Particle and Astroparticle Physics Colloquium Hamburg, 25 May 2021

The Art of the Impossible

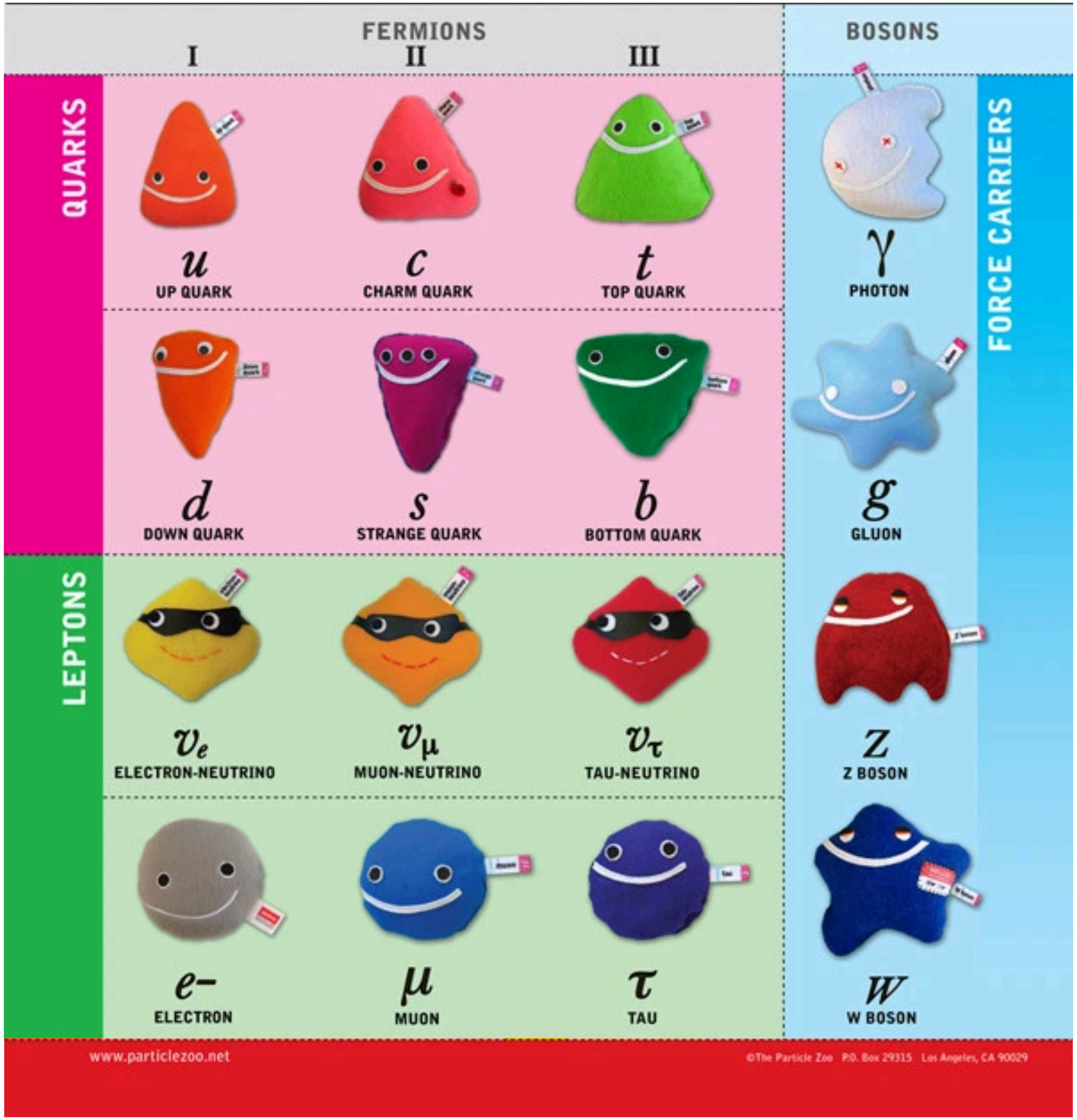
Probing Challenging Higgs Channels at the LHC

Heather M. Gray, UC Berkeley/LBNL

Disclaimer: likely some ATLAS bias in the selection

The Discovery of the Higgs at the LHC

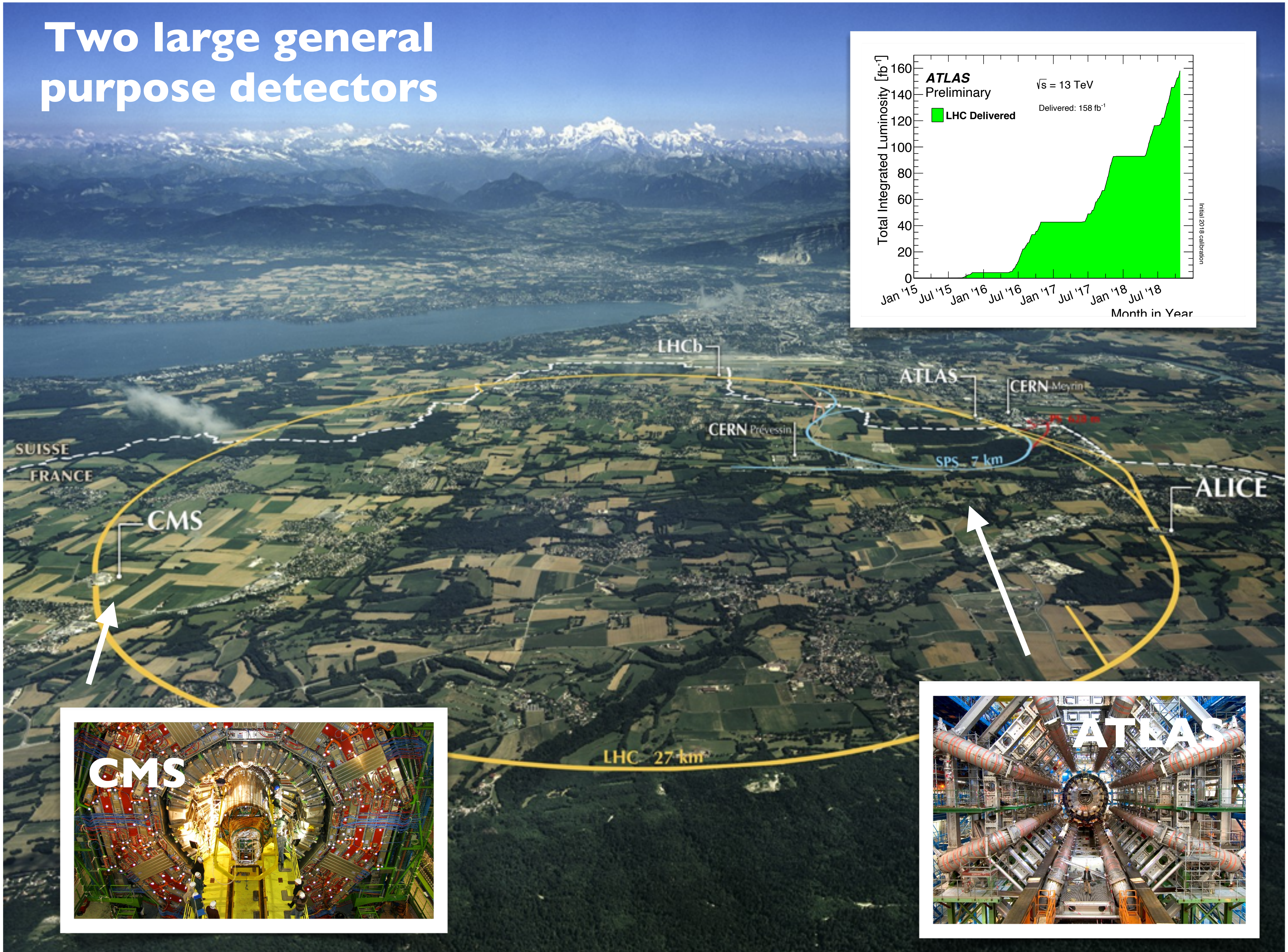
Cast of Characters: The Standard Model



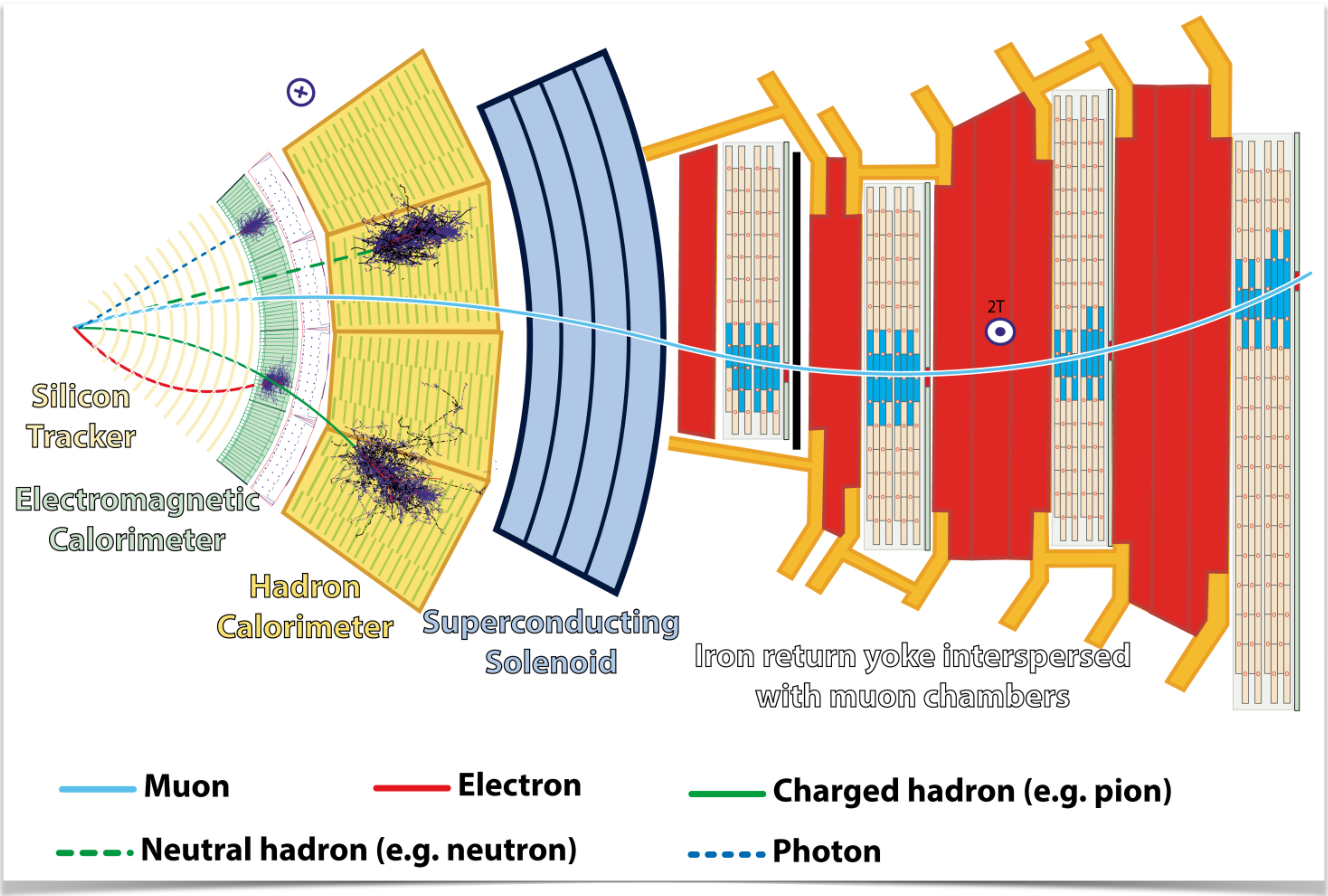
HIGGS BOSON

https://www.particlezoo.net/Particle zoo

The Large Hadron Collider (LHC)



Particle Detection with CMS



4 July 2012: Higgs (In)dependence Day

ps

LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

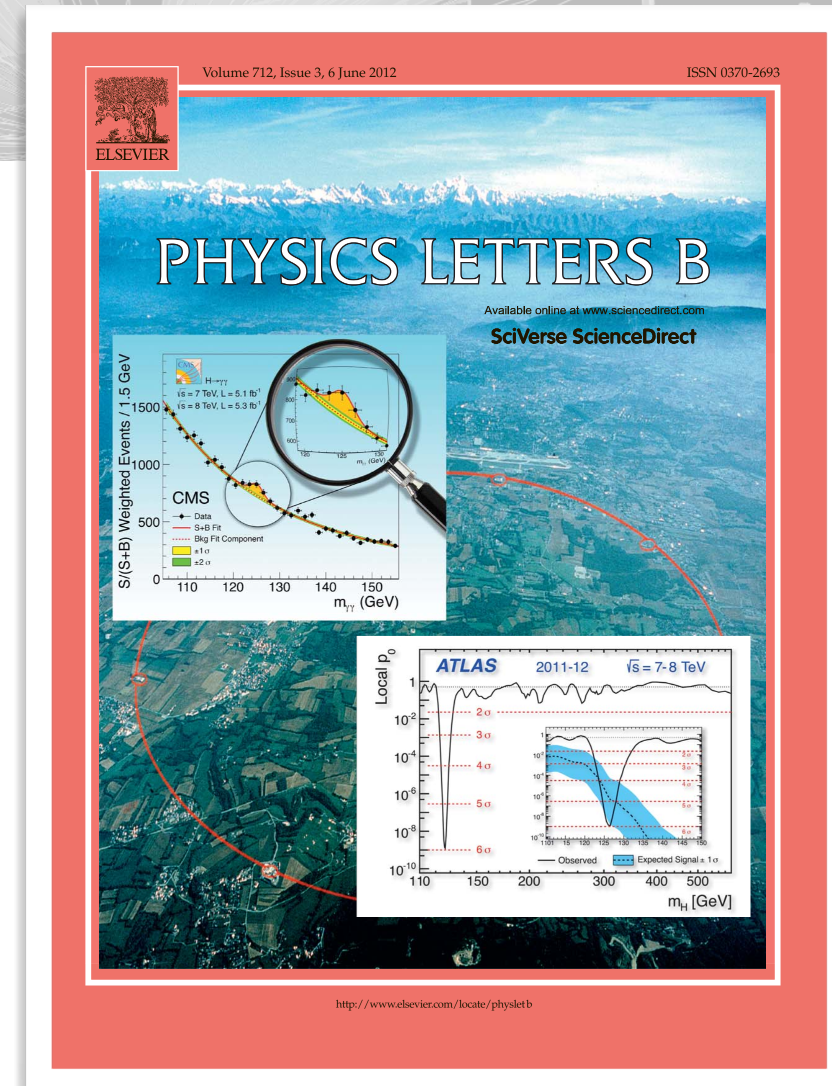
This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

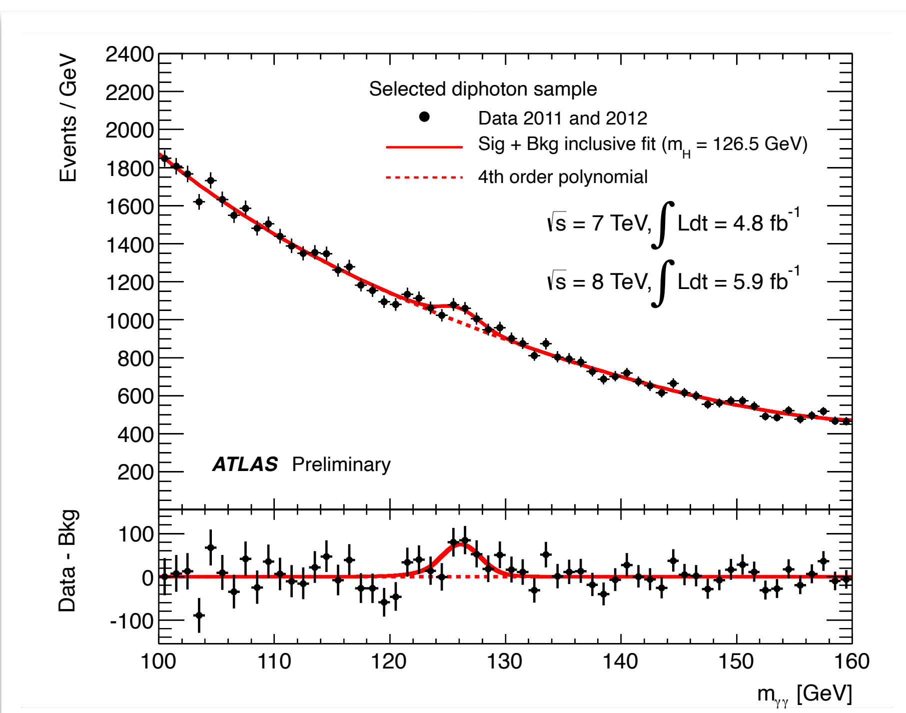
We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

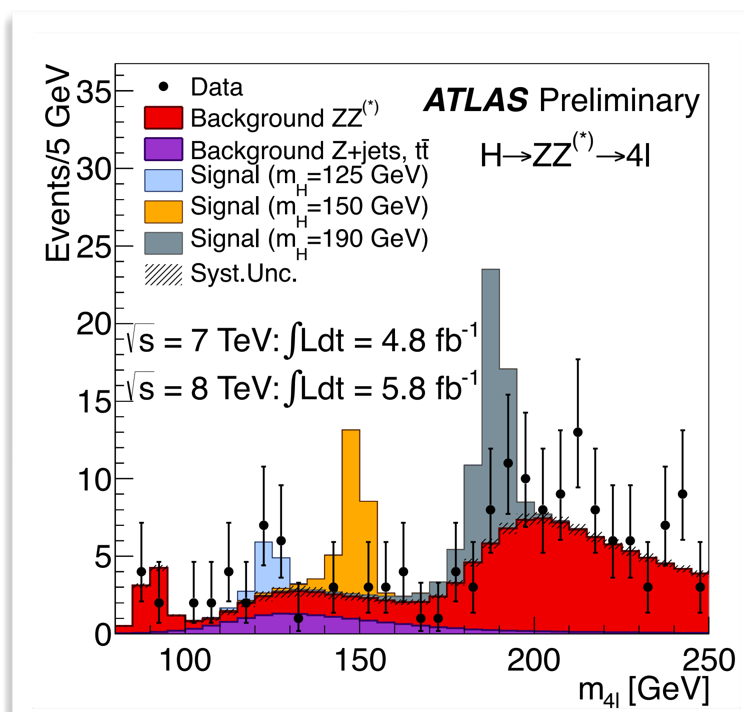
Duration of projects /planning stability:
First LHC workshop 1984 !

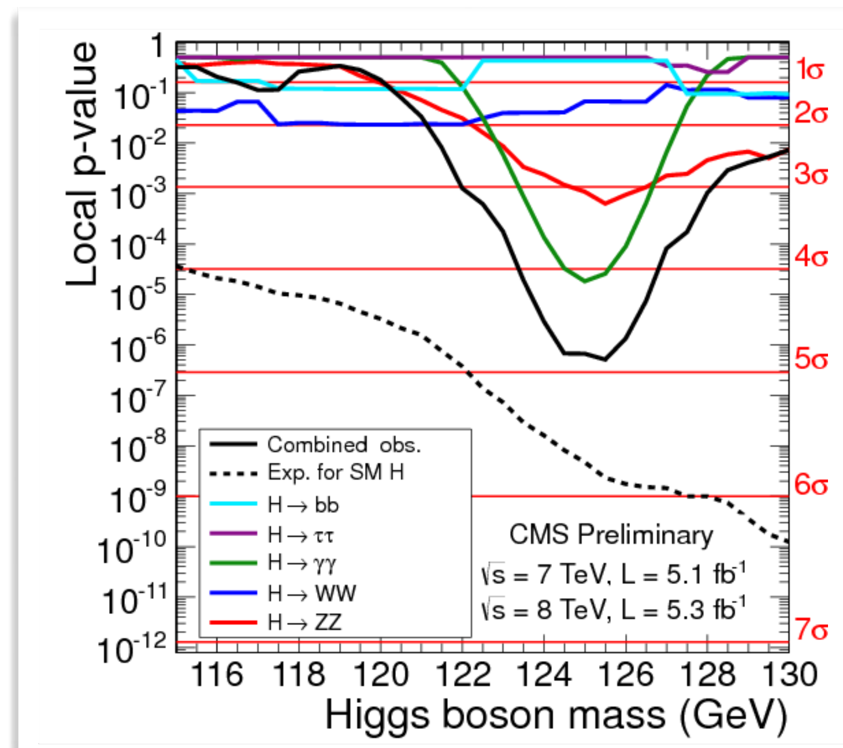
Discovery in One Slide

- 5+5 fb^{-1}: ~5σ observation
- CMS: five Higgs decay modes; γγ, ZZ, WW, bb, ττ
- ATLAS: Only γγ and ZZ(4l), but slightly greater sensitivity
  - Many key contributions from members of the DESY group
- Two papers in PLB
- Nobel Prize for Higgs and Englert in 2013







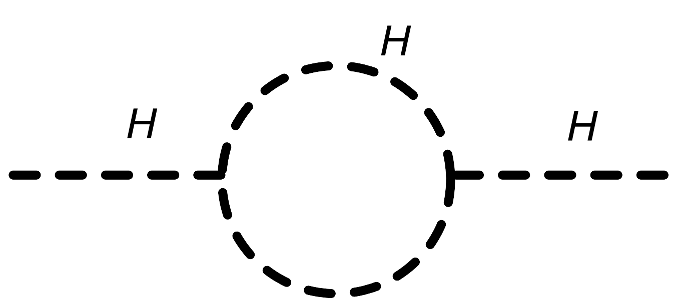


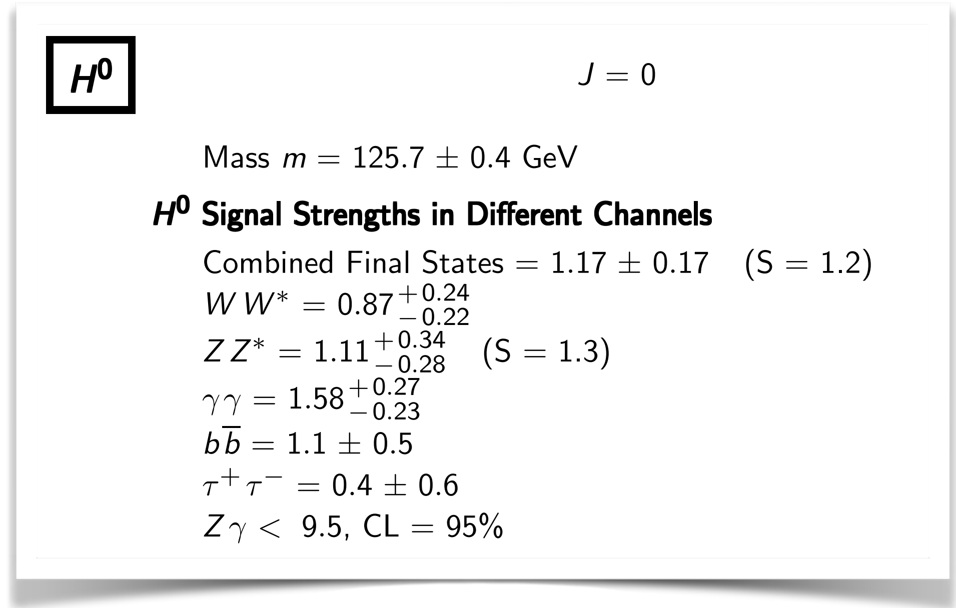
From Discovery to Measurement

- Since the 2012 **discovery**, now measure the **properties** of the Higgs
- **Key properties include**
    - Mass
    - Width
    - Couplings to fermions and gauge bosons
        - Measure production and decay modes
    - Spin/parity

$$J^{PC} = 0^{++}$$

- Self-interaction




H^0 $J = 0$

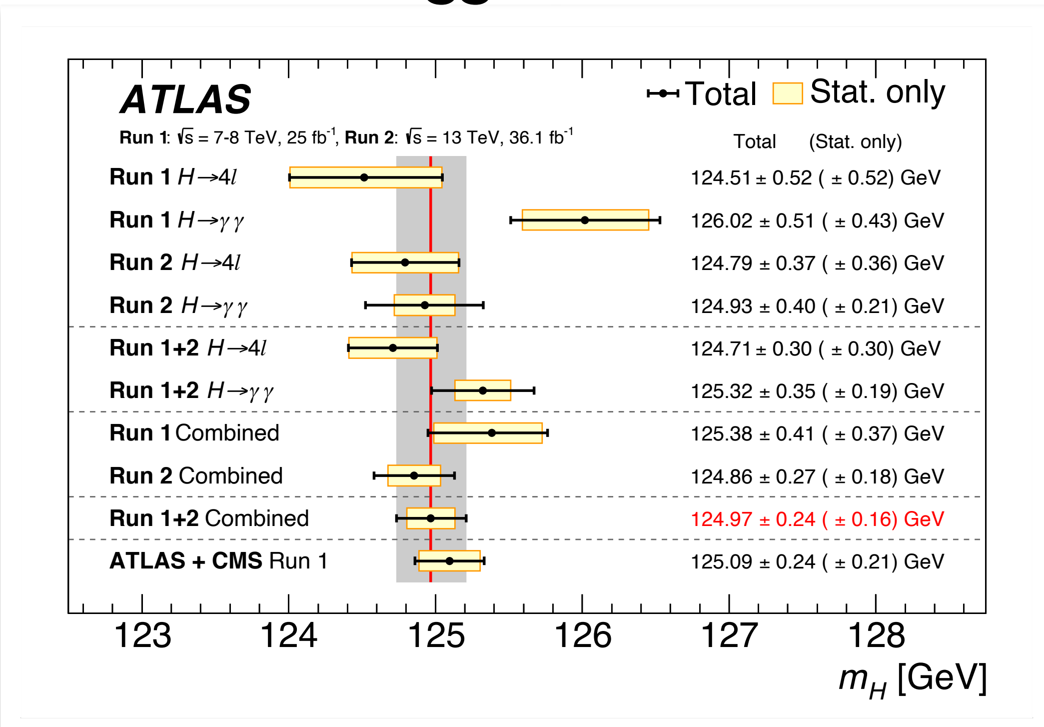
Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

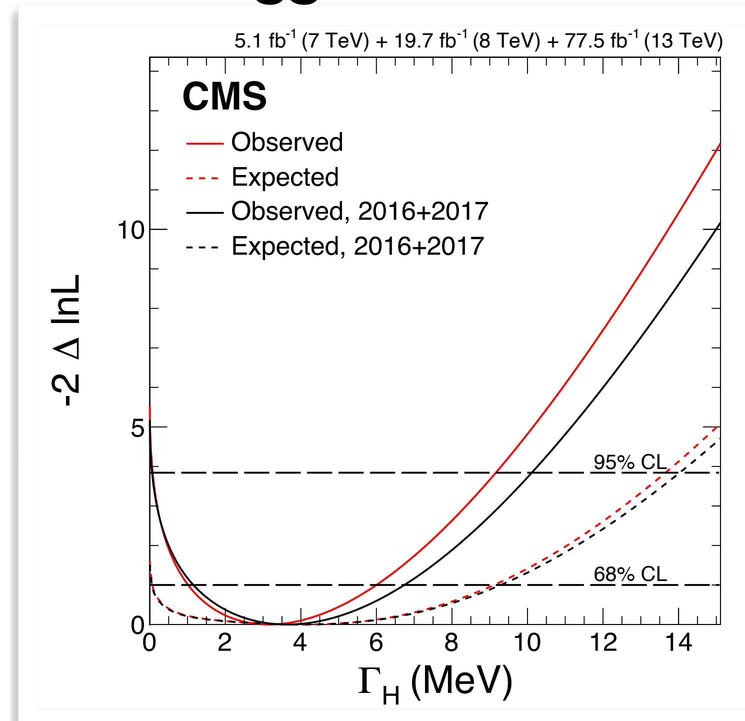
Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$W W^* = 0.87^{+0.24}_{-0.22}$
$Z Z^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$
$b\overline{b} = 1.1 \pm 0.5$
$\tau^+\tau^- = 0.4 \pm 0.6$
$Z\gamma < 9.5$, CL = 95%

Measuring the Properties of the Higgs boson

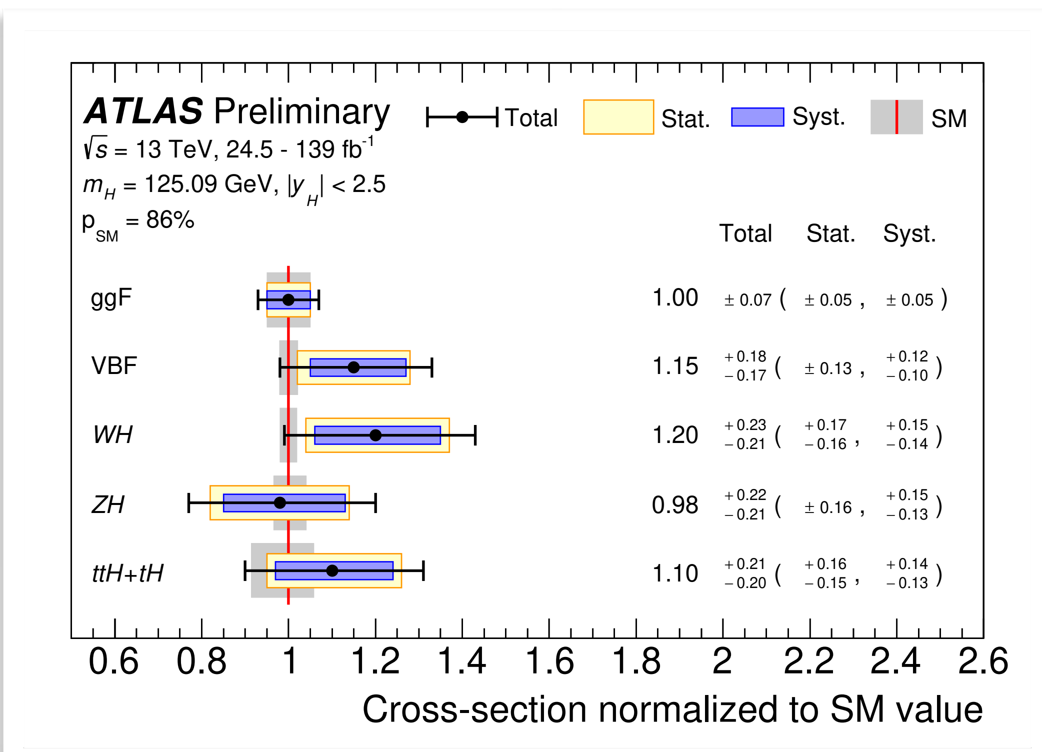
Higgs mass



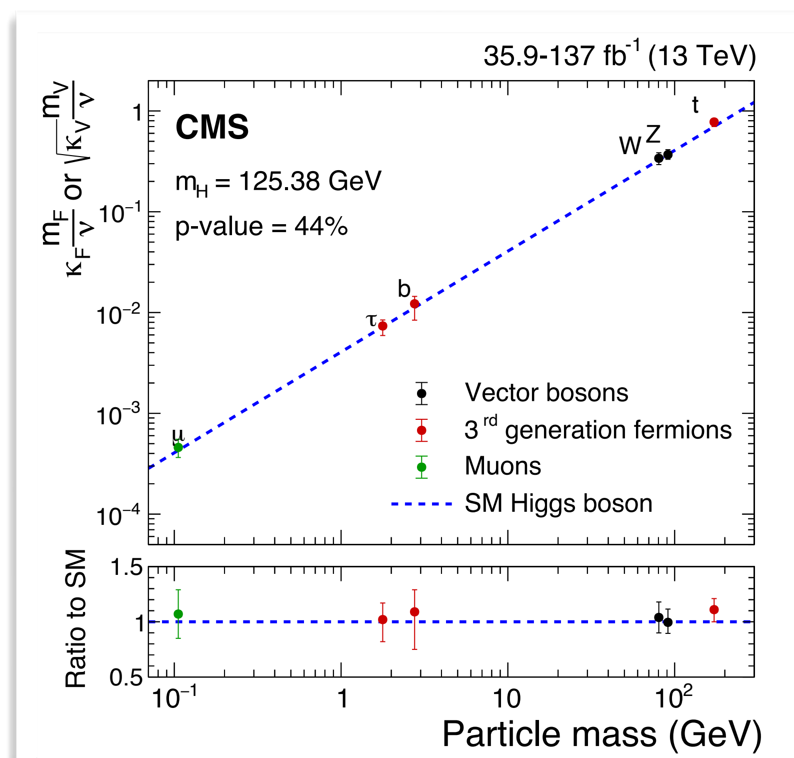
Higgs width



Major production modes



Higgs couplings to SM particles

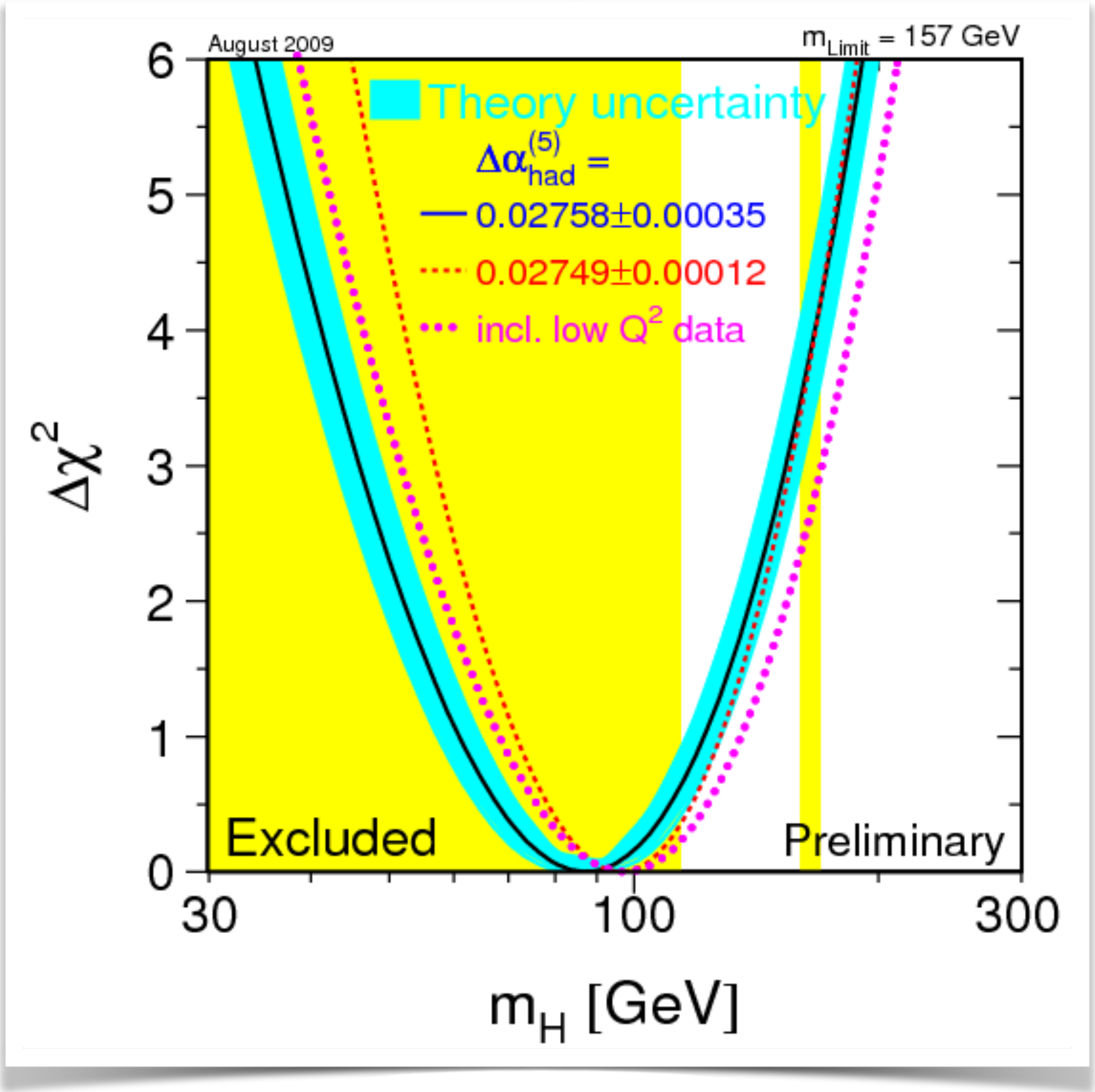


ATLAS-CONF-2020-027, HIG-18-002, HIG-19-006

Designing for Discovery

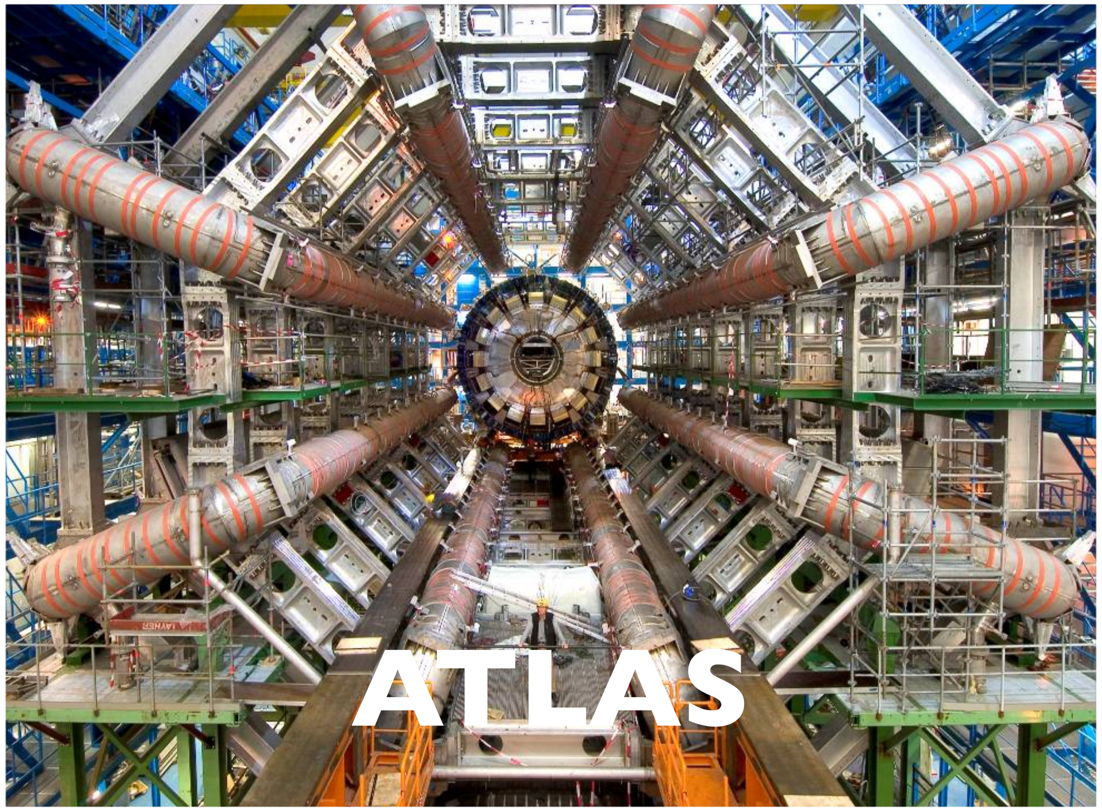
Expected discovery? No lose theorem

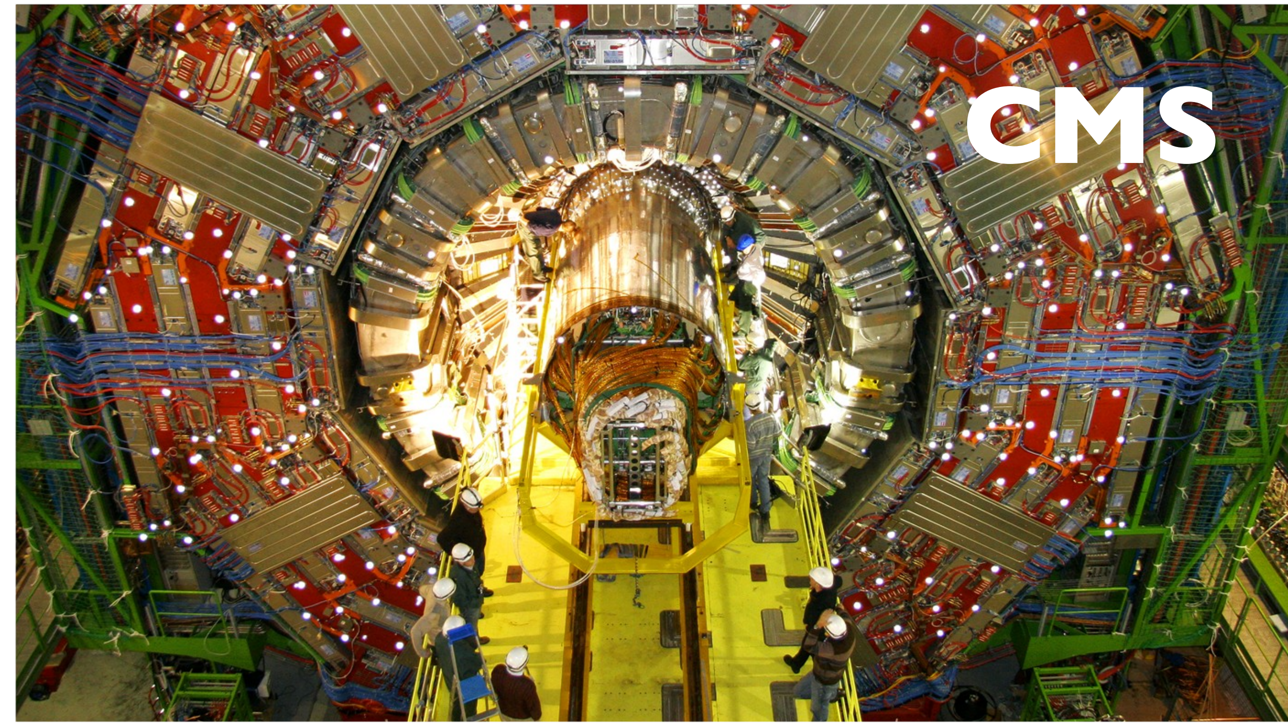
- **Discoveries** are by definition never really expected
- For the LHC, we were very lucky: **strong arguments** that we needed to see something
- **Experiment**
  - Higgs mass between **114 and 200 GeV** from previous accelerators (LEP, Tevatron) and constraints from a fit to electroweak data
- **Theory**
  - Some mechanism needed to give **mass** to the W,Z bosons
  - **Unitarity violated** if nothing found < 1 TeV



arXiv:0911.2604

Designing for Discovery





- γγ and ZZ(4l) analyses played a key role in driving the design requirements for ATLAS and CMS, e.g.
  - good diphoton and dimuon mass resolution: <1% at 100 GeV
  - 'wide' geometric coverage: $|\eta|<2.5$

> The $H \to \gamma\gamma$ analysis covers one of the most promising channels for a low mass Higgs discovery and for precision Higgs mass measurement at the LHC. This channel has been an important motivation for the design of the electromagnetic calorimeter (ECAL) of CMS. It is

CMS Physics TDR

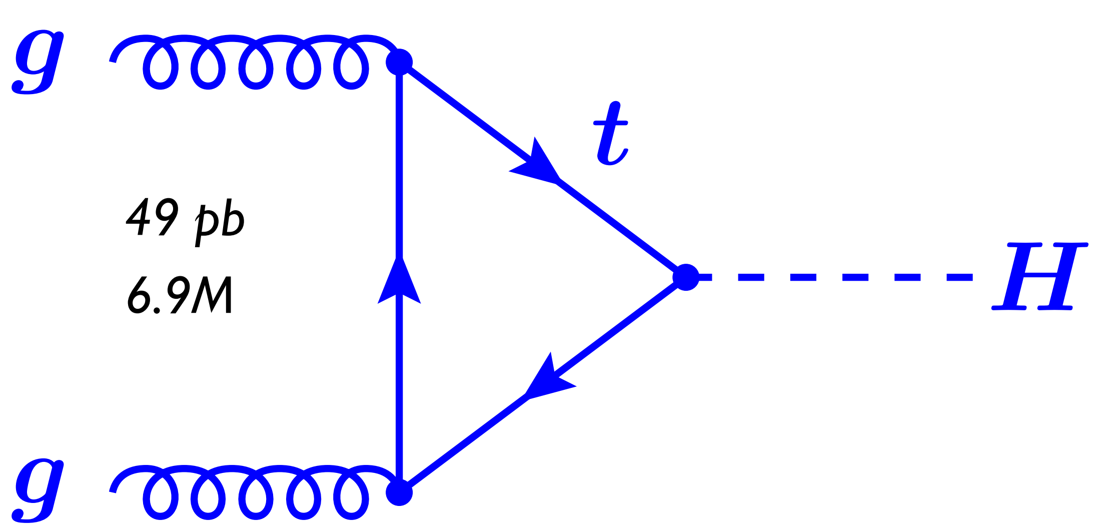
The Unexpected

- The **discovery of the Higgs boson** is the greatest achievement of the LHC
  - ATLAS and CMS were designed to and did discover the Higgs boson
- But today I'd like to focus on something a little different
- What was **not predicted, not expected**
- And some things that were even thought to **be impossible** at the LHC
- Goal: Provide some ideas about what happened to make the **impossible possible**
  - Stimulate creativity for future measurements
- Particle focus on the interaction of the Higgs boson with **quarks**

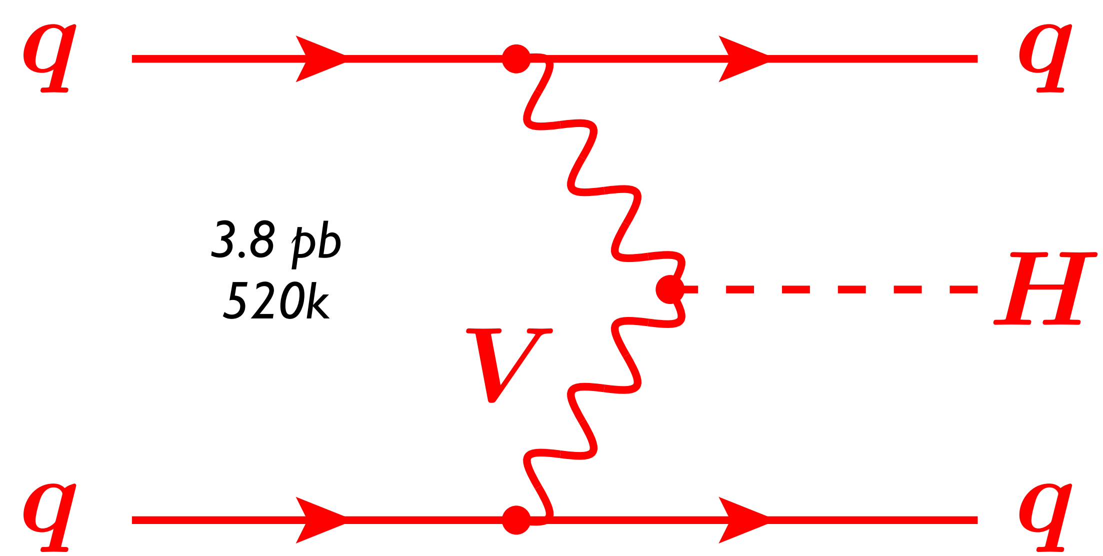
Higgs Production and Decay at the LHC

Higgs Production at the LHC

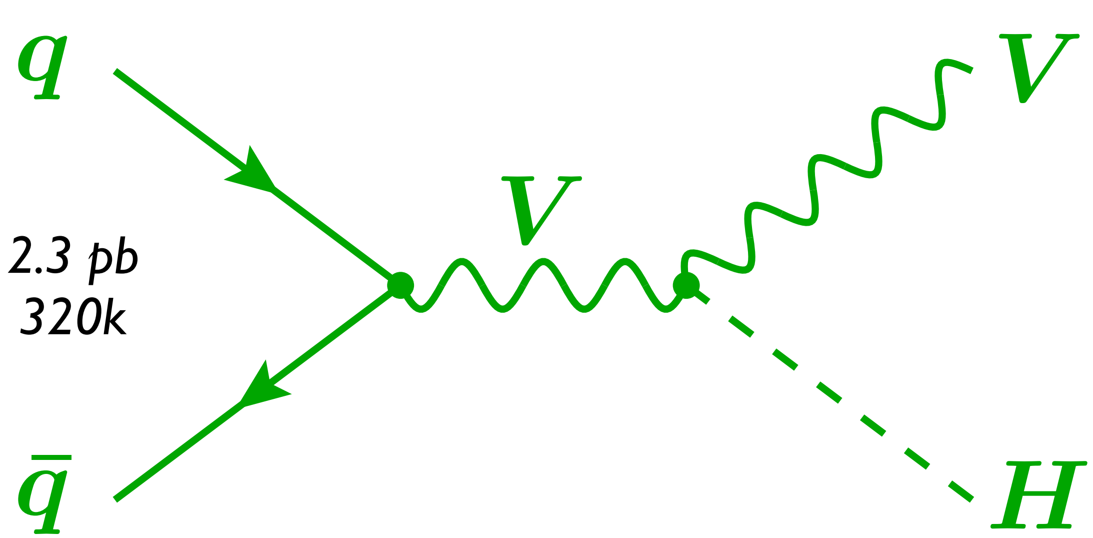
σ [pb]
#Higgs produced during Run-2 at ATLAS



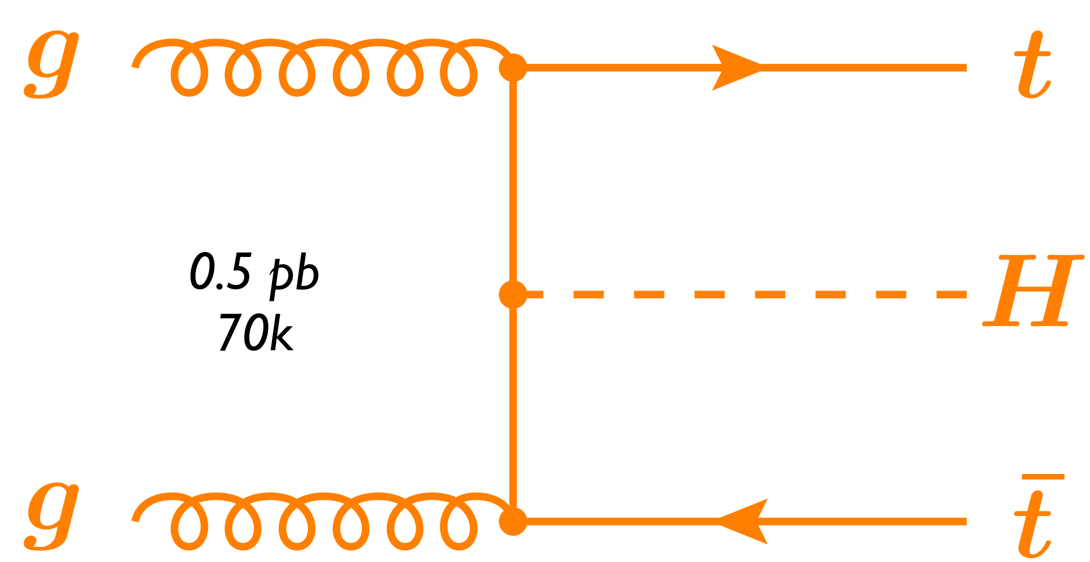
Main production channel: gluon-gluon fusion



2 forward jets, little central hadronic activity



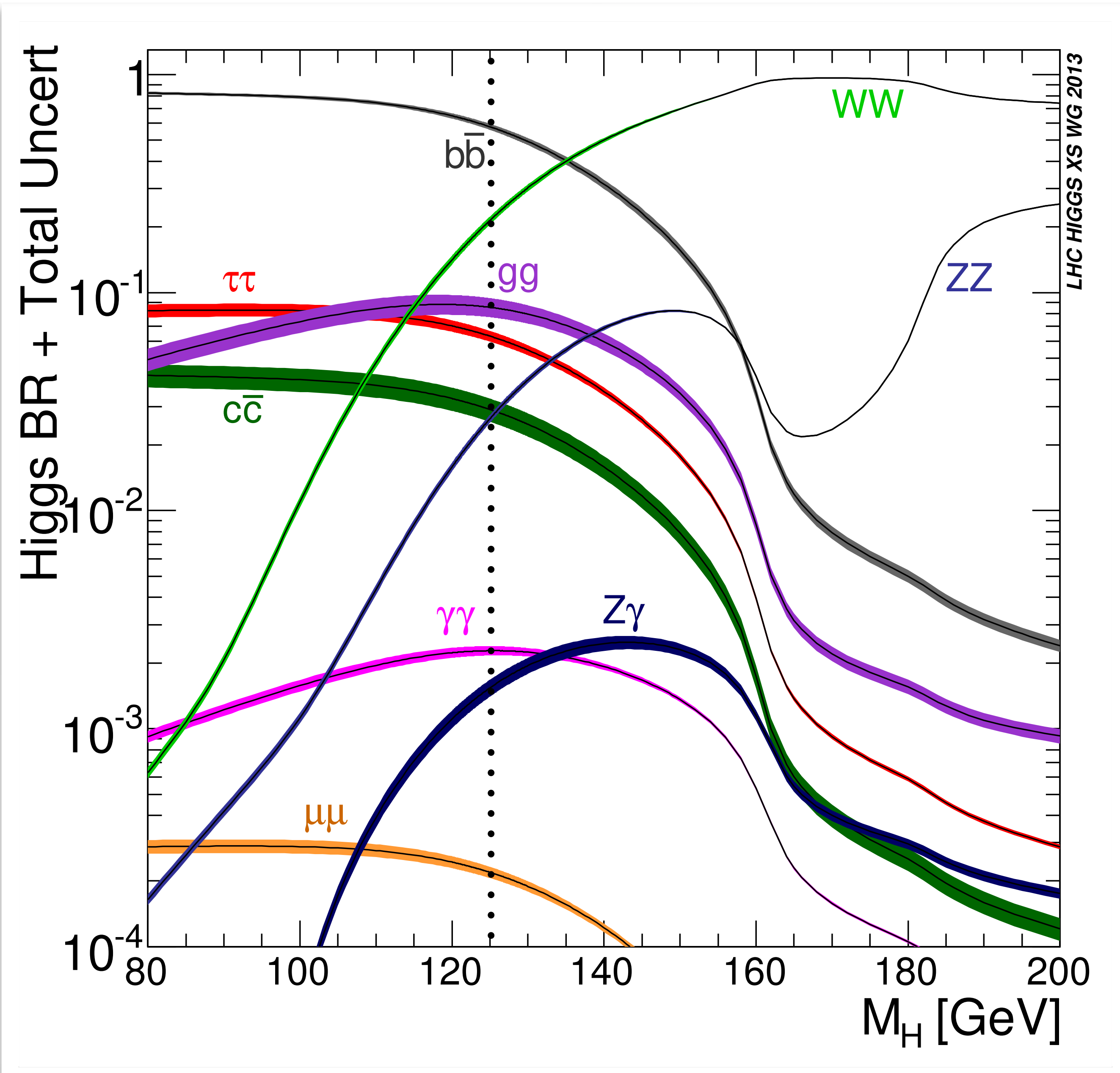
Tag W and Z decays



Tag 2 top quarks

Diagrams courtesy of F. Tackmann

Higgs Decays at the LHC



LHCHWG

A Higgs mass of 125 GeV:
an experimentalist's "dream", but a (SUSY) theorist's "nightmare"

5 main channels at the LHC

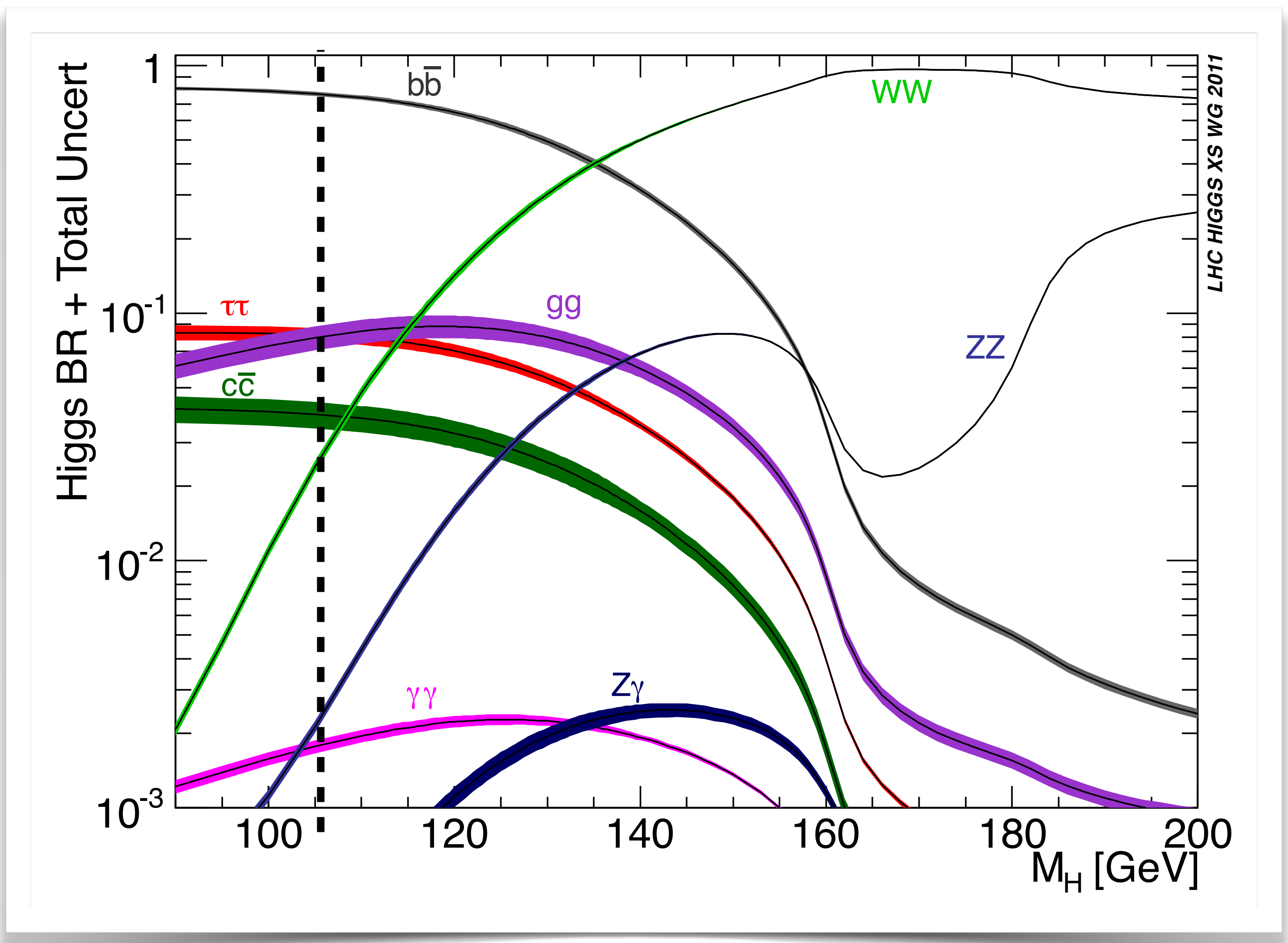
Decay branching fractions for m_H = 125 GeV

- $H \to bb$: 58 %
- $H \to WW^*$: 21%
- $H \to \tau^+\tau^-$: 6.3%
- $H \to ZZ^*$: 2.6%
- $H \to \gamma\gamma$: 0.2%

Coupling to b-quarks

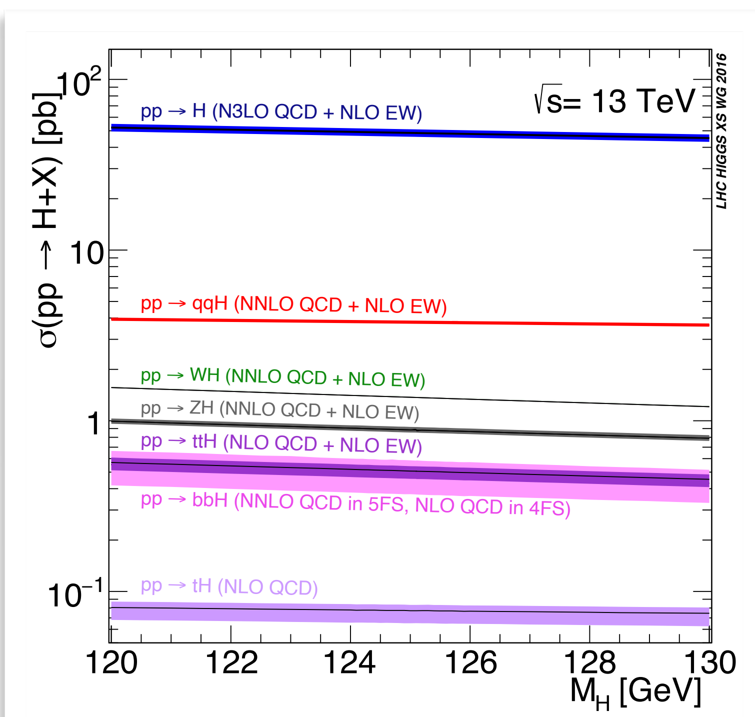
Coupling to b-quarks

- Higgs decays **most often** to a pair of b-quarks (~58%)
- Largest branching ratio: large contribution to **total width**
- Higgs coupling to **fermions**
- Higgs coupling to (third-generation) **quarks**

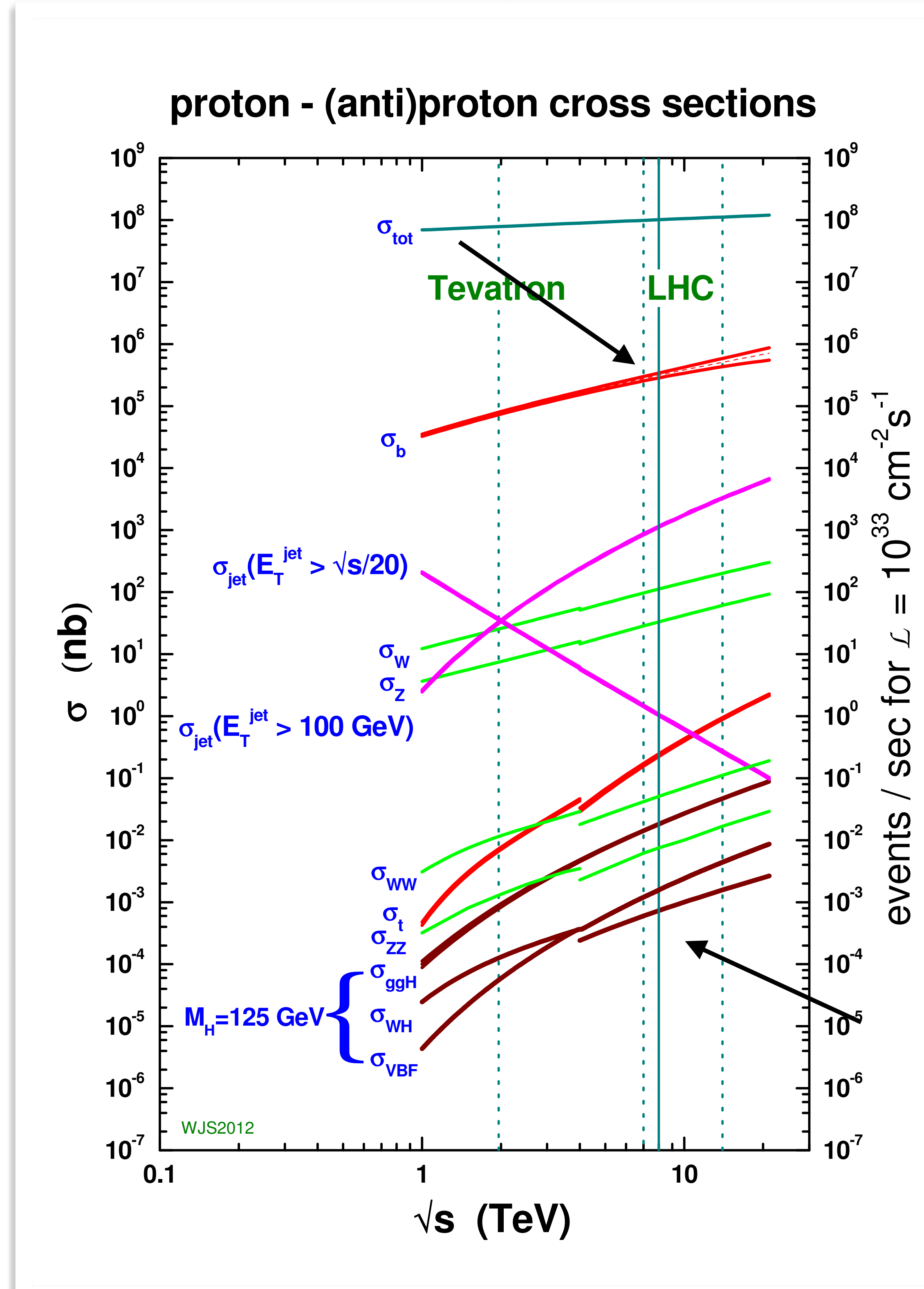


Not an easy measurement

- Using ggF is incredibly challenging*
  - **bb dijet** production cross-section is many orders of magnitude larger
  - no clear **trigger**
- **Associated production** (WH and ZH) has smaller backgrounds and clear trigger



HXSWG



J. Stirling

I used to say 'impossible' but now revised that given HIG-19-003

WH(bb) in the ATLAS TDR

- Three channels for VH(bb)
  - $Z(\nu\nu)H(bb)$ - 0 lepton
  - $W(\ell\nu)H(bb)$ - 1 lepton
  - $Z(\ell\ell)H(bb)$ - 2 lepton
- $W(\ell\nu)H(bb)$ Selection
  - One lepton passing the trigger with $p_T > 20$ GeV (electron) and $p_T > 6$ GeV (muon)
    - No other leptons with $p_T > 6$ GeV
  - Two jets with $p_T > 15$ GeV; $|\eta| < 2.5$
    - No additional jets with $p_T > 15$ GeV and $|\eta| < 5.0$
  - 60% b-tagging efficiency

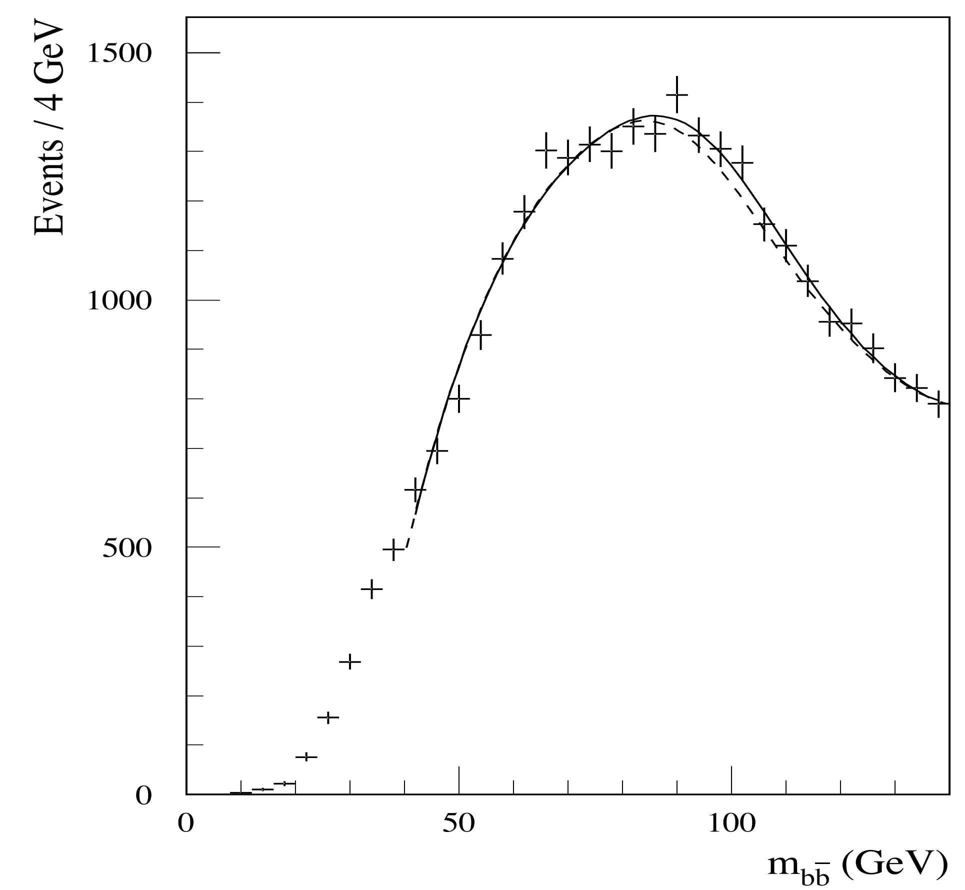


Figure 19-7 Expected *WH* signal with $H \to b\bar{b}$ above the summed background for $m_H = 100$ GeV and for an integrated luminosity of 30 fb^{-1}. The dashed line represents the shape of the background.

ATLAS Physics TDR Vol 2, 1999

Conclusion: WH(bb) will be very difficult

As shown in Table 19-6, a *WH* signal might be extracted if one assumes that the various background distributions are all perfectly known. Even in this optimistic scenario, the signal significance is at best 4.7σ for $m_H = 80$ GeV and is below 3σ for values of m_H above the ultimate sensitivity expected for LEP2. These numbers correspond to an integrated luminosity of 30 fb^{-1} expected to be reached over three years of initial operation at low luminosity. It is not clear in all cases how to achieve an accurate knowledge of the various backgrounds from the data.

In conclusion, the extraction of a signal from $H \rightarrow b\bar{b}$ decays in the *WH* channel will be very difficult at the LHC, even under the most optimistic assumptions for the *b*-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.

ATLAS Physics TDR Vol 2

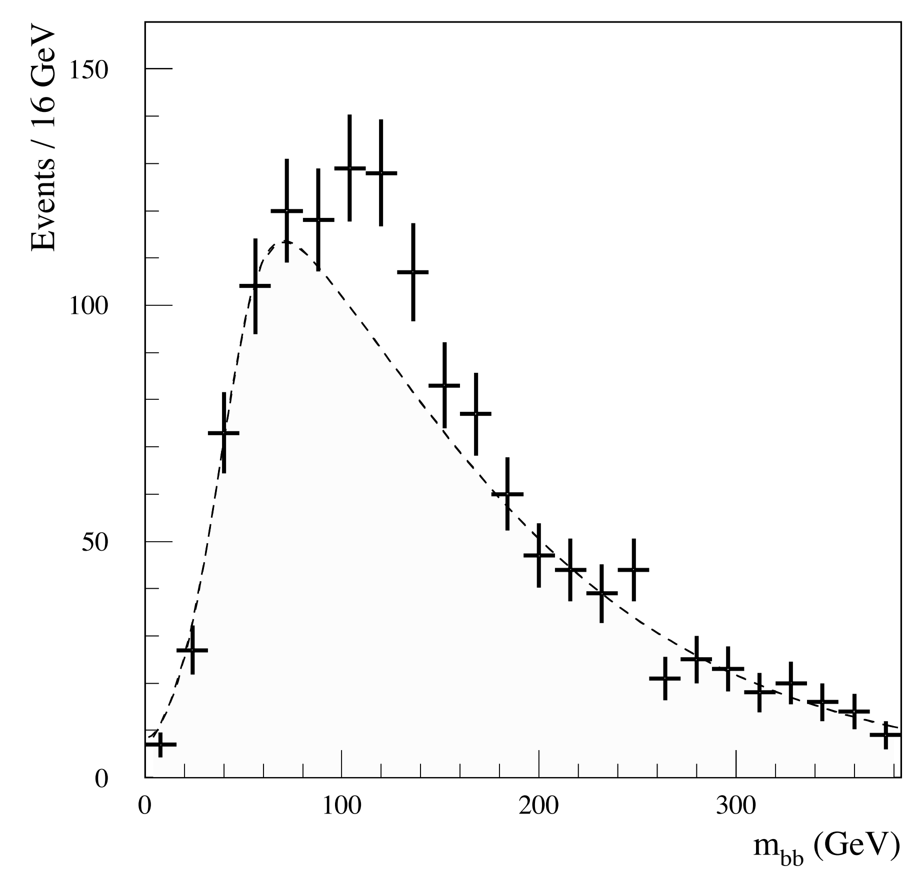
ttH(bb) instead?

In conclusion, the extraction of a Higgs-boson signal in the $t\bar{t}H$, $H \rightarrow b\bar{b}$ channel appears to be feasible over a wide range in the low Higgs-boson mass region, provided that the two top-quark decays are reconstructed completely with a reasonably high efficiency. This calls for excellent b-tagging capabilities of the detector. Another crucial item is the knowledge of the shape of the main residual background from $t\bar{t}jj$ production. If the shape can be accurately determined

using real data from $t\bar{t}$ production, a Higgs-boson signal could be extracted with a significance of more than 5σ in the mass range from 80 to 130 GeV, assuming an integrated luminosity of 300 fb^{-1}. For an uncertainty of ±5% on the absolute normalisation of the background shape, the discovery window would be reduced to the range between 80 and 125 GeV.

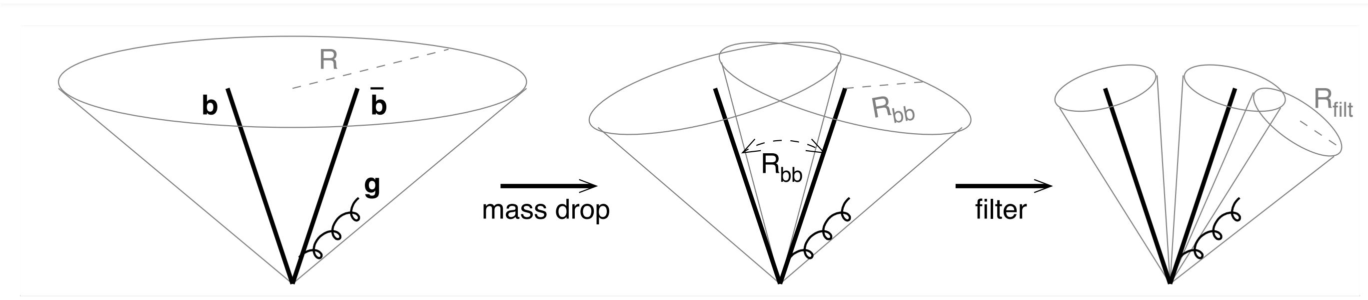
The prospects of VH(bb) considered to be so dire that ttH(bb) was thought to be the more promising channel

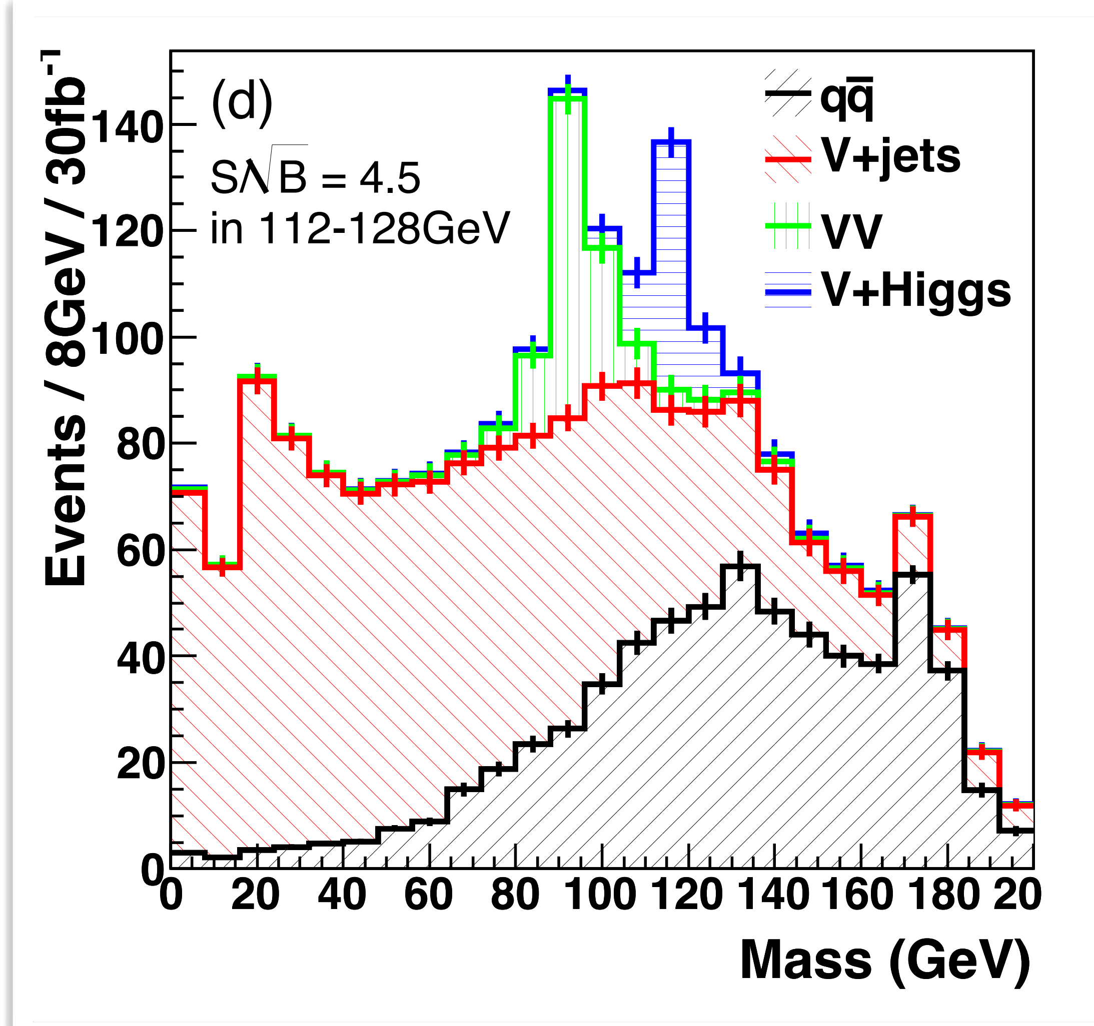
only 300 fb^{-1} needed !



What changed ?

- A paper in 2008 reported a large improvement in H→bb significance from focussing on the high p_T Higgs region and using jet substructure techniques

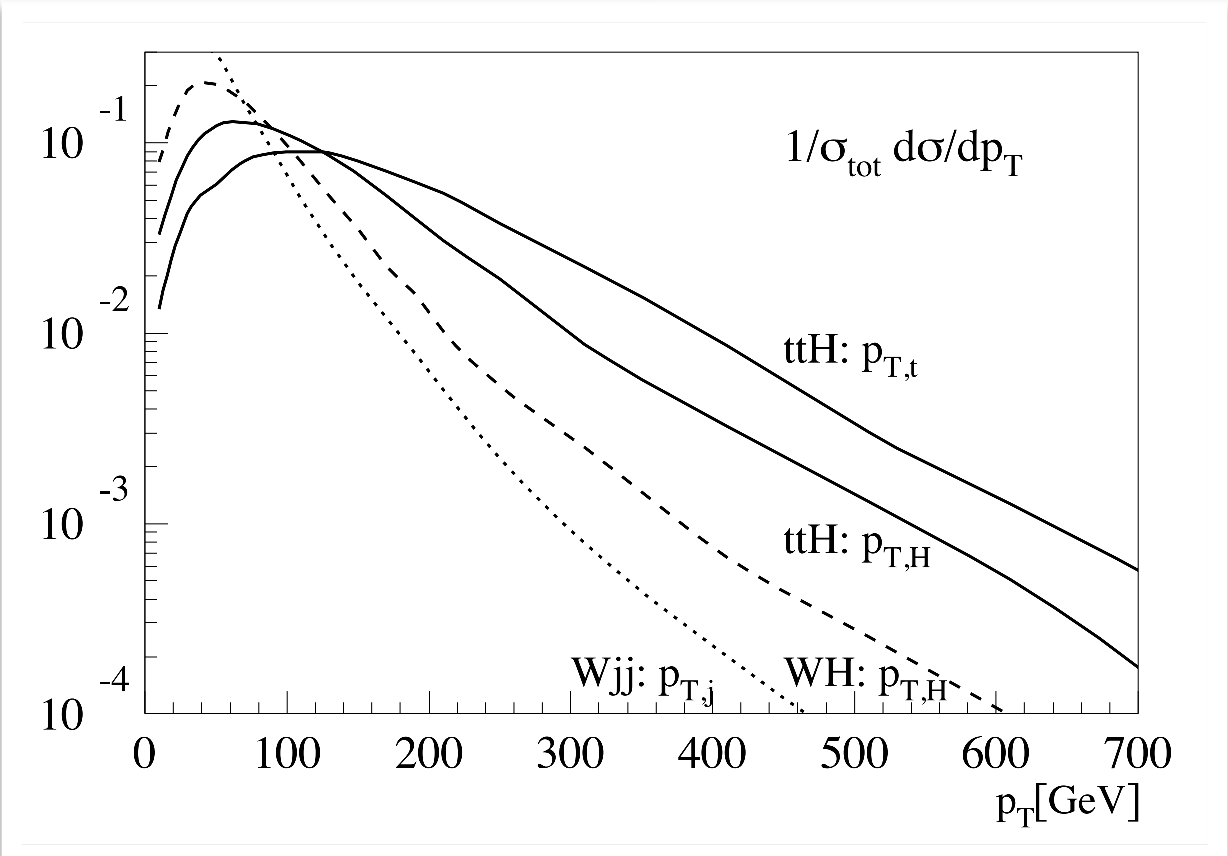




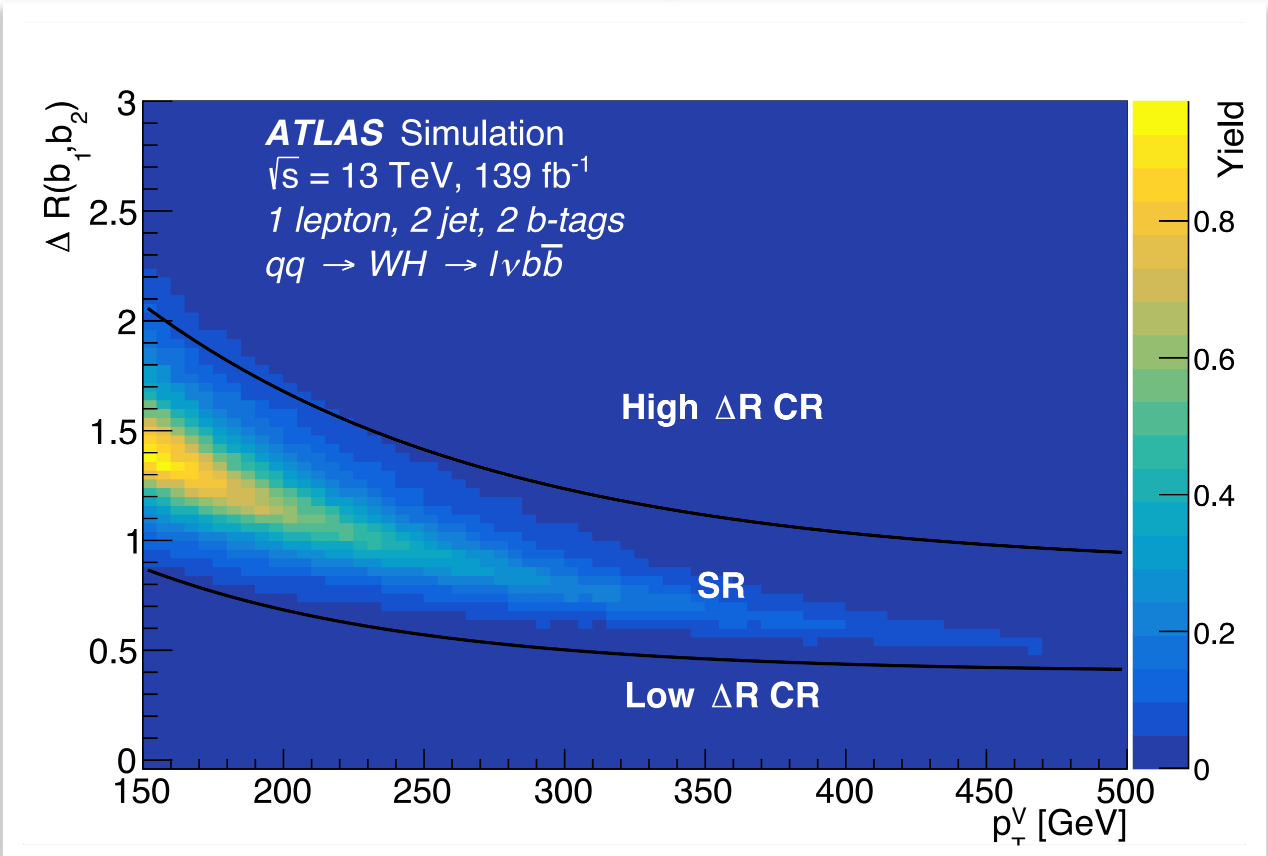
It is widely considered that, for Higgs boson searches at the Large Hadron Collider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

Boost not substructure

- Key observation is that the signal p_T spectrum of the signal is much harder than the background
  - Applying the p_T cut necessary for substructure techniques dramatically improved S/B
  - Exploited in the current ATLAS/CMS analyses by explicit p_T categories and as input variables to BDTs



Plehn et al, arXiv0910.5472



HIGG-2018-51

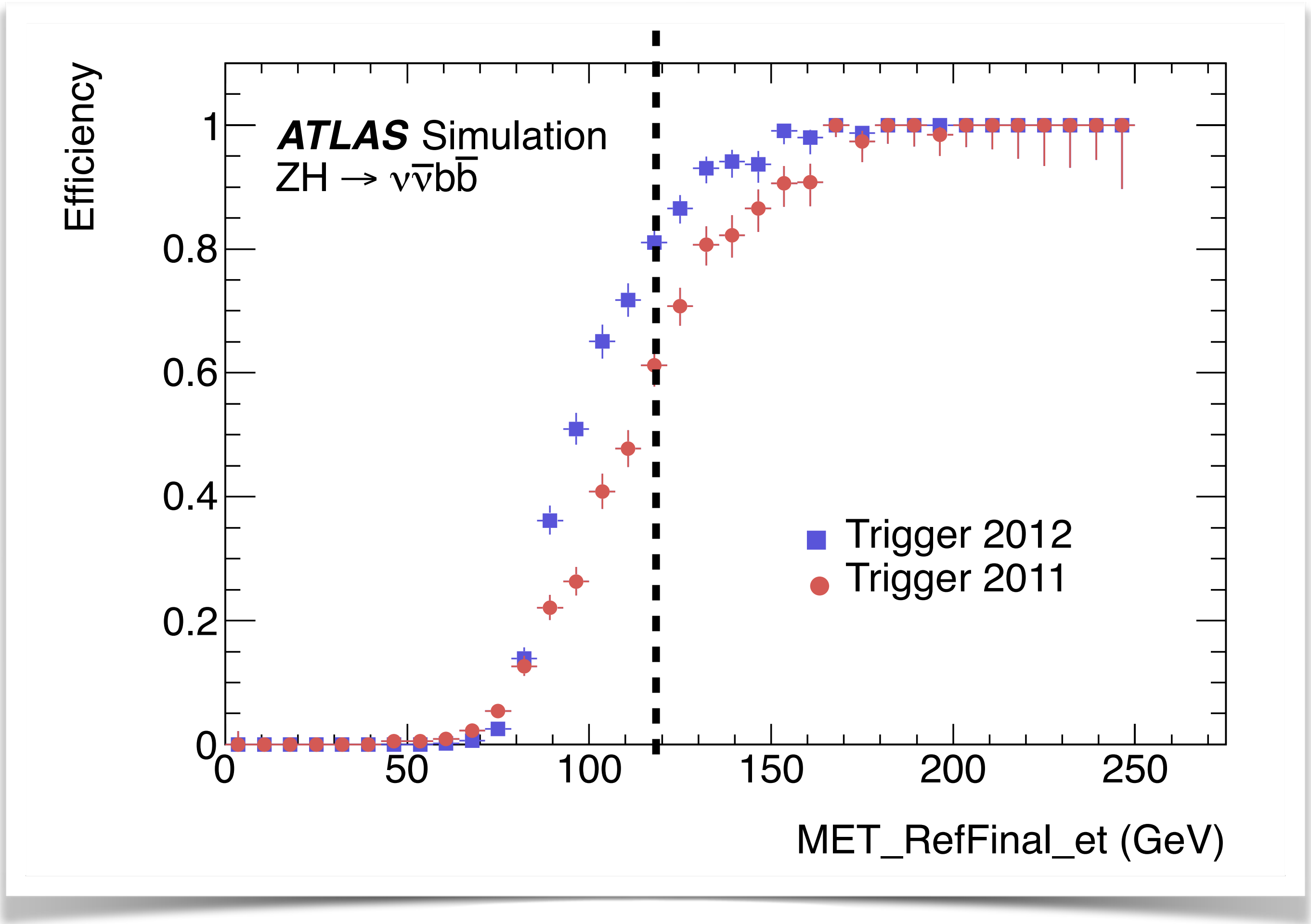
Z(νν)H(bb)

ZH production with $Z \to \nu\nu$: it would be difficult to trigger efficiently on such final states. In addition, this channel suffers from potentially very large experimental backgrounds, given the rather low E_T^{miss} expected for the signal.

Final state contains two b-jets and MET

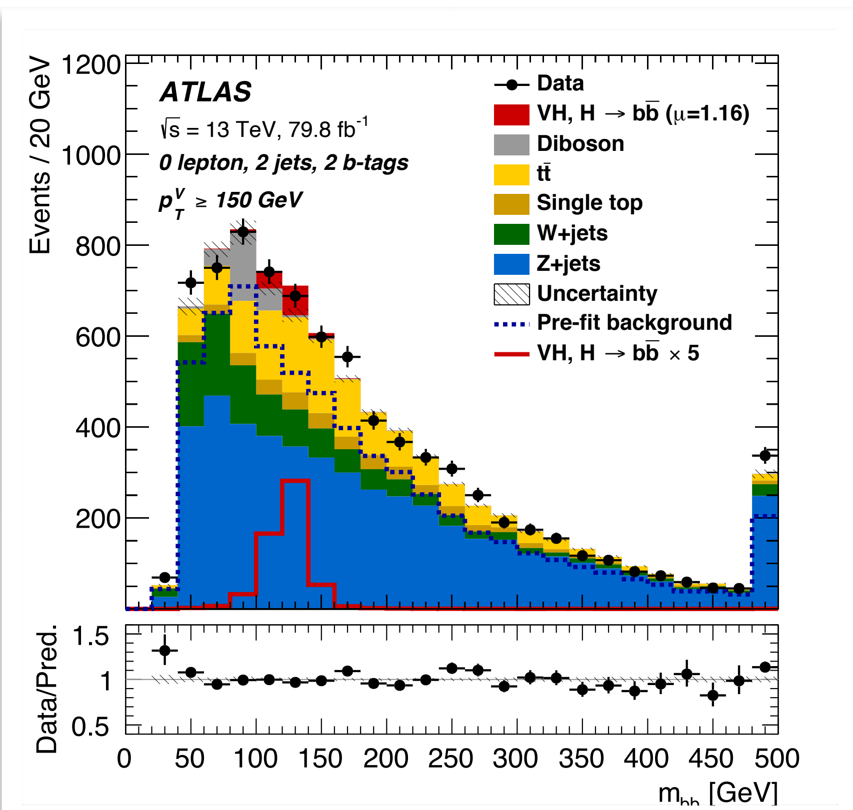
Efficient MET triggers

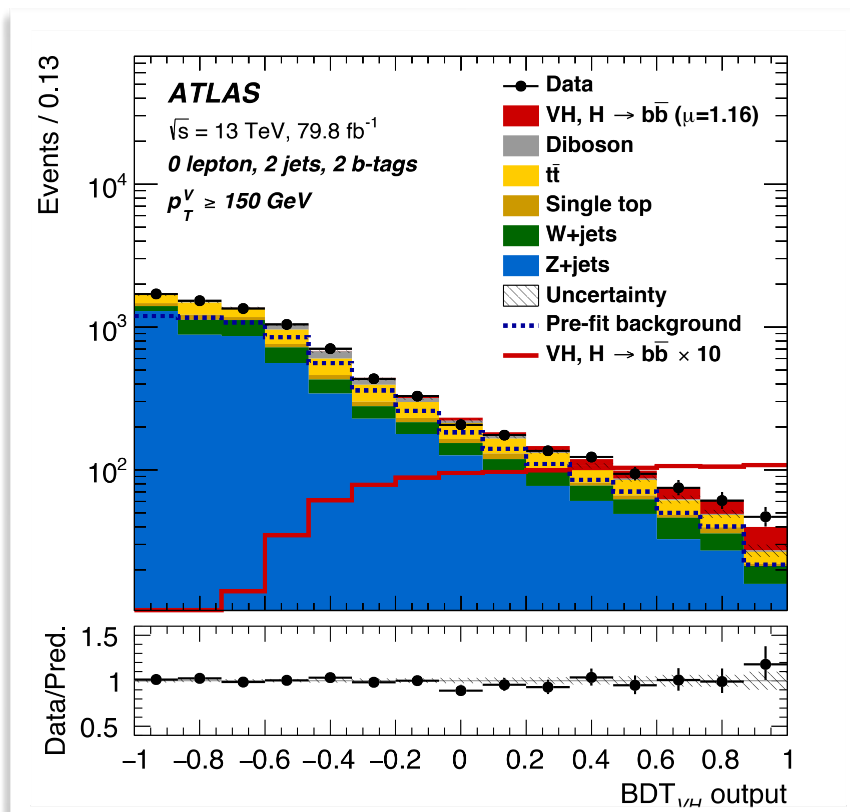
- Development of an efficient MET trigger
    - e.g. L1 noise thresholds, L2 MET trigger
- Accurate measurements of the modelling of the turn-on region allowed the 8 TeV ATLAS analysis to extend to 100 GeV (5% uncertainty)
    - With larger datasets now focus on higher MET region

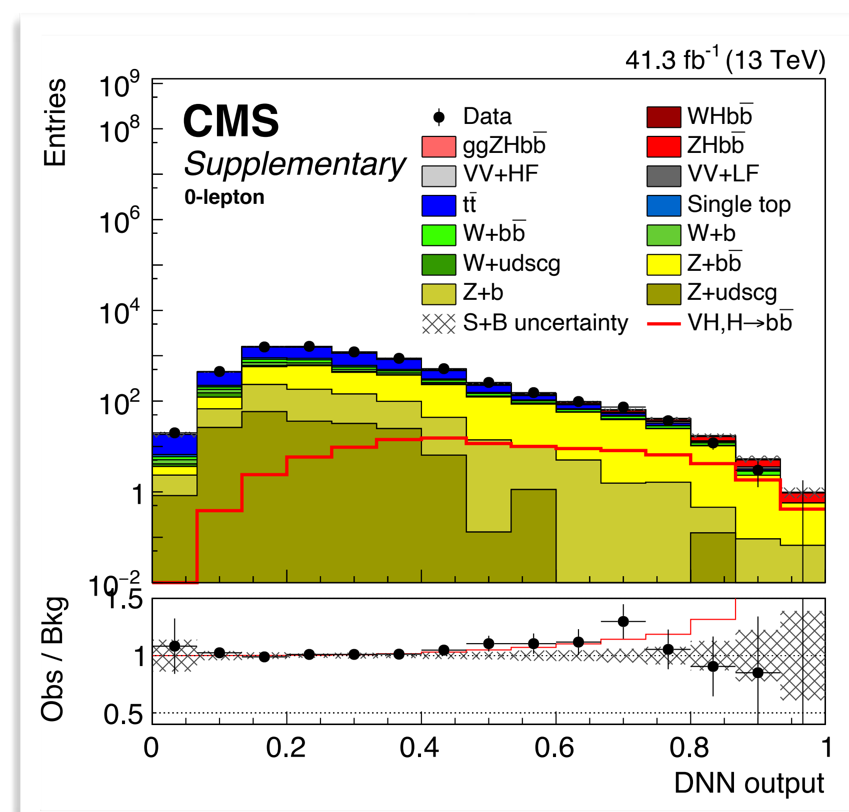


Z(νν)H(bb) Analysis

- Clever topological cuts to reduce backgrounds
- Powerful signal extraction using ML techniques
- Control regions to normalise backgrounds with profile likelihood fits
  - ATLAS: uses signal regions of other VH(bb) channels







HIGG-2018-51

HIG-18-016

Most powerful bb channel!

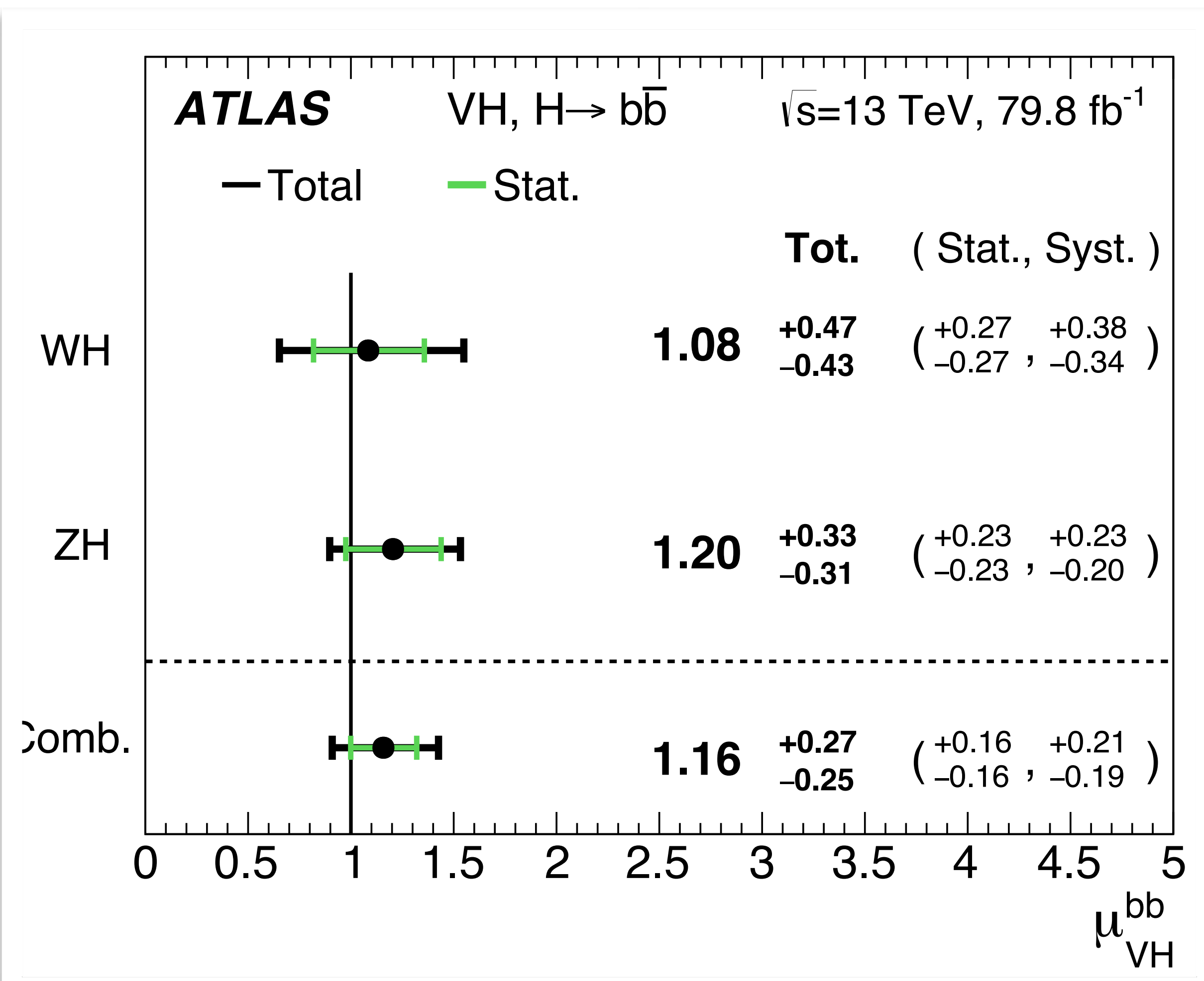
Observation of Higgs decays to b-quarks

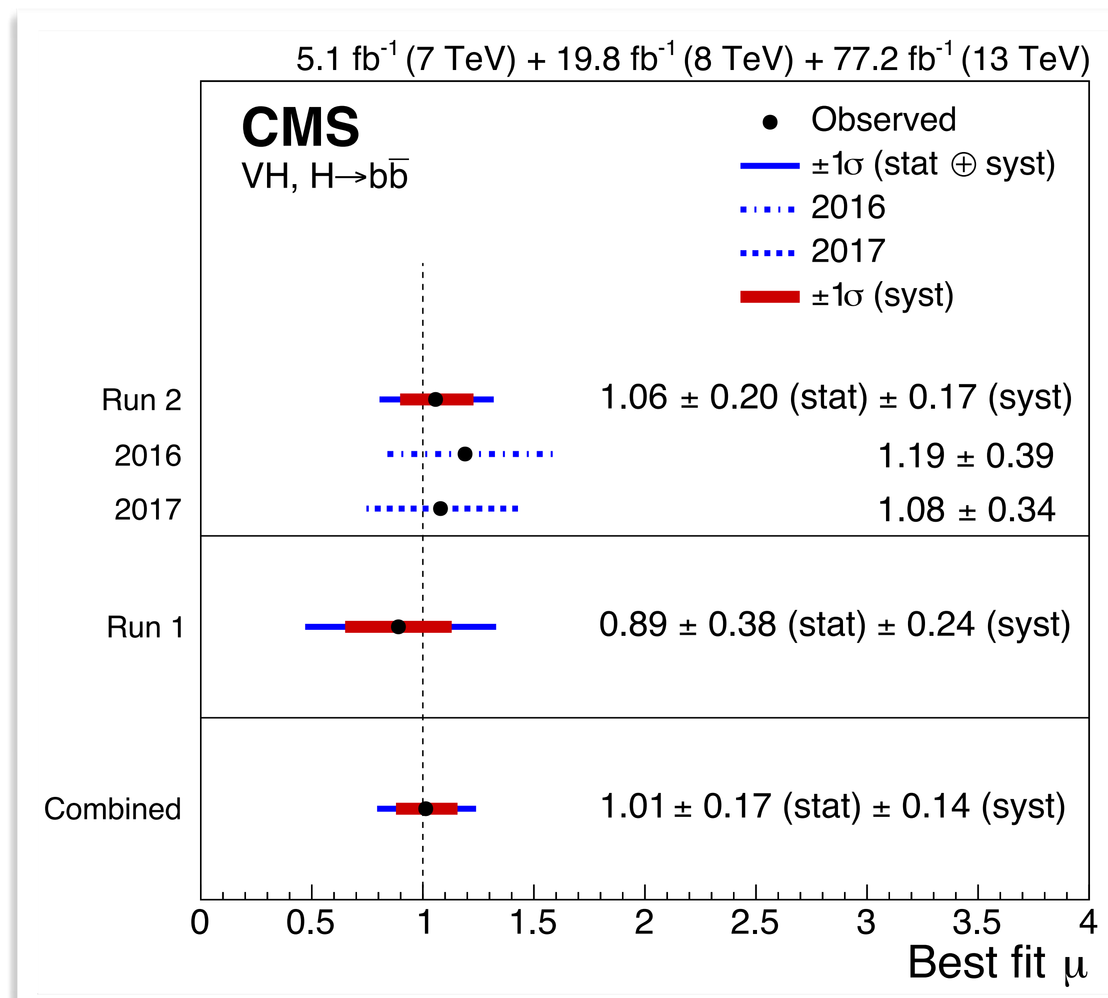
August 2018

Combination of Run-1 and Run-2 searches for Higgs decays to b-quarks using all 3 channels

	Obs	Exp
ATLAS	5.5σ	5.4σ
CMS	4.8σ	4.9σ

Also, observation of VH production!



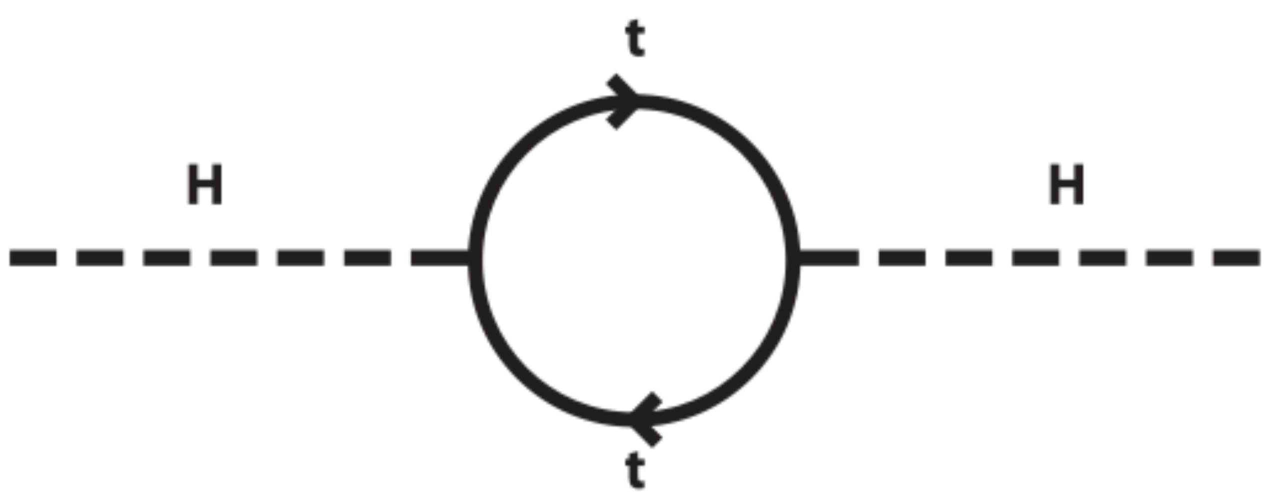


HIGG-2018-04, HIG-18-016

Coupling to Top Quarks

H→tt coupling

- Top quark **couples** very **strongly** to the Higgs boson
- For m_t = 173 GeV, $\lambda_t \sim 1$
- The **top quark**
  - Only quark with a ‘natural mass’
  - Main culprit in the instability of the Higgs mass

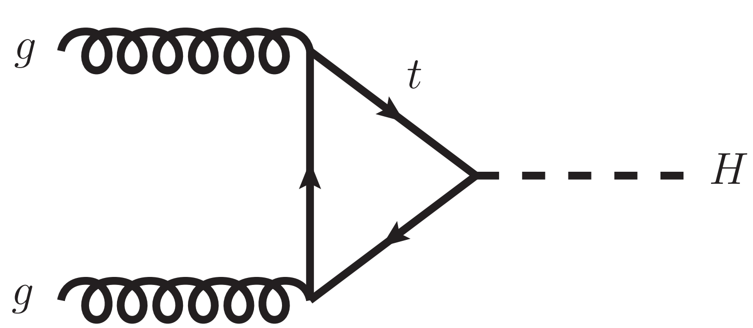


  - Could play a key role in **EWSB** or as a window to **new physics**
- Accurate measurement of the top Yukawa coupling is crucial

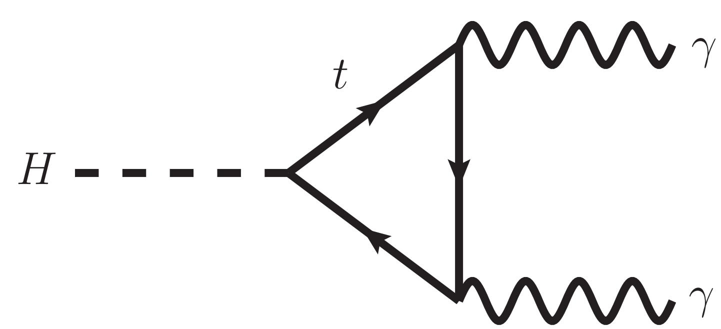
Direct ttH measurements

- **Indirect constraints** on top-Higgs Yukawa coupling can be extracted from channels using **ggH** and **γγH** vertices
  - Assumption: **No new particles**
- ttH production can measure the top-Higgs Yukawa coupling directly
  - Probes **NP contributions** in the ggH and γγH vertices
- **Small production** cross-section at the LHC
  - Need all decay channels to boost sensitivity

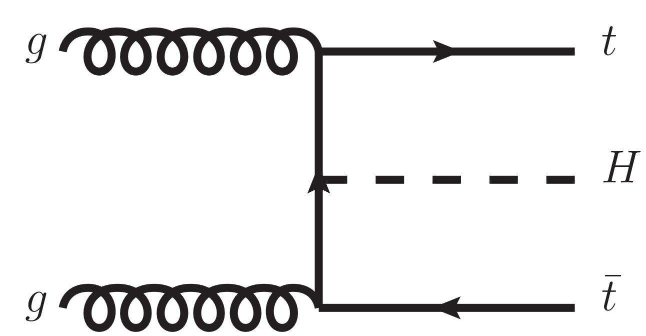
ggF production



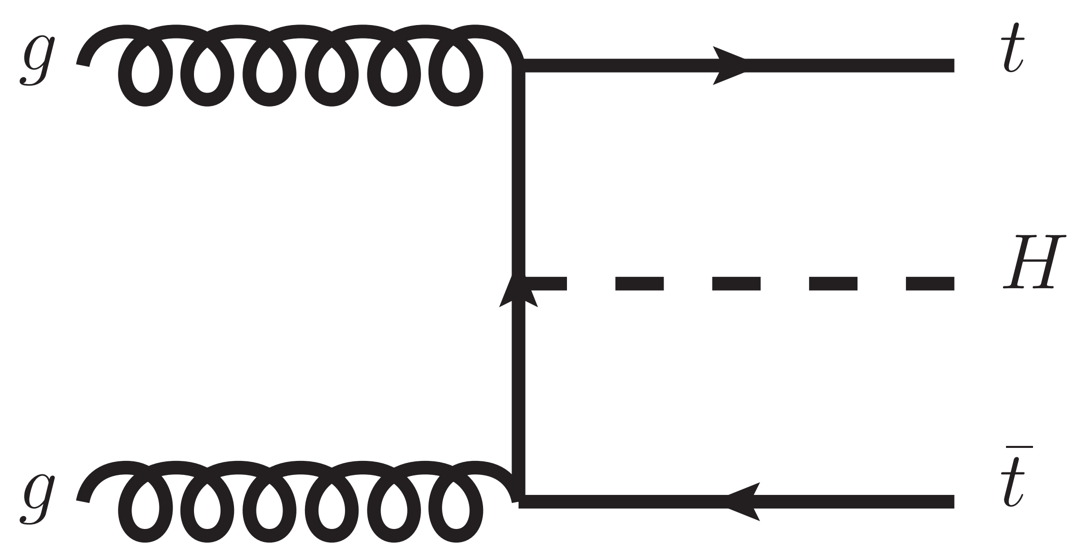
$H \to \gamma\gamma$ **decay**



ttH production

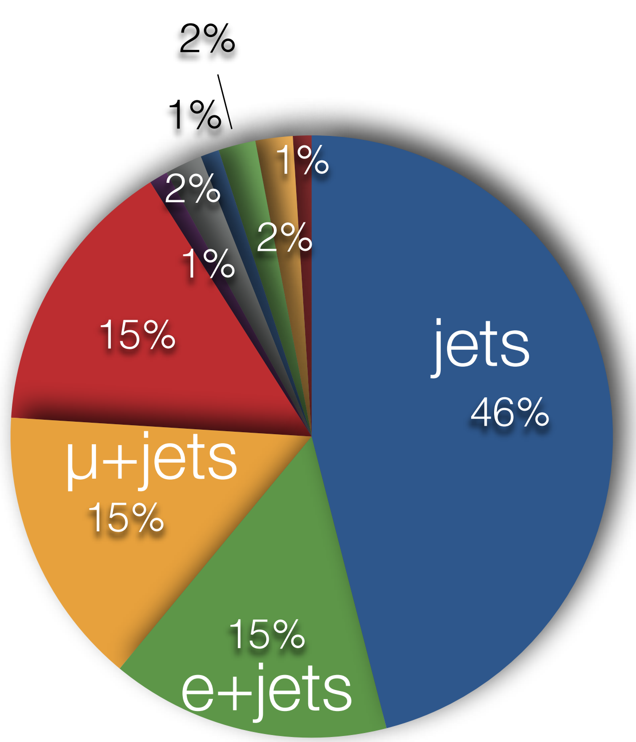


How to search for ttH



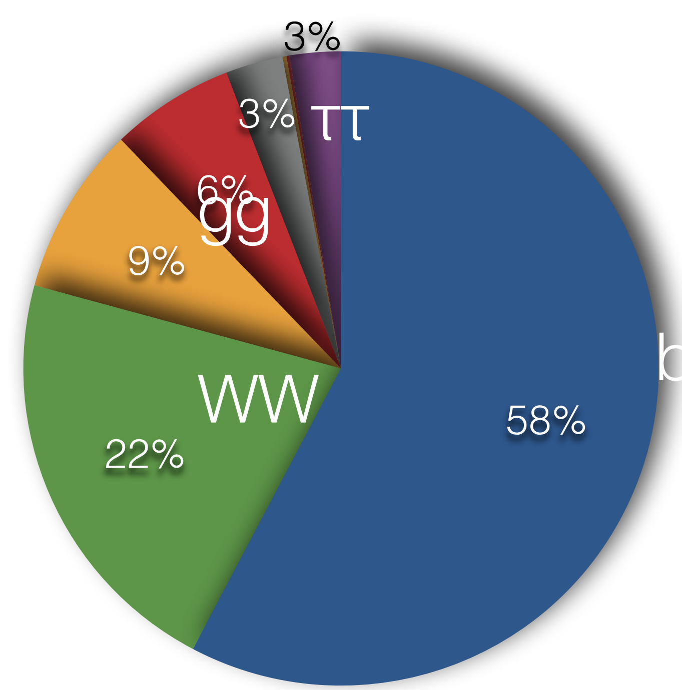
Top Decays

jets
leptons
lepton+jets



$\otimes$

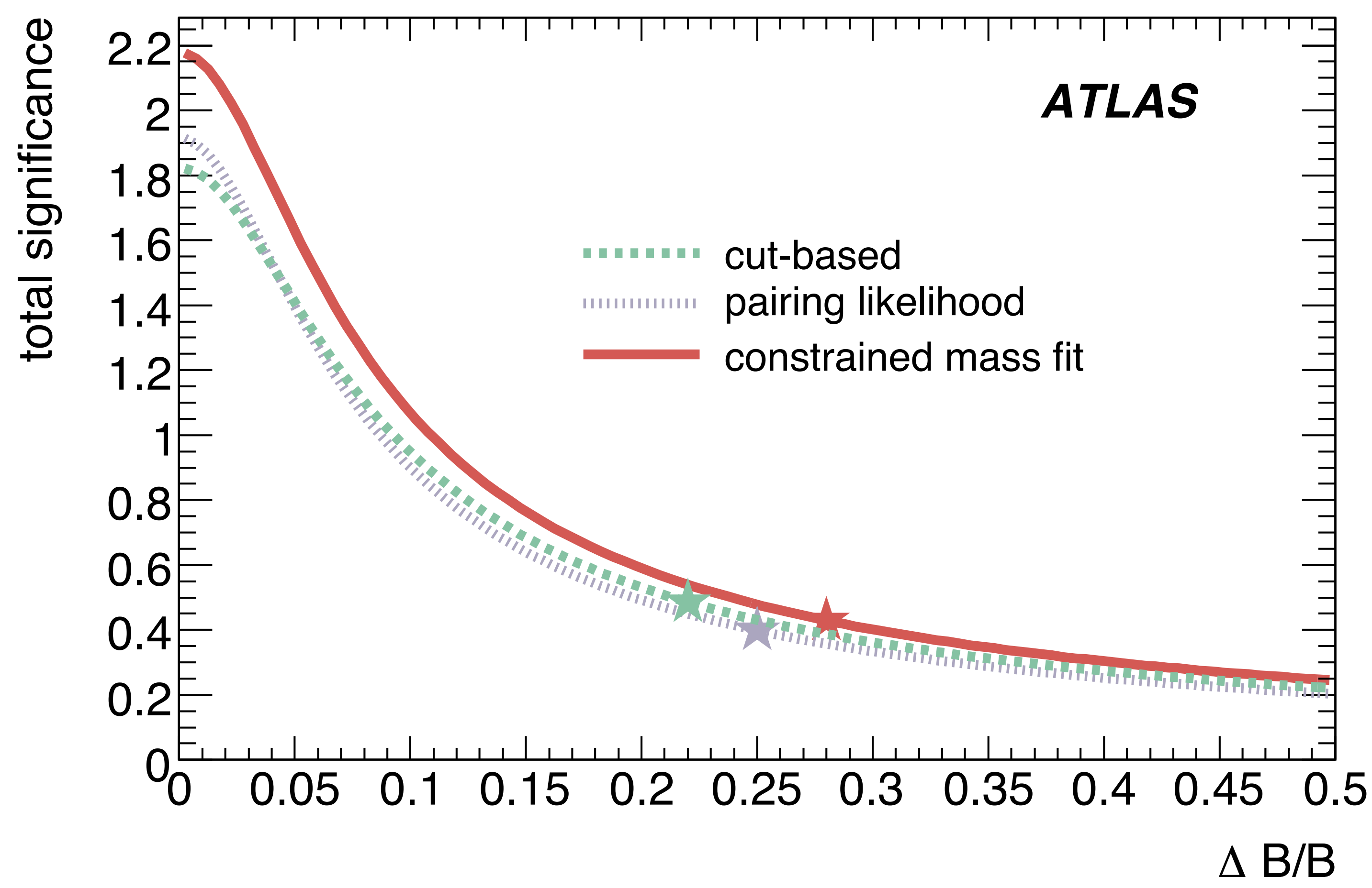
Higgs Decays



- **H→hadrons**
  - bb, ττ
- **H→leptons**
  - WW, ZZ, ττ
- **H→γγ**

Expectations for ttH Measurements

bitrarily chosen reference. It is interesting to note that it does not quite yield a substantial significance, even though background uncertainties of 1% and 4% for $t\bar{t}Nj$ and $t\bar{t}b\bar{b}$ are probably substantially better than what will be accessible in reality. This highlights the challenge that is faced in observing $t\bar{t}H$.



Reminder: expect 5σ from 300 fb^{-1}

Expectations for ttH Production II

ttH(leptons)

The $t\bar{t}H, H \to WW^{(*)}$ and $WH, H \to WW^{(*)}$ processes have been studied using two- and three-lepton final states. The signal and main backgrounds have been estimated using a full GEANT based simulation of the detector. The estimated accepted cross-sections in fb of signal and background for these processes are 1.9:10 ($t\bar{t}H$ 2L), 0.8:3.4 ($t\bar{t}H$ 3L) and 0.3:0.4 (WH 3L) respectively. The signal is small and clear distinguishing features such as resonance peaks have not been established. The backgrounds are larger and their uncertainties have not been fully controlled. The analysis is therefore very challenging.

ttH($\gamma\gamma$)

Table 19-3 Cross-sections times branching ratios, σ x BR, (sum of *WH*, *ZH* and $t\bar{t}H$), acceptances and expected numbers of signal and background events for associated Higgs production with $H \to \gamma\gamma$ decay and for $80 < m_H < 140$ GeV at high luminosity. The expected numbers of events and the statistical significances are given for an integrated luminosity of 100 fb^{-1}.

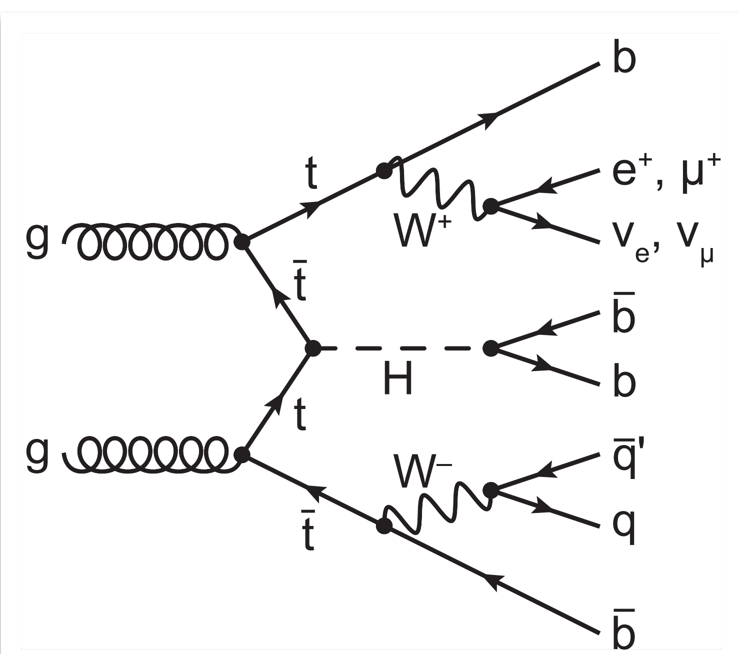
Higgs mass (GeV)	80	100	120	140
σ × BR (fb)	1.55	1.44	1.22	0.65
Acceptance of kin. cuts	0.24	0.30	0.31	0.32
Acceptance of mass cuts	0.70	0.74	0.78	0.79
Signal events	12.2	14.7	13.2	7.5
Irreducible background	6.0	5.7	4.4	3.2
Reducible background	1.3	1.4	1.3	1.3
Statistical significance	3.7	4.3	4.3	2.8

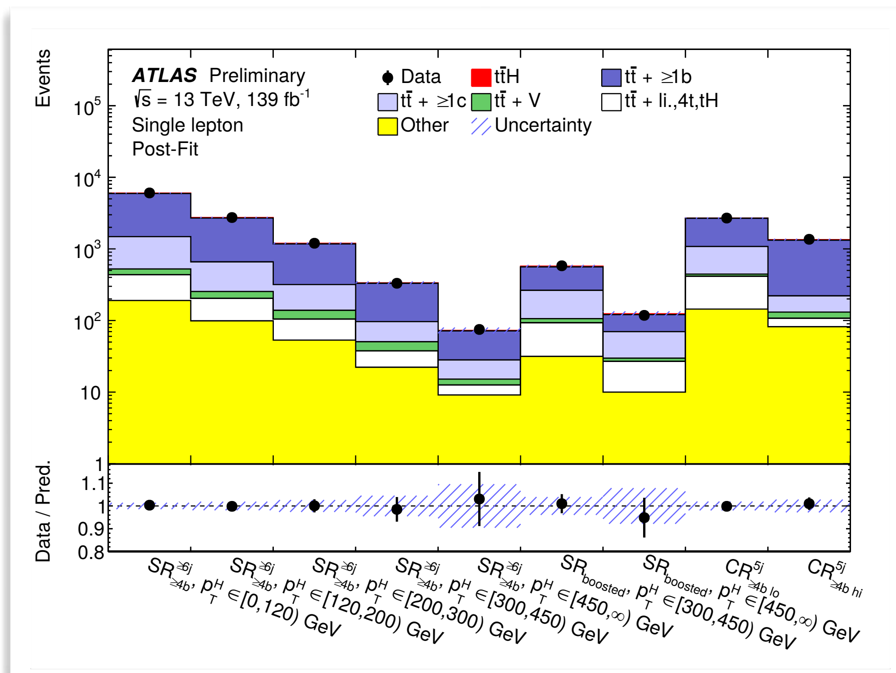
Combine
WH+ZH+ttH

ttH(bb)

ttH(bb) Analysis Strategy

- Select **tt-enriched** samples
  - Lepton+jets and dilepton channels
- **Categorise** events by **jet** and **b-tag** multiplicity and **Higgs p_T**
  - Separate **high** and **low** $S/\sqrt{B}$ channels
  - **Constrain systematic uncertainties** from signal depleted categories
- Fit **MVA discriminants** to separate S from B





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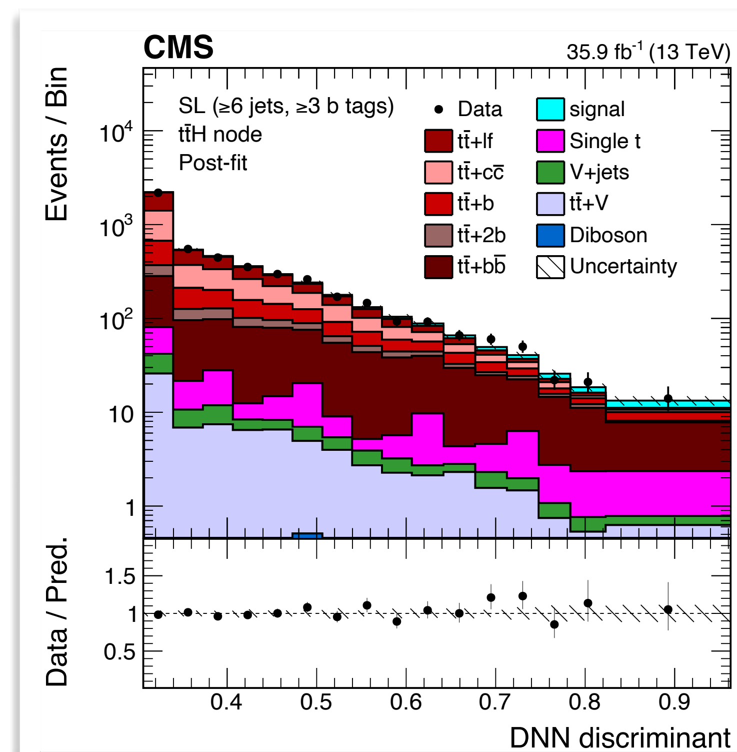
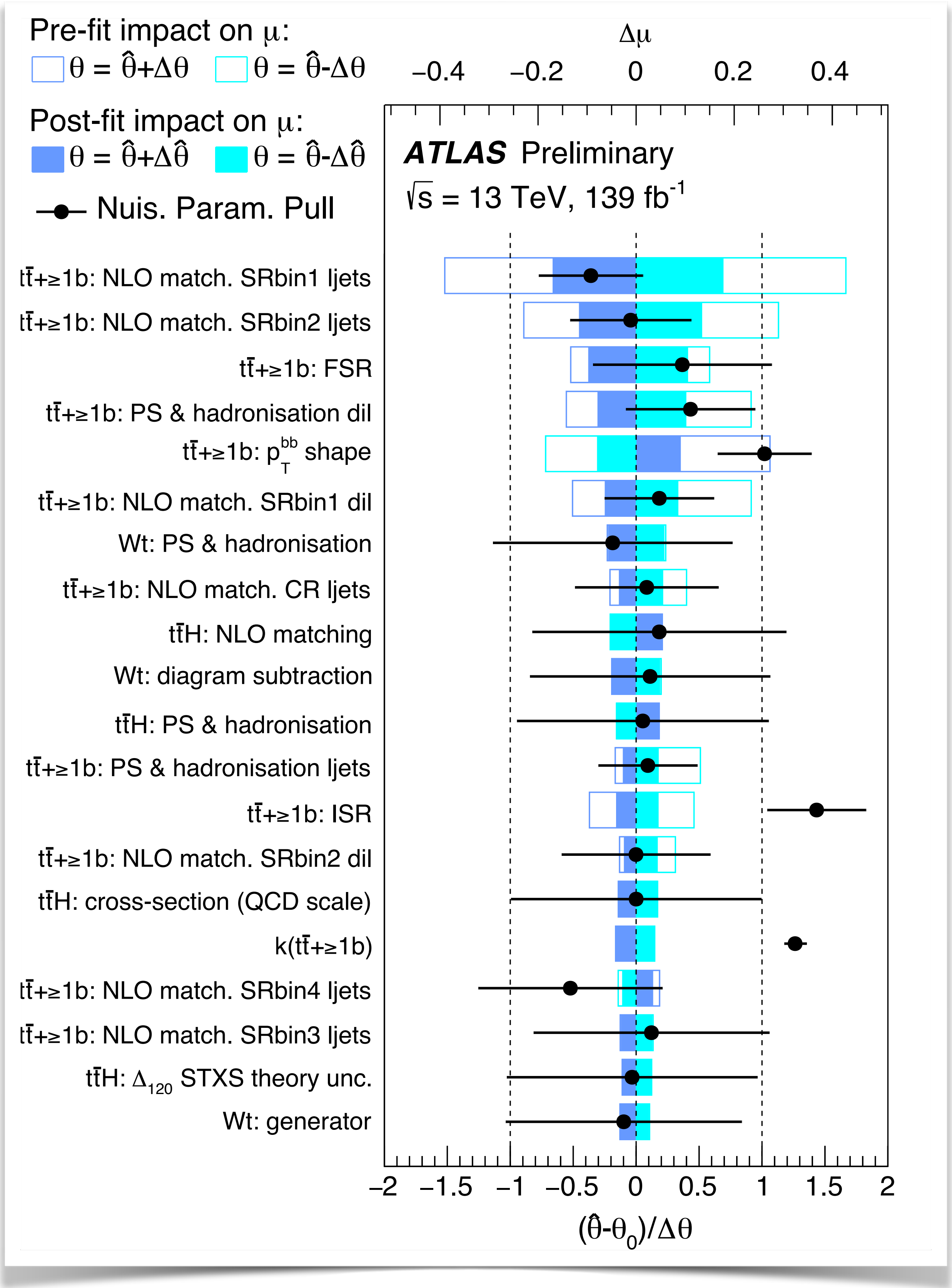


HIG-17-026

ttH(bb) Systematic Uncertainties



Key challenge for ttH(bb) is the modeling of the **tt+bb background**

Profiling this background plays a critical role in the measurement

→**Fit model** is extremely important

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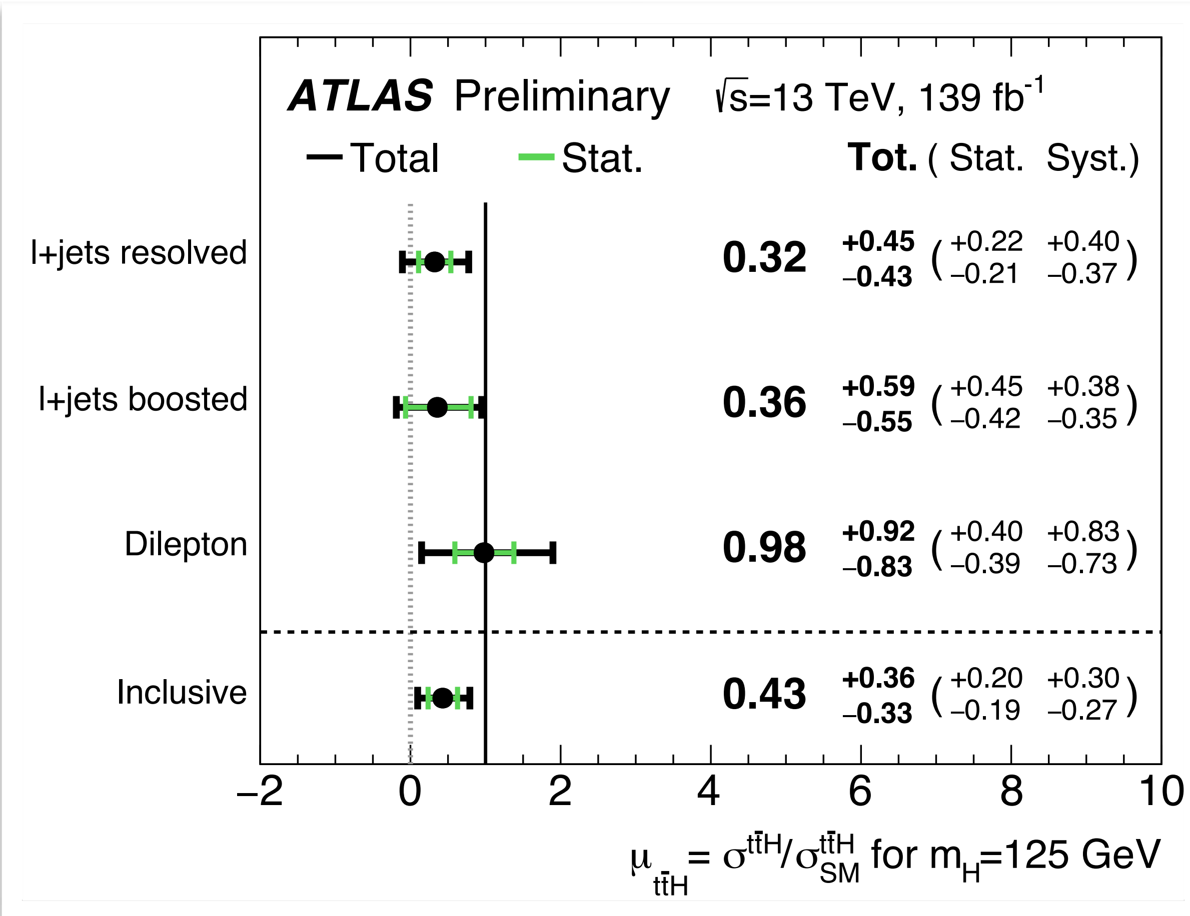
ttH(bb) Results



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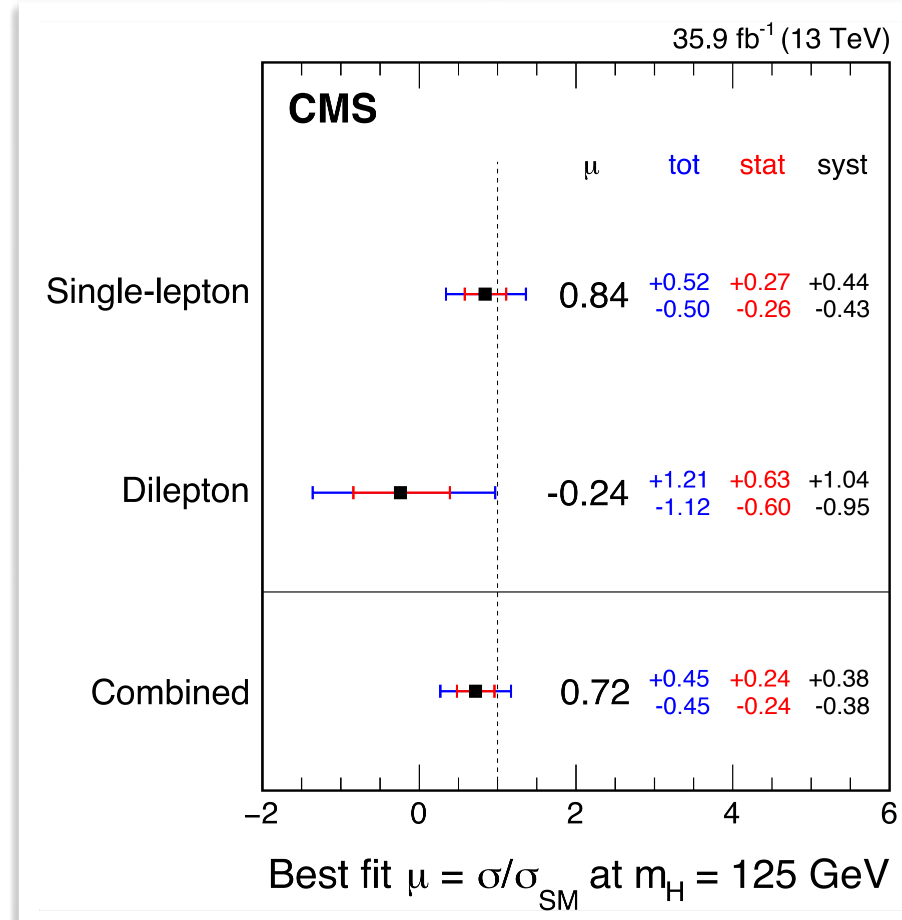

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	Obs	Exp
ATLAS	1.3σ	3.0σ
CMS	1.6σ	2.2σ

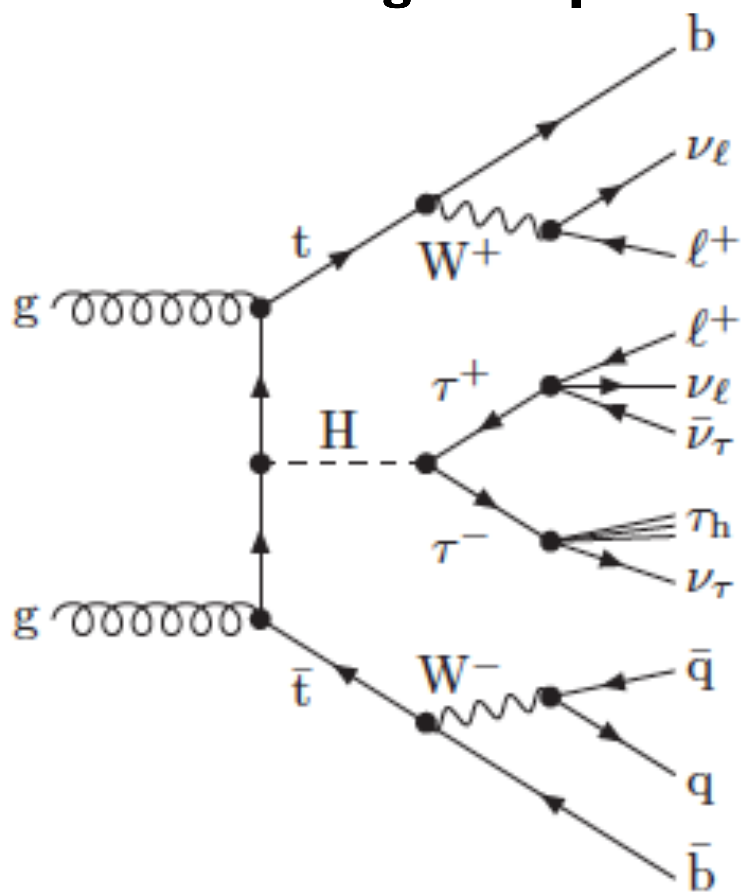
*ATLAS is using 3x more data than CMS

The forgotten leptons

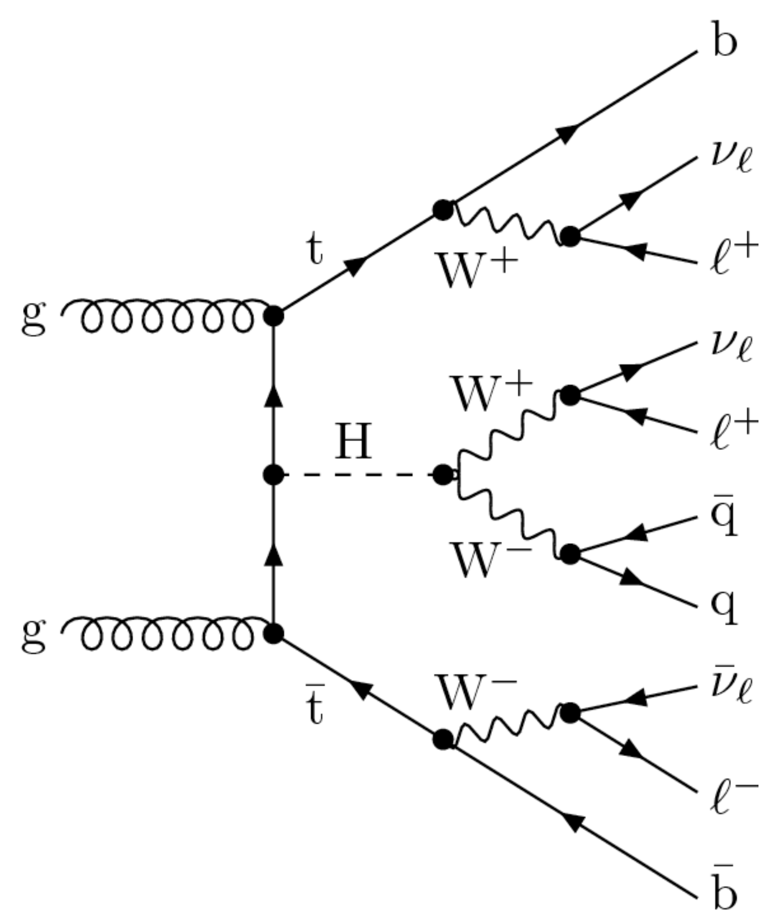
ttH Multileptons

- Despite being studied in the ATLAS, there were **initially no LHC analyses** looking for ttH using multilepton channels
- During 2013, it was realised that these channels would already be **quite sensitive** with the current LHC dataset
  - Multilepton analyses began, but later than many other analyses

Same sign 2-leptons

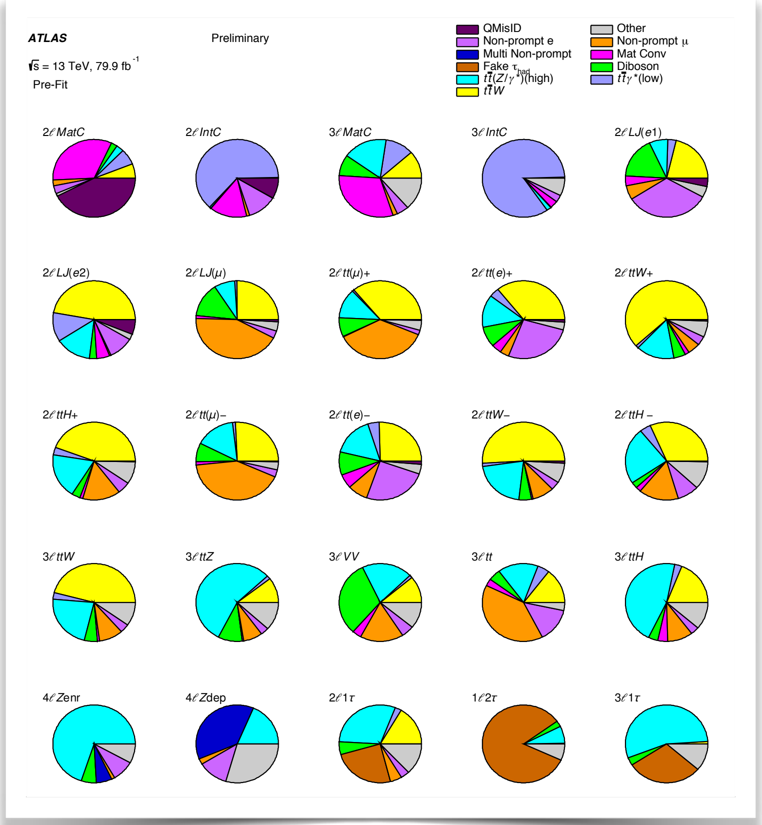


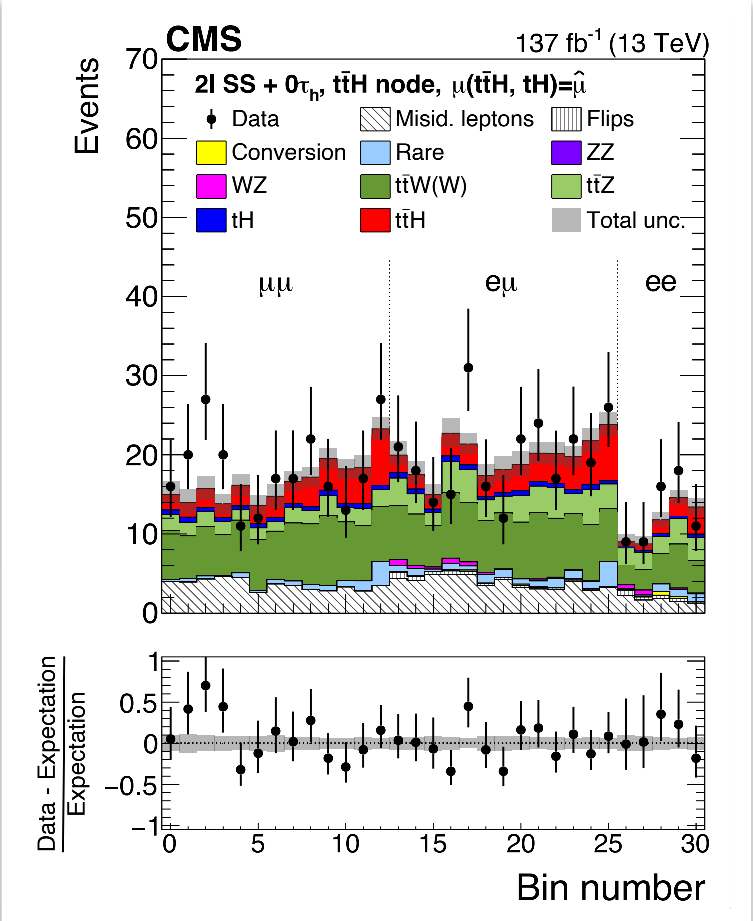
3-leptons



ttH Multileptons Analysis Strategy

- Cannot easily separate the many relevant decay modes, therefore defined channels defined by **number of leptons**
  - **SS 2-leptons**, 6 jets, 2 b-jets
  - **3-leptons**, 4 jets, 2 b-jets
  - **4-leptons**, 2 jets, 2 b-jets
- Low signal rate, but low background
- Main background is **ttW/Z/γ***; also diboson (WZ and ZZ), ttbar (2/3-leptons)
- Combination of **cut-and-count categories** with **multivariate discriminants**
  - Overcome limitations of lack of clear peaks and many backgrounds

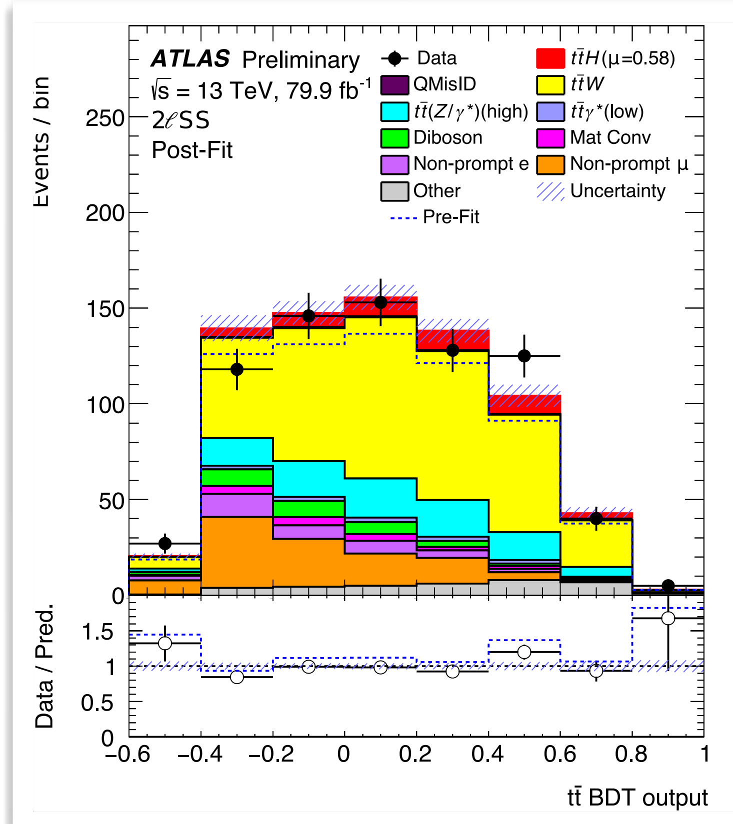


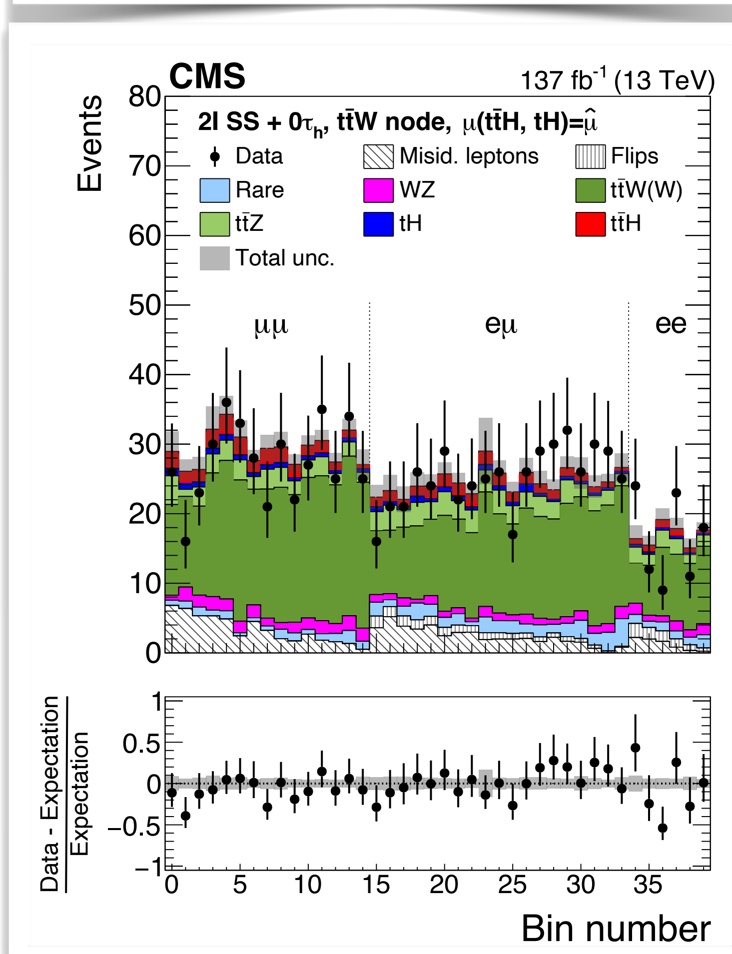


ATLAS-CONF-2019-045 HIG-19-008

The ttW Background

- A large and challenging background for ttH(ML) is the **ttW background**
  - Very similar final state to ttH(WW)
- **Control** regions can be difficult to define
- Difficult to **simulate** accurately
  - Measurements of SM ttW production often show significant deviations from predictions
  - **NLO** QCD and EW **corrections** to ttW+1 jet production (**~O(10%)**)
- Significant **correlations** between ttW and ttH production
  - Important to control for accurate signal measurement

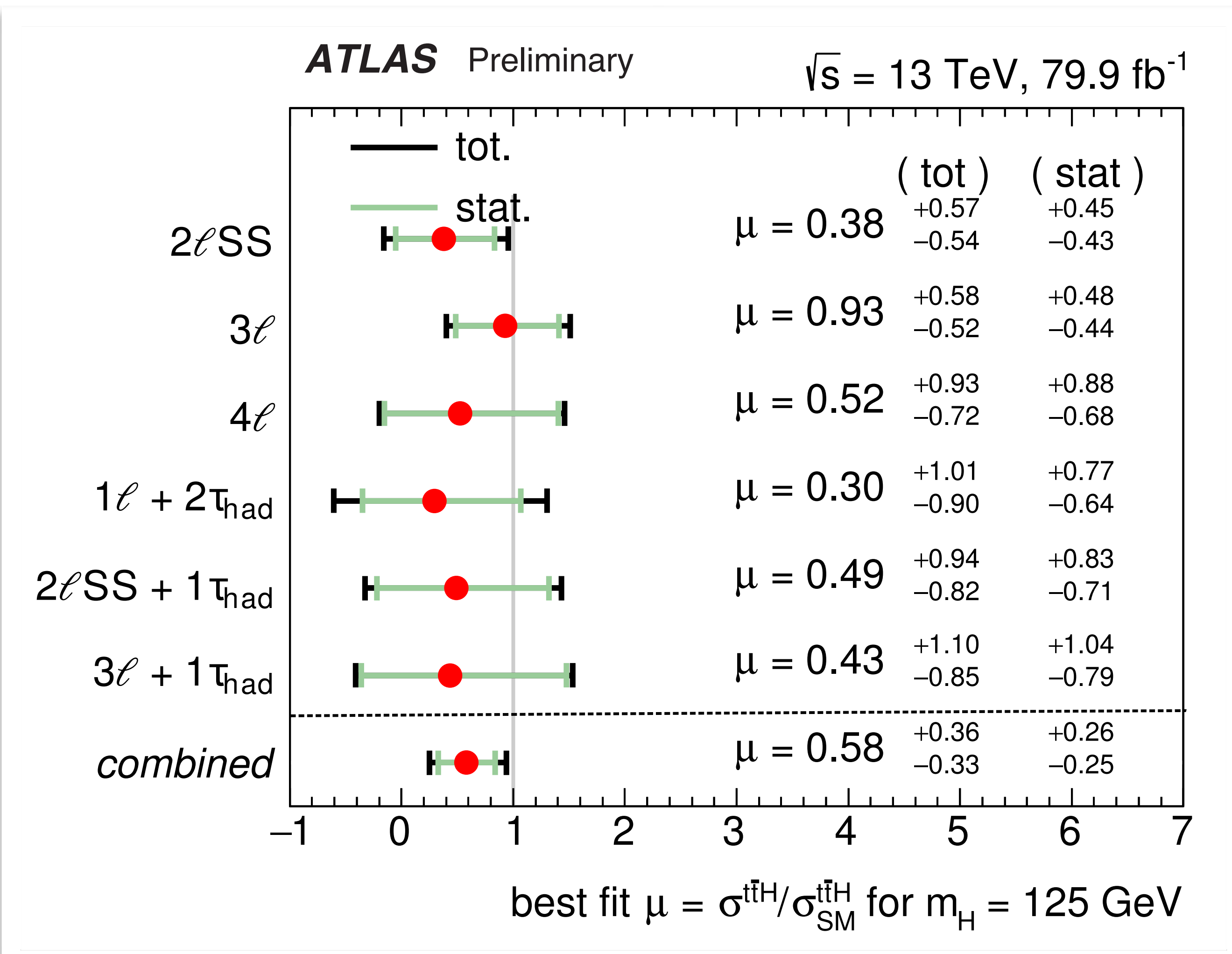




ttH(ML) Results

	Obs	Exp
ATLAS	1.8σ	3.1σ
CMS	4.7σ	5.2σ

CMS uses twice as much data as ATLAS



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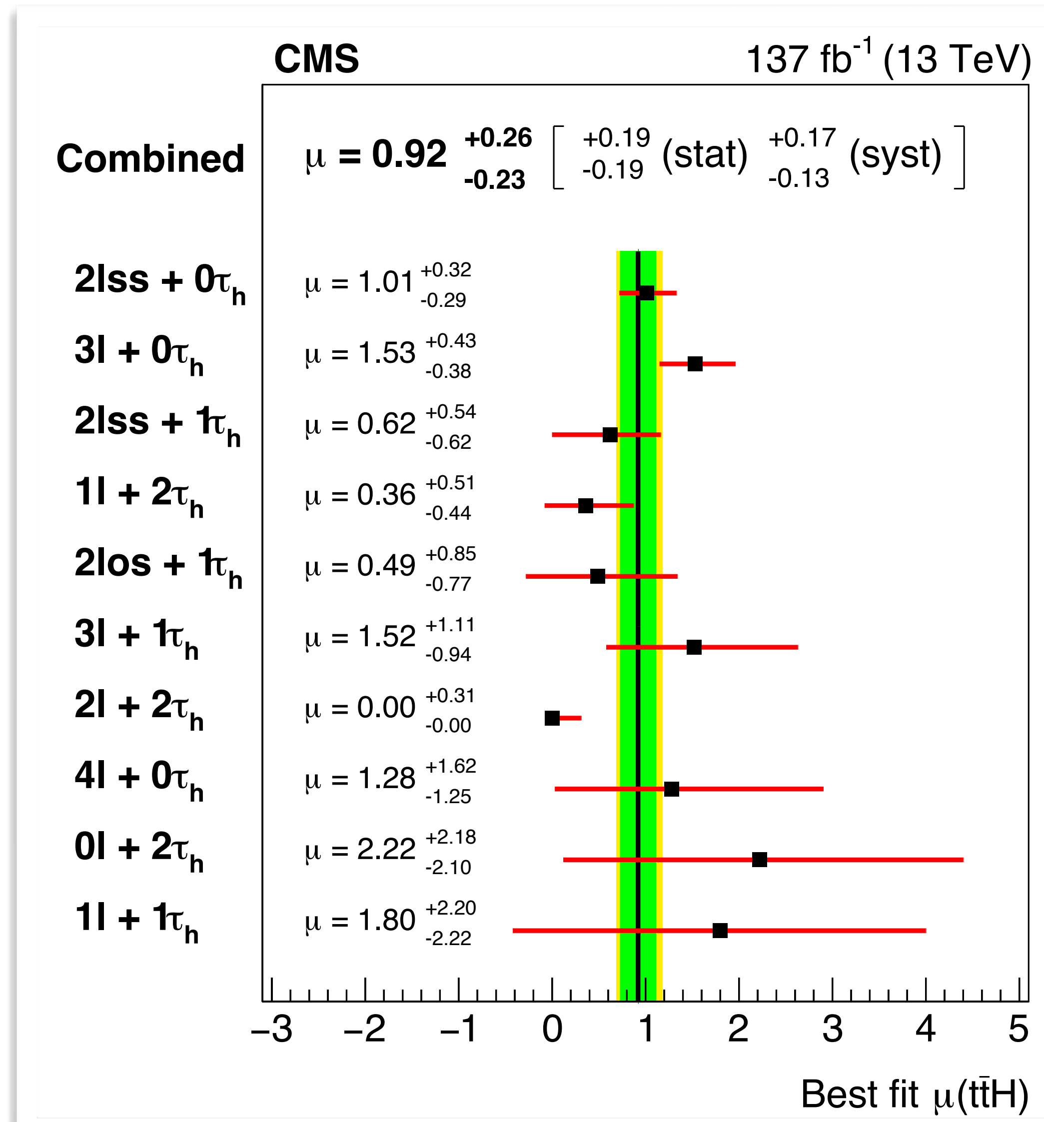


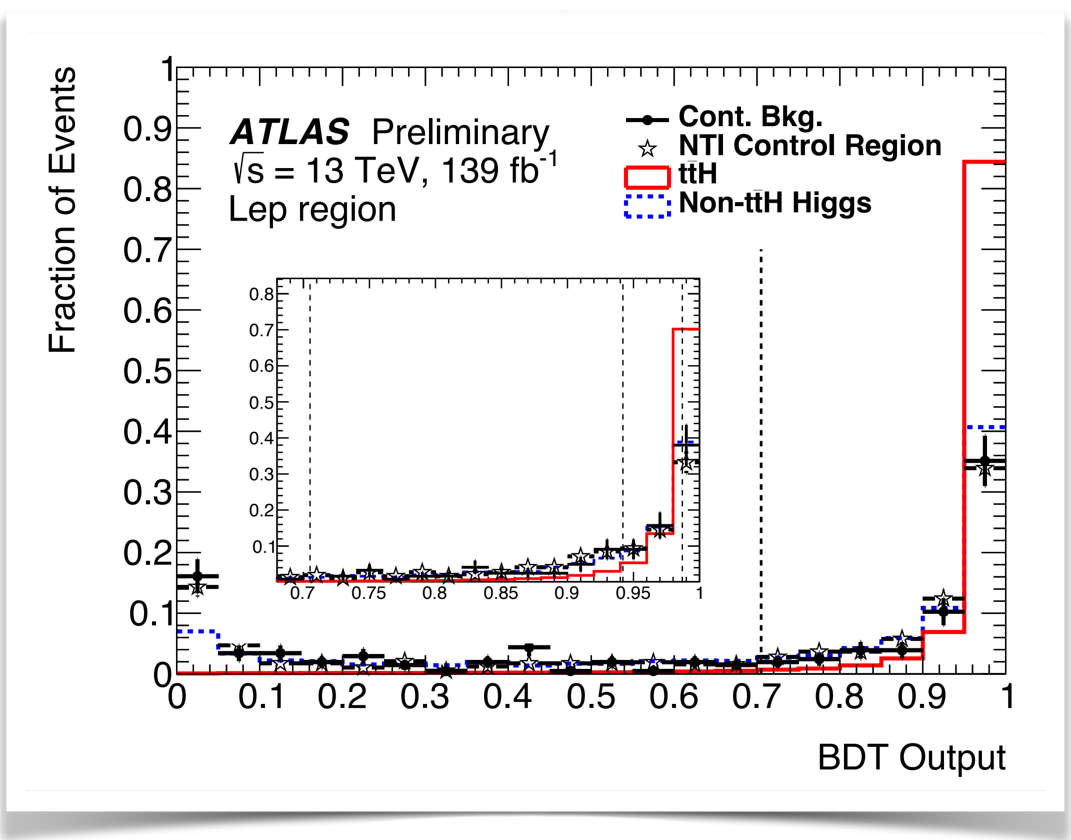
HIG-19-008

$t\bar{t}H(\gamma\gamma)$

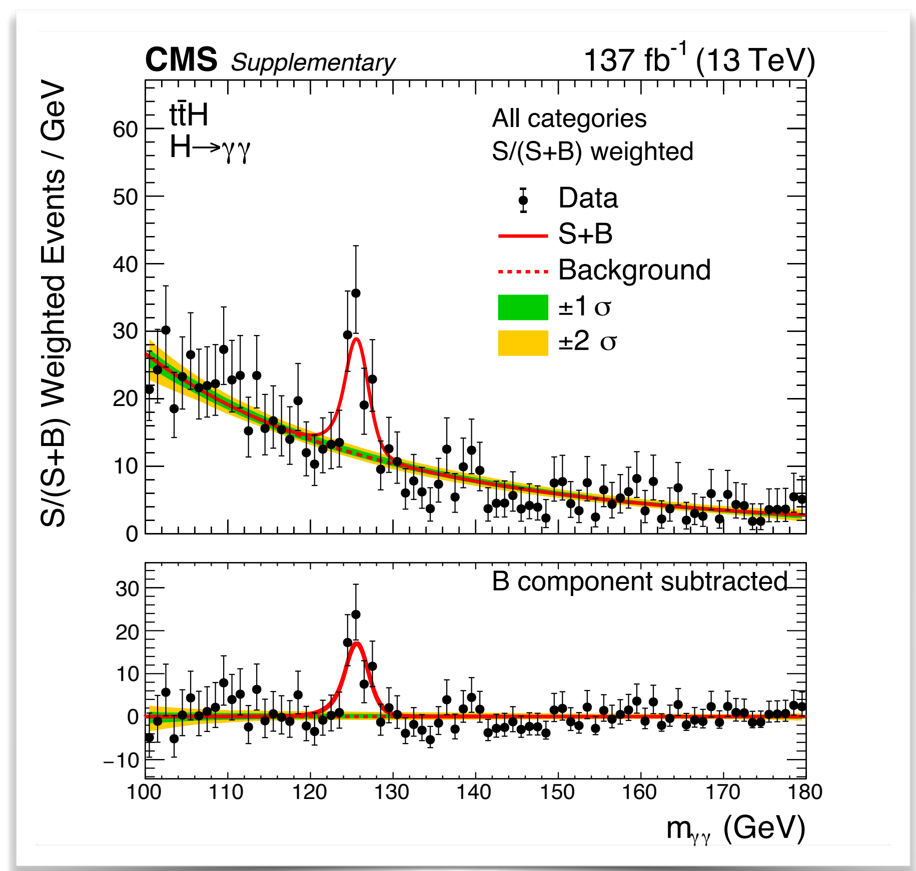
ttH(γγ)

- Select events with two photons and at least one b-jet
- Define two channels
  - **Leptonic**: at least one lepton
  - **Hadronic**: no leptons
- Train a BDT in each channel to define several categories
- Fit diphoton mass in each category
- Background estimation from data sidebands

	Obs	Exp
ATLAS	4.9σ	4.2σ
CMS	6.6σ	4.7σ



ATLAS-CONF-2019-004

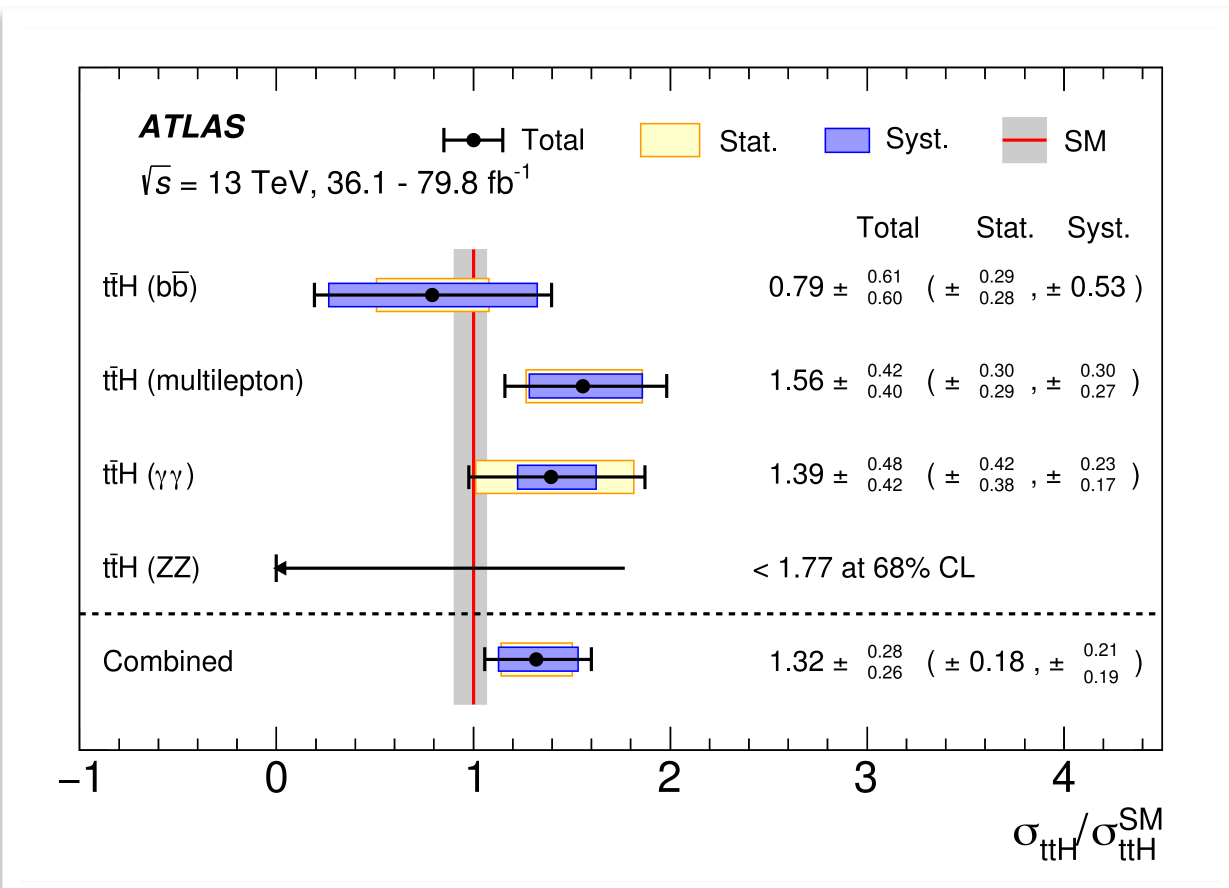


arXiv:2003.10866.pdf

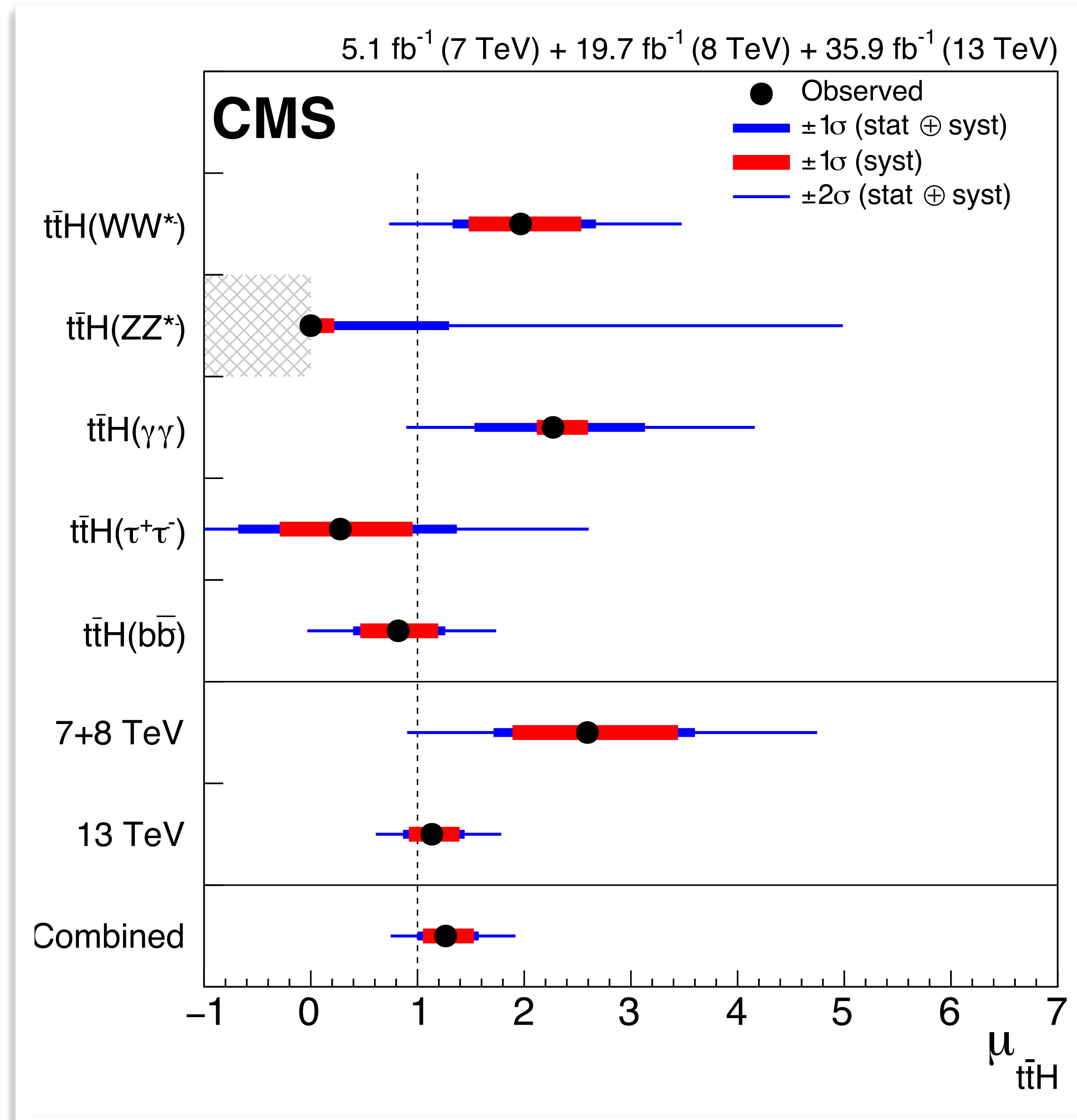
Observation of ttH

Observation of ttH Production

Observation of ttH production in June 2018
Combination of bb, ML and $\gamma\gamma$ decay channels



HIGG-2018-13



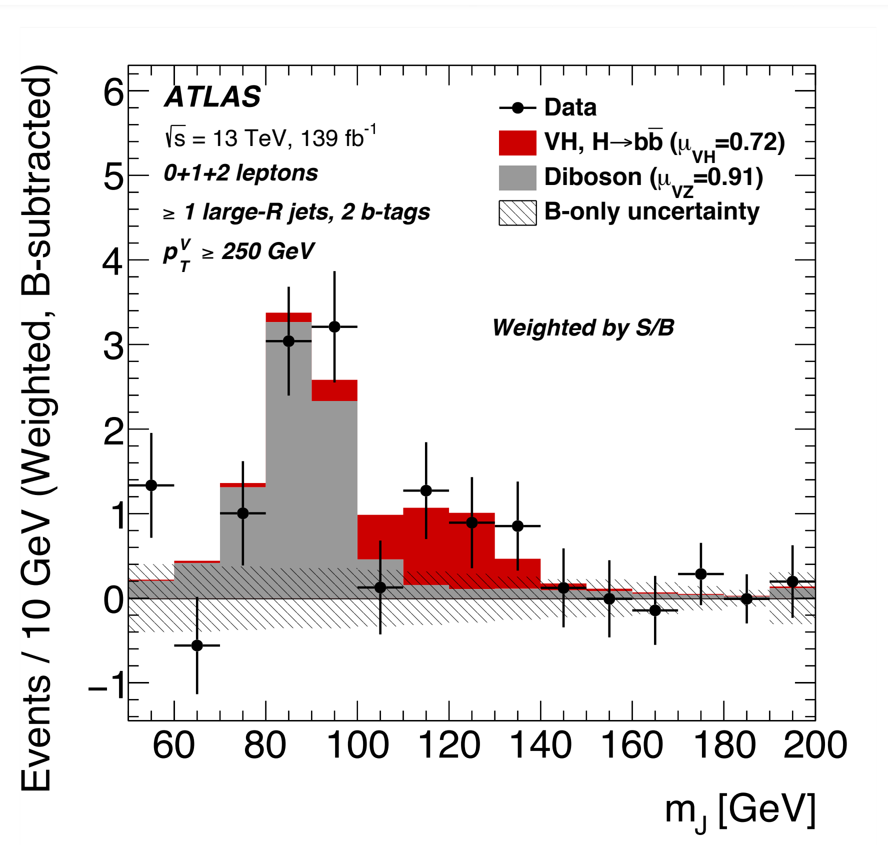
HIG-17-035

Brief Comments on Future Perspectives

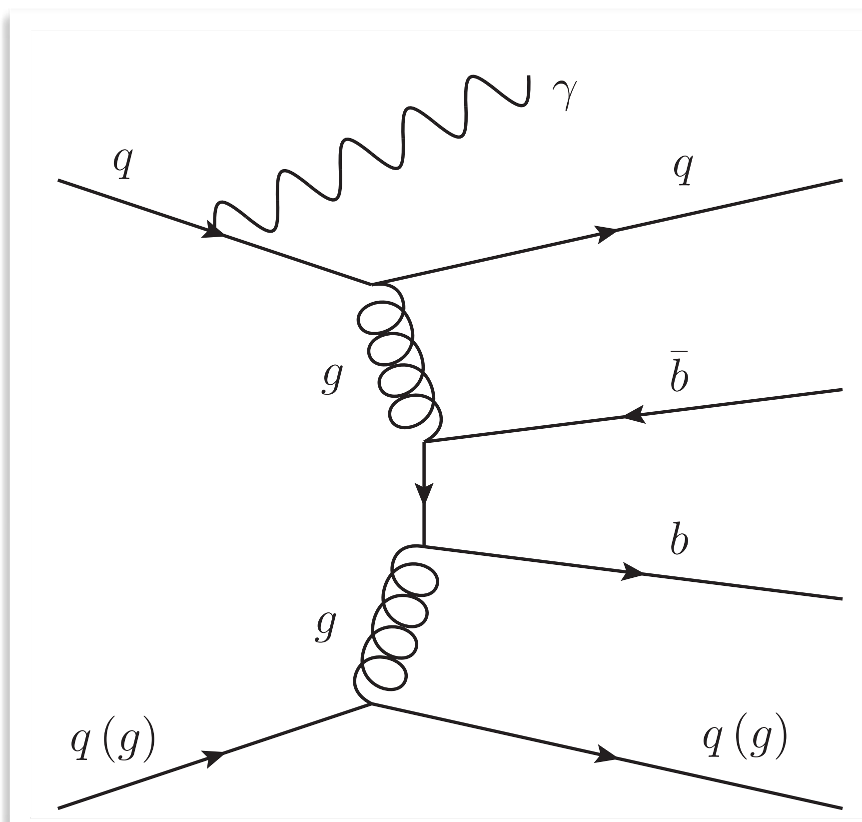
How yesterday's discovery becomes today's tool

Post-observation H→bb

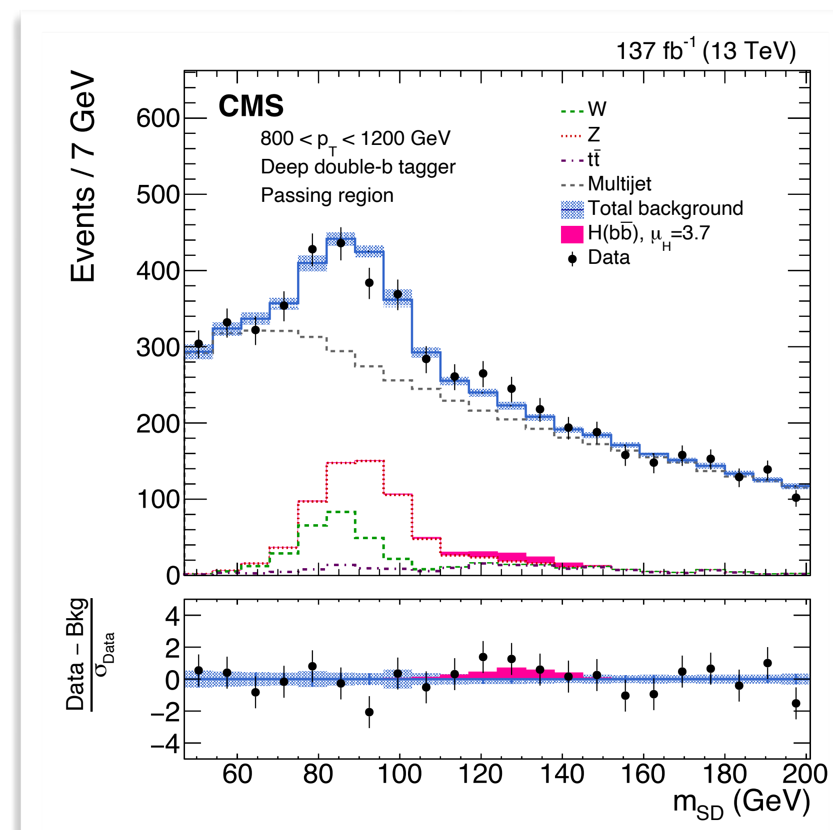
- **Boosted** techniques to probe high p_T region
- **Differential** distributions using the Simplified Template Cross-Section (STXS) approach
- Effective Field Theory (**EFT**) interpretations
- Additional production channels: VBF production w/w-out a photon, ggF
- Will play an important role in Higgs **self-coupling** measurements



HIGG-2018-52



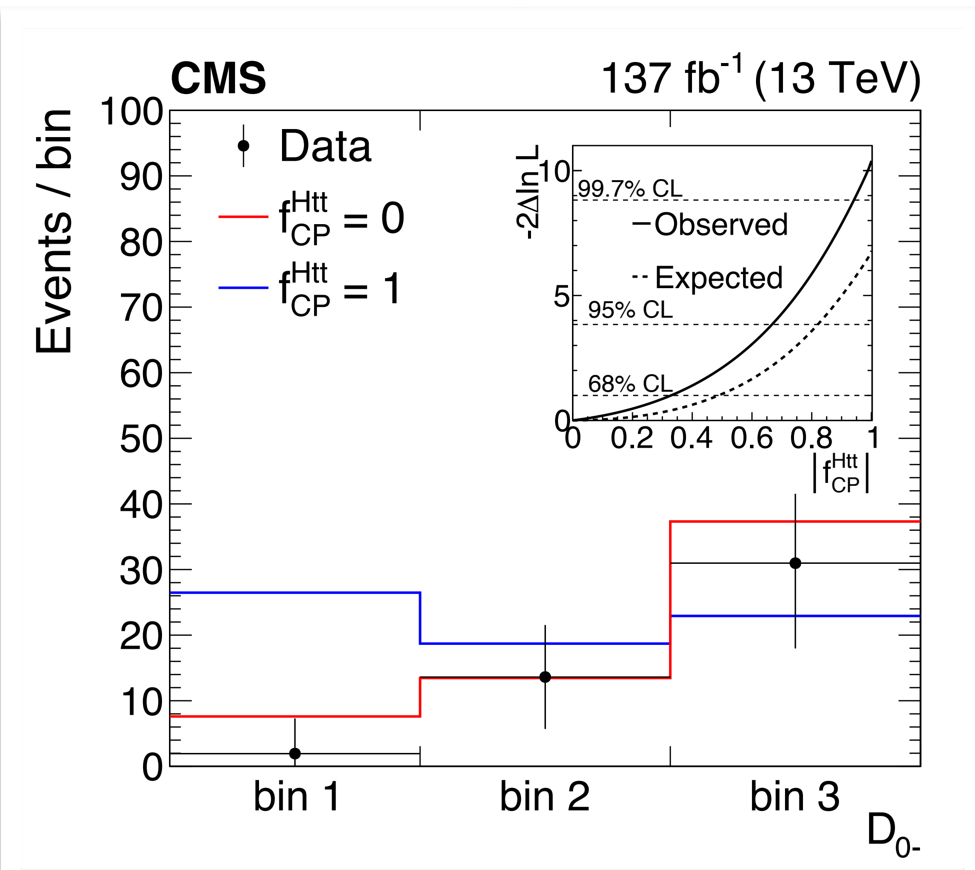
arXiv:2010.13651



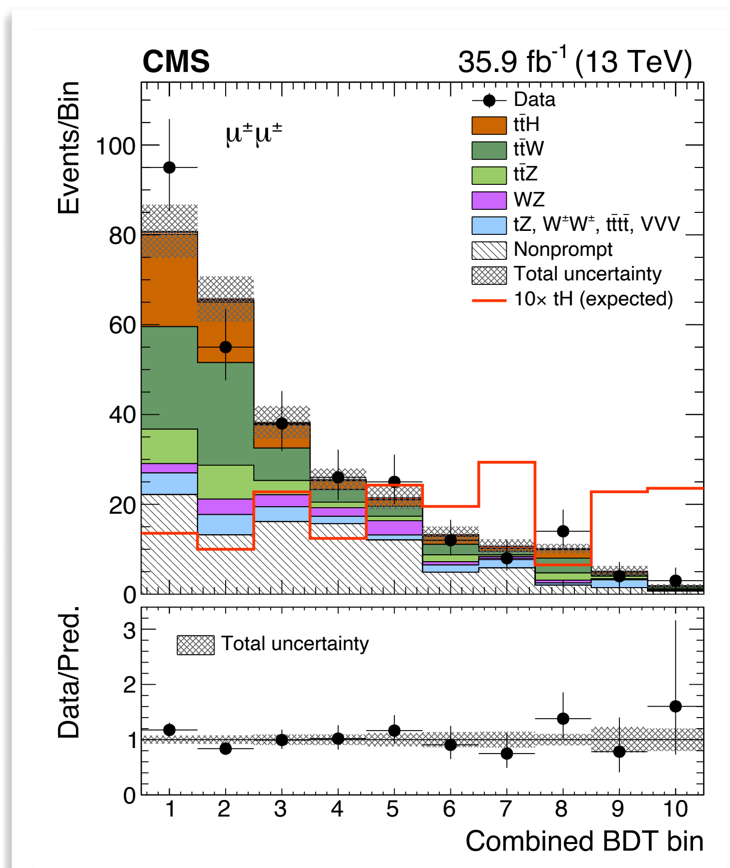
HIG-19-003

Post Observation ttH

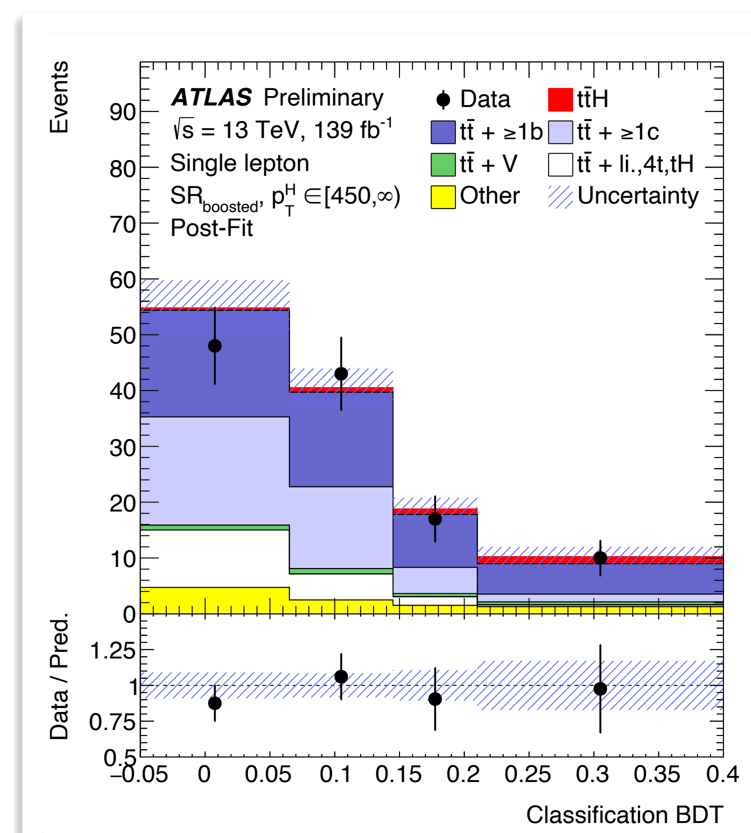
- Solo observation of **ttH($\gamma\gamma$)**
- **CP structure** of the Higgs-top vertex
- Towards observation with additional decay channels: H→bb, H→ML
- **Boosted** ttH
- **tH** production



HIG-19-013



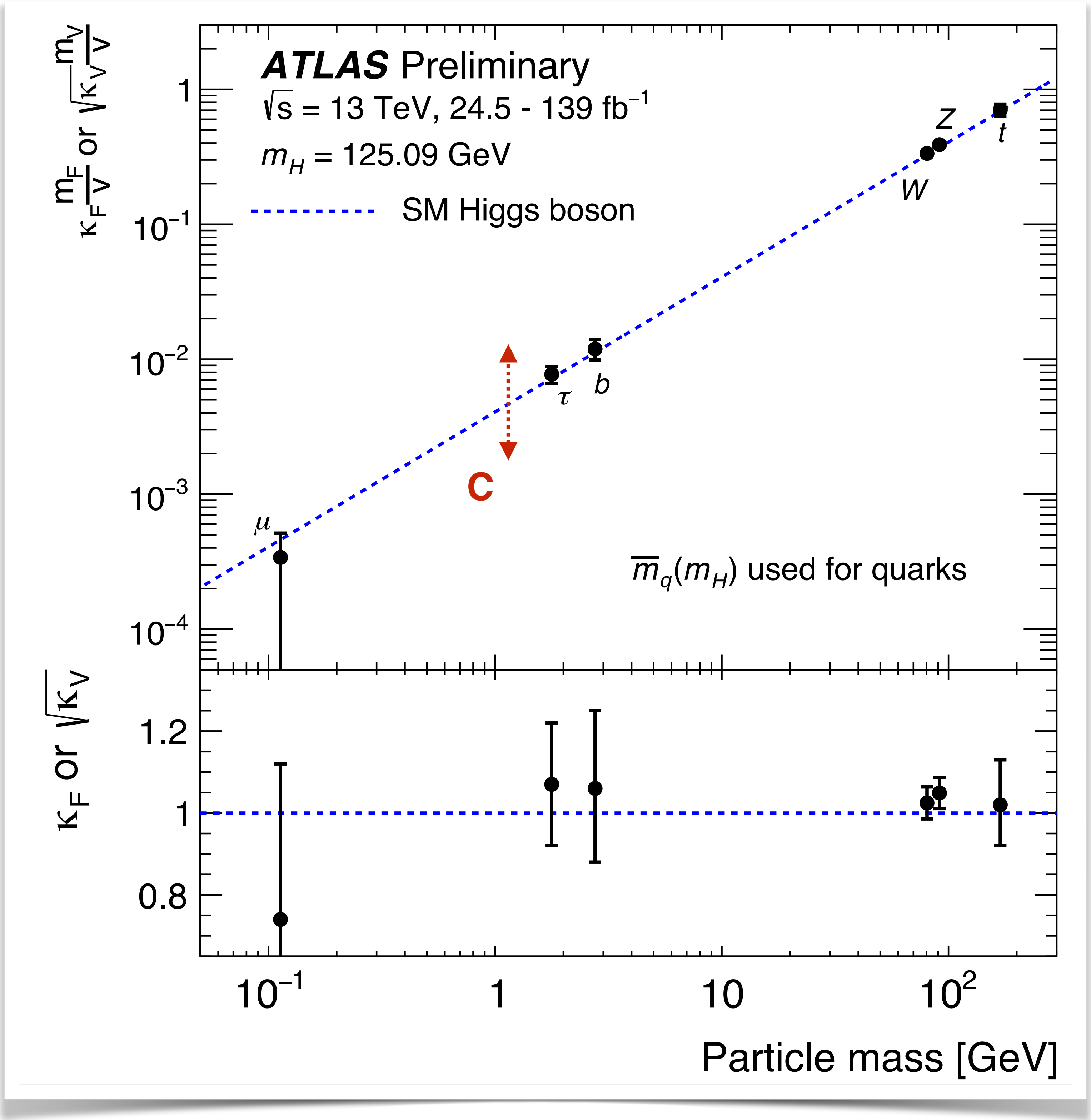
HIG-18-009



ATLAS-CONF-2020-058

BONUS: Coupling to Charm Quarks

What about charm?



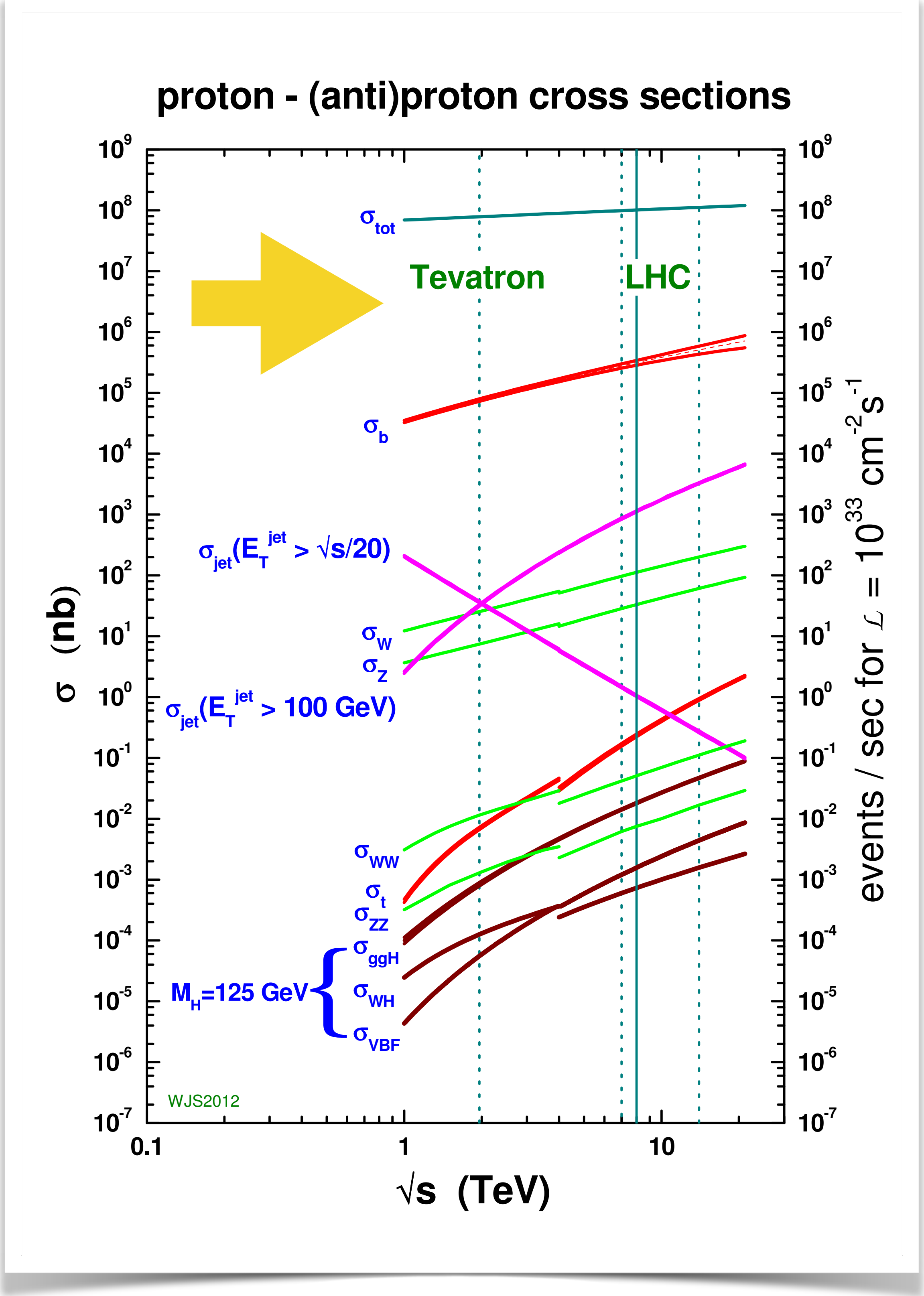
Complex structure in the SM Yukawa couplings

No measurements of Higgs couplings to quarks outside the third generation

Thought to be impossible at hadron colliders

And we thought H→bb was hard

- Cross-section for charm production at the LHC is even higher than for bottom
- BR for H→cc is a factor of 20 smaller than H→bb
  - H→bb will be a significant background to H→cc
- Tagging charm jets is significantly harder than tagging bottom jets
- Theoretical uncertainties on charm production are harder than on bottom
- Initial attempts focused on exclusive charm decays like $J/\psi\gamma$

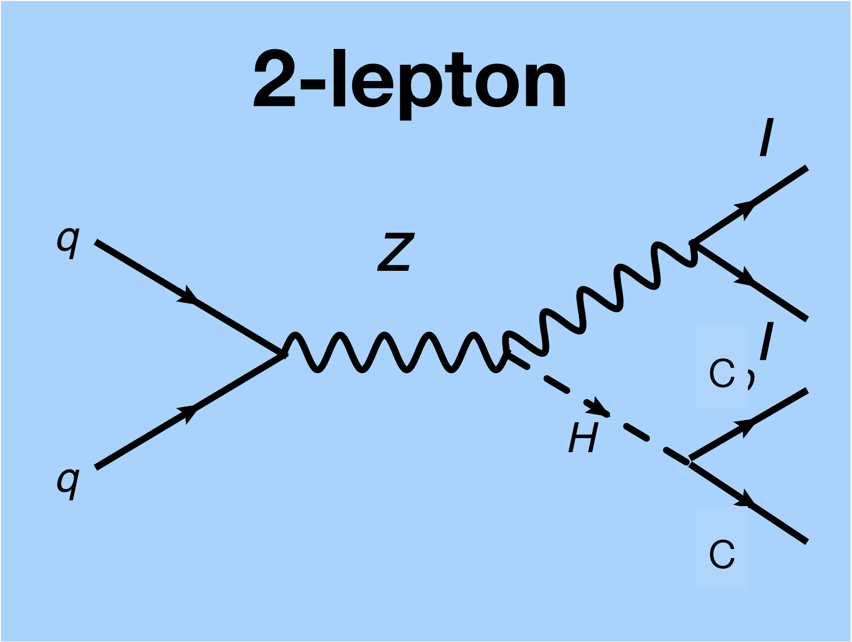


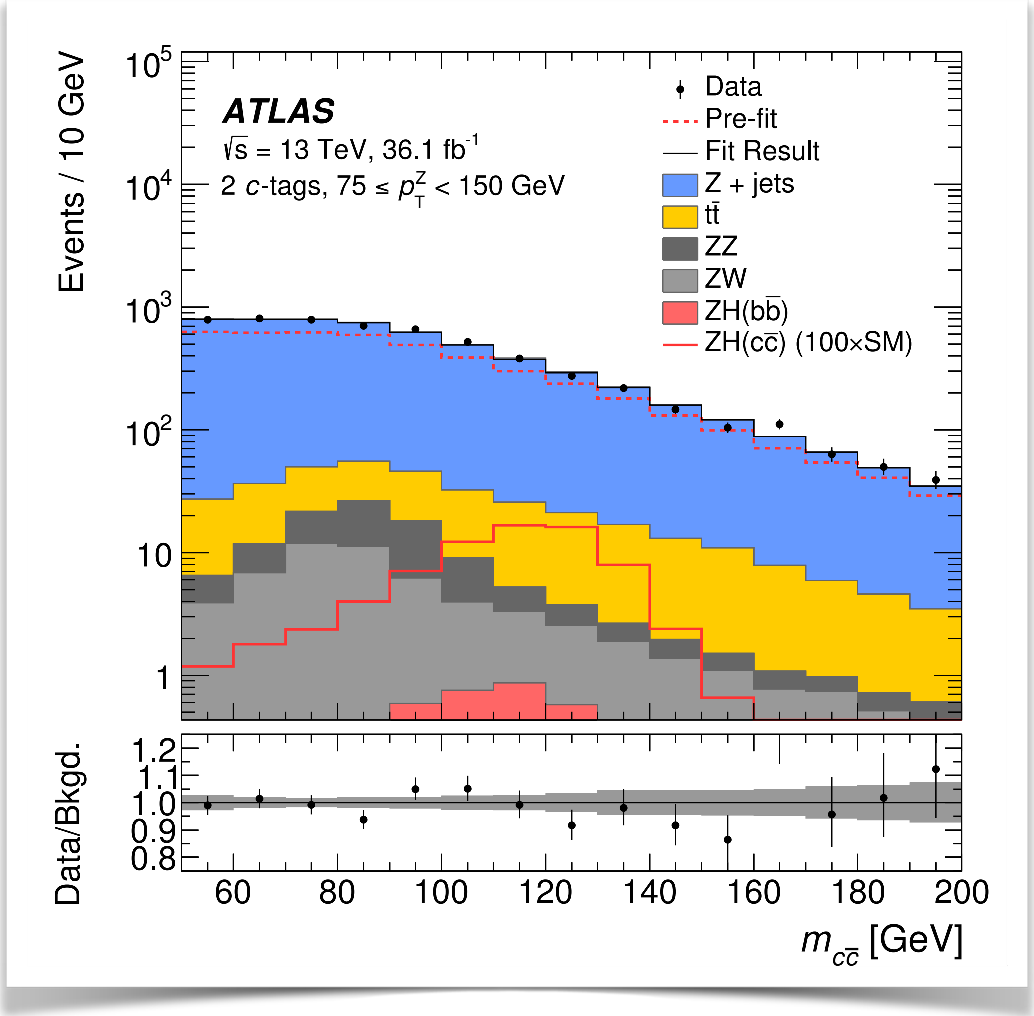
ZH(cc)

- Same strategy as VH(bb)
  - Focus on ZH(cc) channel
- Two electrons or muons: Z(ll)H(cc)
- Lepton triggers
- Fit invariant mass of the two dijets, m_{cc} in categories of **jets** and **c-tags**

Little sister of the VH(bb) analysis

Main feature: charm tagging

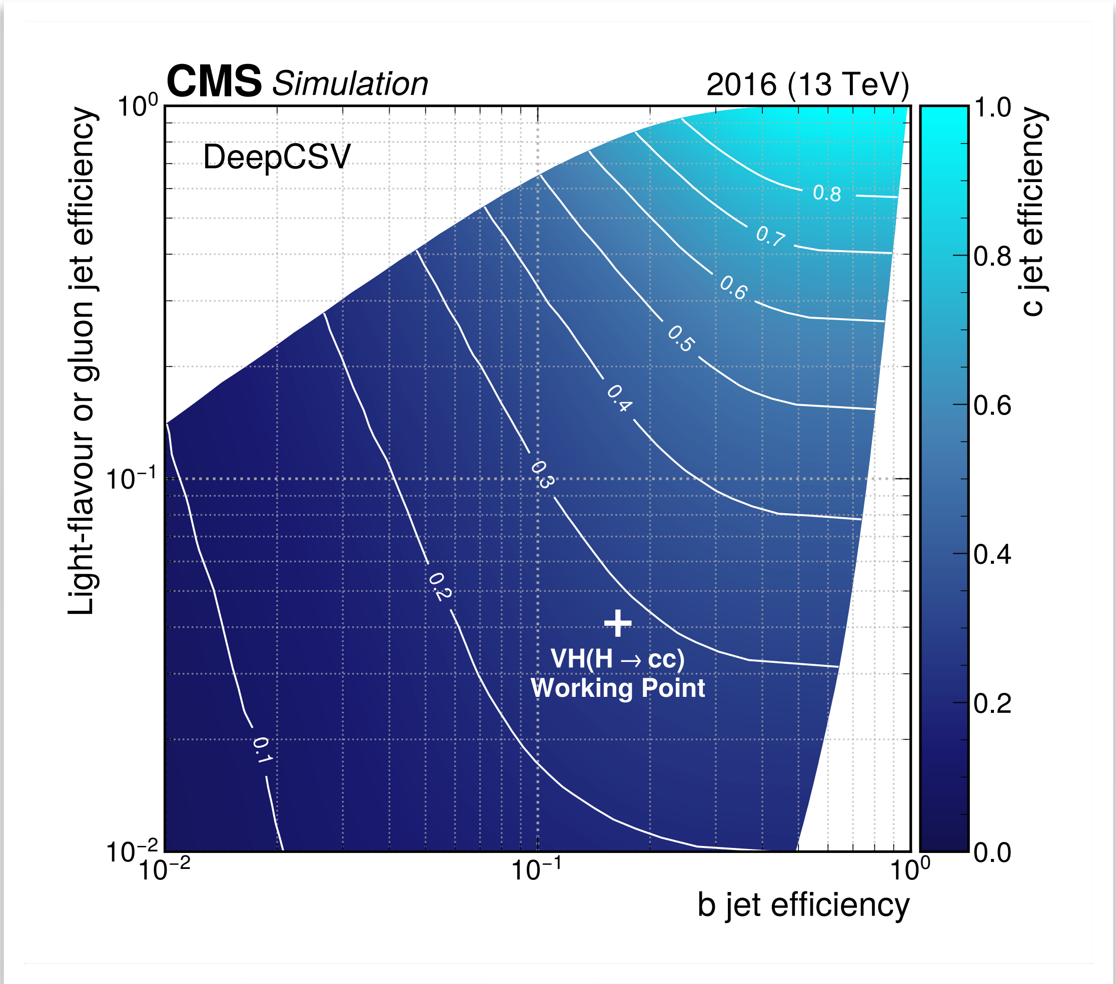


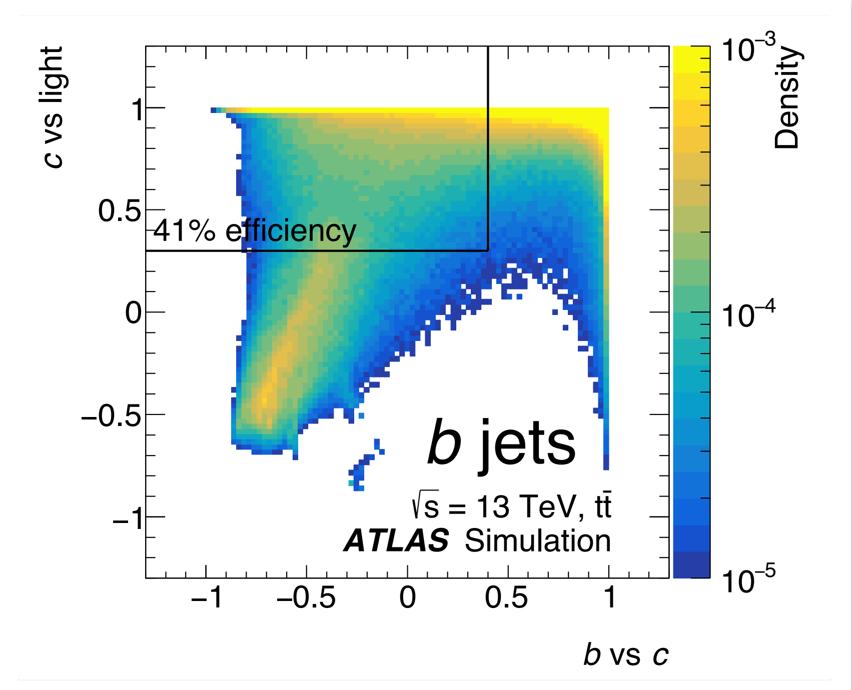


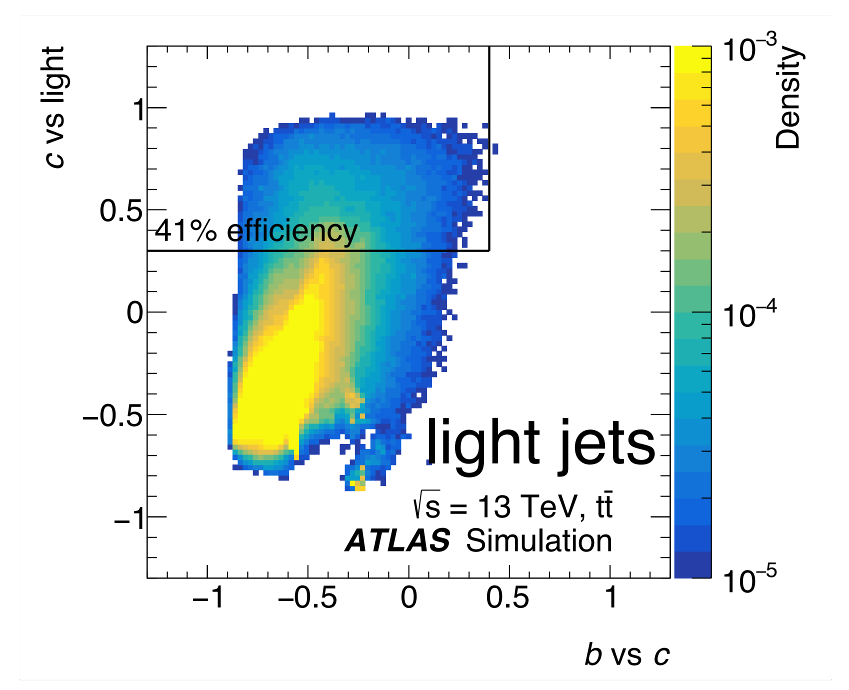
Phys. Rev. Lett. 120 (2018) 211802

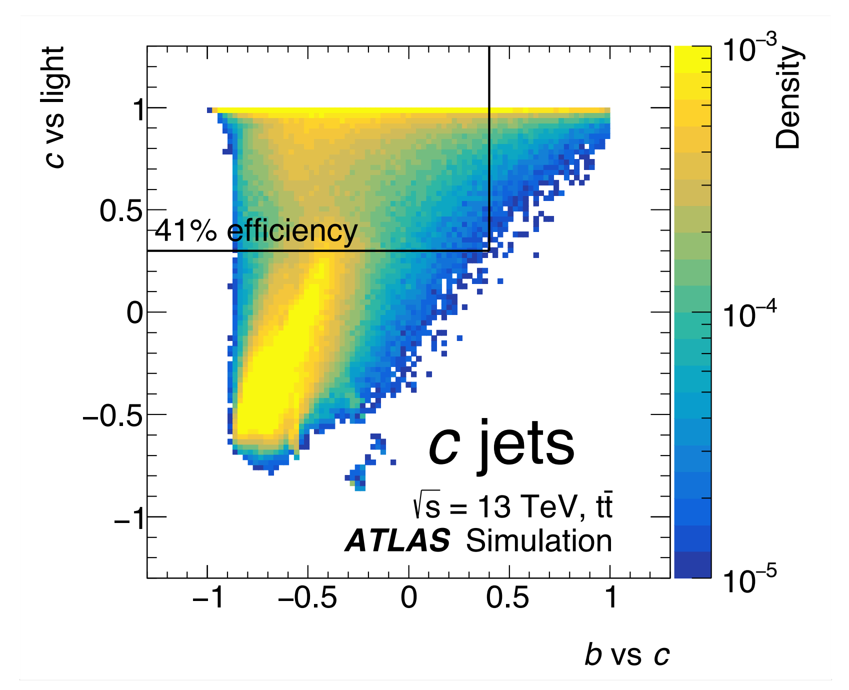
Tagging Charm

- Challenge in tagging charm is that its properties lie between those of the two backgrounds: bottom and light
  - Lifetime, decay multiplicity, mass
- CMS also includes a single tagged merged jet (boosted category)



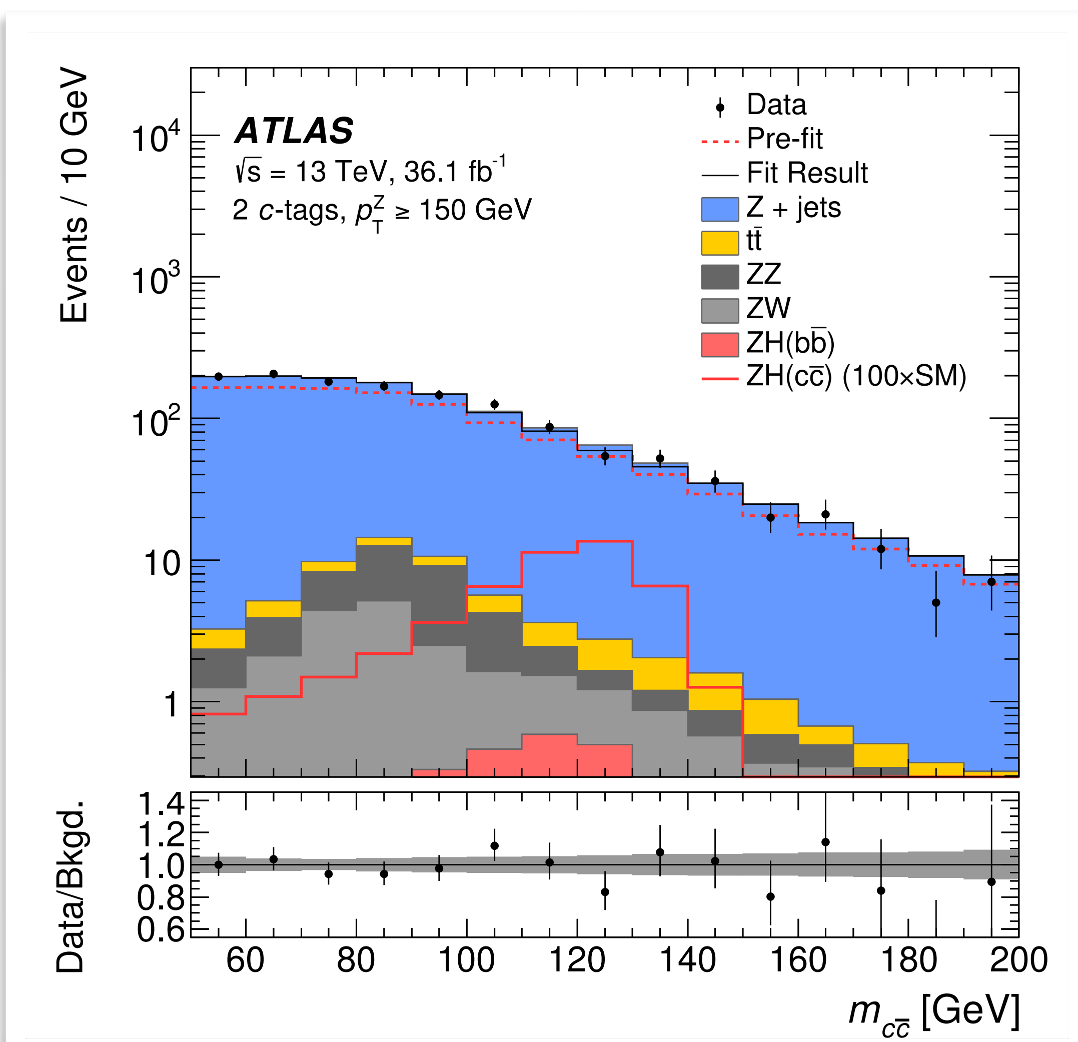




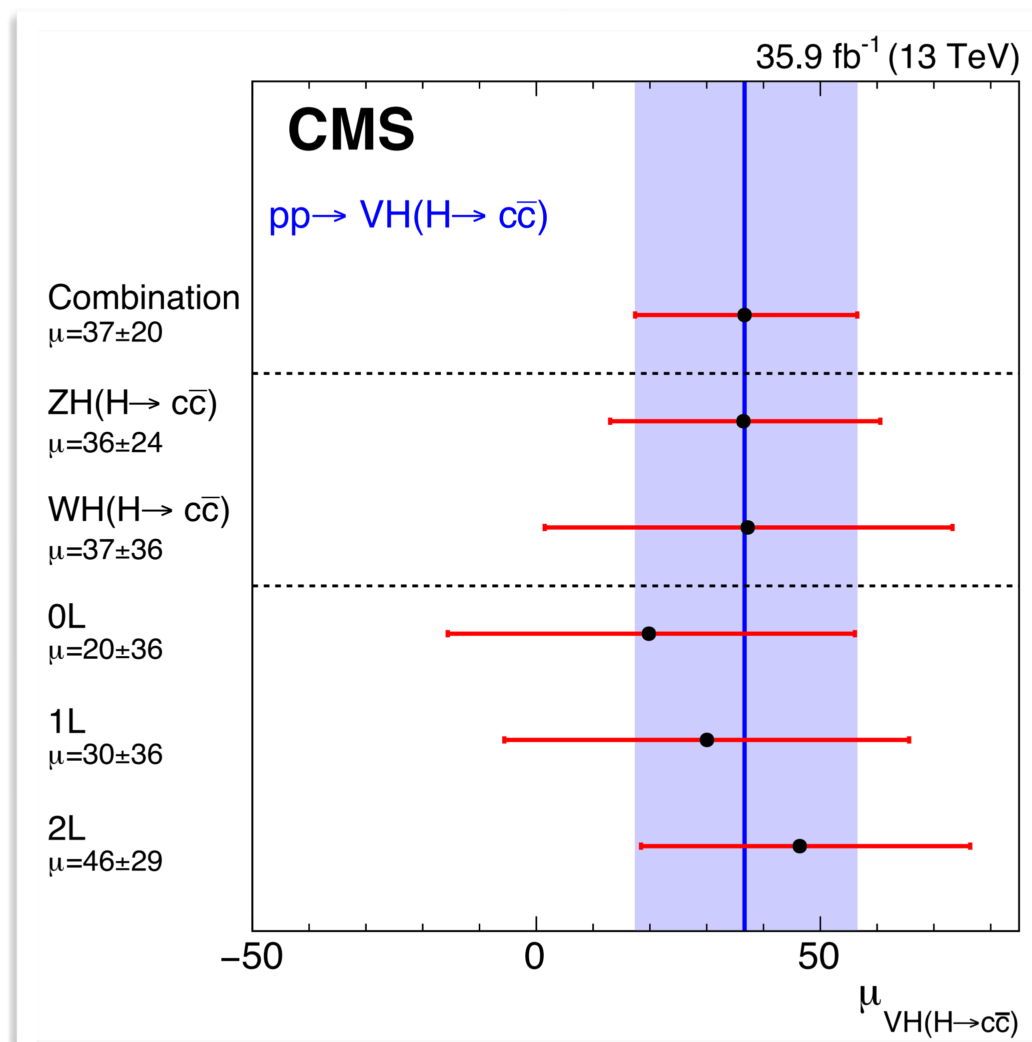


Limits on H→cc

- First upper limits from ATLAS using Z(ll)H(cc)
  - Observed: **110 x SM**, expected: 150 x SM
- Subsequent upper limits from CMS using ZH and WH production and MVA techniques
  - Observed: **70 x SM**, Expected: 37 x SM



PRL120 (2018) 211802



HIG-18-031

Conclusion

- The first and second runs of the LHC have been a **fascinating** and **exciting** time
  - We were privileged to discover a **new elementary particle**
- Extensive property measurement program is currently ongoing
- The channels used for the discovery were anticipated
  - **Benchmark** channels for detector design
- This talk has focussed on some results that were **not anticipated** which allowed us to learn about the interaction of the Higgs with the quarks
  - **bottom, top, charm**
- Some of these were even **thought to be impossible**
- Small message for the future: **always learn from the past, but don't let the past constrain you**
- Clever ideas and innovation can make the **impossible possible**

*Disclaimer; Many other exciting and innovative ideas NOT covered in this talk