# My Projects as an LPC Distinguished Researcher:
# Higgs Physics and L1 Trigger
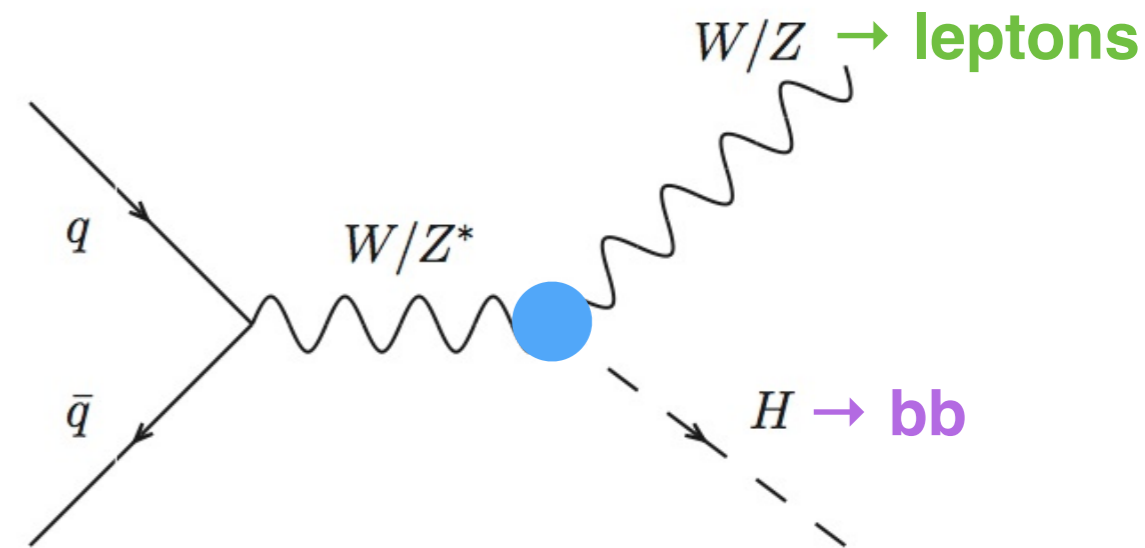
Ben Kreis (FNAL)
May 24, 2016

# VH(bb) and Some LPC History

- Associated production (VH) with H➜bb
  - H➜bb
    - Largest branching fraction
    - Important for establishing Hff coupling
  - V➜leptons for triggering

- The LPC has been a big player in the CMS search for standard model VH(bb) since the beginning
  - Reached 2σ in Run 1 ([arXiv:1310.3687](#))

- Three FNAL postdocs who worked on H➜VV did Snowmass studies showing VH(bb) could be powerful probe of the HVV coupling
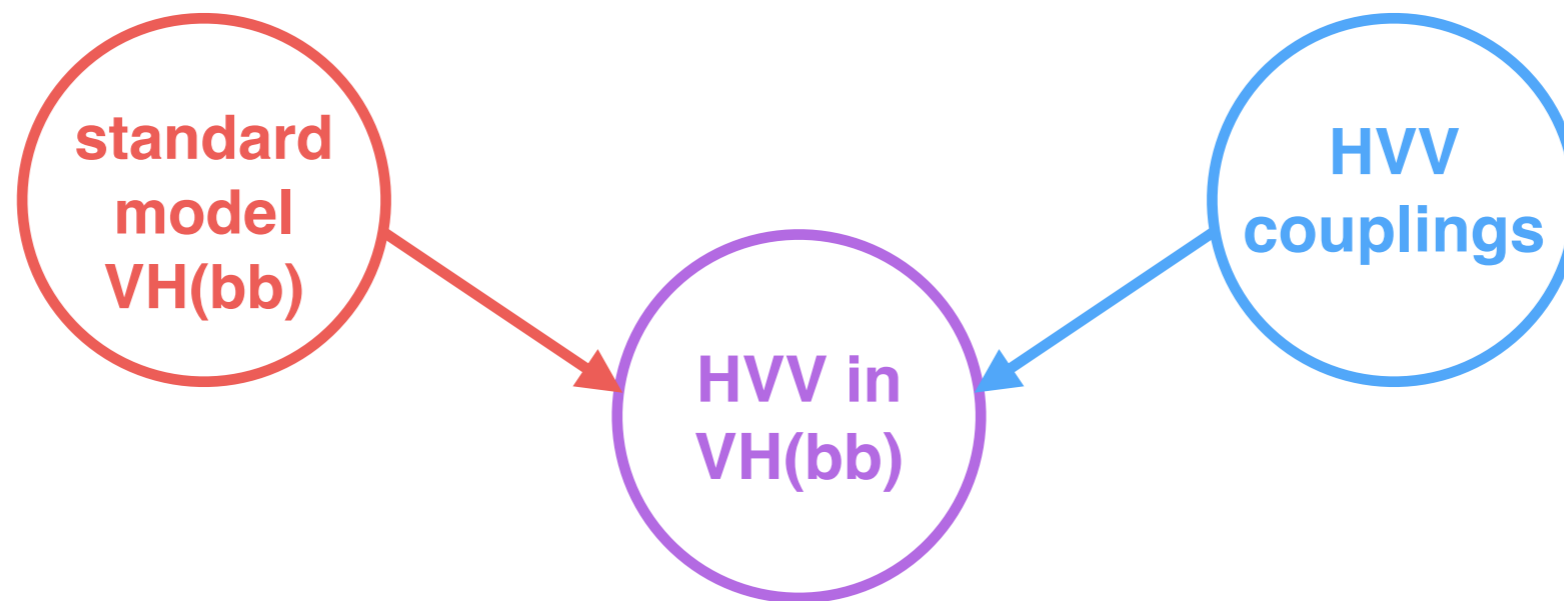  - Y. Gao, N. Tran, A. Whitbeck et al. ([arXiv:1309.4819](#))
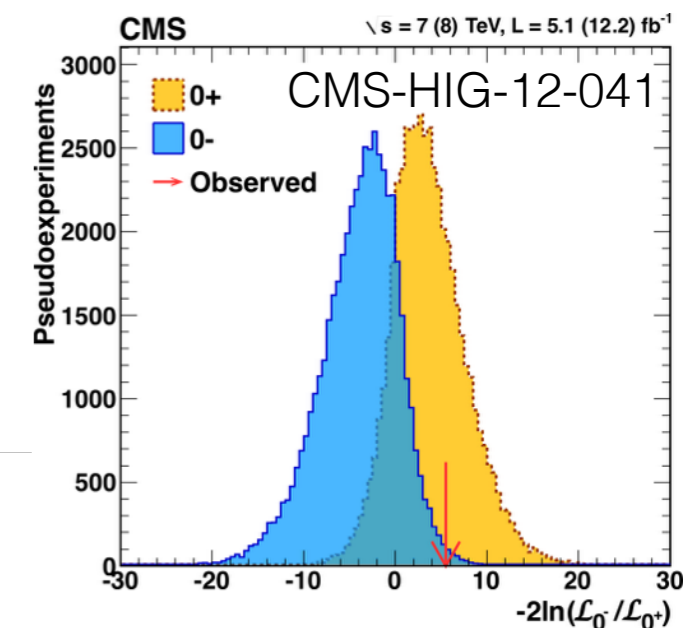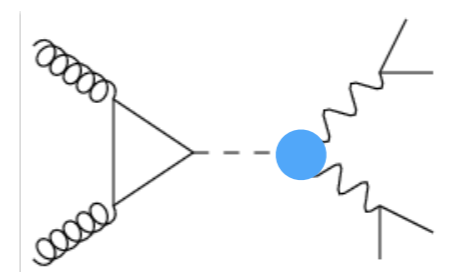
# The LPC Team

New team that drew on LPC experience in

1. The search for standard model VH(bb)
2. HVV coupling studies in H➜VV



J. Berryhill, BK, N.Tran, C. Vernieri, A.Whitbeck - FNAL
A. Garabedian, M. Narain, **S. Sagir** - Brown University
J. Li, Q. Li, Y. Mao, Q. Wang, Z. Xu - Peking University
J. Fu Low - University of Florida
N. Parashar, **J. Stupak III** - Purdue University Calumet
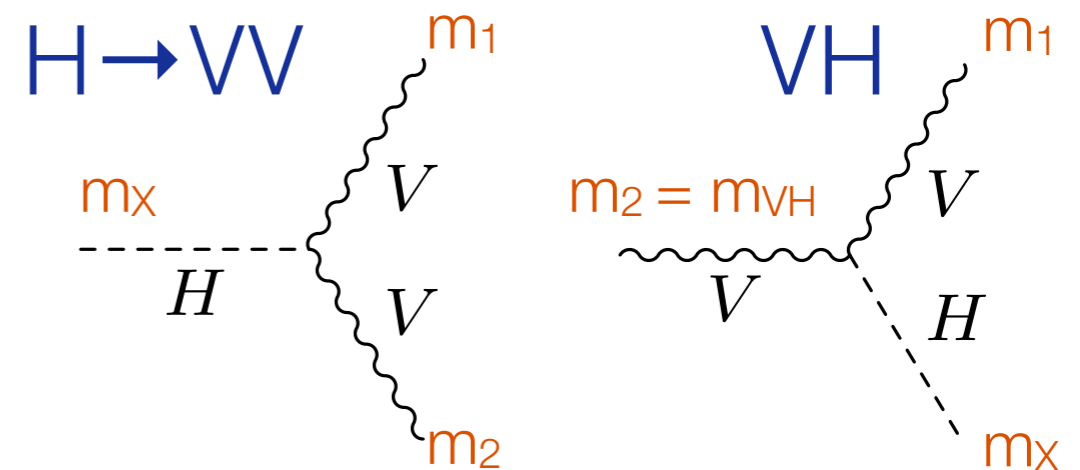M. Xiao - Johns Hopkins University

# The HVV Coupling

Generic HVV scattering amplitudes for spin 0 H:

$$A(m_1, m_2) \sim \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left( a_1 g_{\mu\nu} + a_2 \frac{q_\mu q_\nu}{m_H^2} + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$
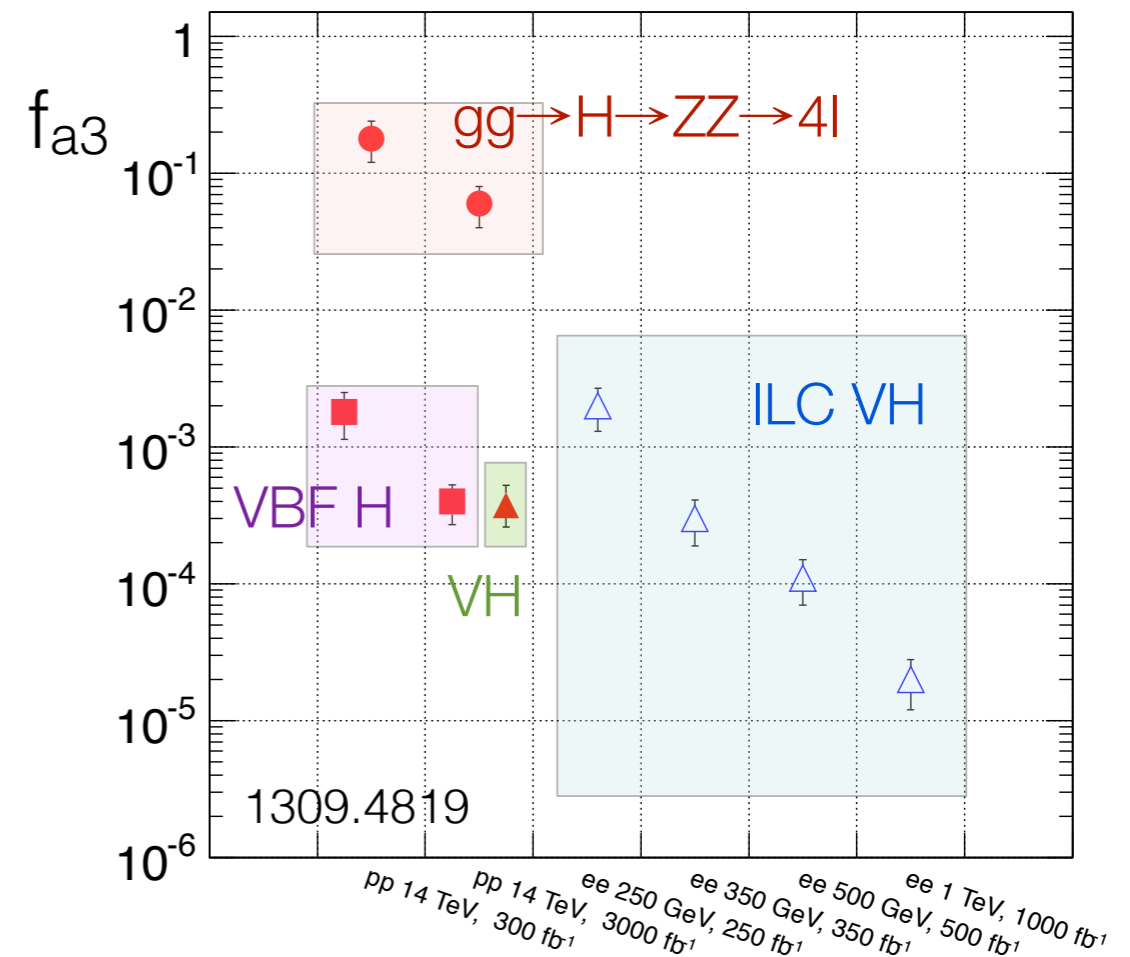
$H \to VV$, VH

- VH sensitivity from order of magnitude larger $m_1 m_2 / m_X$

- Effective fractional cross section to parameterize presence of anomalous pseudoscalar component

$$f_{a3} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_3|^2 \sigma_3}$$

*where $\sigma_i$ is the cross section for $a_i = 1$ and $a_{j \neq i} = 0$*

$$\sqrt{f_{a3}} = \frac{|a_3|\sqrt{\sigma_3}}{|a_1| + |a_3|\sqrt{\sigma_3}}$$

$f_{a1} = 0$ for pure $a_1$ (SM scalar)
$f_{a3} = 1$ for pure $a_3$ (pseudoscalar)

$gg \to H \to ZZ \to 4l$

ILC VH

VBF H

VH

1309.4819

pp 14 TeV, 300 fb⁻¹   pp 14 TeV, 3000 fb⁻¹   ee 250 GeV, 250 fb⁻¹   ee 350 GeV, 350 fb⁻¹   ee 500 GeV, 500 fb⁻¹   ee 1 TeV, 1000 fb⁻¹

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# Run 1 Results

- Individuals and combined

- Combine with H→VV

  - Strongest assumption: $a_i^{HZZ} = a_i^{HWW}$ and no additional anomalous couplings, $f_{a3}^{ZZ} > 0.0034$ excluded at 95% CL
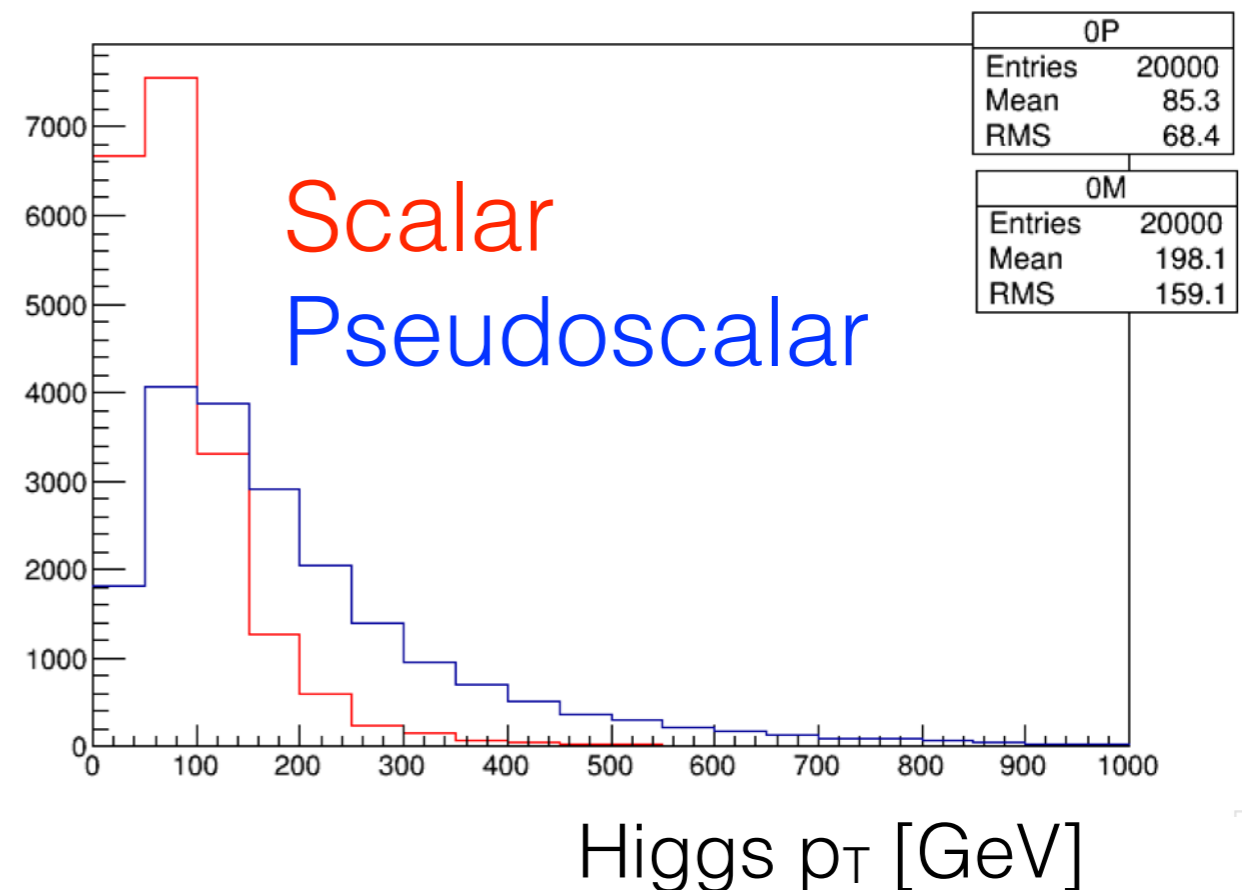
  - Big improvement on $f_{a3}^{ZZ} > 0.28$ exclusion from H→VV alone!
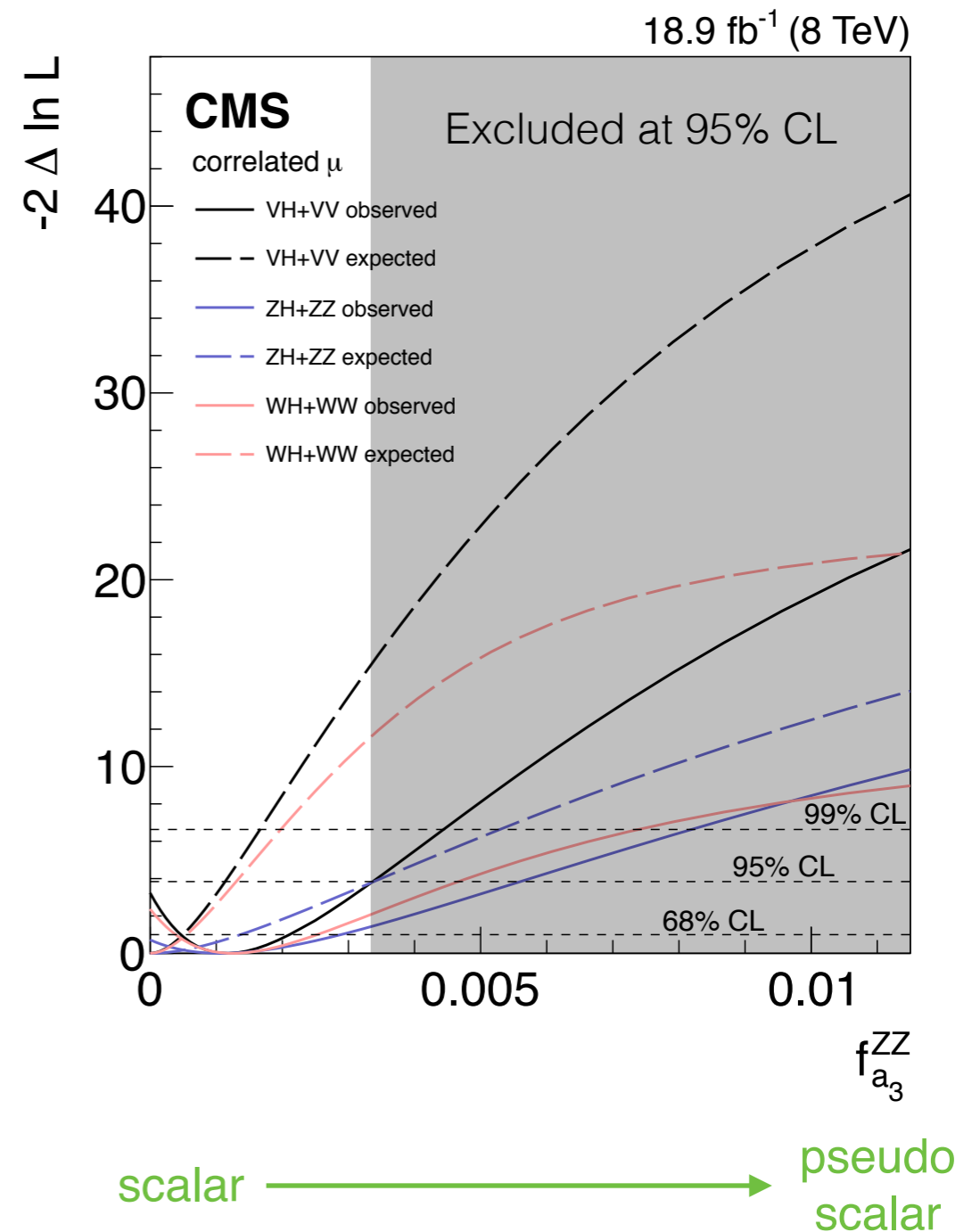
# Plans for Run 2

- Expand interpretation

  - Construct variables sensitive to interference between scalar and pseudo scalar (CP violation in Higgs sector!)

  - Higher order scalar couplings

- Use case for jet substructure in VH?

$$A(\text{HVV}) \sim \left[ a_1^{\text{VV}} + \frac{\kappa_1^{\text{VV}} q_{v1}^2 + \kappa_2^{\text{VV}} q_{v2}^2}{\left(\Lambda_1^{\text{VV}}\right)^2} \right] m_{v1}^2 \epsilon_{v1}^* \epsilon_{v2}^* + a_2^{\text{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\text{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

tree level scalar     higher order scalar     pseudo-scalar



Scalar

Pseudoscalar

| | 0P | |
|---|---|---|
| Entries | | 20000 |
| Mean | | 85.3 |
| RMS | | 68.4 |

| | 0M | |
|---|---|---|
| Entries | | 20000 |
| Mean | | 198.1 |
| RMS | | 159.1 |

Higgs p$_T$ [GeV]

# Higgs➙Long Lived Particles

Current searches according to D. Curtin:
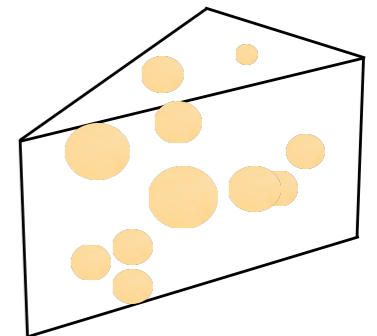
not yet                                     more like

- Can we use associated VH production to access exotic Higgs decays?

- Theorists have suggested this for the search for decays to long lived particles.



Photo by J. Orduna

Matt Strassler @ LPC

# Higgs→Long Lived Particles

- Twin Higgs model provides a solution to the hierarchy problem
  - Original: arXiv:0506256 (2005)
  - Recent interest: arXiv:1501.05310, arXiv:1506.06141, arXiv:1508.01522 (2015)

- Signature is VH with
  <span style="color:green">H→displaced b jets</span>
  - After trigger, factor of ~10 more events than from gluon fusion

- A perfect opportunity for collaboration
  - LPC DRs
    - Long lived: J. Antonelli, M. Walker
    - VH, *b* jets: J. Stupak III, BK
  - J. Hardenbrook (Princeton)

1. Higgs portal to mirror QCD
2. Long lived mirror glueballs
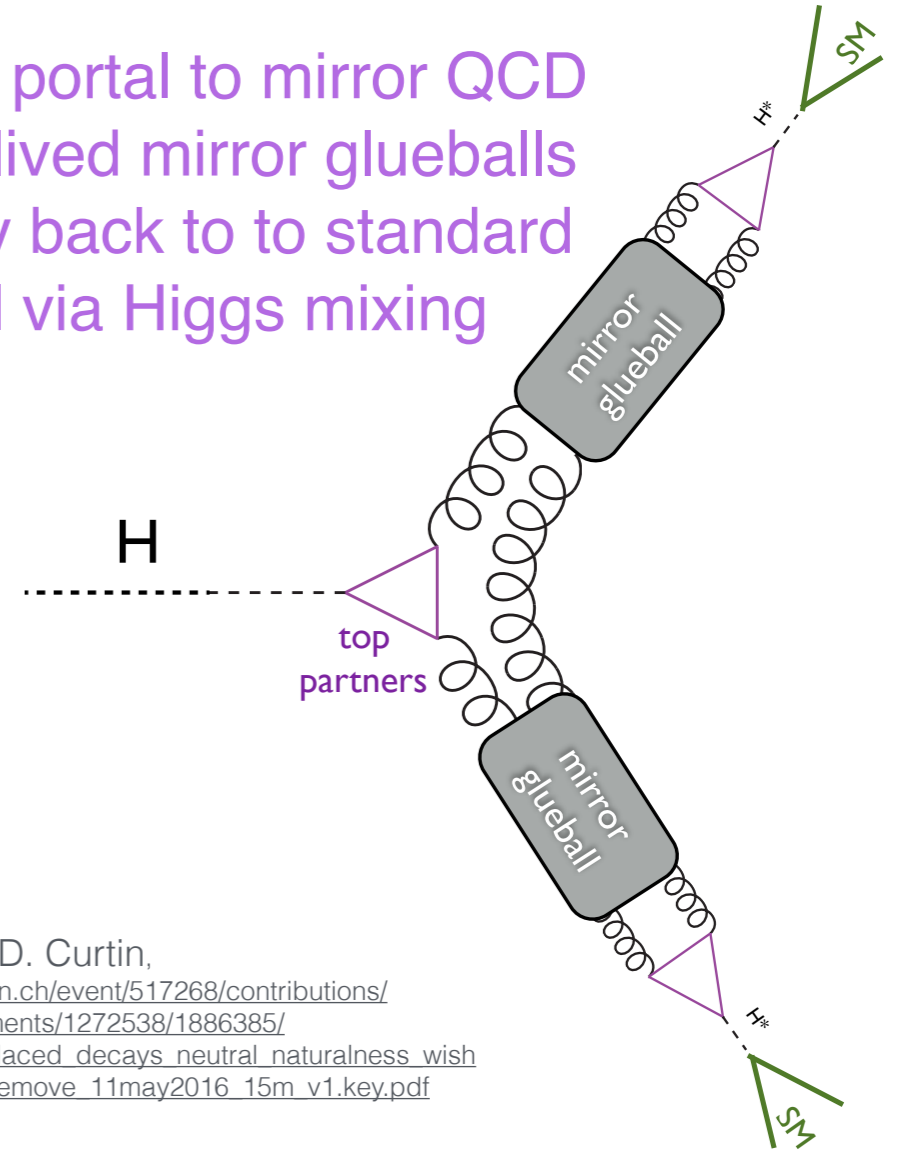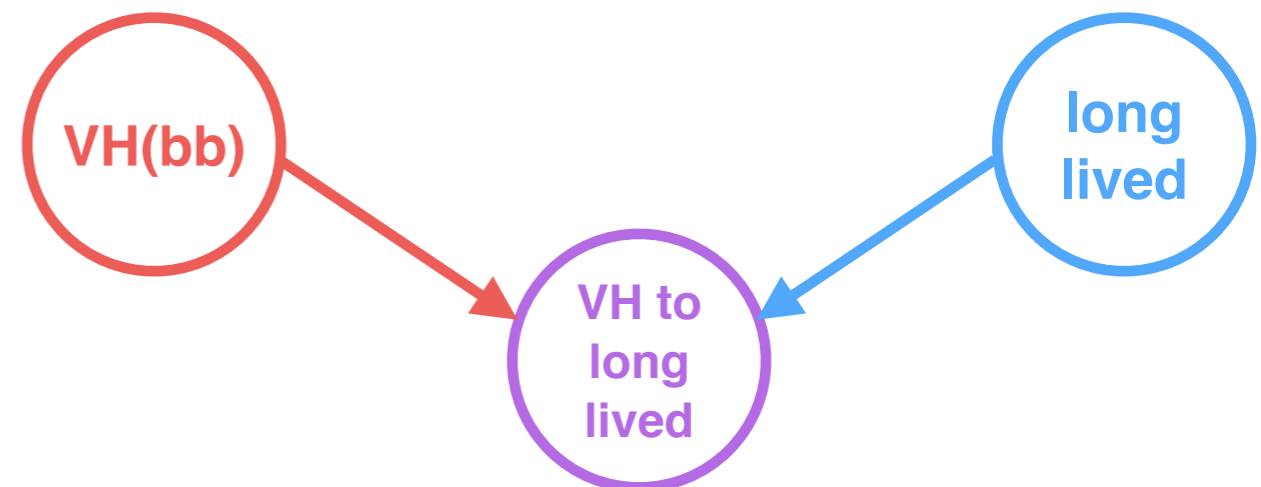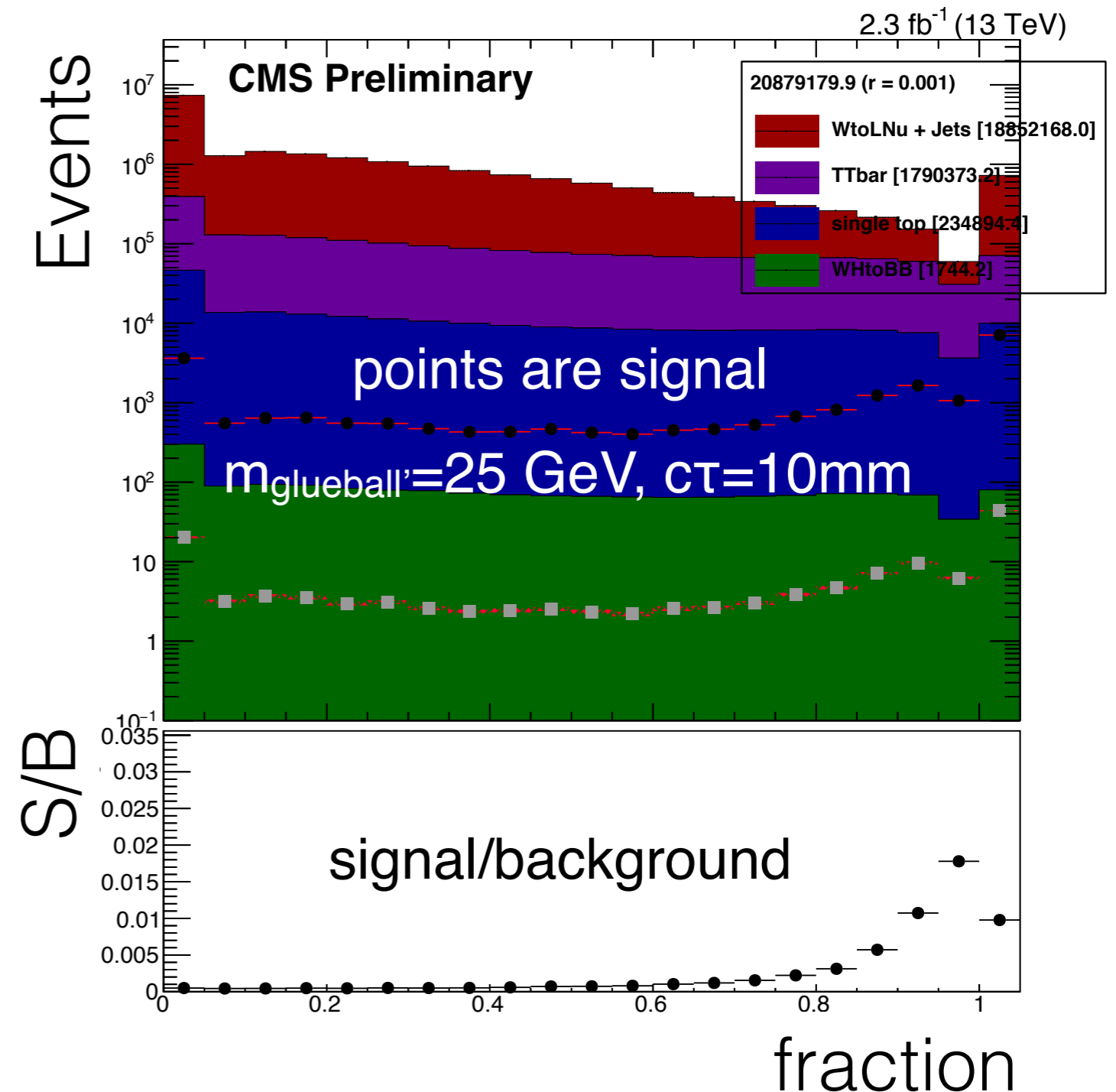3. Decay back to to standard model via Higgs mixing



Image from D. Curtin,
https://indico.cern.ch/event/517268/contributions/2041302/attachments/1272538/1886385/davidcurtin_displaced_decays_neutral_naturalness_wishlist_CERN_LLP_remove_11may2016_15m_v1.key.pdf

# Higgs→Long Lived Particles

- Currently focused on displaced jet tagging

  - Starting with J. Hardenbrook's inclusive search

  - Also vertex-based variables

- E.g. fraction of track $p_T$ in jet not assigned to a primary vertex



2.3 fb$^{-1}$ (13 TeV)

**CMS Preliminary**

20879179.9 (r = 0.001)

WtoLNu + Jets [18852168.0]

TTbar [1790373.2]

single top [234894.4]

WHtoBB [1744.2]

points are signal

$m_{glueball'}$=25 GeV, c$\tau$=10mm

Events

S/B

signal/background

fraction

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# L1 Trigger Upgrades

- 2015 upgrade to Global Calorimeter Trigger

  - "Stage 1" Calorimeter Trigger

  - FNAL, MIT, Rice, Wisconsin, UIC + Europe

- FNAL/UIC responsible for pp algorithm firmware

  -

  -

  -

- Tr
  d

- G
  a

MP7



Run 254790 (13TeV)

**CMS**
*Preliminary*

Number of primary vertices

Number of regions with $E_T > 0$ GeV

Counts

Fri Sep 4 14:21:59 2015



CMS Preliminary     52.0 pb$^{-1}$   $\sqrt{s}$ = 13 TeV

Efficiency

JINST 11 C01051 (2016)

Stage 1, Relaxed: $p_T$ >28 GeV

Stage 1, Isolated: $p_T$ >28 GeV

Legacy: $p_T$ >28 GeV

Offline Tau $p_T$ [GeV]
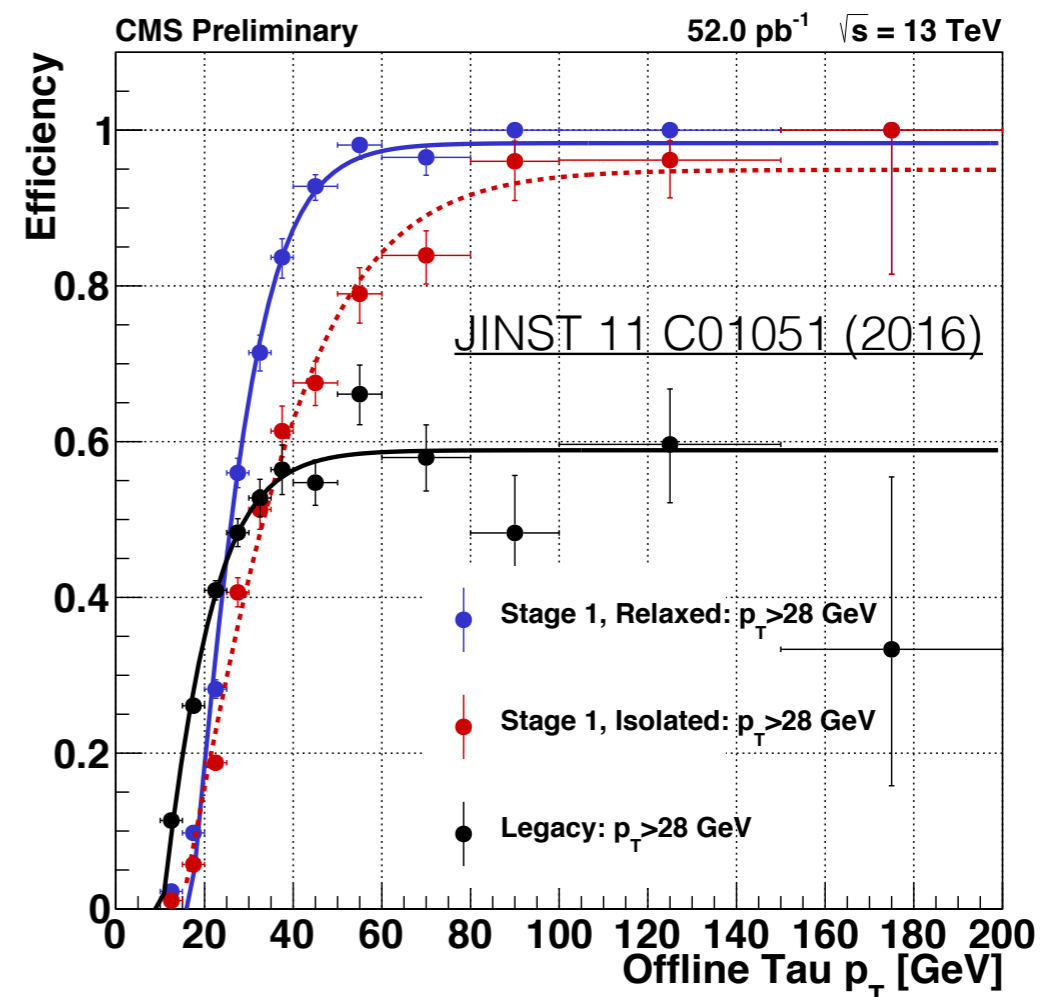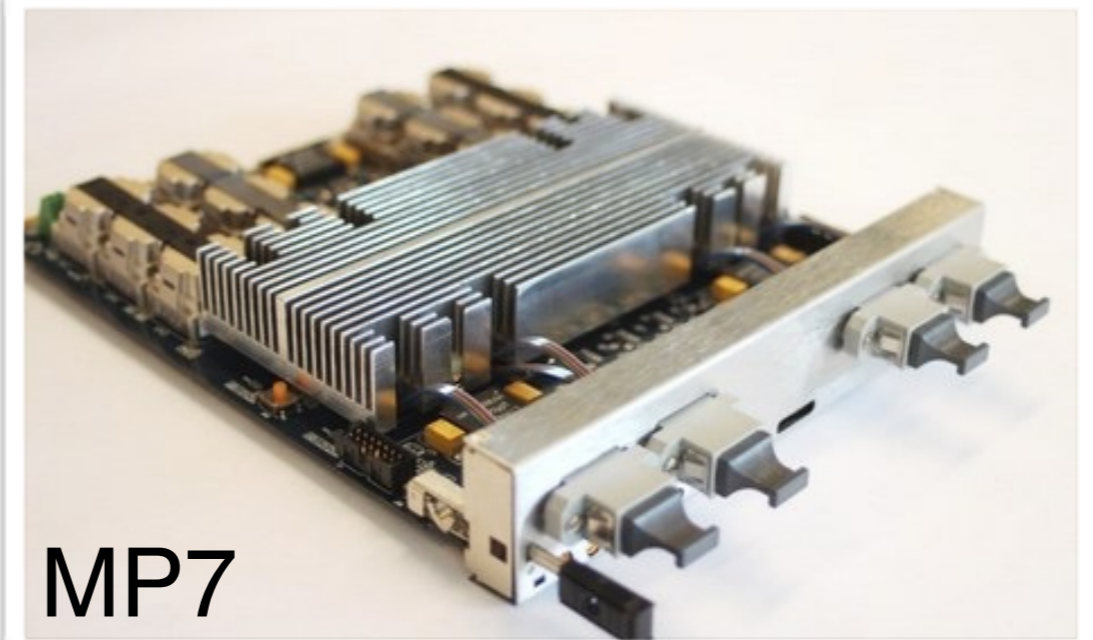
# Future L1 Trigger Projects

- I really enjoyed working on the Stage 1 upgrade

- Looking forward to contributing to future L1 trigger upgrade projects



Pulsar IIb

- Associative memory Phase II track trigger

  - Florida, Northwestern, São Paolo, Texas A&M, …

  - Pullsar IIb has the same FPGA as Stage 1 upgrade

- Particle flow at L1?
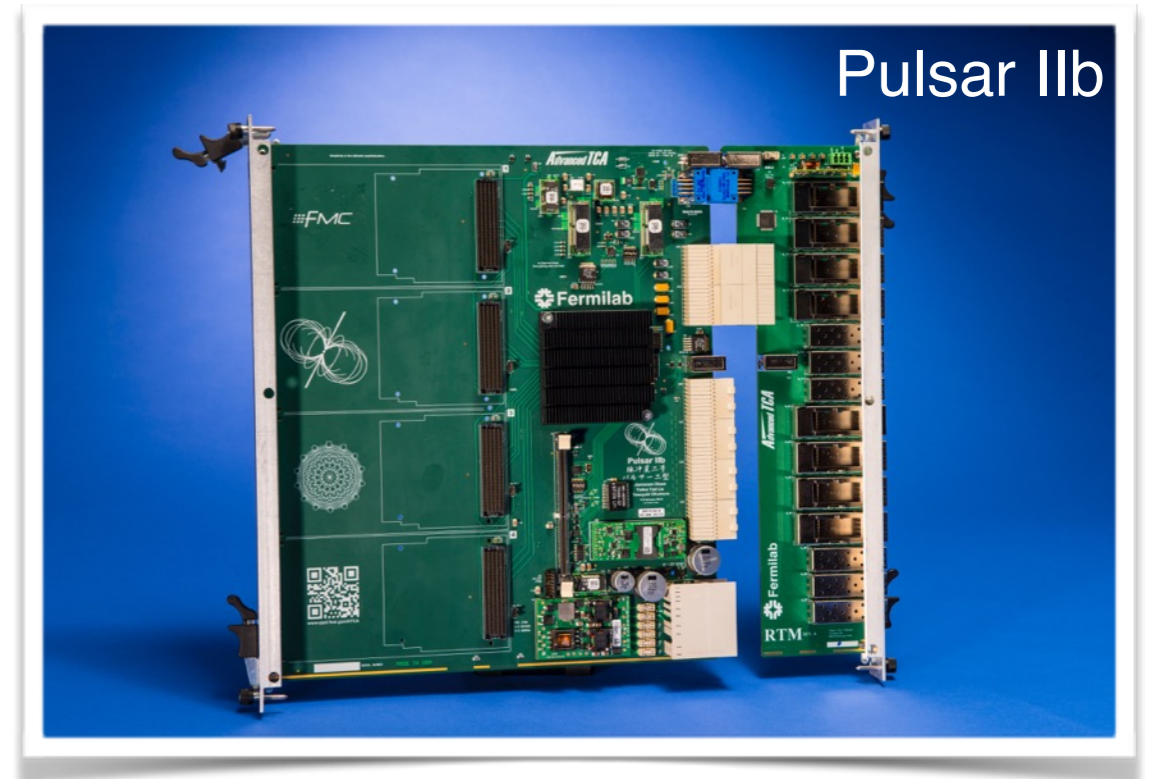
# Summary

Being a Distinguished Researcher has connected me with a huge resource of experience and new collaborators, leading to new, interesting Higgs and trigger projects!

- LPC team benefited from experience with VH(bb) and HVV couplings studies and set new constraints on anomalous HVV couplings using VH(bb) channel in Run 1
  - Will continue the search in Run 2 with expanded interpretation

- New team of Distinguished Researches sharing experience to look for Higgs decays to displaced $b$ jets

- Opportunity to get involved at the very beginning of Phase II L1 trigger upgrades

# Backup

# Run 1 Analysis Strategy

- Boosted Decision Tree discriminator (BDT)
  - Separates VH(bb) signal from backgrounds
  - Re-used from standard model search

- m(VH)
  - Sensitive to HVV coupling (i.e. $f_{a3}$)

- Signal template
  - Constructed for arbitrary $f_{a3}$ from $f_{a3}=0$ and $f_{a3}=1$ simulation
  - Based on H→VV approach



W(μν)H(bb) Channel

Legend (top plot):
— Total Background
– – Wh (CP = $0^+$)
···· Wh (CP = $0^-$)

Legend (bottom plot):
— Total Background
– – Wh (CP = $0^+$)
···· Wh (CP = $0^-$)