Lecture 2:
Higgs Properties

Lecture 2:

Higgs Properties

The Two LHC Combined LEGACY papers

Mass and Couplings

& 2016 ICHEP

Radiohead

Updates

(No Surprises)

eilam gross

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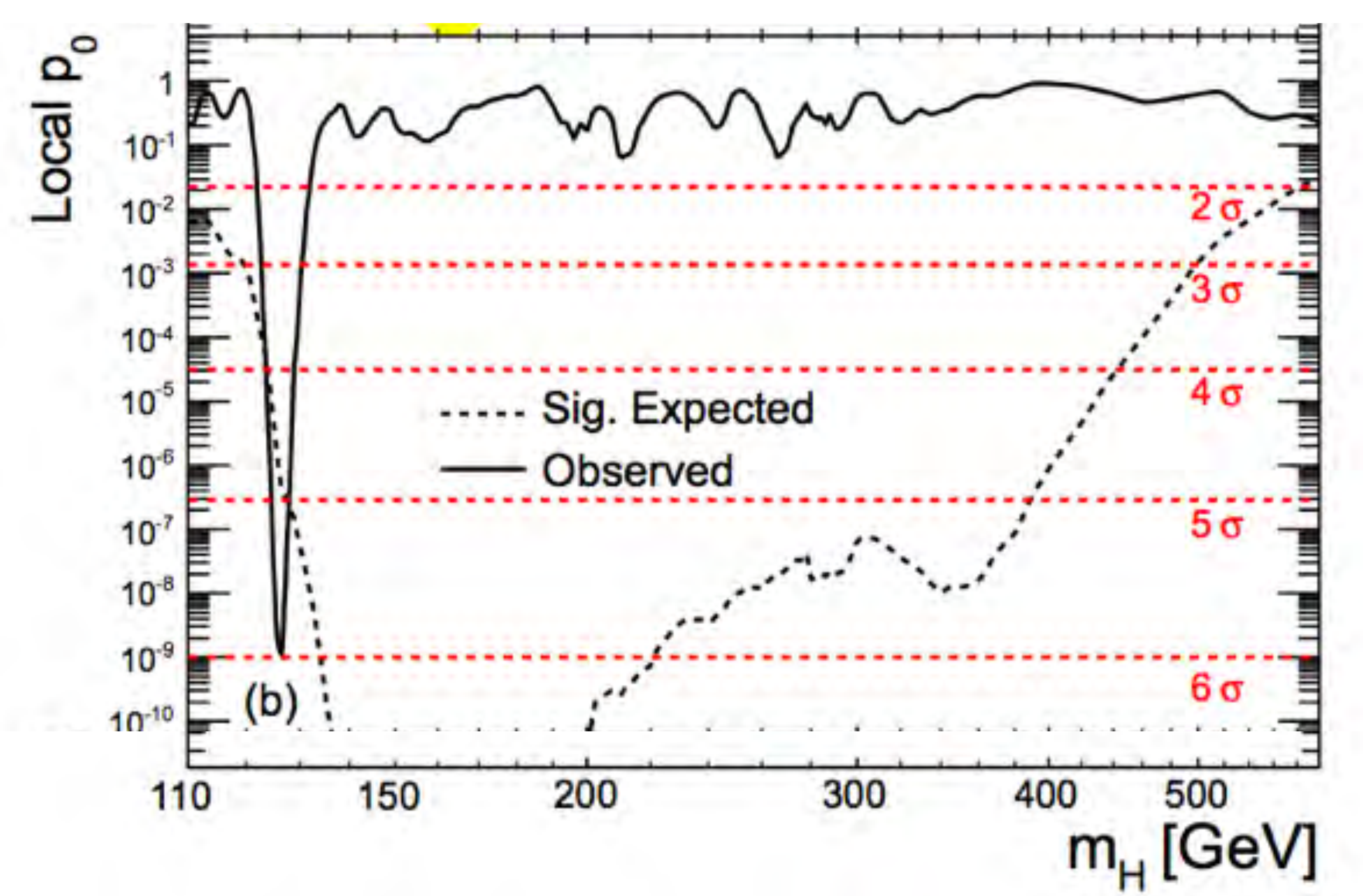
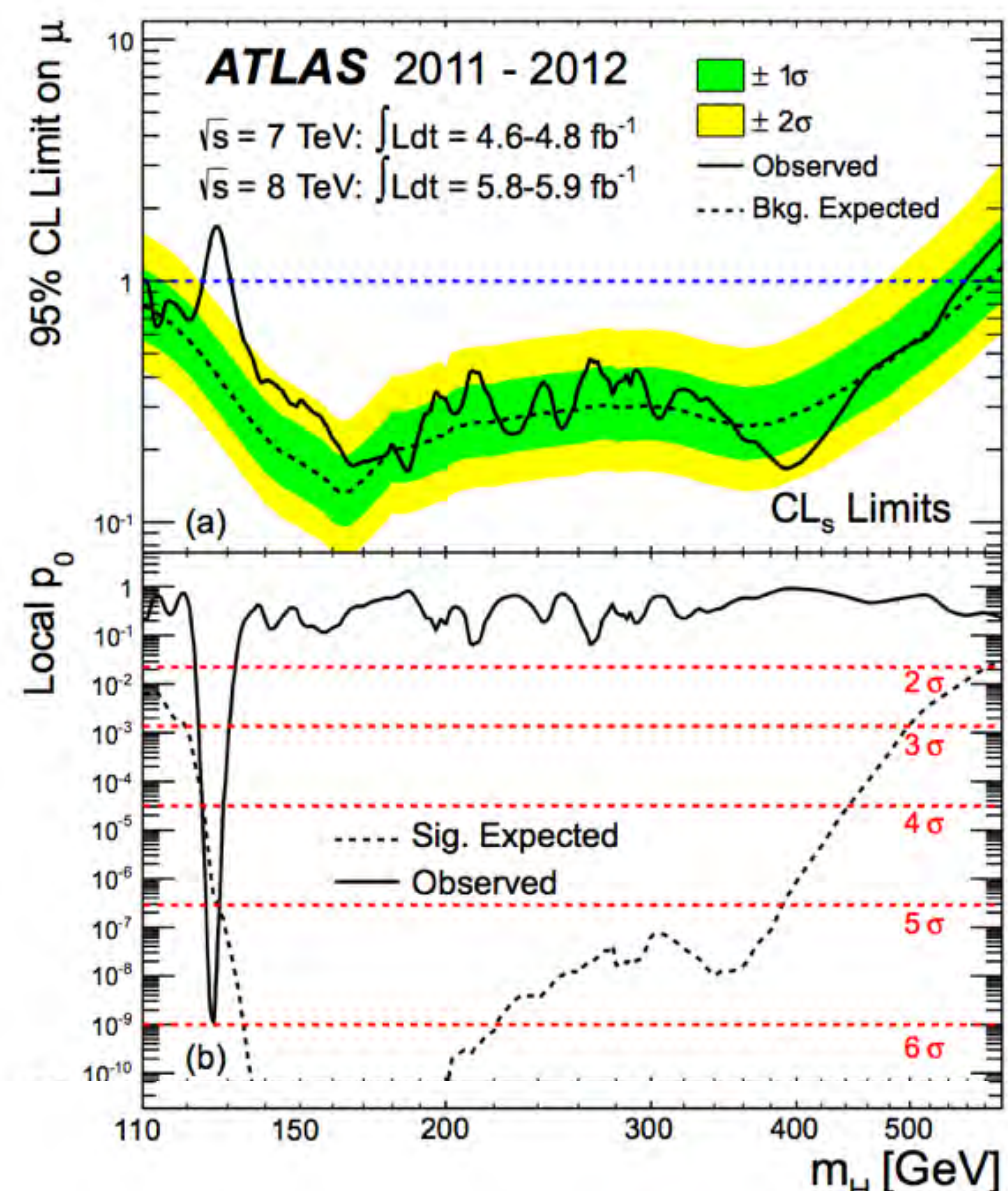
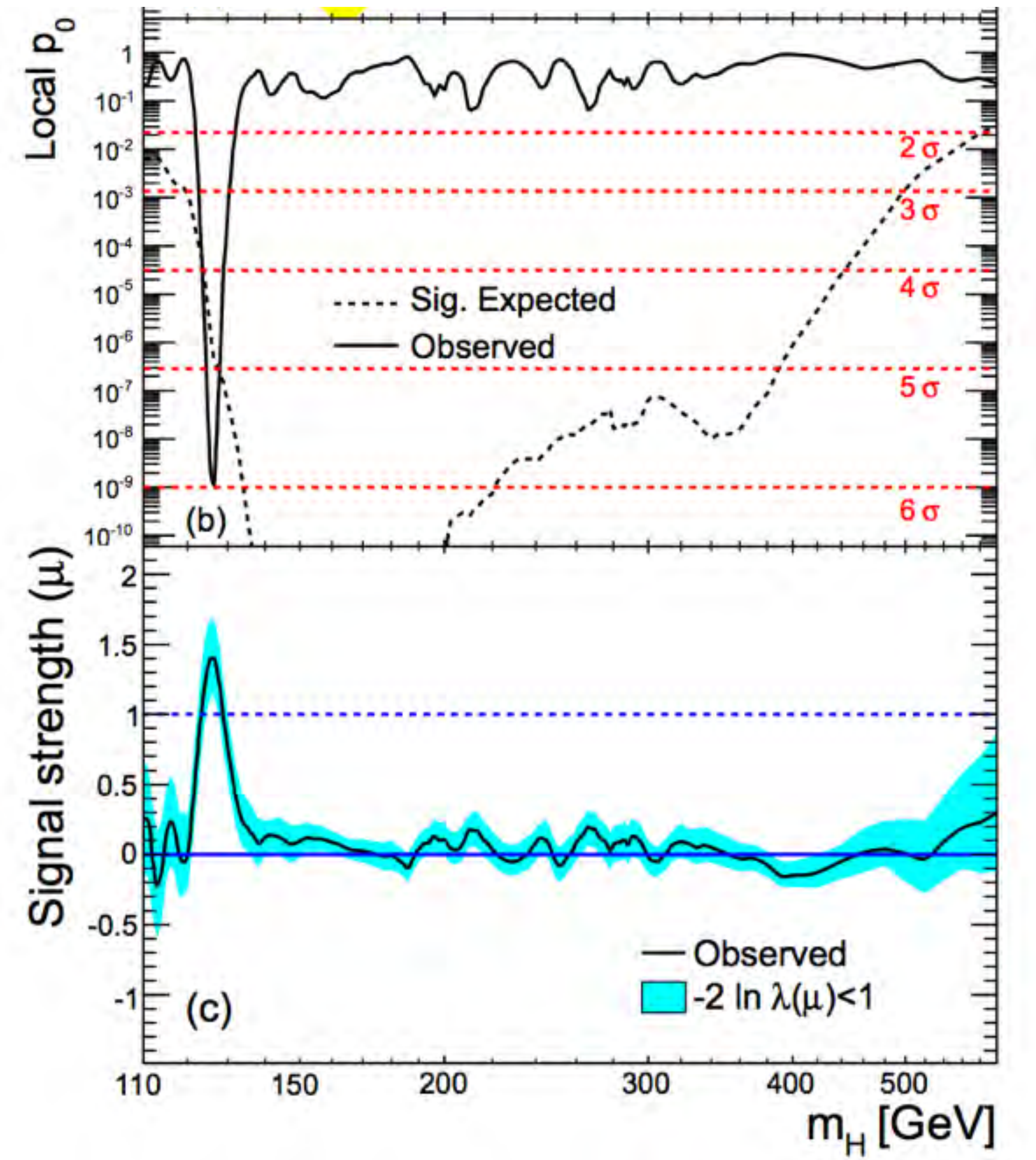
Higgs Discovery 2012

Higgs Discovery 2012




ATLAS 2011 - 2012
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8-5.9 fb^{-1}
± 1σ
± 2σ
Observed
Bkg. Expected
95% CL Limit on μ
CL_s Limits
(a)
Local p_0
Sig. Expected
Observed
2 σ
3 σ
4 σ
5 σ
6 σ
(b)
110
150
200
300
400
500
m_H [GeV]

Higgs Discovery 2012



2 Legacy Papers

Selected for a Viewpoint in *Physics*
PRL **114**, 191803 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

Combined Measurement of the Higgs Boson Mass in *pp* Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments

G. Aad *et al.*[*]

(ATLAS Collaboration)[†]
(CMS Collaboration)[‡]
(Received 25 March 2015; published 14 May 2015)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT CMS CERN

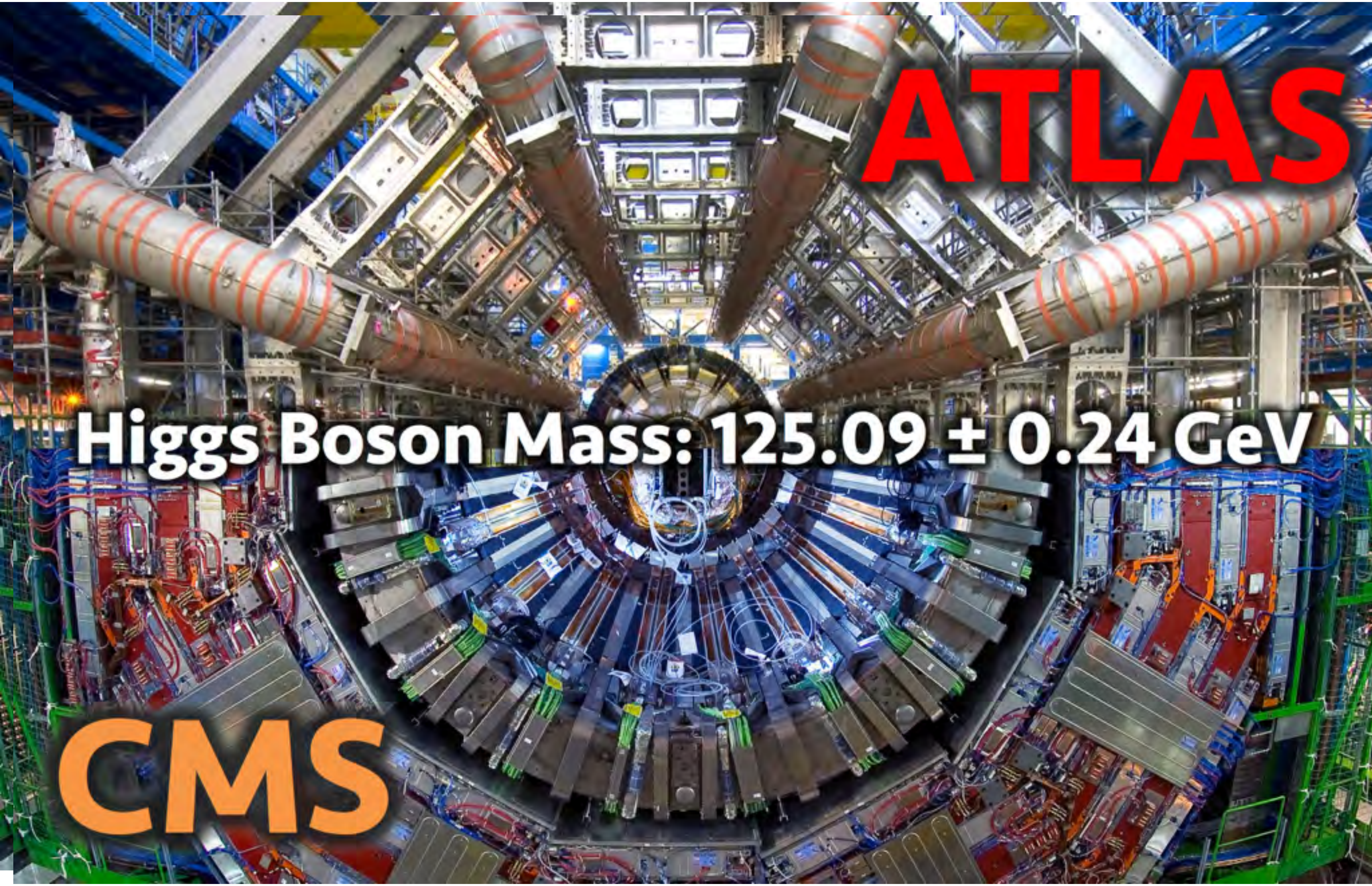
Submitted to: JHEP

CERN-EP-2016-100
8th June 2016

Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC *pp* collision data at $\sqrt{s} = 7$ and 8 TeV

arXiv:1606.02266v1 [hep-ex] 7 Jun 2016

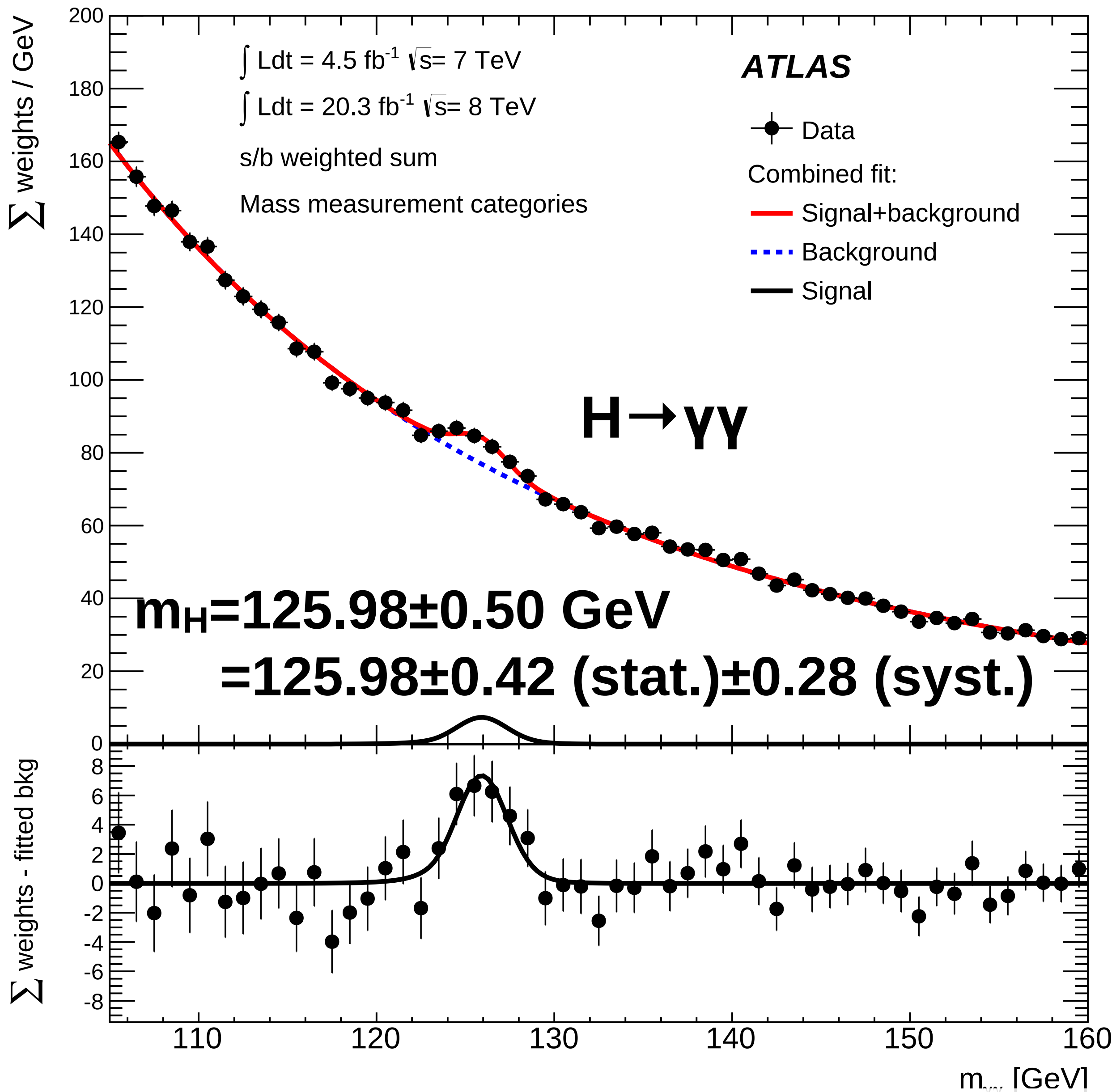
The ATLAS and CMS Collaborations

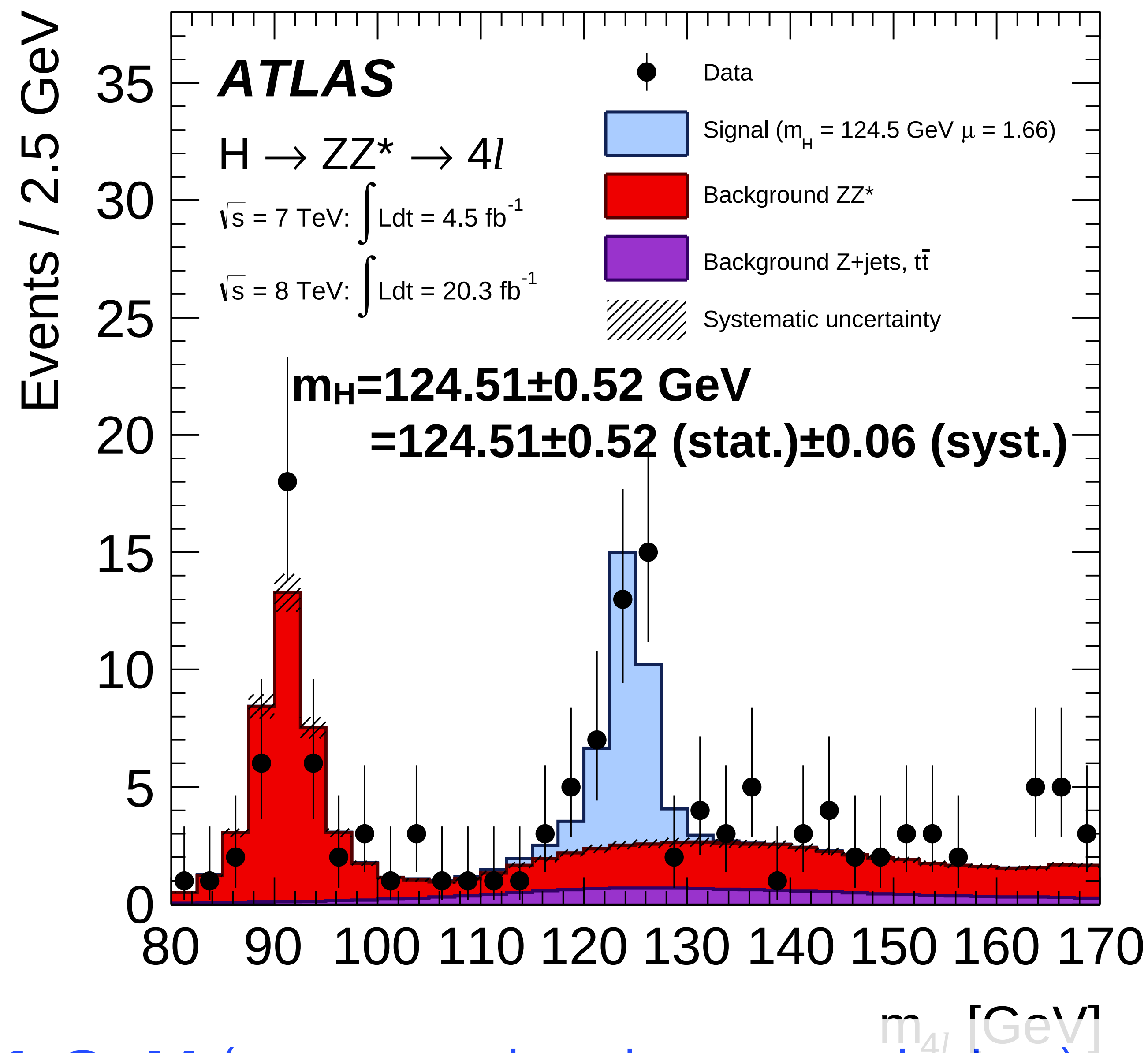

ATLAS
Higgs Boson Mass: 125.09 ± 0.24 GeV
CMS

Input analyses

ATLAS Published analyses

Phys. Rev. D. 90, 052004 (2014)



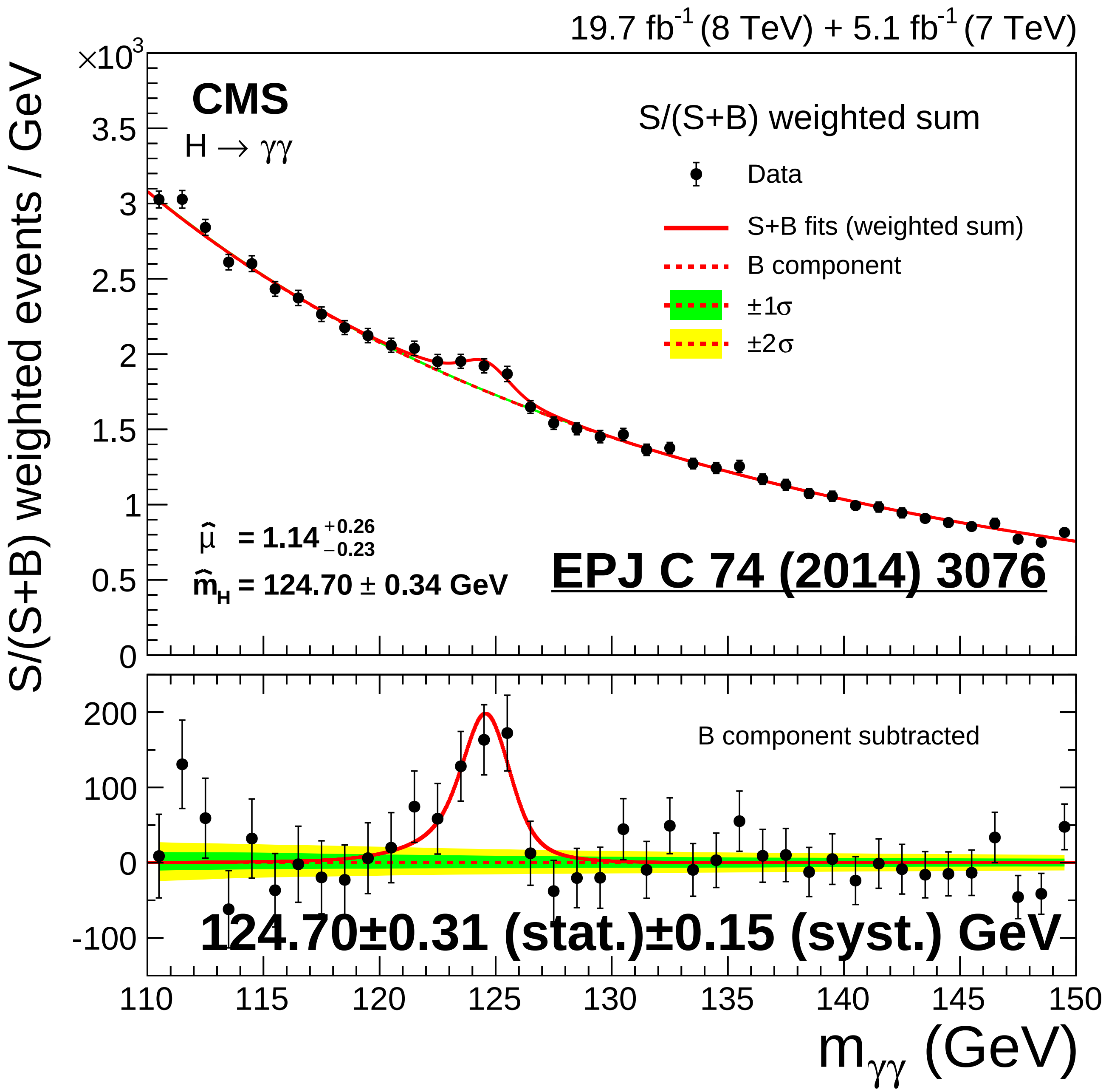


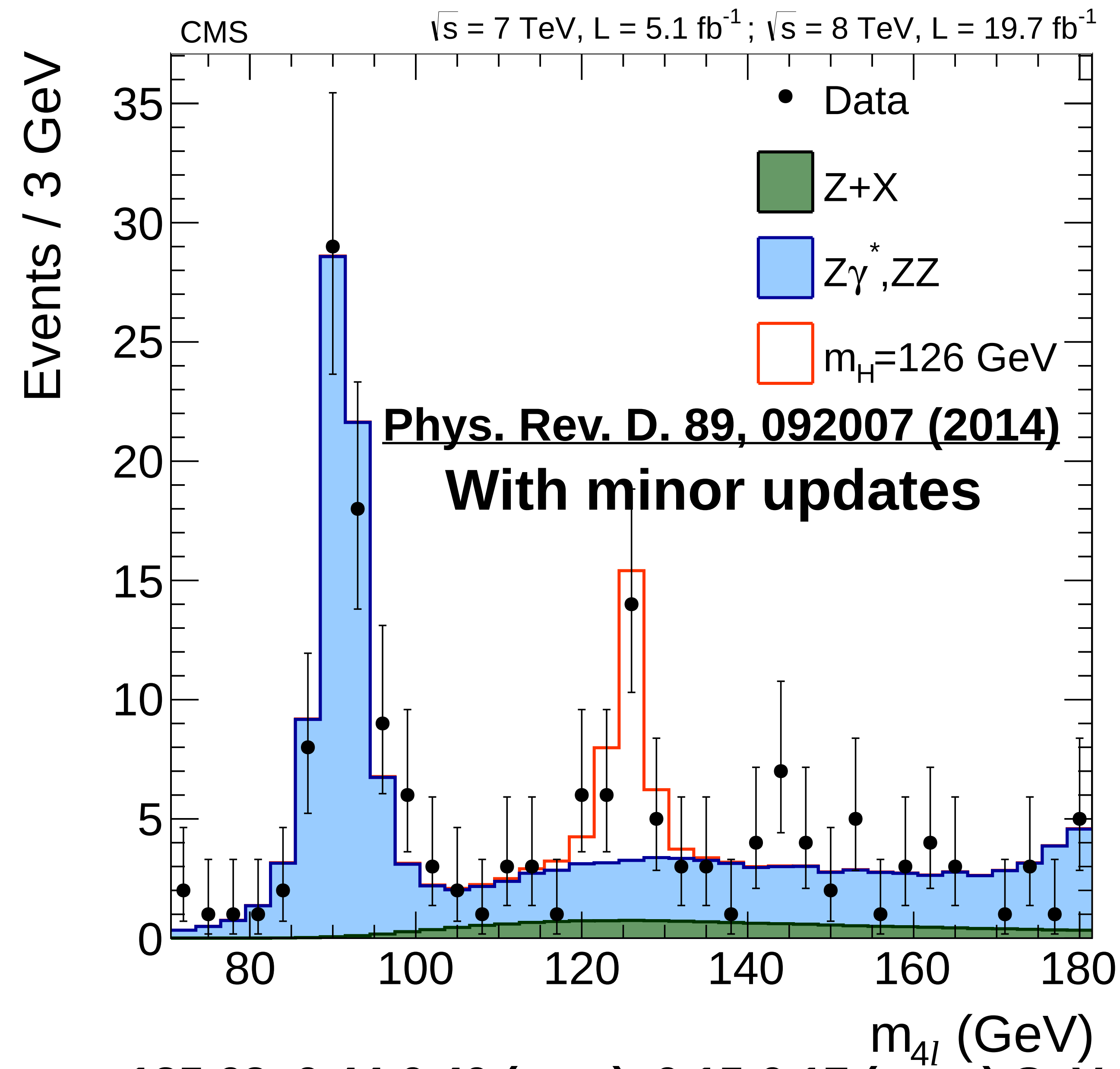
- **ATLAS** Combined: $\mathbf{m_H}$=**125.36±0.41 GeV** (symmetrized uncertainties)

  =**125.36±0.37 (stat.)±0.18 (syst.) GeV**

CMS Published analyses

arXiv:1412.8662 (submitted to EPJ C)





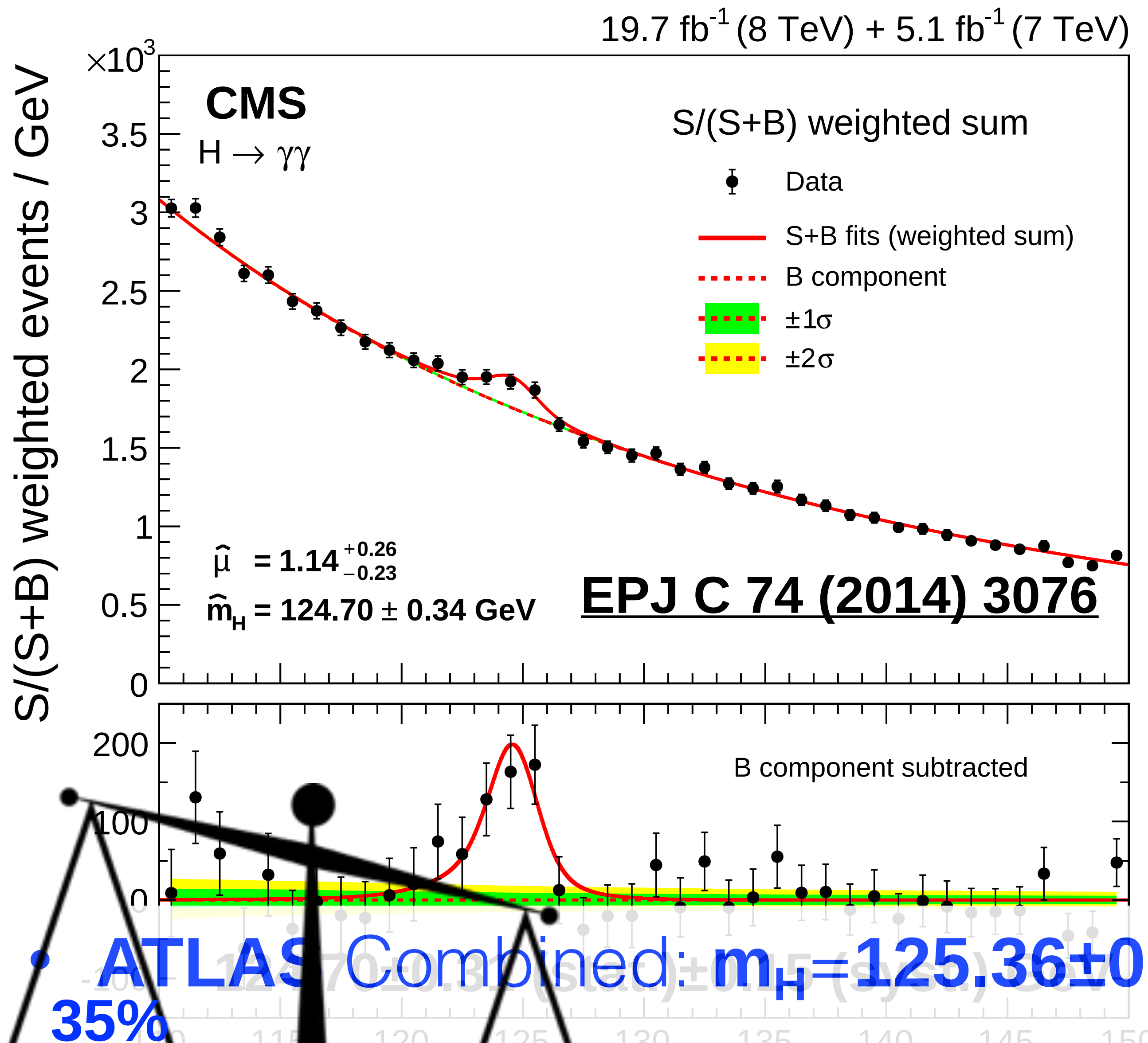
125.63+0.44-0.40 (stat.)+0.15-0.17 (syst.) GeV

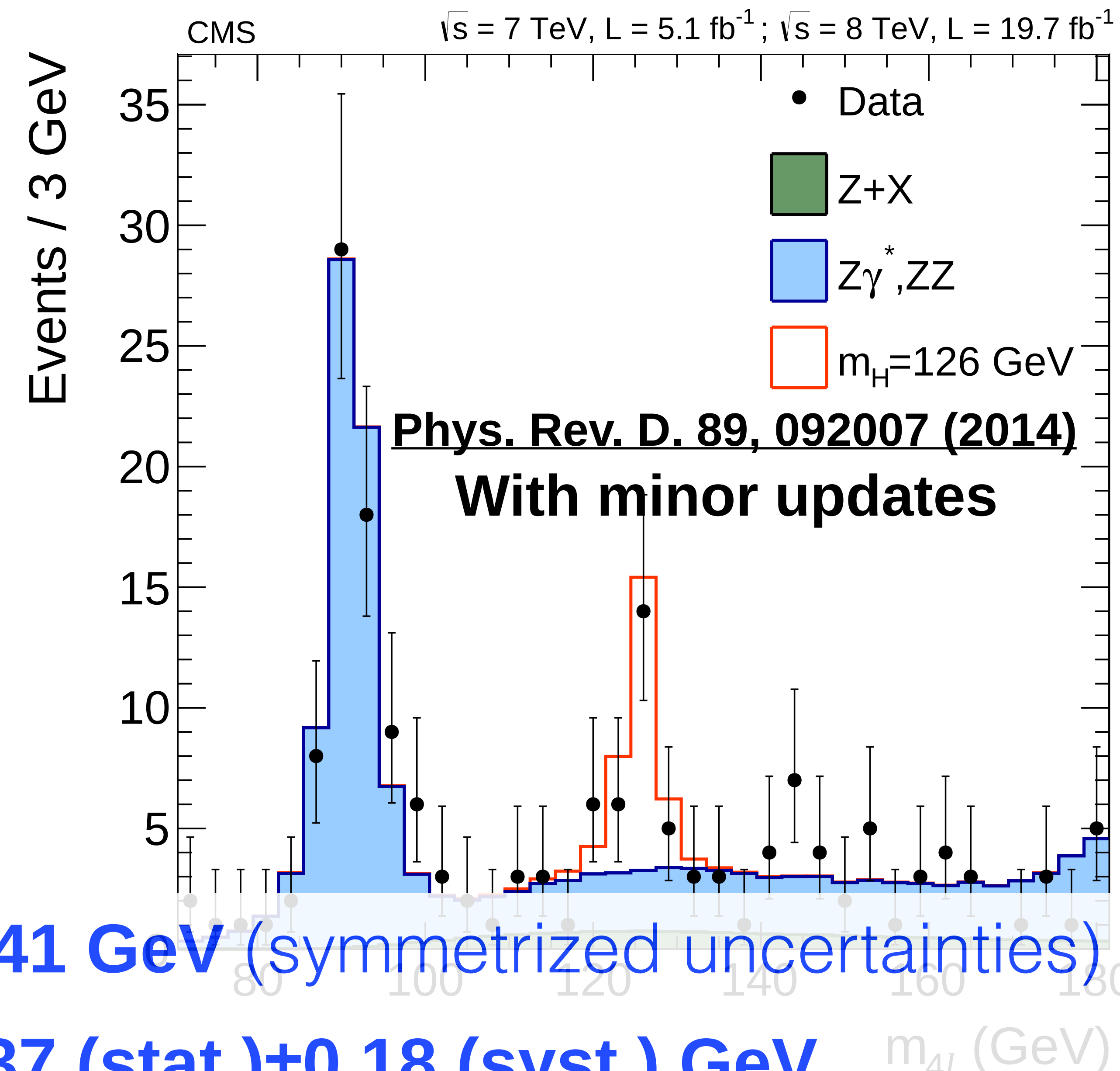
- CMS Combined: $\mathbf{m_H}$**=125.02+0.29-0.31 GeV**

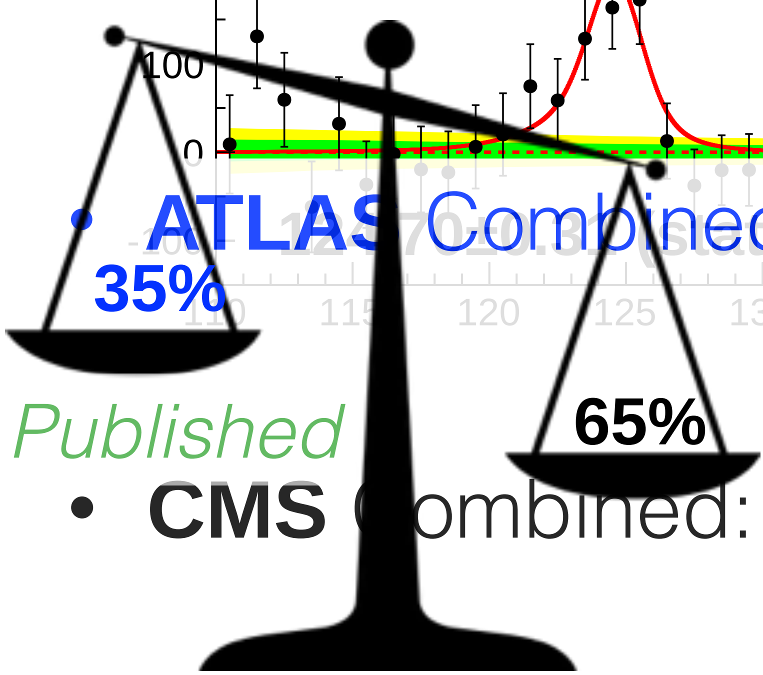
  =**125.02+0.26-0.27 (stat.)+0.14-0.15 (syst) GeV**

CMS and ATLAS Published analyses

arXiv:1412.8662 (submitted to EPJ C)







- **ATLAS** Combined: **m_H=125.36±0.41 GeV** (symmetrized uncertainties)

=**125.36±0.37 (stat.)±0.18 (syst.) GeV**

Published

- **CMS** Combined: **m_H**=**125.02+0.29-0.31 GeV**

=**125.02+0.26-0.27 (stat.)+0.14-0.15 (syst) GeV**

Example

$$L(s(m_H)) = Prob(n \mid s(m_H)+b) = Poiss(s(m_H)+b \mid n)$$

$$Poiss(s(m_H)+b \mid n) = \frac{\left(s(m_H)+b\right)^n e^{-\left(s(m_H)+b\right)}}{n!}$$

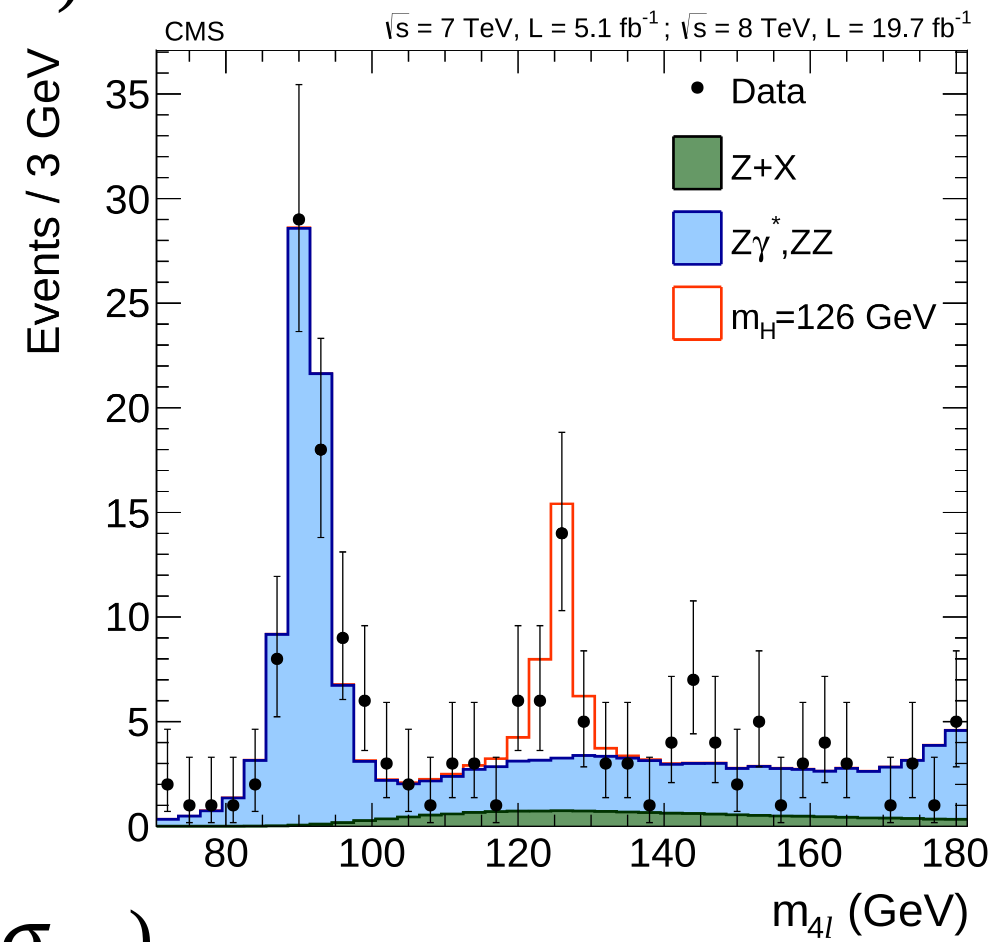
$$b = b(\theta), \quad \theta \sim \mathrm{G}(\theta_0, \sigma_{\theta_0})$$

$$L(s(m_H)) = Poiss(s(m_H)+b(\theta) \mid n)\mathrm{G}(\theta \mid \theta_0, \sigma_{\theta_0})$$

$$\hat{m}_H = \left\{ m_H \left| \frac{\partial L(s(m_H))}{\partial m_H} = 0 \right. \right\}$$

$$b(\theta) \to b_i(\theta_j)$$

$$L(s(m_H)) = \Pi_{i,j} Poiss(s(m_H)+b_i(\theta_j) \mid n_i)\mathrm{G}(\theta_j \mid \theta_{0,j}, \sigma_{\theta_{0,j}})$$



The Task

- The task was **not** to make a comparative study of ATLAS vs CMS
- The task was to combine 4 **published** analyses
- Make the changes needed to make the data analyses "workspaces" of ATLAS and CMS compatible, work out the correlated systematics, combine and test the combination from all possible aspects

Measurement Parameterisation

Nominal fit: which μ to profile?

- The nominal fit has four common parameters:

$$m_H \quad \mu^{\gamma\gamma}_{ggH+ttH} \quad \mu^{\gamma\gamma}_{VBF+VH} \quad \mu^{ZZ}$$

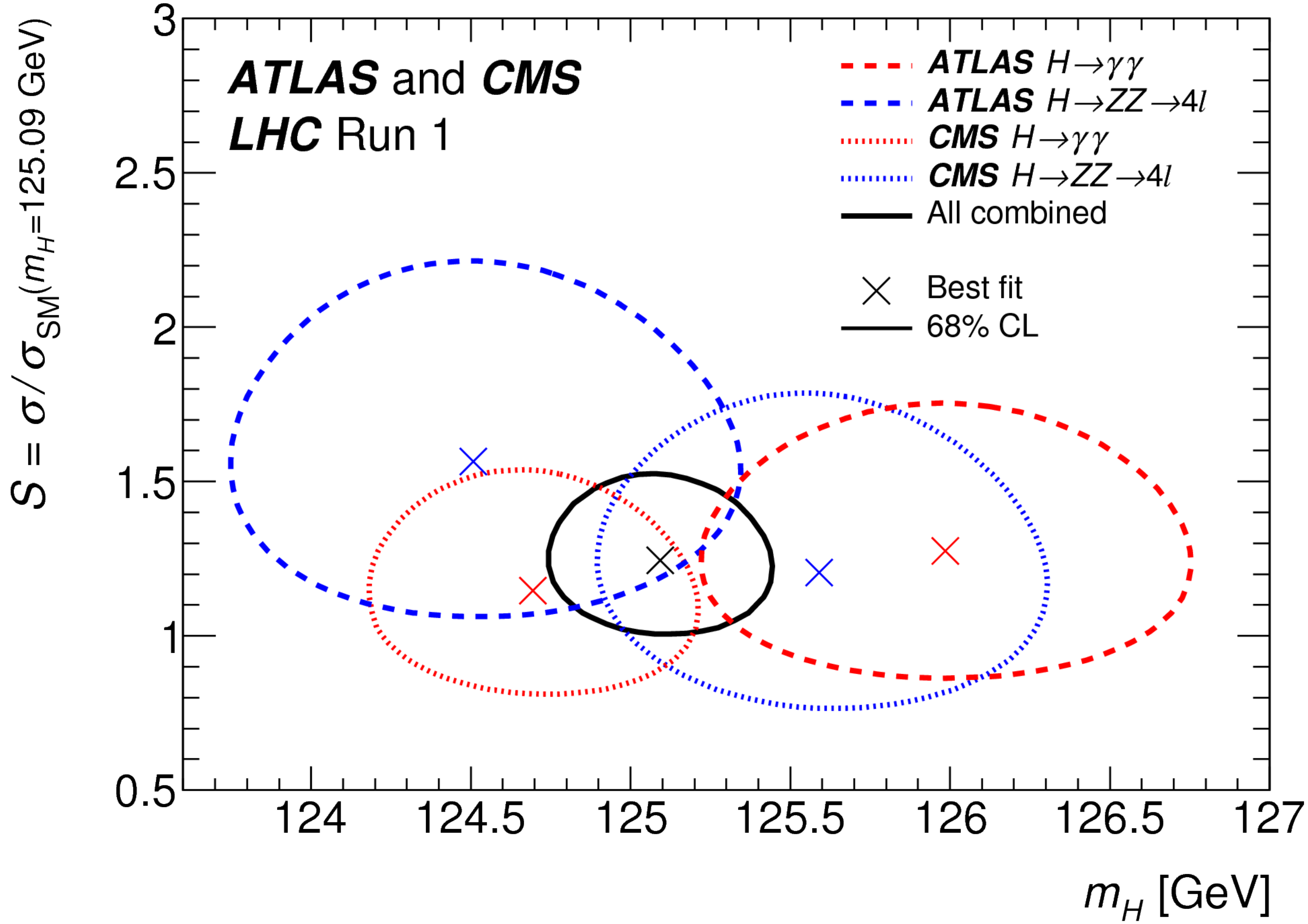
- The combined mass of ATLAS+CMS is therefore given by the following profile likelihood test statistic

$$\Lambda(m_H) = \frac{L\left(m_H\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{ggF+ttH}(m_H)\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\boldsymbol{\theta}}}(m_H)\right)}{L(\hat{m}_H\,,\hat{\mu}^{\gamma\gamma}_{ggF+ttH}\,,\hat{\mu}^{\gamma\gamma}_{VBF+VH}\,,\hat{\mu}_{4\ell},\hat{\boldsymbol{\theta}})}$$

- Systematics is modelled with ~300 Nuisance Parameters
- 100 for shape parameters and normalisation in Hγγ Background model (unconstrained)
- Most of the remaining ones, correspond to experimental or theory (constrained)

Results

m_H vs. μ contours



The best fit mH in contour (×) is not identical as m_H measured

Some Examples

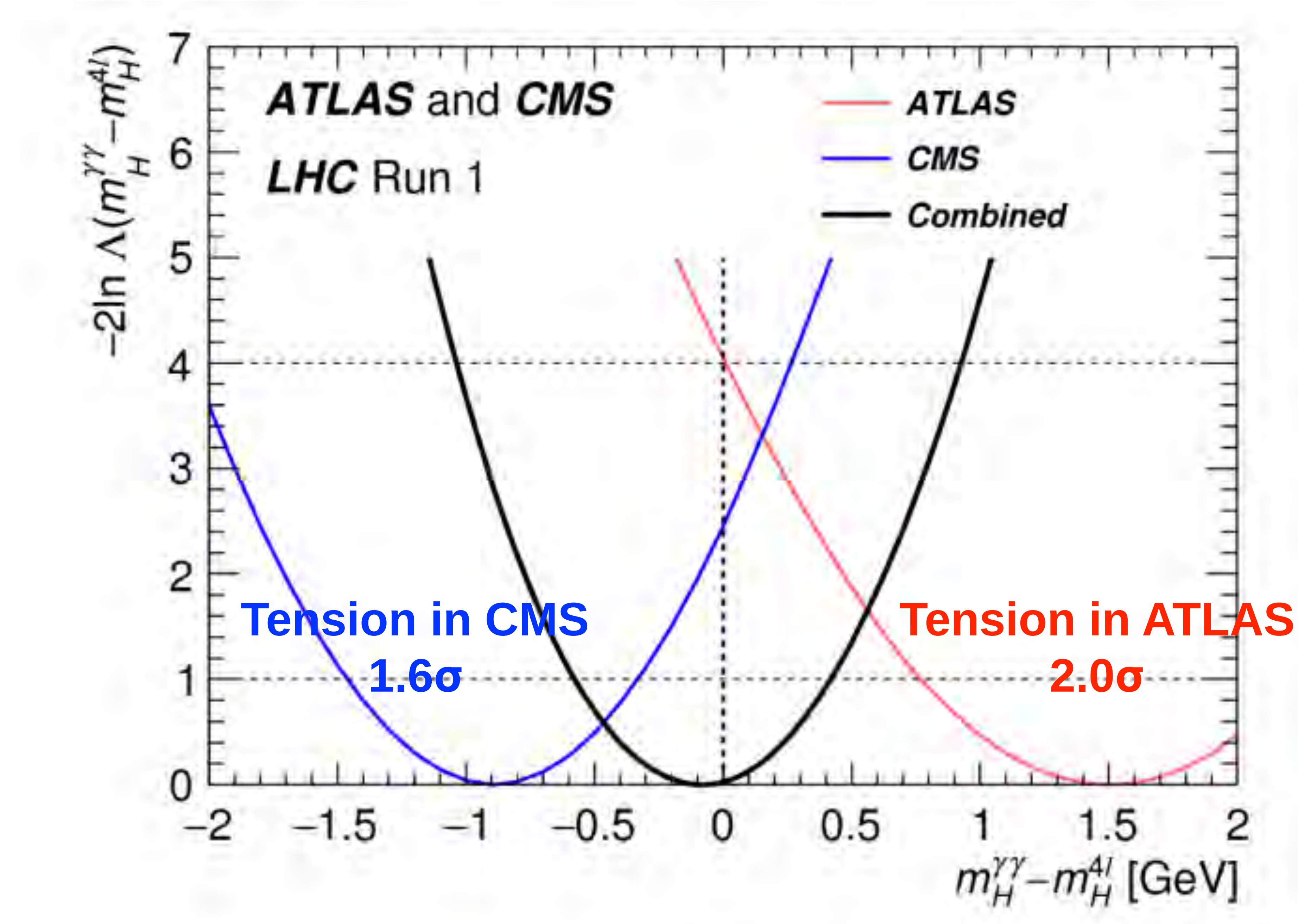
- Asses the tension between channels $\Delta m_H(\gamma\gamma\text{-}4l)$

$$\Lambda(\Delta m_{\gamma Z}) = \frac{L(\Delta m_{\gamma Z}, \hat{\hat{m}}_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+ttH}, \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}, \hat{\hat{\mu}}_{4\ell}, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\Delta} m_{\gamma Z}, \hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}_{4\ell}, \hat{\boldsymbol{\theta}})}$$

- Asses the tension between experiments $\Delta m_H(\text{ATLAS-CMS})$

$$\Lambda(\Delta m^{exp}) = \frac{L(\Delta m^{exp}, \hat{\hat{m}}_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+ttH}, \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}, \hat{\hat{\mu}}_{4\ell}, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\Delta} m^{exp}, \hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}_{4\ell}, \hat{\boldsymbol{\theta}})}$$

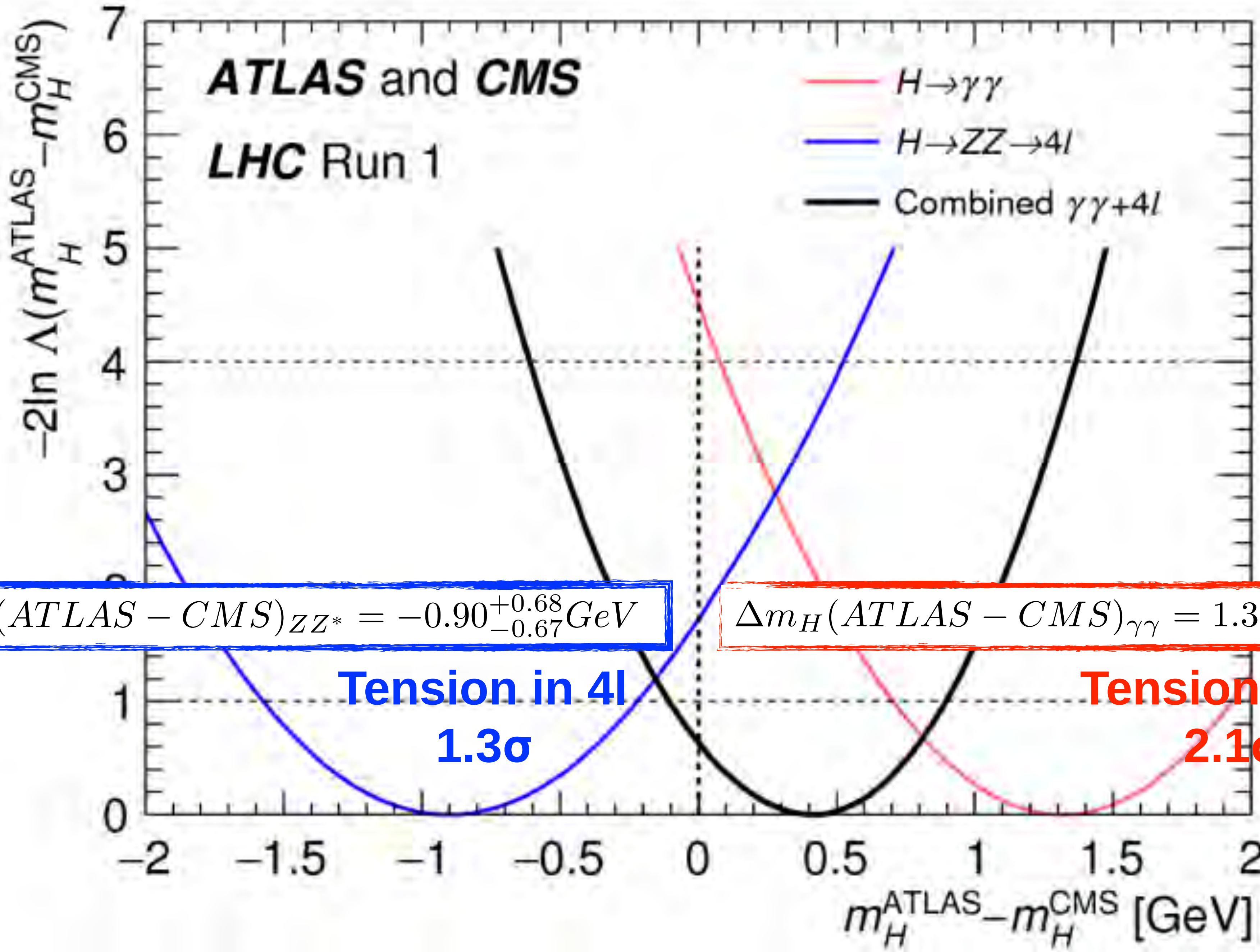
Tension in m_H between decay channels



$$\boxed{\Delta m_H(\gamma\gamma - ZZ^*) = -0.08^{+0.50}_{-0.49}\ \text{GeV}}$$

No observed tension in combined

Tension in m_H between experiments



$\Delta m_H(ATLAS-CMS)_{ZZ^*} = -0.90^{+0.68}_{-0.67} GeV$

$\Delta m_H(ATLAS-CMS)_{\gamma\gamma} = 1.32^{+0.62}_{-0.61} GeV$

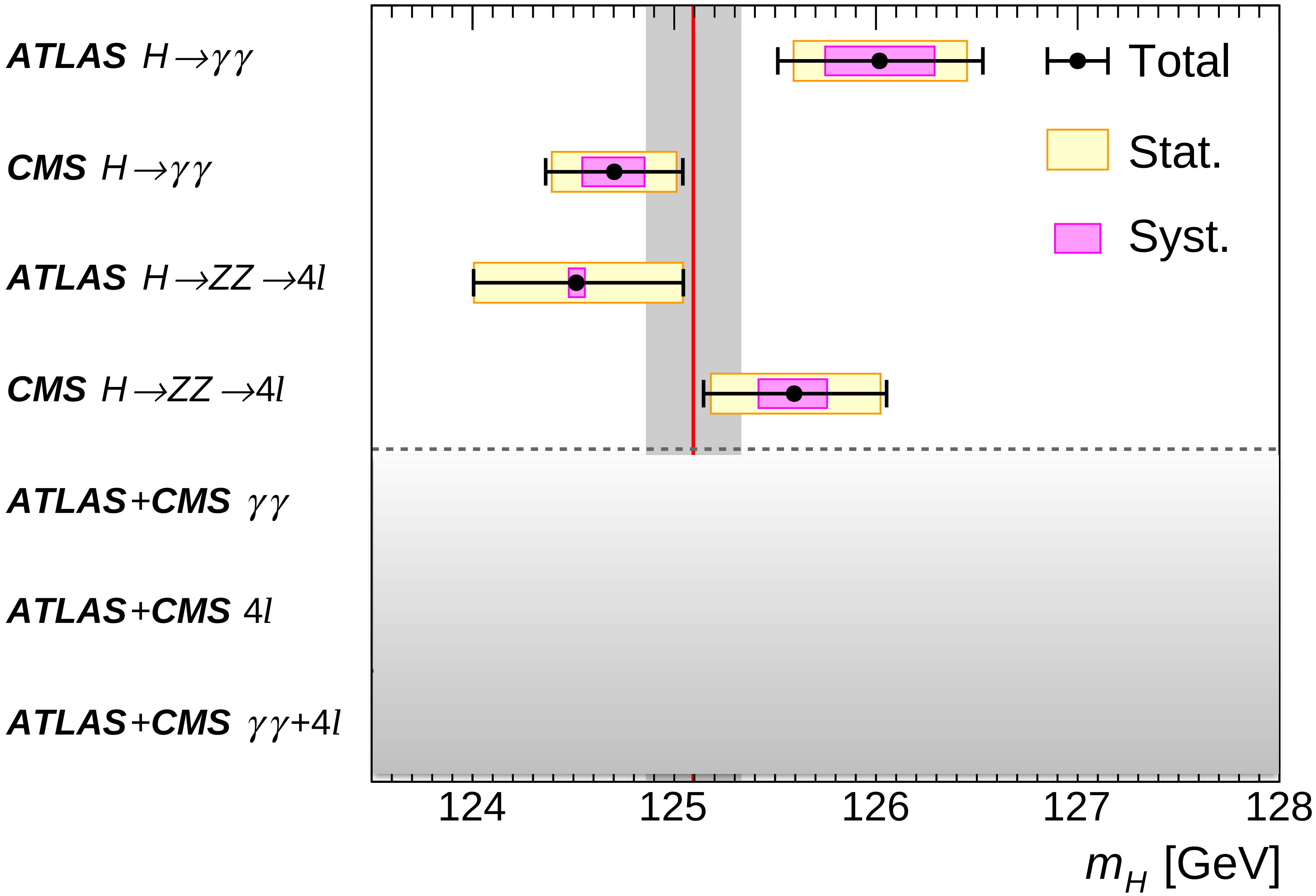
Tension in 4l
1.3σ

Tension in γγ
2.1σ

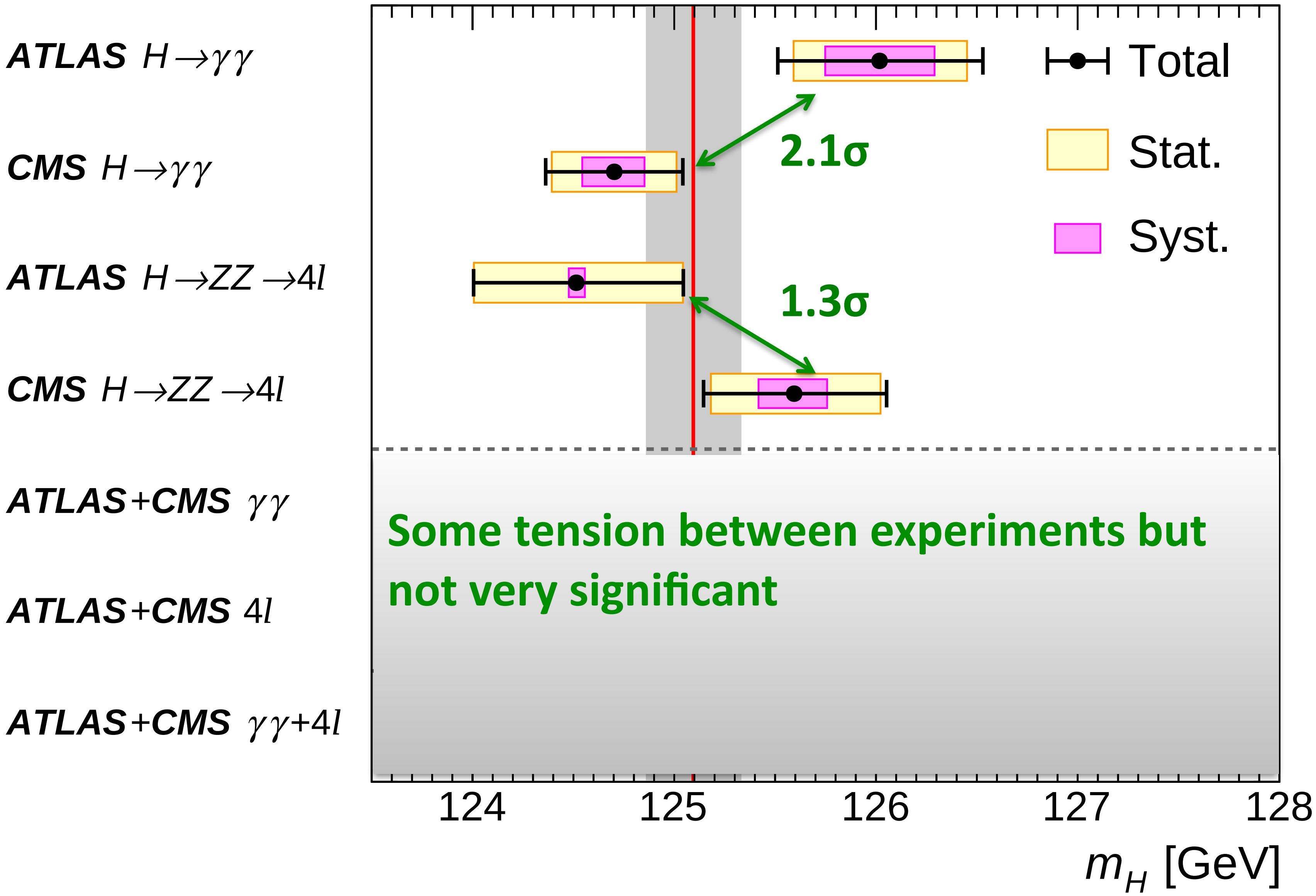
$$\Delta m_H(ATLAS-CMS) = 0.41^{+0.48}_{-0.52}\ \text{GeV}$$

No observed tension in combined measurements between experiments

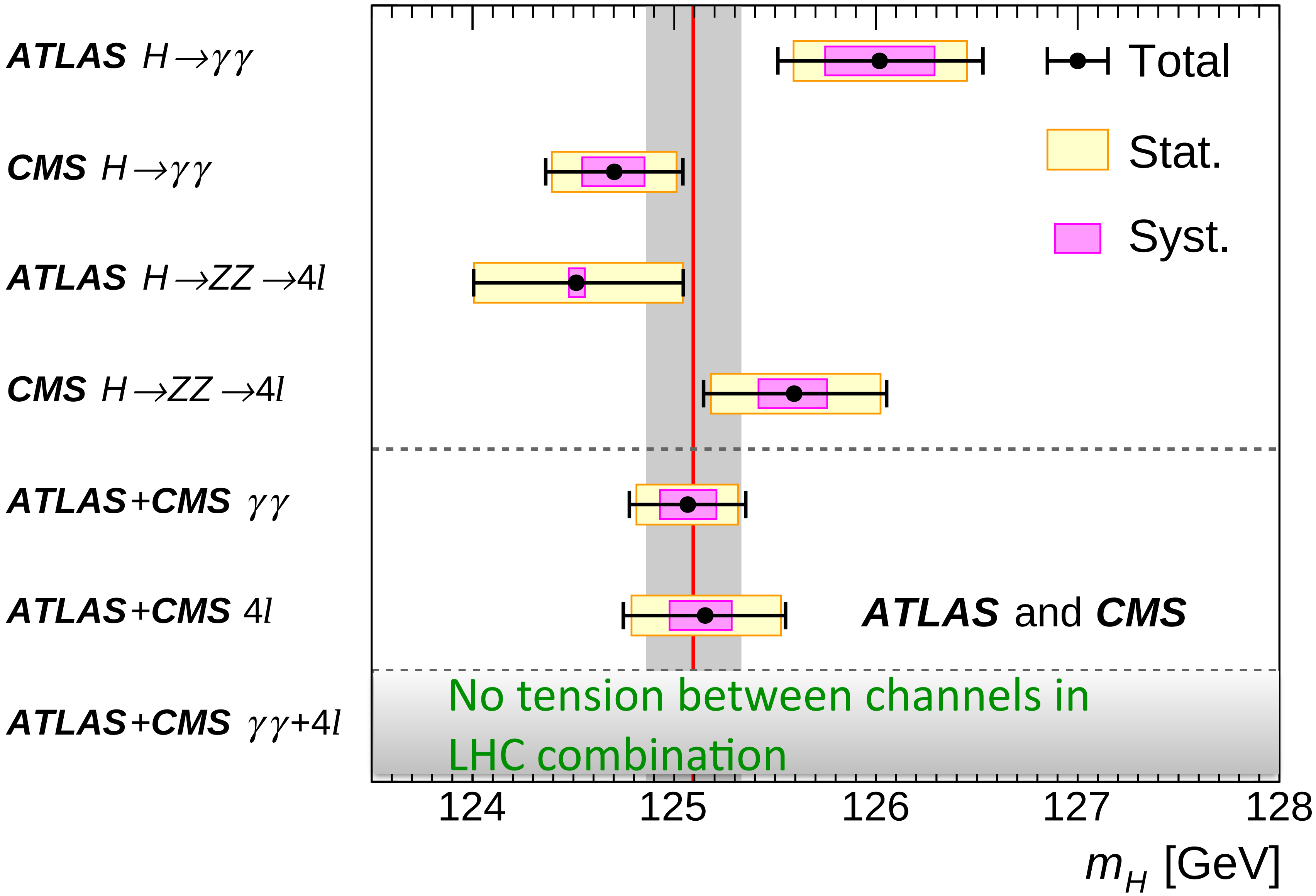
Reproduce Published results



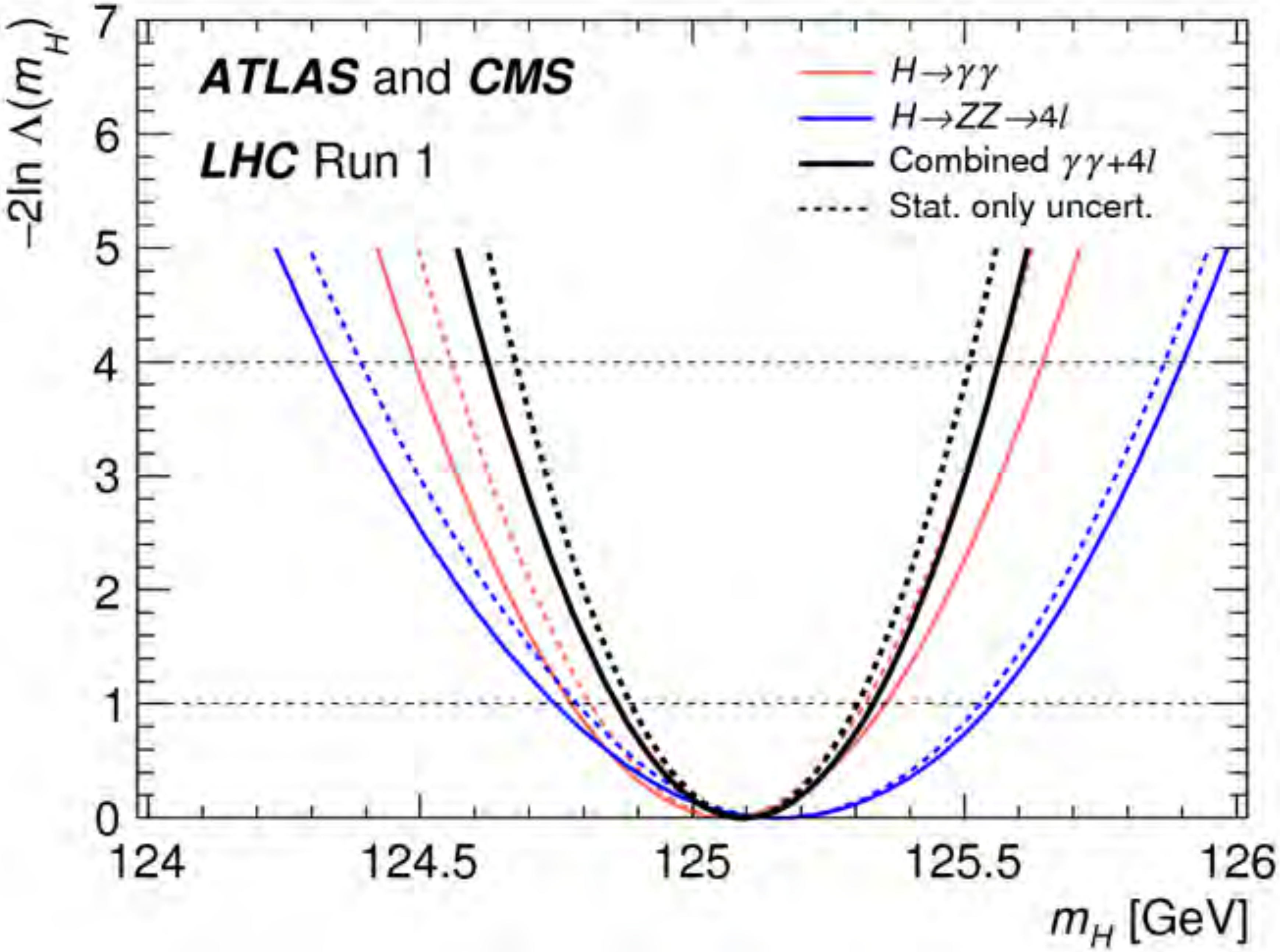
Tension Between Experiments



No Tension Between Combined Channels



Fine Final Scan

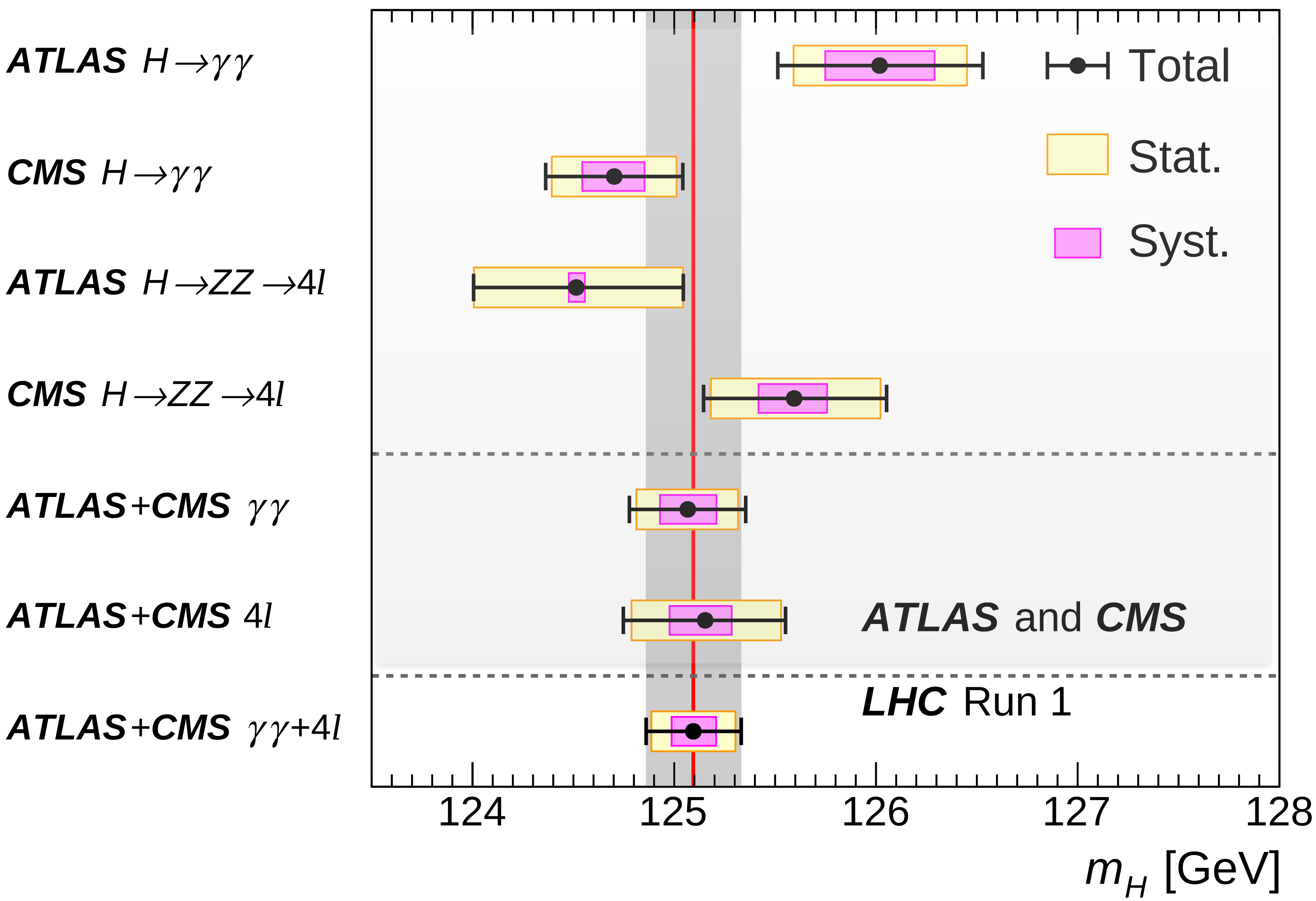


$$-2\ln\Lambda = 1 \Rightarrow \sigma$$

$$\sqrt{\sigma_{tot}^2 - \sigma_{Stat}^2} = \sigma_{syst}$$

$$m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst) GeV$$

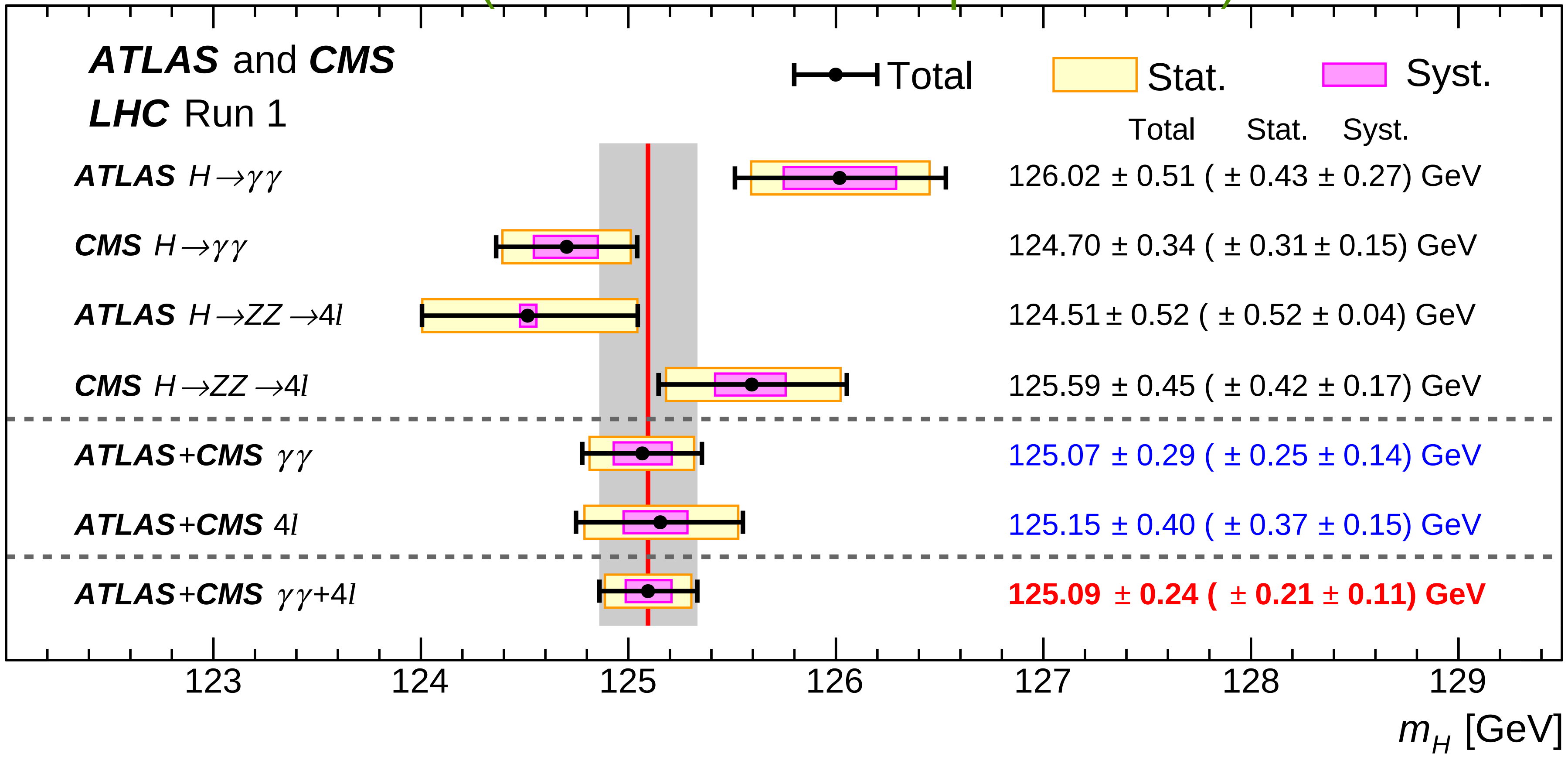
Combined Mass



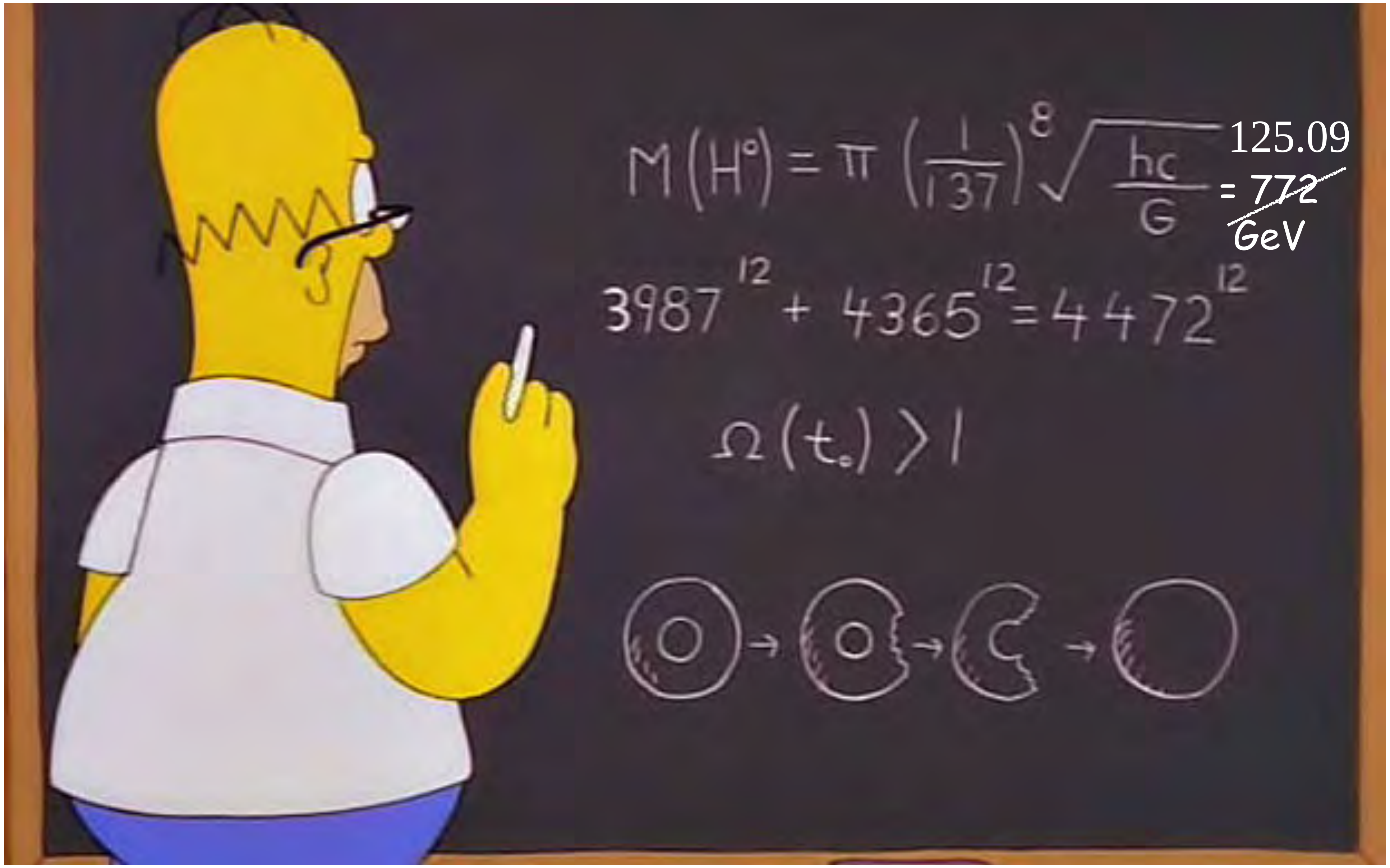
$$m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst) GeV$$

Mass Measurement Summary

- Major legacy results produced for LHC Higgs mass combined measurement
- Best Higgs measurement (well its the only one….)
- Understanding detectors allowed a statistical limited measurement with a precision of <0.2% (better than top mass!)



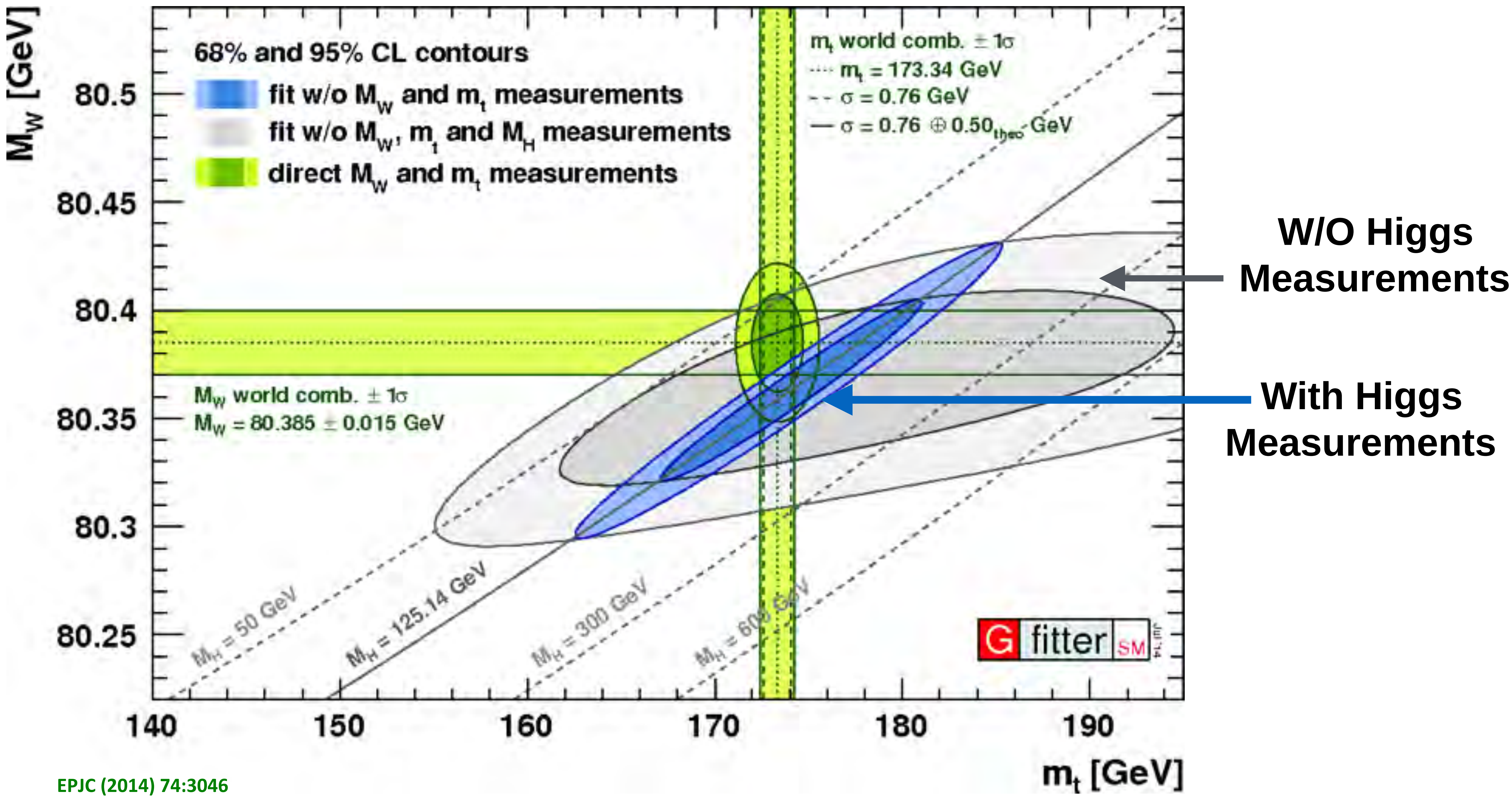
Its Good We Can Correct Simpson



תודה רבה

After Party Comments

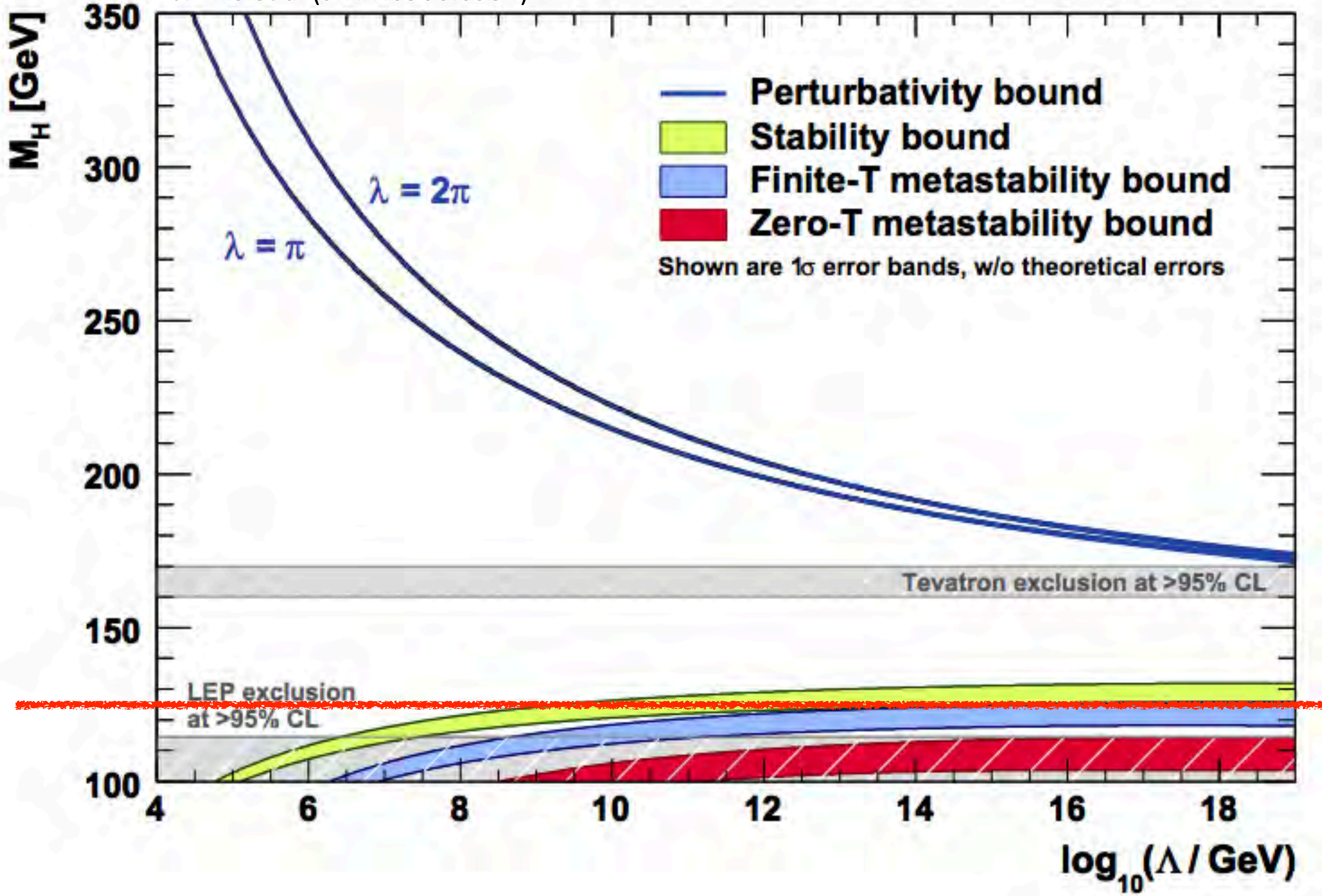
Its Good to Know The Mass



EPJC (2014) 74:3046

Its Good to Know We Are In Danger

J. Ellis et al (arXiv:0906.0954)



Spin and CP

Eur. Phys. J. C75 (2015) 476

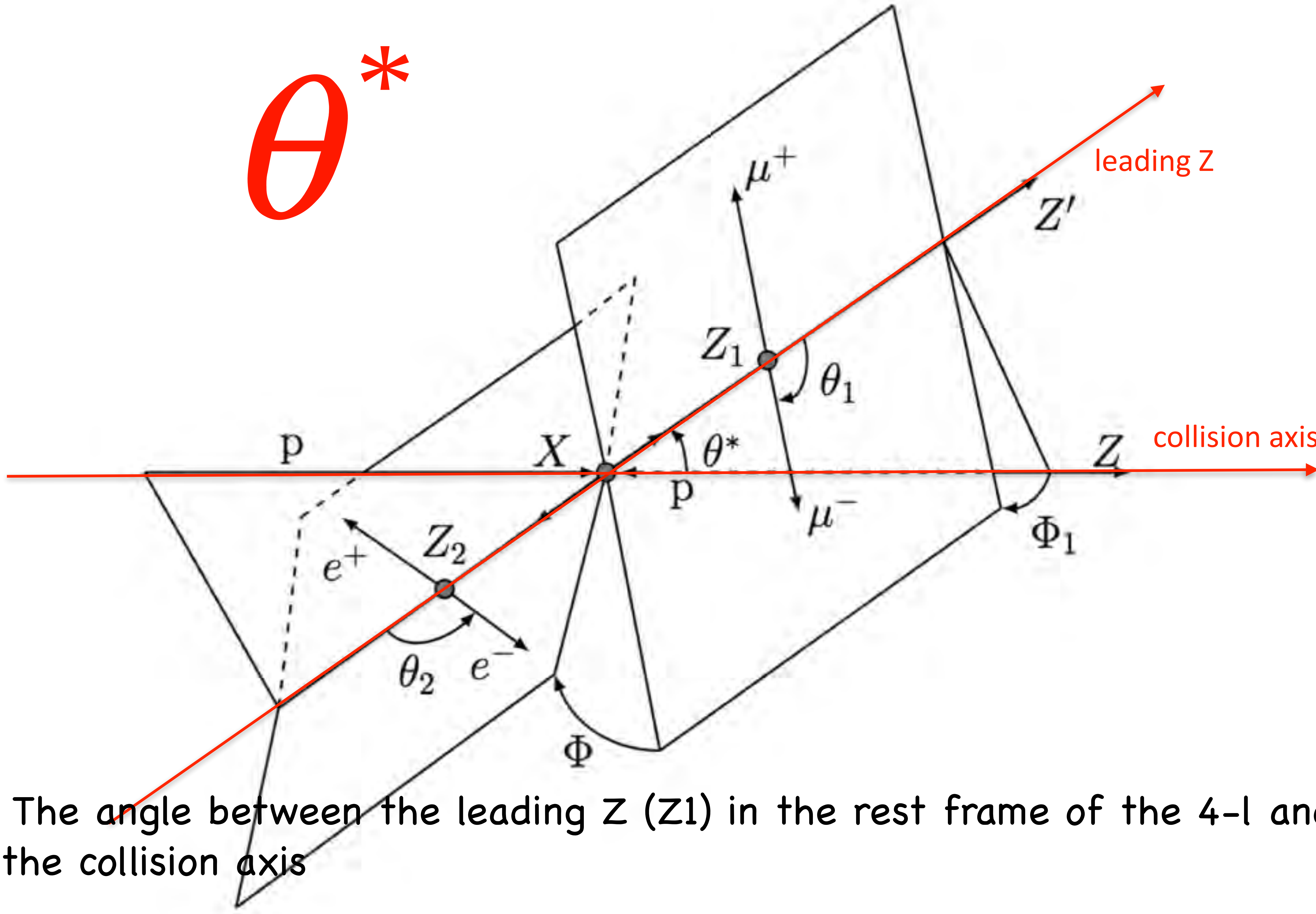
Yang's Theorem (1948) and the Higgs Boson

Yang-Landau theorem states that a massive spin 1 particle cannot decay into two identical massless spin 1 particles.

The observation of $H \to \gamma\gamma$ can be taken as an evidence against a spin 1 nature of the Higgs.

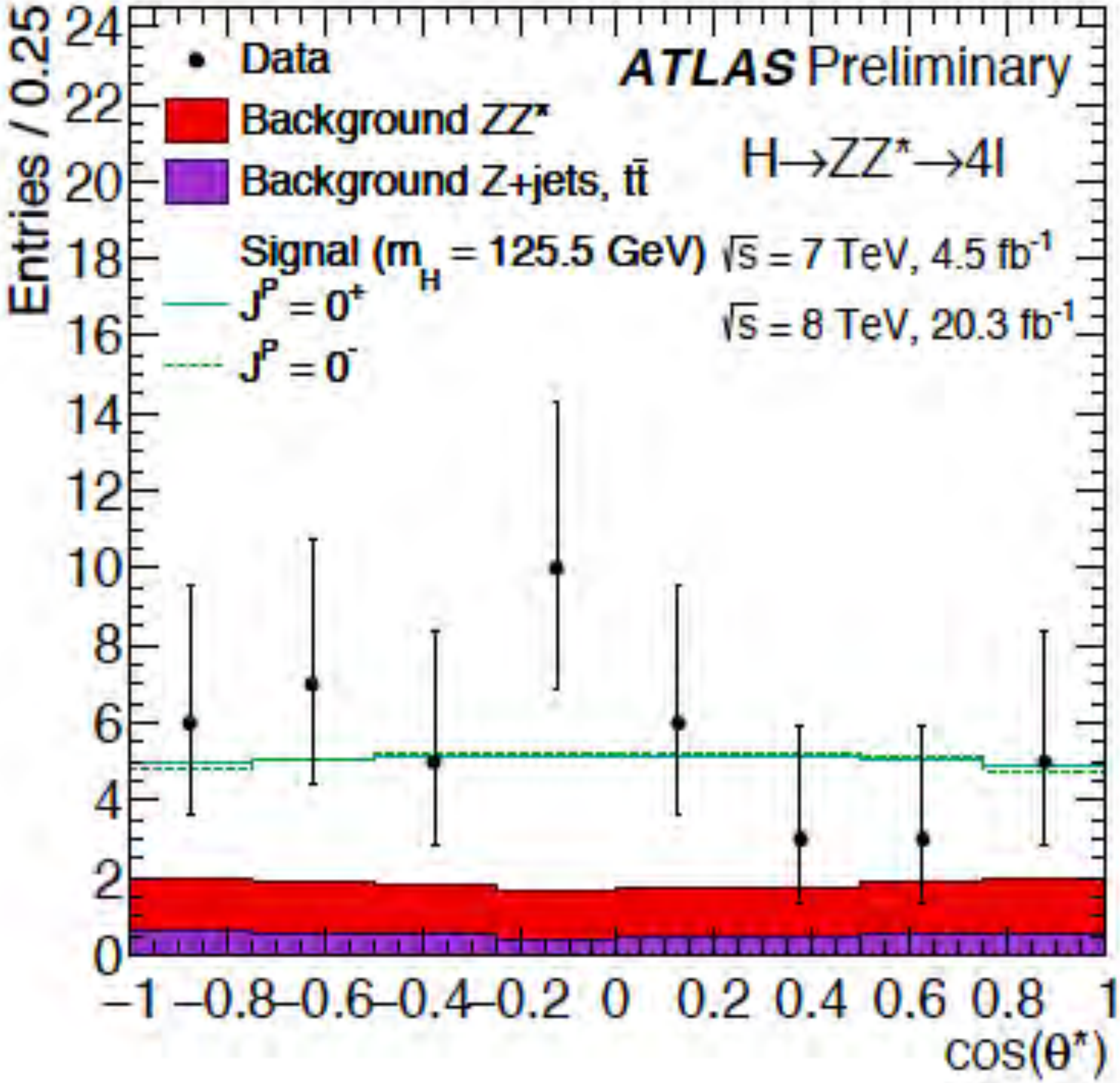
The community concentrated on testing the spin $J^{PC}=0^{++}$ hypothesis of the Higgs against $J^{P}=0^{-}$ and spin 2 hypotheses.

Spin Discriminators



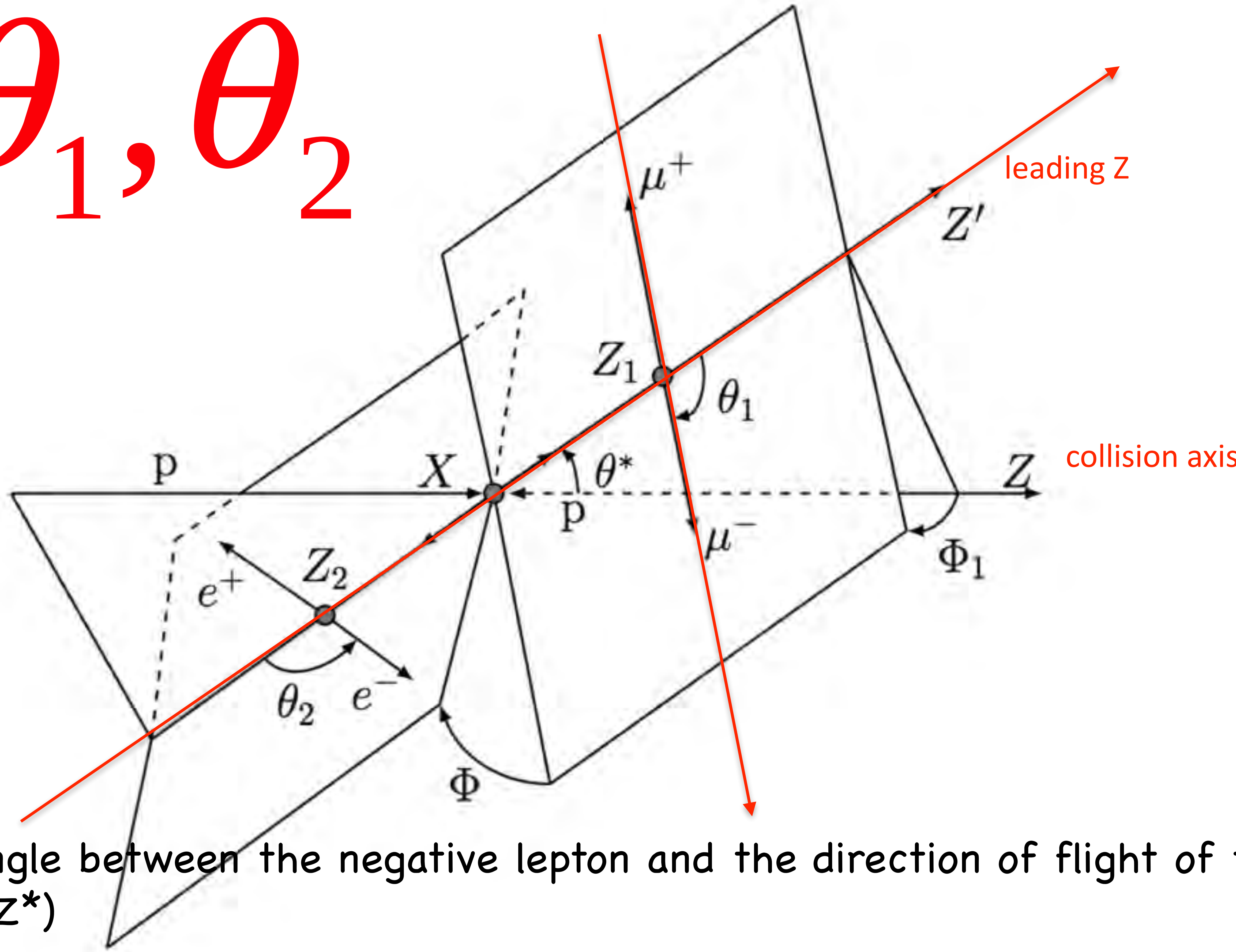
The angle between the leading Z (Z1) in the rest frame of the 4-l and the collision axis

Discriminant Variables



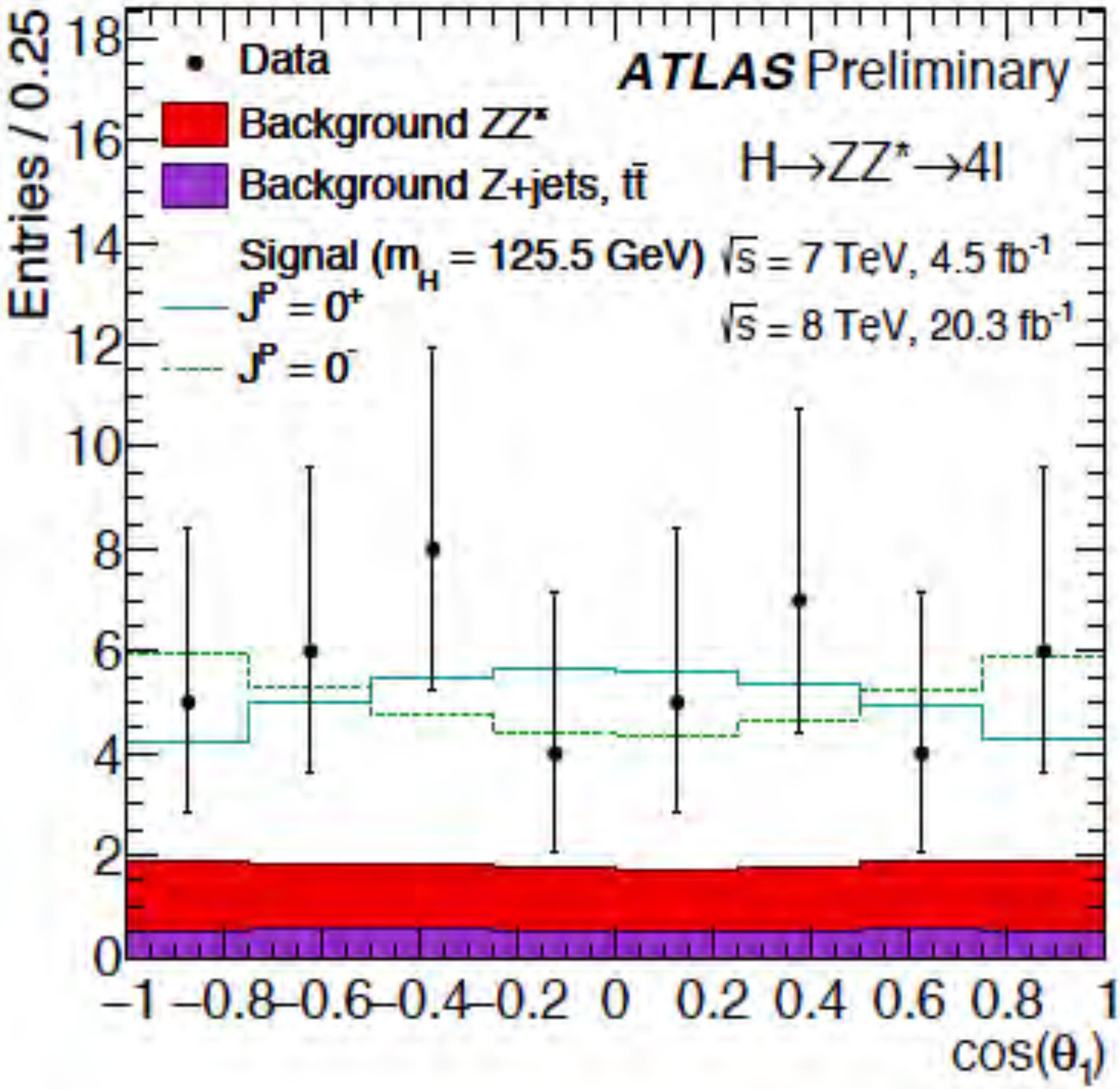
Spin Discriminators

θ_1, θ_2



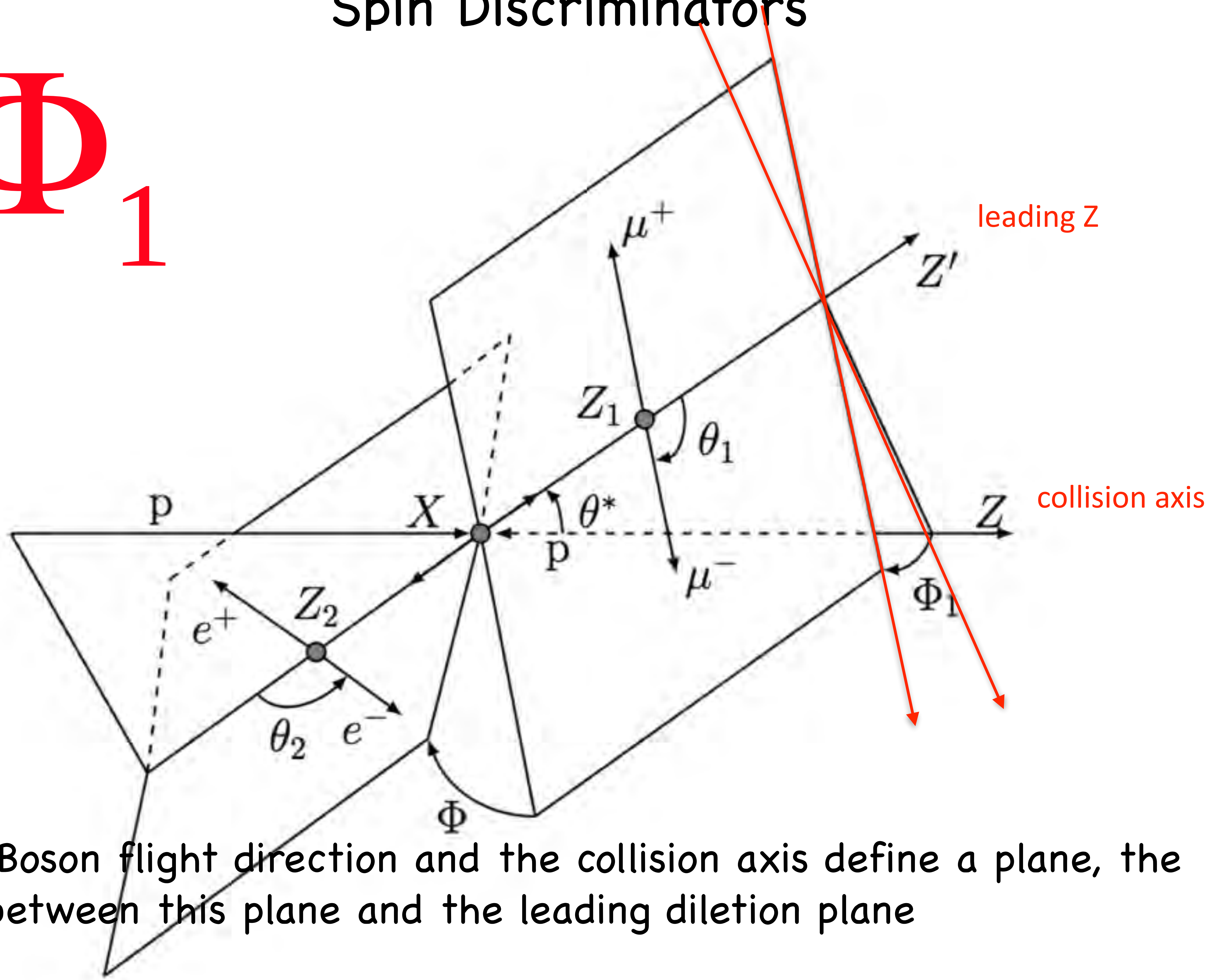
the angle between the negative lepton and the direction of flight of the Z (or Z*)

Discriminant Variables



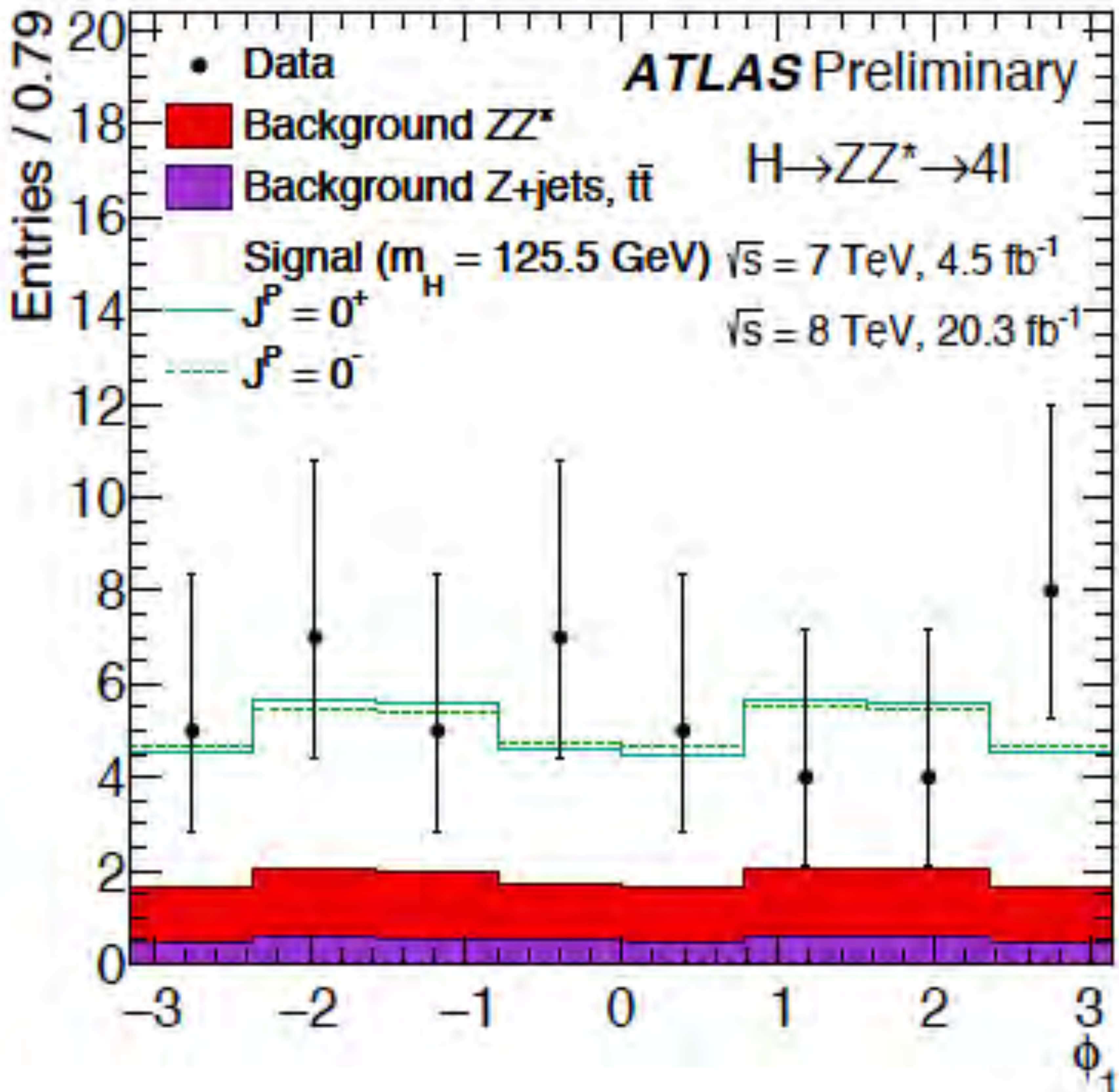
Spin Discriminators

Φ_1



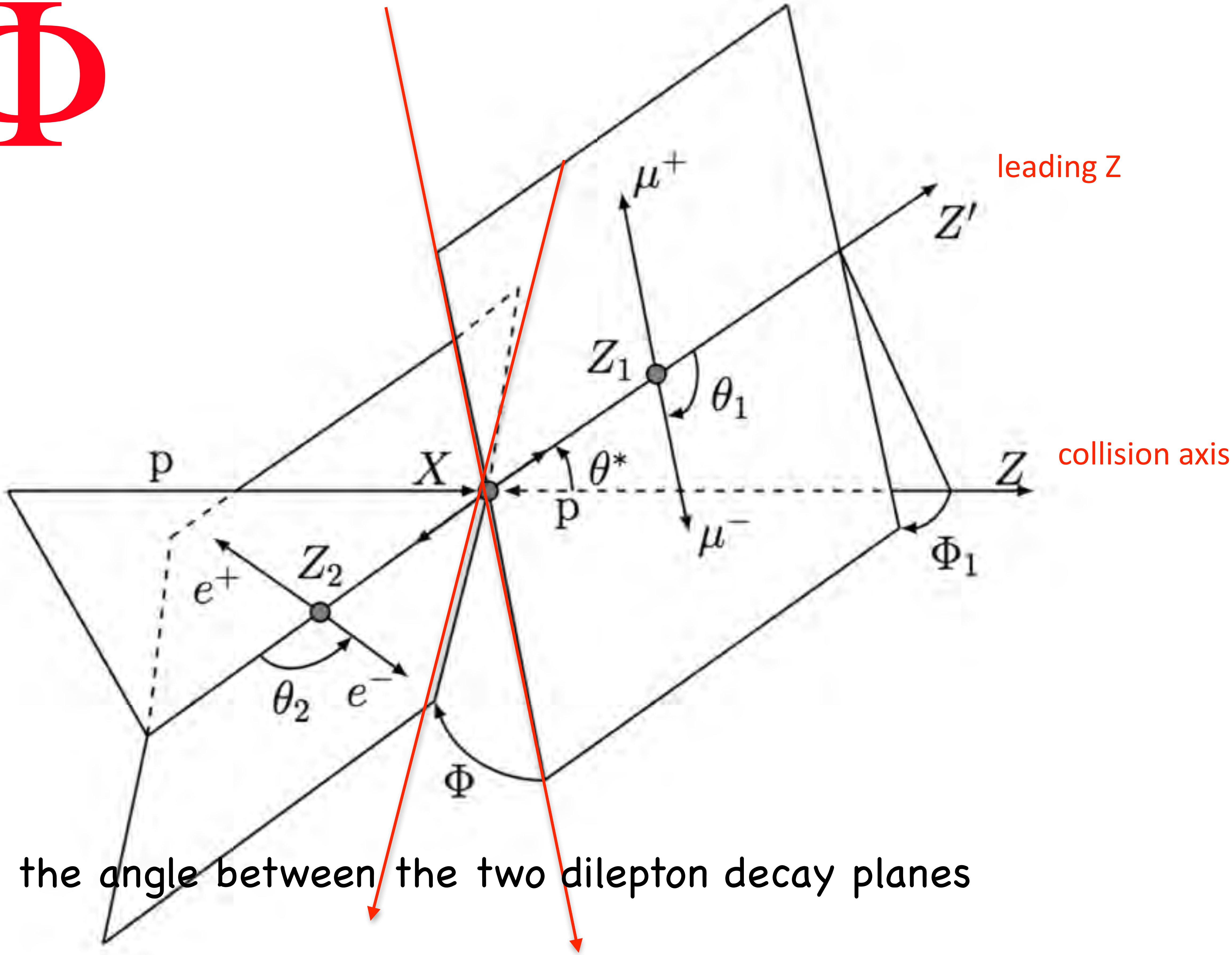
The Z Boson flight direction and the collision axis define a plane, the angle between this plane and the leading diletion plane

Discriminant Variables



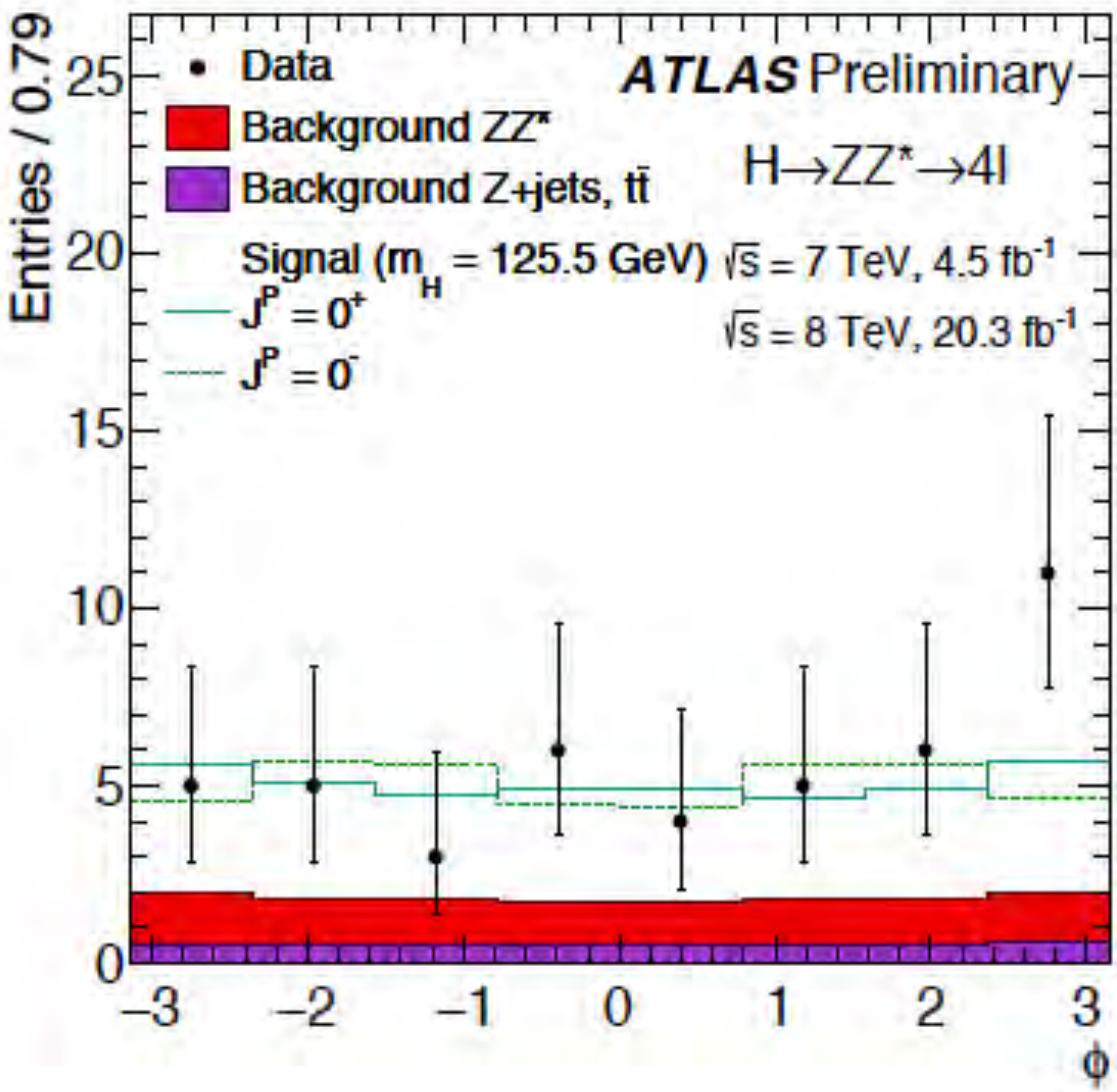
Spin Discriminators

Φ



the angle between the two dilepton decay planes

Discriminant Variables

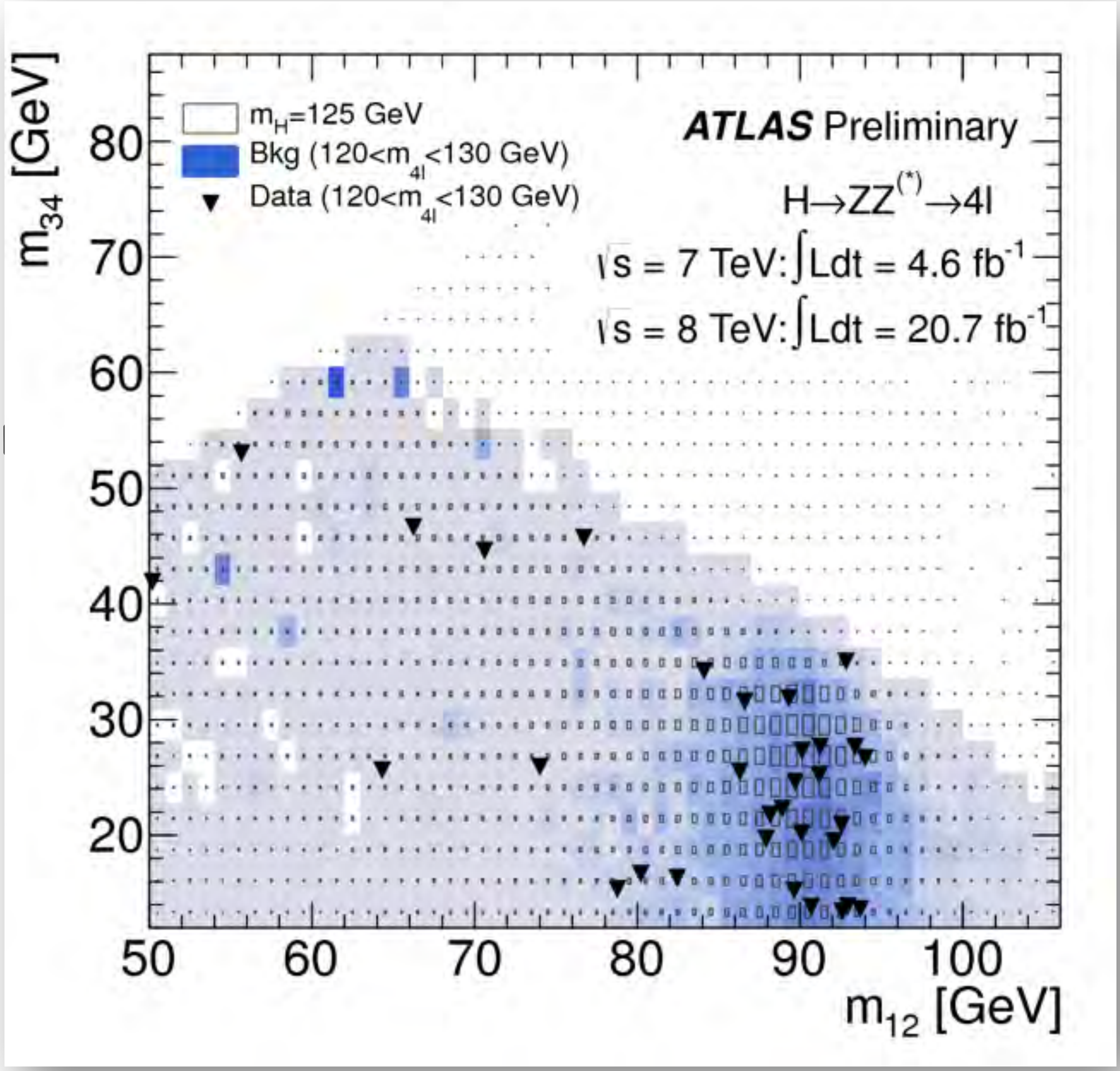


m12 -

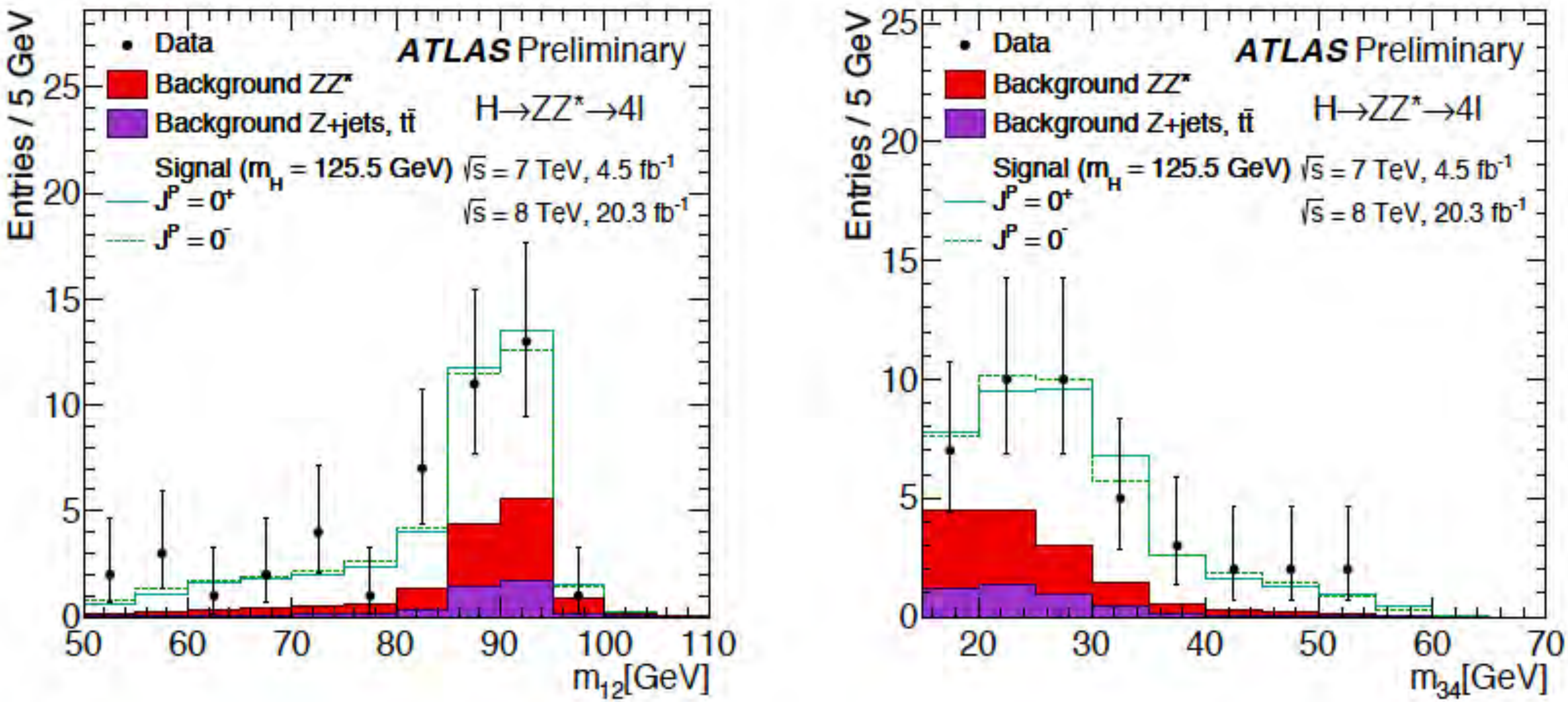
leading deletion

m34-

subleading dilepto



Discriminant Variables



The statistical treatment

Consider the di-photon,WW and ZZ channels.

Various distributions can serve as spin-parity discriminators
(e.g. angles, Higgs momentum).

$$\mathcal{L}(\text{data} \mid J^P, \mu, \vec{\theta}) = \prod_{j}^{N_{\text{chann.}}} \prod_{i}^{N_{\text{bins}}} P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\vec{\theta}) + B_{i,j}(\vec{\theta}))$$

μ_j signal strength

θ Nuisance Pars

$S_{i,j}$ Signal

$B_{i,j}$ Background

Test Statistics q

$$q = \log \frac{\mathcal{L}(J^P_{\mathrm{SM}}, \hat{\hat{\mu}}_{J^P_{\mathrm{SM}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{SM}}})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$

Corrected via the CLs method to protect against insensitive measurements

$$\mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p(J^P_{\mathrm{alt}})}{1 - p(J^P_{\mathrm{SM}})}$$

test the 0-

$$\mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p(J^P_{\mathrm{alt}})}{1 - p(J^P_{\mathrm{SM}})}$$

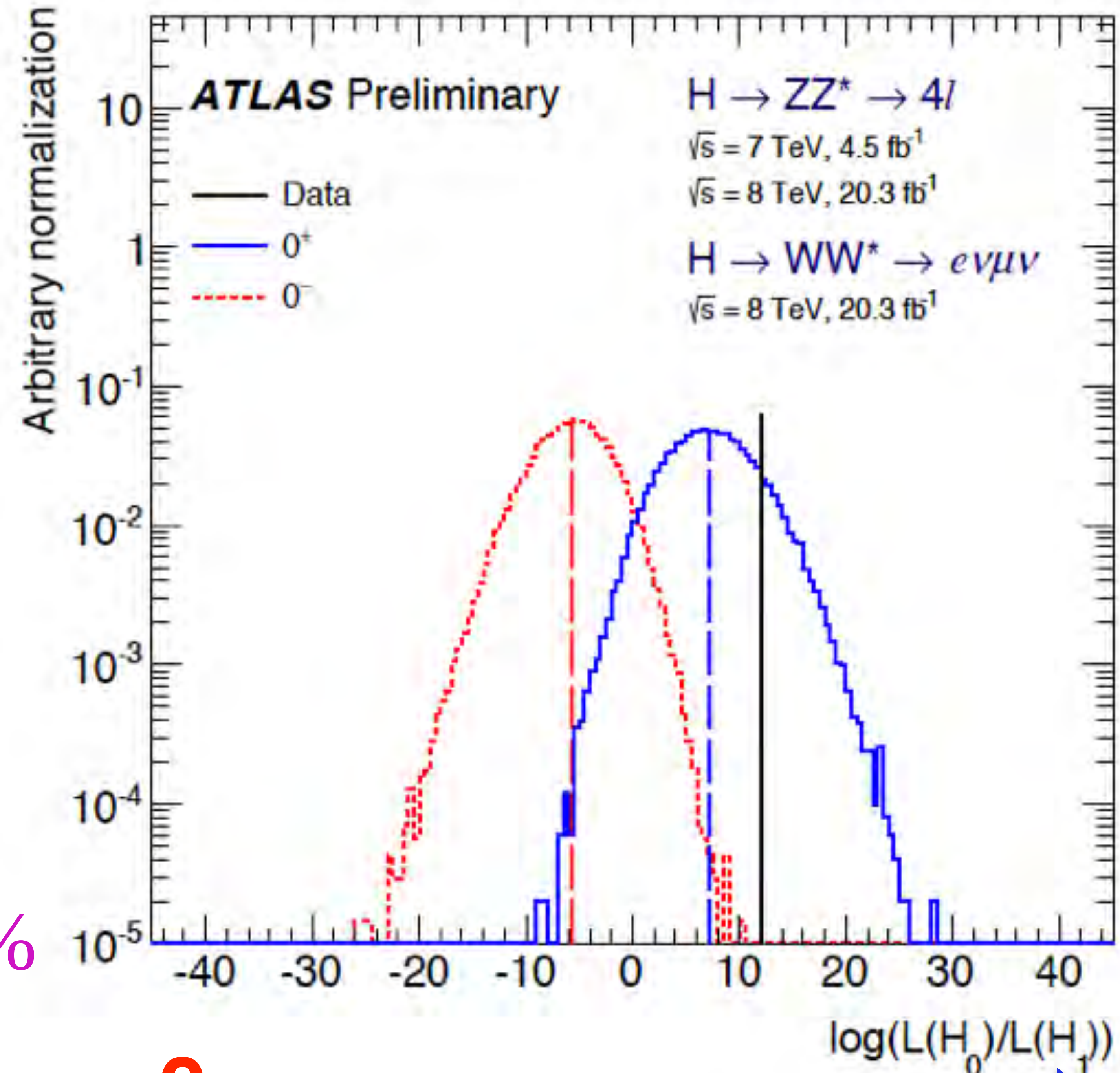
$$p^{0^-}_{obs} \le 3.1 \cdot 10^{-5}$$

$$p^{SM}_{obs} = 0.88$$

$$CLs_{obs} = \frac{3.1 \cdot 10^{-5}}{1 - 0.88} =$$

$$= 2.6 \cdot 10^{-4} = 0.026\%$$

$$CL_{95} = 1 - CLs = 99.7\%$$



0-

0+

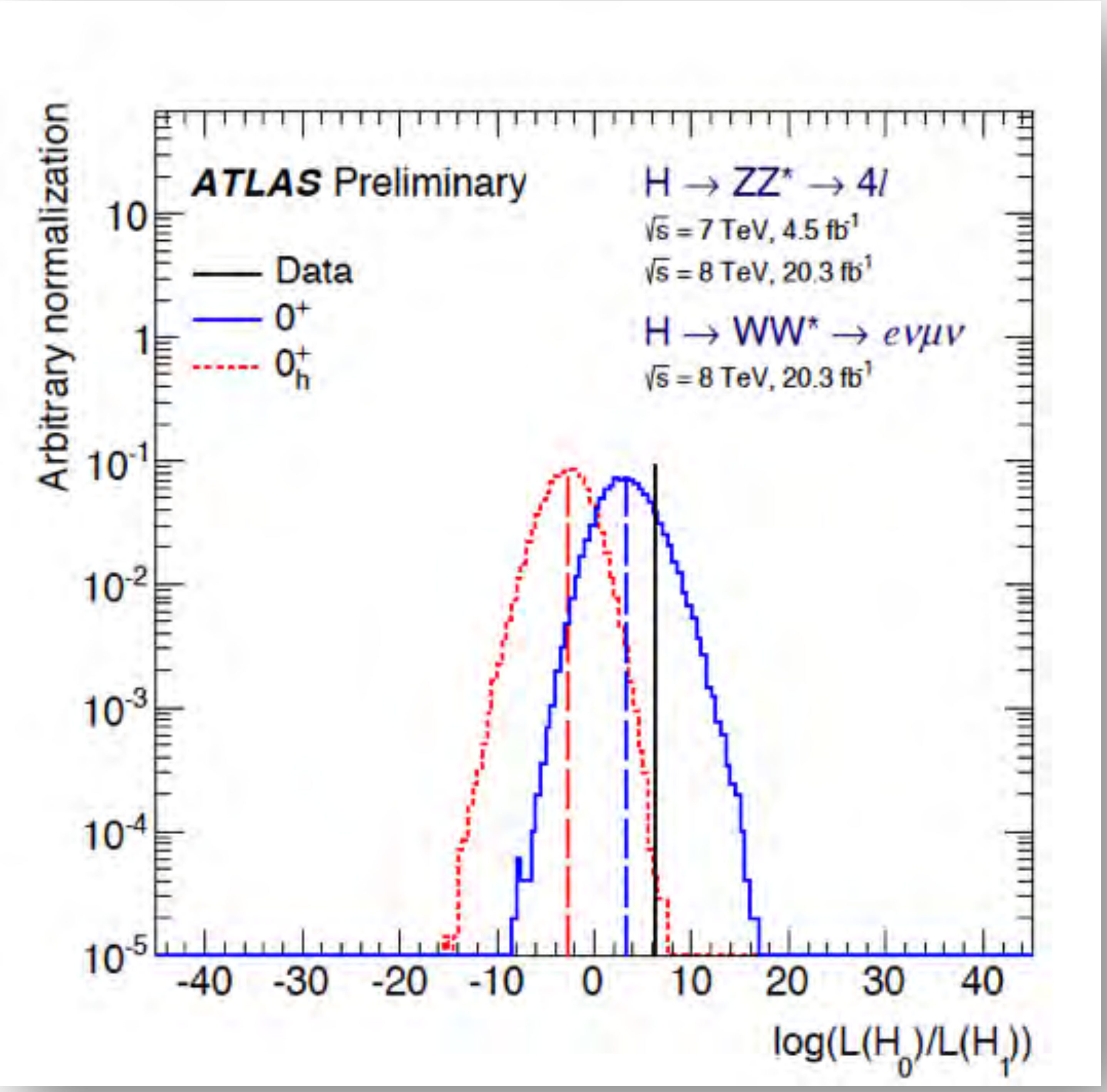
$$p_{obs} \approx 7.1 \cdot 10^{-5}$$

$$p_{obs}^{SM} = 0.85$$

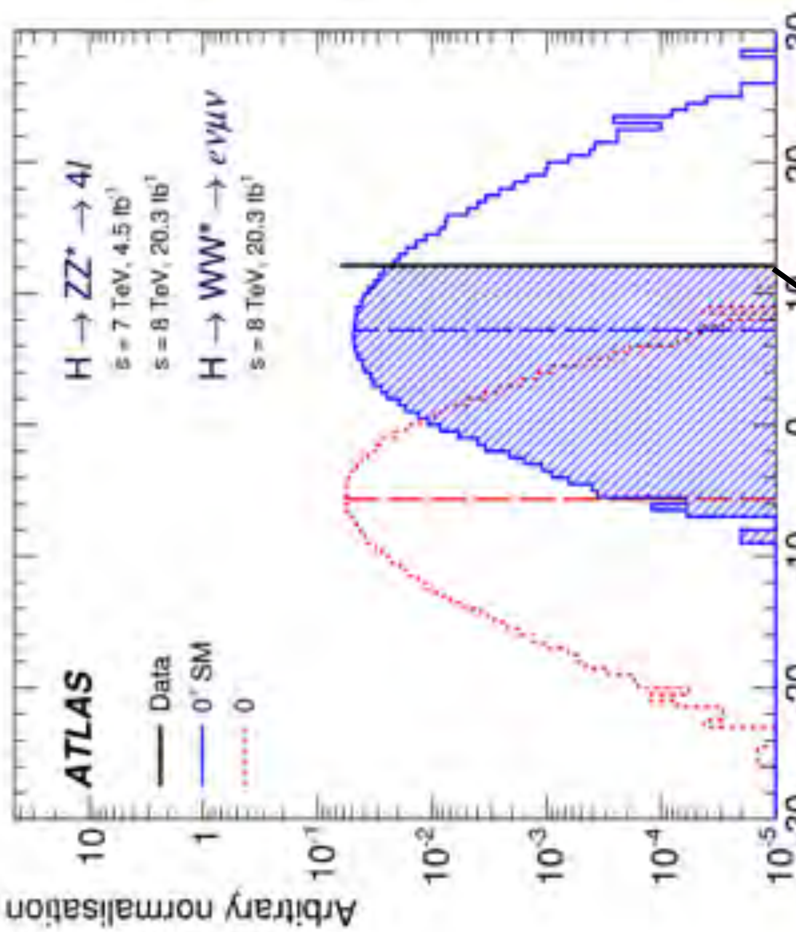
$$CLs_{obs} = \frac{7.1 \cdot 10^{-5}}{1 - 0.85} =$$

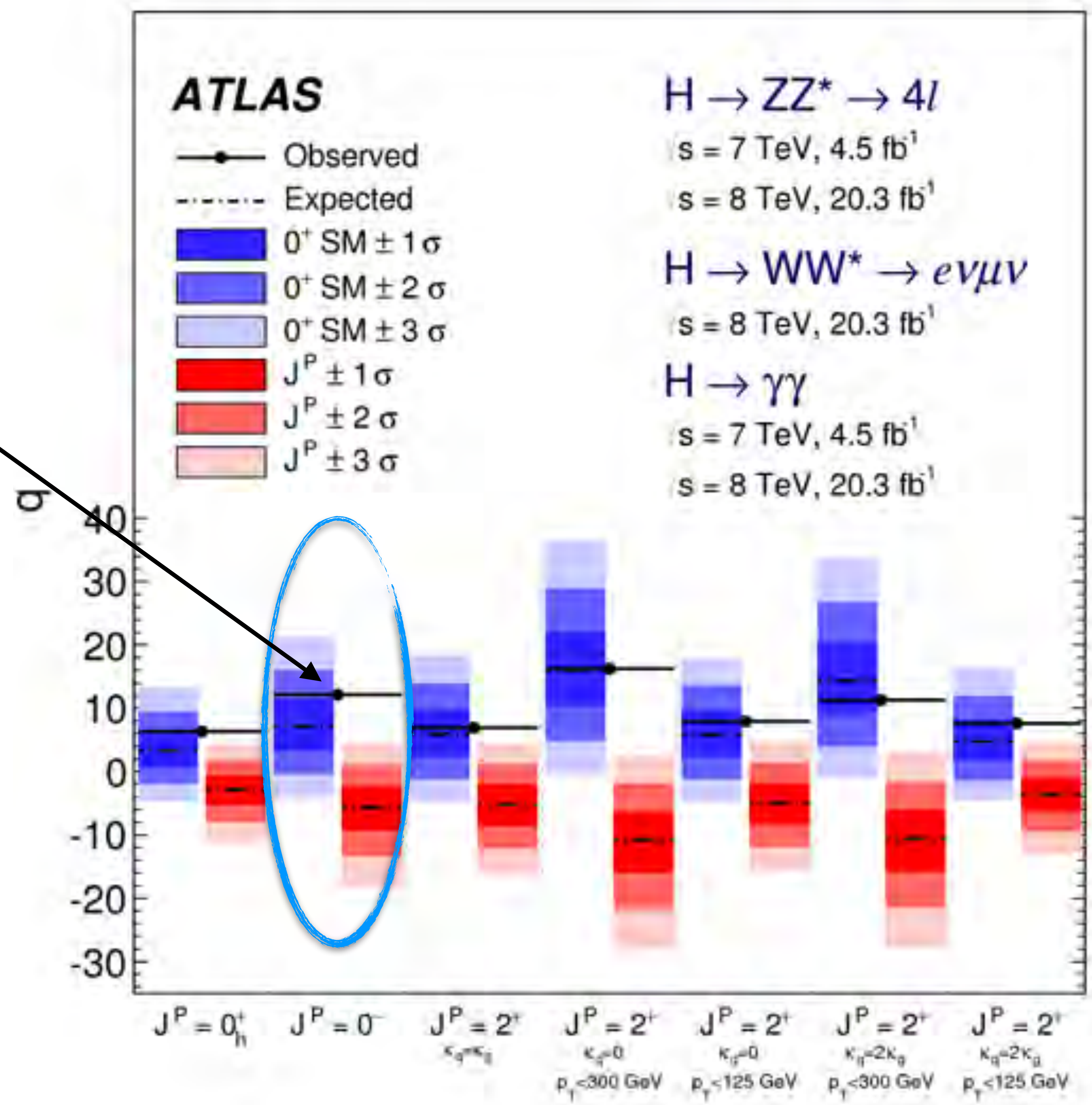
$$= 4.7 \cdot 10^{-4} = 0.047\%$$

$$CL_{95} = 99.95\%$$



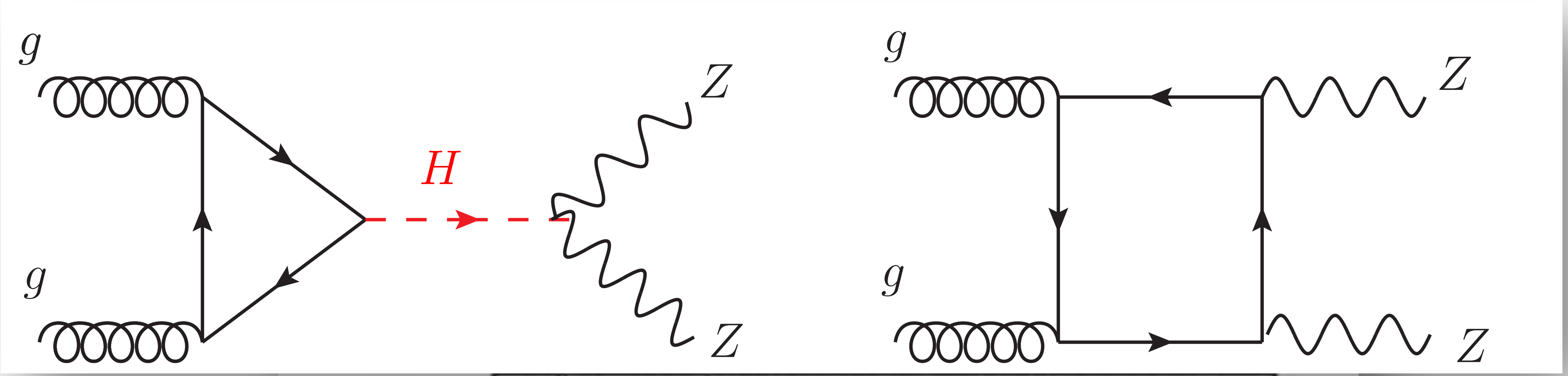
Higgs Spin Visual Summary

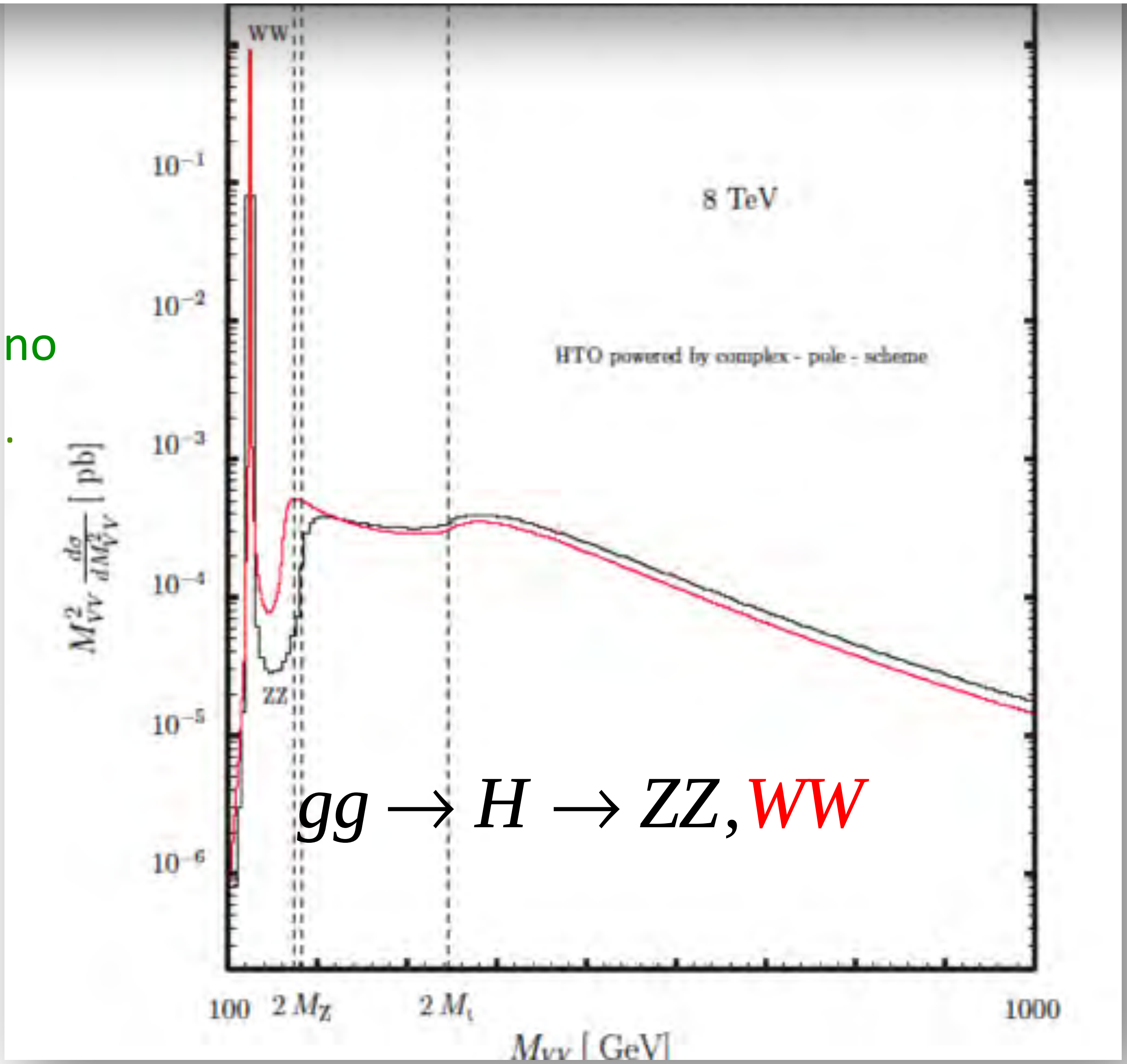





Higgs Width
OffShell in a NutShell

OffShell in a NutShell





N. Kauer and G. Passarino

arXiv:1206.4803 [hep-ph].

F. Caola and K. Melnikov

C. Englert and
M. Spannowsky

Off Shell Simplification

ZWA

$$\sigma_{OnShell}(gg \to H \to ZZ^*) \sim \frac{\Gamma(gg \to H)\Gamma(H \to ZZ^*)}{m_H \Gamma_H}$$

$$\sigma(gg \to H^{(*)} \to ZZ^{(*)}) \sim m_H \Gamma_H \frac{\Gamma(gg \to H^{(*)})\Gamma(H^{(*)} \to ZZ^{(*)})}{(\hat{s} - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

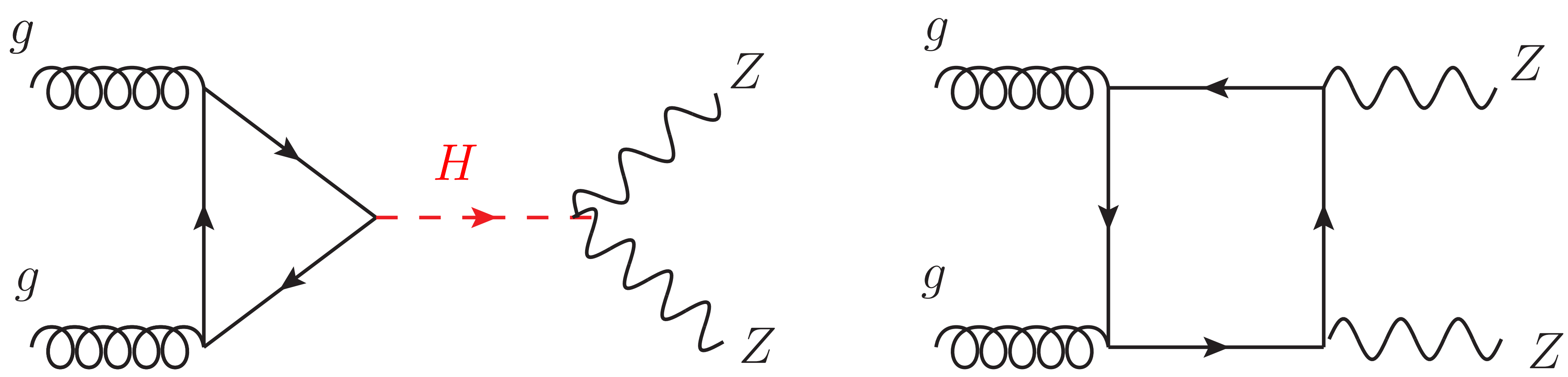
$$\frac{\sigma_{OnShell}(gg \to H \to ZZ^*)}{\sigma_{OnShell}(gg \to H \to ZZ^*)_{SM}} = \frac{\Gamma(gg \to H)}{\Gamma(gg \to H)_{SM}} \frac{\Gamma(H \to ZZ^*)}{\Gamma(H \to ZZ^*)_{SM}} \frac{\Gamma_H^{SM}}{\Gamma_H}$$

$$\mu_{OnShell} \equiv \frac{\sigma_{OnShell}(gg \to H \to ZZ^*)}{\sigma_{OnShell}(gg \to H \to ZZ^*)_{SM}} = \kappa_g^2 \kappa_Z^2 \frac{\Gamma_H^{SM}}{\Gamma_H}$$

$$\frac{\sigma_{OffShell}(gg \to H^* \to ZZ)}{\sigma_{OffShell}(gg \to H^* \to ZZ)_{SM}} \approx \frac{\Gamma(gg \to H^*)}{\Gamma(gg \to H^*)_{SM}} \frac{\Gamma(H^* \to ZZ)}{\Gamma(H^* \to ZZ)_{SM}}$$

$$\mu_{OffShell} \equiv \frac{\sigma_{OffShell}(gg \to H \to ZZ^*)}{\sigma_{OffShell}(gg \to H \to ZZ^*)_{SM}} \approx \kappa_{g,OffShell}^2 \kappa_{Z,OffShell}^2$$

OffShell in a NutShell

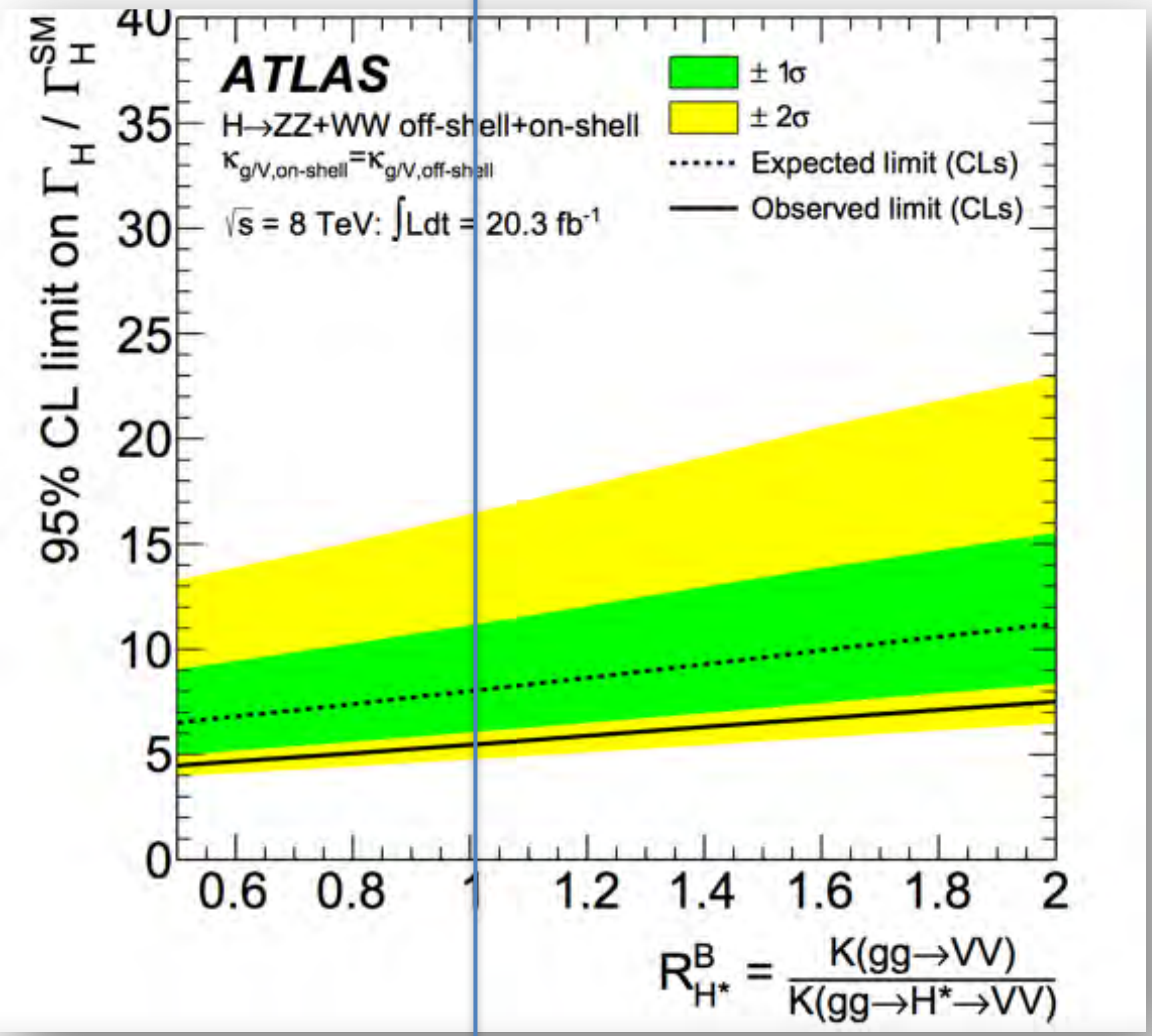


$$\frac{\mu_{OffShell}}{\mu_{OnShell}} = \frac{\kappa^2_{g,OffShell}\kappa^2_{Z,OffShell}}{\kappa^2_g \kappa^2_Z \dfrac{\Gamma^{SM}_H}{\Gamma_H}}$$

$$\frac{\mu_{OffShell}}{\mu_{OnShell}} \geq \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\Gamma_H \leq 5.5\Gamma_H^{SM}$$

$$\Gamma_H \leq 22.8\,MeV$$



$R^B_{H^*}$	Observed 0.5	**1.0**	2.0	Median expected 0.5	**1.0**	2.0	Assumption
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}, \Gamma_H/\Gamma_H^{SM}=1$

Couplings

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: JHEP

CERN-EP-2016-100
8th June 2016

Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC *pp* collision data at $\sqrt{s} = 7$ and 8 TeV

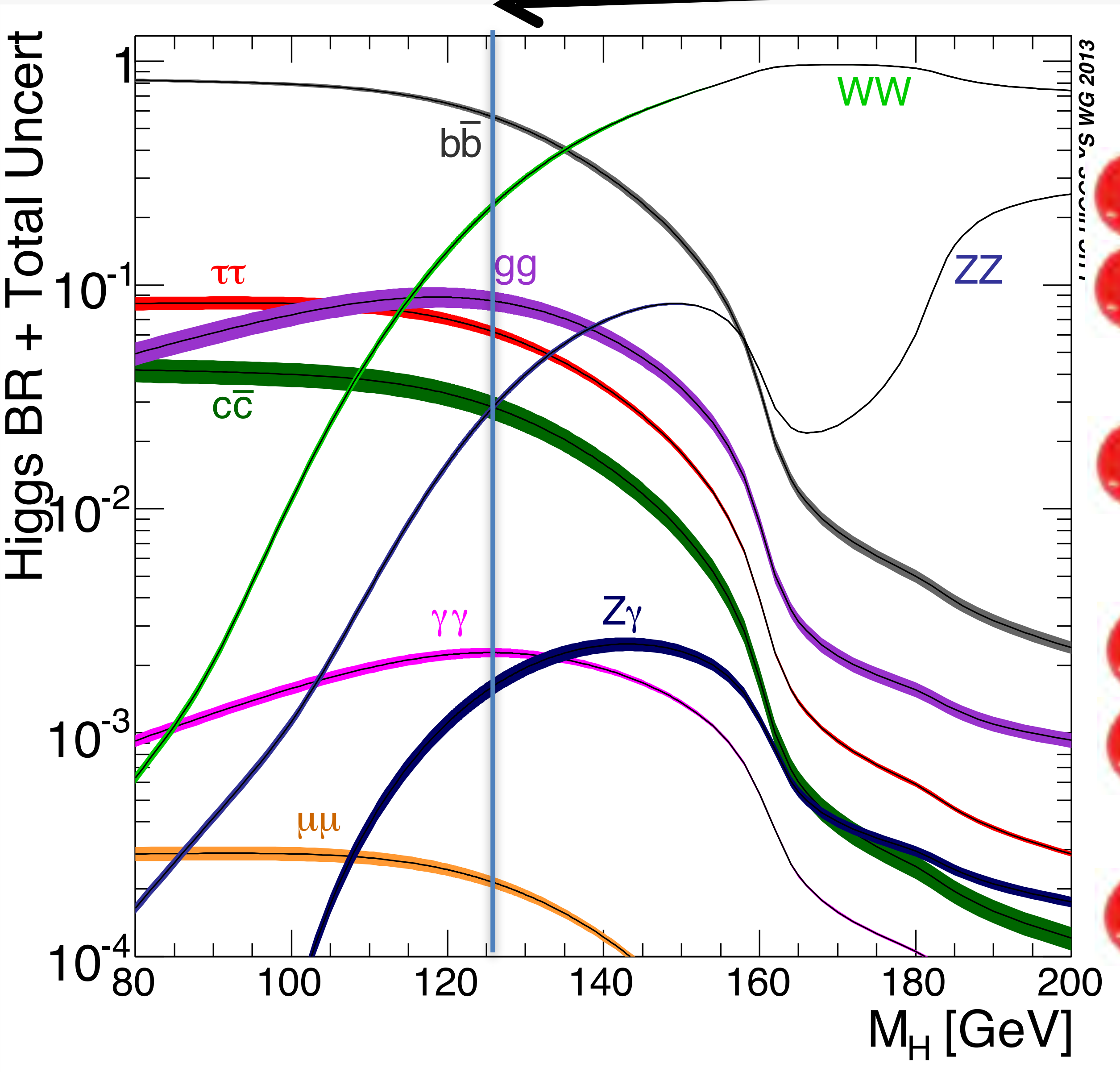
The ATLAS and CMS Collaborations

arXiv:1606.02266v1 [hep-ex] 7 Jun 2016

Signal Strengths

Theory Inputs I: Higgs Decays

m_H=125.09 GeV



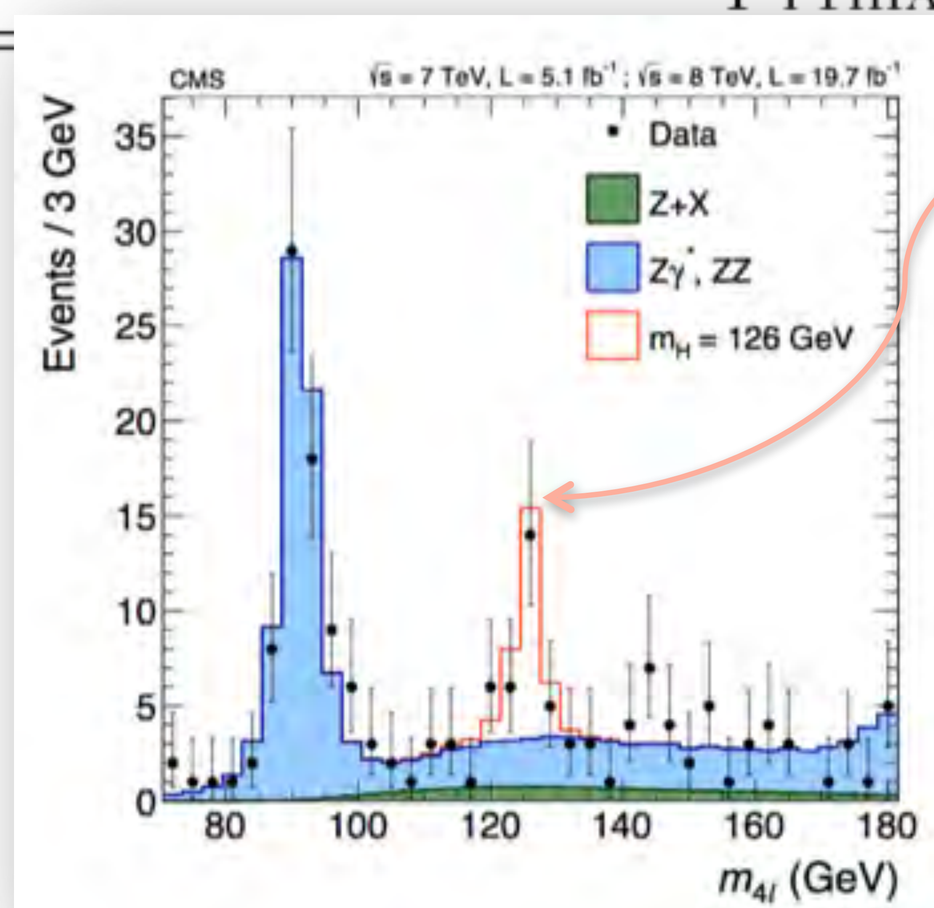
Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

(Note! No 1st or 2nd gen fermions)

The natural width of the Higgs boson is expected to be very small, 4.1 MeV (< resolution)

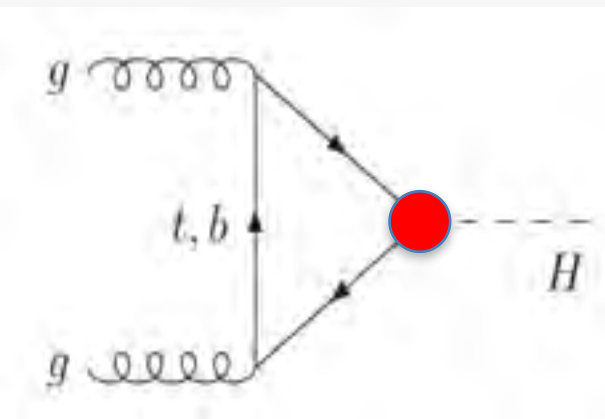
Theory Input : Event (MC) Generators

Production process	Event generator	
	ATLAS	CMS
ggF	Powheg [30,31,32,33,34]	Powheg
VBF	Powheg	Powheg
WH	Pythia8 [35]	Pythia6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	Pythia8	Pythia6.4
$ggZH$ ($gg \to ZH$)	Powheg	See text
ttH	Powhel [44]	Pythia6.4
tHq ($qb \to tHq$)	MadGraph [46]	aMC@NLO [29]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	Pythia8	Pythia6, aMC@NLO

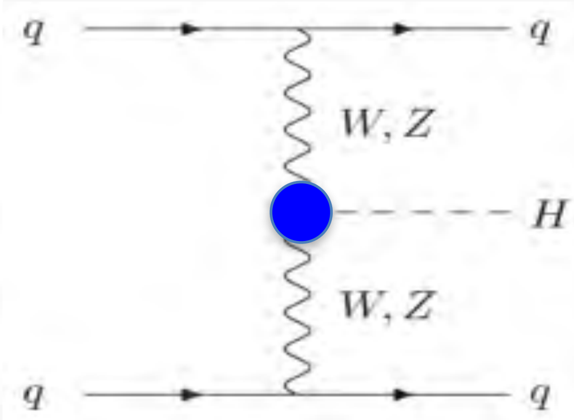


Theory Inputs III: Production Modes

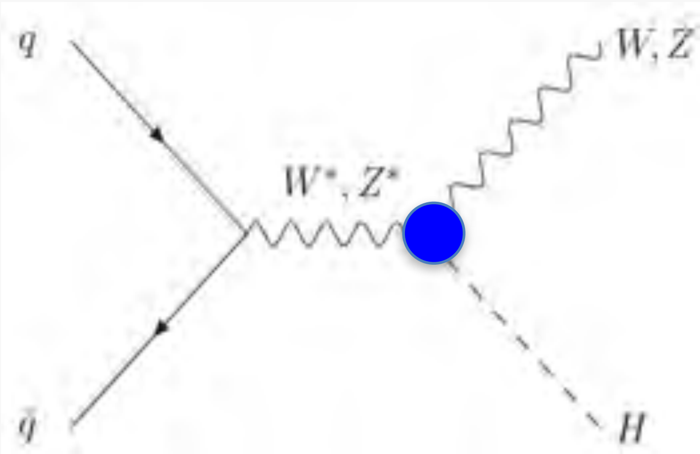
ggH



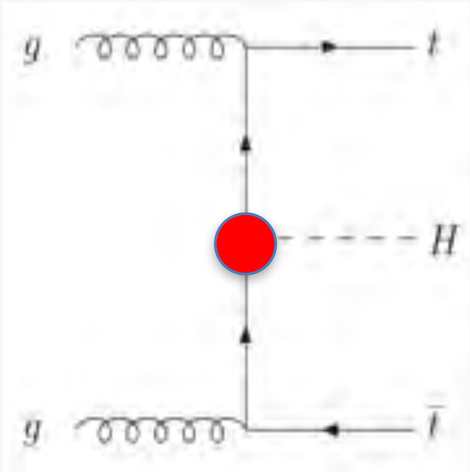
VBF

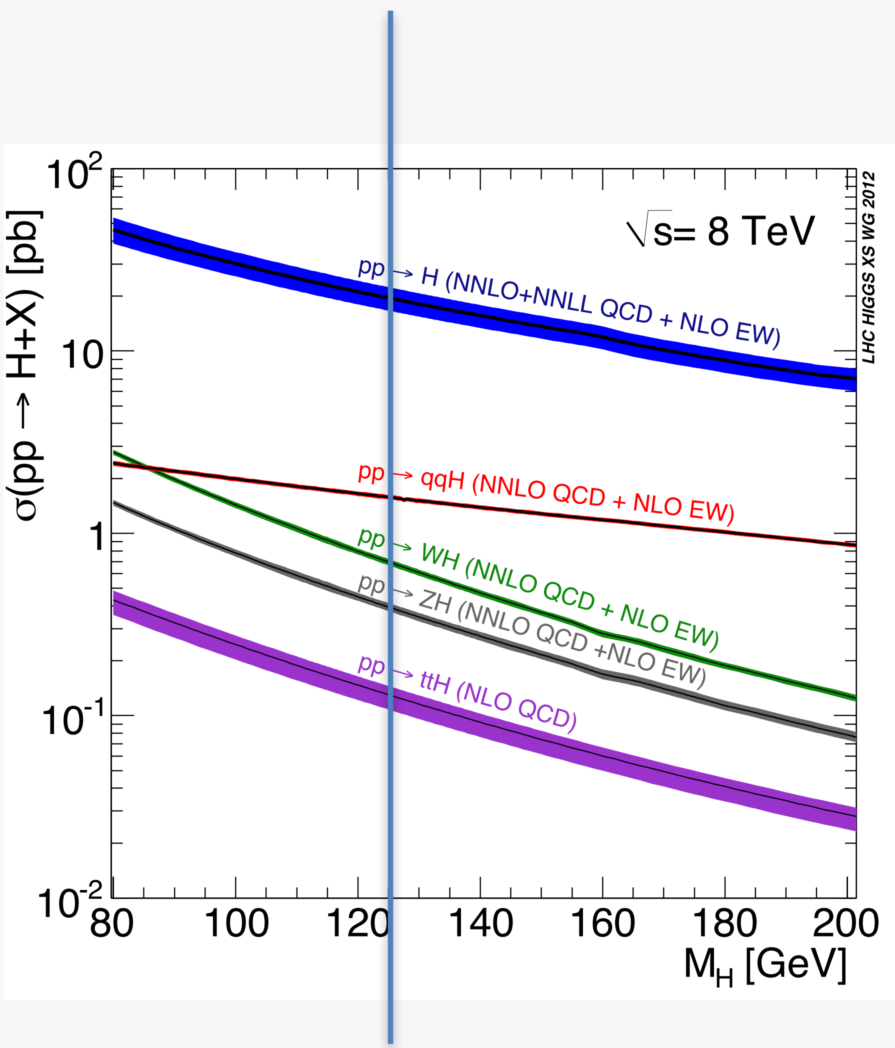


VH



ttH

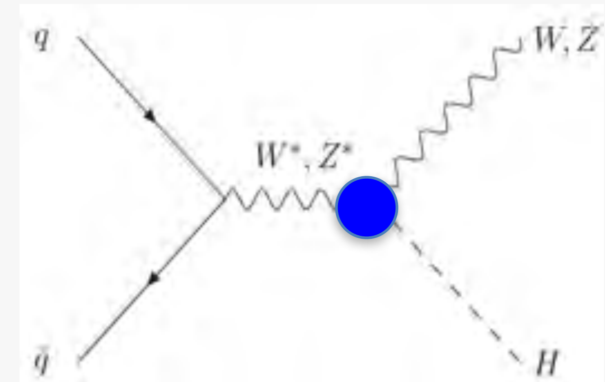




Production process	Cross section [pb] $\sqrt{s}=7$ TeV	$\sqrt{s}=8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

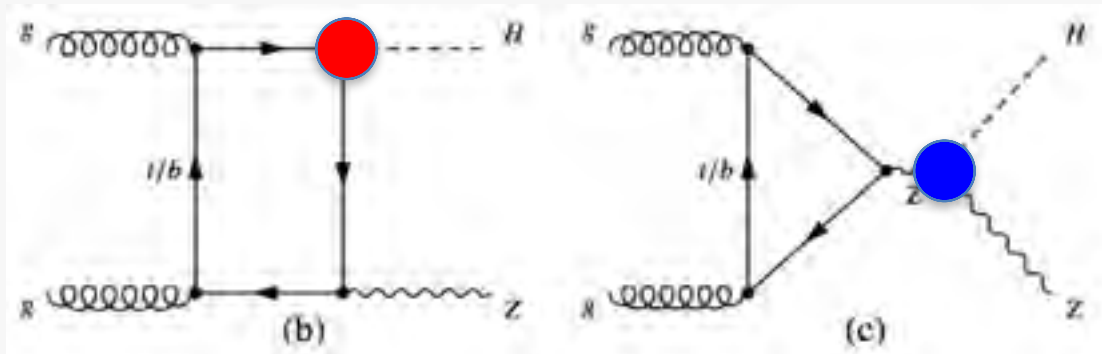
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%

Theory Inputs IV: Other Production Modes



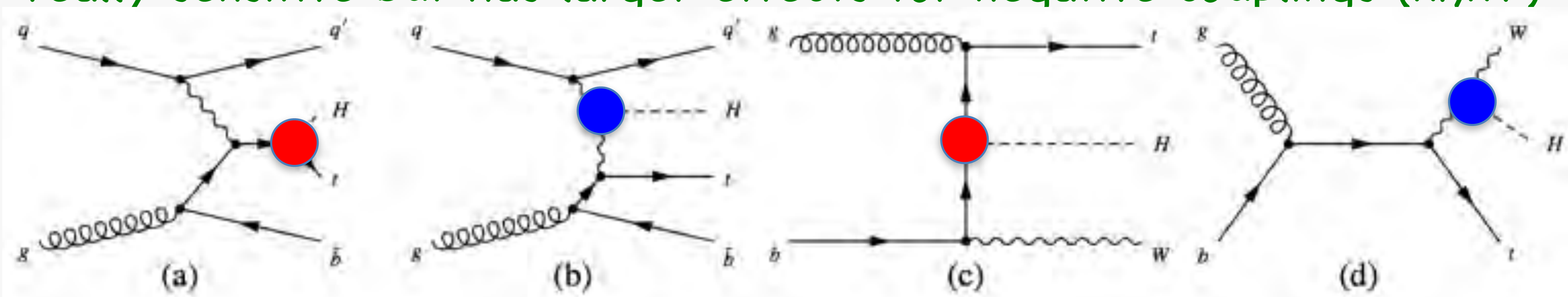
ggZH:

O(10%) effect on VHbb in SM, higher p_T than qqZH



tHq + tHW

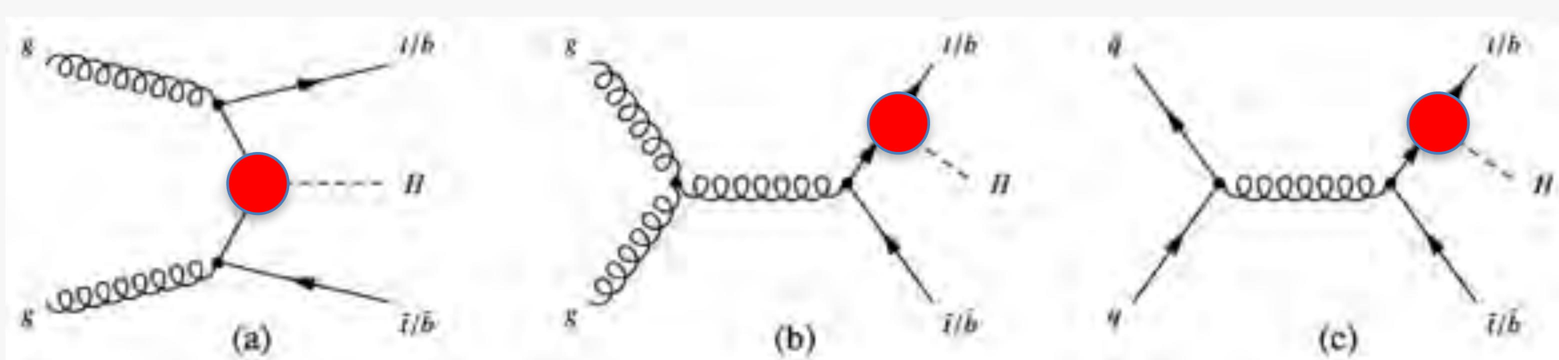
Not really sensitive but has larger effects for negative couplings (kF,kV)



bbH

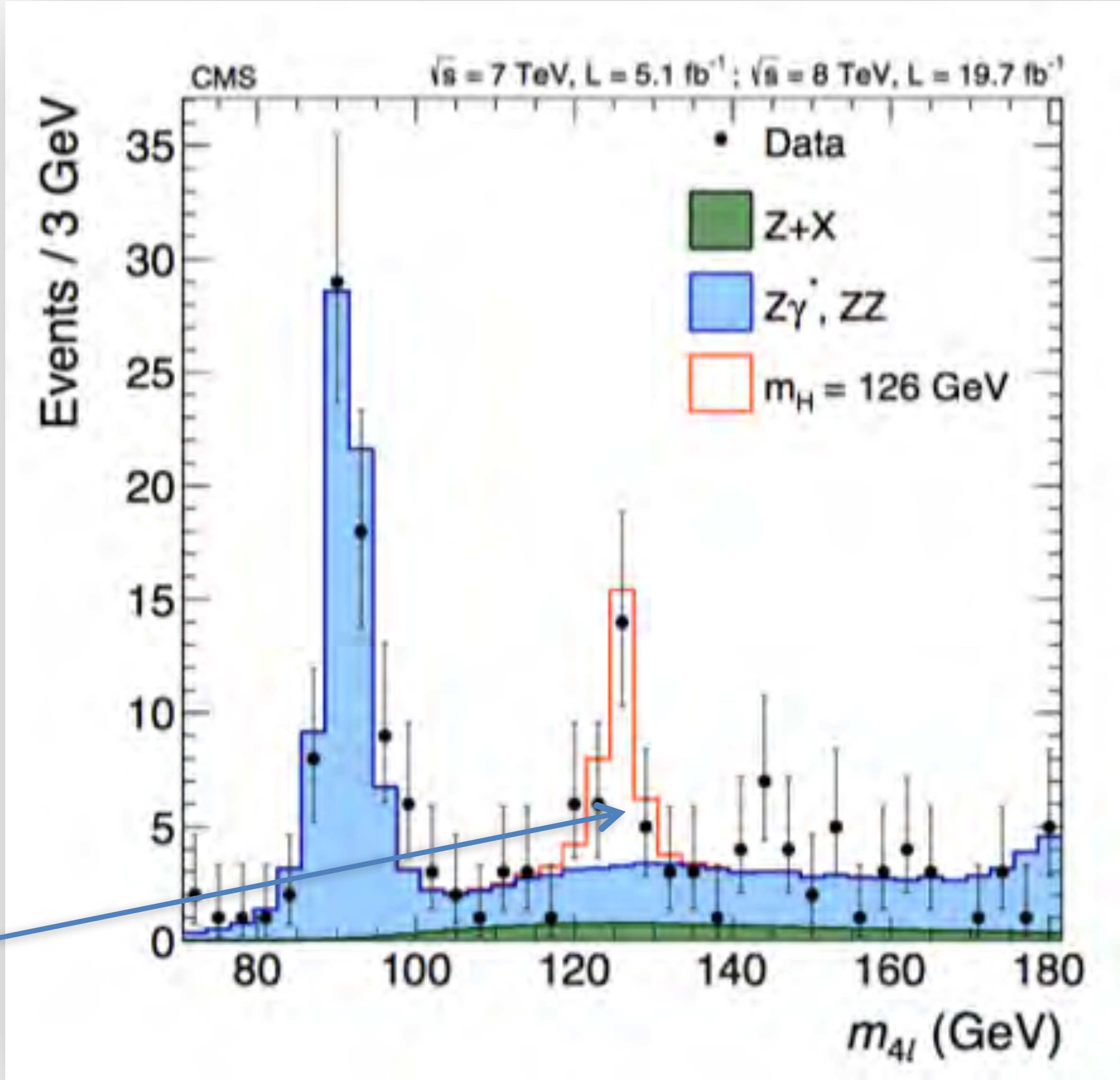
bbH is ~1% of total HXSC.

Similar to ttH but not really distinguishable from ggF



What do we measure (observables)

A simplified view:



We measure event yields

(in bins, i.e. shapes)

We want to derive couplings and signal strengths

The analysis is using discriminators (usually reconstructed mass related) to increase S/B

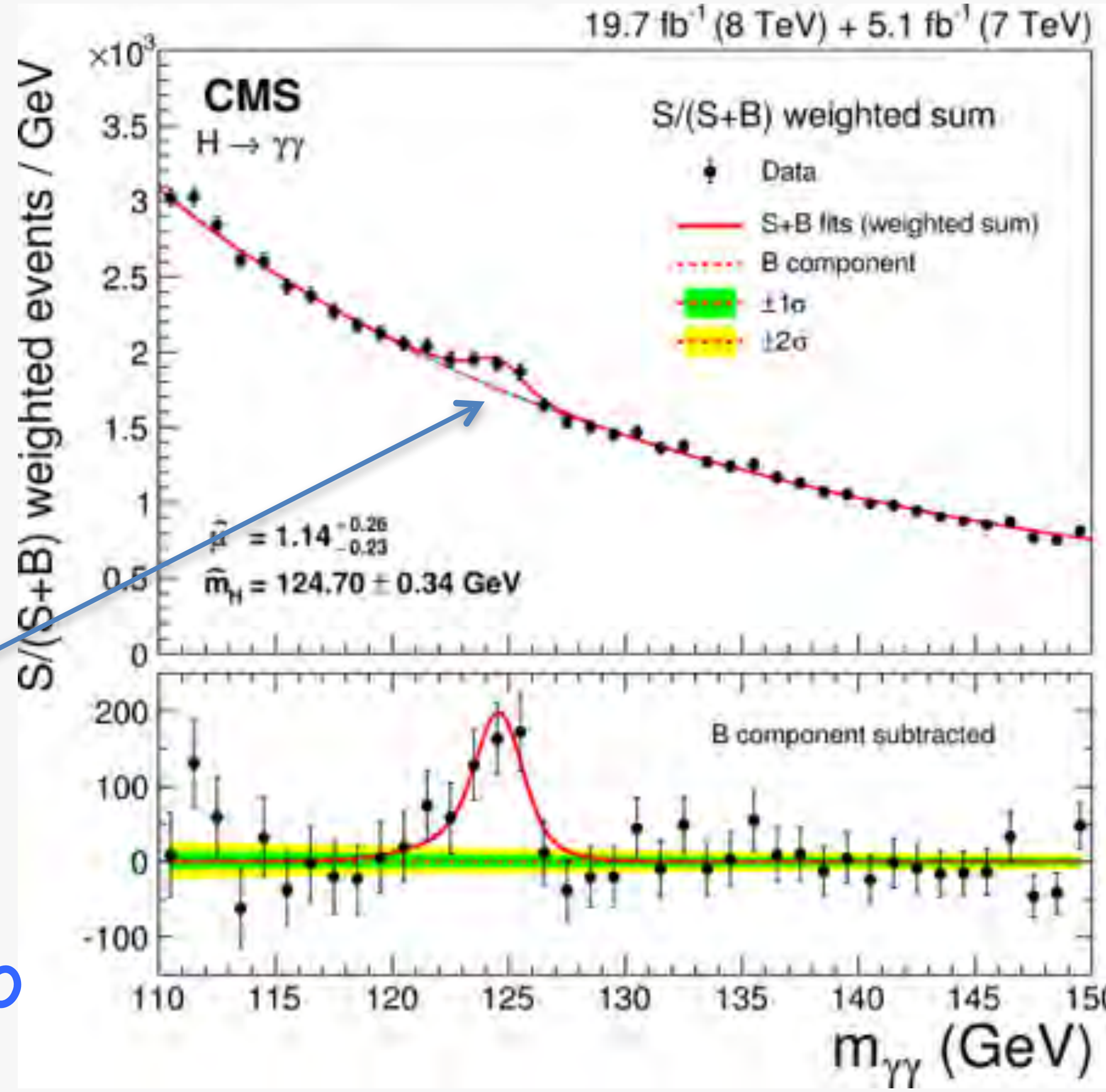
$$n_s(i \rightarrow f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A^i_p \times \varepsilon^i_p \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \quad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

$$\boxed{\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{SM}}}$$

What do we measure (observables)

A simplified view:



We measure event yields

(in bins, i.e. shapes)

We want to derive couplings and signal strengths

The analysis is using discriminators (usually reconstructed mass related) to increase S/B

$$n_s(i \to f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A^i_p \times \varepsilon^i_p \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \quad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

PO

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

What do we Measure?

We measure event yields

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{(\text{BR}^f)_{\text{SM}}}$$

Pseudo Observables

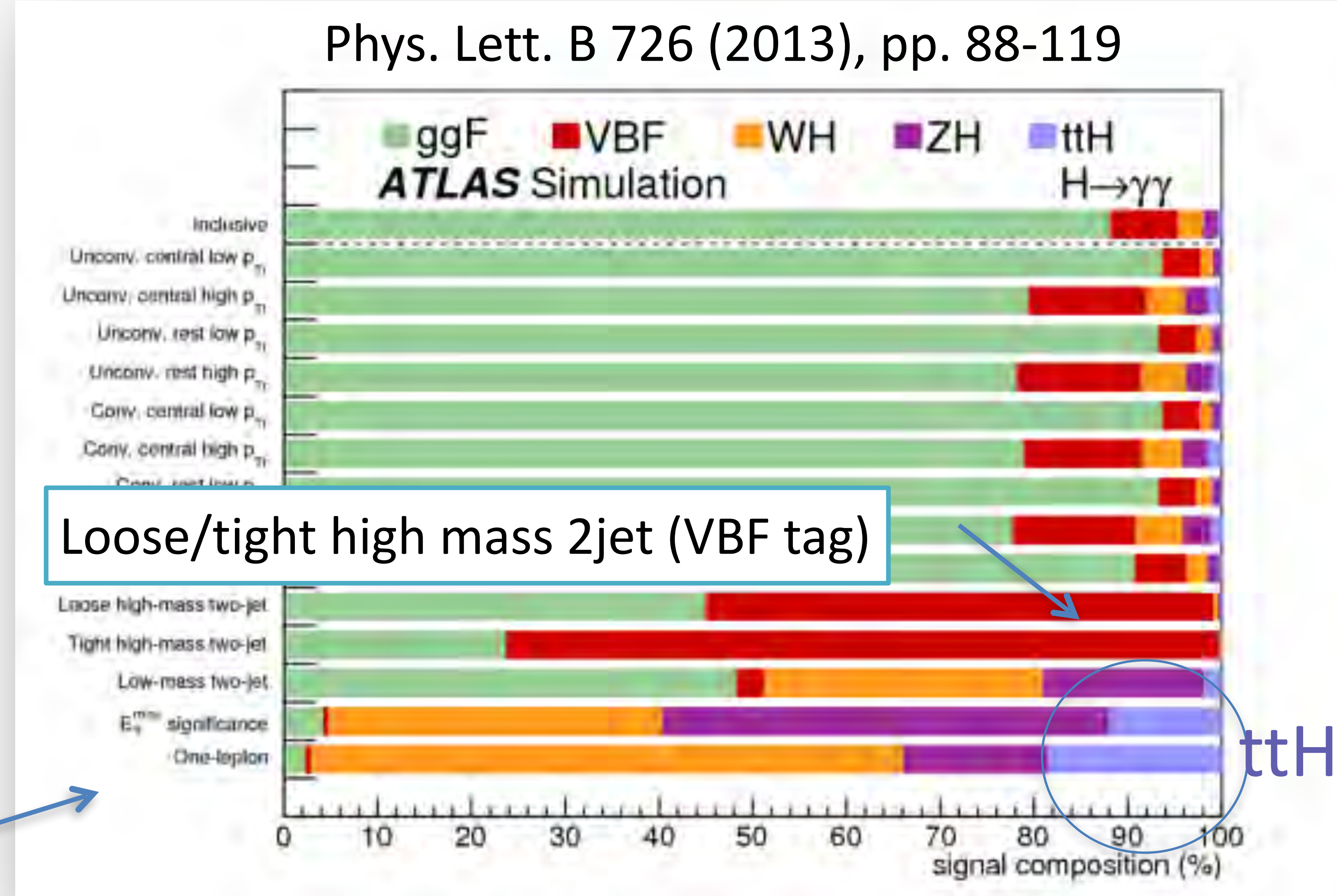
$$\mu_i^f = \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i)_{\text{SM}} \cdot (\text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

$$n_s(i \to f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

Observable | PO | Theory | Theory & Experiment | Accelerator & Experiment

What do we measure (observables)

We increase sensitivity by classifying the events via categories and measure the signal strength per category and then combining them taking all the sytematic and statistical errors uncertainties into account



The categories are also sensitive to different production modes, allowing the measurement of the couplings

$$n_s^c(\gamma\gamma) = \sum_{i,c} \mu^{i,c} \times \mu^{\gamma\gamma,c} \times (\sigma^i \times Br^{\gamma\gamma})_{SM} \times A_i^{\gamma\gamma,c} \times \varepsilon_i^{\gamma\gamma,c} \times Lumi$$

$$i \in (ggF, VBF, VH, ttH)$$

PO

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

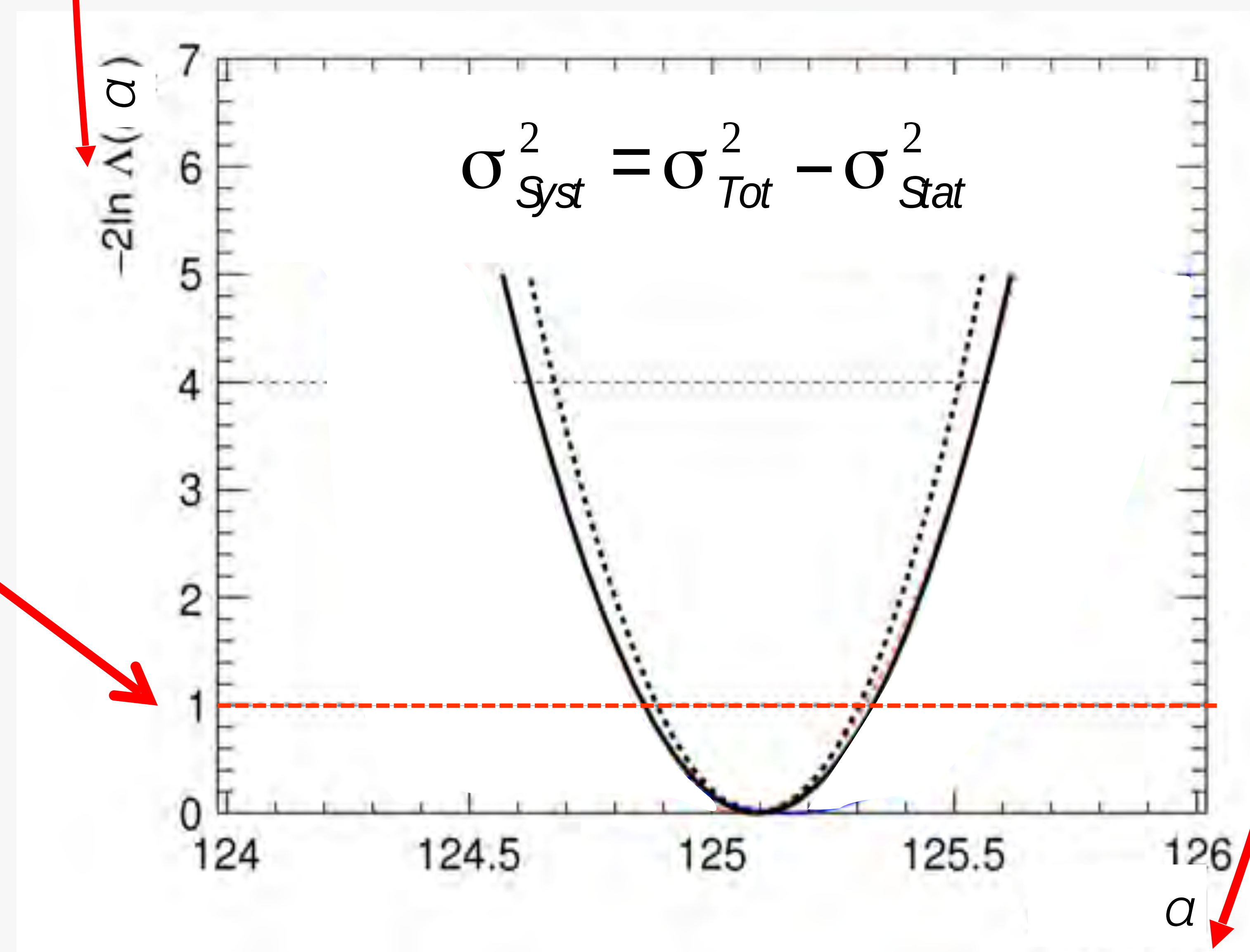
Statistical treatment – profile likelihood

From thw combined data of (ATLAS+CMS) construct the **profile likelihood** with the parameter(s) of interest α

Θ: vector of ~4200 nuisance parameters

$$t_\alpha - 2\ln\frac{L(\alpha,\hat{\hat{\theta}}_\alpha)}{L(\hat{\alpha},\hat{\theta})}$$

68% Confidence interval defined by a rise of 1 unit in t(α) (asymptotic limit)



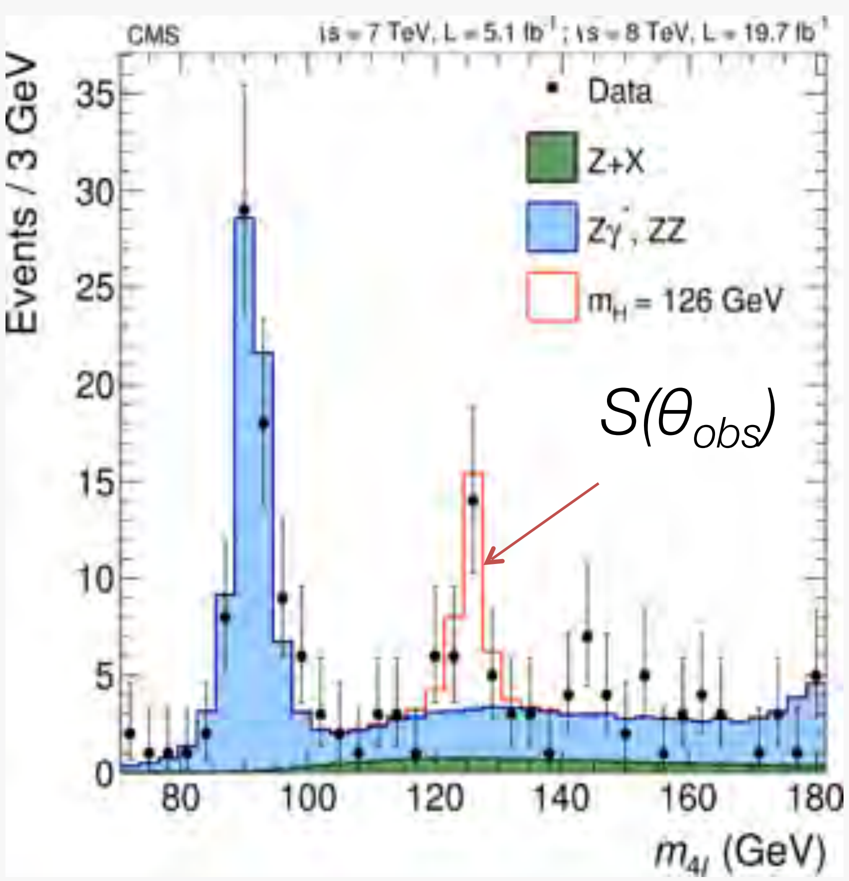
Systematics and Nuisance Parameters

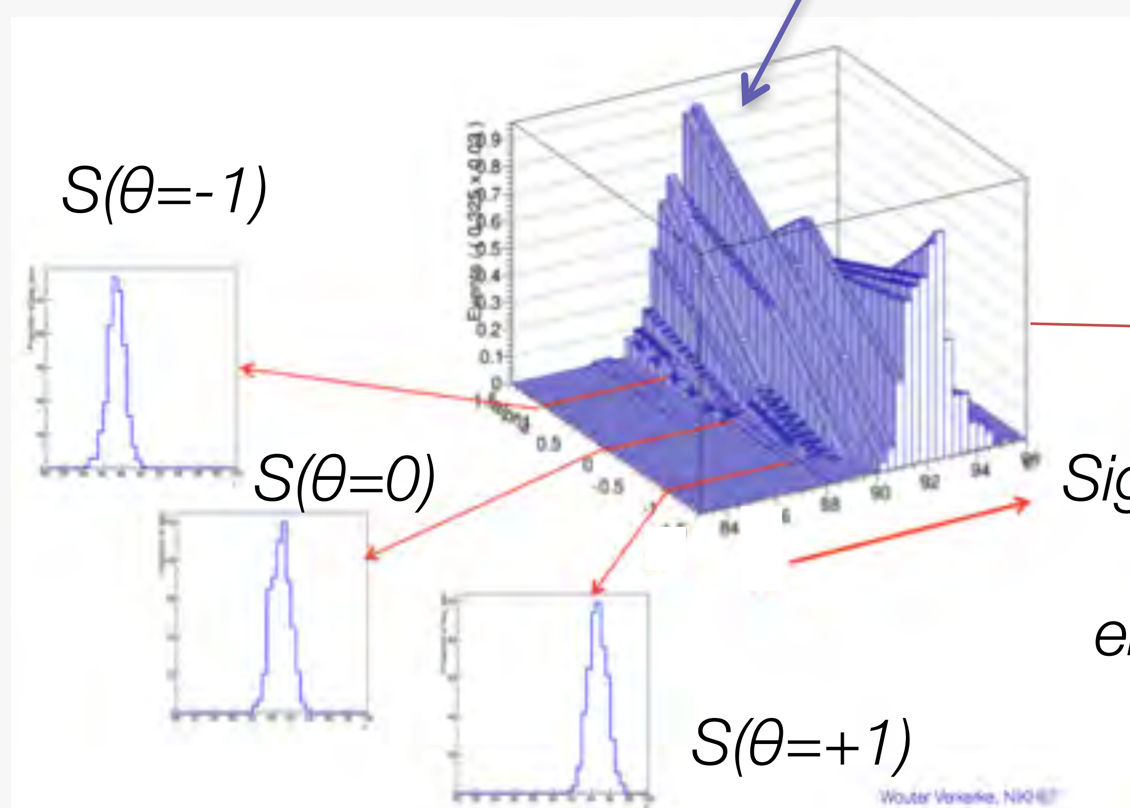
Profile likelihood ratio test statistics:

The signal/background distributions can *describe distributions under a wide range of parameters* for which the true values are unknown
(energy scales, QCD scales…)

Illustration: modeling of energy scale uncertainty

$$n_{s+b}(i \rightarrow f) = \mu^i \mu^f \times s_i^f(\theta) + b$$





S(N|θ)

Signal Probability model for any value of energy scale param θ

Systematics and Nuisance Parameters

Profile likelihood ratio test statistics:

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

- for each likelihood evaluation, all systematic uncertainties (**nuisances**) are varied to maximize the profile likelihood (**profiled**)

~4200 nuisances in the combined fits

- A large part related to the finite MC statistics
- Signal theory normalization uncertainties
- BG theory uncertainties (for BGs not using the data)
- Other experimental uncertainties

Most experimental uncertainties are assumed uncorrelated between the two experiments and many tests have been carried out to check the possible impact that was found negligible

Main signal theoretical sources of uncertainties :

- QCD scales,
- parton distribution functions (PDF),
- UEPS
- Higgs boson branching ratios (BRs).

A care was taken that the state-of-the art calculations of theoretical cross sections and BR, Higgs p_T are common between the two experiments.

Sometimes this care required modifications of the analyses.

Systematics (NPs) details

The PDF uncertainties on the inclusive rates for different Higgs boson production processes are correlated between the two experiments for the same channel but are treated as uncorrelated between different channels, except one case

The WH,ZH & VBF production processes are assumed to be fully correlated

Correlating Experiments and Channels

$$L_{ATLAS,ZZ}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{ATLAS_{Det}},\theta,.....\right)$$

$$L_{ATLAS,\tau\tau}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{ATLAS_{Det}},\theta,.....\right)$$

$$L_{ATLAS,ZH}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{ATLAS_{Det}},\theta,.....\right)$$

$$L_{CMS,ZZ}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{CMS_{Det}},\theta,.....\right)$$

QCD scale and UEPS uncertainties are correlated between the two experiments in the same production channels and are treated as uncorrelated between different channels.

The WH,ZH & VBF production processes are assumed to be fully correlated

$$L_{CMS,ZH}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{CMS_{Det}},\theta,.....\right)$$

$$L_{CMS,WH}\left(\mu.\theta_{QCDscale},\theta_{PDF},\theta_{CMS_{Det}},\theta,.....\right)$$

Systematics

In the paper the systematics will be classified to four groups and given in that way for some chosen cases:

Stat

Statistical in nature (Data control regions)

thsig

uncertanties affecting Higgs Boson signal

thbgd

uncertainties affecting background processes, not correlated wit

.

expt

experimental and those related to finite size MC statistics

Experimental Assumptions

- We assume a SM-like Higgs boson with $J^P=0^+$ and with a narrow width (NWA) such that production and decay are decoupled

$$\boxed{\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}}$$

- The mass of the Higgs is assumed to be

$$\boxed{m_H = 125.09\ \mathrm{GeV}}$$

- We cannot separate the production from the decay @ the LHC.
  We measure event yields and deduce
  (for example)the global signal strength $\sigma_i \times BR^f$

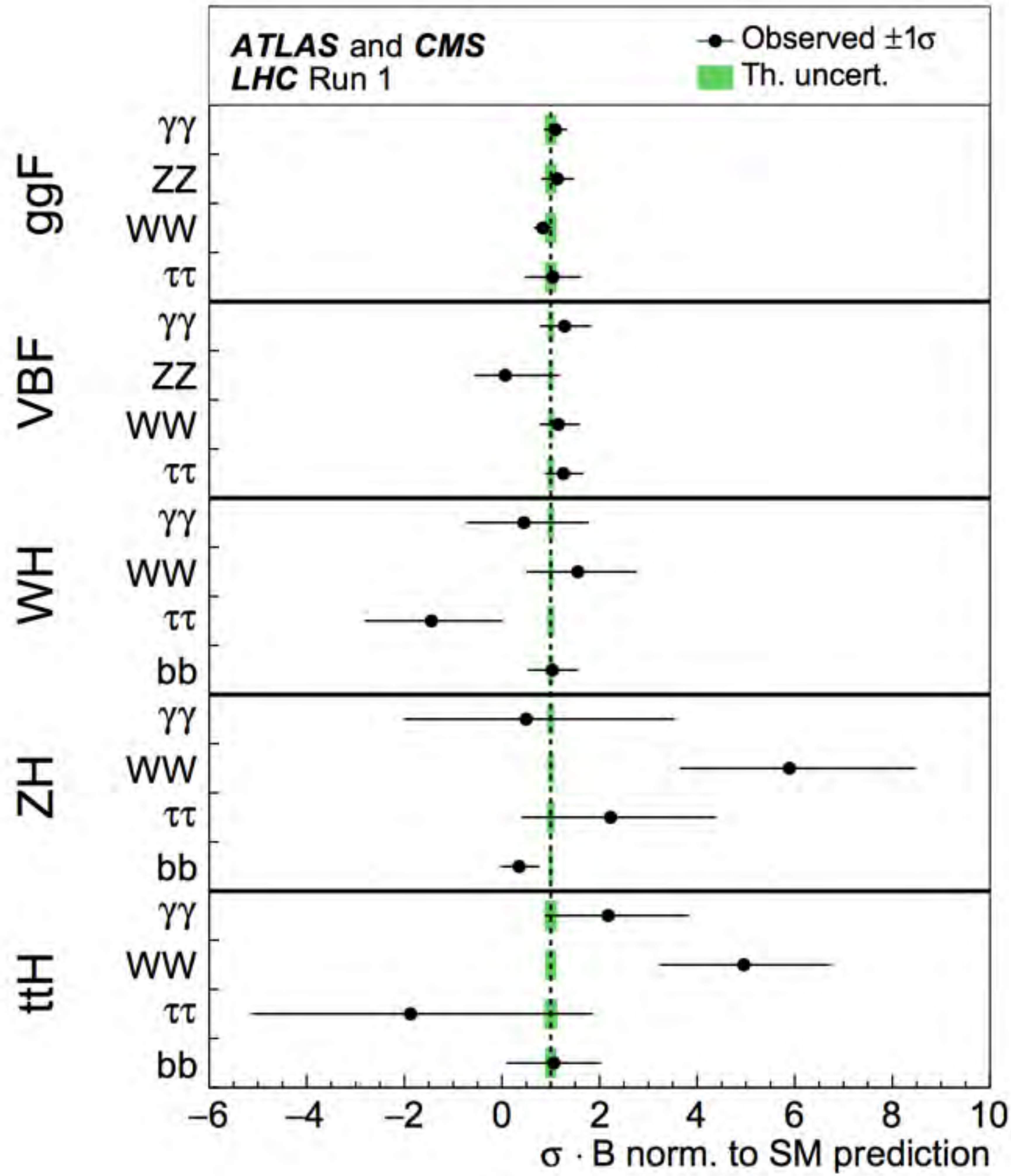
$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

- To measure the global signal strength for a specific channel (f) we need to make assumptions, e.g. all production modes are related to each other via the SM ratios.
  Assumptions should also be made when combining 7 and 8 TeV measurements. **All these assumptions bring some model dependence**

The Mother of all Fits (5x5)

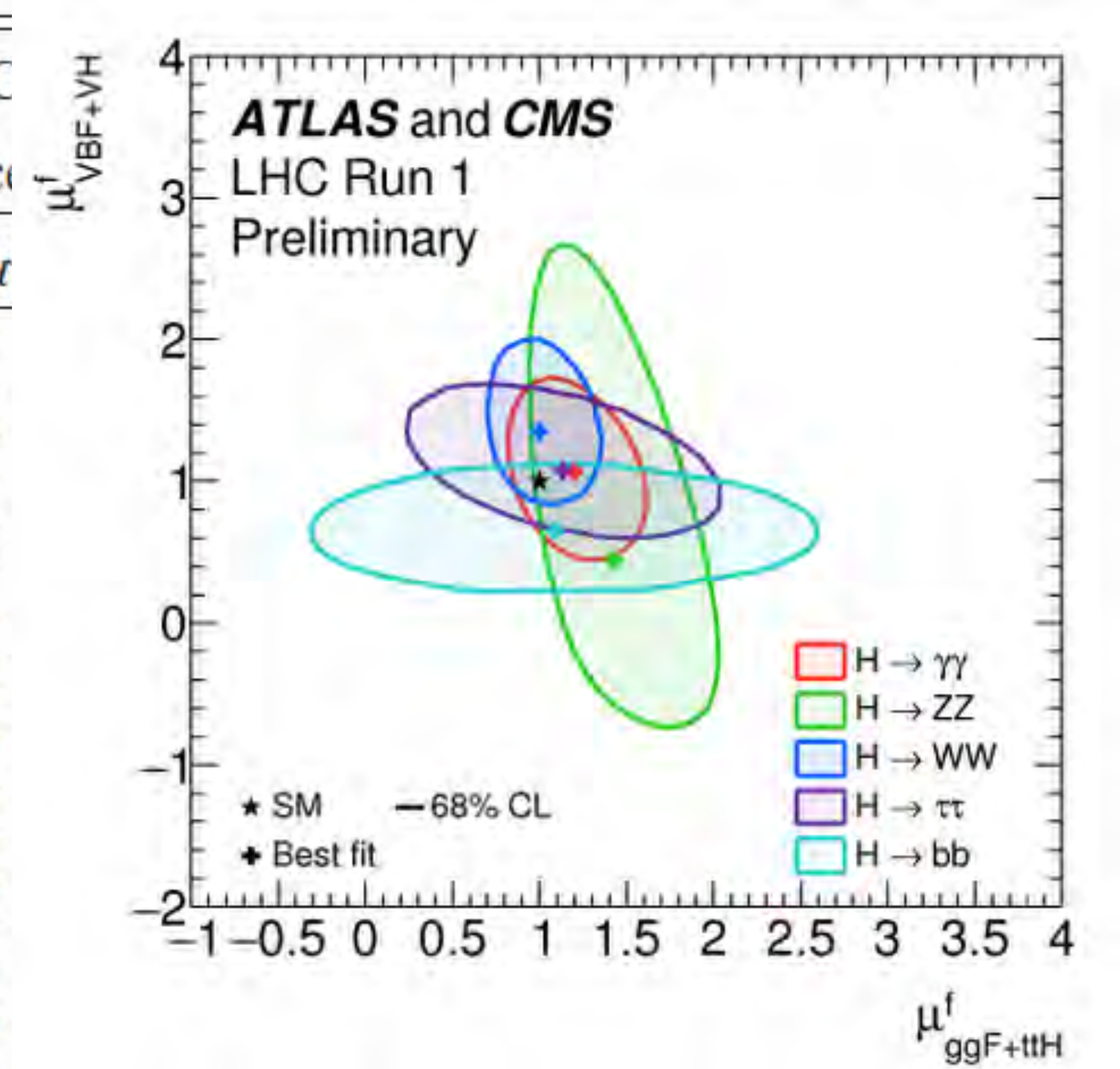
Production mode	Decay channel				
	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggF	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{ggF}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{ggF}$	$(\sigma \cdot \mathrm{BR})^{WW}_{ggF}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{ggF}$	
VBF	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{VBF}$	$(\sigma \cdot \mathrm{BR})^{ZZ}_{VBF}$	$(\sigma \cdot \mathrm{BR})^{WW}_{VBF}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{VBF}$	
WH	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{WH}$	$\cancel{(\sigma \cdot \mathrm{BR})^{ZZ}_{WH}}$	$(\sigma \cdot \mathrm{BR})^{WW}_{WH}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{WH}$	$(\sigma \cdot \mathrm{BR})^{bb}_{WH}$
ZH	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{ZH}$	$\cancel{(\sigma \cdot \mathrm{BR})^{ZZ}_{ZH}}$	$(\sigma \cdot \mathrm{BR})^{WW}_{ZH}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{ZH}$	$(\sigma \cdot \mathrm{BR})^{bb}_{ZH}$
ttH	$(\sigma \cdot \mathrm{BR})^{\gamma\gamma}_{ttH}$	$\cancel{(\sigma \cdot \mathrm{BR})^{ZZ}_{ttH}}$	$(\sigma \cdot \mathrm{BR})^{WW}_{ttH}$	$(\sigma \cdot \mathrm{BR})^{\tau\tau}_{ttH}$	$(\sigma \cdot \mathrm{BR})^{bb}_{ttH}$

- The ggF and VBF production processes are not considered in the case of the H → bb decay channel and are assumed to have the values predicted by the SM,
- The Z H, WH, and ttH production processes cannot be measured with meaningful precision in the H → Z Z decay channel because of the low overall expected and observed yields in the current data.
- The fit results are therefore quoted only for the remaining 20 parameters.
- A CLEAR ASSUMPTION HERE IS THAT THERE IS ONLY ONE HIGGS BOSON


ATLAS and CMS
LHC Run 1
Observed ±1σ
Th. uncert.
ggF
VBF
WH
ZH
ttH
γγ
ZZ
WW
ττ
bb
−6
−4
−2
0
2
4
6
8
10
σ · B norm. to SM prediction

Measuring Signal Strengths

Parameter	ATLAS+CMS Measured	ATLAS+C Expected unc
	10-parameter fit of μ	
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$



SM p-value 88% (10p)

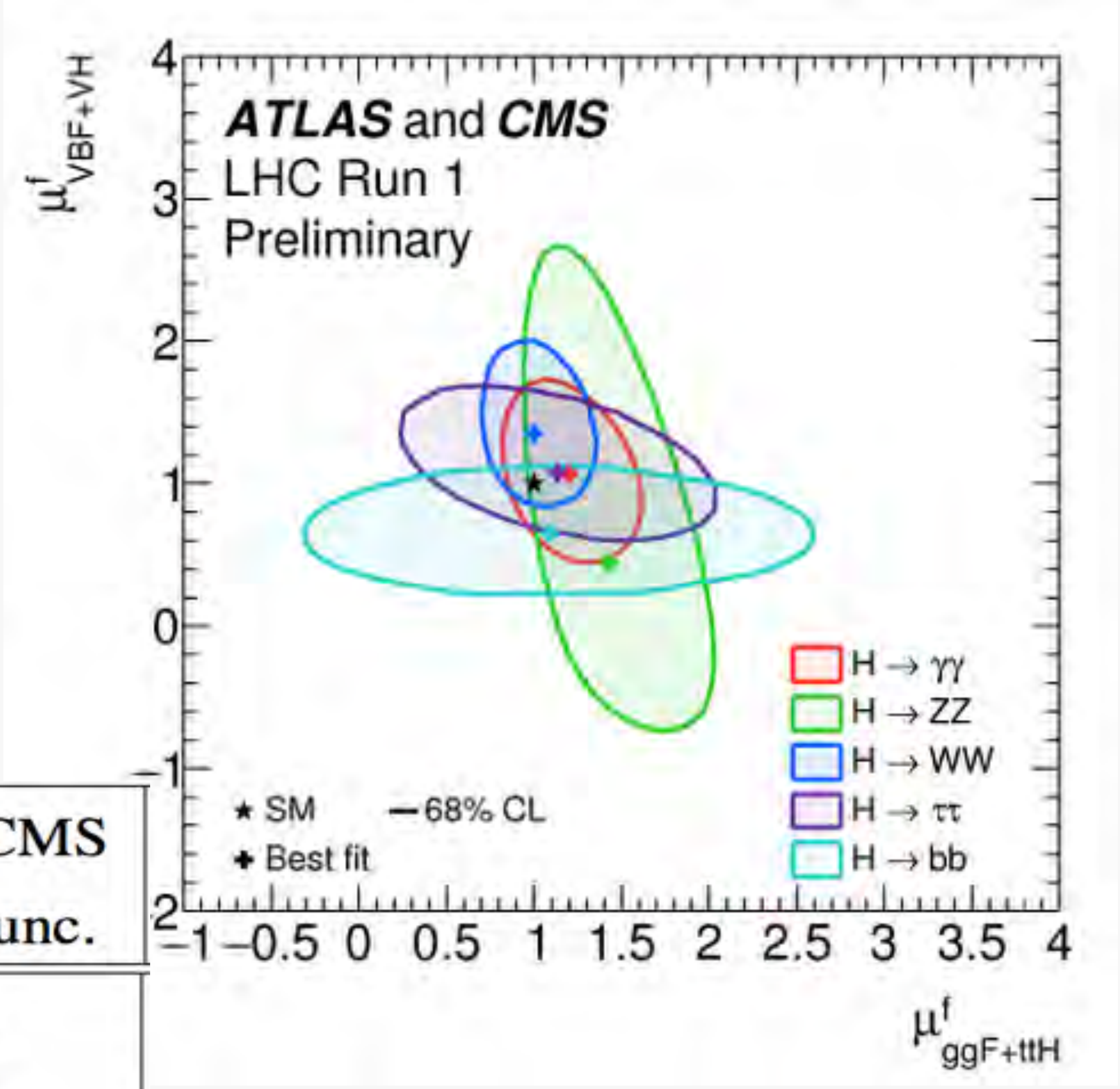
$$\mu_V^f = \mu_V \cdot BR(H \to f)$$

Measuring Signal Strengths

$$\frac{\mu_V^f}{\mu_F^f} = \frac{\mu_V \times BR^f}{\mu_F \times BR^f} = \frac{\mu_V}{\mu_F}$$

$\mu_{V/}\mu_F$ can be measured in the different decay channels and combined:

$$\mu_V/\mu_F = 1.06^{+0.35}_{-0.27}$$



Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$

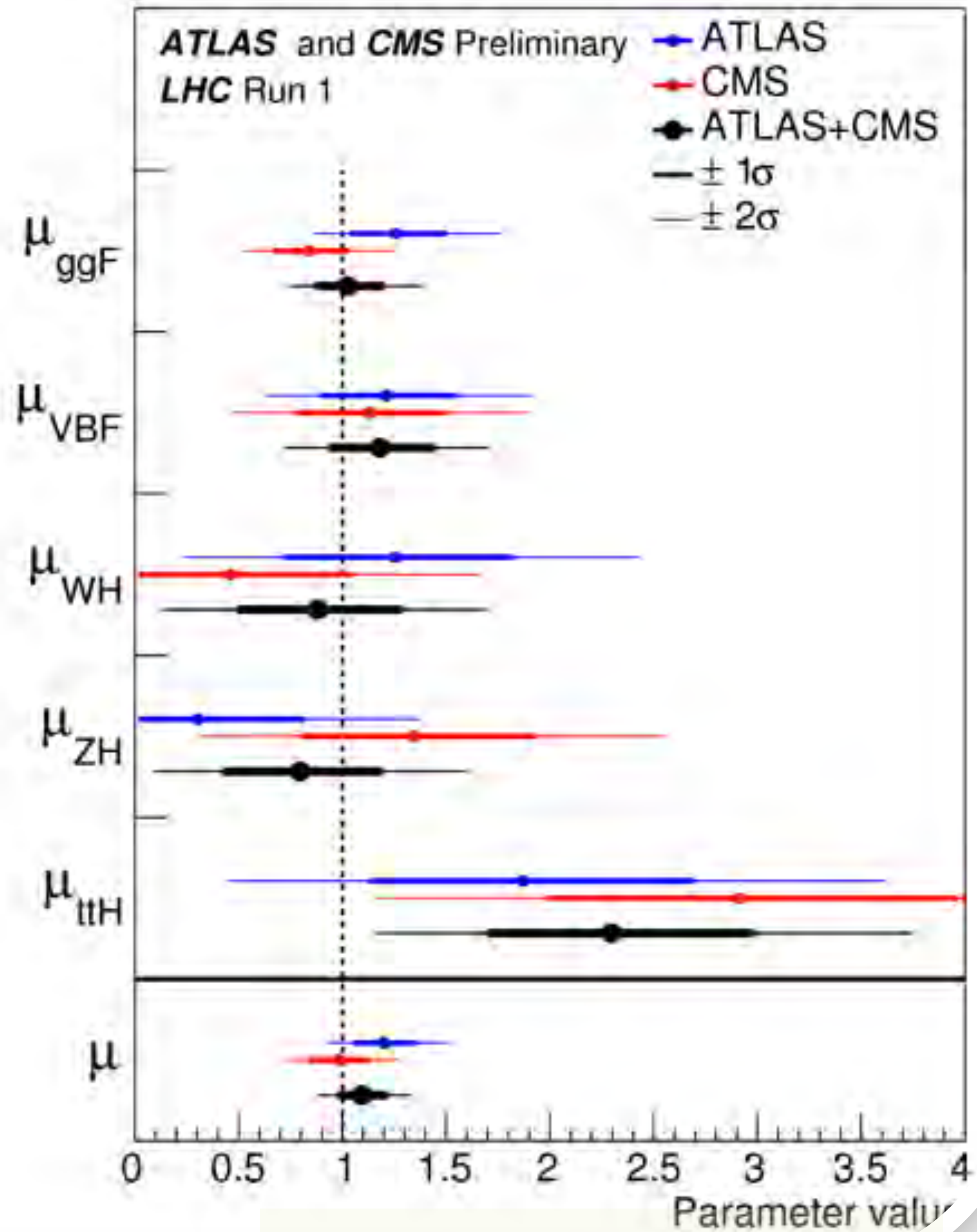
SM p-value
72% (6p)

Measuring Production Signal Strengths

Assuming SM BR we can measure the signal production strengths.

Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

SM p-value 24% (5p)



A subtlety:
Assume signal strengths are equal @ 7 and 8 TeV

Largest difference in ttH: 2.3σ excess with respect to SM

Over 5 sigma in VBF

Main uncertainty from ggF xsc

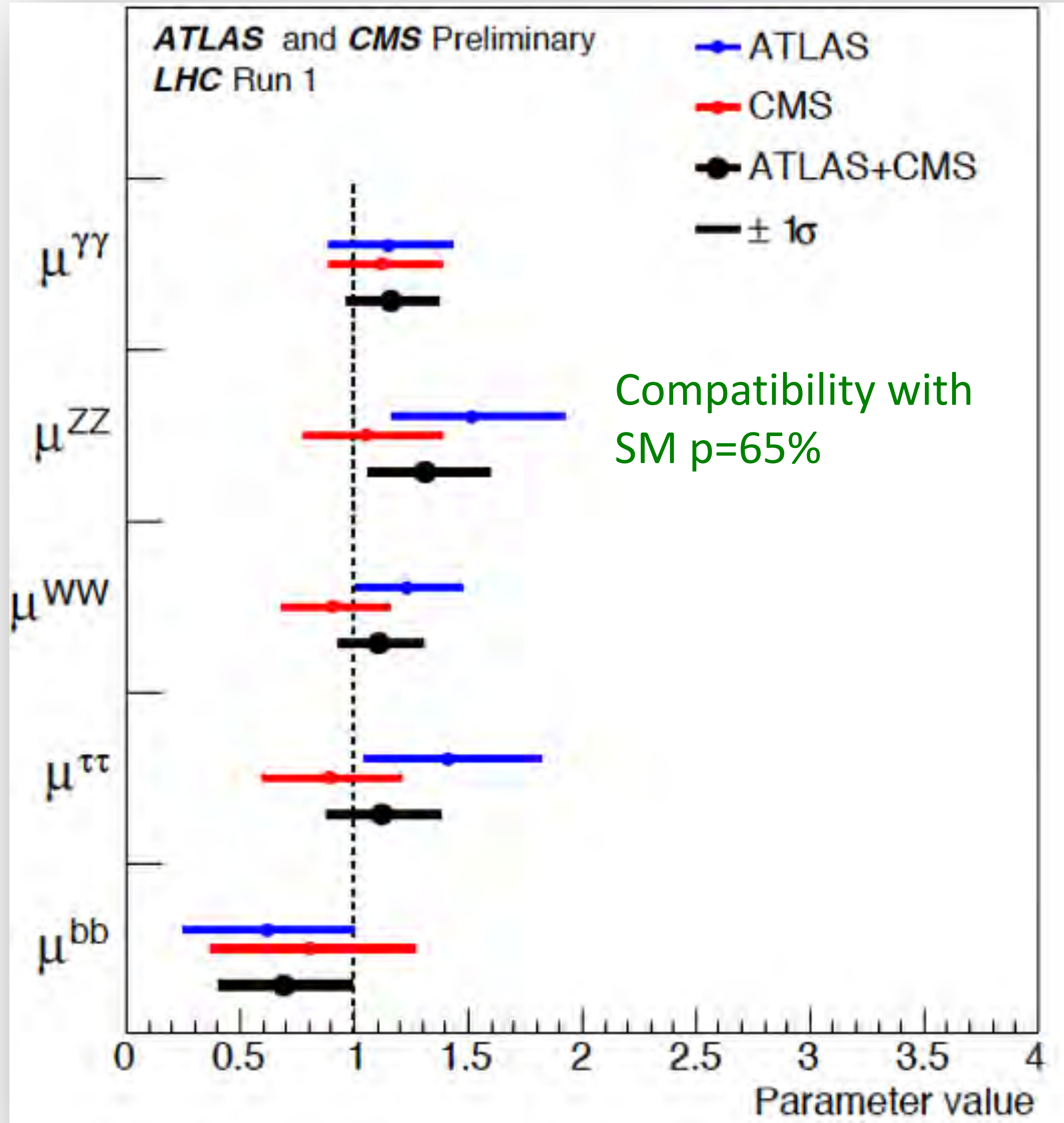
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})\ ^{+0.07}_{-0.06}\ (\text{thsig})$$

Measuring the Higgs Decay Modes

Assuming SM signal production strengths, we can measure the Higgs Decay BRs

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

Over 5 sigma in ττ



Significance in the different channels

Comparing likelihood of the best-fit with μ_{prod}=0 and μ^{decay}=0 we obtain:

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Combination largely increases the sensitivity

VBF and H→$\tau\tau$ now established at over 5 σ.

Same as ggF and H→ZZ, $\gamma\gamma$, WW from single experiments

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement (i→H→f) , 4 ratios of cross sections and 4 ratios of BRs

$$\sigma_x \times BR^y = \sigma(i \to H \to f)\left(\frac{\sigma_x}{\sigma_i}\right)\cdot\left(\frac{BR^y}{BR^f}\right)$$

9 *pars*

$ref : \sigma_i \cdot BR^f$, $e.g.\ \sigma_{ggH} \cdot BR^{ZZ}$

$\frac{\sigma_{VBF}}{\sigma_{ggH}}$

$\frac{\sigma_{WH}}{\sigma_{ggH}}$

$\frac{\sigma_{ZH}}{\sigma_{ggH}}$

$\frac{\sigma_{ttH}}{\sigma_{ggH}}$

$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$

$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

$\frac{BR^{bb}}{BR^{ZZ}}$

This way, we make no assumptions on the Higgs boson total width, which can freely vary, **provided the narrow width approximation is still valid.**

Furthermore, many theoretical and experimental systematic uncertainties cancel in these ratios. In particular, they are not subject to the dominant signal theoretical uncertainties on the inclusive cross sections for the various production processes.

These measurements will therefore remain valid, for example when improved theoretical calculations of Higgs boson production cross sections will become available. The remaining theoretical uncertainties are reduced to those related to the acceptances and selection efficiencies in the various categories.

This is the most generic parameterisation considered yet recast should be done with care

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement (i→H→f), 4 ratios of cross sections and 4 ratios of BRs

9 pars

$ref : \sigma_i \cdot BR^f$, e.g. $\sigma_{ggH} \cdot BR^{ZZ}$

$$\frac{\sigma_{VBF}}{\sigma_{ggH}}$$

$$\frac{\sigma_{WH}}{\sigma_{ggH}}$$

$$\frac{\sigma_{ZH}}{\sigma_{ggH}}$$

$$\frac{\sigma_{ttH}}{\sigma_{ggH}}$$

$$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$$

$$\frac{BR^{WW}}{BR^{ZZ}}$$

$$\frac{BR^{\tau\tau}}{BR^{ZZ}}$$

$$\frac{BR^{bb}}{BR^{ZZ}}$$

reference process: $i \to f$

$$\sigma_x \cdot BR_y = \frac{\sigma_x}{\sigma_i}\frac{BR_y}{BR_f} \cdot \left(\sigma_i \cdot BR_f\right)$$

$$\mu_x^y \cdot \left(\sigma_x \cdot BR_y\right)_{SM} = \frac{\sigma_x}{\sigma_i}\frac{BR_y}{BR_f} \cdot \left(\sigma_i \cdot BR_f\right)$$

$$\mu_x^y = \frac{\mu_x}{\mu_i}\frac{\mu_y}{\mu_f} \cdot \mu_i^f$$

e.g. ref=gg $\to H \to ZZ$

$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right]$$

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement (i→H→f), 4 ratios of cross sections and 4 ratios of BRs

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$ref : \sigma_i \cdot BR^f$, e.g. $\sigma_{ggH} \cdot BR^{ZZ}$

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$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

$\frac{BR^{bb}}{BR^{ZZ}}$

reference process: $i \to f$

$$\sigma_x \cdot BR_y = \frac{\sigma_x}{\sigma_i}\frac{BR_y}{BR_f} \cdot (\sigma_i \cdot BR_f)$$

$$\mu_x^y \cdot (\sigma_x \cdot BR_y)_{SM} = \frac{\sigma_x}{\sigma_i}\frac{BR_y}{BR_f} \cdot (\sigma_i \cdot BR_f)$$

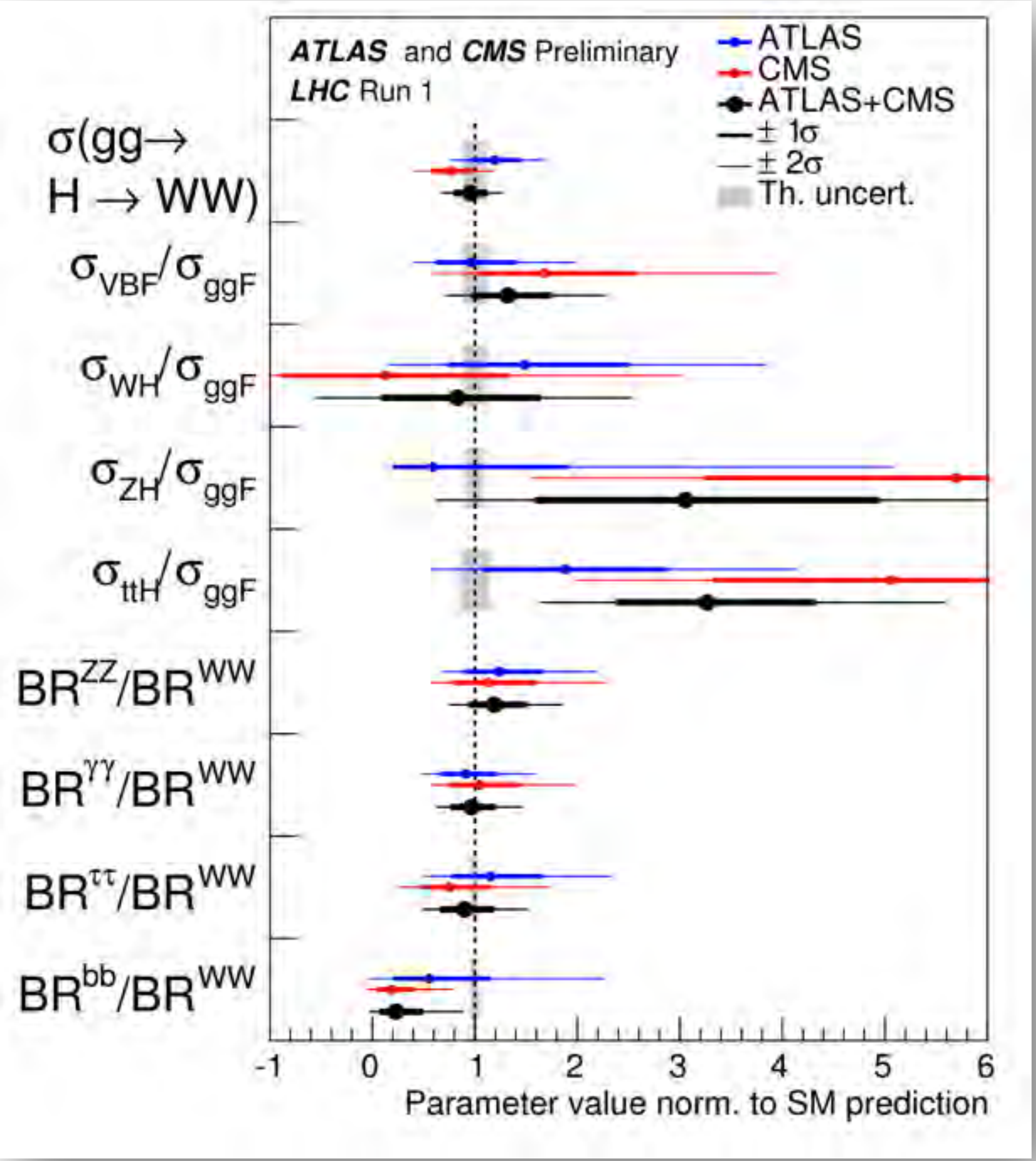
$$\mu_x^y = \frac{\mu_x}{\mu_i}\frac{\mu_y}{\mu_f} \cdot \mu_i^f$$

e.g. ref=gg $\to H \to ZZ$

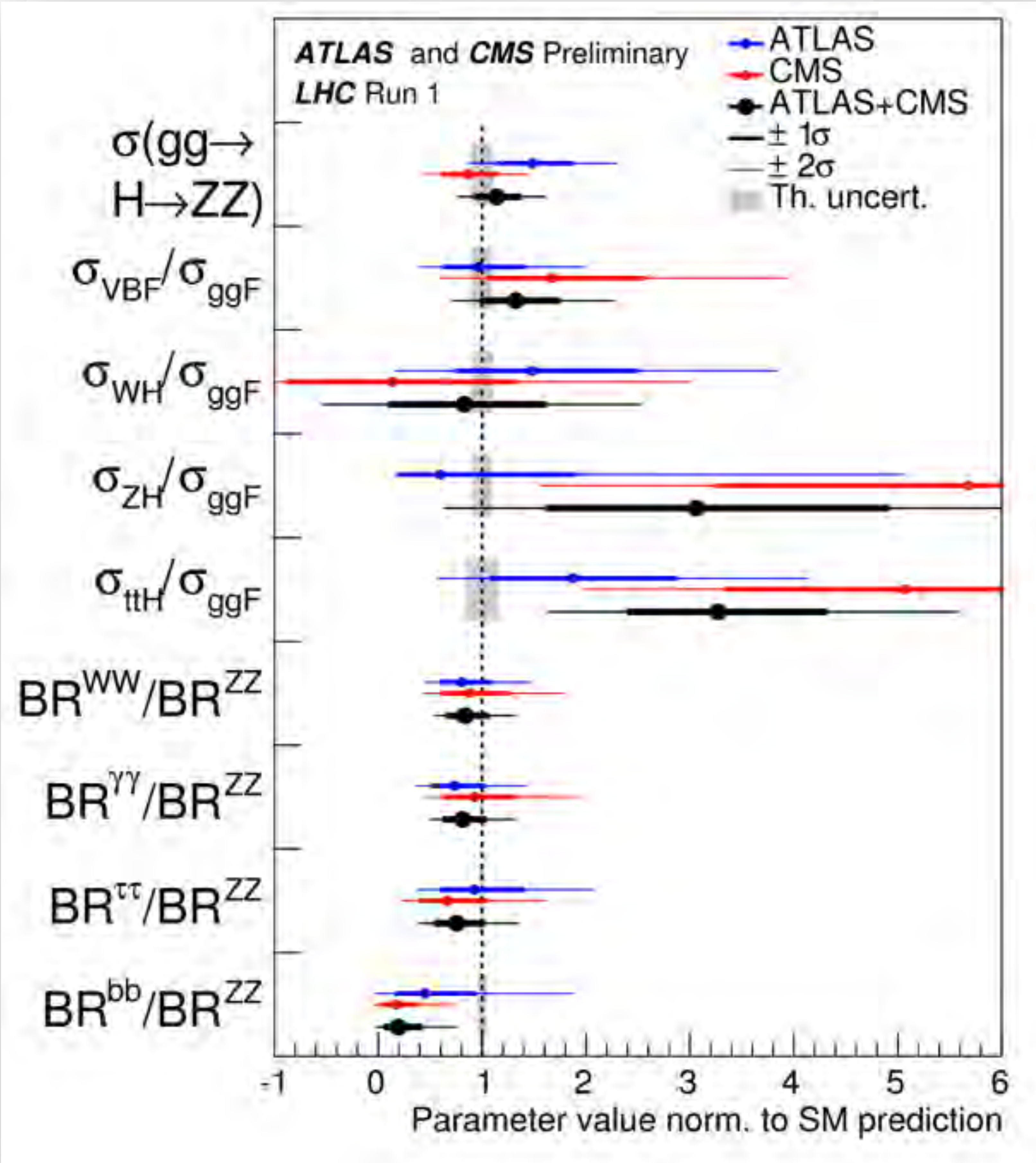
$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right]$$

WHICH REF?

Model Independent Ratios (Generic I)

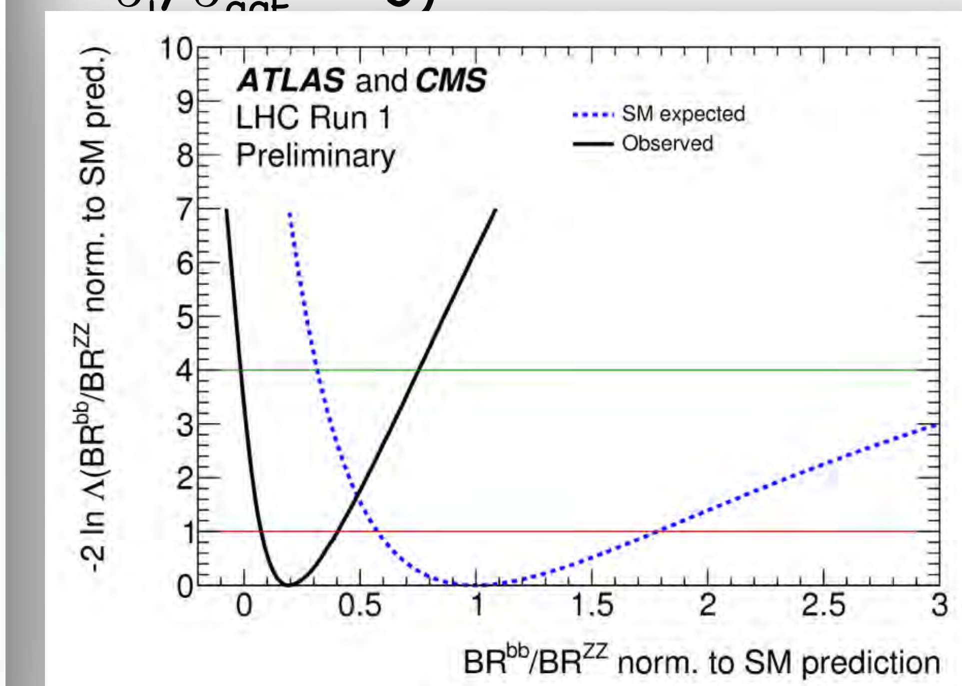


Model Independent Ratios (Generic I)



Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

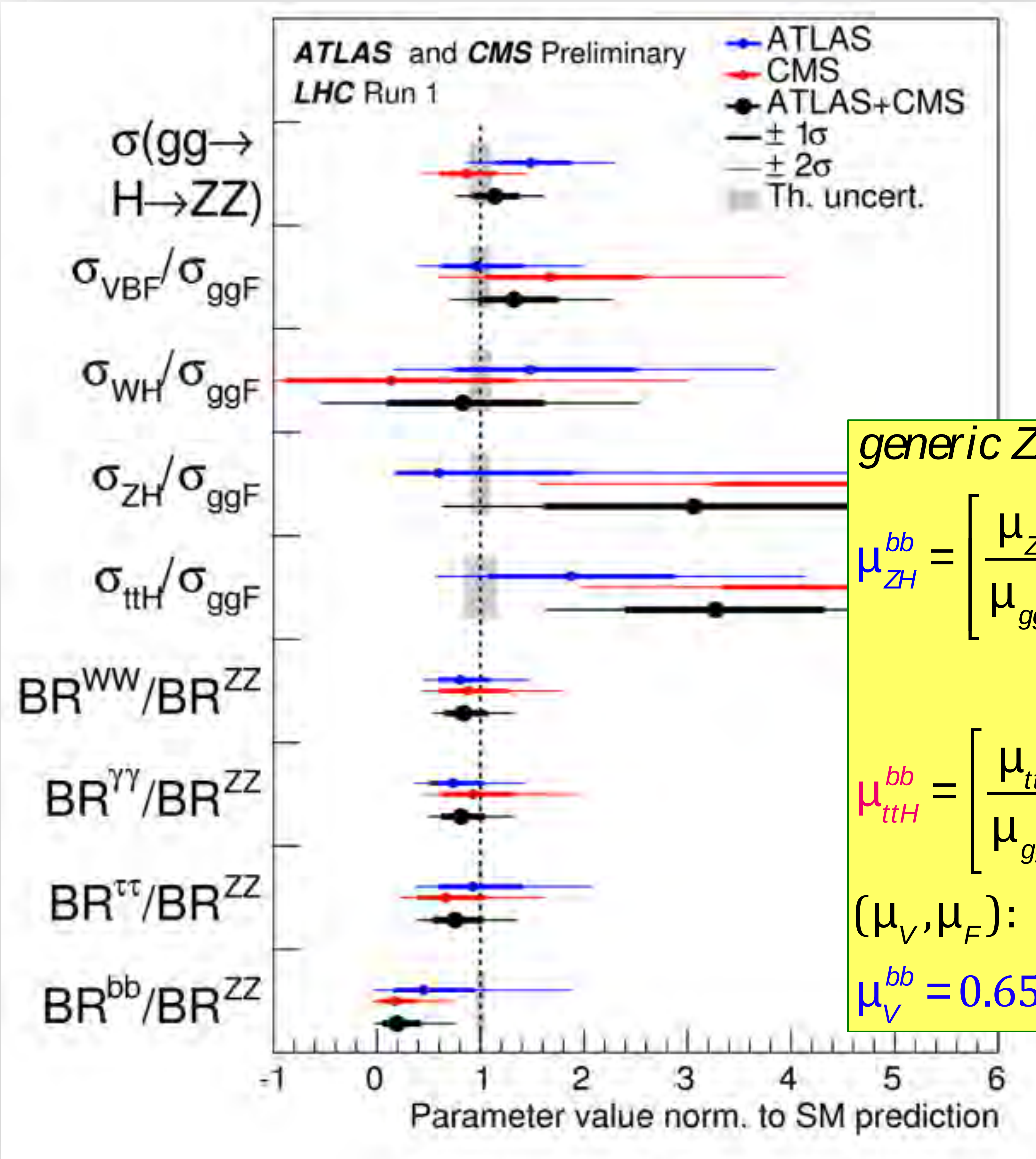
Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3)



ttH excess due to multilepton categories

ZH excess due to CMS two-jet categories

Model Independent Ratios (Generic I)



Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3)

generic ZZ:

$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.1 \cdot 1.14 \cdot 0.2 = 0.7$$

$$\mu_{ttH}^{bb} = \left[\frac{\mu_{ttH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.3 \cdot 1.14 \cdot 0.2 = 0.8$$

(μ_V, μ_F):

$\mu_V^{bb} = 0.65, \mu_F^{bb} = 1.09$


Couplings

The κ-framework

The k-framework has been developed within the LHC Higgs Cross Section WG

Higgs boson couplings are scaled by coupling modifiers κ

The definition is such that:

$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$ for production $\kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$ for decay

There are obvious drop backs to the Kappa framework
Higher order QCD and EW accuracies might not be preserved for $\kappa \neq 1$

The κ-framework

$$k_f^2 = \frac{\Gamma_f}{\Gamma_H} \qquad \Gamma_{i,u} = \Gamma_{BSM}$$

BR_{BSM} = $BR_{inv,und}$=BR invisible + undetected

$$\Gamma_H = \Sigma_f \Gamma_f + \Gamma_{i,u} \qquad i = invisible, u = undetected$$

$$k_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}} = \sum_f \frac{\Gamma_f}{\Gamma_H^{SM}} + \frac{\Gamma_{i,u}}{\Gamma_H^{SM}} = \sum_f \frac{\Gamma_f}{\Gamma_f^{SM}} \frac{\Gamma_f^{SM}}{\Gamma_H^{SM}} + \frac{\Gamma_{i,u}}{\Gamma_H} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$k_H^2 = \sum_f k_f^2 BR_f^{SM} + BR_{i,u} k_H^2$$

$$k_H^2 = \frac{\sum_f k_f^2 BR_f^{SM}}{1 - BR_{i,u}}$$

The κ-framework

Experimental Assumptions:

The current LHC data are insensitive to the coupling modifiers κ_c and κ_s, and have limited sensitivity to κ_μ.

Thus, it is assumed that κ_c varies as κ_t, κ_s as κ_b, and κ_μ as κ_τ.

Other coupling modifiers $(\kappa_u, \kappa_d$ and $\kappa_e)$ are irrelevant for the combination as long as they are order of unity.

$$BR_{BSM} = BR_{inv,und}$$

Undetected decays can be either non SM decays or come from non SM BRs of known but not measured decays such as cc, gg.

Measuring Higgs Couplings

$$n_s(i \to f) = \mu^i \mu^f \times (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \quad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

Can we resolve the degeneracy, disentangle $[\mu^i \mu^f]$

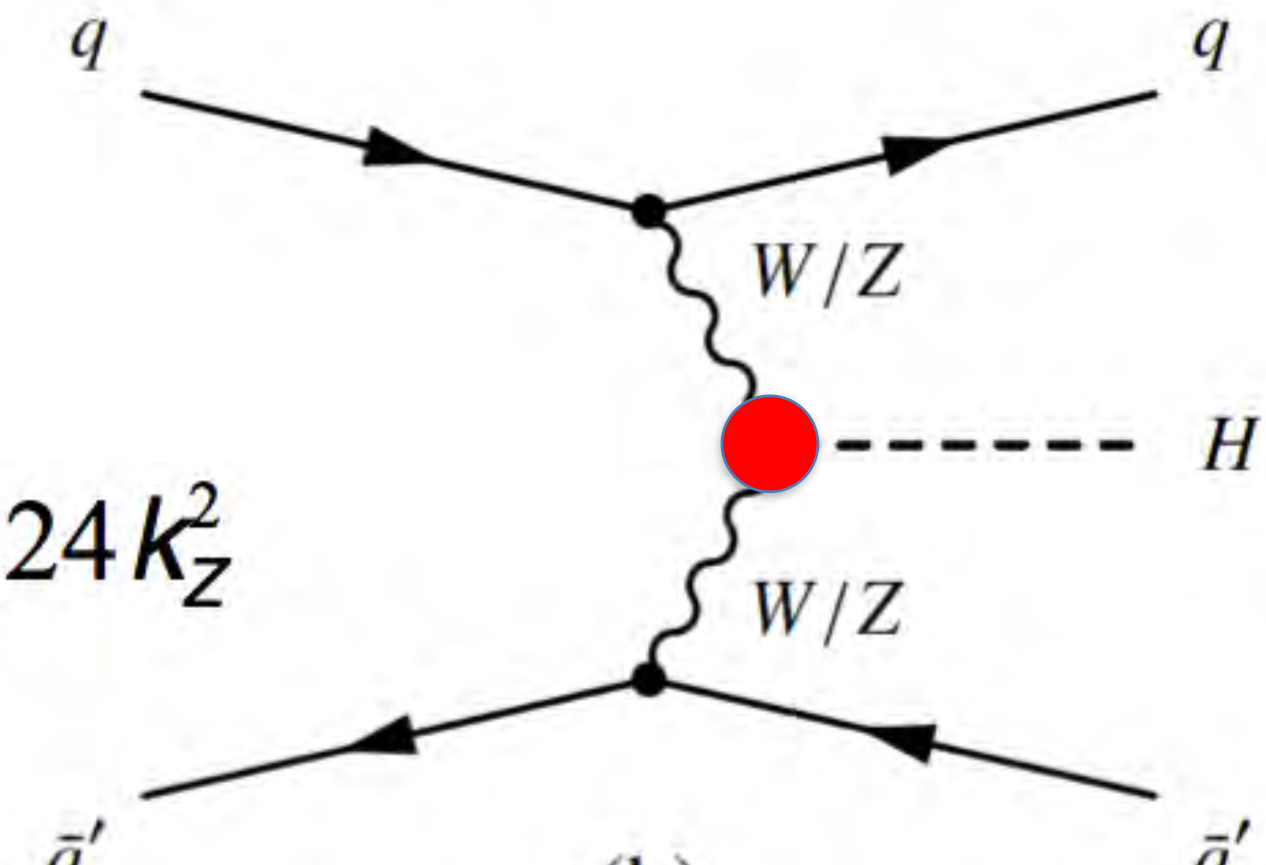
The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

$$k_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}, \frac{\sigma_j}{\sigma_j^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}} = \sum k_j^2 BR_j^{SM}$$

VBF Composition

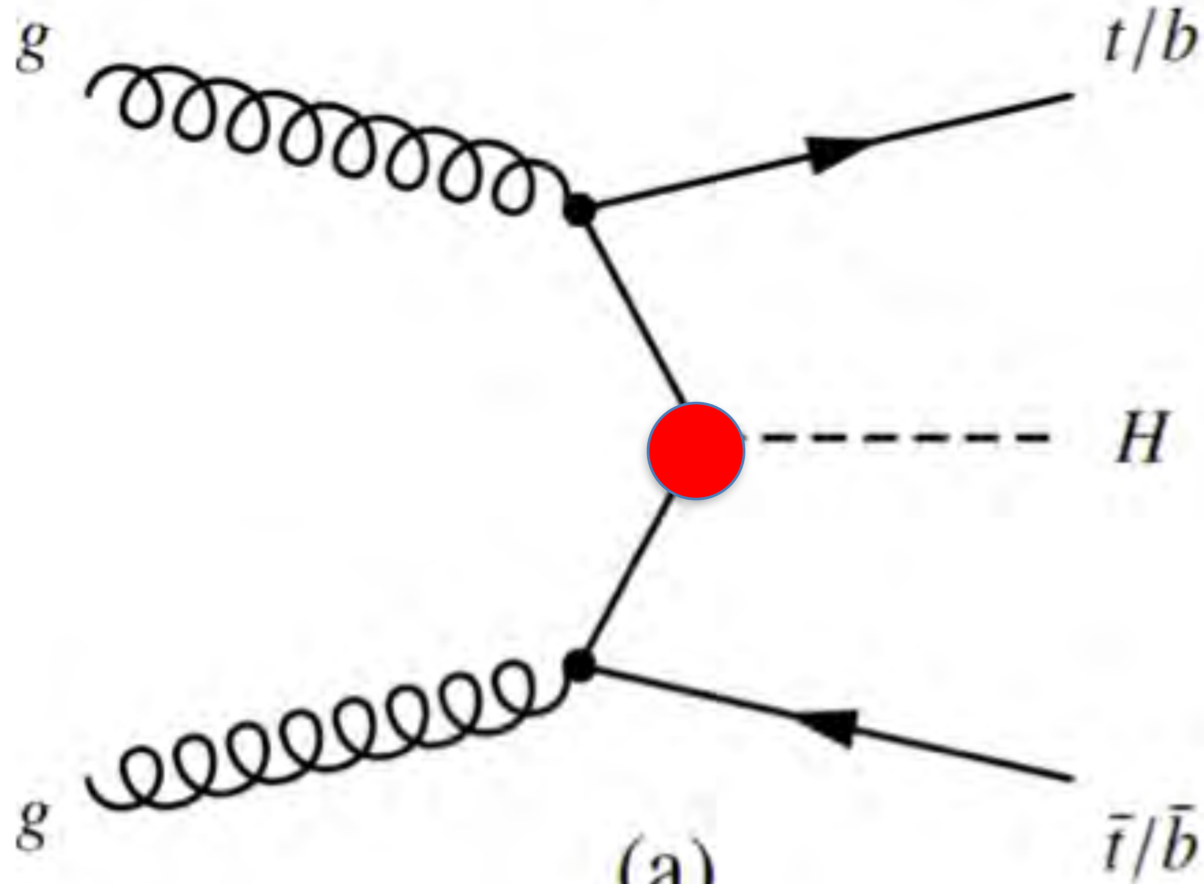
$$q\bar{q}' \rightarrow q\bar{q}' H$$

$$\mu_{VBF} = k_{VBF}^2 \approx 0.74\,k_W^2 + 0.24\,k_Z^2$$



(b)

ttH



(a)

$$gg \to ttH, bbH$$

$$\mu_{ttH} = k_t^2$$

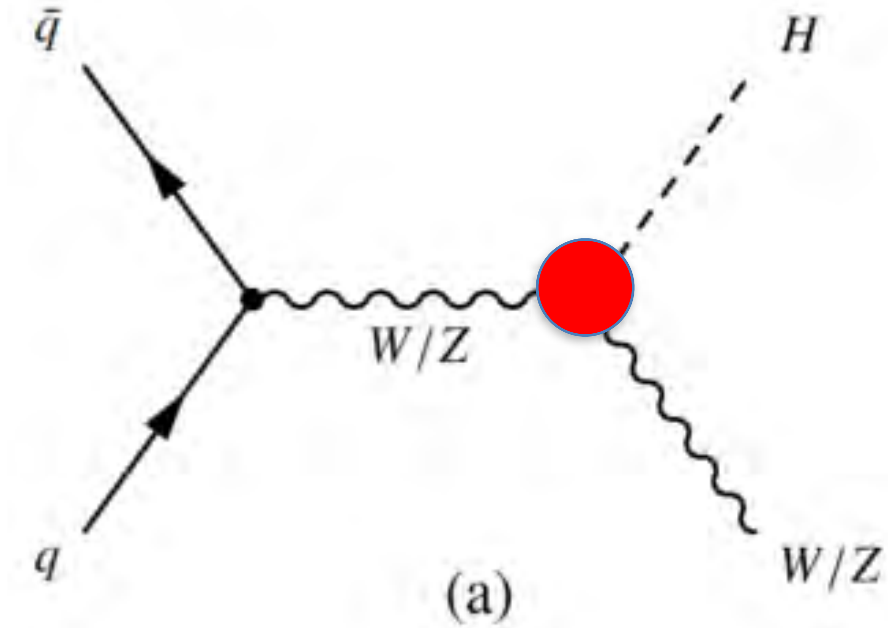
$$\mu_{bbH} = k_b^2$$

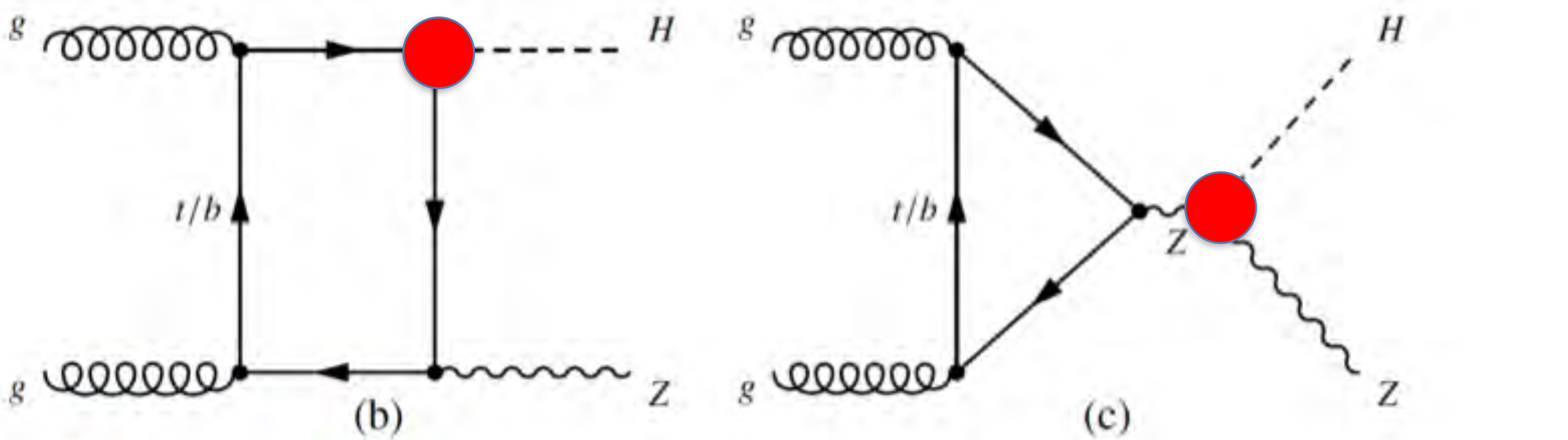
ZH Production

$$\sigma(q\bar{q} \to ZH) \sim k_Z^2$$

$$\sigma(q\bar{q} \to WH) \sim k_W^2$$

$$\sigma(gg \to ZH) \sim k_{ggZH}^2$$

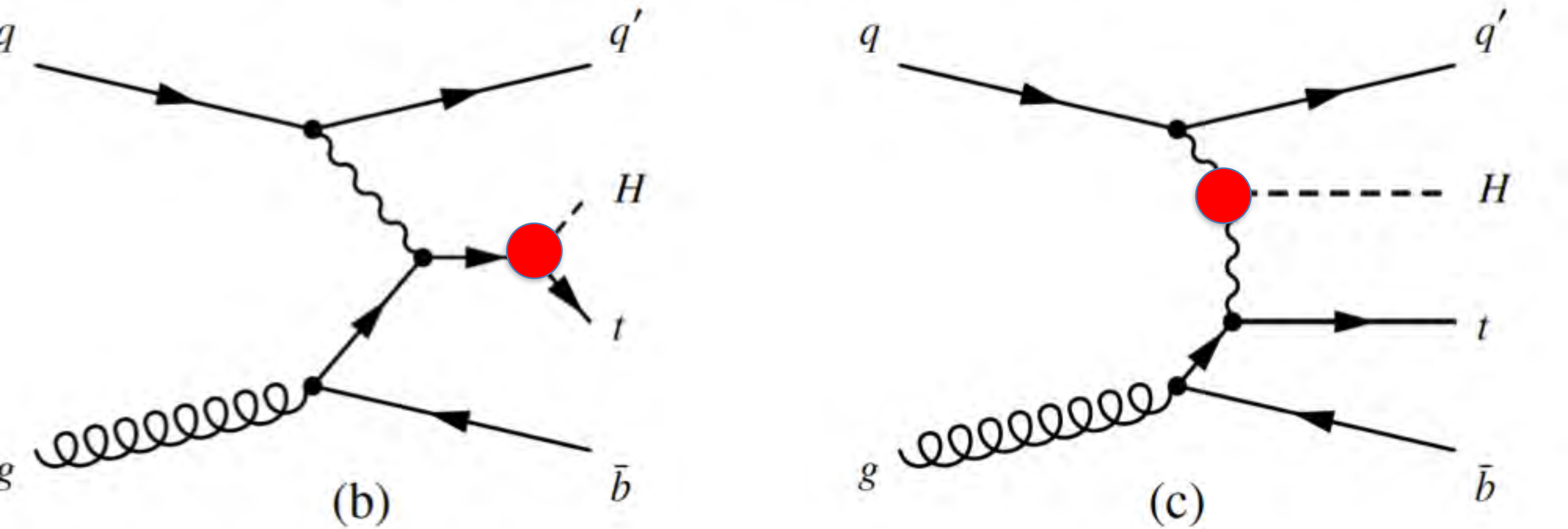




(Q:Why not gWH?)

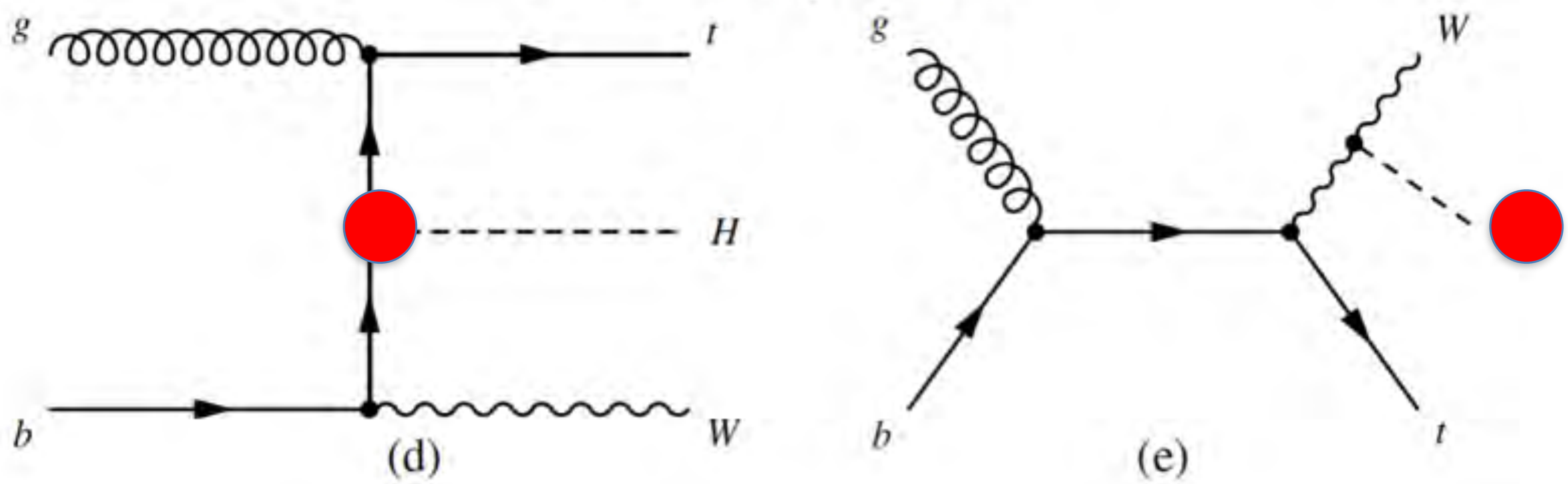
$$\kappa_{ggZH}^2 \sim \quad 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$$

tHq composition (W,t) interference



$$\sigma\left(qg \rightarrow tHq'(b)\right) \sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$$

WtH composition



$$\sigma(gb \rightarrow tHW) \sim \quad 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$$

Note that if $K_t K_W = -1$, *tHW* increases by a factor 6,

tHq by a factor 13

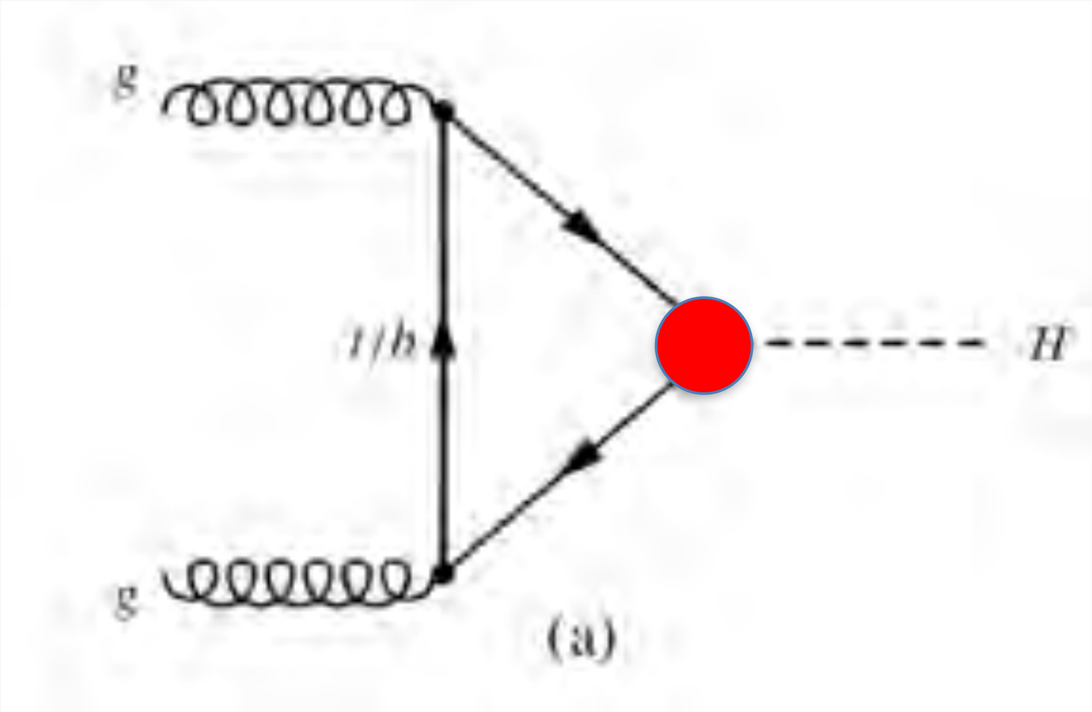
tH which makes only 14% of *ttH* becomes important

We still have no sensitivity, yet

it is important to

take negative values into account

Higgs does not couple
to to Gluons and Photons
in leading order



The production of the Higgs Boson

and its discovery

are due to a pure quantum loop

$$k_g^2 \approx 1.06 k_t^2 + 0.01 k_b^2 - 0.07 k_t k_b$$

Hgg Approximate Calculation

Why a NEGATIVE interference term?

$$\sigma_{\rm LO}(gg \to h) = \sigma_0^h m_h^2 \delta(\hat{s} - m_h^2)$$

$$\sigma_0^h = \frac{G_f \alpha_s^2}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q A_{1/2}^H(\tau_q) \right|^2$$

$$\tau_q = 4m_q^2/m_h^2$$

$$\tau_t = 7.65 \text{ and } \tau_b = 2 \times 10^{-3} \text{ for } m_b(m_h) \approx 2.8\,\text{GeV}$$

$$A_{1/2}^H(\tau) = 2\tau\left[1 + (1-\tau)f(\tau)\right],$$

$$f(\tau) = \begin{cases} -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \\ \arcsin^2(1/\sqrt{\tau}) & \tau \geq 1 \end{cases}$$

$$A_{1/2}^H = \begin{array}{ll} \tau \gg 1: & 4/3 \\ \tau \ll 1: & 2\tau\left[1 - \frac{1}{4}\left(\log\frac{\tau}{4} + i\pi\right)^2\right] \approx -\frac{\tau}{2}\left(\log\frac{\tau}{4}\right)^2 \end{array}$$

$$\frac{\sigma_0^h}{[\sigma_0^h]_{\rm SM}} = \left| \frac{\kappa_t A_{1/2}^H(\tau_t) + \kappa_b A_{1/2}^H(\tau_b)}{A_{1/2}^H(\tau_t) + A_{1/2}^H(\tau_b)} \right|^2 = \kappa_t^2 1.09 - 0.09\kappa_b\kappa_t + 0.0021\kappa_b^2$$

The Seven Decay Modes Probes

$$\Gamma_{b\bar{b}} \sim k_b^2$$

$$\Gamma_{\tau\tau} \sim k_\tau^2$$

$$\Gamma_{WW} \sim k_W^2$$

$$\Gamma_{ZZ} \sim k_Z^2$$

$$\Gamma_{\mu\mu} \sim k_\mu^2$$

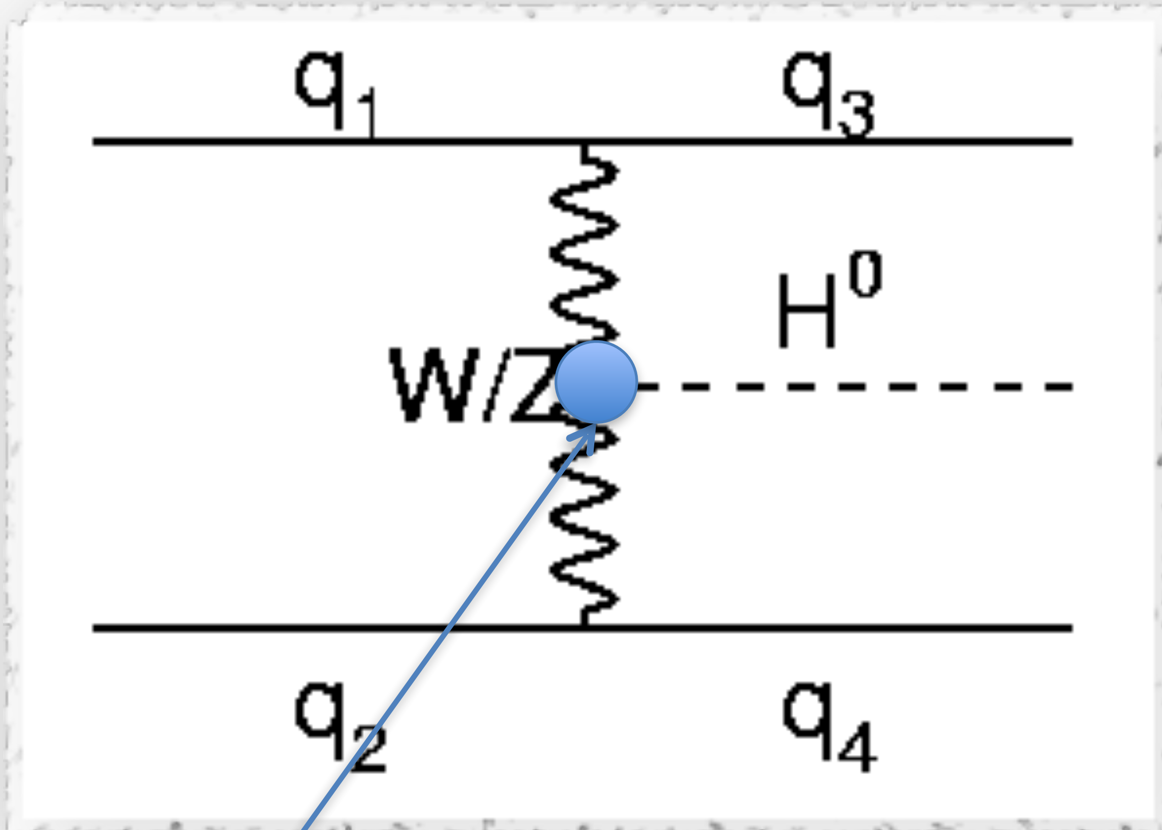
$$\kappa_{Z\gamma}^2 \sim \quad 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$$

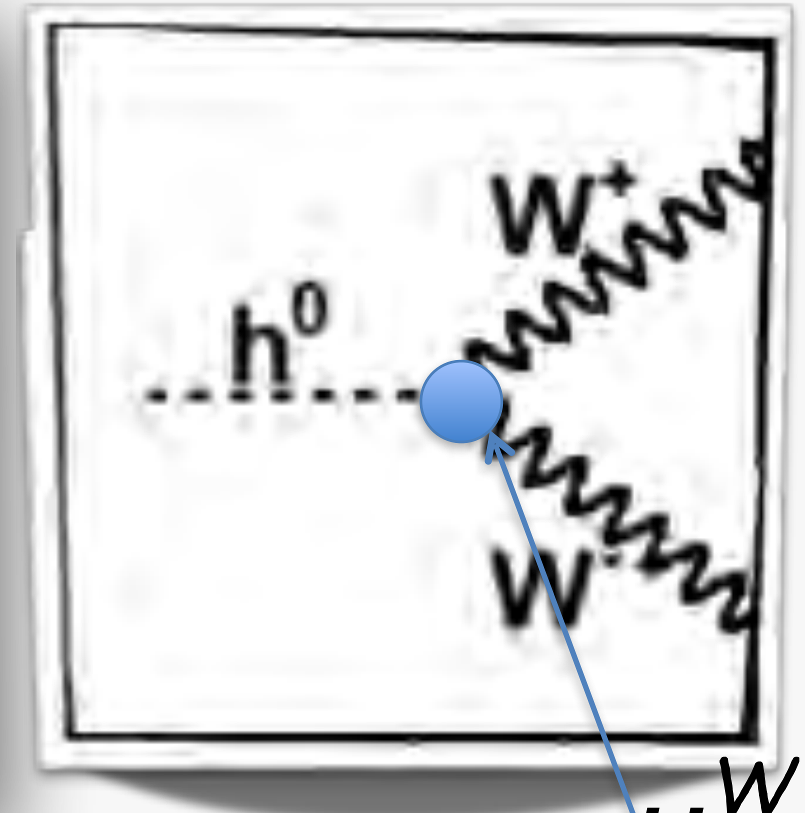
$$\kappa_\gamma^2 \sim \quad 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

$$k_H^2 = \sum_f k_f^2 BR_f^{SM}$$

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

Disentangling The Couplings





$$\mu^{W}_{VBF} = [\mu_{VBF}\mu^{W}]$$

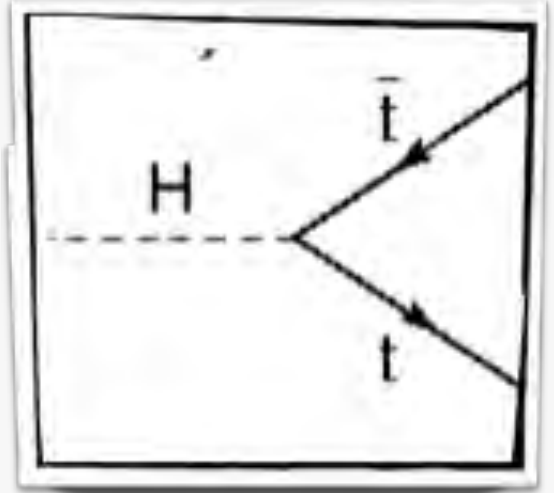
$$\mu^{W} = \frac{k_{W}^{2}}{k_{H}^{2}}$$

$$\mu_{VBF} = k_{VBF}^{2} = k_{w}^{2} BR_{SM}^{WW} + k_{Z}^{2} BR_{SM}^{ZZ}$$

The simplest non-trivial model is ($k_{F,}$ k_V) where all Fermion couplings are set to k_F and all Boson couplings to k_V

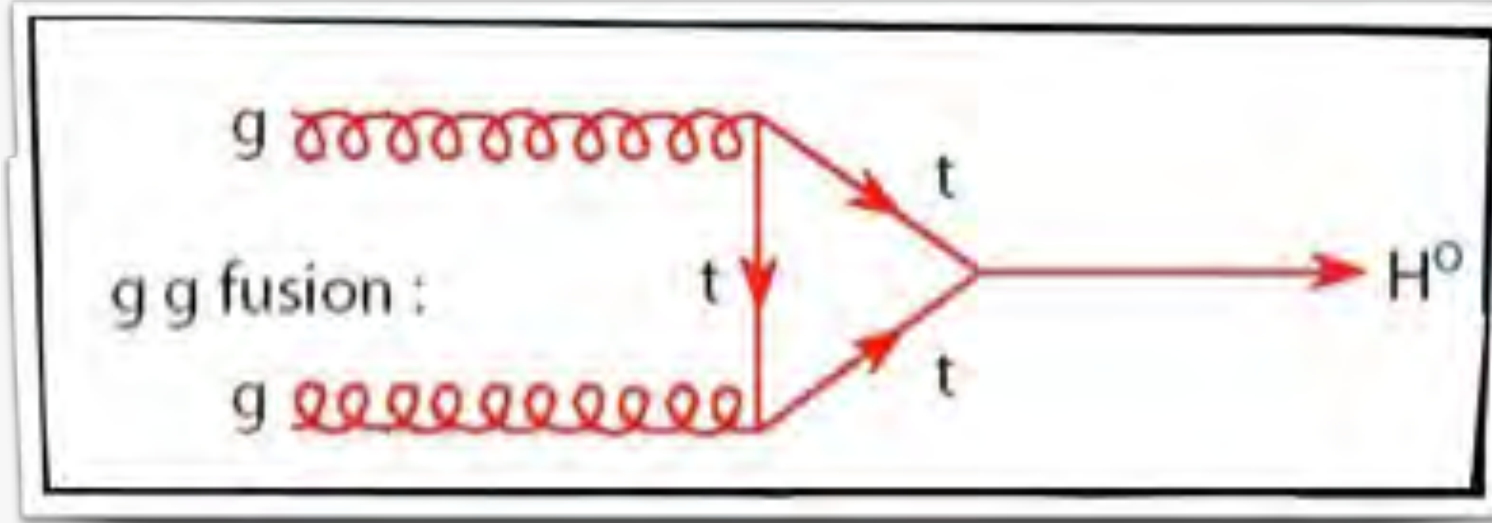
$$\frac{\sigma^{WW}_{VBF}}{\sigma^{WW}_{VBF}(SM)} = \frac{k_V^2 \cdot k_V^2}{0.75 k_F^2 + 0.25 k_V^2}$$

Indirect Sensitivity to Fermion Couplings



$$k_t^2 = \frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}}$$

$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$

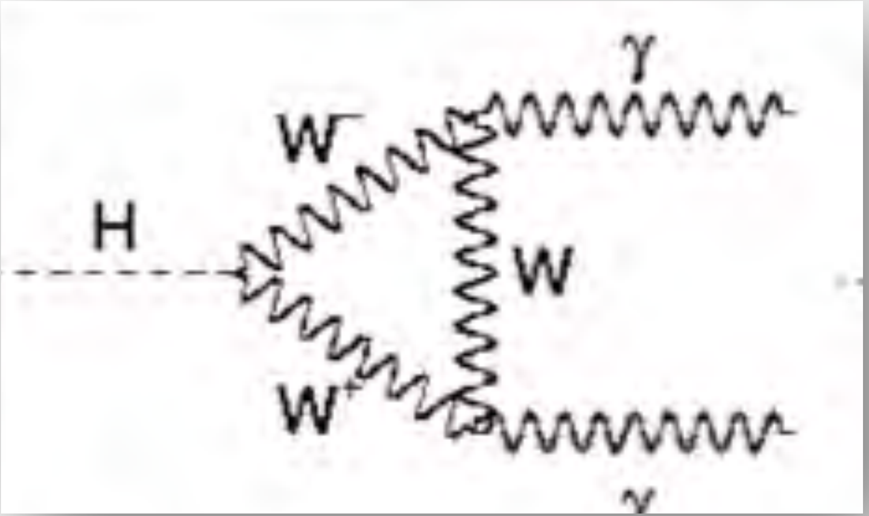


$$\kappa_g^2(\kappa_b,\kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t\kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

Note that if all fermion couplings are set to be equal,

$$k_g^2 = k_F^2$$

$$k_\gamma^2 = \left|1.28\,k_W - 0.28\,k_t\right|^2$$



The κ-framework

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

The κ-framework

Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $\mathrm{BR_{BSM}} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

Coupling Scenarios

To make reasonable fits we introduce physics motivated scenarios.

Testing the compatibility of the discovered Higgs with the SM is to test also where is it NOT compatible, spotting where NP might sneak in.

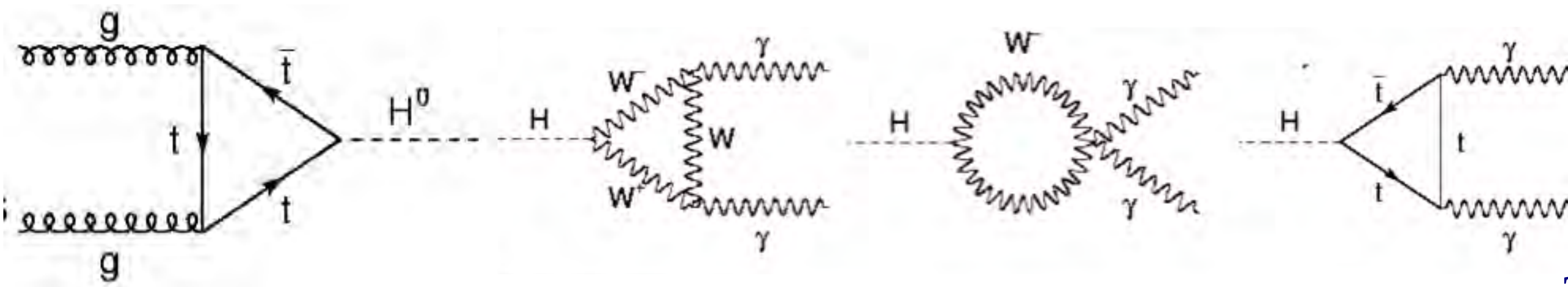
NP can appear in either the Higgs width and/or in the loops.

$$k_H^2 = \frac{\sum_{j=Z,W,t,b,\tau} k_j^2 \Gamma_j^{SM} + k_\gamma^2 \Gamma_\gamma^{SM} + k_g^2 \Gamma_g^{SM}}{\Gamma_H^{SM}} \qquad \Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$$

Γ_H	k_γ	k_g	Scenario
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	only SM particles in loops
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	k_γ	k_g	m_{NP} could be $< \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	k_γ	k_g	$m_{NP} > \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	NP (not in the loops)

Negative Couplings?

is



$$n_s^{\gamma\gamma} \sim k_g^2(k_t, k_b) \times k_\gamma^2(k_t, k_W) \quad k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$

k_t k_W

ggF
$k_g^2 \sim k_t^2$

$Br_{\gamma\gamma}$
$k_\gamma^{\ 2} \sim -k_W k_t$

BR_{WW}
k_W^2

If k_t=-1 ggF slightly affected
WW unaffected
$\gamma\gamma$ increases

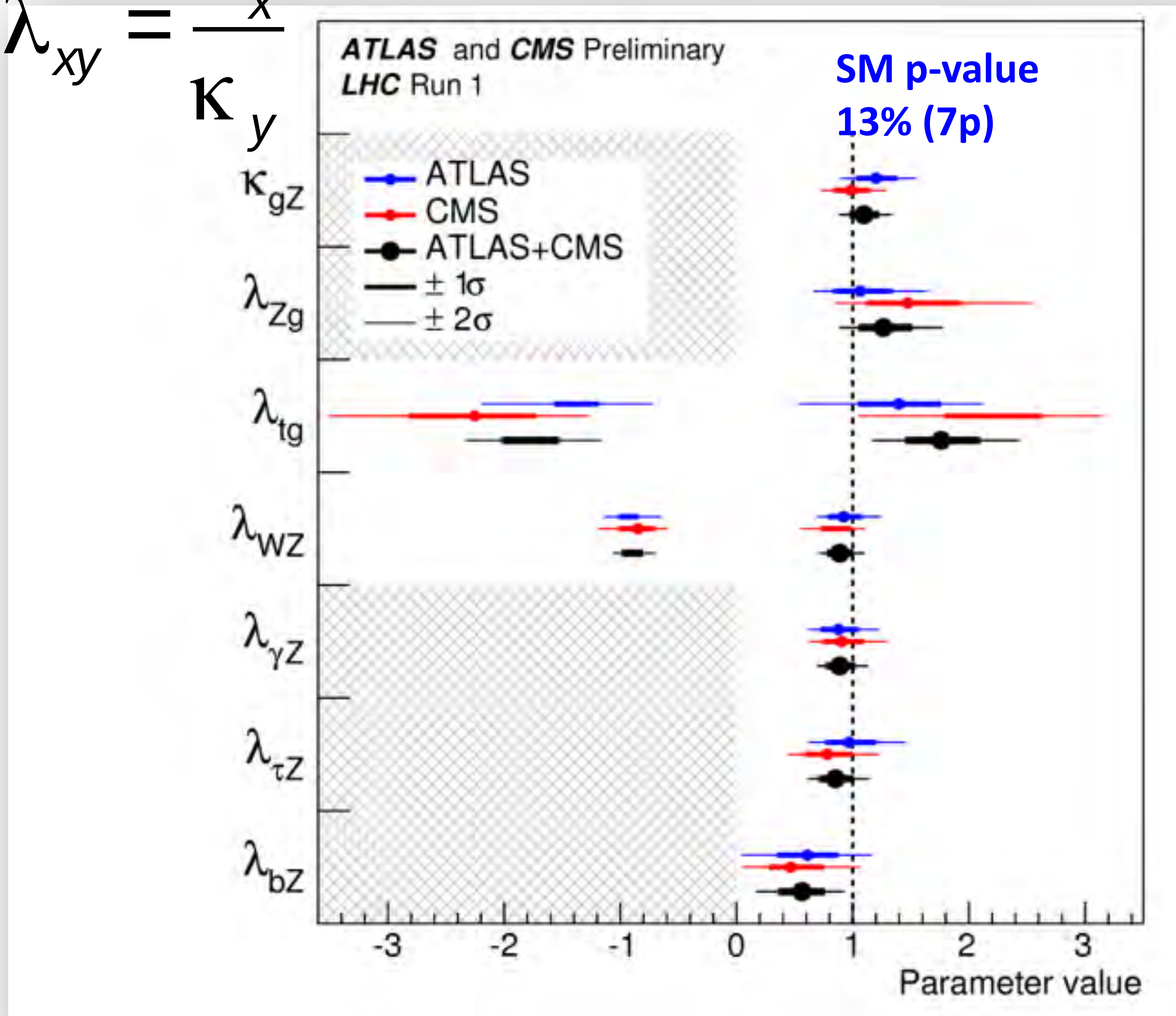
Testing negative k_t is extremely important

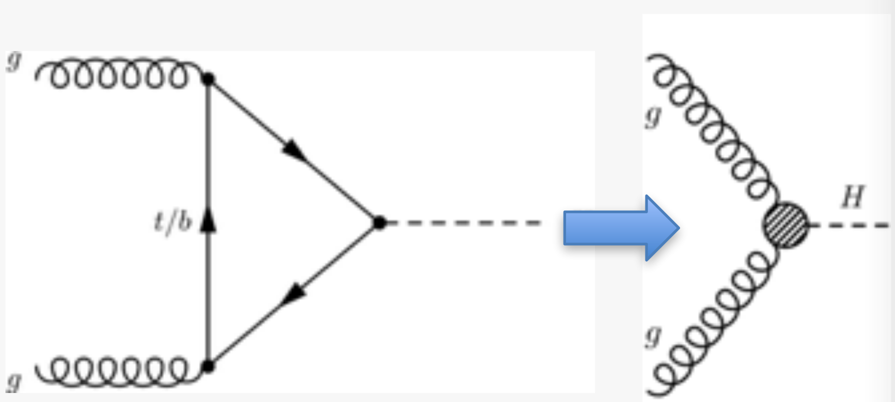
Couplings Generic Model

LHC is not able to measure the Higgs full width.

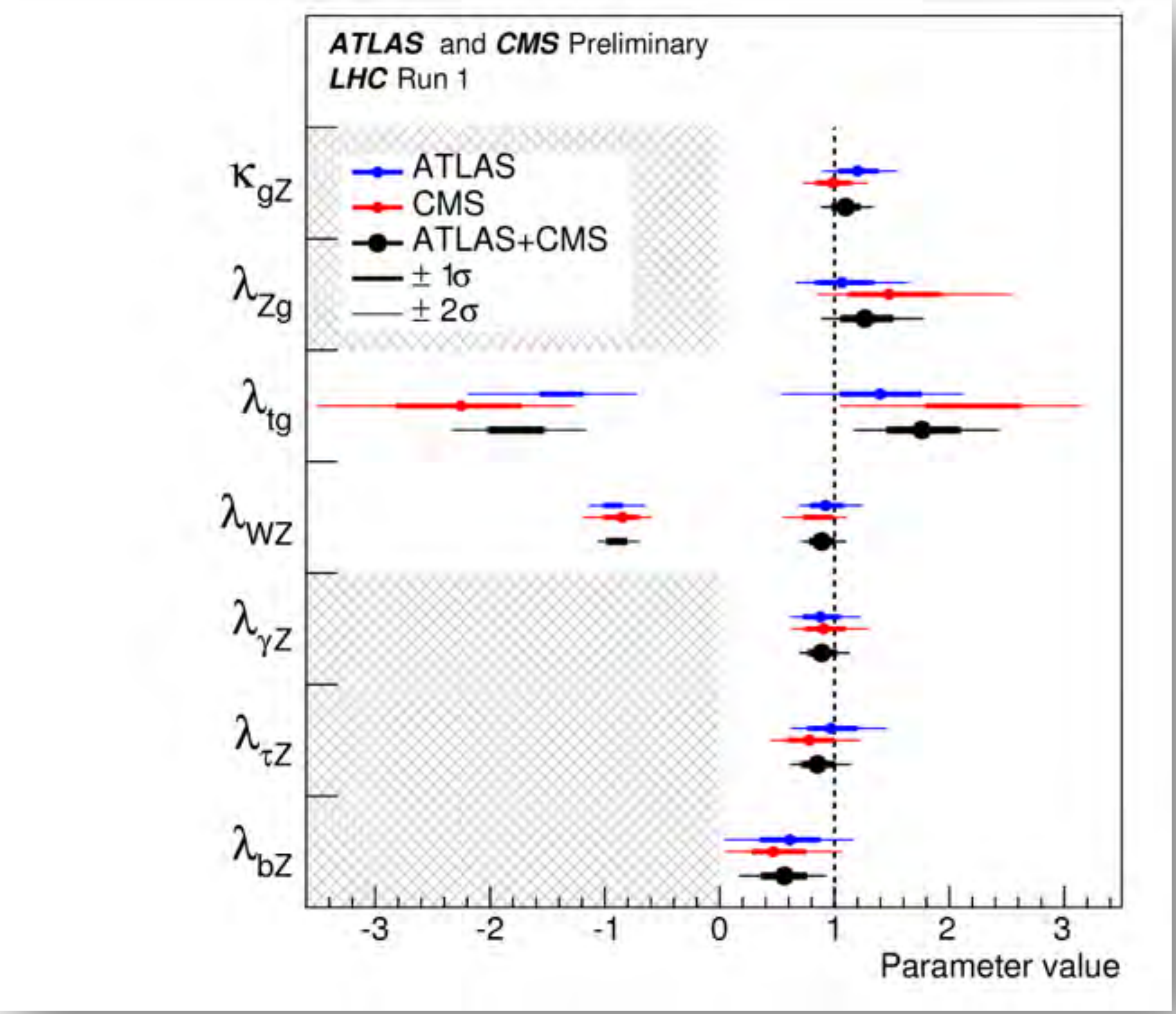
The only way to get minimal assumptions measurement is using ratios, and use effective couplings for Gamma and Gluon

$$\lambda_{xy} = \frac{\kappa_x}{\kappa_y}$$





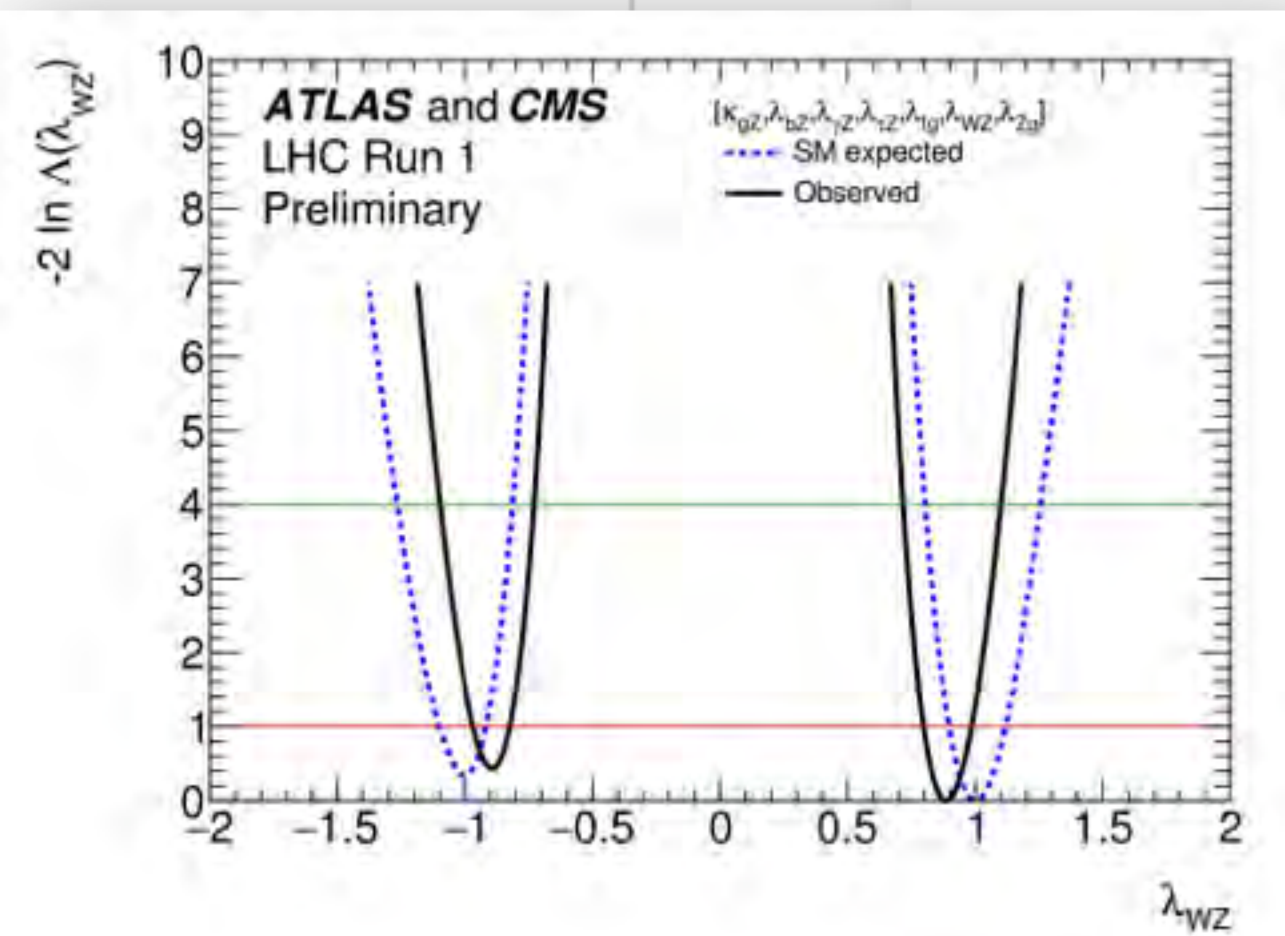
Couplings Generic Model

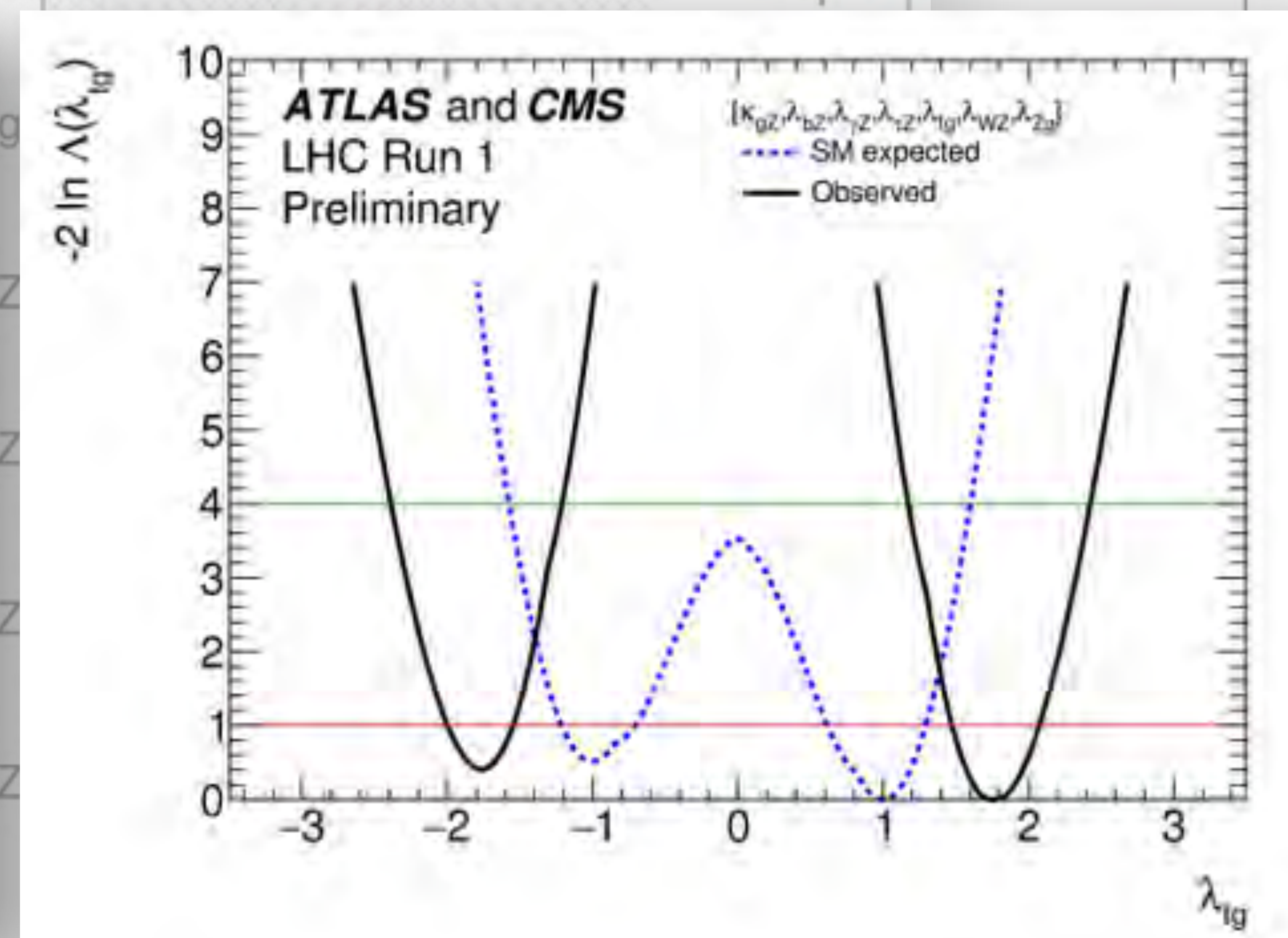


Couplings Generic Model

ggZH and *tH* →

possible solutions with negative λ_{tg} and λ_{WZ}





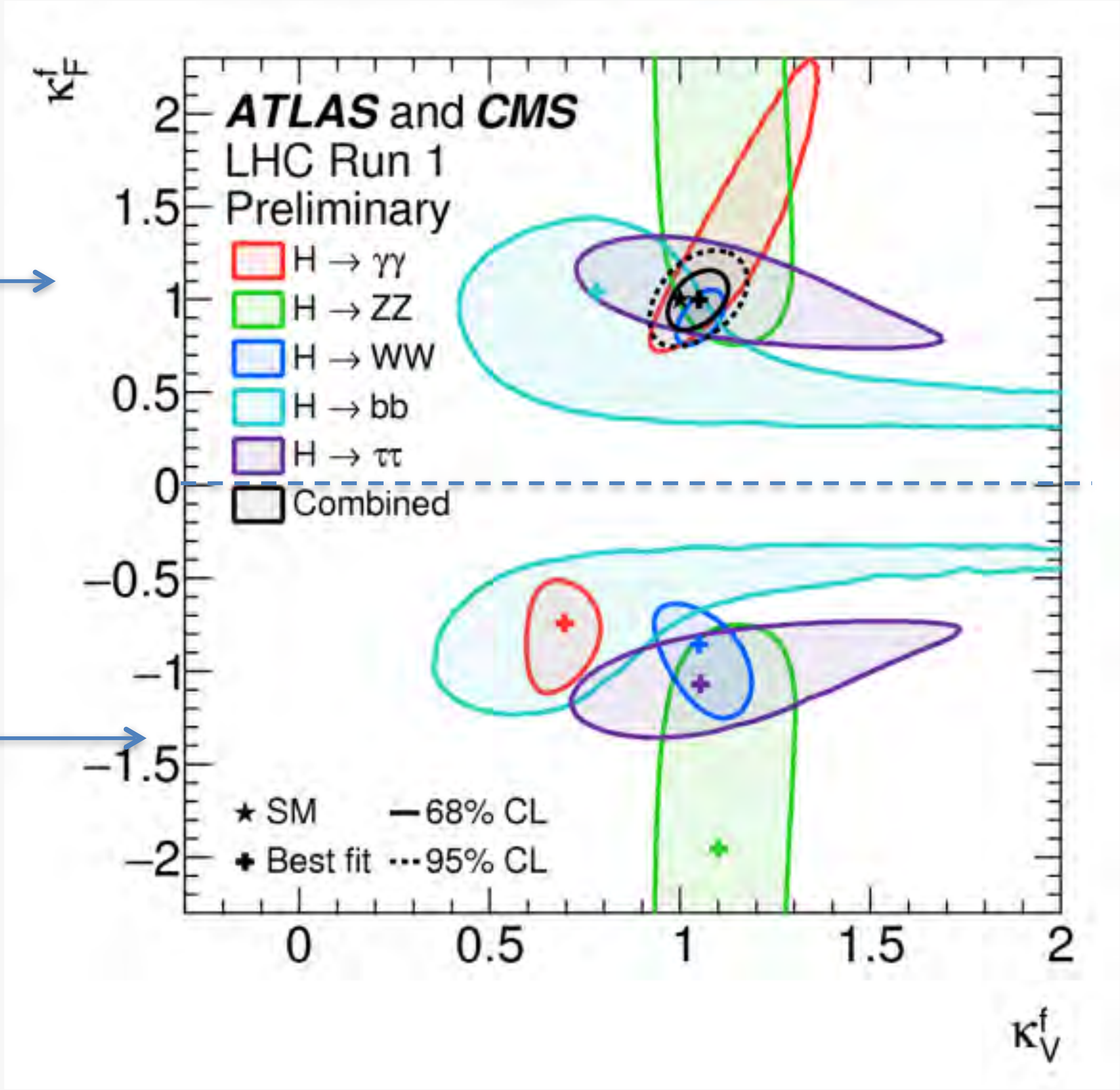
kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
AND THAT ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

~ 5σ exclusion of κ_F<0

SM – No Tension

Tension Drifting apart



kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
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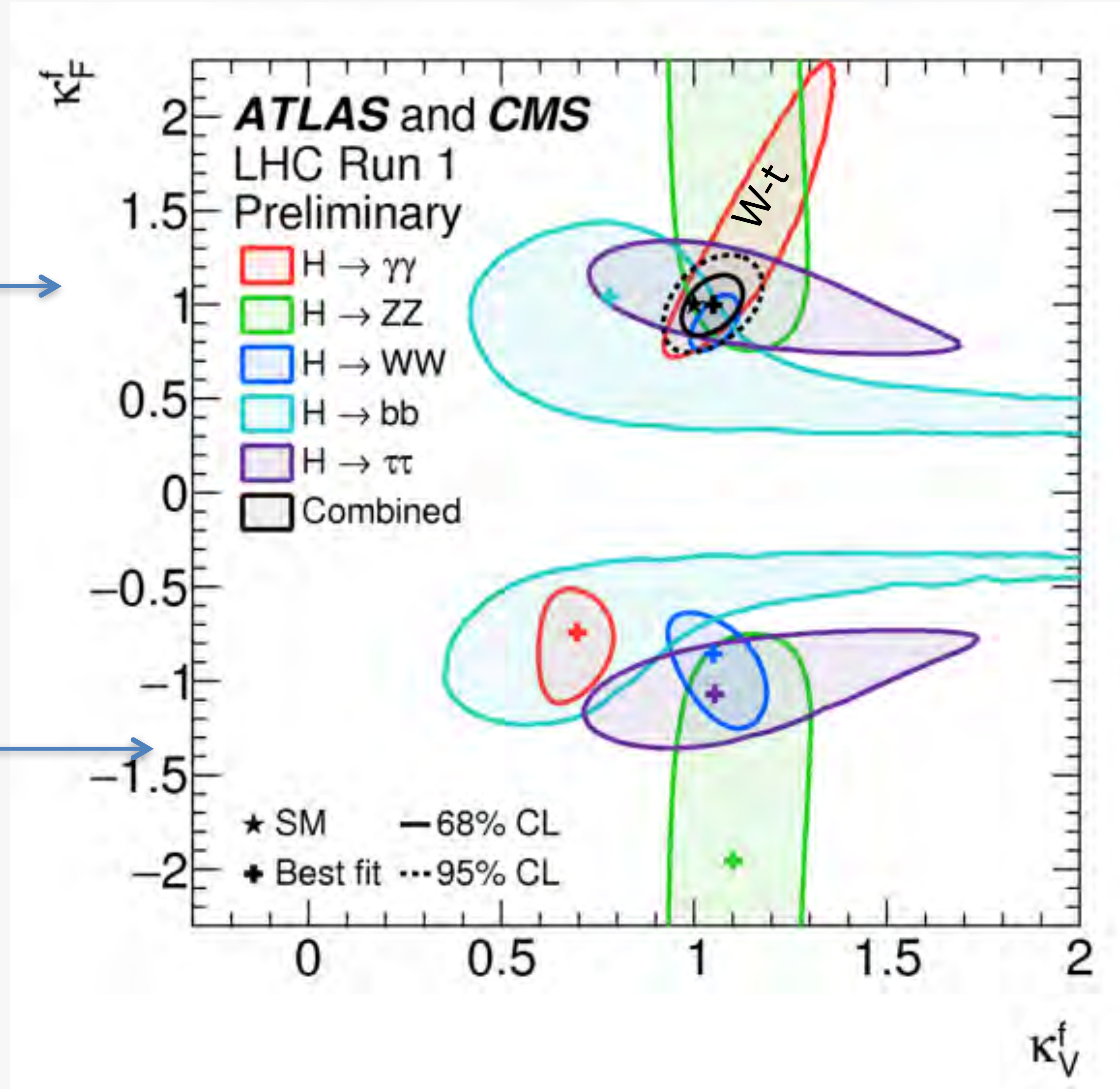
SM –
No Tension

Tension
Drifting
apart



kV & kF: The pedagogic plot

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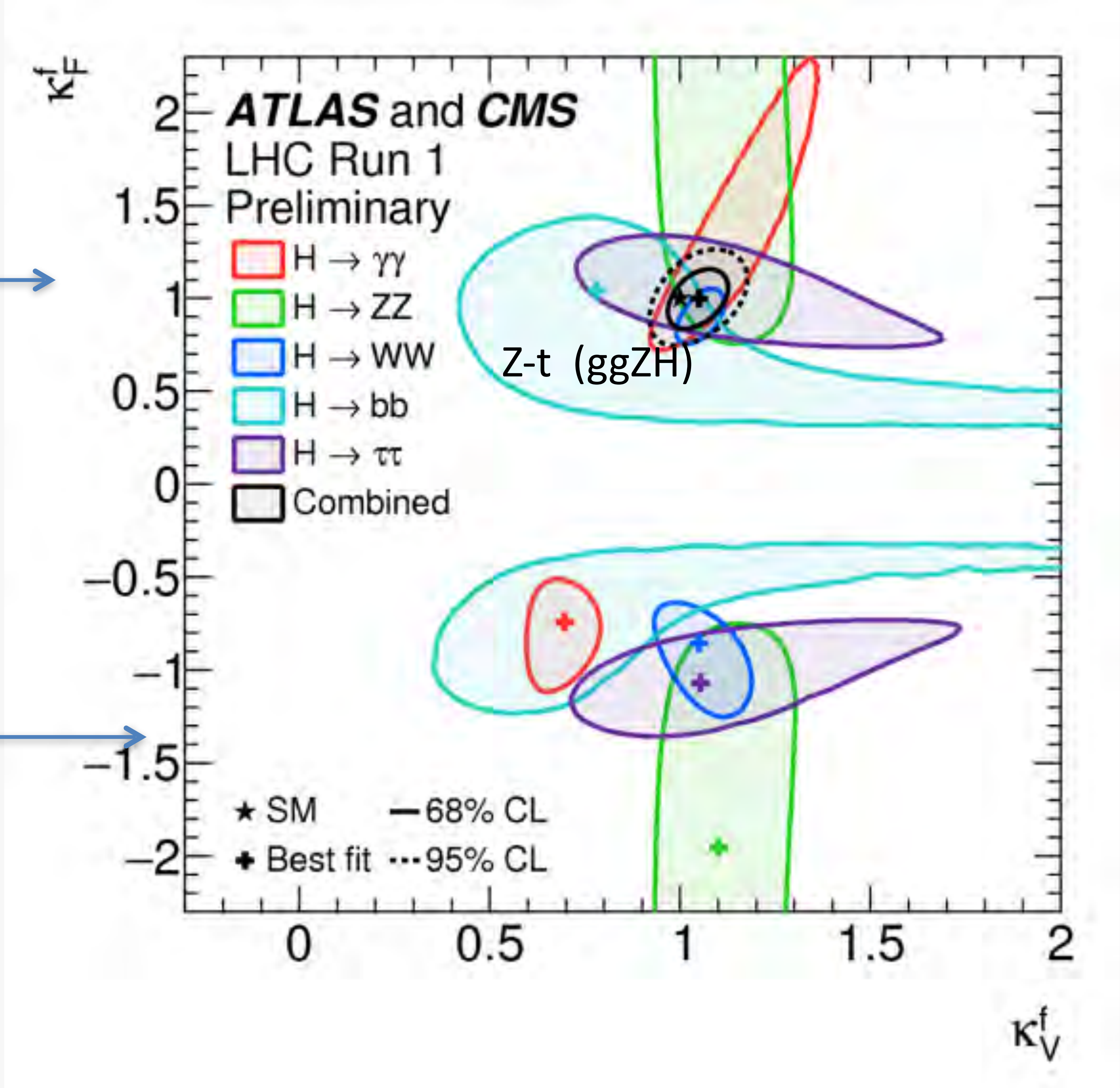
SM – No Tension

Tension Drifting apart



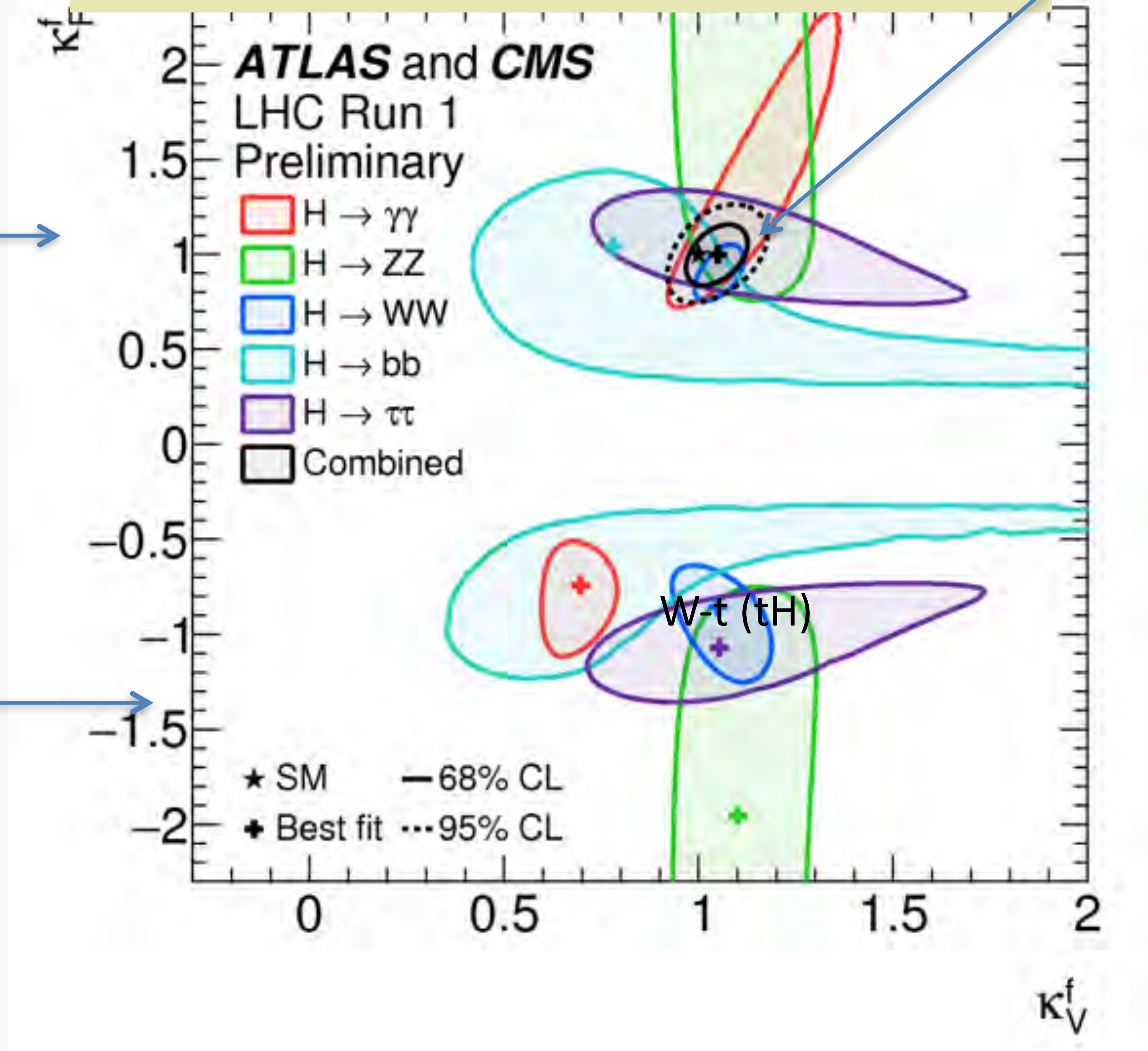
kV & kF: The pedagogic plot

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP
AND THAT ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

Looks like we get better resolution with WW alone

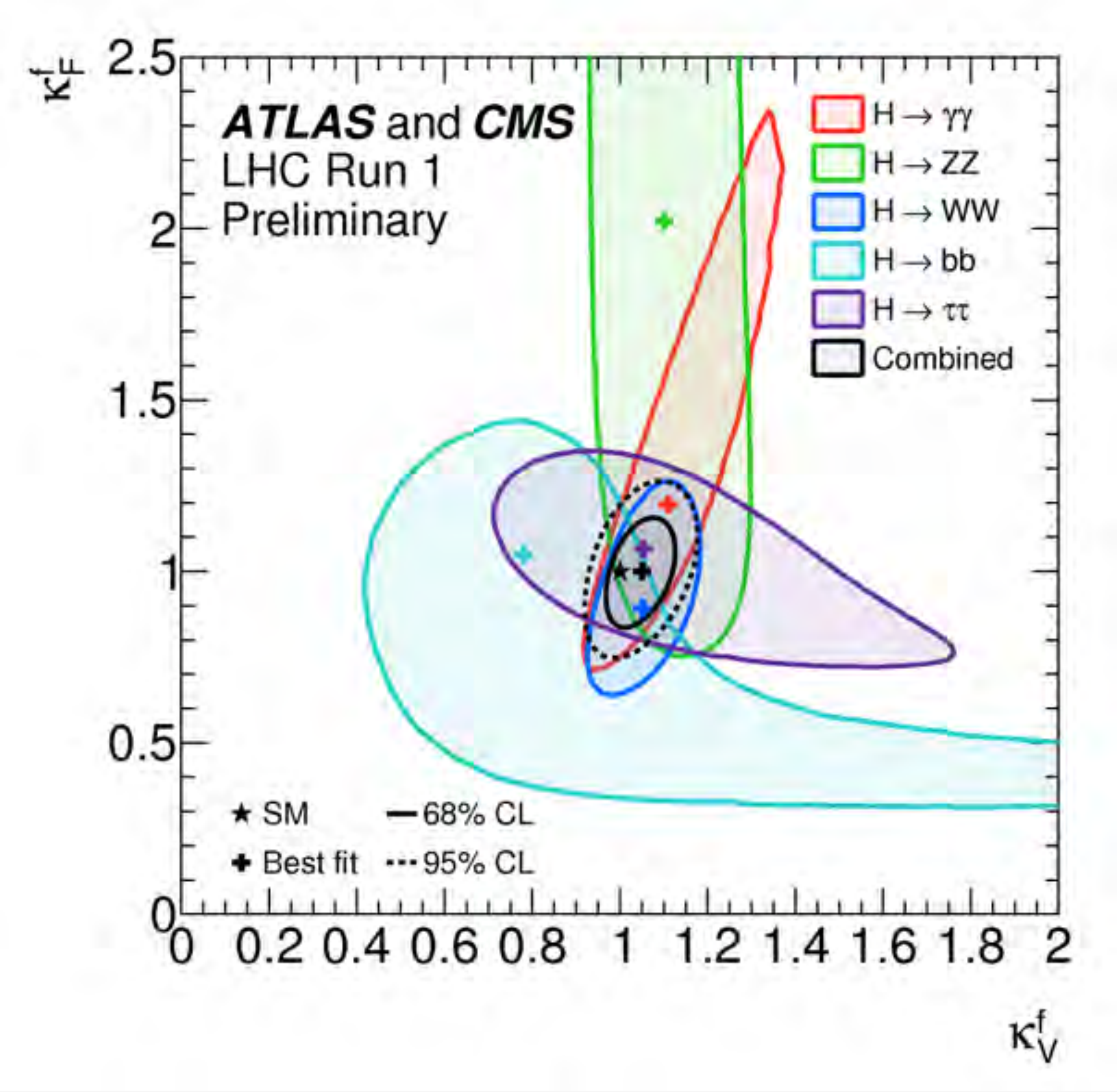
SM –
No Tension

Tension
Drifting
apart



kV & kF: The pedagogic plot

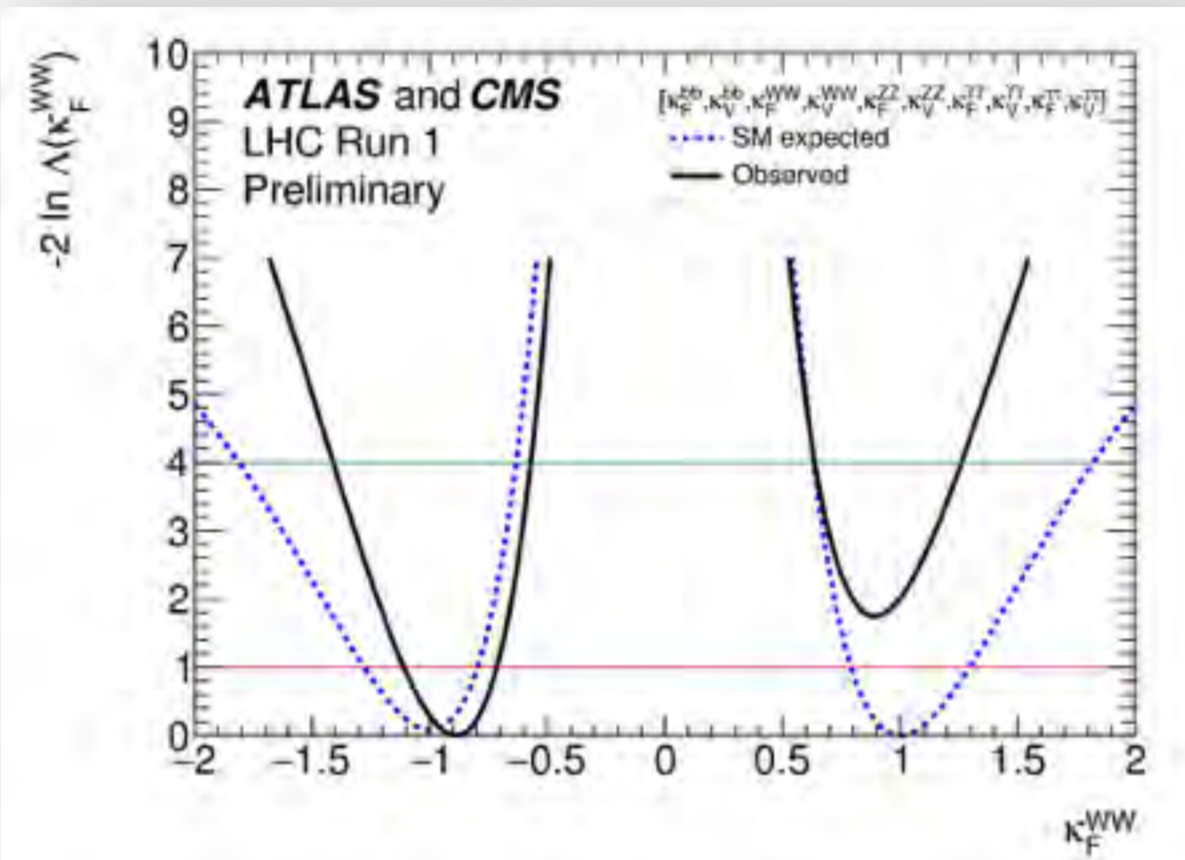
Fitting only positive Kappas, tautology resolved

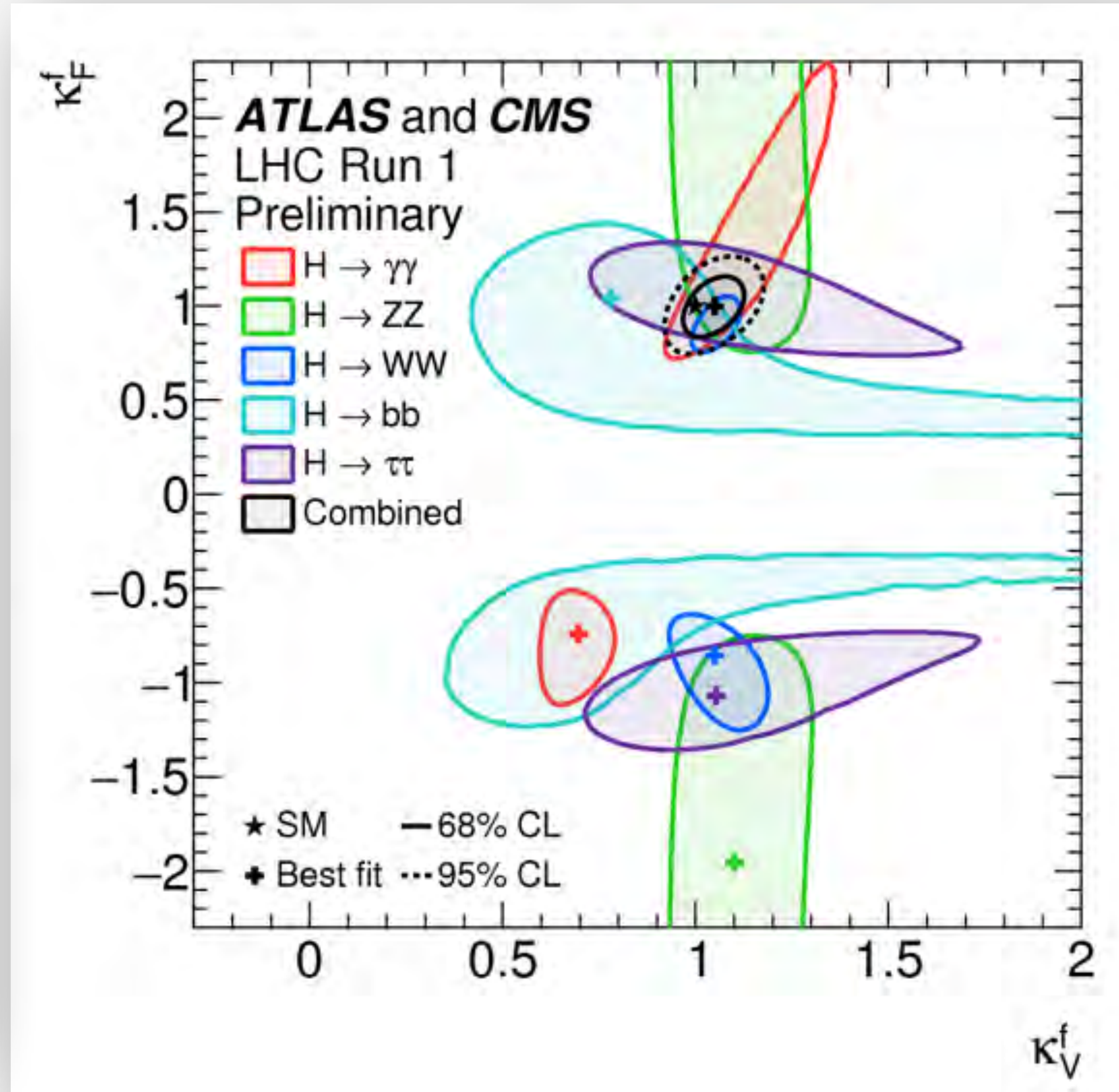


kV & kF: The pedagogic plot

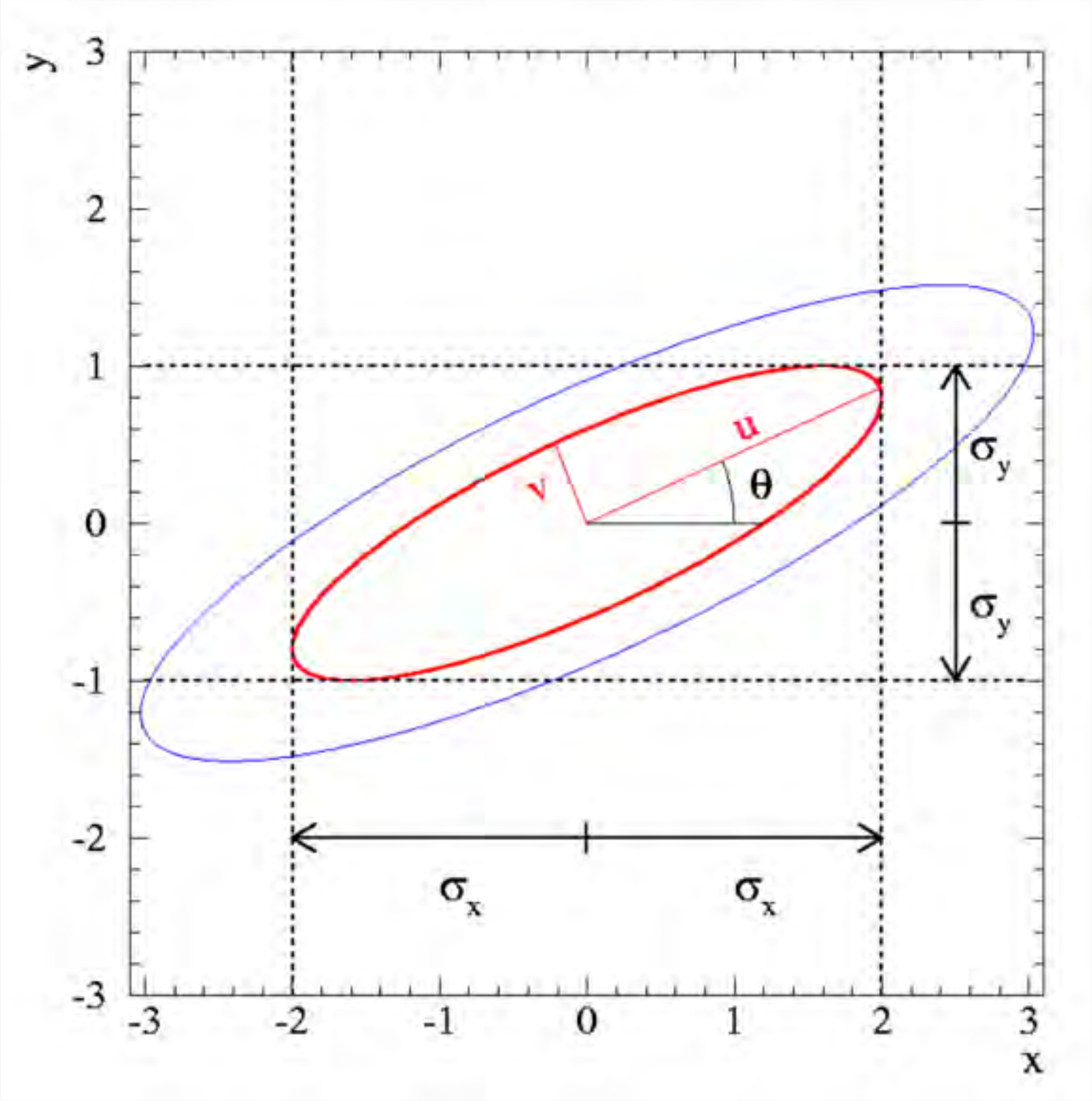
Another interesting point

Why in 1D we do not see a positive Confidence Interval for WW





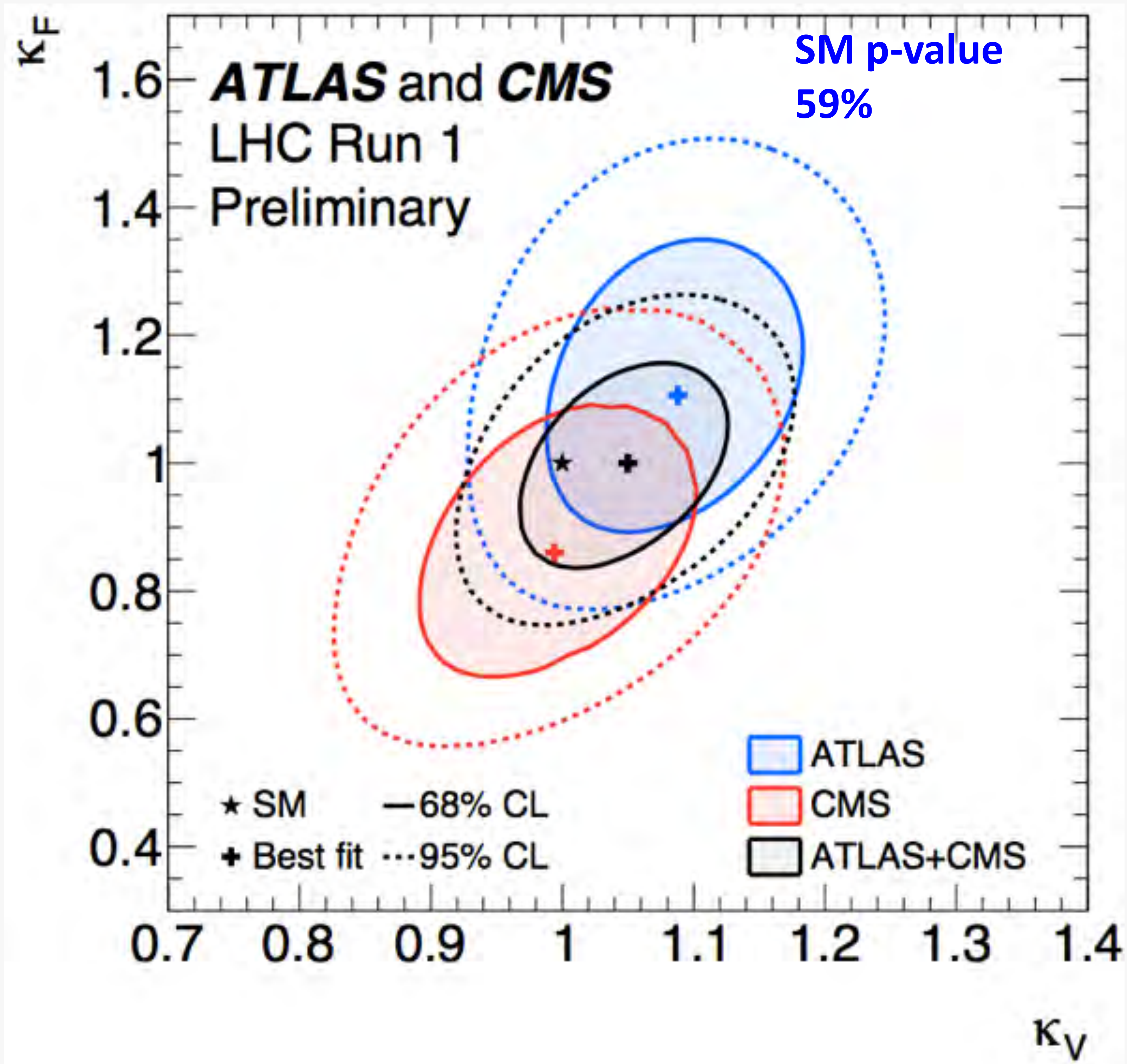
1D vs 2D Confidence Interval



$\Delta\chi^2 = 1$

$\Delta\chi^2 = 2.3 \ \ (68\% \ CL)$

The CERN Courier PR plot



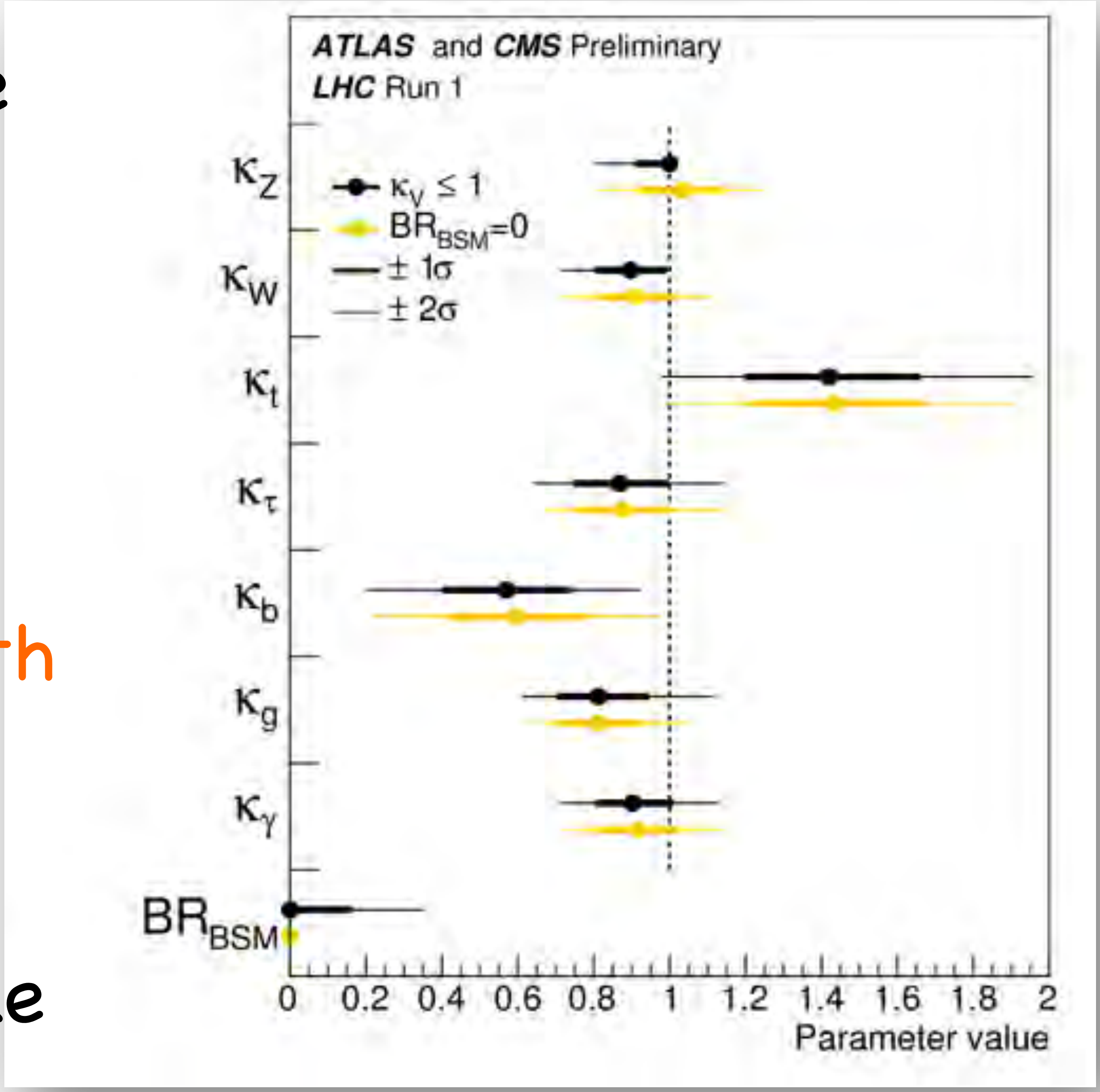
In the presence of NewPhysics

Here NP will enter in the loop and might contribute to BR_{BSM}

We introduce effective couplings k_γ, k_g

To be able to fit we need to constrain the width by either assume $BR_{BSM}=0$ (NP>mH/2)

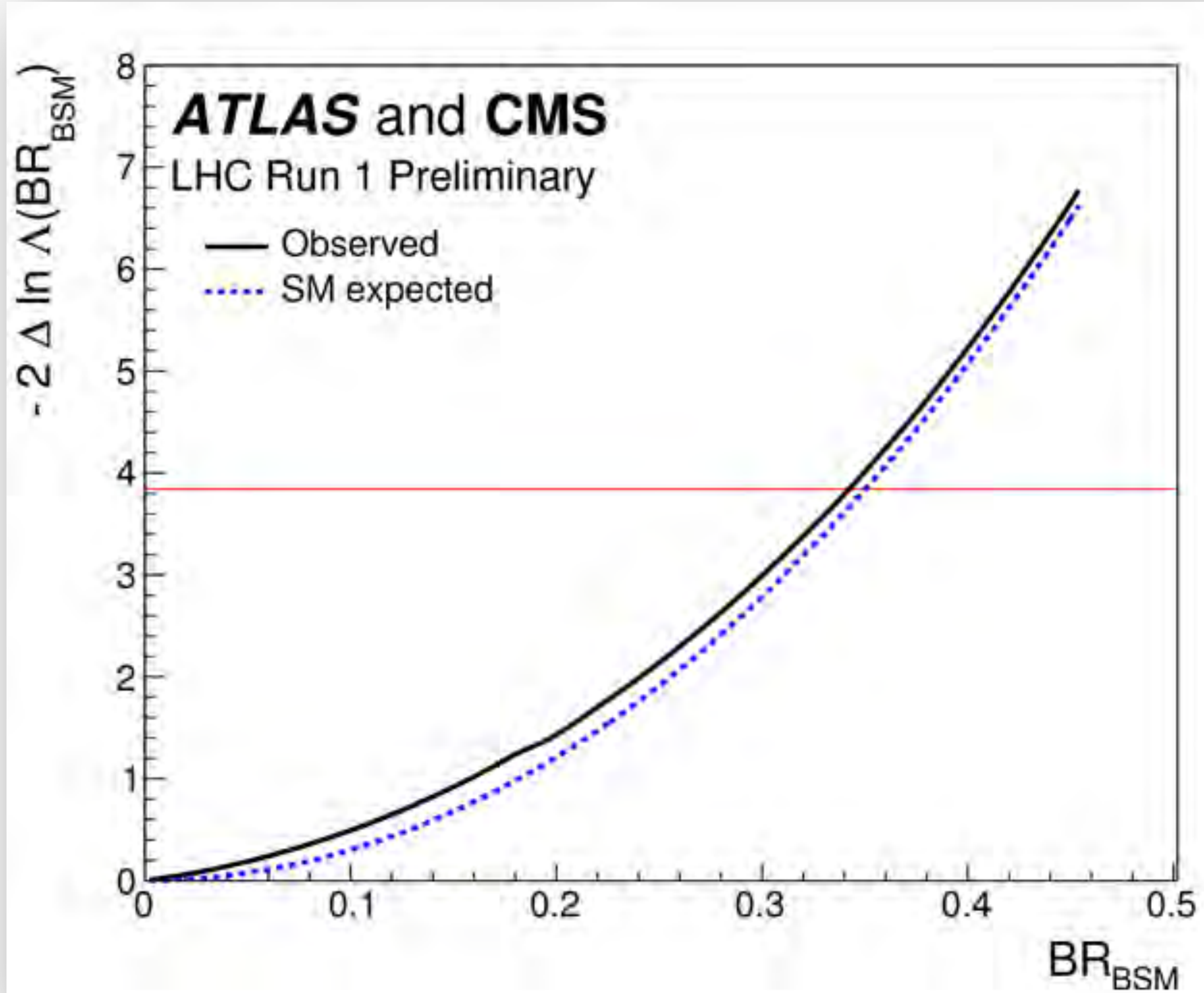
or $k_V \leq 1$ and $BR_{BSM}>0$ (like in many BSM physics such as MSSM)



Bounds on BR_{BSM}

BR_{BSM}<0.34 @ 95% CL

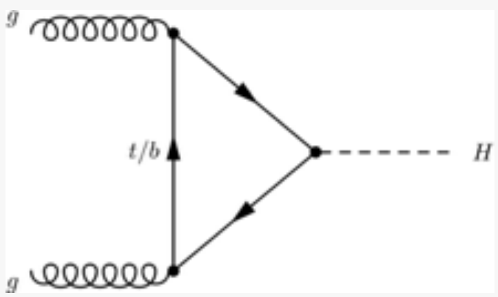
This is using a $\tilde{t}_{BR}$ (BR>0; FC) test statistics Which does not Allow negative BRs, leading to Possible Overcoverage (conservative)



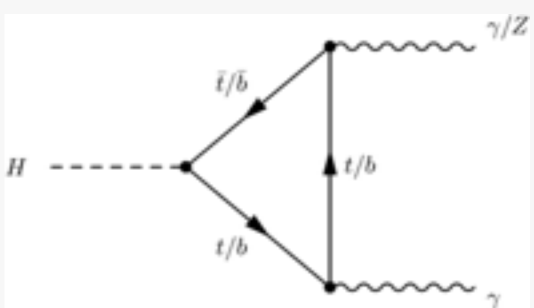
κ_g and κ_γ

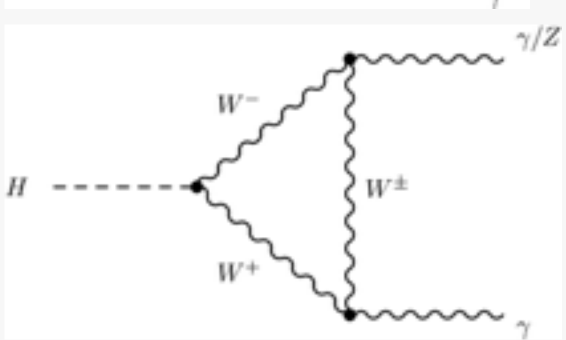
Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and H→γγ

ggF loop

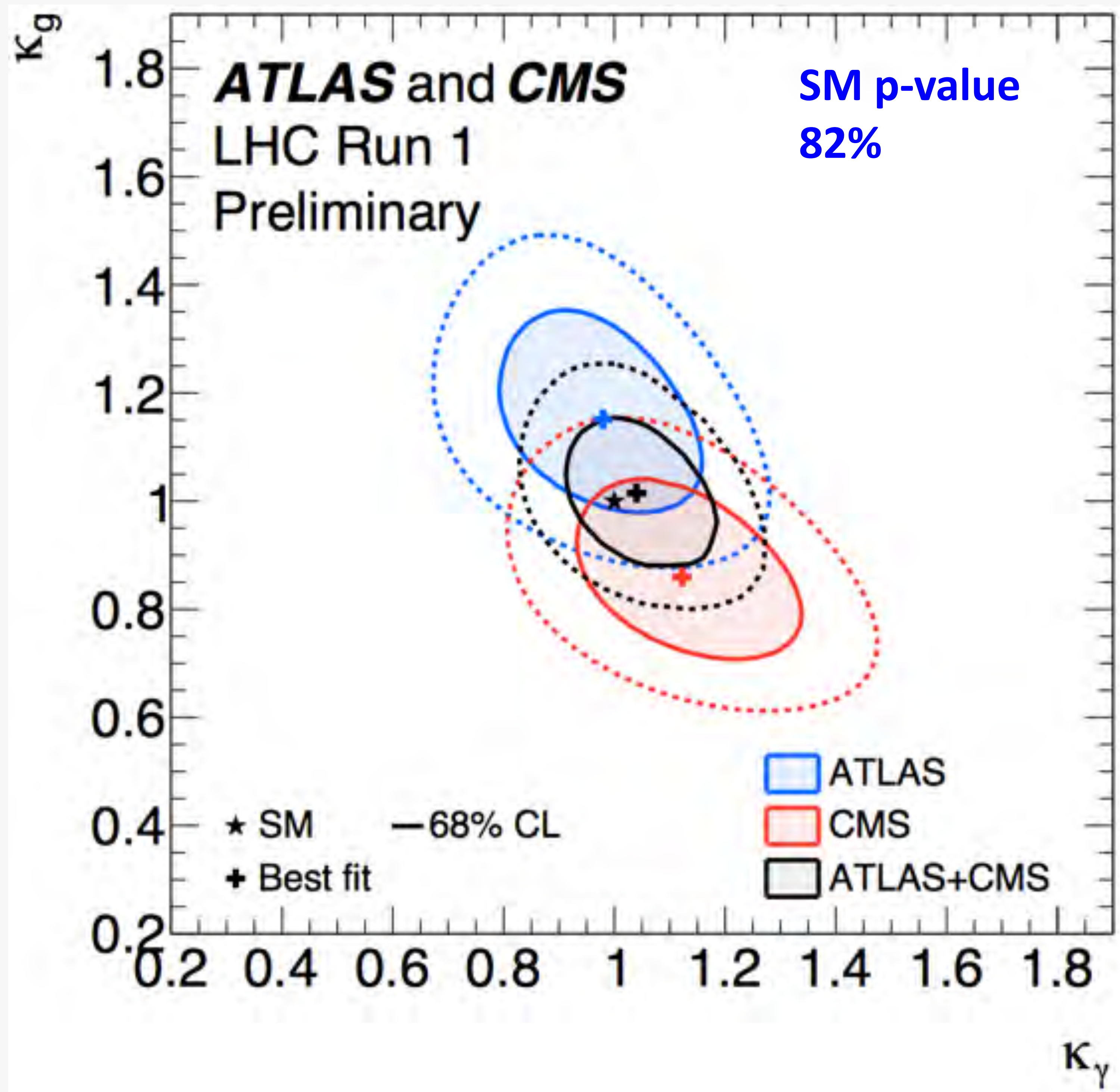


H→γγ loop





Additional heavy fermions or charged Higgs boson would modify the effective couplings



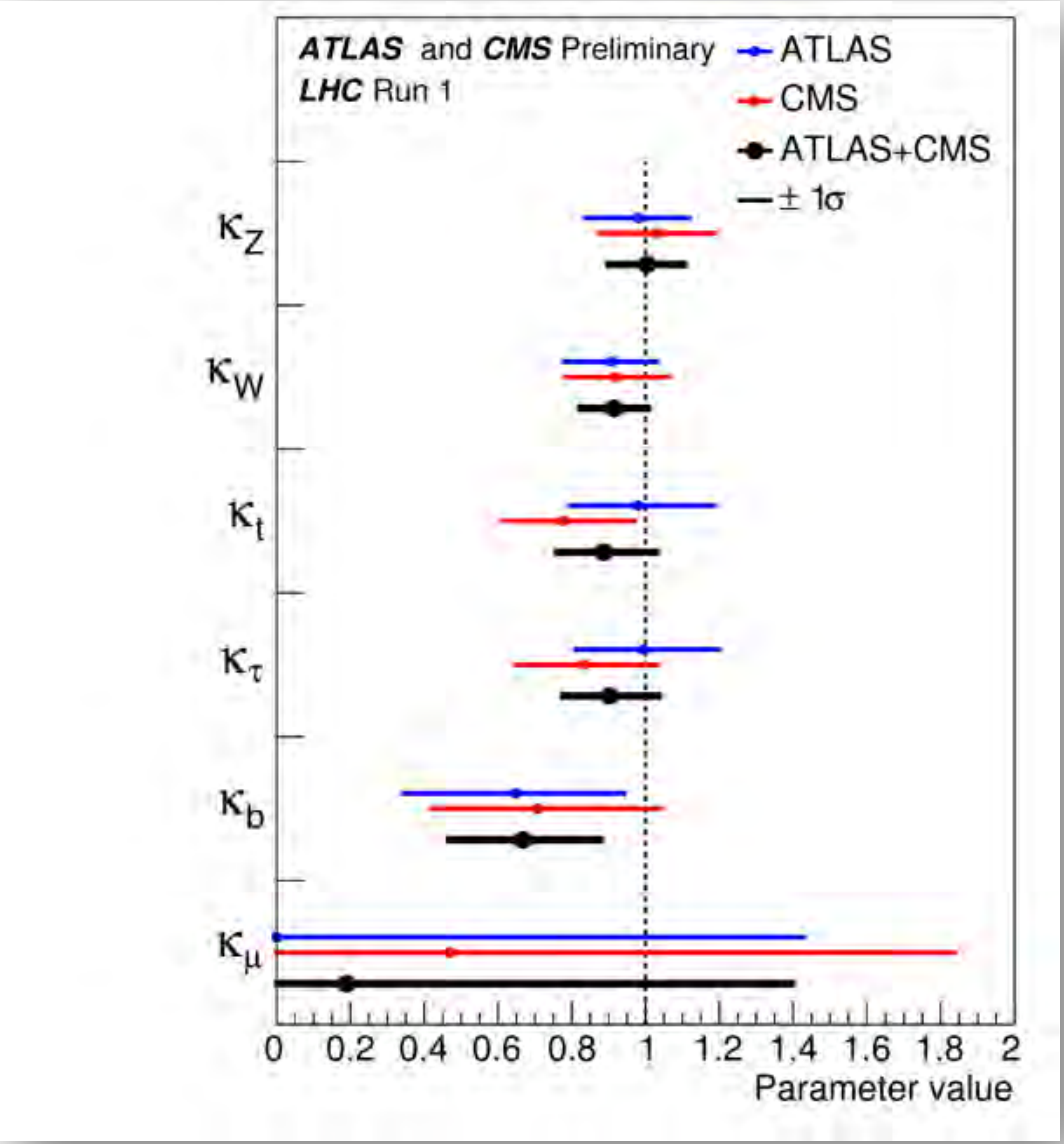
“SM” fit

This is the olny fit where the MuMu coupling was included in the 6p fit. Loops content was assumed (all loops resolved) and $BR_{BSM}=0$ was assumed.

Why all values<1?

Kb is low and it dominates the width (makes it small, reducung all Kappas)

This is actually a SM fit which leads to the “Money Plot”

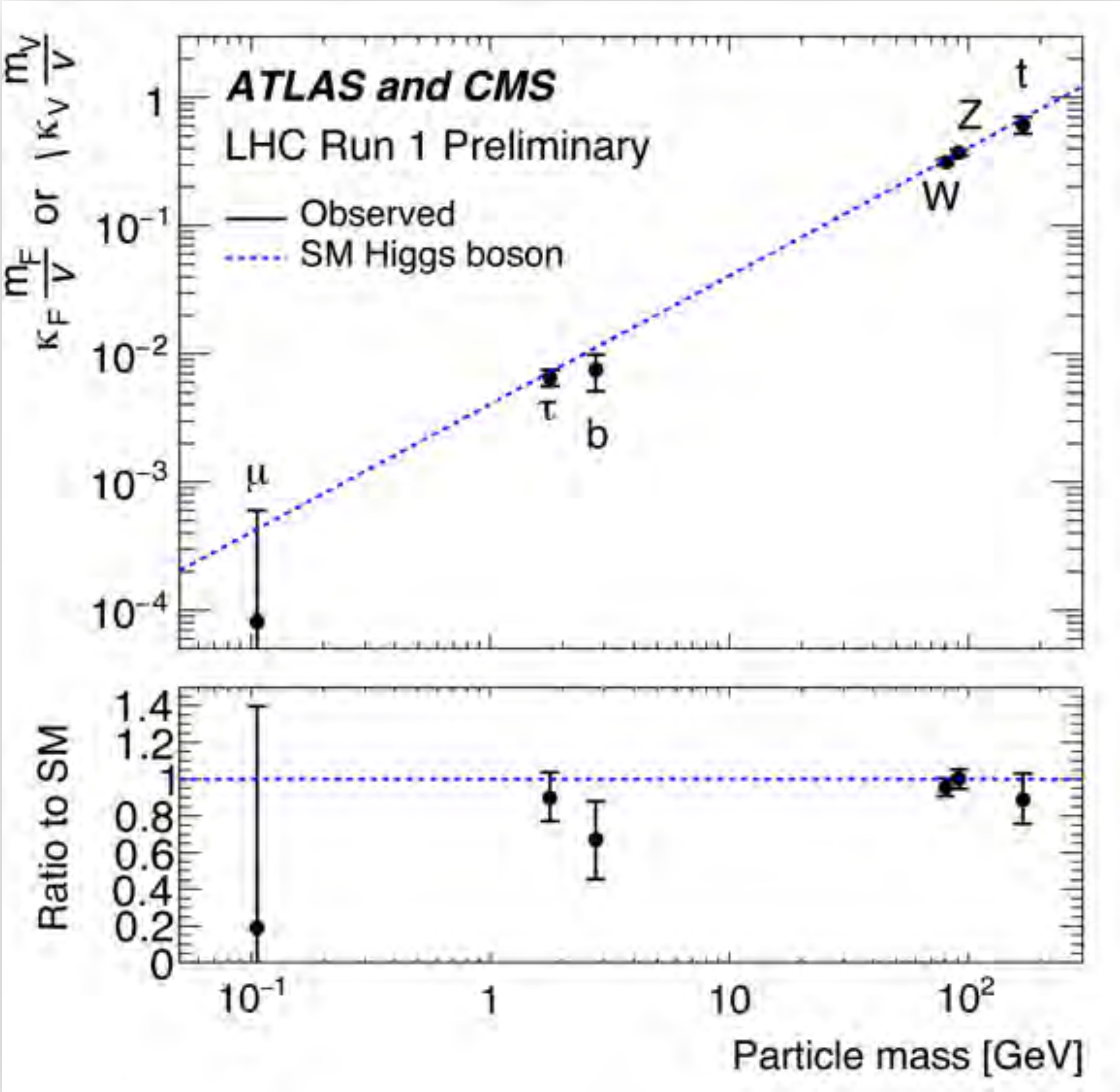


The PR Plot (an alternative version)

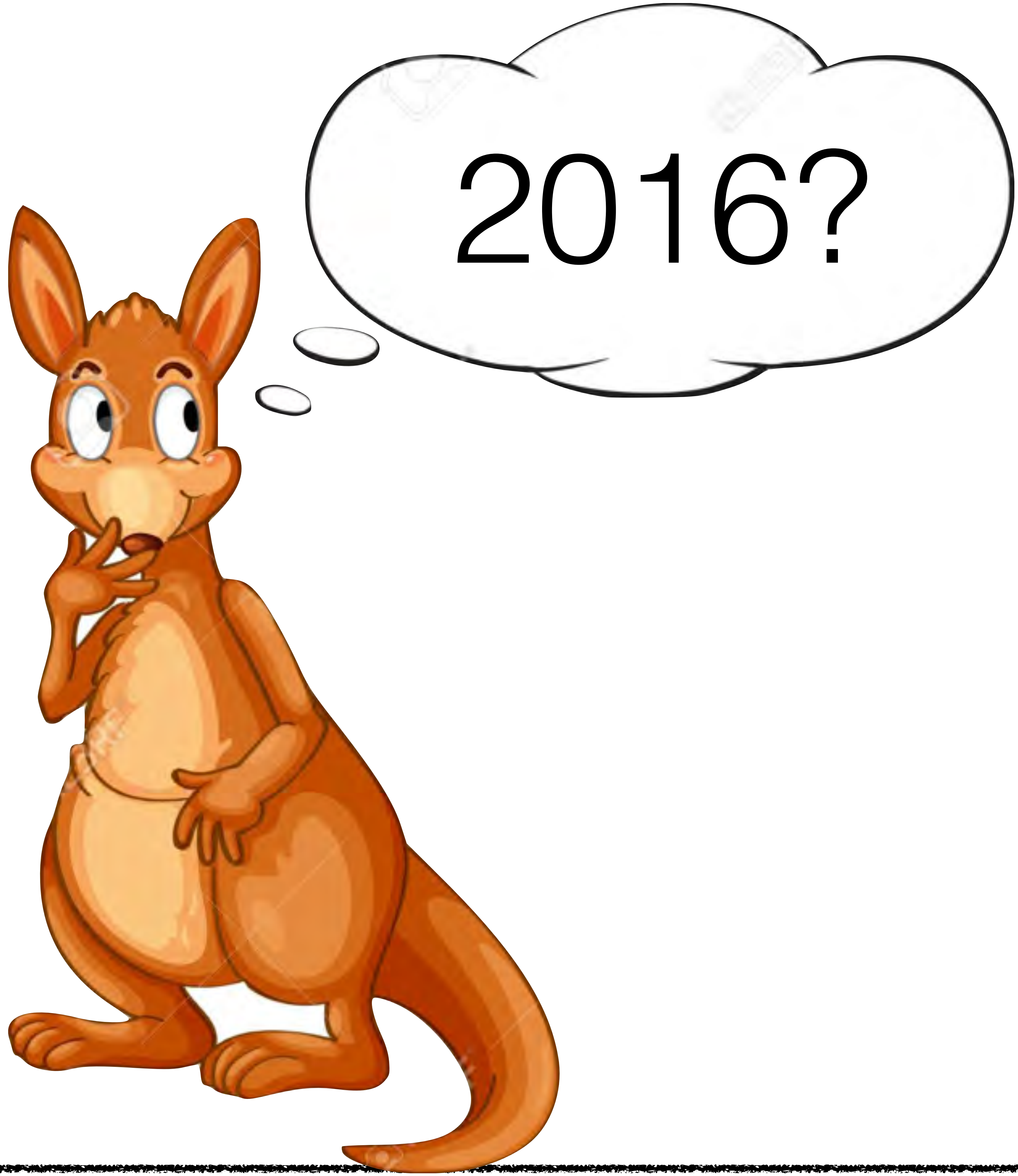
$$g_{Hff} = \frac{g_{Hff}}{g_{Hff}^{SM}} g_{Hff}^{SM} = \kappa_f g_{Hff}^{SM} \sim \kappa_f m_f$$

$$g_{HVV} = \frac{g_{HVV}}{g_{HVV}^{SM}} g_{HVV}^{SM} = \kappa_V g_{HVV}^{SM} \sim \kappa_V m_V^2$$

$$\text{reduced coupling } \sqrt{g_{HVV}} \sim \sqrt{\kappa_V} m_V$$

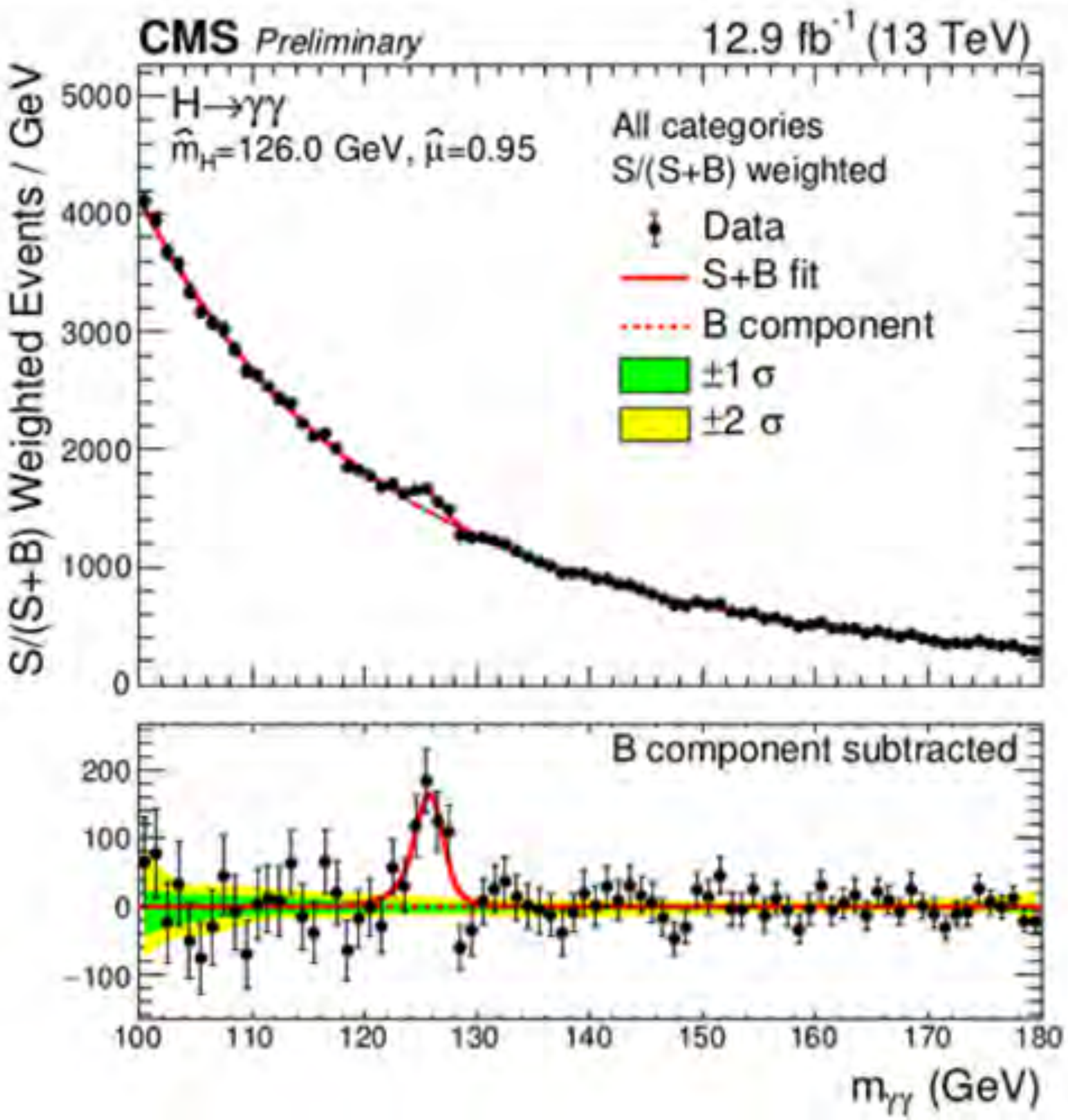


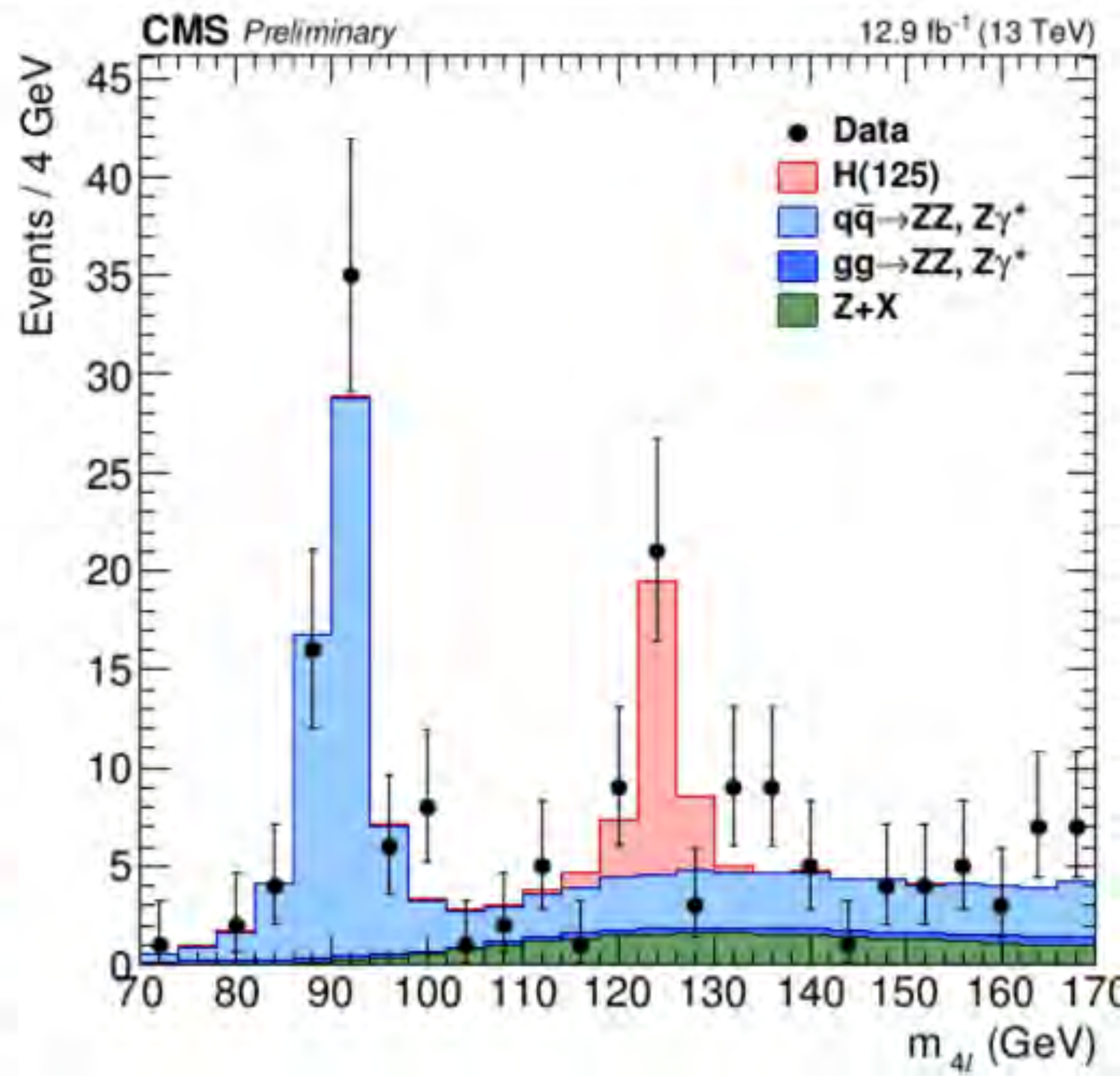
$$k_F \text{ or } \sqrt{k_V}$$


2016?

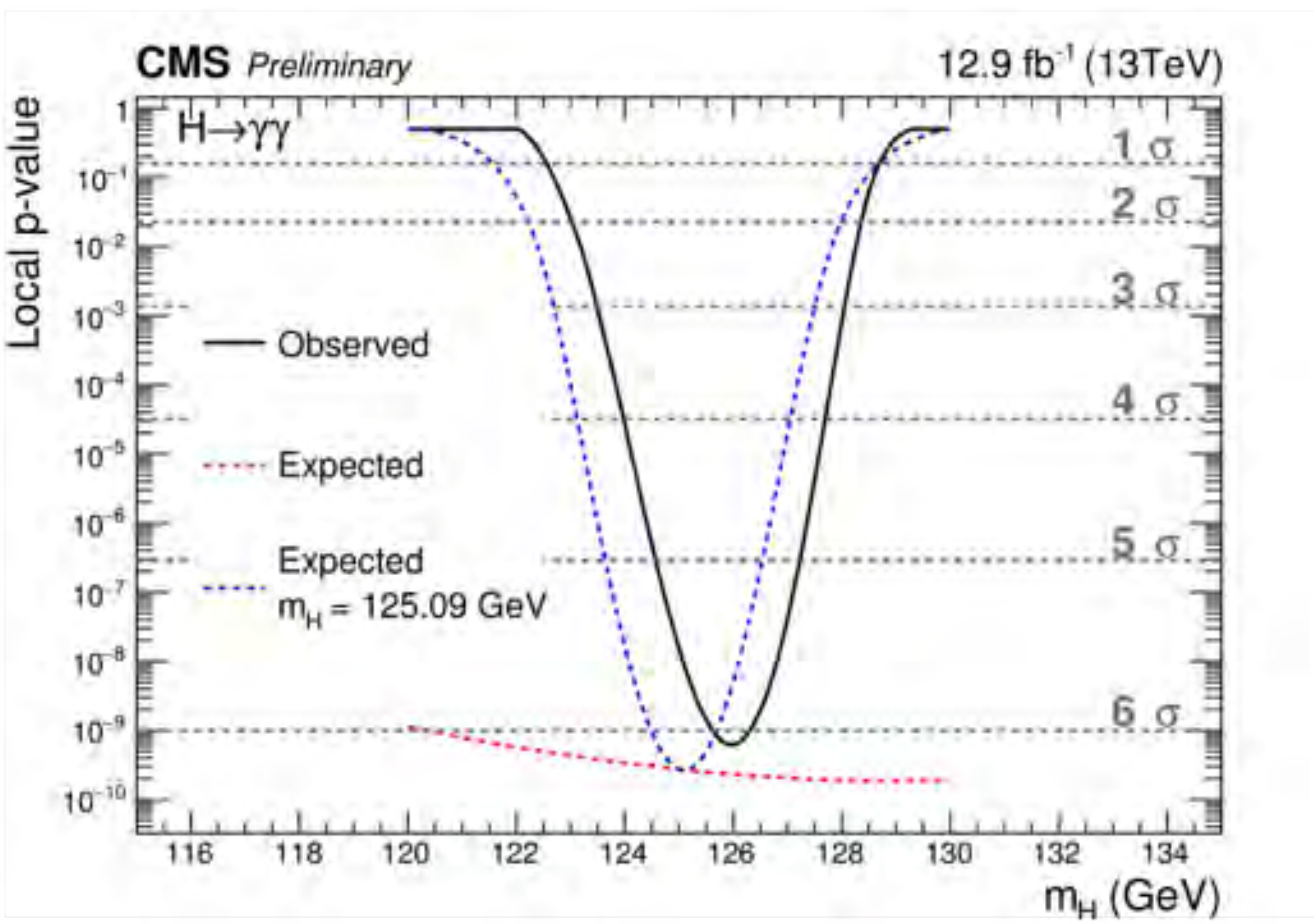
Higgs Re-Discovery 2016

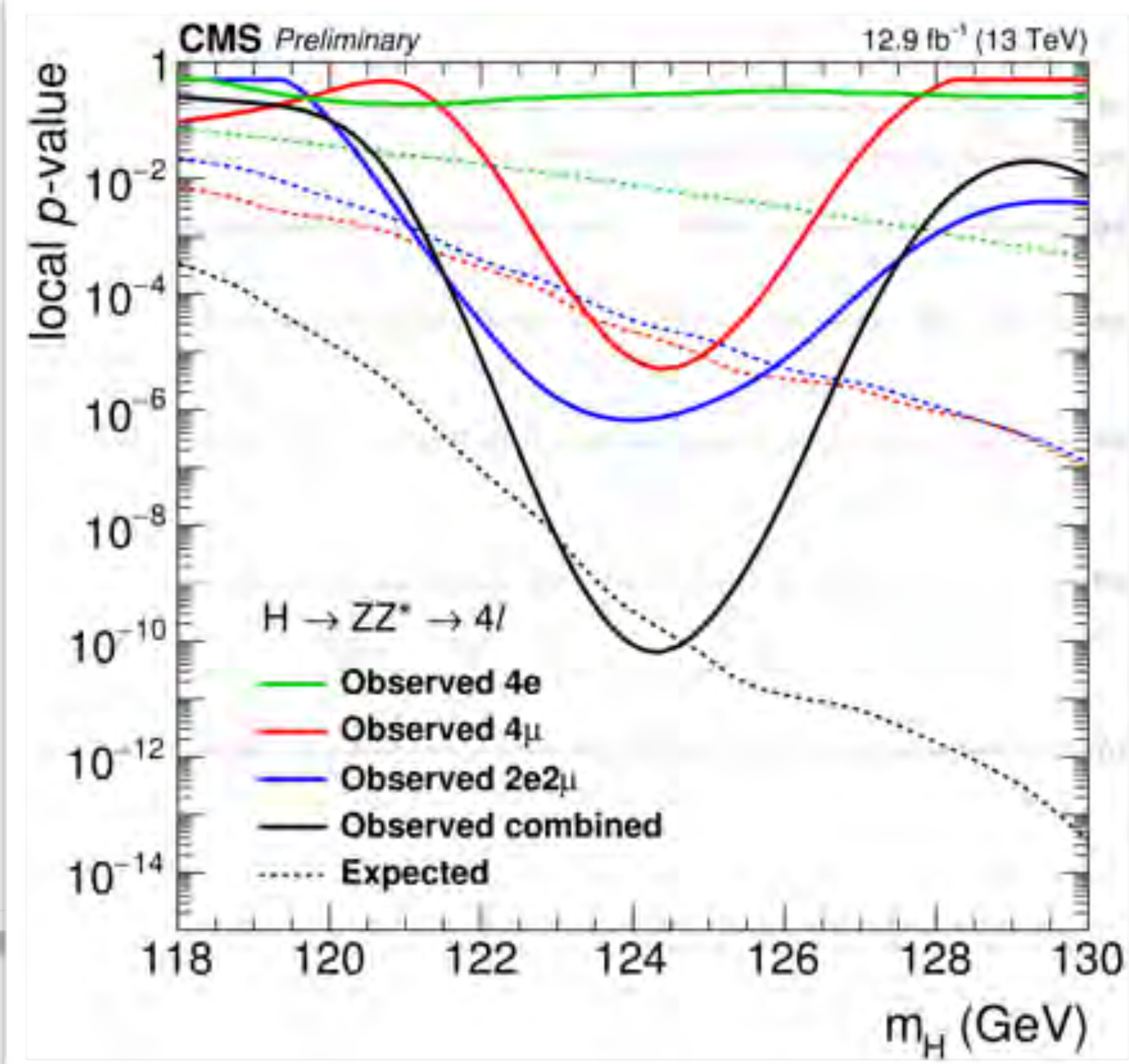
Re Discovery of the Higgs





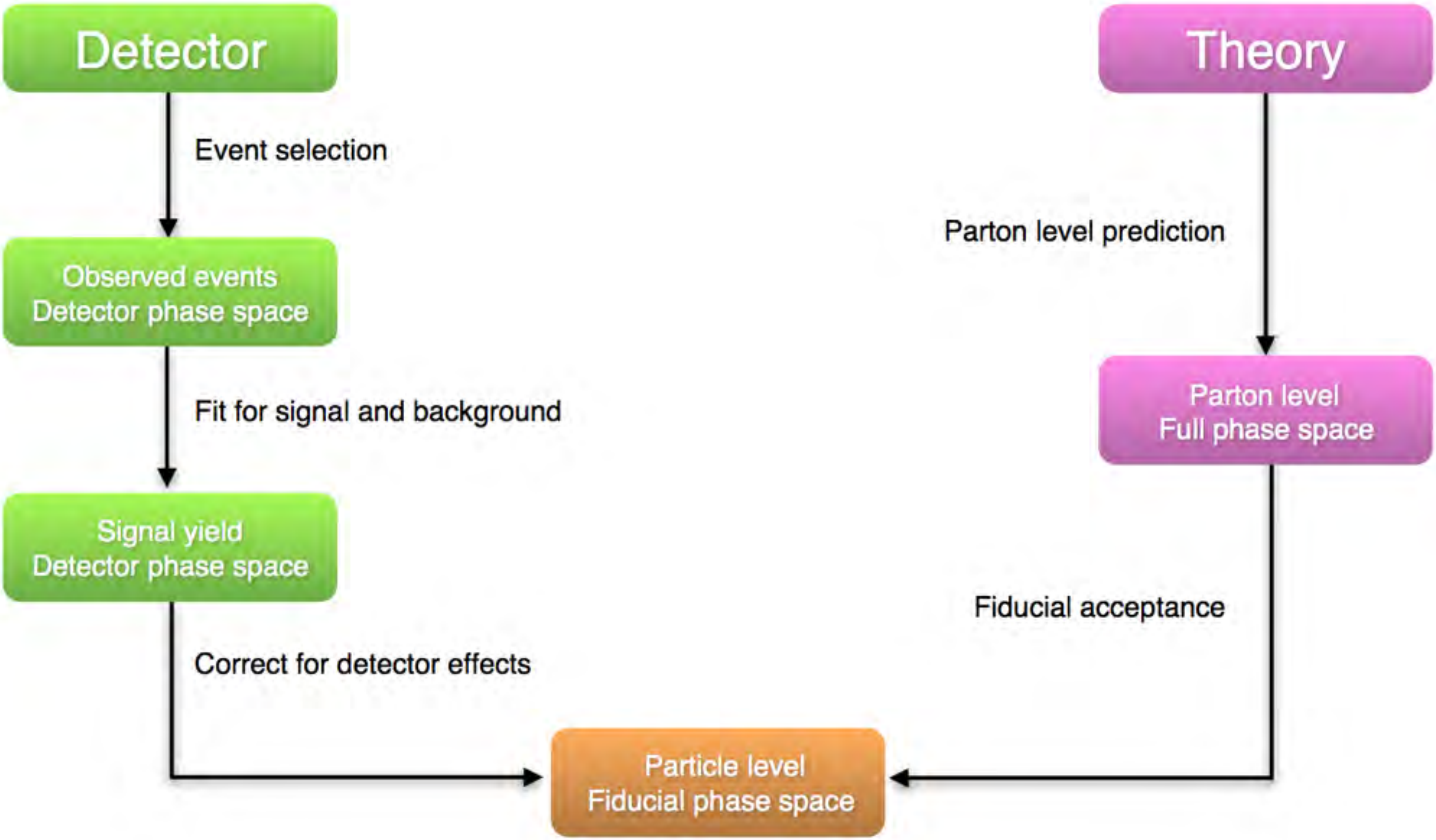
Rediscovery of Higgs Boson





Simplified Templates (Fiducial Cross Sections)

The Fiducial PhaseSpace

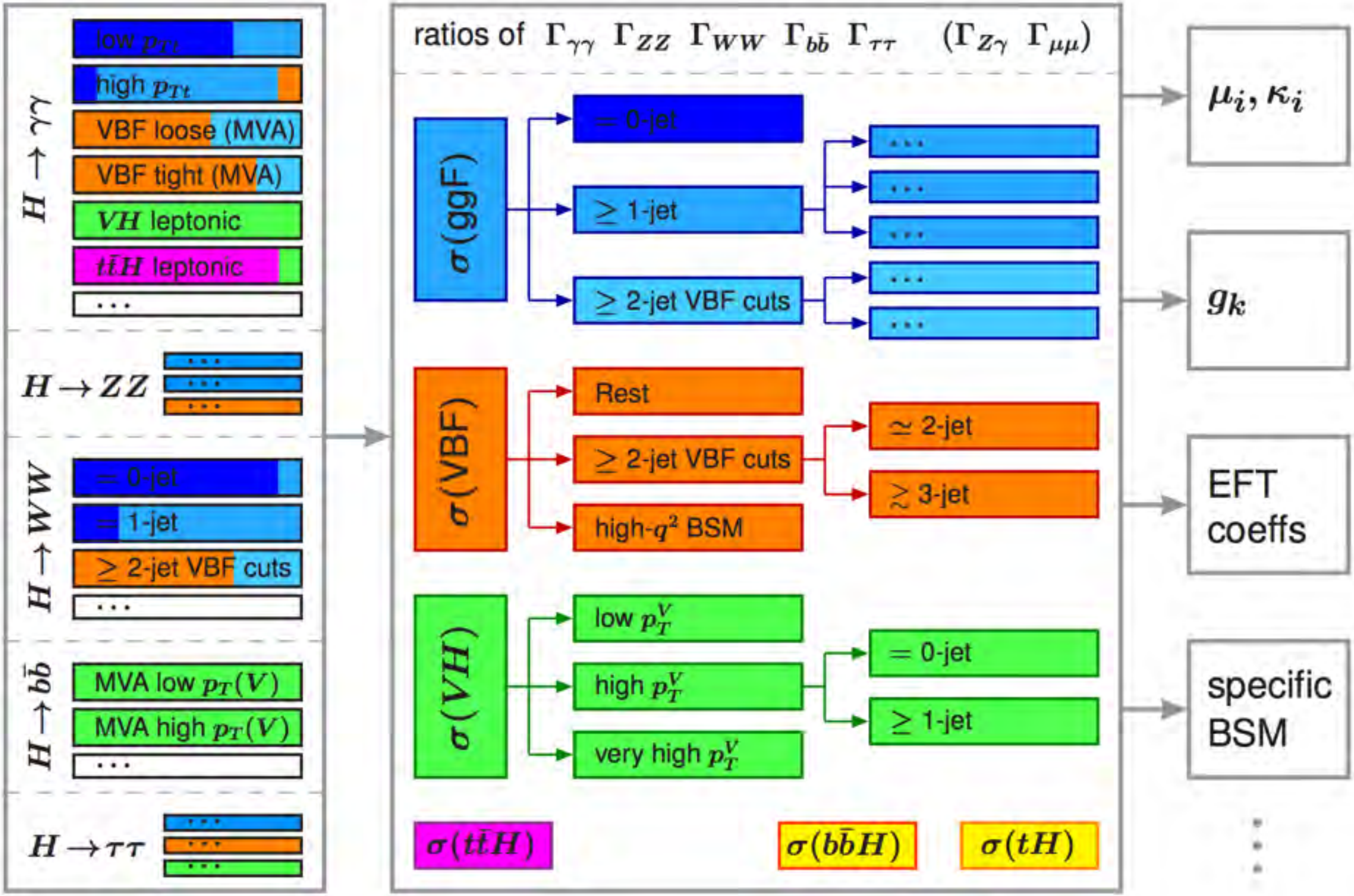


- First steps towards a new analysis philosophy cooked in Les Houches 2015
  - Provide more finely-grained measurements to supply more information for theoretical interpretations without having to redo analyses when a new theoretical model is under the table
  - Still allowing and benefitting from the global combination of the measurements in all decay channels
    - —>Maximising the sensitivity of the measurements while at the same time minimising their theory dependence.

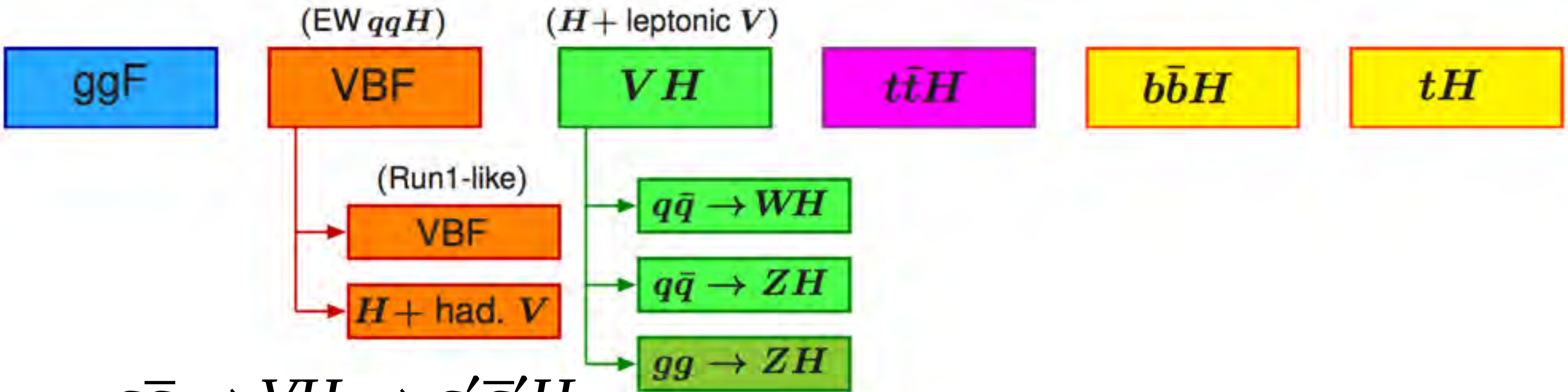
The simplified template cross section framework

- Combination of all decay channels
- Measurement of cross sections instead of signal strengths, in mutually exclusive regions of phase space
- Measurement of Decay rate Ratios
- Cross sections are measured for specific production modes Measurements are performed in abstracted/ simplified fiducial volumes
- Allow the use of advanced analysis techniques such as event categorization, multivariate techniques, etc.

The simplified template cross section framework



Stage 0 Template

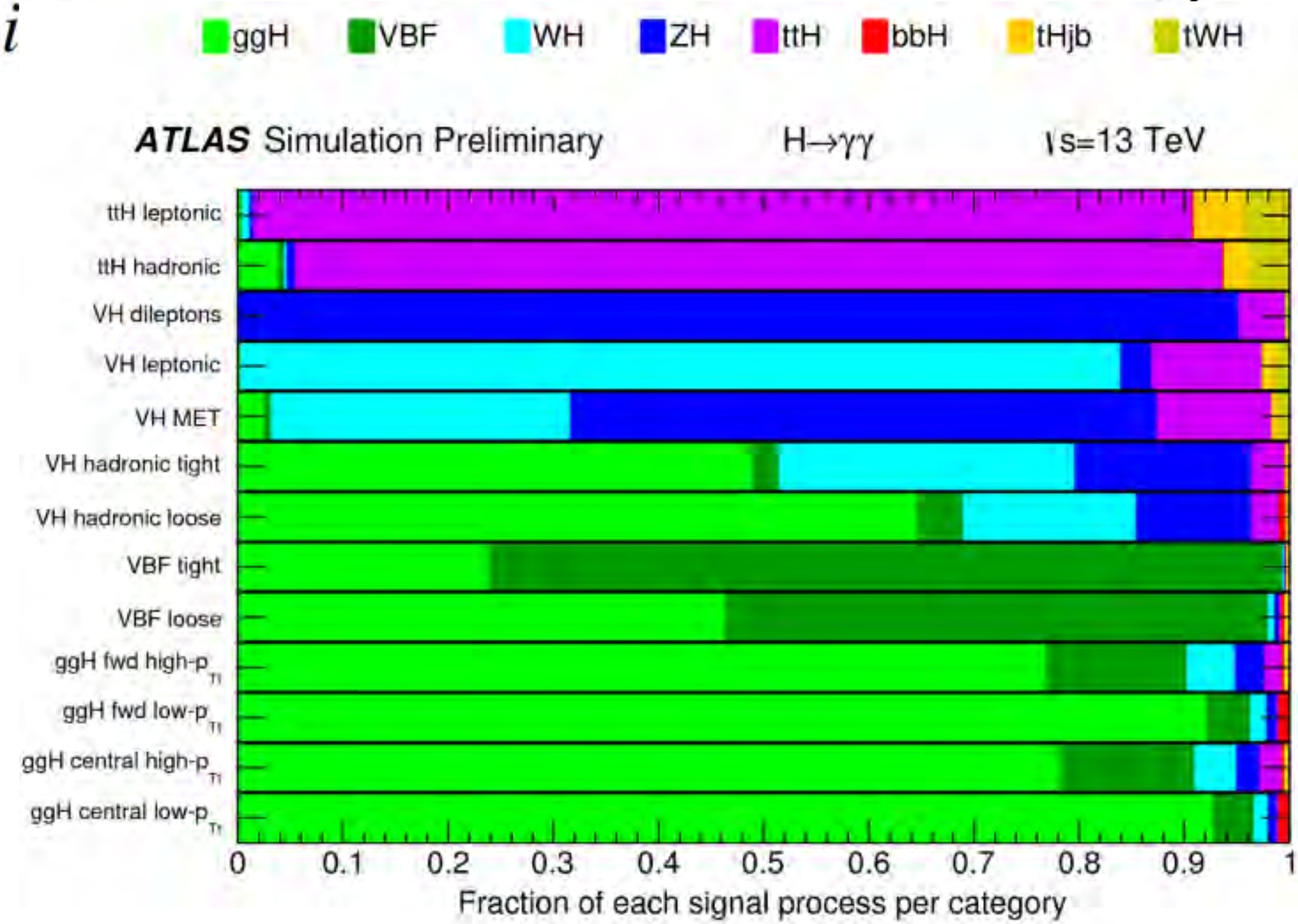


$$q\bar{q}\to VH\to q'\bar{q}'H$$

$$q\bar{q}'\to q\bar{q}'H$$

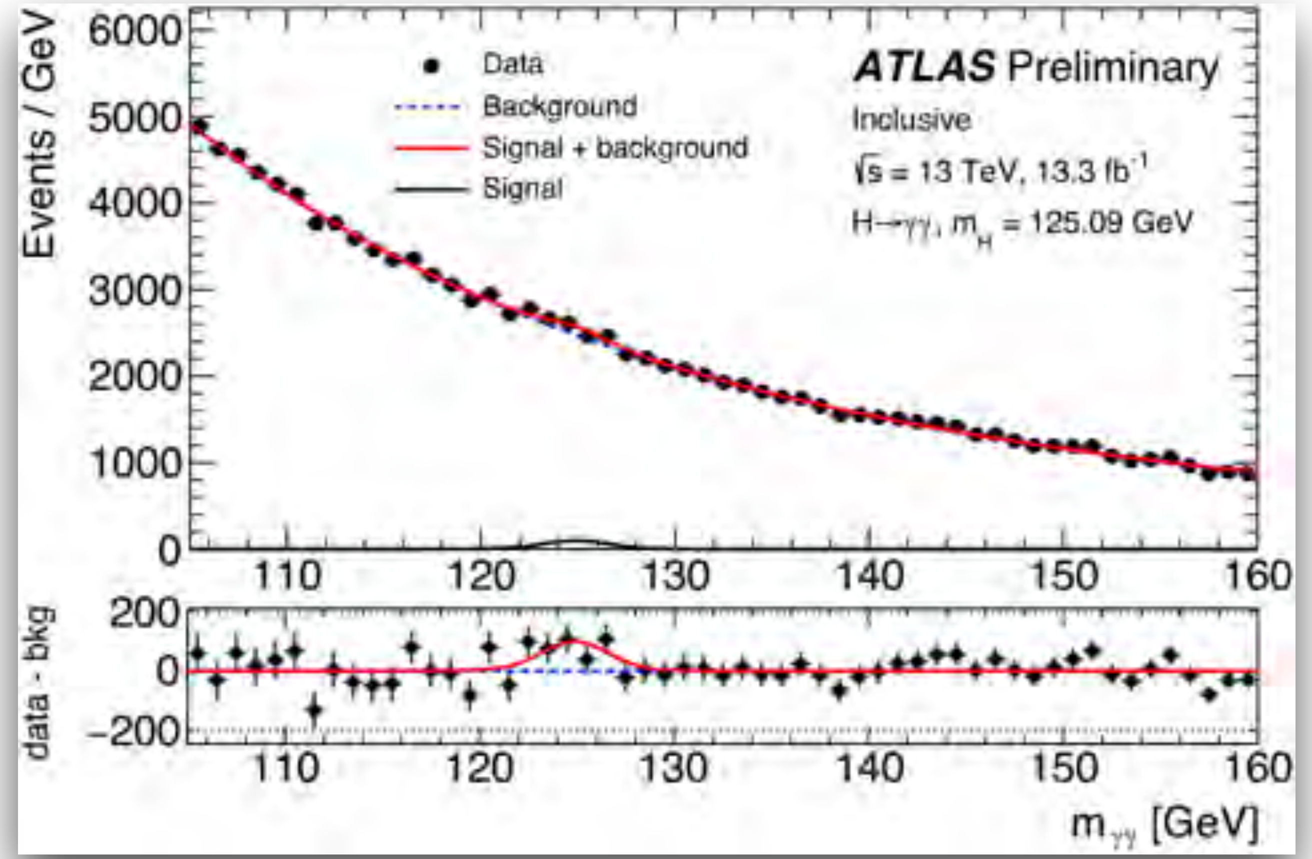
Di Photon Categorisation

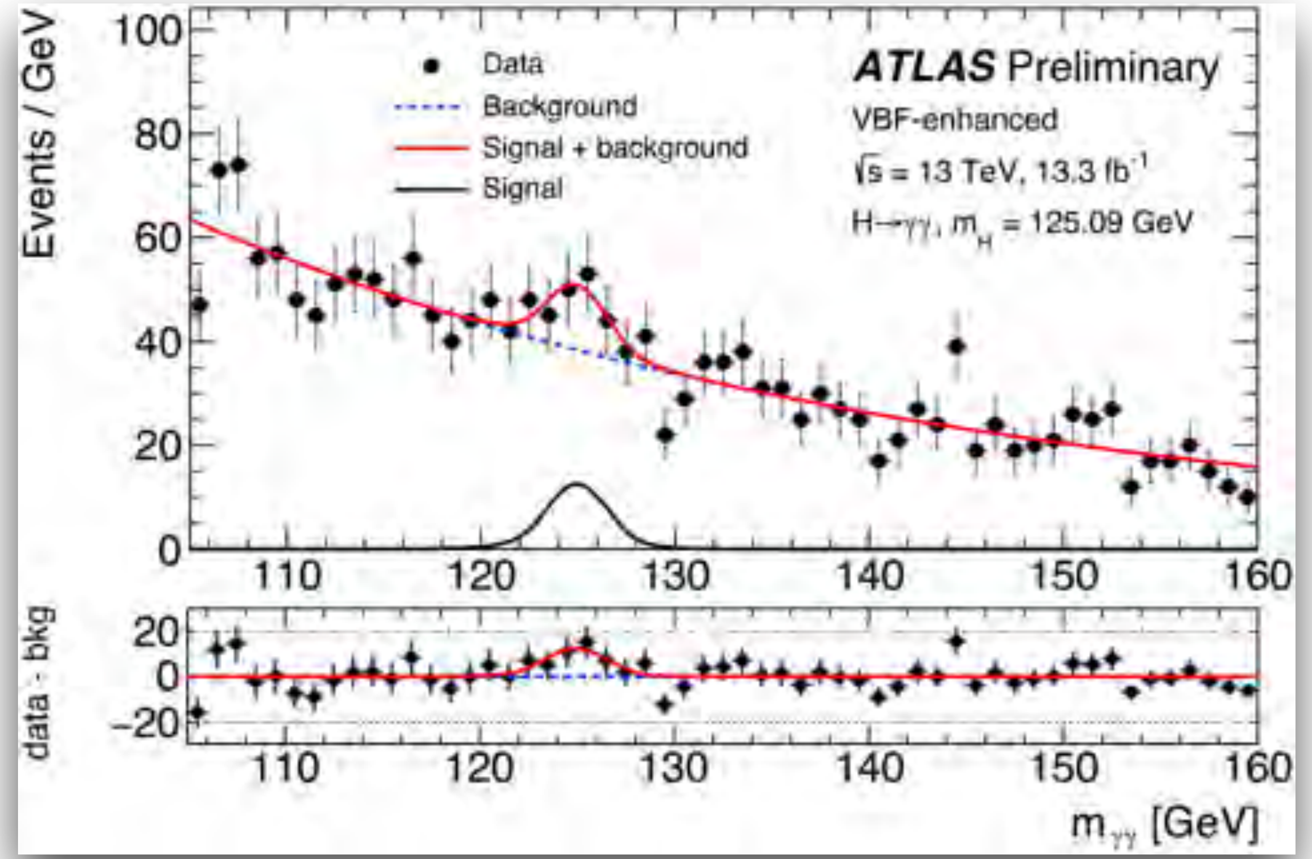
$$N_k^{\mathrm{sig}} = \sum_i \sigma_i \cdot \mathcal{B}(H \to \gamma\gamma) \cdot \epsilon_{ik} \cdot A_{ik} \cdot \int L\,\mathrm{d}t$$



Di Photon Fiducial Regions

	diphoton baseline	VBF enhanced	single lepton
Photons	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30\,\mathrm{GeV}$, $\|y\| < 4.4$ $m_{jj} > 400\,\mathrm{GeV}$, $\|\Delta y_{jj}\| > 2.8$ $\|\Delta\phi_{\gamma\gamma,jj}\| > 2.6$	- - -
Leptons	-	-	$p_T > 15\,\mathrm{GeV}$ $\|\eta\| < 2.47$





The New $s/\sqrt{b}$

We test the BG hypothesis
Null = BG
alt = Signal
Asimov = $s(m_H)+b$

The new $s/\sqrt{b}$

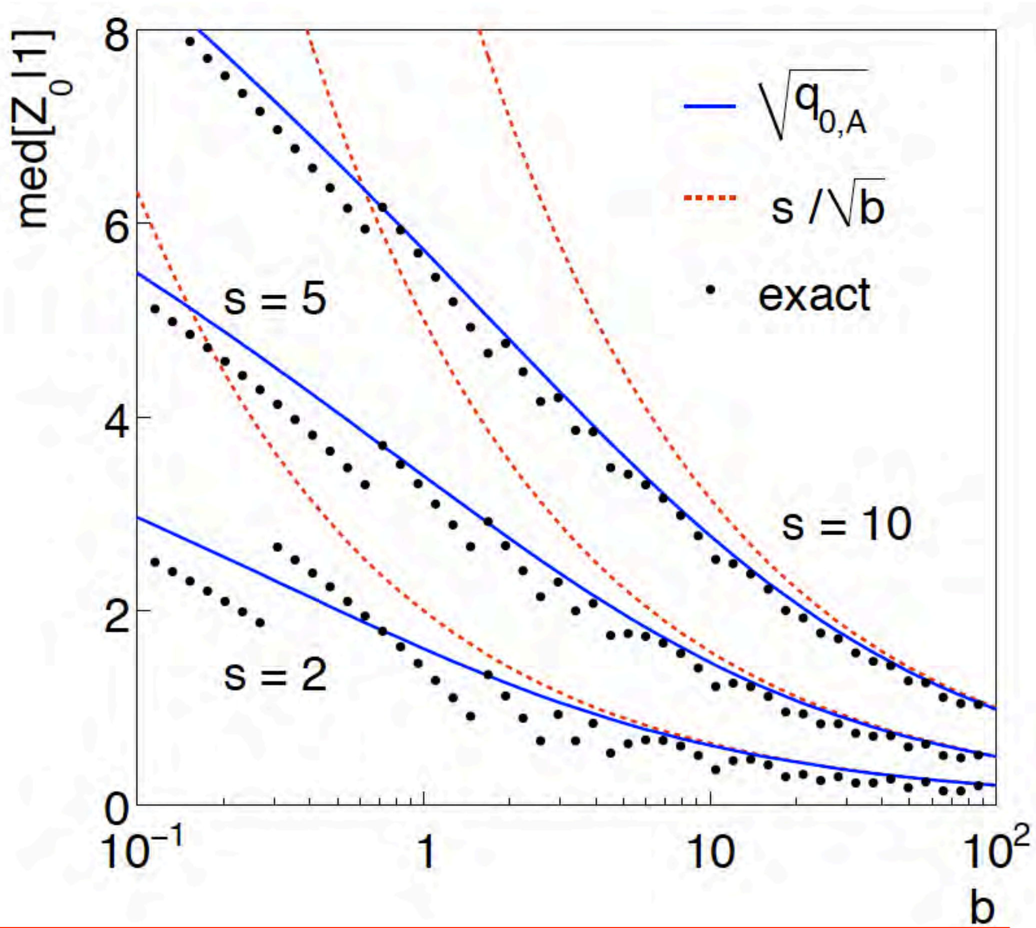
$$Z_A = \sqrt{q_{0,A}}$$

$$\mathrm{med}[Z_0|1] = \sqrt{q_{0,\mathrm{A}}} = \sqrt{2\left((s+b)\ln(1+s/b) - s\right)}$$

$$Z_A = \sqrt{q_{0,A}} \xrightarrow{s/b \ll 1} \frac{s}{\sqrt{b}} + O(s/b)$$

The New $s/\sqrt{b}$

$s/\sqrt{b}$?



The new $s/\sqrt{b}$

$$\mathrm{med}[Z_0|1] = \sqrt{q_{0,\mathrm{A}}} = \sqrt{2\left((s+b)\ln(1+s/b)-s\right)}$$

Formulae

$$N_k^{\mathrm{sig}} = \sum_i \sigma_i \cdot \mathcal{B}(H \to \gamma\gamma) \cdot \epsilon_{ik} \cdot A_{ik} \cdot \int L\,\mathrm{d}t$$

$$\mathcal{L} = \prod_k \mathcal{L}_k = \prod_k P(n_k|N_k(\theta)) \cdot \prod_{j=1}^{n_k} \mathcal{F}_k(m^j_{\gamma\gamma}, \theta) \cdot \prod_l G_l(\theta)$$

$$\mathcal{F}_k(m^j_{\gamma\gamma}) = \left[\left(\sum_i N_{ik}^{\mathrm{sig}}(\theta_{ik}^{\mathrm{yield}}, \theta_{ik}^{\mathrm{mig}}, m_H) + N_k^{\mathrm{spur}} \cdot \theta_k^{\mathrm{spur}}\right) \cdot \mathcal{F}_k^{\mathrm{sig}}(m^j_{\gamma\gamma}, \theta_k^{\mathrm{sshape}}) + N_k^{\mathrm{bkg}} \cdot \mathcal{F}_k^{\mathrm{bkg}}(m^j_{\gamma\gamma}, \theta_k^{\mathrm{bshape}})\right] / N_k$$

k= category

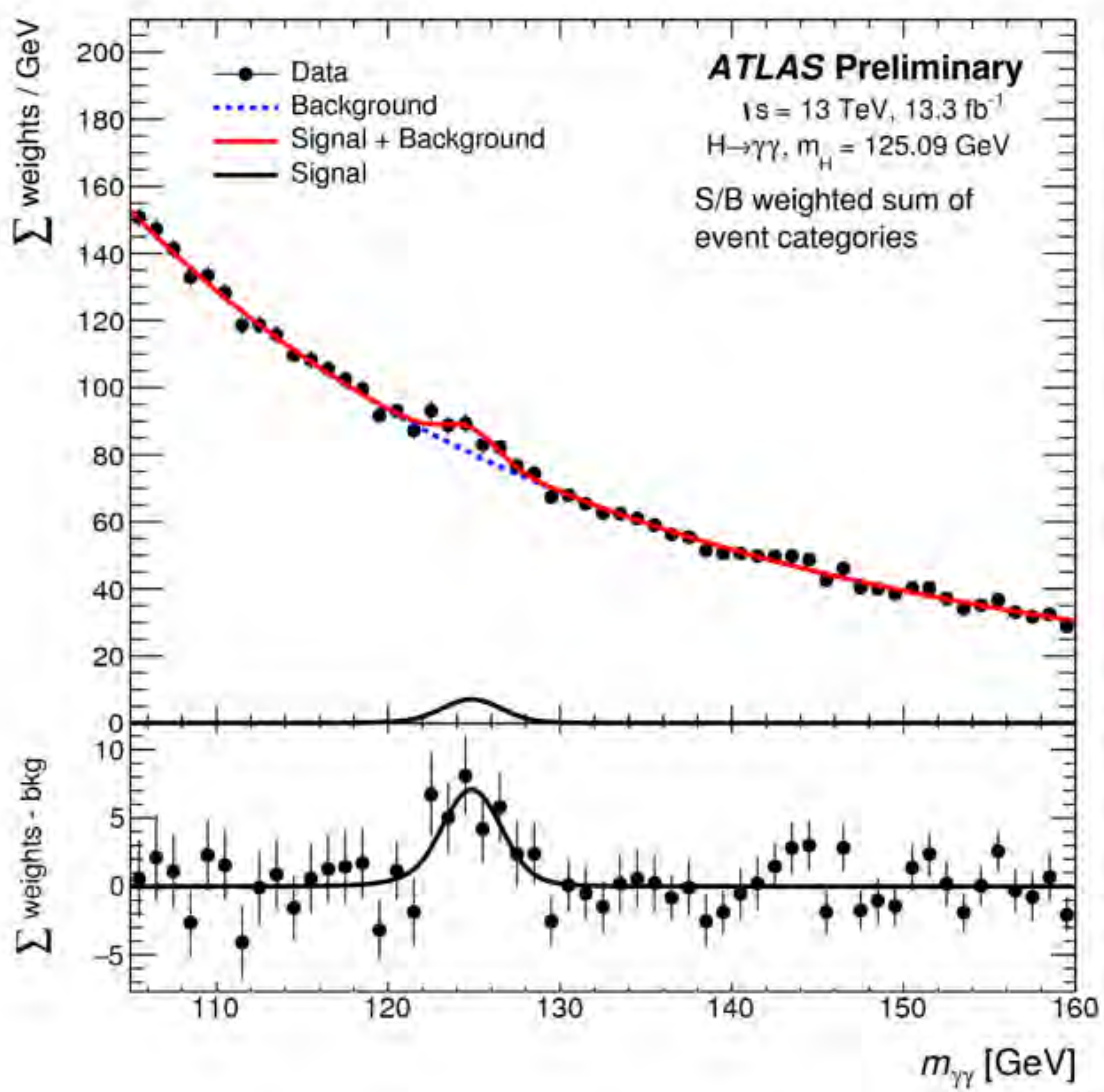
mig = migration between categories

θ are Nuisance Parameters

$$Z_{90} \equiv \sqrt{2((S_{90} + B_{90})ln(1 + S_{90}/B_{90}) - S_{90})}$$

Fit Result

$$w = \ln\left(1+\frac{s}{b}\right)$$



Nuisance Parameters

$$q_\mu = -2ln\frac{L(\mu,\hat{\hat{\theta}}_\mu)}{L(\hat{\mu},\hat{\theta})}$$

The pull of θ_i is given by $\dfrac{\hat{\theta}_i - \theta_{0,i}}{\sigma_0}$

without constraint $\sigma\left(\dfrac{\hat{\theta}_i - \theta_{0,i}}{\sigma_0}\right) = 1 \quad \left\langle \dfrac{\hat{\theta}_i - \theta_{0,i}}{\sigma_0} \right\rangle = 0$

It's a good habit to look at the pulls of the NPs and make sure that
Nothing irregular is seen

In particular one would like to guarantee that the fits do not over constrain
A NP in a non sensible way

- Let $$L = L(\mu, \epsilon, \theta)$$

- To get the impact of a NP (on order to rank them by their importance)

Say we want the impact of ϵ

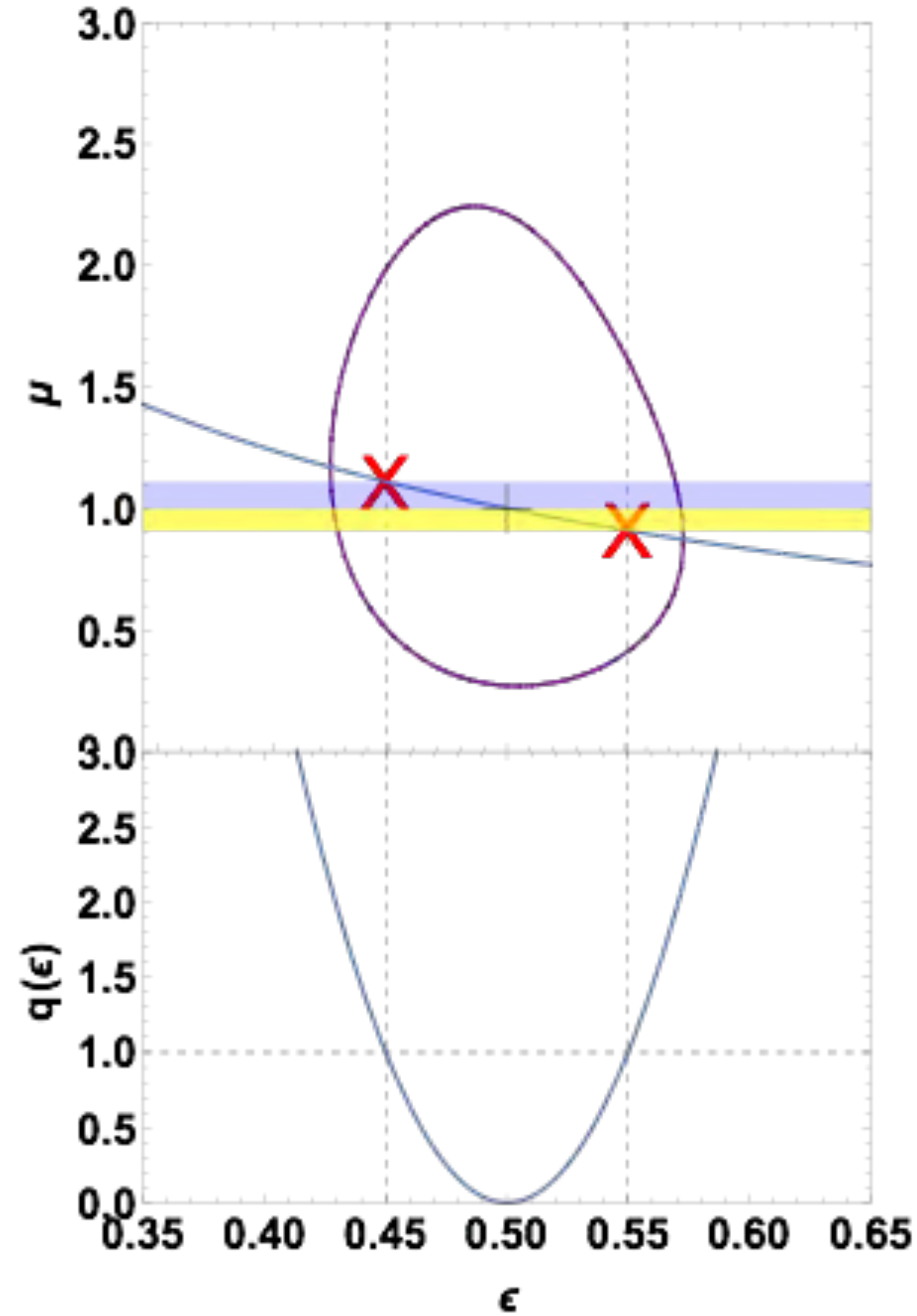
–Scan q(ϵ), profiling all other NPs

–Find $\hat{\epsilon}$

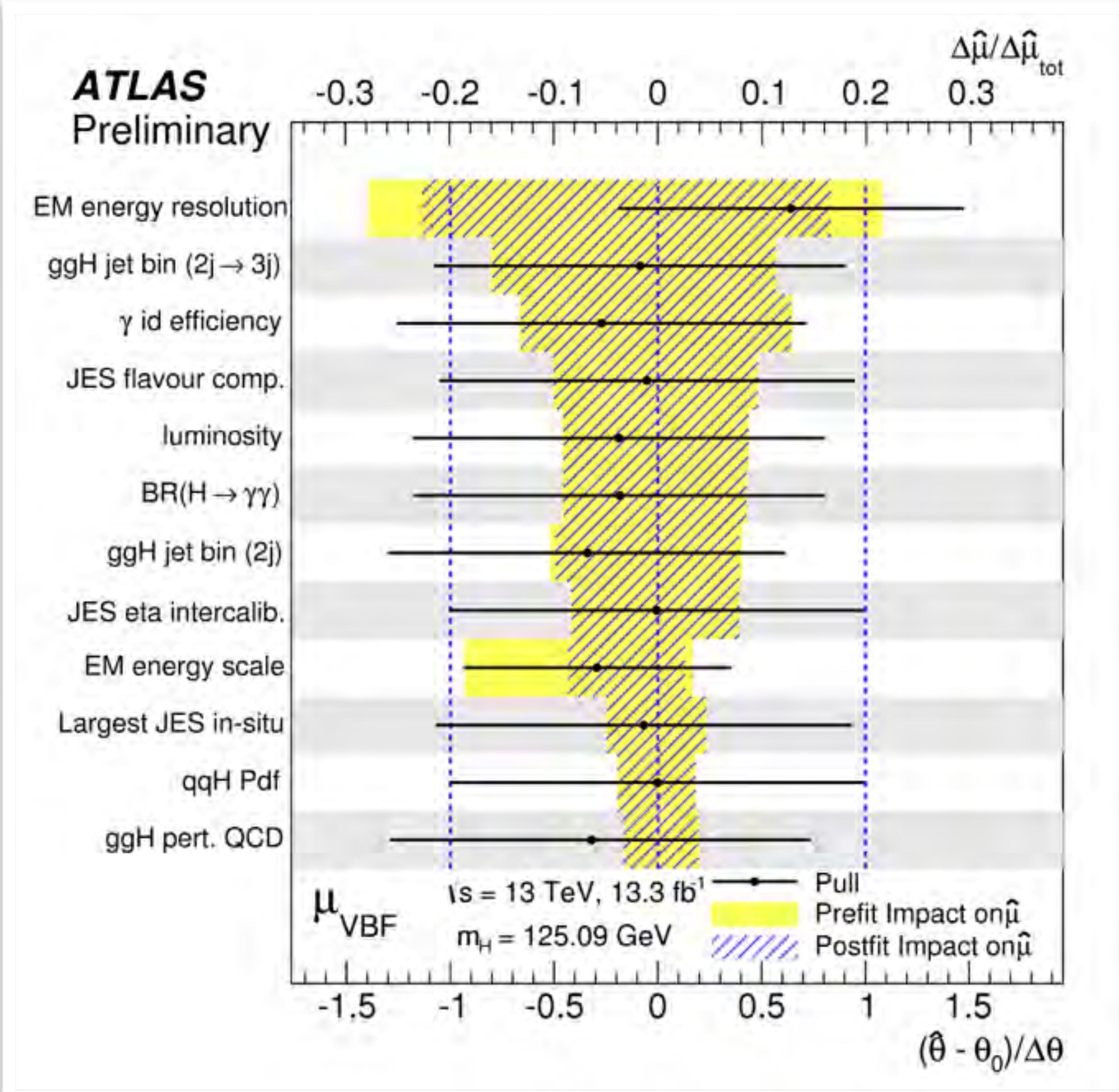
–(note that $\hat{\mu}_{\hat{\epsilon}} = \hat{\mu}$)

–Find $\hat{\mu}_{\hat{\epsilon}\pm\sigma_{\epsilon}^{\pm}} = \hat{\hat{\mu}}_{\hat{\epsilon}\pm\sigma_{\epsilon}^{\pm}}$

–The impact is given by $\Delta\mu^{\pm} = \hat{\hat{\mu}}_{\hat{\epsilon}\pm\sigma_{\epsilon}^{\pm}} - \hat{\mu}$

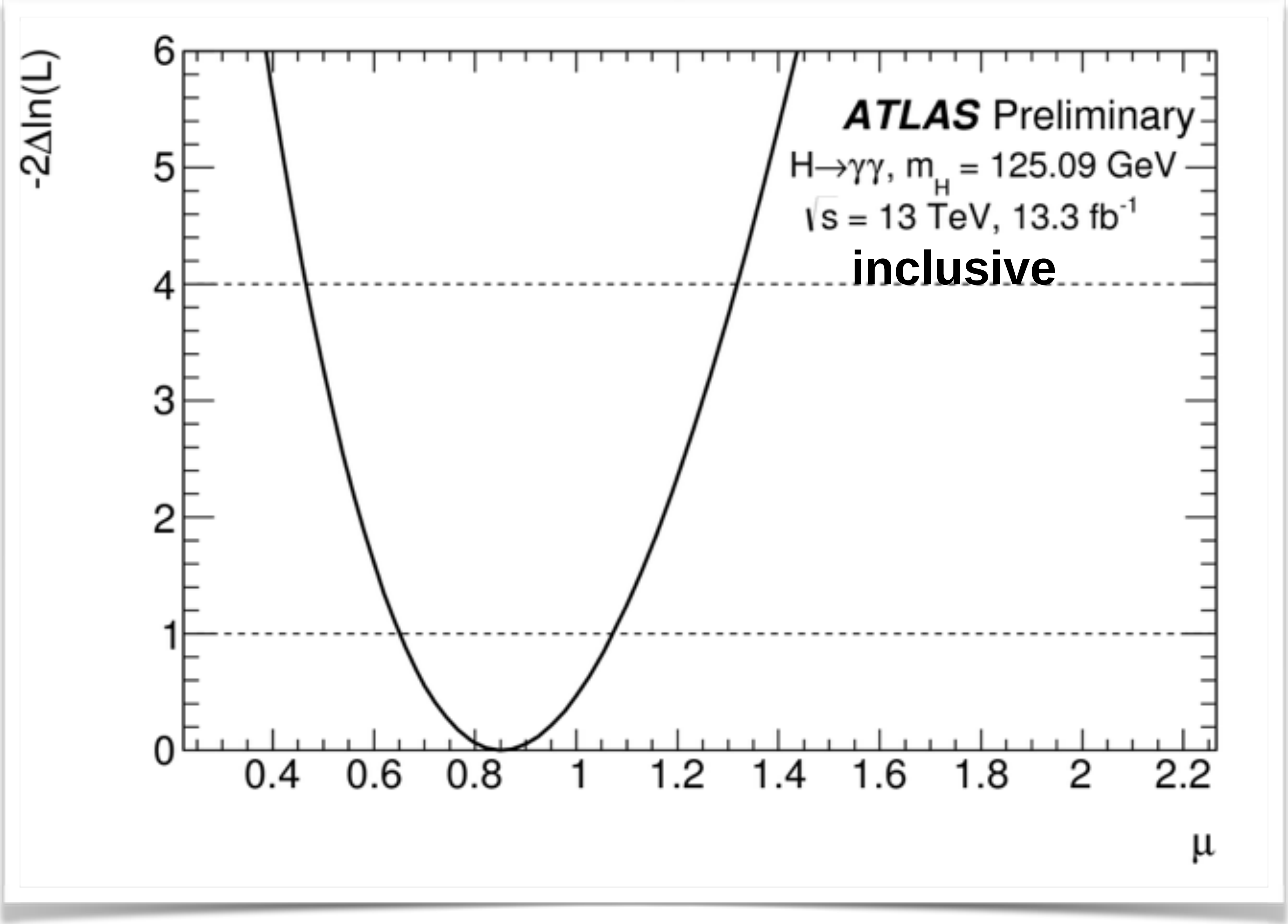


Impact of NPs in DiPhoton analysis

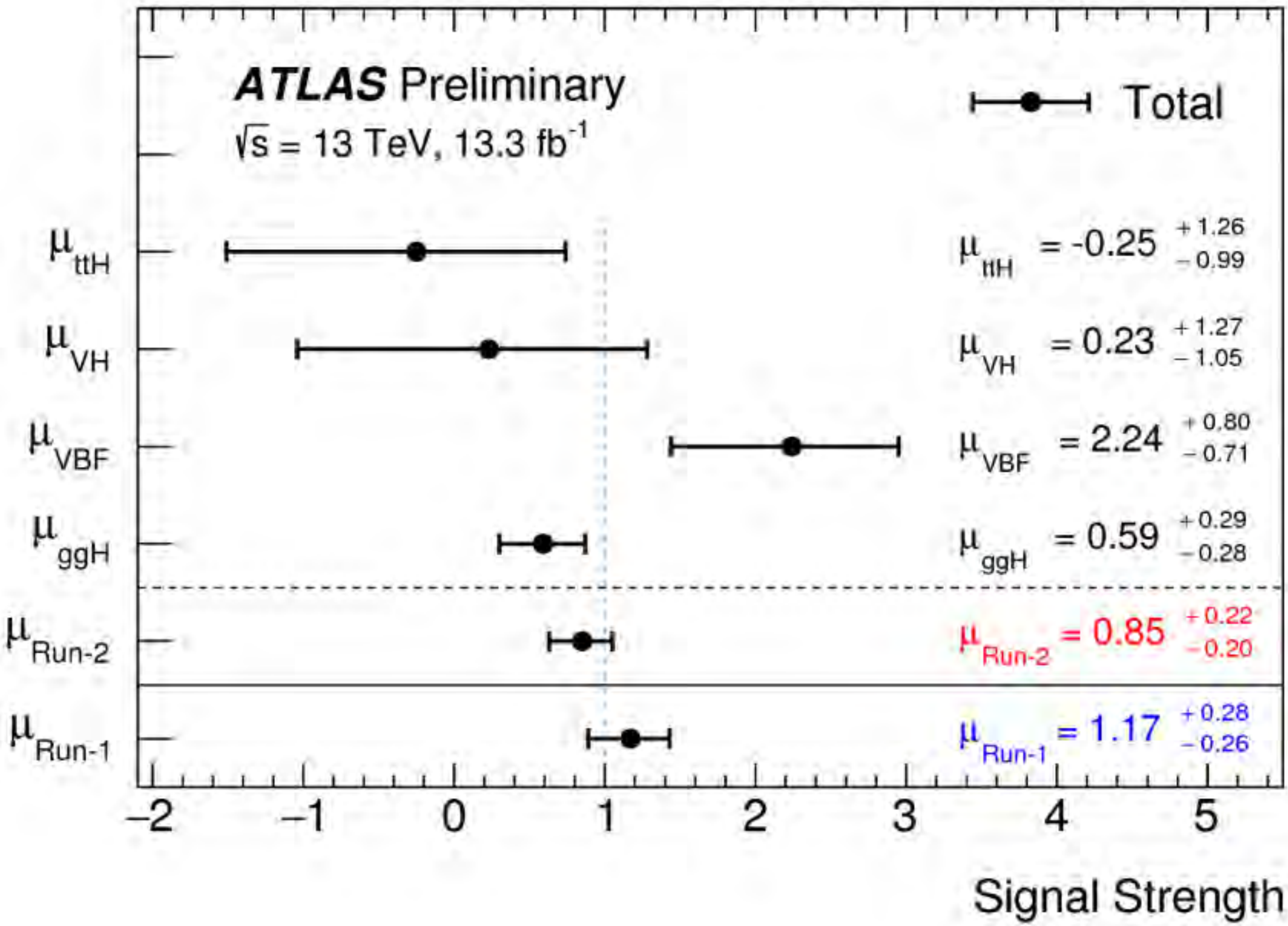


Results

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8\,^{+3.4}_{-4.4}$	$[\text{N}^3\text{LO} + \text{XH}]$
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	$[\text{NNLOPS} + \text{XH}]$
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	$[\text{NNLOPS} + \text{XH}]$



Higgs DiPHoton Results



4l+$\gamma\gamma$
2016

ATLAS NOTE

ATLAS-CONF-2016-081

8th August 2016

Combined measurements of the Higgs boson production and decay rates in $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ final states using pp collision data at $\sqrt{s} = 13$ TeV in the ATLAS experiment

Categories

$H \to ZZ^* \to 4\ell$		$H \to \gamma\gamma$	
Category	Target	Category	Target
VH-leptonic	VHlep	$t\bar{t}H$ leptonic	top
0-jet	ggF	$t\bar{t}H$ hadronic	top
1-jet	ggF	VH dilepton	VHlep
2-jet VBF-like	VBF	VH one-lepton	VHlep
2-jet VH-like	VHhad	VH Emiss	VHlep
		VH hadronic loose	VHhad
		VH hadronic tight	VHhad
		VBF loose	VBF
		VBF tight	VBF
		ggH central low-$p_{\mathrm{T}t}$	ggF
		ggH central high-$p_{\mathrm{T}t}$	ggF
		ggH fwd low-$p_{\mathrm{T}t}$	ggF
		ggH fwd high-$p_{\mathrm{T}t}$	ggF

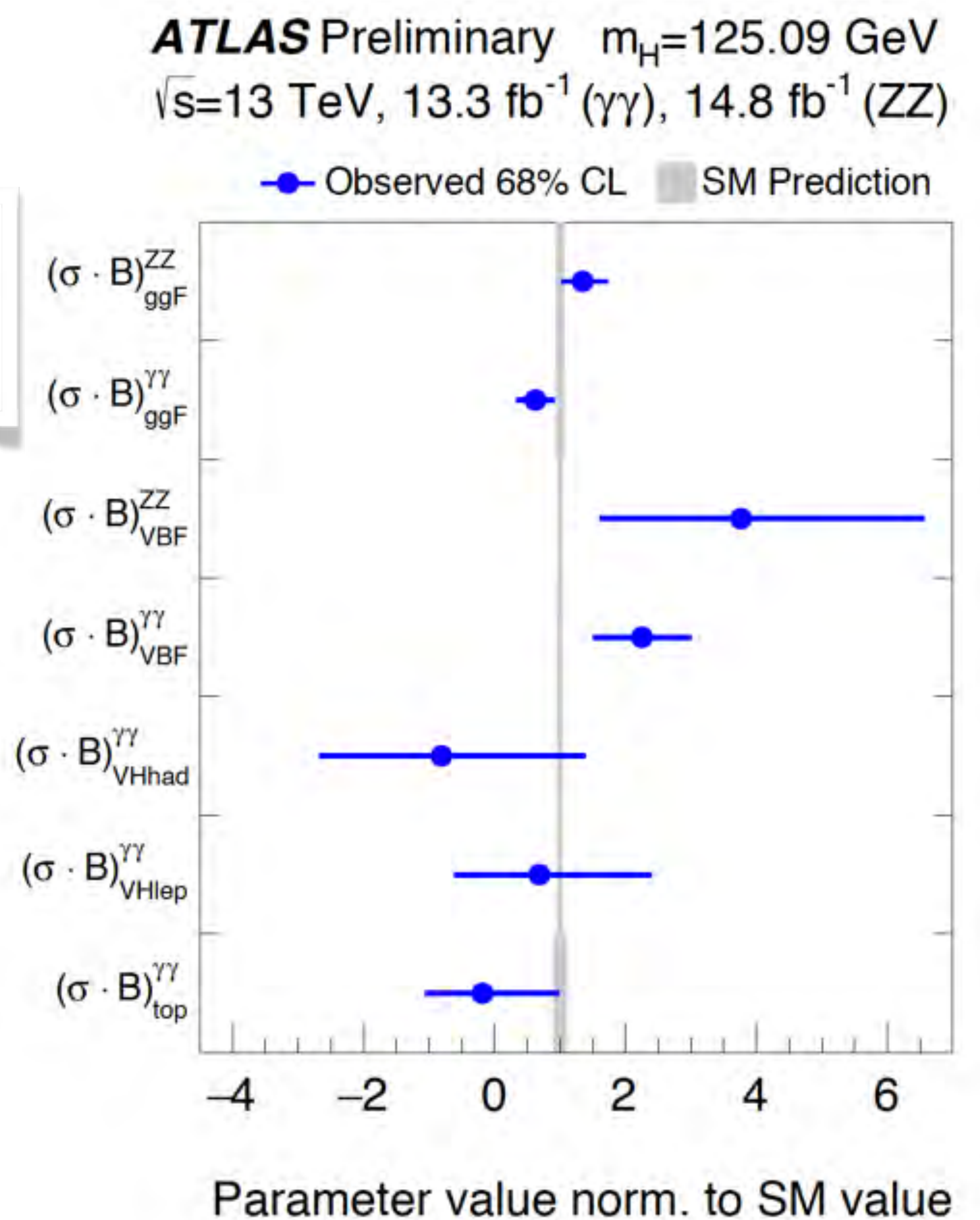
Process	Contributing to	$\sigma_i(\lvert y_H\rvert < 2.5)/\sigma_i$
$gg \to H$	ggF	0.907
$qq' \to qq'H$	VBF	0.932
$q\bar{q}' \to WH(W \to \text{had.})$	VHhad	0.870
$q\bar{q}/gg \to ZH(Z \to \text{had.})$	VHhad	0.900
$q\bar{q}' \to WH(W \to \text{lep.})$	VHlep	0.869
$q\bar{q} \to ZH(Z \to \text{lep.})$	VHlep	0.900
$gg \to ZH(Z \to \text{lep.})$	VHlep	0.965
$q\bar{q}/gg \to t\bar{t}H$	top	0.985

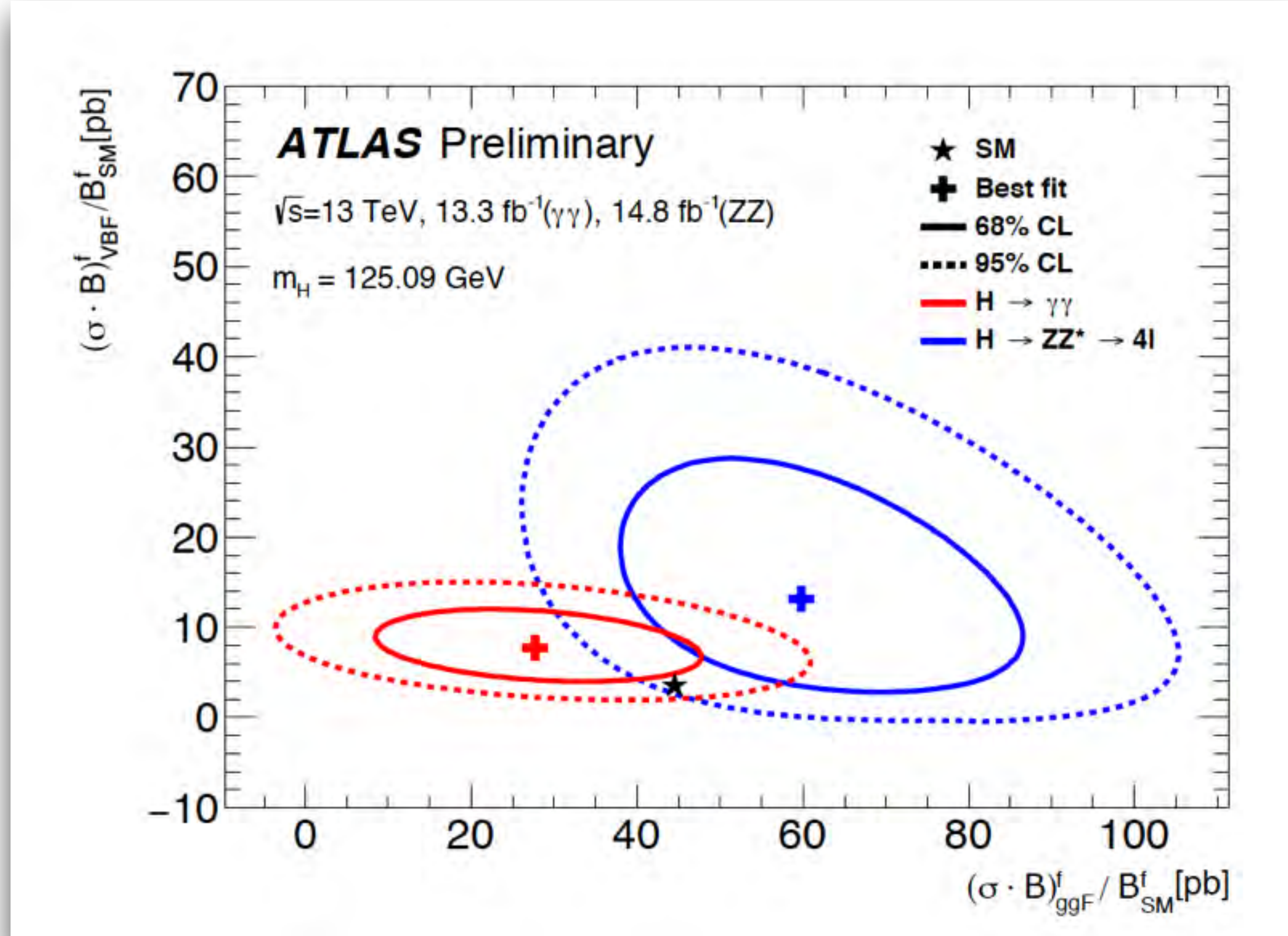
7 dof Fit

ggF coupled bbH

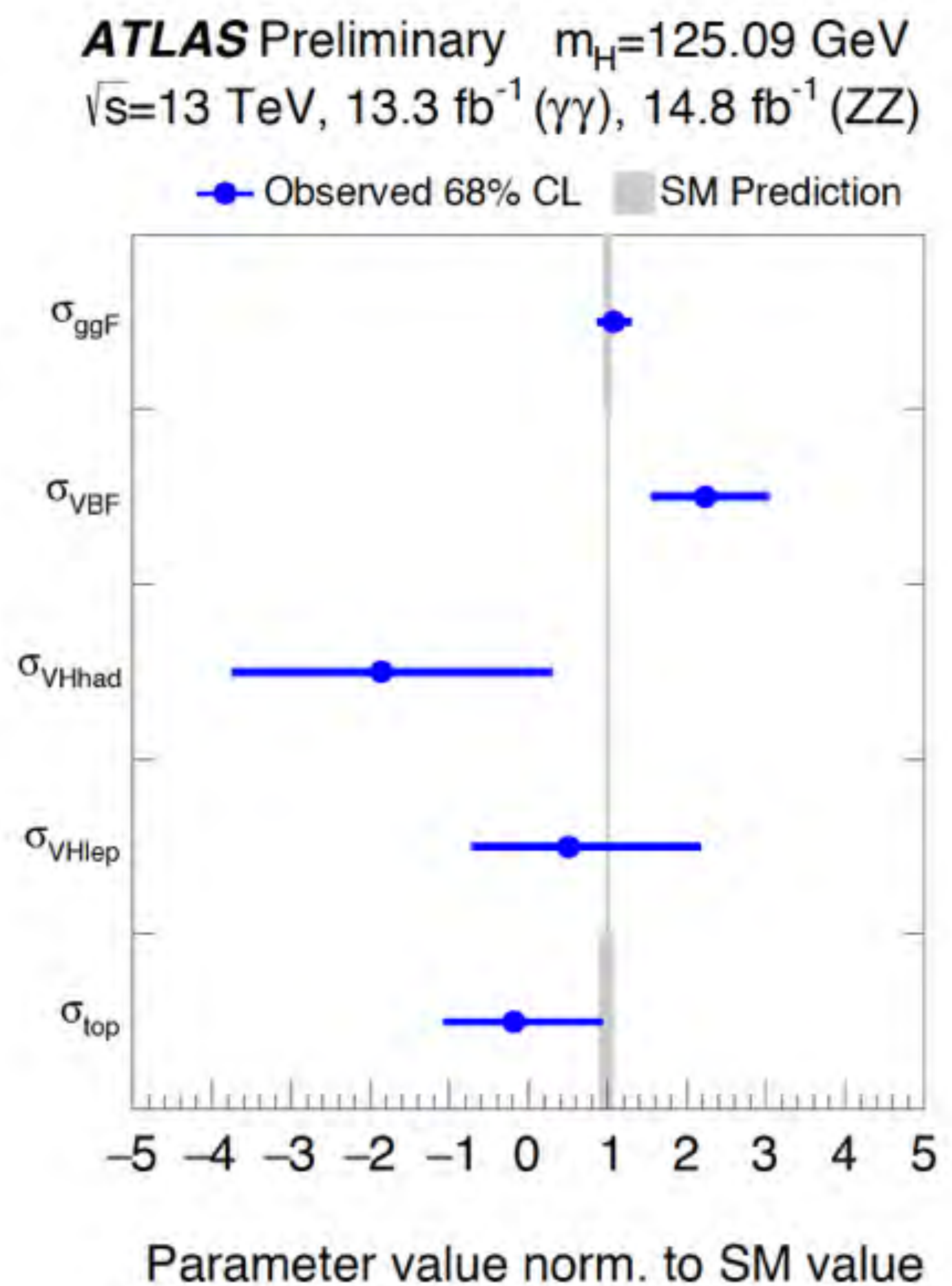
tH coupled ttH

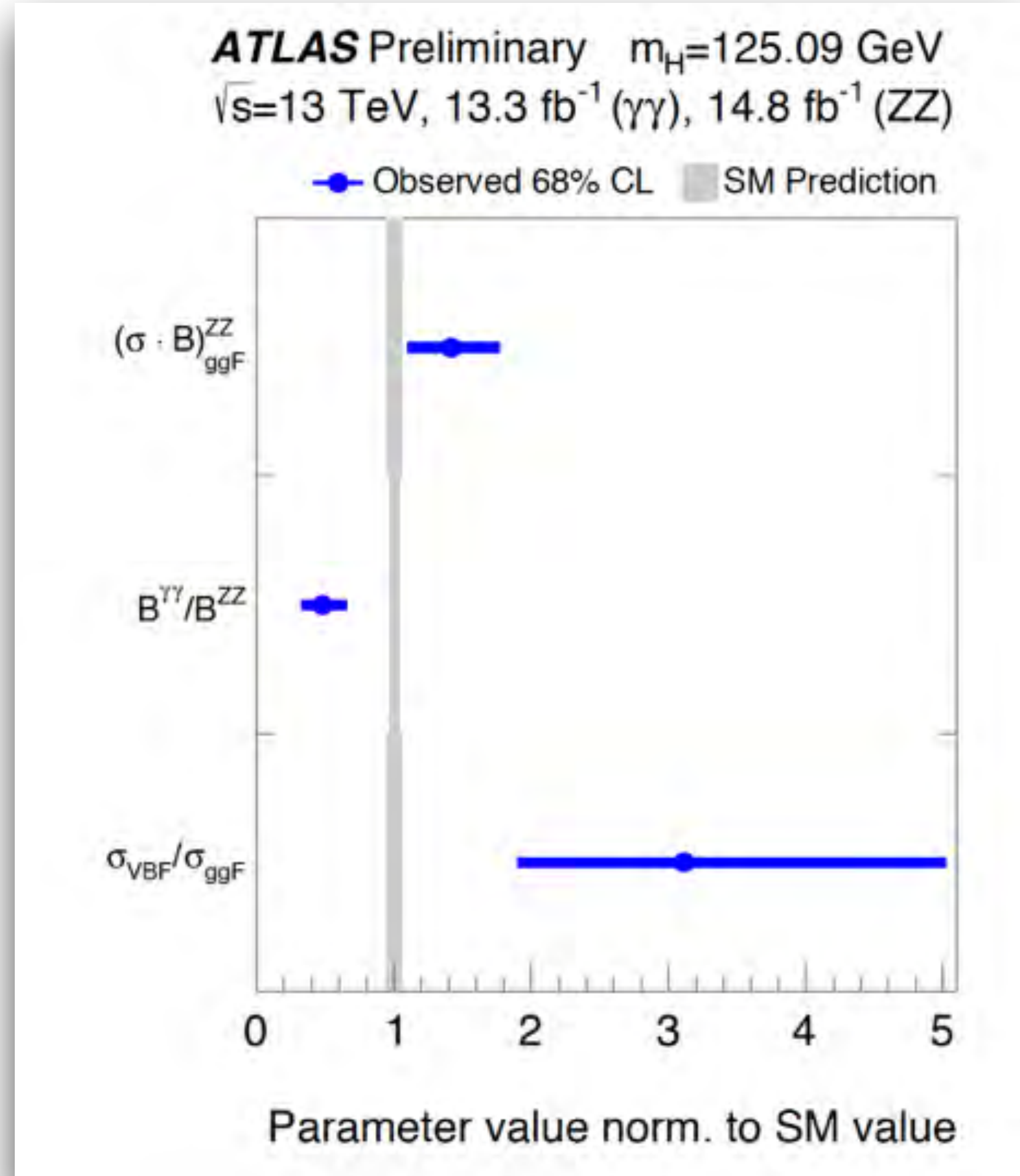
WH merged with ZH



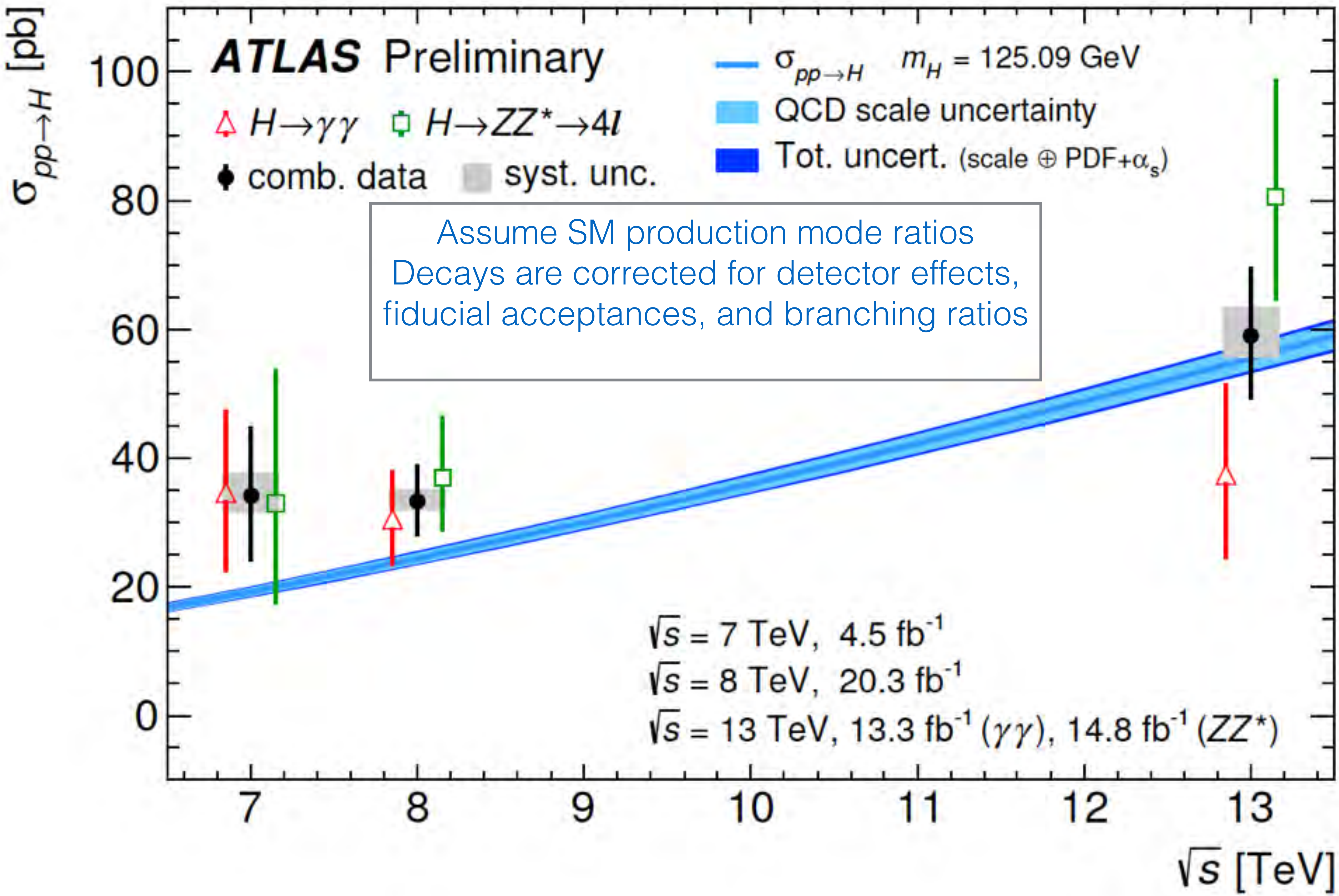

ATLAS Preliminary
√s=13 TeV, 13.3 fb⁻¹(γγ), 14.8 fb⁻¹(ZZ)
m_H = 125.09 GeV
SM
Best fit
68% CL
95% CL
H → γγ
H → ZZ* → 4l
(σ · B)^f_VBF / B^f_SM [pb]
(σ · B)^f_ggF / B^f_SM [pb]
70
60
50
40
30
20
10
0
−10
0
20
40
60
80
100

Assume SM BRs

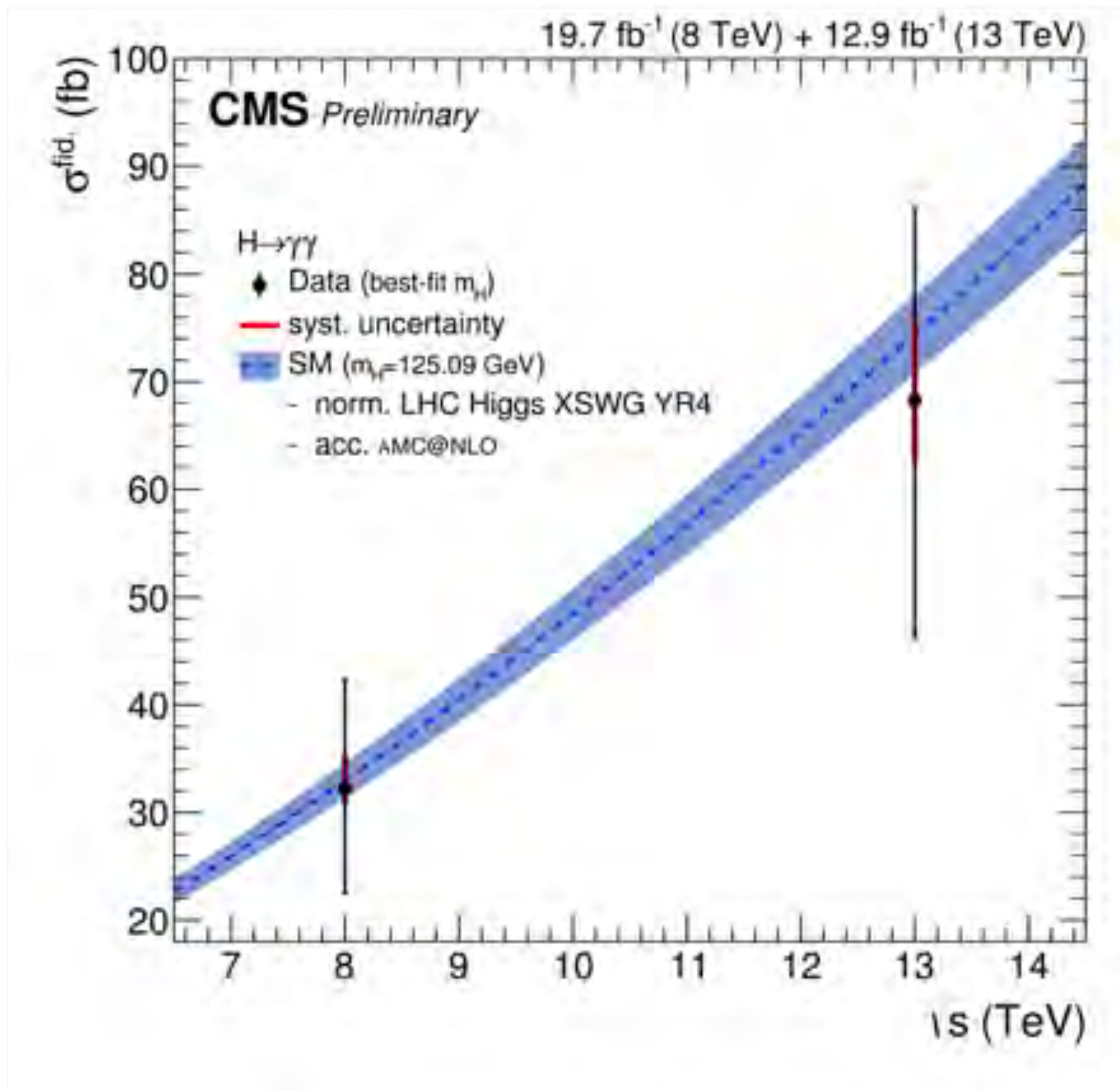


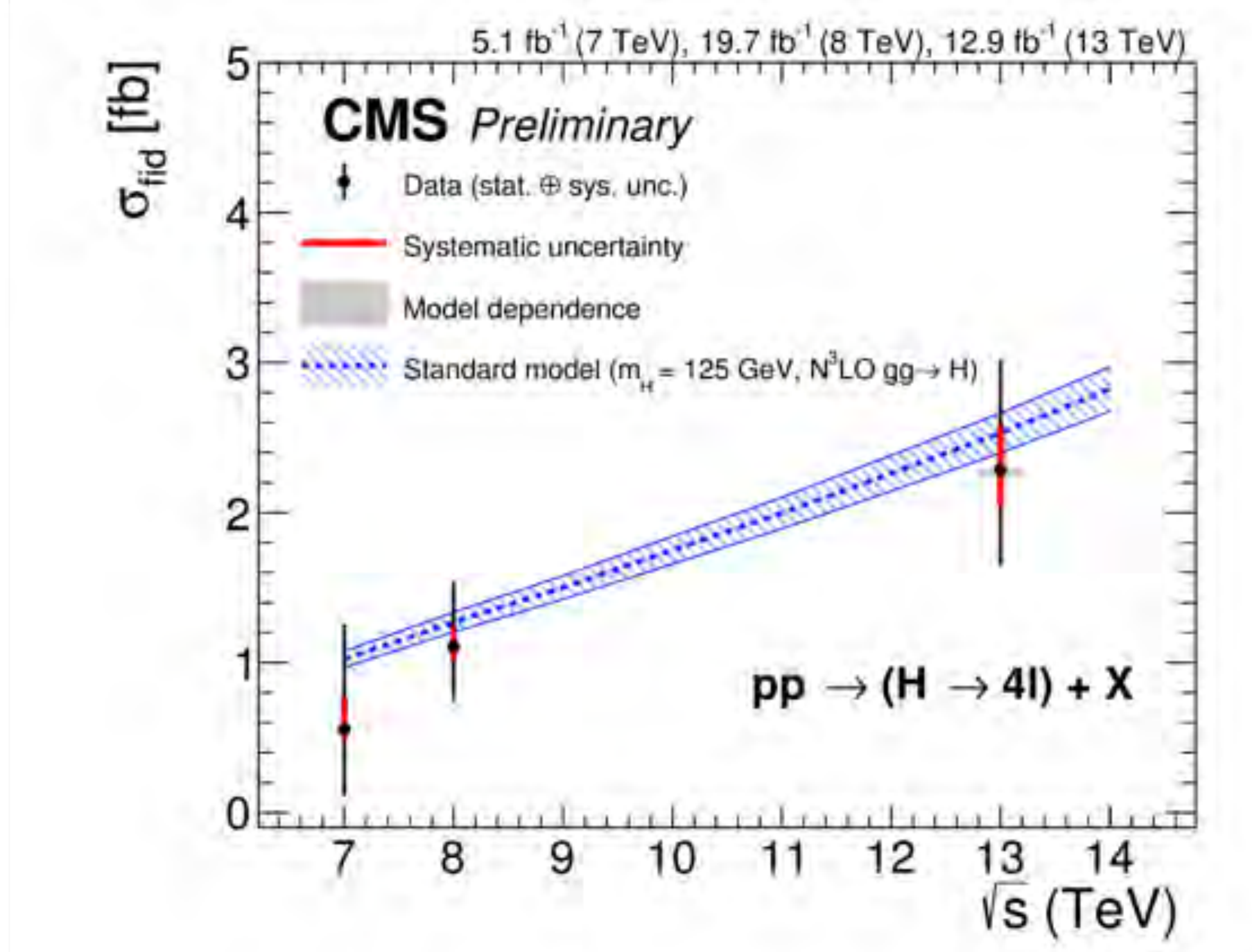


p-value with SM is 5%



ATLAS Preliminary
$H\rightarrow\gamma\gamma$
$H\rightarrow ZZ^*\rightarrow 4l$
comb. data
syst. unc.
$\sigma_{pp\rightarrow H}$ m_H = 125.09 GeV
QCD scale uncertainty
Tot. uncert. (scale ⊕ PDF+α_s)
Assume SM production mode ratios
Decays are corrected for detector effects,
fiducial acceptances, and branching ratios
$\sqrt{s}$ = 7 TeV, 4.5 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$\sqrt{s}$ = 13 TeV, 13.3 fb^{-1} ($\gamma\gamma$), 14.8 fb^{-1} (ZZ^*)
$\sigma_{pp\rightarrow H}$ [pb]
$\sqrt{s}$ [TeV]
0
20
40
60
80
100
7
8
9
10
11
12
13


19.7 fb⁻¹ (8 TeV) + 12.9 fb⁻¹ (13 TeV)
CMS Preliminary
σ^fid. (fb)
H→γγ
Data (best-fit m_H)
syst. uncertainty
SM (m_H=125.09 GeV)
- norm. LHC Higgs XSWG YR4
- acc. AMC@NLO
√s (TeV)


5.1 fb⁻¹ (7 TeV), 19.7 fb⁻¹ (8 TeV), 12.9 fb⁻¹ (13 TeV)
CMS Preliminary
σ_fid [fb]
Data (stat. ⊕ sys. unc.)
Systematic uncertainty
Model dependence
Standard model (m_H = 125 GeV, N³LO gg→ H)
pp → (H → 4l) + X
√s (TeV)

fiducial volume definition 4l CMS

Table 6: Summary of requirements and selections used in the definition of the fiducial phase space for the $H \rightarrow 4\ell$ cross section measurements.

Requirements for the $H \rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\text{GeV} < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12\,\text{GeV} < m_{Z_2} < 120\,\text{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 140\,\text{GeV}$

Combined ATLAS CMS

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})$$

Combined ATLAS only

$$\mu = 1.13^{+0.18}_{-0.17}$$

We are not yet beating the combination of ATLAS and CMS, but soon will…..


End of Lectures
Thank You
Lyceum Alpinum Zuoz