Anomalies in the Higgs boson data at the LHC and the potential for a new scalar with a mass around 300 GeV

B. Mellado for the HEP group

University of the Witwatersrand

With N. Chakrabarty

T.Mandal and B. Mukhopadhyaya

Wits HEP Seminar, Johannesburg 26/05/15

People from Wits who are or will be directly involved in the project

Stefan von Buddenbrock, Alan Cornell, Shell-May Liao, Deepak Kar, Mukesh Kumar, Oscar Kureba, Luis March, Mthokozisi Masuku, Tshidiso Molupe, Chuene Mosomane, Chad Pelwan, Xifeng Ruan, Robert Reed, Kehinde Tomiwa

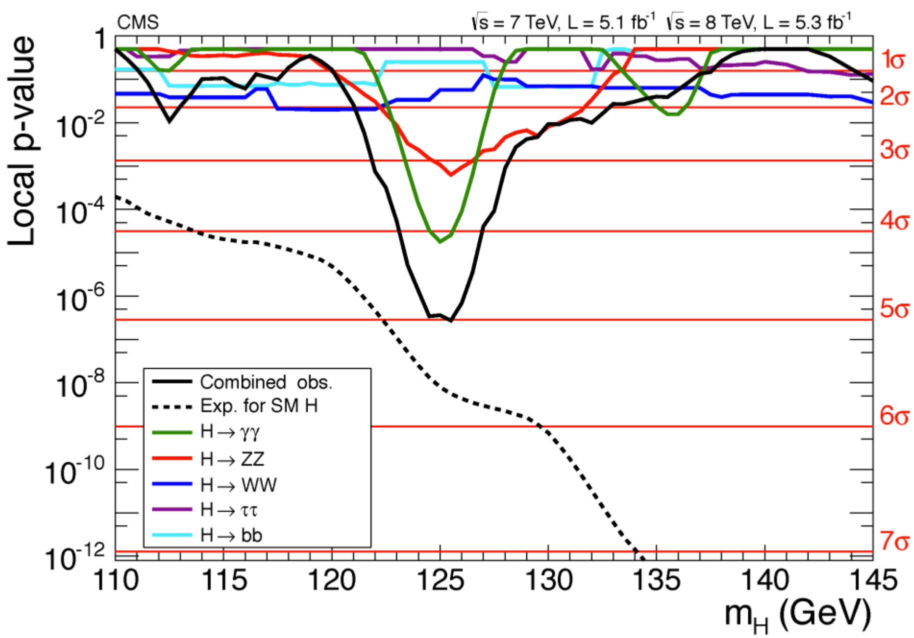
Very important to commend the group members that are devoted to instrumentation and the MAC project, without whom this effort would not be possible

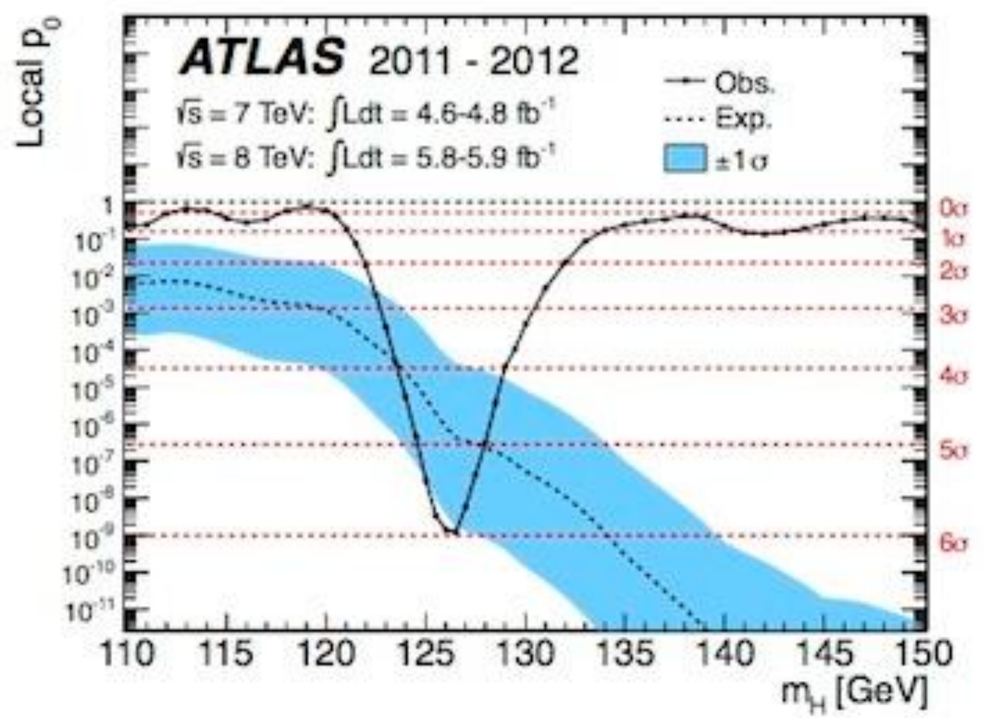
Outline

- **Habemus Novum Boson**
  - **The Discovery**
  - **Global consistency with the SM**
    - **0^+ hypothesis**
    - **Evidence for VBF production**
    - **Global fits**
- **The Anomalies**
  - **Higgs transverse momentum**
  - **Excesses around 300 GeV**
- **The theory framework**
  - **Finding consistency in the anomalies**
- **Prospects with Run II**

Habemus novum Boson

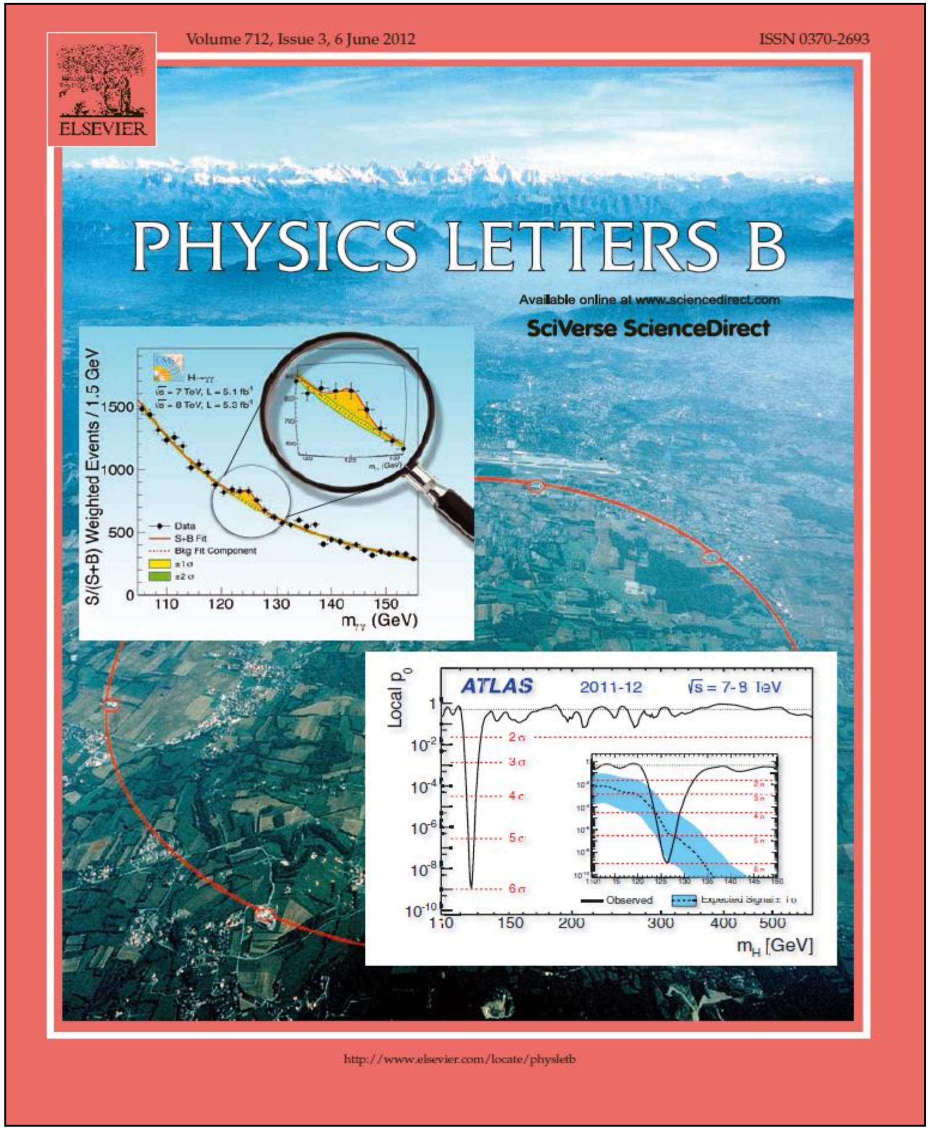
An amazing discovery indeed on its own.
It is also the beginning of a new era for HEP





We need to understand to the best of the capabilities of the LHC what boson it is we discovered and whether we see more than one

Habemus novum Boson



Pick a language

Wits play key role in historic find

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

4 July 2012

A Wits team, who plays a visible and strong role in the search for the Higgs boson at the ATLAS detector, is part of a team of researchers at the European Organization of Nuclear Research (CERN) who today announced that they have observed a particle consistent with the Higgs boson.

The announcement that started at 09:00 South African time in Geneva, Switzerland, this morning, is hailed as the birth of a new era in the field of fundamental physics.

According to the Wits team, tantalizing hints of a new particle with a mass around 126 GeV were reported in December 2011. The ATLAS experiment has confirmed this excess with data taken in 2012. This is consistent with reports from the CMS experiment. The observed excess is consistent with the existence of a Higgs-like particle.

The statistical significance of the measurement is 5 sigma. The size of the statistical significance makes it unlikely that the excess observed is due to a statistical fluctuation (by less than a one in a million chance).

MEDIA COVERAGE:

Online coverage

Print: (pdf)

City Press, 8 July 2012

Beeld, 5 July 2012

Mail & Guardian, 6 July 2012

Citizen, 5 July 2012

The Times, 5 July 2012

The Witness, 5 July 2012

Broadcast: (mp3)

Radio Today, 5 July 2012

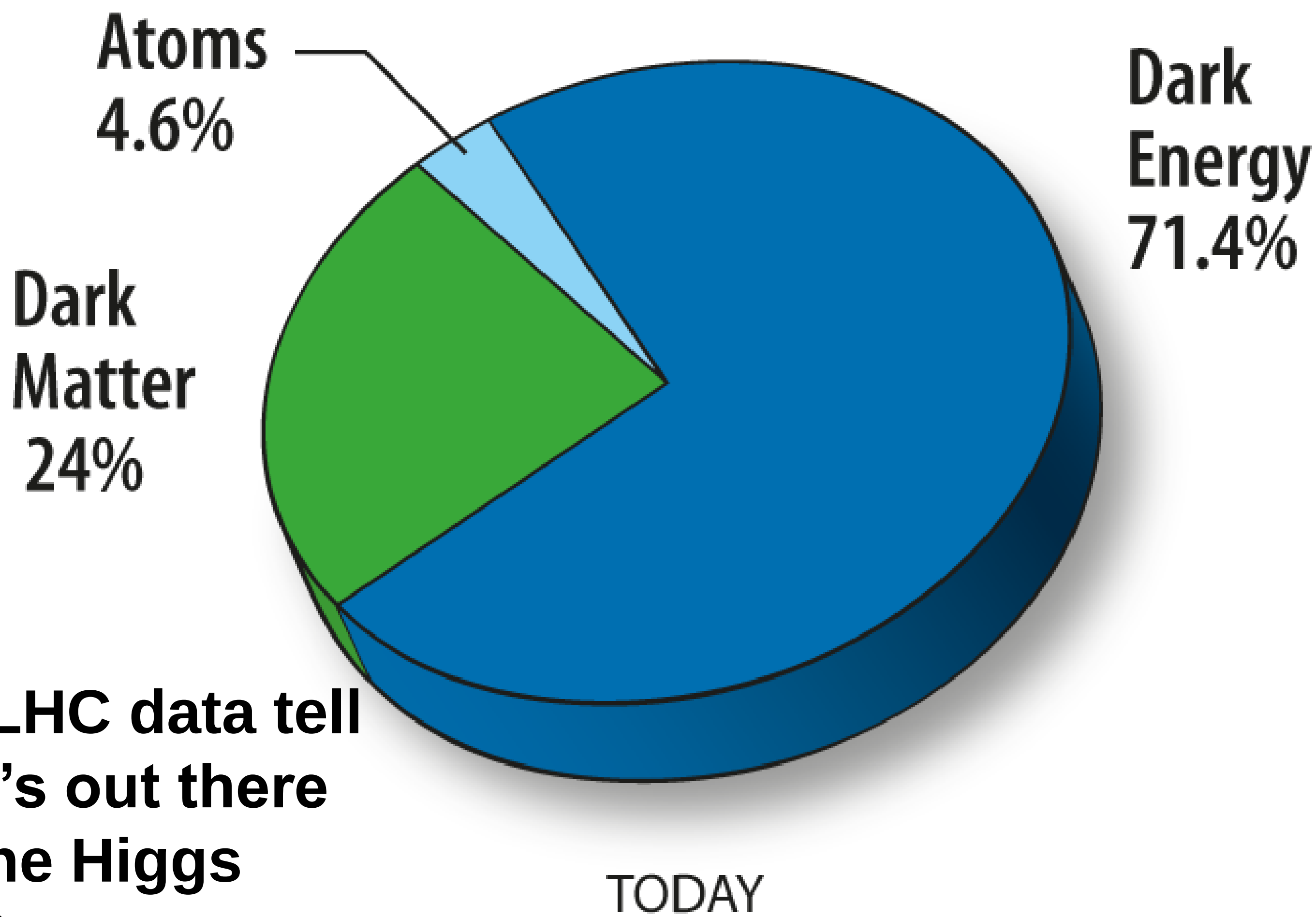
http://www.wits.ac.za/newsroom/newsitems/201207/16724/news_item_16724.html

Statement from the DST on July 4th 2012

"The Department of Science and Technology selected CERN as one of its global large-scale infrastructure projects; it supports scientists in the South Africa-CERN consortium to participate in experiments to investigate the existence of the Higgs boson particle and other expected discoveries. The Department is proud of these scientists who are part of this major scientific breakthrough and celebrates this achievement with the rest of the world."

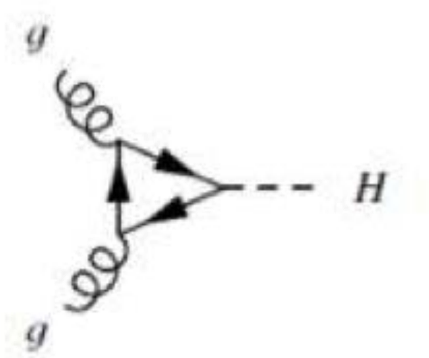
A strong boost of the SA-CERN program followed in 2013

Do we live in the P.H.D (Post Higgs Depression) or are we ready to start digging further into fundamental questions of nature?

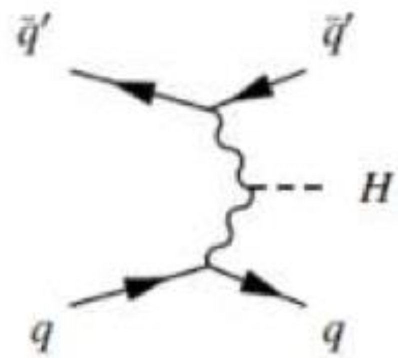


What can the LHC data tell us about what's out there by means of the Higgs boson sector?

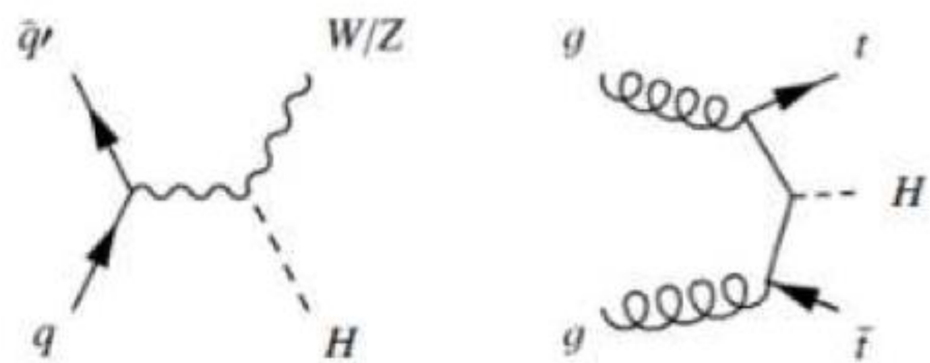
Higgs production at Hadron Colliders and decays



Gluon-gluon fusion

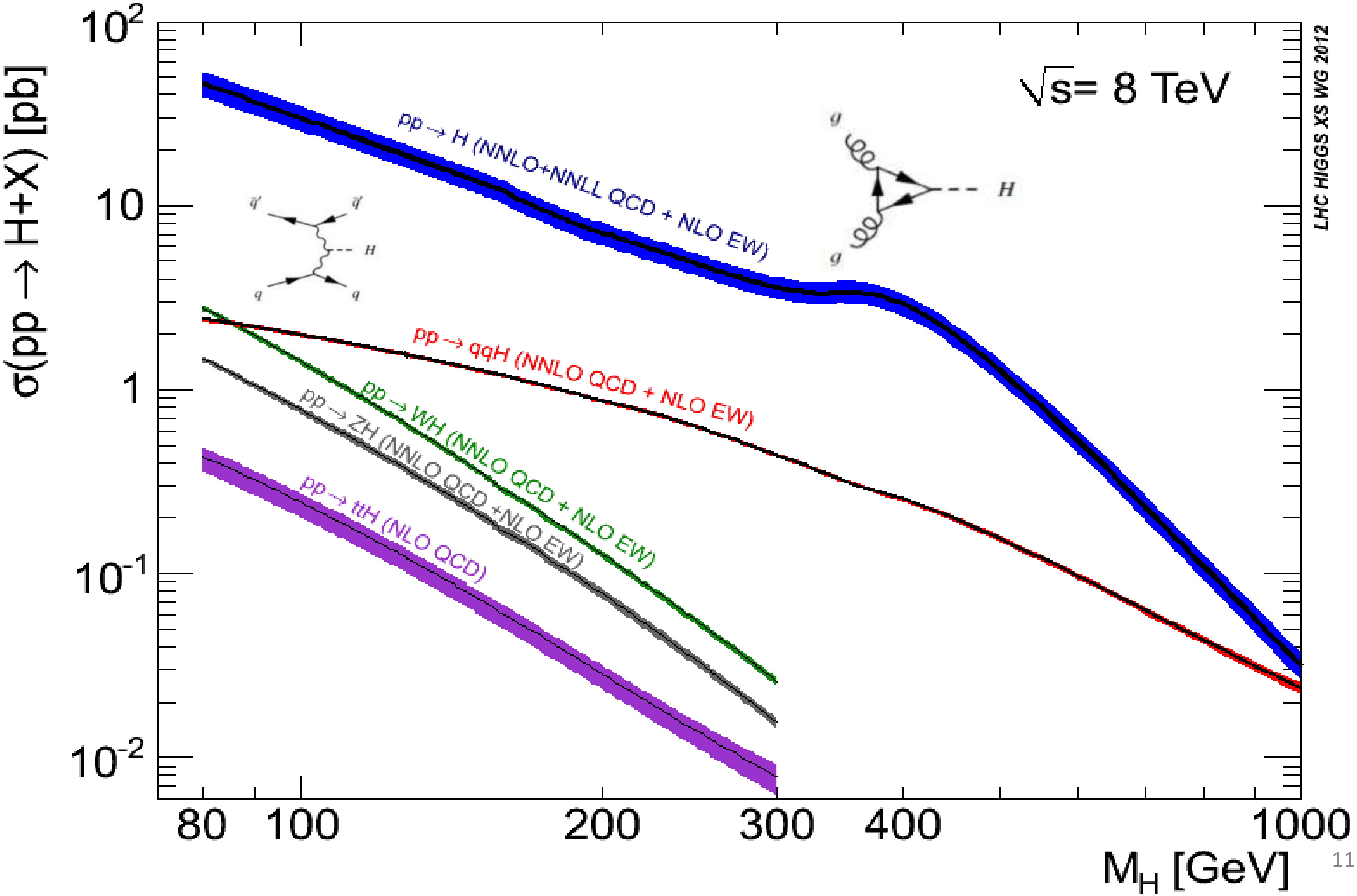


Vector Boson Fusion

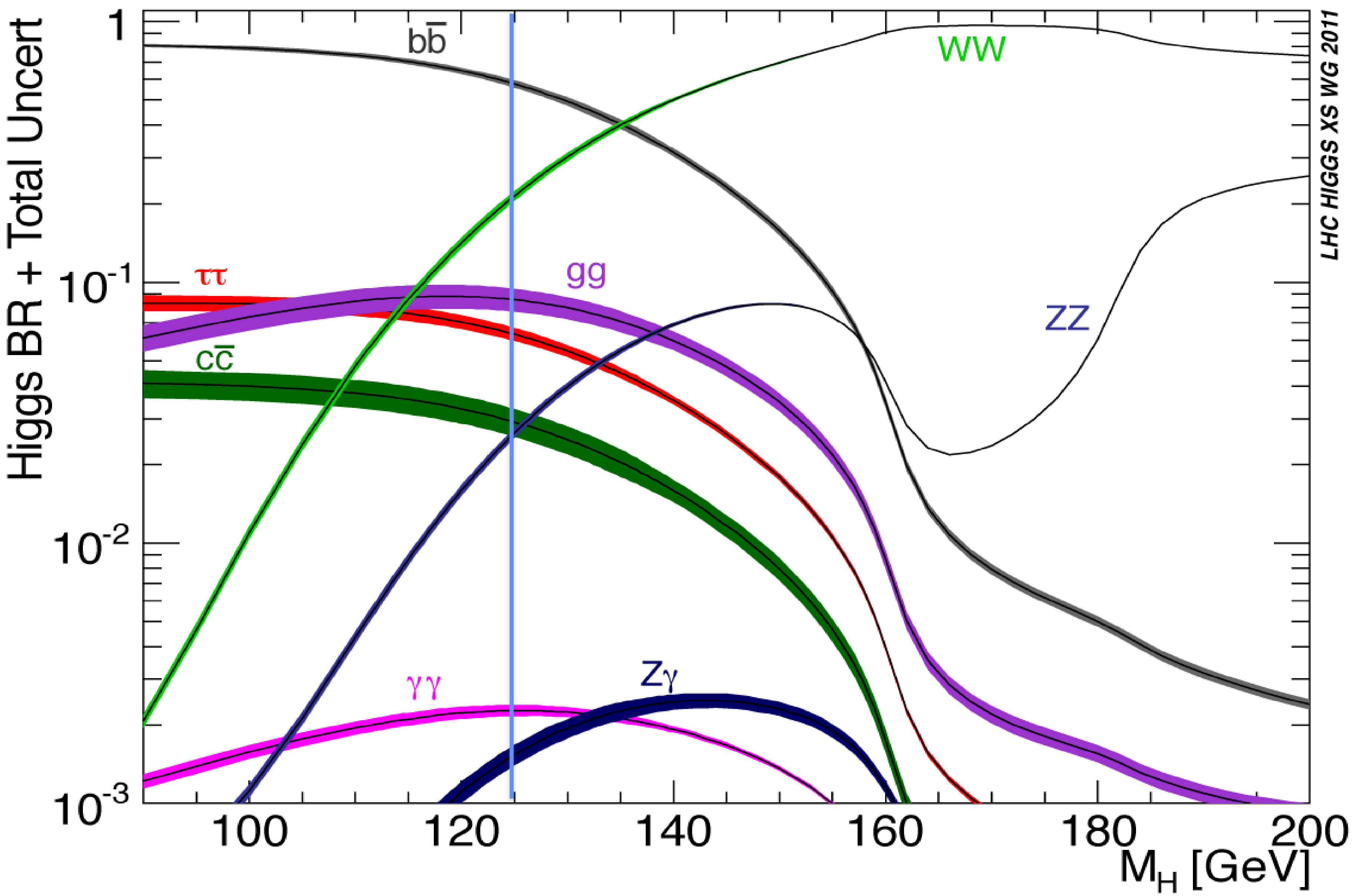


Associated Production

Higgs Cross-Sections at LHC



Main Decay Modes

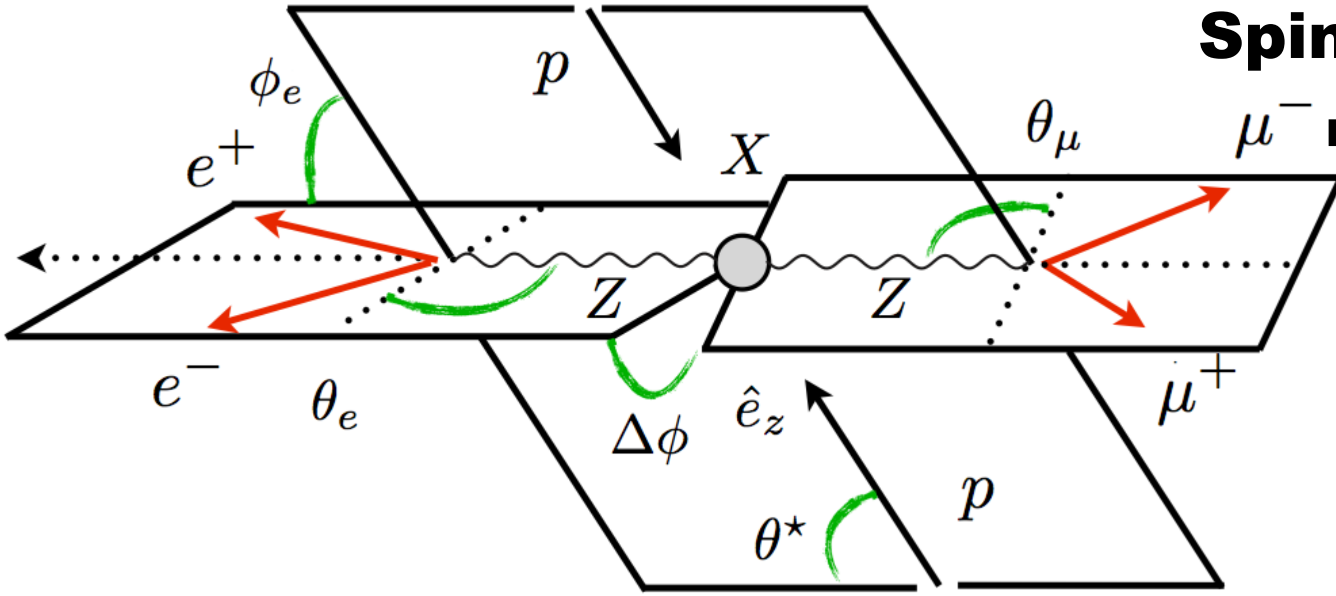


Consistency with SM 0^+ hypothesis

The SM predicts that the Higgs boson have the quantum number $J^{CP} = 0^+$

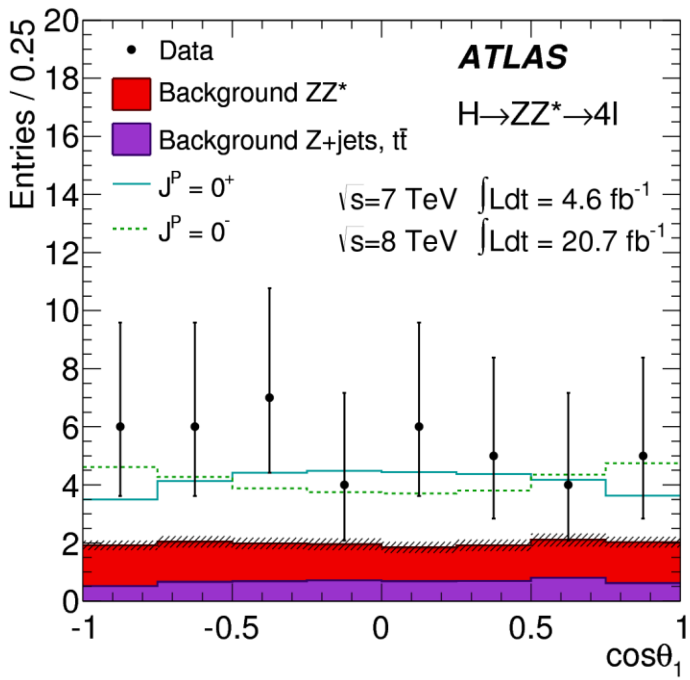
Spin/CP in H->ZZ->4l

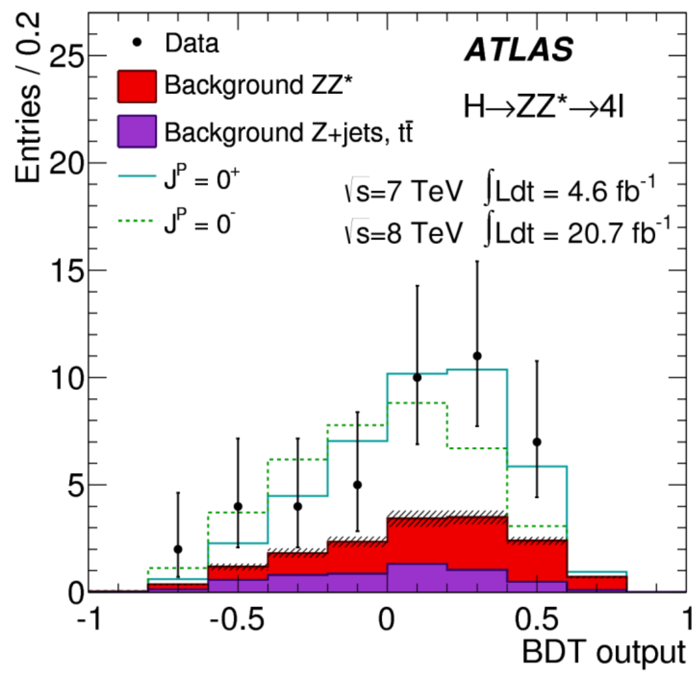
Phys.Lett. B726 (2013) 120-144



Exploit full 4-lepton kinematics, combined into a multivariate analysis (BDT)

Most sensitive channel in decay to 0-

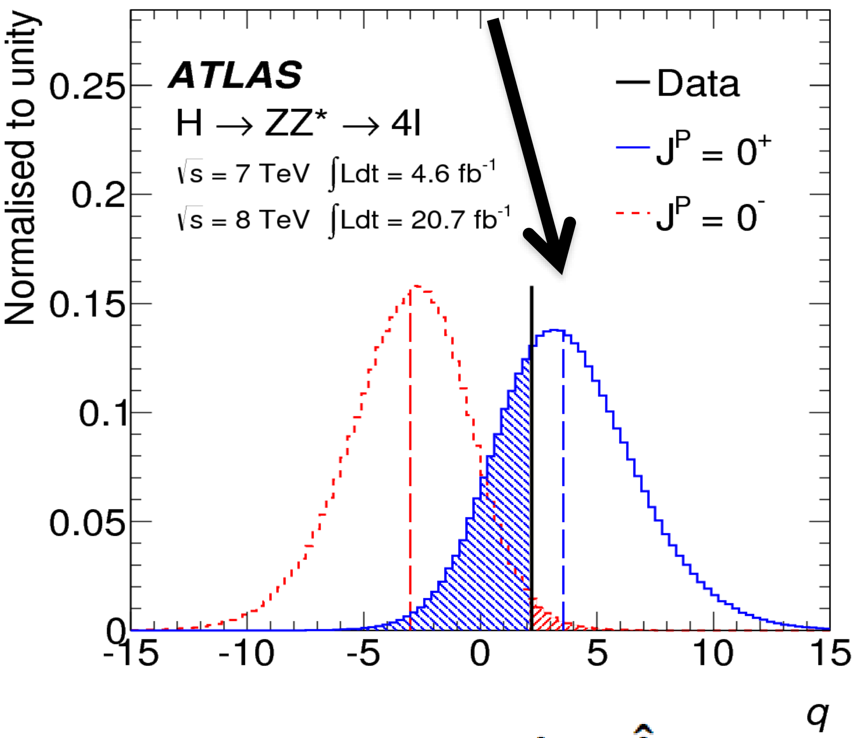




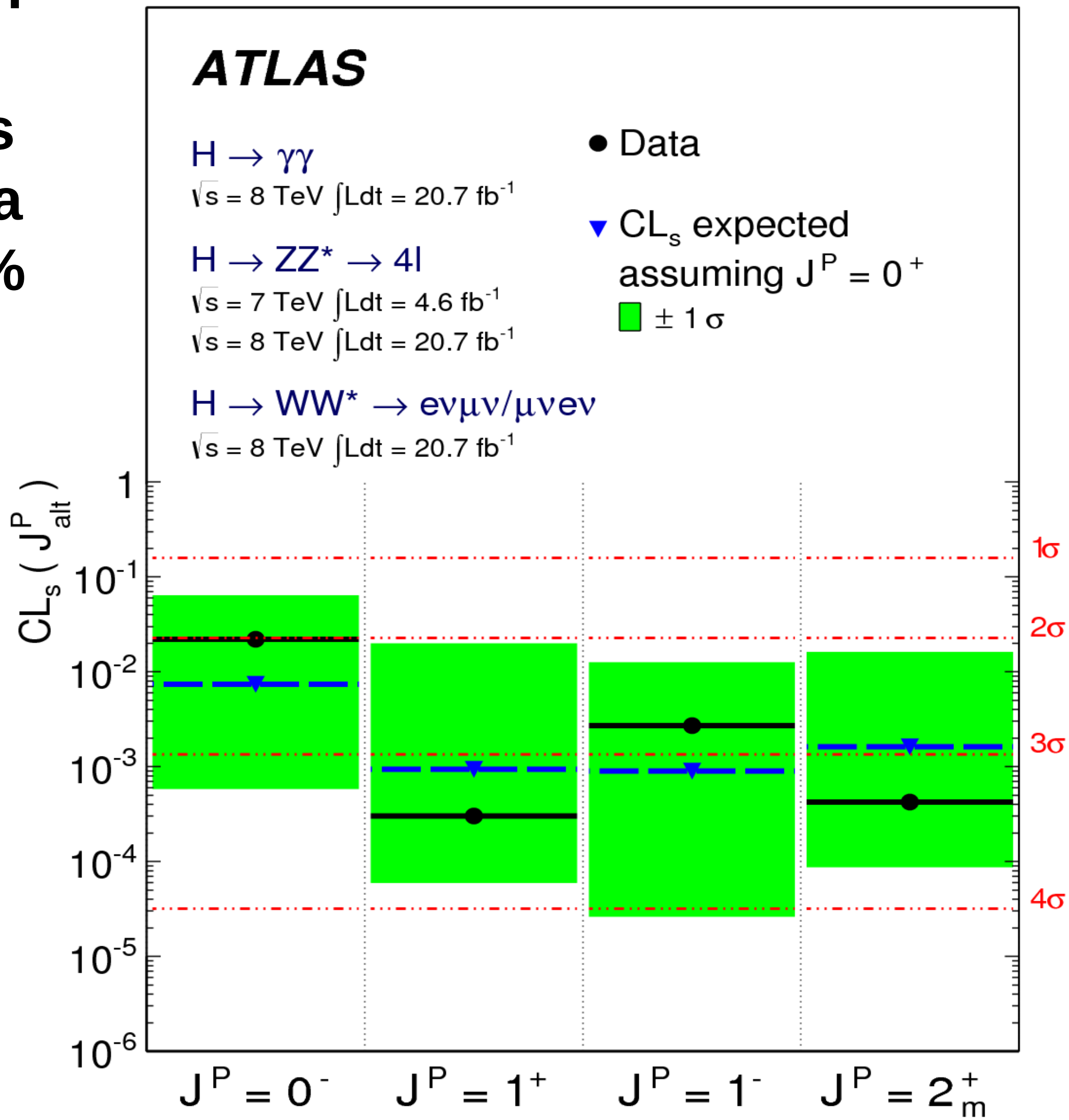
Phys.Lett. B726 (2013) 120-144

Data show compatibility with the SM 0^+ hypothesis while other alternative hypotheses considered are excluded at a confidence levels above 95%

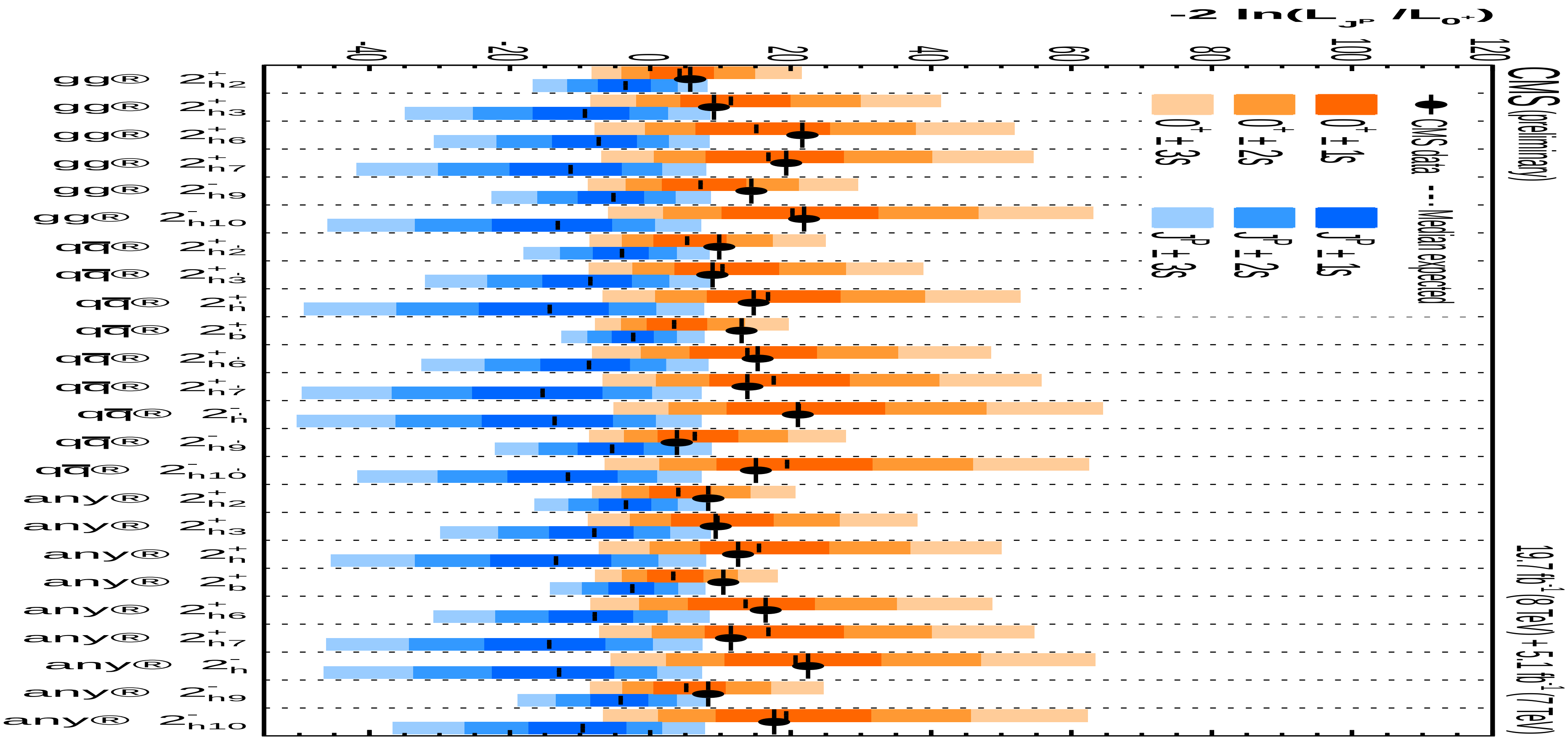
Observation



$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$



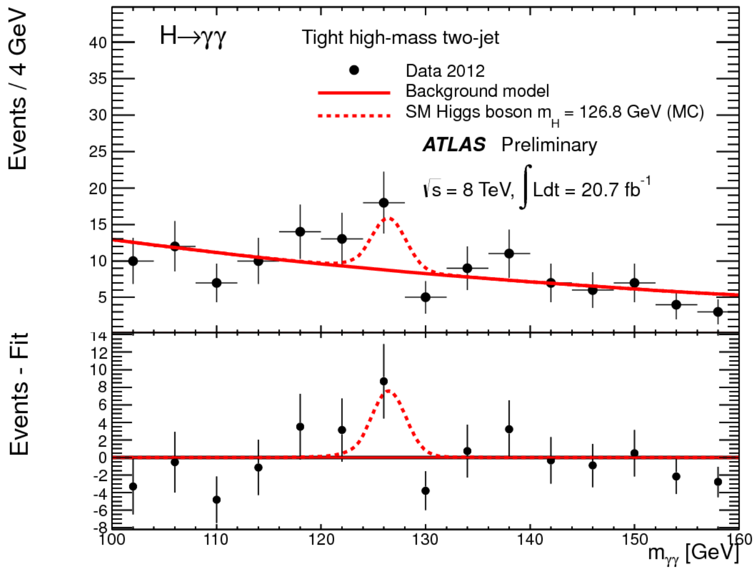
Exclusion of Spin-2 hypotheses

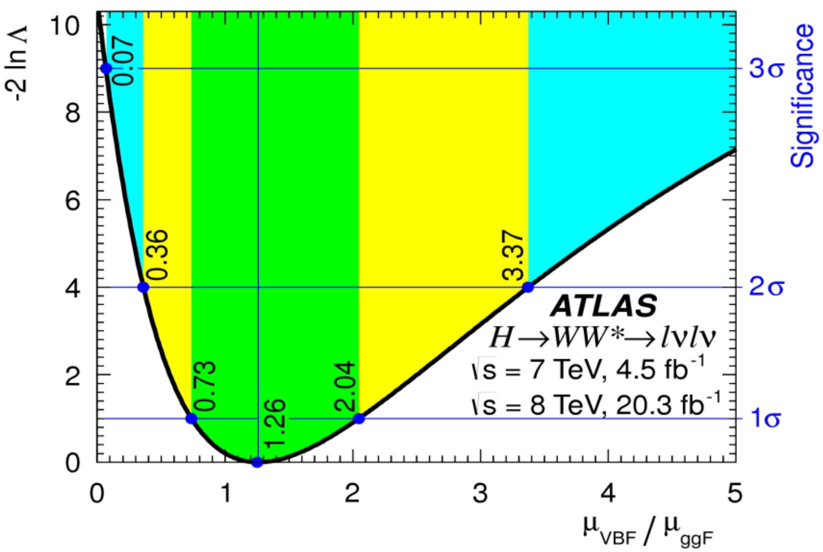


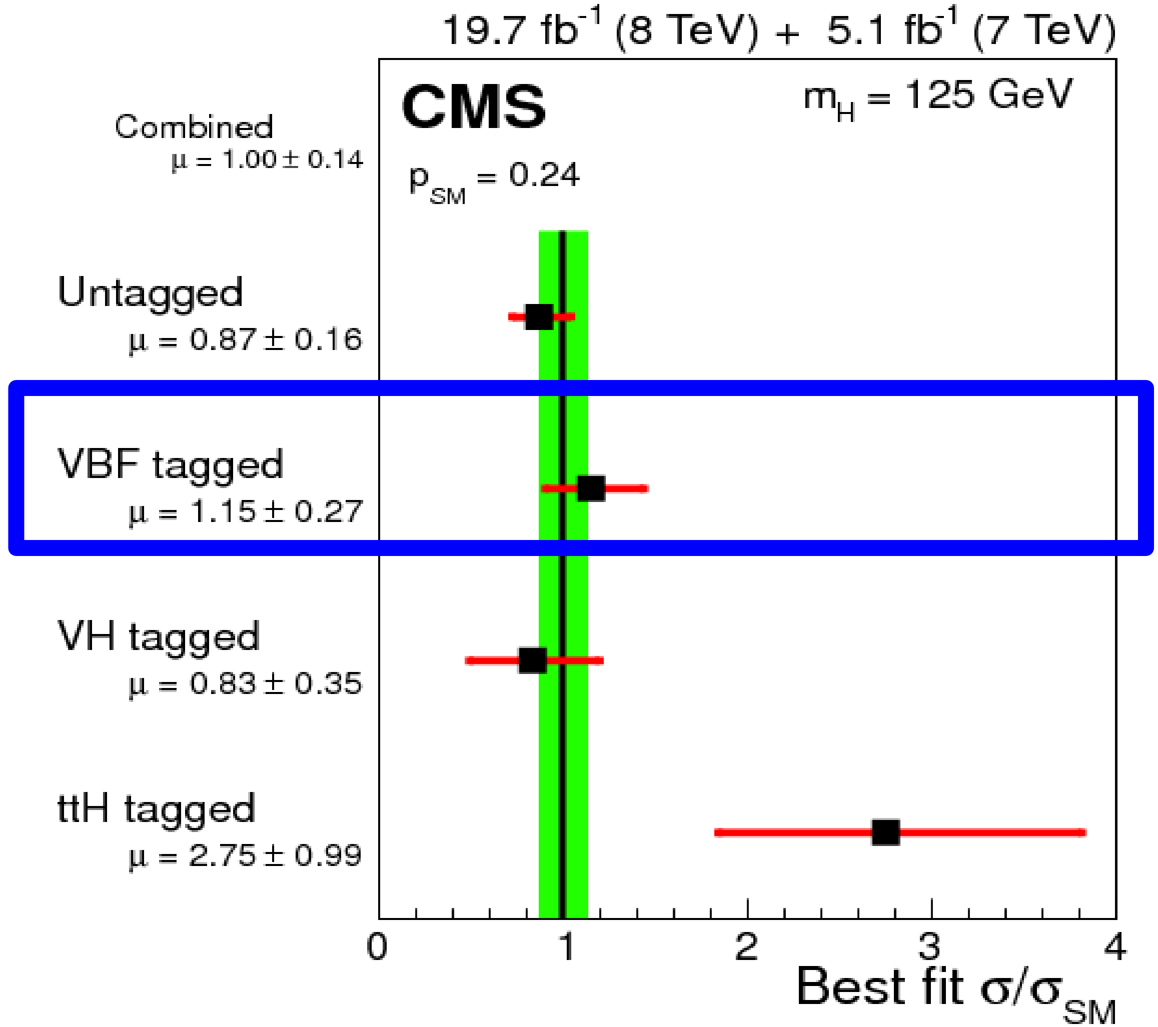
Observation of the VBF production mechanism at the LHC

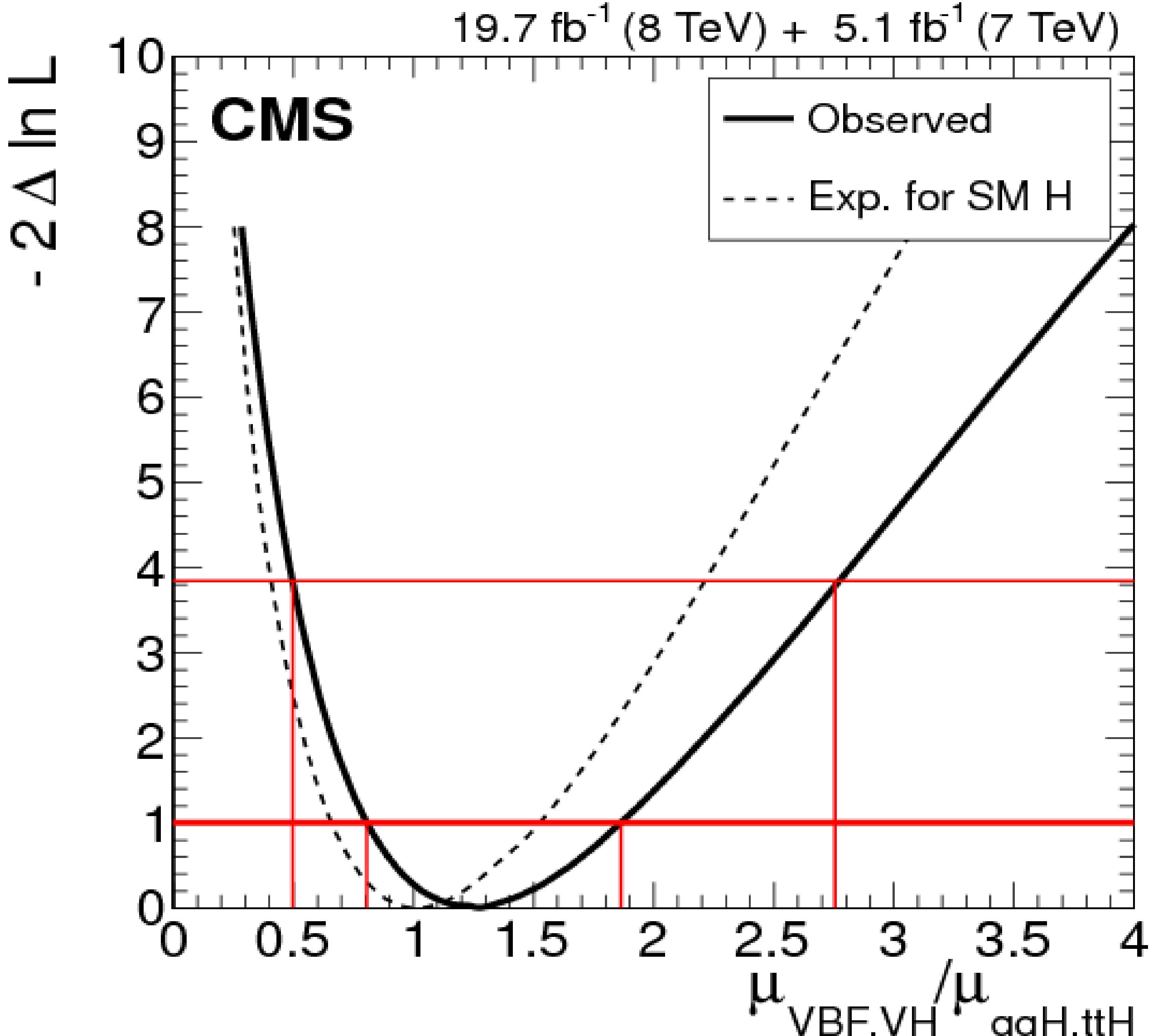
The observation of the VBF production mechanism with the so-called VBF-topology is an important milestone for the demonstration of the SM-like nature of the coupling of the newly discovered scalar to EW bosons.

The VBF Signal at the LHC








19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
Observed
Exp. for SM H
- 2 Δ ln L
$\mu_{VBF,VH}/\mu_{ggH,ttH}$
0
1
2
3
4
5
6
7
8
9
10
0
0.5
1
1.5
2
2.5
3
3.5
4

Exploration of Coupling Strengths

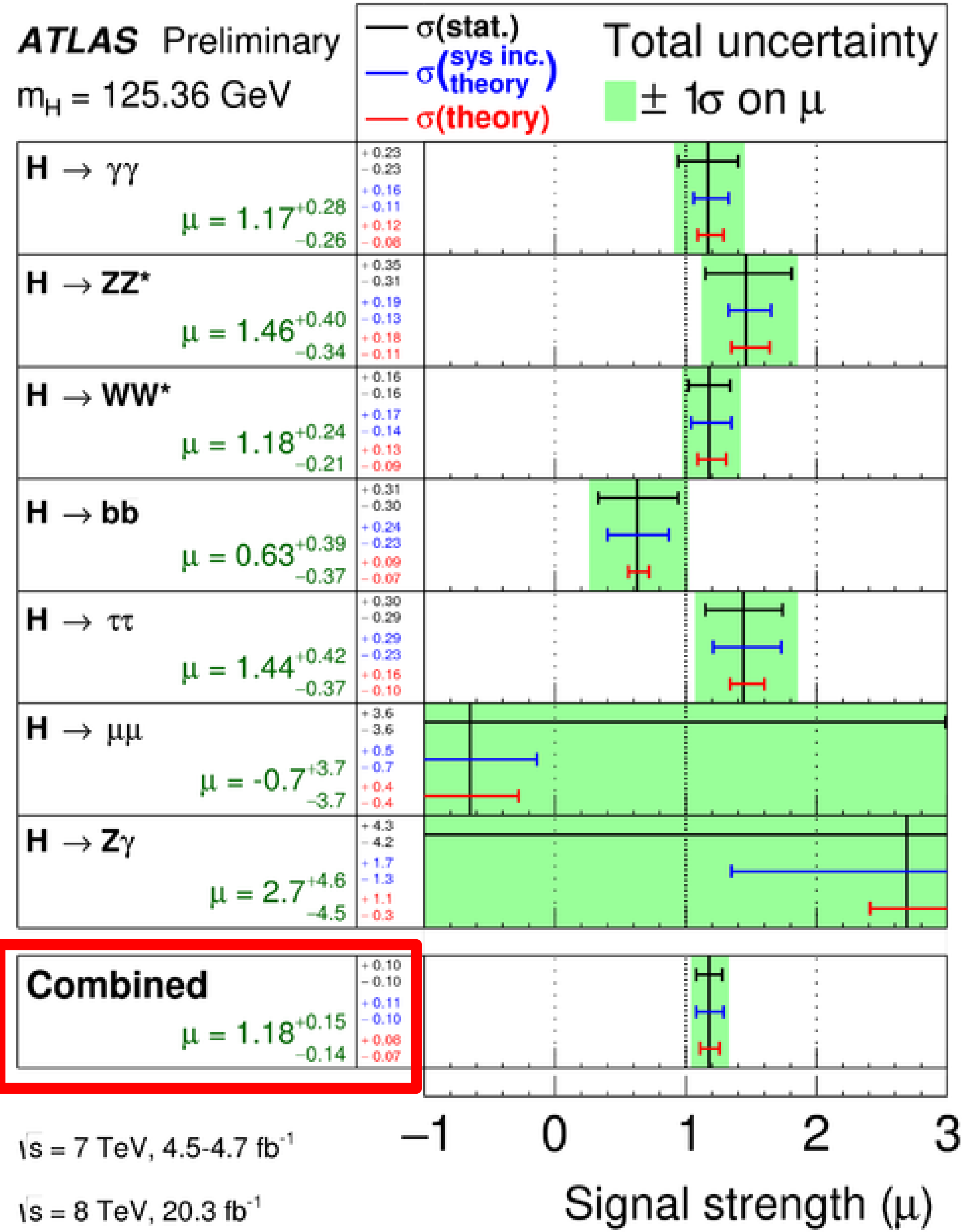
The ATLAS and CMS experiments perform global fits to their available data in order to check compatibility with the Standard Model. Higgs boson couplings are assumed to be that of the SM and scaling parameters are introduced.

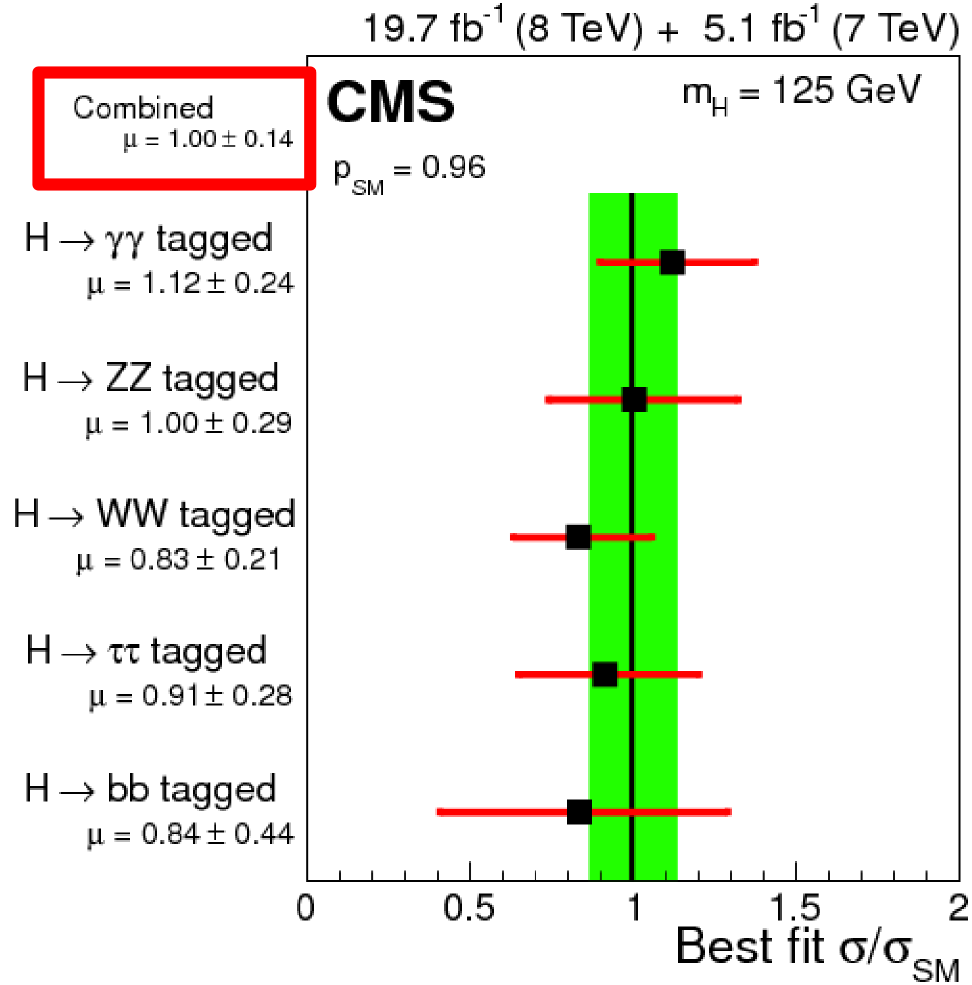
In the standard model there is a physical state, a Higgs boson with well defined couplings to weak bosons, fermions and self interactions

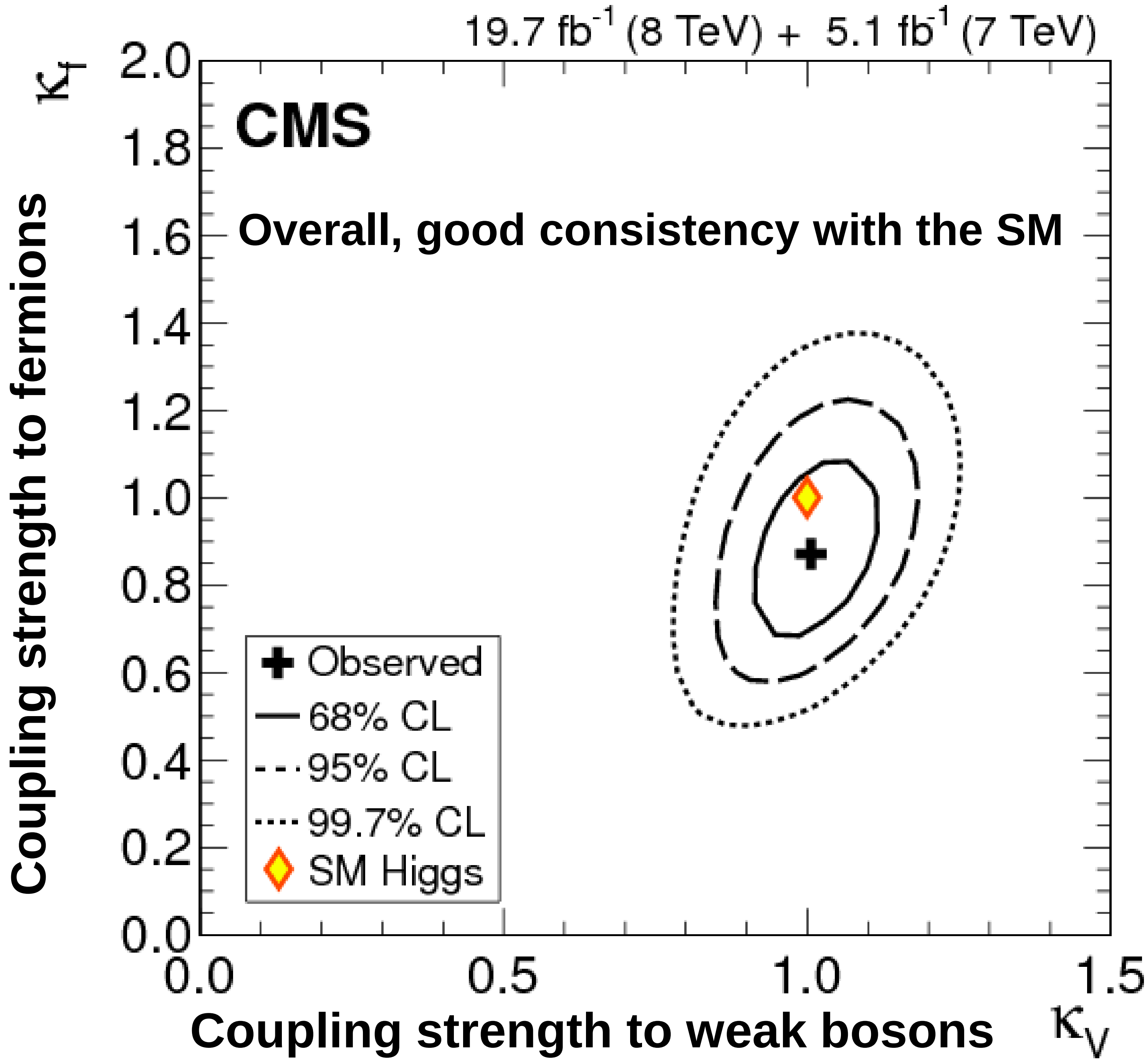
Gauge	Self-interaction	Fermion
$HW^+_\mu W^-_\nu : (-ig_{\mu\nu})2\frac{m_W^2}{\nu}$	$HHH : (i)3\frac{m_H^2}{\nu}$	$H\bar{f}f : (i)\frac{m_f}{\nu}$
$HZ_\mu Z_\nu : (-ig_{\mu\nu})2\frac{m_Z^2}{\nu}$	$HHHH : (i)3\frac{m_H^2}{\nu^2}$	
$HHW^+_\mu W^-_\nu : (-ig_{\mu\nu})2\frac{m_W^2}{\nu^2}$		
$HHZ_\mu Z_\nu : (-ig_{\mu\nu})2\frac{m_Z^2}{\nu^2}$		

The exploration of the coupling to weak bosons plays now a pivotal role in understanding the nature of the scalar boson observed experimentally. New physics can be hidden in these couplings.

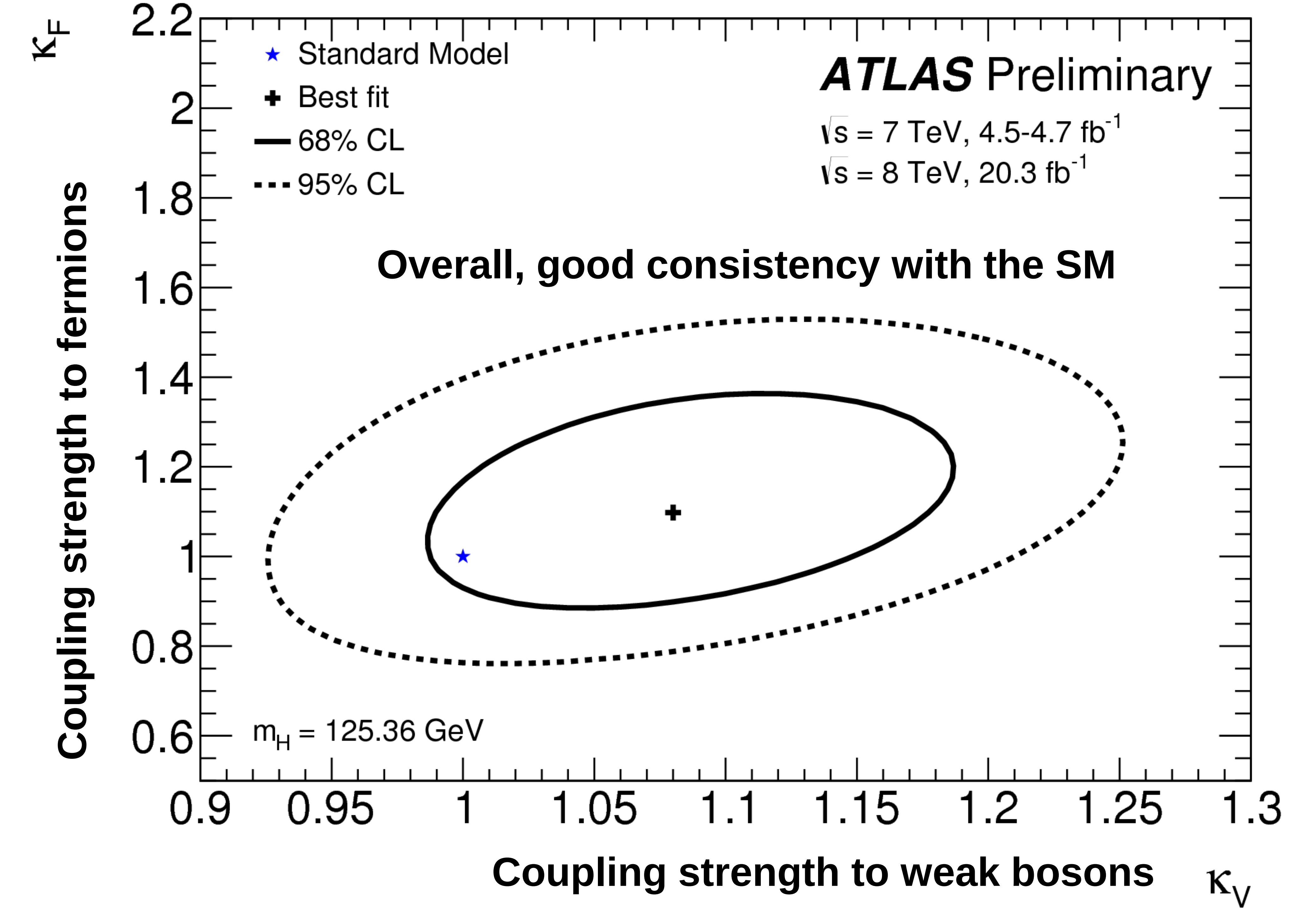
Overall, good consistency with the SM



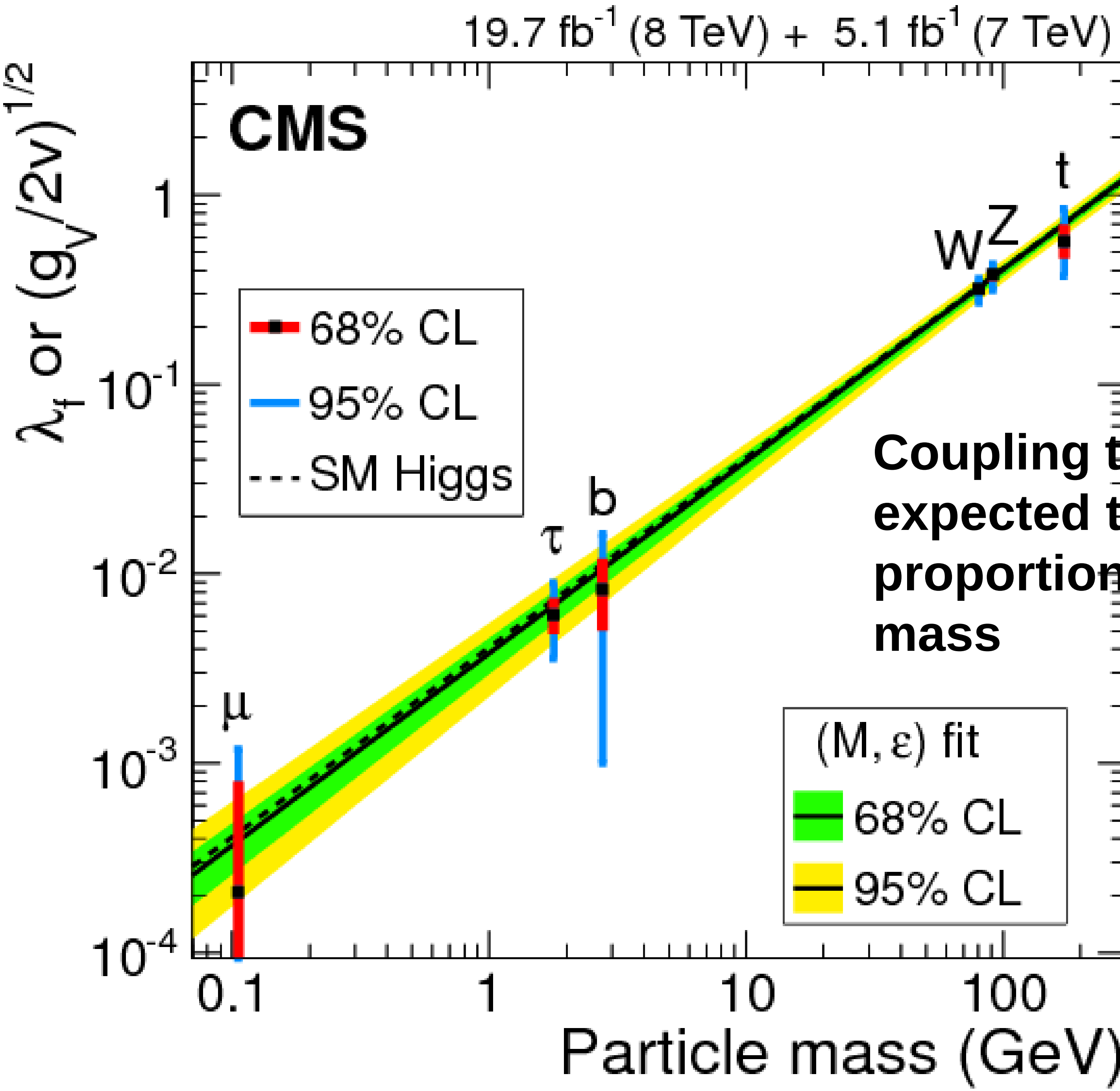




19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Overall, good consistency with the SM
Observed
68% CL
95% CL
99.7% CL
SM Higgs
Coupling strength to fermions
κf
Coupling strength to weak bosons
κV
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5



ATLAS Preliminary
√s = 7 TeV, 4.5-4.7 fb-1
√s = 8 TeV, 20.3 fb-1
Standard Model
Best fit
68% CL
95% CL
Overall, good consistency with the SM
m_H = 125.36 GeV
Coupling strength to fermions
κF
Coupling strength to weak bosons
κV
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25
1.3



Coupling to particles expected to be proportional to their mass

Word of caution:
Results related to global fits by the experiments assume that the Higgs is produced as it is expected by the Standard Model. By means of a likelihood formalism the phase-spaced is reweighted according to the ratio of Signal to Background (S/B) Therefore results on global fits above are to be considered as a consistency check.
Strictly speaking, this approach is not optimized to search for deviations from the Standard Model

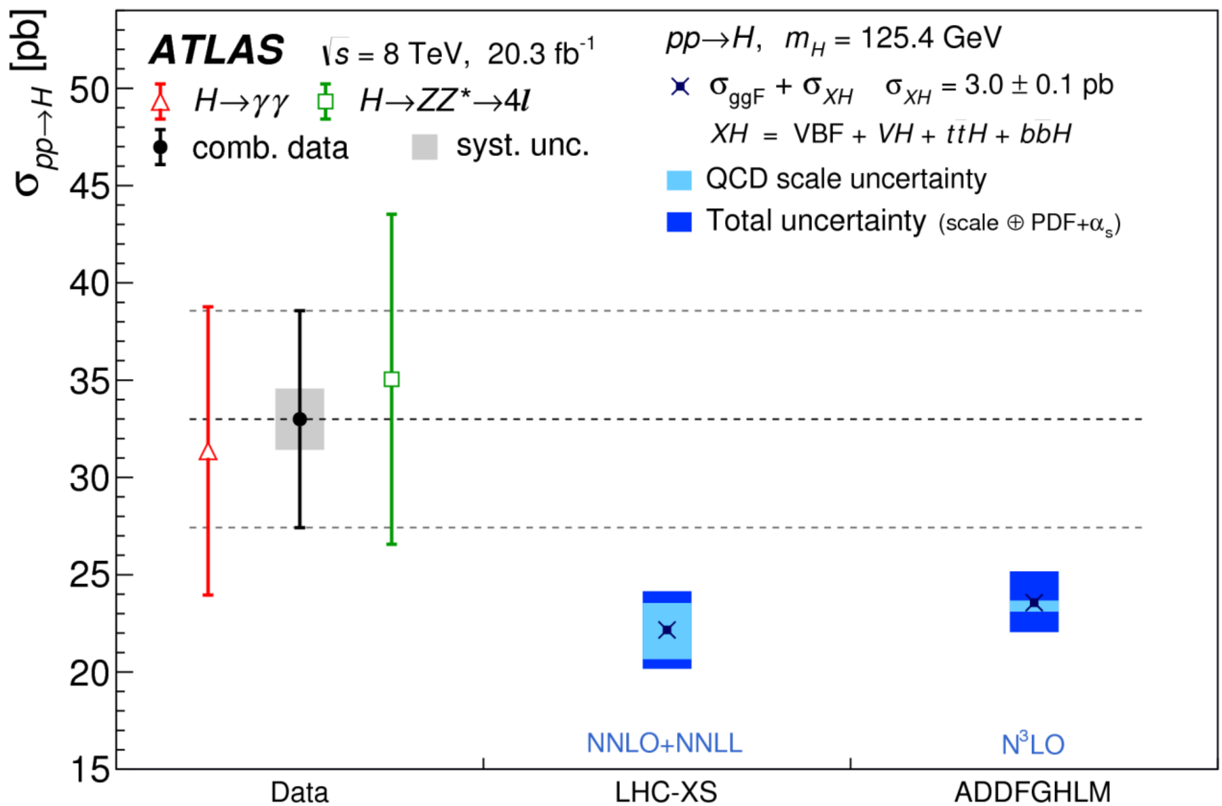
What happens if we remove these biases and measure fiducial (no assumptions on how the higgs is produced) cross-sections?

An example of a potential bias introduced by assuming the Higgs is produced as in the Standard Model:

When assuming the Standard Model the signal strength of H->γγ is 1.17
when releasing that condition we get 1.42

Results are still compatible statistically. More data will be needed to understand if the tension increases.

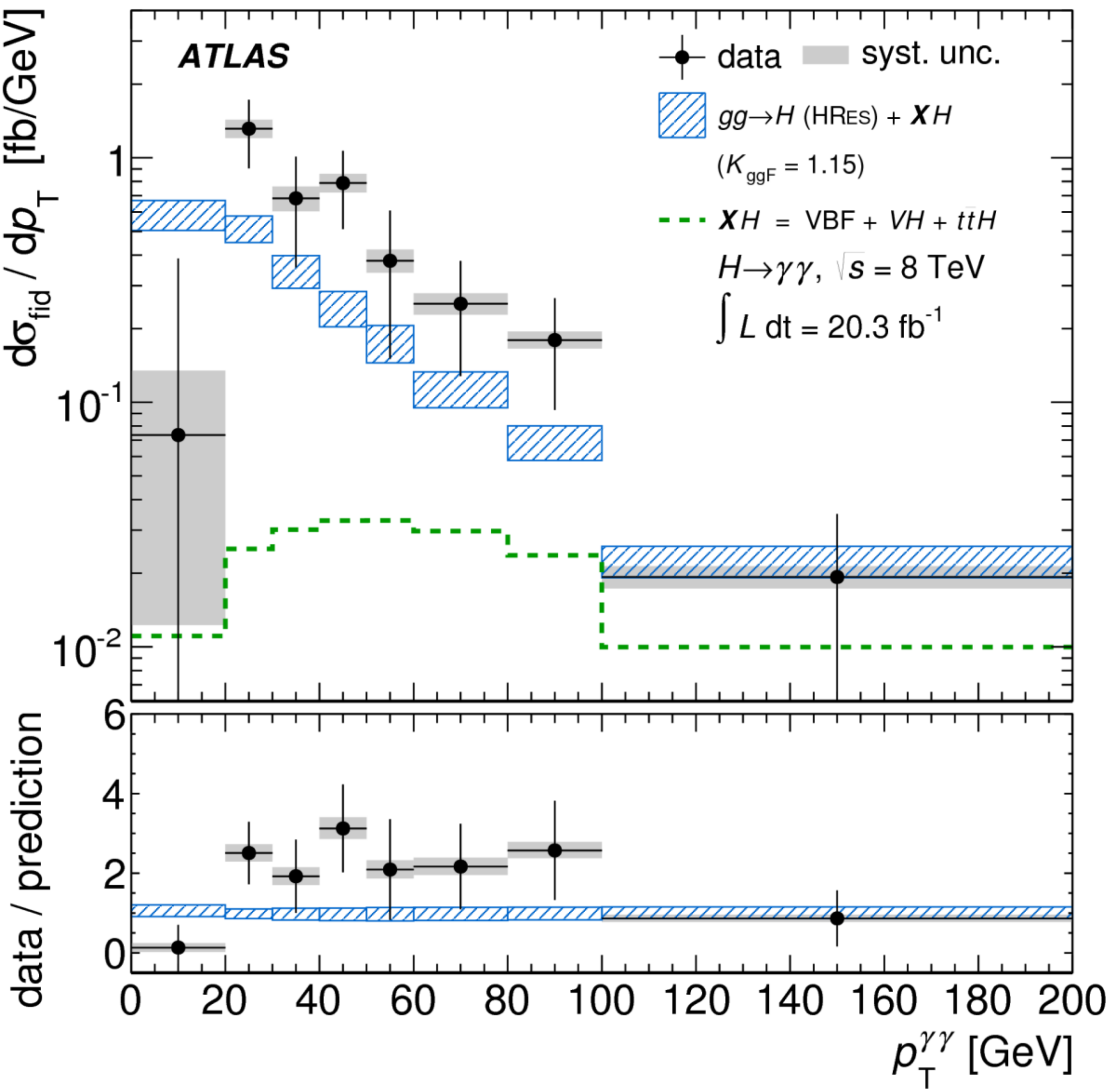
Fiducial, unbiased cross-sections



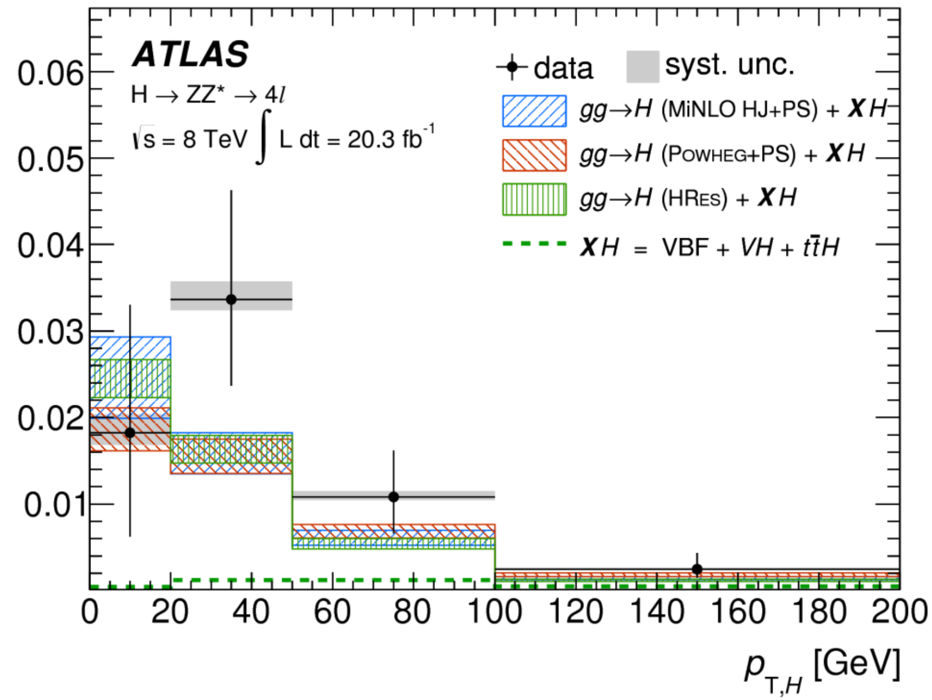
The Anomalies

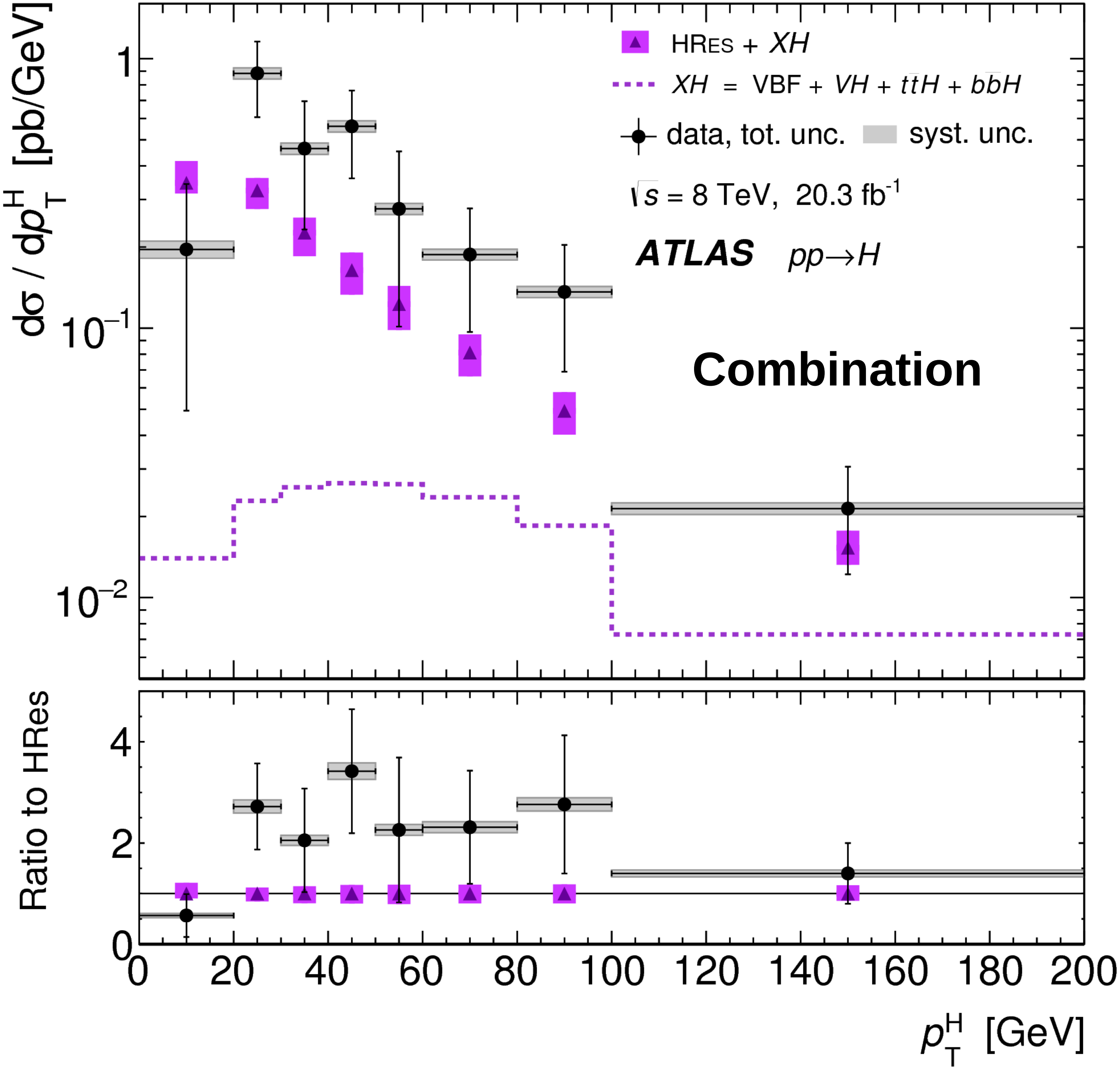
When measuring the Higgs boson transverse momentum certain discrepancies were found with the Standard Model

$$H \to \gamma\gamma$$



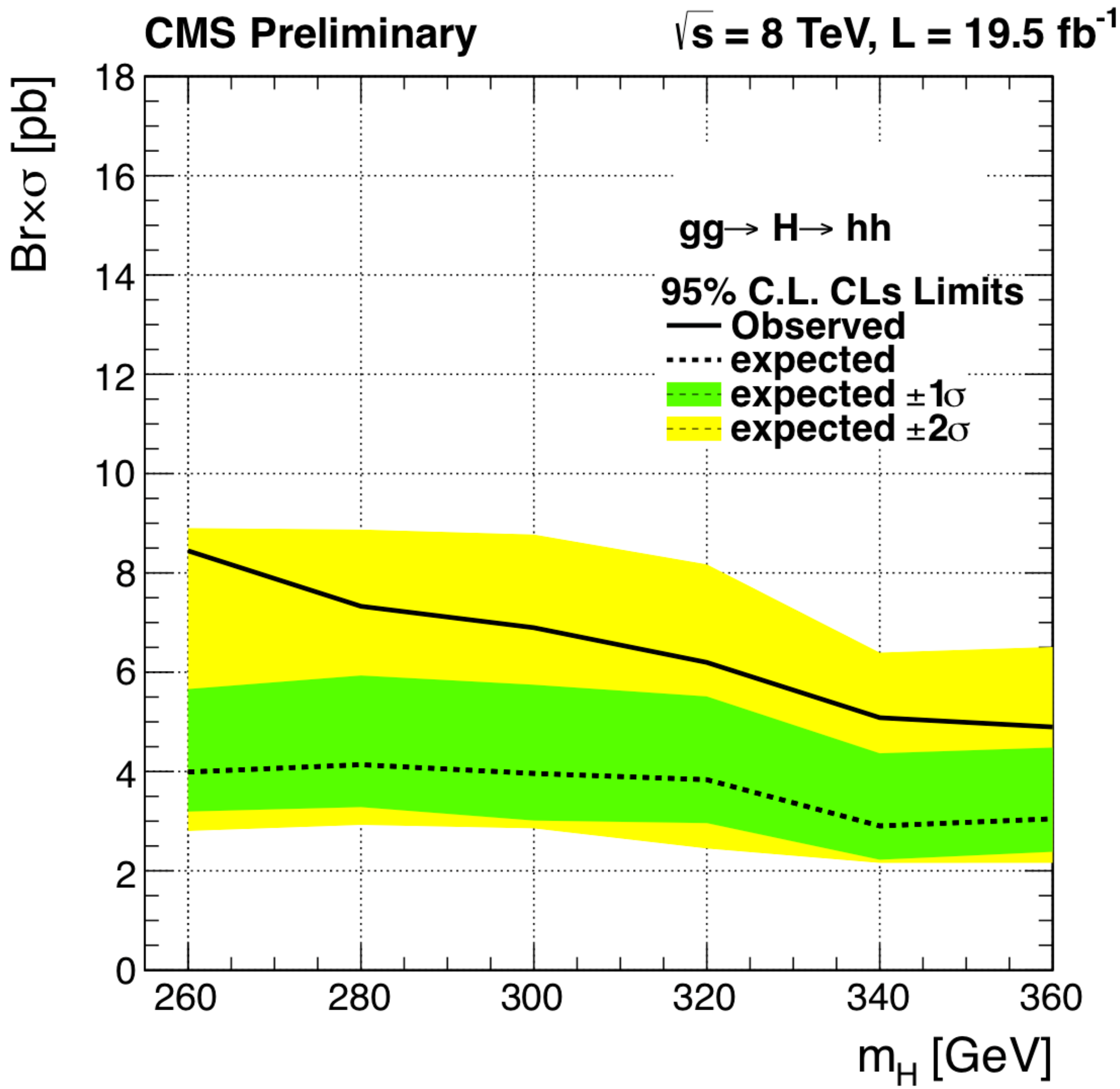
$$H \to ZZ^* \to 4\ell$$





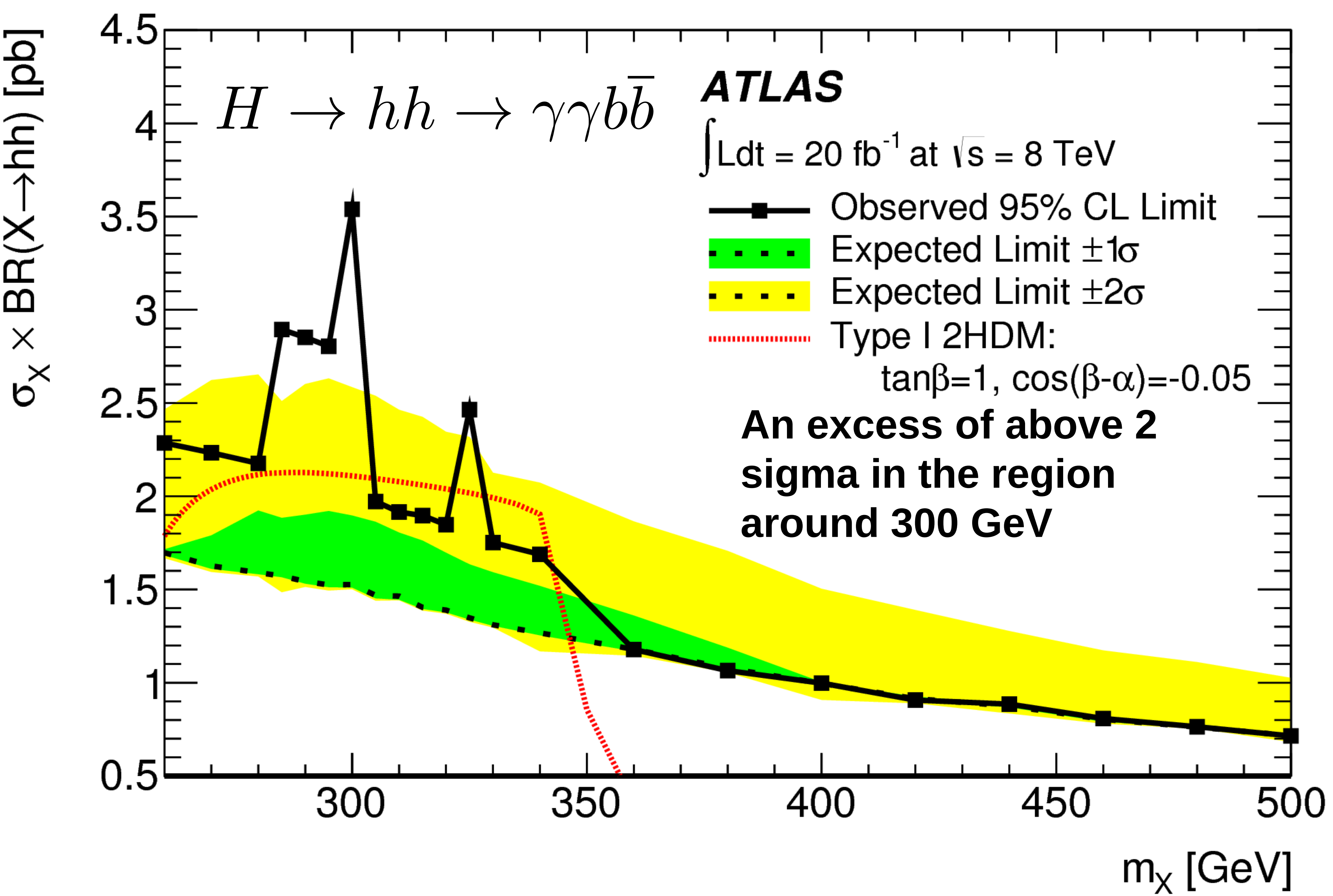
HRes + XH
XH = VBF + VH + $t\bar{t}H$ + $b\bar{b}H$
data, tot. unc.
syst. unc.
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
ATLAS $pp \rightarrow H$
Combination
$d\sigma / dp_T^H$ [pb/GeV]
Ratio to HRes
p_T^H [GeV]

Excesses in the search for a double Higgs resonance

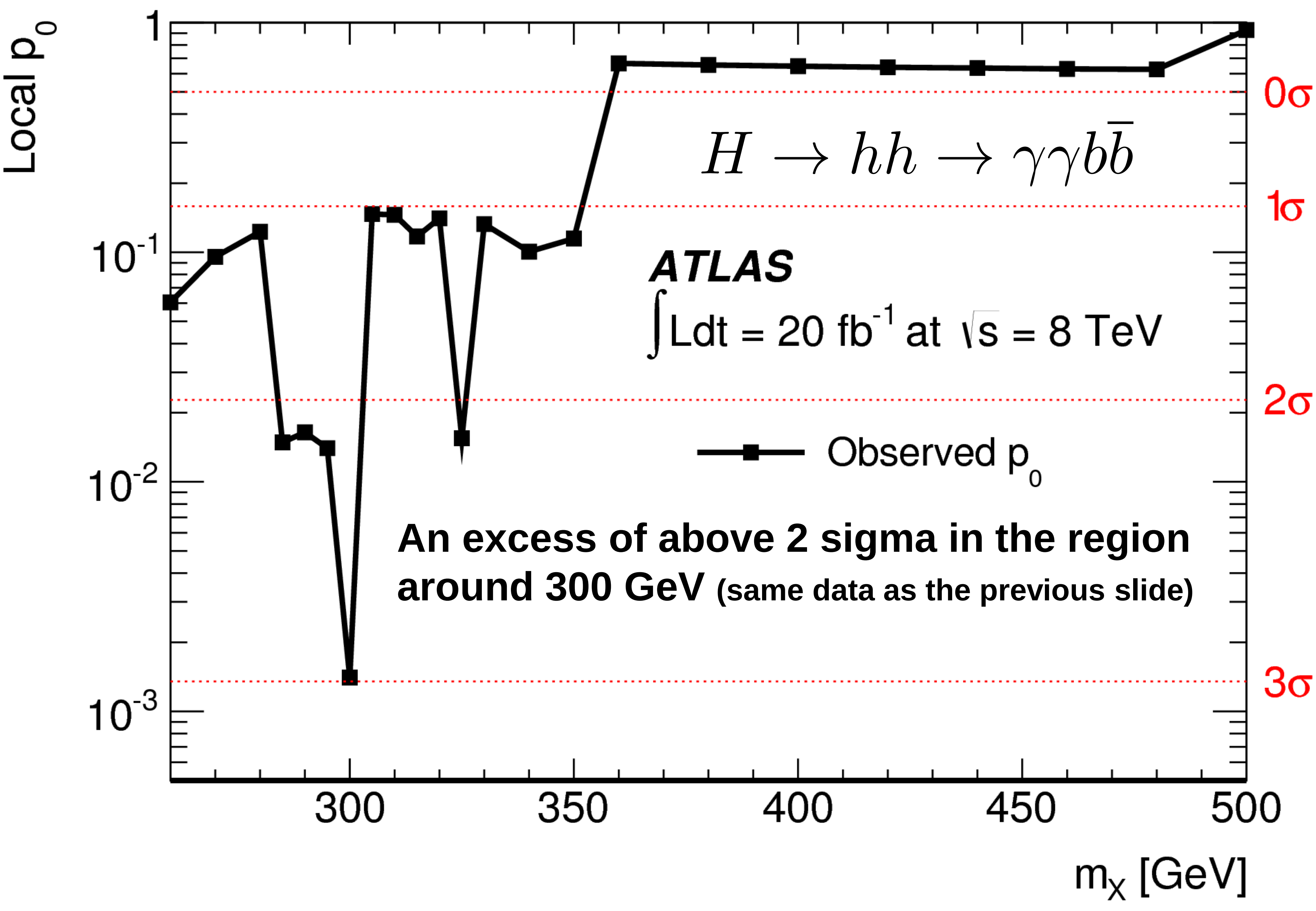


An excess of less than 2 sigma in the region around 300 GeV

In the SM double h production has too of a small cross-section to yield an excess at this point

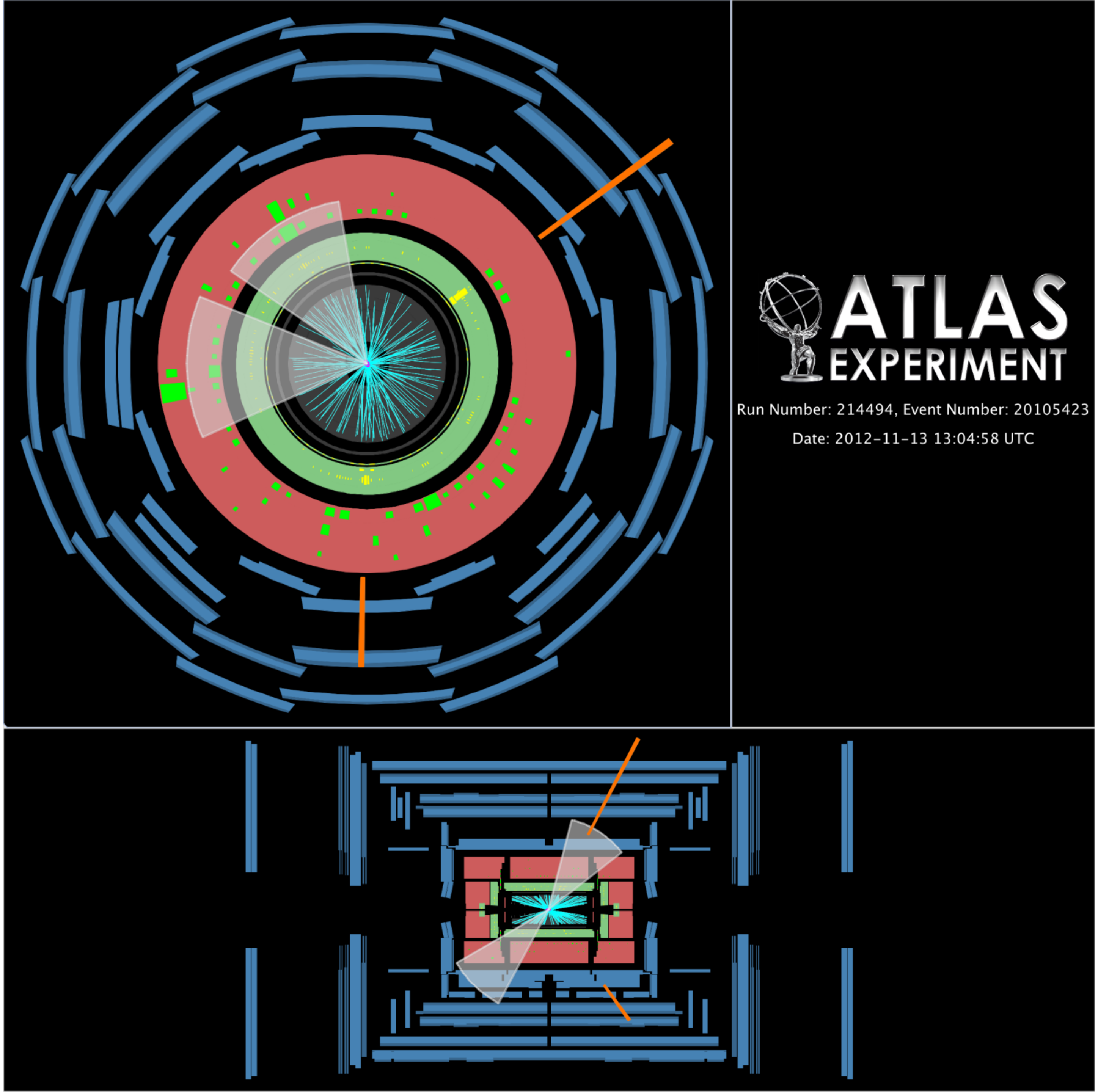


ATLAS
$\int$Ldt = 20 fb^{-1} at $\sqrt{s}$ = 8 TeV
$H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$
Observed 95% CL Limit
Expected Limit ±1σ
Expected Limit ±2σ
Type I 2HDM:
tanβ=1, cos(β-α)=-0.05
An excess of above 2 sigma in the region around 300 GeV
$\sigma_X \times$ BR(X→hh) [pb]
m_X [GeV]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
300
350
400
450
500

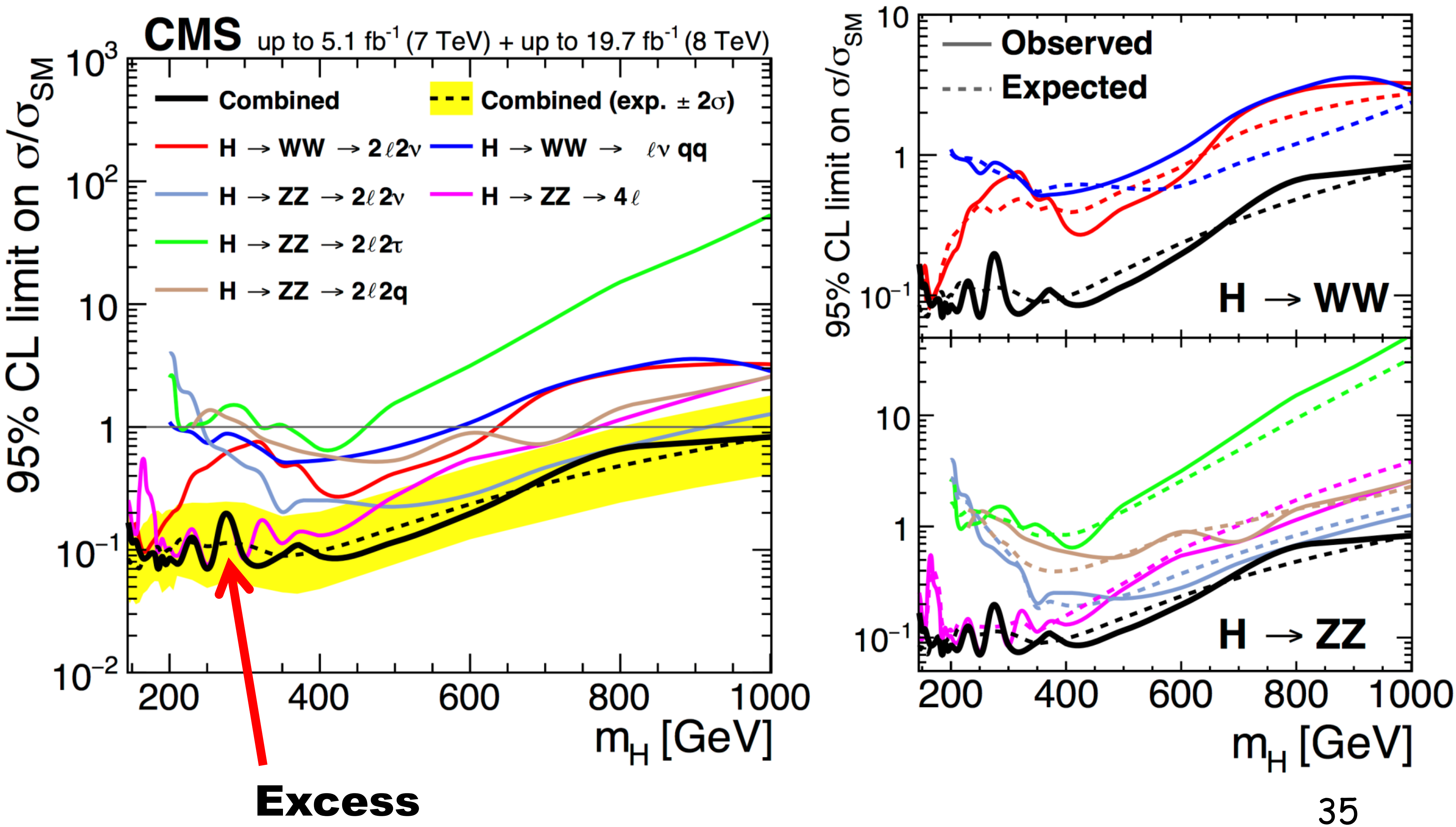


Local p_0
1
10^{-1}
10^{-2}
10^{-3}
300
350
400
450
500
m_X [GeV]
0σ
1σ
2σ
3σ
$H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$
ATLAS
$\int Ldt$ = 20 fb^{-1} at $\sqrt{s}$ = 8 TeV
Observed p_0
An excess of above 2 sigma in the region around 300 GeV (same data as the previous slide)

$H \to hh \to \gamma\gamma b\bar{b}$



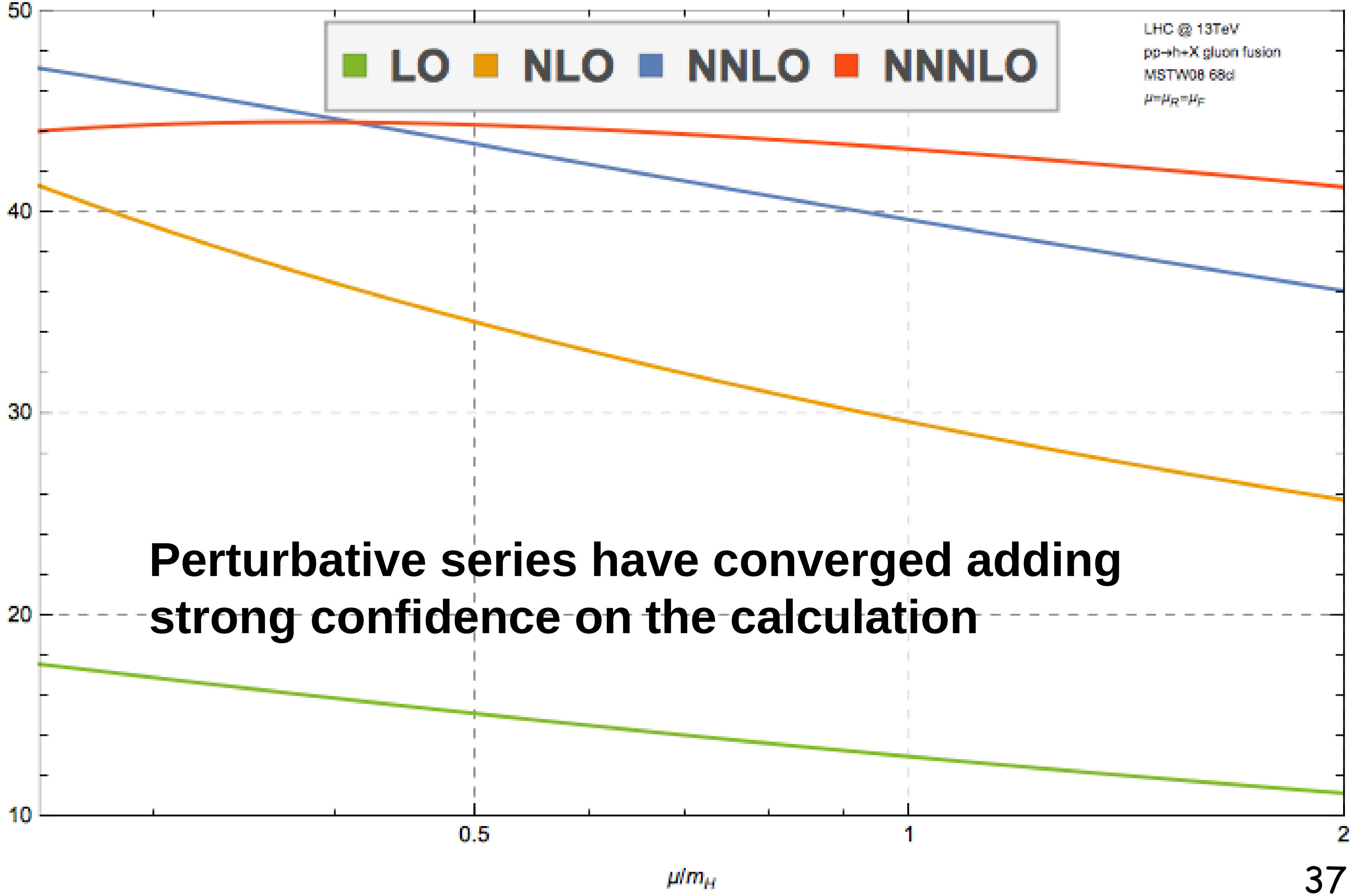
The CMS experiment has an excess shy of 2 sigma at 275 GeV in the search for VV, V = Z, W.



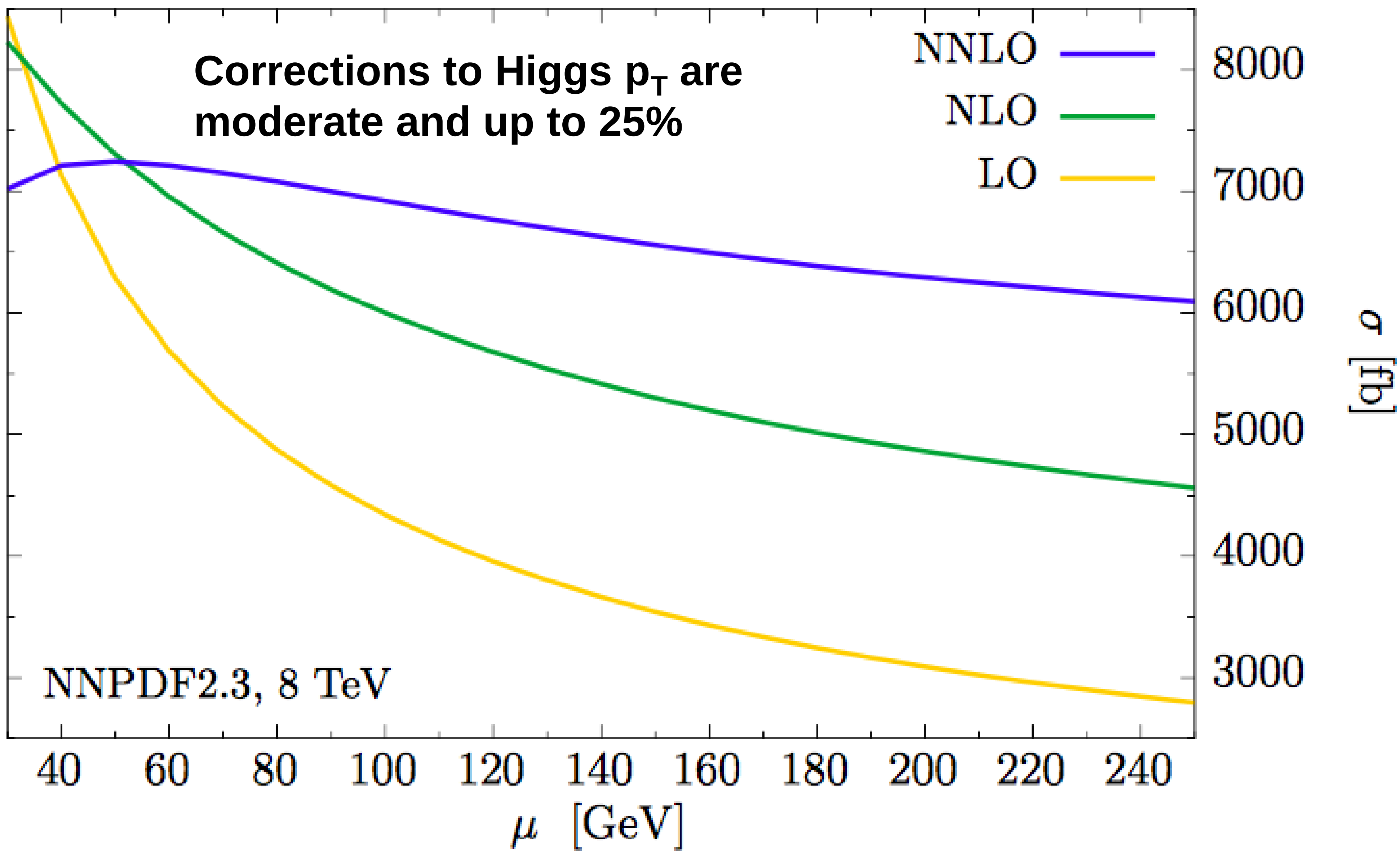
Recent Progress in QCD Higher Order Corrections

How robust is the total gluon-gluon fusion and differential transverse momentum distribution?

arXiv:1503.06056v1, C. Anastasiou et al.
First Complete N3LO calculation for the total gluon-gluon fusion cross-section showing small N3LO/NNLO corrections



arXiv:1504.07922v1, R. Boughezal et al. First complete calculation of ggF+1j at NNLO, showing strong reduction of scale variation



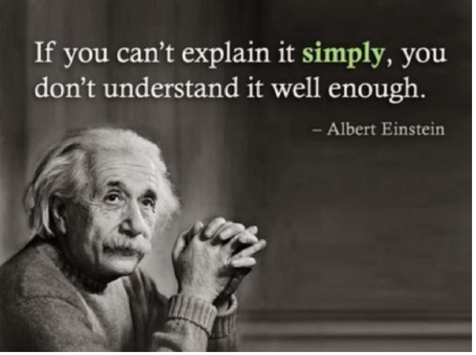
Can the Higgs p_T anomaly be connected with the excesses at around 300 GeV?
If so, how?

The Phenomenological Framework

The minimal extension of the Higgs sector

Minimal Extension of Higgs sector

- Try to approach the problem as generally as possible.
- The 2HDM approach, even if more general than MSSM, remains a model
- Instead investigating a minimal extension of the Higgs sector via the introduction of a real singlet and a SU(2) singlet (DM)
  - Introduce a weakly interactive, stable particle (DM candidate). H would play, in a sense, the role of a mediator. The dynamics behind this DM candidate not of concern now
  - Flexible framework that be eventually be mapped to a flavor of 2HDM, if necessary



The Lagrangian

Introduce H and X fields with the interactions listed below

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

$$\mathcal{L}_{BSM} = \mathcal{L}_K + \mathcal{L}_T + \mathcal{L}_Q + \mathcal{L}_{Hgg} + \mathcal{L}_{HVV}$$

$$\mathcal{L}_K = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}M_X^2 X^2 - \frac{1}{2}M_H^2 H^2$$

$$\mathcal{L}_T = -\frac{1}{2}\mu_1 h^2 H - \frac{1}{2}\mu_2 X^2 h - \frac{1}{2}\mu_3 X^2 H$$

$$\mathcal{L}_Q = -\frac{1}{4}\lambda_1 H^2 h^2 - \frac{1}{4}\lambda_2 X^2 h^2 - \frac{1}{4}\lambda_3 H^2 X^2 - \frac{1}{2}\lambda_4 H h X^2$$

$$\mathcal{L}_{Hgg} = -\frac{1}{4}\beta_g \ \kappa_{hgg}^{SM} G_{\mu\nu} G^{\mu\nu} H$$

$$\mathcal{L}_{HVV} = \frac{2M_W^2}{v}\beta_W \ W_\mu W^\mu H + \frac{M_Z^2}{v}\beta_Z \ Z_\mu Z^\mu H$$

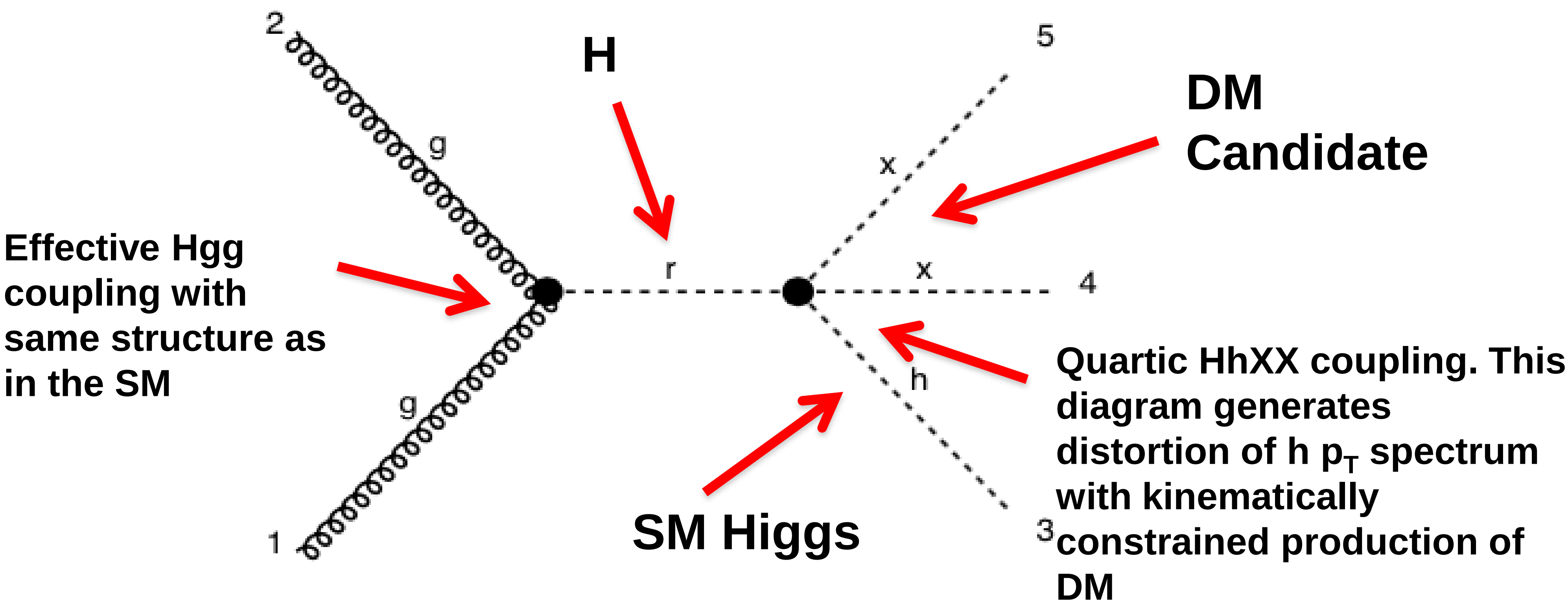
Parameters and MG5 Feynrules

Generated by N.Chakrabarty, T.Mandal and B.Mukhopadyaya

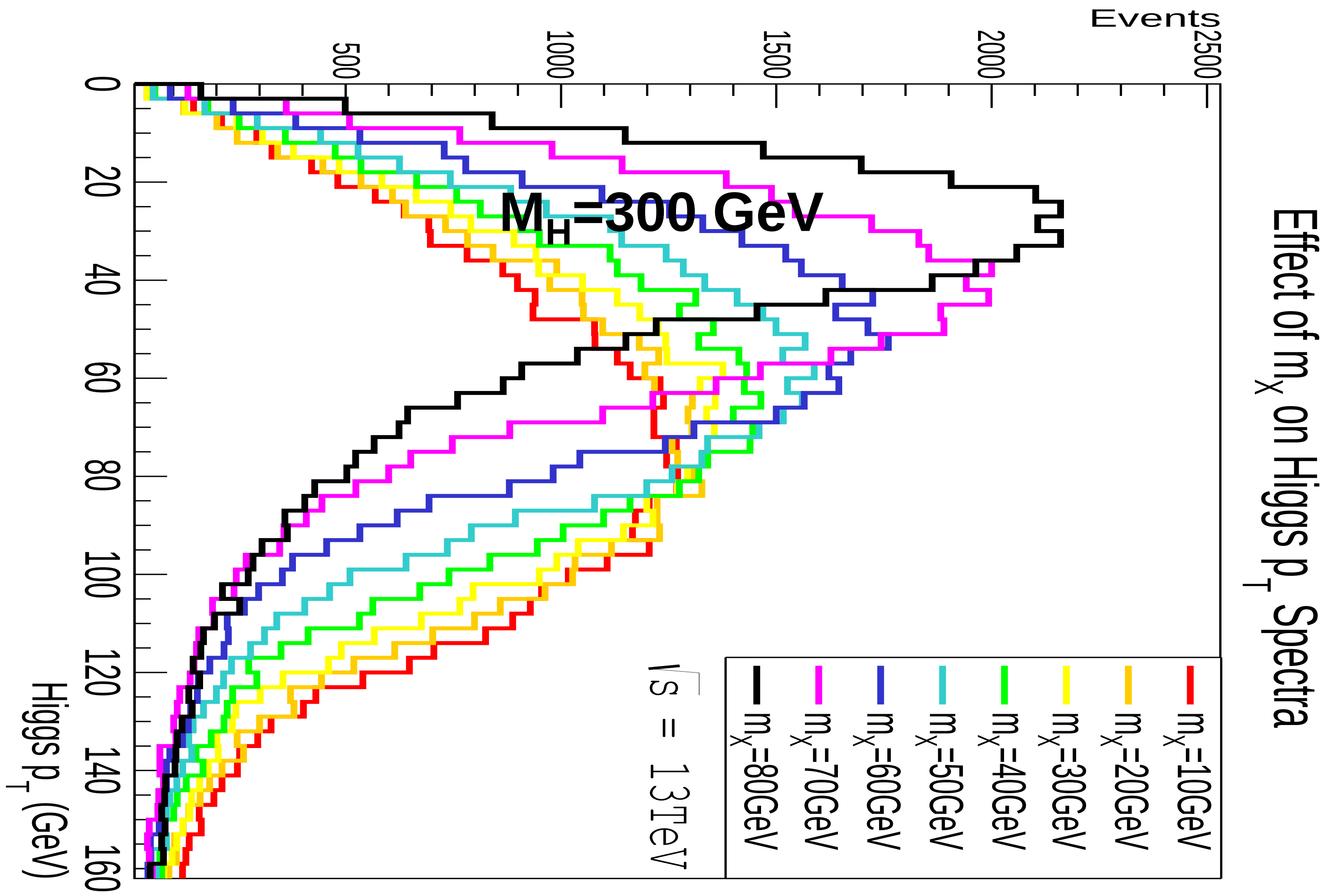
Parameter in paper	Corresponding parameter in MG paramcard
h	H
X	X
H	R
M_h	MH
M_X	MX
M_H	MR
$\frac{\mu_1}{v}$	lHHR
$\frac{\mu_2}{v}$	lHXX
$\frac{\mu_3}{v}$	lRXX
λ_1	lHHRR
λ_2	lHHXX
λ_3	lRRXX
λ_4	lHRXX
β_g	btg
β_W	btW
β_Z	btZ

Event Generation

Generated complete Gauge invariant set of diagrams.
Suppressed hXX and hhXX couplings to study diagram below

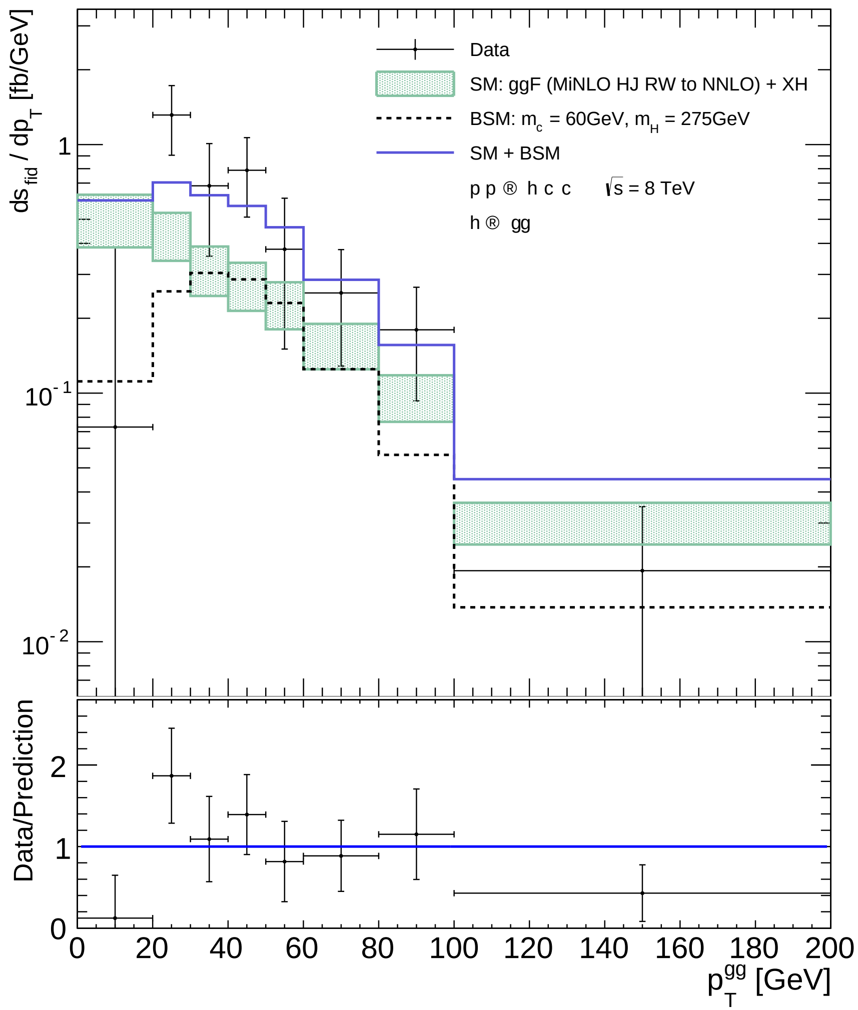


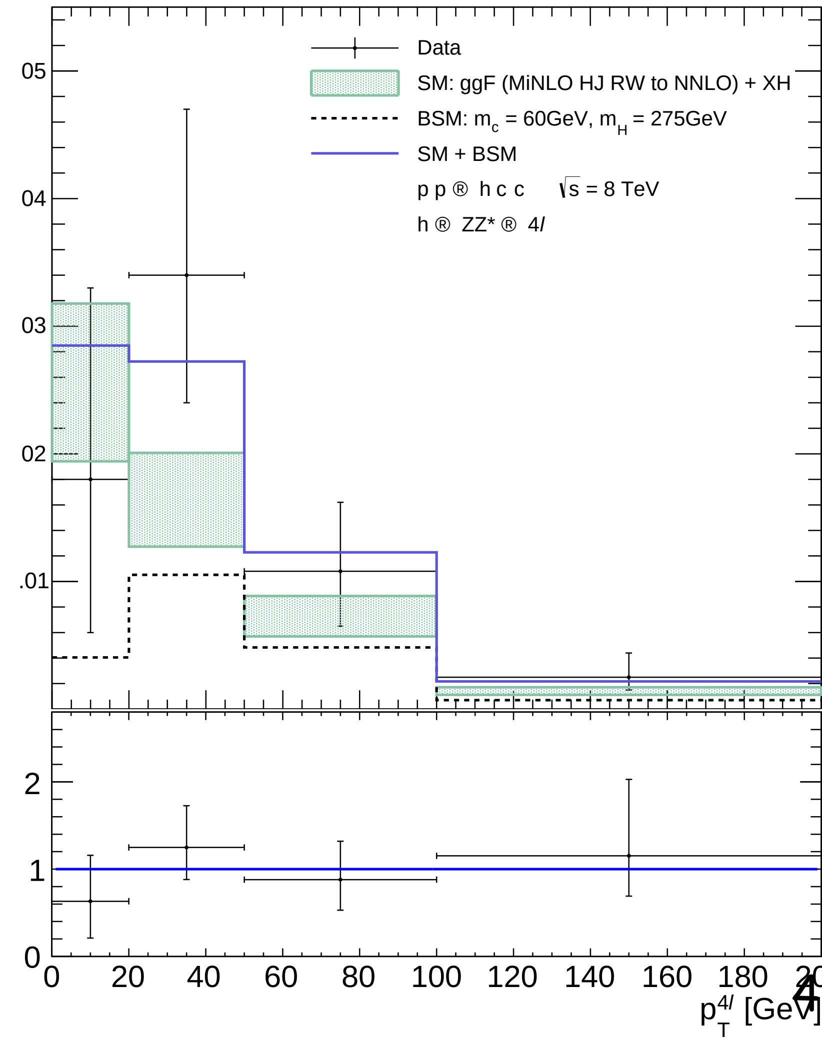
H p_T and MET Spectra



How does this hypothesis fit the data?

Templates are fit to the Higgs p_T data. Best fit is obtained with M_H=275 GeV with M_X=60 GeV. Good fit quality.





Submitting article this week to the archive

Explaining the excess in the Higgs p_T distributions at the LHC

Stefan von Buddenbrock,[1,*] Alan S. Cornell,[2,†] Nabarun Chakrabarty,[3,‡] Deepak Kar,[1,§] Mukesh Kumar,[2,¶] Tanumoy Mandal,[3,**] Bruce Mellado,[1,††] Biswarup Mukhopadhyaya,[3,‡‡] and Robert Reed[1,§§]

[1]*School of Physics, University of the Witwatersrand, Wits 2050, South Africa*

[2]*National Institute for Theoretical Physics; School of Physics and Mandelstam Institute for Theoretical Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa*

[3]*Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad - 211 019, India.*

(Dated: May 24, 2015)

With the discovery of a new scalar boson at the Large Hadron Collider (LHC) new tasks and explorations have come to the fore. Global fit studies indicate that the newly observed boson displays properties consistent with those predicted by the Standard Model (SM). Despite the lack of signifcant deviations from the SM expectations in these studies, there are certain excesses in the data that deserve close attention. Among those is the transverse momentum of the Higgs boson and the results pertaining to searches of di-Higgs boson resonances. The aim of the paper is to explain some of the excesses simultaneously using a phenomenological framework obtained by extending the SM with a heavy scalar with a mass, $m_H \approx 300$ GeV and a dark matter candidate. A fit is performed that provides a reasonable description of the Higgs boson transverse momentum, favoring a dark matter candidate of mass in the range of 50-60 GeV, while satisfying cosmological constraints. This inevitably leads to the production of the Higgs boson in association with intermediate missing transverse momentum and its partial width to a pair of dark matter particles to be small. Another consequence of this framework is the possible decay of the heavy scalar into $VV, V = Z, W^{\pm}$.

PACS numbers: 14.80.Bn,14.80.Ec,12.60.Cn,12.60.Fr
Keywords:

INTRODUCTION

With the discovery of a new scalar boson, h, at the Large Hadron Collider (LHC) [1, 2] new tasks and explorations have come to the fore. The ATLAS and CMS experiments have done a superb job exploring the properties of this new particle and will continue to do so in the years to come. Both collaborations have performed global analyses of their data pertaining to the compability with the Standard Model (SM). This includes tests of the spin/CP hypothesis and variations of the Higgs boson couplings. Overall, the global fit approach indicates that the newly observed boson displays properties consistent with those predicted by the SM. Despite the lack of significant deviations from the SM expectations in these studies, there are certain features in the data that deserve close attention.

The ATLAS collaboration has recently reported on the differential distributions using the di-photon [3] and the $h \to ZZ^* \to 4\ell$ [4] decays.[1] These measurements are designed to incorporate the least model dependence possible, as opposed to the global analyses eluded to above. Of particular interest to understand the dynamics behind the production of the scalar boson, is the measurement of the transverse momentum, p_{Th}. The spectra measured with both decays are compatible with each other and display certain discrepancies with the prediction from the SM in the region of intermediate p_{Th}. No significant excess with p_{Th} is seen in the data with respect to the SM prediction. If related to physics beyond the SM, one can argue that the discrepancy in the region of intermediate p_{Th} could be driven by a not very heavy new particle whose decays involve h.

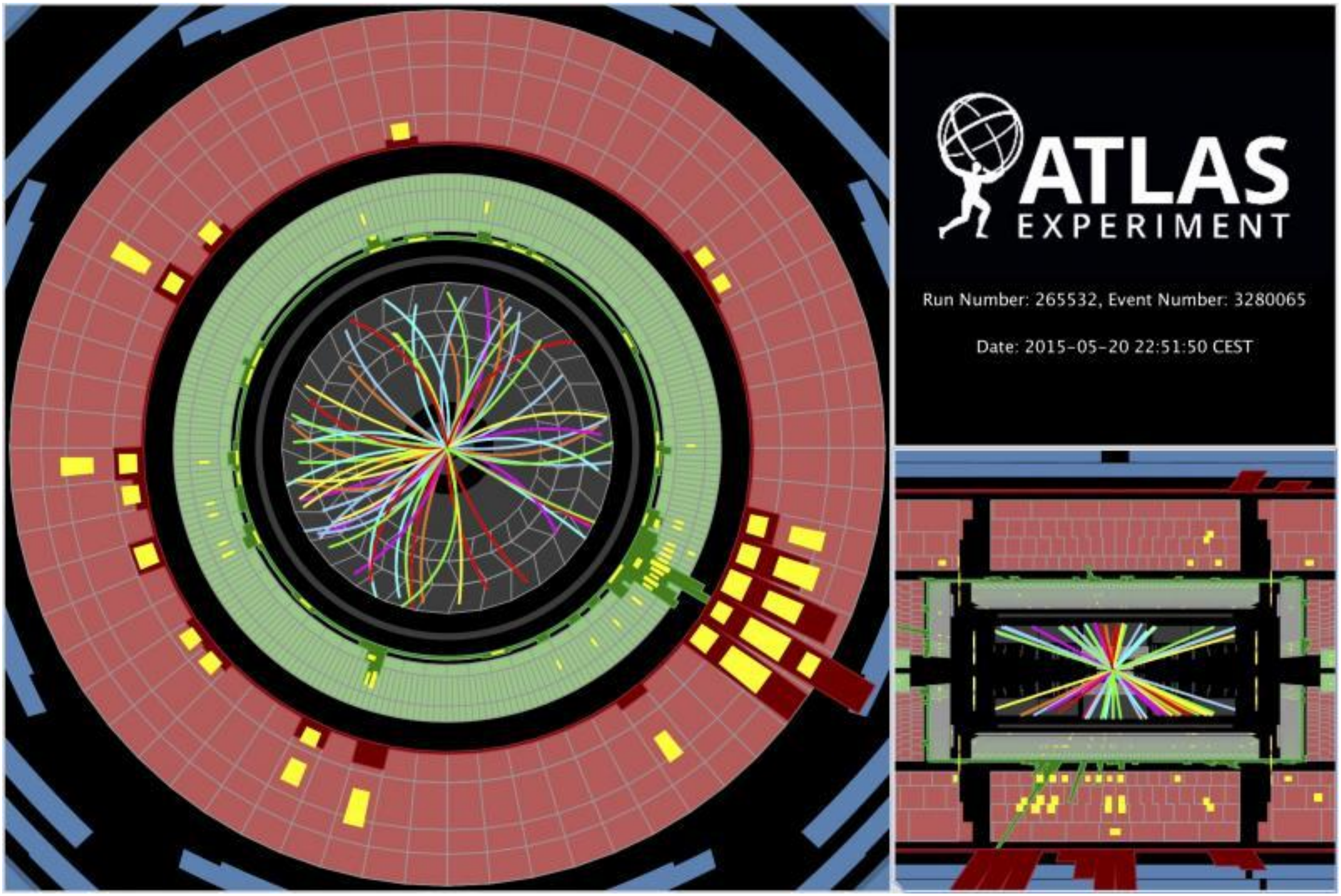
Within the current reach of the LHC, it is not possible to observe the pair production events of the SM Higgs boson. The ATLAS and CMS experiments have reported excesses of different degrees in the search for di-Higgs boson resonances in the vicinity of 300 GeV involving multi-lepton, di-photon and $b\bar{b}$ decays [7–9]. While the excesses remain far from conclusive, in this paper we consider the implications of a hypothetical new scalar, H, with a mass around 300 GeV.

It is tantalizing to connect these two features with a simple model. The aim of the paper is to explain some of the excesses simultaneously using a phenomenological framework obtained by extending the SM with a heavy scalar with a mass, $m_H \approx 300$ GeV and a dark matter candidate. The decay of this hypothetical heavy scalar could accommodate the features observed in the search for di-Higgs boson resonances and the Higgs boson transverse momentum. We adopt a bottom-up approach to explain the experimental discrepancies simultaneously.

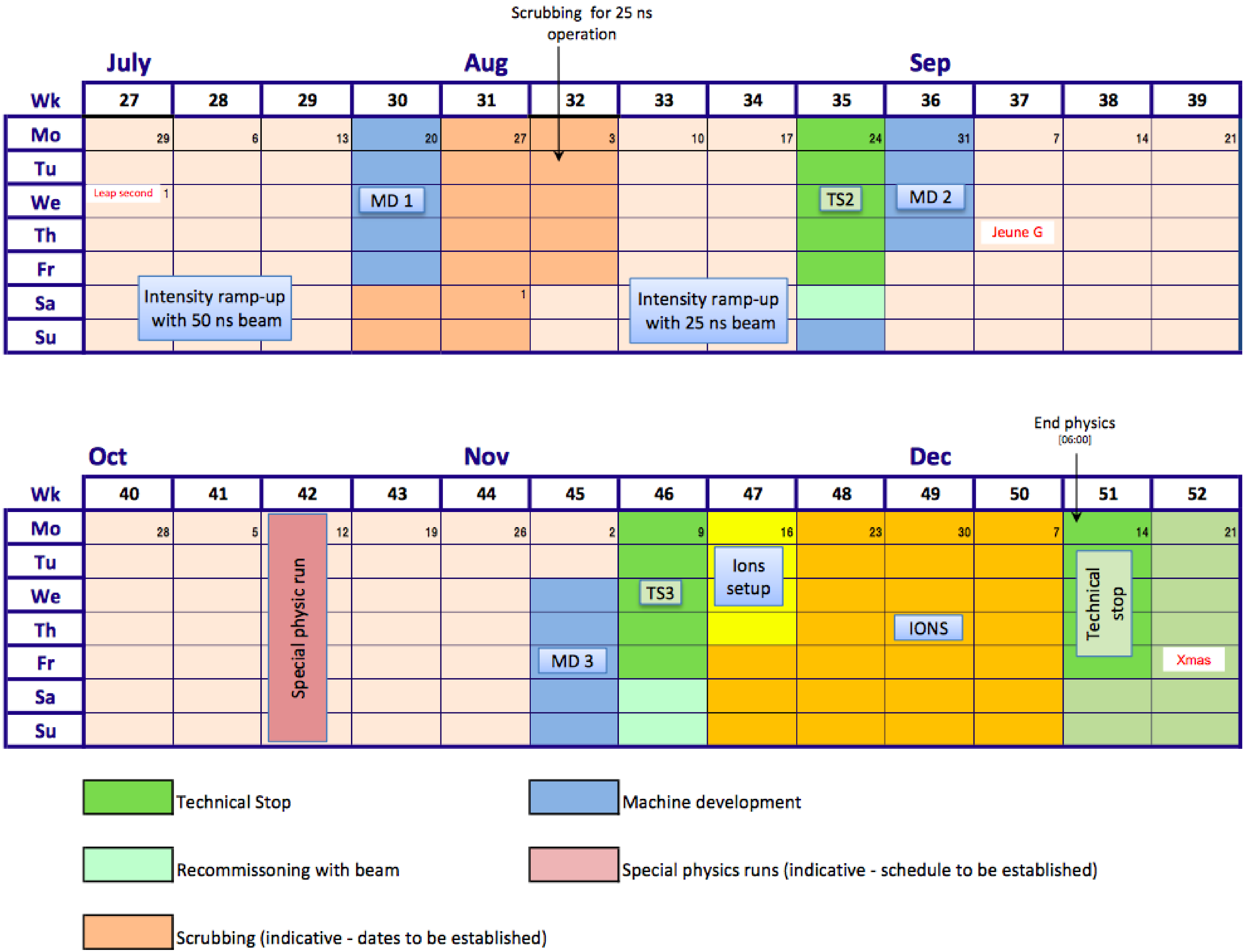
[1] The CMS collaboration reported a sPlot signal-weighted distribution of p_{Th} with the $h \to ZZ^* \to 4\ell$ decay [5]. This result is not used in this paper due to the complexity of the interpretation. The ATLAS collaboration has recently reported on the combination of the differential distributions obtained with the di-photon and the $h \to ZZ^* \to 4\ell$ decays [6].

Prospects With Run II

First collisions recorded by the LHC experiments at the record 13 TeV proton-proton Center of mass energy on May 20^{th}



Prospects for 2015



What to expect from Run II

By the end of 2015 we should get sufficient data to gain sensitivity comparable to that we gained up until 2012. At this point we could confirm the excesses and be on the way to a new discovery

Before summer (Northern Hemisphere) of 2016 will get sufficient data to declare discovery, if excesses are confirmed.

From my summary talk of a workshop in Pittsburg, January 15th 2012, few months before the Higgs discovery

**Excesses come,
excesses go.
We really hope that this one is here to stay.
In any case, the future is bright!**

Same applies now!