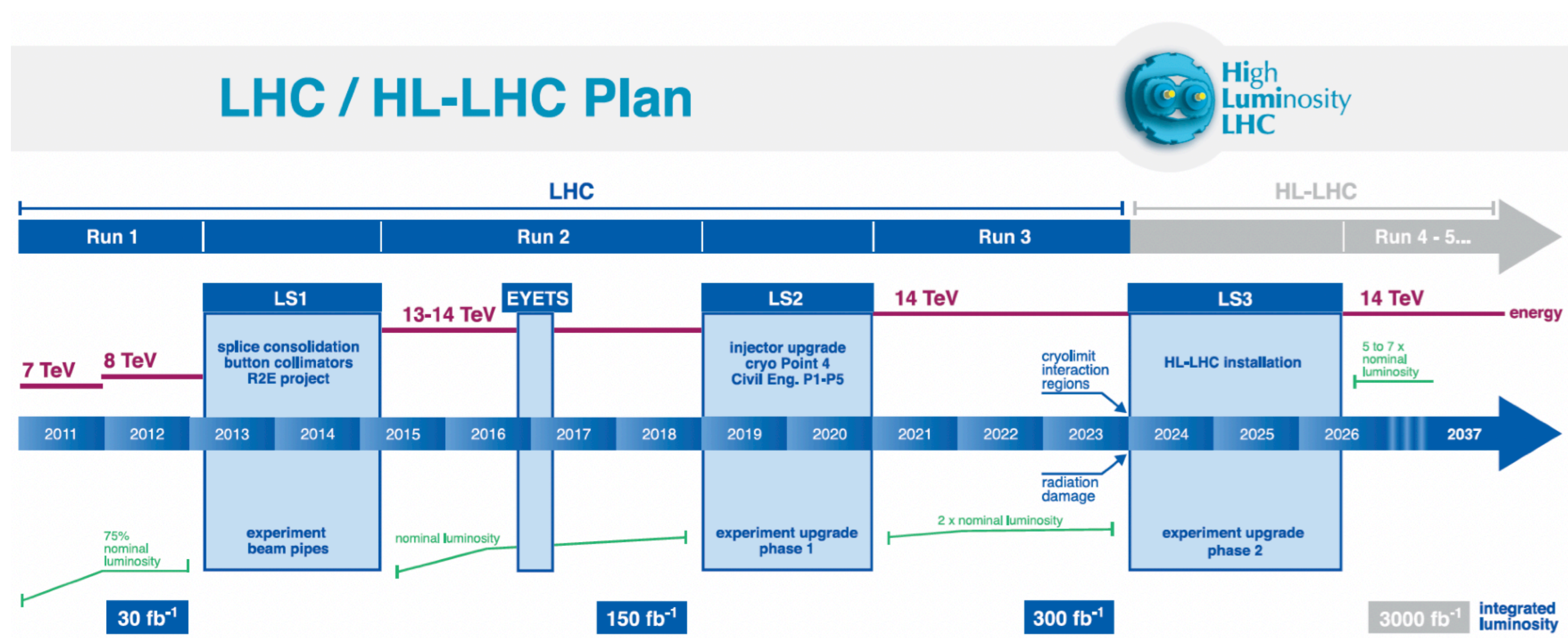
σ_t 8TeV + 7 TeV + 13 TeV + differential + *W* helicity

New first time results

- observation of **Yukawa coupling** with third generation: ***t*, *b*, *τ***

What's next

- Run-2 data doubles/quadruplicates
- improved couplings, FCNC/LFV test and BSM sensitivity
- only < 3% of the final LHC data analysed → much more to come!



Future directions

- HE-LHC @ 27 TeV
- FCC-hh @ 100 TeV
- more options on the horizon: CEPC, CLIC, ILC, FCC-xx, ...

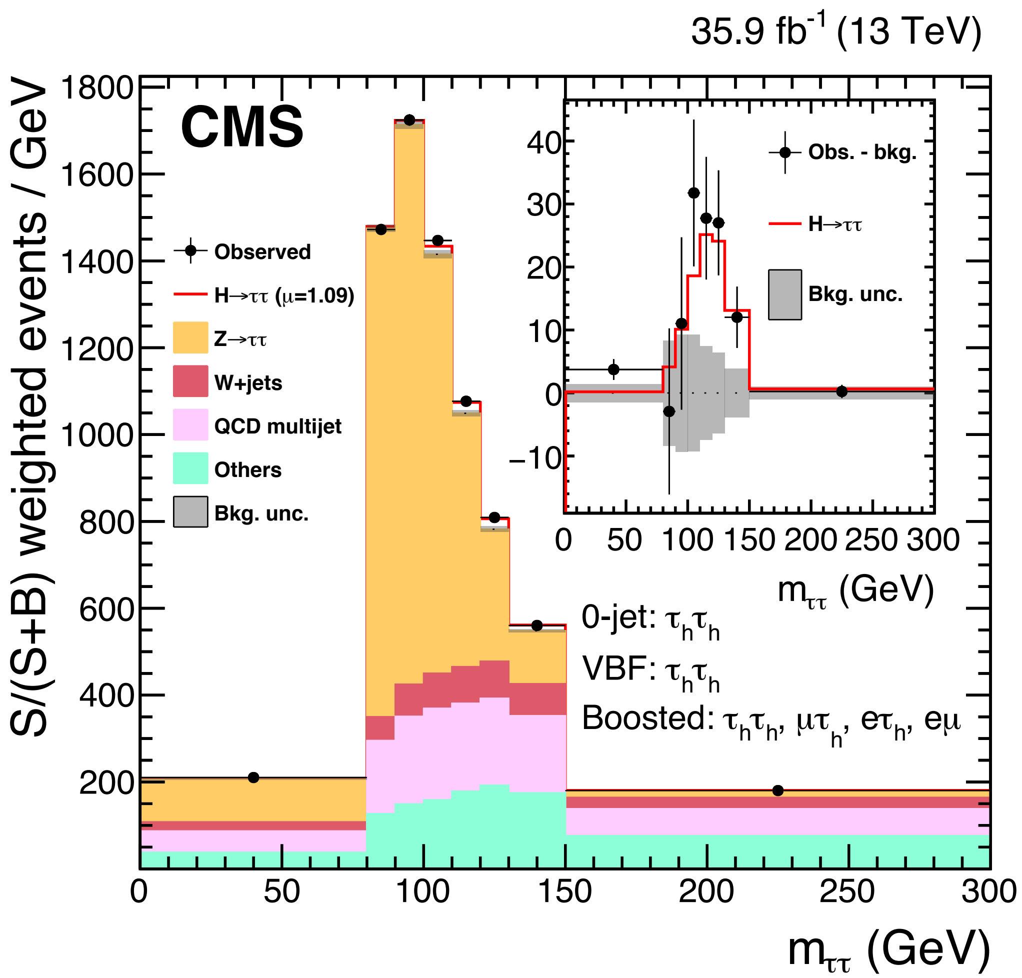
Backup

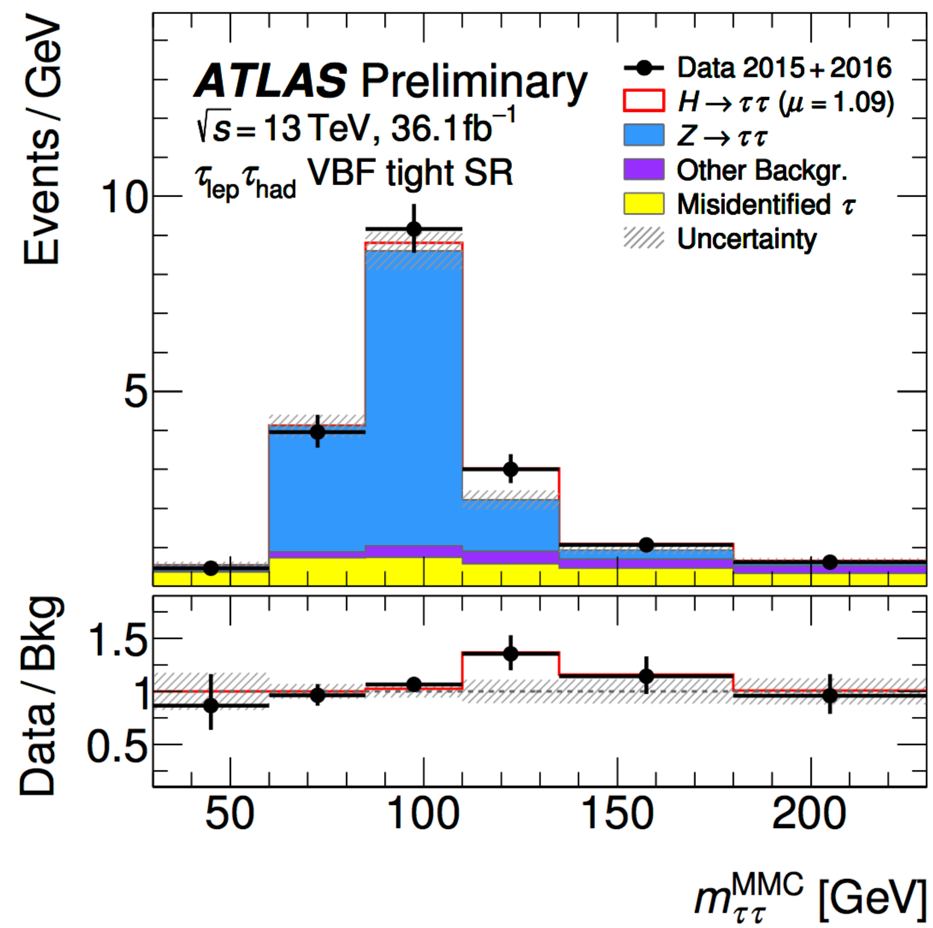
Higgs and *tau* leptons

- All τ leptonic and hadronic decay modes considered
- now observed in each experiment separately
- main discriminant: $m_{\tau\tau}$, crucial to distinguish $H\rightarrow\tau\tau$ and $Z\rightarrow\tau\tau$

CMS PLB 779 (2018) 283

ATLAS-CONF-2018-021





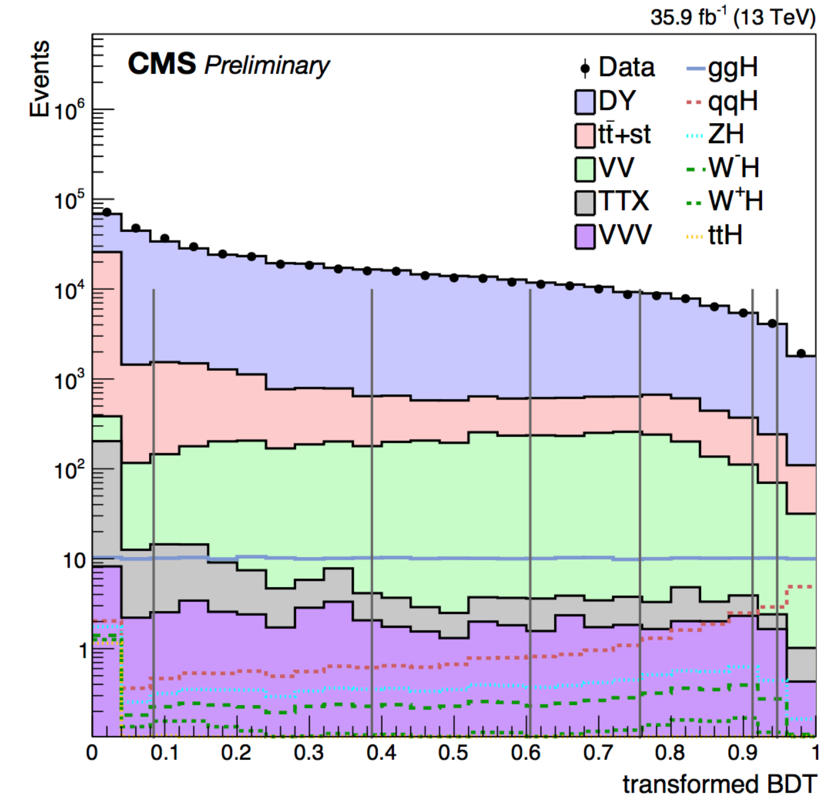
	CMS	ATLAS
$\mu_{\tau\tau}$	$1.09^{+0.15}_{-0.15}(\mathrm{stat})^{+0.16}_{-0.15}(\mathrm{syst})^{+0.10}_{-0.08}(\mathrm{th})^{+0.13}_{-0.12}(\mathrm{MCstat})$ *	$1.09^{+0.18}_{-0.17}(\mathrm{stat})^{+0.27}_{-0.22}(\mathrm{syst})^{+0.16}_{-0.11}(\mathrm{th})$
	Significance: **5.9σ** (5.9σ) observed (exp.) *	Significance: **6.4σ** (5.4σ) observed (exp.) *

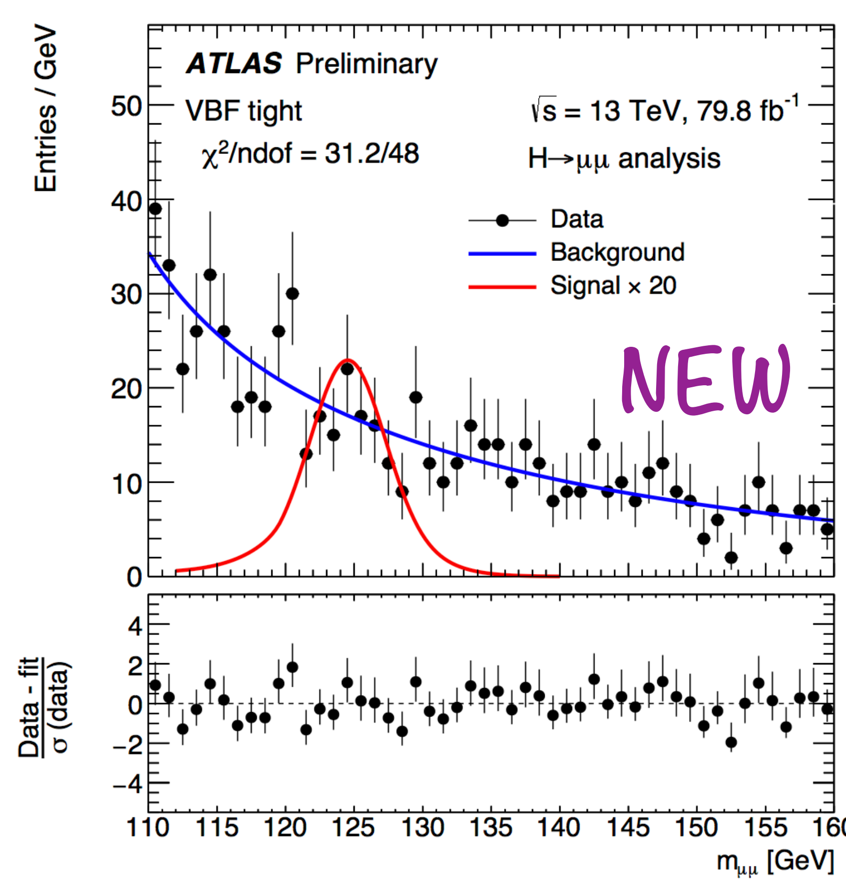
$H \rightarrow \mu\mu$

- events with two isolated OS muons, $p_T(\mu_1)$ > 25 GeV
- categories according to η_μ , $p_T(\mu)$ and BDT enhancing VBF
- fit to $m_{\mu\mu}$ distribution in each category
- background from sidebands using analytic function

	CMS PAS HIG-17-019 **CMS (36fb^{-1})**	ATLAS-CONF-2018-026 **ATLAS (80fb^{-1})**
$\mu_{\mu\mu}$	0.7 ± 1.0	$0.1^{+1.0}_{-1.1}$
95% CL	$\mu_{\mu\mu} < 2.6\ (2.1\ \mathrm{exp})$	$\mu_{\mu\mu} < 2.1\ (2.0\ \mathrm{exp})$

Getting close to SM sensitivity!





$t\bar{t}H$ evidence and observation

Run-1 7 and 8 TeV

- ATLAS 2.7σ (1.6σ exp.)
- CMS 3.6σ (1.3σ exp.)

JHEP 08 (2016) 045

Run-2 13 TeV 36/fb (2015-16)

- ATLAS 4.2σ (3.8σ exp.)
- CMS 3.2σ (2.8σ exp.)

PRD 97 (2018) 072003

Run-2 13 TeV up to 80/fb (2015-17)

- ATLAS 5.8σ (4.9σ exp.)

PLB 784 (2018) 173

Combination Run-1 + Run-2

- ATLAS 6.3σ (5.1σ exp.)
- CMS 5.2σ (4.2σ exp.)

PLB 784 (2018) 173