SMU Physics Department Seminar Series: Higgs Particle and Bottom Quark Interactions

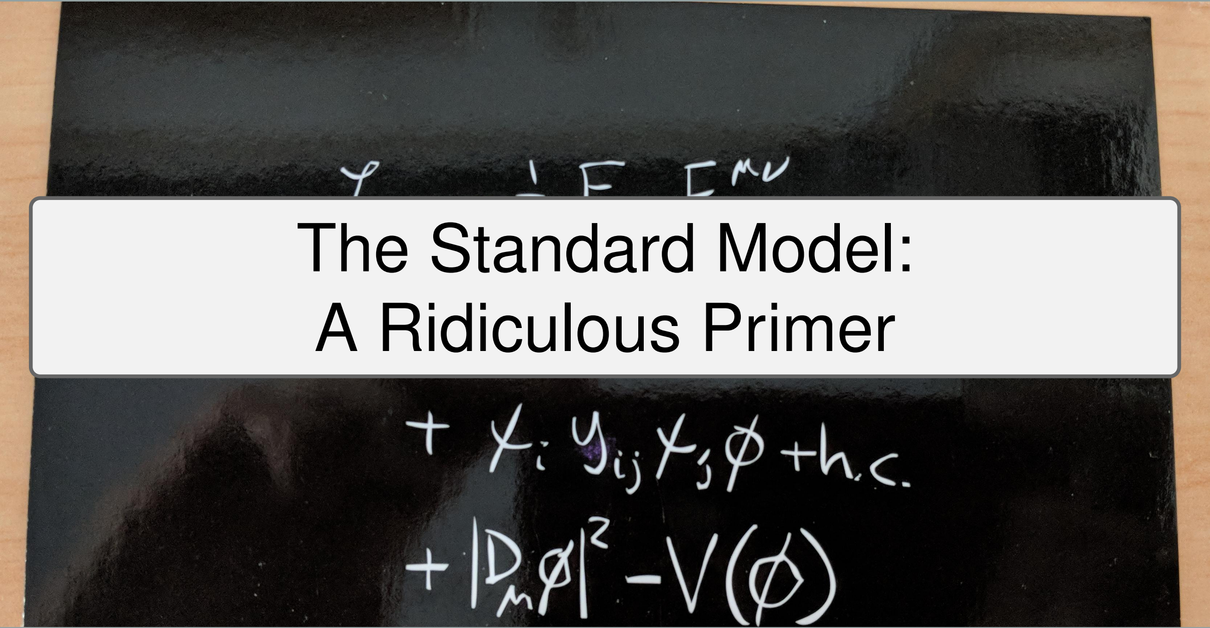
Stephen Sekula[1]

[1]Southern Methodist University
Dallas, TX, USA

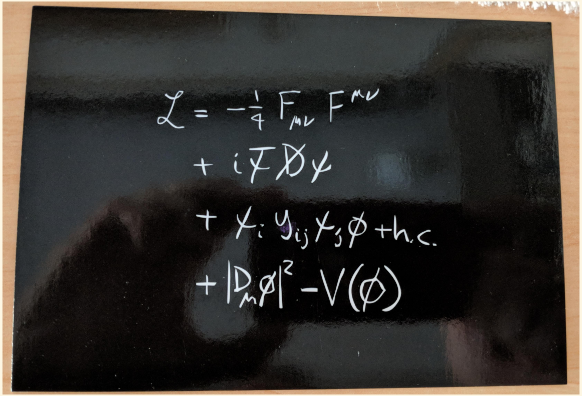
SEPTEMBER 10, 2018

Outline

The Standard Model: A Ridiculous Primer



Higgs-Quark Interactions in the Standard Model



One key parameter of the standard model is the Higgs mass, measured to be $m_H = (124.97 \pm 0.24)\ \mathrm{GeV}$ using ATLAS and CMS Experiment data from 2010-2016.

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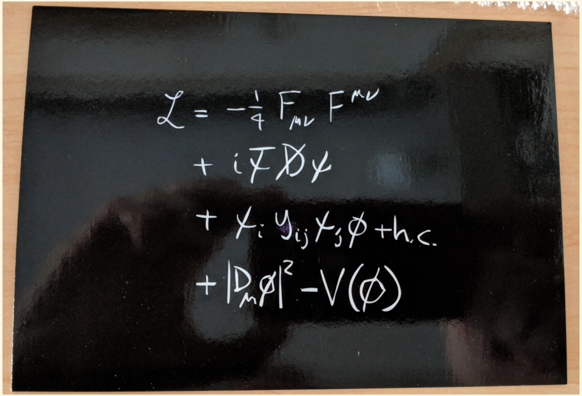

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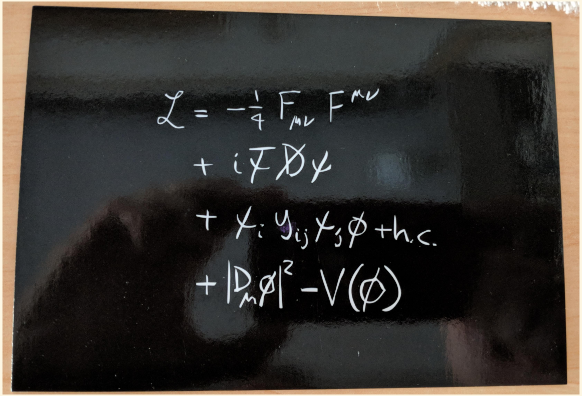

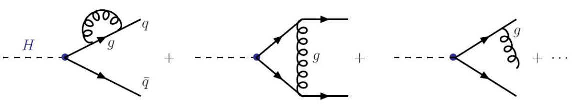

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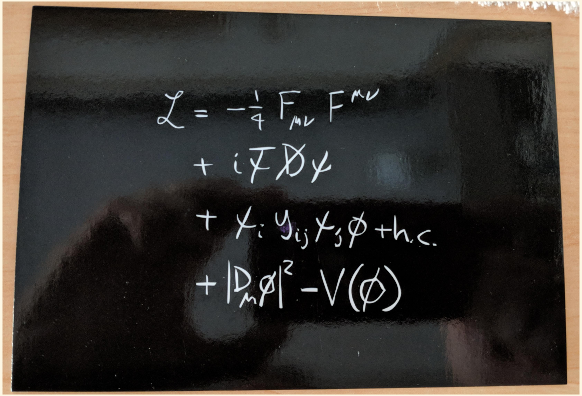

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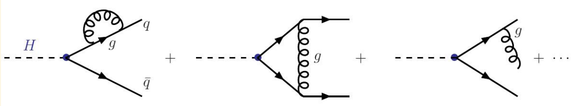

The partial width of the Higgs decay to (heavy) quarks can be written as [1]:

$$\Gamma(H \to q\bar{q}) = \frac{3G_\mu}{4\sqrt{2}\pi} M_H \overline{m}_q^2(M_H) \left[1 + \Delta_{qq} + \Delta_H^2\right]$$

where Δ_{qq} and Δ_H hide all the corrections due to the strong coupling constant, Higgs mass, and most quark properties.

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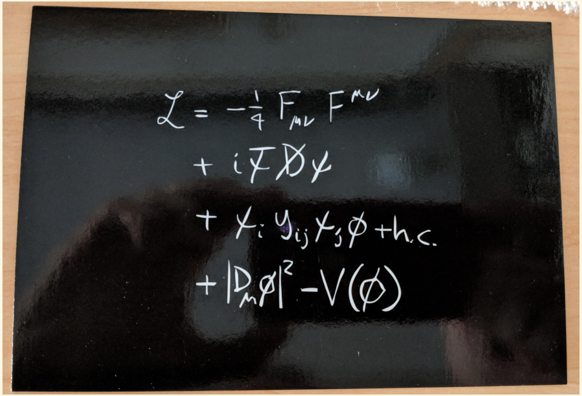

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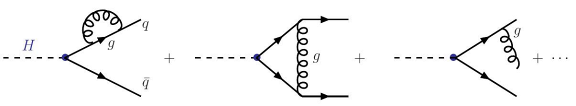

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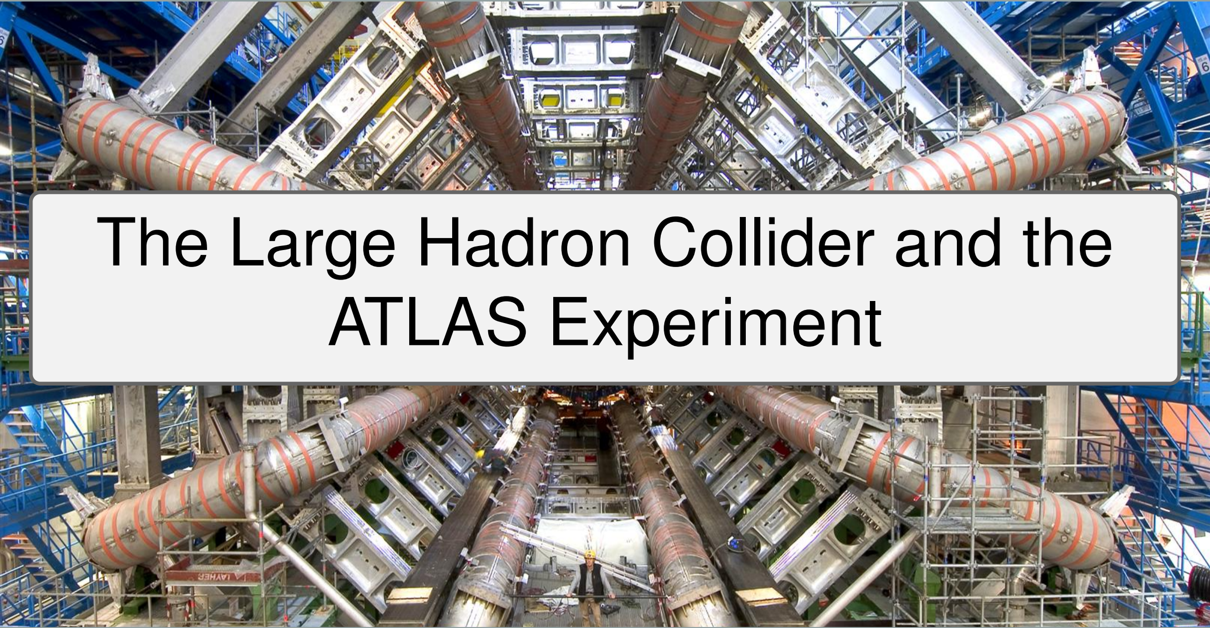
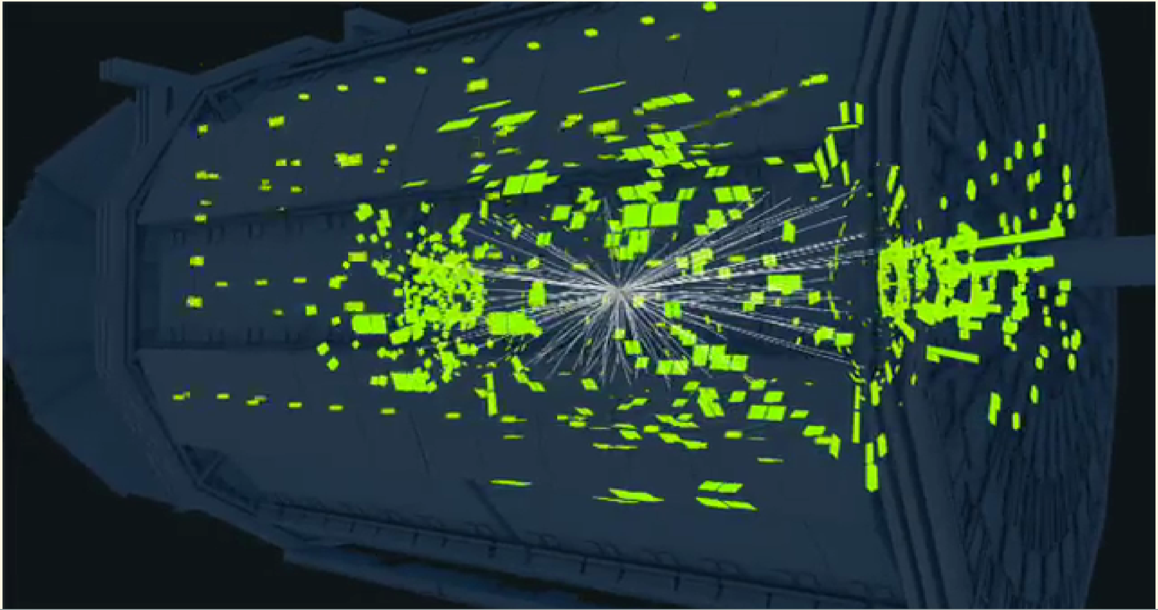
where Δ_{qq} and Δ_H hide all the corrections due to the strong coupling constant, Higgs mass, and most quark properties.

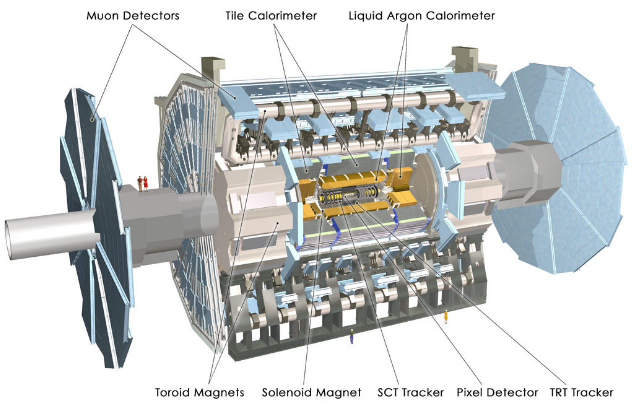
The rate of $H^0 \to b\bar{b}$ is expected to be about 60%, and is the single-largest decay mode of the Higgs particle. It went unobserved in earlier LHC data due to the difficulty of identifying this Higgs decay.



The Large Hadron Collider and the ATLAS Experiment



The ATLAS Detector — Schematic Overview

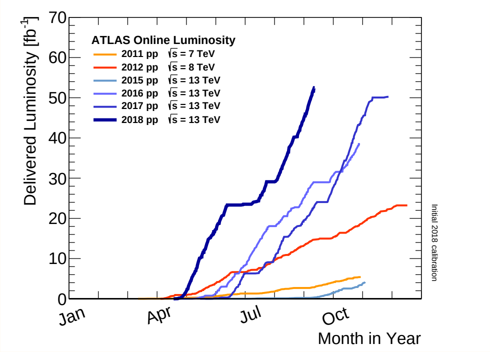


Major SMU contributions:

- Liquid Argon Calorimeter
  - Original readout electronics, Phase I and Phase II upgrade readout electronics
  - Operations and Monitoring
- Trigger/Data Acquisition
  - Data Quality Monitoring Framework
  - Core Software Development and Maintenance
  - **Trigger Rate Prediction Monitoring**
  - **Bottom-quark-initiated jet triggers and online track reconstruction systems**

(bold items are places where my students, post-doctoral researchers, and I have played/are playing major roles; bold-underlined are active and ongoing contributions)

$p-p$ Collision Data Collected by the ATLAS Experiment



A rough way of use the chart:

$$L \times \sigma = N \quad (1)$$

Read integrated luminosity (L) off chart at any time; get σ, the prediction of the cross-section of a physical process, from your friendly neighborhood theorist (e.g. $\sigma(pp \to H) \approx 60 \times 10^3 \mathrm{fb}$ at $\sqrt{s} = 13$ TeV). Estimate the number of occurrances of that process in your data set. For example, for each $1 \mathrm{fb}^{-1}$ the LHC produces 60×10^3 Higgs bosons at $\sqrt{s} = 13$ TeV.

For the current running period, 2015-2018, we anticipate having $\sim 150 \mathrm{fb}^{-1}$, which would give us access to ~ 9 million Higgs particles — this is just what the collider would deliver, not what we would capture with ATLAS.

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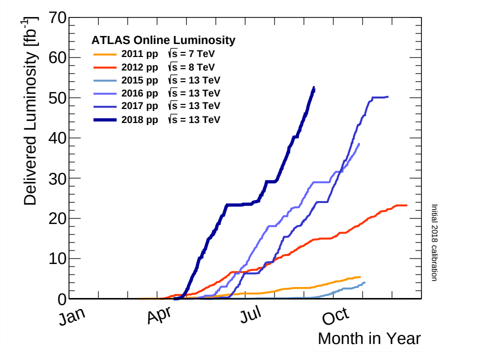

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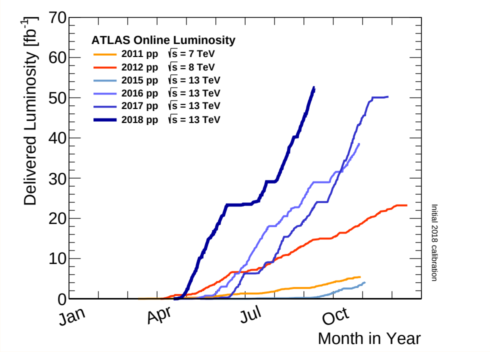

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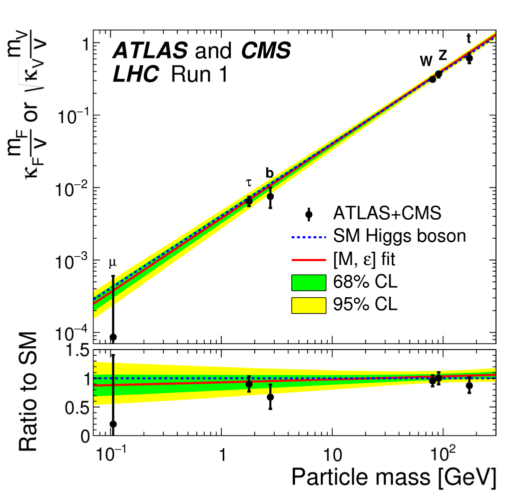
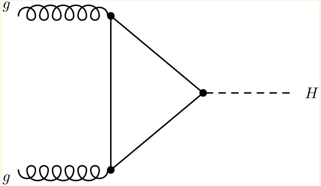
The Higgs-Bottom Quark Landscape

2010-2012: The Run 1 LHC Perspective on Higgs Couplings

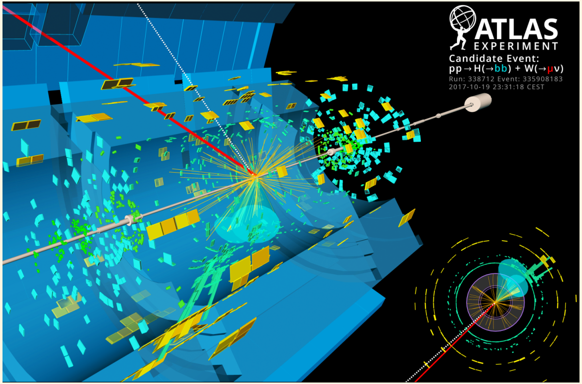


We learned about the bottom-quark and Higgs interaction in Run 1 [2] without ever laying eyes, reliably, on a single Higgs particle decaying to bottom quarks (e.g. $H^0 \to b\bar{b}$). This was done via quantum mechanical processes like this:



where bottom quarks "running in the loop" influence the rate of the above process, and have consequences for how often we observed Higgs bosons being produced in Run 1.

2015-2018: Run 2 and the "Edge of a Major Success"



The "gold-plated" approach to direct observation of $H^0 \to b\bar{b}$ is $pp \to (W, Z)H^0$ with $W \to \ell^+\nu$, $Z \to \nu\bar{\nu}$, or $Z \to \ell^+\ell^-$ [3, 4]. By itself, this method is still not definitive but is rapidly approaching that point.

SMU has contributed to discovery by this approach via software framework development and leadership (e.g. speeding development through automated builds of the "Hbb" analysis software and improved analysis software) and improved modeling of a major background process, $pp \to t\bar{t}$. *PH.D. THESIS: PEILONG WANG*

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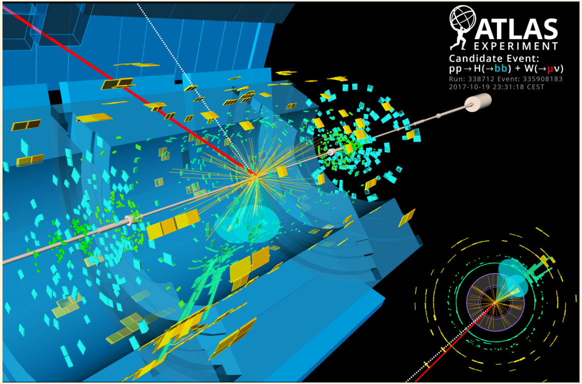

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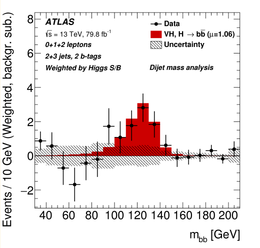

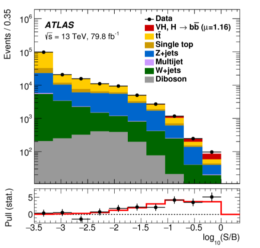

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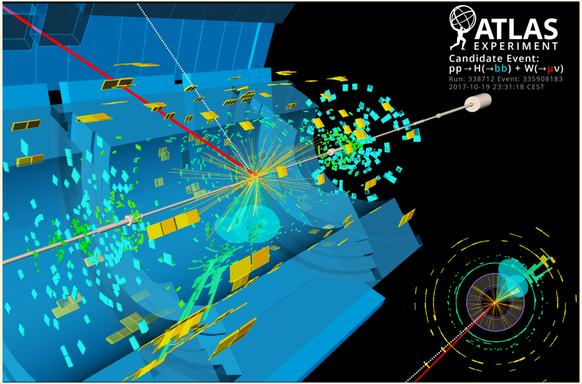

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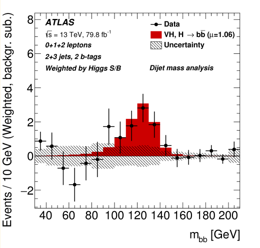

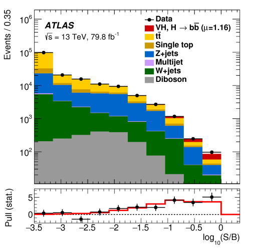

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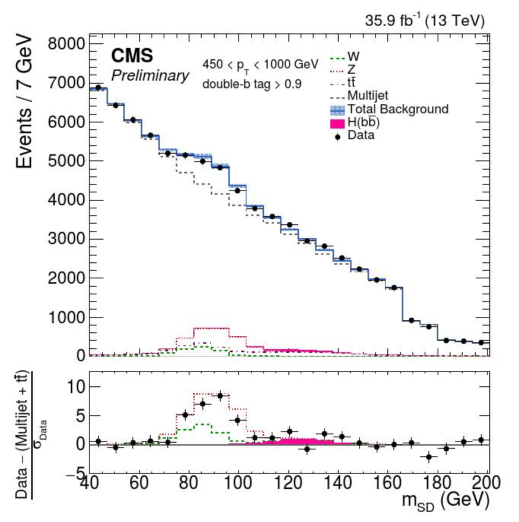
$H \rightarrow b\bar{b}$ as a tool for new discoveries: "The Tail of the Higgs" and other stories



SMU partnered with the SLAC National Accelerator Laboratory to pioneer this analysis in ATLAS, recognizing that there are significant physics improvements to be made in this analysis to improve its scope (e.g. addition of top quark resonances from $t\bar{t}$ and single-top production. *PH.D. THESIS: MATTHEW FEICKERT*)

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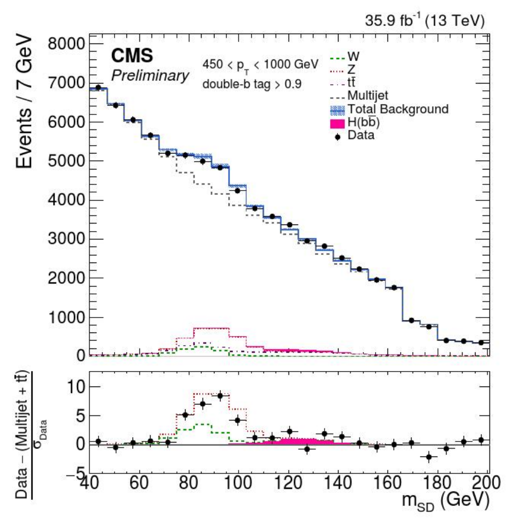

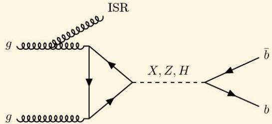

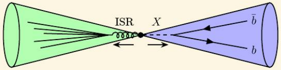

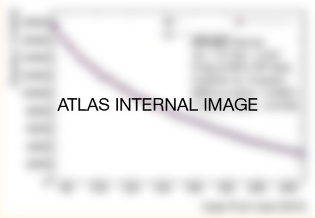

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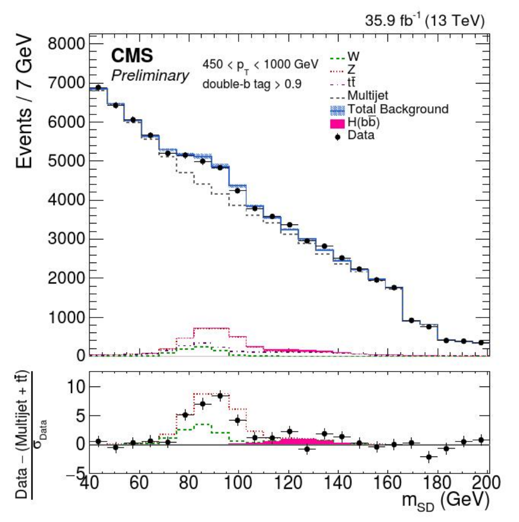

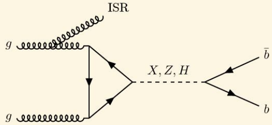

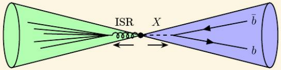

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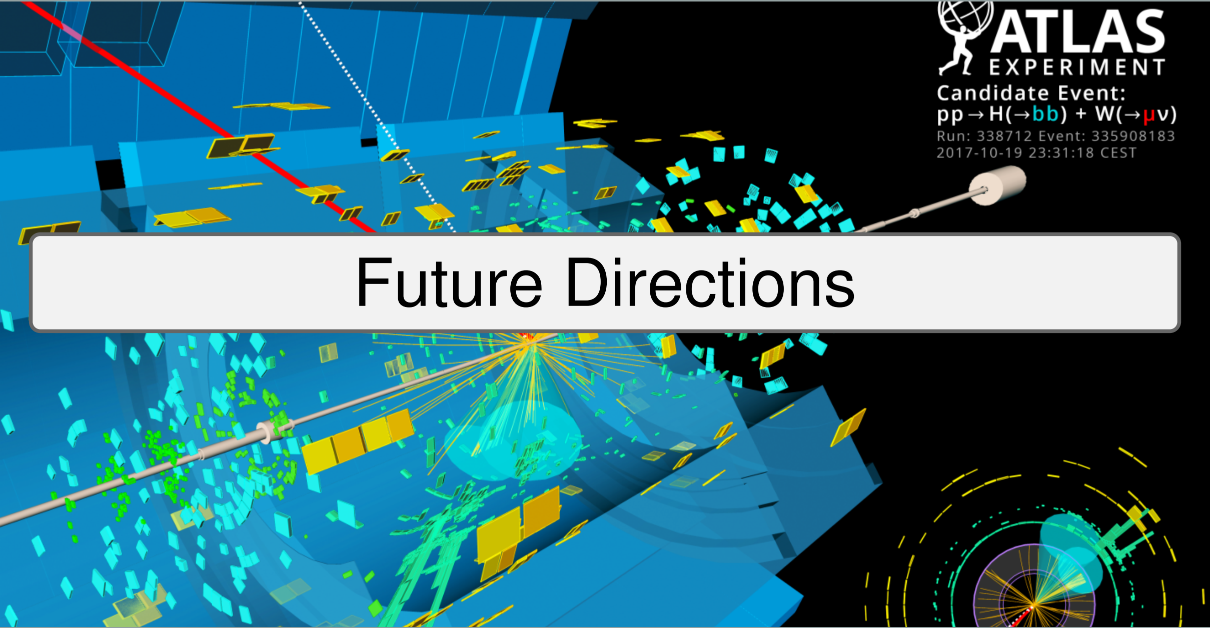

Future Directions

So Much To Say

Every one of the items below is an area where a student could walk in and get started on something of importance to the future of Higgs physics.

- **Bottom-quark identification in dense environments:** as the LHC collision intensity climbs over the next 20 years, it will become more important to work harder to "tag" the presence of bottom quarks from Higgs decay in increasingly information-dense environments.
  - "Xbb" tagging, quark/gluon jet-tagging, charm tagging, hadron-level tagging, deep learning applications in jet identification
- **Bottom-quark-initiated jet triggers:** Heavy quarks and signs of new physics may go hand-in-hand; securing data with such signatures right at the time of data-taking grows in importance over the next 20 years.
  - Implementation of new jet-tagging algorithms in the online system, use of the new hardware-based charged particle reconstruction systems (FTK and HTT), deployment of algorithms in the new ATLAS framework ("AthenaMT"), physics needs and impact of design choices.

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- $H^0 \to b\bar{b}$ **as a tool:** we will have definitively established the Higgs-bottom quark coupling as directly observable at the conclusion of Run 2 data analysis (ca. 2019-2020)
  - increased emphasis on probing rare Higgs production processes now that its largest decay mode is reliably established, use of this decay mode for a new round of Higgs property measurements, and emphasis on using this decay mode to distinguish Higgs decays from possible new particles/signatures involving bottom quarks (the "Higgs as background" problem)

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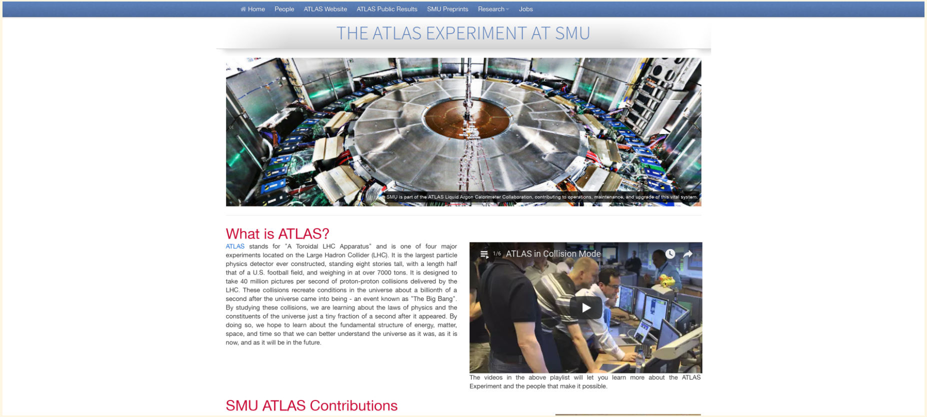
SMU ATLAS Group Website



https://www.physics.smu.edu/web/research/atlas.html

My ATLAS Research Page

Higgs studies of both $H \to bb$ and $pp \to (Z,W)H$. The results were presented for the first time at 2018 International Conference on High Energy Physics (ICHEP) in South Korea.

- **[Fri Apr 13 2018]** *SMU Physics Major Rebecca Moore earns a Hamilton Scholar Award to Support her ATLAS Research* -- SMU undergraduate and physics major Rebecca Moore has earned a Hamilton Scholar Award to support her summer research with the SMU ATLAS Group. Rebecca will explore the details of gluon splitting in the context of LHC physics, and consider new ideas in the study of decays of the Higgs bosons where only hadrons appear in the final state.

Hot Topics Archive

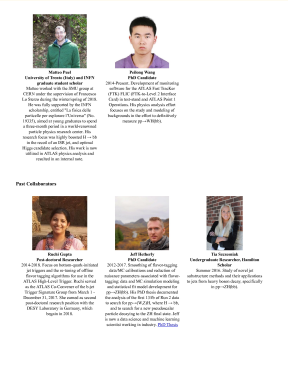
Current and Past Collaborators

Current Collaborators

Matthew Feickert
PhD Candidate
2014-Present. Study of ATLAS Fast TracKer (FTK) tracks in the development of bottom-quark-initiated jet triggers in signature definitions for the ATLAS High-Level Trigger. His physics analysis efforts focus on the development of strategies to model and assess the impact of backgrounds in the study of highly boosted $H \to bb$ topologies.

Francesco Lo Sterzo
Post-doctoral Researcher
2017-Present. Optimization of online flavor-tagging algorithms for bottom-quark-initiated jet triggers in the ATLAS High-Level Trigger and Higgs and heavy-flavor physics, with emphasis on the study of Standard Model $H \to bb$. He is the top quark simulation expert in the ATLAS Hbb group, and is developing strategies to improve our understanding of the top pair background in the $pp \to VH(bb)$ topology in preparation for a full-scale observation of this process in Run 2. He also works on highly boosted $H \to bb$ processes, probing alternative production mechanisms.

Rebecca Moore
Undergraduate Researcher, Hamilton Scholar
Spring and Summer 2018. Study of gluon splitting and hadronic Higgs boson decays.



Matteo Puel
University of Trento (Italy) and INFN graduate student scholar
Matteo worked with the SMU group at CERN under the supervision of Francesco Lo Sterzo during the winter/spring of 2018. He was fully supported by the INFN scholarship, entitled "La fisica delle particelle per esplorare l'Universo" (No. 19335), aimed at young graduates to spend a three-month period in a world-renowned particle physics research center. His research focus was highly boosted $H \to bb$ in the recoil of an ISR jet, and optimal Higgs candidate selection. His work is now utilized in ATLAS physics analysis and resulted in an internal note.

Peilong Wang
PhD Candidate
2014-Present. Development of monitoring software for the ATLAS Fast TracKer (FTK) FLIC (FTK-to-Level 2 Interface Card) in test-stand and ATLAS Point 1 Operations. His physics analysis effort focuses on the study and modeling of backgrounds in the effort to definitively measure $pp \to WH(bb)$.

Past Collaborators

Ruchi Gupta
Post-doctoral Researcher
2014-2018. Focus on bottom-quark-initiated jet triggers and the re-tuning of offline flavor tagging algorithms for use in the ATLAS High-Level Trigger. Ruchi served as the ATLAS Co-Convener of the b-jet Trigger Signature Group from March 1 - December 31, 2017. She earned as second post-doctoral research position with the DESY Laboratory in Germany, which begain in 2018.

Jeff Hetherly
PhD Candidate
2012-2017. Smoothing of flavor-tagging data/MC calibrations and reduction of nuisance parameters associated with flavor-tagging; data and MC simulation modeling and statistical fit model development for $pp \to ZH(bb)$. His PhD thesis documented the analysis of the first 13/fb of Run 2 data to search for $pp \to (W,Z)H$, where $H \to bb$, and to search for a new pseudoscalar particle decaying to the ZH final state. Jeff is now a data science and machine learning scientist working in industry. PhD Thesis

Tia Szczesniak
Undergraduate Researcher, Hamilton Scholar
Summer 2016. Study of novel jet substructure methods and their applications to jets from heavy boson decay, specifically in $pp \to ZH(bb)$.

Nicole Hartman
Undergraduate Researcher, Hamilton Scholar, Physics Major
2013-2016. Went on to pursue her PhD in Physics at Stanford University. At SMU, she developed a study of novel jet substructure methods and their applications to jets from heavy boson decay, specifically in $pp \to HH \to 2b2\gamma$.

Tingting Cao
PhD Candidate
2009-2016. Earned her PhD in 2016. Went on to Post-doctoral position at Tel Aviv University on the ATLAS Experiment. Her PhD was on the measurement of the spin and parity quantum numbers of the 126-GeV boson discovered in 2012. PhD Thesis

Aidan Randle-Conde
Post-doctoral Researcher
2010-2013. Went on to second Post-doctoral Researcher position at the Universite Libre de Bruxelles on the CMS Experiment. His SMU research included searches for an electrically charged Higgs boson and the first ATLAS search for $h \to Z\gamma$.

Matthew Rispoli
Undergraduate Researcher
2011-2012. SMU Presidents Scholar and Physics Major. Pursued his PhD in Physics at Harvard University starting in 2012. His research focused on methods of assessing the background, due to multi-jet projection, contaminating the search for an electrically charged Higgs boson.

Opportunities at SMU

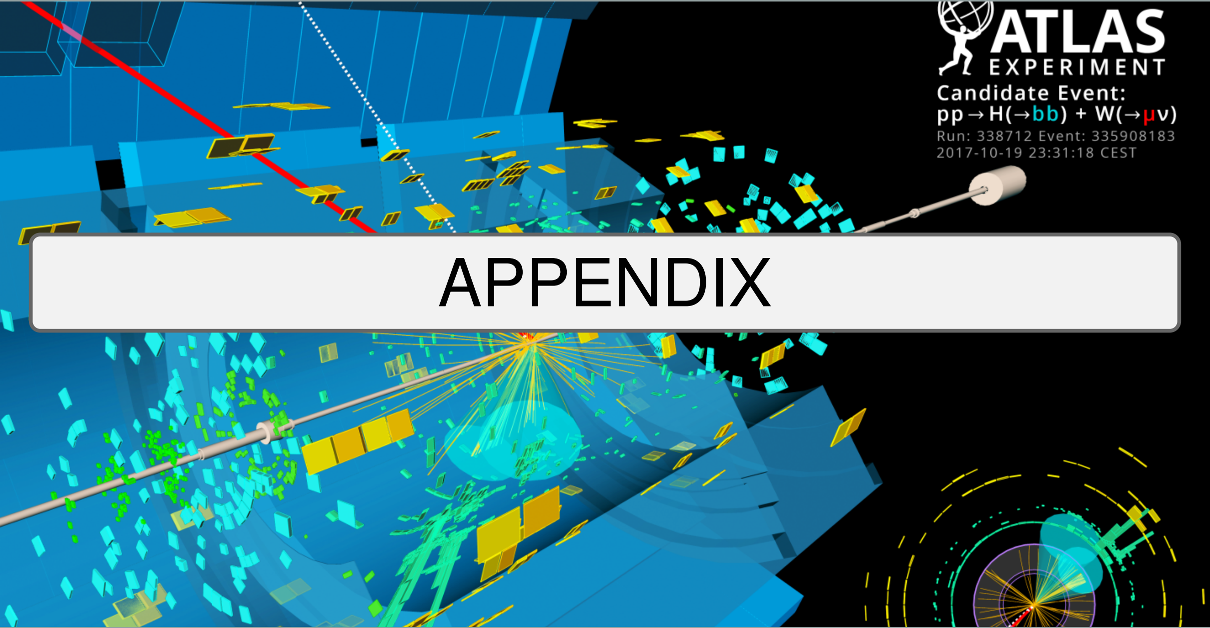
The SMU ATLAS group is involved in both technical and physics analysis contributions to the ATLAS experiment. My own effort is focused on two areas: the coupling of the Higgs bosons to heavy quark flavors, with emphasis on the bottom quark, and technical contributions related to that physics in b-jet triggers, flavor tagging, and hardware-based tracking.

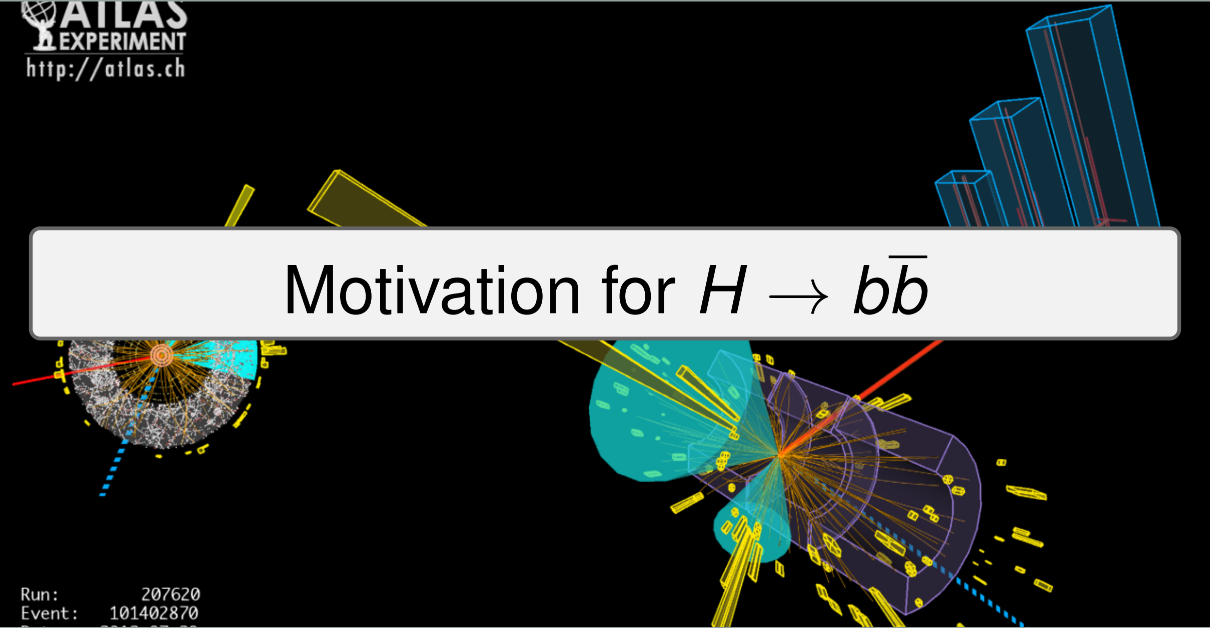
If you are interested in any of these areas, please consider applying to our PhD program and pursuing your research with me on the ATLAS Experiment, or if you've already completed or are soon-to-complete your PhD you should consider applying for any open post-doctoral positions within the SMU ATLAS group.

SMU is home to a world-class optoelectronics research laboratory that currently supports R&D work for ATLAS upgrades. In addition, we are home to an ATLAS Tier 3 high-performance computing cluster, called "ManeFrame", that provides priority computing access to local users. The SMU Physics Department focuses only on particle physics and astroparticle physics, providing a deep concentration on areas that would be of most interest to LHC physicists.

https://www.physics.smu.edu/sekula/atlas/

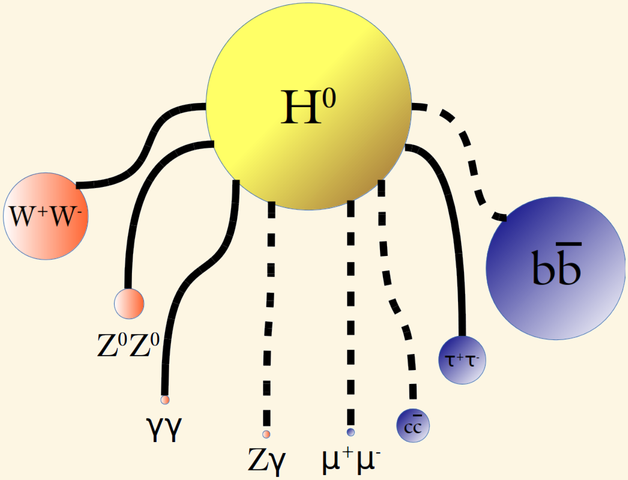
APPENDIX


ATLAS
EXPERIMENT
Candidate Event:
pp → H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST



Motivation for $H \to b\bar{b}$

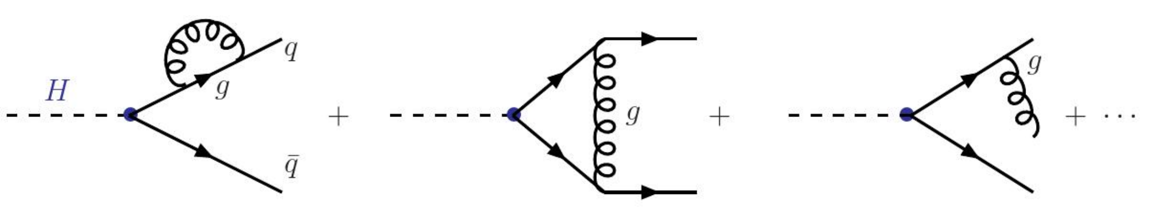
Expected Higgs Decays — Standard Model Picture



A visual representation of the expected pattern of decay for $m_H = 125\ \mathrm{GeV}$. The areas of final-states are relatively proportional to the expected rate of $H \to b\bar{b}$.

Solid lines indicate channels that have been directly observed in data as of the spring of 2017. Dashed lines indicate those channels that had not yet been observed at that time.

$H \to b\bar{b}$ Example Feynman Diagrams



The Feynman diagrams above are from Ref. [1]. These illustrate examples of the leading-order QCD corrections to the Born-level (tree-level) diagram with a single vertex.

$H \to b\bar{b}$ Partial Width

In the standard model, the partial width of the Higgs decay to (heavy) quarks is given at NNLO in QCD by [1]:

$$\Gamma(H \to q\bar{q}) = \frac{3G_\mu}{4\sqrt{2}\pi} M_H \, \overline{m}_q^2(M_H) \left[1 + \Delta_{qq} + \Delta_H^2\right] \tag{2}$$

where

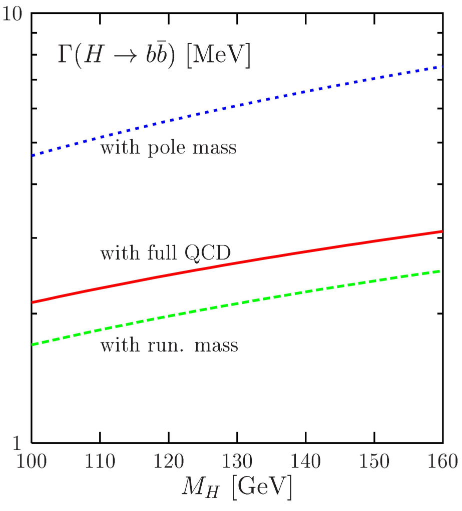
$$\begin{aligned}\Delta_{qq} &= 5.67\frac{\bar{\alpha}_s}{\pi} + (35.94 - 1.36N_f)\frac{\bar{\alpha}_s^2}{\pi^2} \\ &\quad +(164.14 - 25.77N_f + 0.26N_f^2)\frac{\bar{\alpha}_s^3}{\pi^3}\end{aligned} \tag{3}$$

and

$$\Delta_H^2 = \frac{\bar{\alpha}_s^2}{\pi^2}\left(1.57 - \frac{2}{3}\log\frac{M_H^2}{m_t^2} + \frac{1}{9}\log^2\frac{\overline{m}_q^2}{M_H^2}\right) \tag{4}$$

Comments on the partial width in the standard model

- The partial width depends on well-established fundamental constants, the running quark mass, and the mass of the Higgs boson
- The established Higgs mass is 125.09 GeV based on the Run 1 ATLAS+CMS combination
- At the measured value of the mass, the full width is 4.100 MeV (with an uncertainty of about 2%)
- Focus on the "Full QCD curve" - at measured m_H, $\Gamma_{bb} \approx 2.5$ MeV yielding $\mathcal{B}_{\mathbf{bb}} \approx$ 60%



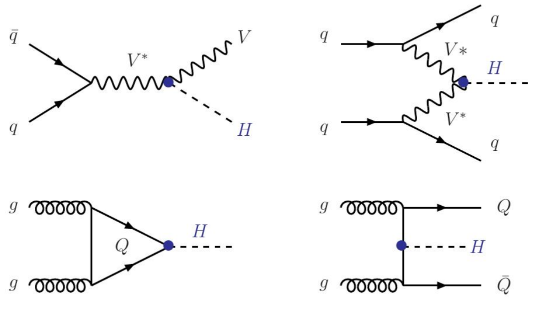
State-of-the-art branching ratio calculation

The state-of-the-art branching fraction calculations for $H \to b\bar{b}$ include next-to-leading order (NLO) electroweak corrections, as well as massless QCD corrections up to NNNNLO (c.f. Ref. [5, 6]). The current prediction in the SM for $m_H = 125.09\ \mathrm{GeV}$ is:

$$\mathcal{B}(H \to b\bar{b}) = 0.5809 \pm 0.65\%(\mathrm{THU})^{+0.72\%}_{-0.74\%}(\mathrm{PU})(m_q)^{+0.77\%}_{-0.79\%}(\mathrm{PU})(\alpha_s) \qquad (5)$$

where "THU" refers to theory undertainties due to missing higher-order corrections, "PU(m_q)" to parametric uncertainties from the quark masses, and "PU(α_s)" to parametric uncertainties from the strong coupling constant.

Production Mechanisms



The above are the leading-order diagrams [1] for the leading Higgs production mechanisms at the LHC. Clock-wise from upper-left, these are: vector boson associated (VBA) production, vector boson fusion (VBF), $(t\bar{t}/b\bar{b})H$ production, and gluon fusion (ggF).

Mode	Cross-section (pb)
ggF	48.52
VBF	3.779
WH	1.369
ZH	0.8824
ttH	0.5065
bbH	0.4863

$(\sqrt{s} = 13\ \text{TeV}$ [5])

References I

[1] A. Djouadi, "The Anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model," *Phys. Rept.* **457** (2008) 1–216, `arXiv:hep-ph/0503172 [hep-ph]`.

[2] ATLAS and C. Collaborations, "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:1606.02266`. `http://arxiv.org/abs/1606.02266http://dx.doi.org/10.1007/JHEP08(2016)045`.

[3] T. ATLAS Collaboration, "Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector," *ATLAS-CONF-2018-036* (2018) 50. `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-036/ATLAS-CONF-2018-036.pdf`.

[4] **ATLAS** Collaboration, M. Aaboud *et al.*, "Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector," `arXiv:1808.08238 [hep-ex]`.

[5] **The LHC Higgs Cross Section Working Group** Collaboration, D. de Florian *et al.*, "Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector," `arXiv:1610.07922 [hep-ph]`.

References II

[6] A. Denner, S. Heinemeyer, I. Puljak, D. Rebuzzi, and M. Spira, "Standard Model Higgs-Boson Branching Ratios with Uncertainties," *Eur. Phys. J.* **C71** (2011) 1753, `arXiv:1107.5909 [hep-ph]`.