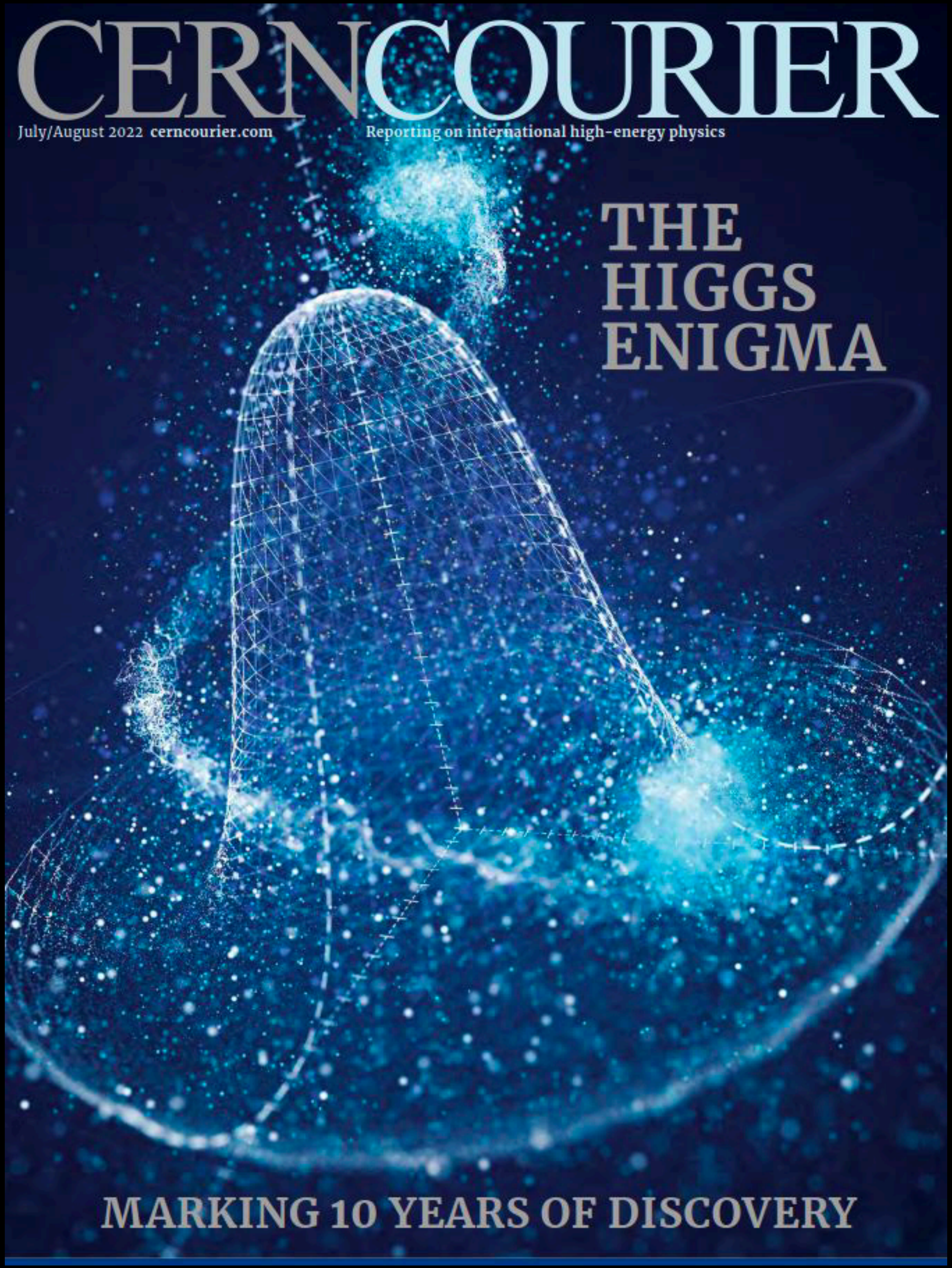


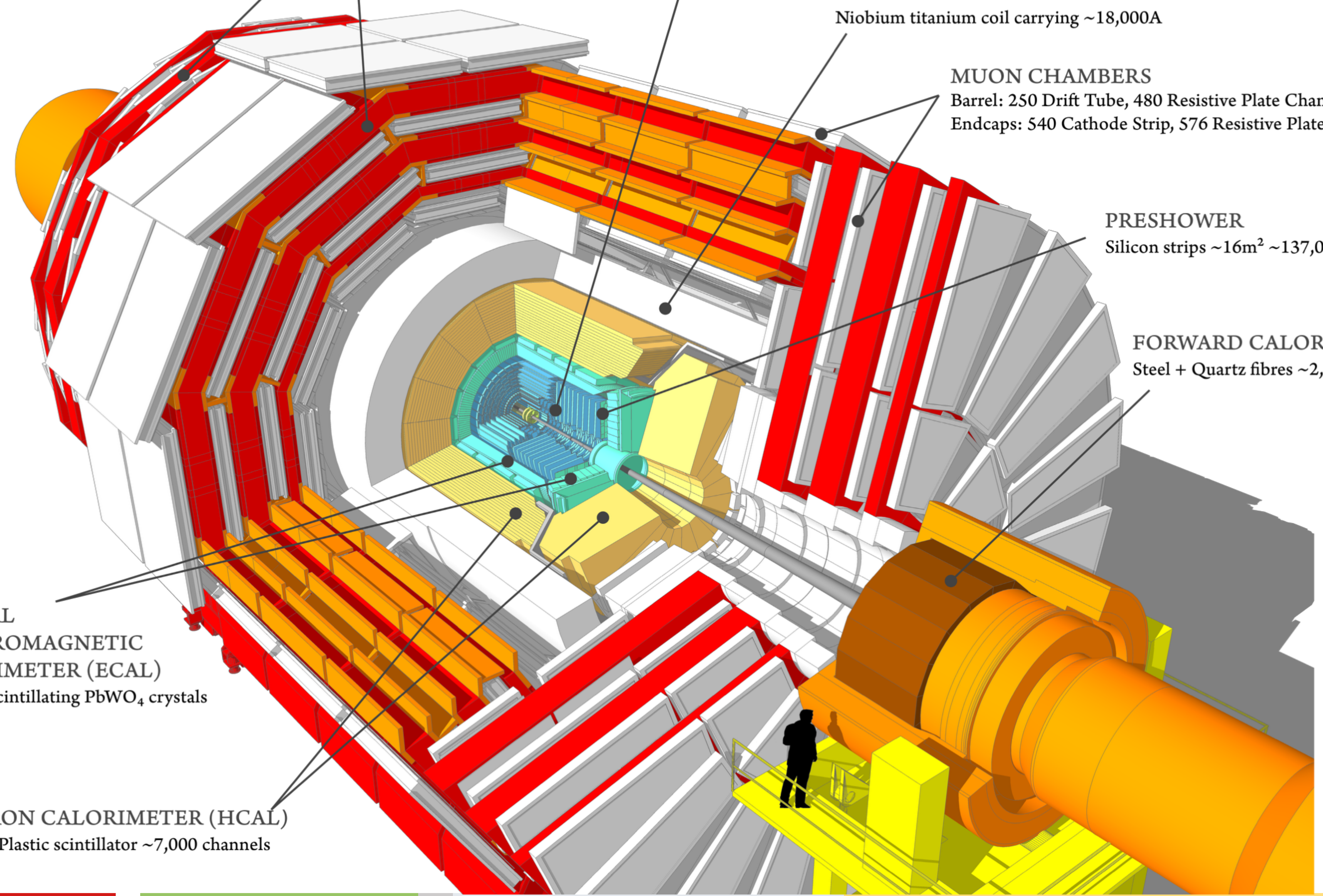
10 Years of Higgs Boson in CMS

Gautier Hamel de Monchenault
CEA-IRFU

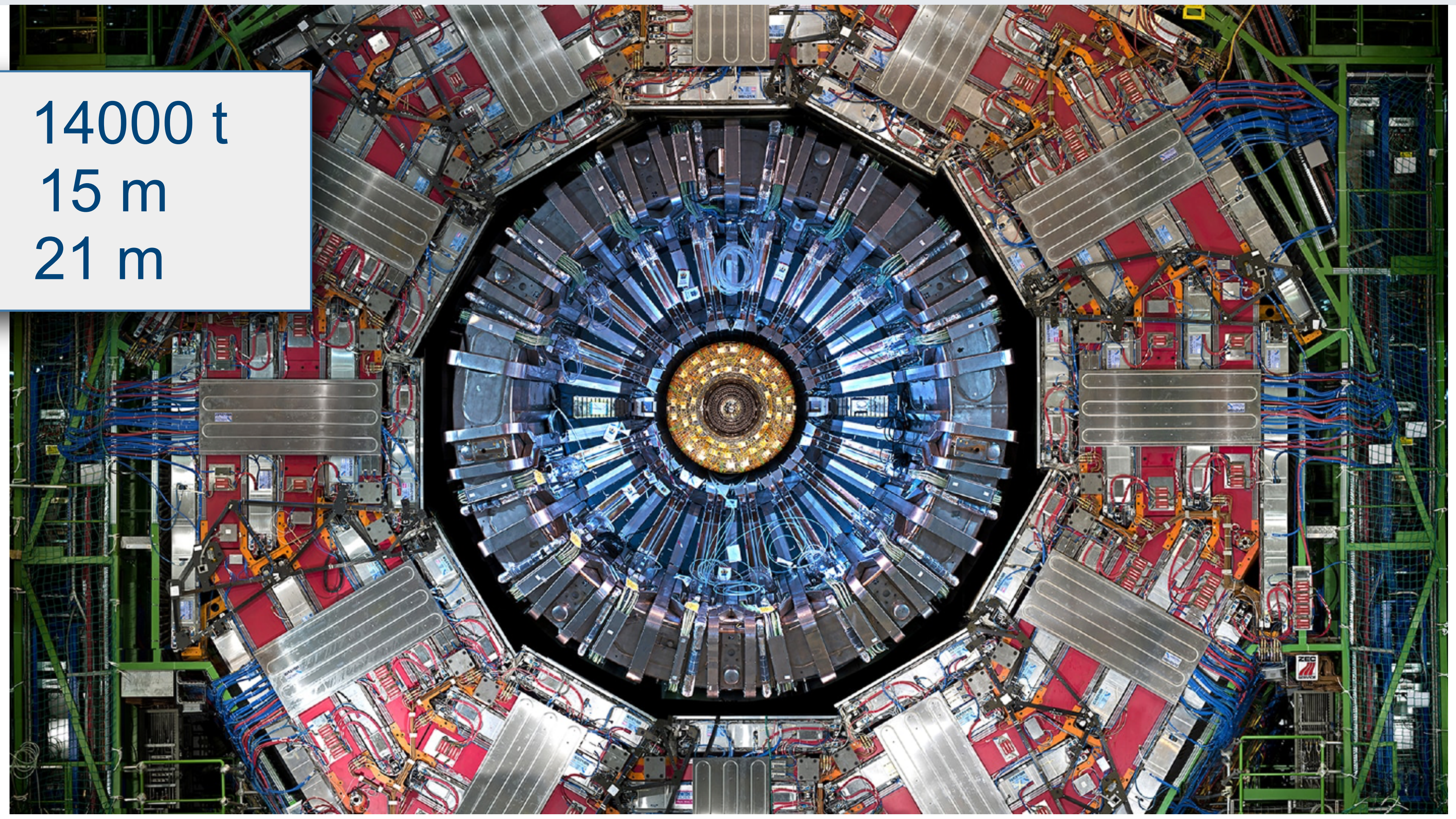
IRN Terascale, Nantes
— October 2022

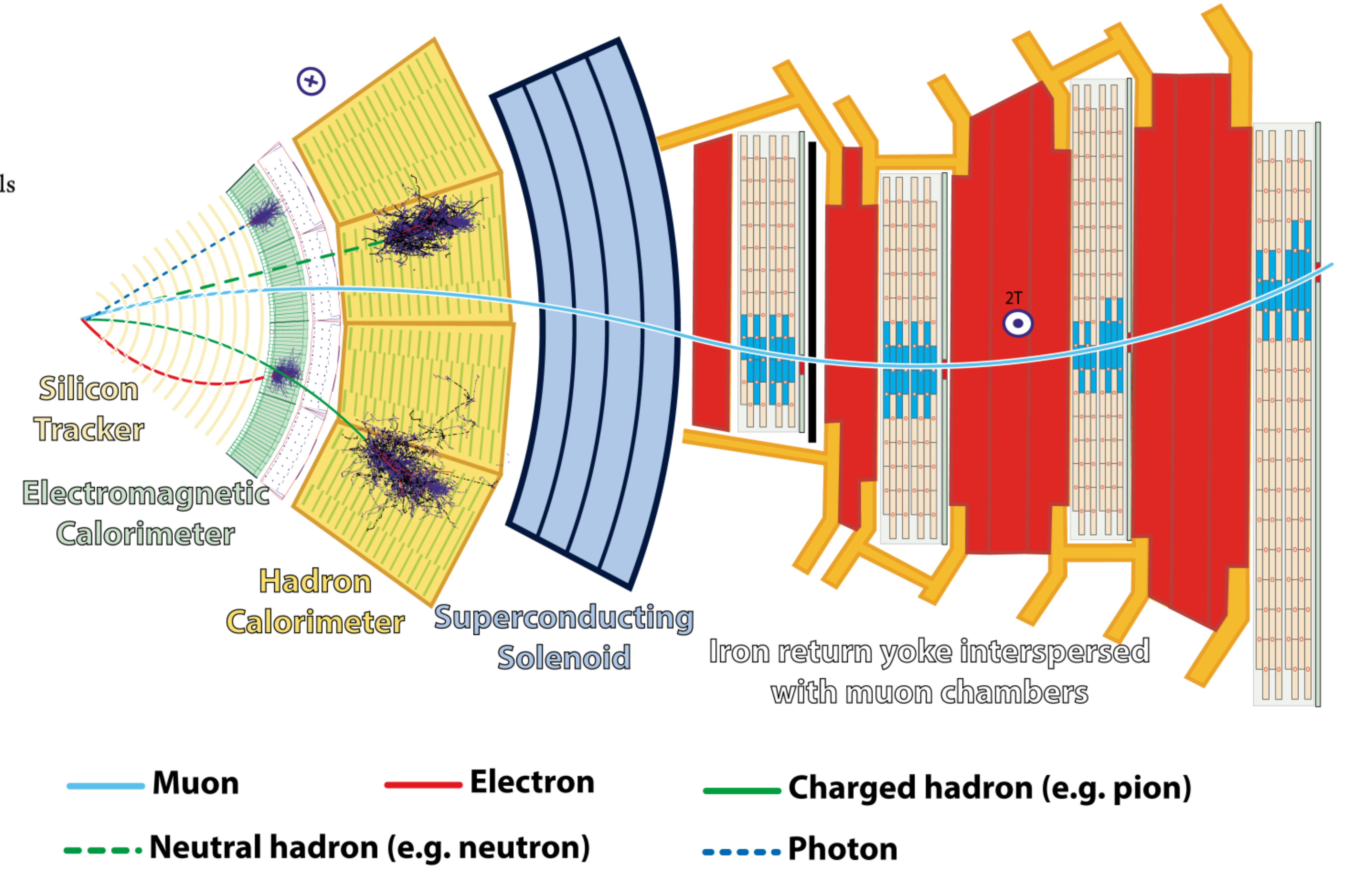
CMS at the Large Hadron Collider

General-purpose LHC detector

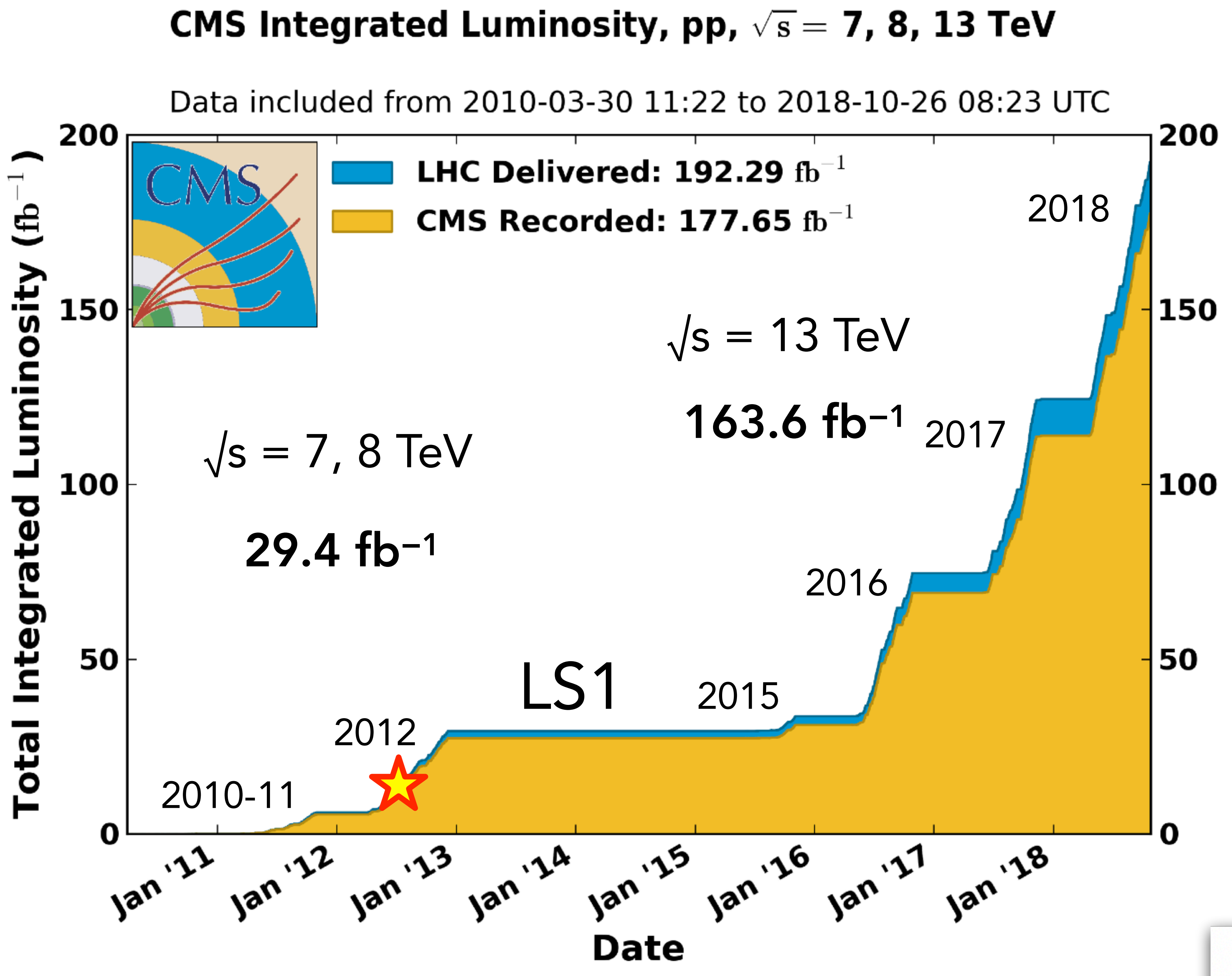


Total weight	14000 t
Overall diameter	15 m
Overall length	21 m





CMS pp Data at LHC



Excellent performance of the LHC in Run-2

- $\sqrt{s}$ = 13 TeV
- max LHC luminosity (2018):
  $\mathscr{L}_{max} = 2.14 \times 10^{34}\ cm^{-2}s^{-1}$
  (factor of 2 higher than design)

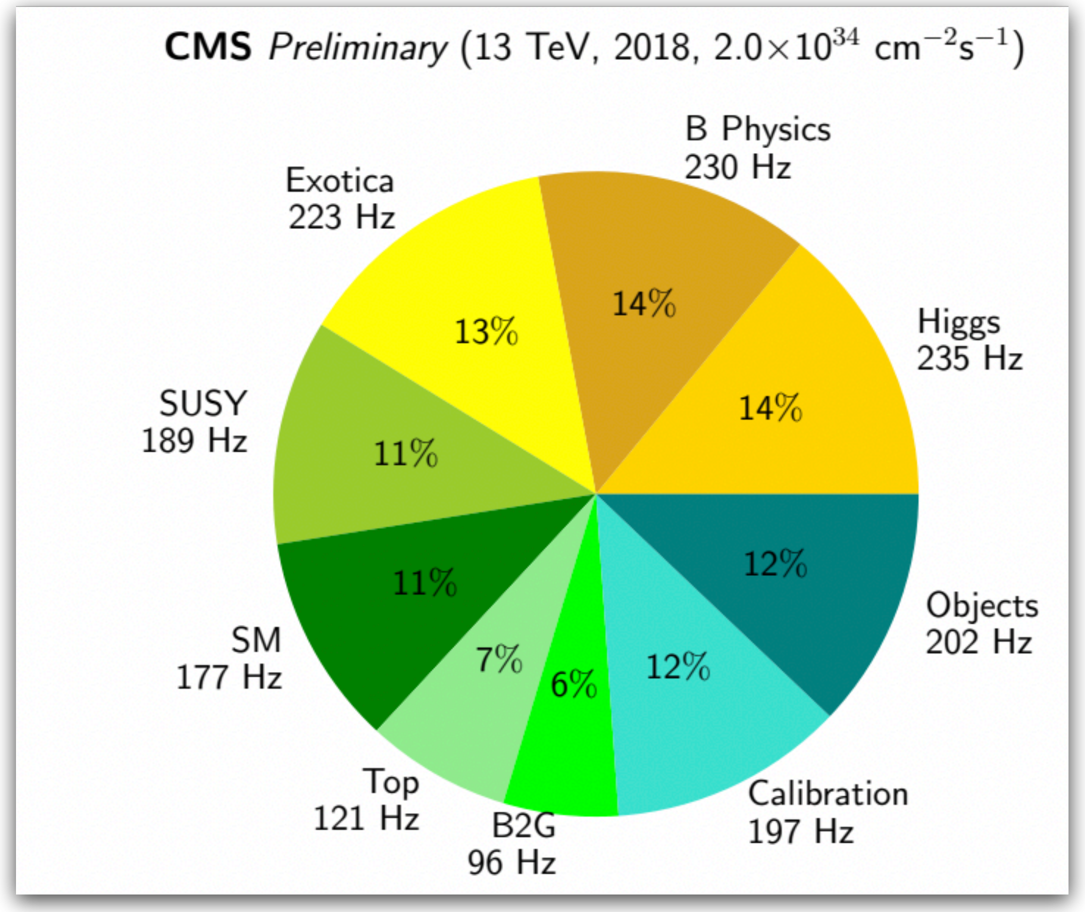
At 13 TeV, σ_{tot} ~ 100 mb, 1 fb^{-1} corresponds to **one hundred thousand billion** proton-proton interactions

CMS Dataset Run-2

- 2016-2018: **137 fb^{-1}** of pp data "good for physics"
- data-taking efficiency > 92% (2018: 94%)
- number of pp interactions per beam crossing (PU): <μ> = 34

CMS Triggers for Run-2 (1.6 kHz)

- Standard triggers (leptons, jets, MET)
- **B-parking triggers** (up to 5 kHz)
  10B events enriched in un-biased B decays
- Scouting triggers
  reduced events with physics objects



Delivered integrated pp luminosity

expressed in inverse-femtobarn (fb^{-1})

Run-1

5 fb^{-1} at 7 TeV (2011)

20 fb^{-1} at 8 TeV (2012)

Run-2

140 fb^{-1} at 13 TeV (2015-2018)

Run-3 (on-going)

190 fb^{-1} at 13.6 TeV (2022-2025)

Pile-up: an Experimental Challenge

Pile-up (*PU*) = <μ> = number of inelastic p-p interactions per bunch crossing (every 25 ns)

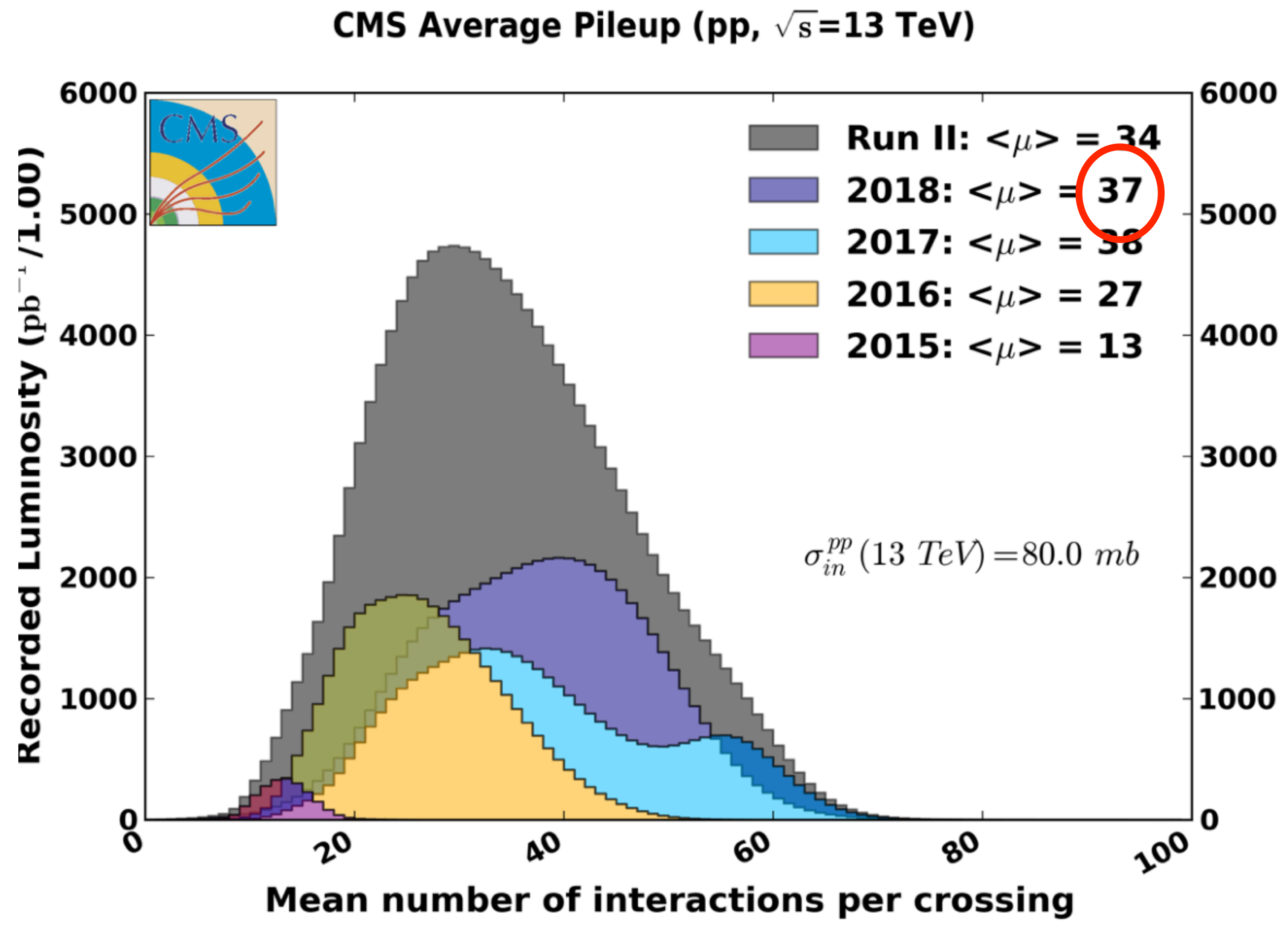
For instance, for Run-2 in 2018

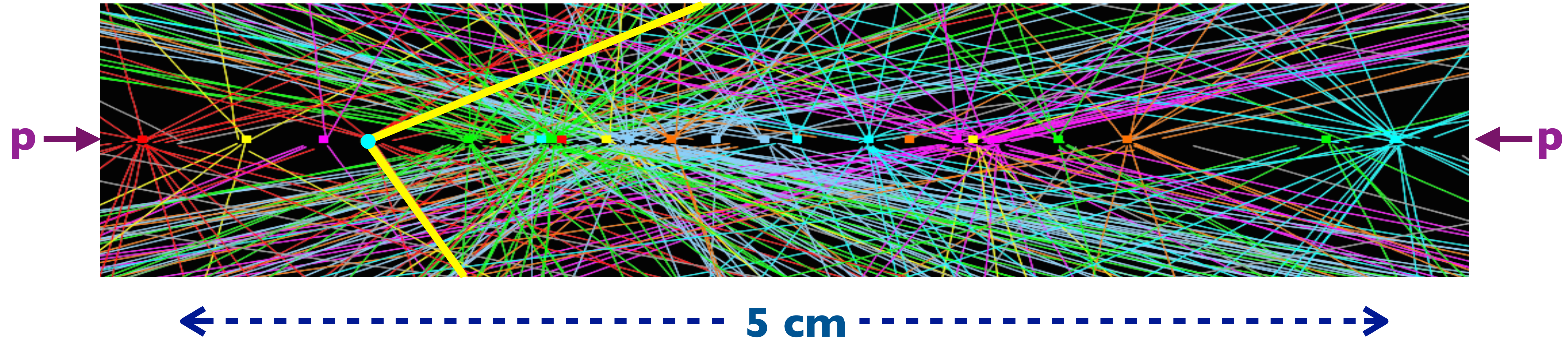
$\langle\mu\rangle \sim \sigma_{inel} \times \mathscr{L}$ x bunch crossing separation time

$\langle\mu\rangle \sim 80\ \text{mb} \times 2\times10^{34}\ \text{cm}^{-2}\text{s}^{-1} \times 25\ \text{ns}$

$\langle\mu\rangle \sim$ **40**

➠ about 40 inelastic collisions are superimposed on the event of interest





(zoom of the interaction region)

40 × 40 MHz = 1.6 billion proton-proton interactions per second!

O(1000) particles emerge from the interaction region every 25 ns

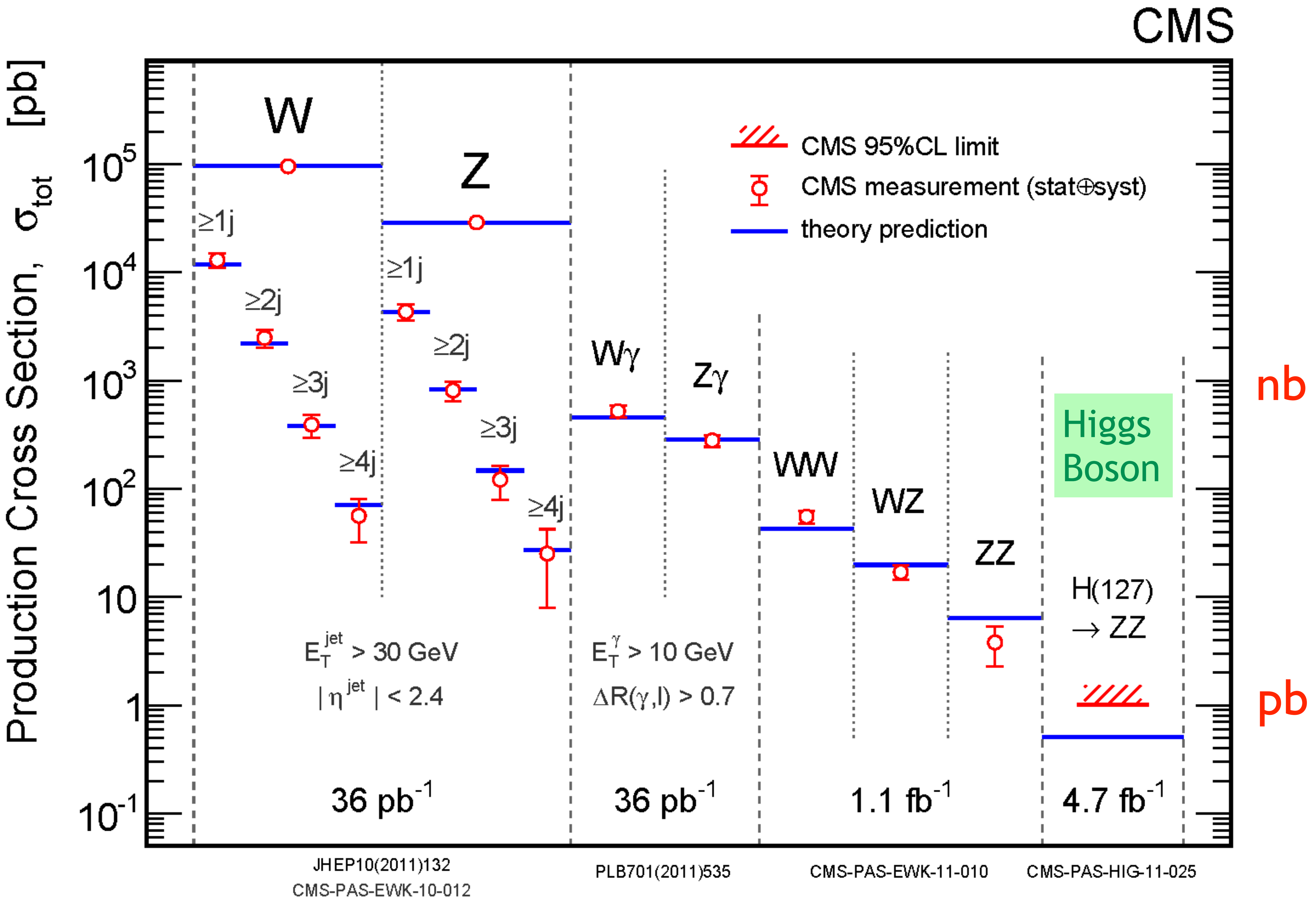
This implies

- **high-granularity detectors** with good time resolution, resulting in low occupancy
- **millions of electronic channels** with good synchronization
- **radiation hardness**

SM Production Cross Sections

10 years ago

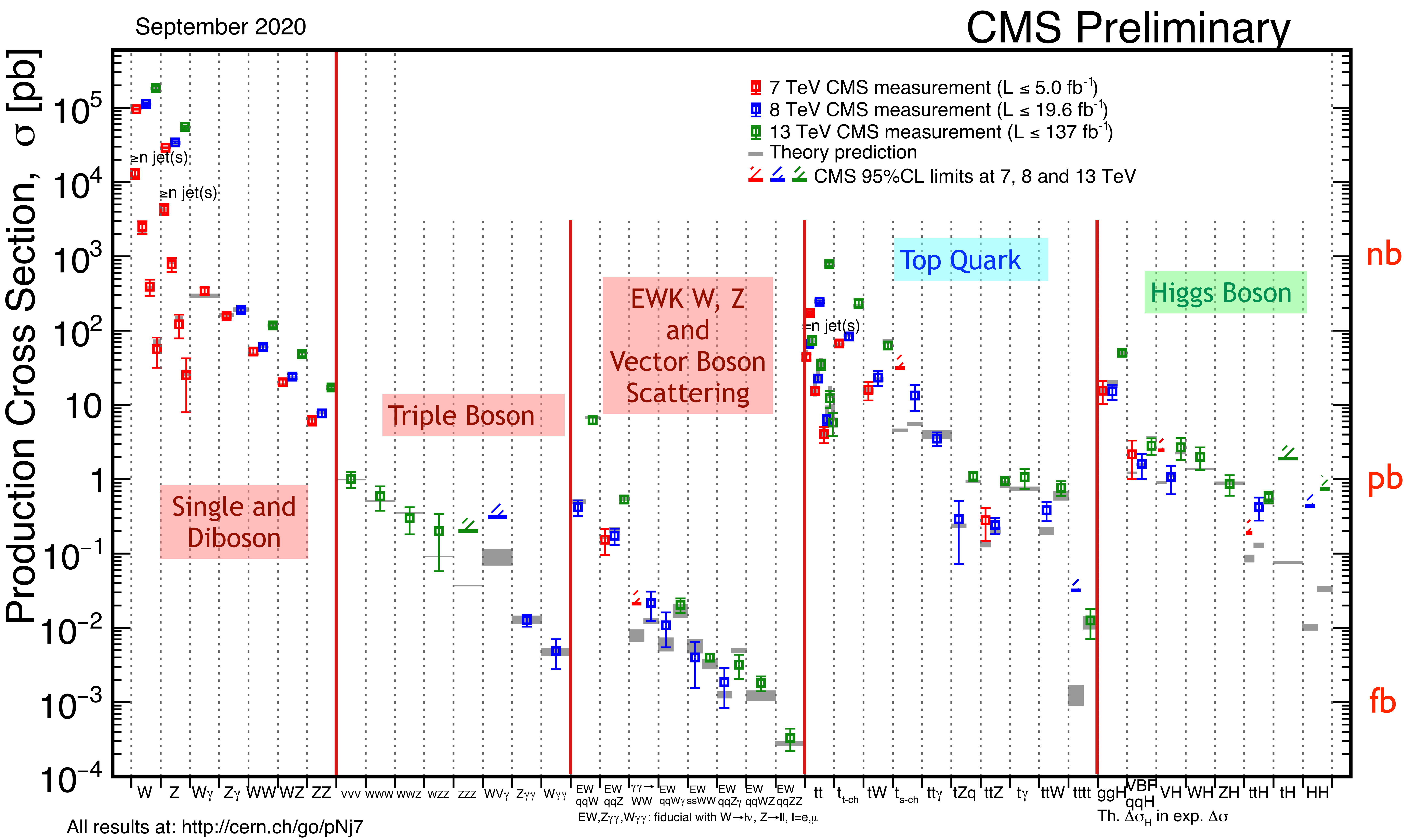
Single and Diboson



$$\sigma \times \mathcal{B} = \frac{N_{\text{sig}}}{A \times \varepsilon \times L}$$

one million events per inverse-femtobarn for a cross section of **one nanobarn**

SM Production Cross Sections



[Summaries of physics results]

$$\sigma \times \mathcal{B} = \frac{N_{\text{sig}}}{A \times \varepsilon \times L}$$

one million events
per inverse-femtobarn
for a cross section
of **one nanobarn**

Produced (*) at Run-2:

- 30B W bosons
- 7B Z bosons
- 300M top quarks
- 8M Higgs bosons
- 40 EW qqZZ(→4ℓ) [fid]

Other main physics motivation
- explore the energy domain around 1 TeV
- study the yet unknown physics at the TeV energy scale

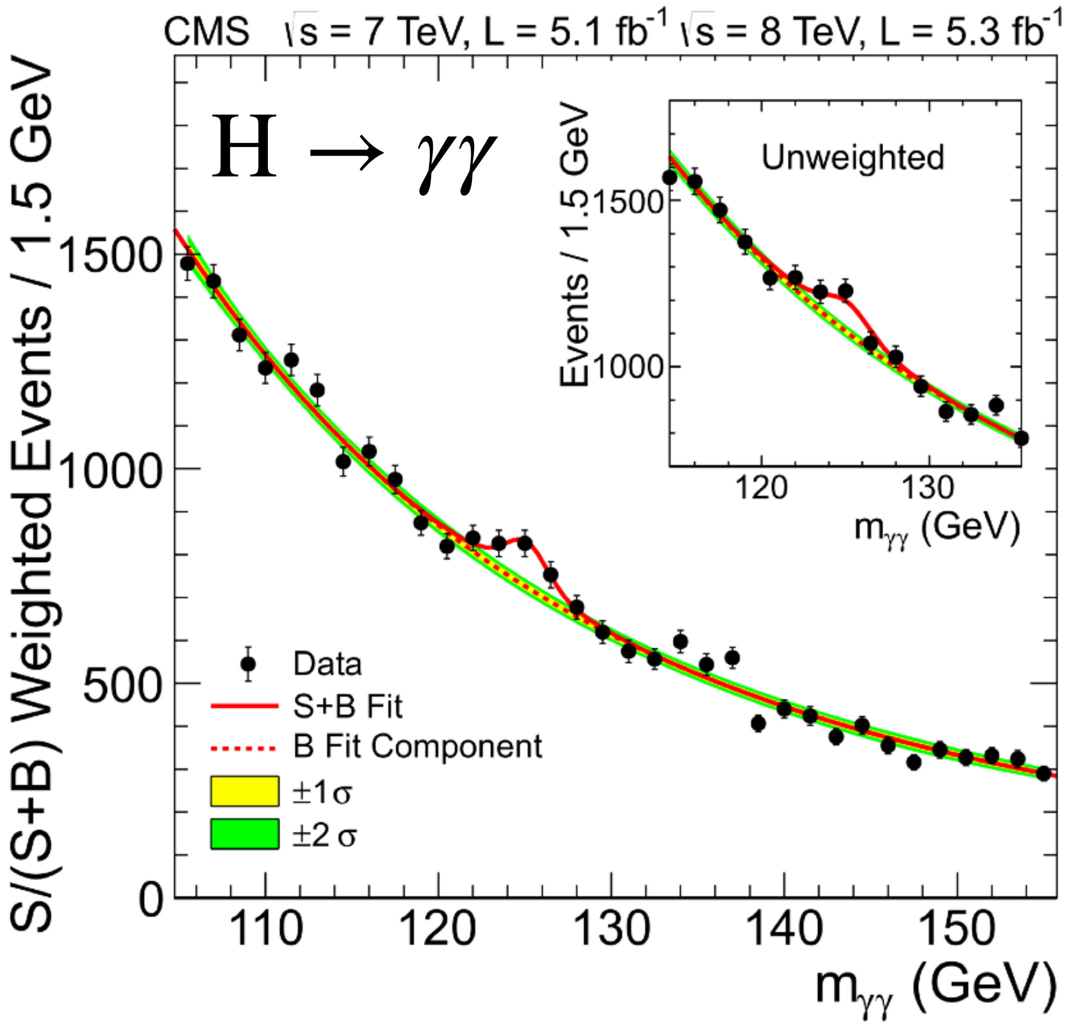
(*) approx… much less are triggered and detected!

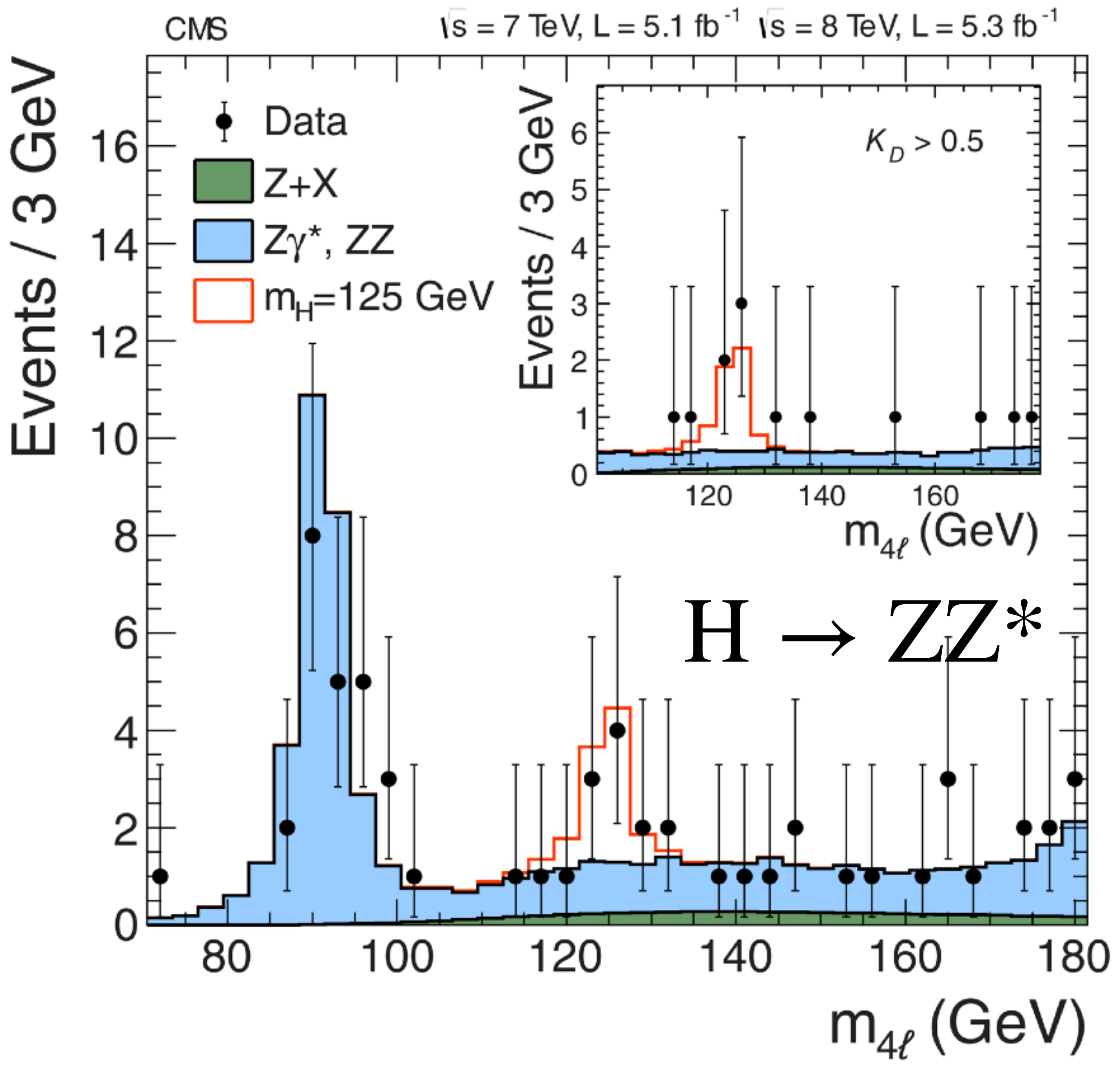
The Higgs Boson Turns 10!

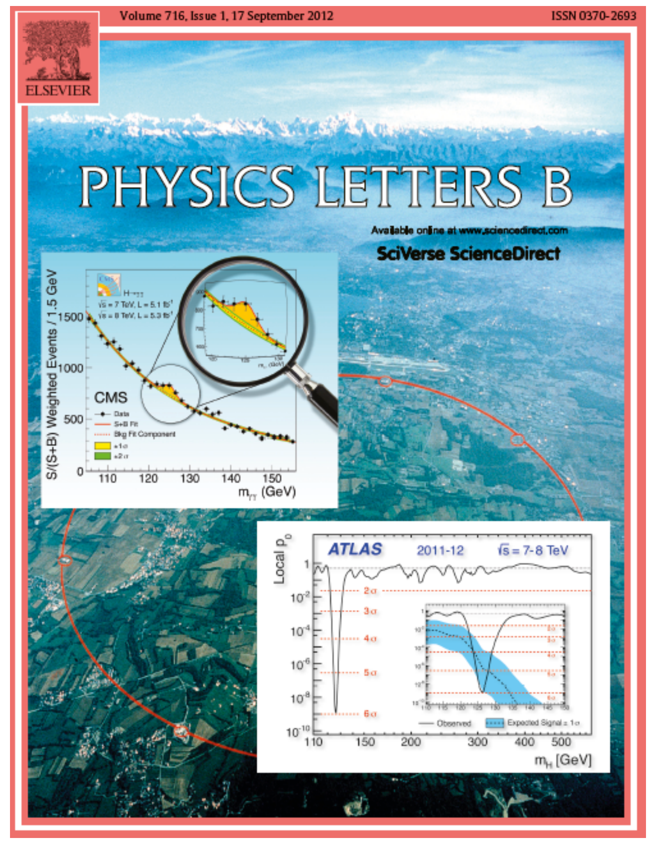
10 years HIGGS boson discovery

July 4 2022

4th of July 2012



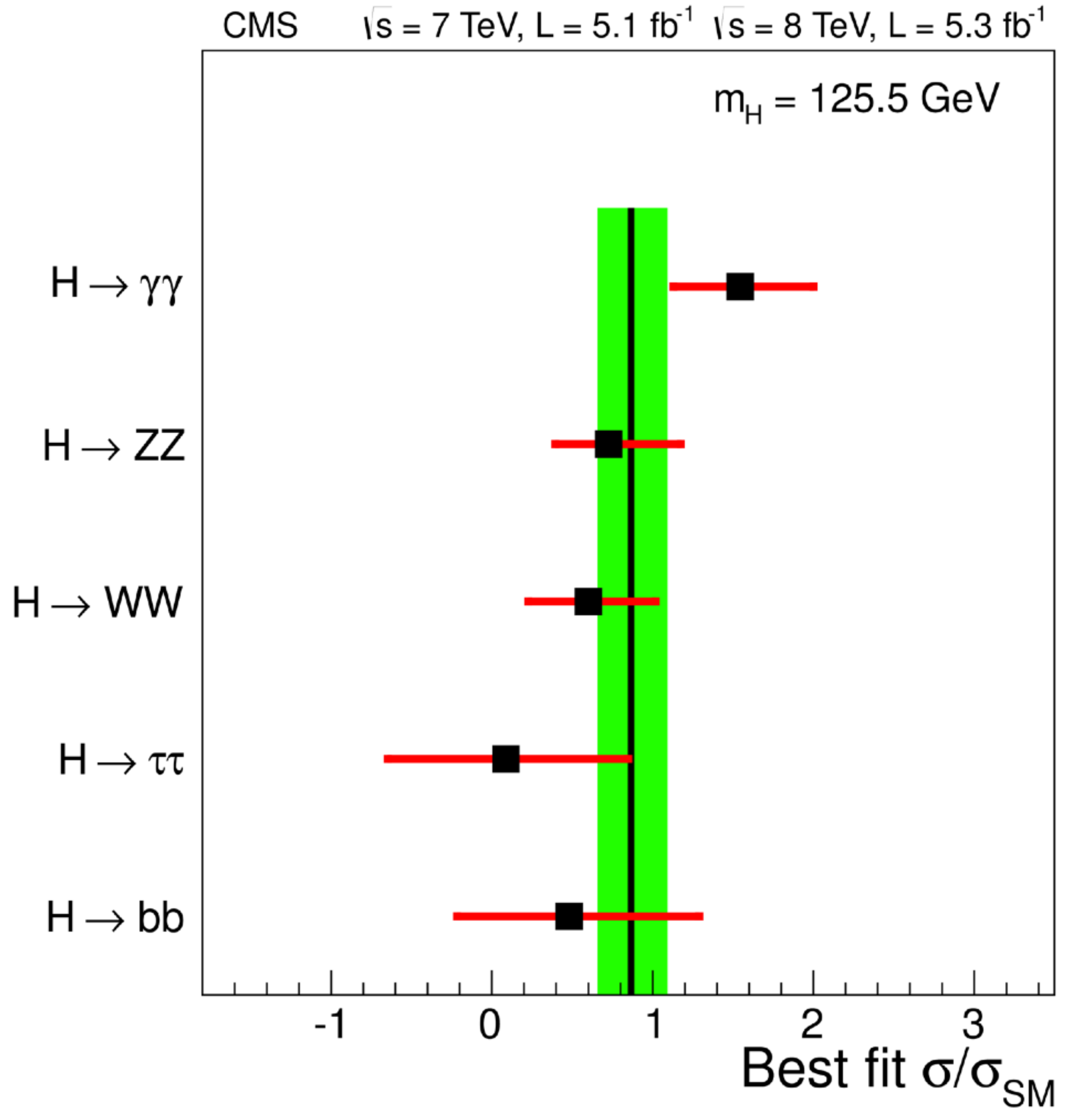


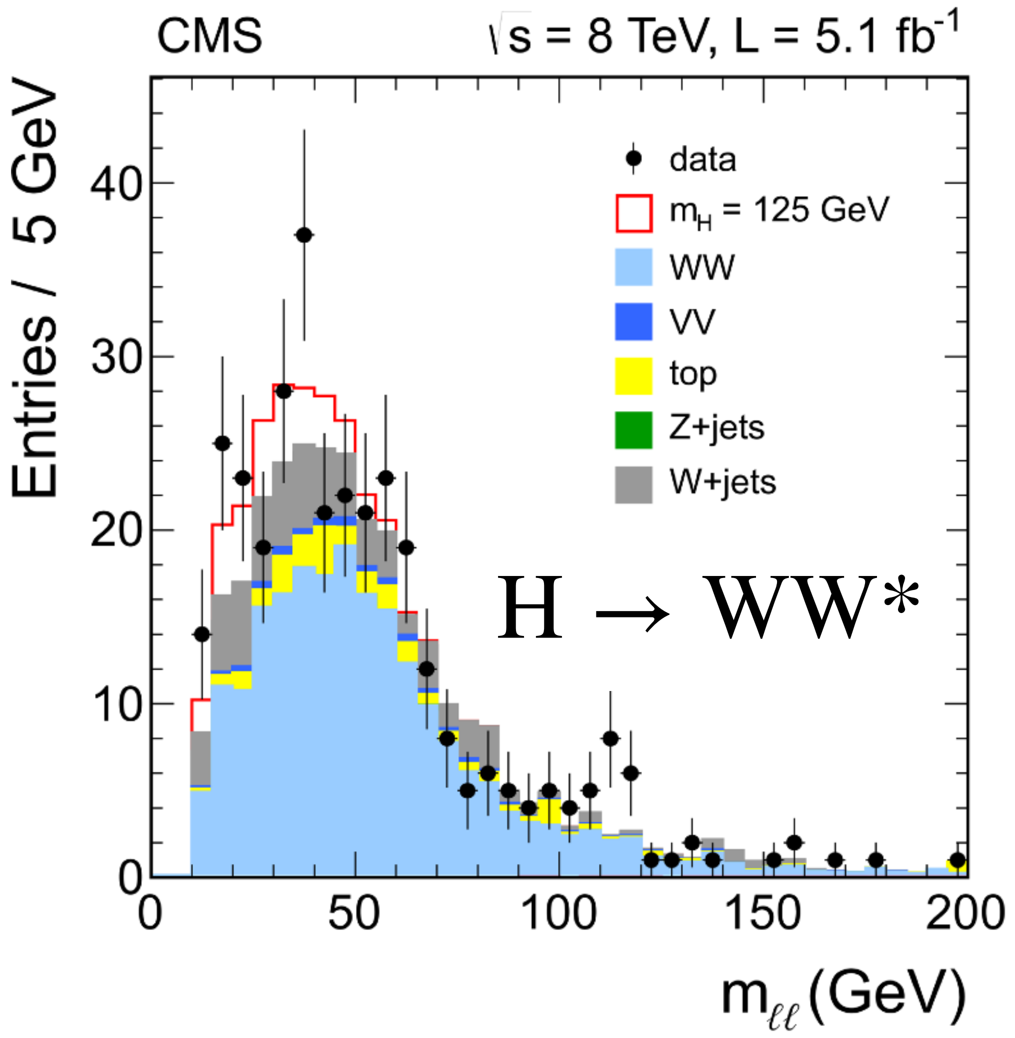


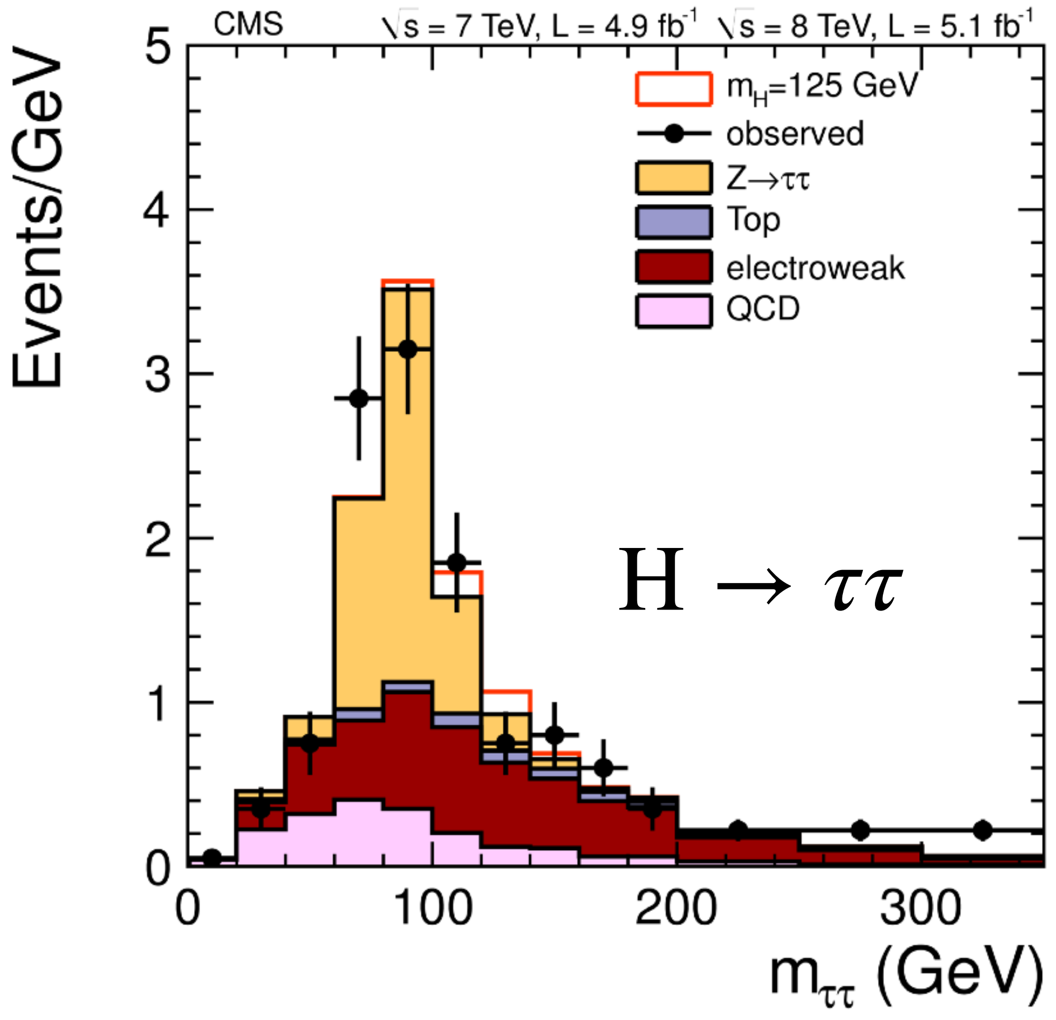
CMS-HIG-12-028

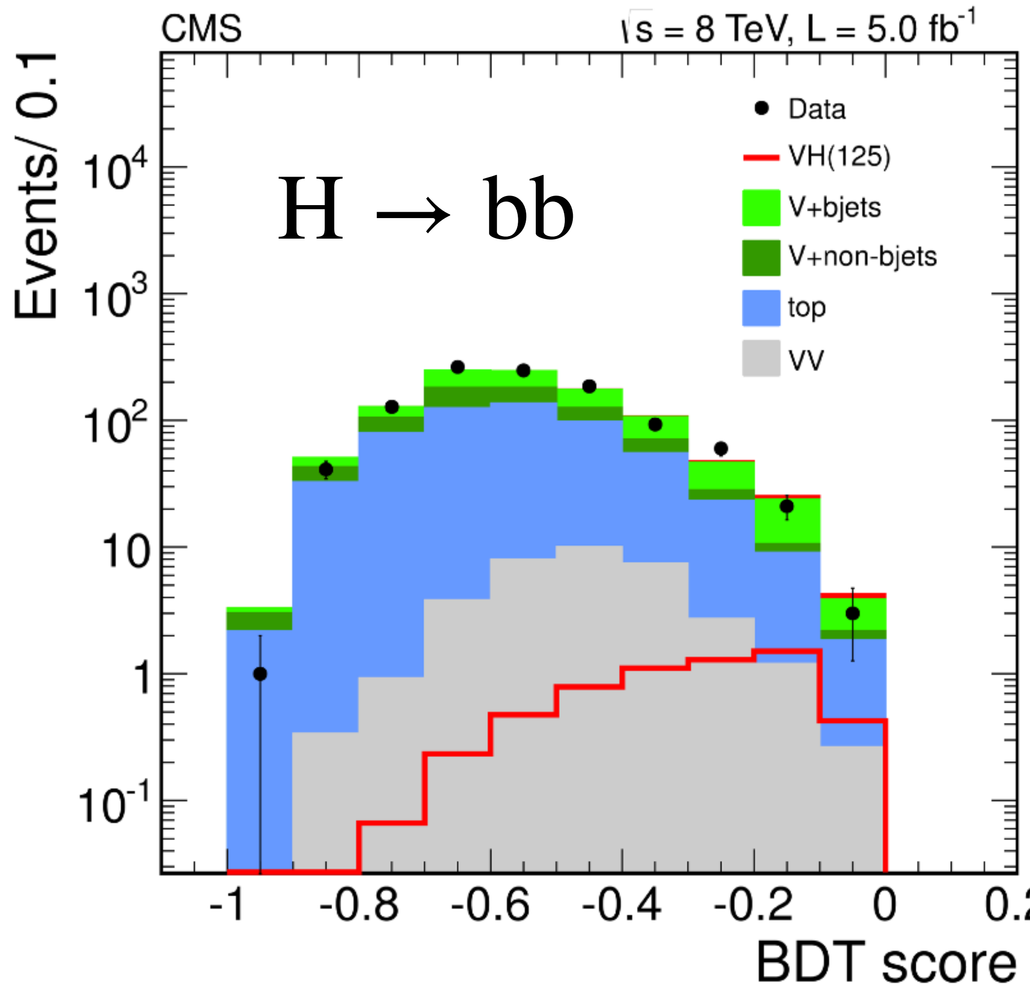
PLB 716 (2012) 30

Observation (5.0σ significance) combining the 5 modes









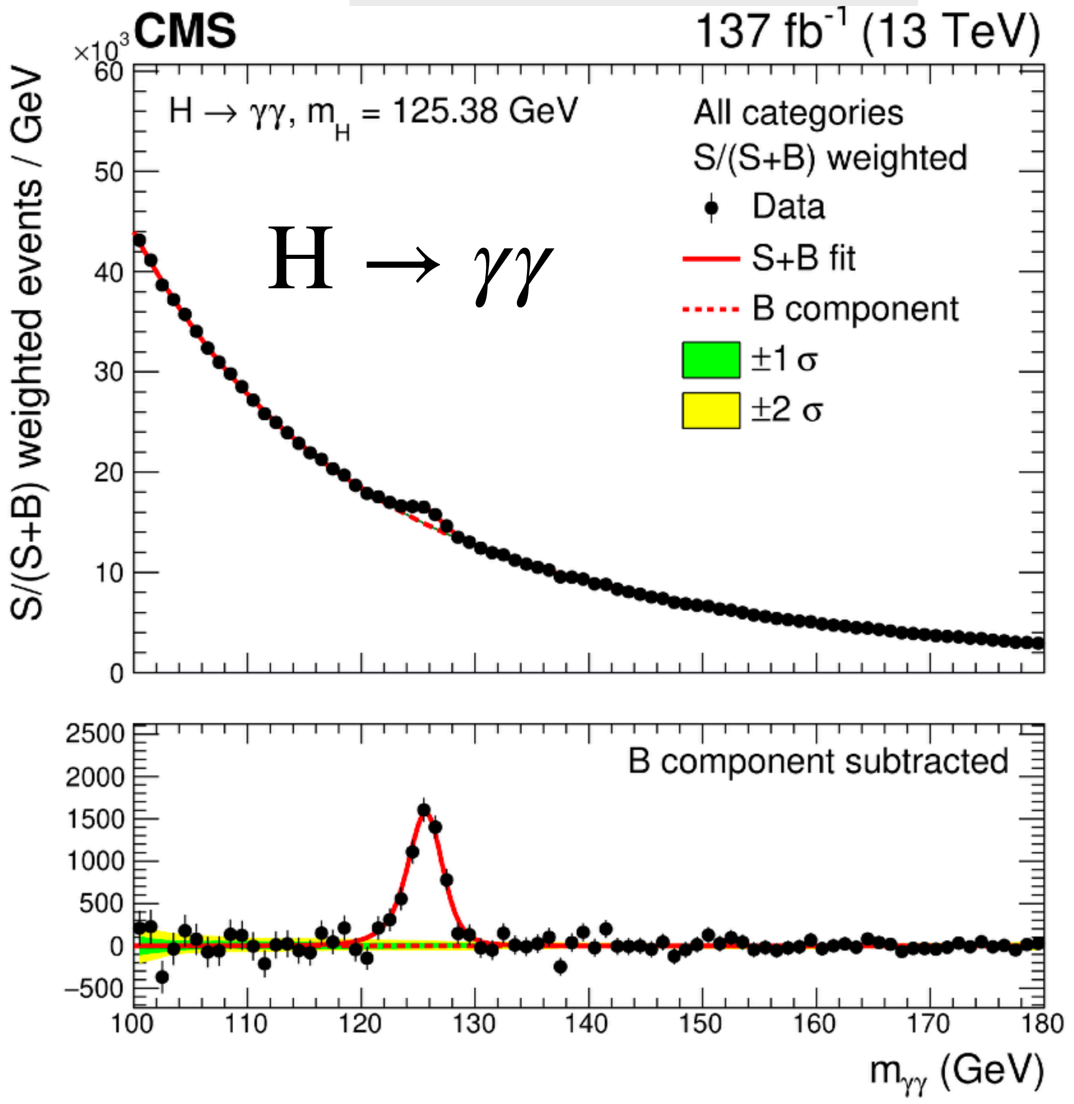
The Higgs Boson Turns 10!

10 years HIGGS boson discovery

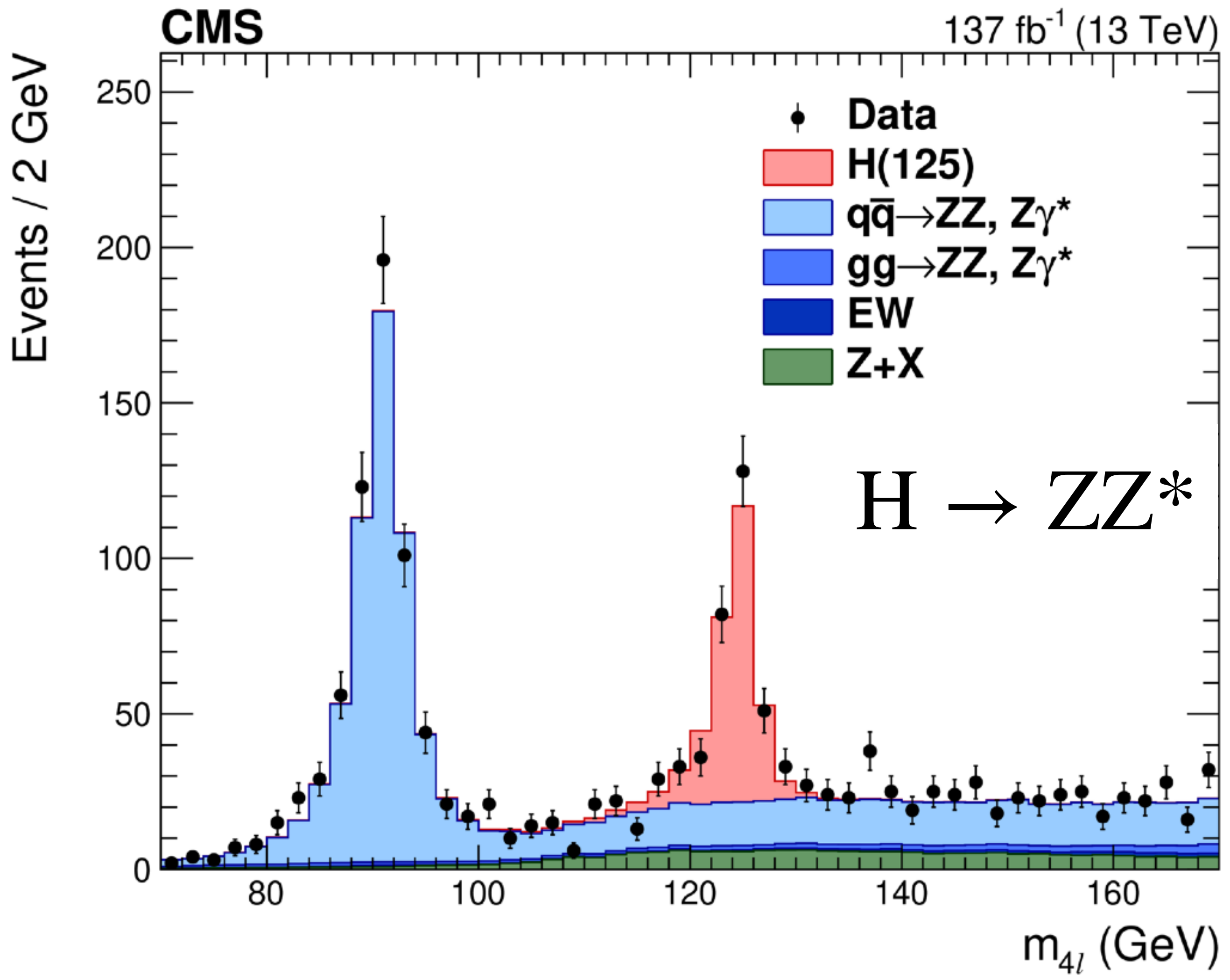
July 4 2022

$m_{\mathrm{H}} = 125.38 \pm 0.14\,(\mathrm{total})\ \mathrm{GeV}$

CMS-HIG-19-015
JHEP 07 (2021) 027

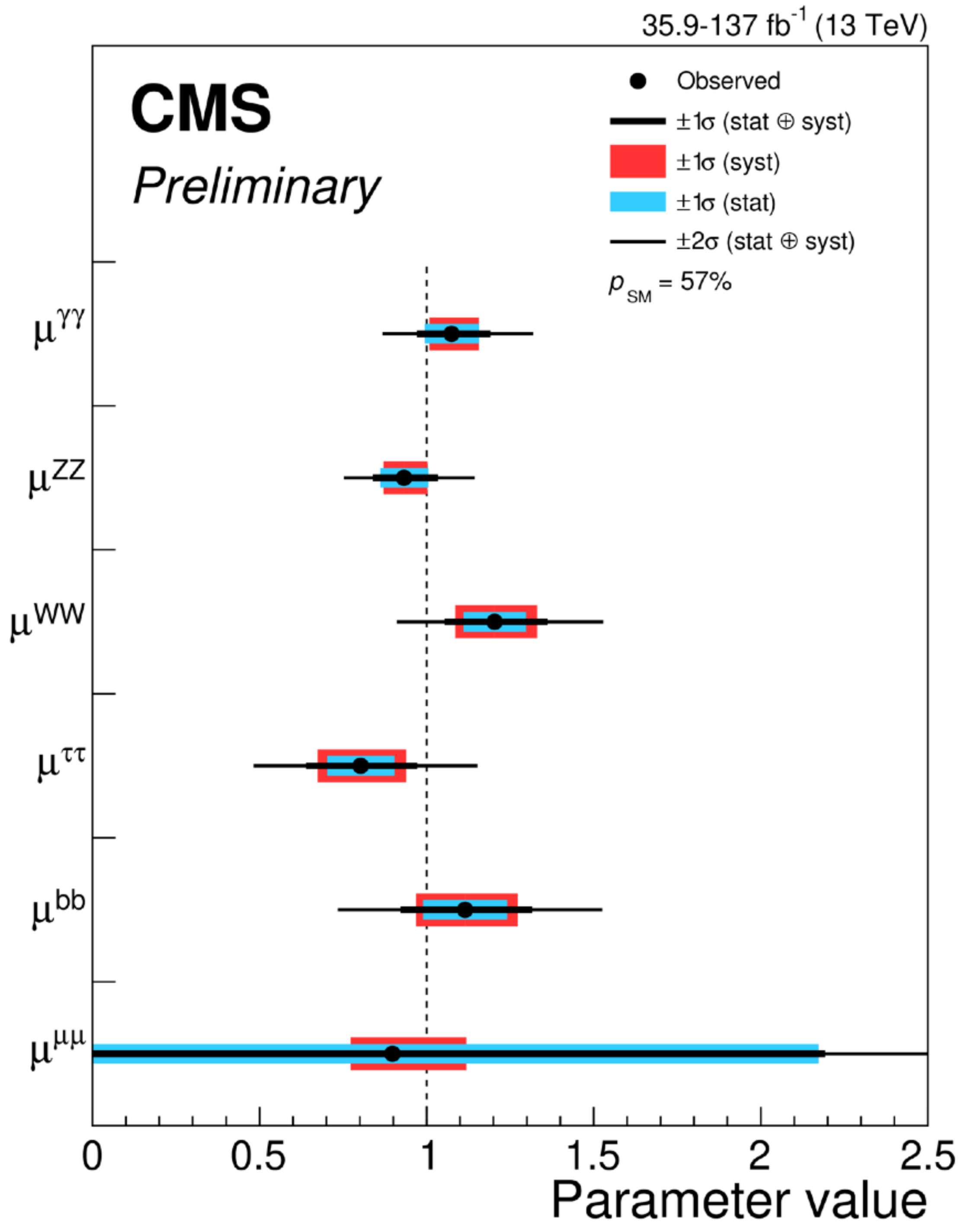


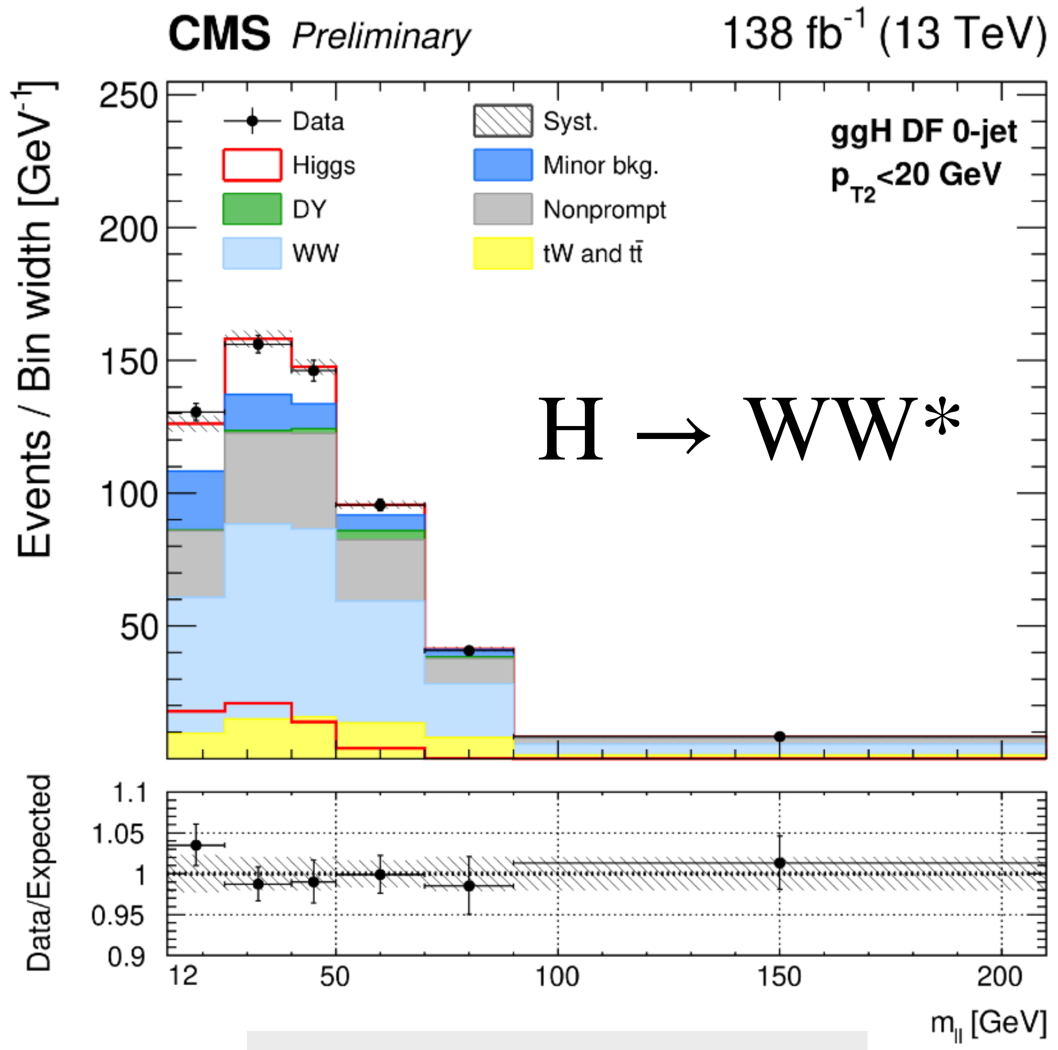
CMS-HIG-19-001
EPJC 81 (2021) 488



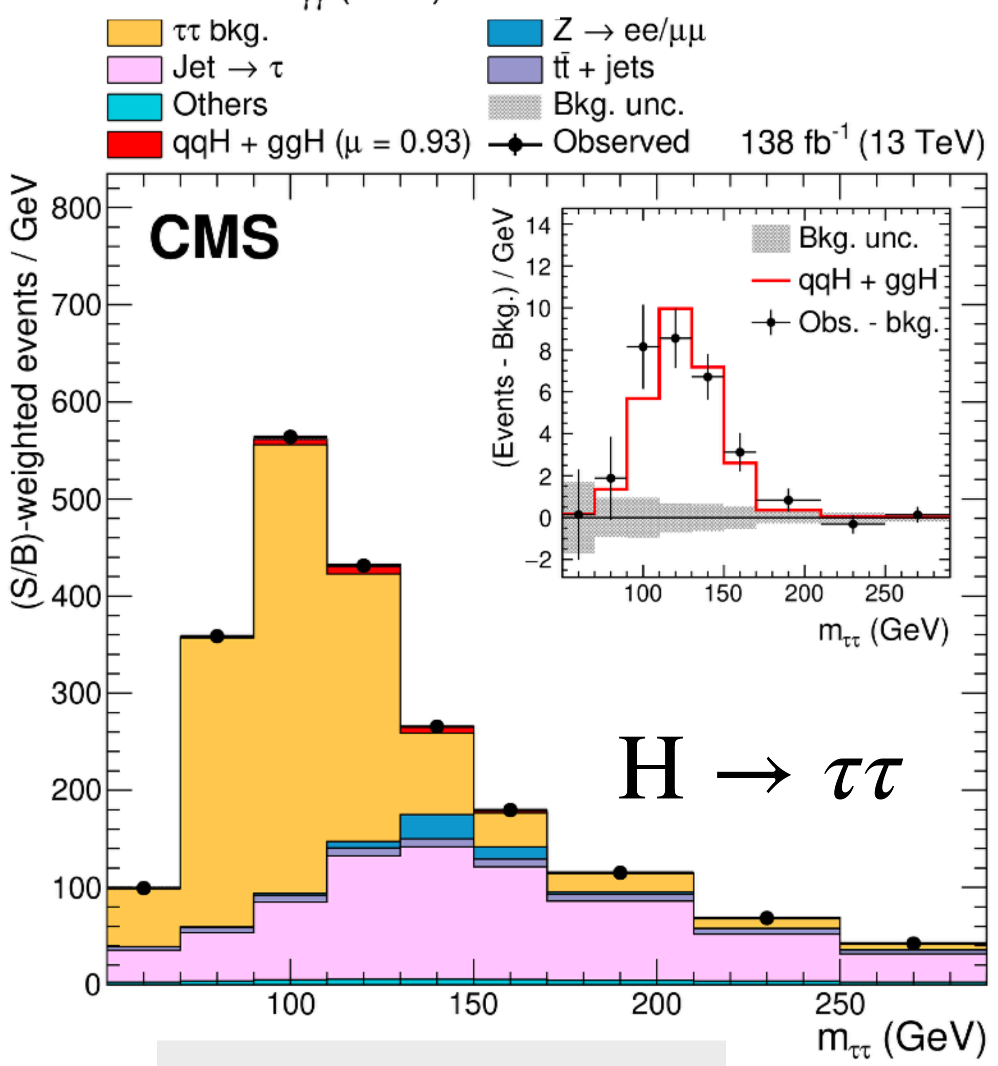
CMS-PAS-HIG-19-005

Observation independently in all 5 decay modes

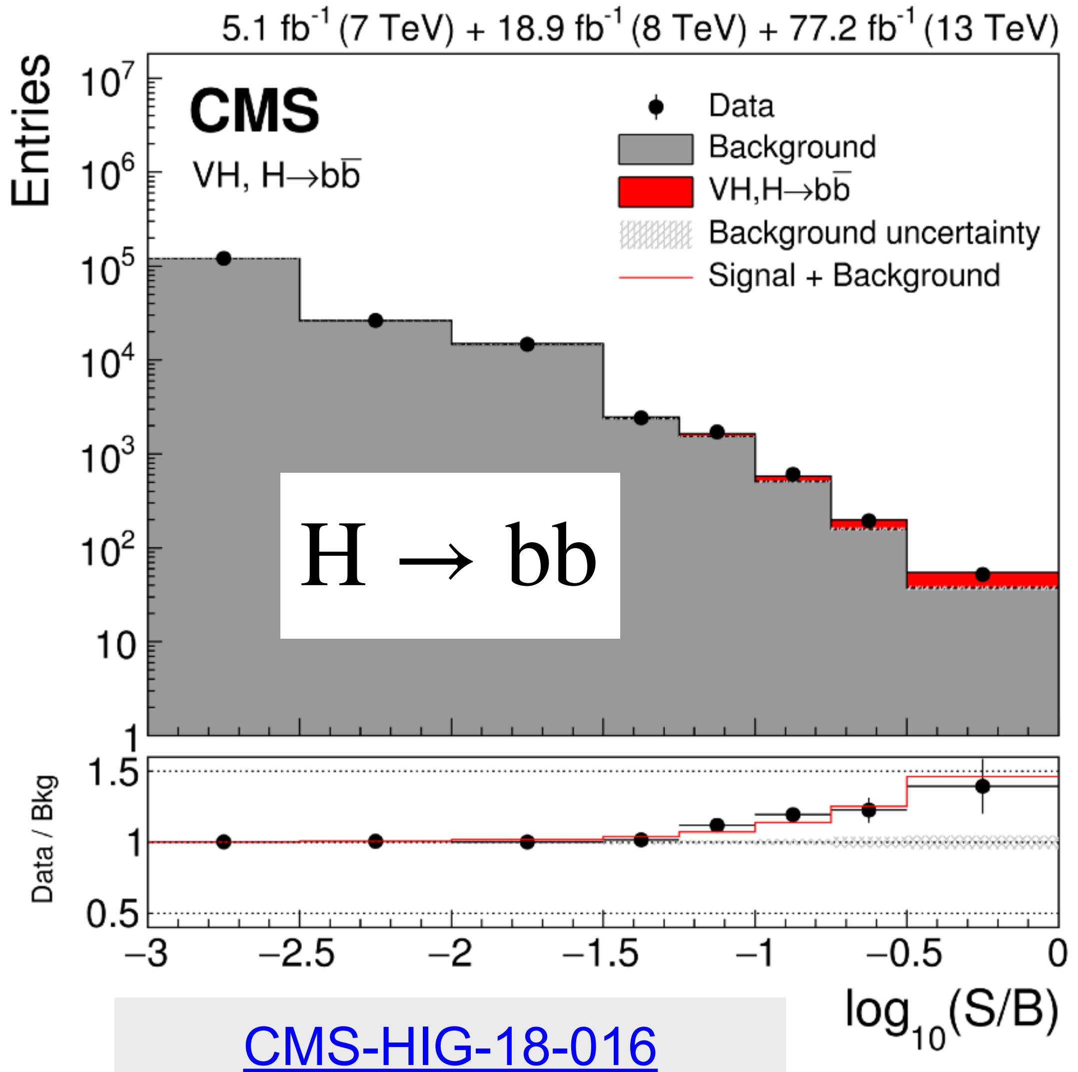




CMS-PAS-HIG-20-013



CMS-HIG-19-010
Submitted to EPJC



CMS-HIG-18-016
PRL 121 (2018) 121801

Higgs Boson Production and Decay

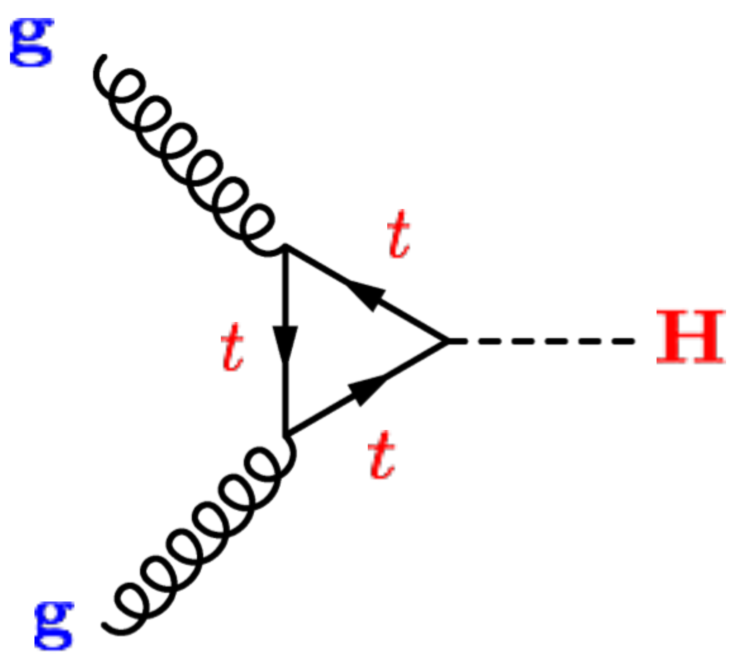
Main production modes
at 13 TeV (events for 140 fb^{-1})

Gluon fusion

ggH

86%

~8M

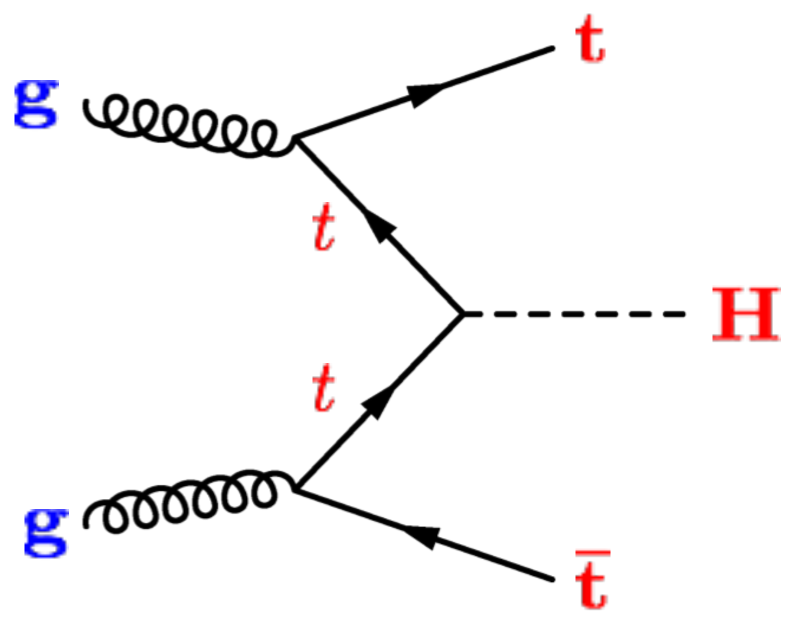


Top associated production

ttH

<1%

~80k

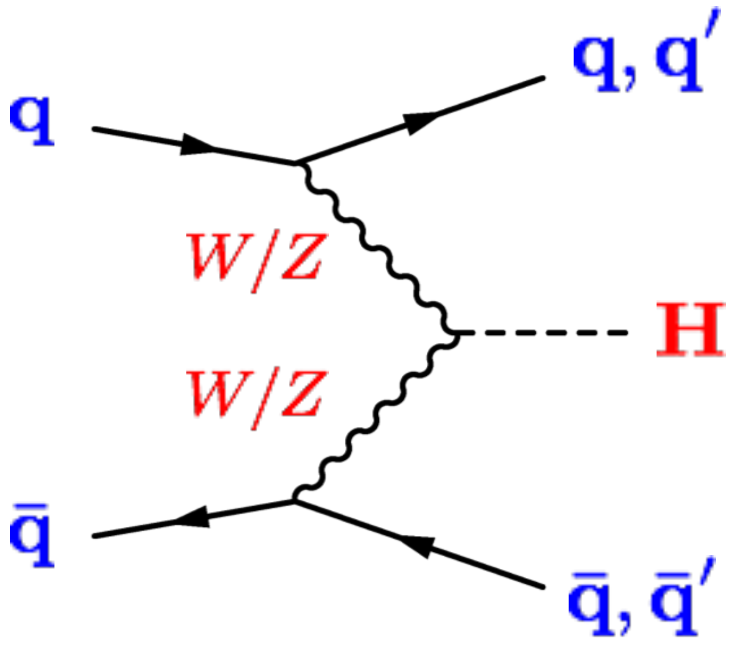


Vector Boson Fusion

VBF

7%

~600k

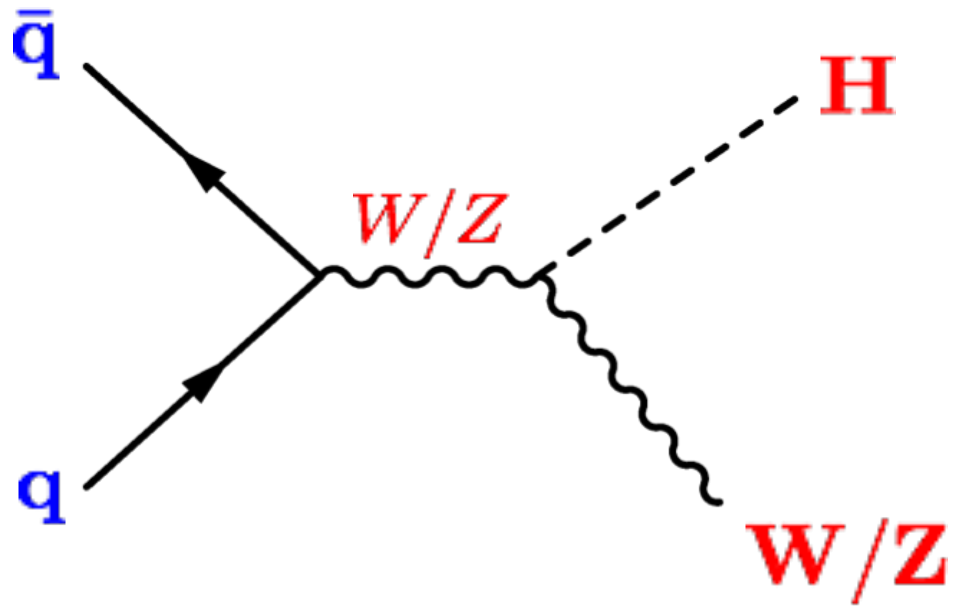


W and Z associated production

WH, ZH

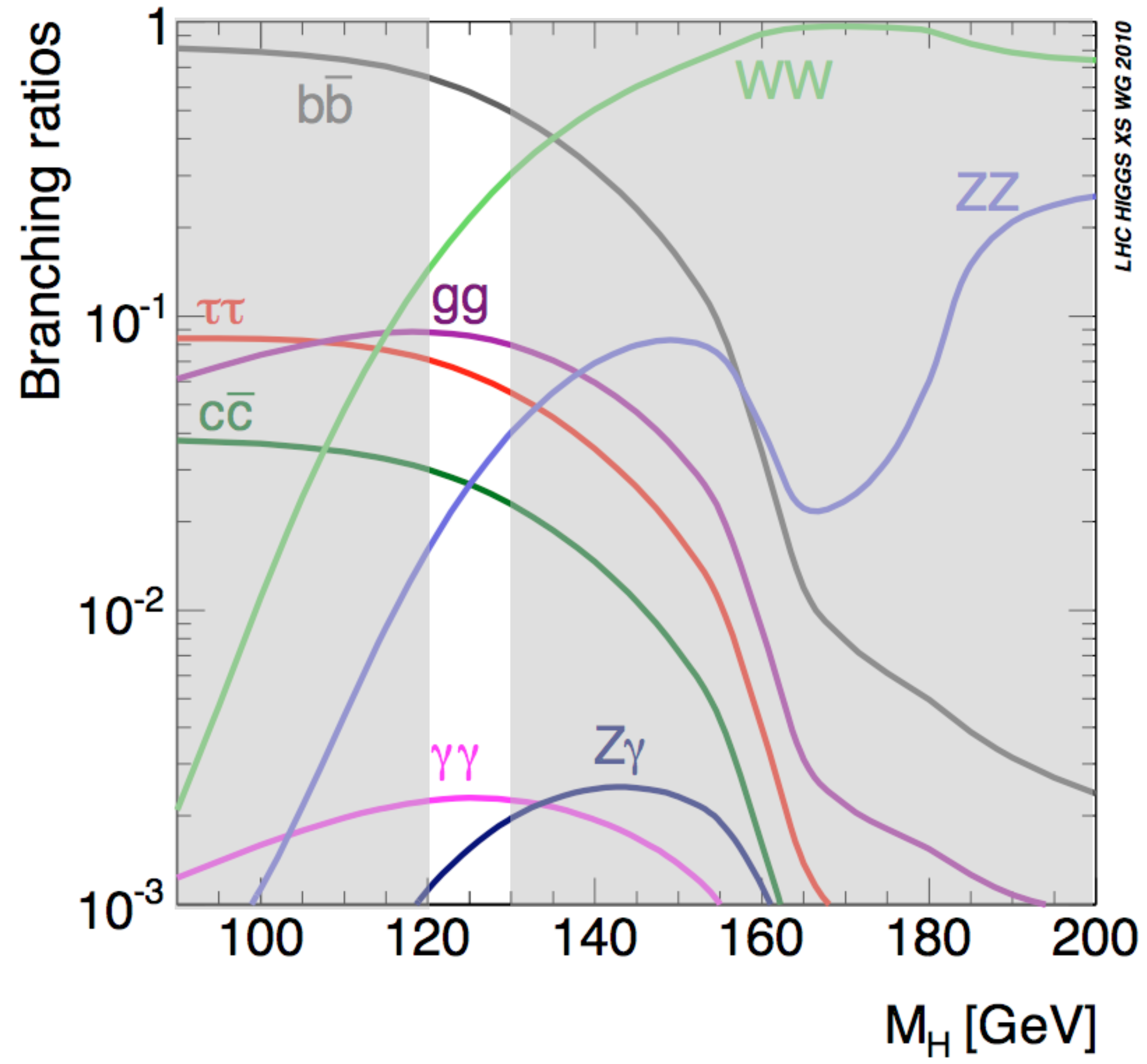
5%

~400k



theoretical uncertainties

ggH	7 %
VBF	3 %
VH	4 %
ttH	10 %

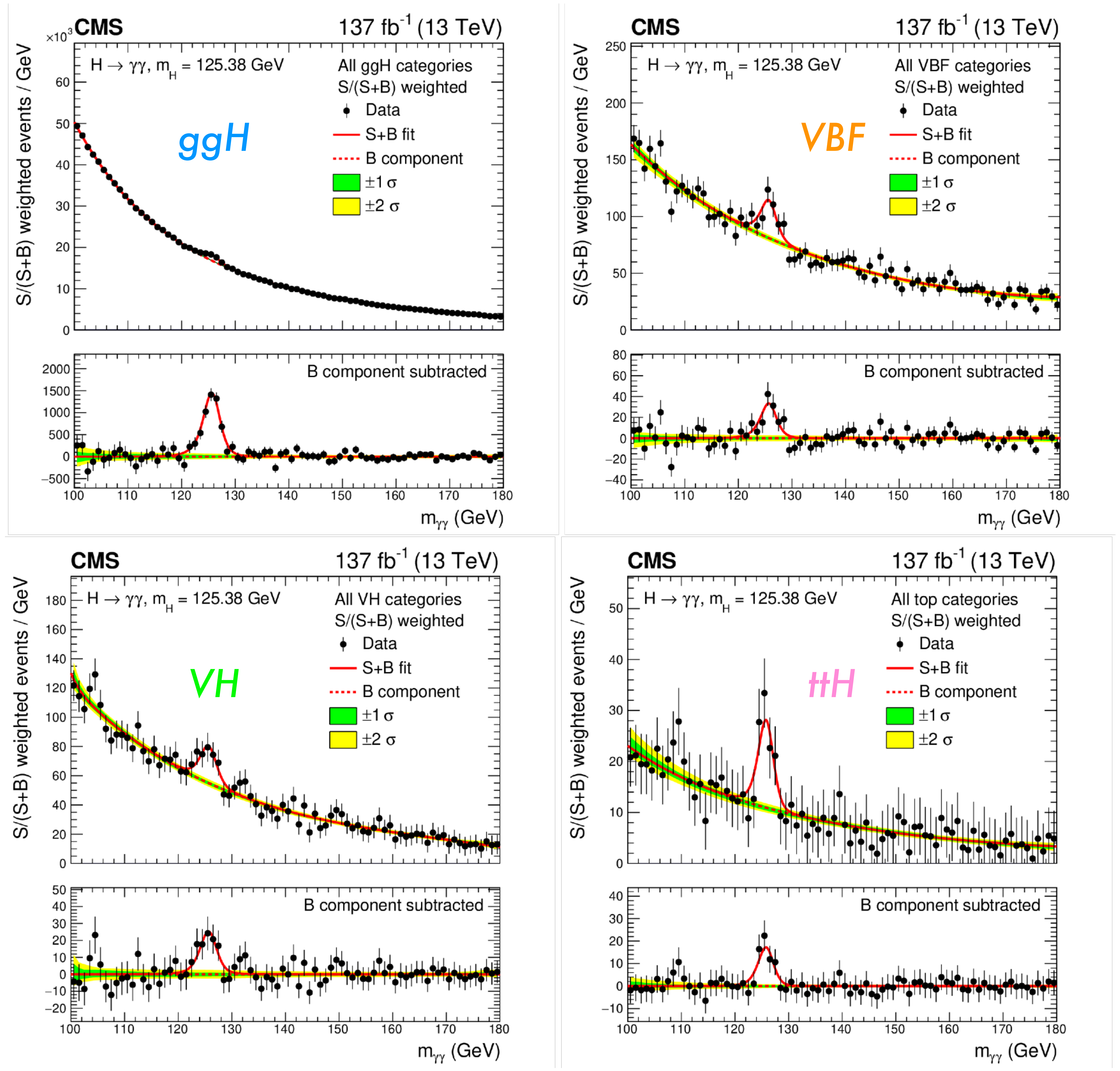


Main decay channels

BF (m_H = 125 GeV)

$H \to b\bar{b}$	57%
$H \to WW^*$	21%
$H \to gg$	8%
$H \to \tau\tau$	6.3%
$H \to c\bar{c}$	3%
$H \to ZZ^*$	2.7%
$H \to \gamma\gamma$	0.25%
$H \to Z\gamma$	0.15%
$H \to \mu\mu$	0.022%

$H \to \gamma\gamma$



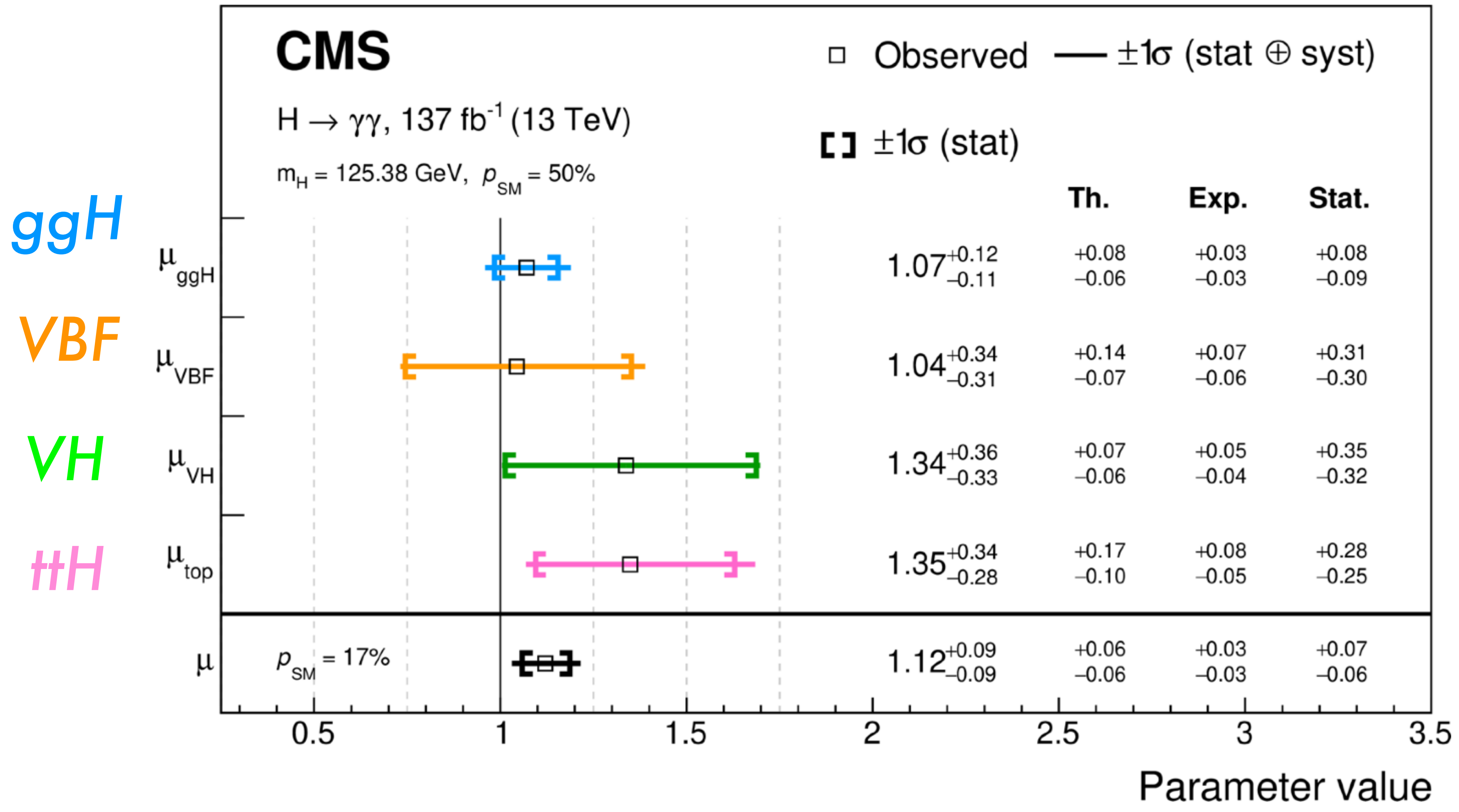
[CMS-HIG-19-015](CMS-HIG-19-015)
JHEP 07 (2021) 027

Discovery channel

- small signal yield
- large background
- excellent mass resolution (1-2%)

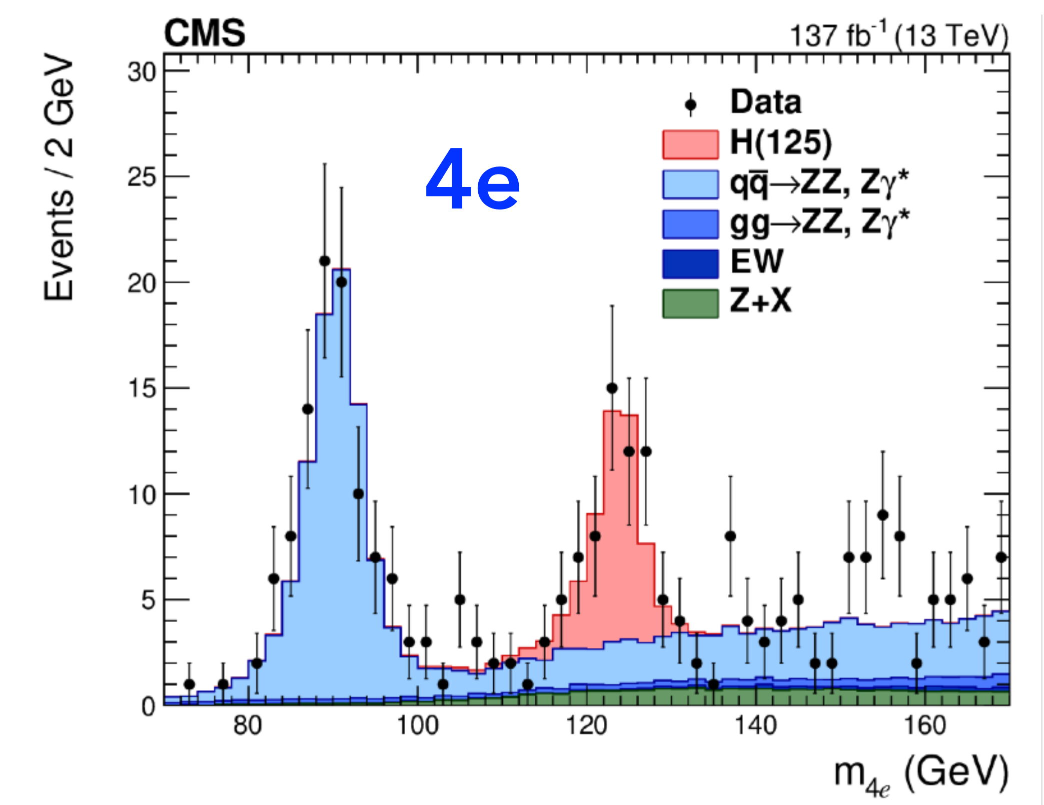
Signal Strength Modifiers μ: ratios between the measured Higgs boson yields and SM expectations

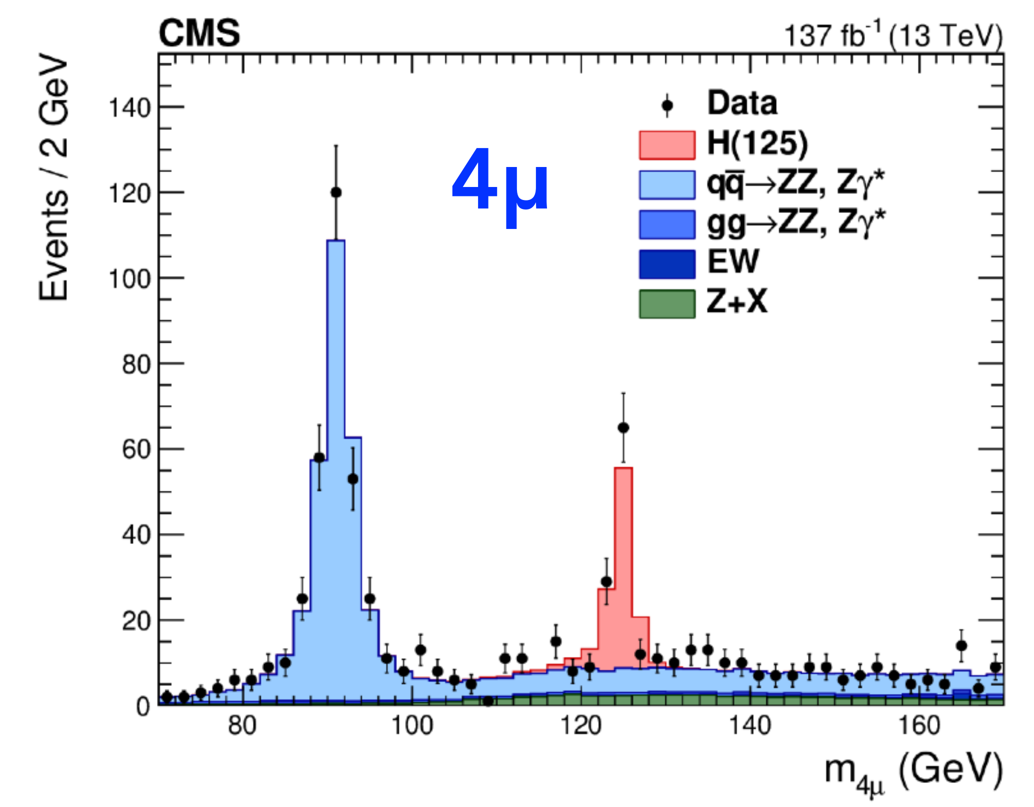
$$\mu(\mathrm{pp} \to \mathrm{H} \to \gamma\gamma) = 1.12 \pm 0.09$$

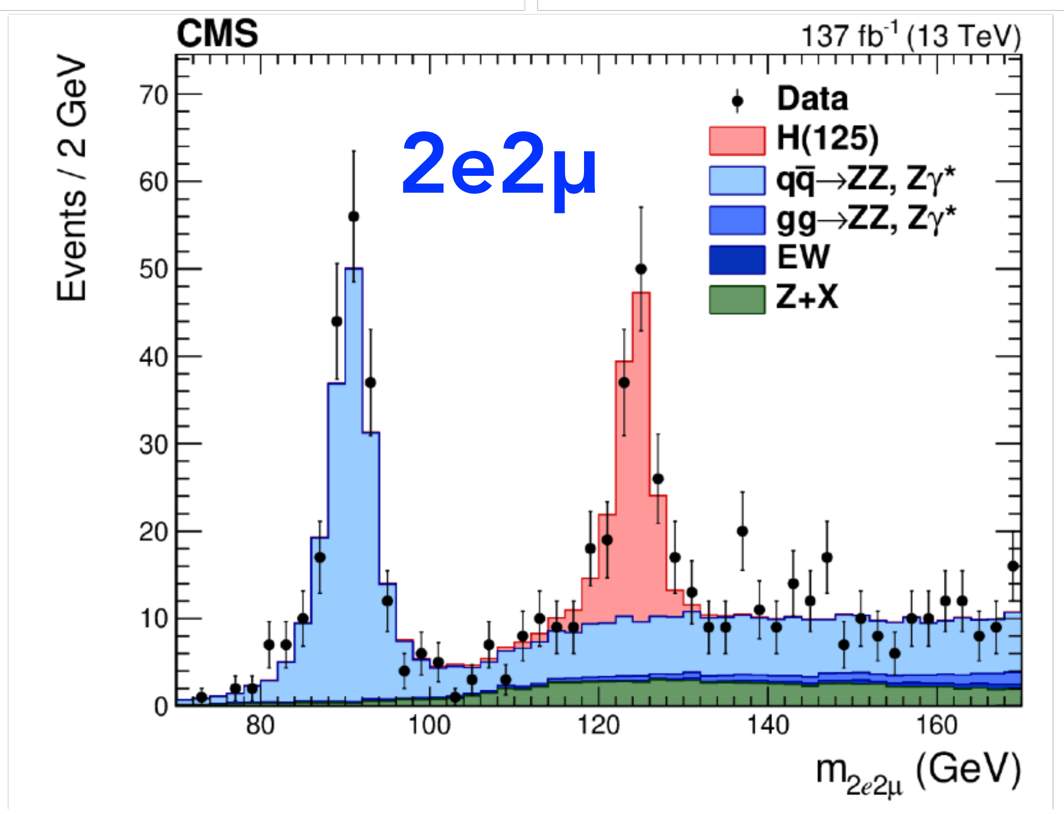


Clear H → γγ signals in all four main production modes, including pp → $t\bar{t}$H (>5σ)

$H \to ZZ^* \to 4\ell$

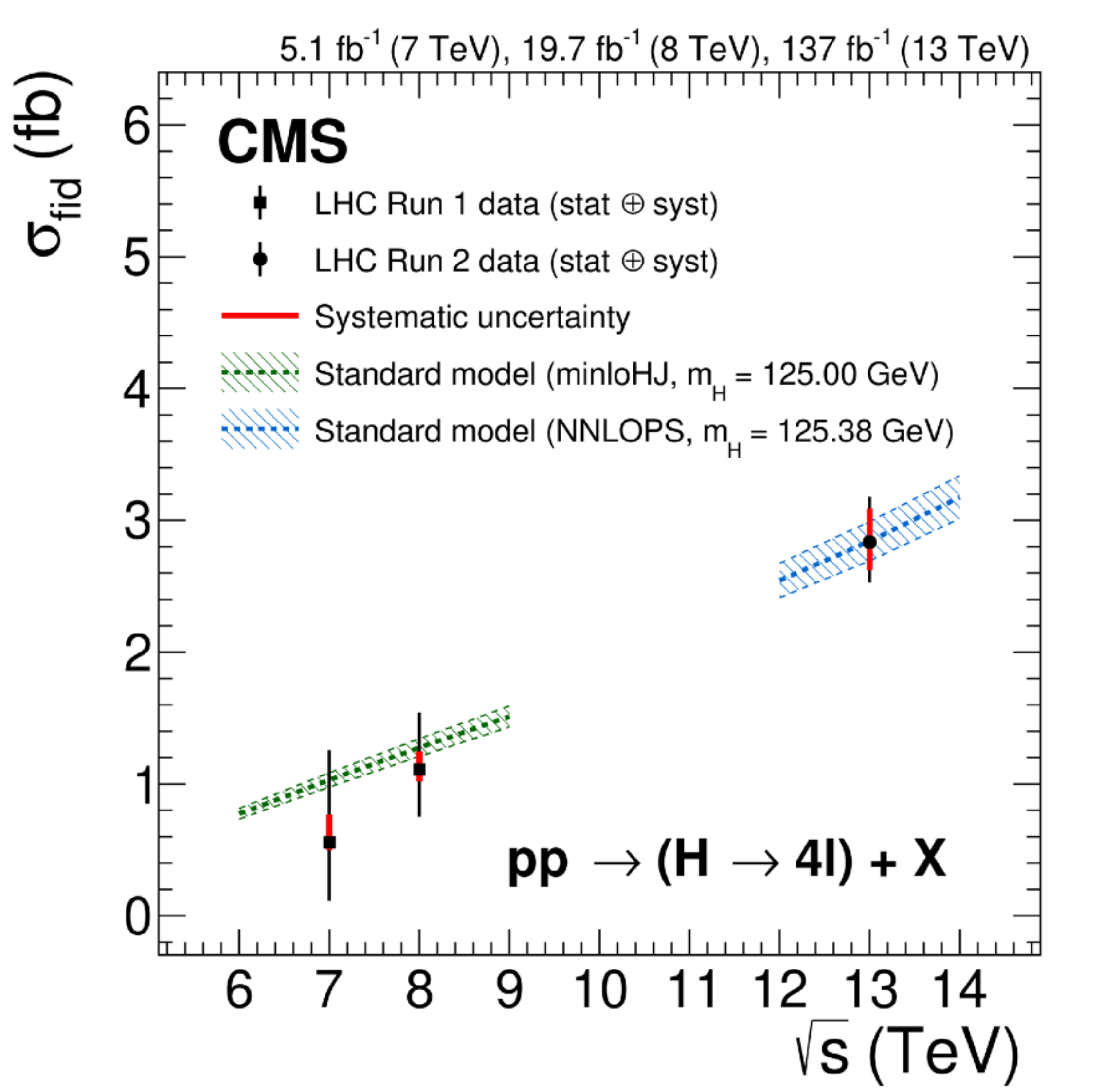


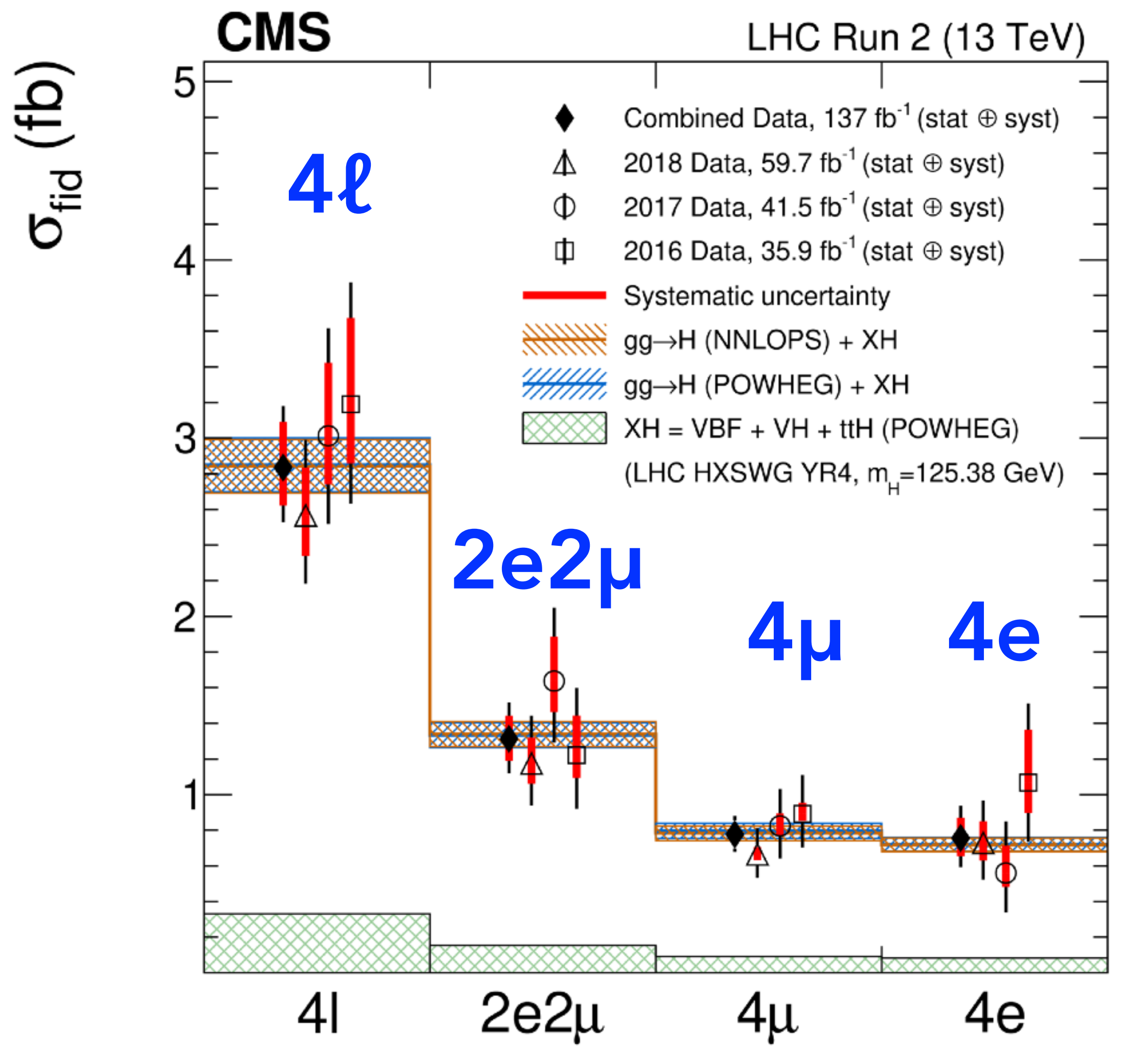


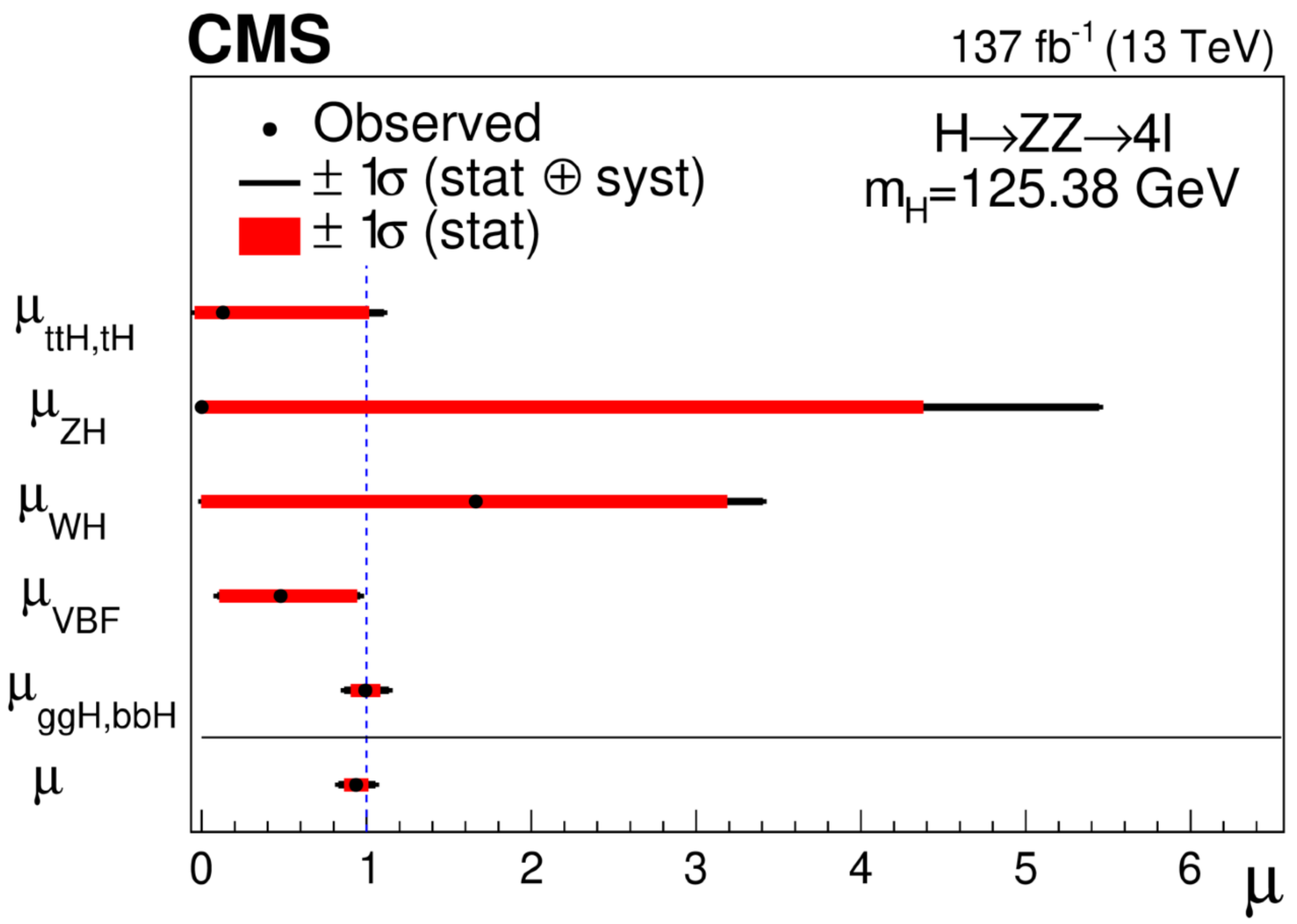


The Golden channel

- excellent mass resolution: 1% (4μ), 2% (4e)
- small background mostly from non resonant ZZ*
- but **very small signal yield**

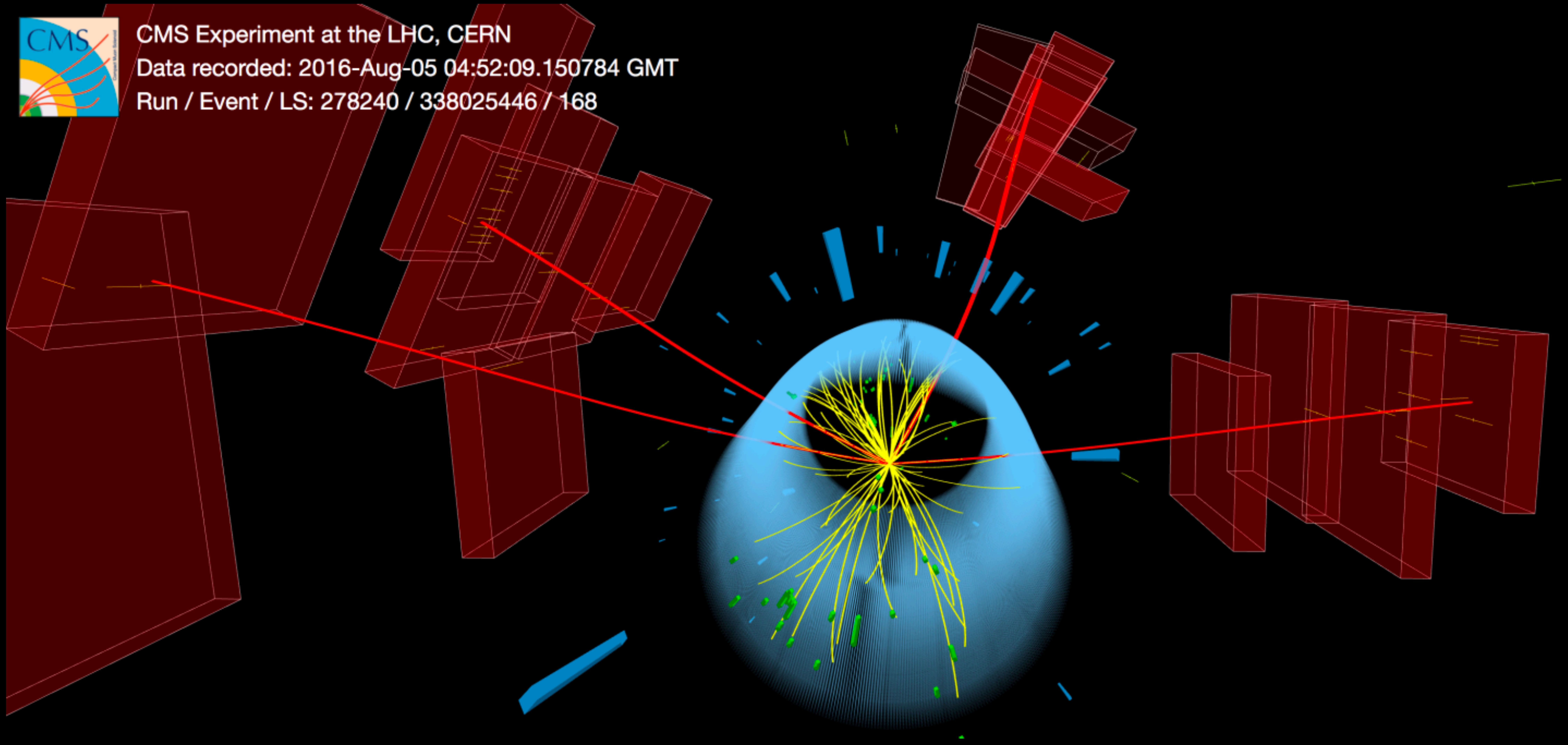






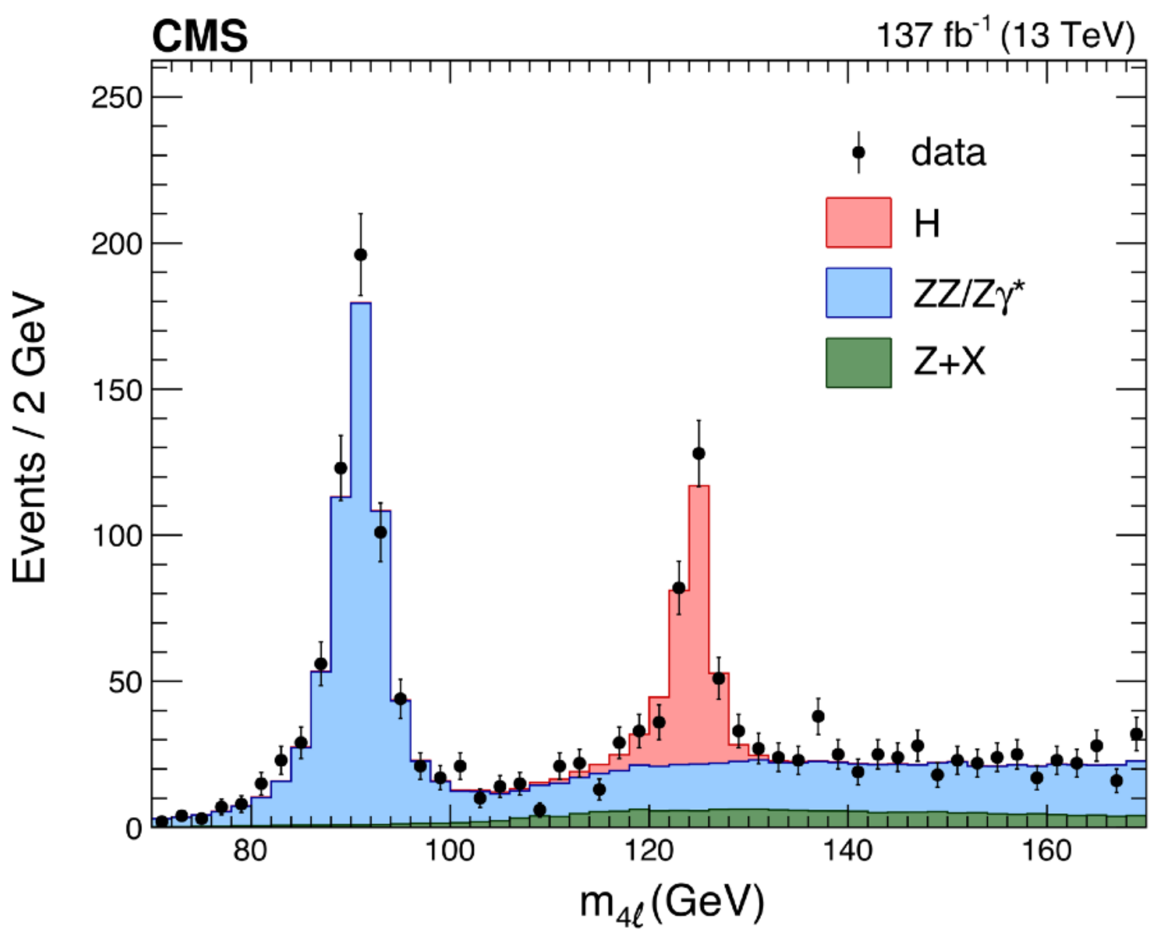
[CMS-HIG-19-001](#)
EPJC 81 (2021) 488

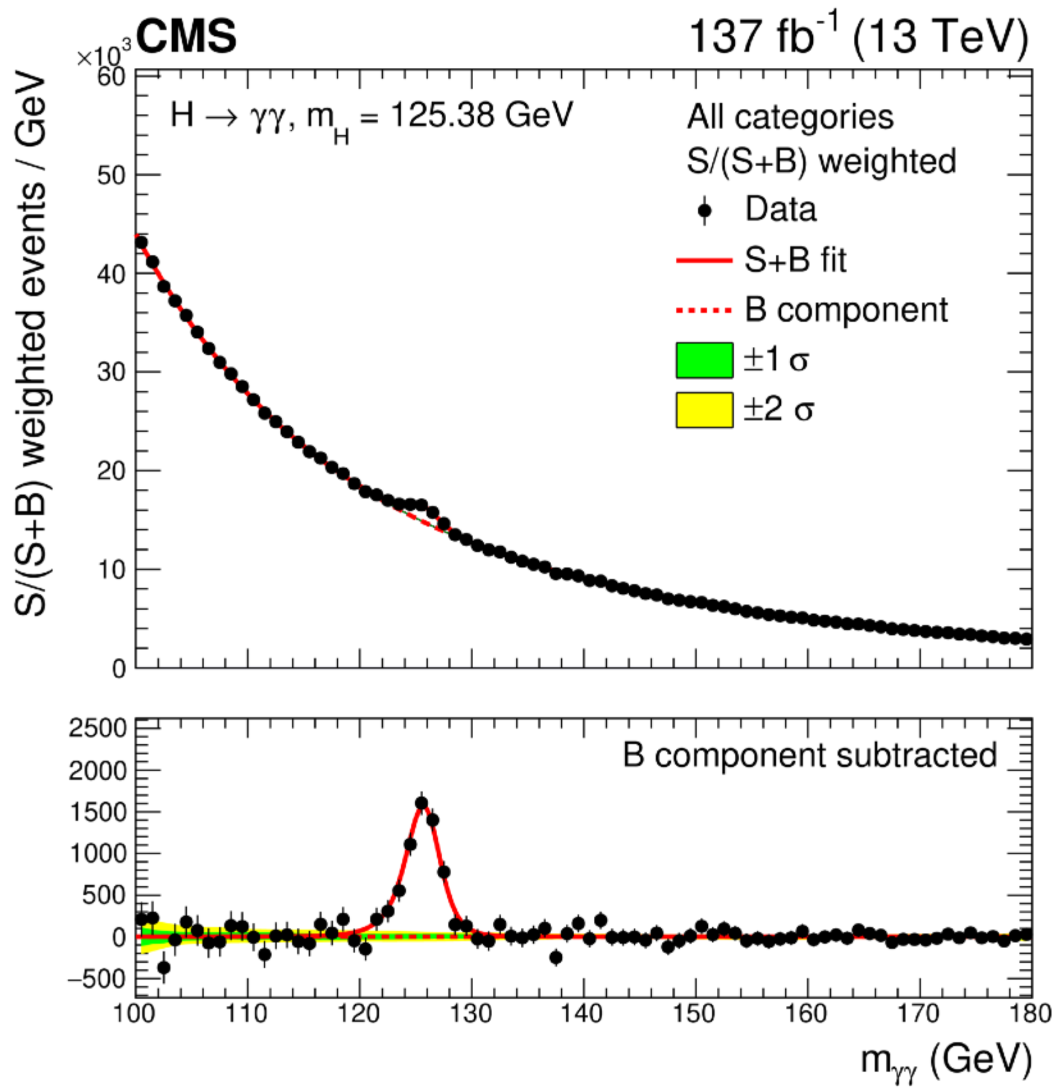
$H \to 4\ell$



a $H \to 4\mu$ candidate

Higgs Mass Measurements





H → ZZ → 4ℓ

$$m_{\rm H} = 125.26 \pm 0.21\,({\rm total})\,{\rm GeV}$$

CMS-HIG-16-041
JHEP 11 (2017) 047

H → γγ

- using a refined calorimeter calibration

$$m_{\rm H} = 125.78 \pm 0.26\,({\rm total})\,{\rm GeV}$$

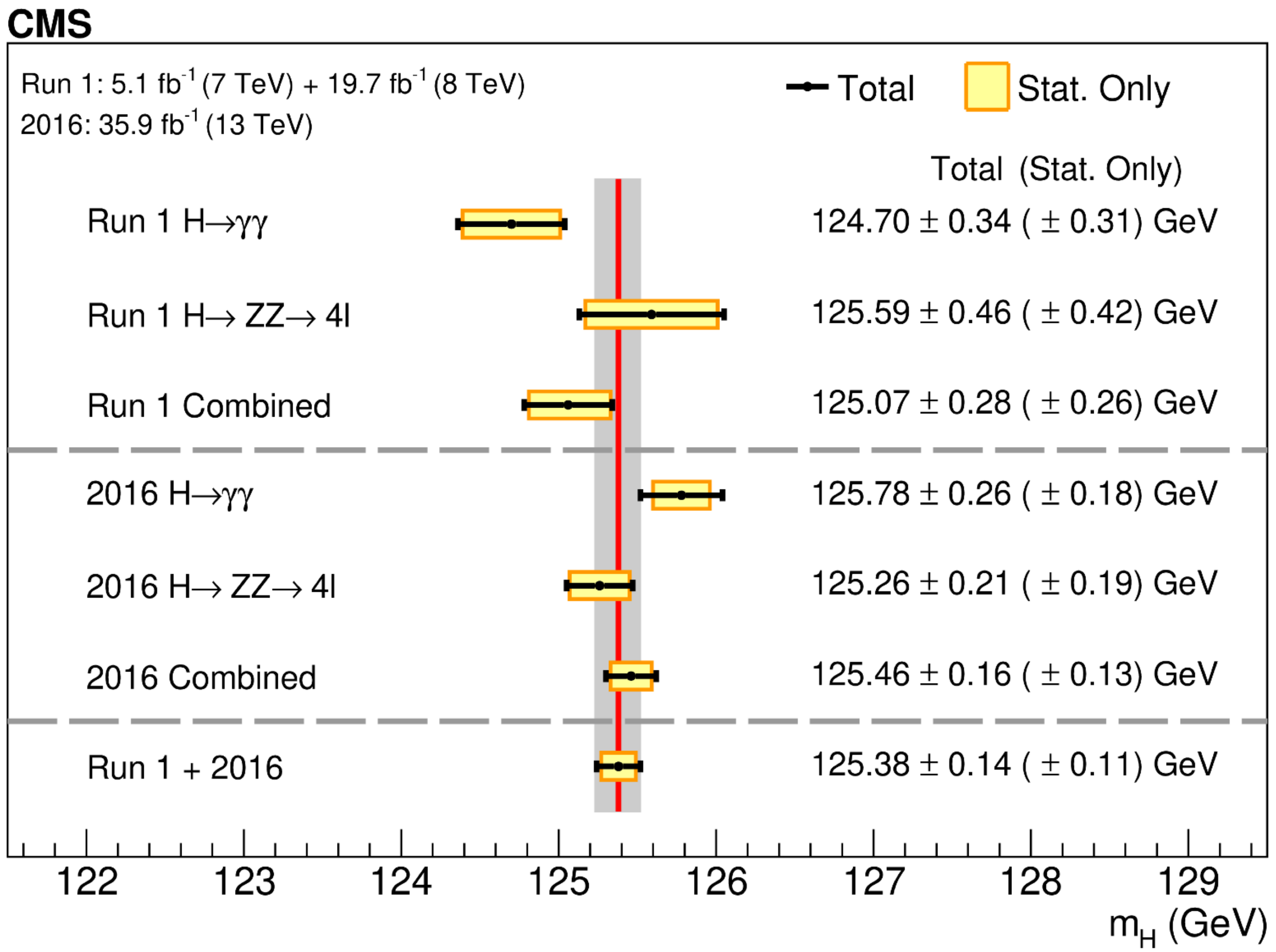
Run-2/2016 combination

CMS-HIG-19-004
PLB 805 (2020) 135425

$$m_{\rm H} = 125.46 \pm 0.16\,({\rm total})\,{\rm GeV}$$

The Higgs boson mass measurement uncertainty is still dominated by statistics

Run-2 2016, 35.9 fb−1



Combination with Run-1 result

$$m_{\rm H} = 125.38 \pm 0.14\,({\rm total})\,{\rm GeV}$$

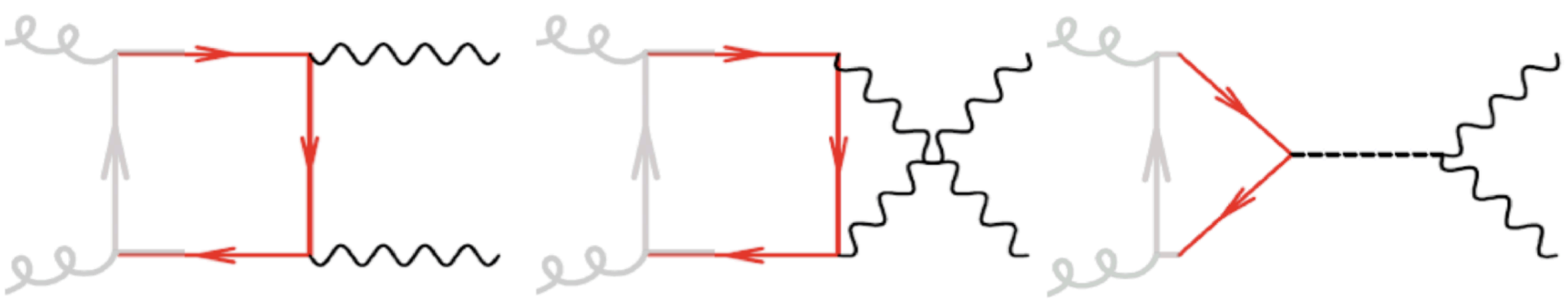
- currently the most precise measurement (1.1‰)
- central value consistently used in CMS analyses

Off-Peak Production and Higgs Width

CMS-HIG-18-002
PRD 99 (2019) 112003

CMS-HIG-21-013
Submitted to Nature Physics

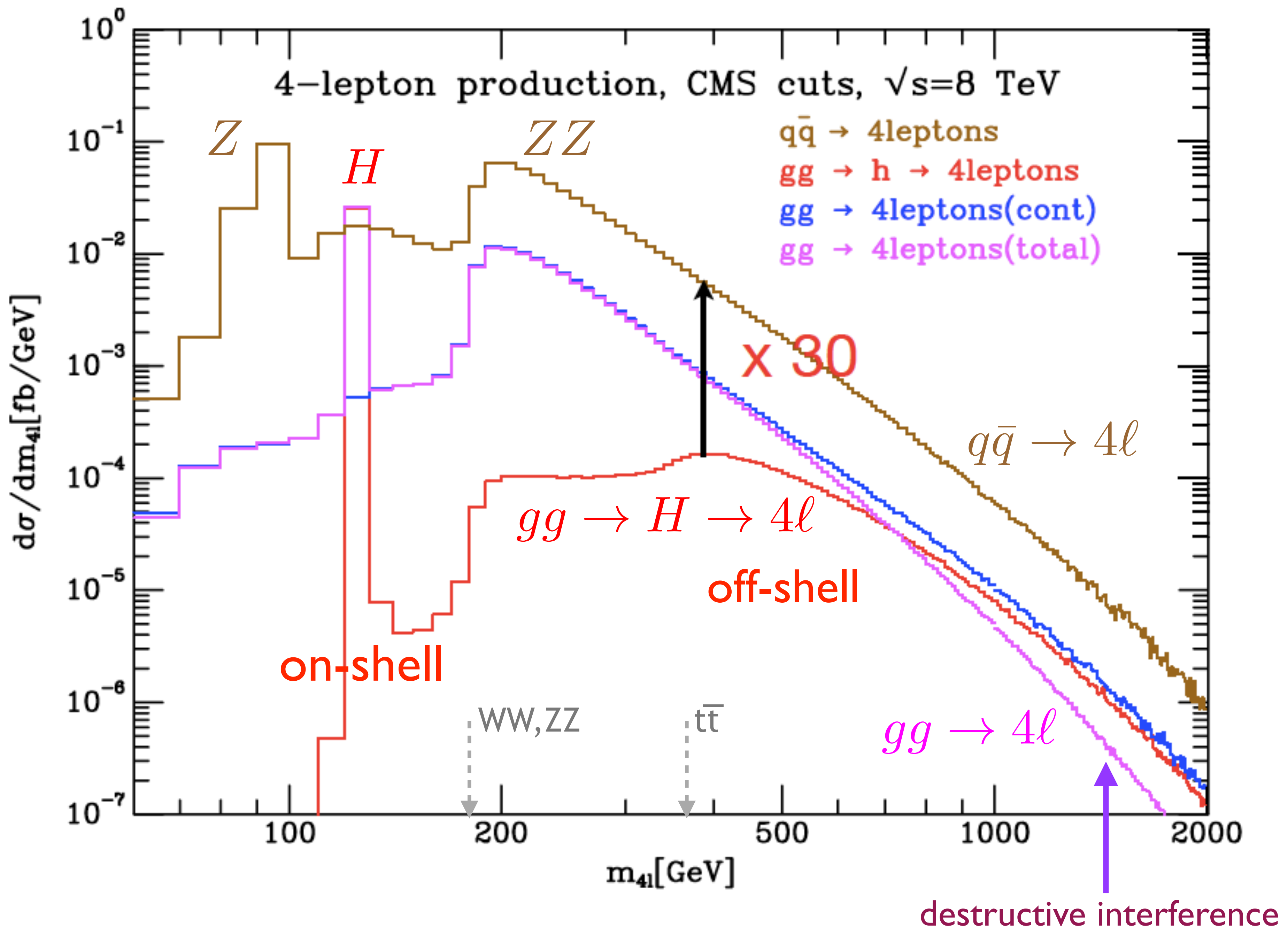
gg → ZZ   gg → H → ZZ



$aE^2 + (b+c)m_tE$ $-aE^2 + (d-c)m_tE$ $-(b+d)m_tE$

- negative interference between the gg → ZZ and gg → H → ZZ
- dominant background: qq → ZZ

By studying the high mass gg → ZZ region *indirect* constraints on Γ_H



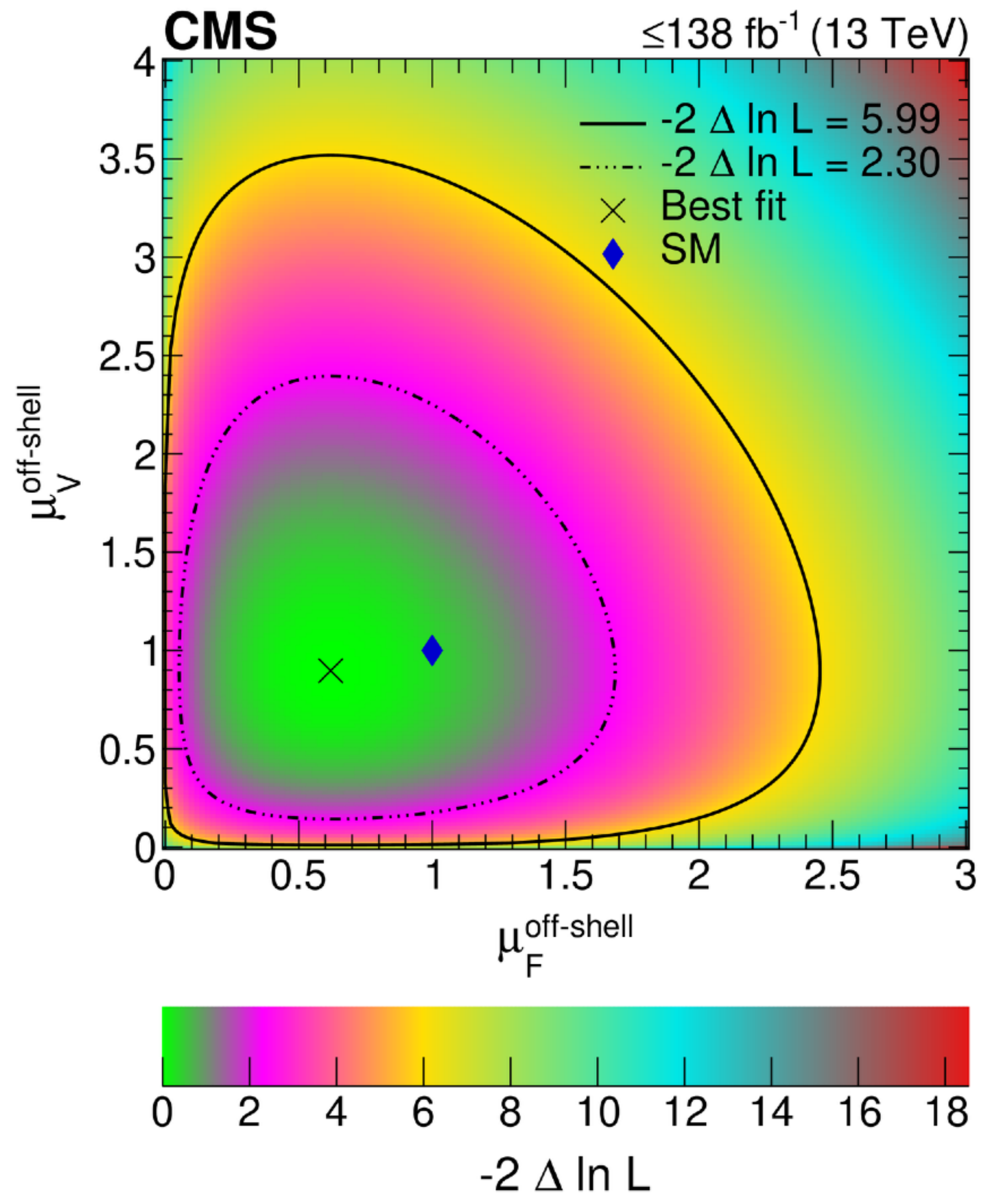
Assuming equal couplings on- and off-shell:

$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$

Combination $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$

- evidence for off-shell production at 3.6σ
- $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

$(\Gamma_H^{SM} = 4\,\text{MeV})$

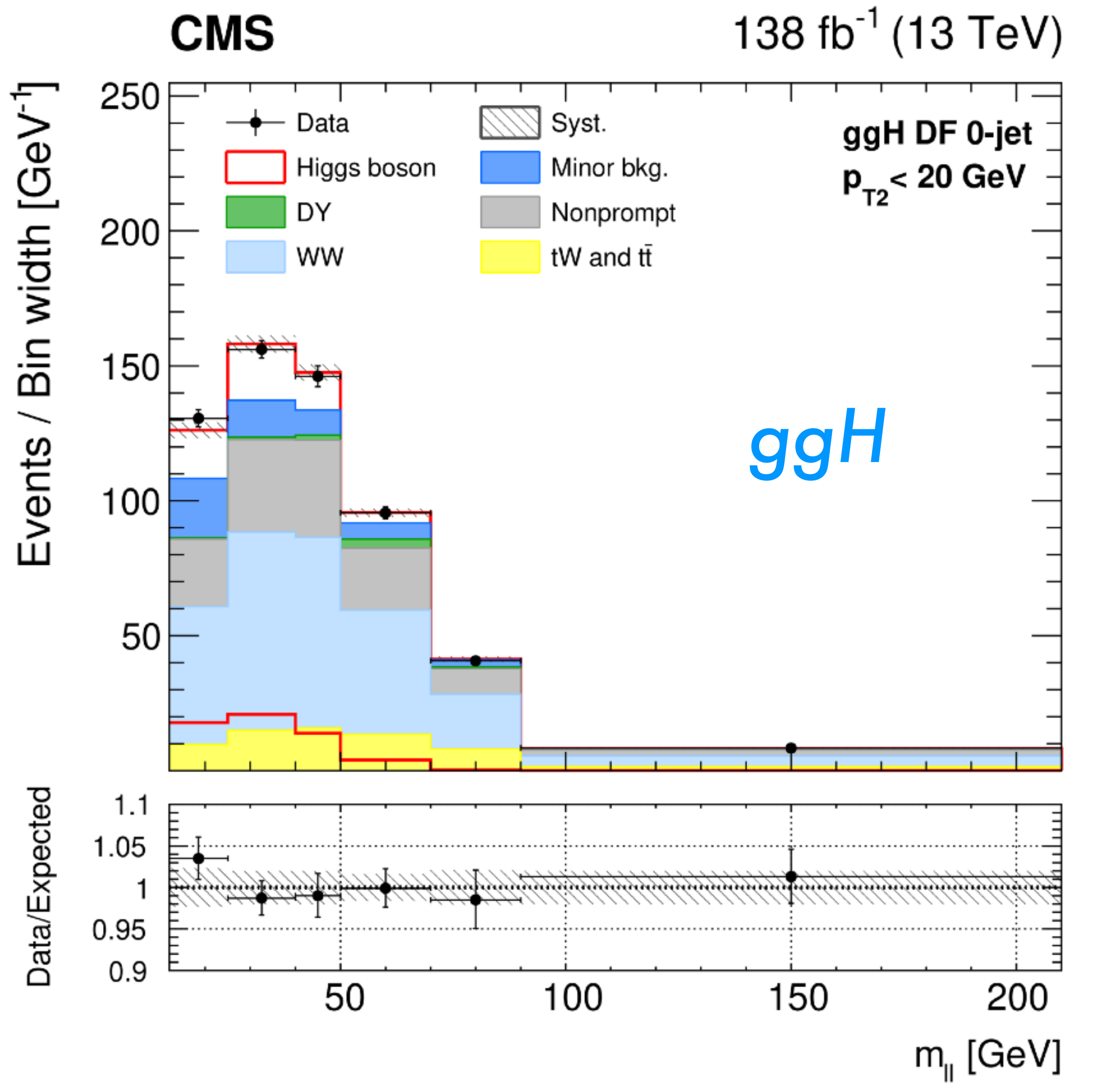


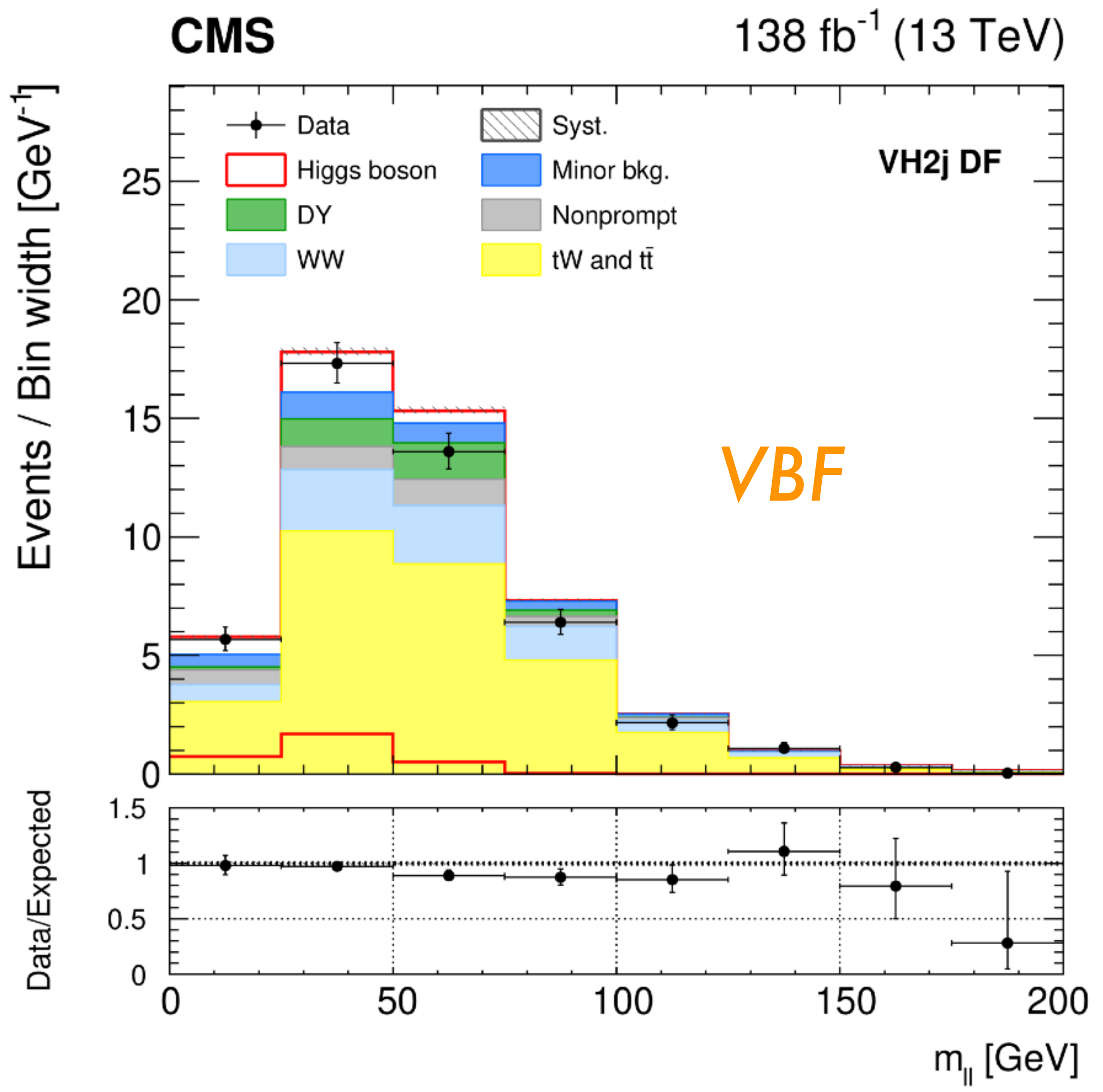
Direct measurement:

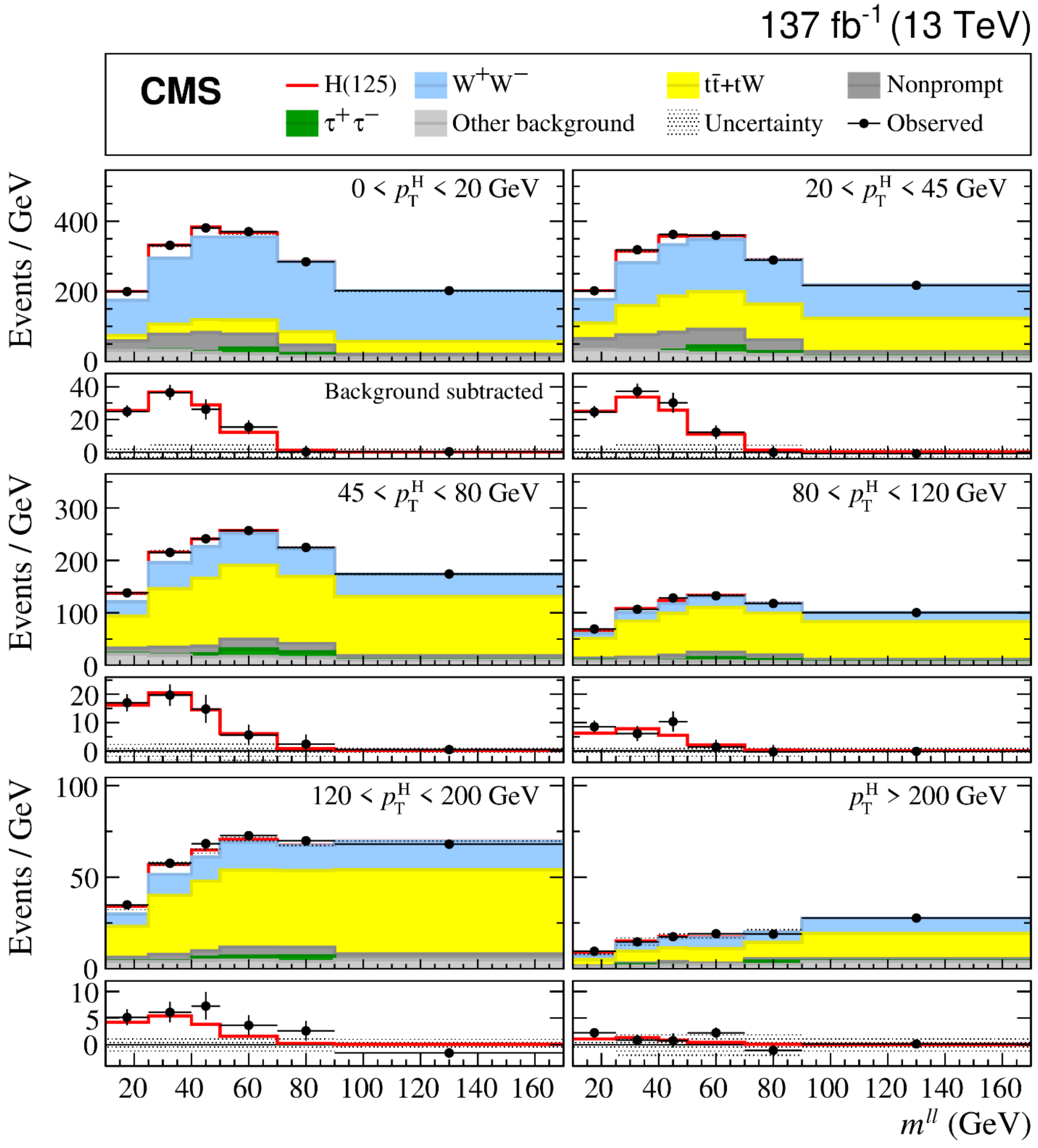
$\Gamma_H < 2.4\ (3.1)$ GeV

CMS-HIG-13-001
EPJC 74 (2014) 3076

$H \rightarrow WW^* \rightarrow 2\ell 2\nu$

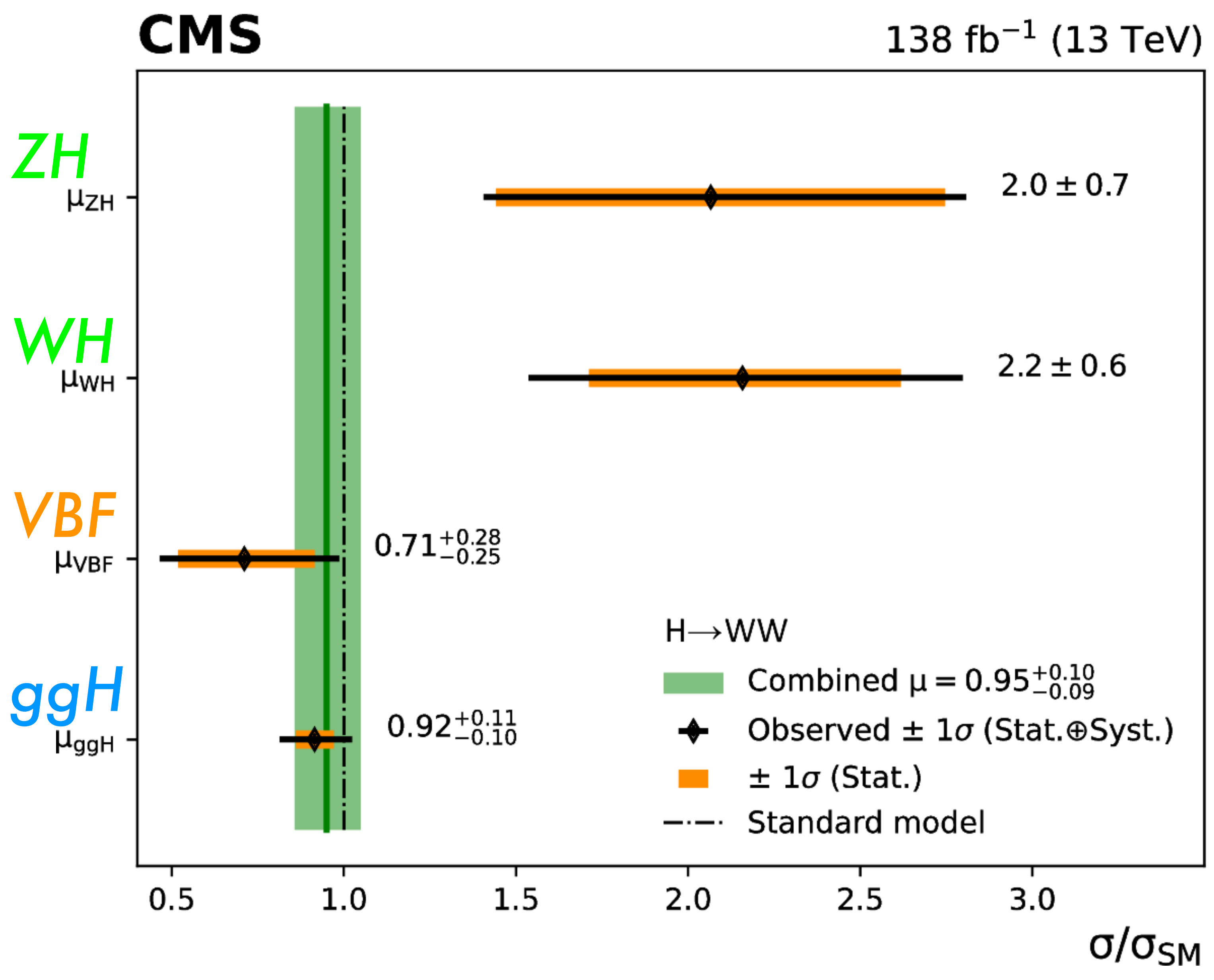






[CMS-HIG-20-013](CMS-HIG-20-013)

Accepted by EPJC



Discovery channel

- large signal yield
- large background from WW at low p_T and tt at large p_T

Higgs Decays to Fermions

Summer 2017:

first observation by CMS of $H \rightarrow \tau^+\tau^-$

CMS-HIG-16-043
PLB 779 (2018) 283

Summer 2018:

first observation by CMS of $H \rightarrow b\bar{b}$

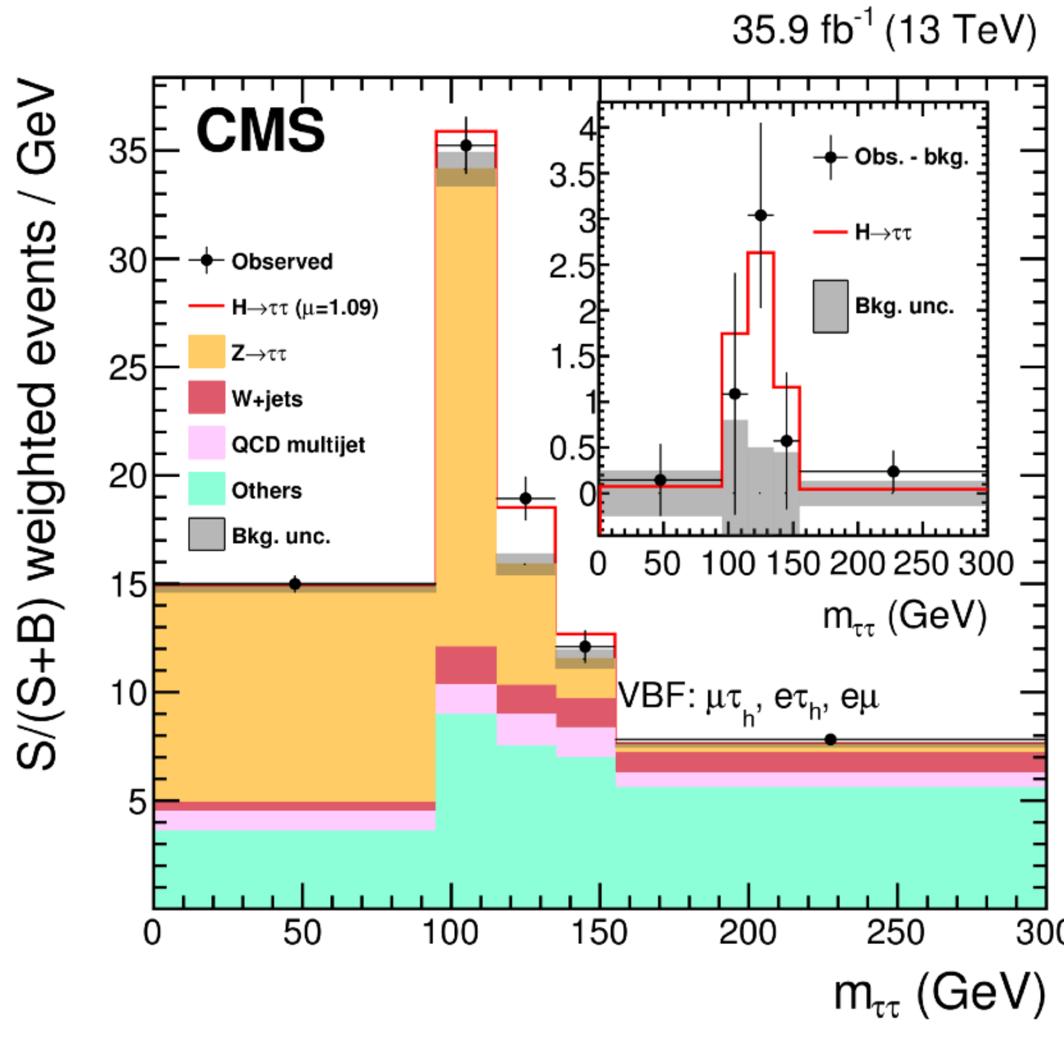
CMS-HIG-18-016
PRL 121 (2018) 121801

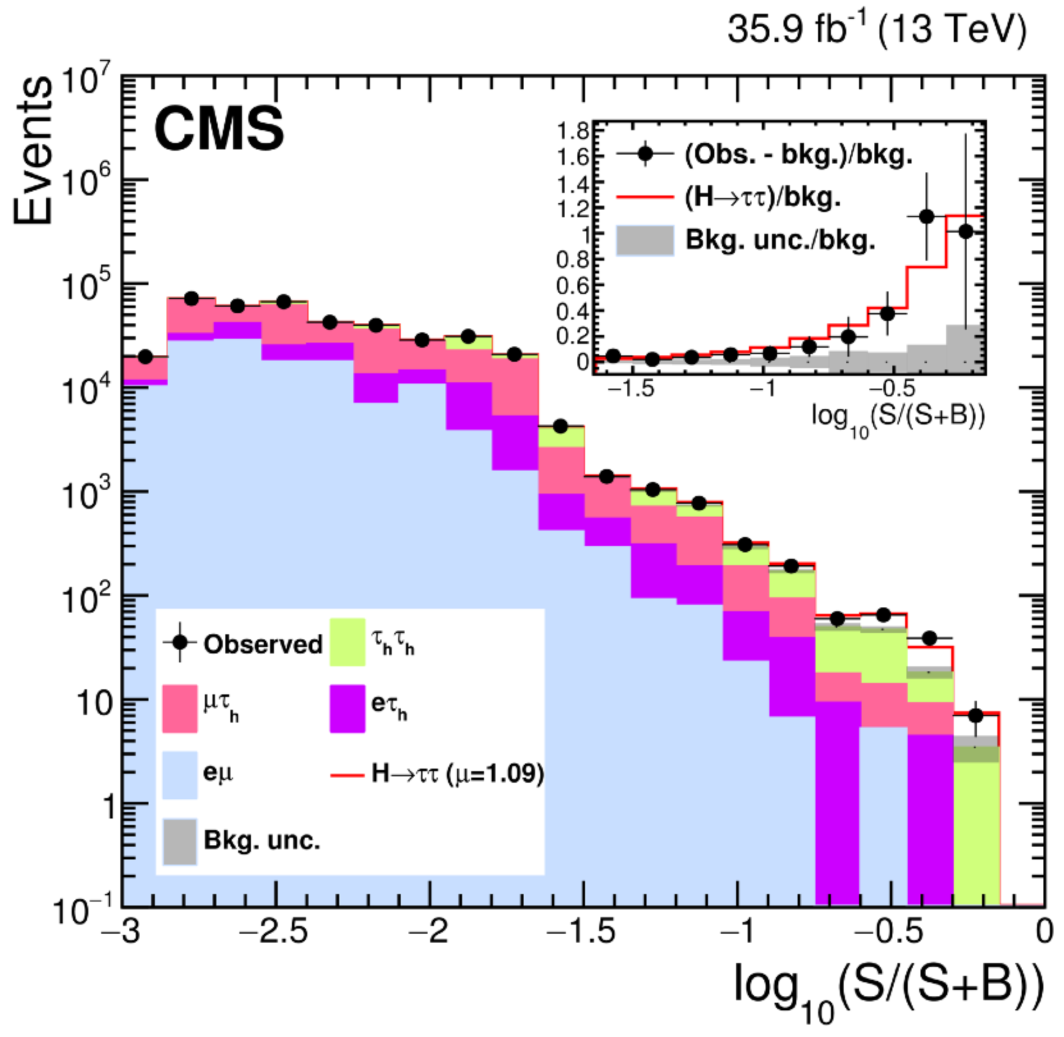
Winter 2019:

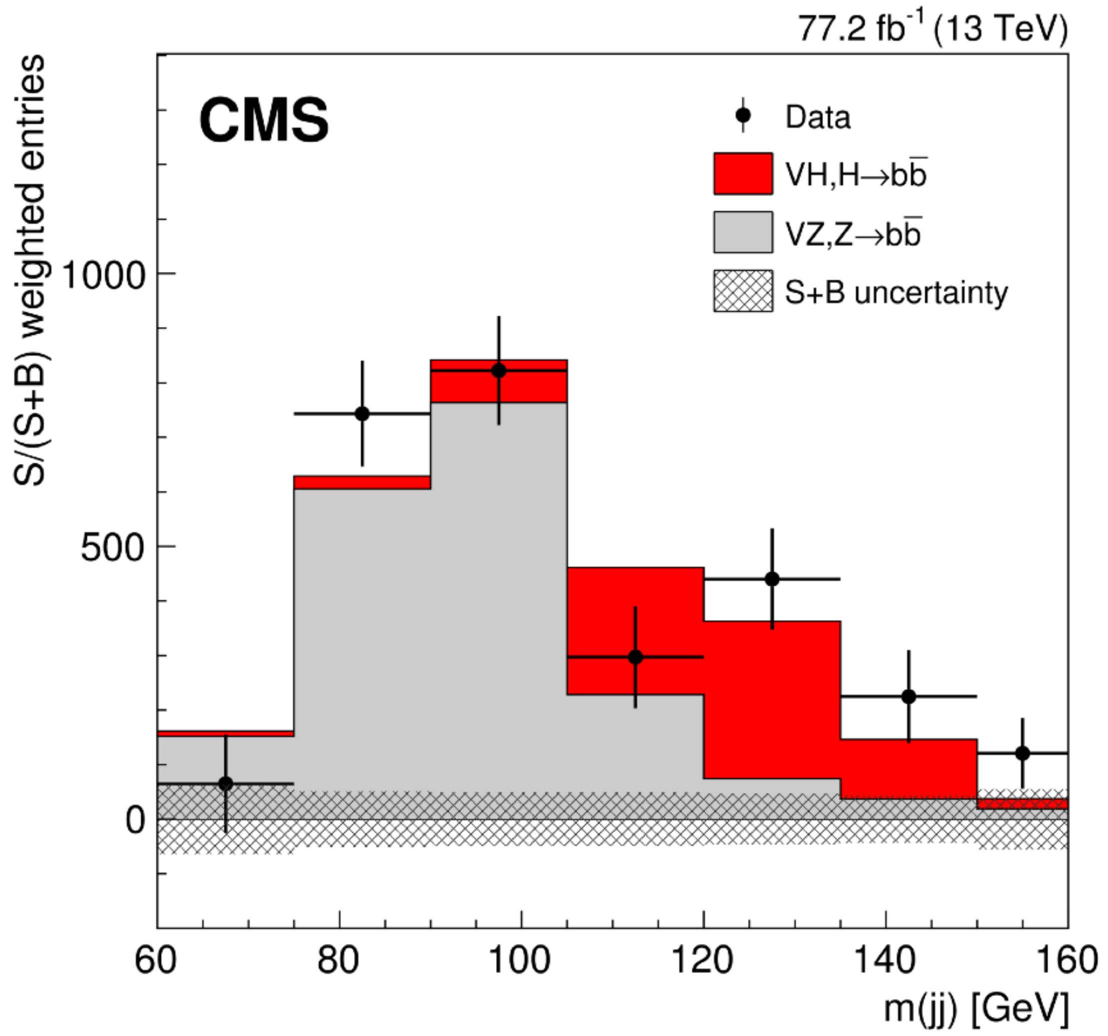
Obs. (exp.) limit on $pp \rightarrow VH(H \rightarrow c\bar{c})$

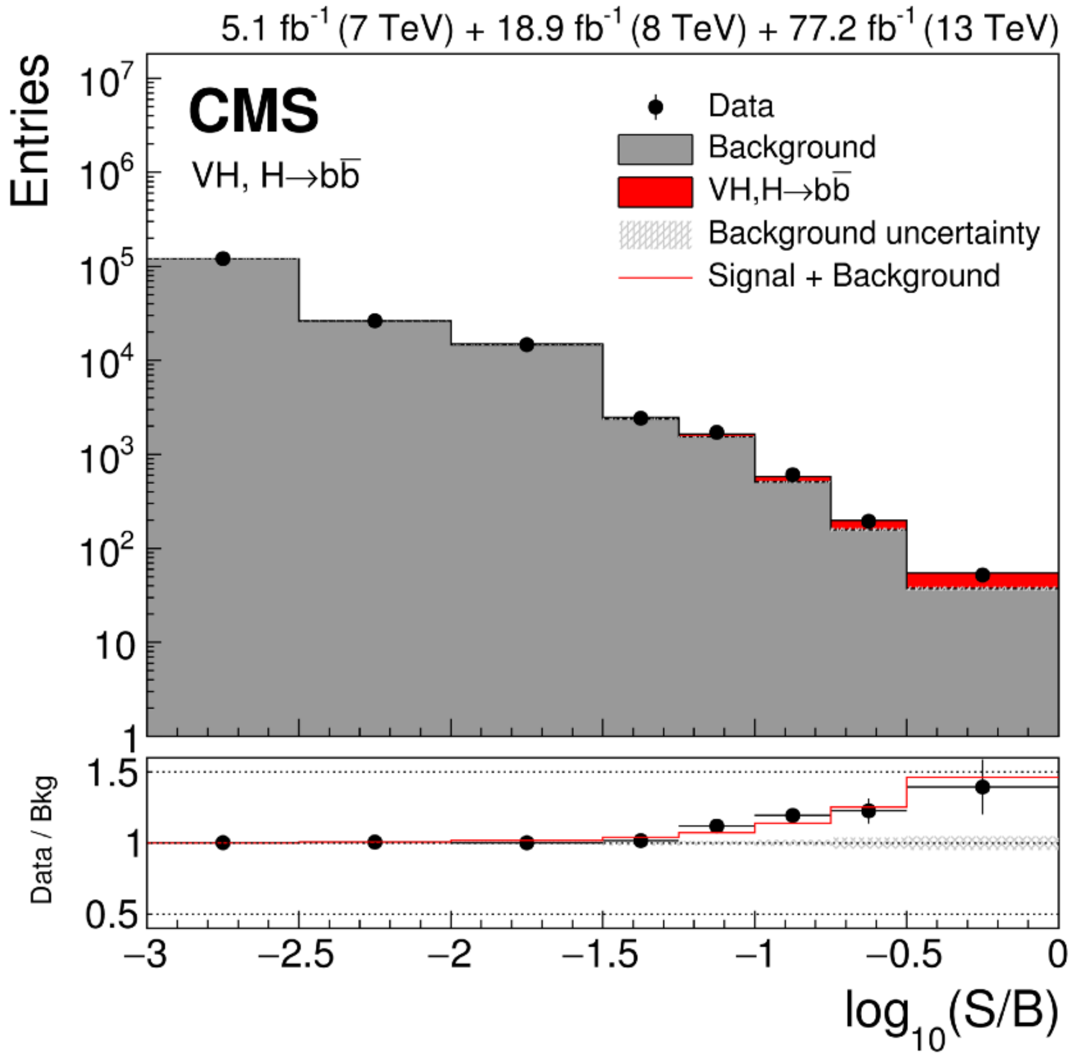
70 (35) × SM (35.9 fb^{-1})

CMS-HIG-18-031
JHEP 03 (2020) 131









$H \to \tau\tau$

CMS-TAU-18-001
JINST 14 (2019) P06032

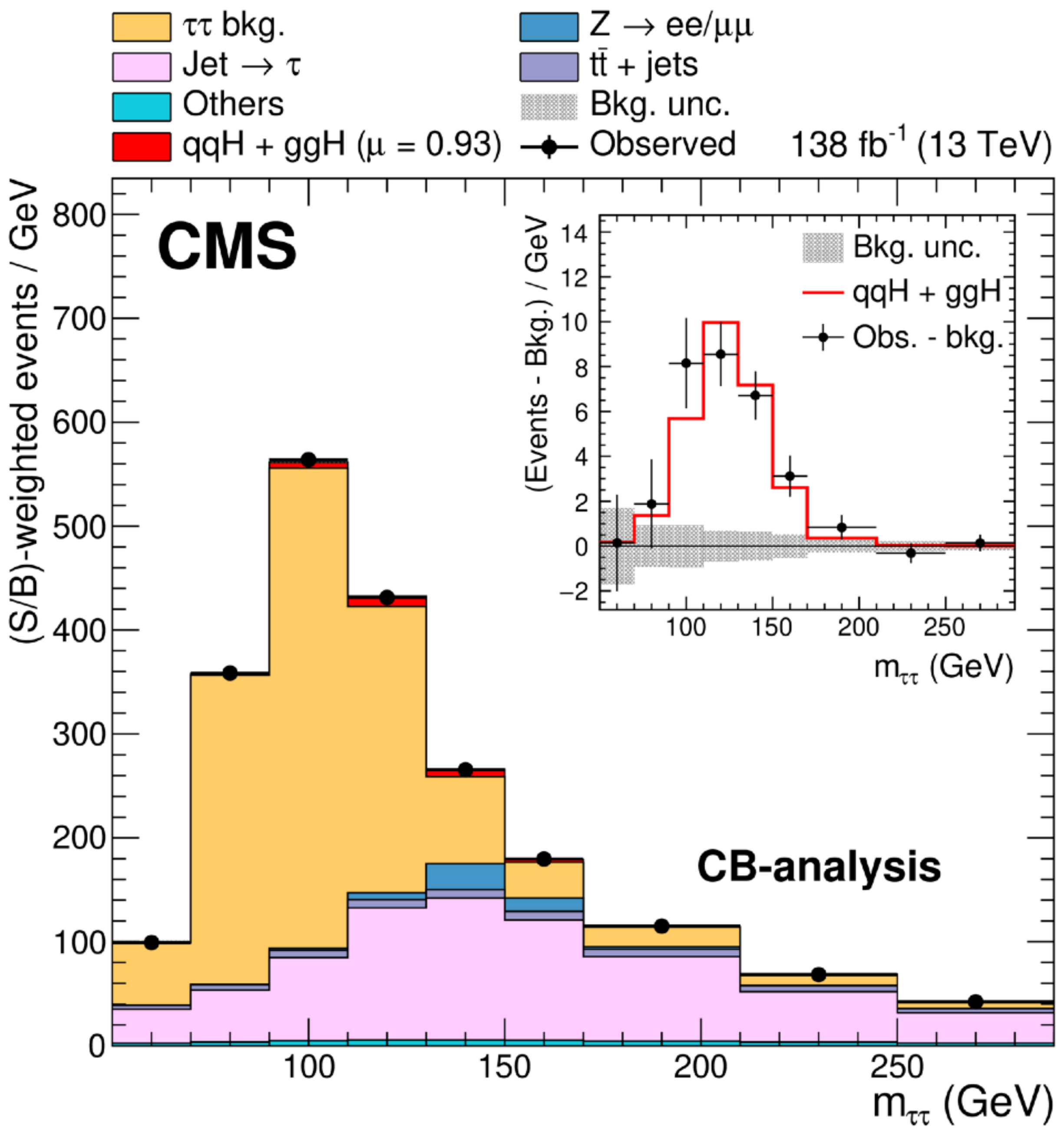
First observed Higgs decay to leptons

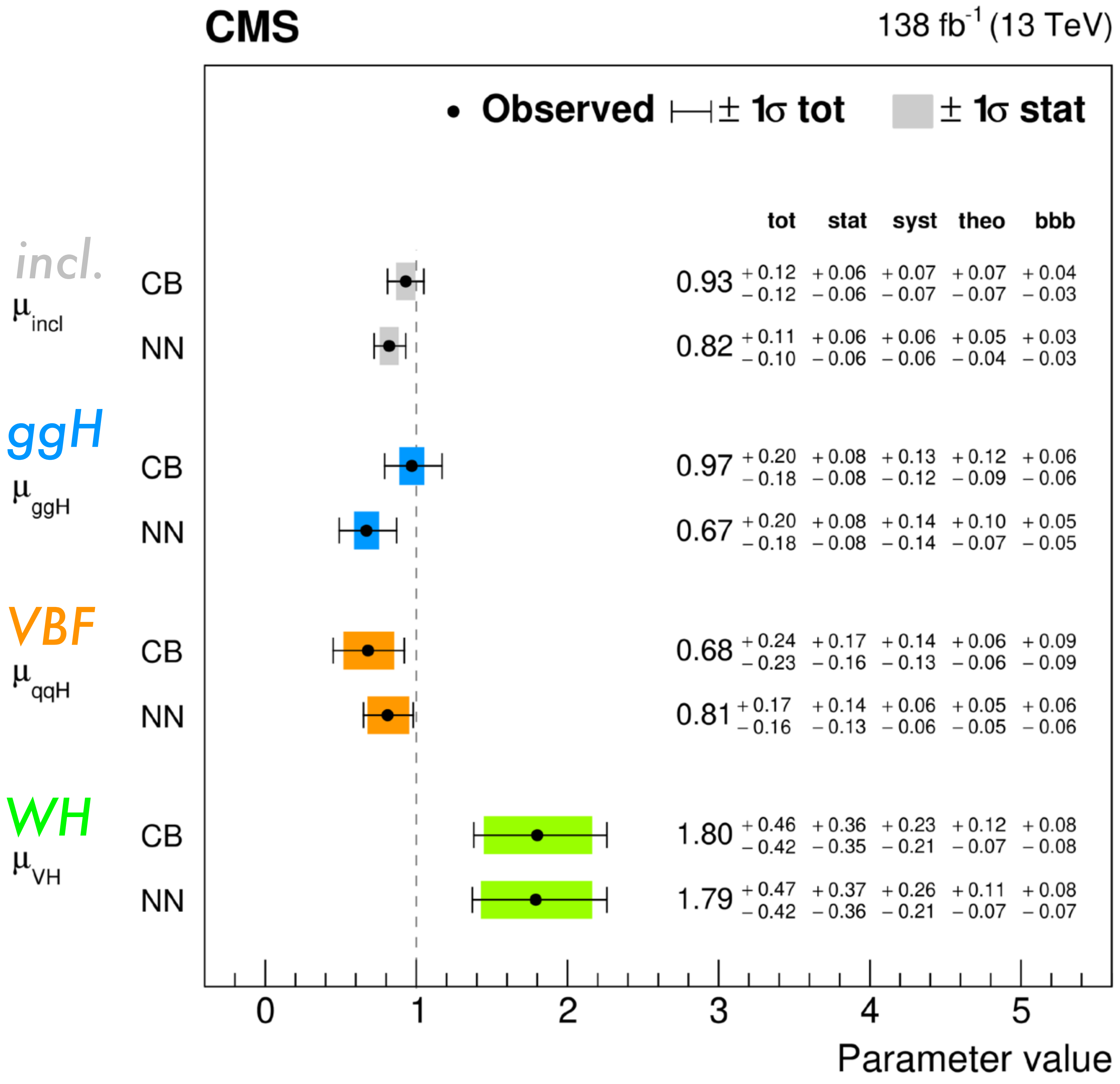
- Relatively large branching fraction (6%)
- main irreducible background: DY → ττ
  (estimated with τ-embedding technique)

Two analyses targeting ggF and VBF production

- cut based (CB)
- neural network (NN)

combined with a dedicated analysis targeting the associated production with W/Z

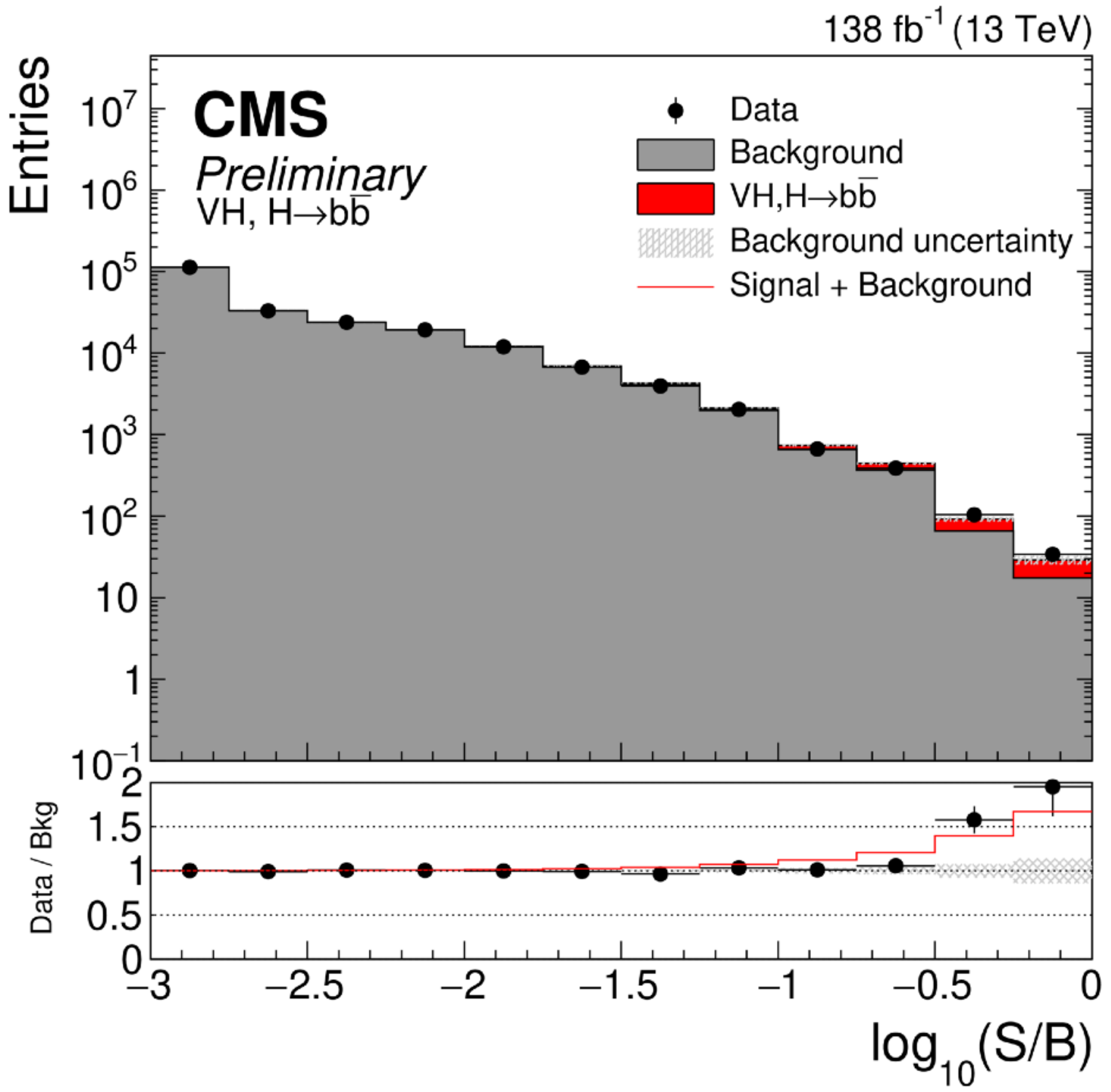


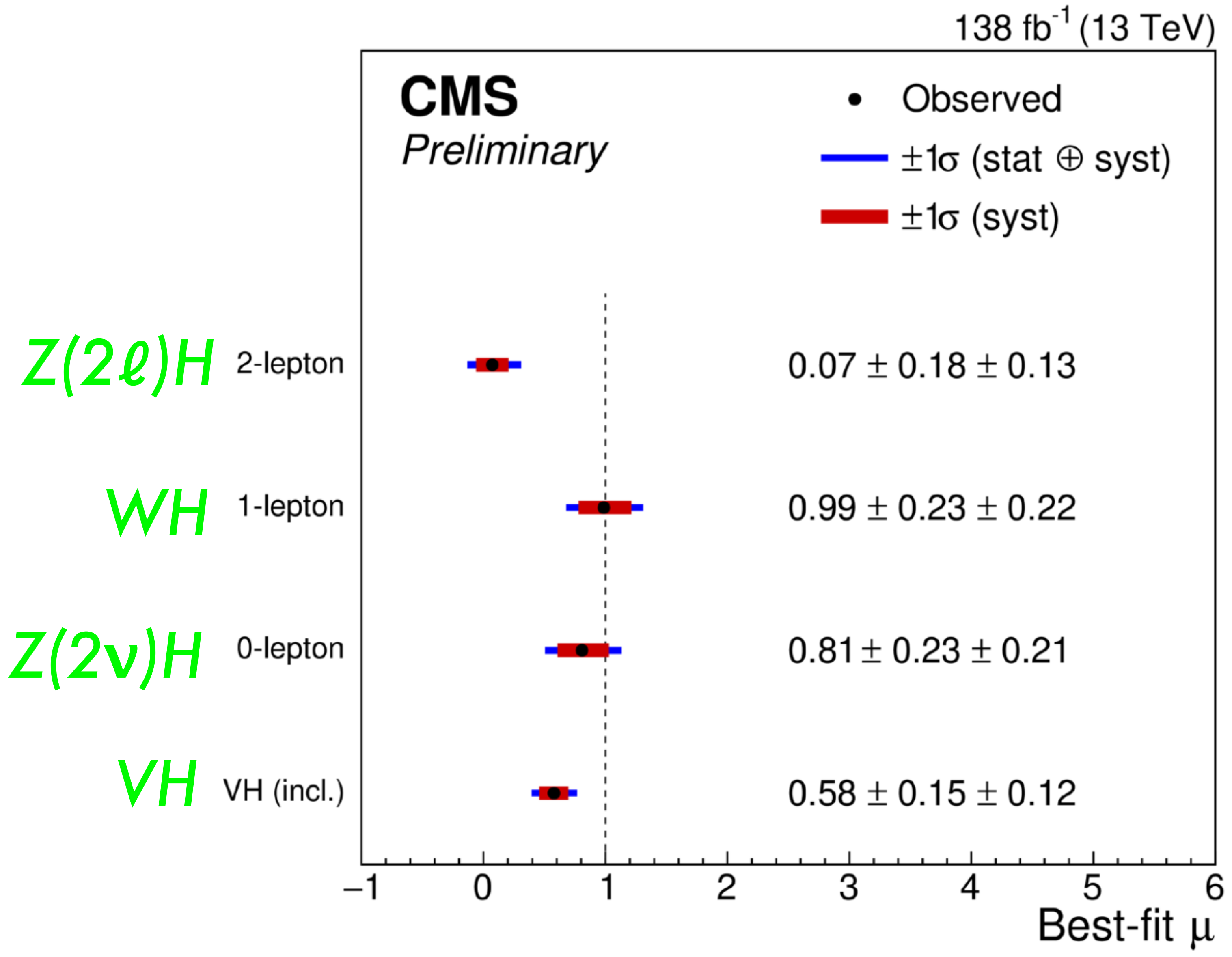


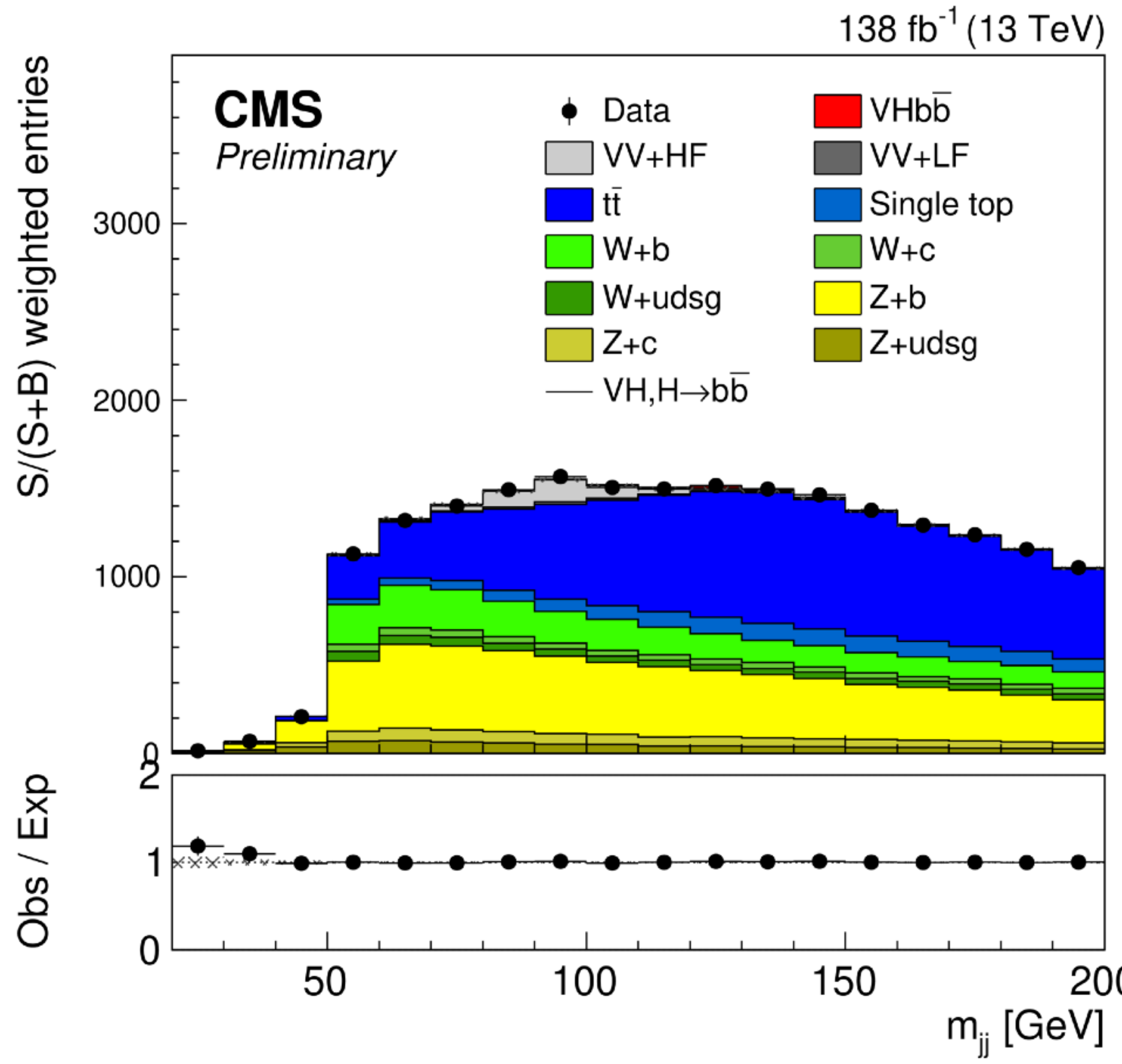
VH, H→bb

[CMS-PAS-HIG-20-001](CMS-PAS-HIG-20-001)

Largest branching fraction (57%)
but overwhelming QCD backgrounds





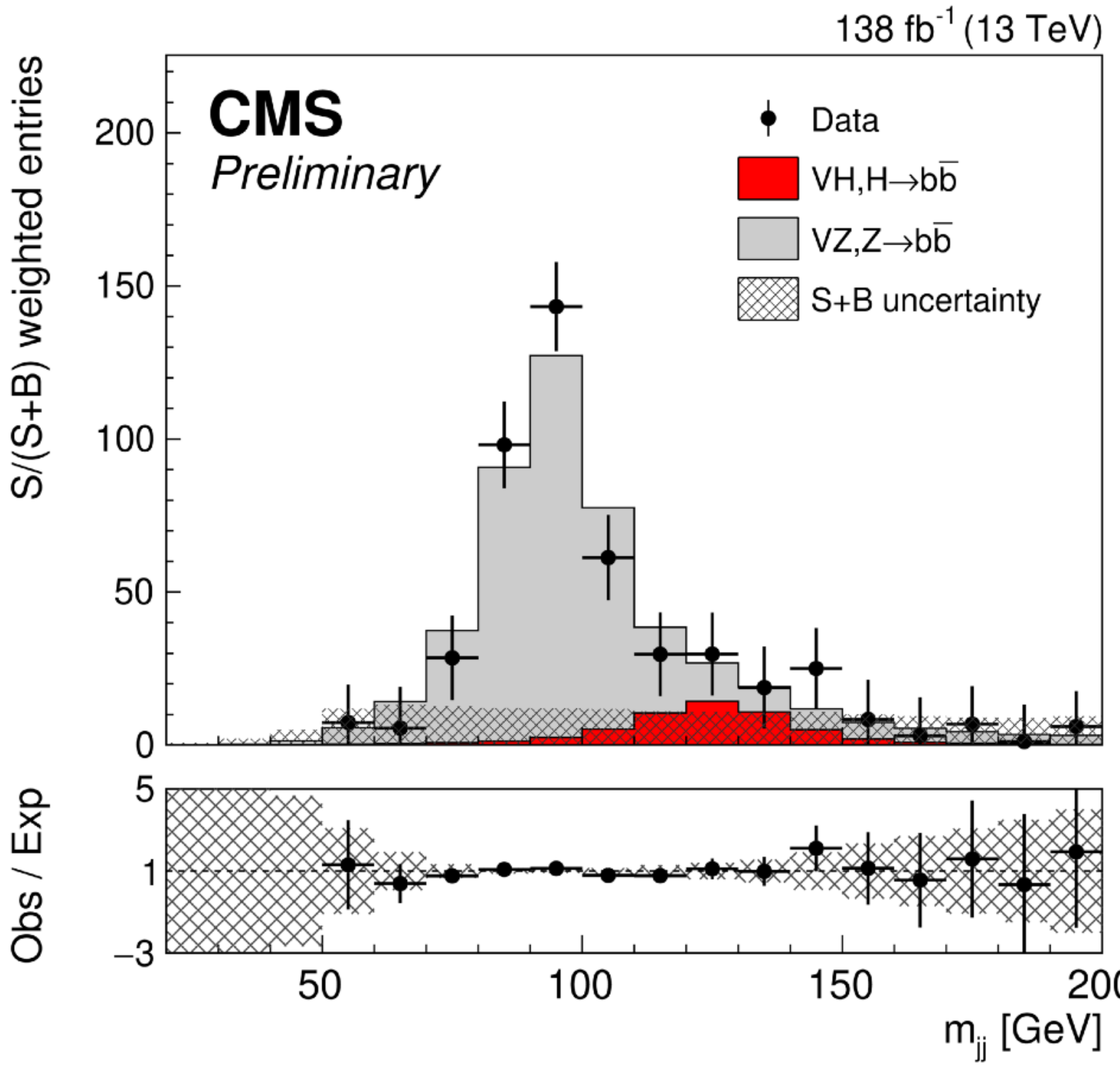


Main analysis

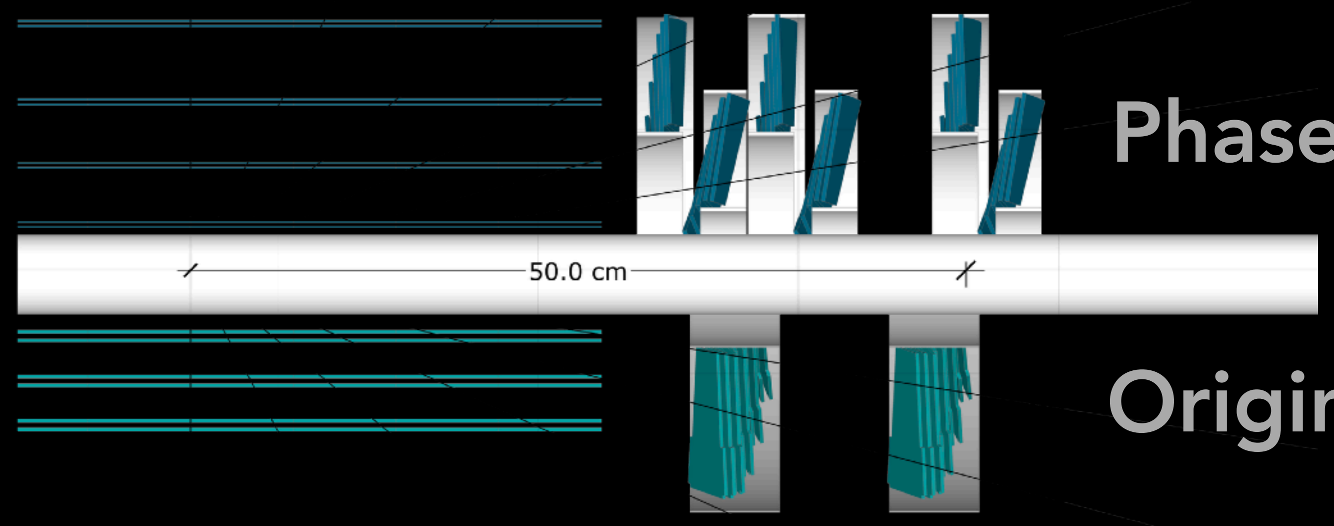
- $\mu_{VH(b\bar{b})} = 0.58\,^{+0.19}_{-0.18}$
- significance: 3.3σ (5.2σ)

Cross check analysis (mass-decorrelated DNN for event categorization):

- $\mu_{VH(b\bar{b})} = 0.34 \pm 0.34$
- $\mu_{VZ(b\bar{b})} = 1.16 \pm 0.13$



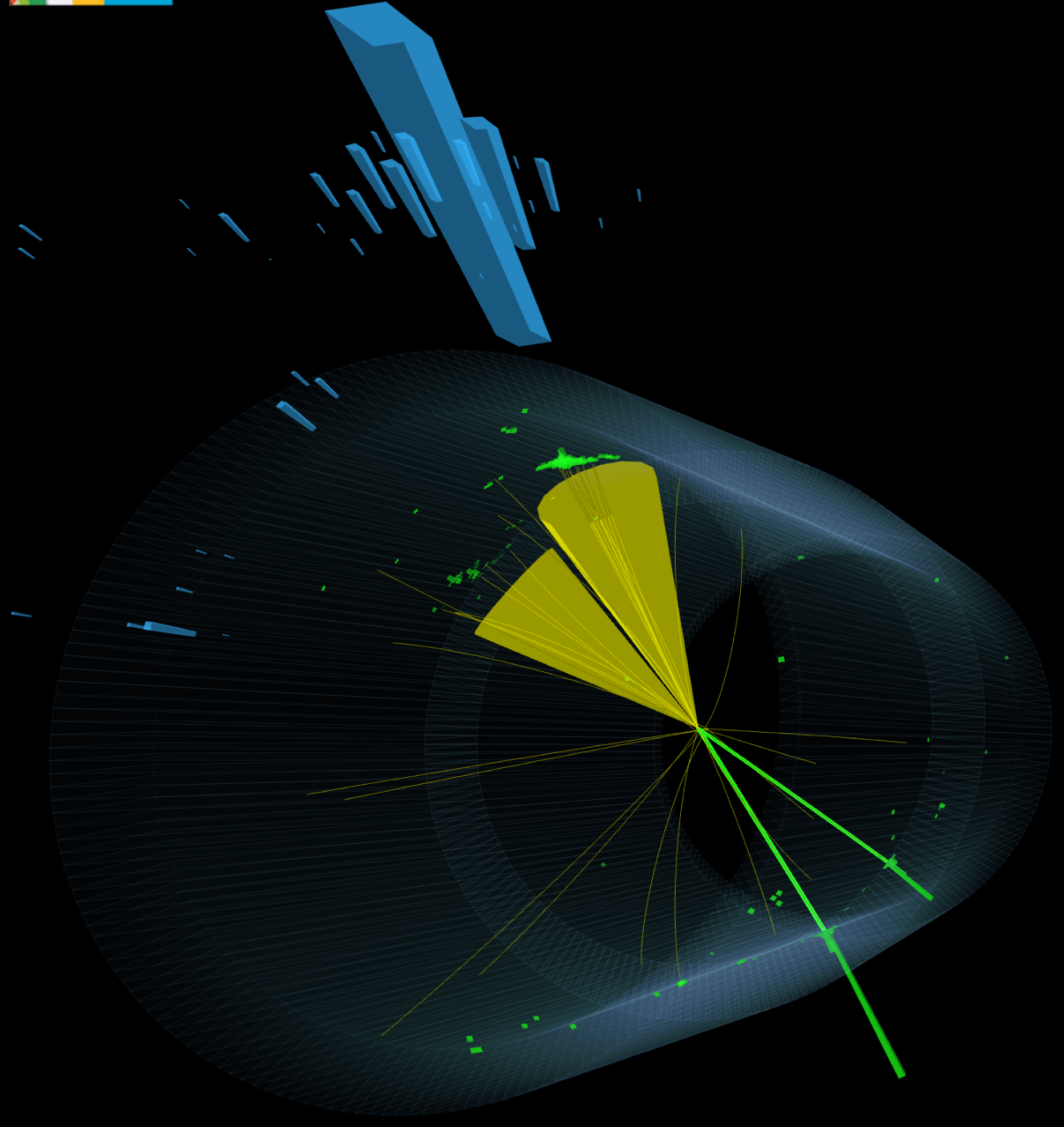
ZH (H → bb)

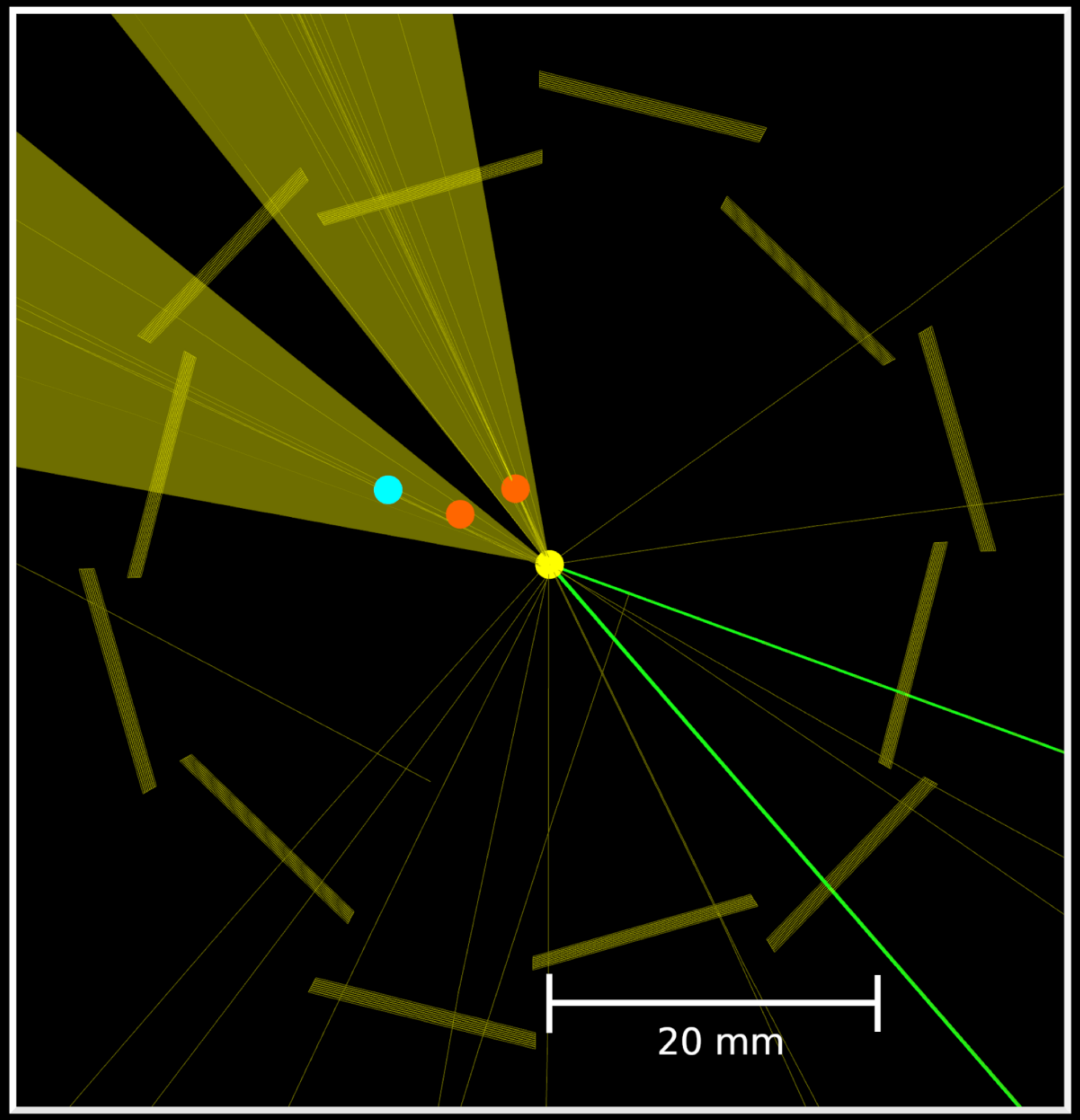


Phase-1 upgrade

Original

CMS Experiment at the LHC, CERN
Data recorded: 2017-Aug-20 18:16:45.926208 GMT
Run / Event / LS: 301472 / 634226645 / 664





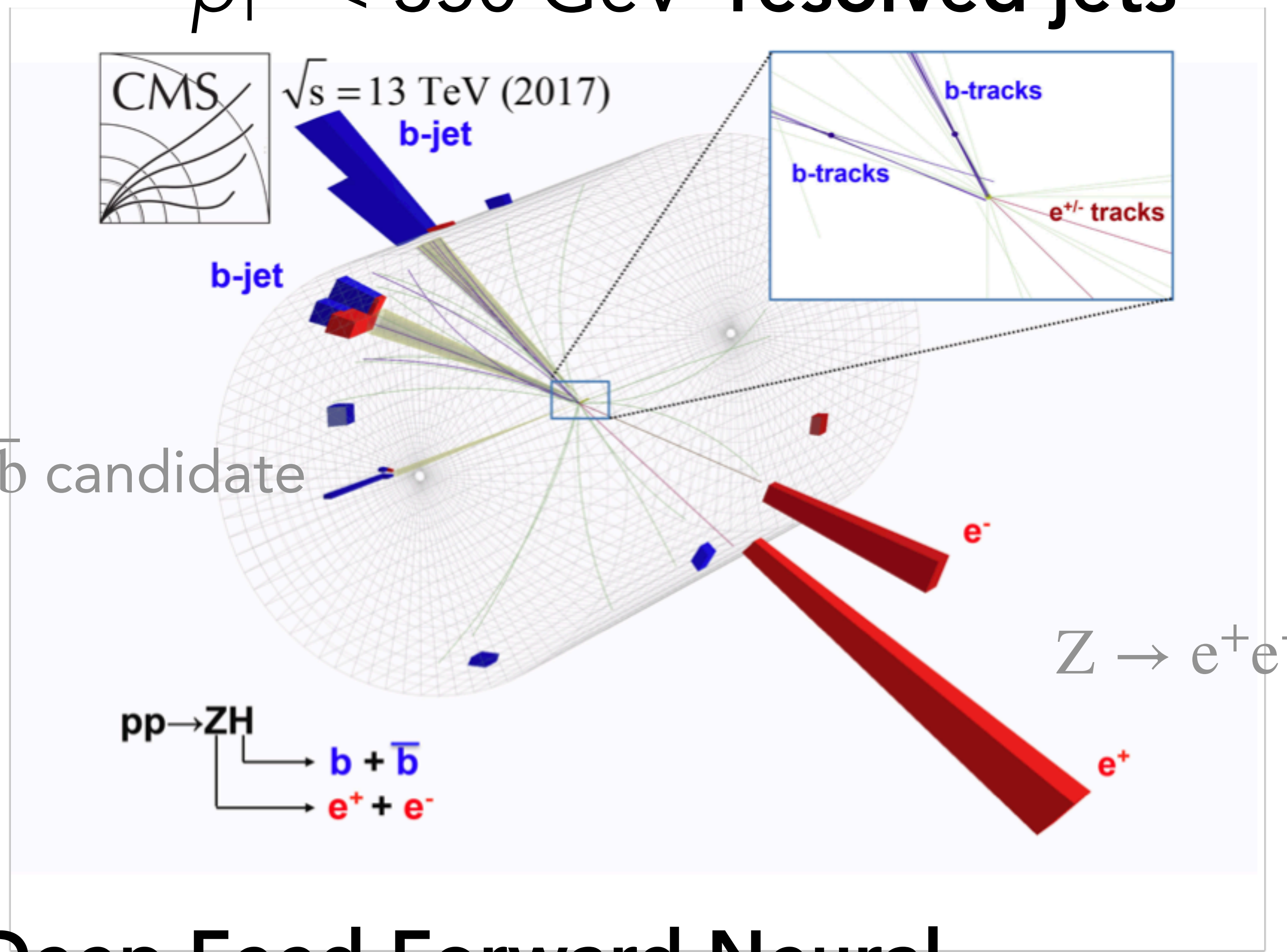
New pixel detector installed in YETS 2016

First layer: 2.9 mm

a ZH (Z → ee, H → bb) candidate

Boosted Higgs Boson

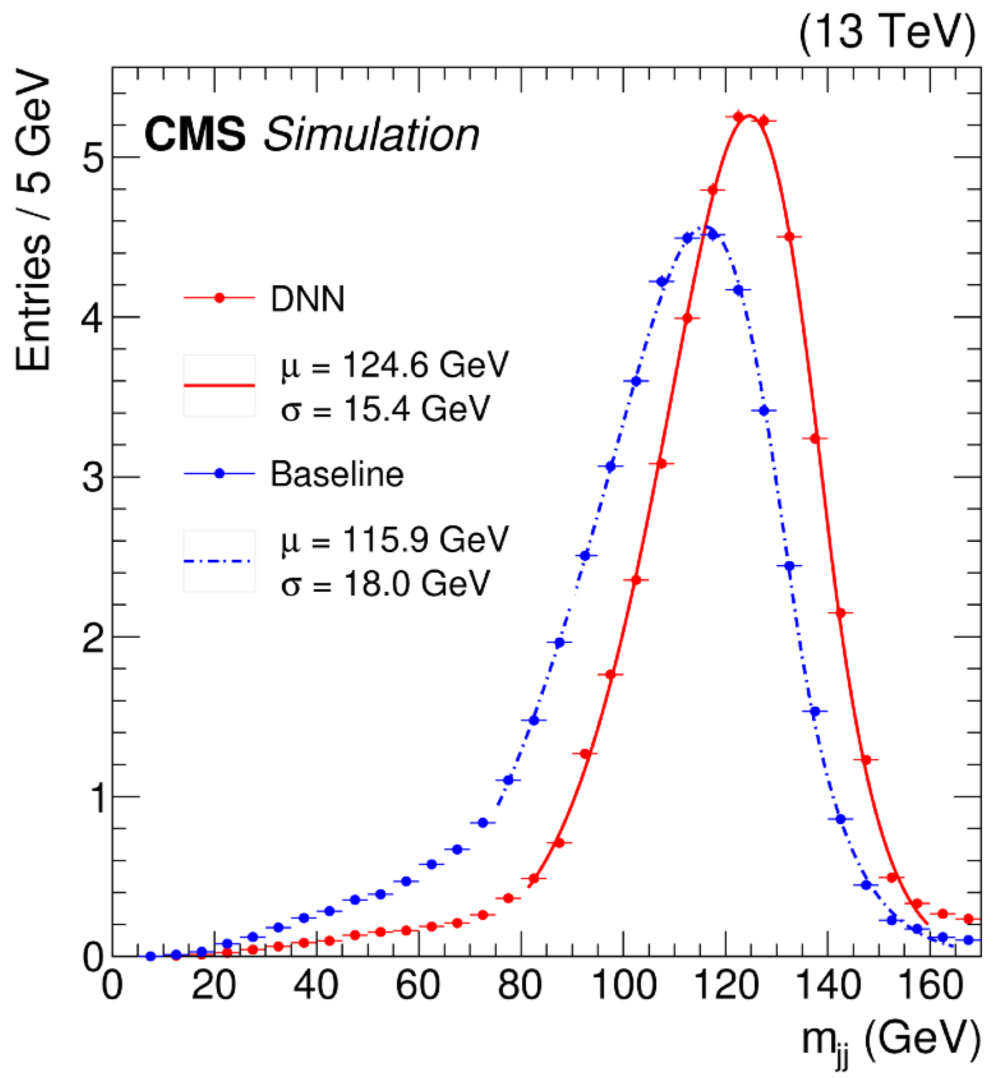
p_T^H < 350 GeV **resolved jets**



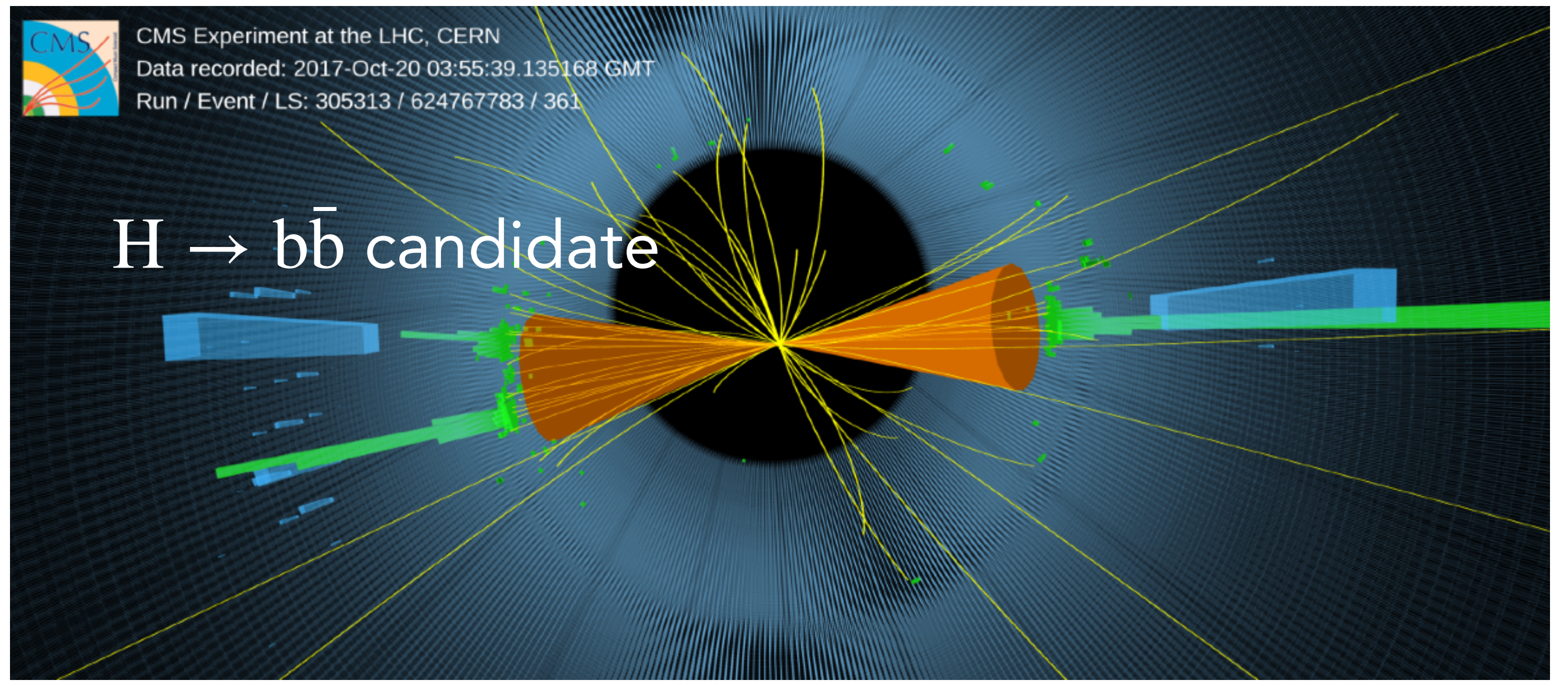
A Deep Feed-Forward Neural Network using jet properties information and secondary vertices associated to the jets (43 input variables)

- 13% improvement in jet resolution
- 20% improvement in di-jet mass resolution (as measured in data)

CMS-HIG-18-027
CSBS 4 (2020) 10



p_T^H > 450 GeV **merged jets**



huge improvement thanks to dedicated "deep double b tagger" (DDBT)

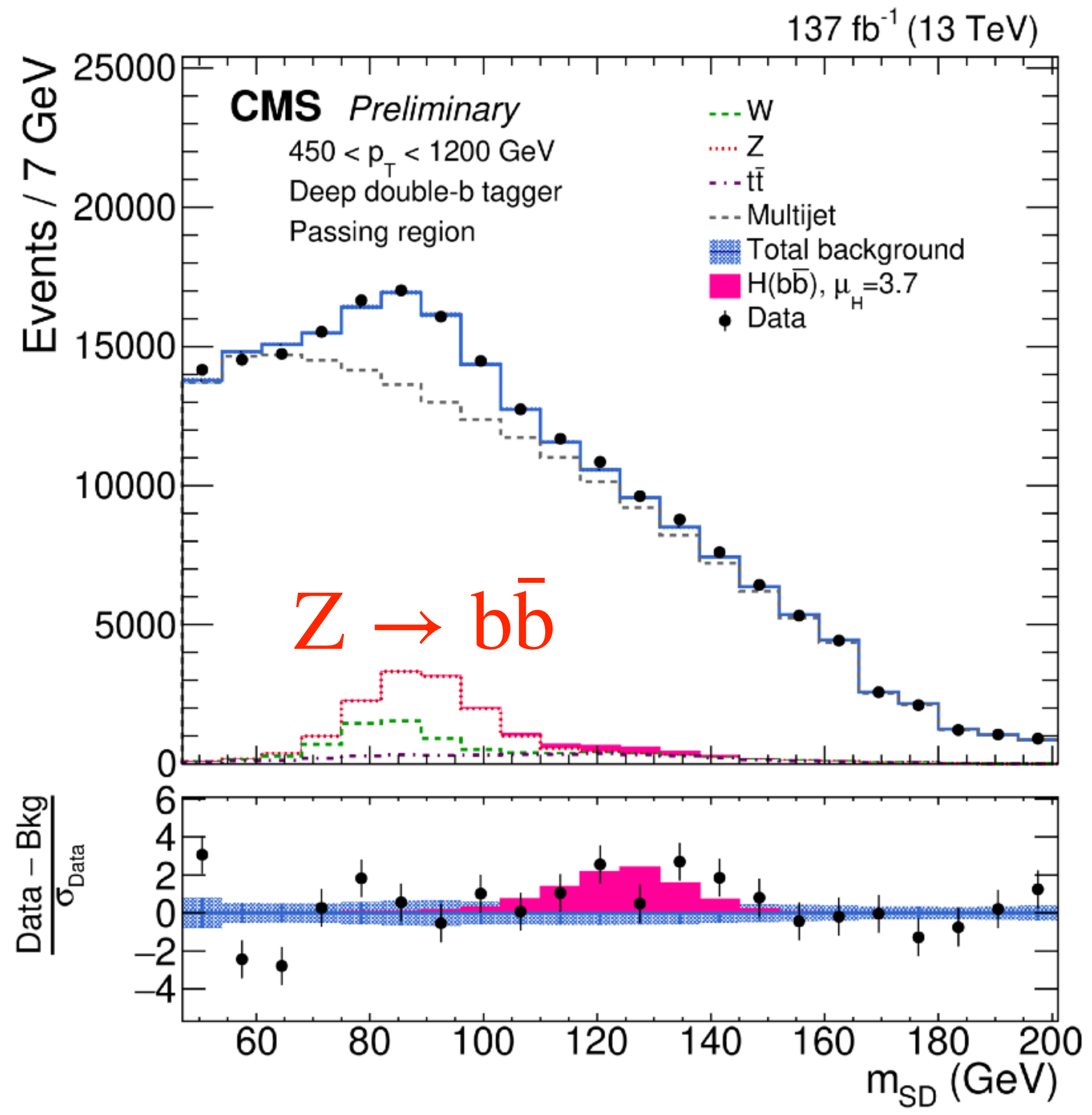
CMS-BTV-20-001
JINST 17 (2022) P03014

a technique validated with $Z \to b\bar{b}$

CMS-HIG-19-003
JHEP 12 (2020) 085

Phys. Briefing

An **inclusive** search for **highly-boosted** $H \to b\bar{b}$



- a small (1.9σ) excess is observed

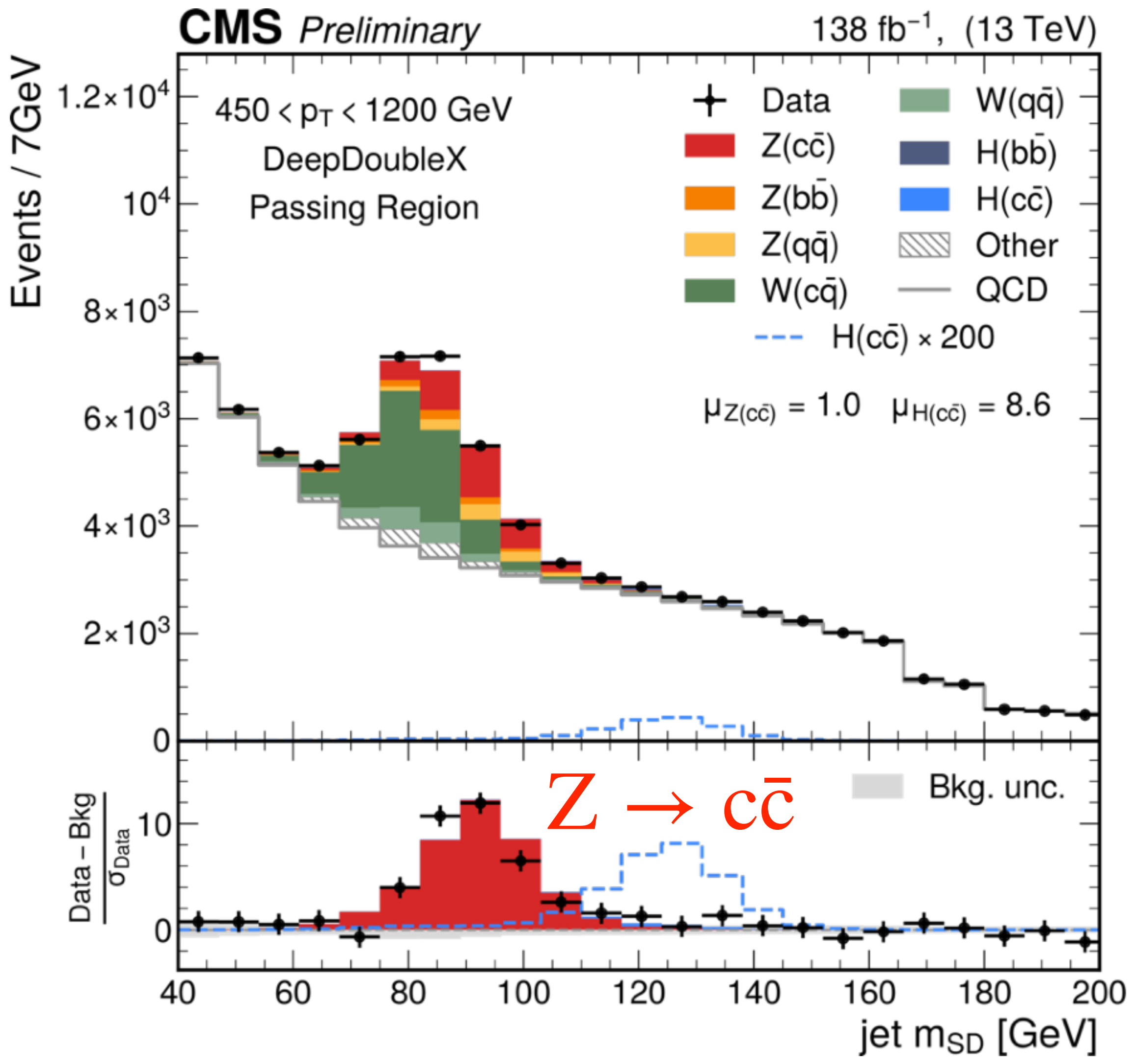
$\mu_H = 3.7^{+1.6}_{-1.5}$ 2.5σ (0.7σ exp)

also spectacular improvement in c-jet tagging

CMS-BTV-16-002
JINST 13 (2018) P05011

Boosted Higgs Boson and Charm Decay

An **inclusive** search for
highly-boosted $\mathrm{H} \to \mathrm{c\bar{c}}$
$p_T^H > 450$ GeV



Validation:

$$\mu_{Z\to c\bar{c}} = 1.06^{+0.18}_{-0.15} \quad (>10\sigma)$$

H($\mathrm{c\bar{c}}$) signal strength (fixing Z($\mathrm{c\bar{c}}$) to SM)

- $\mu_H = 8\,^{+20}_{-19}$
- obs (exp) upper limit @95% CL: 45 (38) × SM

CMS-PAS-HIG-21-012

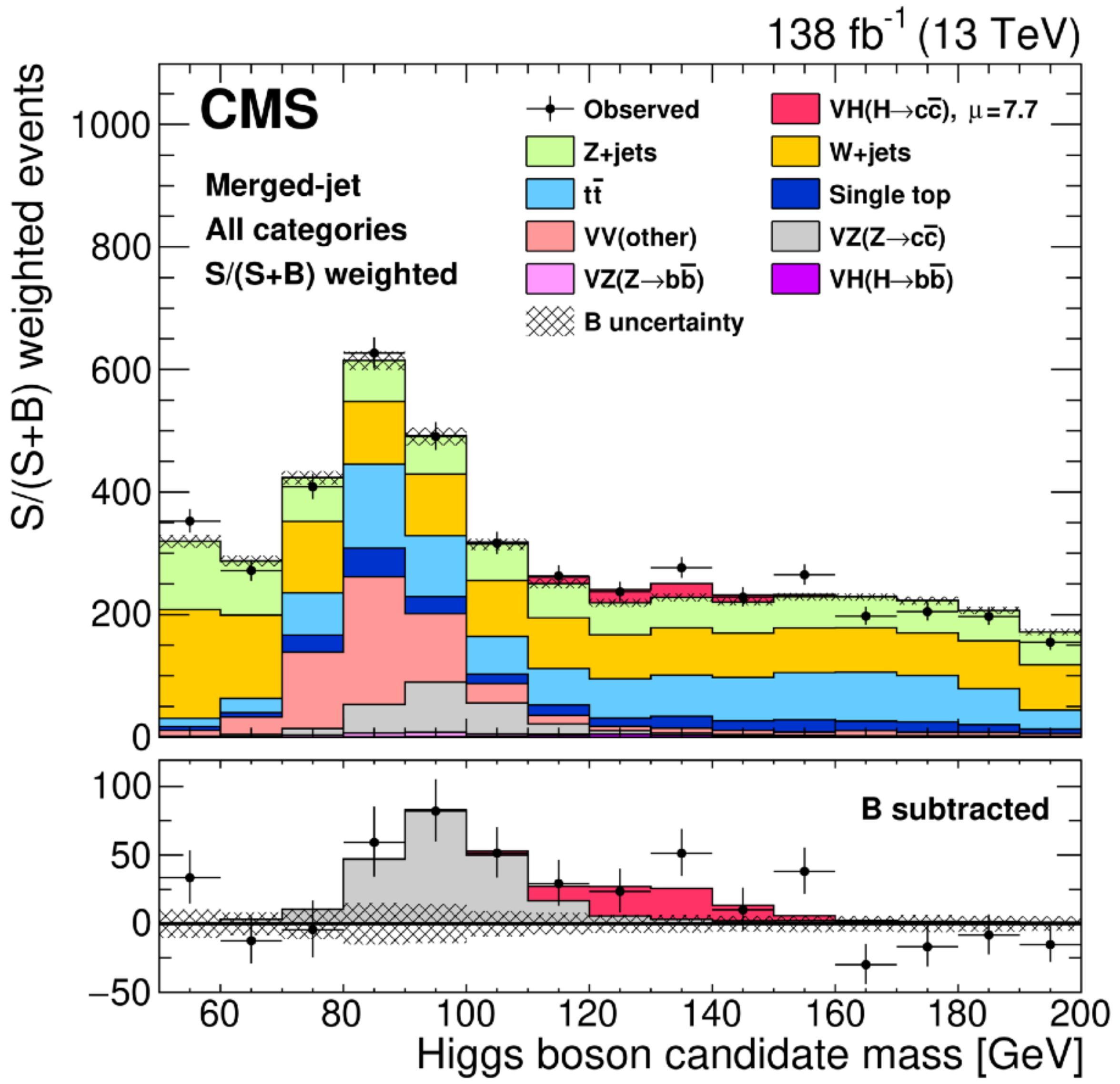
A search for $\mathrm{VH(H \to c\bar{c})}$

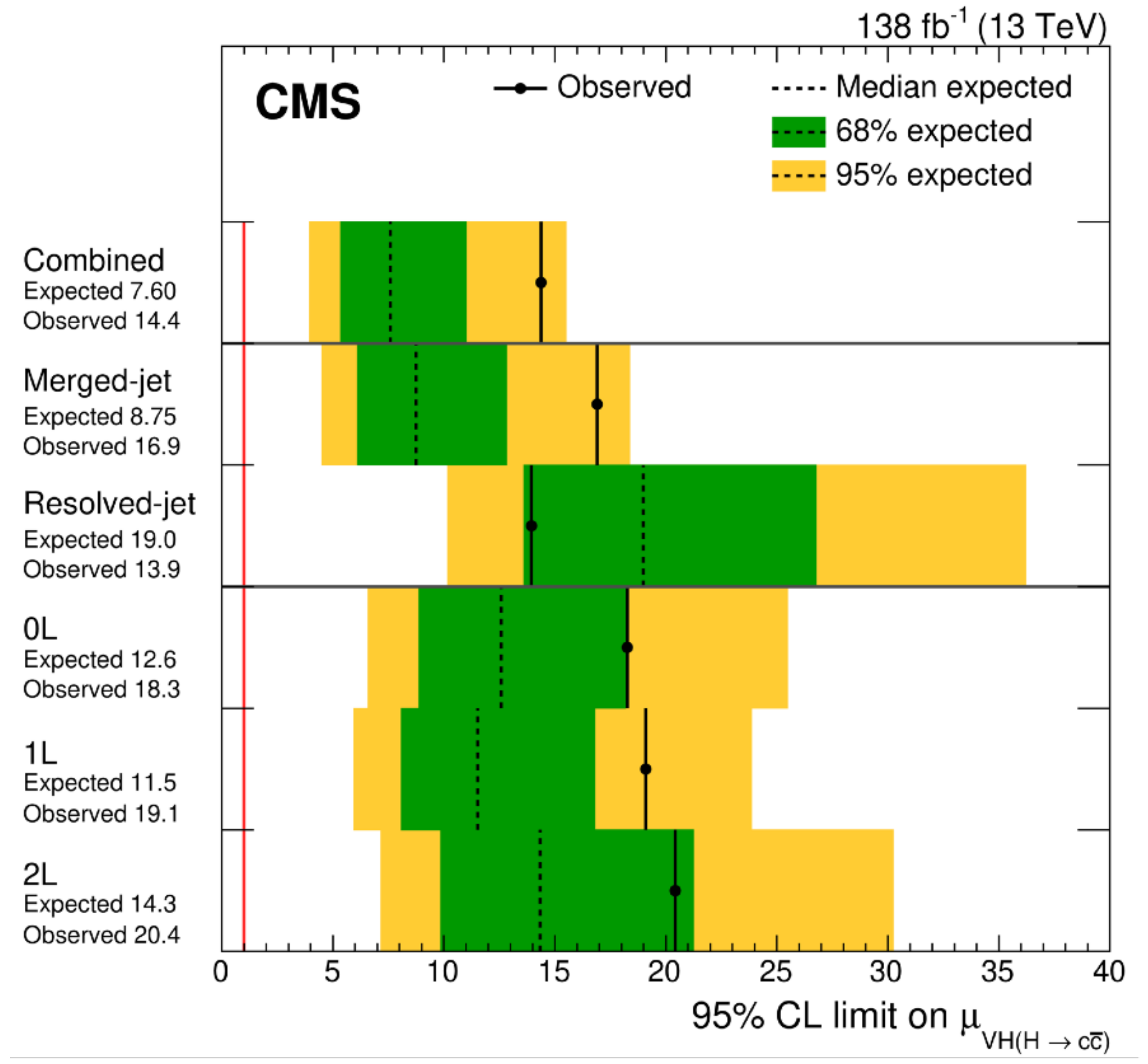
CMS-HIG-21-008
Accepted by PRL

Phys. Briefing

BDTs against background
resolved
- c-jet charm tagging with **DeepJet**
- c-jet energy regression using **DNN**
- kinematic fit in 2-lepton channels

merged (boosted: $p_T^H > 300$ GeV)
- mass regression using **ParticleNet**



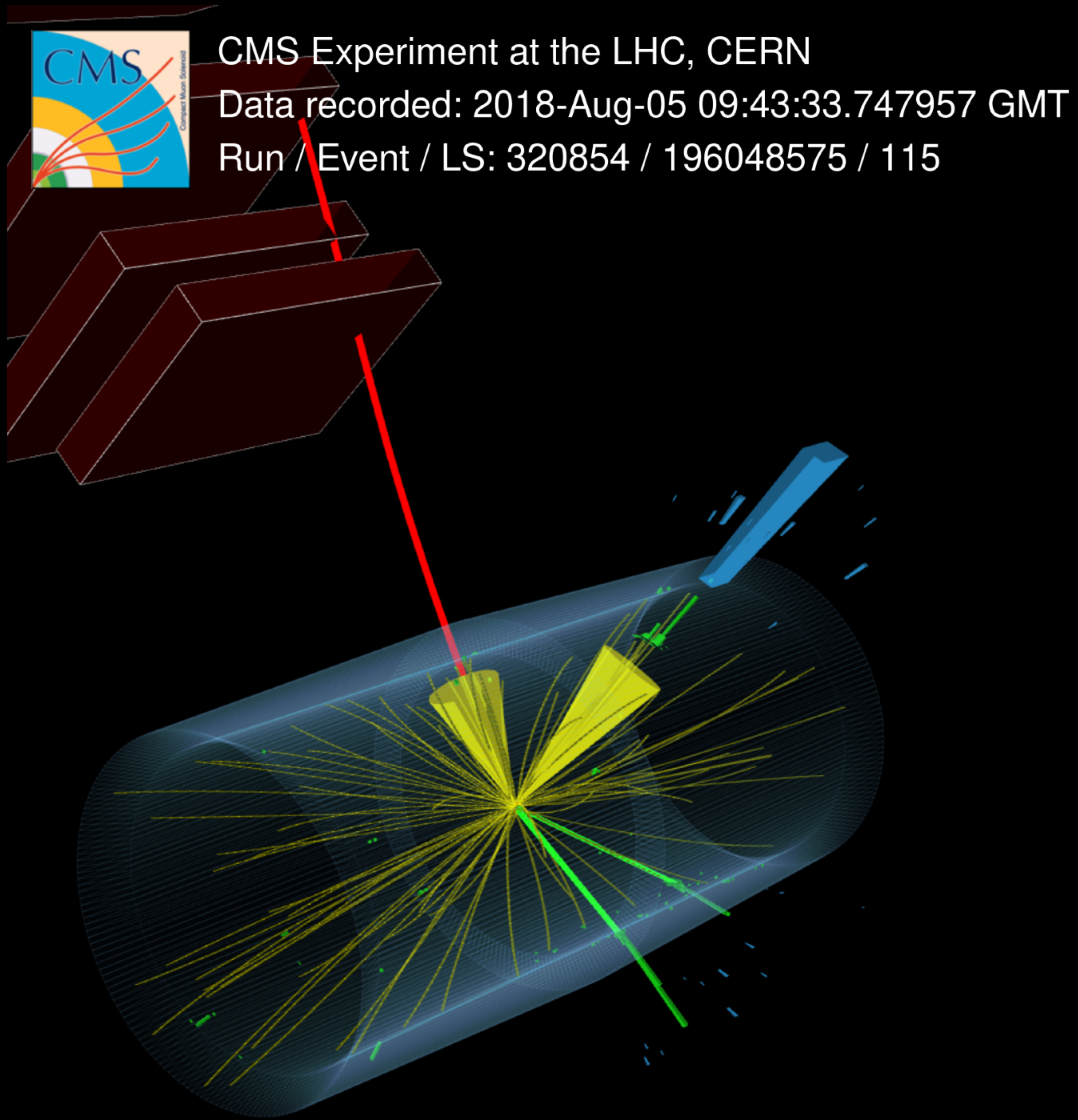


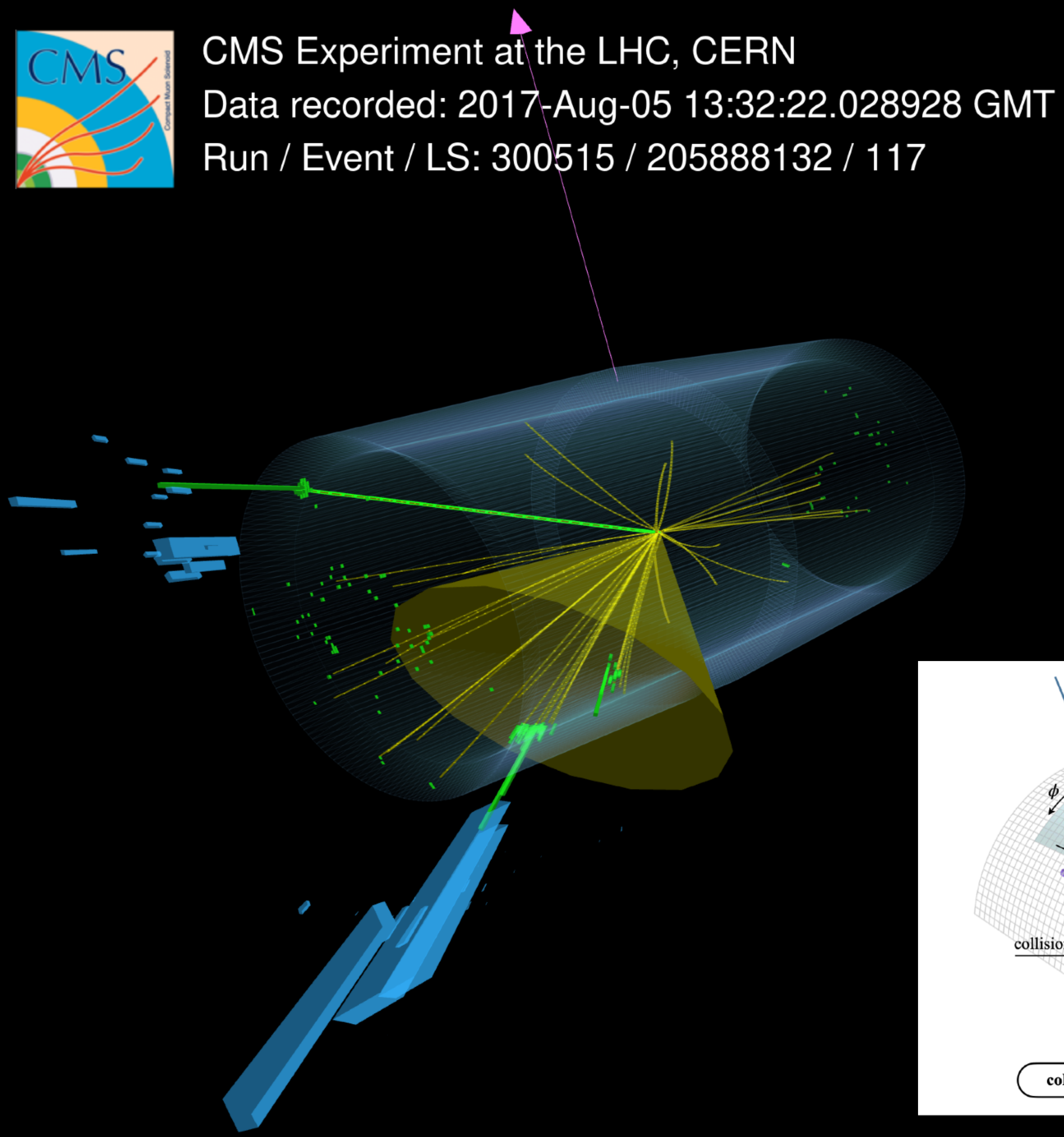
Validation:

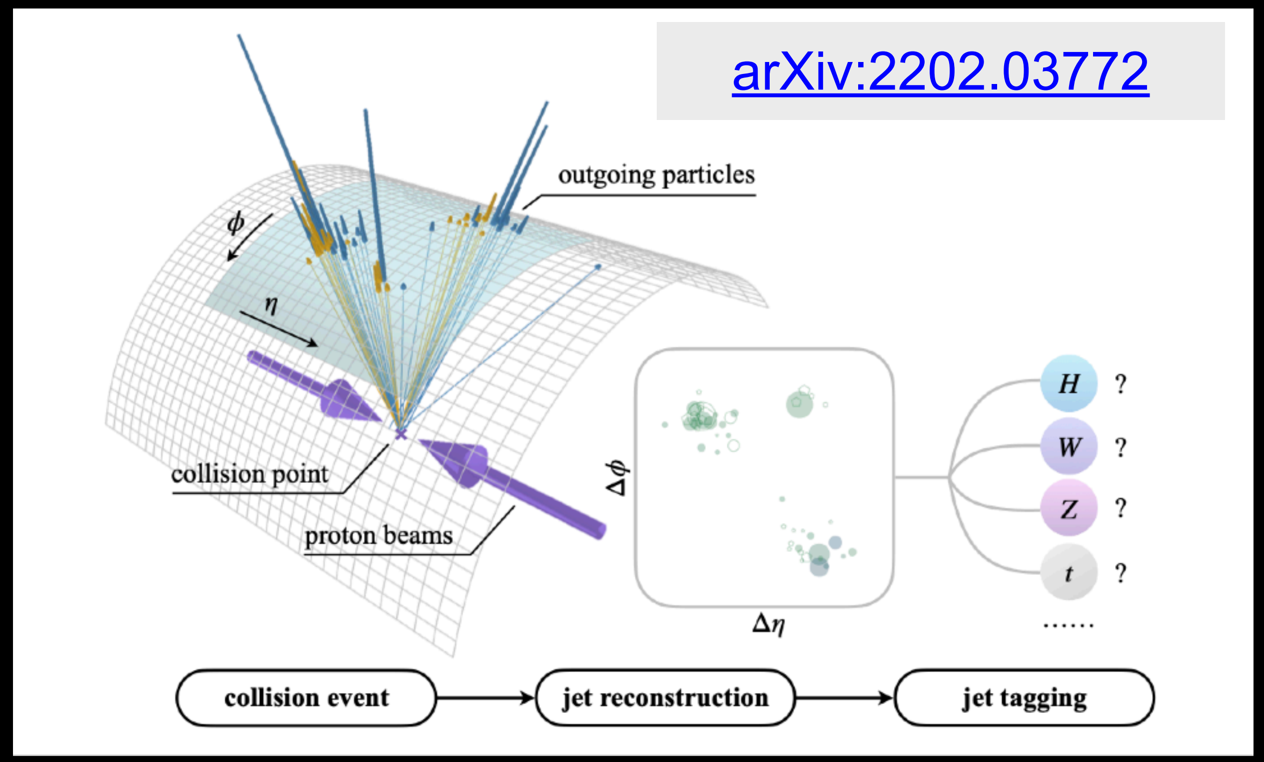
$$\mu_{VZ(Z\to c\bar{c})} = 1.01^{+0.23}_{-0.21} \quad 5.7\sigma\ (5.9\sigma\ \text{exp})$$

VH($\mathrm{c\bar{c}}$) signal strength
- $\mu_{VH(c\bar{c})} = 7.1\,^{+3.8}_{-3.5}$
- obs (exp) upper limit @95% CL: 14 (7.6) × SM
- Constraint of the charm Yukawa $1.1 < |\kappa_c| < 5.5$ @ 95%CL

VH ($H \to cc$)







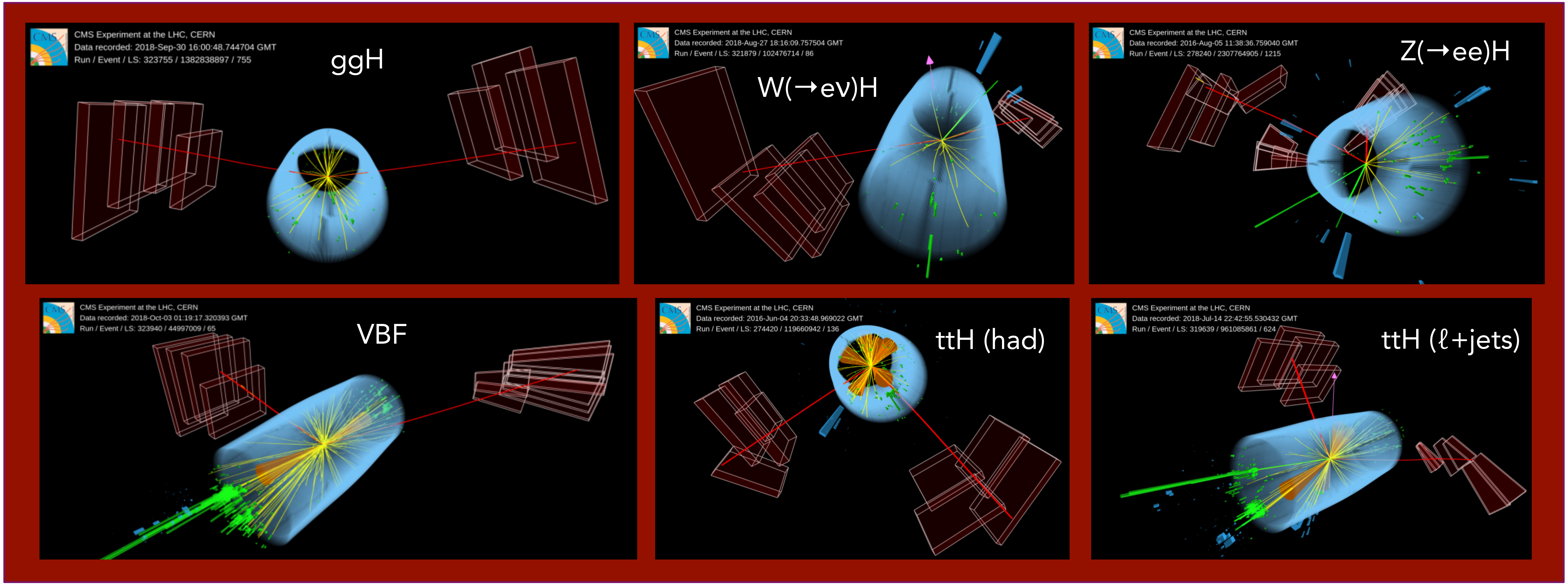
Particle Transformer for jet tagging
(ParticleNet Dynamic Graph CNN)

Z(ee)H(cc) ***resolved*** candidate

W(eν)H(cc) ***boosted*** candidate

$H \rightarrow \mu\mu$

Exclusive categories: ggH, VBF, VH and ttH



CMS-HIG-19-006
JHEP 01 (2021) 148

Phys. Briefing

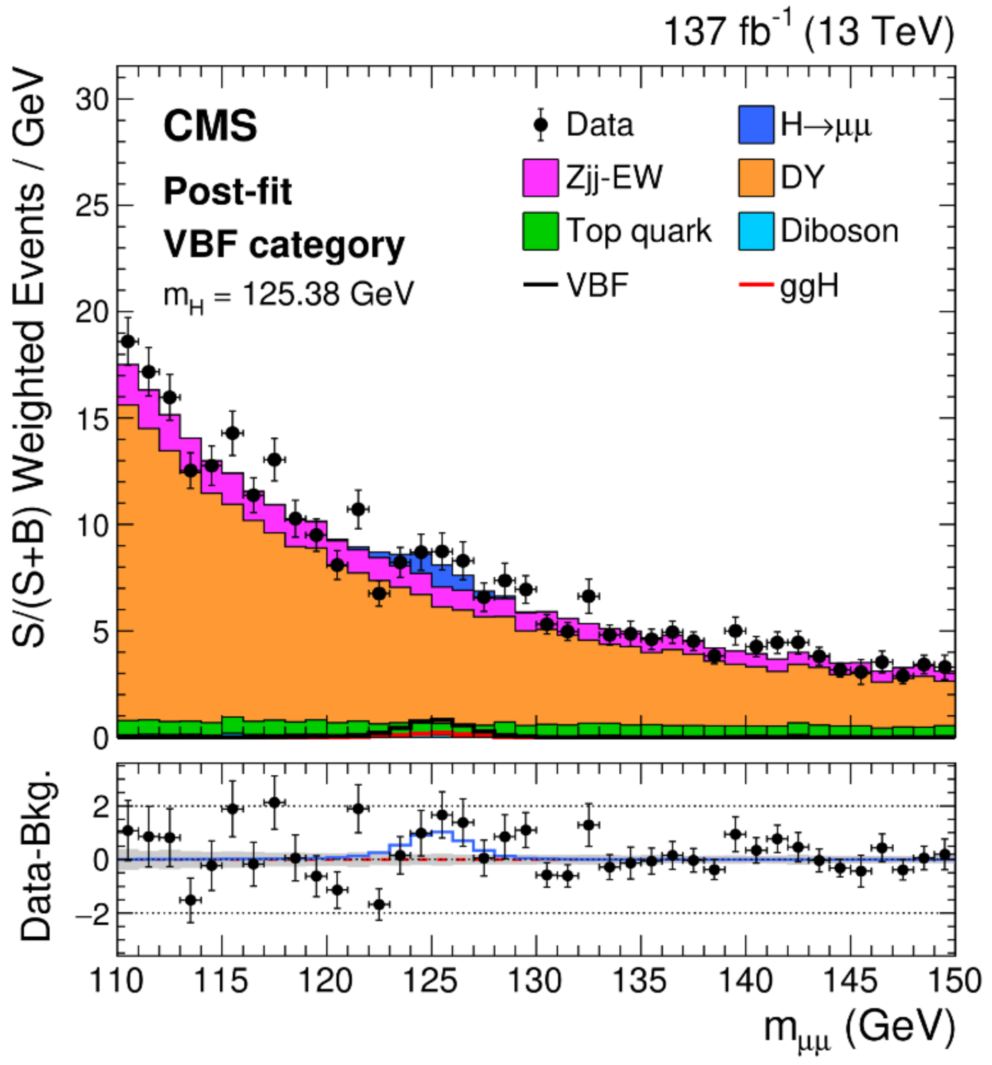
$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\mathrm{stat})^{+0.17}_{-0.16}\,(\mathrm{syst})$$

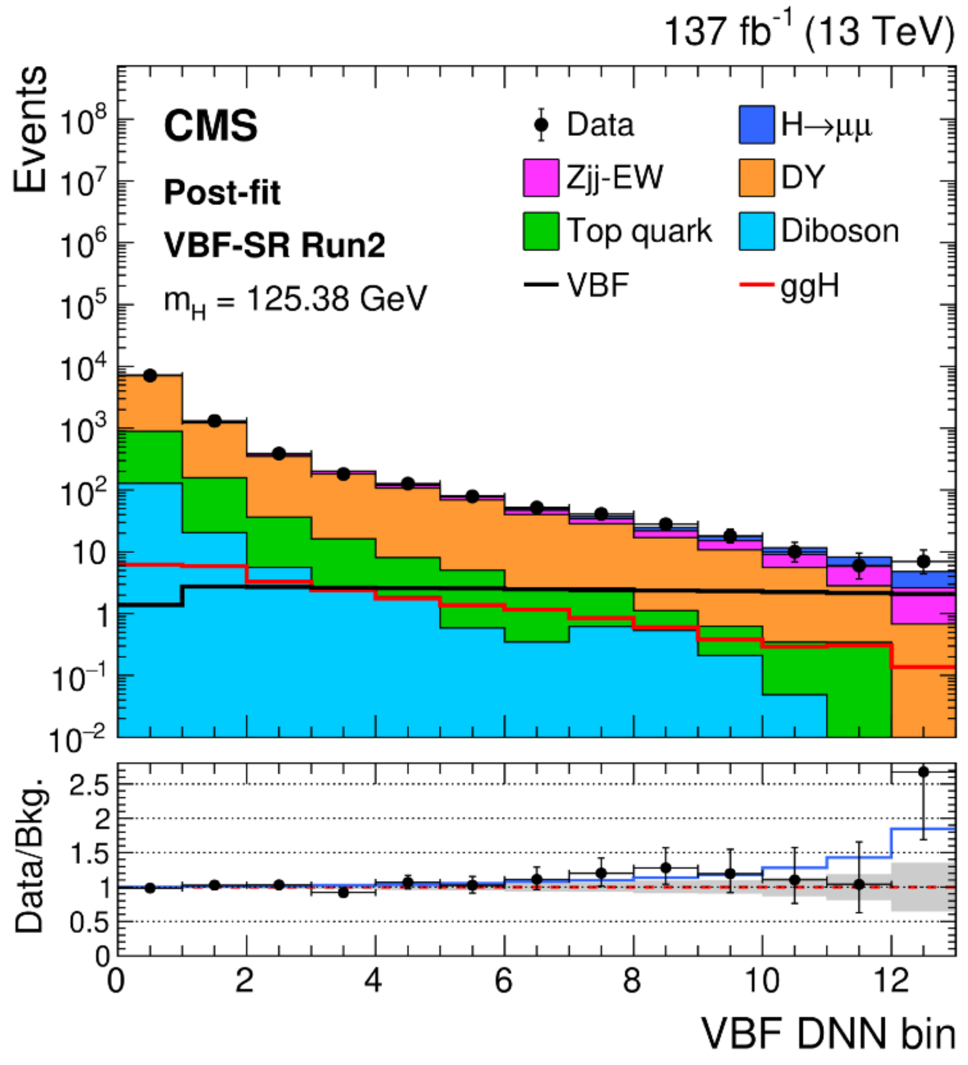
Obs. (exp.) significance: 3.0 (2.5) σ

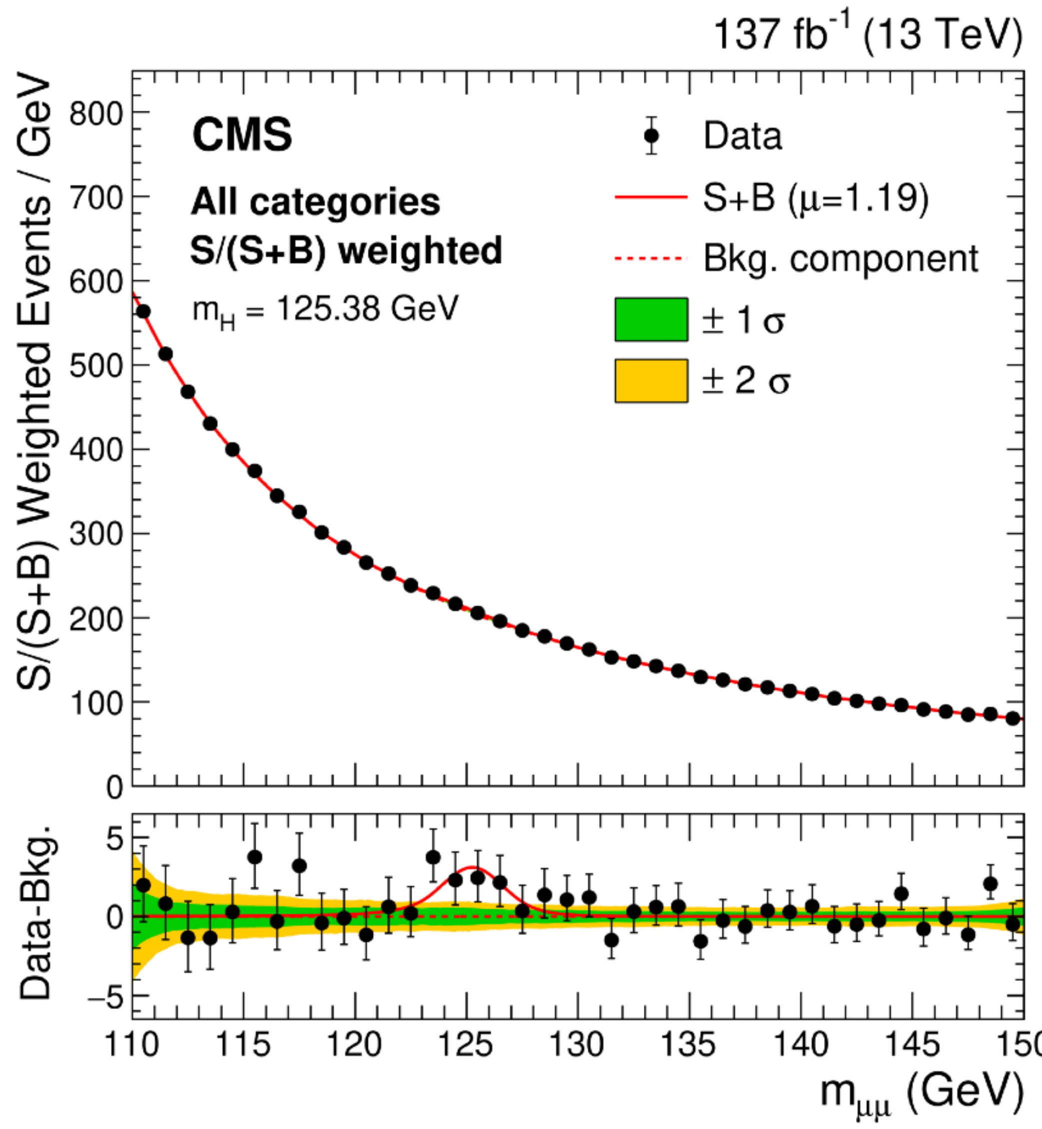
evidence made possible thanks to the use of advanced ML techniques in the VBF analysis

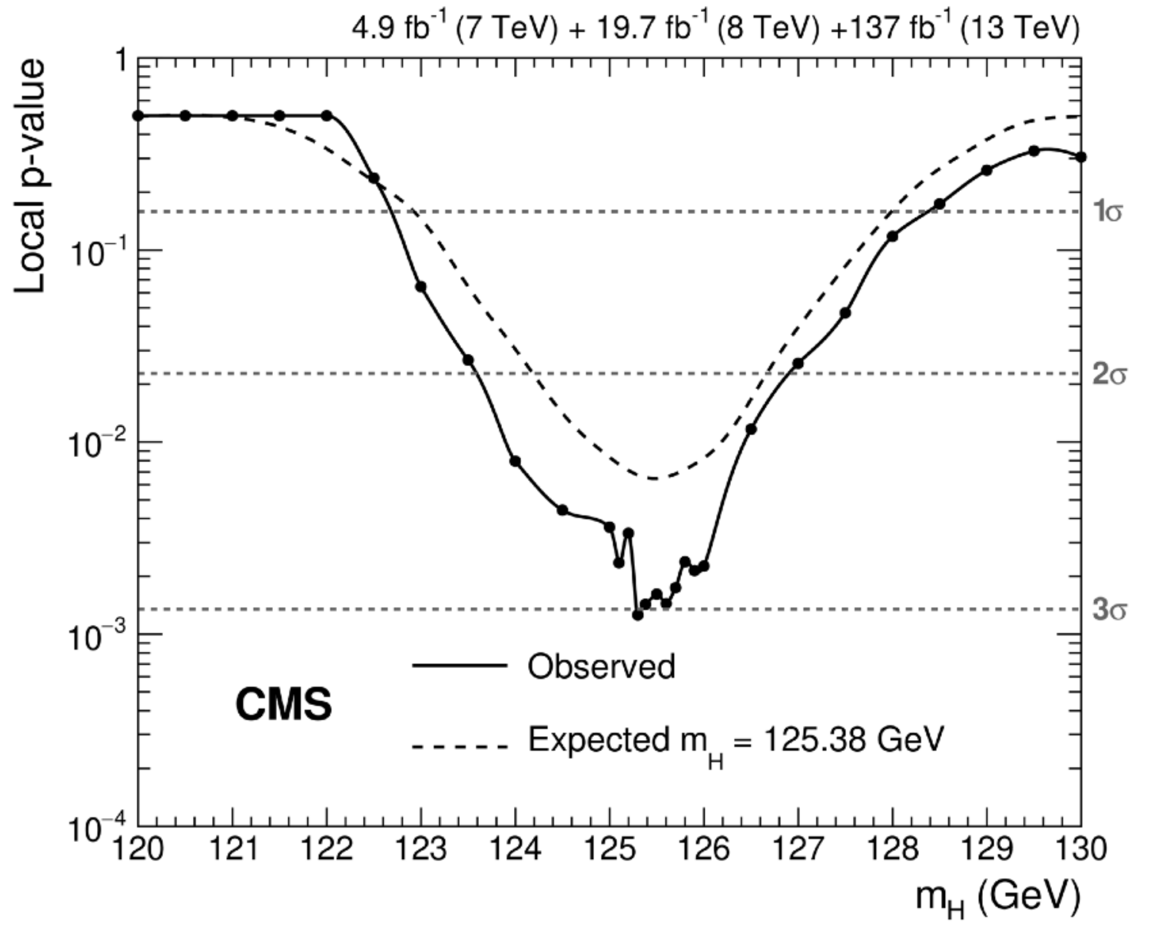
$H \to \mu\mu$

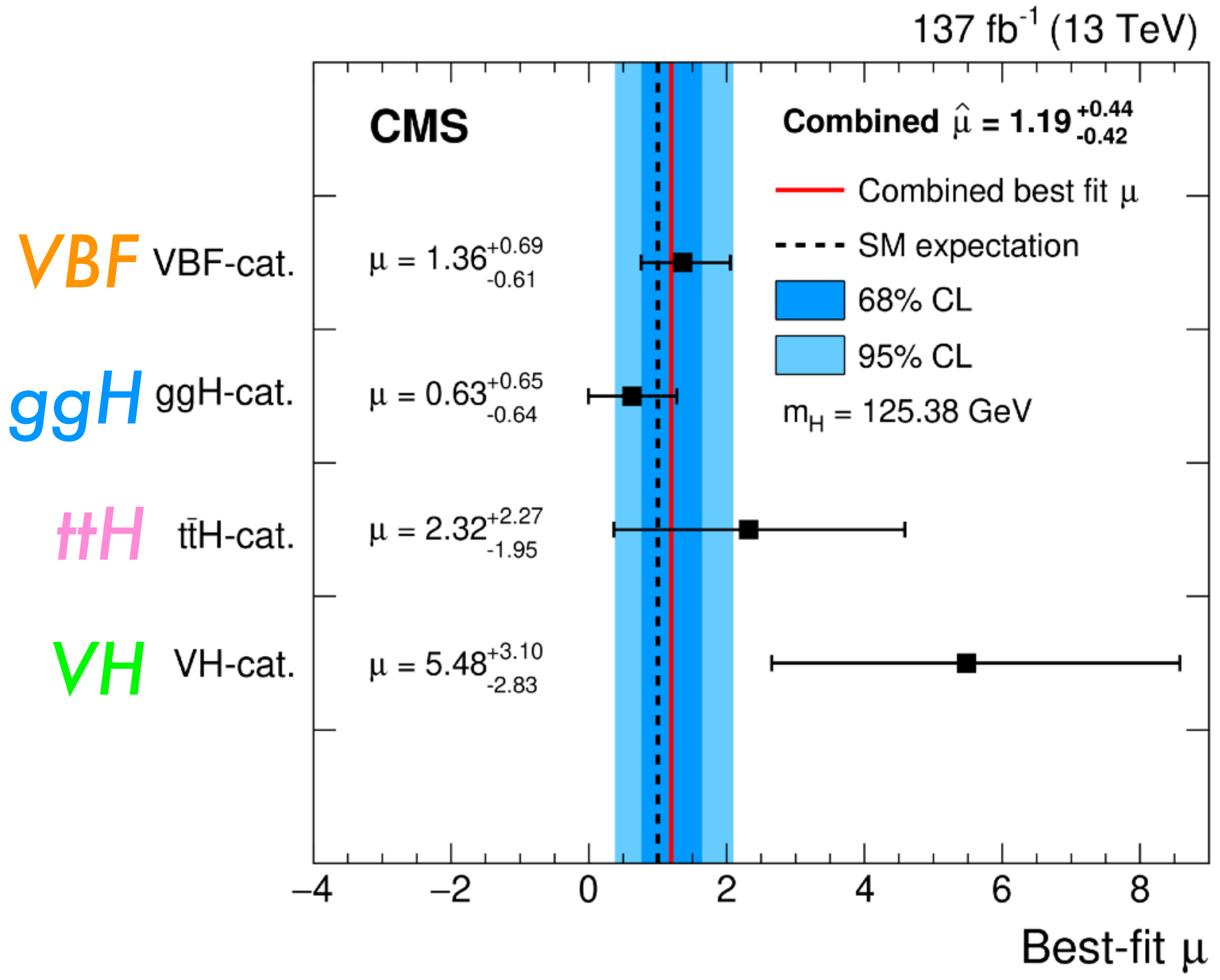
First evidence of Higgs coupling to the second generation

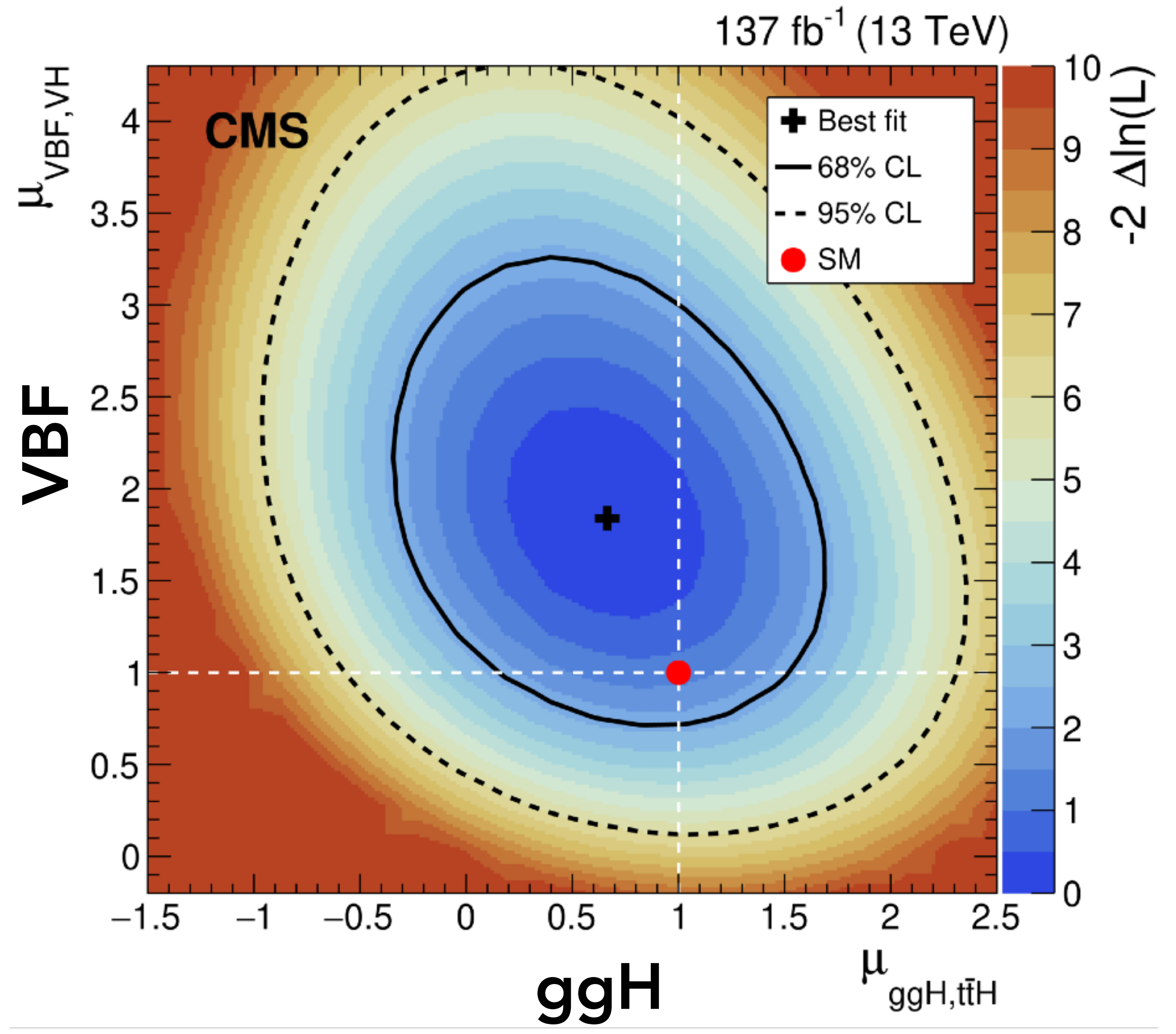












[CMS-HIG-19-006](#)
[JHEP 01 (2021) 148](#)

[Phys. Briefing](#)

$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39}\,(\text{stat})^{+0.17}_{-0.16}\,(\text{syst})$$

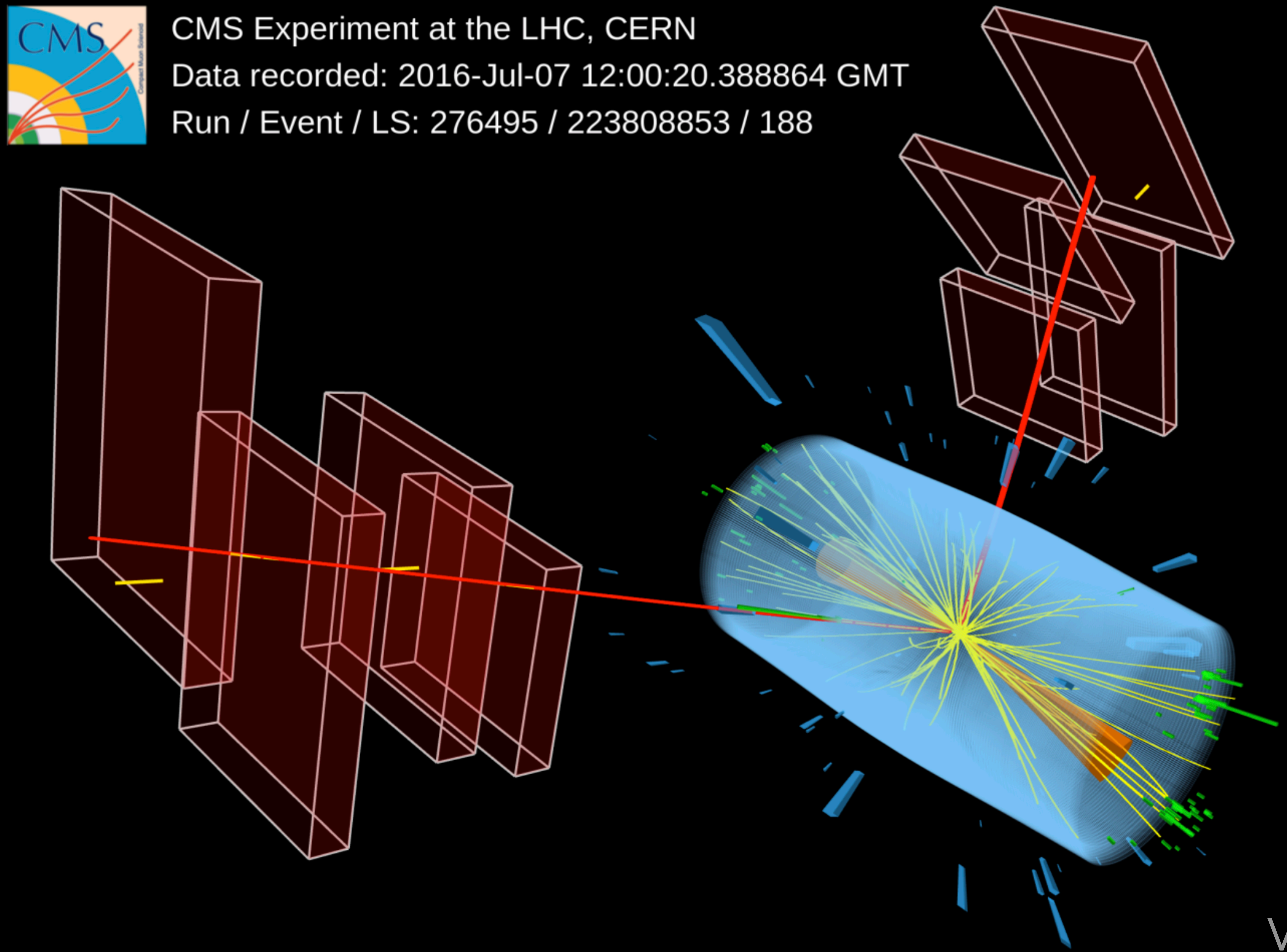
Obs. (exp.) significance: 3.0 (2.5) σ

Analysis in VBF category

- makes use of advanced machine learning techniques
- provides sensitivity similar to that in ggH

using $m_{\rm H} = 125.38$ GeV (best CMS result)

$H \rightarrow \mu\mu$ (VBF)

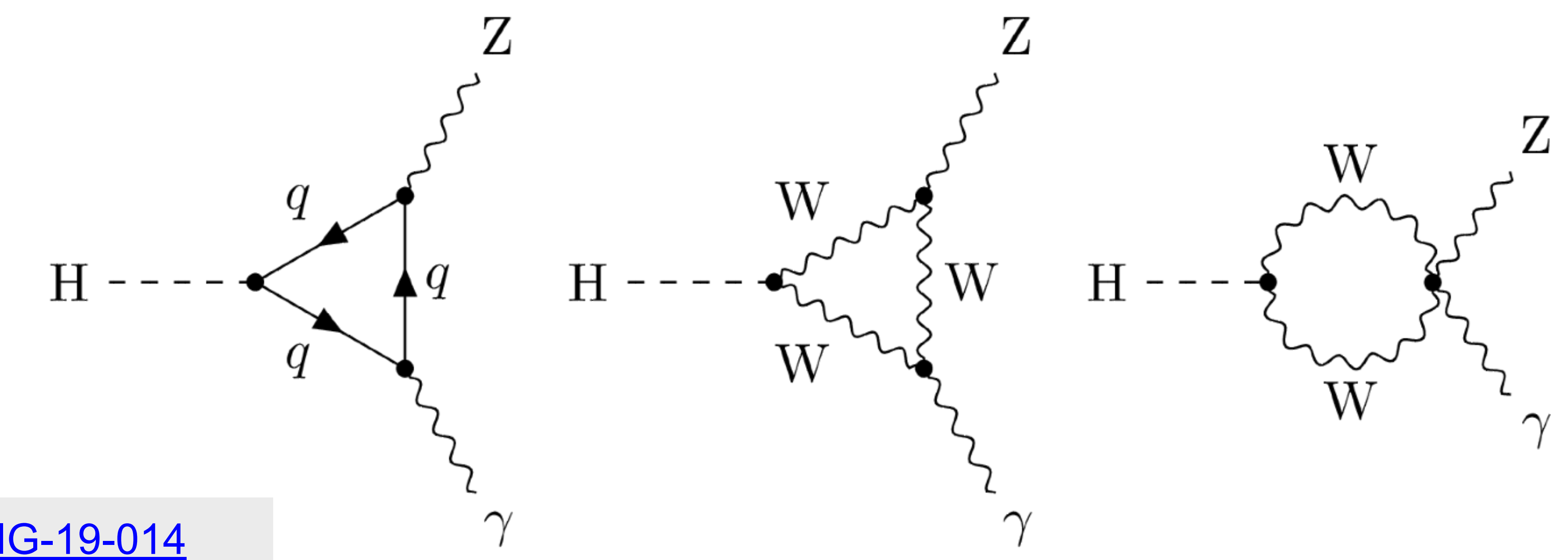


Drell-Yan background considerably reduced by VBF topology requirement (two forward jets)

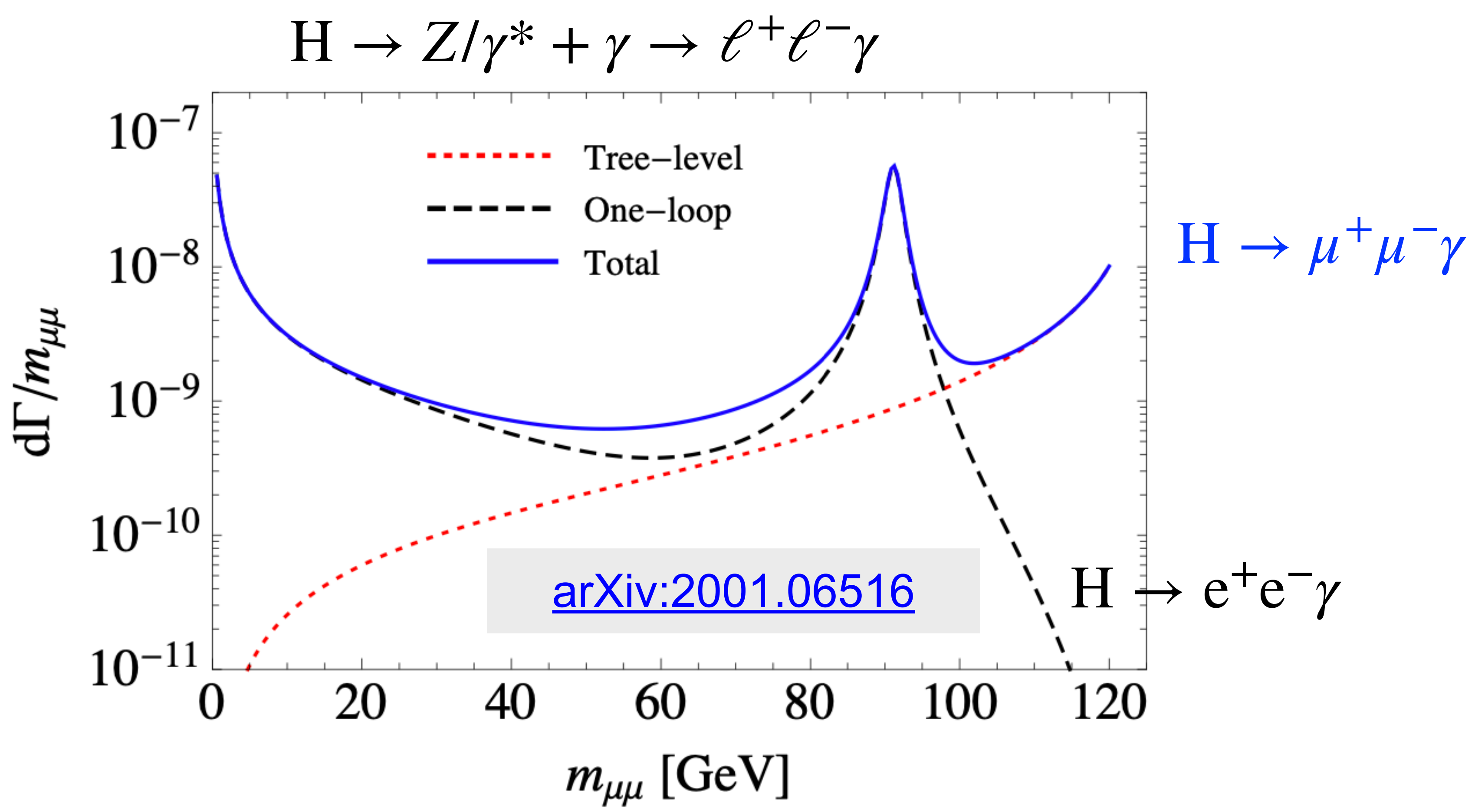
VBF $H \rightarrow \mu\mu$ candidate

$H \to Z\gamma \to \ell\ell\gamma$

A rare decay that proceeds mostly through loops similar to $H \to \gamma\gamma$

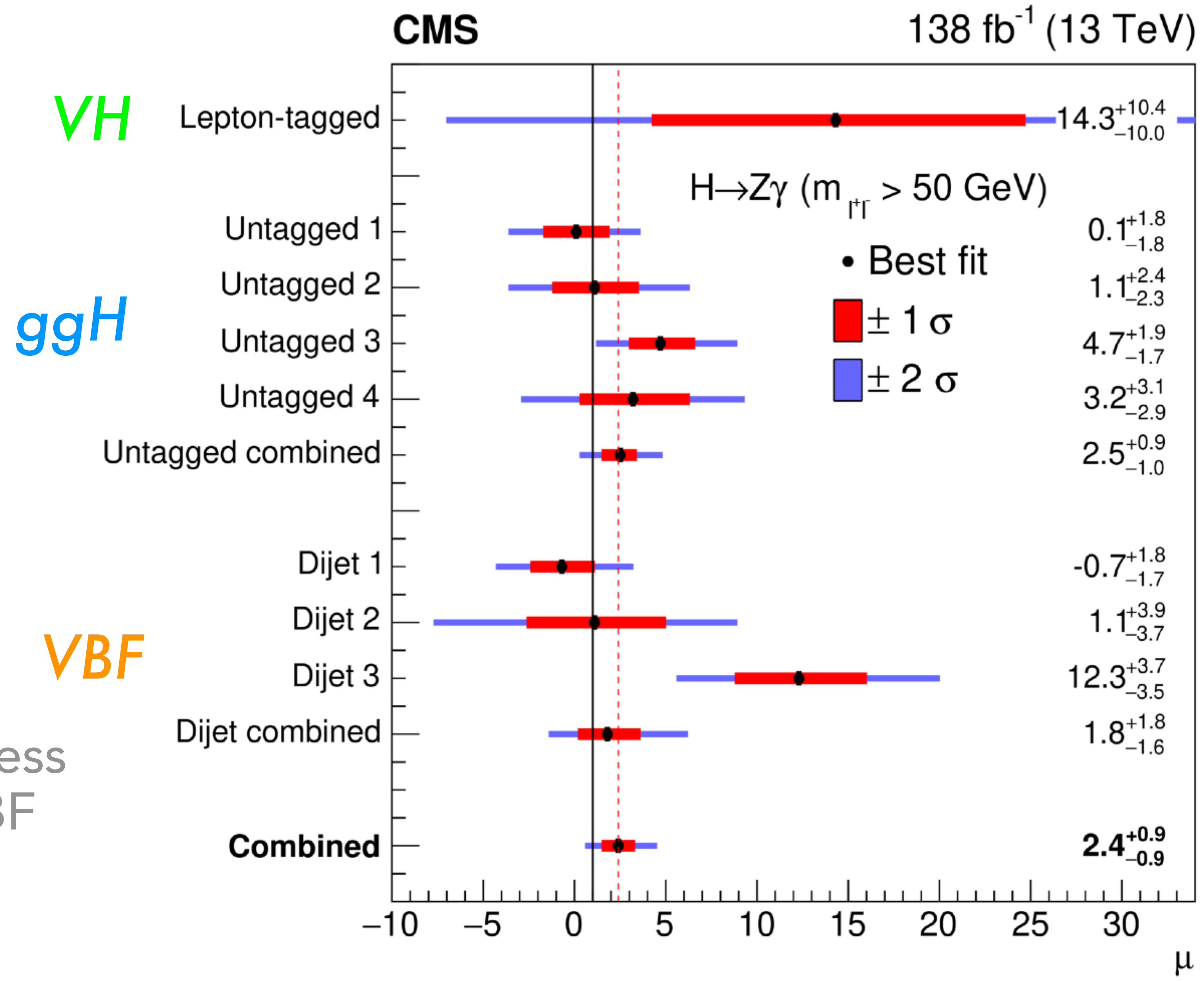


CMS-HIG-19-014
Accepted by JHEP

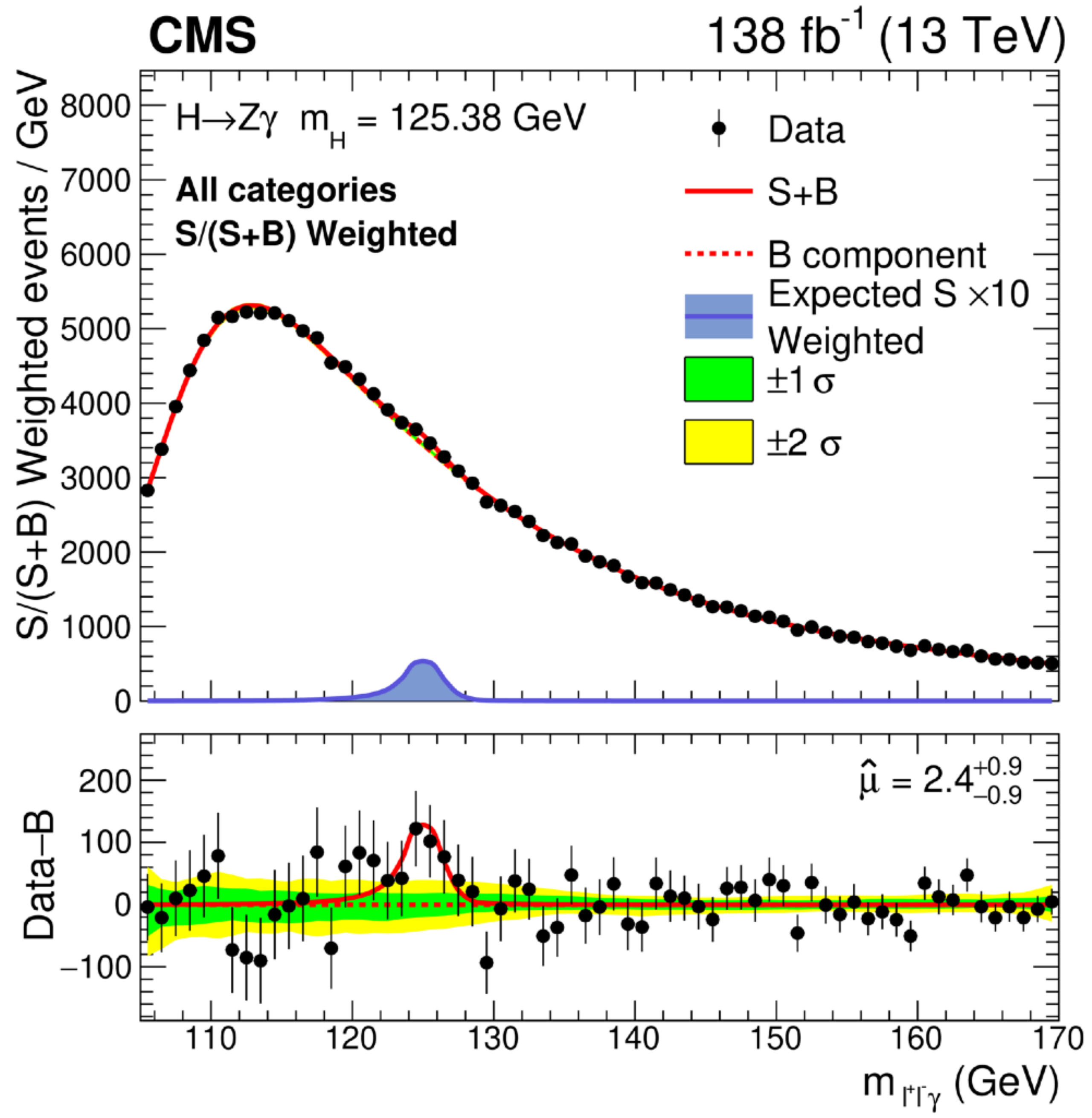


Tree contribution not negligible in the μμγ channel

$m(\ell^+\ell^-) > 50\,\mathrm{GeV}$



most of the excess in one of the VBF categories



Obs. (exp.) significance:
2.7 (1.2) σ

$B(\mathrm{H} \to Z\gamma)/B(\mathrm{H} \to \gamma\gamma) = 1.5^{+0.7}_{-0.6}$
consistent with the SM expectation (0.69 ± 0.04) at the 1.5σ level

Signal Strength Modifiers

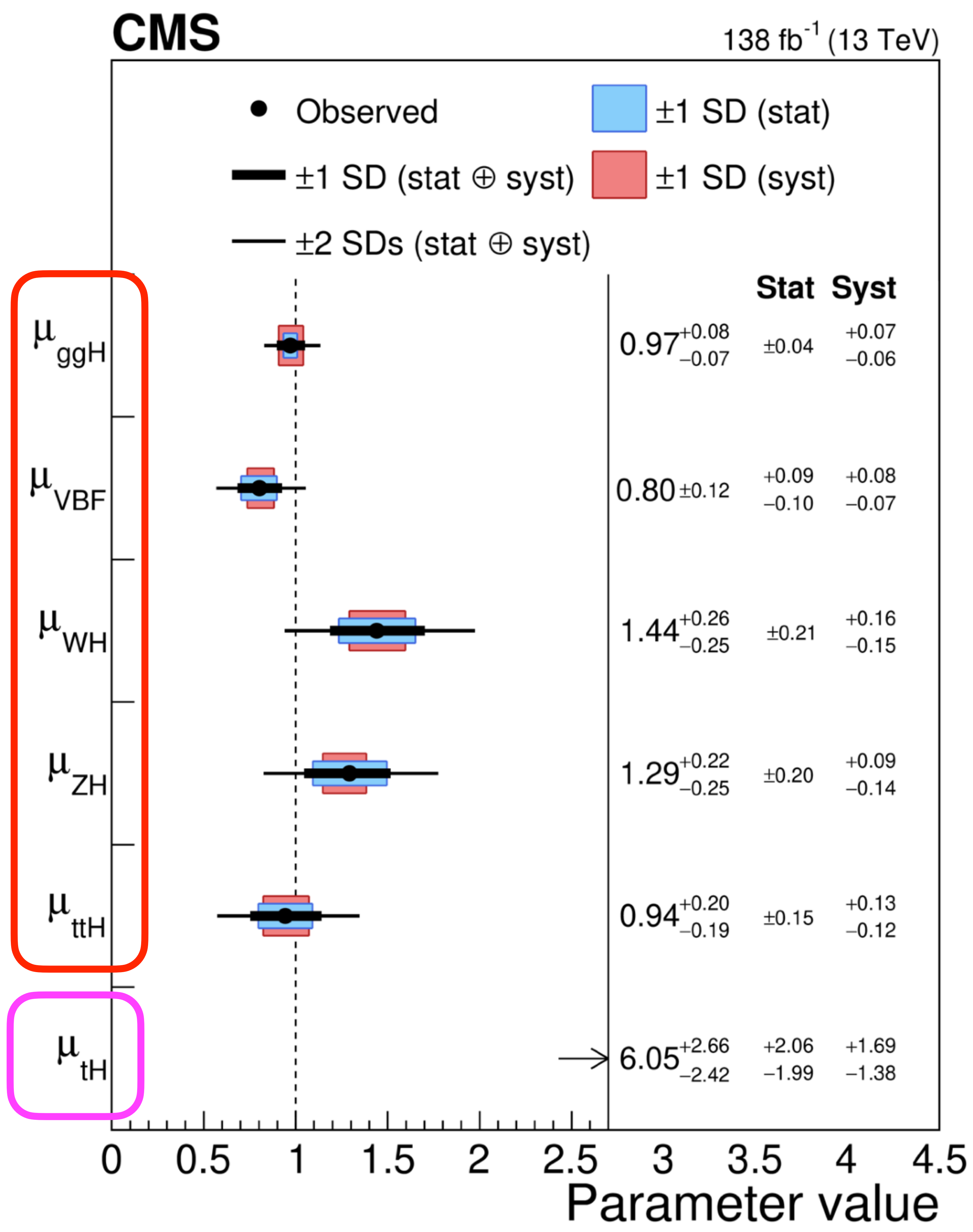
Signal Strength Modifiers μ: ratios between the measured Higgs boson yields and SM expectations

[CMS-HIG-22-001](#)
Nature 607 (2022) 60

Production Modes

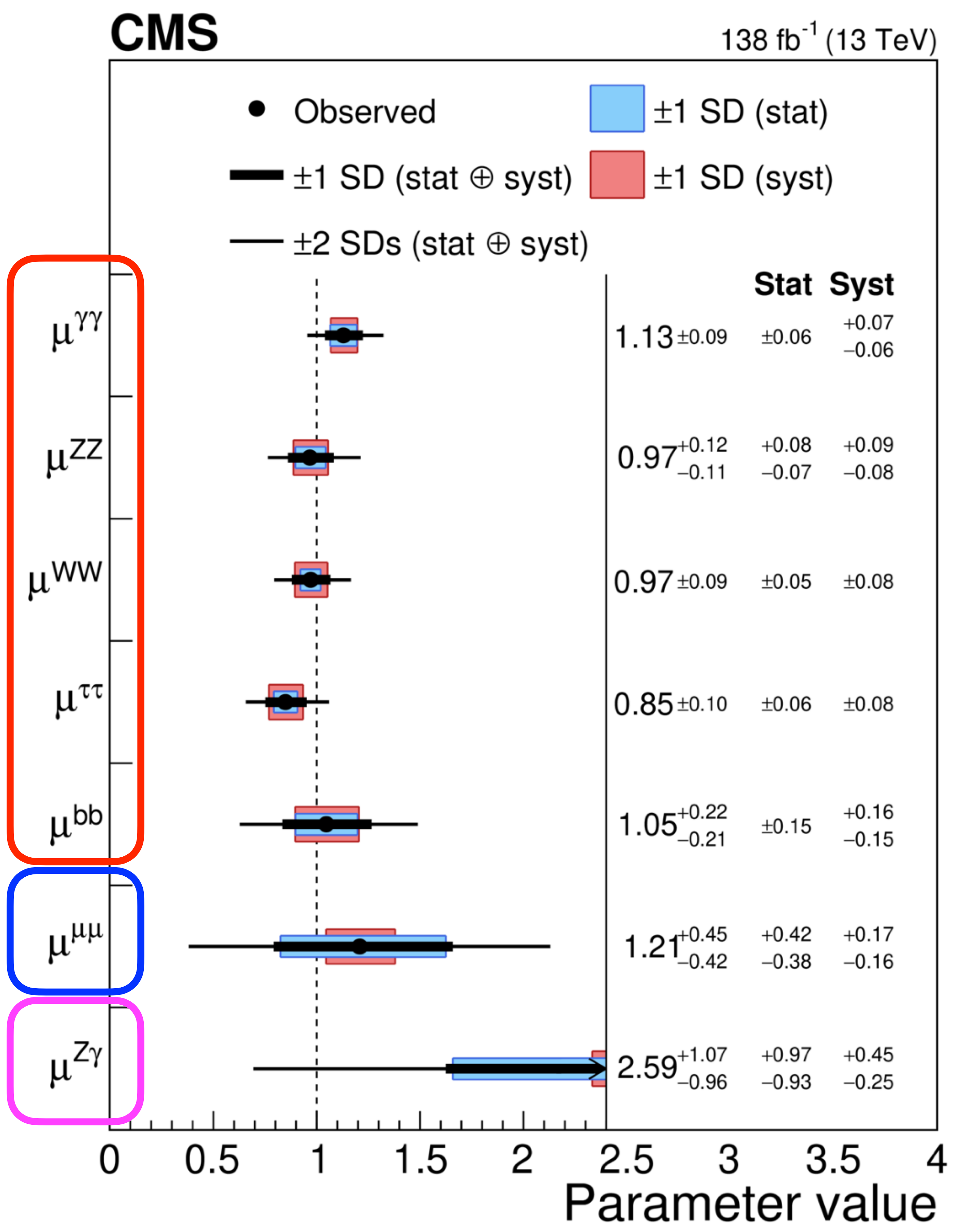
observed

yet to be observed



Decay Channels

evidence



Signal Strength Modifiers

Evolution of common signal strength

Higgs Discovery

- up to 10.4 fb^{-1} at 7-8 TeV
- $\mu = 0.87 \pm 0.23$ (mostly stat)

Run 1 combination

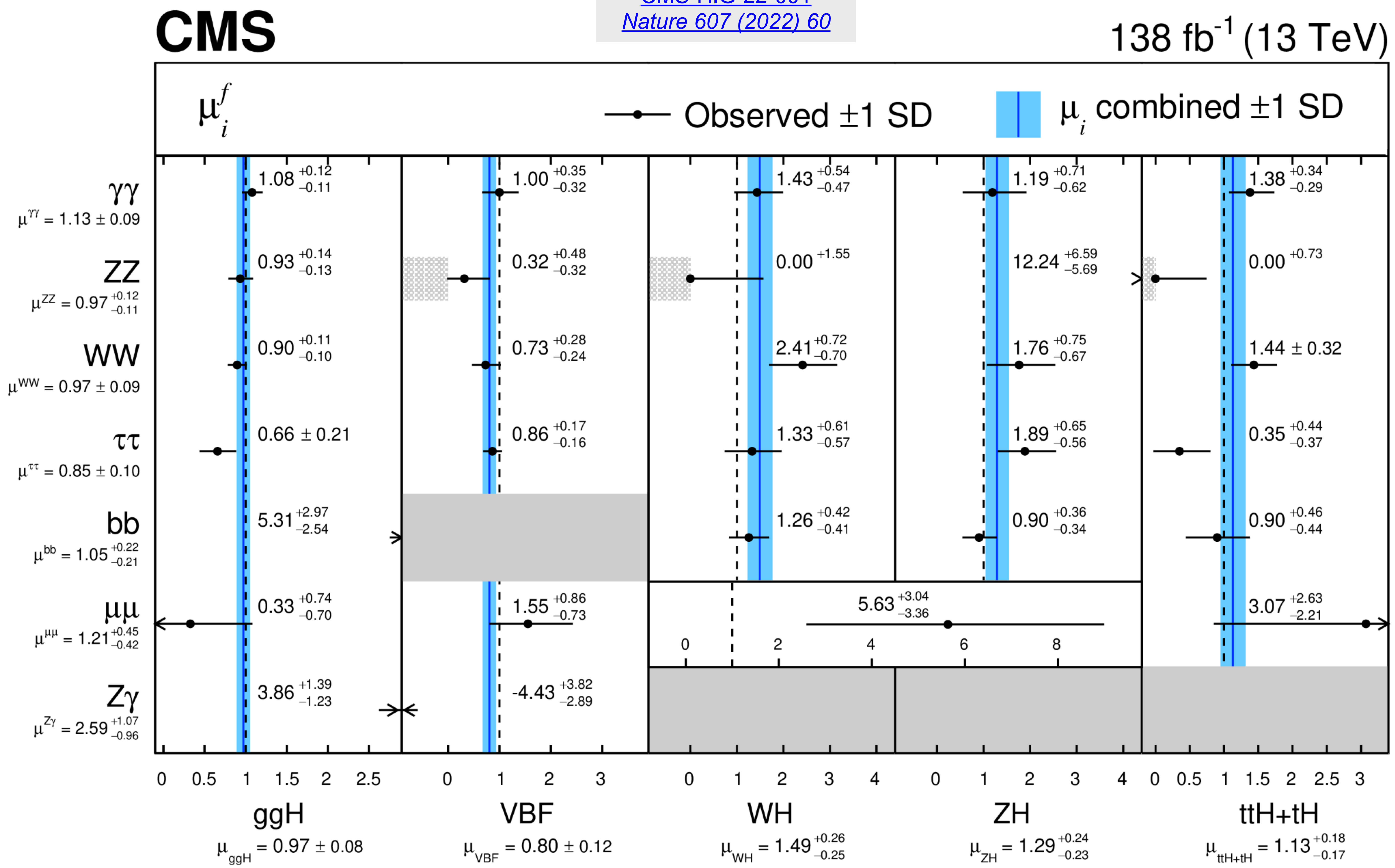
- up to 24.8 fb^{-1} at 7-8 TeV
- $\mu = 1.00 \pm 0.13$ [± 0.09 (stat) ± 0.07 (exp) $^{+0.08}_{-0.07}$ (theory)]

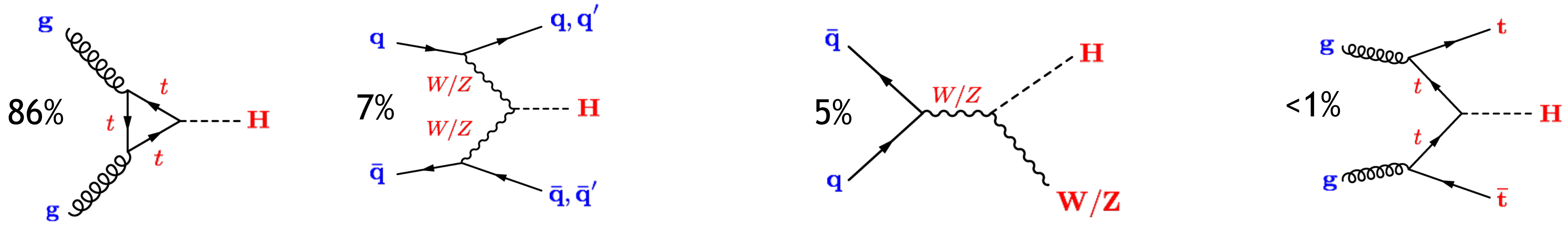
Run 2 combination

- up to 138 fb^{-1} at 13 TeV
- $\mu = 1.002 \pm 0.057$ [± 0.029 (stat) ± 0.033 (exp) ± 0.036 (theory)]

CMS *p*-value for SM hypothesis: **5.8%**

CMS-HIG-22-001
Nature 607 (2022) 60





Kappa Framework

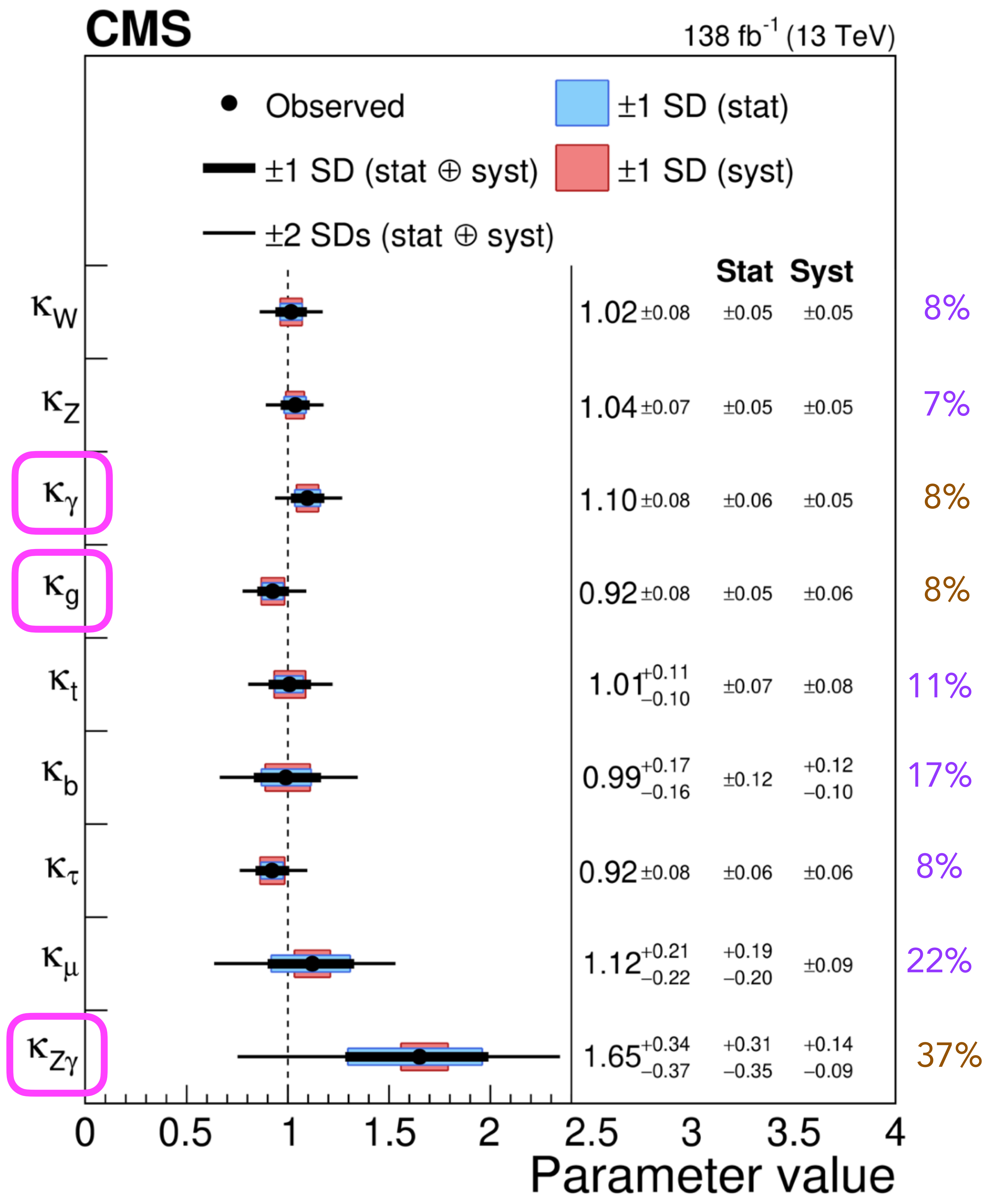
κ coupling modifiers (*) introduced in order to quantify deviations in the **couplings** of the Higgs boson to other particles

κ_γ or $(1.26\,\kappa_W - 0.26\,\kappa_t)$

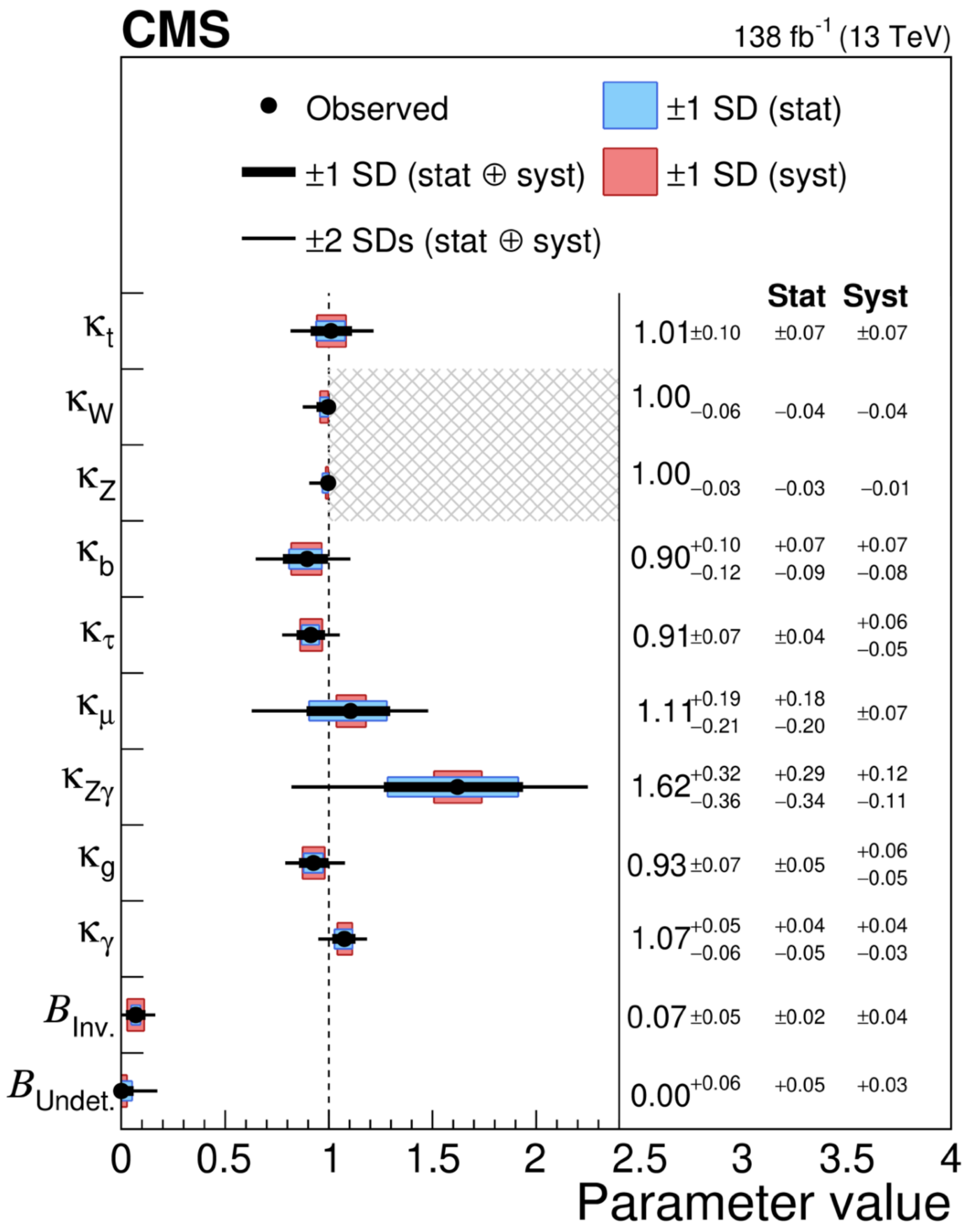
CMS-HIG-22-001
Nature 607 (2022) 60

(*) see backup slides

assuming effective couplings to ggH, Hγγ and HZγ

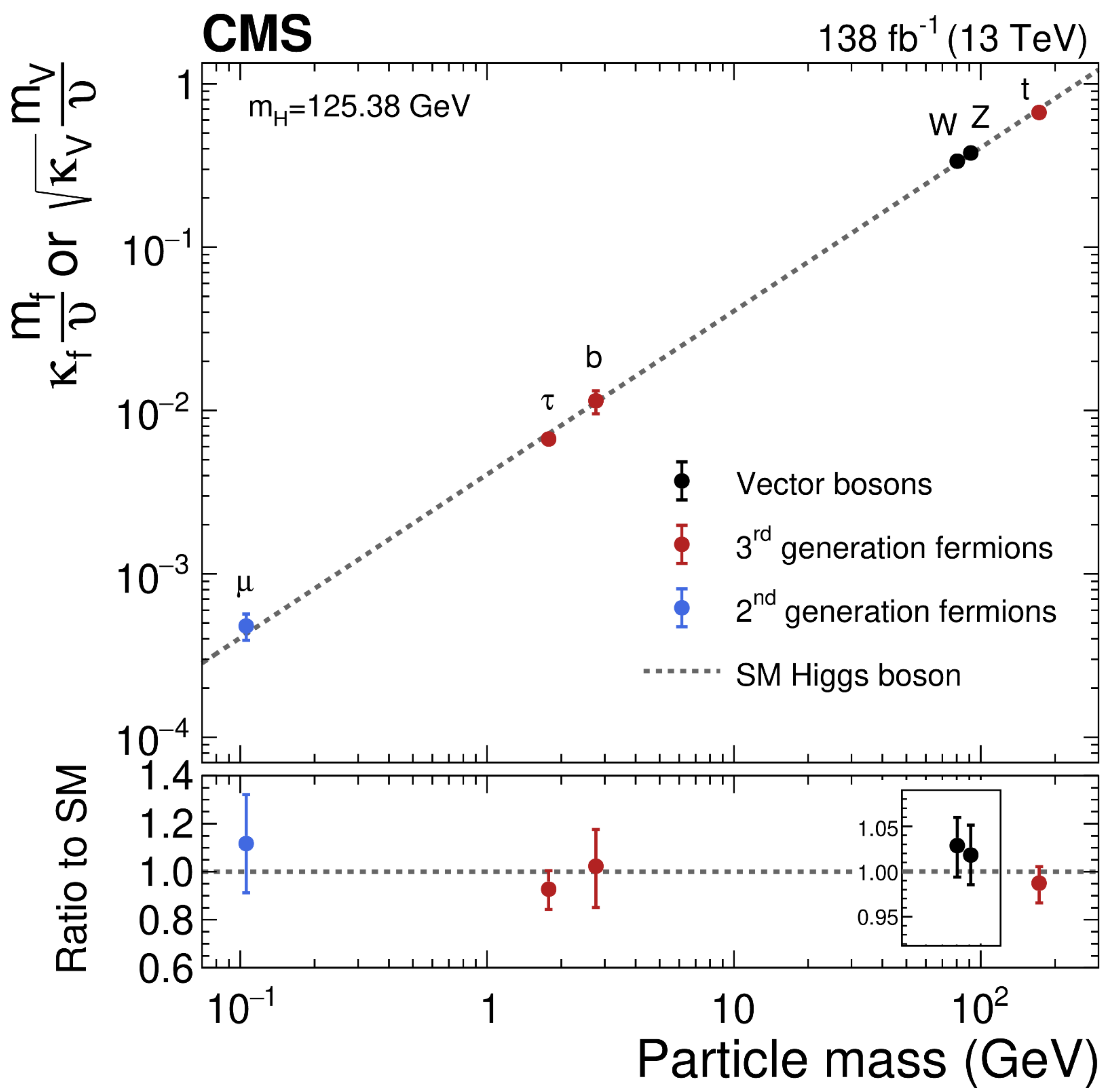


considering also Higgs decays to
- invisible
- undetectable (non closure of other BFs to 1)

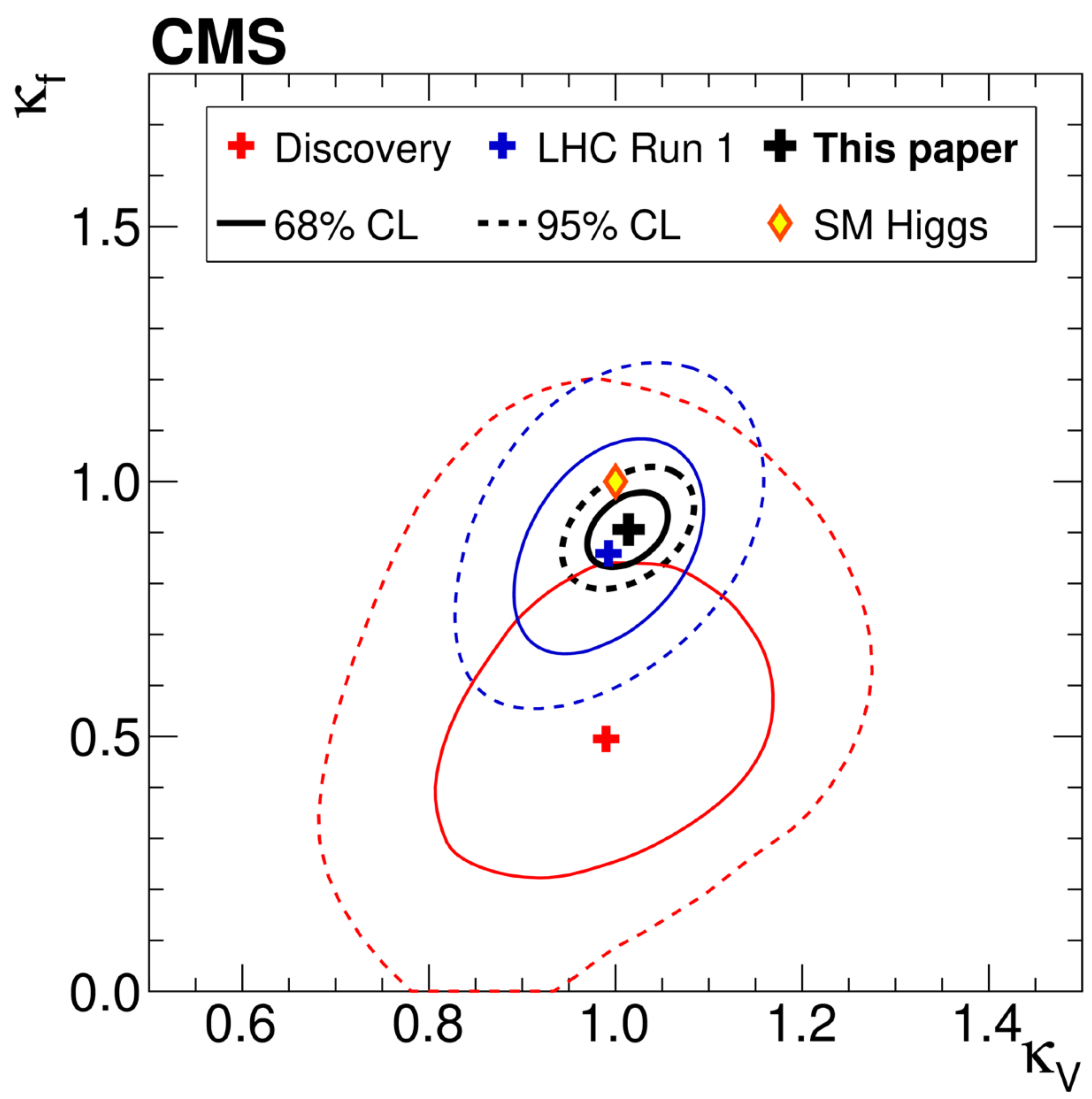


both invisible and undetectable are consistent with 0

Kappa Framework



- Compatibility with SM within 10%
- 5 fold improvement since discovery



CMS-HIG-22-001
Nature 607 (2022) 60

Higgs Differential, STSX, EFT

Run-2 2016, 35.9 fb^{-1}

Differential distributions

Distributions unfolded for selection efficiency and resolution effects and compared to theoretical calculations

- p_T^H, y^H, n(jets), n(b-jets), n(leptons), etc.

STSX (Simplified Template Cross Sections)

Fiducial x-section measurements by production mode in various kinematic regions

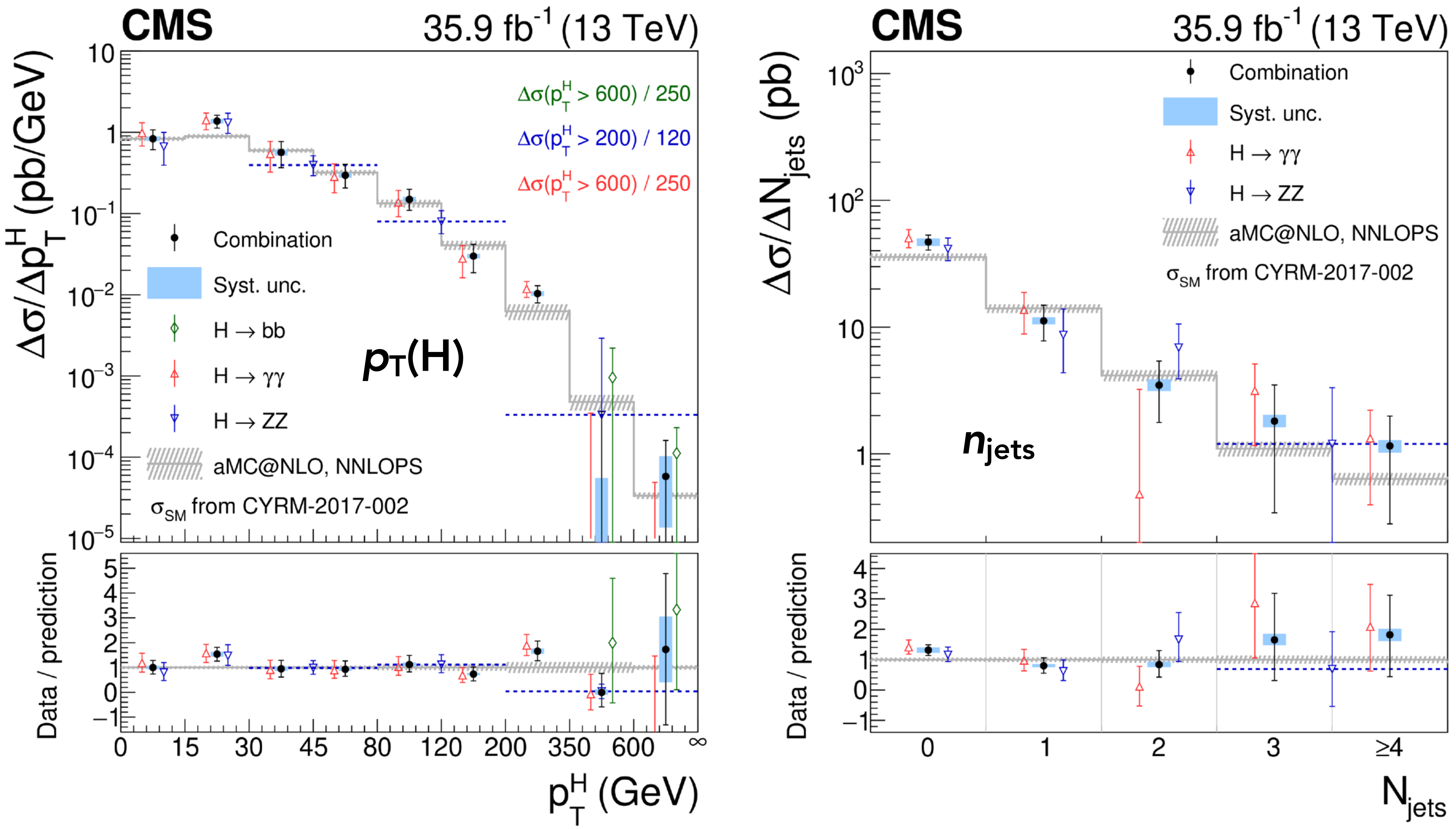
- no unfolding of detector effects
- reduced theory uncertainties

EFT (Effective Field Theory)

Consistent set of perturbations of the SM

- assume no NP at LHC energies
- mostly preserves symmetries of SM

- $H \to b\bar{b}, \gamma\gamma, ZZ^*$

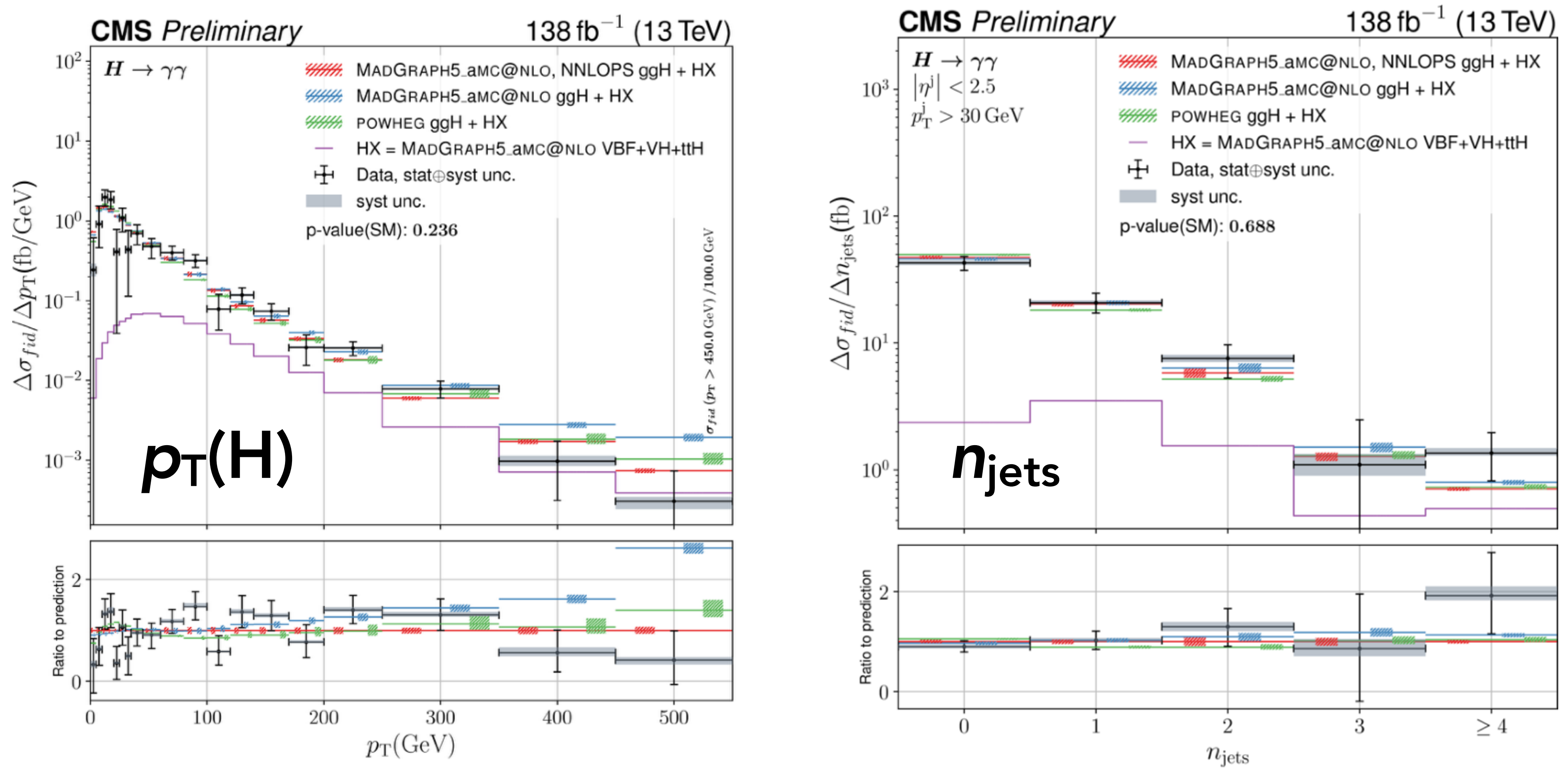


[CMS-HIG-17-028](#)
PLB 792 (2019) 369

Higgs Differential Cross Sections

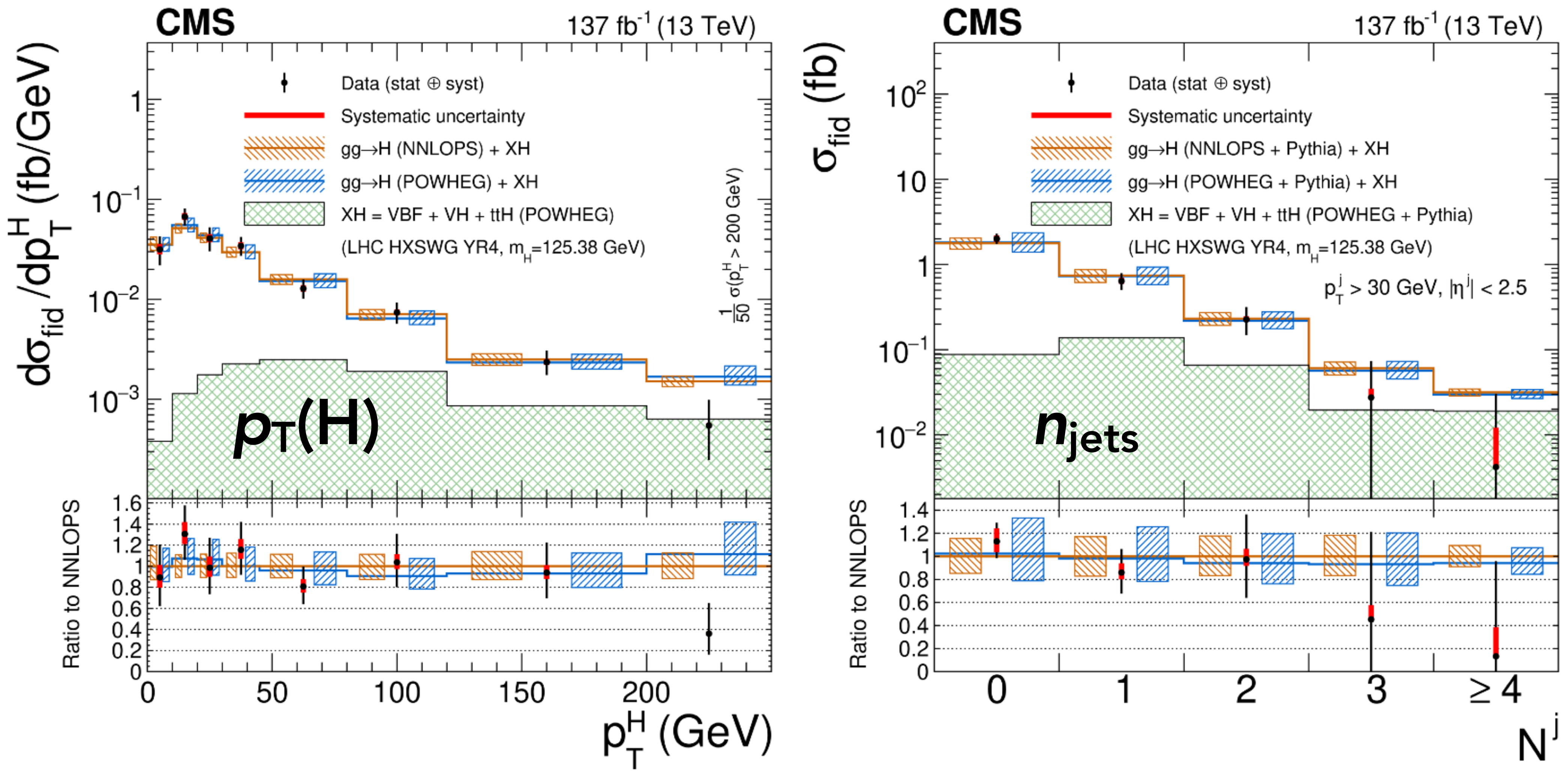
- H → $\gamma\gamma$

CMS-HIG-19-016
Submitted to JHEP



- H → ZZ* → 4ℓ

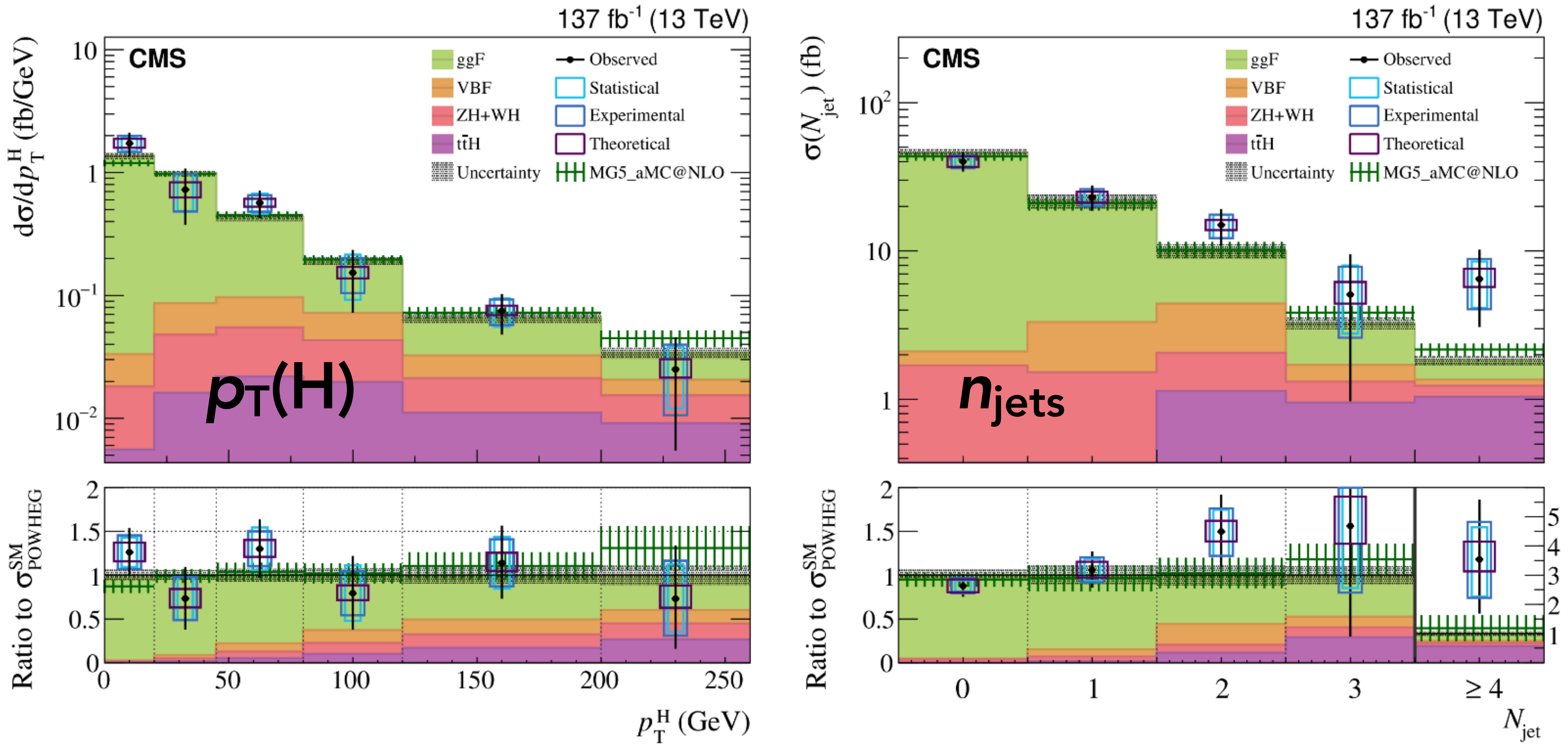
CMS-HIG-19-001
EPJC 81 (2021) 488



- H → WW* → $e^{\pm}\mu^{\mp}\nu\bar{\nu}$

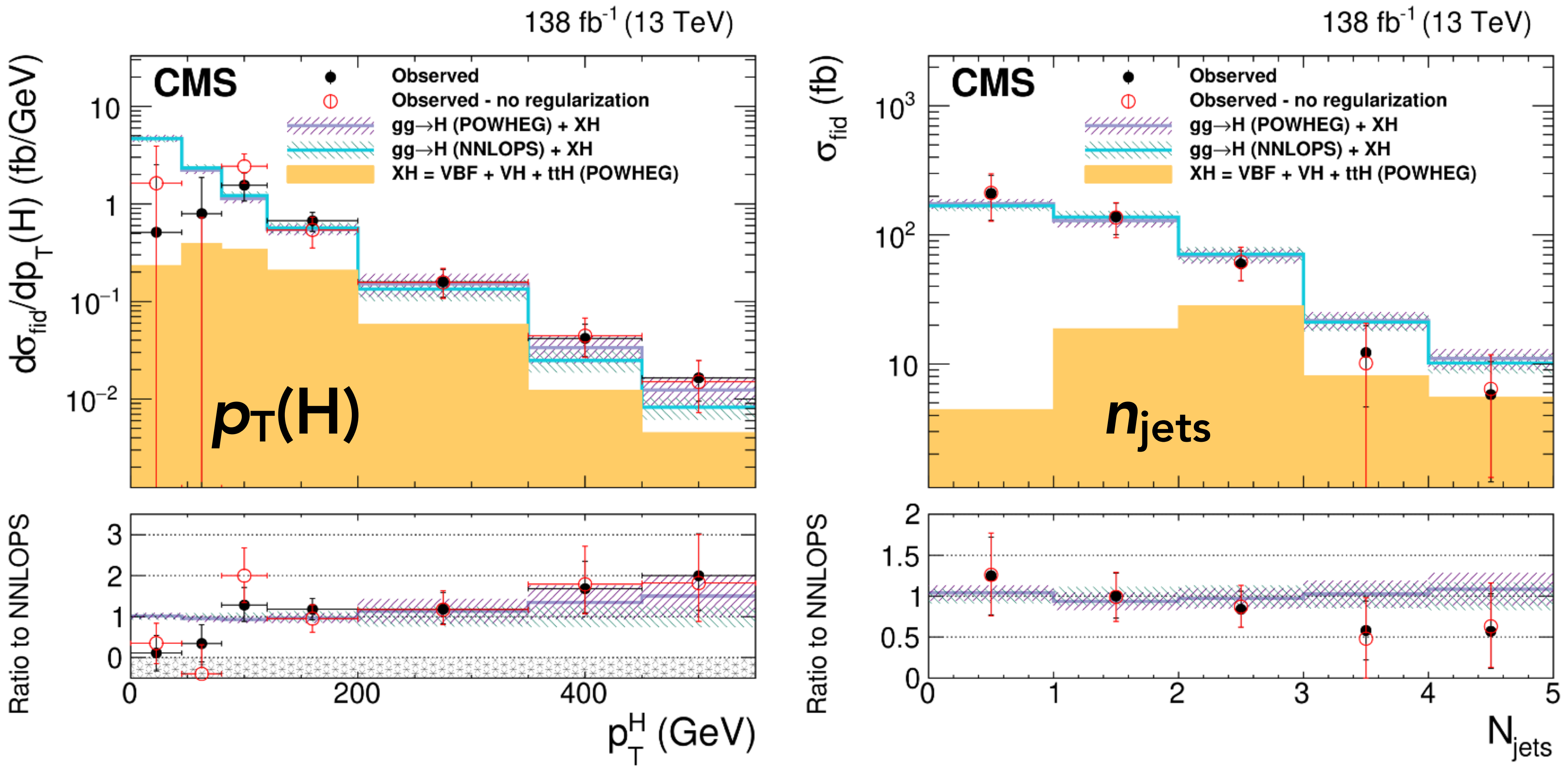
CMS-HIG-19-002
JHEP 03 (2021) 003

Phys. Briefing



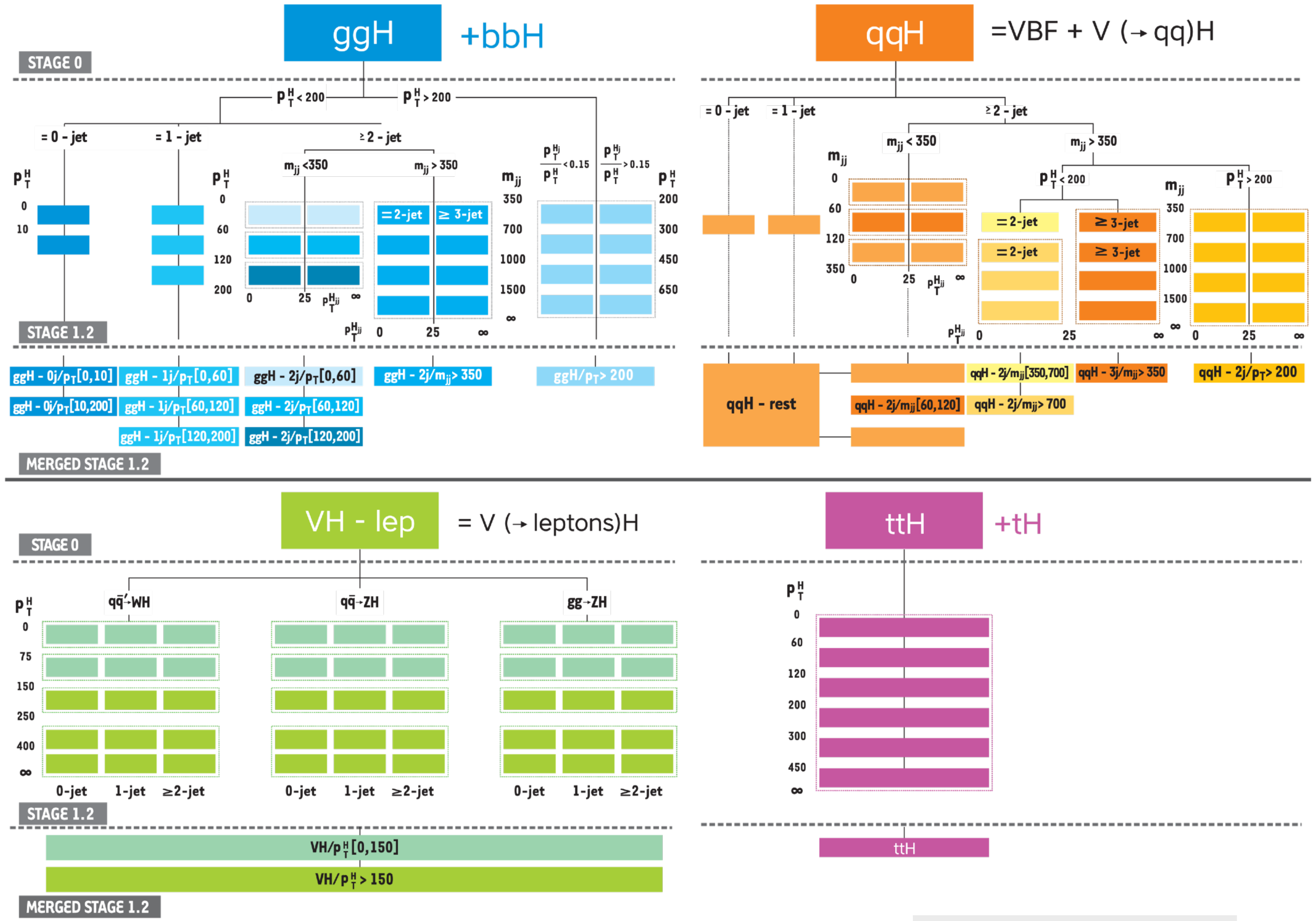
- H → $\tau\tau$

CMS-HIG-20-015
PRL 128 (2022) 081805



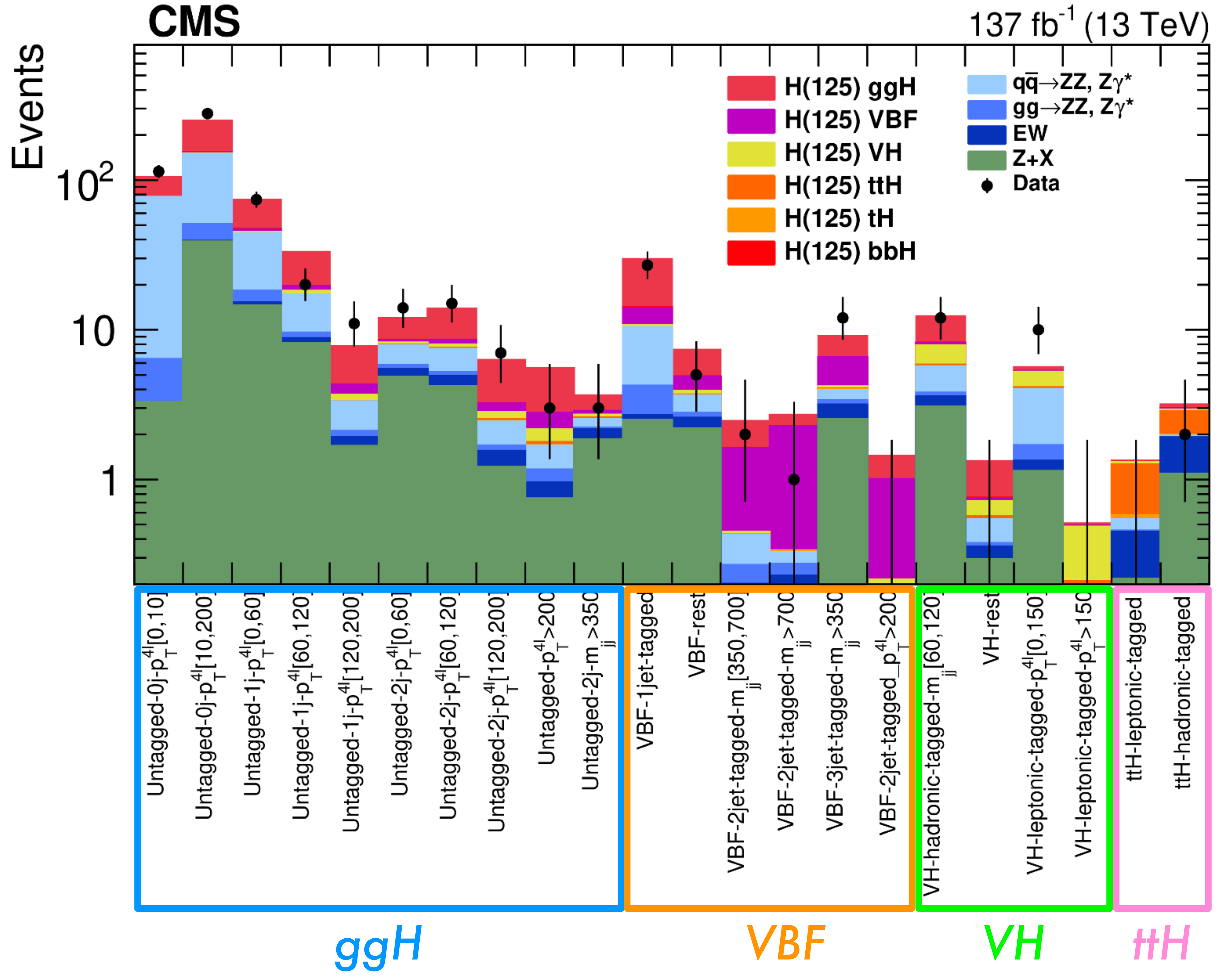
STSX

Maximising sensitivity to BSM physics while limiting model dependence



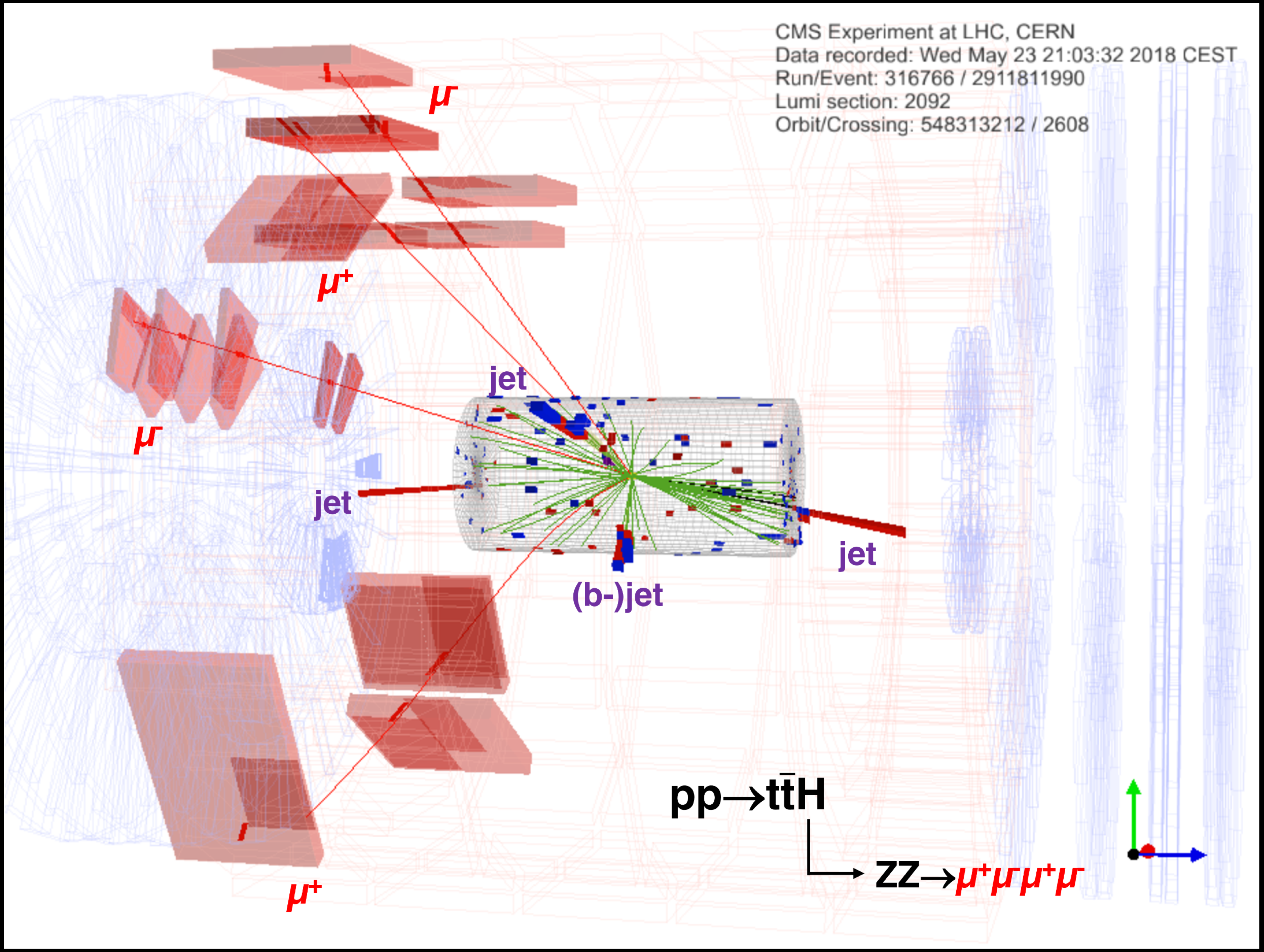
From Z →4ℓ analysis, examples of

- STSX bin definition
- yields in bins and bin migration



[CMS-HIG-19-001](#)
[EPJC 81 (2021) 488](#)

ttH (H → 4ℓ)

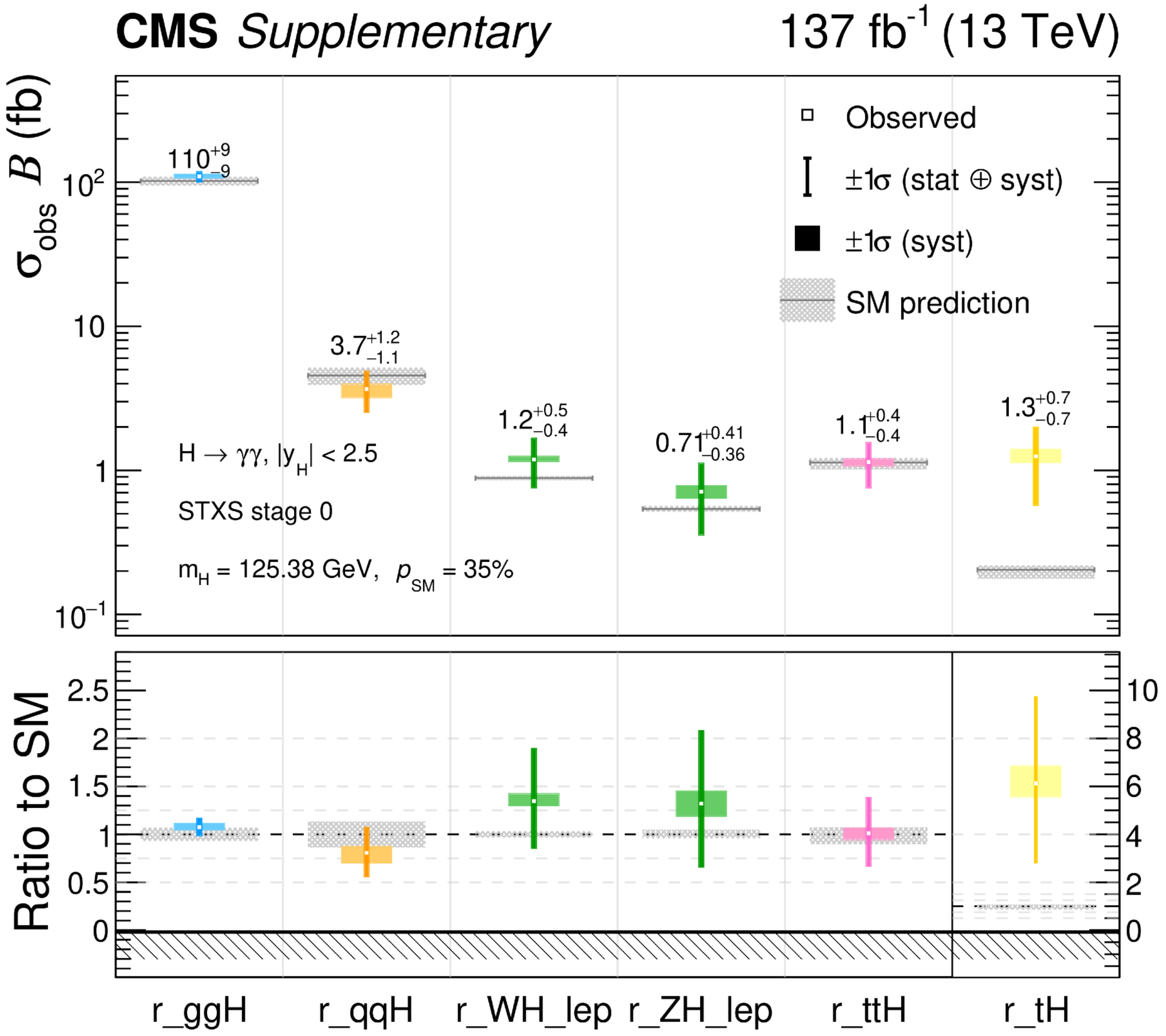


a ttH (H → 4μ) candidate

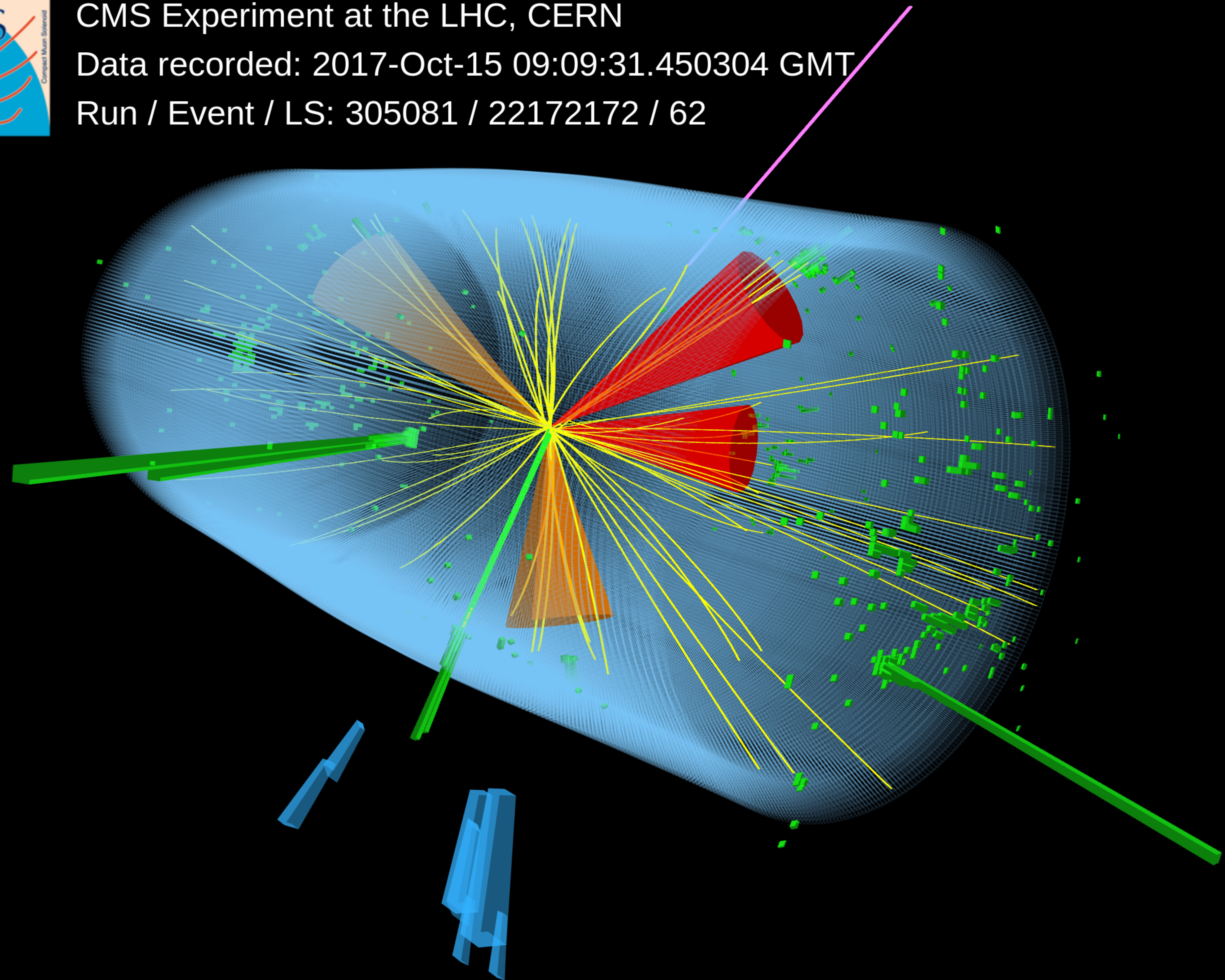
$H \rightarrow \gamma\gamma$

Stage 0 STSX

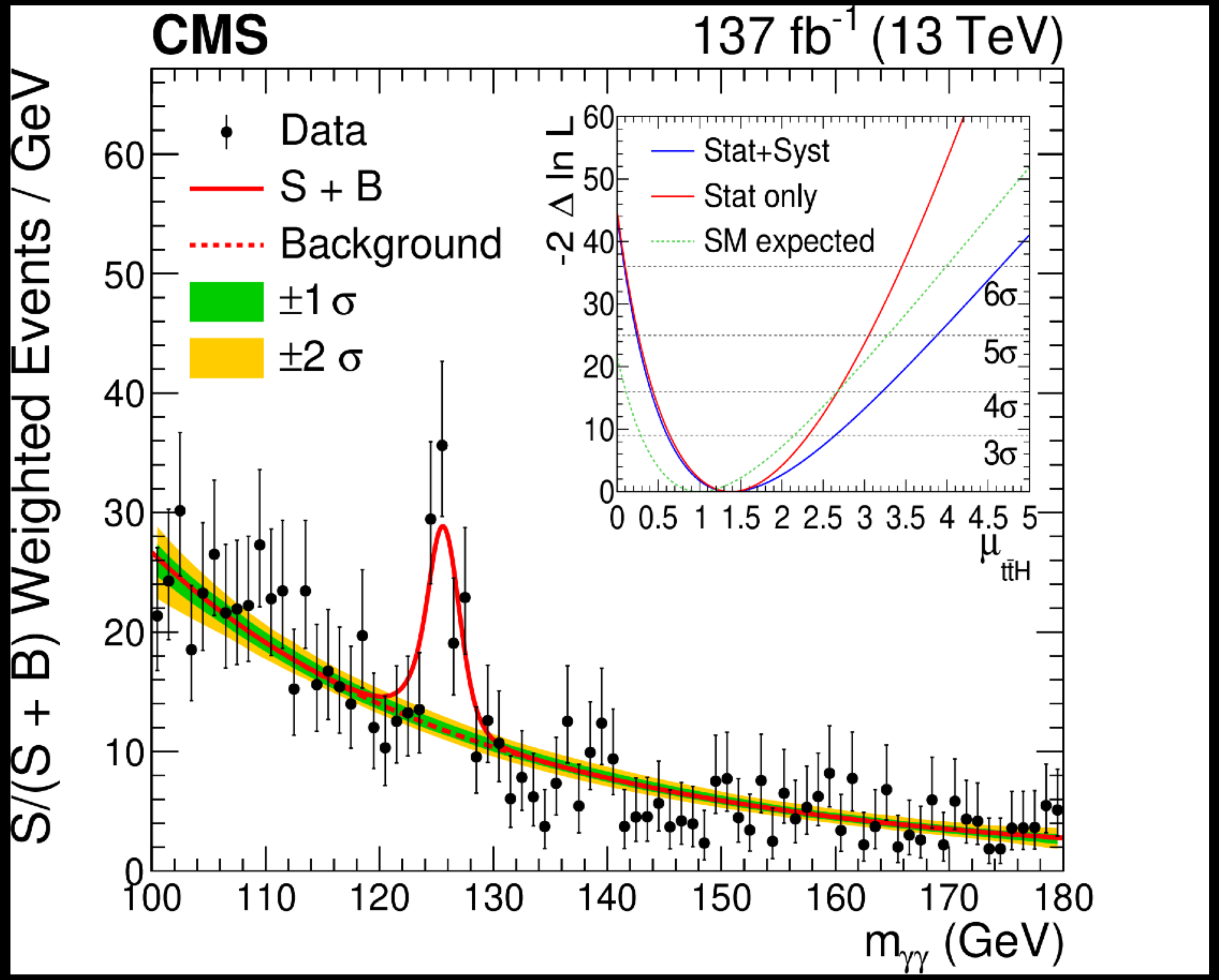
Cross sections per production modes



ttH (H → γγ)



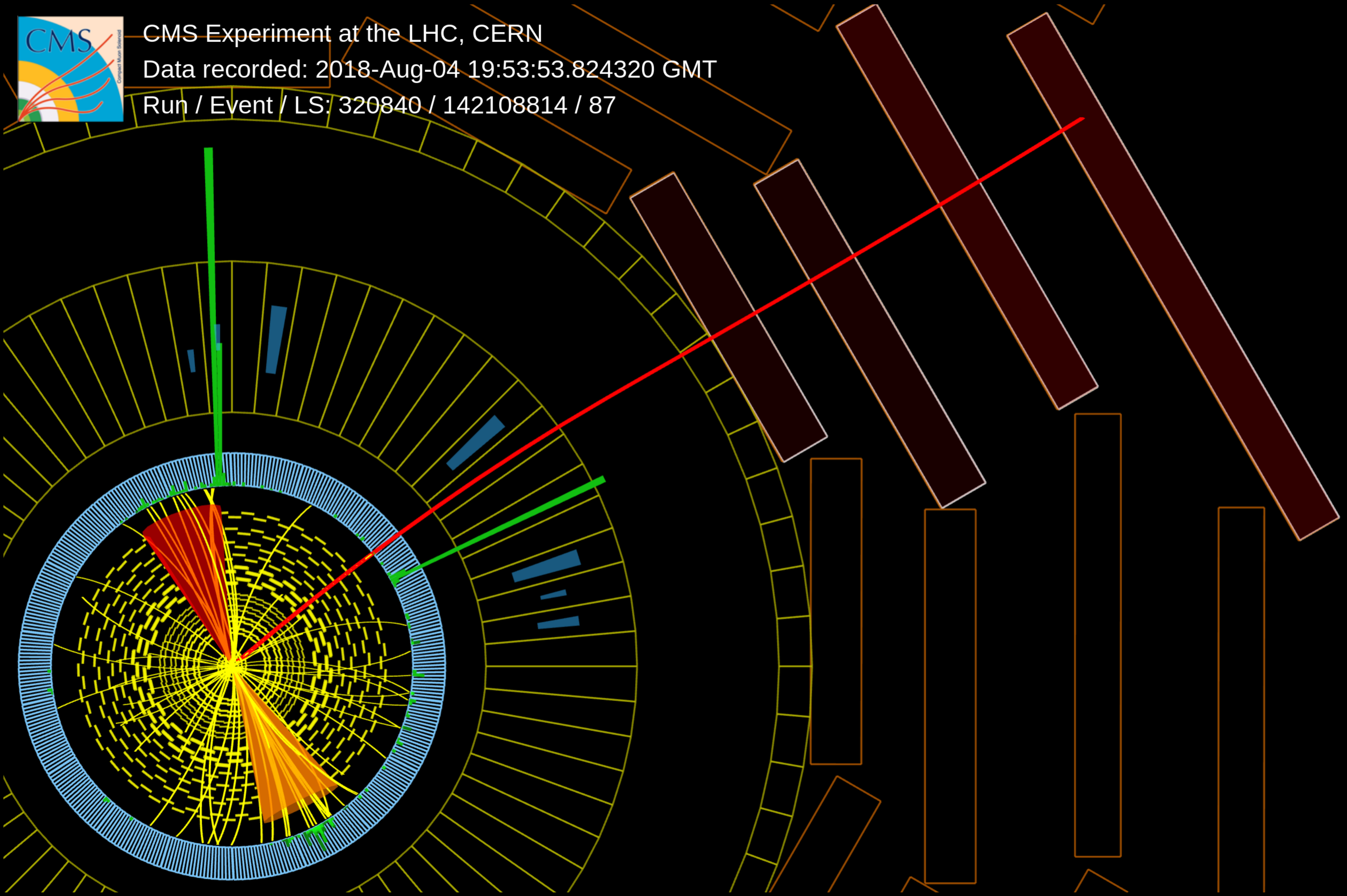
ttH signal in H → γγ



- $\sigma(t\bar{t}H) \times \mathscr{B}_{\gamma\gamma} = 1.56^{+0.34}_{-0.43}$ fb
- $\mu_{t\bar{t}H} = 1.38\ ^{+0.29}_{-0.27}$ (stat) $^{+0.21}_{-0.11}$ (syst)
- 6.6σ (4.7σ exp.)

a ttH (H → γγ) candidate

tHq (H → γγ)

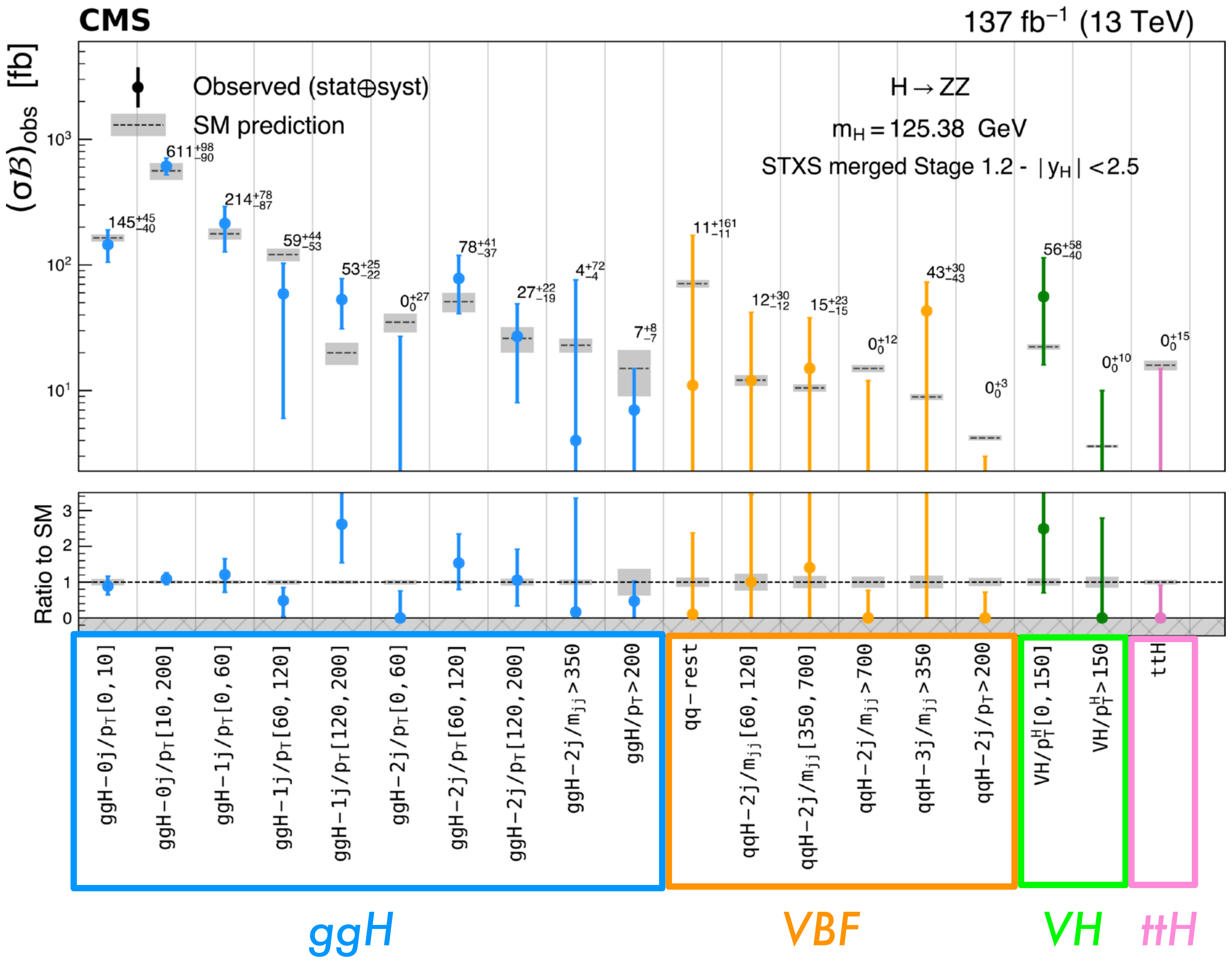


a tHq (H → γγ) candidate

STSX

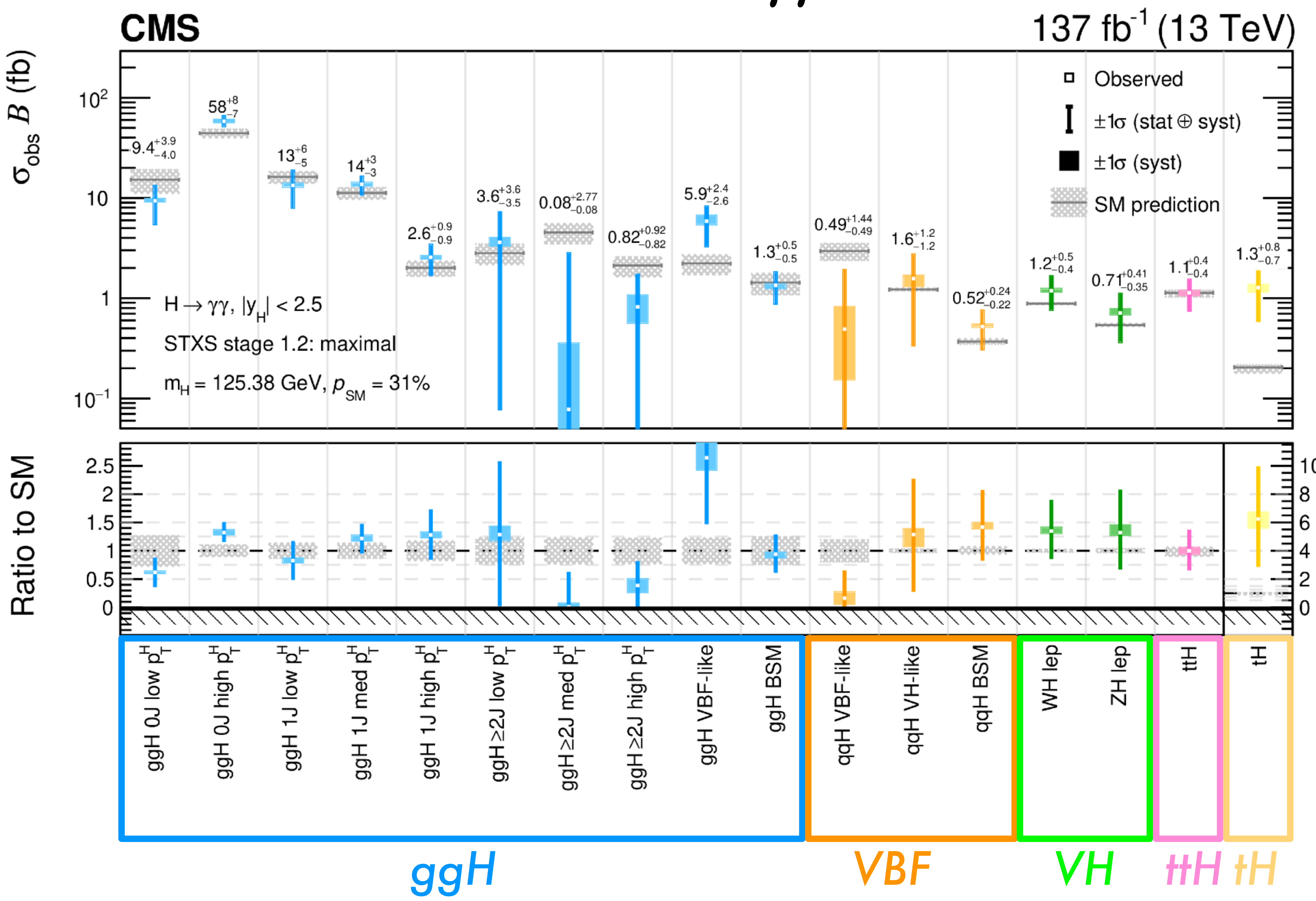
Stage 1.2 STSX

$H \rightarrow ZZ^* \rightarrow 4\ell$



[CMS-HIG-19-001](#)
[EPJC 81 (2021) 488](#)

$H \rightarrow \gamma\gamma$



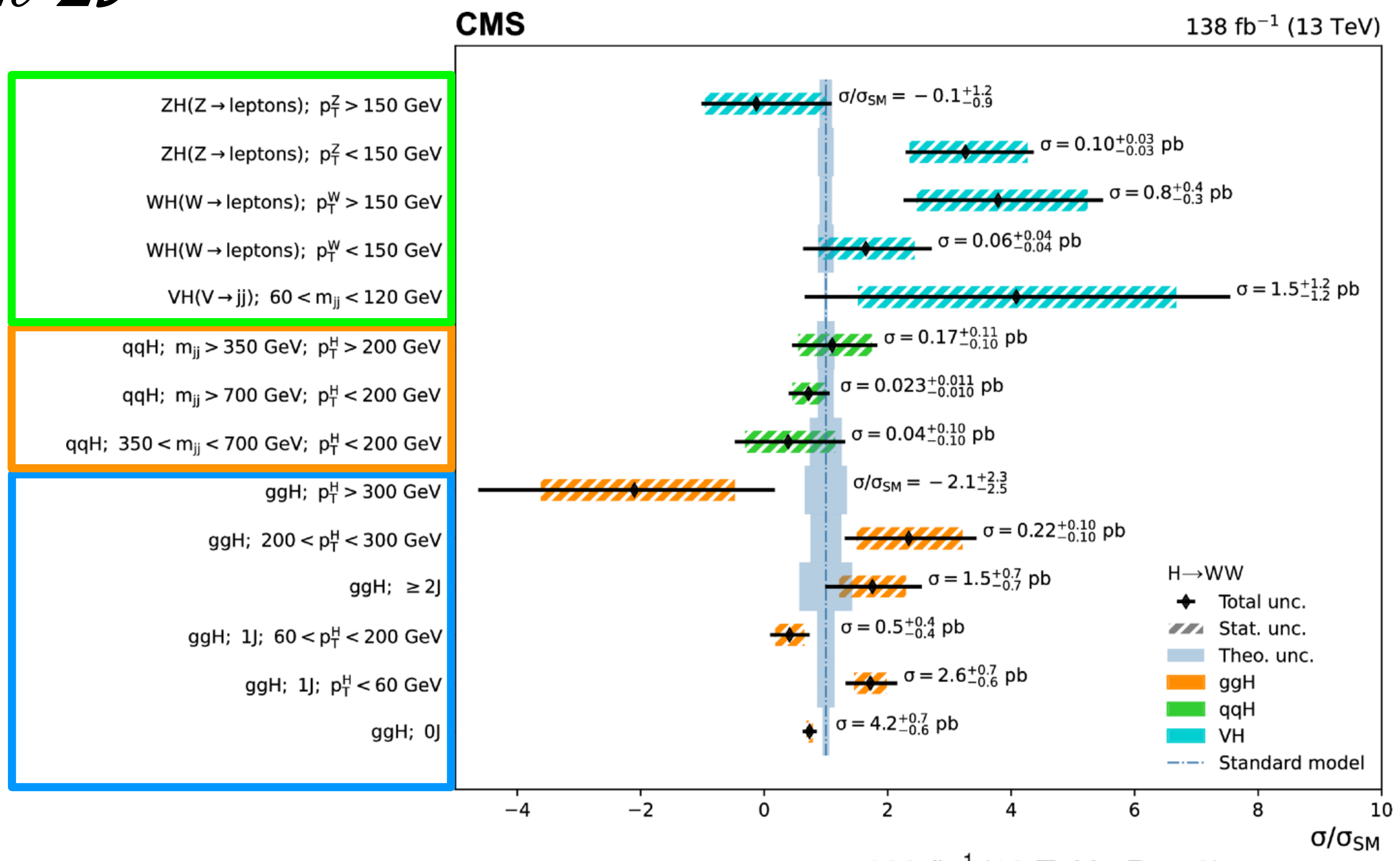
[CMS-HIG-19-015](#)
[JHEP 07 (2021) 027](#)

[Phys. Briefing](#)

STSX

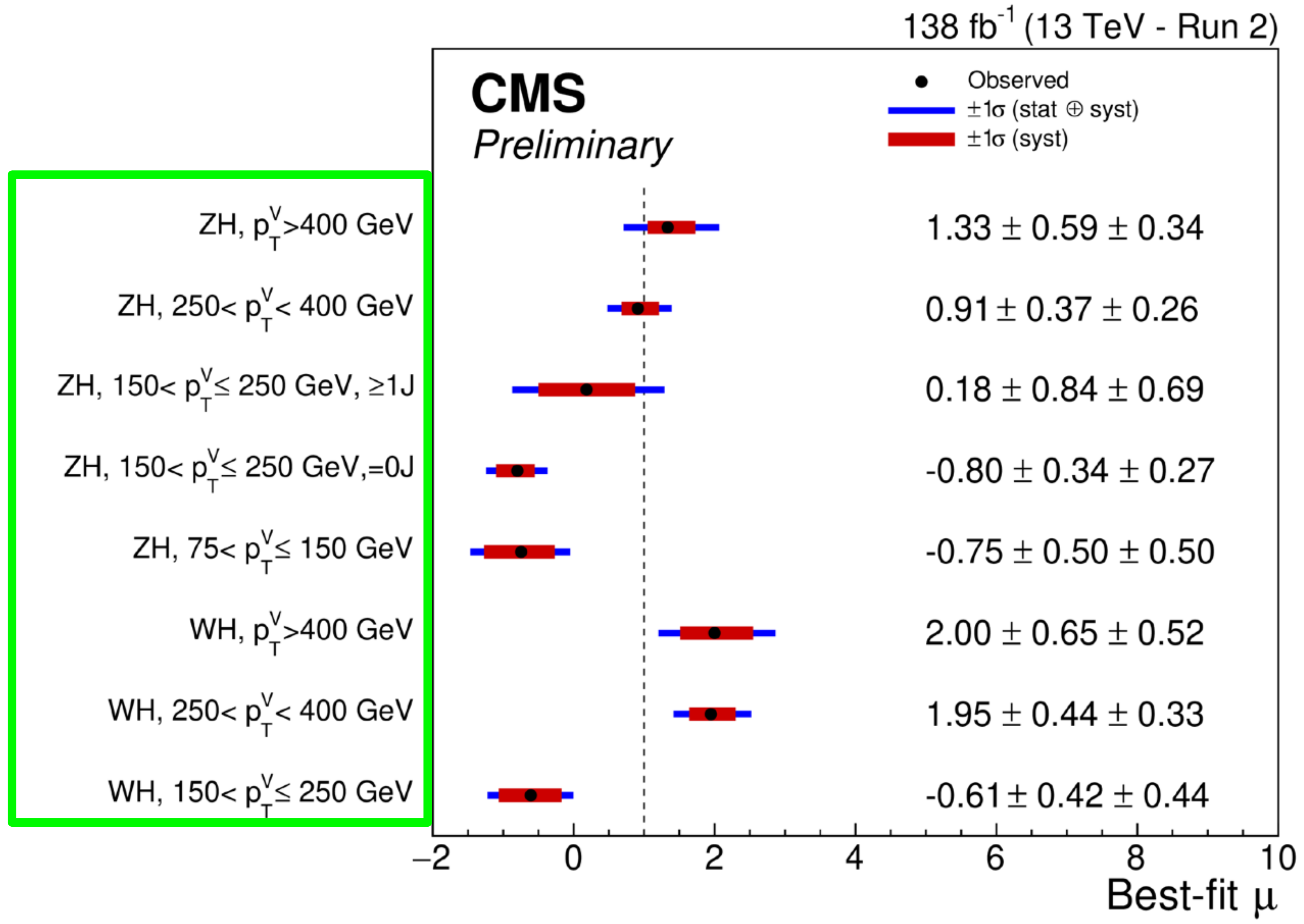
$H \rightarrow WW^* \rightarrow 2\ell 2\nu$

CMS-HIG-20-013
Accepted by EPJC

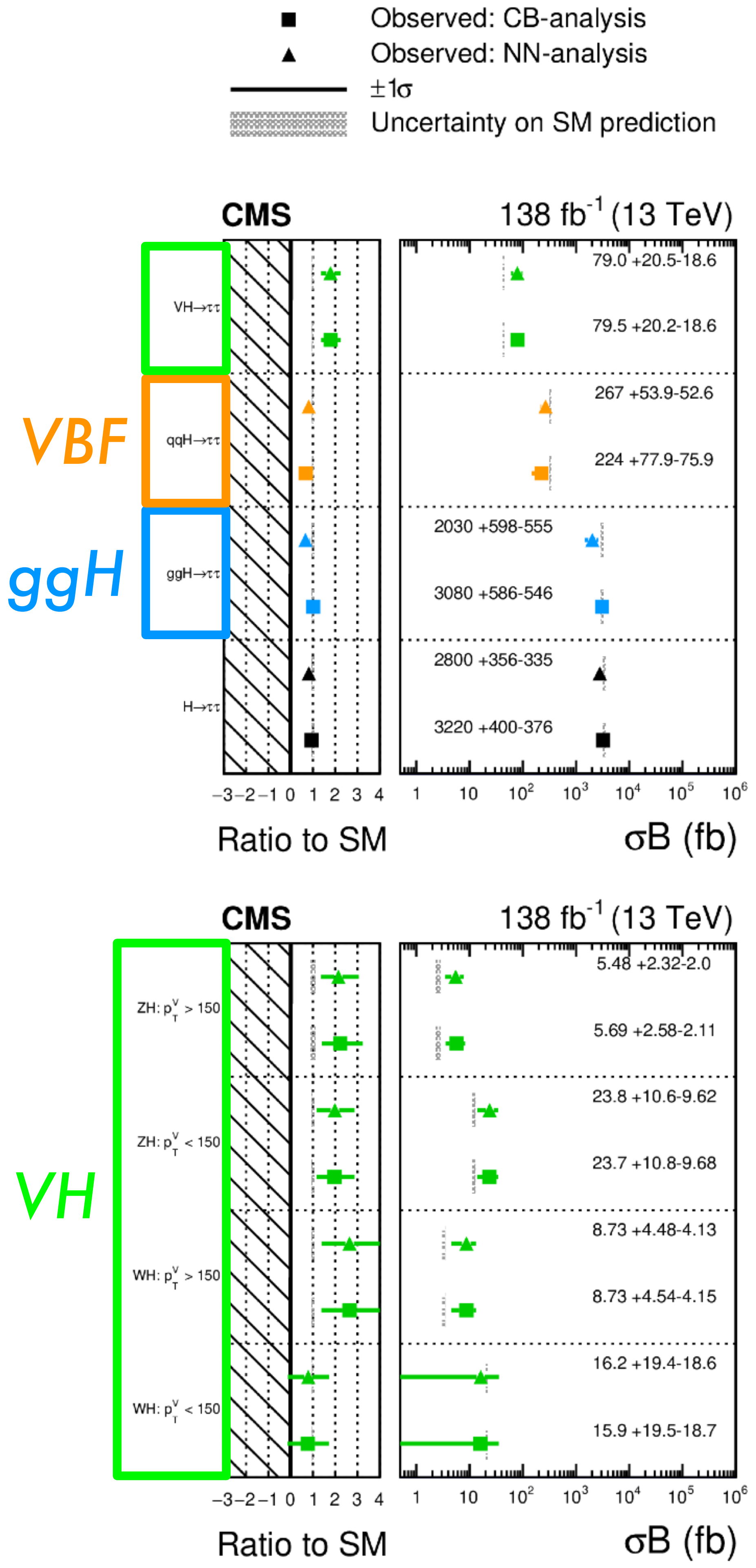


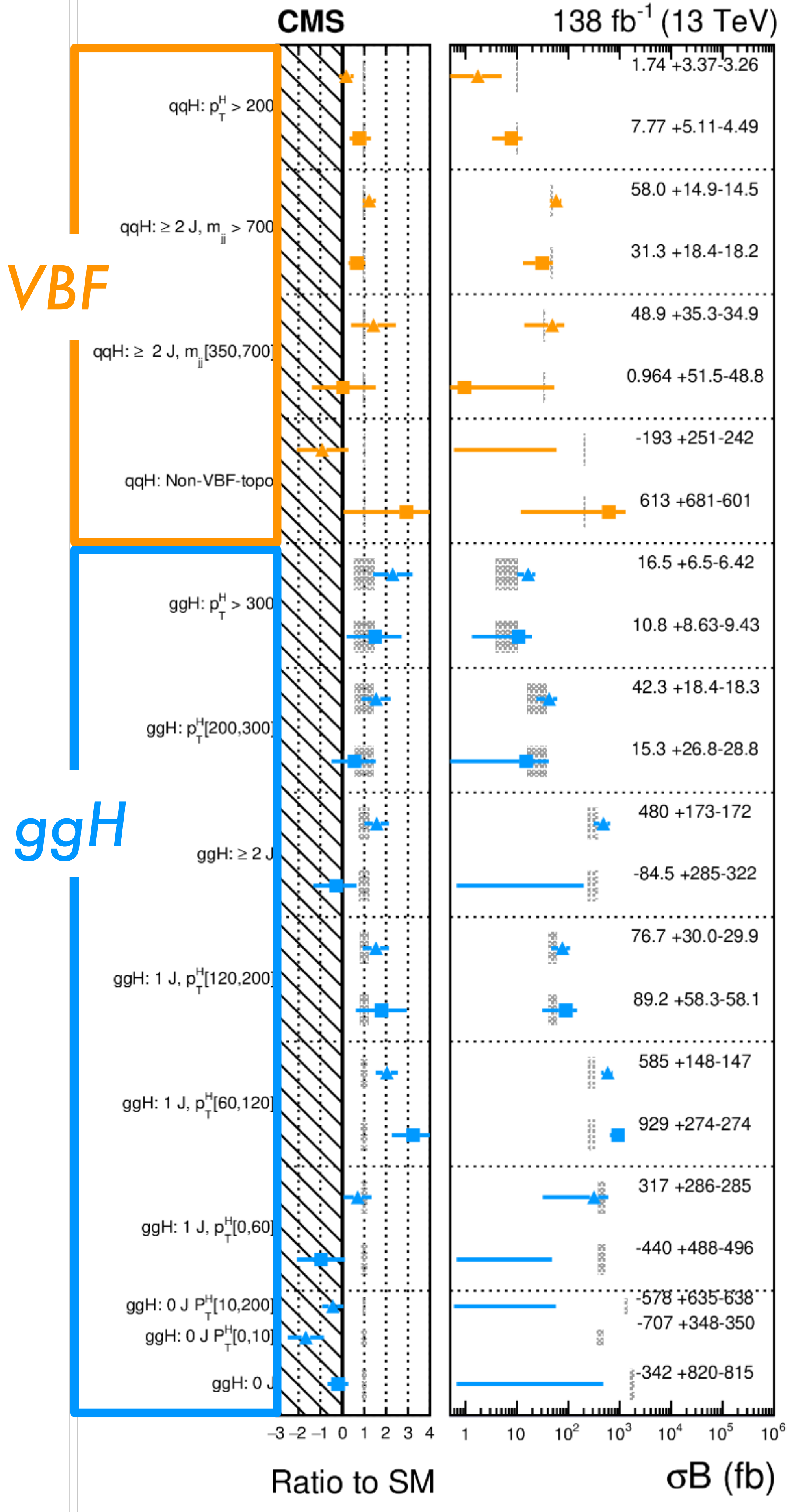
$H \rightarrow b\bar{b}$

CMS-PAS-HIG-20-001



$H \rightarrow 2\tau\tau$





CMS-HIG-19-010
Submitted to EPJC

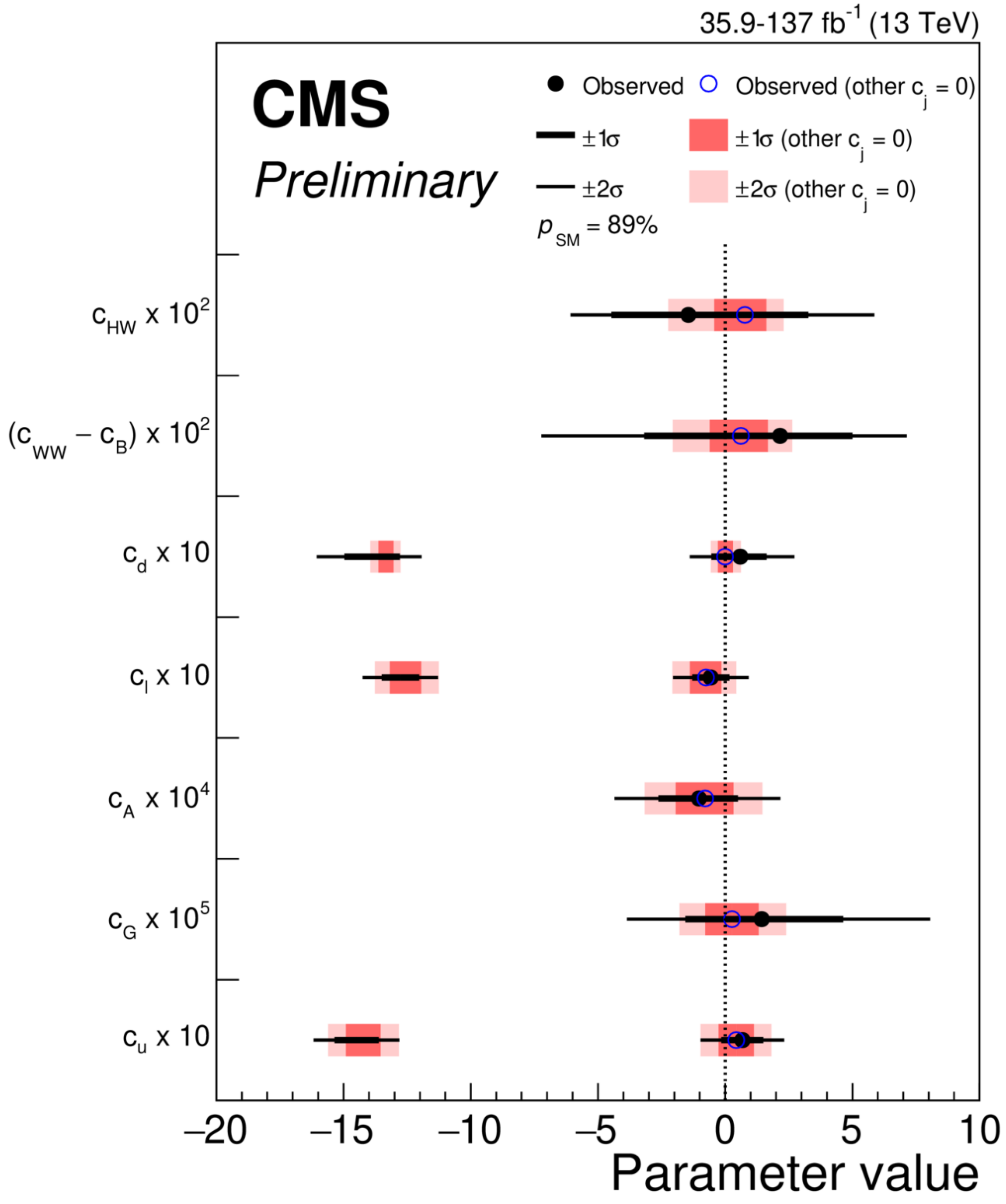
Effective Field Theories

HEL: **H**iggs **E**ffective **L**agrangian (*)

$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \mathcal{O}_j f_j/\Lambda^2$$

- flavour-independent **dim-6** operators $\mathcal{O}_j$
- Wilson coefficients f_j/Λ^2 (non-zero → NP)
- Λ = scale of physics beyond the SM (BSM)

Constraints obtained using parametrisation of the EFT variations in bins of the STXS, including
- all Higgs decay channels
- specific analyses targeting nth



CMS-PAS-HIG-19-005
(combination of modes)

HEL Parameters	Definition
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2}\frac{f_A}{\Lambda^2}$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2}\frac{f_G}{\Lambda^2}$
$c_u \times 10$	$c_u = -v^2\frac{f_u}{\Lambda^2}$
$c_d \times 10$	$c_d = -v^2\frac{f_d}{\Lambda^2}$
$c_\ell \times 10$	$c_\ell = -v^2\frac{f_\ell}{\Lambda^2}$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g}\frac{f_{HW}}{\Lambda^2}$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g}\frac{f_{WW}}{\Lambda^2}, c_B = \frac{2m_W^2}{g'}\frac{f_B}{\Lambda^2}$

Simultaneous maximum likelihood fit with 7 **HEL** parameters:
c_G, c_A, c_u, c_d, c_l, c_{HW}, $c_{WW} - c_B$

(*) see backup slides

CP Properties of Coupling to Vector Bosons

Study of CP structure of HVV

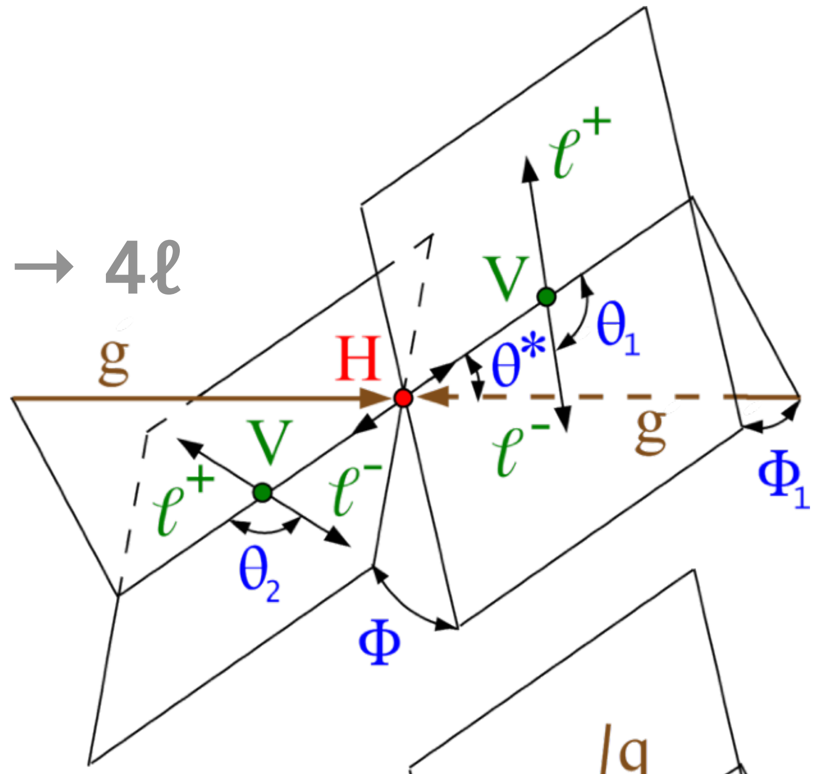
- $H \to ZZ^* \to 4\ell$
- VBF

Spin-parity 0^+ of the Higgs boson established with Run-1 data

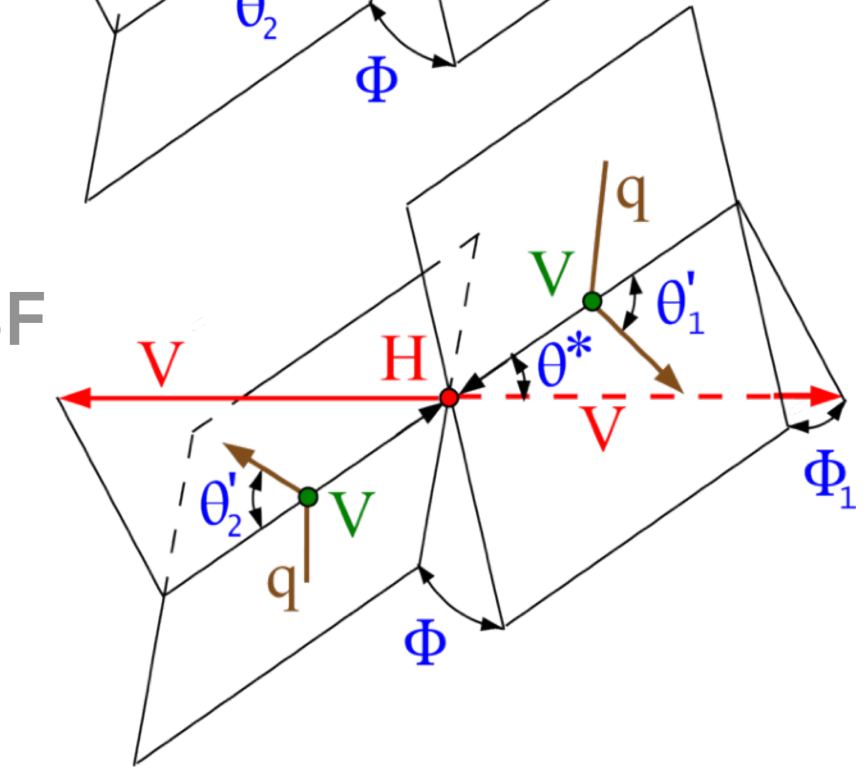
Run-1 7-8 TeV, 5-19.7 fb^{-1}

CMS-HIG-13-002
PRD 89 (2014) 092007

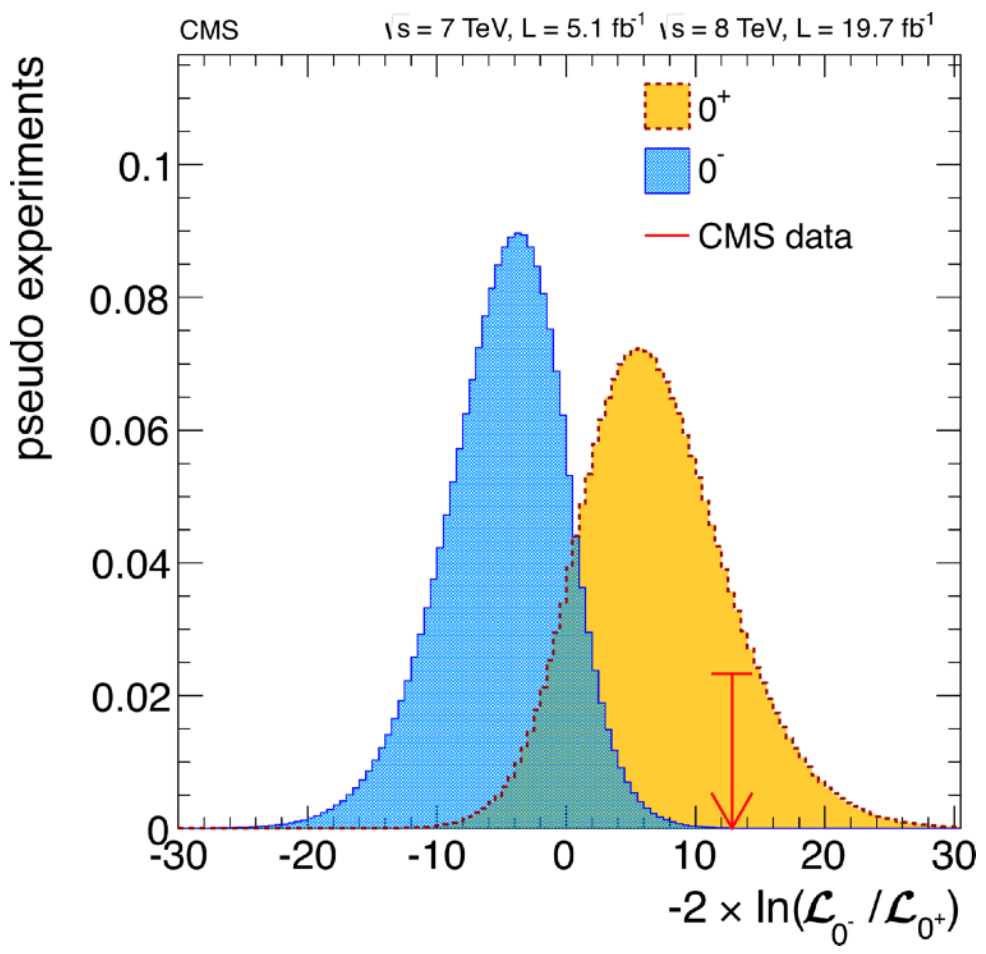
$H \to 4\ell$

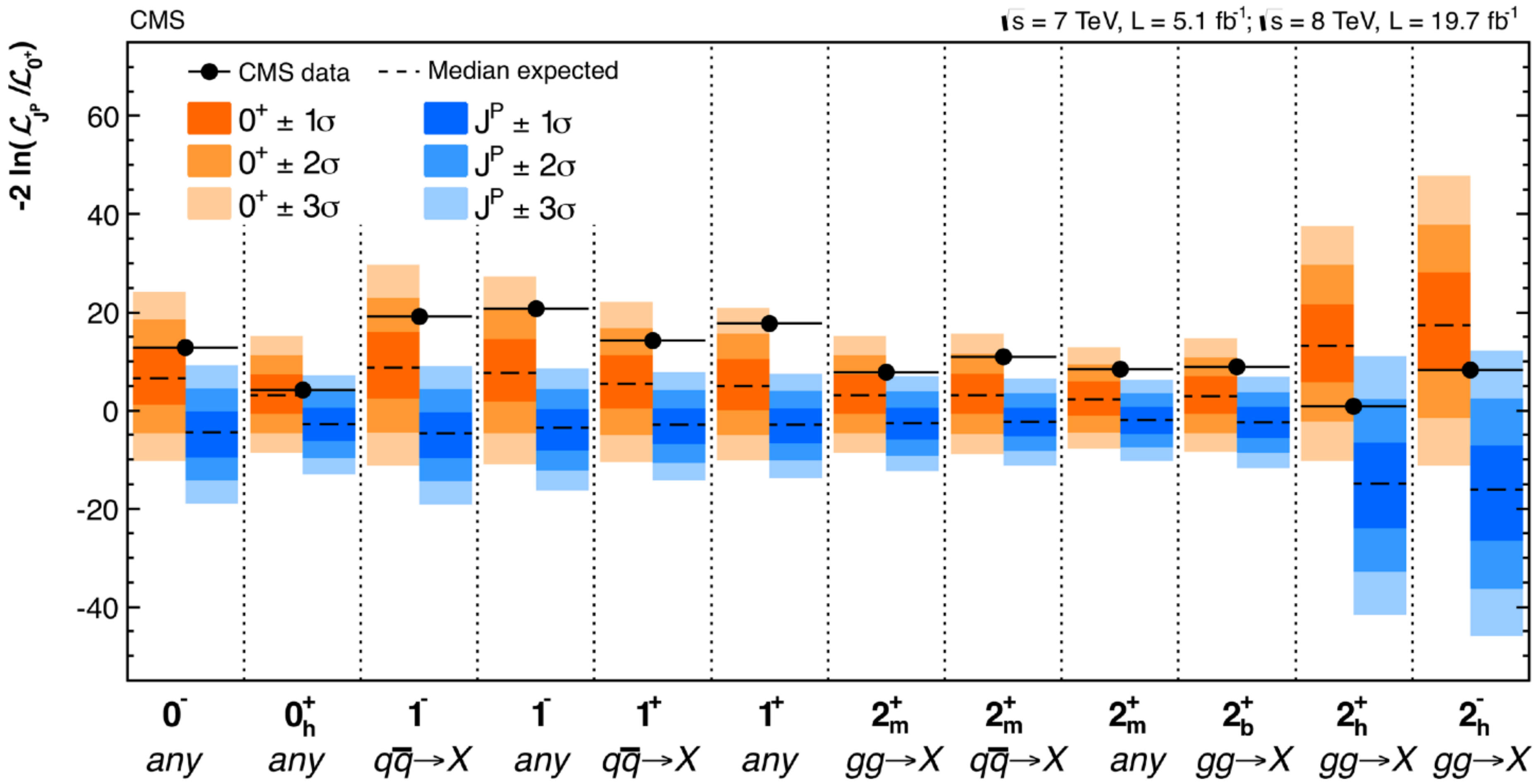


VBF



Production and decay angles sensitive to CP





$$\mathscr{A}(HVV) \simeq \left[a_1^{VV} + \frac{k_1^{VV} q_1^2 + k_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV} (q_1+q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_V^2 \varepsilon_{V1}^* \varepsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

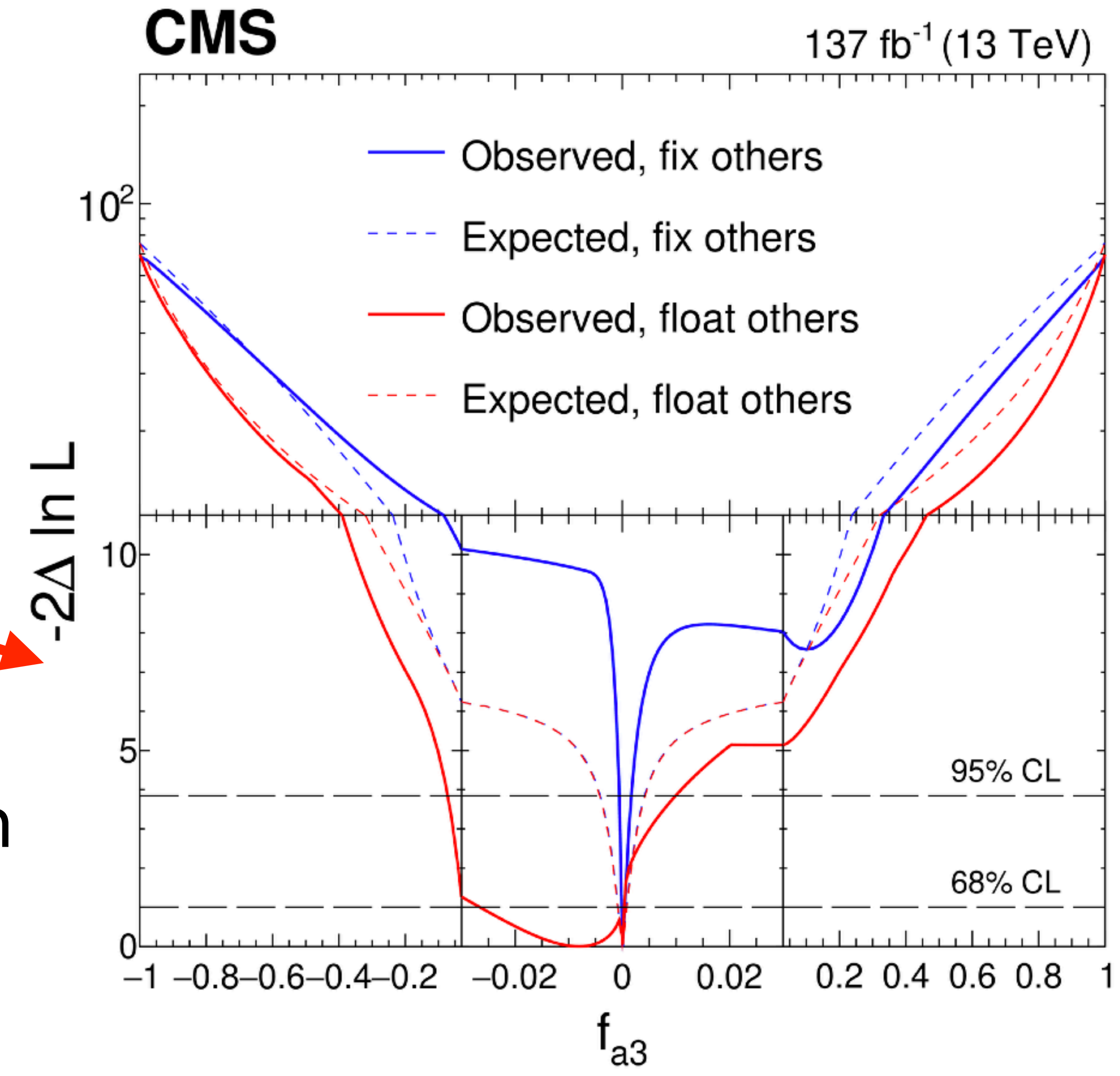
anomalous CP-even

anomalous CP-even

CMS-HIG-19-009
PRD 104 (2021) 052004

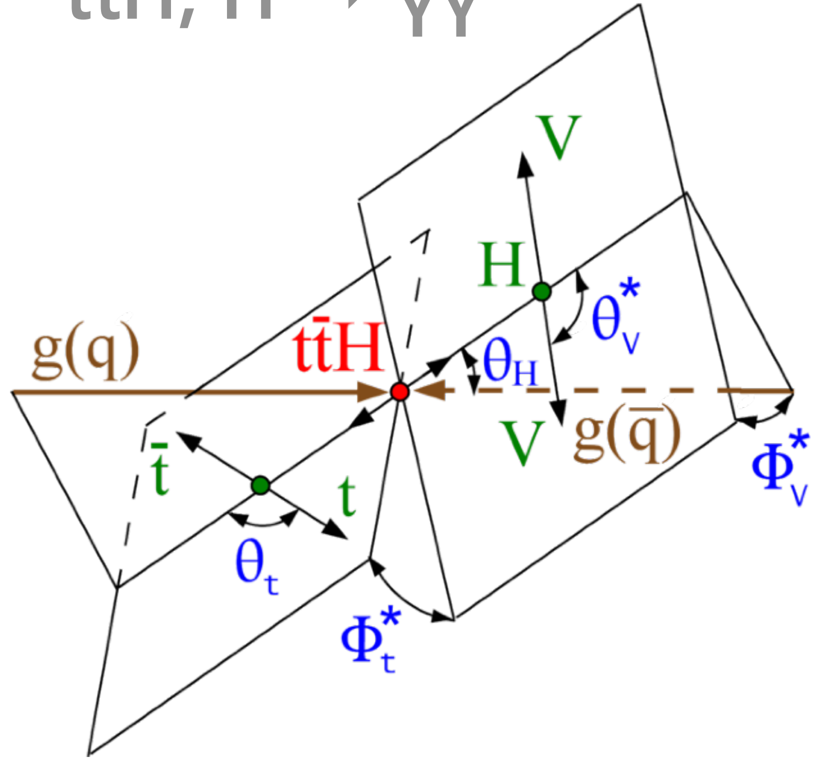
Run-2, 13 TeV, 137 fb^{-1}

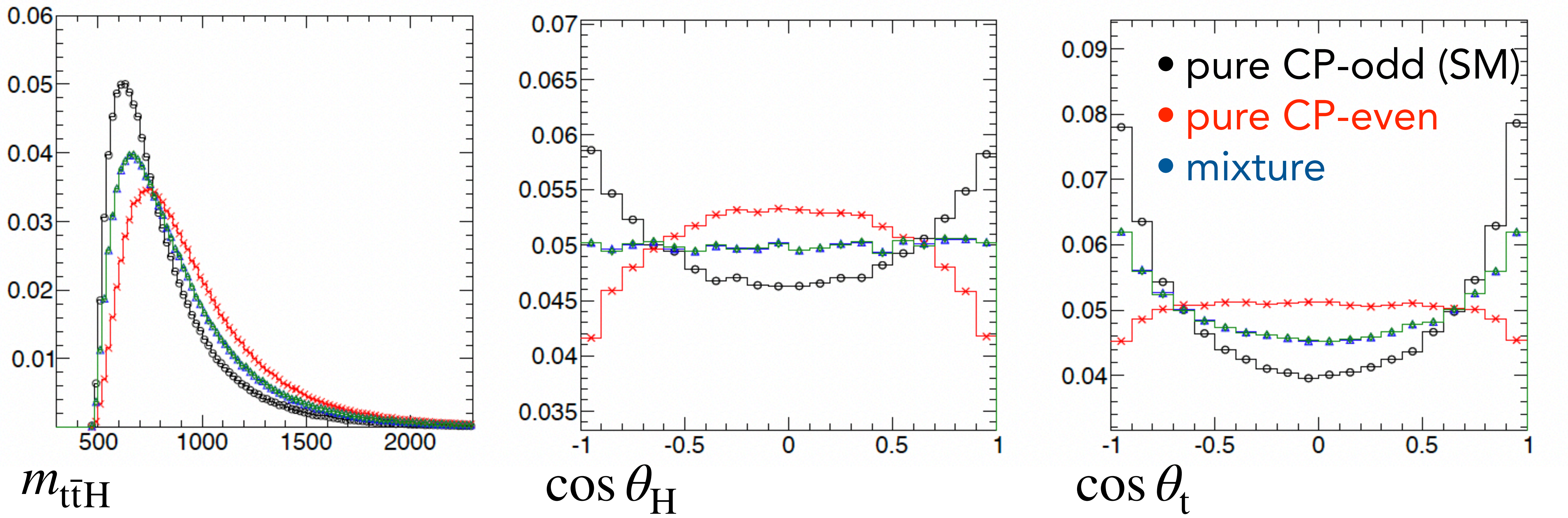
Higgs coupling to vector boson consistent with pure CP-even



CP Properties of top Yukawa

ttH, H → γγ





CP structure of the Htt amplitude:

$$\mathcal{A}(Ht\bar{t}) = -\frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\tilde{\kappa}_t\gamma_5)\psi_t$$

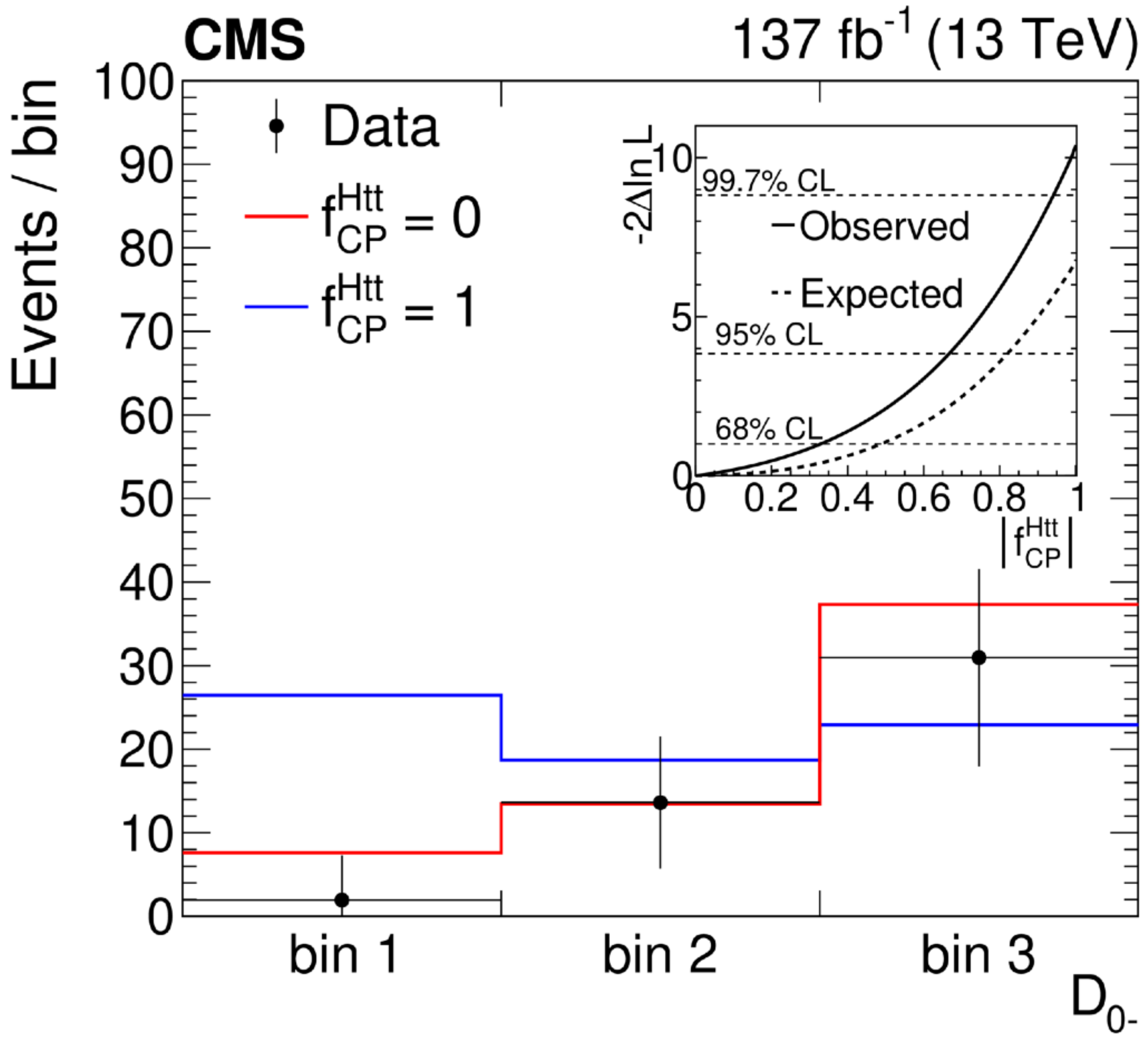
$$f_{CP}^{Ht\bar{t}} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\kappa_t\tilde{\kappa}_t)$$

[CMS-HIG-19-013](#)
[*PRL 125 (2020) 061801*](#)

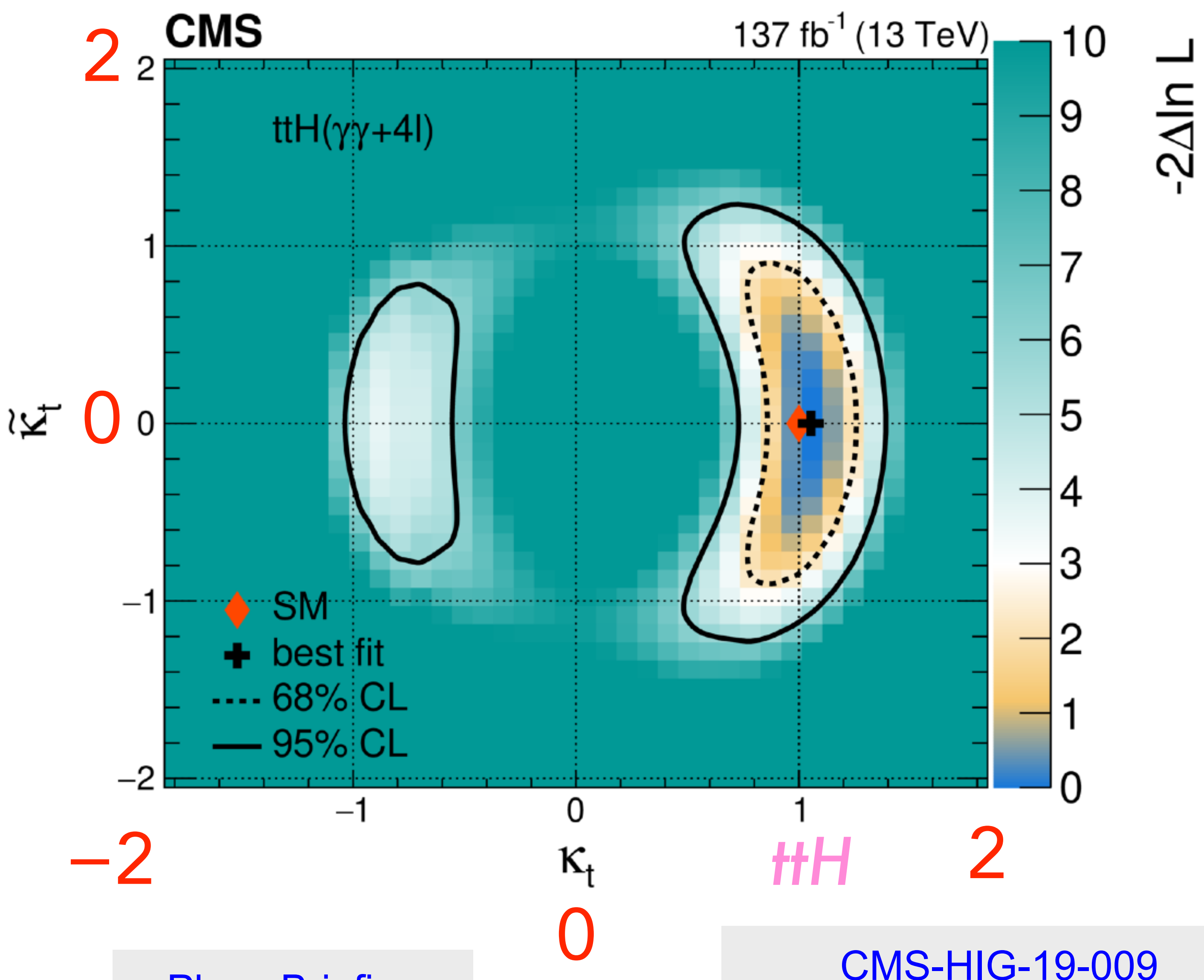
ttH (H → γγ) (6.6σ)

- categories optimised for best CP sensitivity
- 3 bins in D_{0-} score (BDT trained with CP-odd and CP-even samples (JHU)

  - $f_{CP}^{Ht\bar{t}} = 0.00 \pm 0.33$ @68 % CL
  - pure CP-odd hypothesis excluded at 3.2σ (2.5σ exp.)



combining $H \to 4\ell$ and $H \to \gamma\gamma$



[Phys. Briefing](#)

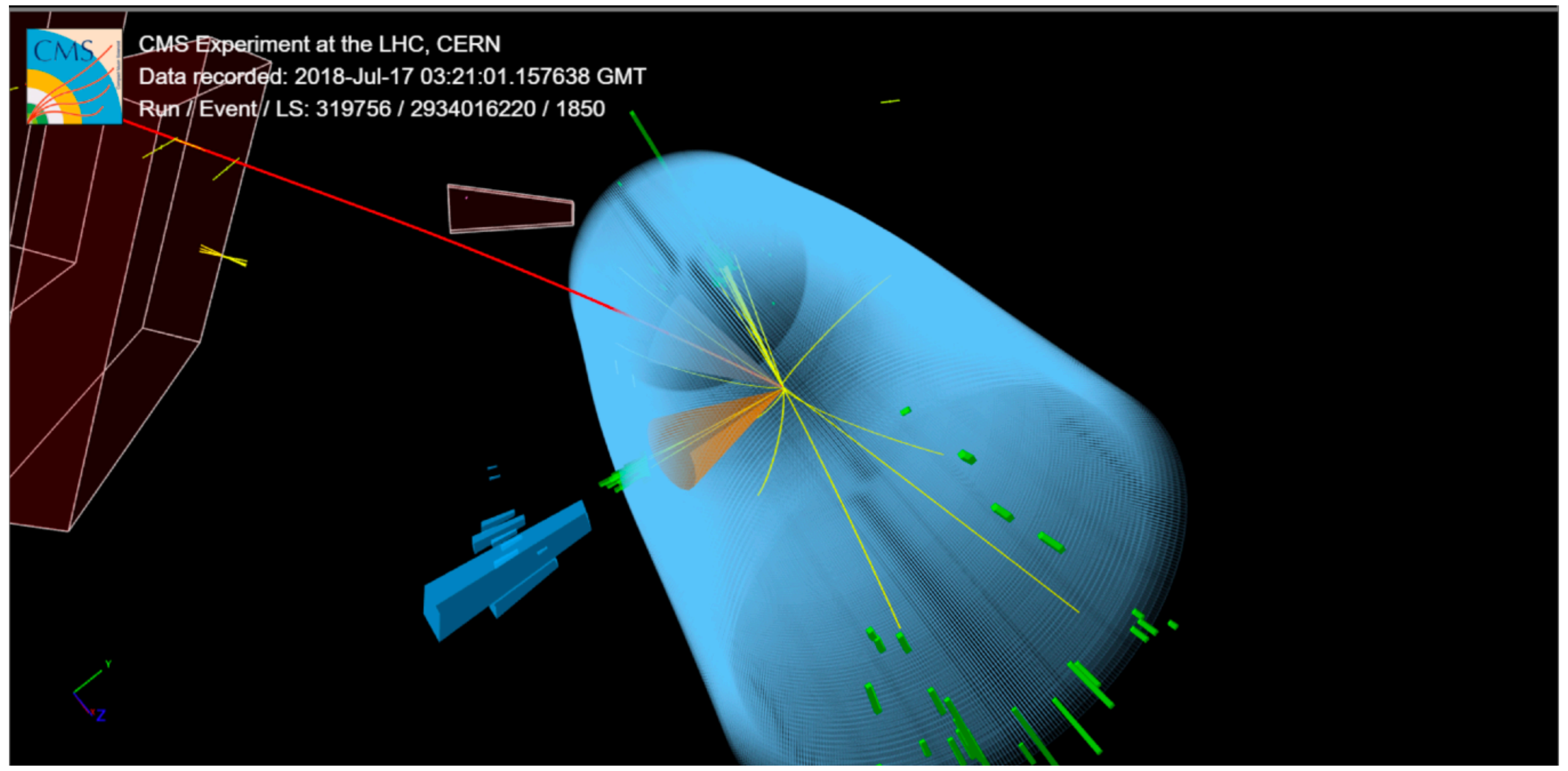
[CMS-HIG-19-009](#)
[*PRD 104 (2021) 052004*](#)

CP Properties of the $H \rightarrow \tau\tau$ Decay

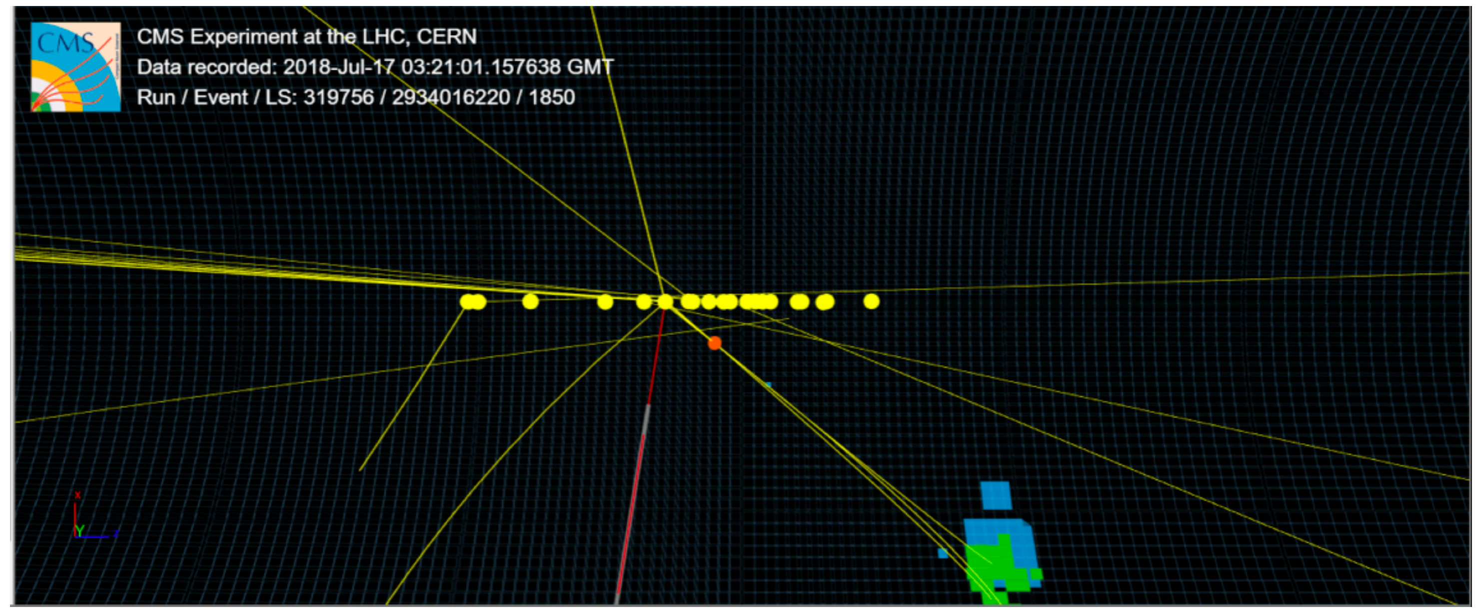
ϕ_{CP} : a variable sensitive to the **polarisation of the τ leptons**

- angle between the τ decay planes in the H rest frame
- 0° in the CP-even case (SM) vs ±90° in the CP-odd case
- measured using either the 1-prong momentum and impact parameter vector, the $\pi^0(\rightarrow\gamma\gamma)$ momentum or $\rho^0(\rightarrow\pi^+\pi^-)$ momentum (3-prong)

An example $\tau^+(\rightarrow \mu^+\nu\nu)\ \tau^-(\rightarrow \pi^+\pi^-\pi^-\nu)$ candidate



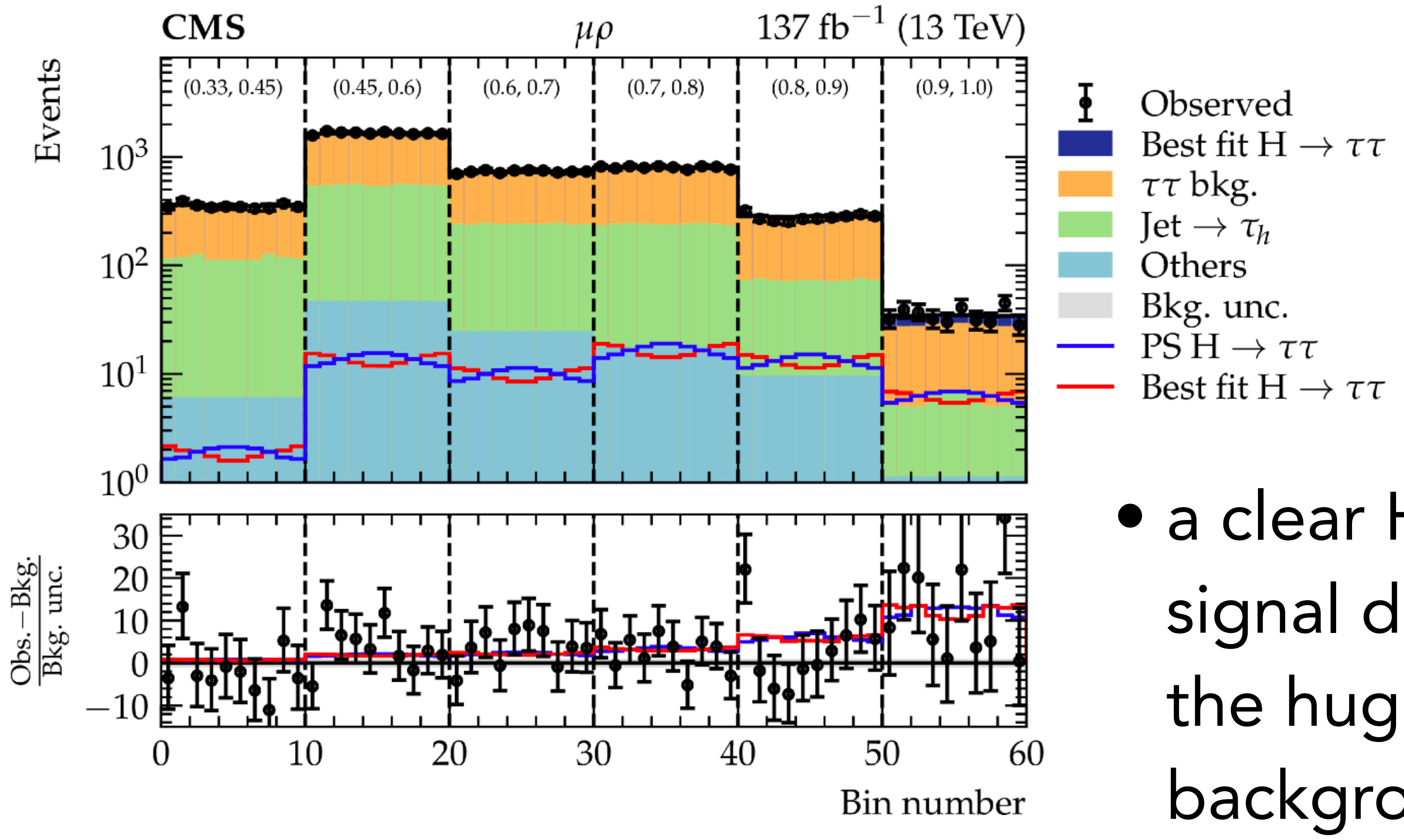
Zoom on the interaction region: impact parameter and secondary vertex



CMS-HIG-20-006
JHEP 06 (2022) 012

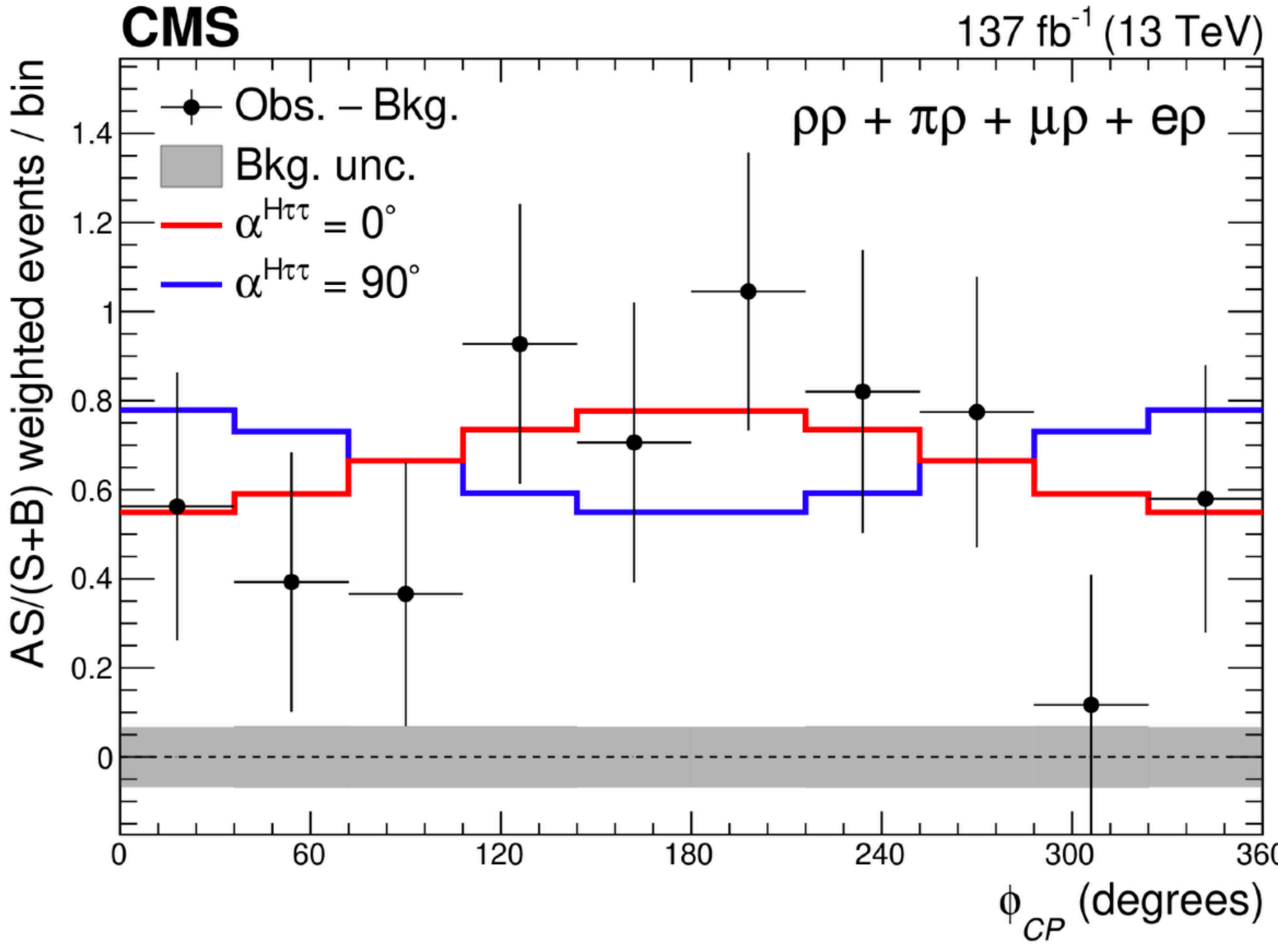
Full Run-2, 137 fb^{-1}

ϕ_{CP} distribution considered in different bins of a BDT score



- a clear H→ττ signal despite the huge Z→ττ background

Overall weighted distribution



$\phi_{CP} = 4^\circ \pm 17^\circ$

- **CP-even** preferred to CP-odd at the ~3σ level!

Direct Searches for Invisible Higgs

Higgs as a **portal to new physics?** $H \to \chi\bar{\chi}$

From global fit : $\mathscr{B}(H \to \text{invisible}) = 7 \pm 5\,\%$

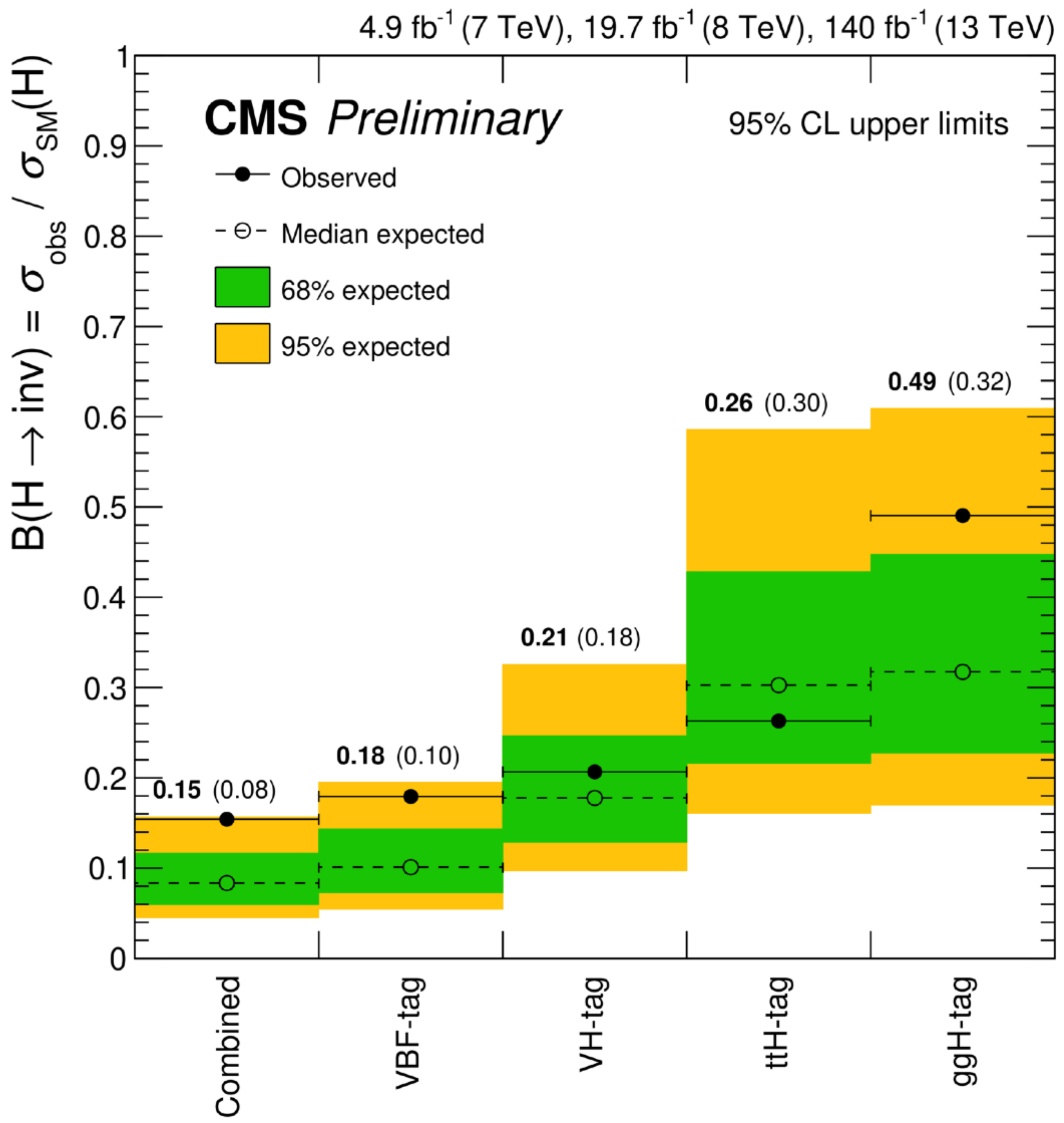
Considered topologies

- monojet (ISR gluon)
- VH hadronic, resolved or not
- ZH leptonic
- VBF
- ttH

Main backgrounds

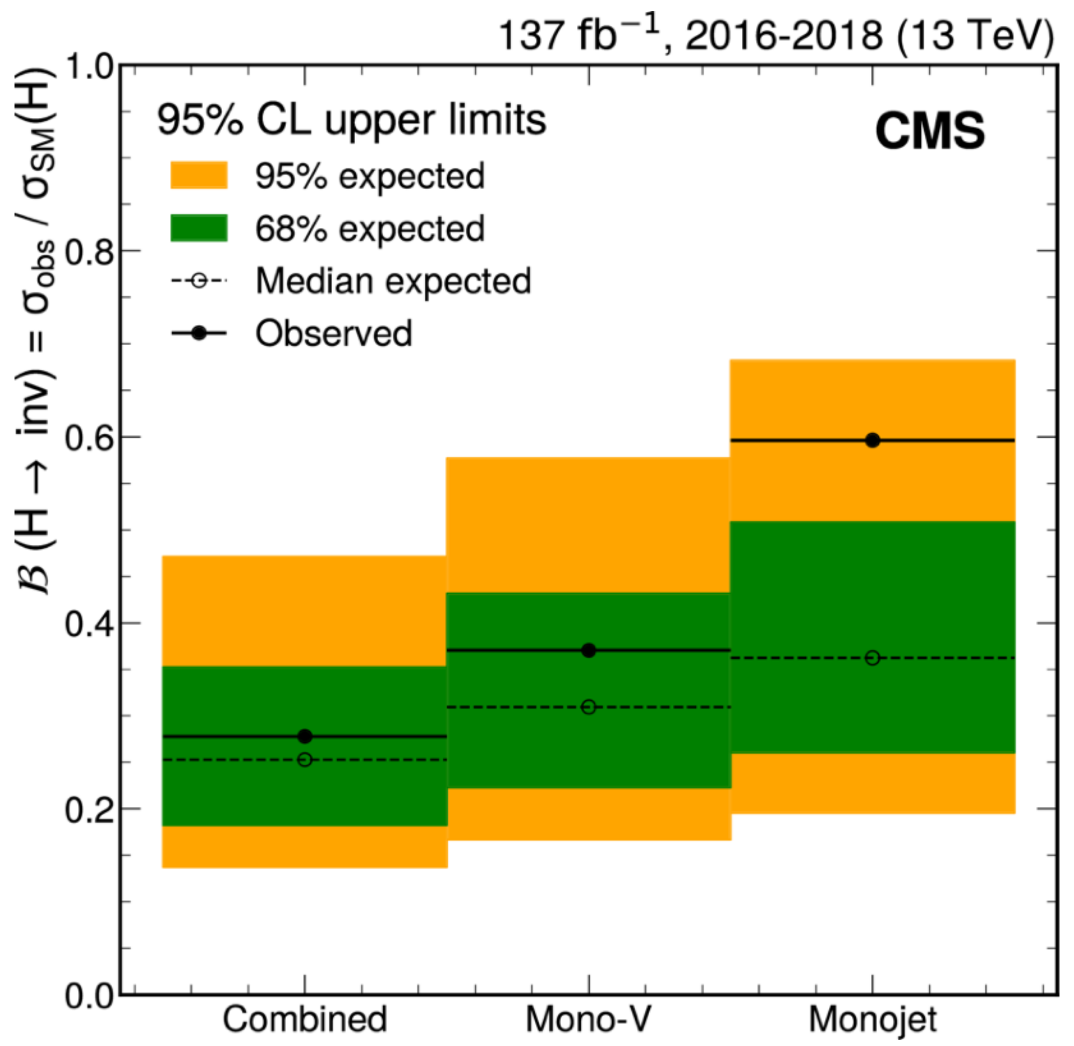
- $Z \to \nu\bar{\nu}$
- W + jets with "lost" lepton
- QCD multijet

CMS-PAS-HIG-21-007



Combination of direct limits

$\mathscr{B}(H \to \text{invisible}) < 15\,(8)\,\%$ @ $95\,\%$ CL



CMS-EXO-20-004
JHEP 11 (2021) 153

Monojet et Mono-V:

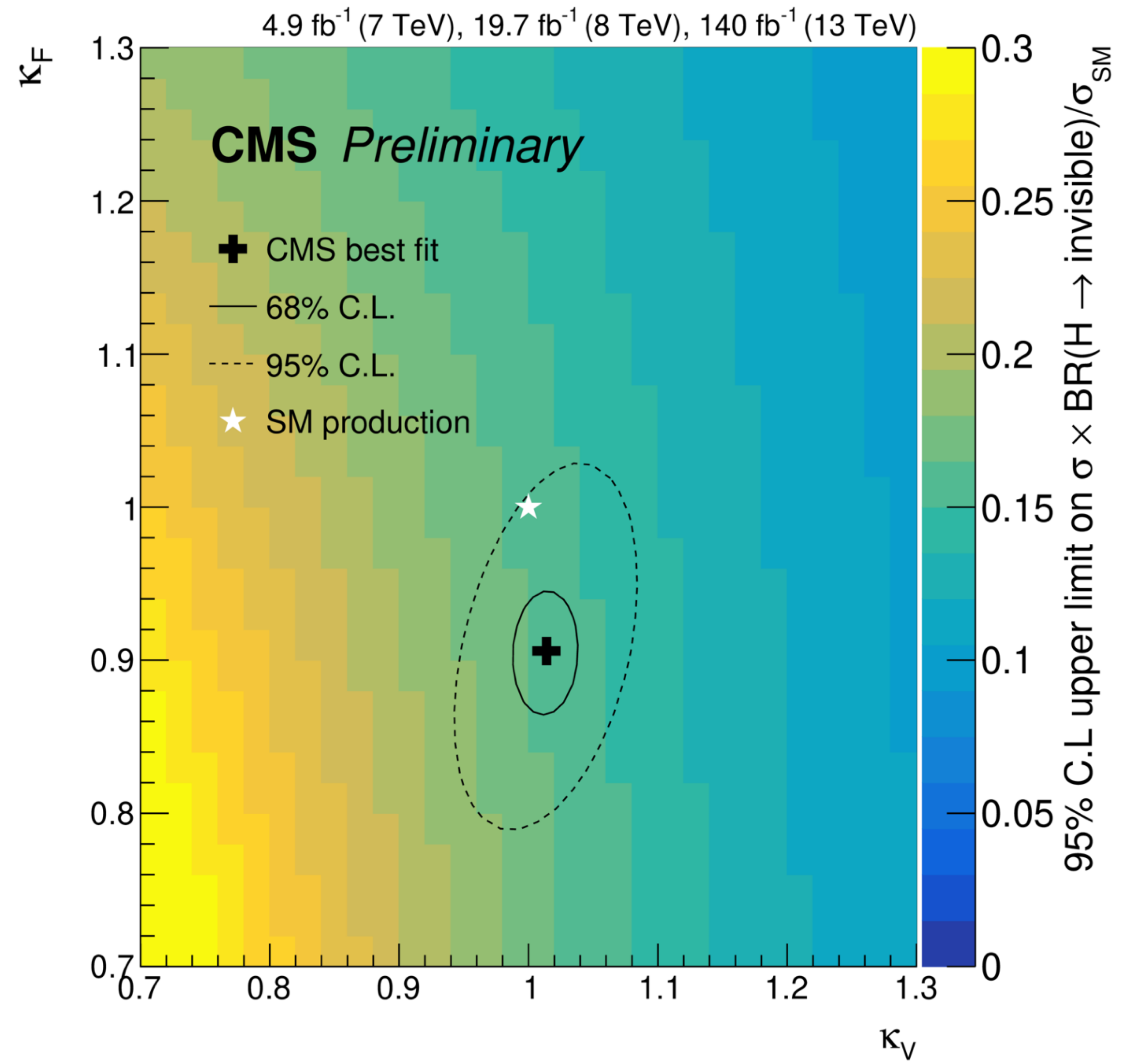
$\mathscr{B}(H \to \text{invisible}) < 28\,(25)\,\%$ @ $95\,\%$ CL

CMS-HIG-20-003
PRD 105 (2022) 092007

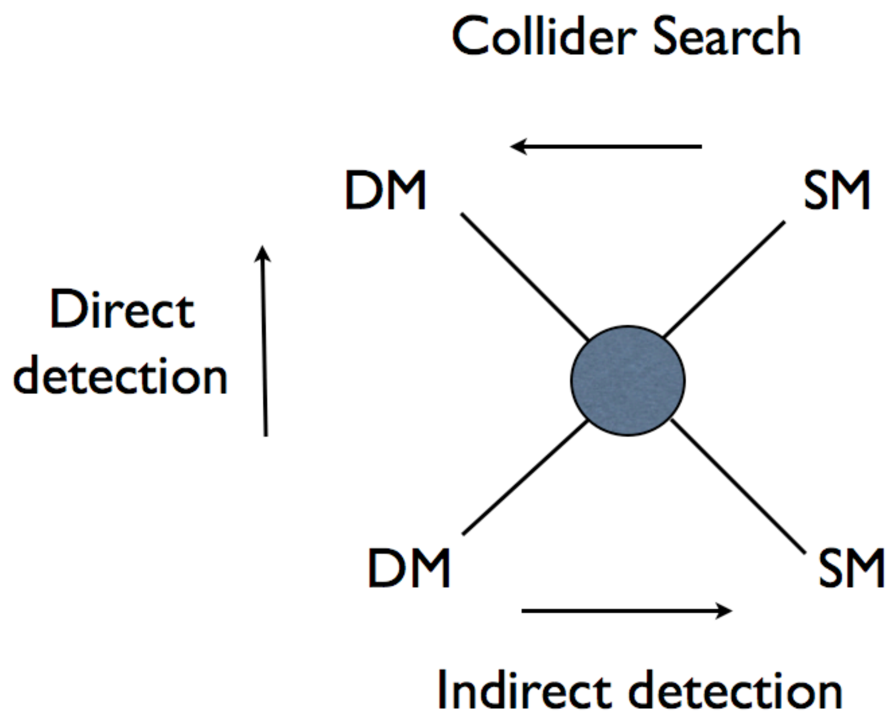
VBF:

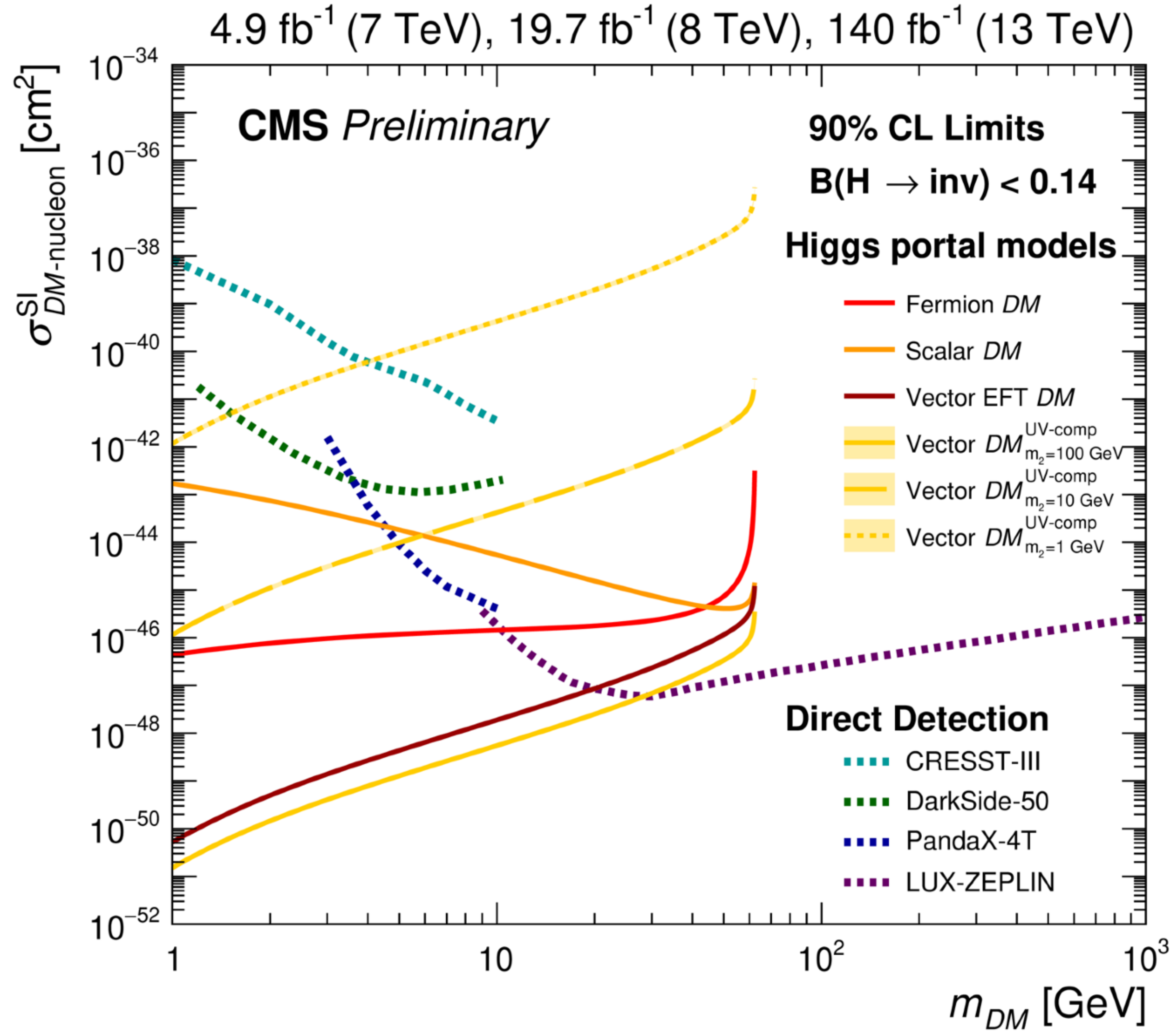
$\mathscr{B}(H \to \text{invisible}) < 18\,(10)\,\%$ @ $95\,\%$ CL

Constraints on Dark Matter



Observed limit as a function of κ_F and κ_V in the “global-fit 95%CL ellipse”, the limit ranges between 14% and 17%





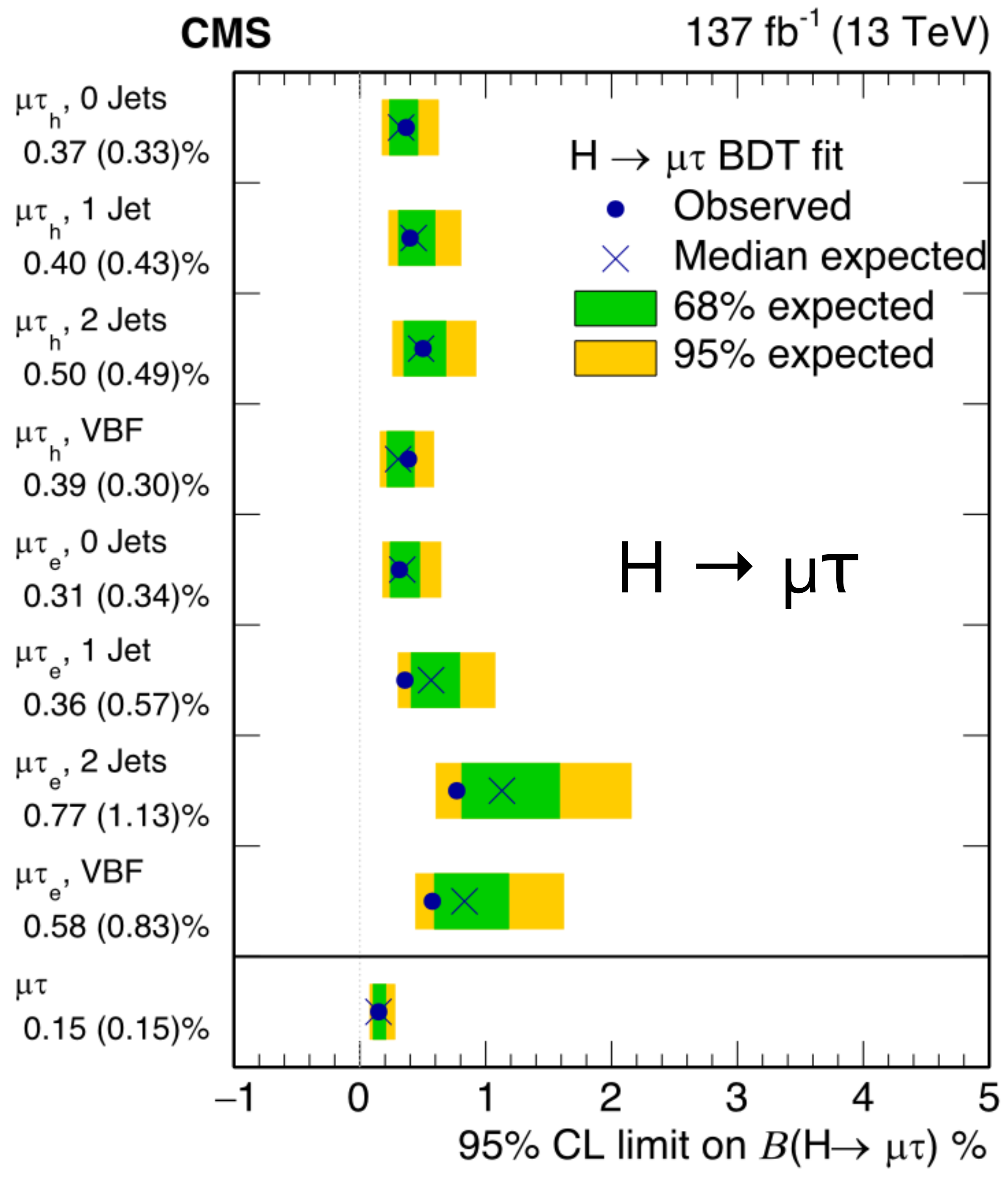
Interpretations in the framework of **Higgs portal models of Dark Matter**

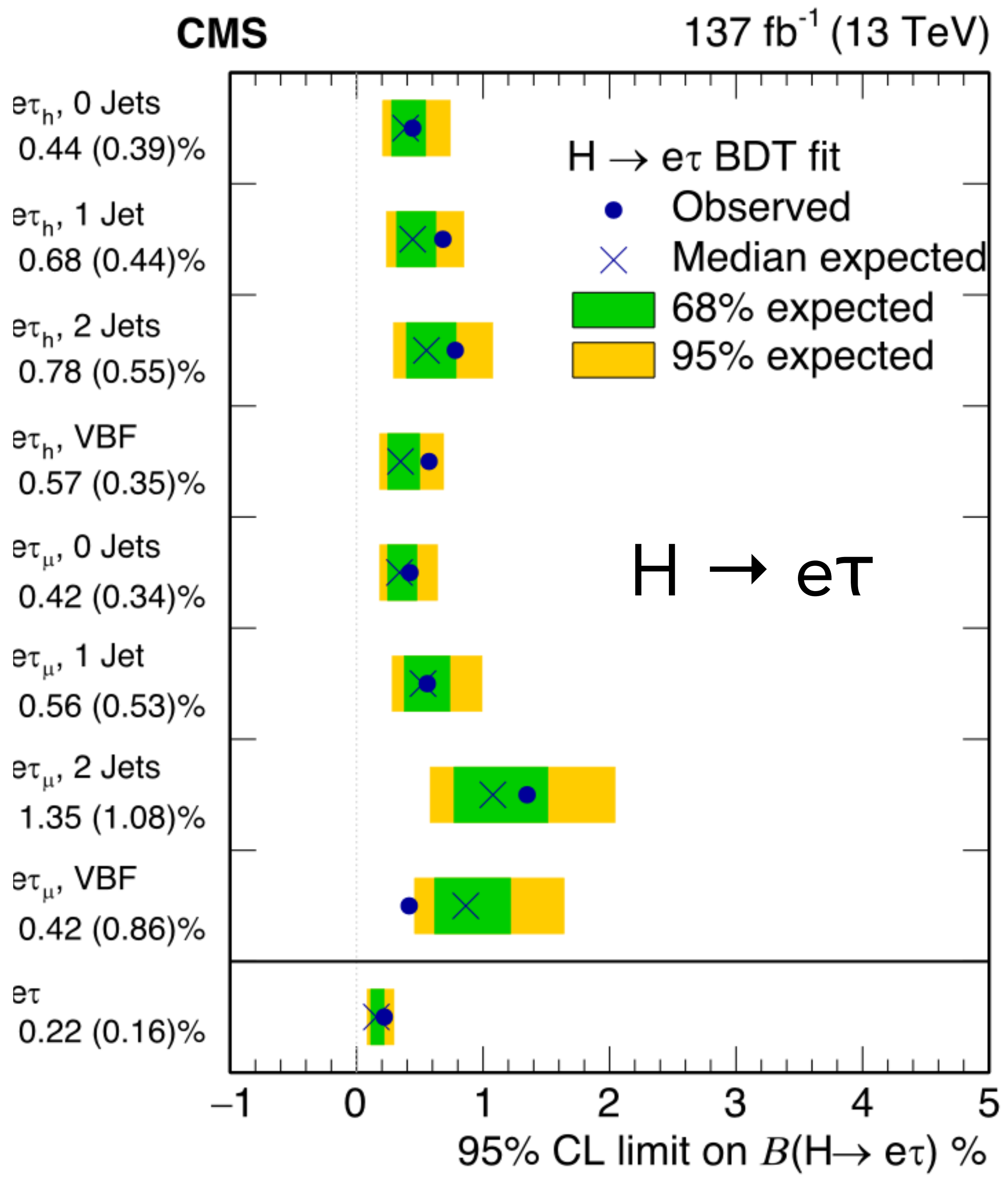
Complementary at low mass with limits from direct detection experiments

See presentations by **Thomas Biekoetter**

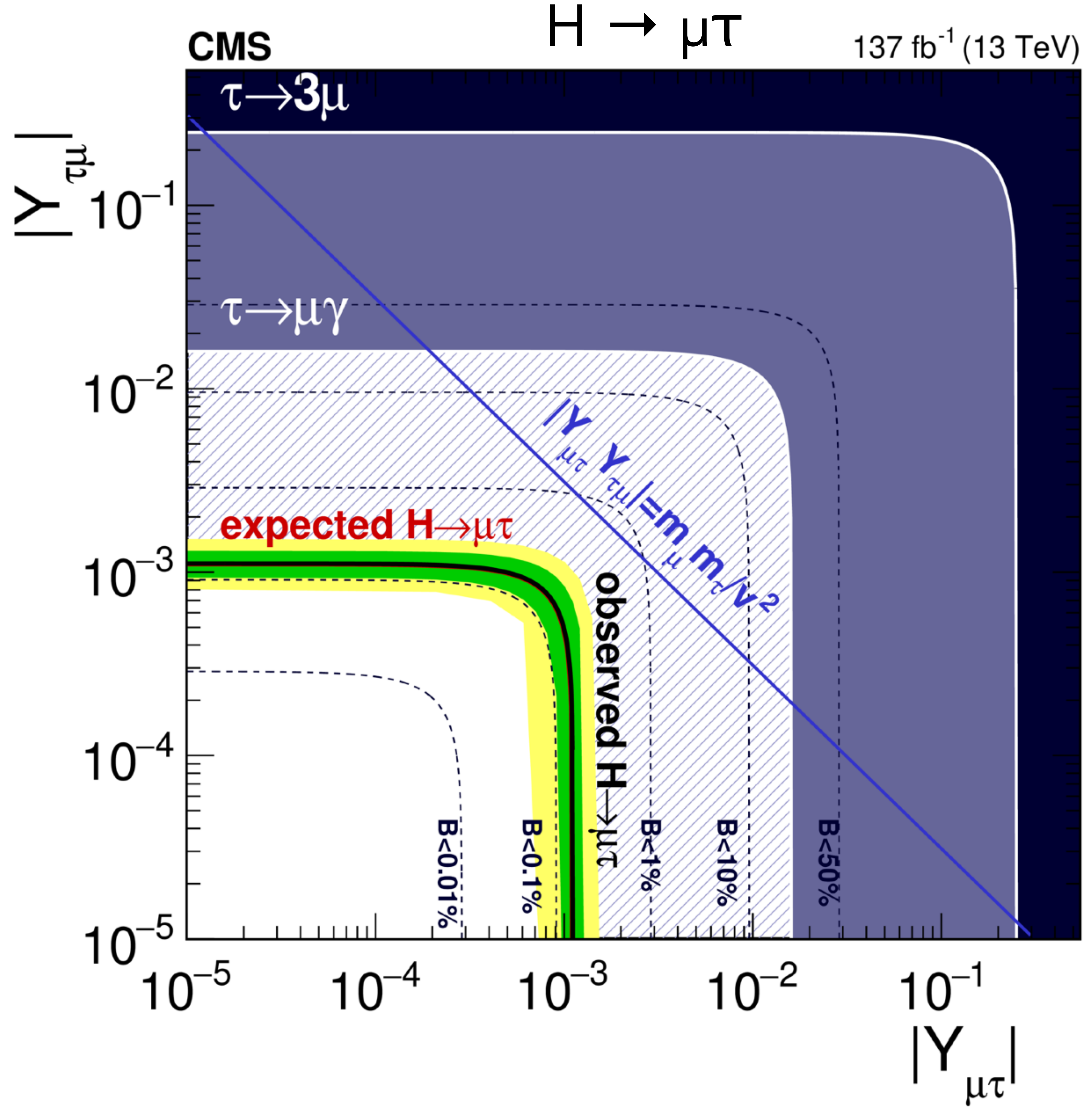
Search for Lepton Violating Decays

CMS-HIG-20-009
PRD 104 (2021) 032013





$$\mathscr{B}(\mathrm{H} \to e\tau) < 0.22\,\%$$
$$\mathscr{B}(\mathrm{H} \to \mu\tau) < 0.15\,\%$$



Lepton flavour violating Yukawa couplings constrained typically to below 10^{-3}

Limits are competitive with other searches, such as $\tau \to 3\mu$ and $\tau \to \mu\gamma$

Search for Additional Higgs Bosons

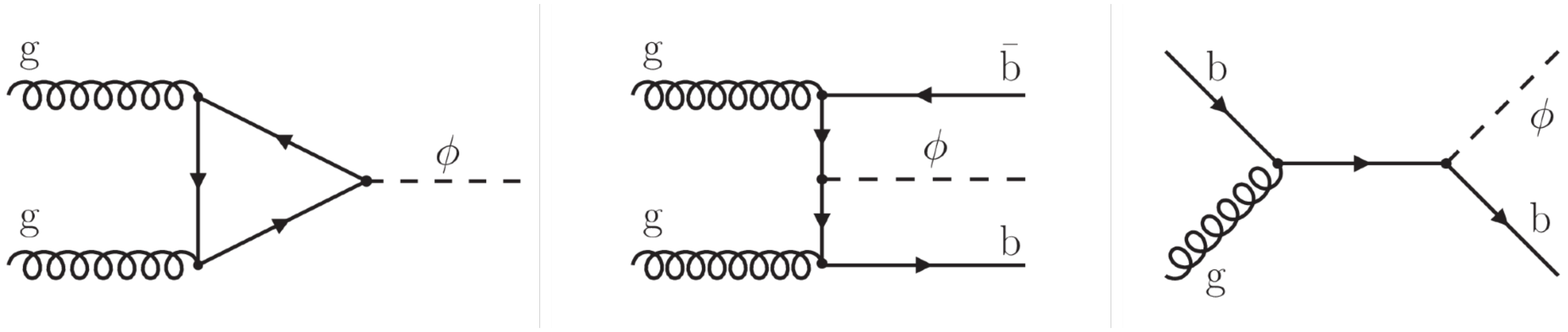
CMS-HIG-21-001
Submitted to JHEP

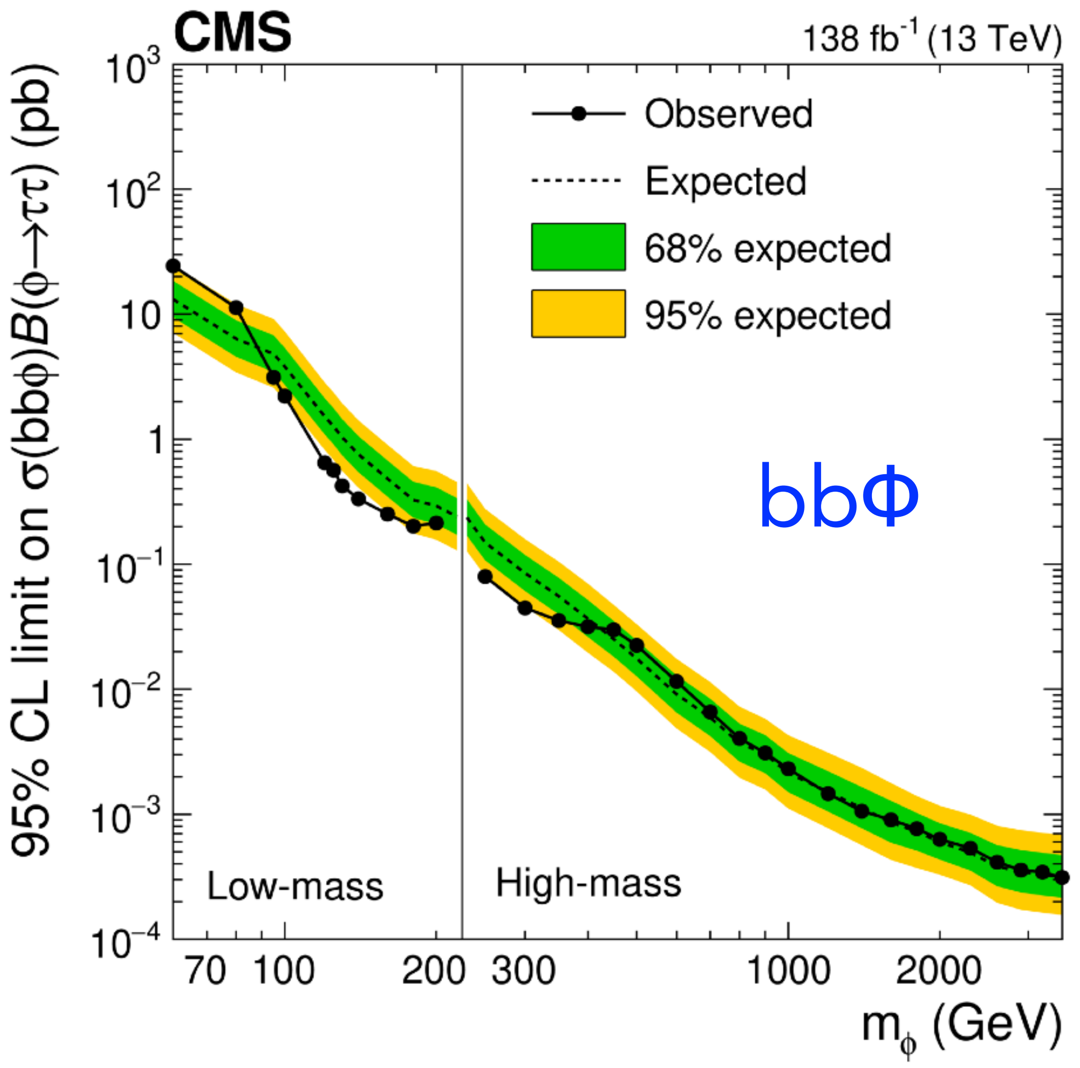
Most of the extensions of the Higgs sector compatible with data predicts the existence of multiple scalars mixing together

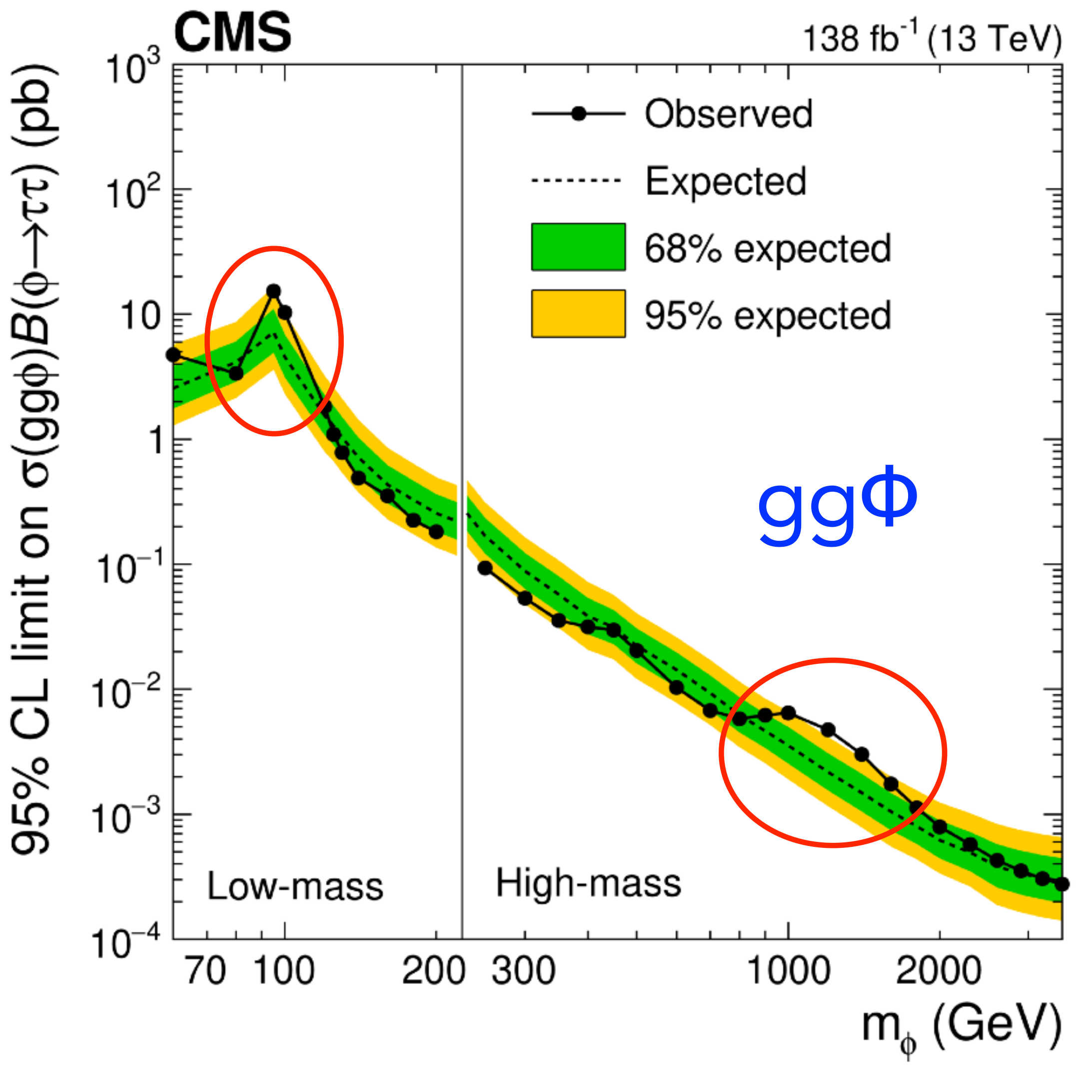
- deviations on H(125) couplings, BSM decays
- **additional scalars**

Searches for physics beyond the SM (BSM) in ττ final states

classified in number of b jets

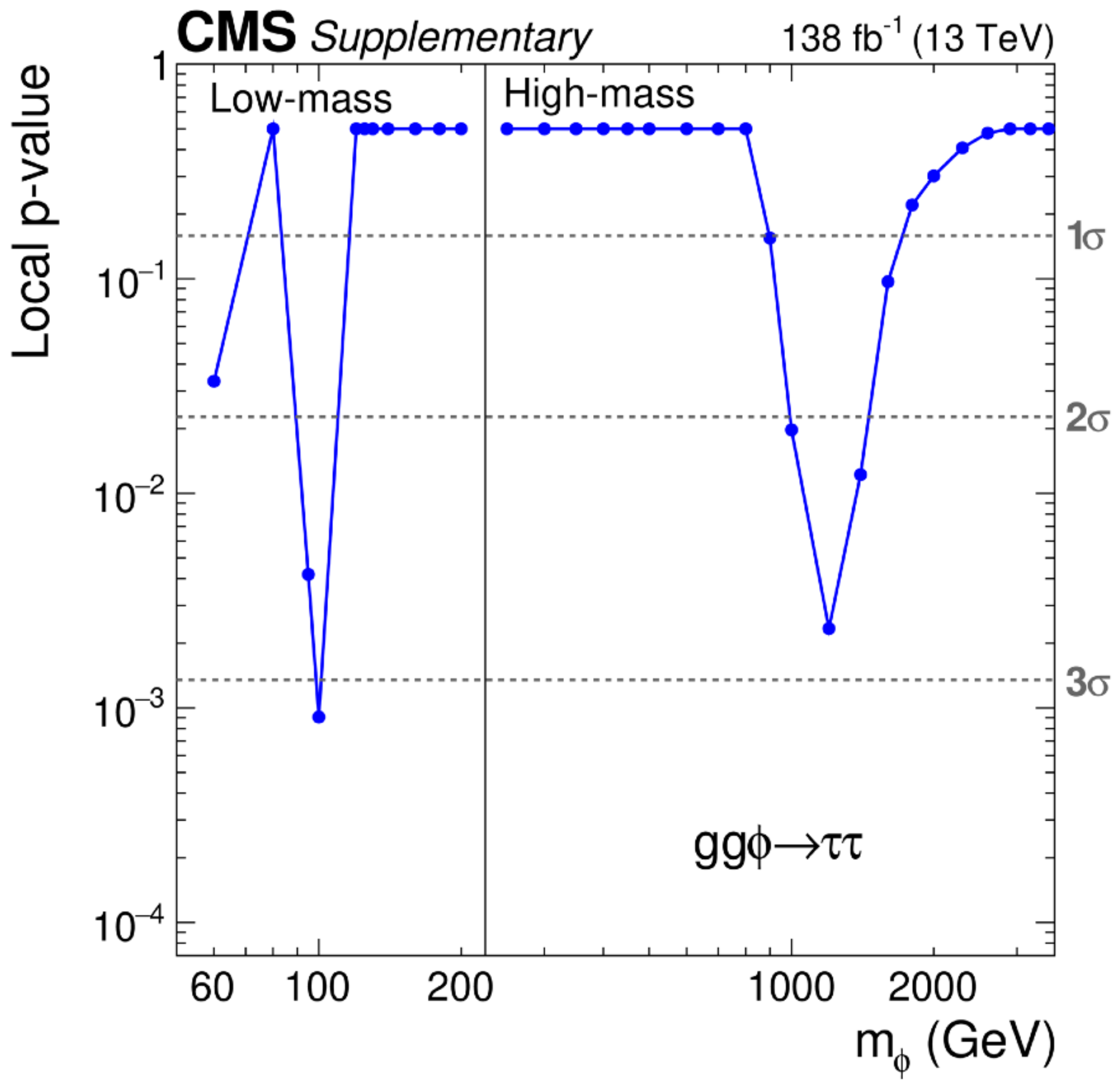






- model-independent limits at low and high mass
- model-dependent limits for MSSM benchmarks:
  additional scalars excluded below 350 GeV

two 3σ (local) excesses for ggΦ around **100 GeV** and **1.2 TeV**



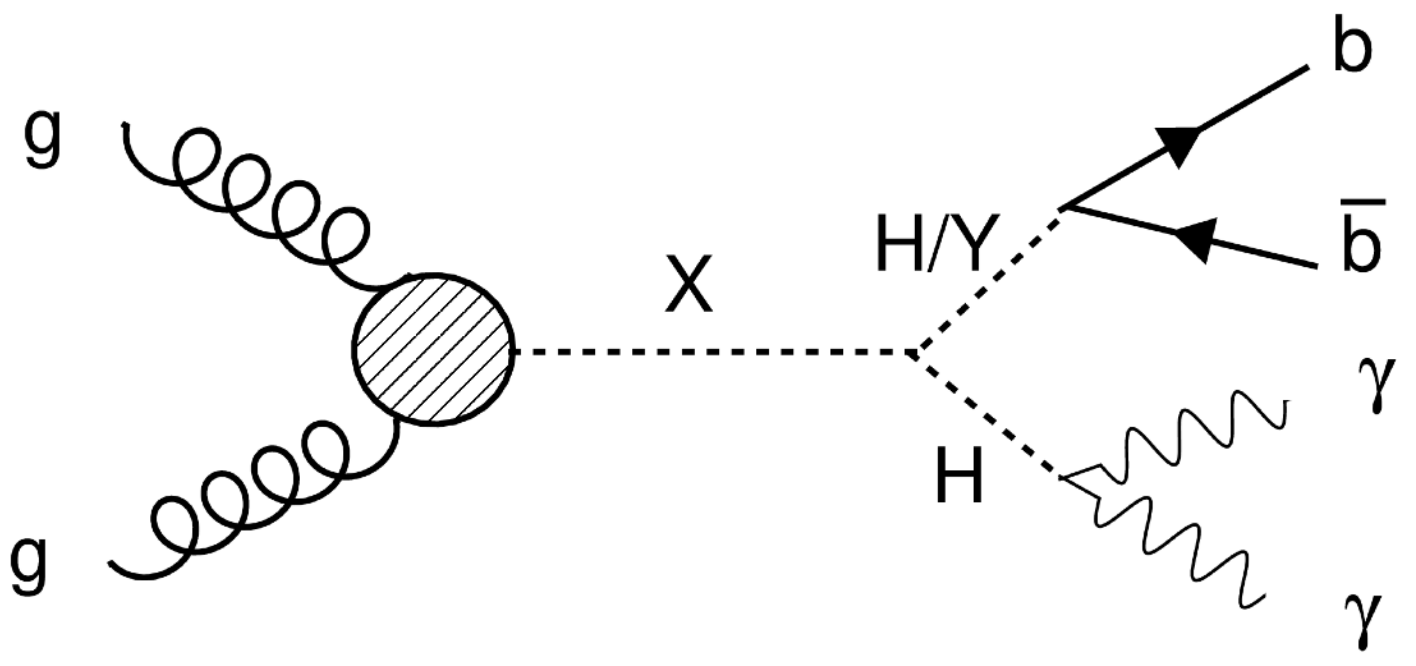
Searches for X → YH

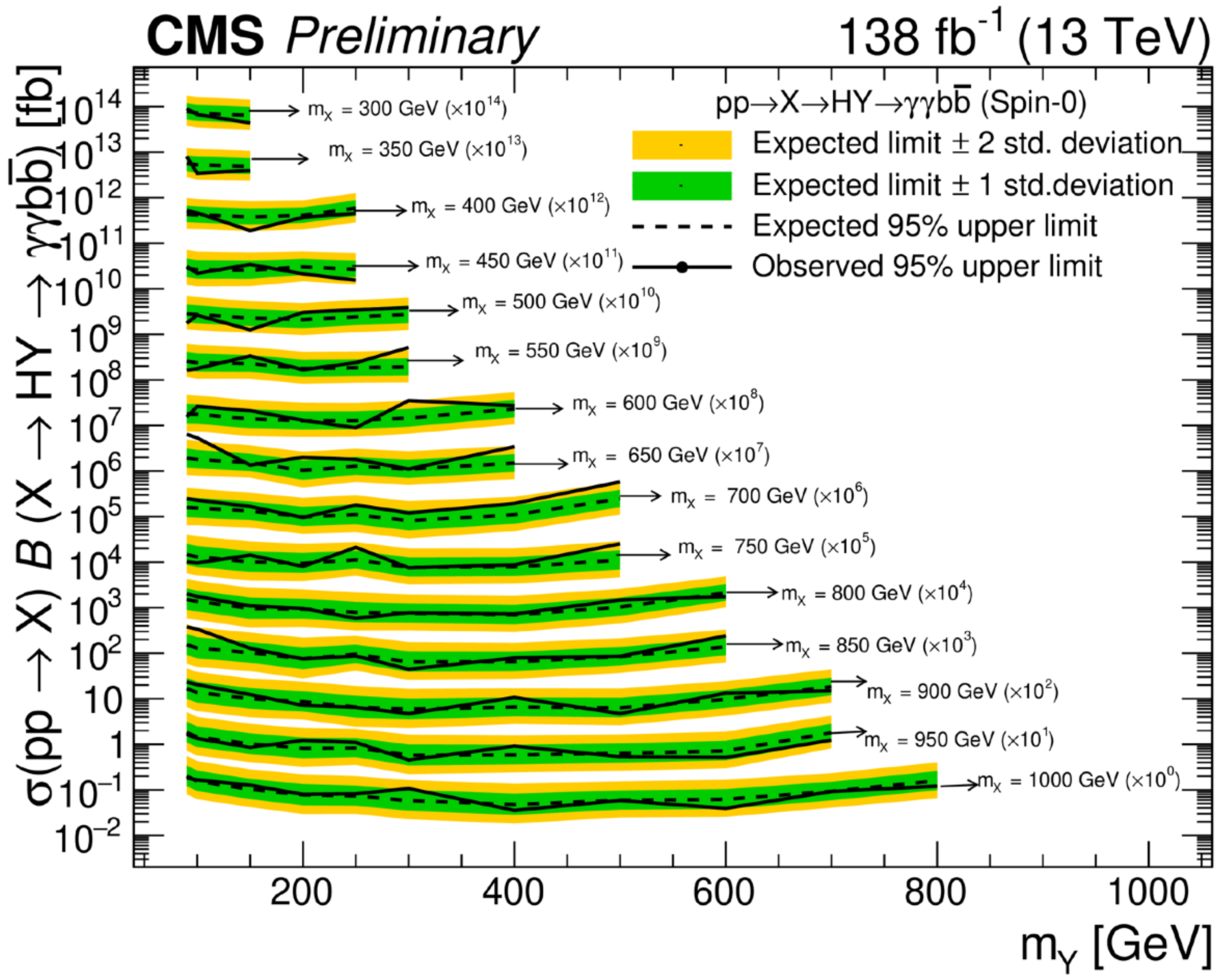
CMS-PAS-HIG-21-011

Search for $\mathrm{X} \rightarrow \mathrm{YH}, \mathrm{Y} \rightarrow \mathrm{b\bar{b}}, \mathrm{H} \rightarrow \gamma\gamma$

topologies encountered in extensions of MSSM

- NMSSM: extended with complex singlets
- TRSML: extended with two real singlet fields





Largest deviation:
local significance of 3.8σ for
(m_{X}, m_{Y}) = (650, 90) GeV

Search for $\mathrm{X} \rightarrow \mathrm{YH}, \mathrm{Y} \rightarrow \mathrm{b\bar{b}}, \mathrm{H} \rightarrow \mathrm{b\bar{b}}$

CMS-B2G-21-003
Accepted by PLB

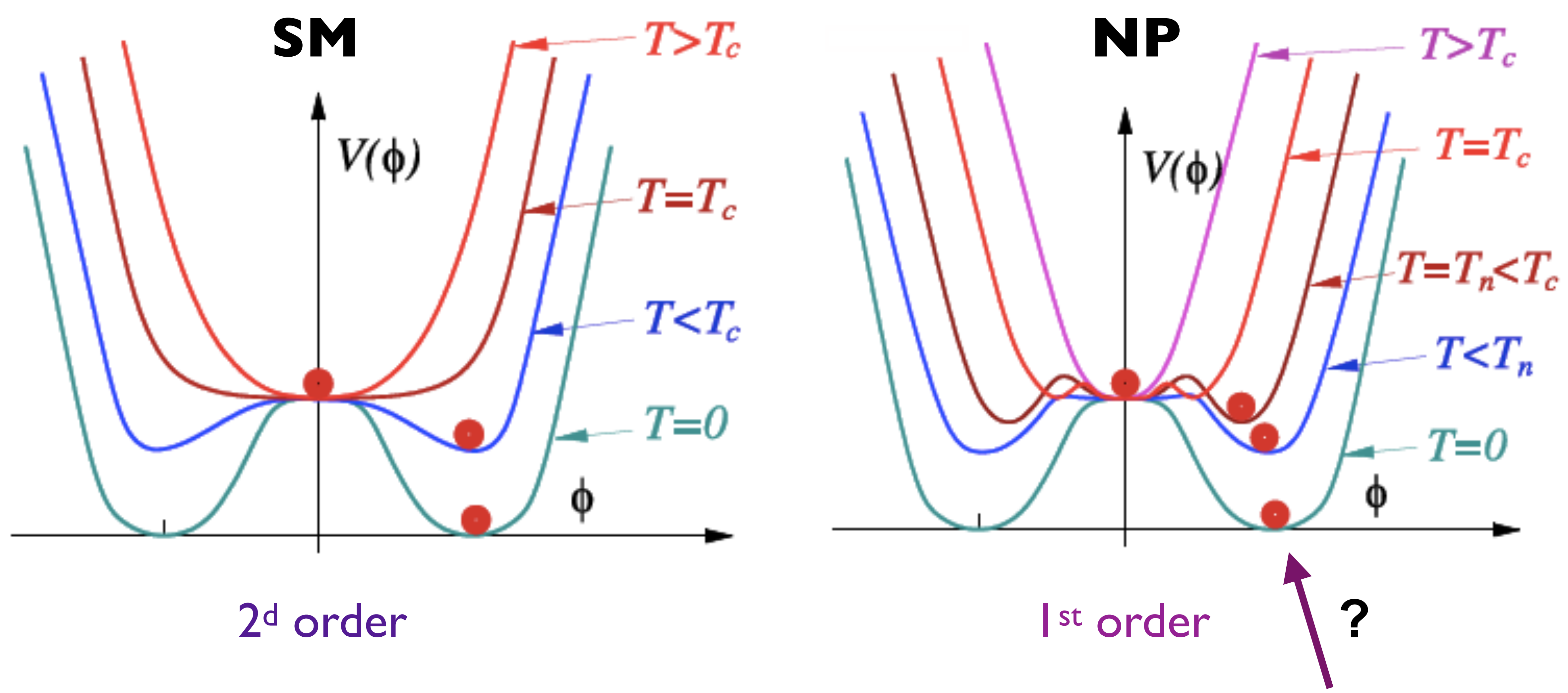
- in the boosted regime: m_X in 0.9–4 TeV
- both Y and H are boosted
- ParticleNet GNN technique used

Largest deviation:
local significance of 3.1σ for
(m_{X}, m_{Y}) = (1600, 90) GeV

See presentations by **Lata Panwar** and **Stéphanie Beauceron**

Higgs Potential and Self-Coupling

Higgs field potential: $V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$



- **Baryon Asymmetry of the Universe (BAU)**
  baryogenesis requires 1st order phase transition
  to sustain *out of equilibrium condition* during EWSB
- ***m_H* > 80 GeV → 2d order**
  EWK BAU *implies* a modification of the Higgs potential
  New Physics must modify the potential and the self-coupling

$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

tri-linear self-coupling | quartic

in the SM $\lambda_{3,4} = \lambda = \frac{m_H^2}{2v^2}$

First order EW transition implies large deviation from the SM prediction (κ_λ = 1)

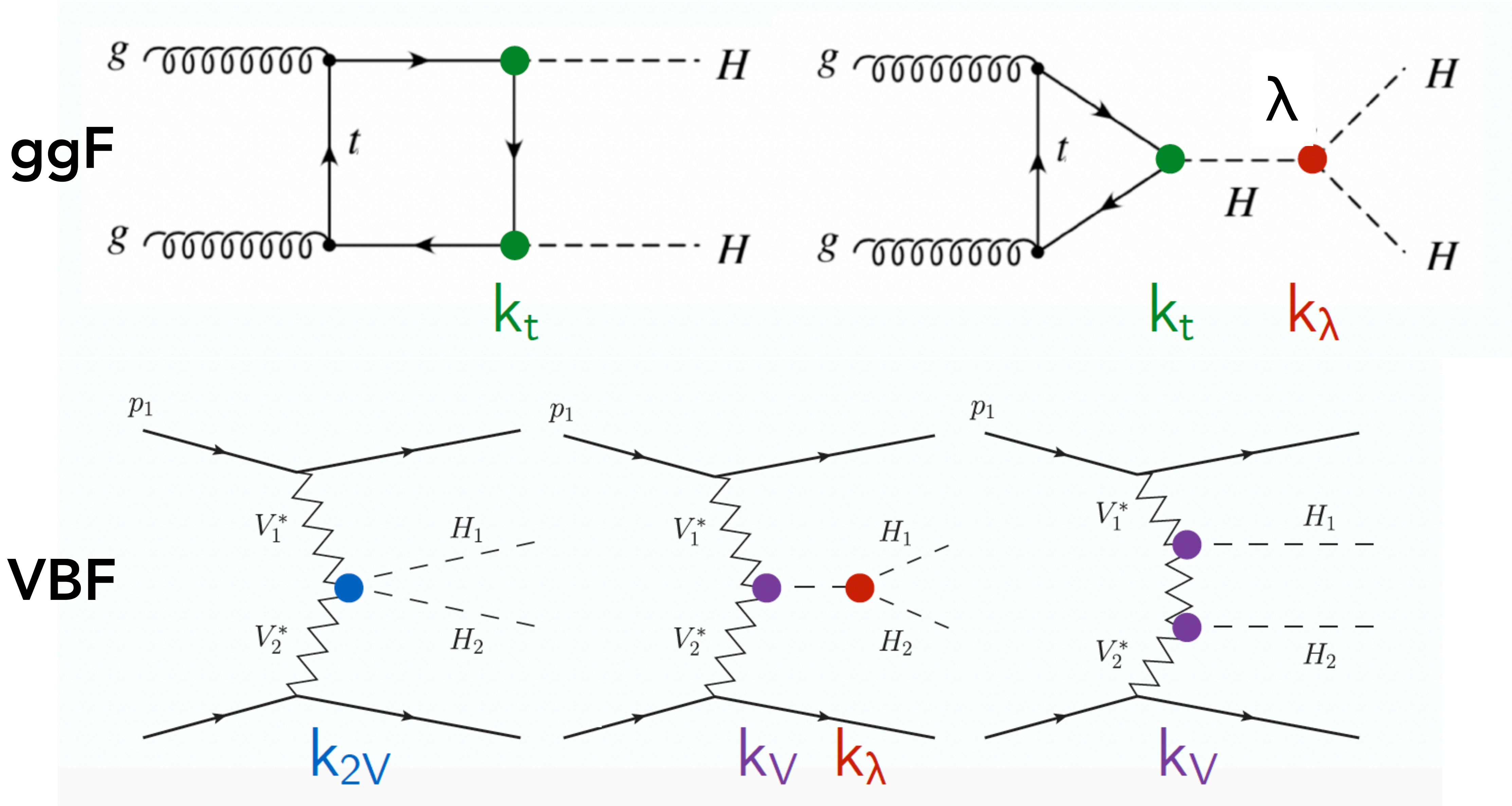
Double Higgs Production

The direct measurement of the tri-linear **self-coupling** λ is a key goal at future colliders

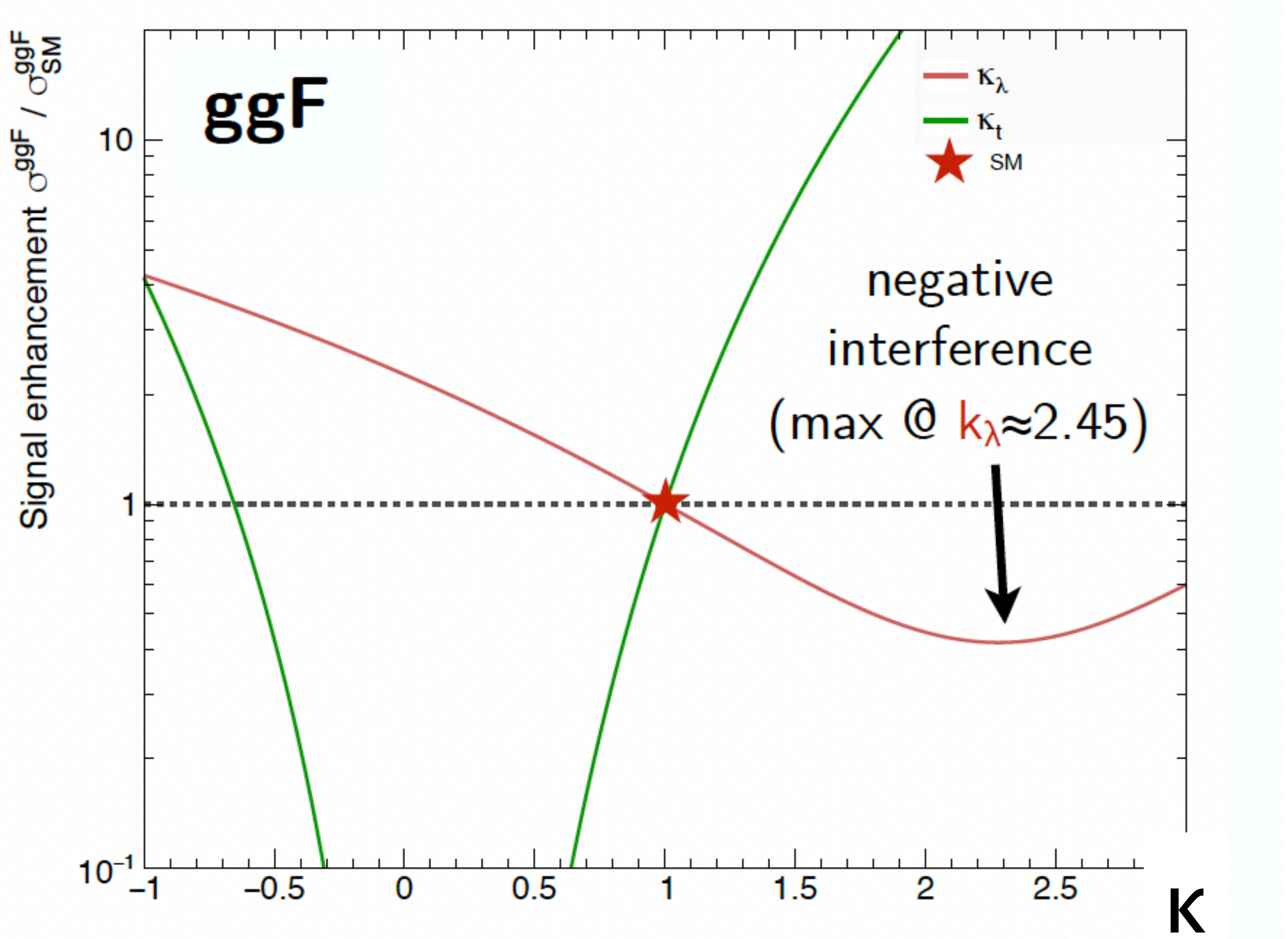
At the LHC/HL-LHC, the most sensitive process is **double Higgs production**

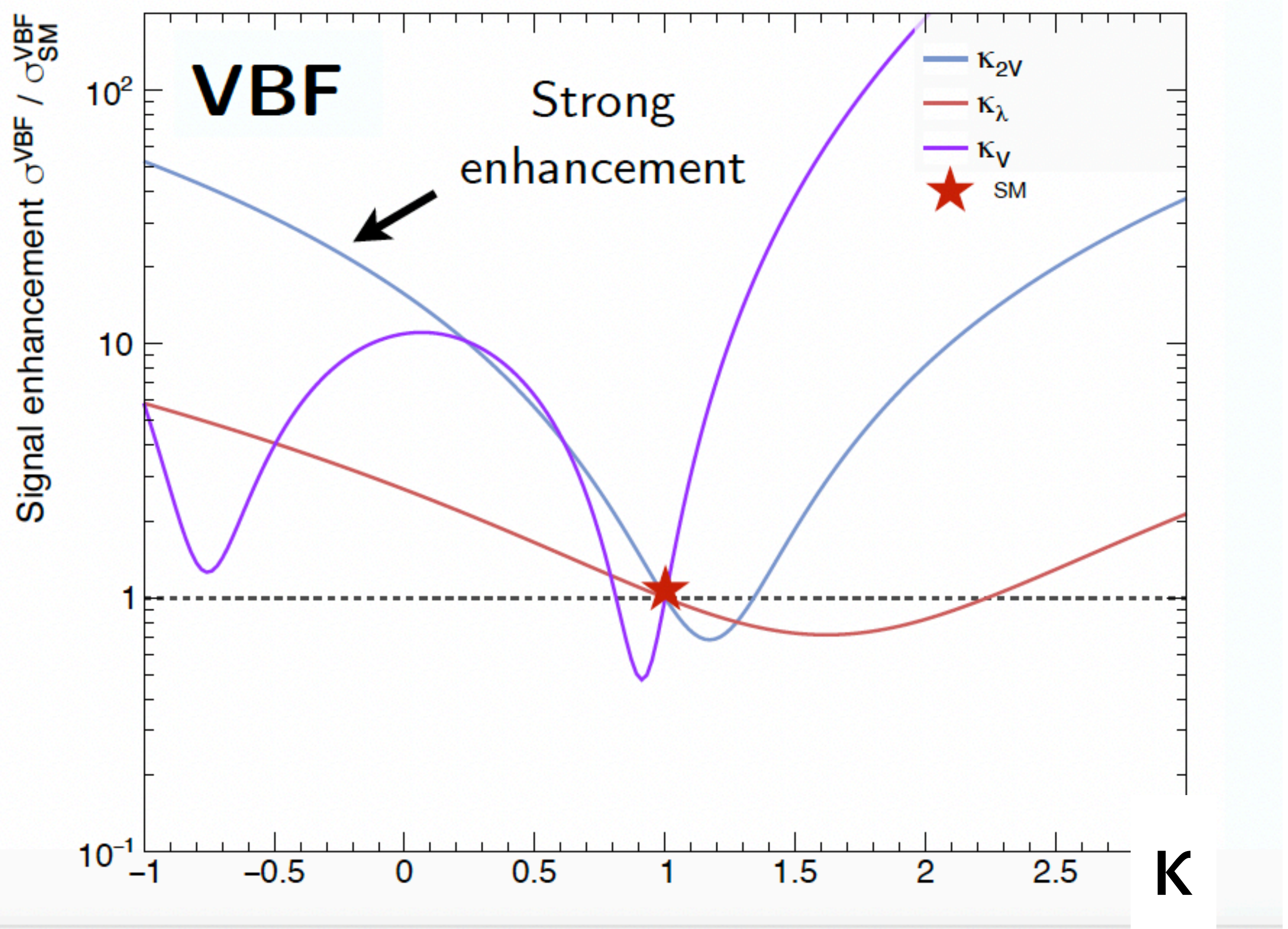
The m_H spectrum depends on κ_λ

- softer at large values of $|\kappa_\lambda|$
  - reduced selection efficiency
- harder close to maximum interference (double structure)
  - clear signatures (possible boosted)



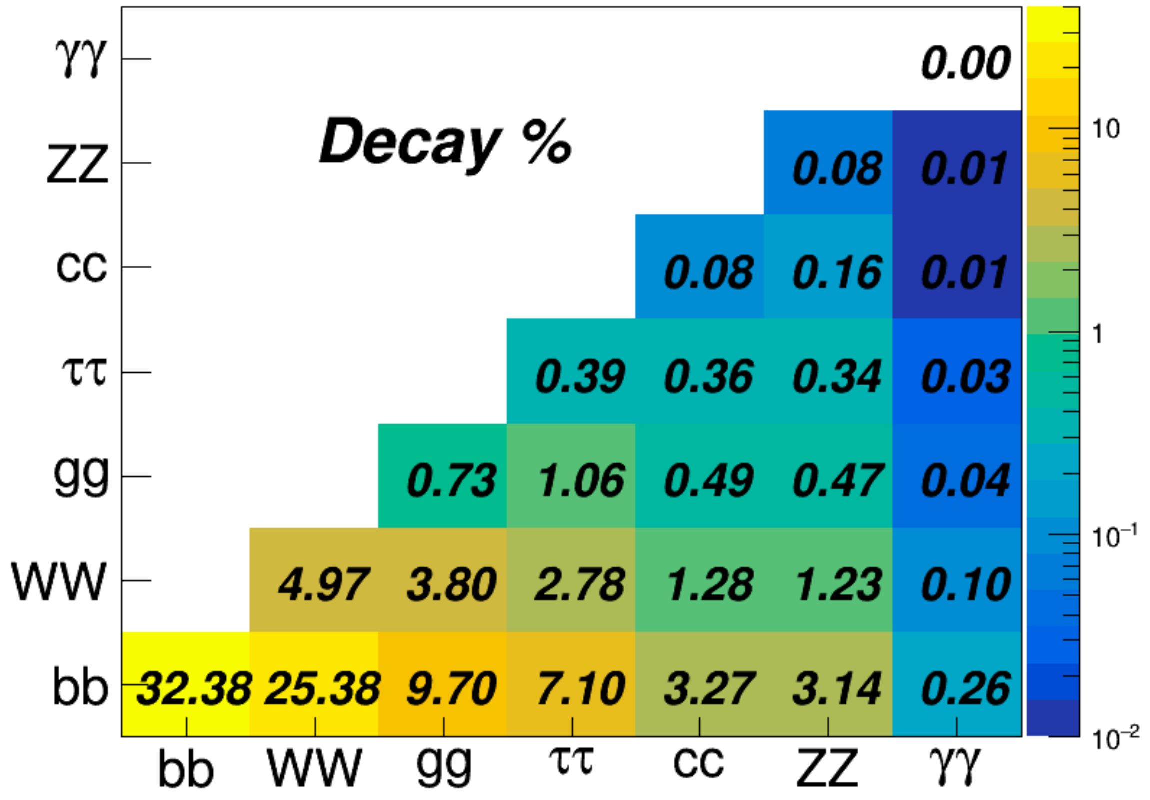
In a non-trivial way, limits on double-Higgs ggF and VBF production cross-sections are a way to put constraints on κ_λ and κ_{2V}





inspired from M. Rieger, HH 2022

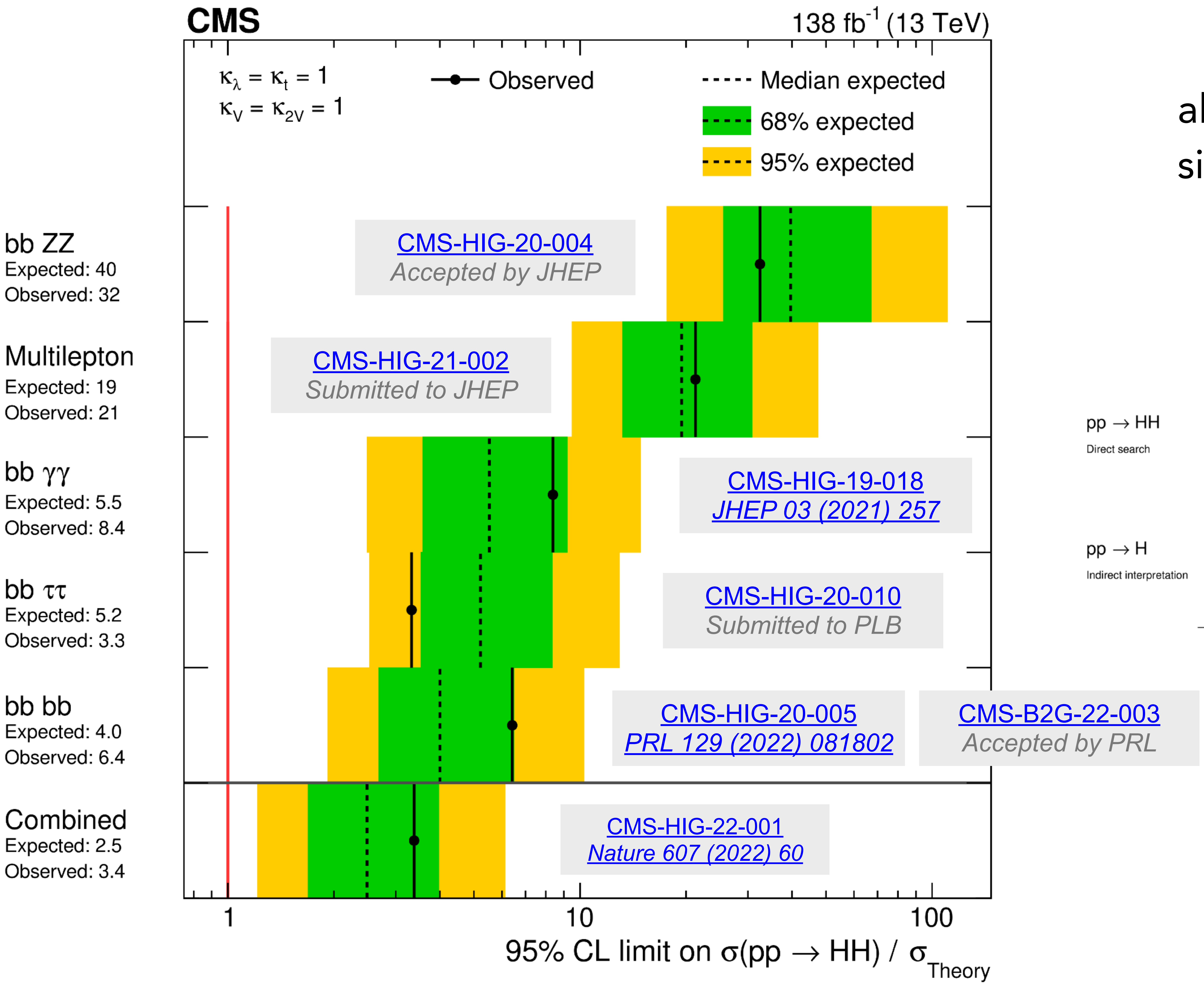
Double Higgs Production



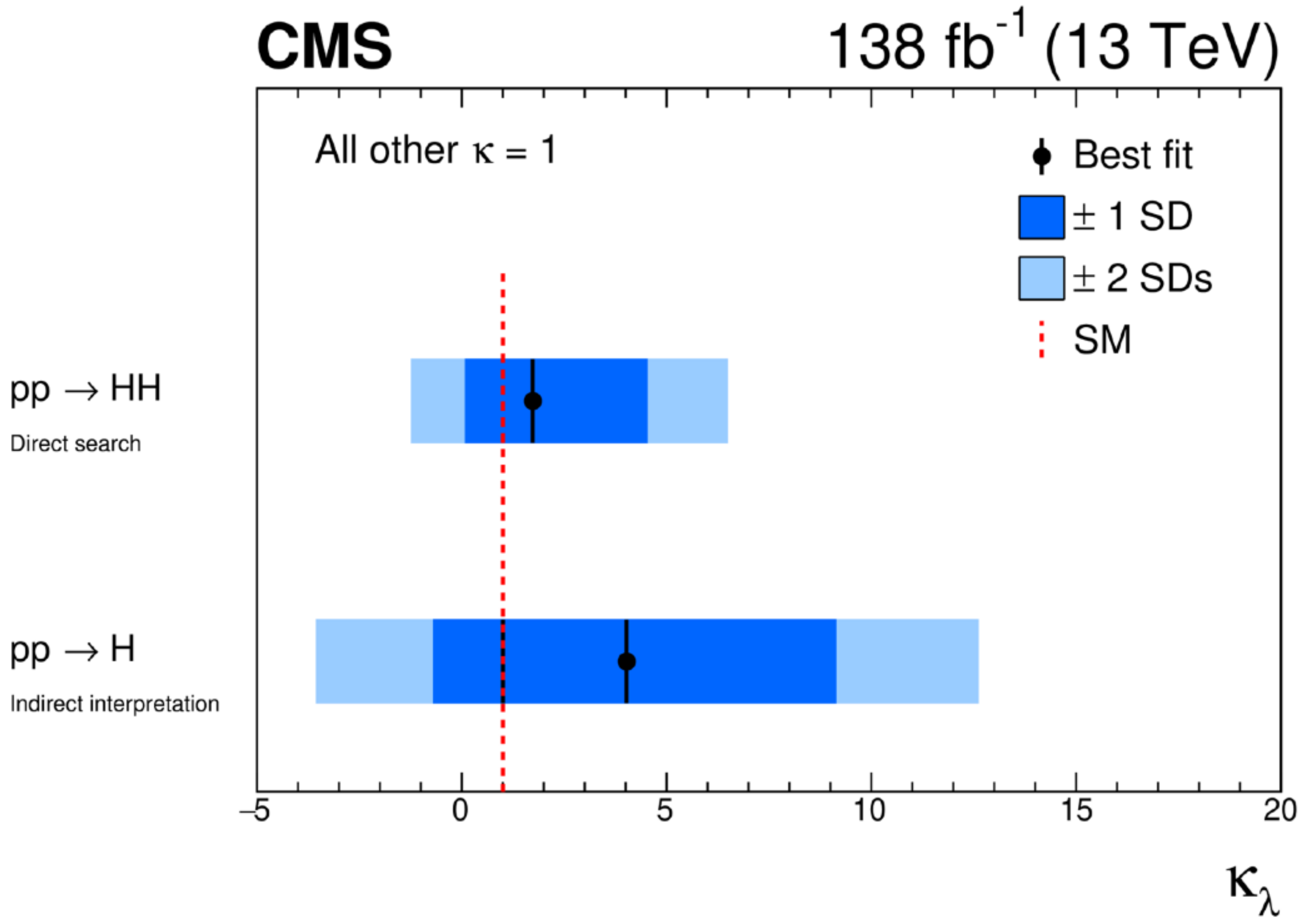
Most sensitive channels

- bbbb
- bbττ
- bbγγ
- multi-leptons (4W, WWττ, ττττ)
- bbZZ(4ℓ)

Search for non-resonant double Higgs production



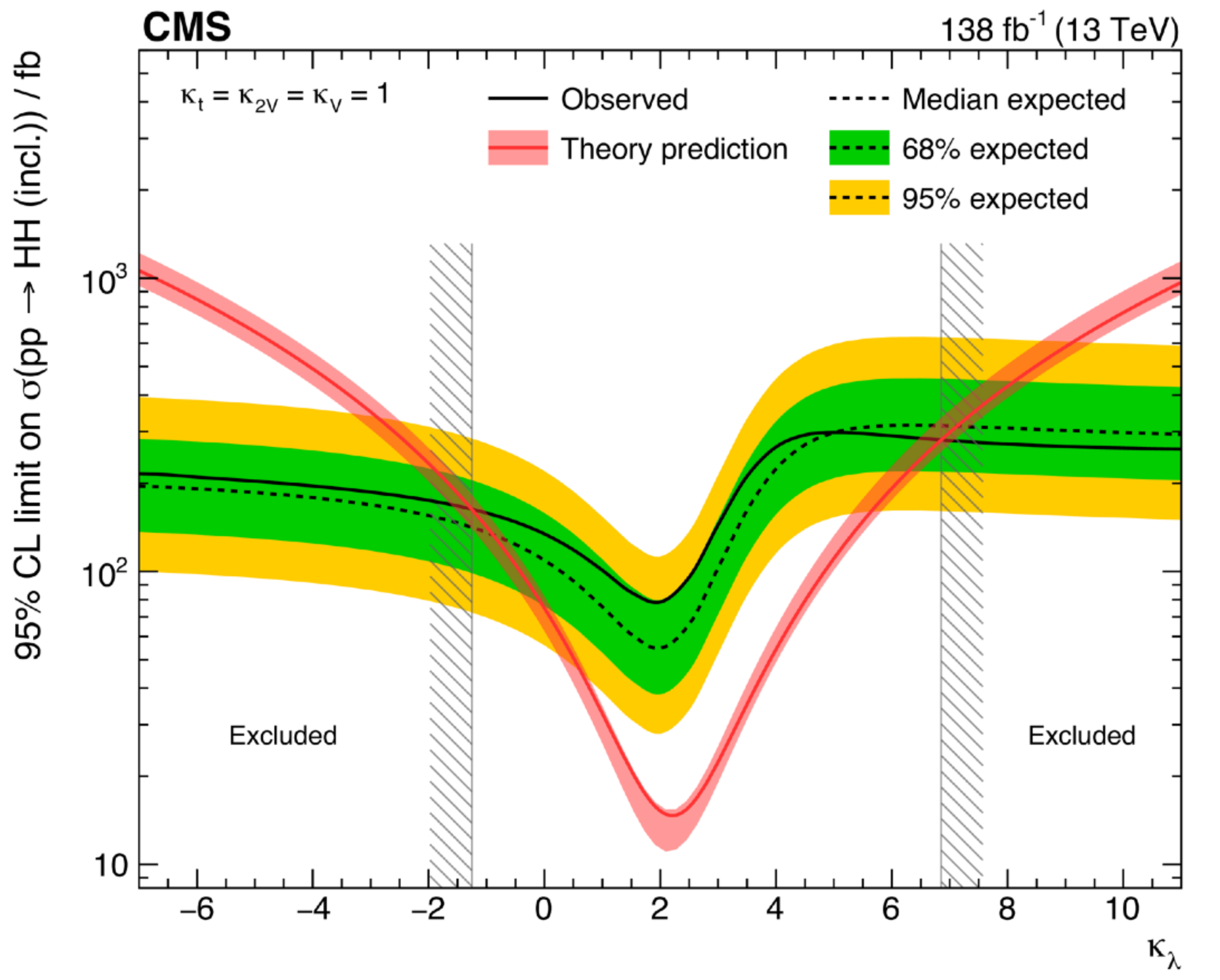
also constraints on λ through single Higgs production



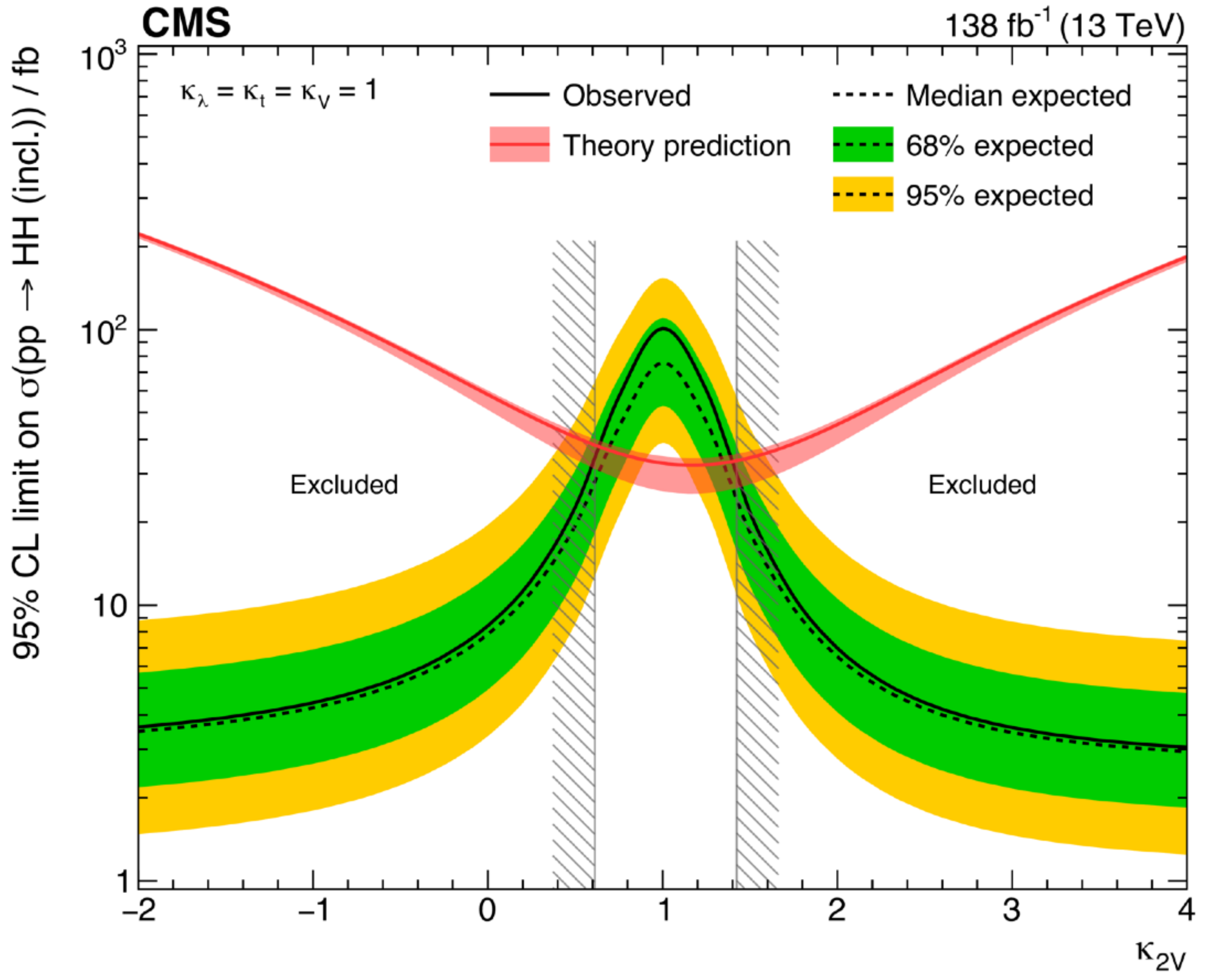
Most sensitive so far:
bbbb boosted analysis
Obs (exp) : 9.9 (5.1) × SM

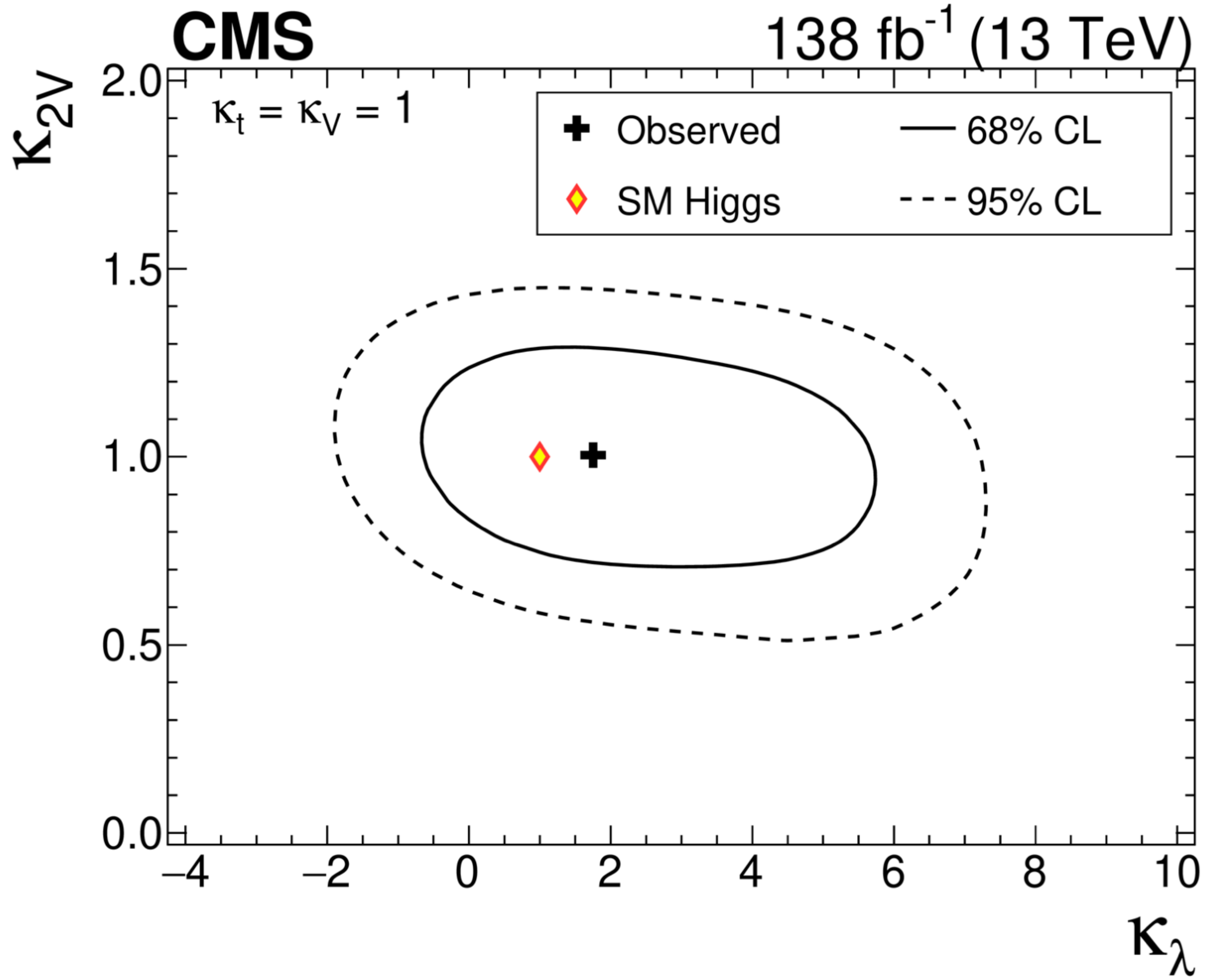
Combined Constraints on κ_λ and κ_{2V}

κ_λ



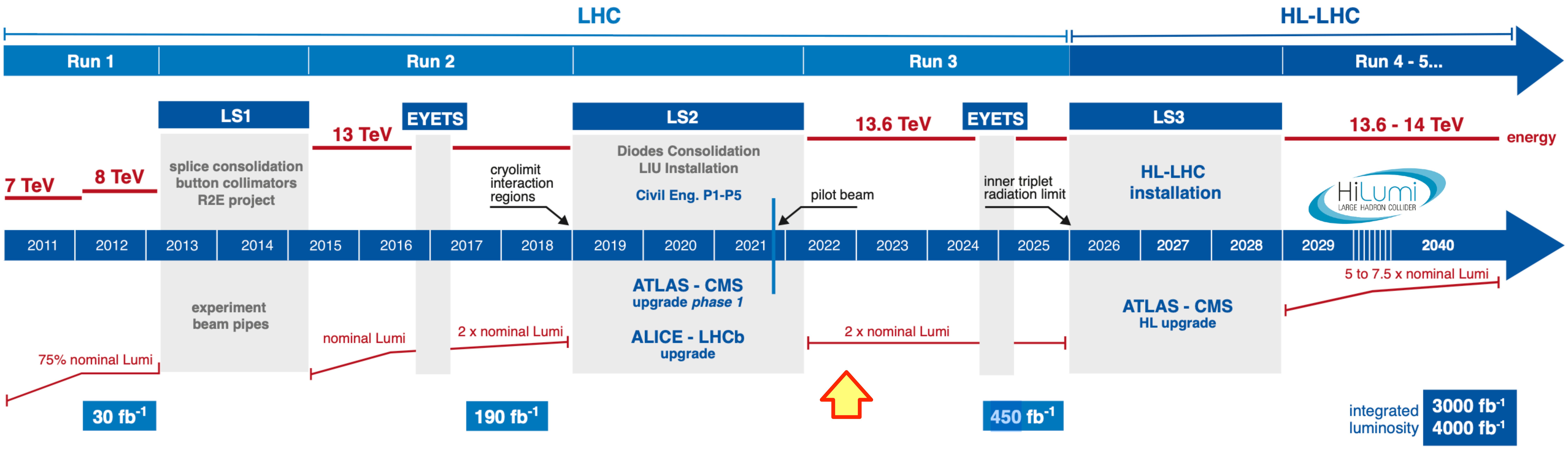
κ_{2V}





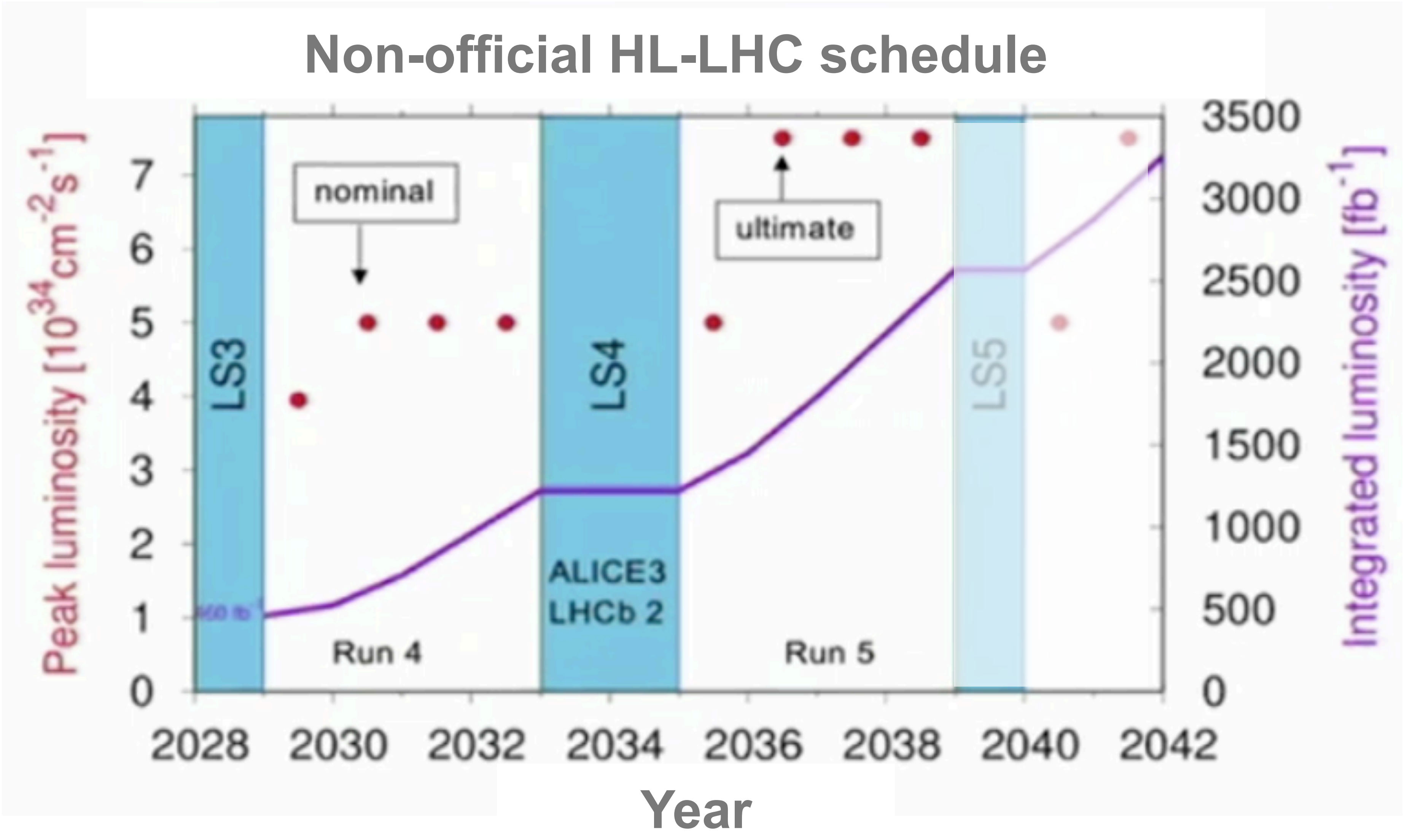
- $\kappa_\lambda \in [-1.24, 6.49]$ and $\kappa_{2V} \in [0.67, 1.38]$ @ 95% CL
- $\kappa_{2V} = 0$ excluded with a significance of 6.6σ, establishing the existence of the quartic coupling VVHH

Towards High-Luminosity LHC



New LS3 schedule

- Run-3 extended by 1 year
  → 2022-2025
  270 fb^{-1} (PU50)
- LS3 extended to 3 years
  → 2026-2028
- start of Run-4: 2029

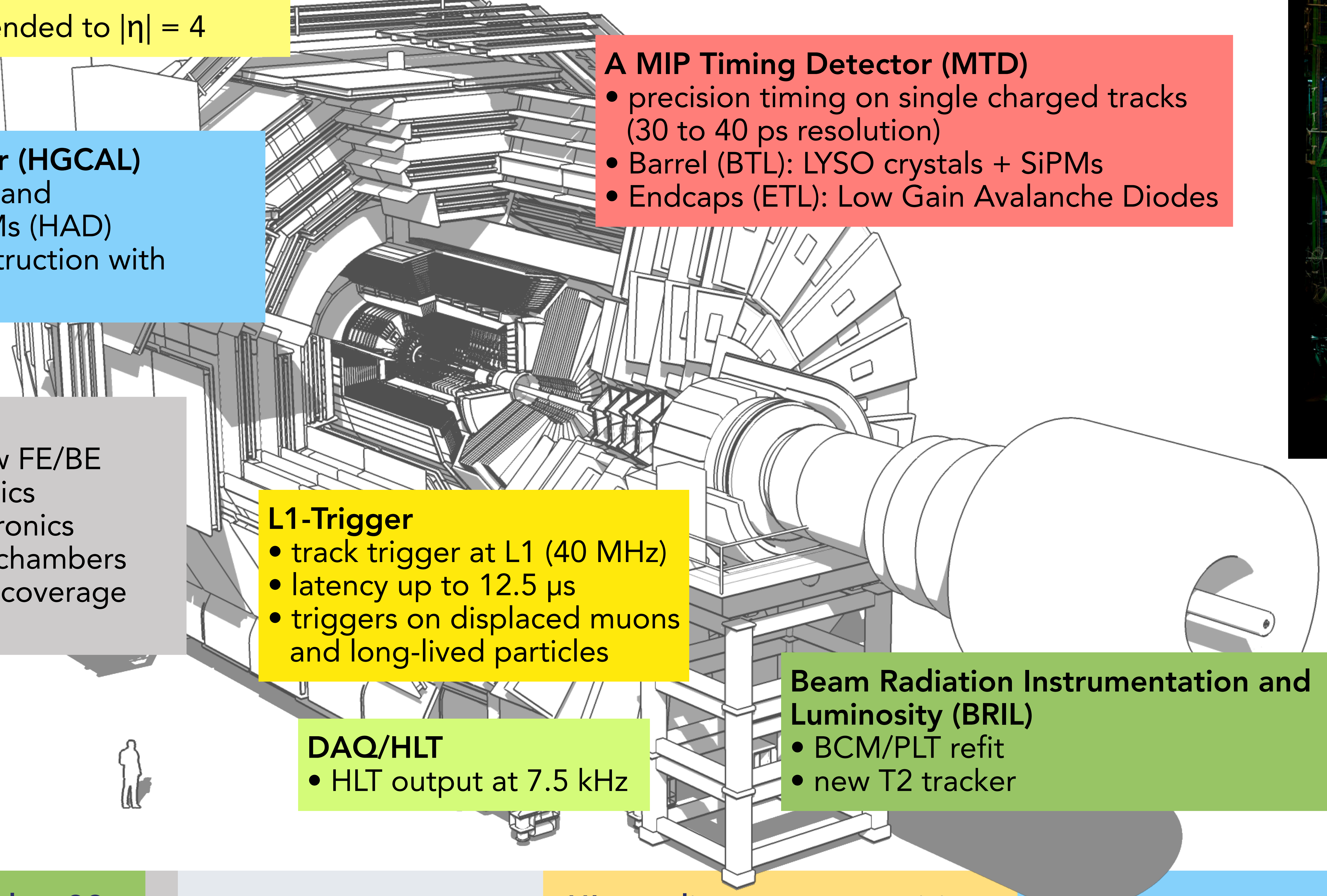


Possible scenario (CERN DG, Jan. 2022)

- Run 4 (2029-2032) = 740 fb^{-1} (PU140)
- Run 5 (2035-2038) = 1300 fb^{-1} (PU200)
- Run 6? (2040-2042) = 750 fb^{-1} (PU200)

Expect **2500 fb^{-1}** by the end of **2038**
3250 fb^{-1} by the end of **2042**

CMS Phase-II Upgrades



Tracker
- all silicon (strips and pixels)
- higher granularity (>2B channels)
- less material
- coverage extended to $|\eta| = 4$

Barrel Calorimeters
- crystal granularity readout at 40 MHz
- precise timing for e/γ > 30 GeV
- ECAL operation at low temperature (10°)
- upgraded laser monitoring system

A MIP Timing Detector (MTD)
- precision timing on single charged tracks (30 to 40 ps resolution)
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes

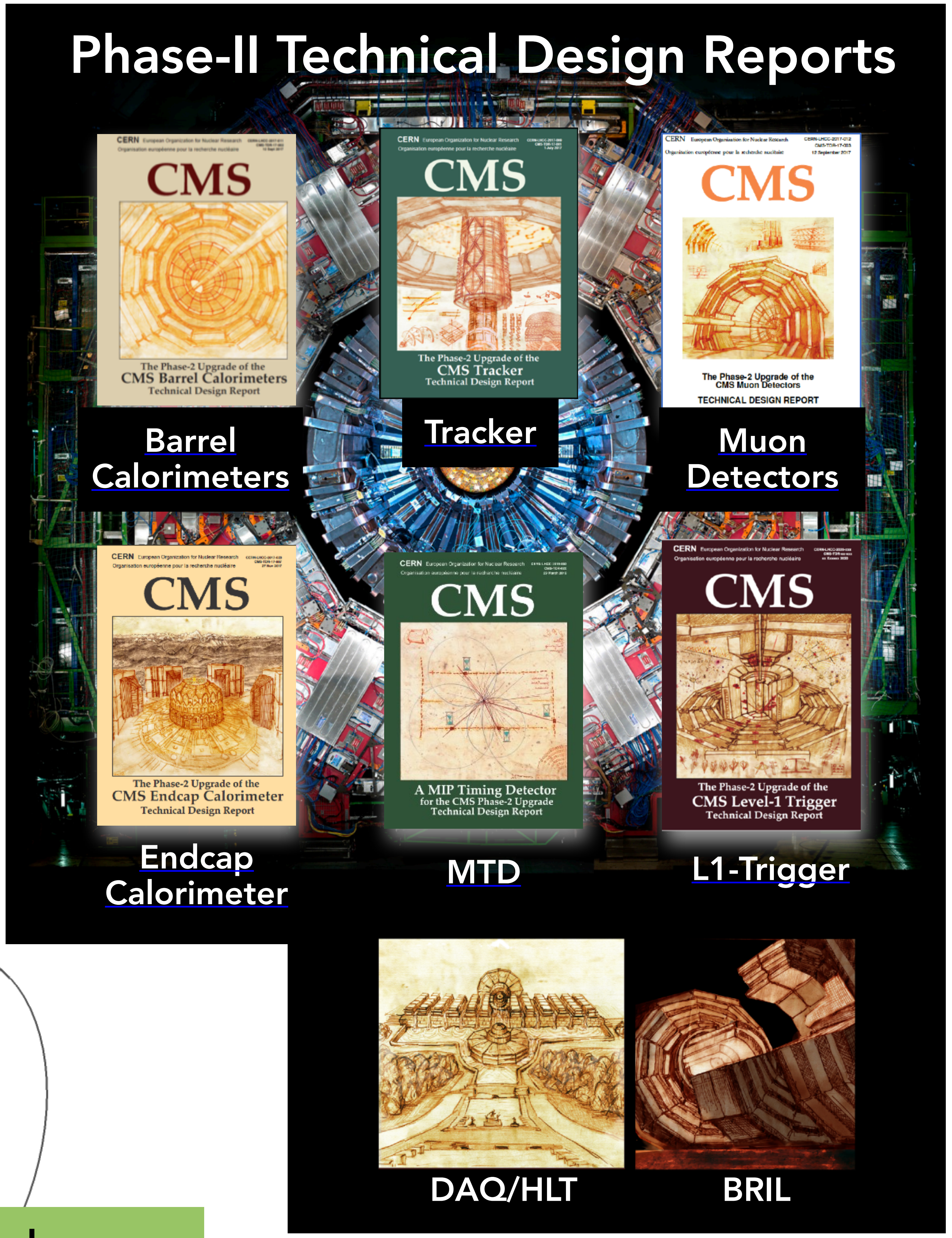
Endcap Calorimeter (HGCAL)
- silicon pixels (EM) and scintillators + SiPMs (HAD)
- 3D shower reconstruction with precise timing

Muon Detectors
- DTs & CSCs: new FE/BE readout electronics
- RPCs: new electronics
- new GEM/iRPC chambers
- extended muon coverage to $|\eta| = 3$

L1-Trigger
- track trigger at L1 (40 MHz)
- latency up to 12.5 μs
- triggers on displaced muons and long-lived particles

DAQ/HLT
- HLT output at 7.5 kHz

Beam Radiation Instrumentation and Luminosity (BRIL)
- BCM/PLT refit
- new T2 tracker

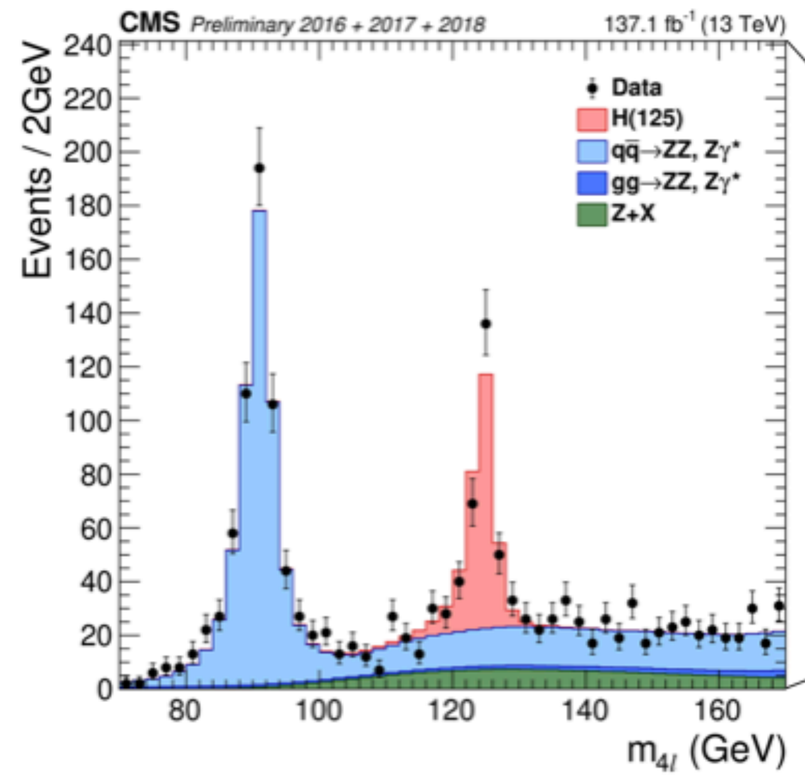


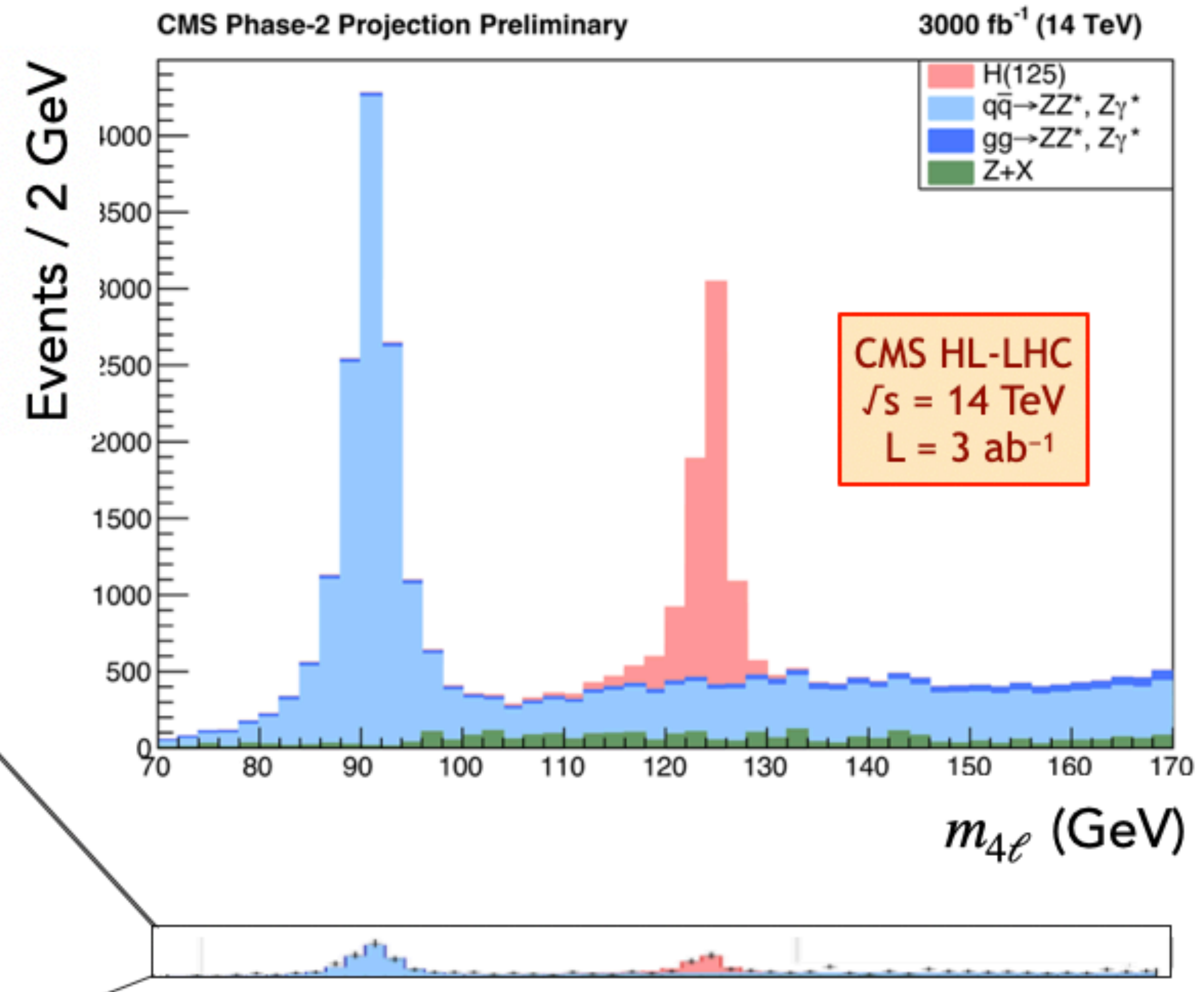
HL-LHC: A Huge Step in Sensitivity

HL-LHC (Run 4-5)
- starting 2029
- $\sqrt{s}$ = 14 TeV
- $<\mu>$ = 140-200
- $\mathcal{L}$ up to 7.5 10^{34}
- L > 2500 fb^{-1}

so far < 10% of the total expected dataset

CMS Run-2
$\sqrt{s}$ = 13 TeV
L = 137 fb^{-1}



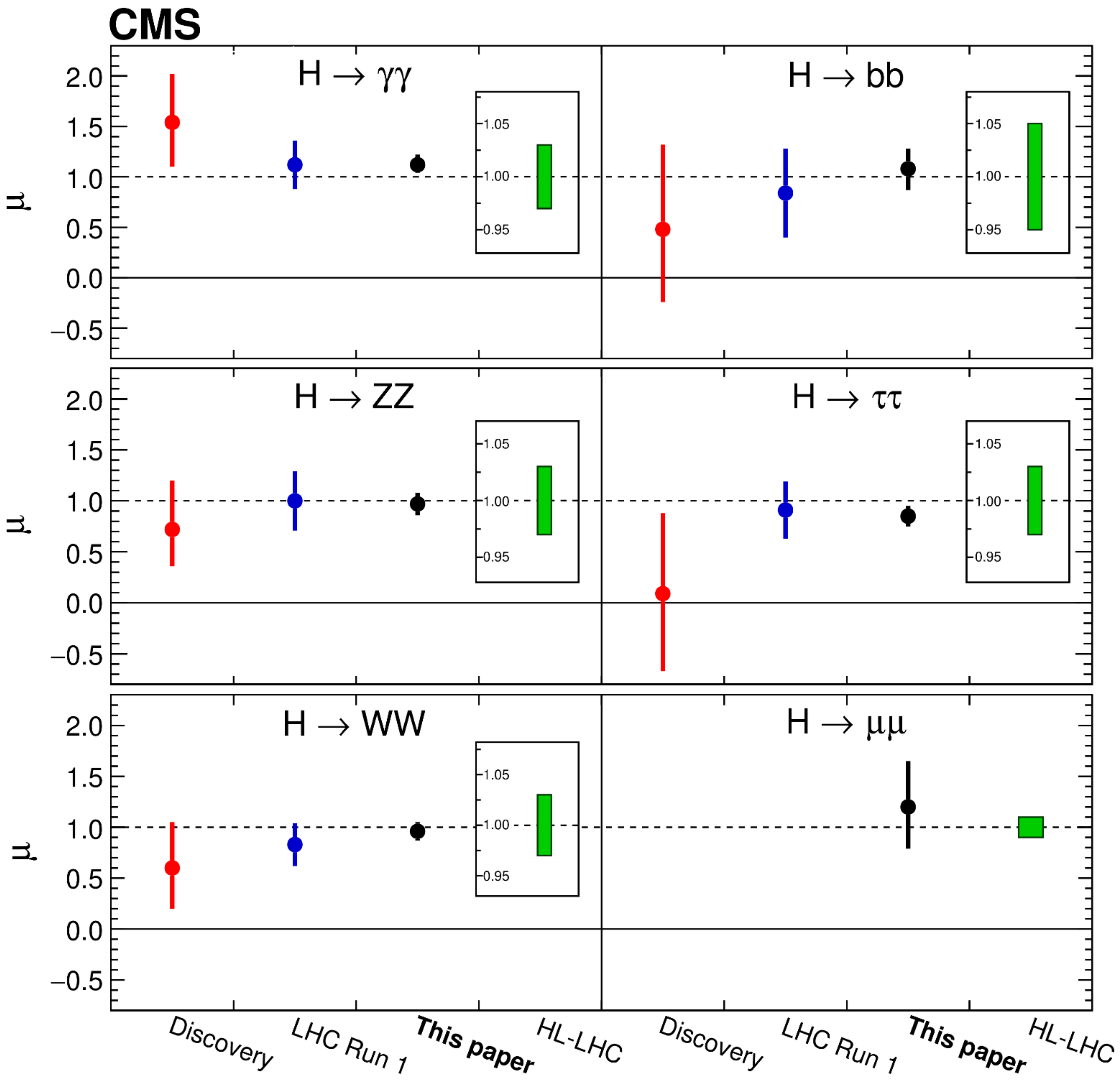


CMS HL-LHC
$\sqrt{s}$ = 14 TeV
L = 3 ab^{-1}

ATLAS/CMS White Paper for Snowmass

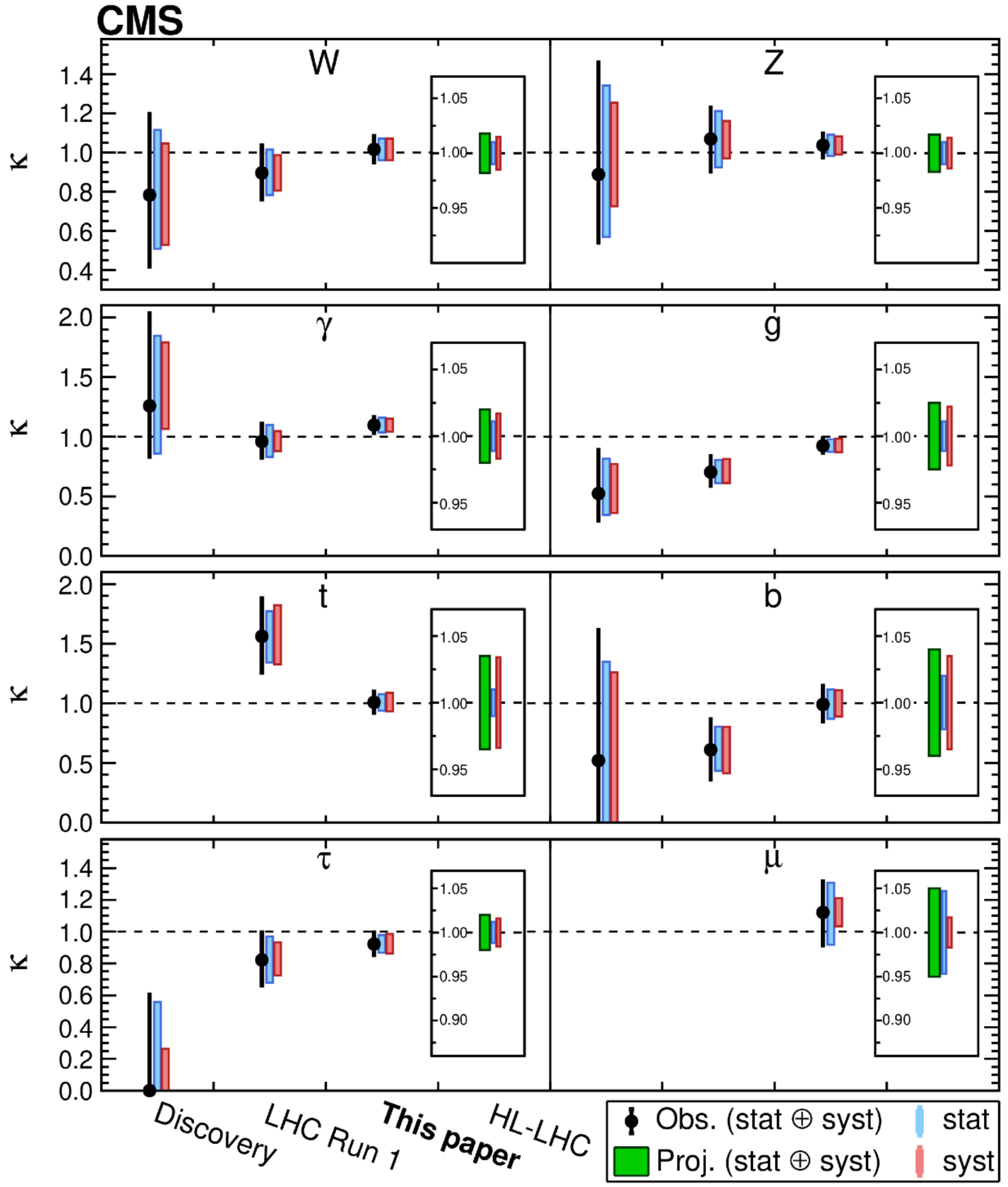
With HL-LHC (3000 fb^{-1})
- $m_H^{\gamma\gamma} = 125.38 \pm 0.07\,(\text{tot})\;[\pm 0.02\,(\text{stat})]$ GeV
- $m_H^{4\ell} = 125.38 \pm 0.03\,(\text{tot})\;[\pm 0.02\,(\text{stat})]$ GeV
- $\Gamma_H^{4\ell} < 0.18$ GeV @ 95 % CL

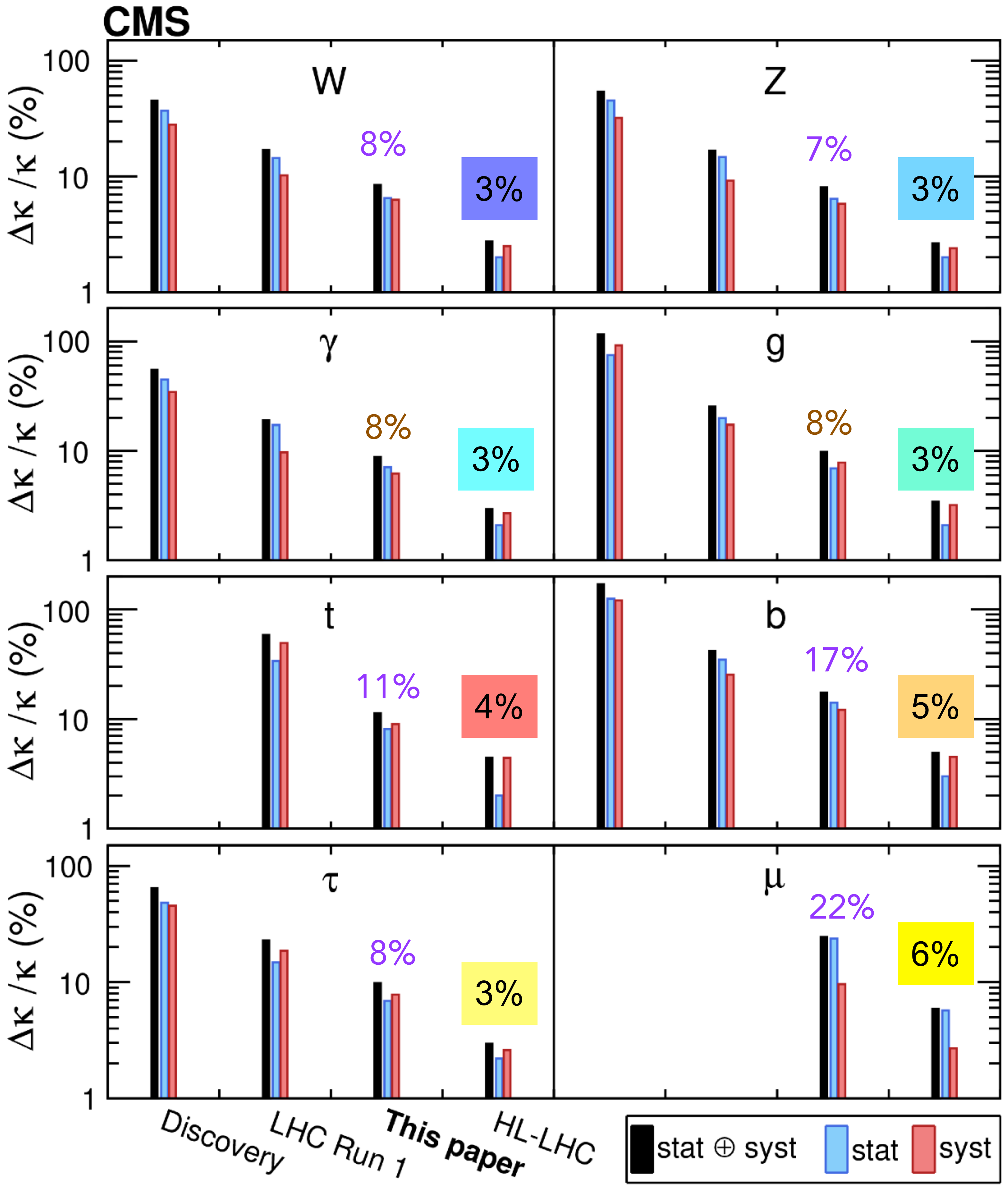
CMS-HIG-22-001
Nature 607 (2022) 60



HL-LHC: Couplings Modifiers

CMS-HIG-22-001
Nature 607 (2022) 60

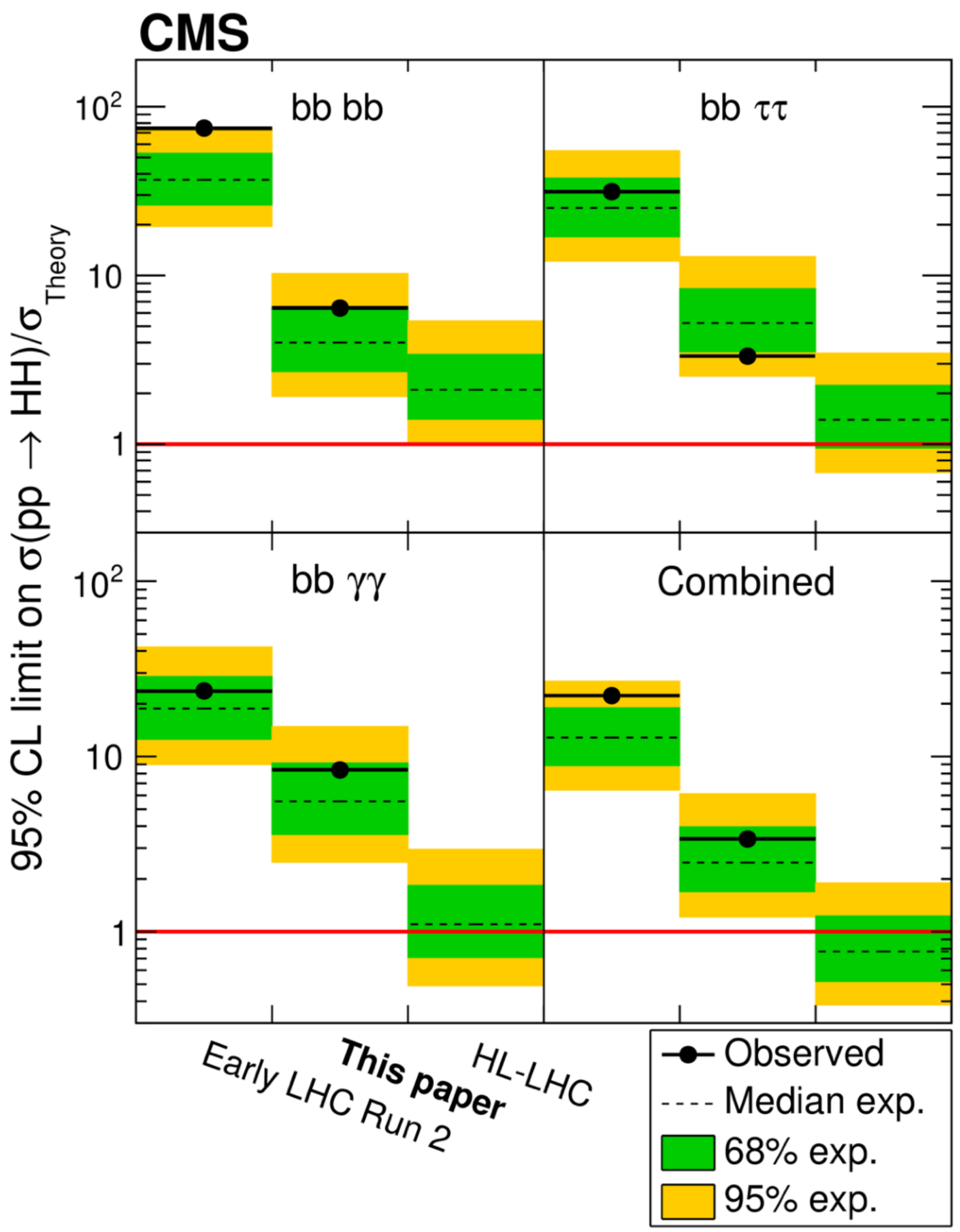




At the HL-LHC, high precision tests of the SM precision below 5% for all considered couplings

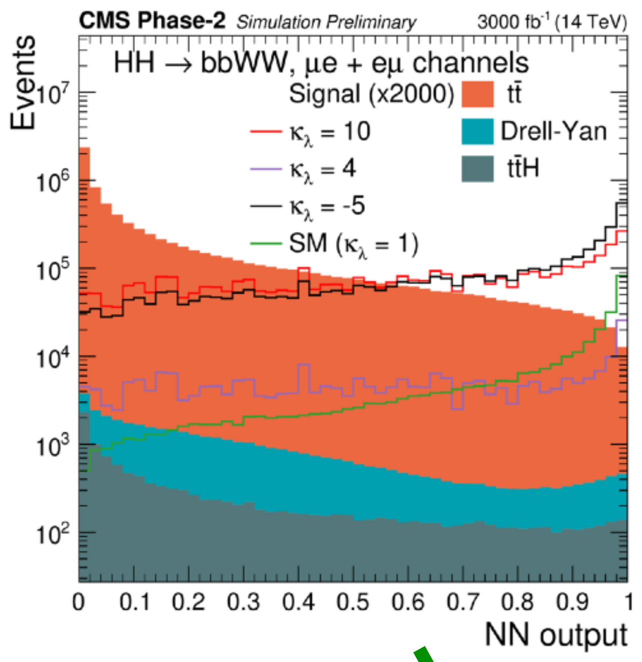
Potential for more sophisticated tests of the SM (e.g., EFT)

HL-LHC: Higgs Self Coupling



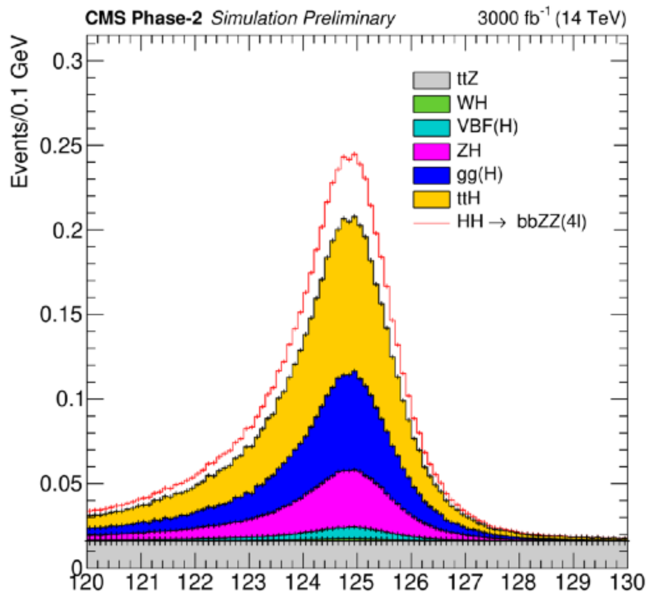
CMS-HIG-22-001
Nature 607 (2022) 60

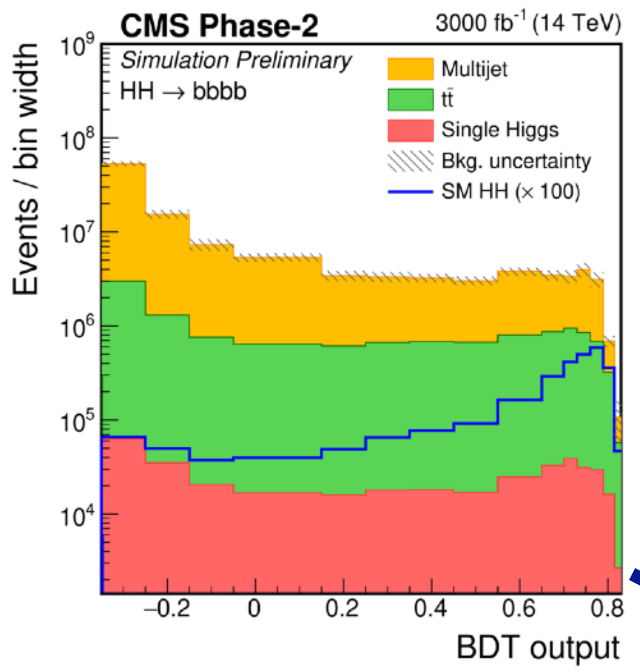
bb̄bb̄
exploit resolved and
boosted b-jets

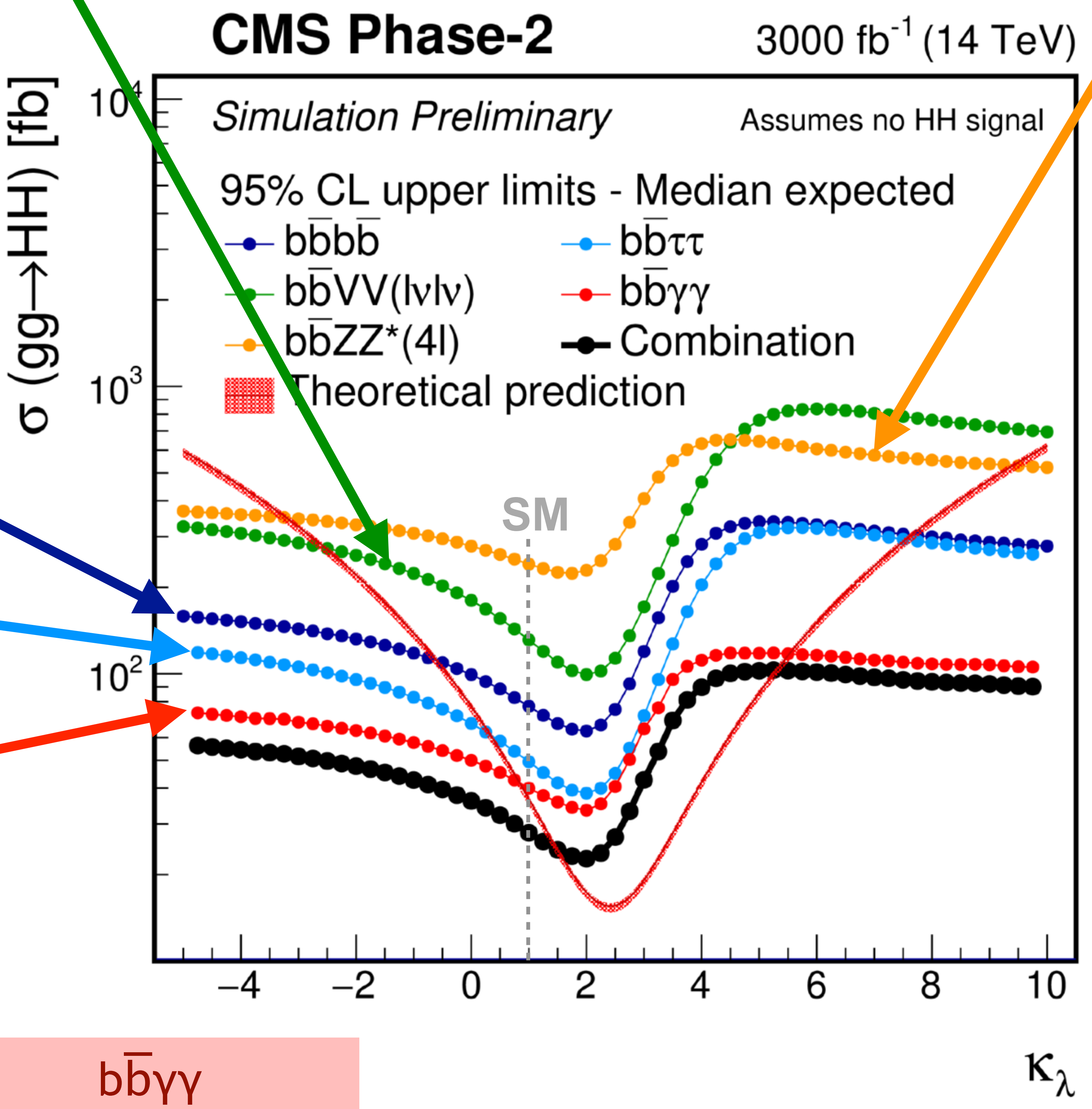


bb̄WW*(ℓνℓν)
main bkg: tt̄

bb̄ZZ*(4ℓ)
very rare but
clean final state

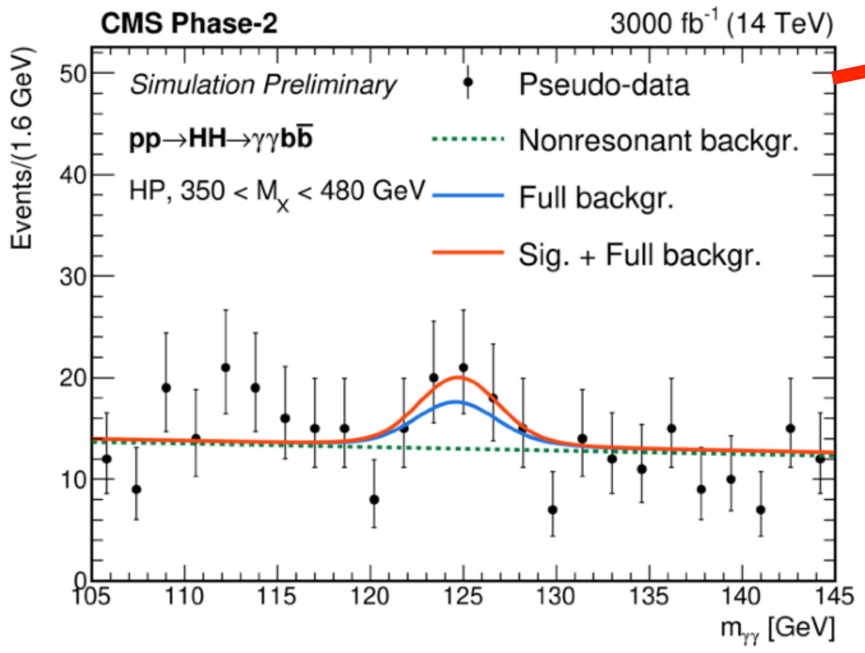






bb̄ττ
irreducible bkg: Z(ττ)bb̄

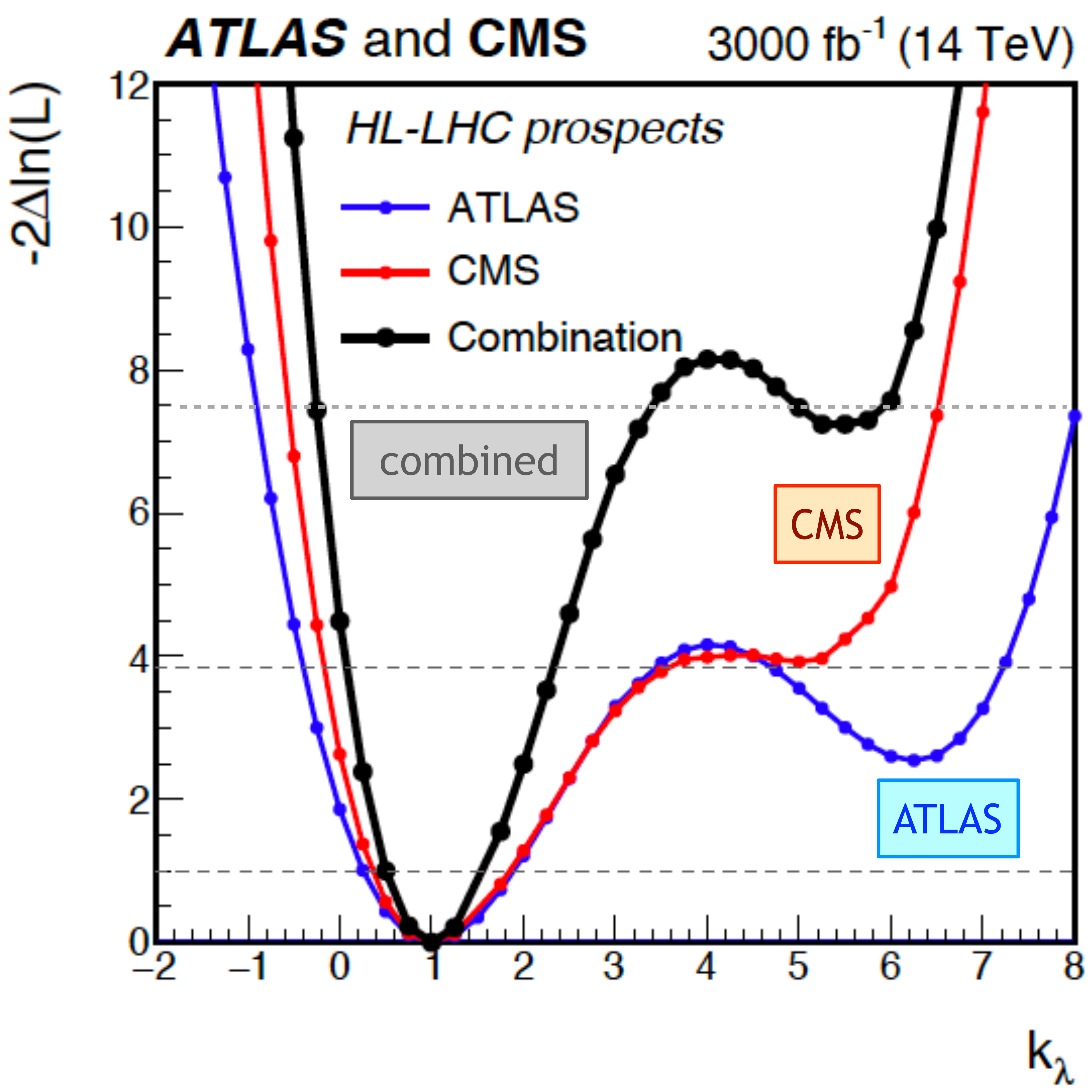
for most channels, tt̄H is the main background

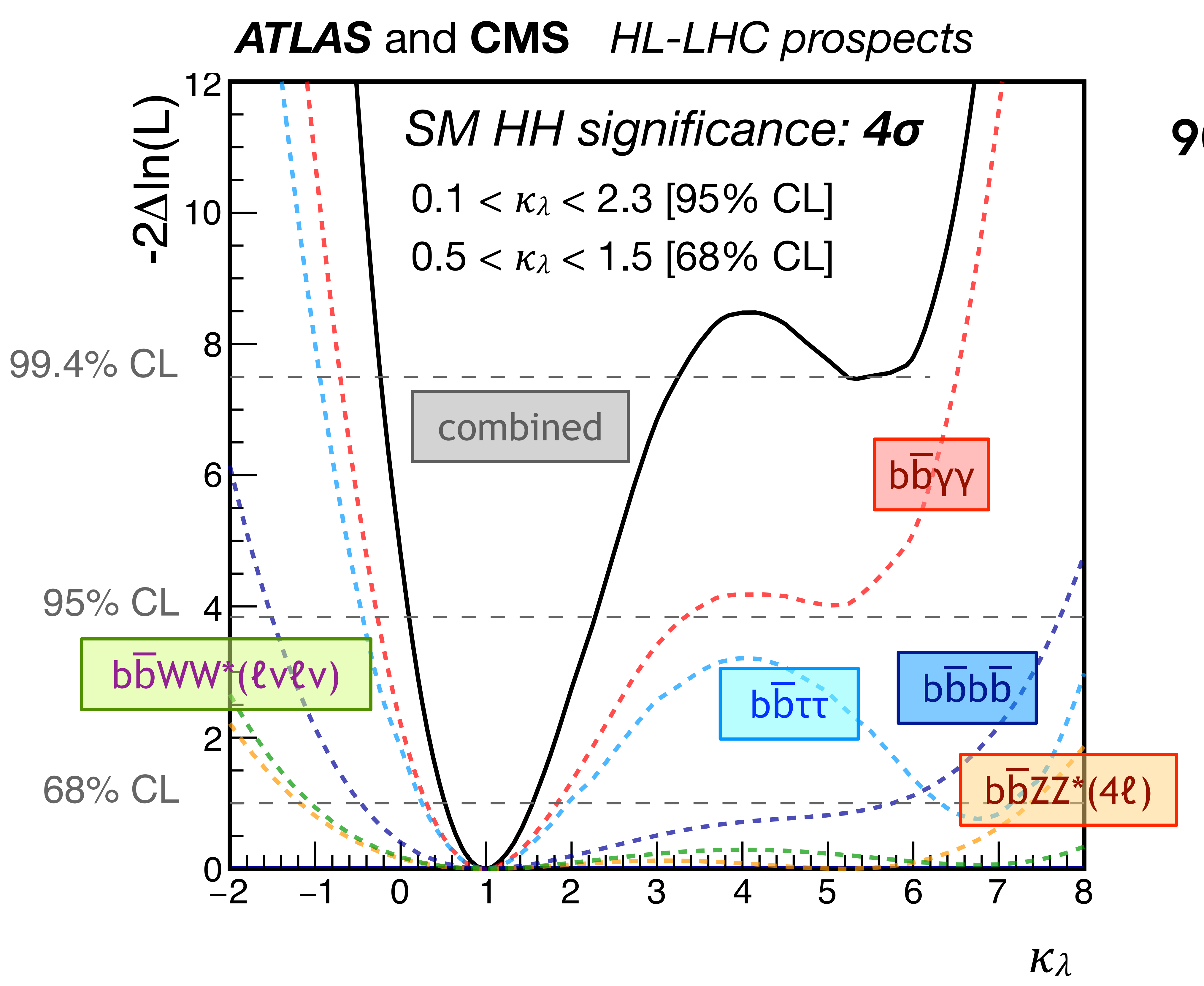


bb̄γγ
peaking tt̄H and
non-resonant bb̄γγ

CMS-PAS-FTR-18-019

HL-LHC: Higgs Self-Coupling





90k HH pairs produced

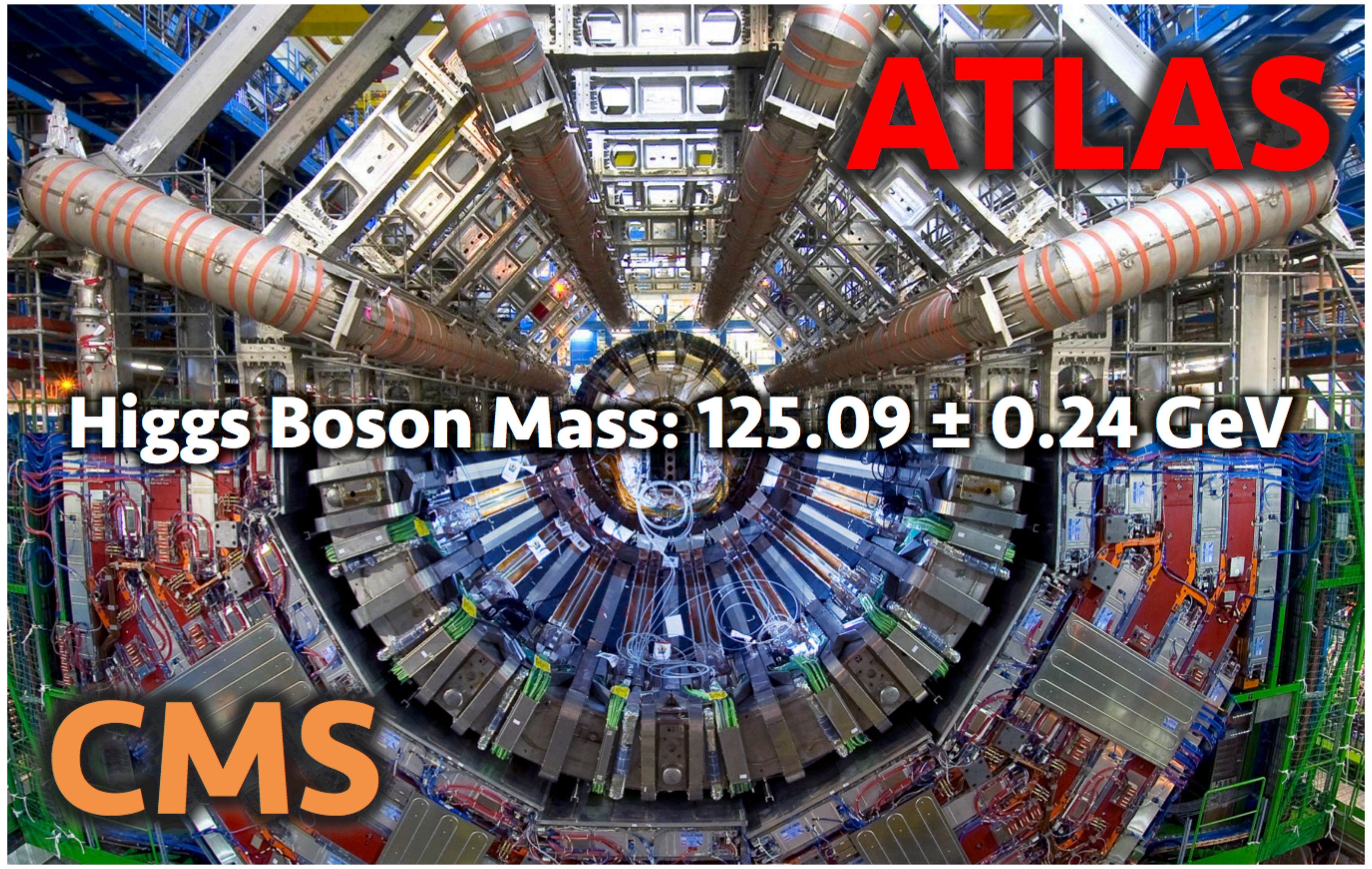
combined significance: 4σ

κλ "measured" with a precision of ±50%

HL/HE-LHC WG2

Conclusion

After the discovery in 2012 with Run-1 data ATLAS(*) and CMS have firmly established that the discovered state was consistent with being the Higgs boson, a **scalar particle** (spin-parity 0^+) with **couplings to the gauge bosons** W and Z at the level required to **restore unitarity** at the TeV scale. The mass of the Higgs boson was already measured precisely with Run-1 data (< 2‰). The **coupling to the top quark** was inferred from the gluon fusion production mode and the decay to two photons. Strong evidence for the **decay to tau leptons** confirmed the non-universal coupling of the Higgs boson to quarks and leptons.



See presentation by Giovanni Marchiori

Conclusion

With Run-2 data CMS has entered **precision Higgs physics**:

- observation of **VBF and VH production** and of **decay to bottom quarks** (2018)
- observation of **ttH production** by combining many channels (2017)
  and with H → γγ alone (2018)
- **Higgs couplings** with precision 10% or better for W, Z, t and τ, 20% for b and μ
- evidence for **H → μμ** and first hint of **H → Zγ**;
  huge improvement in the search for **H → cc**
- evidence for **off-peak production** and constraints on the **total width**;
  constraints on the **invisible width**
- **spin-parity** probed via angular correlation in di-boson decays, VBF, ttH and H → ττ
- **differential cross-sections**, simplified template cross-sections,
  effective field theory **interpretations**
- **searches for new scalars** in extensions of the SM,
  from the very low to the very high mass
- **searches of heavy resonances** decaying to Higgs bosons
  (resolved and boosted topologies)
- **search for double-Higgs production**;
  first meaningful **constraints on Higgs self-coupling**

Run-2

- L x 5.6
- σ(H) x 2.3
- better detector
- improved analysis techniques

Very exciting Higgs physics programme with Run-3 and HL-LHC data to come!


Thank You !

Backup

CMS at the Large Hadron Collider

CMS
Compact
Muon
Solenoid

100 m underground
at LHC Point-5 (P5)

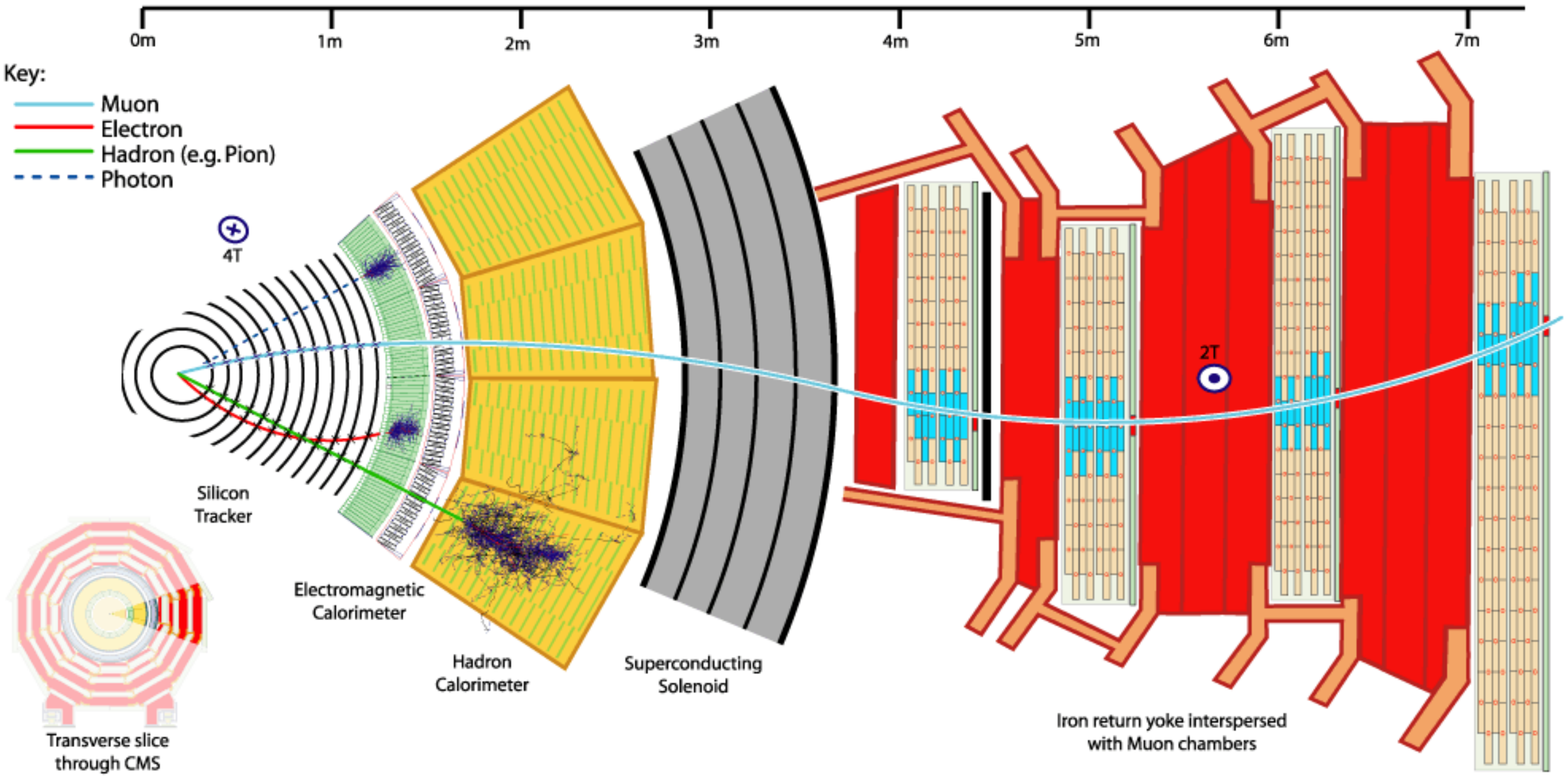
close to the village
of Cessy

at the foot of the
Jura mountains

Particle Flow

A global description of the event, using optimal combination from all sub detectors

Reduces the impact of energy resolution in HCAL
- in multijet events, only 10% of energy goes to stable neutral hadrons



Detection and measurement of "particules" produced at the interaction point
- muons
- electrons
- charged hadrons
- photons
- neutral hadrons

- light-flavour jets (u, d, s quarks or gluon)
- heavy-flavour jets (c or b quarks)
- tau-lepton jets
- "fat" jets with sous-structures (W/Z, H, t…)
- missing transverse momentum (neutrino, DM…)

for each object specific energy and position calibrations are applied

The Kappa Framework

Parameterisation based on **multiplicative coupling modifiers**, used to characterise Higgs boson couplings

- *tree-level* couplings to particles: κ_W, κ_Z, κ_t, κ_b, κ_c, κ_τ, κ_μ
- additional *effective* couplings: κ_g, κ_γ, $\kappa_{Z\gamma}$

Way to identify potential deviations in HIggs couplings to bosons and fermions

Link to signal strength measurements:

$$\mu_{if} \equiv \frac{\sigma_i \times B_f}{(\sigma_i \times B_f)^{\rm SM}} = \frac{\kappa_i^2 \times \kappa_f^2}{\kappa_{\rm H}^2}, \text{ where } \begin{cases} \kappa_i^2 = \sigma_i / \sigma_i^{\rm SM} \\ \kappa_f^2 = \Gamma_f / \Gamma_f^{\rm SM} \end{cases}, \text{ and } \quad \kappa_{\rm H}^2 = \Gamma_{\rm H} / \Gamma_{\rm H}^{\rm SM}$$

assumes narrow width approximation

Generalisation to incorporate a BSM (invisible) width and untagged decays:

$$\Gamma_{\rm H} = \frac{\kappa_{\rm H}^2 \times \Gamma_{\rm H}^{\rm SM}}{1 - (B^{\rm inv} + B^{\rm unt})}, \text{ where } \quad \kappa_{\rm H}^2 = \sum_f B_f^{\rm SM} \kappa_f^2$$

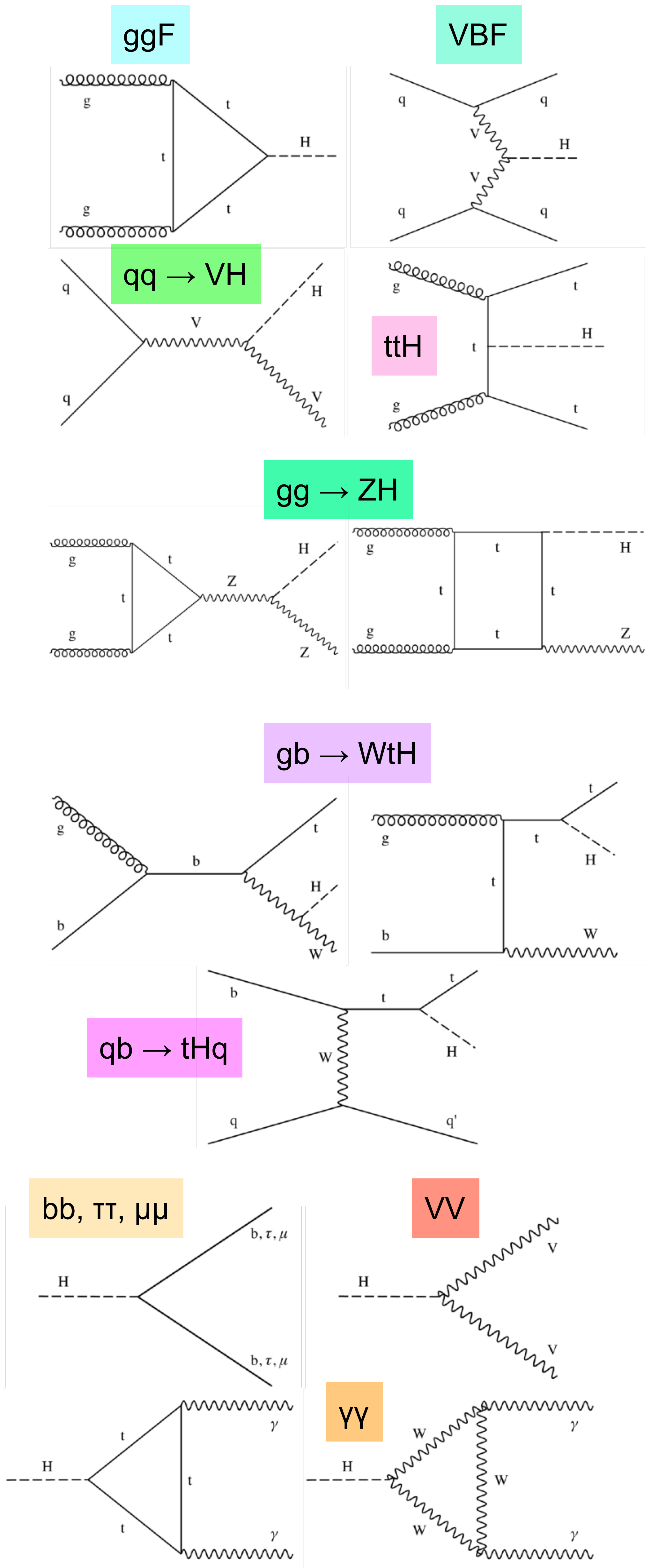
Untagged decays: rare SM (or BSM) decays that are not directly probed by searches

Ratio of coupling modifiers, immune from dependance in $\Gamma_{\rm H}$

$$\lambda_{ij} = \kappa_i / \kappa_j \text{ , compared to } \quad \kappa_{\rm gZ} = \kappa_{\rm g} \kappa_{\rm Z} / \kappa_{\rm H}$$

Resolved and Effective Kappas

		Loops	Interference	Effective scaling factor	Resolved scaling factor
	Production				
production modes	$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
	$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
	$\sigma(\mathrm{WH})$	—	—		κ_W^2
	$\sigma(qq/qg \to \mathrm{ZH})$	—	—		κ_Z^2
	$\sigma(gg \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
	$\sigma(\mathrm{ttH})$	—	—		κ_t^2
	$\sigma(gb \to \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
	$\sigma(qb \to \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
	$\sigma(\mathrm{bbH})$	—	—		κ_b^2
	Partial decay width				
decay channels	Γ^{ZZ}	—	—		κ_Z^2
	Γ^{WW}	—	—		κ_W^2
	$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
	$\Gamma^{\tau\tau}$	—	—		κ_τ^2
	Γ^{bb}	—	—		κ_b^2
	$\Gamma^{\mu\mu}$	—	—		κ_μ^2
	Total width for $\mathcal{B}_{\mathrm{BSM}} = 0$				
	Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 +$ $+ 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 +$ $+ 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 +$ $+ 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$



[EPJC 79 (2019) 421]

[K Coupling Modifiers, LHC Physics (2017) CERN YR4]

Global SMEFT Fit

see P. Hernándes & J. deBlas @ EPPSU Granada

Effective Field Theories (EFT) are tools to probe indirectly New Physics (NP)

SMEFT :
bottom-up approach

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{c^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2} + \dots$$

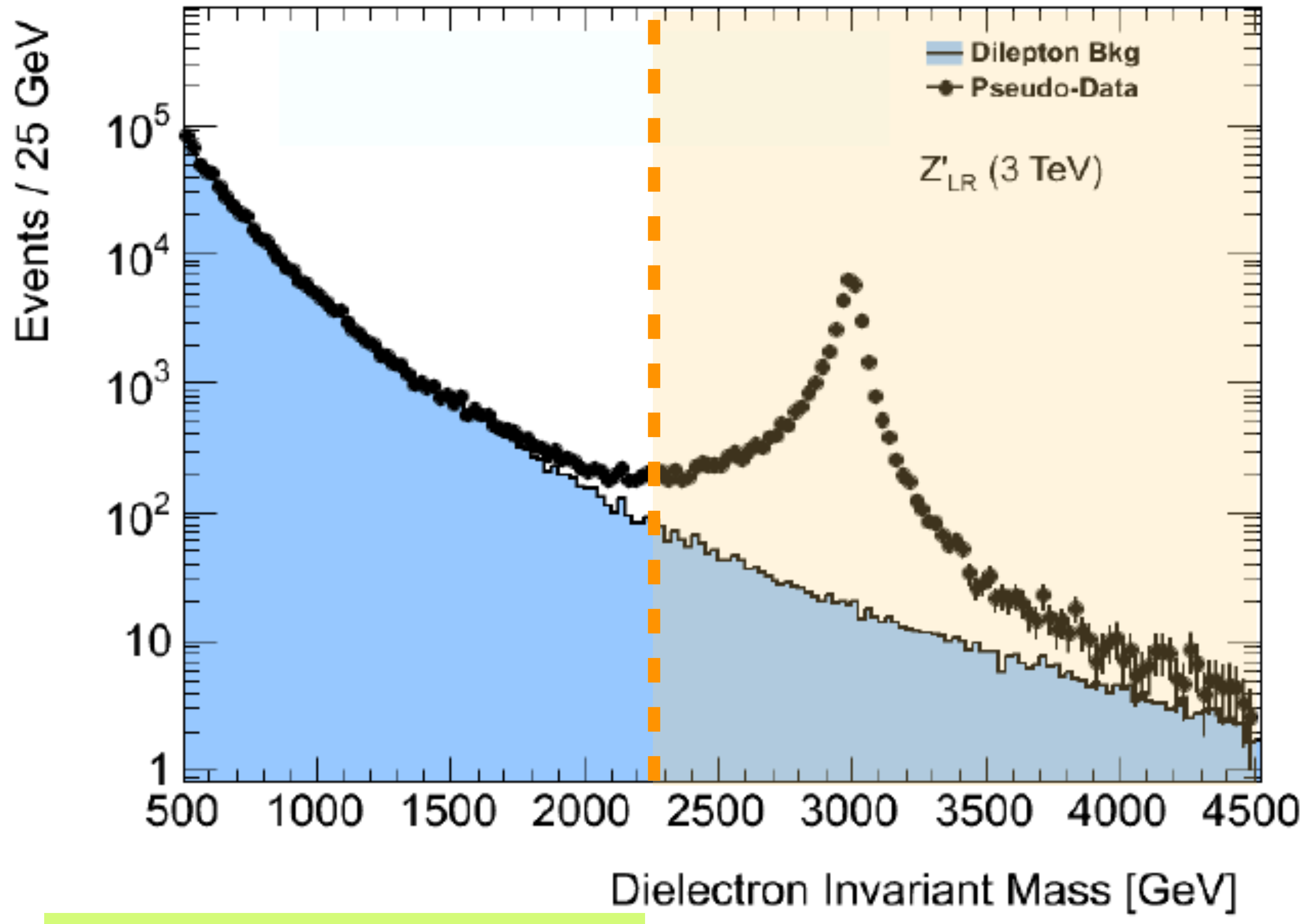
1 operator
ΔL = 2

2499 operators
(59 B-, L-, F-Conserving)

Beyond the κ-framework
global fit include also the di-boson and EWK precision observables

Λ = cut-off of the EFT

effect of a Z' in the dilepton spectrum



no resonance seen
but *deviations* wrt SM

☛ Non-renormalisable terms imply violation of unitarity at high energies

$$\sigma \propto \left(c_i^{(6)}/\Lambda^2\right)^2 s$$

☛ NP must manifest itself before unitarity is violated

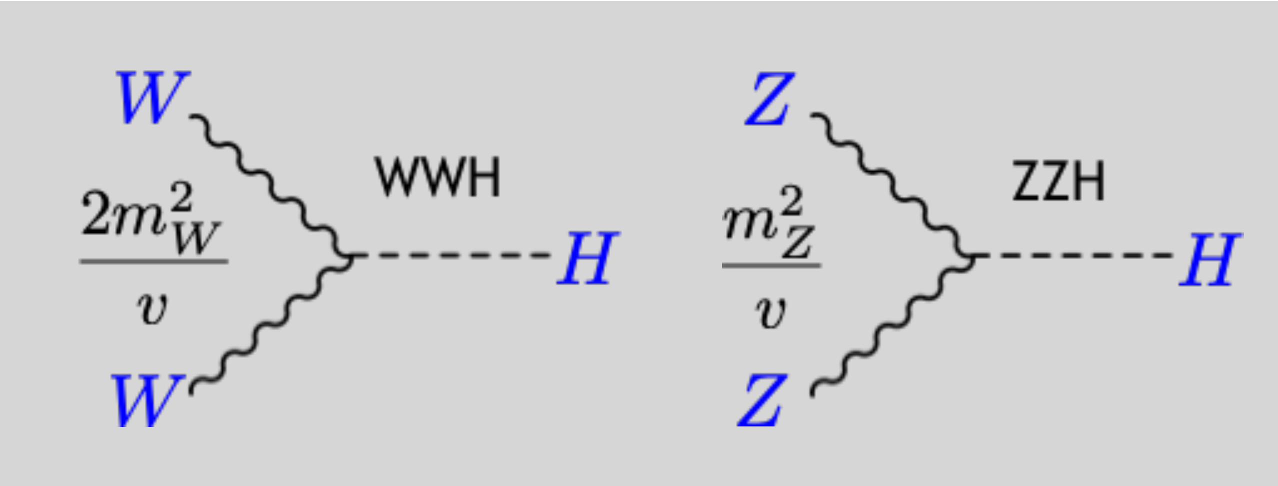
$$E_i^{\max} \lesssim \Lambda/\sqrt{c_i^{(6)}}$$

$c_i^{(6)}$ can modify gauge, Higgs, and top couplings

Anomalous hVV Couplings

☛ SM hVV Lagrangian:

$$\mathcal{L}^{hVV}_{\rm SM} = \frac{h}{v}\left[2m_W^2 W^+_\mu W^-_\mu + m_Z^2 Z_\mu Z_\mu\right]$$



☛ dim-6 SMEFT hVV Lagrangian:

$$\begin{aligned}\Delta\mathcal{L}^{hVV}_{6} = \frac{h}{v}\Big[& 2\delta c_w m_W^2 W^+_\mu W^-_\mu + \delta c_z m_Z^2 Z_\mu Z_\mu \\ & + c_{ww}\frac{g^2}{2} W^+_{\mu\nu} W^-_{\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^+_{\mu\nu} + \text{h.c.}\right) \\ & + c_{gg}\frac{g_s^2}{4} G^a_{\mu\nu} G^a_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} \\ & + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}\Big]\end{aligned}$$

➠ 7 independent parameters

☛ Parameters are related by gauge invariance:

$$\delta c_w = \delta c_z + 4\delta m$$

NP contributions to m_W: only source of custodial symmetry breaking

$$c_{ww} = c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma}$$

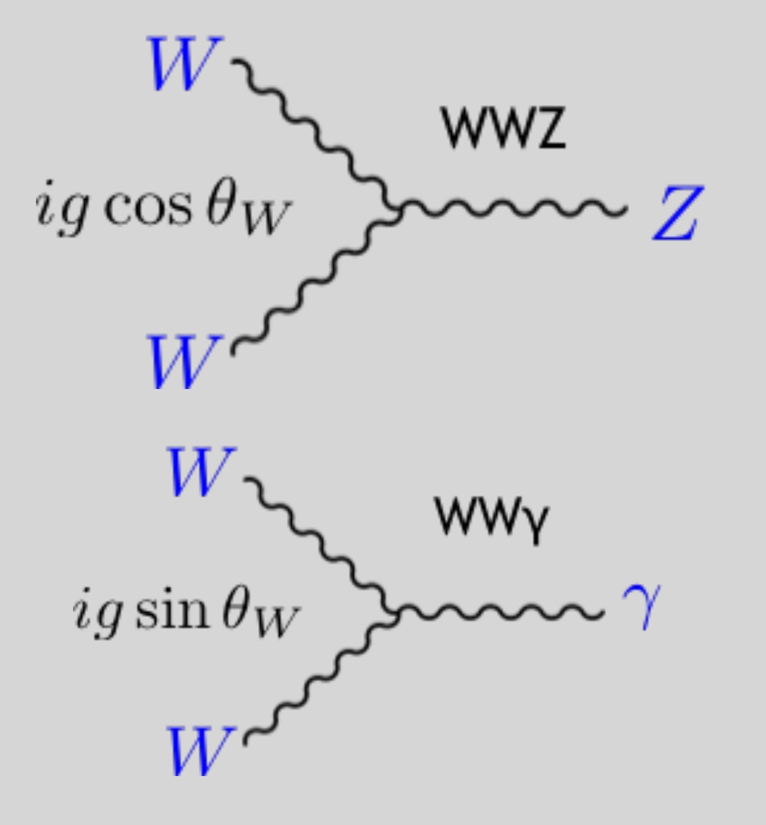
$$c_{w\Box} = \frac{1}{g^2 - g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\sin^2\theta_w c_{\gamma\gamma} - (g^2 - g'^2)\sin^2\theta_w c_{z\gamma}\right]$$

$$c_{\gamma\Box} = \frac{1}{g^2 - g'^2}\left[2g^2 c_{z\Box} + (g^2 + g'^2) c_{zz} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{z\gamma}\right]$$

A. Falkowski arxiv:1505.00046

de Blas et al, arxiv:1907.04311

Anomalous TGC



☛ SM TGC Lagrangian:

$$\mathcal{L}_{\rm SM}^{\rm TGC} = ig\cos\theta_w\left[(W^-_{\mu\nu}W^{+\mu} - W^+_{\mu\nu}W^{-\mu})Z^\nu \;+ Z_{\mu\nu}W^{+\mu}W^{-\nu}\right] + ig\sin\theta_w\left[(W^-_{\mu\nu}W^{+\mu} - W^+_{\mu\nu}W^{-\mu})A^\nu \;+ F_{\mu\nu}W^{+\mu}W^{-\nu}\right]$$

☛ dim-6 SMEFT TGC Lagrangian:

$$\Delta\mathcal{L}^{\rm aTGC} = ie\delta\kappa_\gamma A^{\mu\nu}W^+_\mu W^-_\nu + ig\cos\theta_w\Big[\delta g_{1Z}(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})Z^\nu + (\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma)Z^{\mu\nu}W^+_\mu W^-_\nu\Big] + \frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W^{+\nu}_\mu W^{-\rho}_\nu A^\mu_\rho + \cos\theta_w W^{+\nu}_\mu W^{-\rho}_\nu Z^\mu_\rho\right)$$

☛ 2 aTGC parameters can be expressed in terms of anomalous hVV parameters:

$$\delta g_{1,z} = \frac{1}{2(g^2-g'^2)}\left[c_{\gamma\gamma}e^2g'^2 + c_{z\gamma}(g^2-g'^2)g'^2 - c_{zz}(g^2+g'^2)g'^2 - c_{z\Box}(g^2+g'^2)g^2\right]$$

$$\delta\kappa_\gamma = -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right)$$

➠ 1 independent parameter

A. Falkowski arxiv:1505.00046

de Blas et al, arxiv:1907.04311

Anomalous hff and (h)Vff Couplings

☛ dim-6 SMEFT hff Lagrangian:

$$\Delta\mathcal{L}_6^{hff} = -\frac{h}{v}\sum_{f\in u,d,e}(\delta y_f)_{ij}\,(m_f)_{jj}\,\bar{f}_i f_j + \text{h.c.}$$

- CP-violating phases are set to zero and off-diagonal terms are not considered

➠ keep 5 independent hff parameters

δy_t (=$(dy_u)_{33}$), δy_c (=$(dy_u)_{22}$), δy_b (=$(dy_d)_{33}$), δy_τ (=$(dy_e)_{33}$), δy_μ (=$(dy_e)_{22}$)

☛ dim-6 SMEFT (h)Vff Lagrangian:

$$\Delta\mathcal{L}_6^{(h)Vff} = \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left((\delta g_W^\ell)_{ij}\,\bar{\nu}_L^i\gamma^\mu \ell_L^j + (\delta g_{W,L}^q)_{ij}\,\bar{u}_L^i\gamma^\mu d_L^j + (\delta g_{W,R}^q)_{ij}\,\bar{u}_R^i\gamma^\mu d_R^j + \text{h.c.}\right)$$
$$+\sqrt{g^2+g'^2}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}(\delta g_{Z,L}^f)_{ij}\,\bar{f}_L^i\gamma^\mu f_L^j + \sum_{f=u,d,e}(\delta g_{Z,R}^f)_{ij}\,\bar{f}_R^i\gamma^\mu f_R^j\right]$$

with

$$\delta g_W^\ell = \delta g_{Z,L}^\nu - \delta g_{Z,L}^\ell$$
$$\delta g_{W,L}^q = \delta g_{Z,L}^u V_{CKM} - V_{CKM}\,\delta g_{Z,L}^d$$

- assume flavour-diagonal couplings
- impose U(2) for the first 2 families

➠ keep 15 independent parameters: 6 (Zℓℓ) + 3 (Wℓν) + 2 (Zu$\bar{u}$) + 4 (Zd$\bar{d}$)

Equivalence Theorem: Vff ↔ hVff

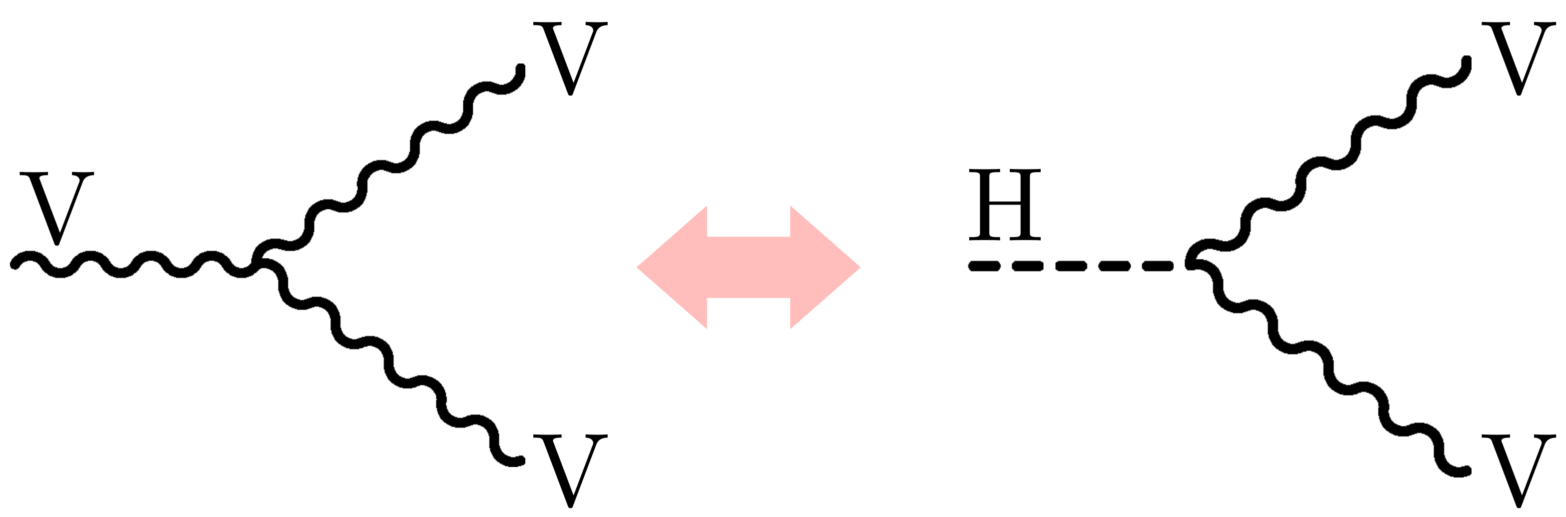
In the SM, the Higgs boson field *h* is one of
4 ddl as part of an $SU(2)_L$ doublet

F. Riva, HL/HE-LHC symposium, 2019
Ch. Grojean, ECFA/EPS, 2019

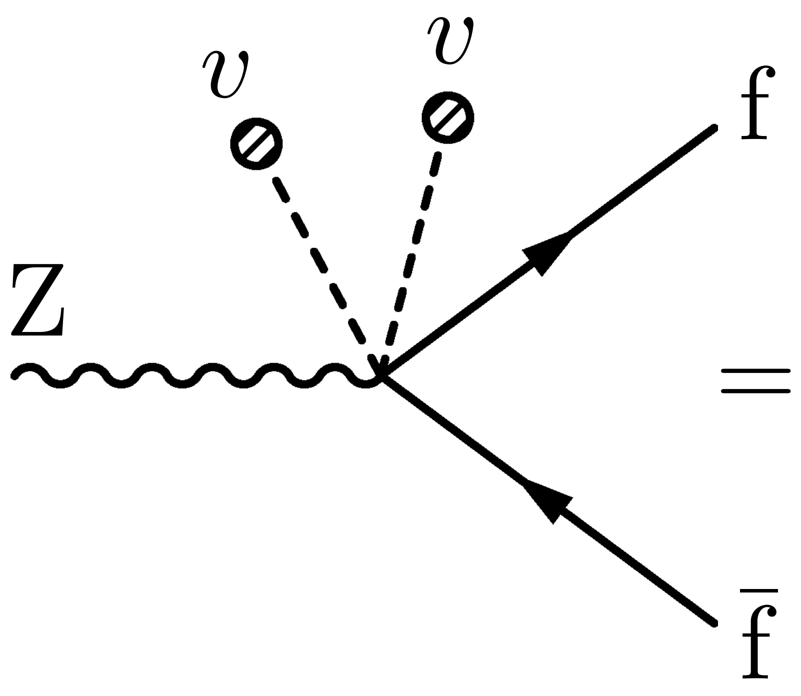
$$\phi = \begin{pmatrix} h^{\pm} \\ (v+h) + ih^0 \end{pmatrix}$$

$W_L^{\pm}$ ($h^{\pm}$), H (h), Z_L (h^0)

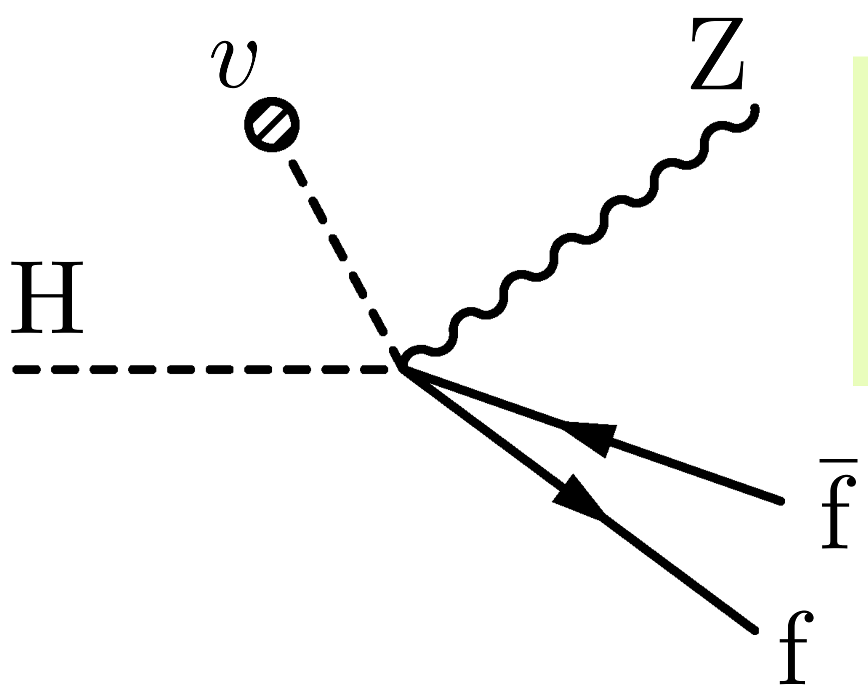
At some level of precision (not yet reached at the LHC) electroweak and diboson processes will interfere with Higgs measurements



connection between vector boson scattering and Higgs couplings to bosons



$$= \frac{1}{2v} \times$$



connection between Z decays to fermions and Higgs decay to $Zf\bar{f}$

contact interaction term (grows with energy)

one of the purposes of SMEFT is to exploit fully the connections between the electroweak and Higgs sectors

SMEFT Fit Parameters for Higgs Studies

Neutral Diagonal (ND) scenario

- a sufficient set of SMEFT parameters to describe Z-pole EWPO, diboson and single Higgs processes at colliders
- assumes flavour-diagonal neutral couplings
- assumes flavour universality for the first two families

- 1 (δm) + 6 (hVV/aTGC) + 1 (aTGC)
- 5 (hff)
- 6 ($Z\ell\ell$) + 3 ($W\ell\nu$) + 2 ($Zu\bar{u}$) + 4 ($Zd\bar{d}$)

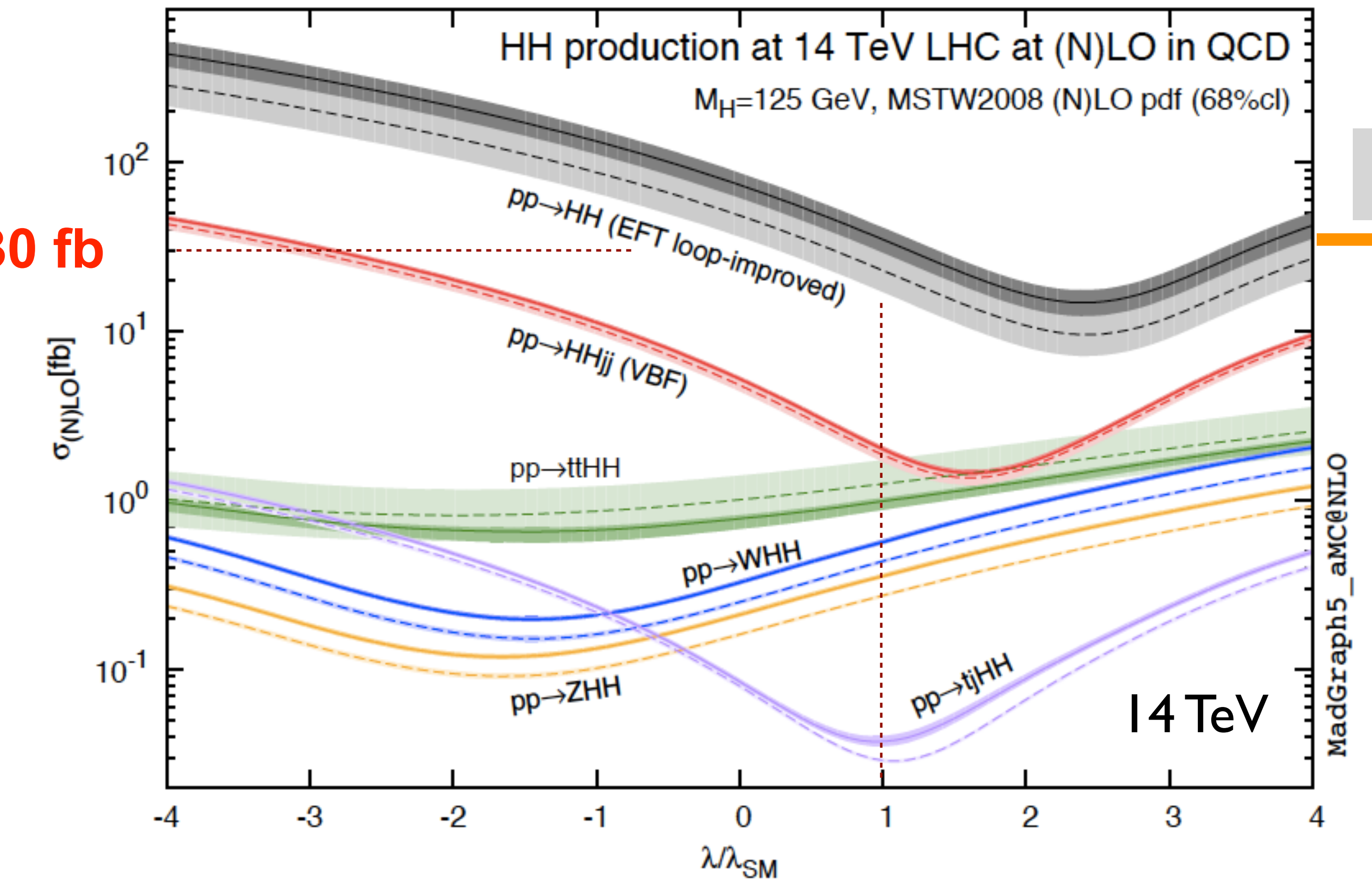
➠ 28 new physics parameters

To compare with results from the kappa-framework studies

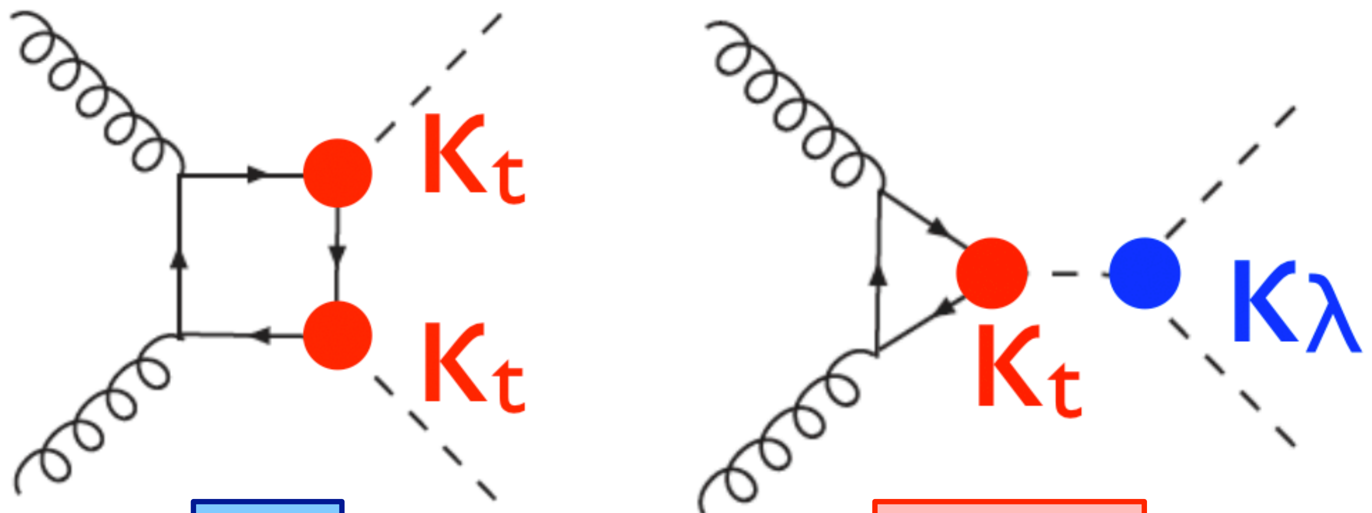
- project the ND SMEFT fit results onto observables similar to Higgs coupling modifiers and Zff effective couplings
- complete with TGC modifiers to get the correct number of independent parameters

HH Production & Self-Coupling at LHC

pp → HH



ggF

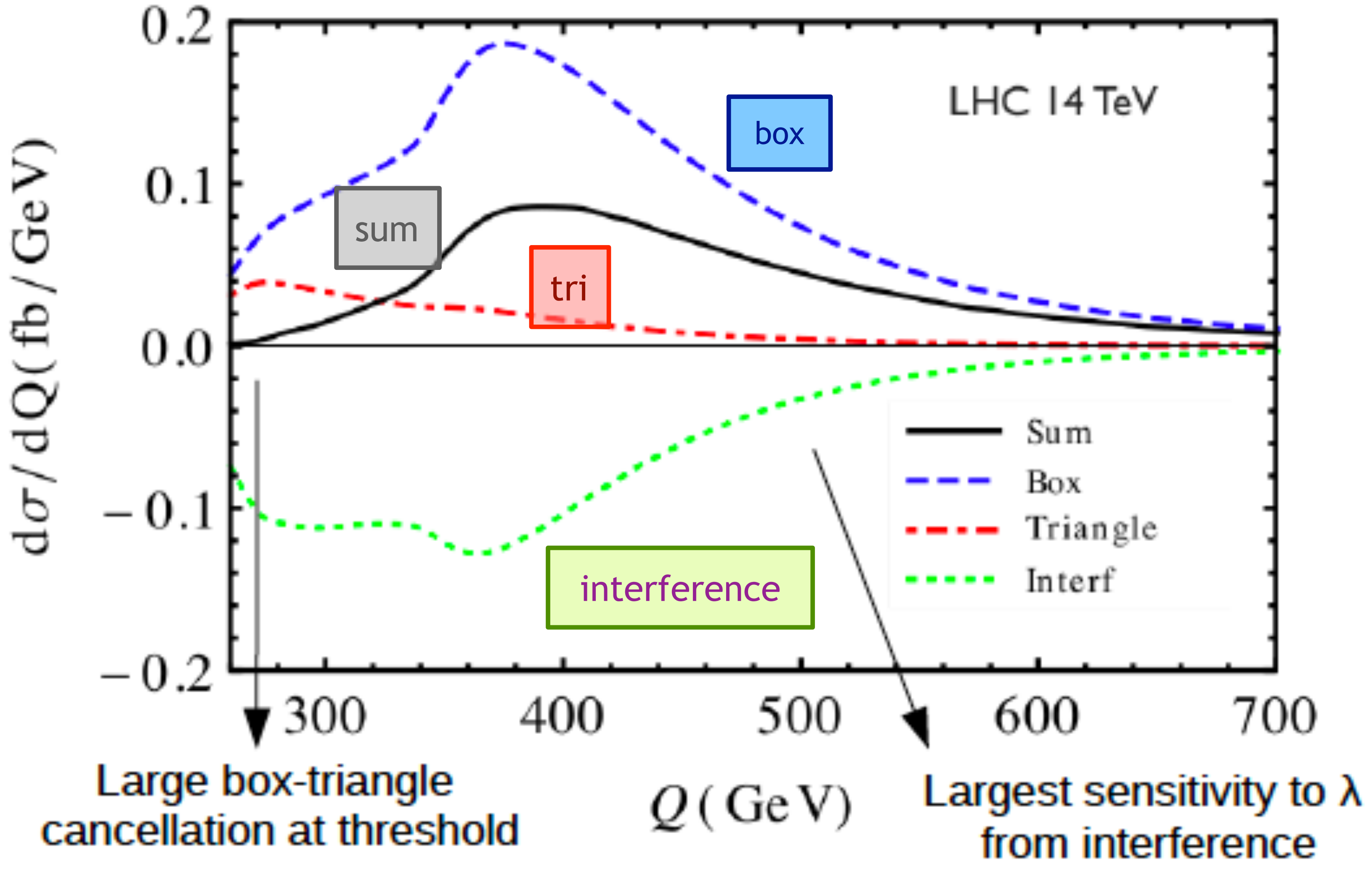


box

triangle

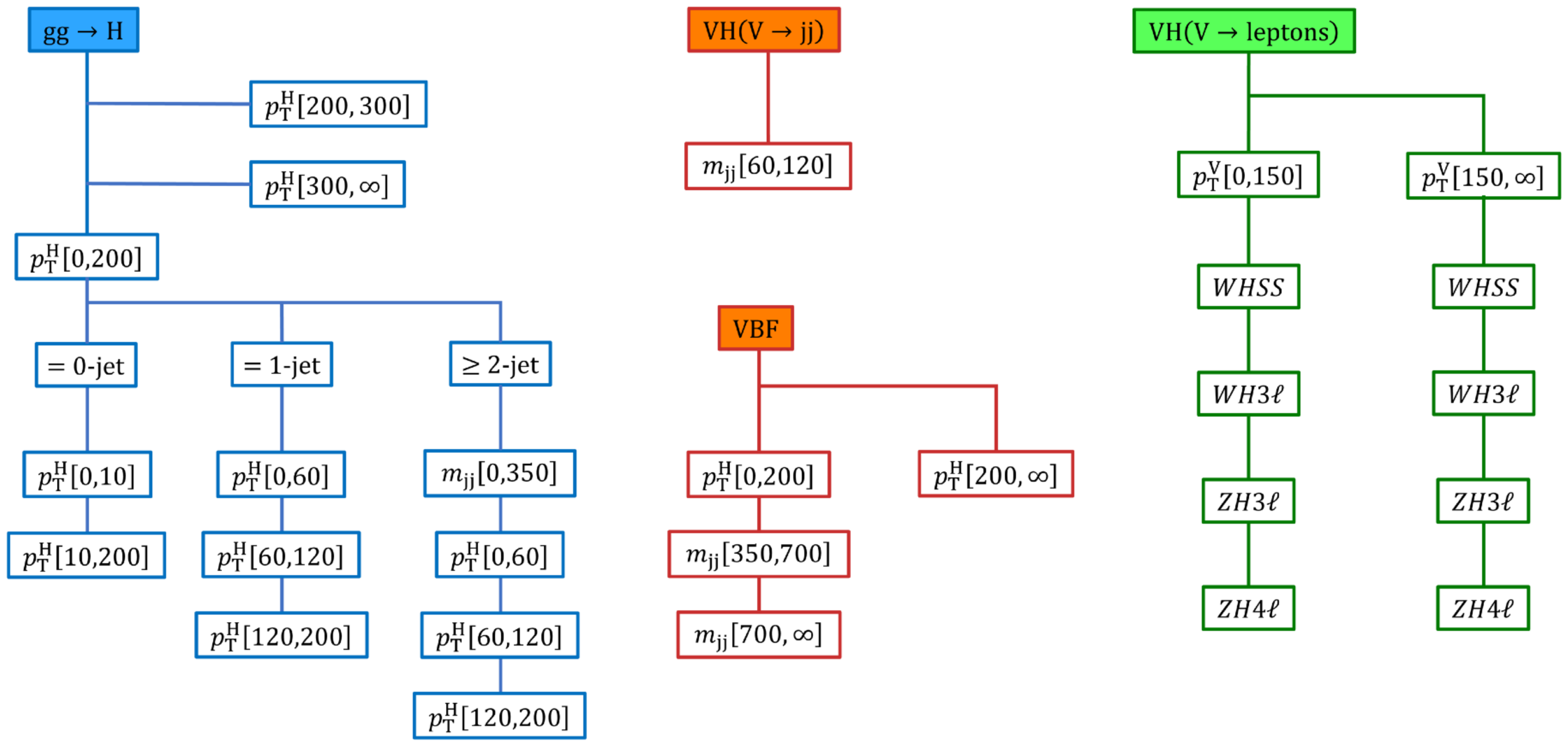
- $\sigma(pp \to HH)$ = 30 fb at $\sqrt{s}$ = 14 TeV
- $\sigma(pp \to HH)/\sigma(pp \to H)$ = 1‰

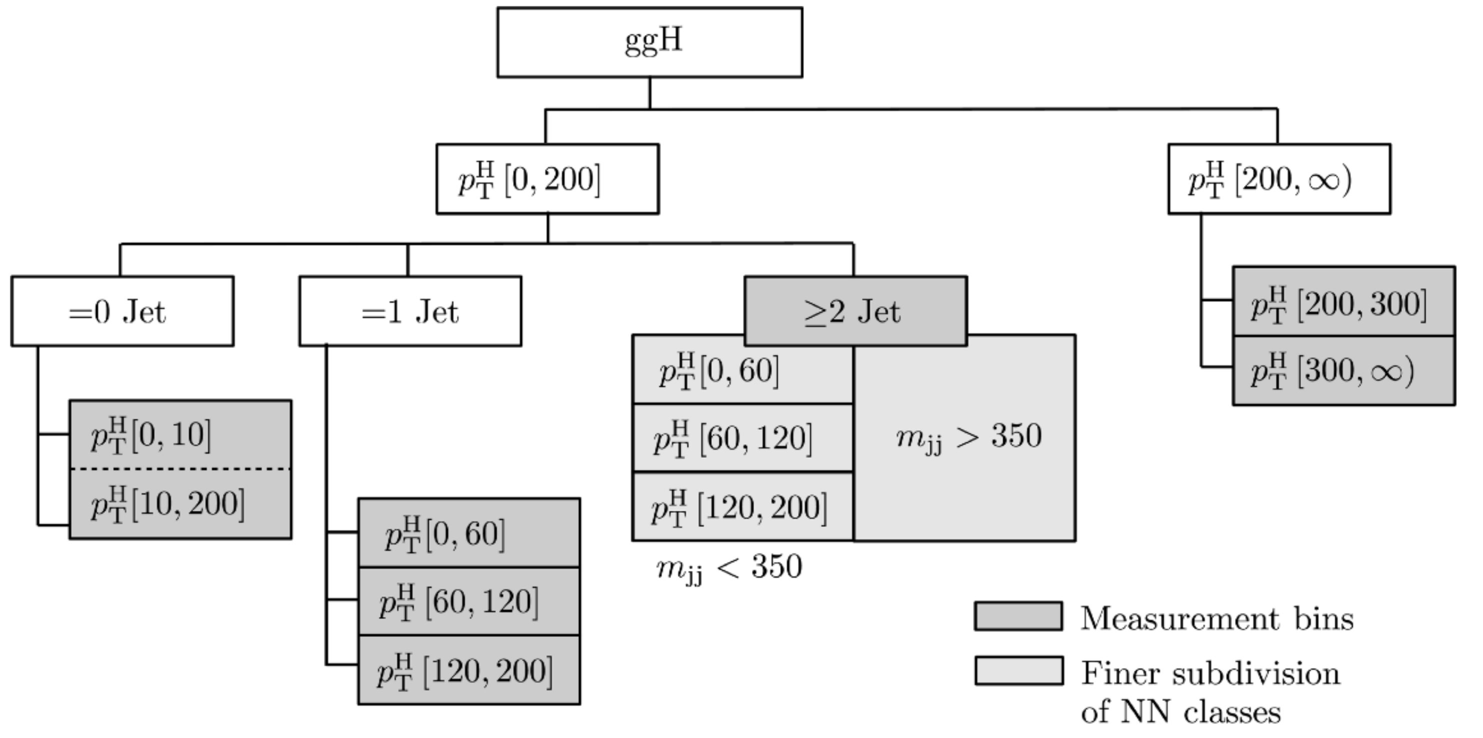
destructive interference between box and triangle

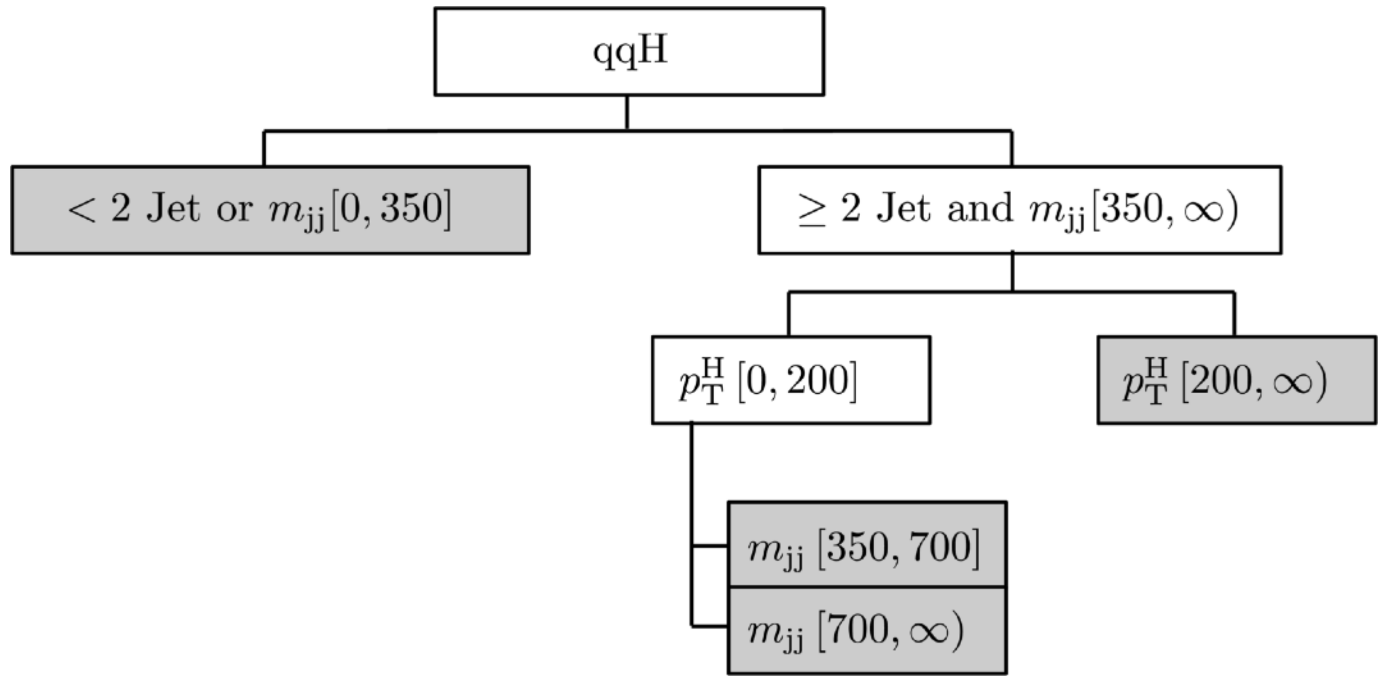


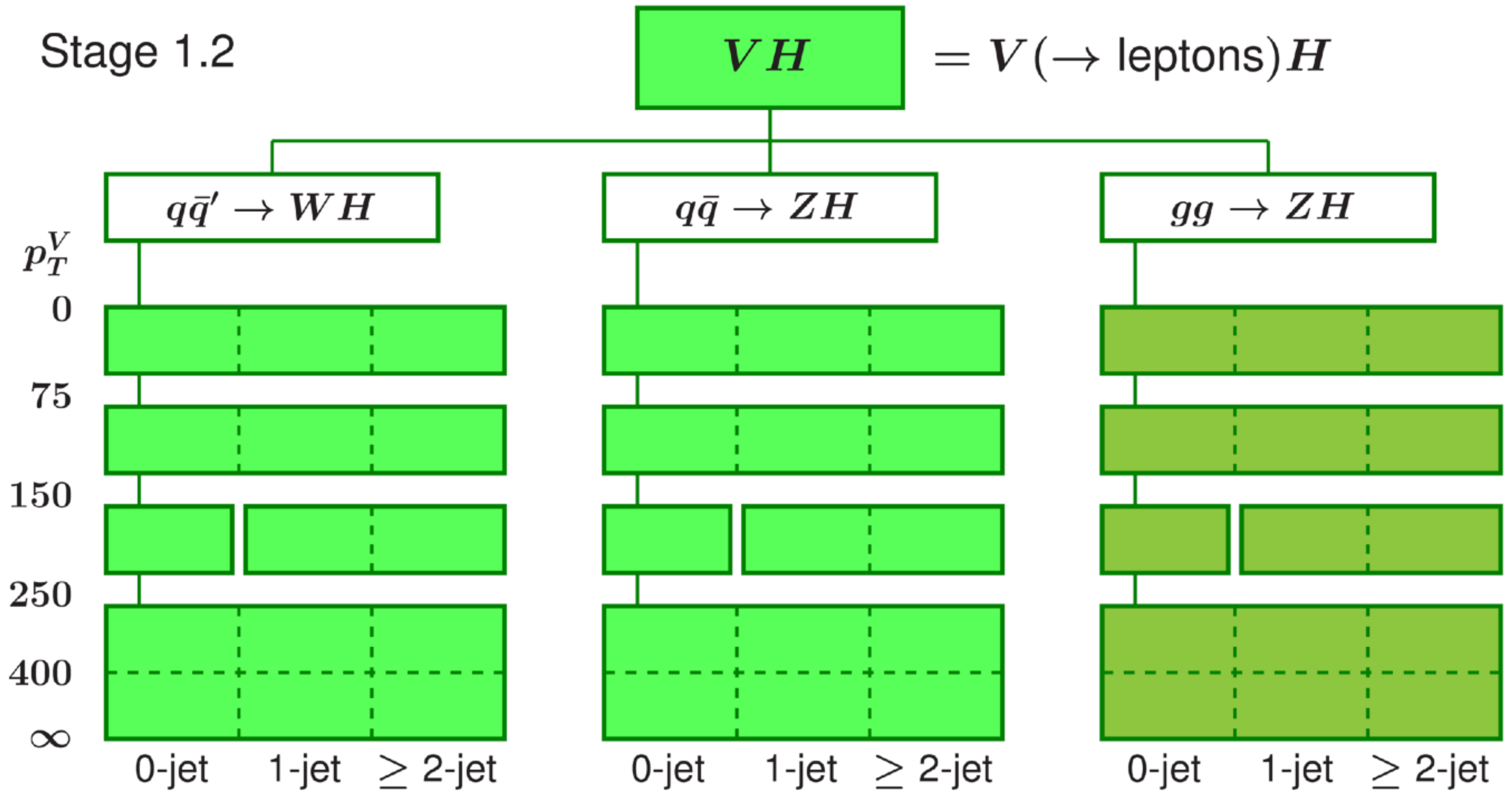
☛ lots of information from differential cross section in m_{HH}

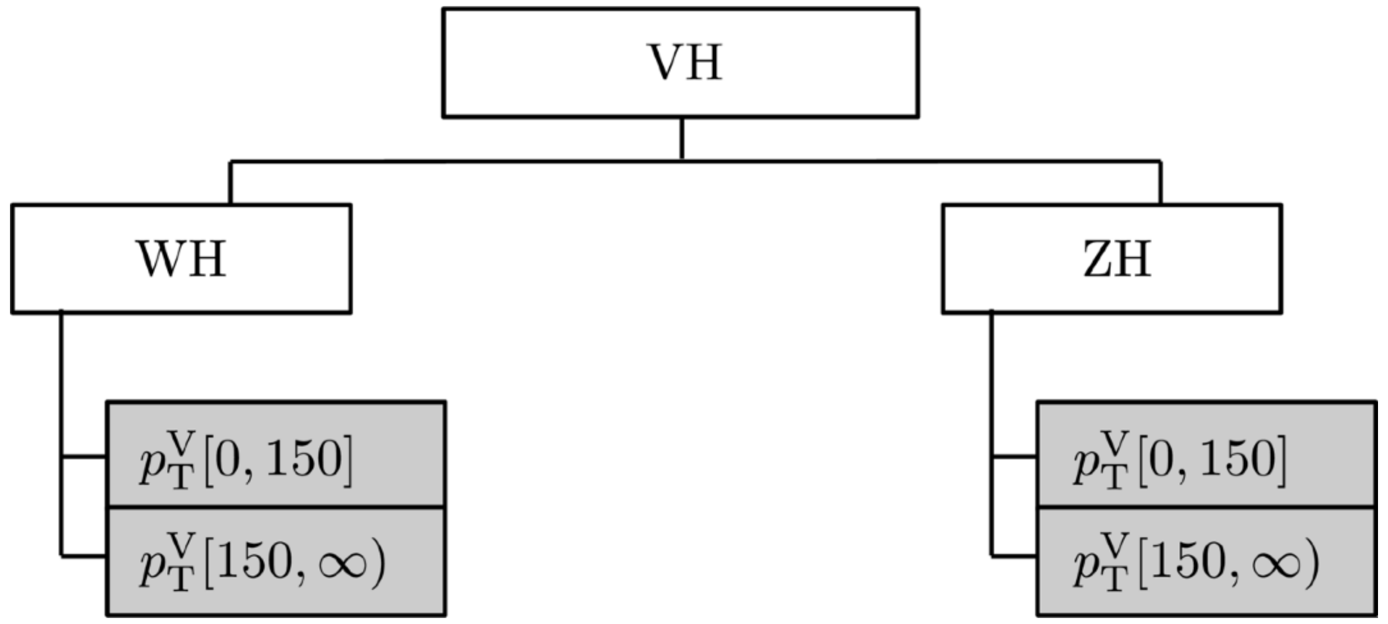
STSX Bin Definitions











ttH Measurements

Multi-lepton final states (e, μ, τ_h)

mostly $\mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}, \tau\tau$

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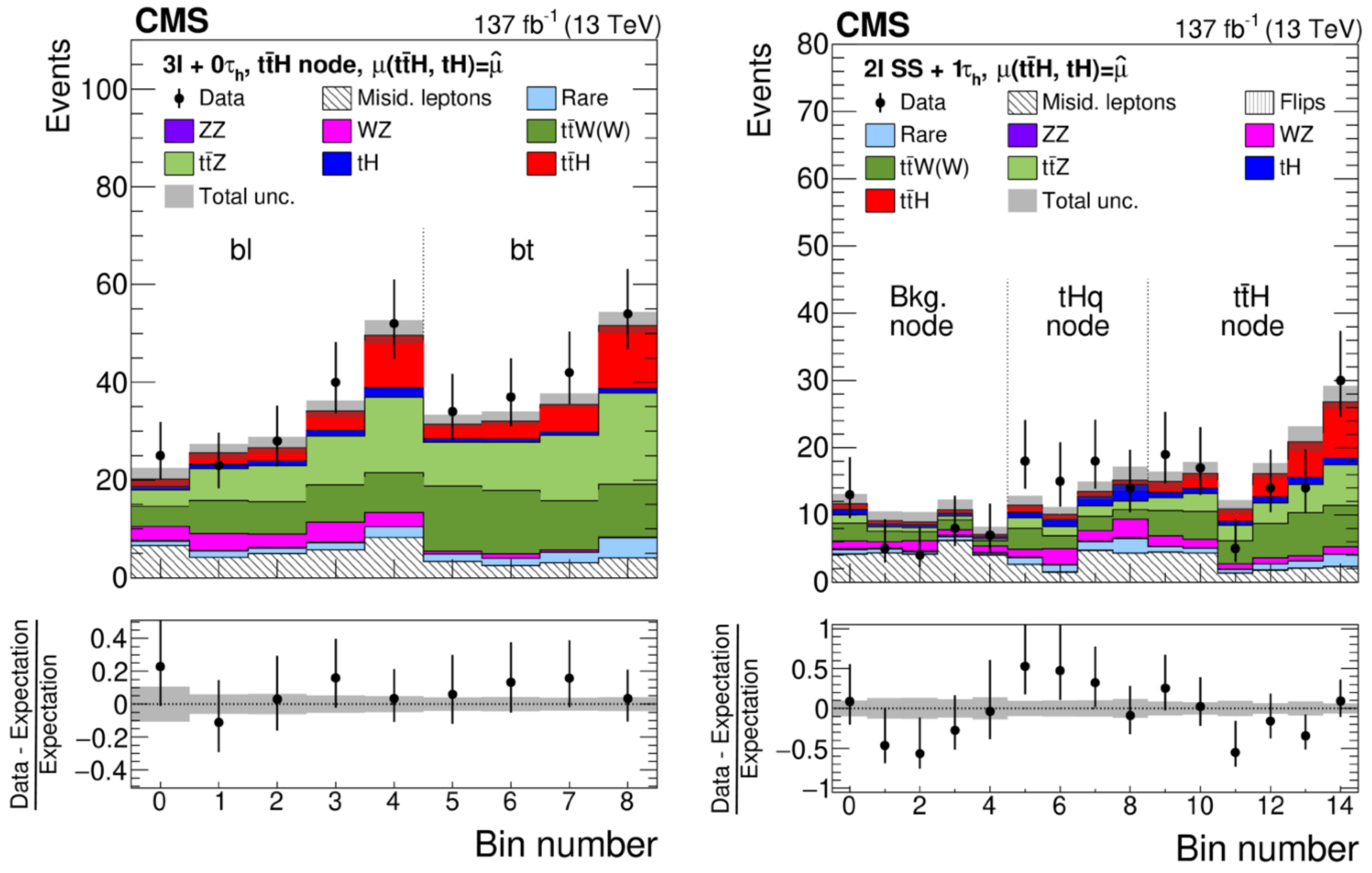
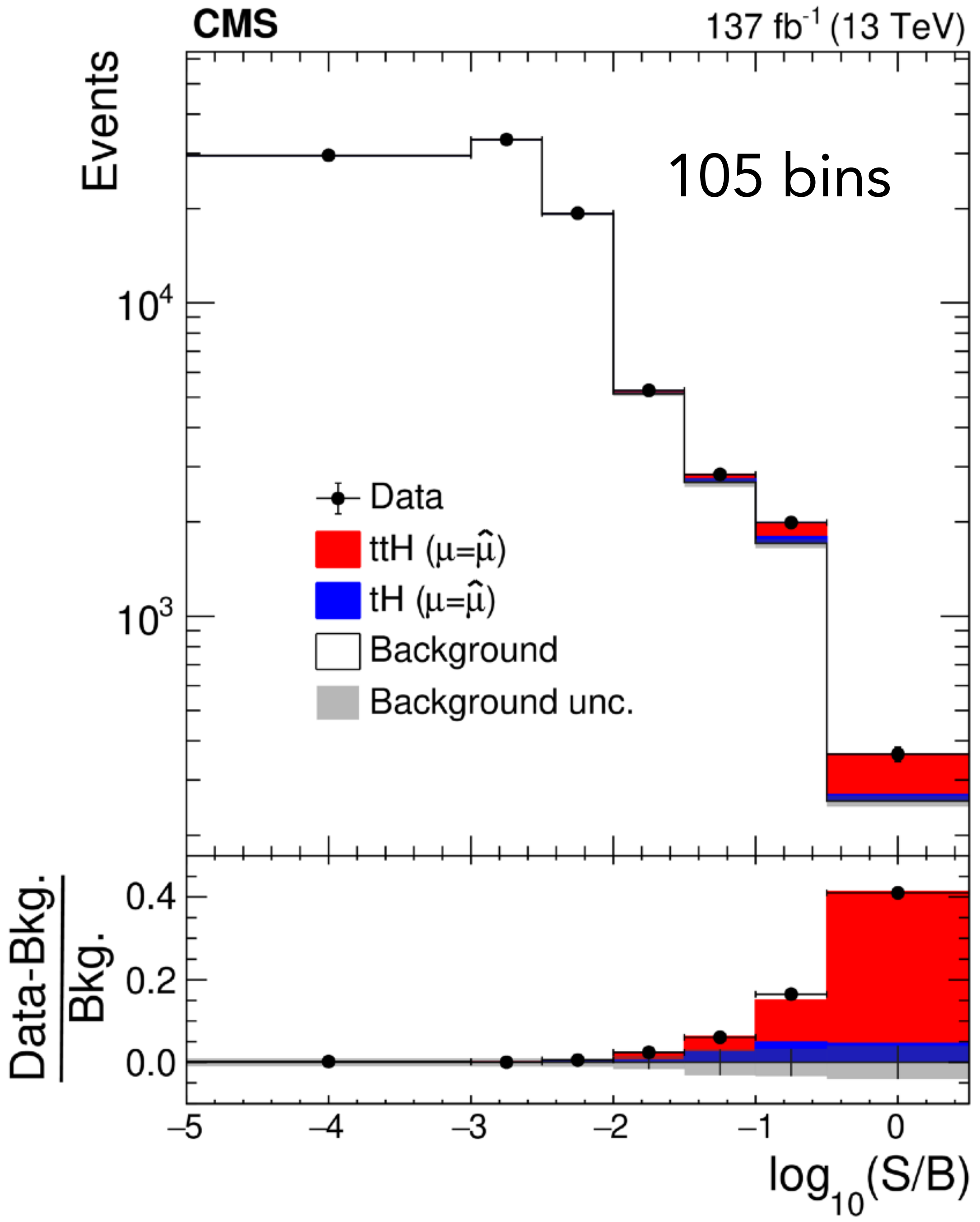
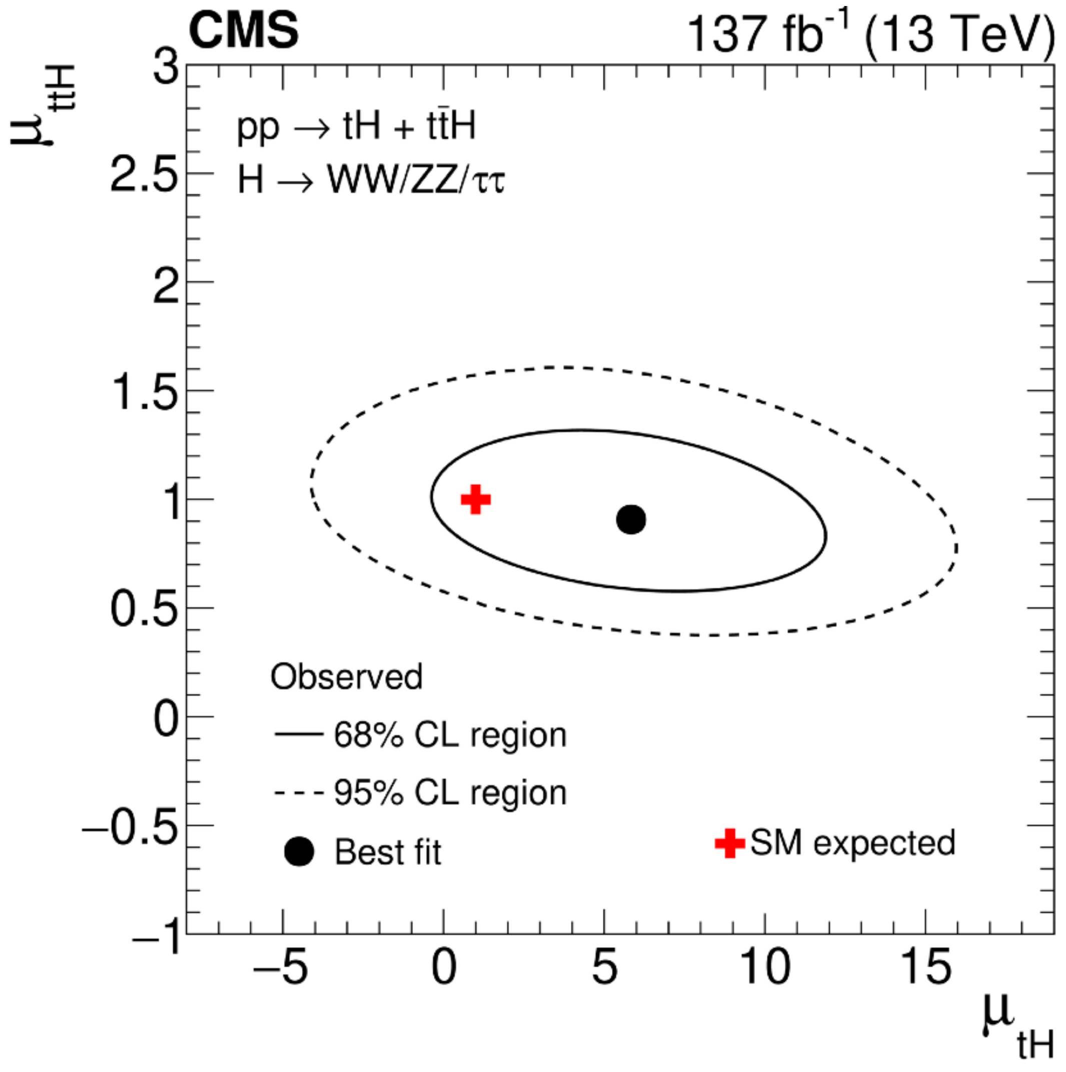
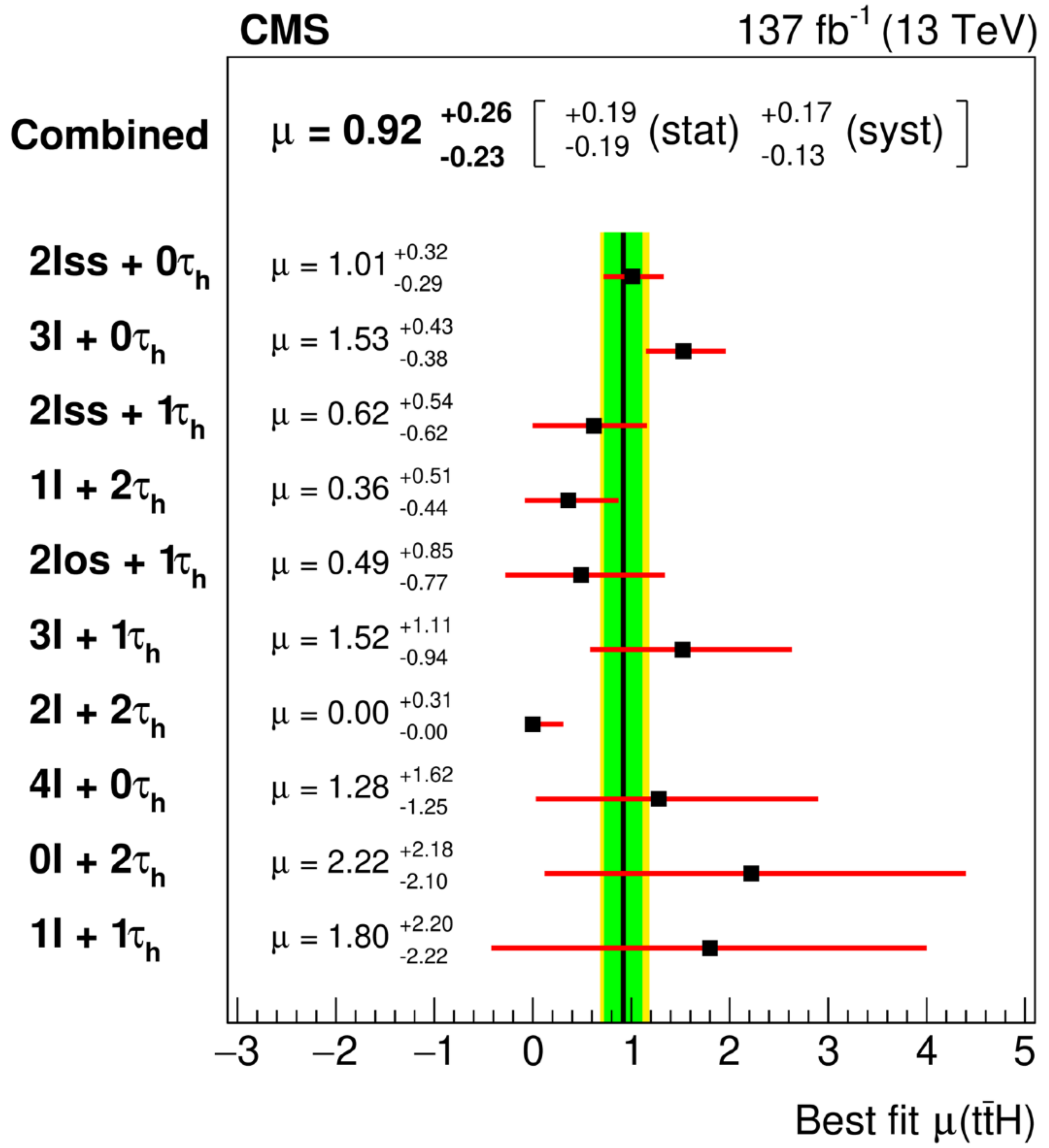


activation value of the ANN output node with the highest activation value







$$\mu(\mathrm{t\bar{t}H}) = 0.92 \pm 0.19\,(\mathrm{stat})^{+0.17}_{-0.13}(\mathrm{syst})$$

Obs. (exp.) significance: 4.7 (5.2) σ

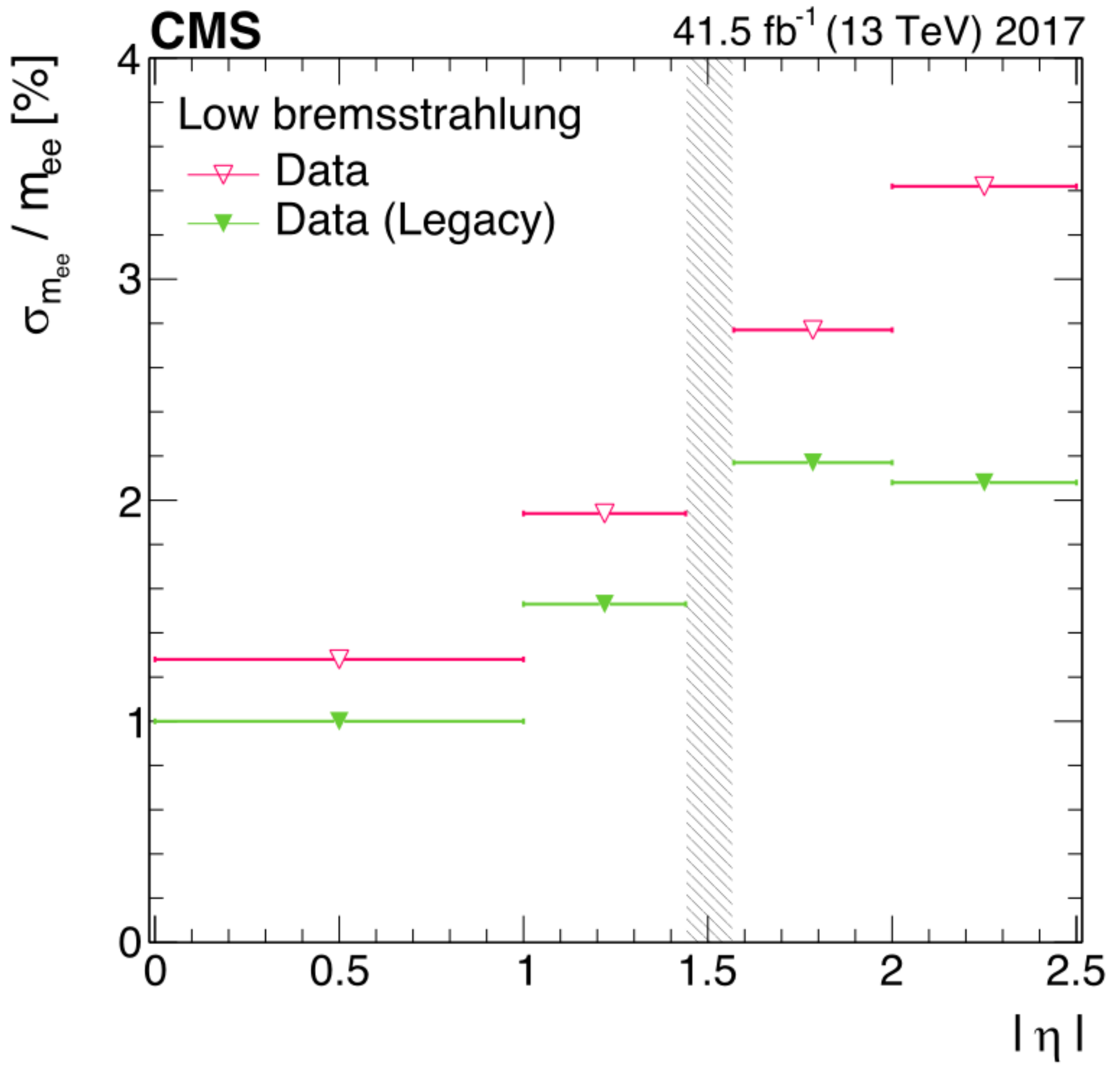
$$\mu(\mathrm{tH}) = 5.7 \pm 2.7\,(\mathrm{stat}) \pm 3.0\,(\mathrm{syst})$$

Phys. Briefing

Run-2 Performance

Thanks to a huge effort of improvement in **calibration procedures** and **software tools**, CMS Run-2 analyses are performed on an **optimally calibrated data sample** (Legacy Run-2 data)

Comparison of Z mass resolution before and after **final calibration** included in Legacy Run 2 data



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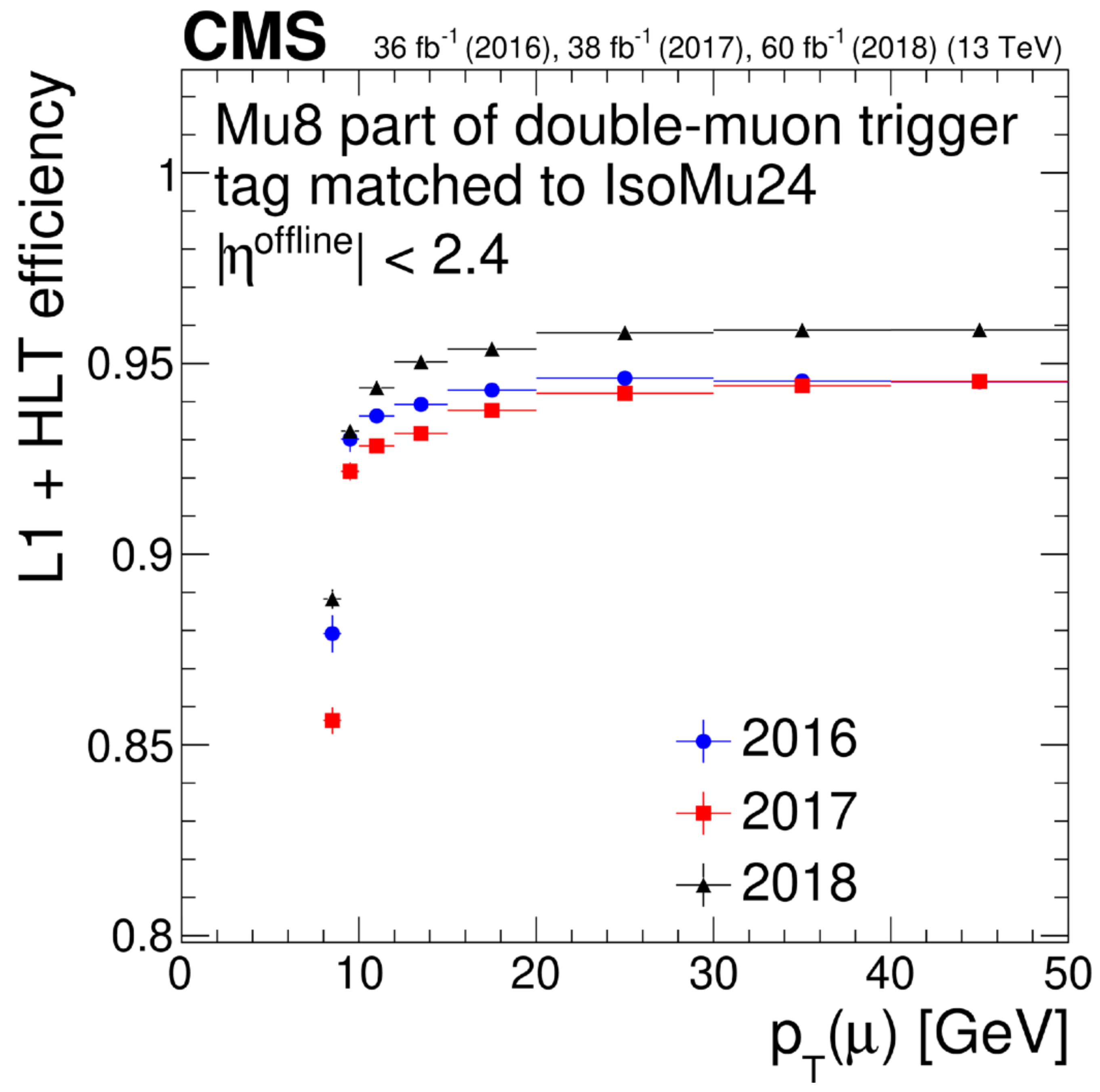
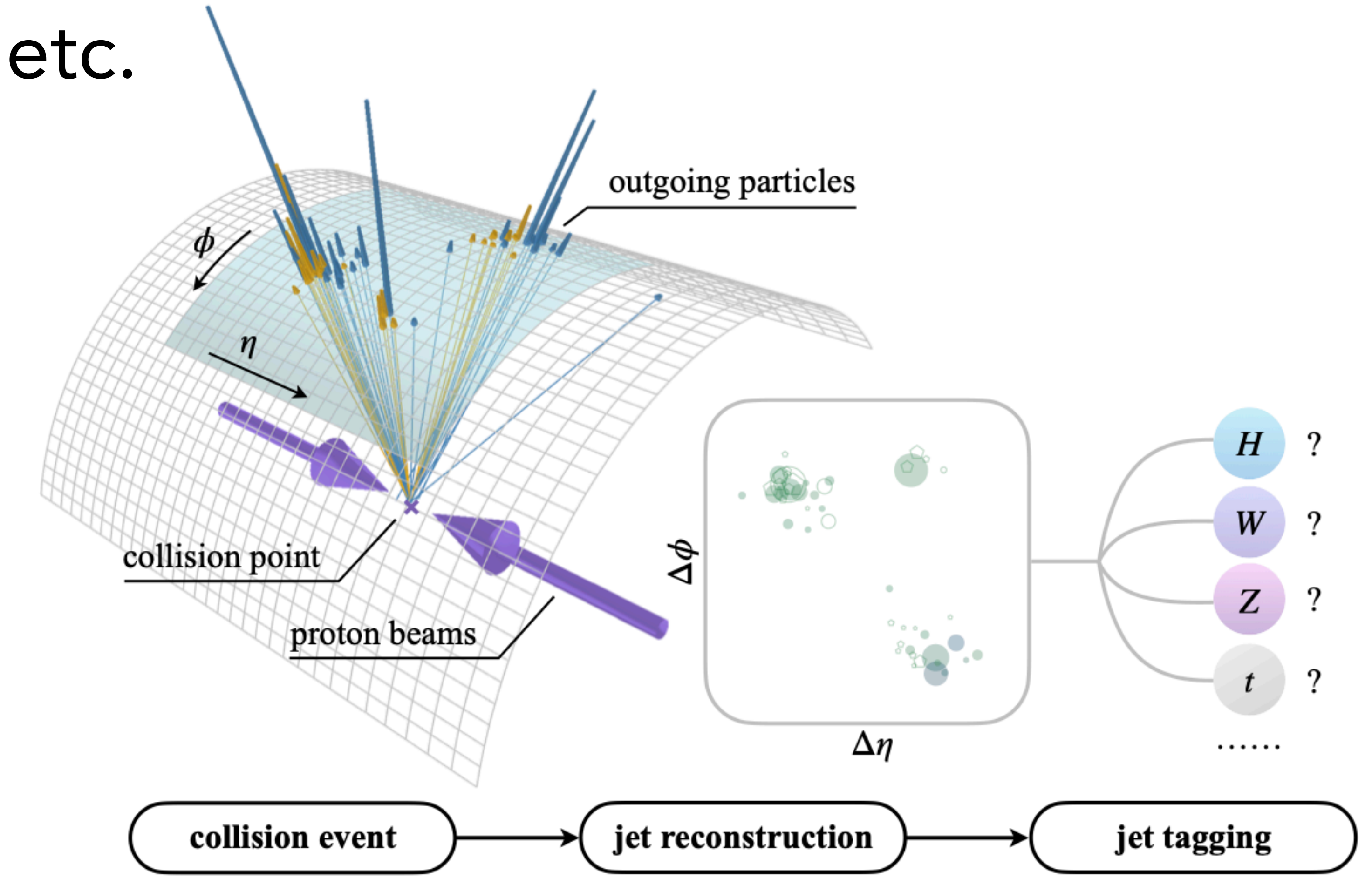
Extensive measurements of Run-2 **L1 and HLT trigger performance**



CMS-MUO-19-001
JINST 16 (2021) P07001

Impressive improvement in analysis techniques with intensive use of **state-of-the-art ML techniques**, deep-learning neural nets, etc.

- PU mitigation
- b- and c-jet tagging
- τ-lepton reconstruction
- Lorentz-boosted jet tagging and mass
- etc.



arXiv:2202.03772

Particle Transformer for jet tagging