Observation of H→bb In CMS with VHbb

May 2nd, 2019
Game of Flavours

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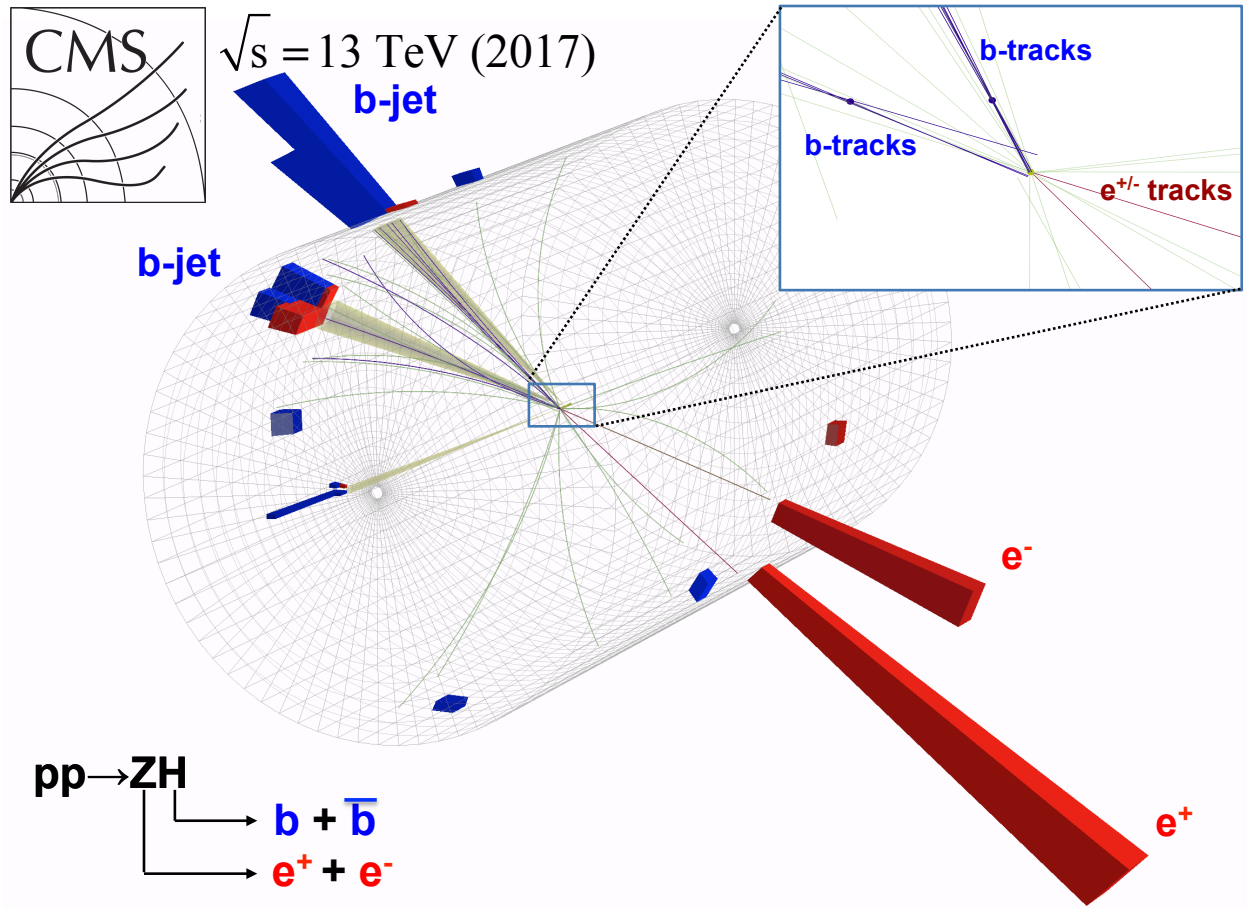
Princeton University

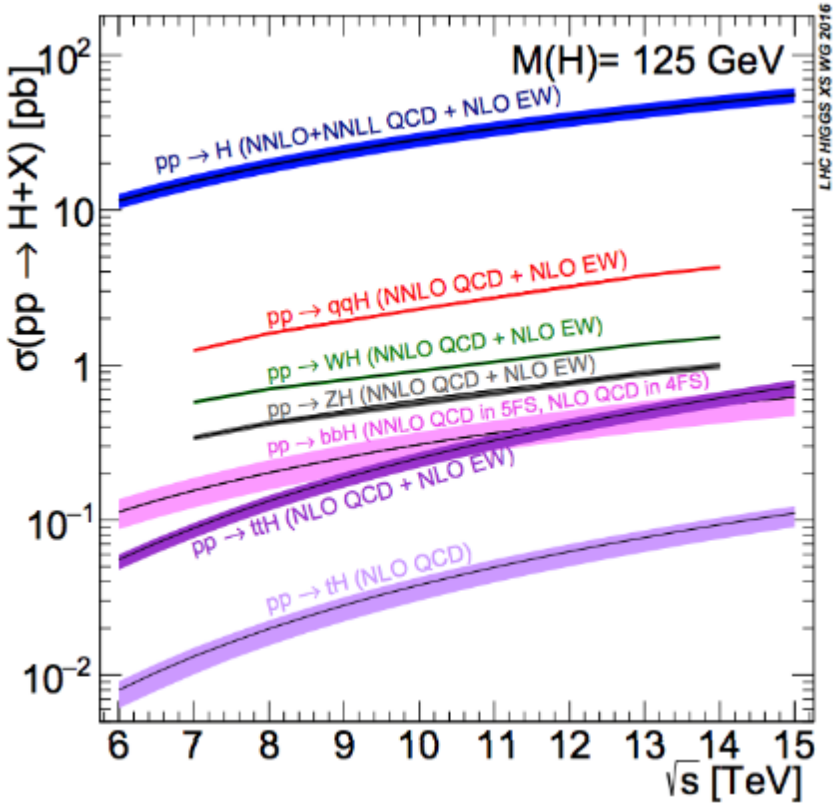


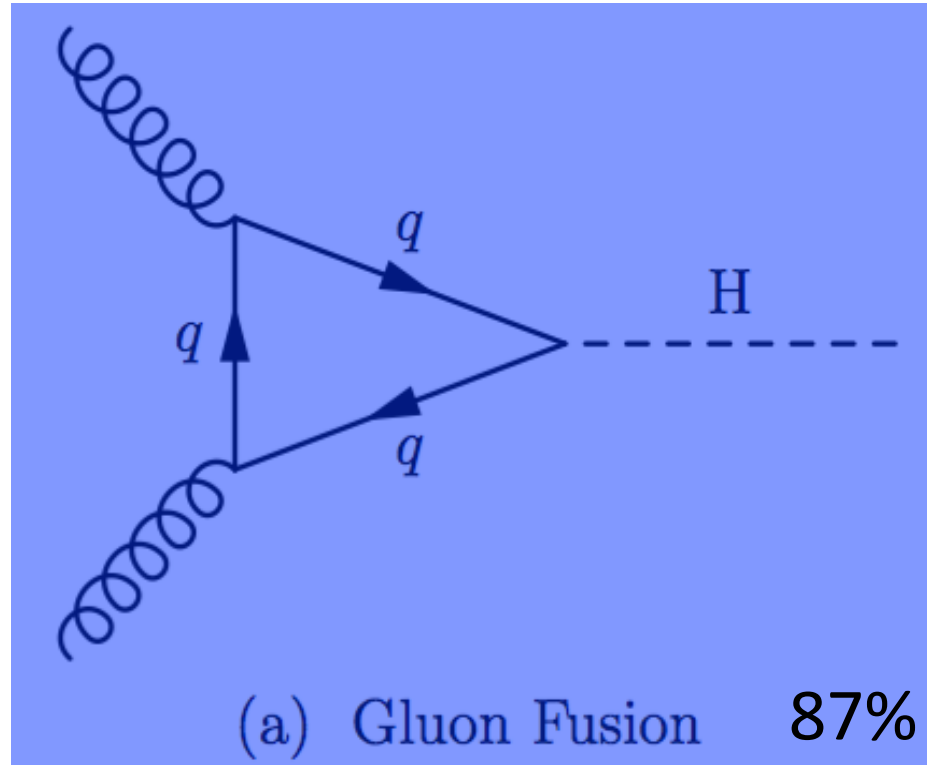
Phys. Rev. Lett. 121 (2018) 121801

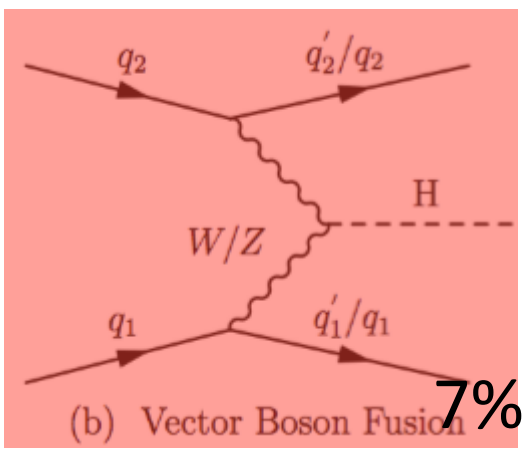
Outline

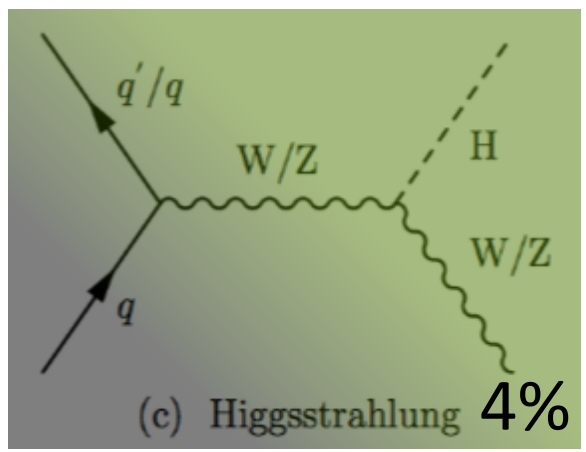
- VHbb motivation/history
- CMS VHbb 2017 data analysis
- CMS Hbb Observation
- Outlook

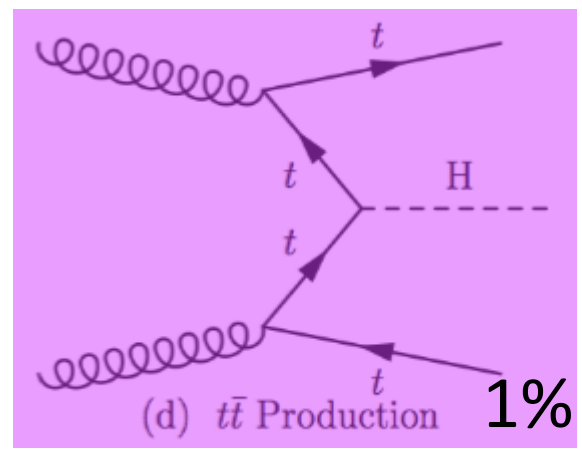
SM Higgs Production at LHC



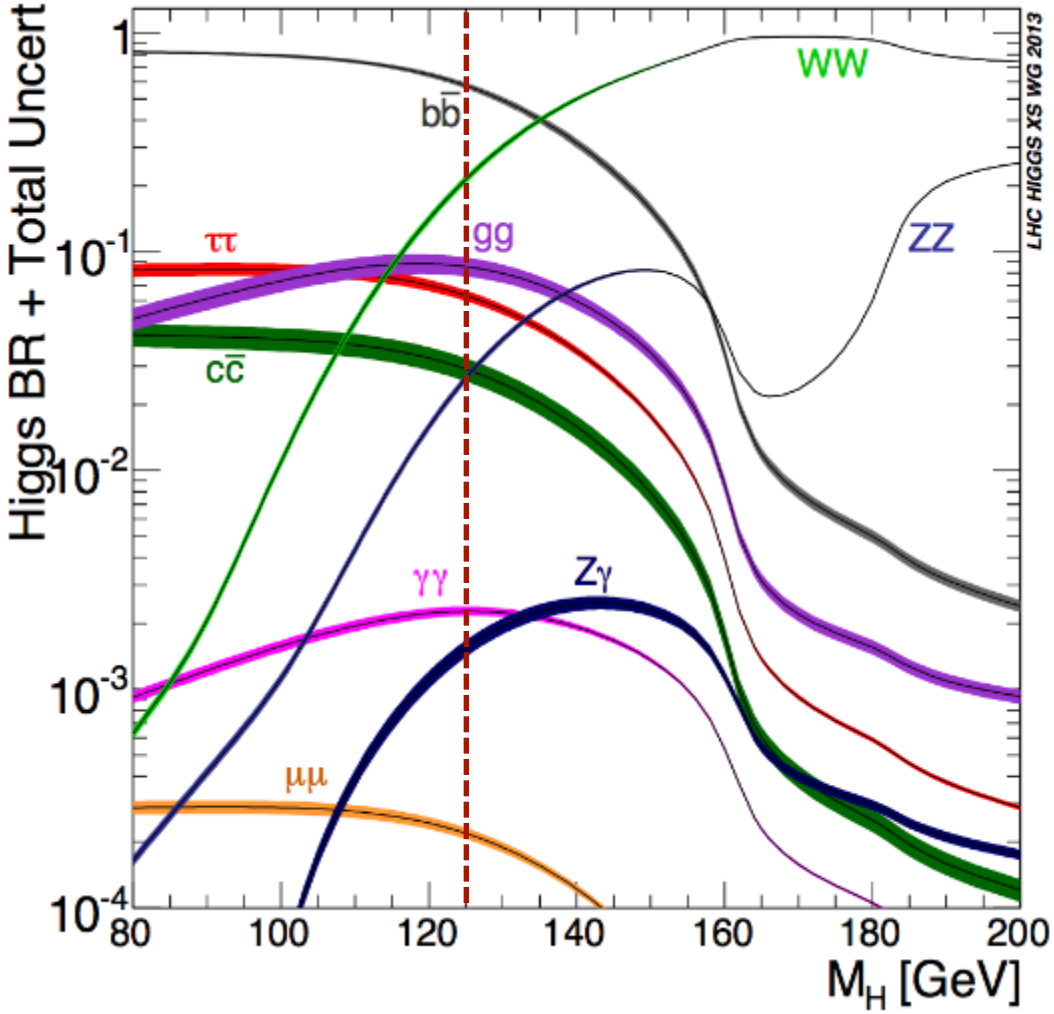








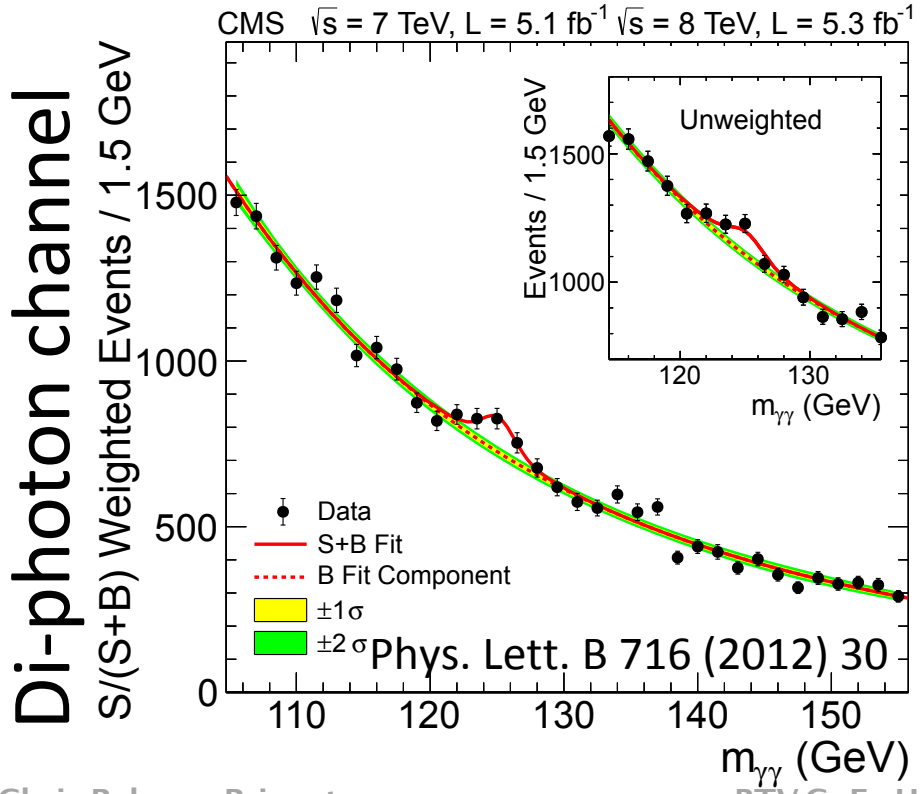
SM Higgs Boson Decay

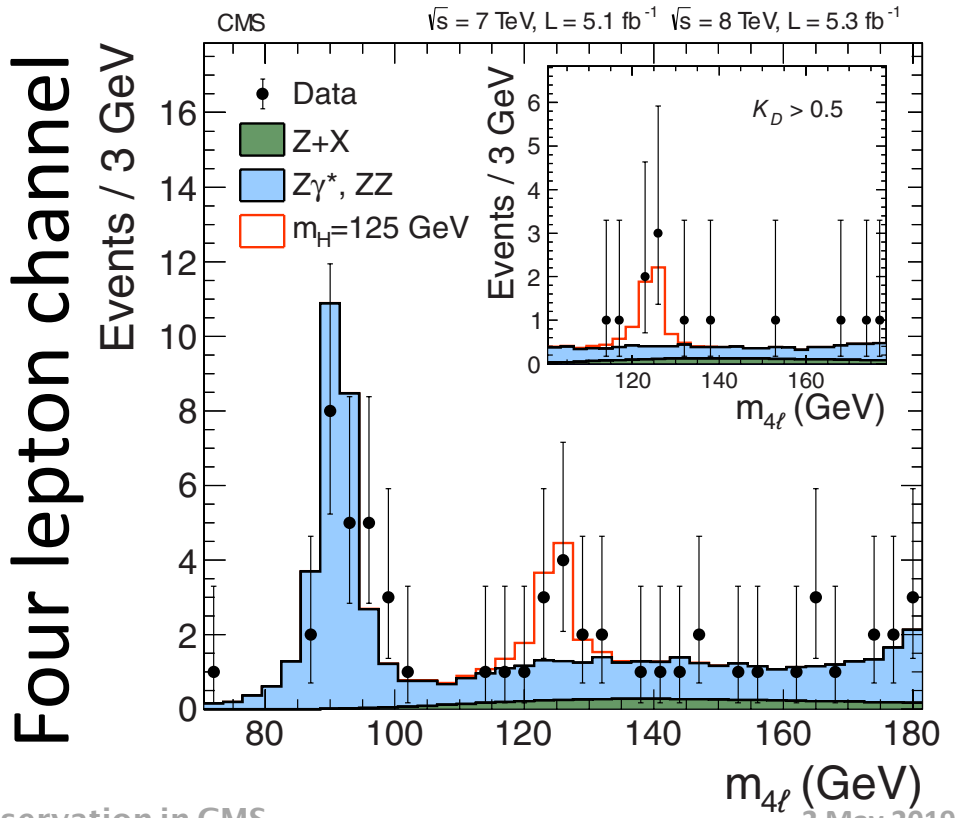


	Channel	BR	Resolution	S/B
Fermion	H→bb	0.58	10-15%	low
Fermion	H→ττ	0.063	15-20%	med
Fermion	H→μμ	0.0002	1-3%	low
Gauge	H→ZZ→ 4 leptons	2.7e-4	1-4%	high
Gauge	H→WW →2l2ν	0.022	15%	med
Loop	H→γγ	0.002	0.8-2%	low

July 4th, 2012: Higgs boson discovery

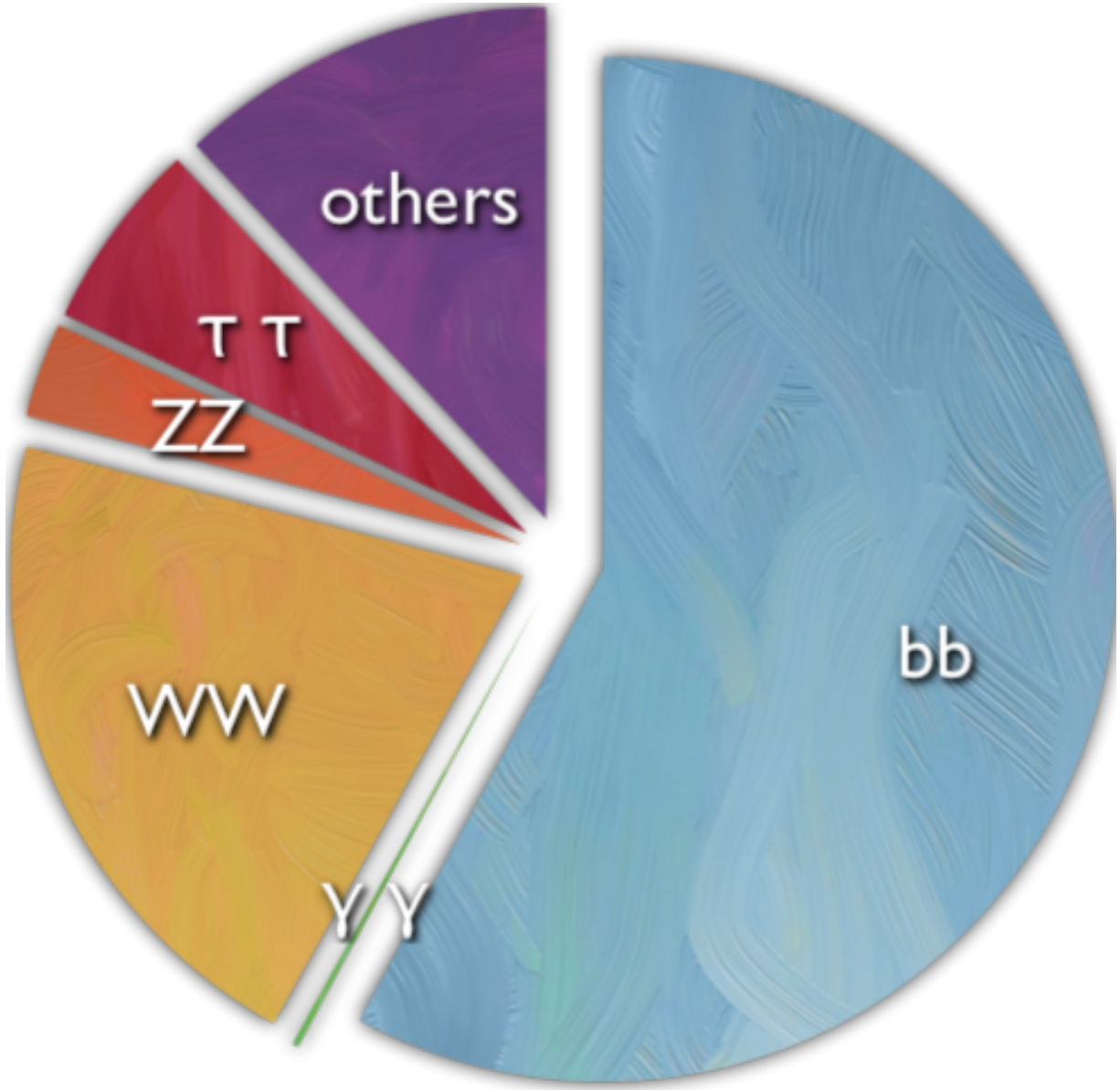
- Fully reconstructed Higgs boson decay channels with excellent mass resolution drove the discovery.
- Peter Higgs and François Englert won the 2013 Nobel Prize in physics.





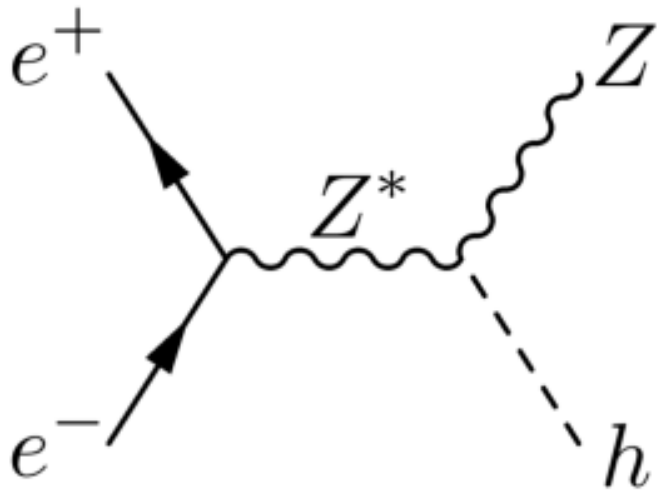
The Importance of H→bb

- The H→bb final state uniquely measures the coupling with down-type quarks
- Largest branching fraction ~58%
  - Will drive total uncertainty of the total Higgs boson width and thus on the measurement of absolute couplings
  - Important for constraining BSM coupling of the Higgs.

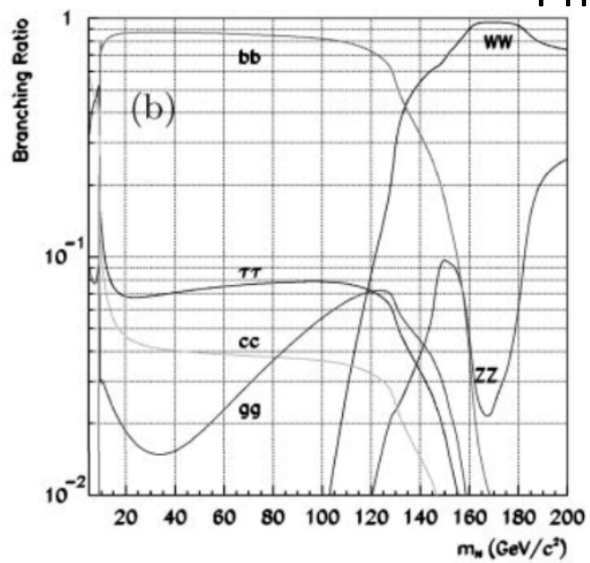


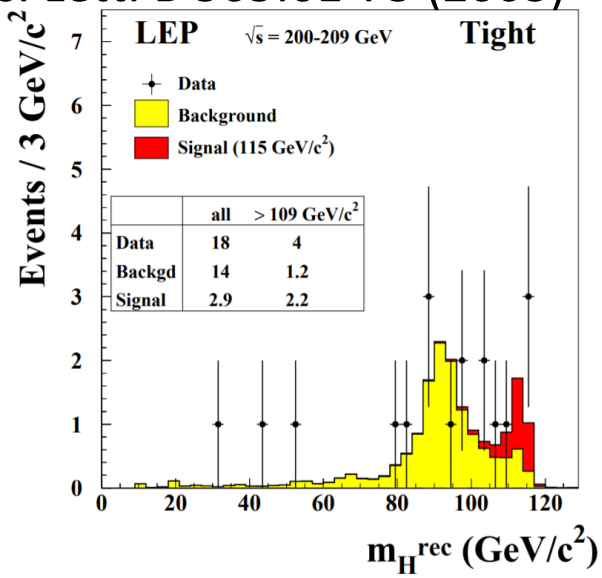
Pre-LHC VHbb

LEP

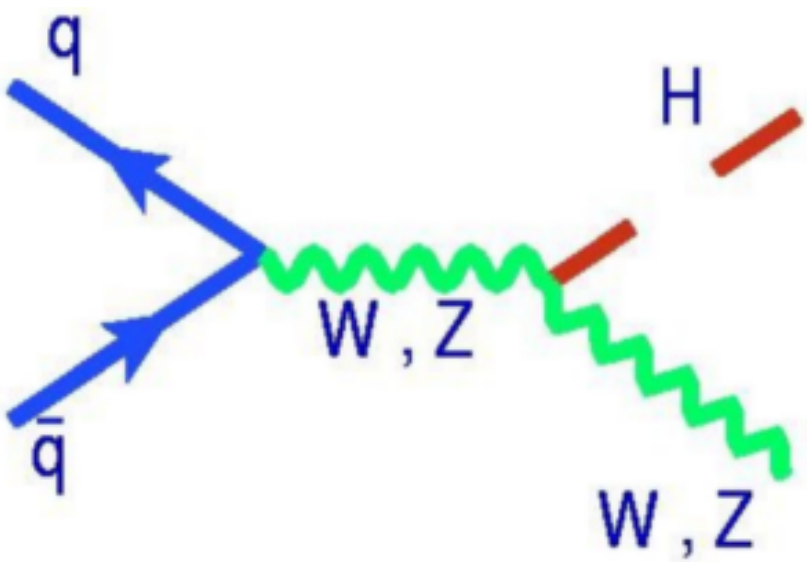


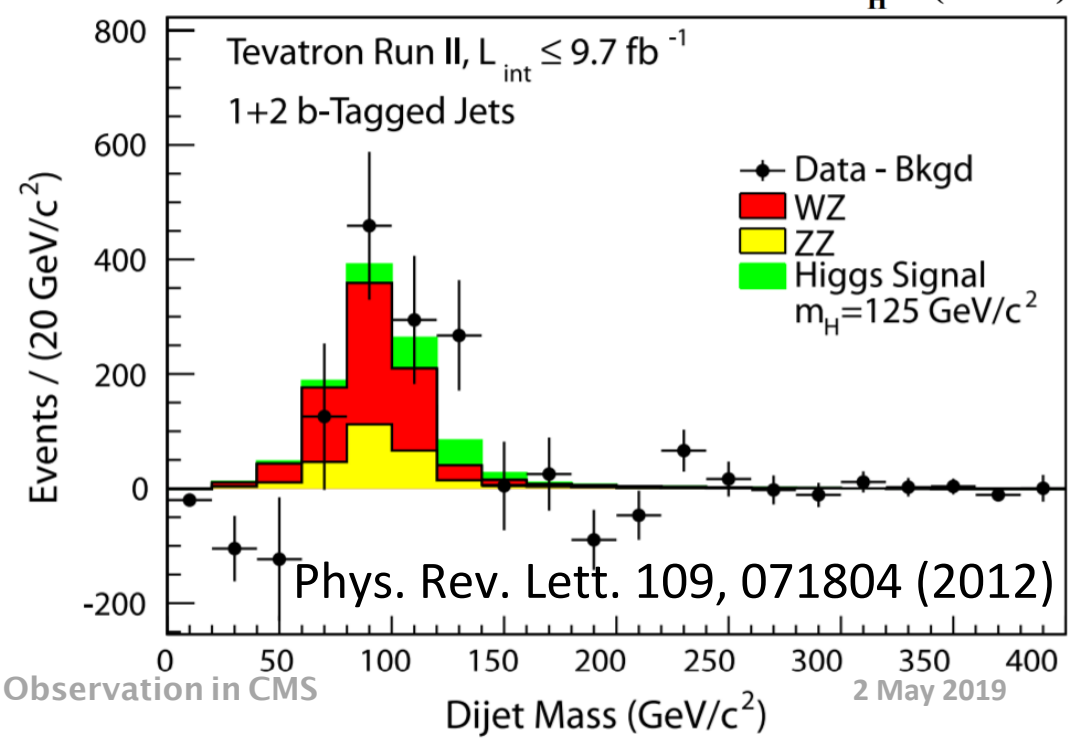
Phys. Lett. B 565:61-75 (2003)





Tevatron



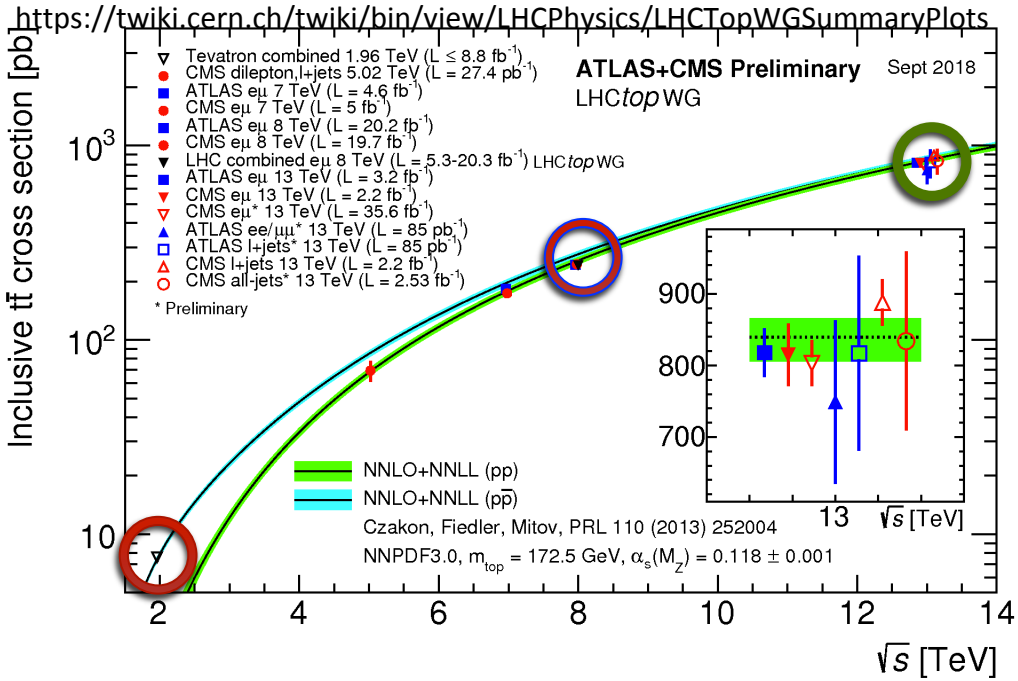


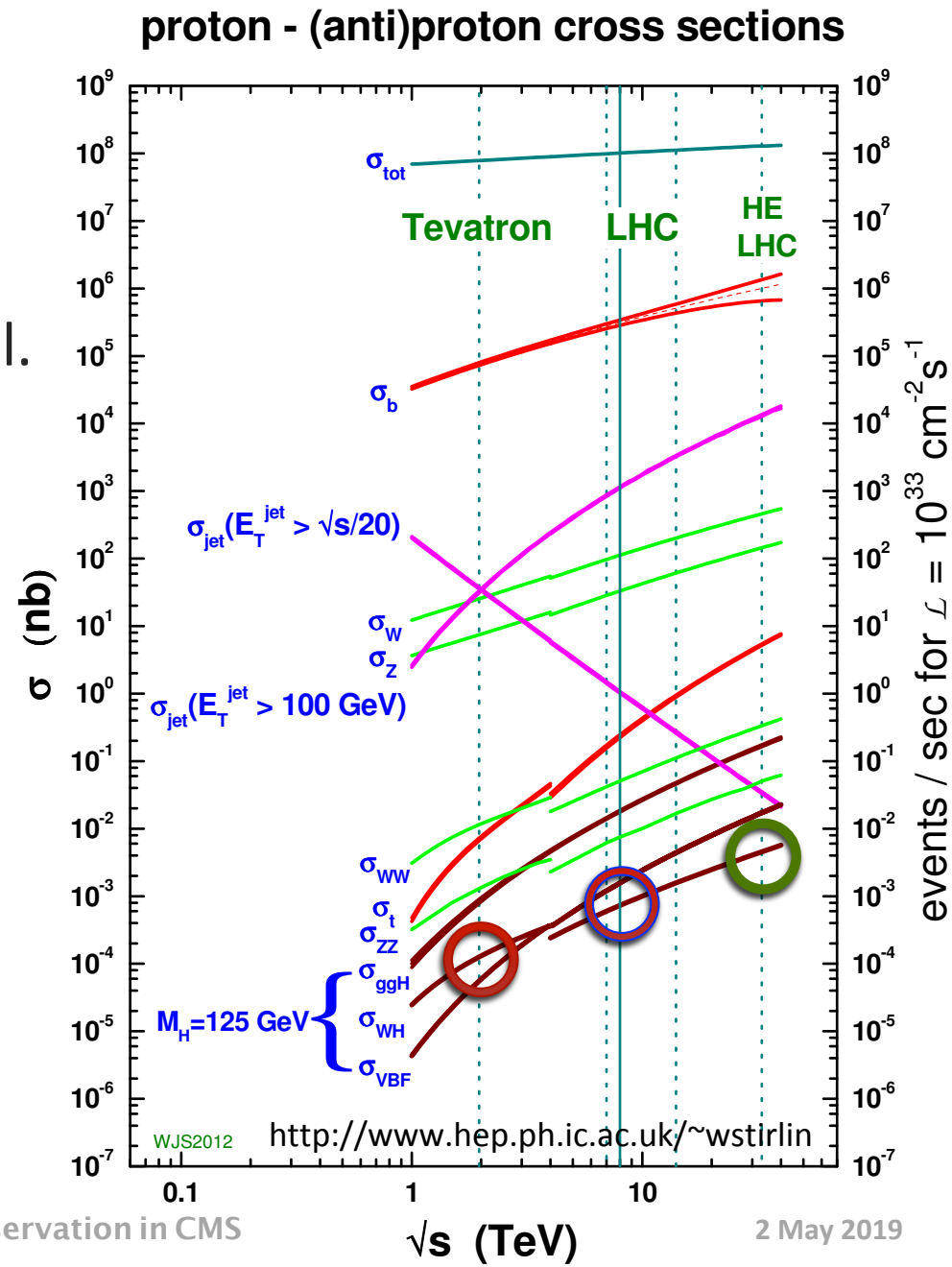
Phys. Rev. Lett. 109, 071804 (2012)

Expectations for (V)Hbb at LHC

- With backgrounds—like ttbar—growing faster than VHbb by:
  - 2.5 at 8 TeV
  - 8 at 13 TeV
- ttHbb was the most hopeful channel.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots





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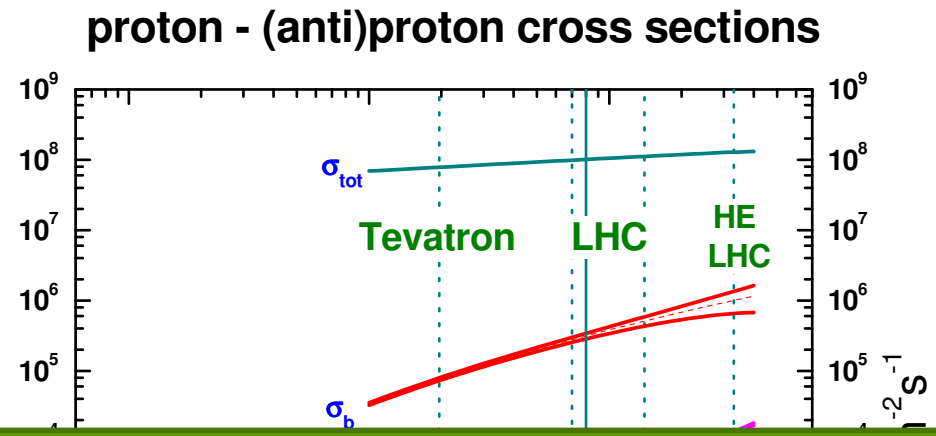
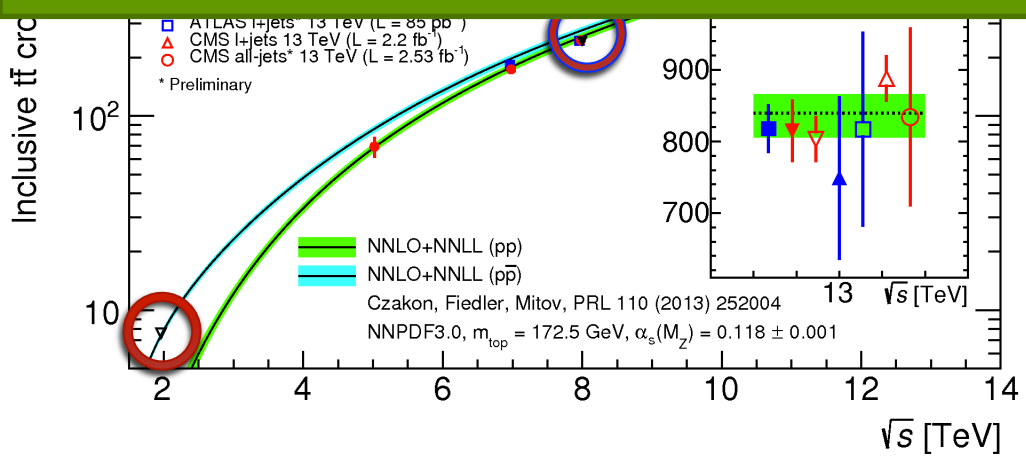
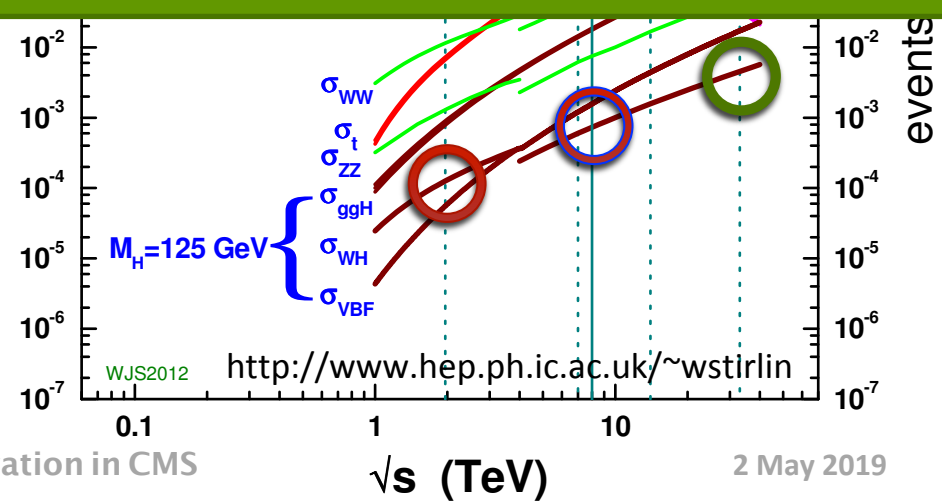


"uncertainty of ± 5 %. on the shape of the $Wb\bar{b}$ background in the $H \to b\bar{b}$ signal region. In conclusion, the extraction of a signal from $H \to b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the b-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself."

— SNOWMASS-2001-P111





A new hope for VHbb at LHC

Jet substructure as a new Higgs search channel at the LHC

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Department of Physics & Astronomy, University College London.

Mathieu Rubin, Gavin P. Salam
LPTHE; UPMC Univ. Paris 6; Univ. Denis Diderot; CNRS UMR 7589; Paris, France.

In this letter we investigate VH production in a boosted regime, in which both bosons have large transverse momenta and are back-to-back. This region corresponds to only a small fraction of the total VH cross section (about 5% for $p_T > 200\,\mathrm{GeV}$), but it has several compensating advantages: (i) in terms of acceptance, the

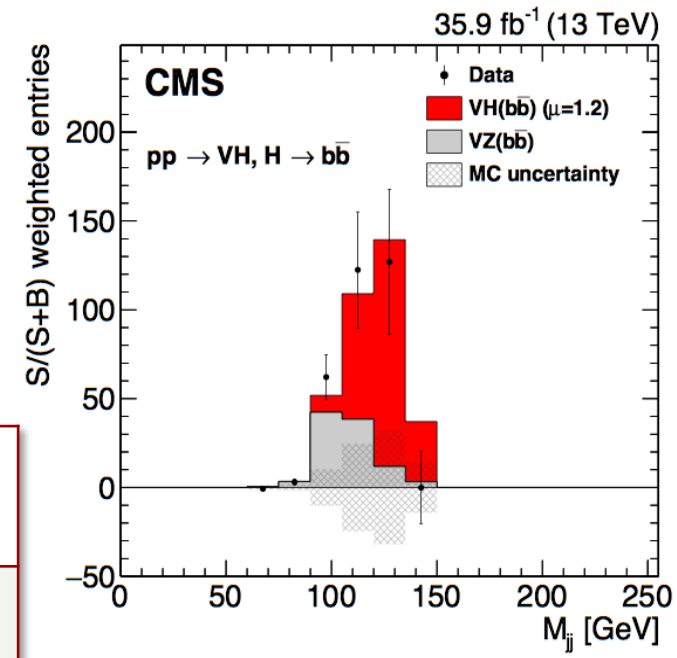
- Boosting has indeed been critical to LHC VHbb searches.
- Jet substructure is a powerful tool employed in CMS's ggHbb search.

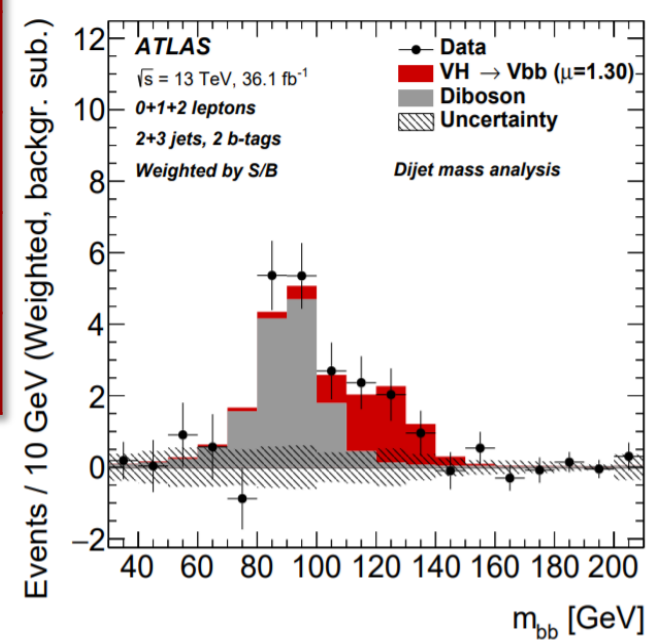
Phys.Rev.Lett. 100 (2008) 242001

Evidence of VHbb at LHC

- VH(bb) evidence at LHC established with 2016 data by both ATLAS and CMS
  - Detectors clearly demonstrated ability to deal with very high pile-up in such complex analyses
- Signal strength uncertainty ~40%

	signal strength	significance (exp)	significance (obs)
ATLAS Run 1 [1]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run 1 [2]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run 1 [3]	$0.79^{+0.29}_{-0.27}$	3.7σ	2.6σ
ATLAS 2015+2016 [4]	$1.20^{+0.42}_{-0.36}$	3.0σ	**3.5σ**
CMS 2016 [5]	$1.19^{+0.40}_{-0.38}$	2.8σ	**3.3σ**

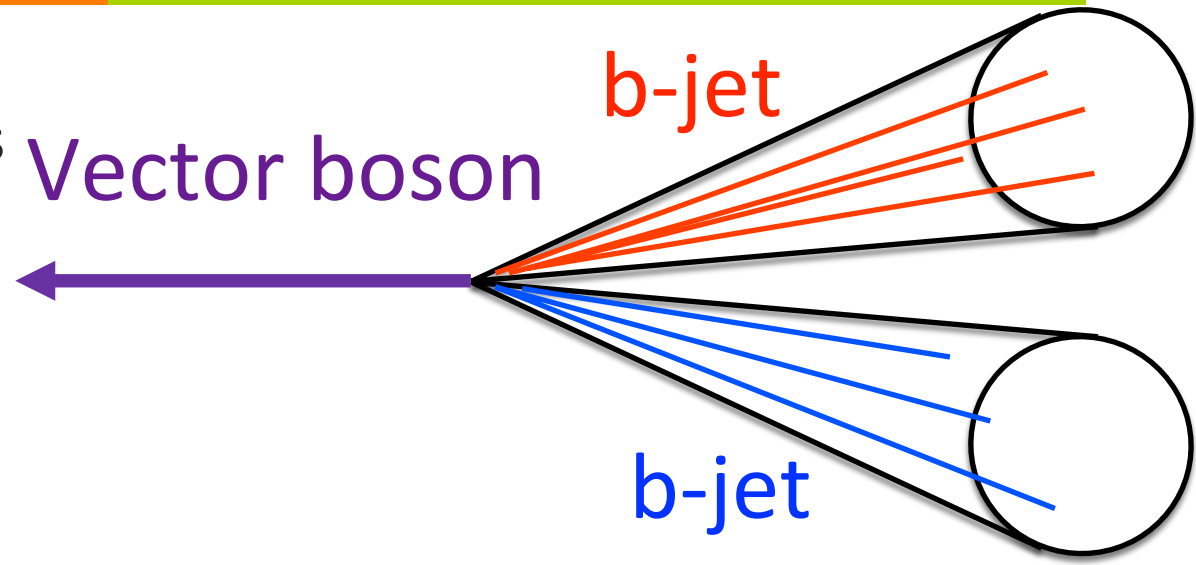




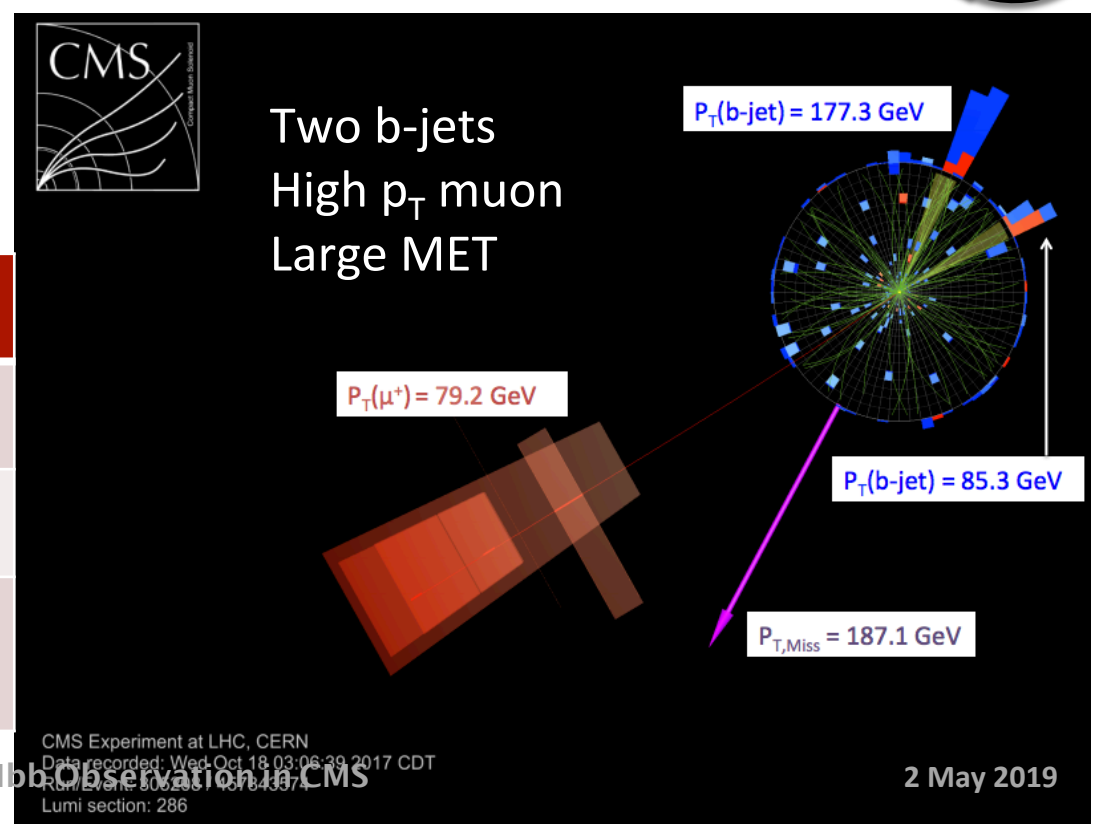
[1] JHEP 01 (2015) 069
[2] JHEP 08 (2016) 045
[3] JHEP 08 (2016) 045
[4] JHEP 12 (2017) 024
[5] PLB 780 (2018) 501

VHbb Topology

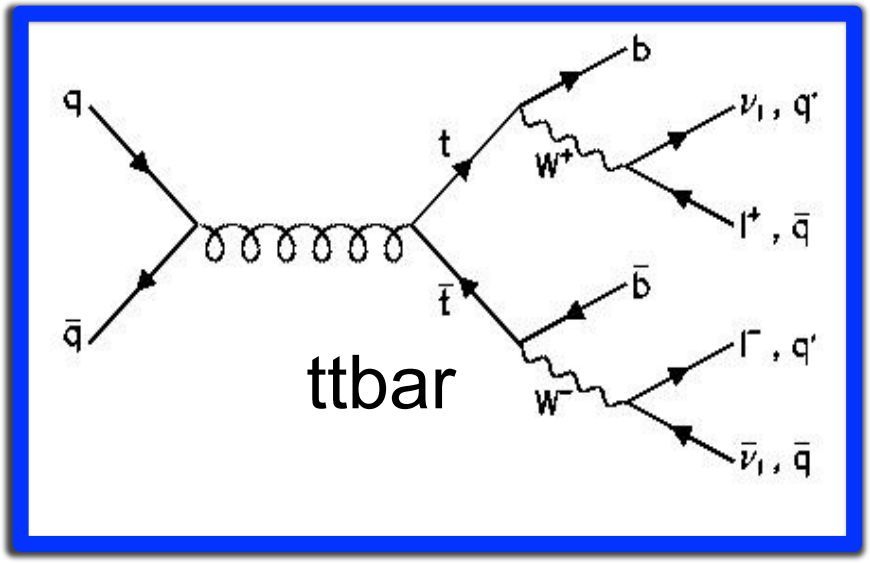
- As in many searches for the Higgs boson, S/B is increases with the Higgs' P_T.
- Given the correlation between the P_T of the V and H, requiring V to be transversely boosted gets into the most sensitive phasespace.

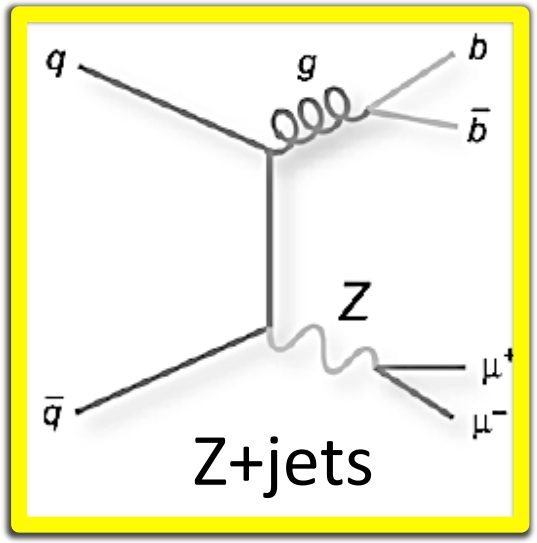


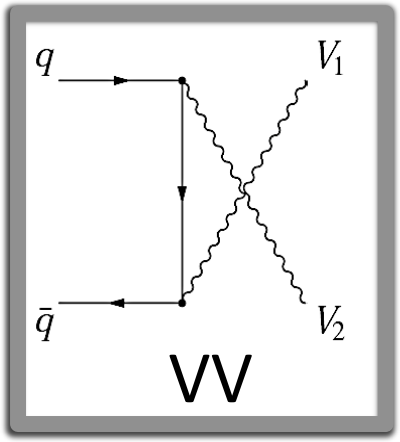
Channel	Boosting
$Z \rightarrow \nu\nu$ (0-lep)	$P_{T,Z} > 170$ GeV
$W \rightarrow l\nu$ (1-lep)	$P_{T,W} > 150$ GeV
$Z \rightarrow ll$ (2-lep)	$P_{T,Z} > 150$ GeV $50 < P_{T,Z} < 150$ GeV

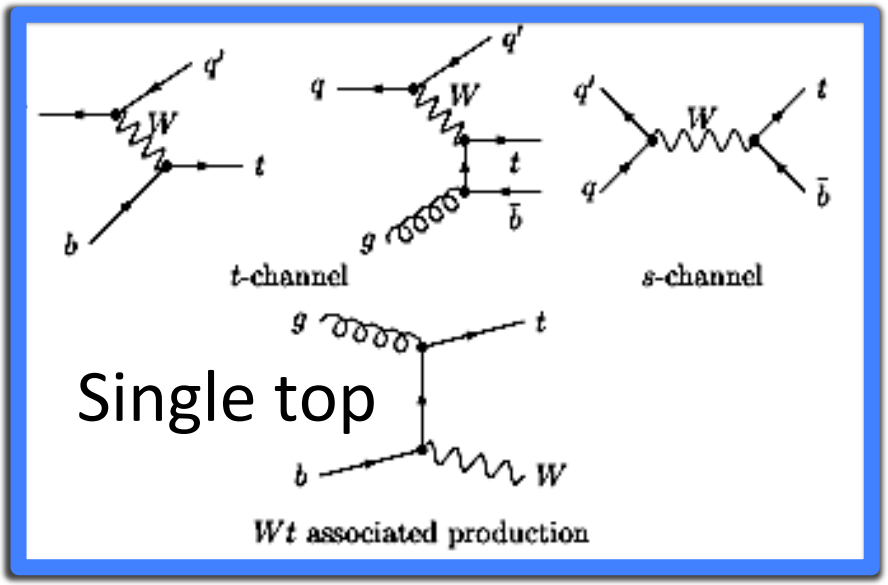


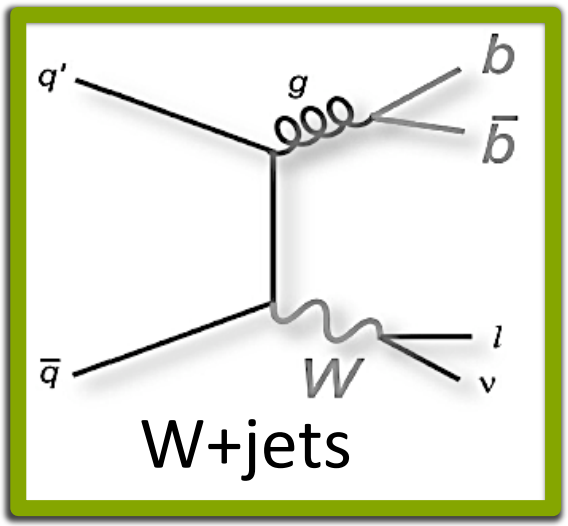
VHbb Backgrounds





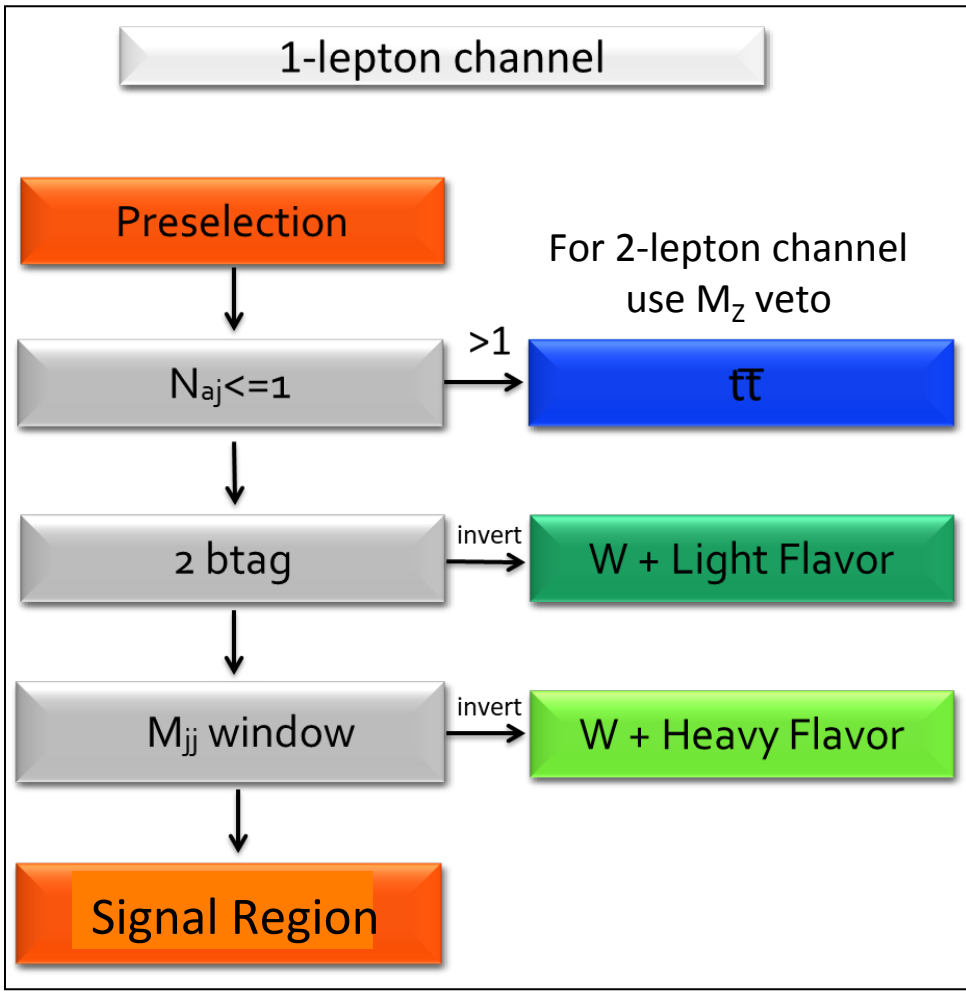






VHbb Analysis Strategy

- Start with boosted W or Z
- 3 channels with 0, 1, and 2 leptons and 2 b-tagged jets
  - Targeting Z(νν)H(bb), W(lν)H(bb), and Z(ll)H(bb) processes
- Signal region designed to increase S/B
  - Multivariate analysis exploiting the most discriminating variables ($m_{b\bar{b}}$, $P_{T,V}$, b-tagging discriminator values)
- Control regions to validate analysis variables and control/constrain background normalizations
- Simultaneous fit of signal regions and control regions
  - Background normalization and signal extracted in one fit.



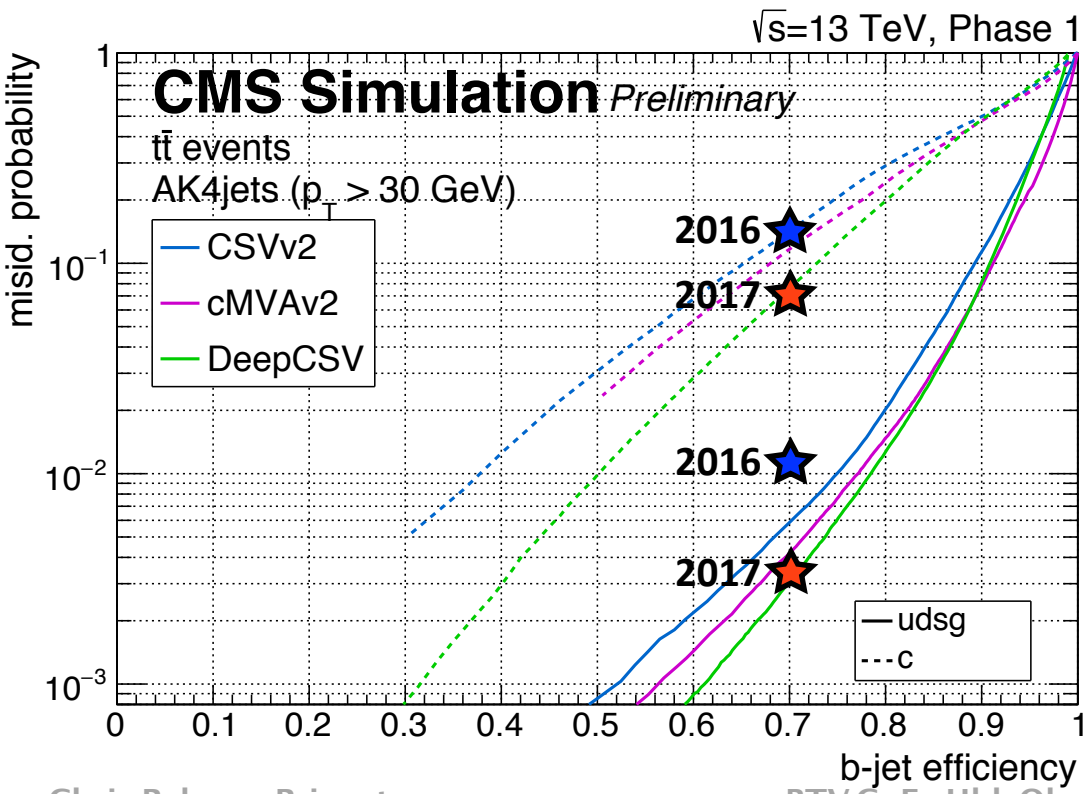
[*] Number of additional jets in the event

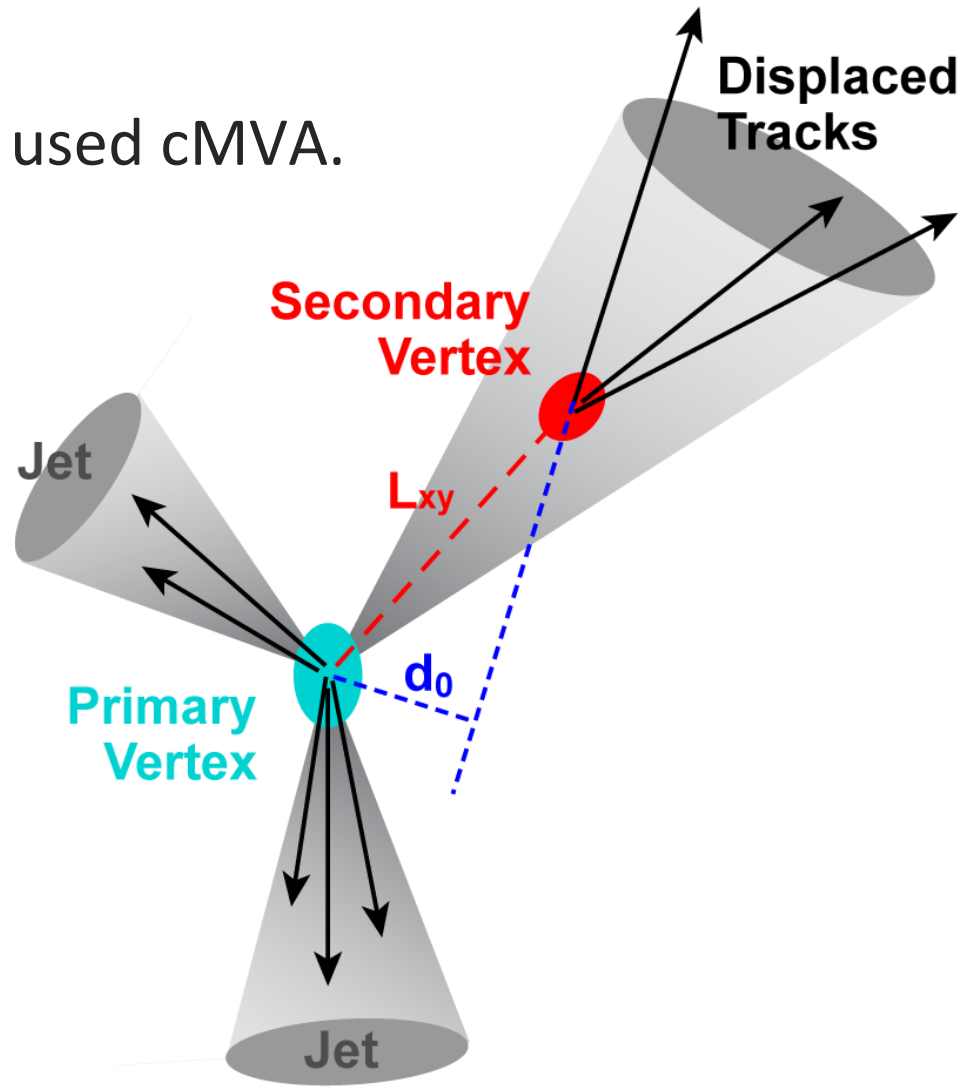
2017 analysis improvements

- Improved b-tagging
  - New pixel detector (additional barrel layer)
  - New algorithm (deep neural network)
- Improving mass resolution
  - Better b-jet energy regression
  - Introduction of kinematic fit in 2-lepton channel
  - Final state radiation (FSR) jet recovery
- Improved background discrimination in vector boson plus heavy flavor targeted control regions

B-tagging Performance

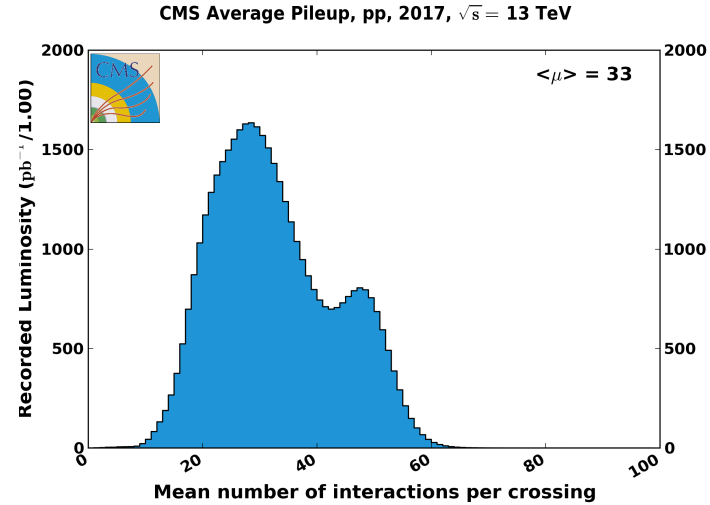
- Continuous effort to improve b-tagging algorithms
  - New pixel detector, new algorithm with track-level info (DeepCSV)
  - 2016 analysis was the same but used cMVA.

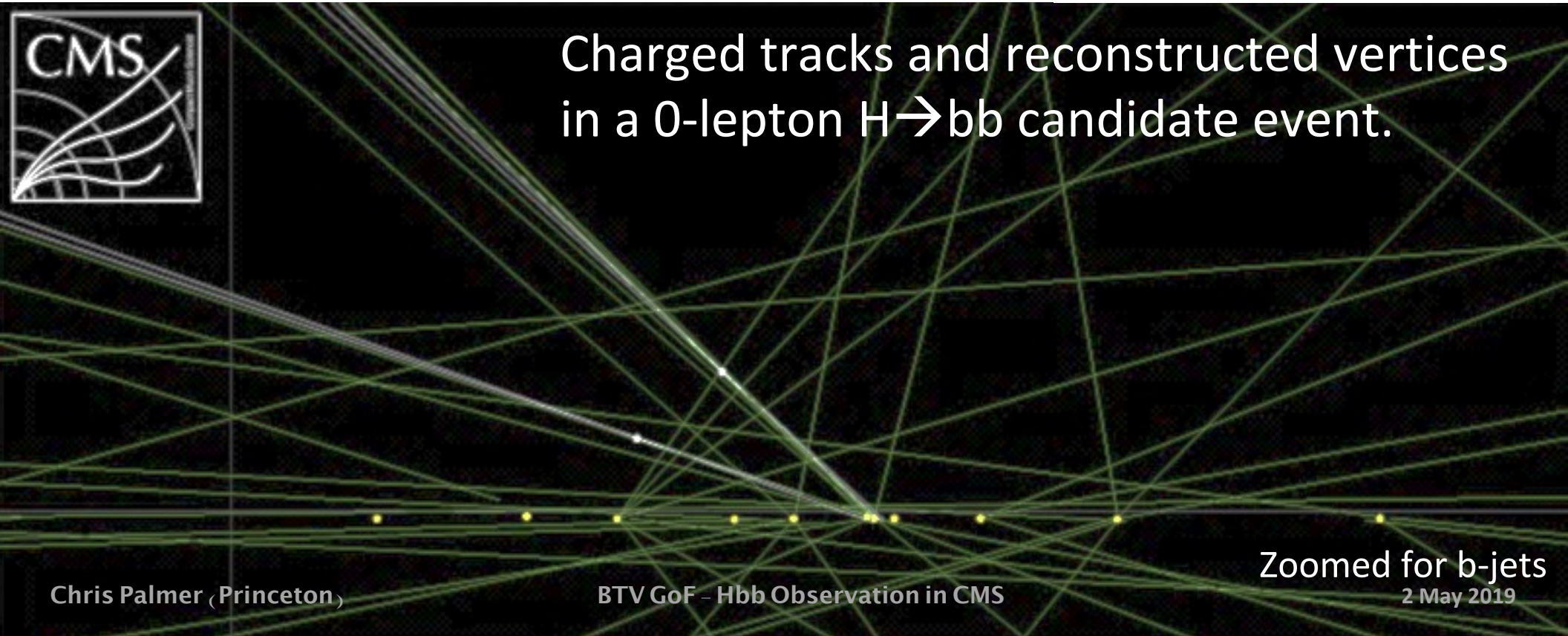




Some of the best

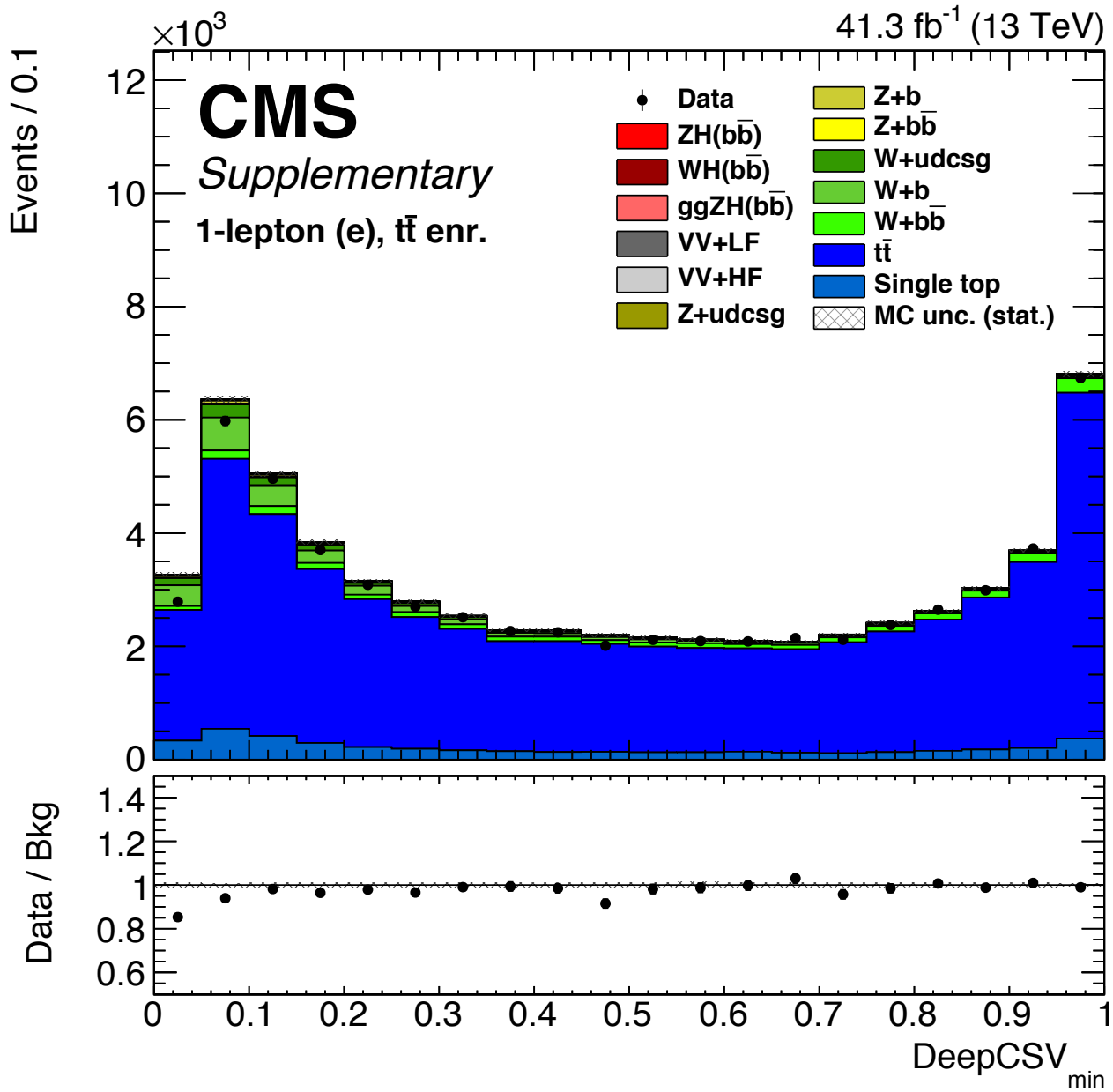
- Very well separated secondary vertices in our more signal-like events





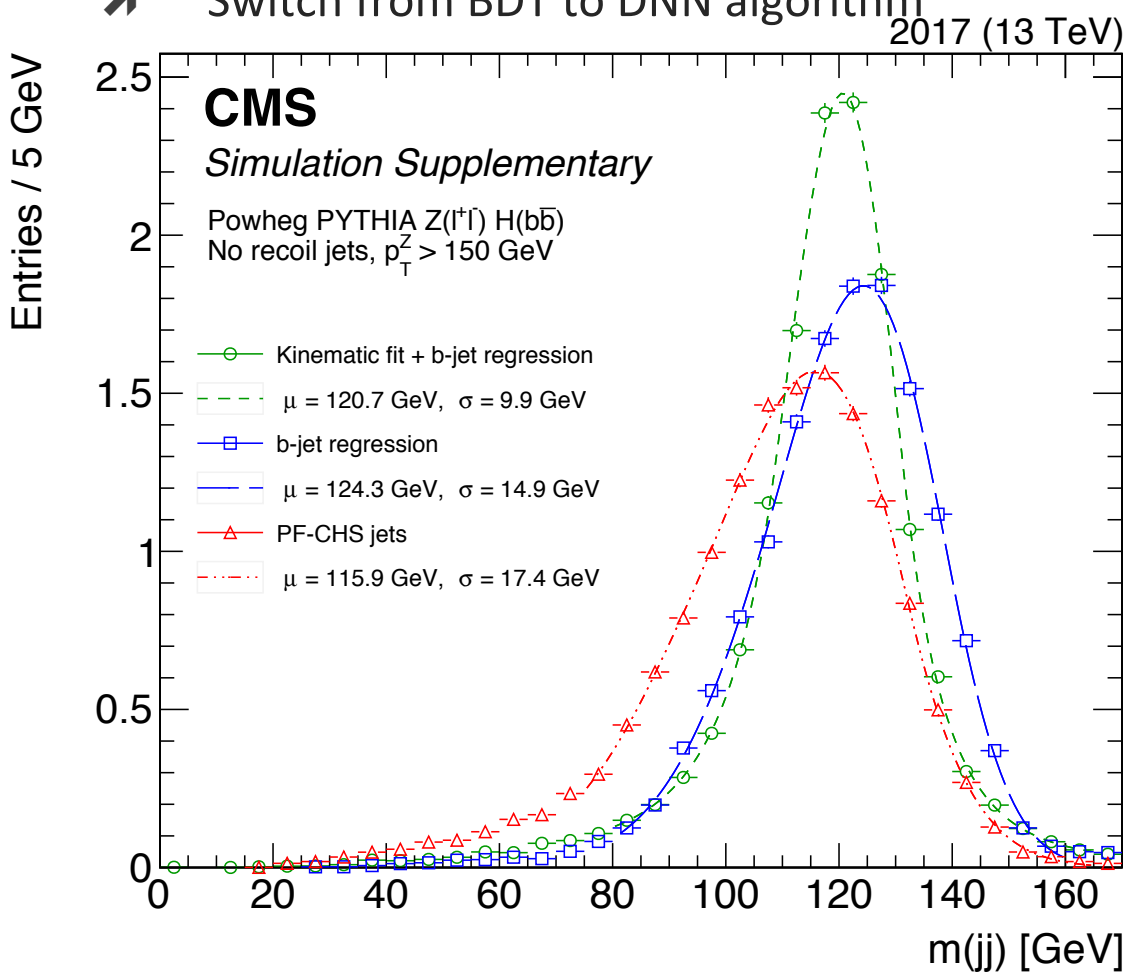
B-tagging Validation

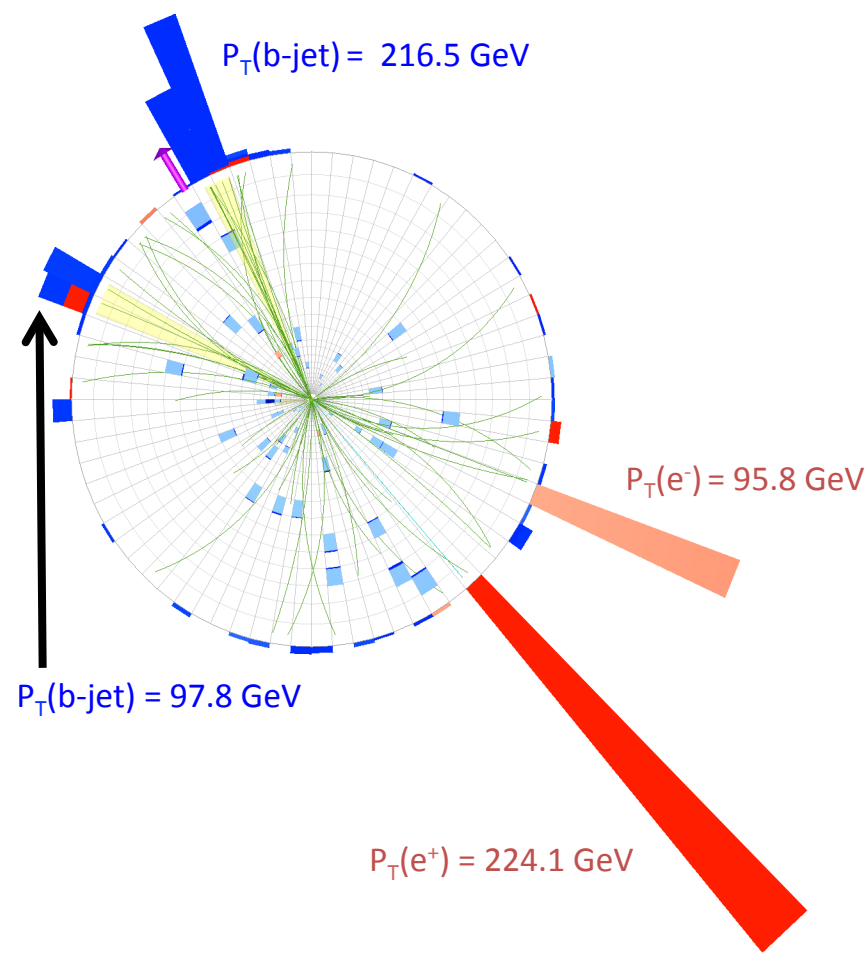
- B-tagging efficiency measured in 2-lepton ttbar control region
- Applied as a re-weighting per jet as function of η, P_T and tagging score.
- We validate these re-weightings in all of our control regions.



Mass resolution

- Improved energy regression for b-jets
  - Inputs include jet kinematics and b-tagging variables
  - Extended inputs: lepton flavor, energy rings, and more
  - Switch from BDT to DNN algorithm
- In 2-lepton channel kinematic fit using constraint of vector sum of transverse momentum being 0.
  - Effectively constraining jet resolution using superior lepton resolution.





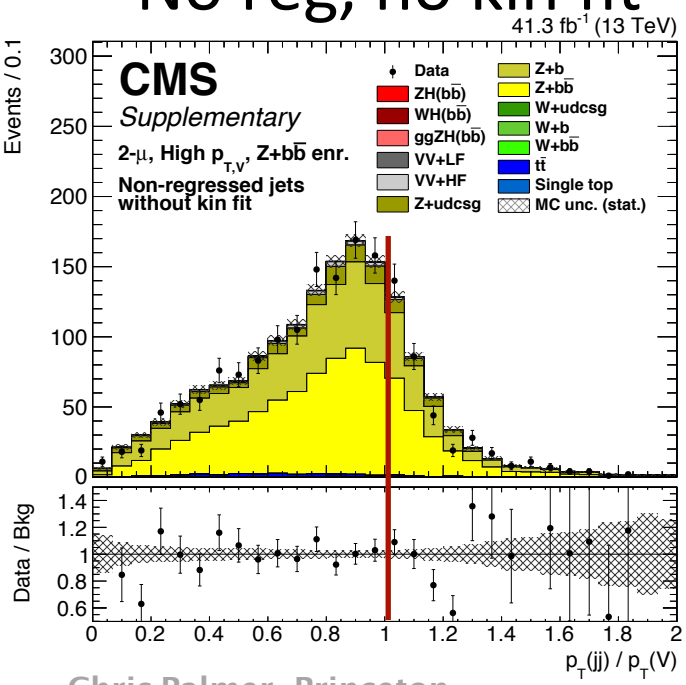
Validating mass resolution

- Regression validated using dedicated Z+1jet analysis
  - 10% uncertainty applied (conservative)
- Visual validation using $P_{T,jj}/P_{T,ll}$ in 2-lepton system
  - Data/MC is very good at each step
  - Distribution narrows as expected with regression and kinematic fit.

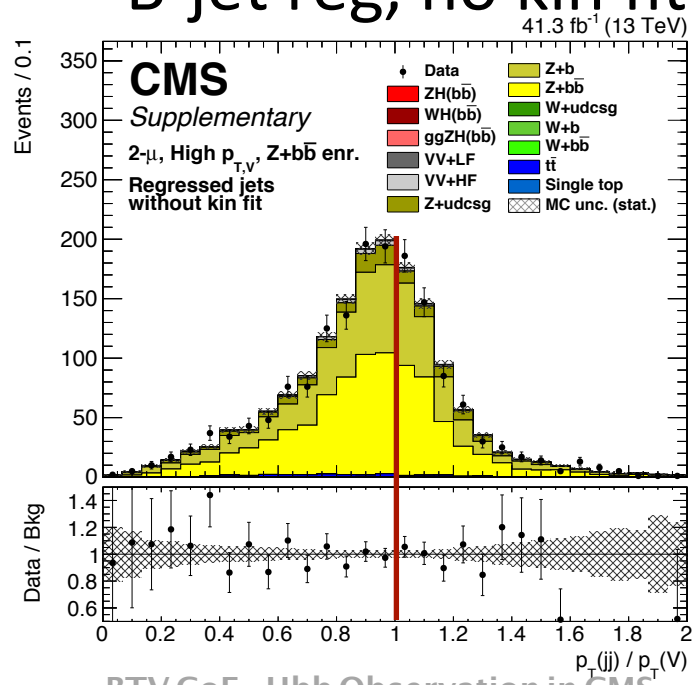
Resolution 10-13%

$p_T(V)$	#ISR Jets	σ_{std}	σ_{reg}	σ_{fit}
> 150	0	17.4	14.9	9.9
> 150	1	17.9	15.4	12.4
> 150	> 1	18.9	15.9	14.4

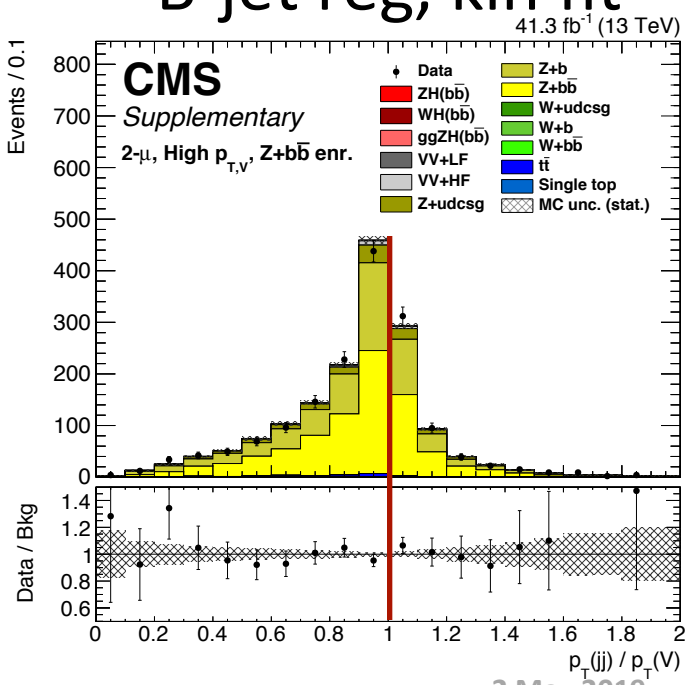
No reg, no kin fit



B-jet reg, no kin fit



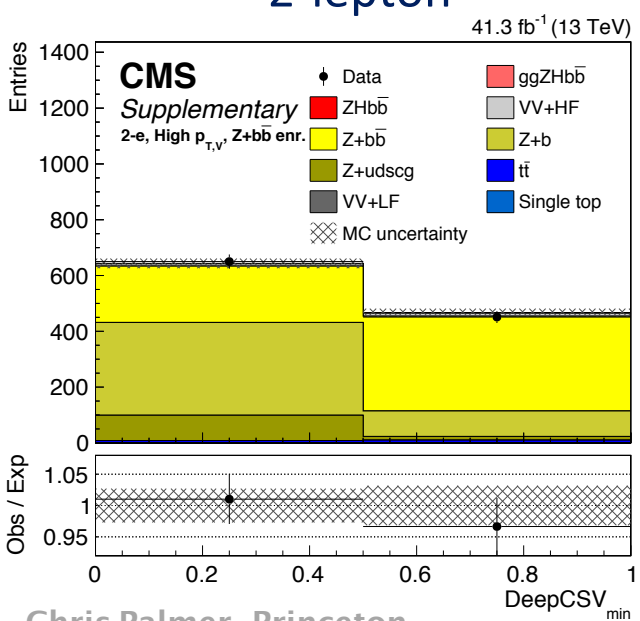
B-jet reg, kin fit



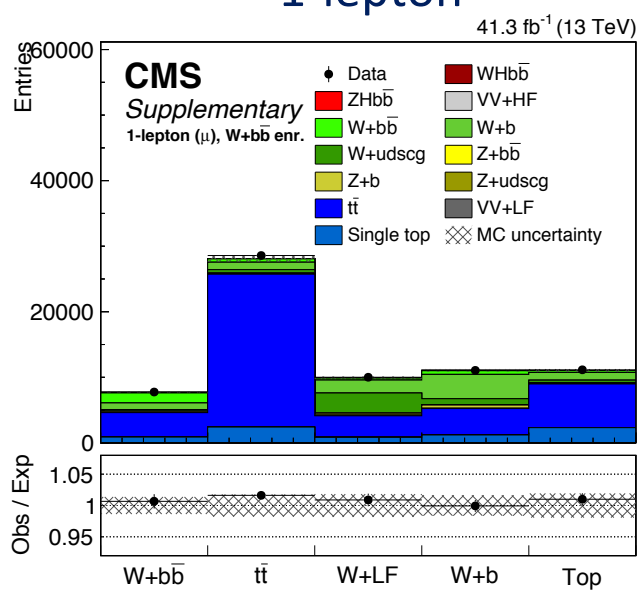
Heavy Flavor control region discriminators

- Reminder: leading systematic uncertainty from normalization of V+(b)b
- 2-lepton channel control region very pure
  - Fit b-tag shape (DeepCSV) to discriminate processes
- 0- and 1-lepton channel control regions less pure
  - Fit DNN multi-categorizer to distinguish among background components
    - Use same input variables as Signal vs Background discriminator

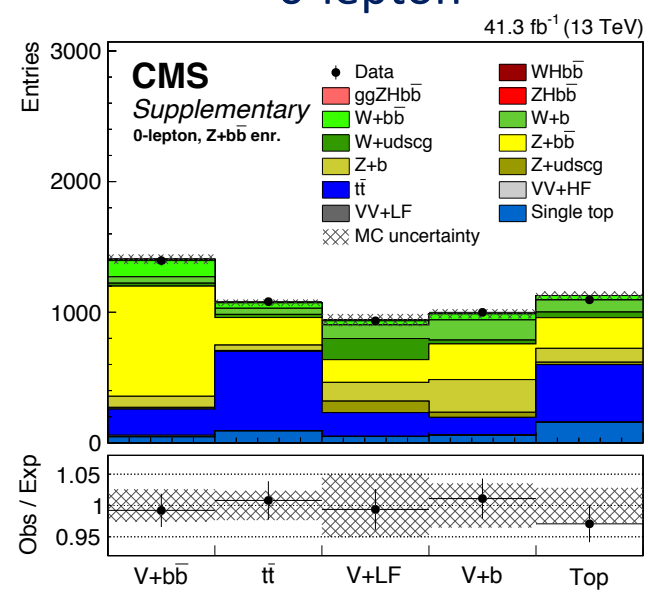
2-lepton



1-lepton



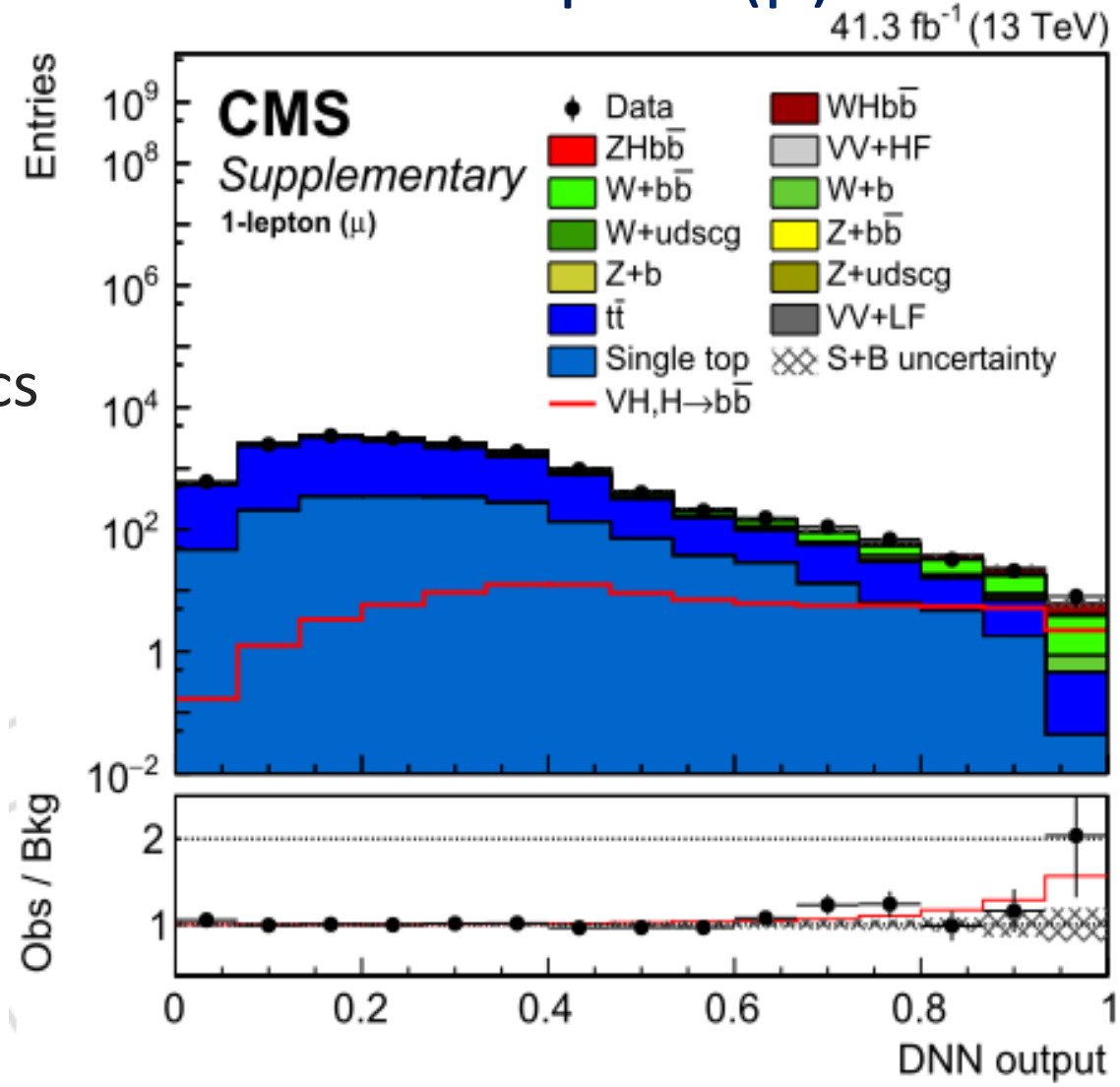
0-lepton



Signal vs Background discriminator

- DNN discriminator used to extract signal
- Input variables:
  - b-jet properties
  - H, V candidate kinematics
  - Carefully validated through data/MC comparisons
- Optimized separately in each channel
- Performance optimization with blind analysis

1-lepton (μ)



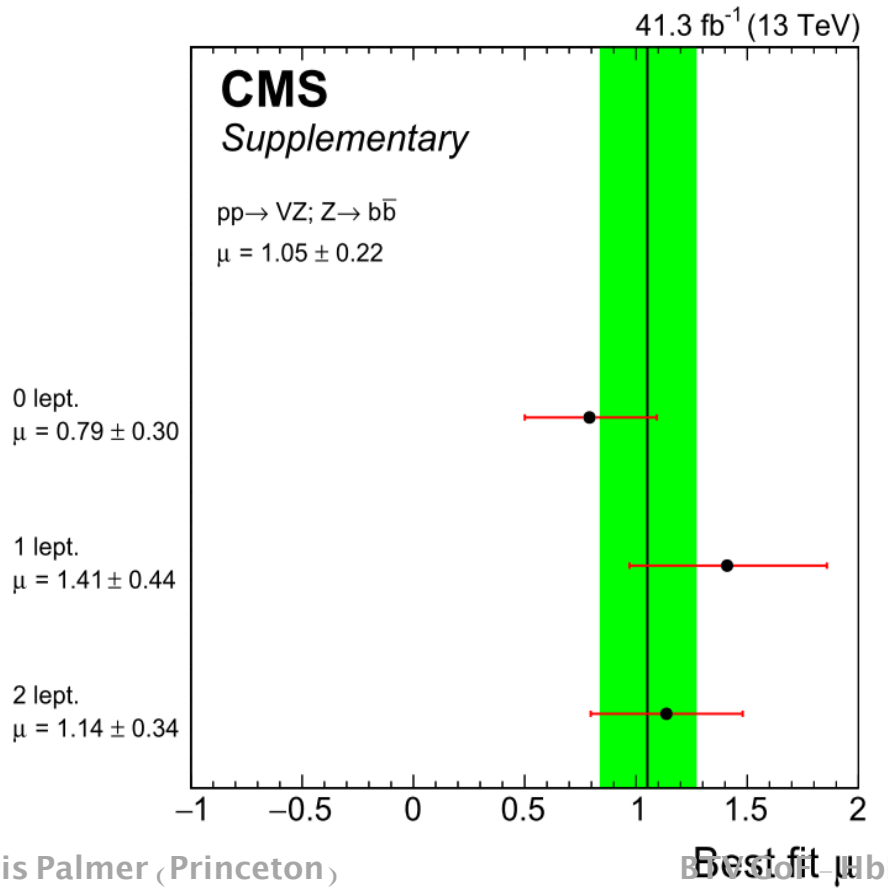
Systematic uncertainties

- Total uncertainty ~34%, statistically dominated
- Major sources of systematic uncertainties from background normalization and modeling, b-tagging, MC sample size

Uncertainty source	$\Delta\mu$	
Statistical	$+0.26$	-0.26
Normalization of backgrounds	$+0.12$	-0.12
Experimental	$+0.16$	-0.15
b-tagging efficiency and misid	$+0.09$	-0.08
V+jets modeling	$+0.08$	-0.07
Jet energy scale and resolution	$+0.05$	-0.05
Lepton identification	$+0.02$	-0.01
Luminosity	$+0.03$	-0.03
Other experimental uncertainties	$+0.06$	-0.05
MC sample size	$+0.12$	-0.12
Theory	$+0.11$	-0.09
Background modeling	$+0.08$	-0.08
Signal modeling	$+0.07$	-0.04
Total	$+0.35$	-0.33

Validation: VZ(bb)

- VZ analysis using Z(bb) standard candle next to H(bb) peak
- Same "technology" used for VH(bb) fit
  - Same DNN inputs (but dedicated training), same Control Regions, VH(bb) normalized to SM and left free to float
  - Larger m(bb) window in Signal Region to fully include Z(bb) peak



Significance

5.0σ expected

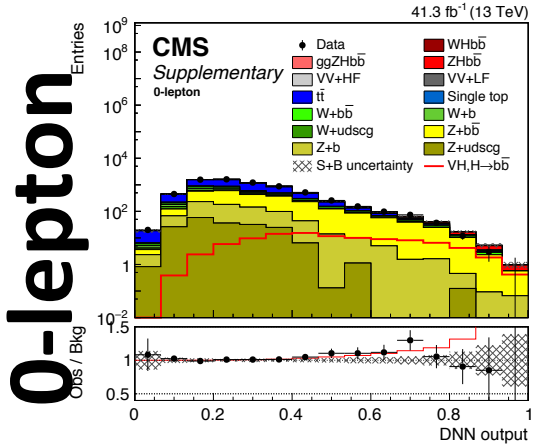
5.2σ observed

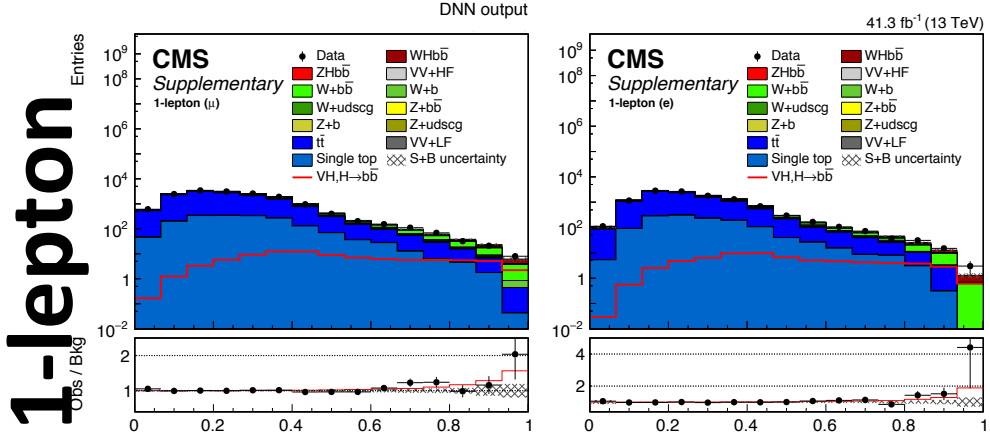
Signal strength

μ = 1.05 ± 0.22

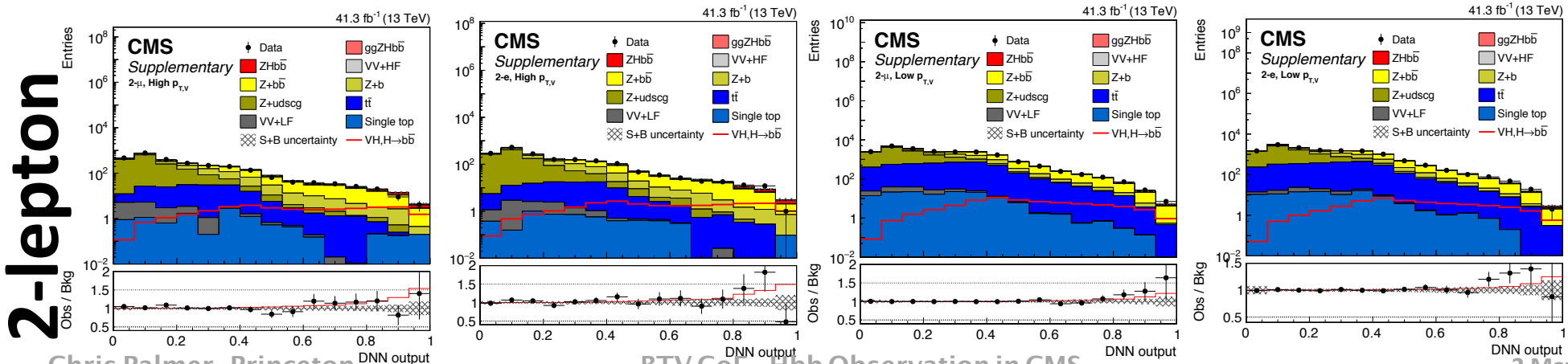
Putting all 2017 channels together

- Discriminator (DNN) distributions with systematic uncertainties from signal extraction fit.
- Coarsely one can see that the data to simulation agreement is very good after fitting with shape systematics.



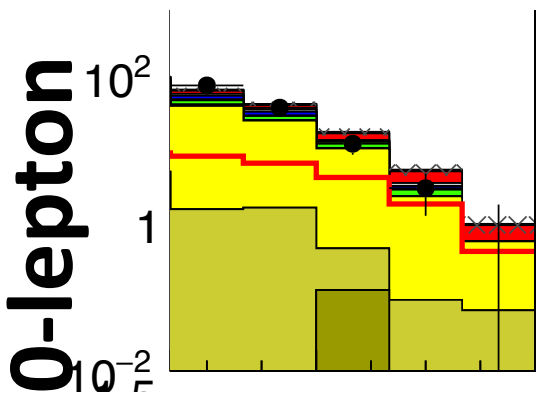


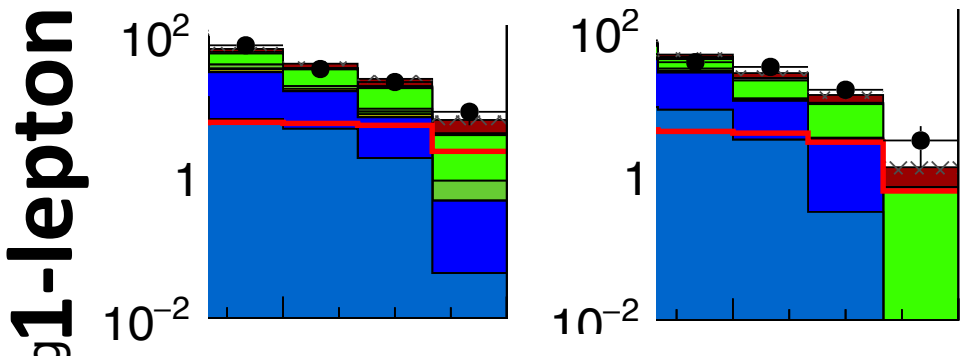
Channel	# Signal Regions	# Control Regions
0-lep	1	3
1-lep	2	6
2-lep	4	12
Total	7	21

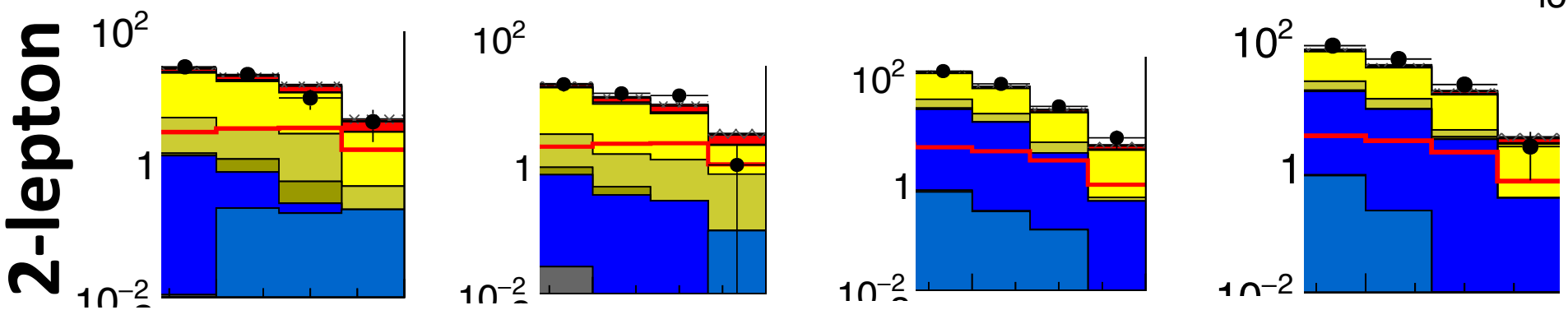


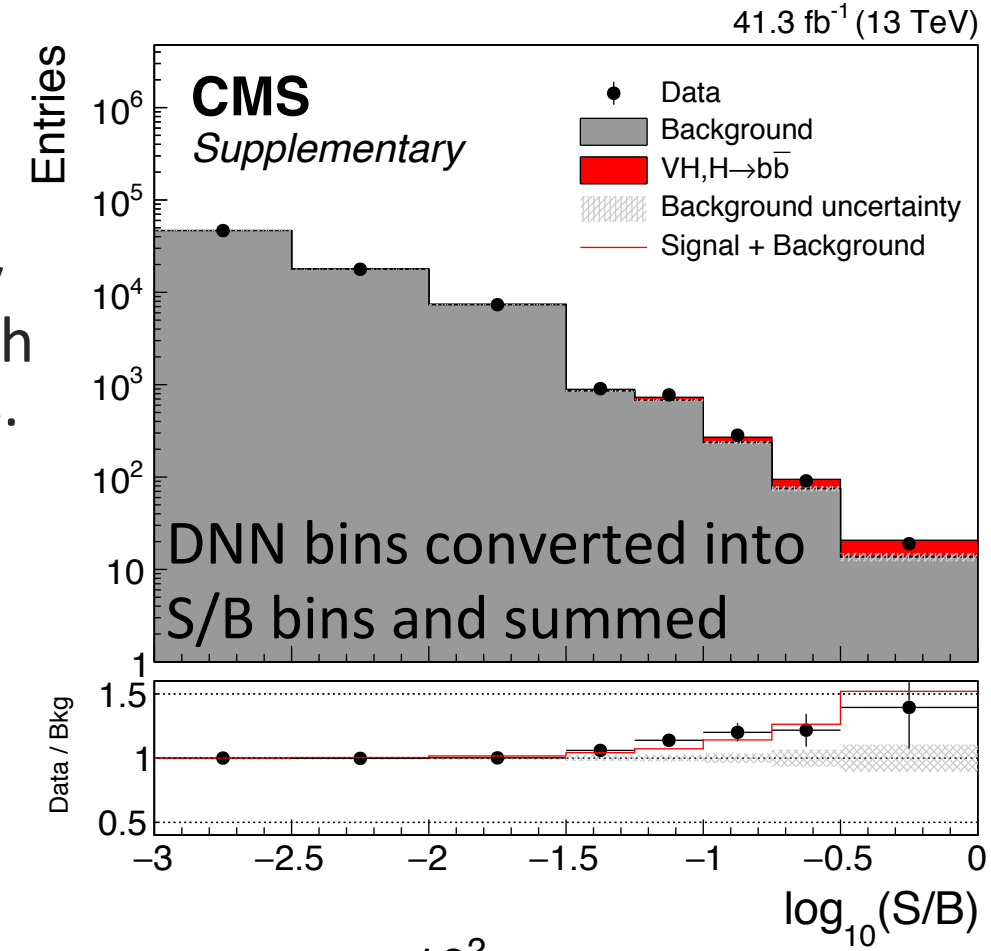
Putting all 2017 channels together

- Zooming into high sensitivity region.
- Overall visually compatible with S+B hypothesis.





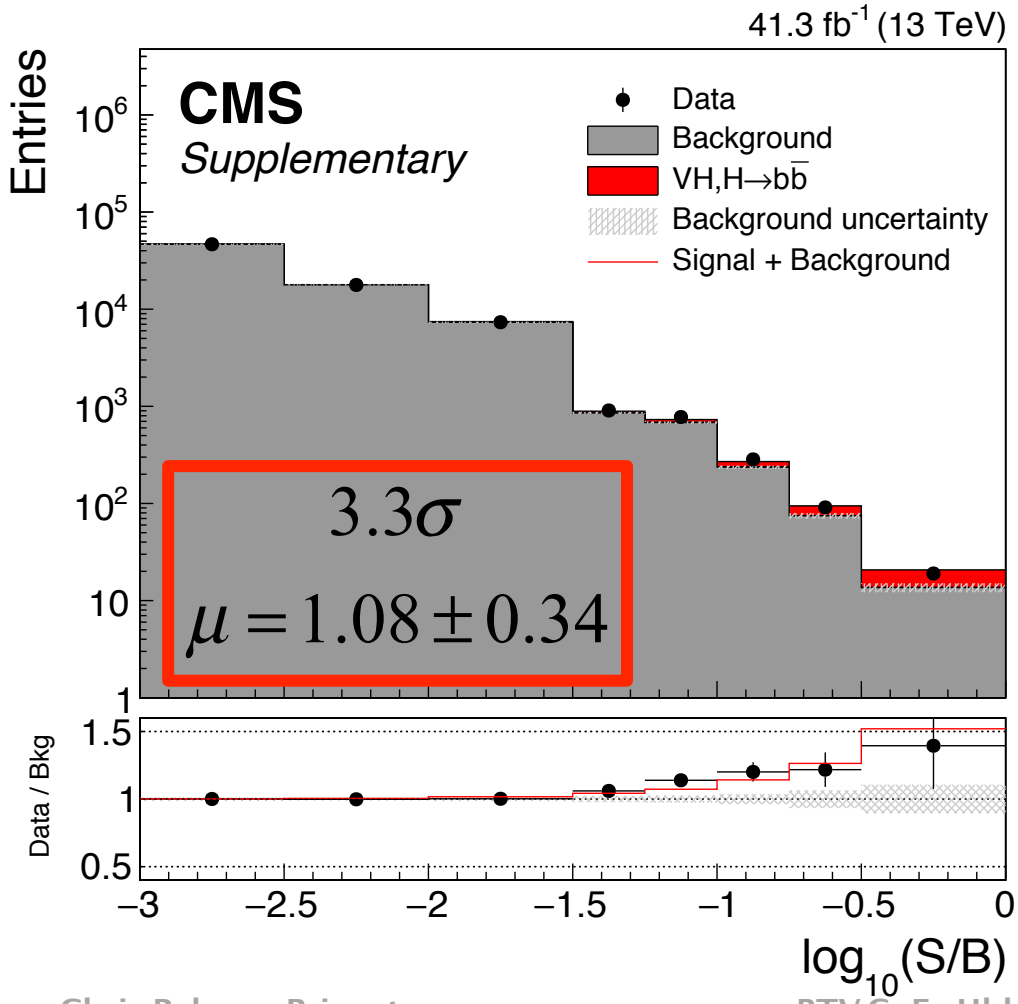


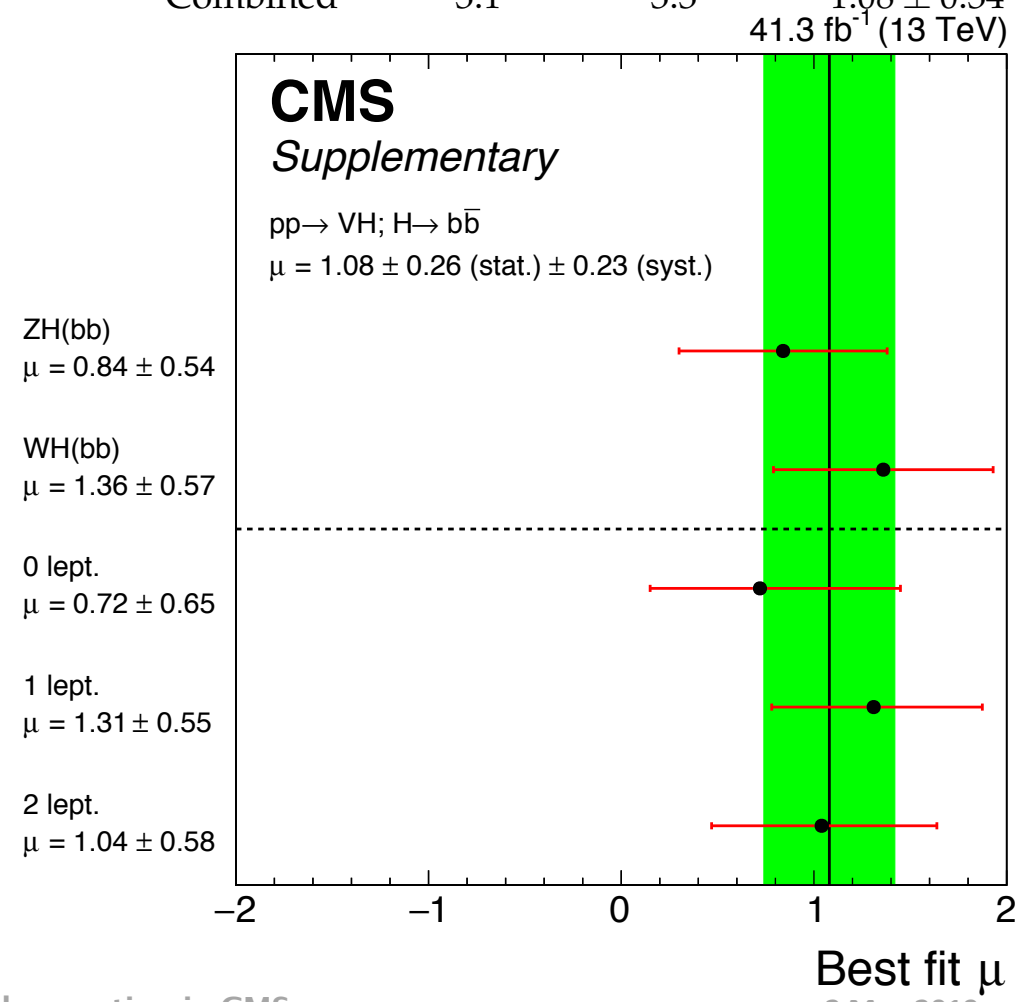


2017 VHbb

- Results constitute standalone evidence for the VHbb process

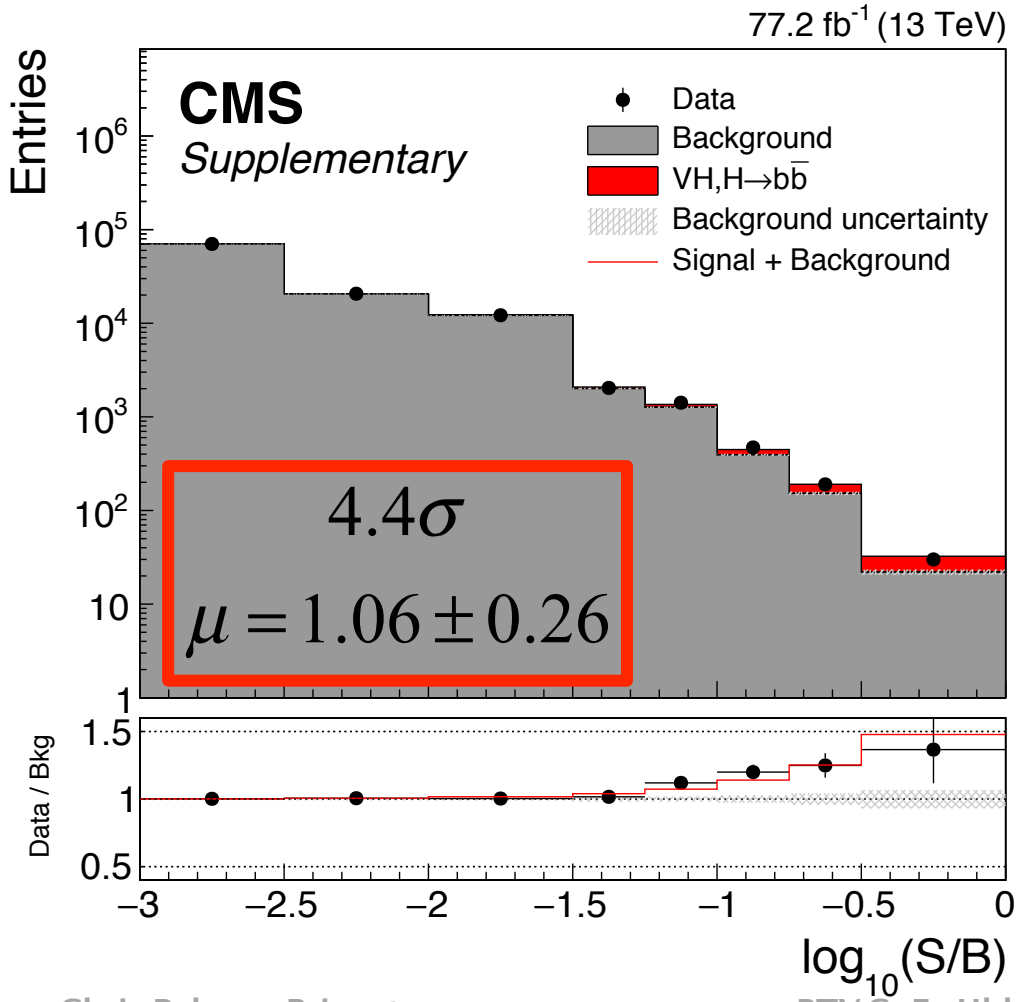
Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34

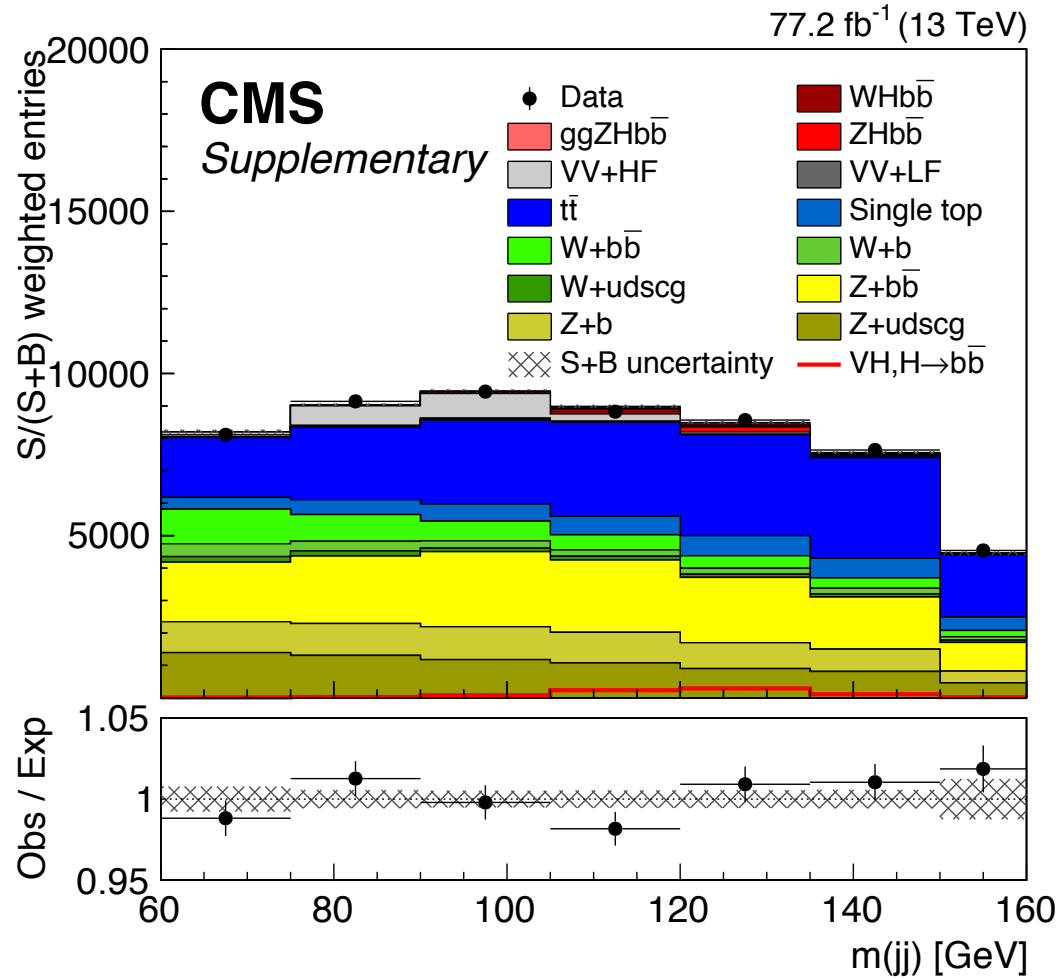




"Run 2": 2016+2017 VHbb

- Combining with published 2016 results with 2017 VHbb
  - (AKA "Run 2")
- Cross-check mjj analysis
  - Categorize events with "mass-blind" DNN (four categories per channel)
  - Plot categories weighted by S/(S+B)





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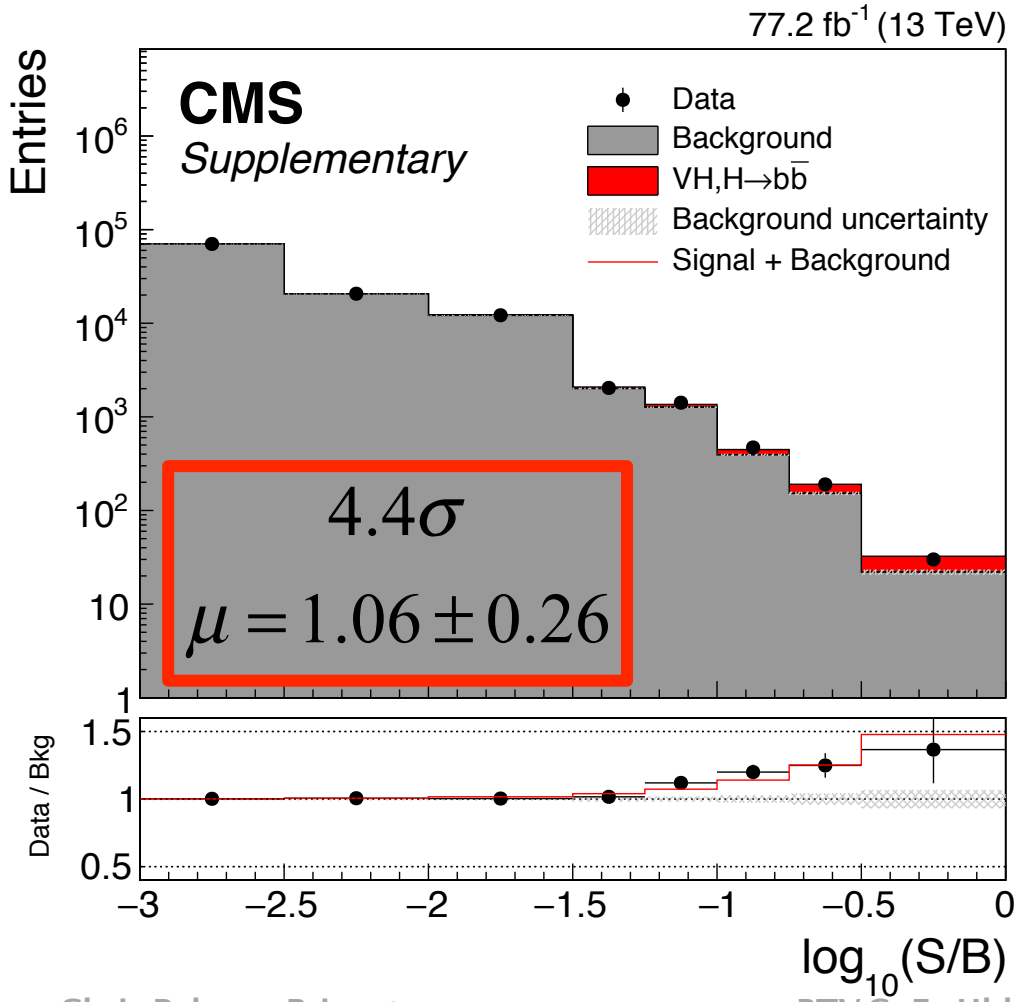
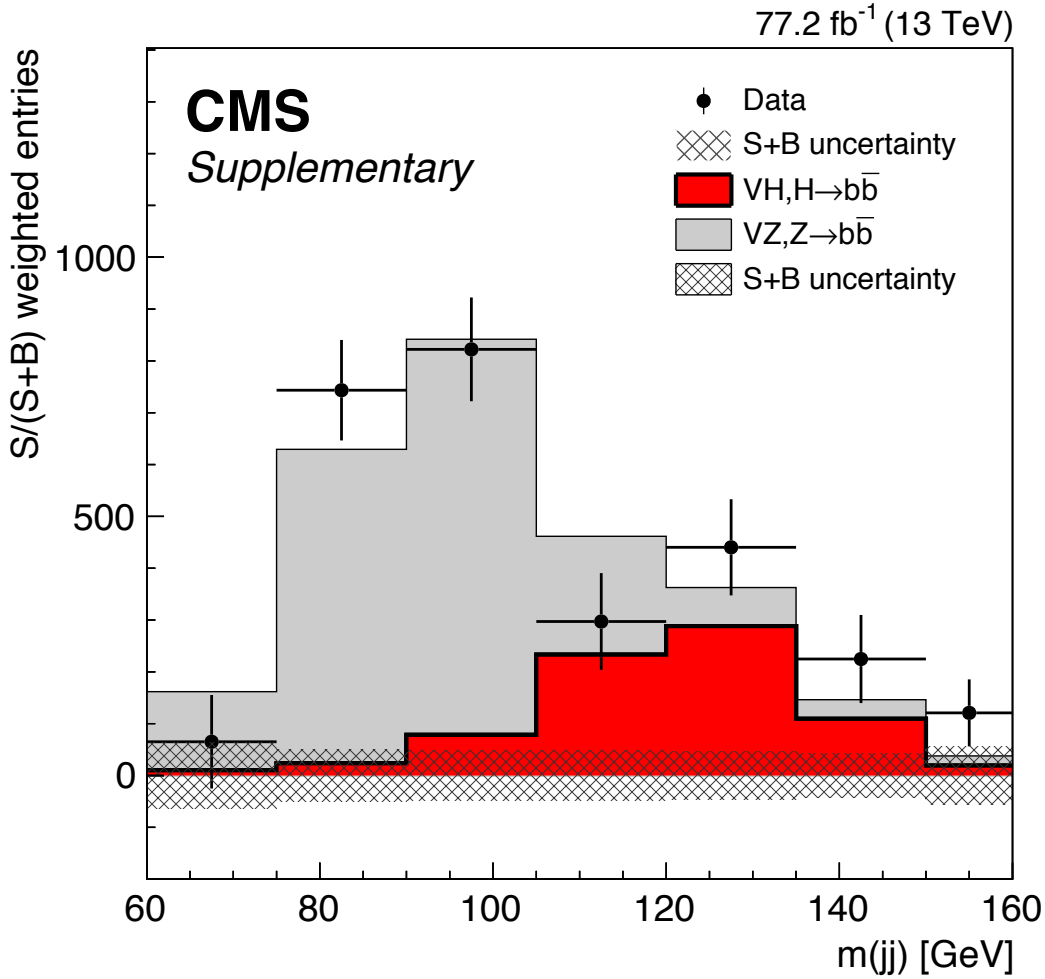
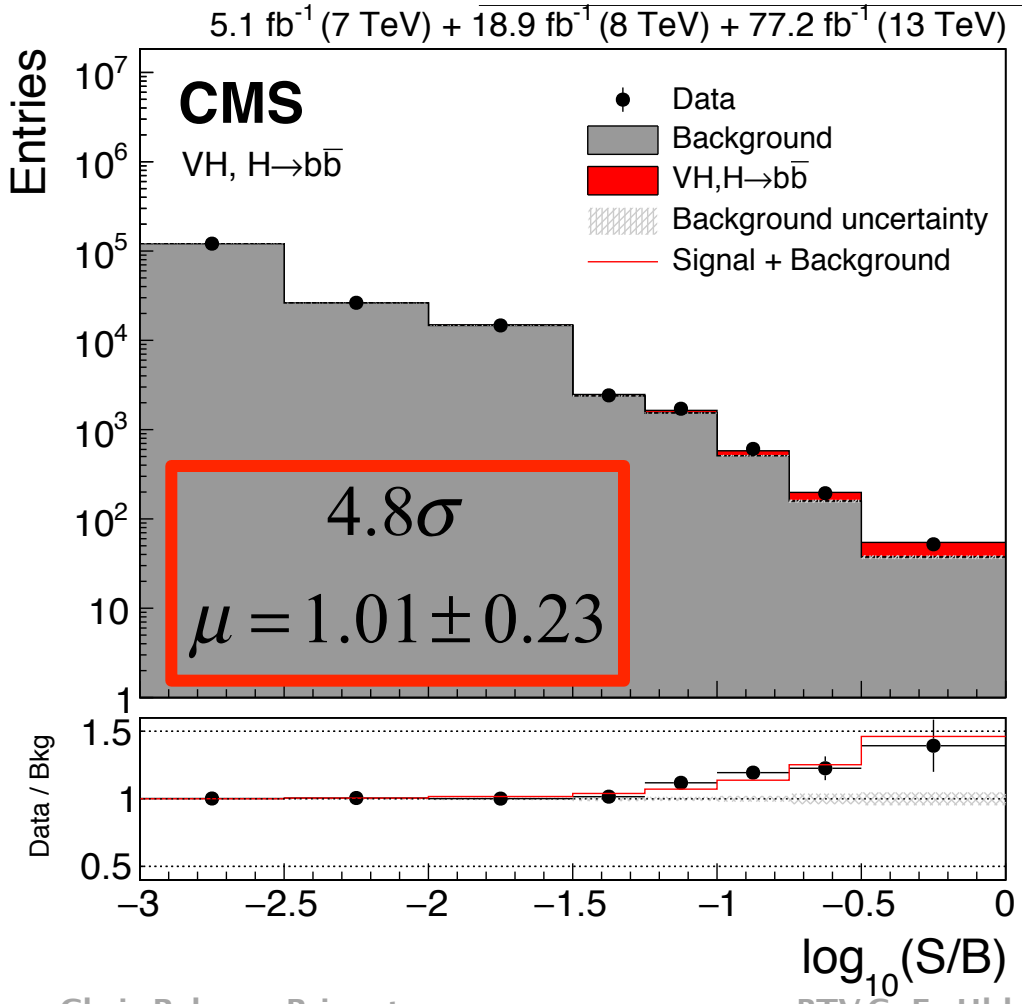
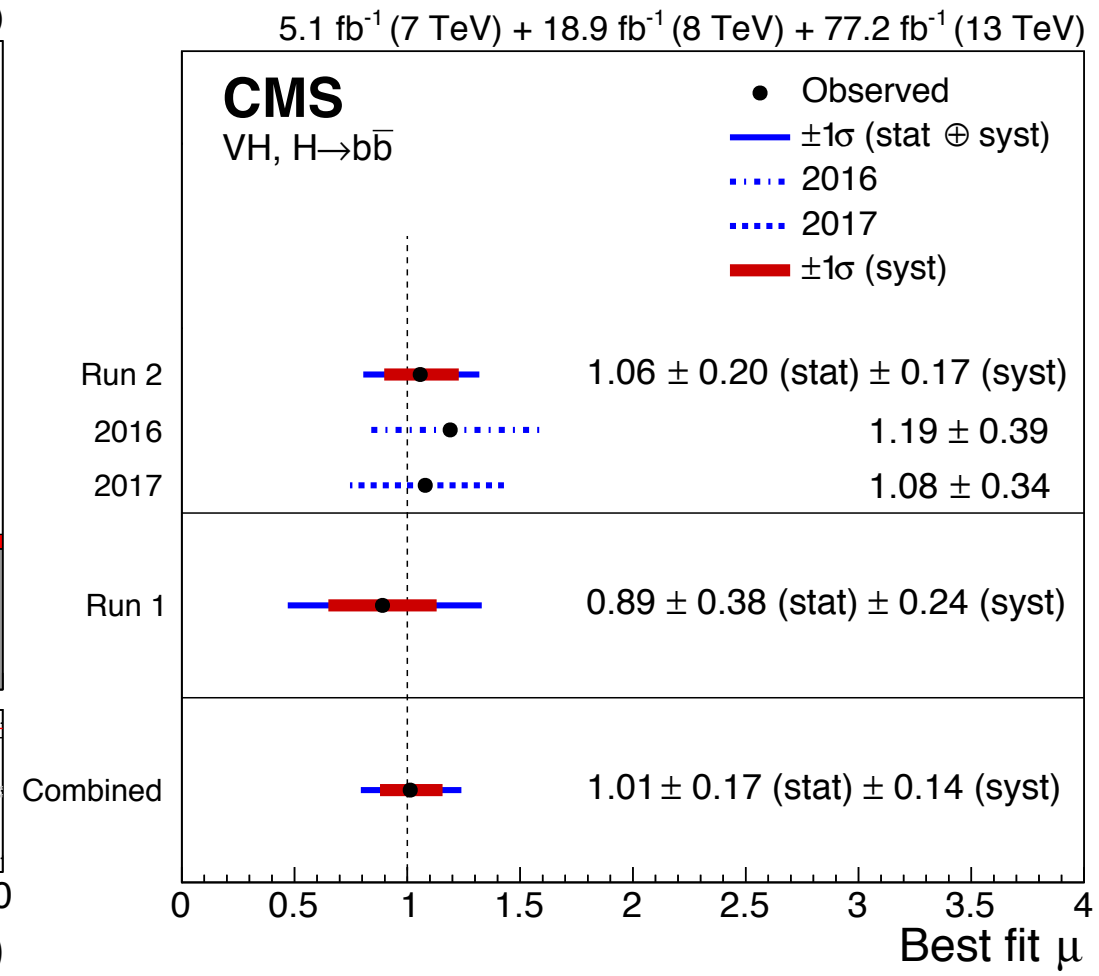




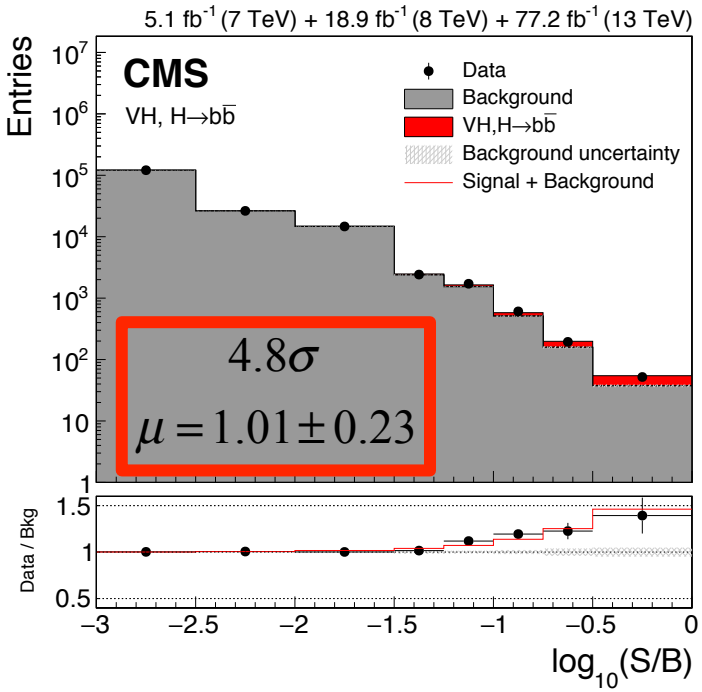
Run 1+2016+2017 VHbb

Data set	Significance (σ) Expected	Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

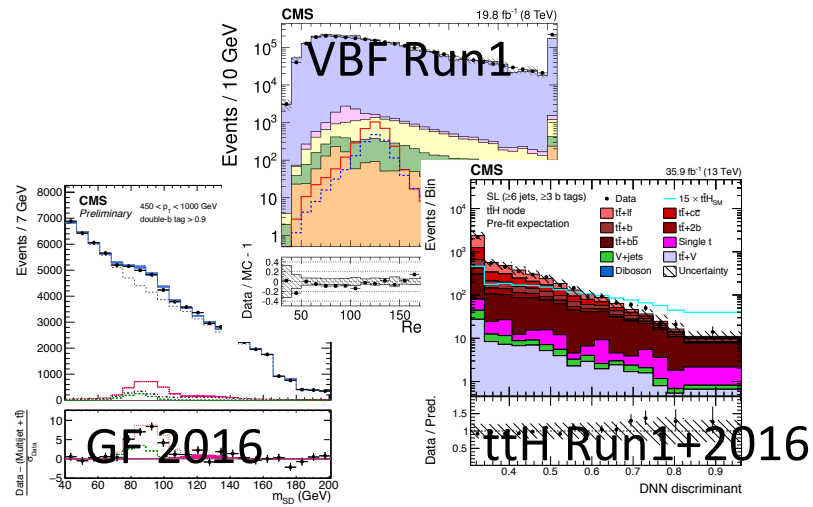




Combination of H→bb measurements



+

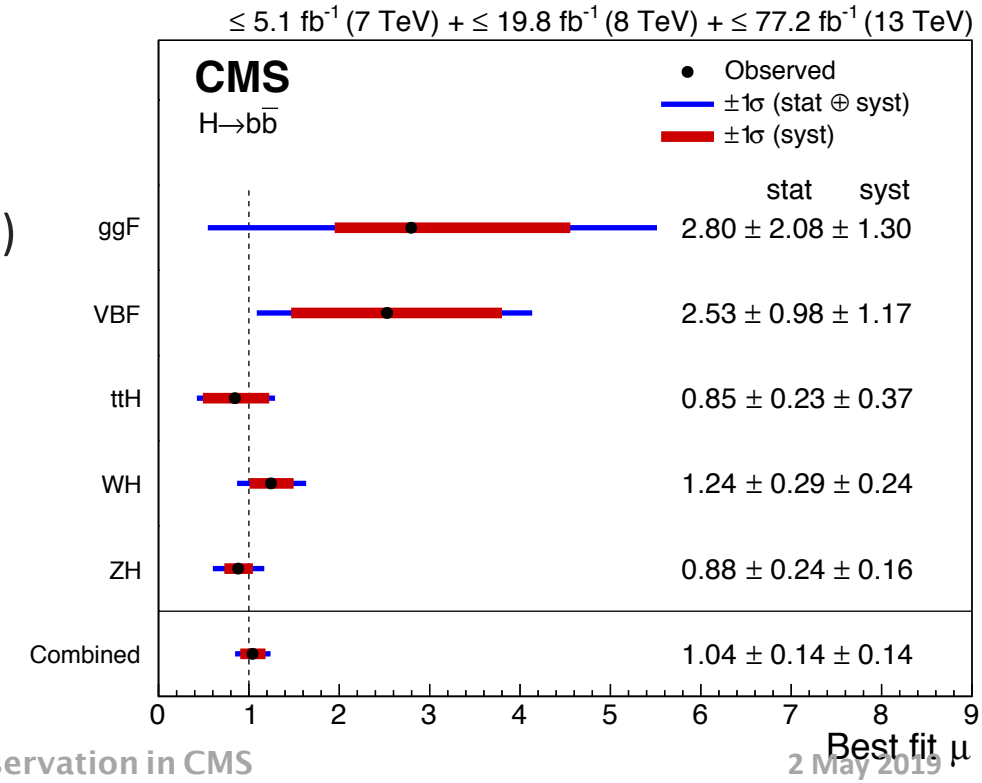


Theory uncertainties are correlated between all processes and data sets. (Most others uncorrelated)

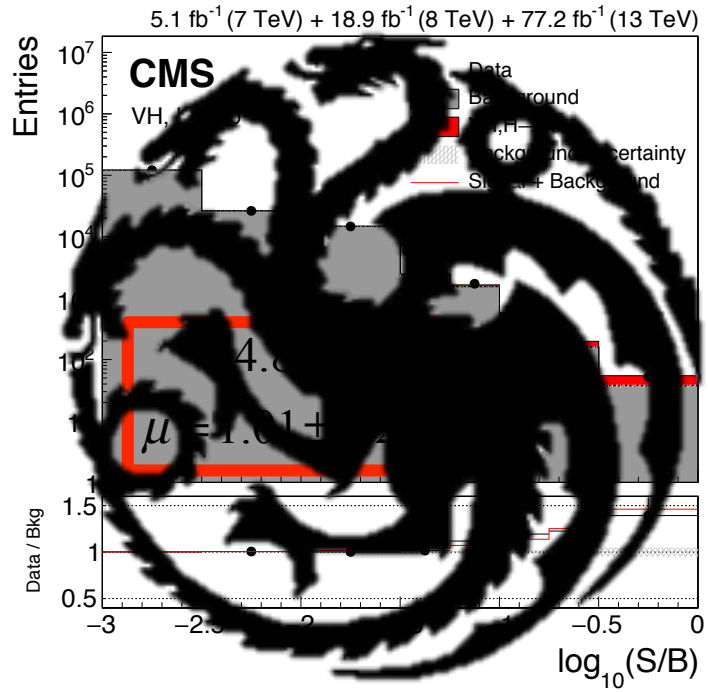
$$5.6\sigma \ (5.5\sigma)$$

$$\mu = 1.04 \pm 0.20$$

Observation of the H→bb decay by the CMS Collaboration



Combination of H→bb measurements



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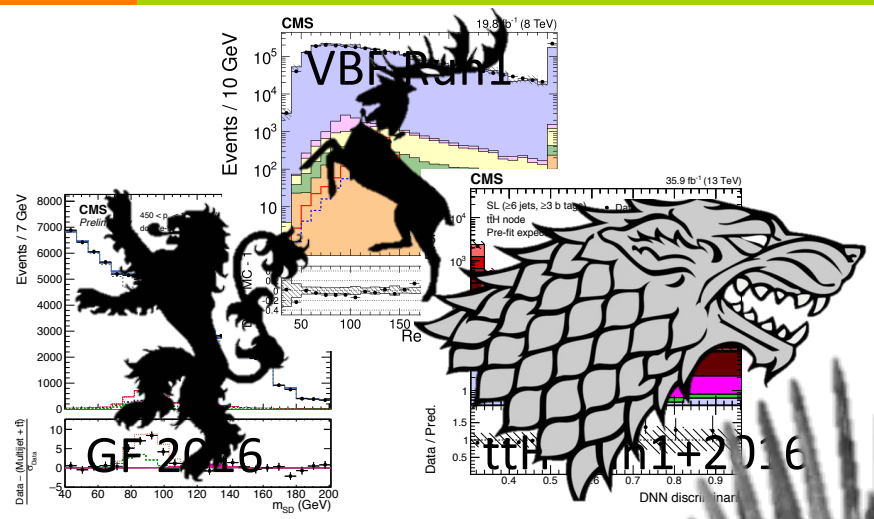


Dragons alone do not win the iron throne!

Higgs' Quest

Fermilab (Chicago, USA)

Tevatron Run II
In progress

LEP (Geneva, Switzerland)

LEP Dismantling
November 2000

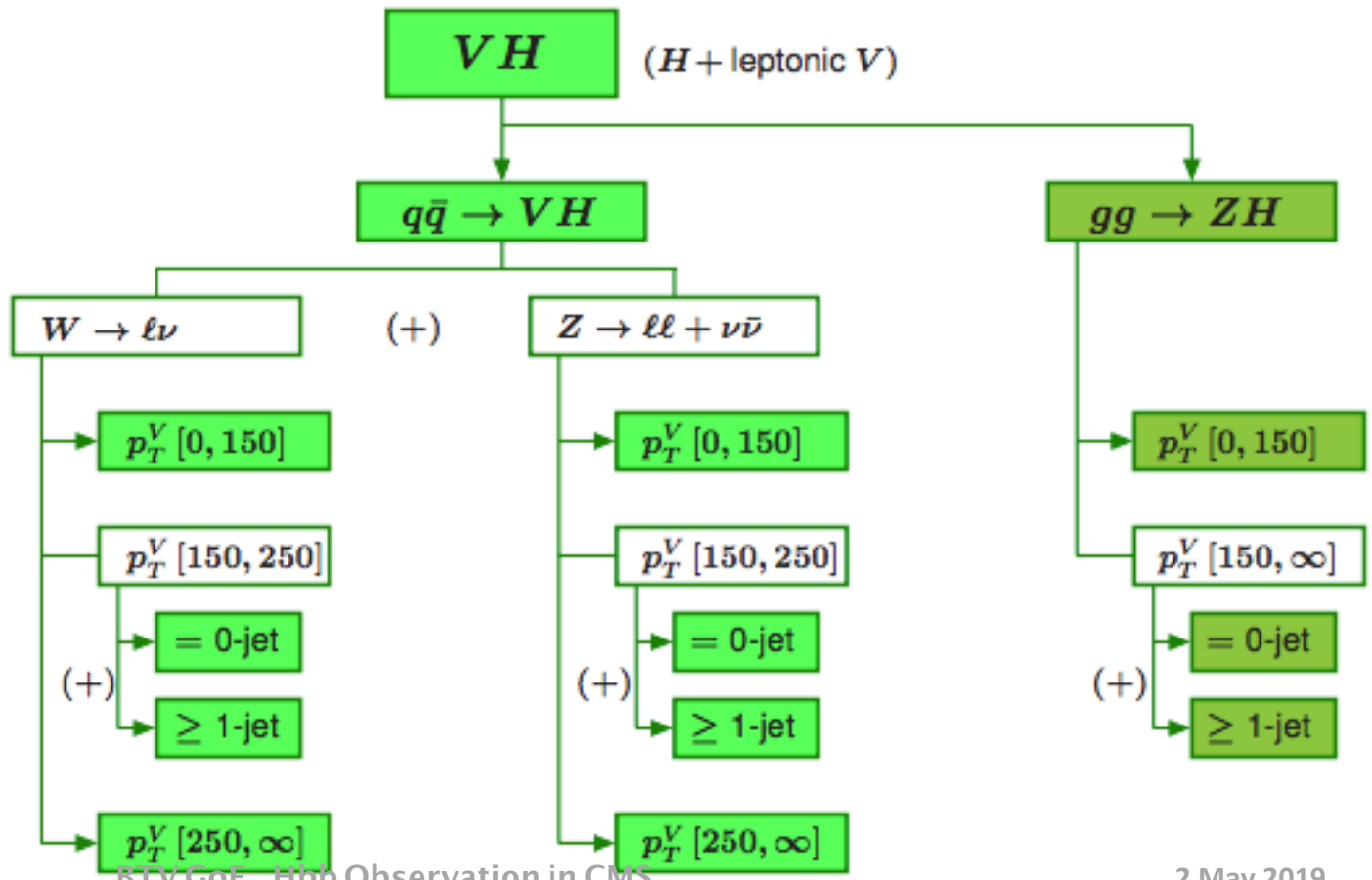
6 years

Startup of LHC
2006 or later

Simplified Template Cross Sections

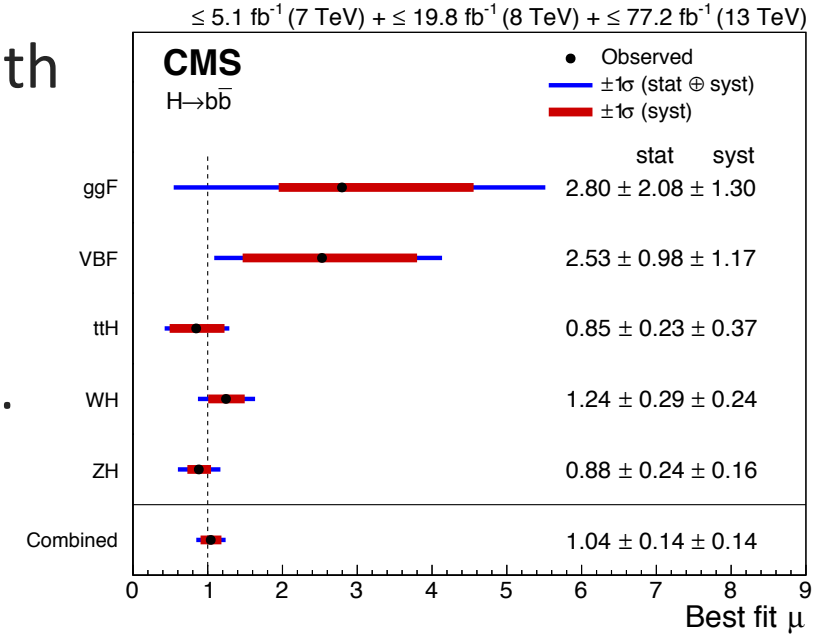
- As we approach precision higgs boson measurements, the LHC Higgs Cross Section Working Group devised a framework that should
  1. Reduce the impact of theoretical uncertainties on CMS and ATLAS measurements
  2. Improve the accessibility/utility of Higgs cross sections to theorists such that they can constrain their BSM models based on data.

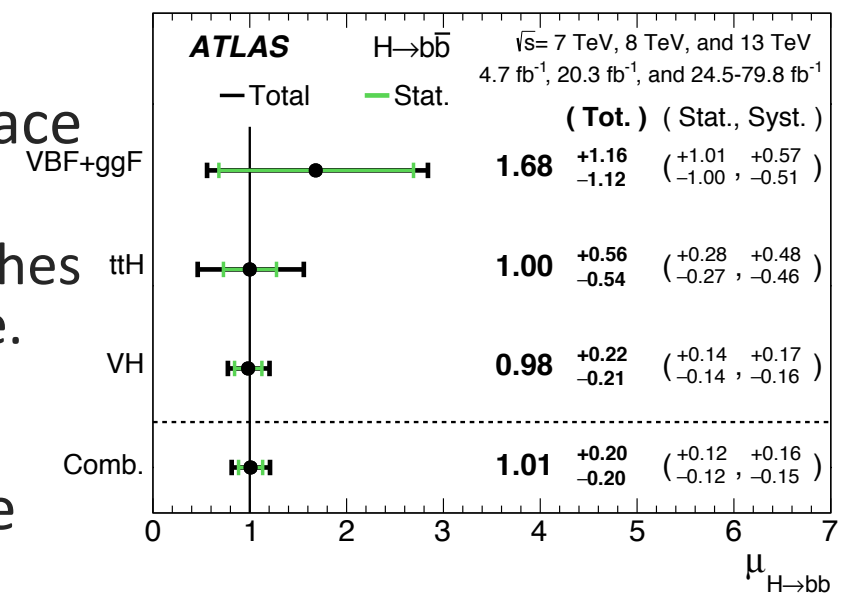
- Independent analysis bins are made in variables that are both useful for the analysis and so that theory systematic impact can be reduced.



Conclusions

- CMS and ATLAS have both independently observed the decay of the Higgs boson with signal strength compatible with SM and 20% uncertainty.
  - In each case multiple production tag searches were combined with combo dominated by VHbb (~90% of sensitivity).
- The Higgs bonon's Yukawa coupling to bottom quarks is firmly and directly established.
- The shoulders of giants is a wonderful place to stand.
  - LEP and tevatron pioneered VHbb searches and their work deserves note and praise.
- Of course none of this could be possible without the excellent performance of the LHC.

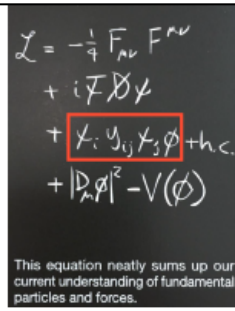


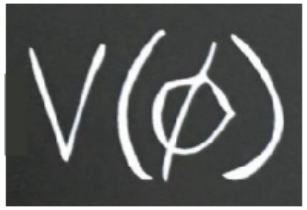


Thank you!
Questions?

Higgs sector of SM Lagrangian

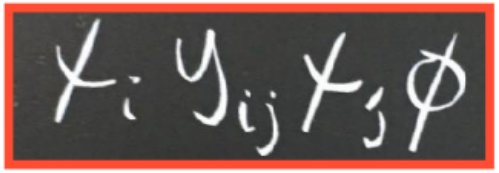
Why do Yukawa couplings matter?
(1) A part of the Higgs sector that's unlike any other experimentally-probed interaction





($-\mu^2\varphi^2 + \lambda\varphi^4$, HHH) the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature

(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like what we've seen before



(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we've probed before

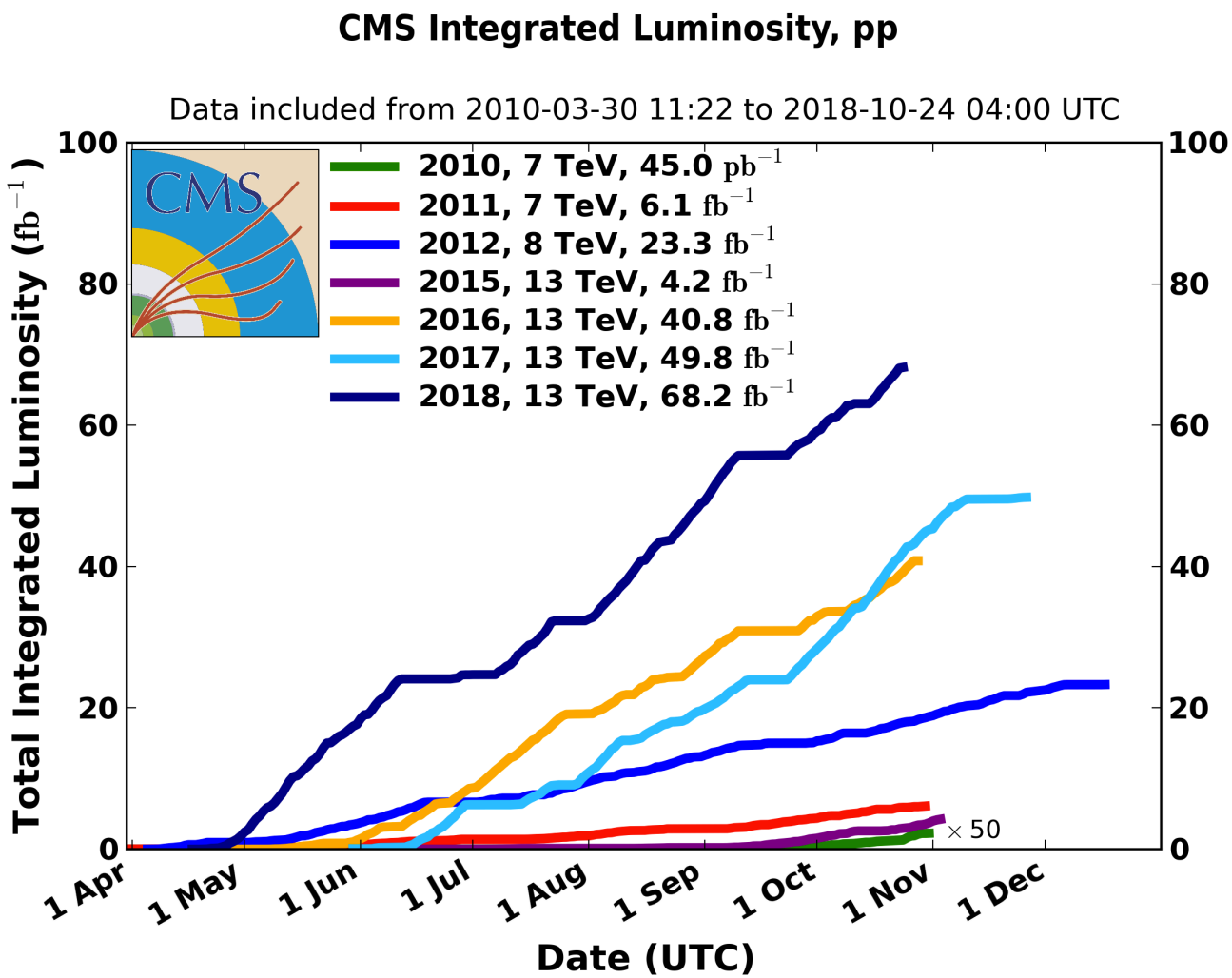
G. Salam, LHCP '18

- Using the same tunnel used for LEP in the 1990s.
- Colliding protons (and heavier ions)
- Build for finding the Higgs boson and discovering new particles up to the few TeV scale.

Large Hadron Collider (LHC)

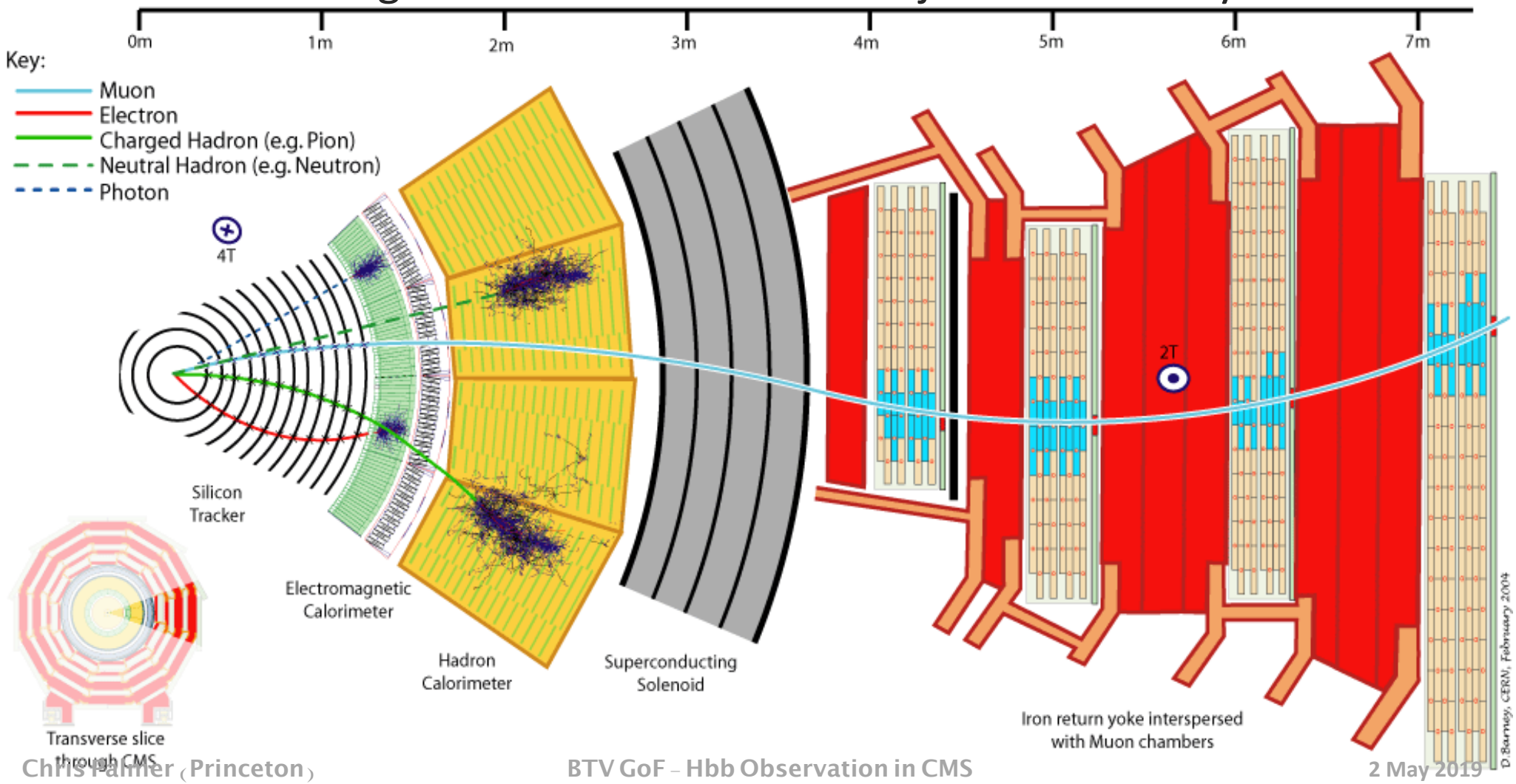
LHC Data Summary

- Excellent LHC performance in data delivery in Run 2
  - Running now at TWICE design rate!
- CMS and ATLAS are able to reach numerous milestone measurements with 2016+2017 data.
  - ~80 fb^{-1} of recorded data for each experiment



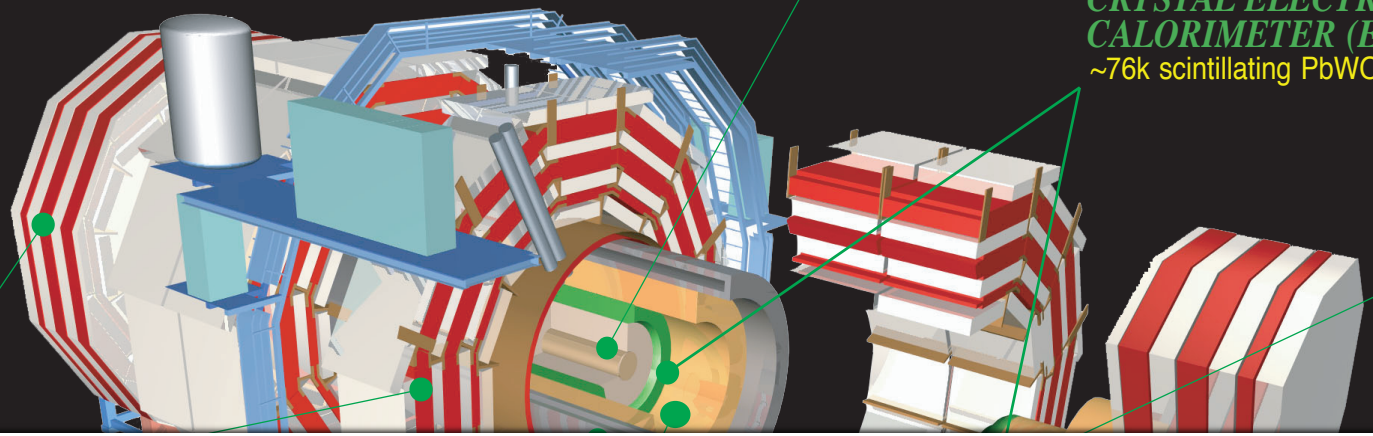
Particle Detection in CMS

- Muons, electrons, b-jets, and missing energy are necessary components for the VHbb analysis.
- Particle flow algorithm reconstructs all objects coherently.

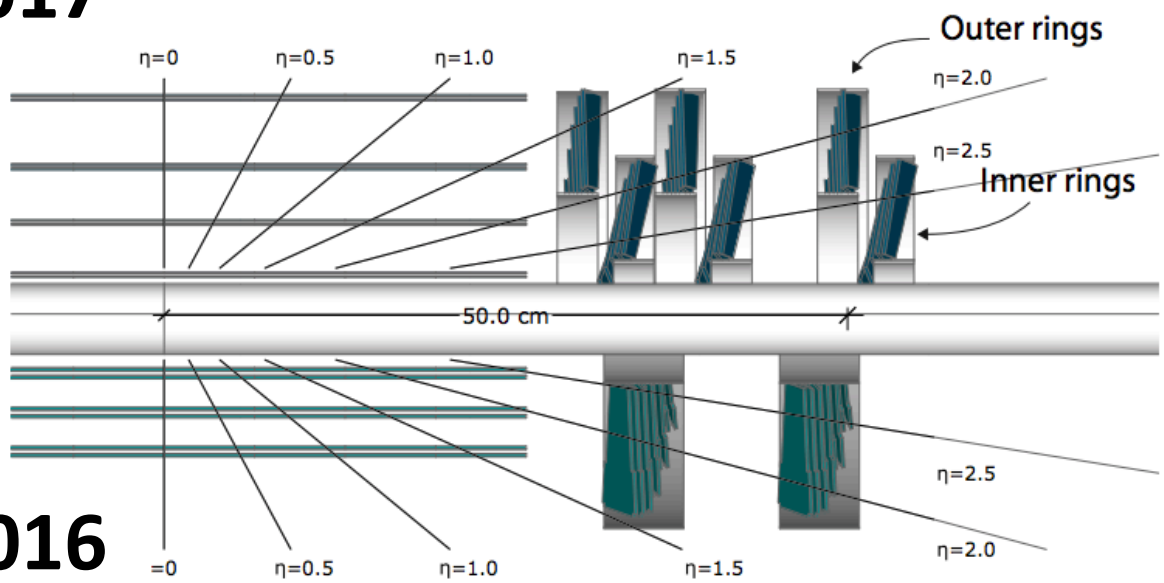


CMS Detector Upgrades

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

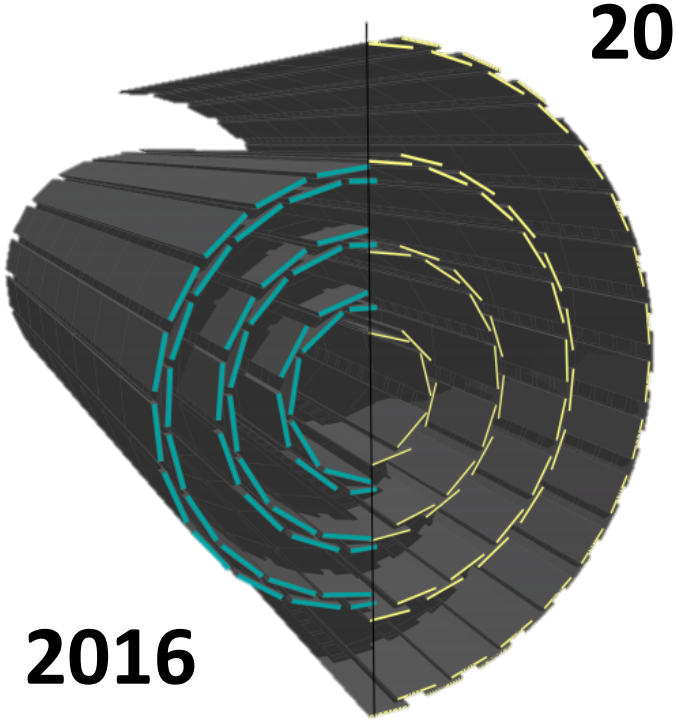


2017



2016

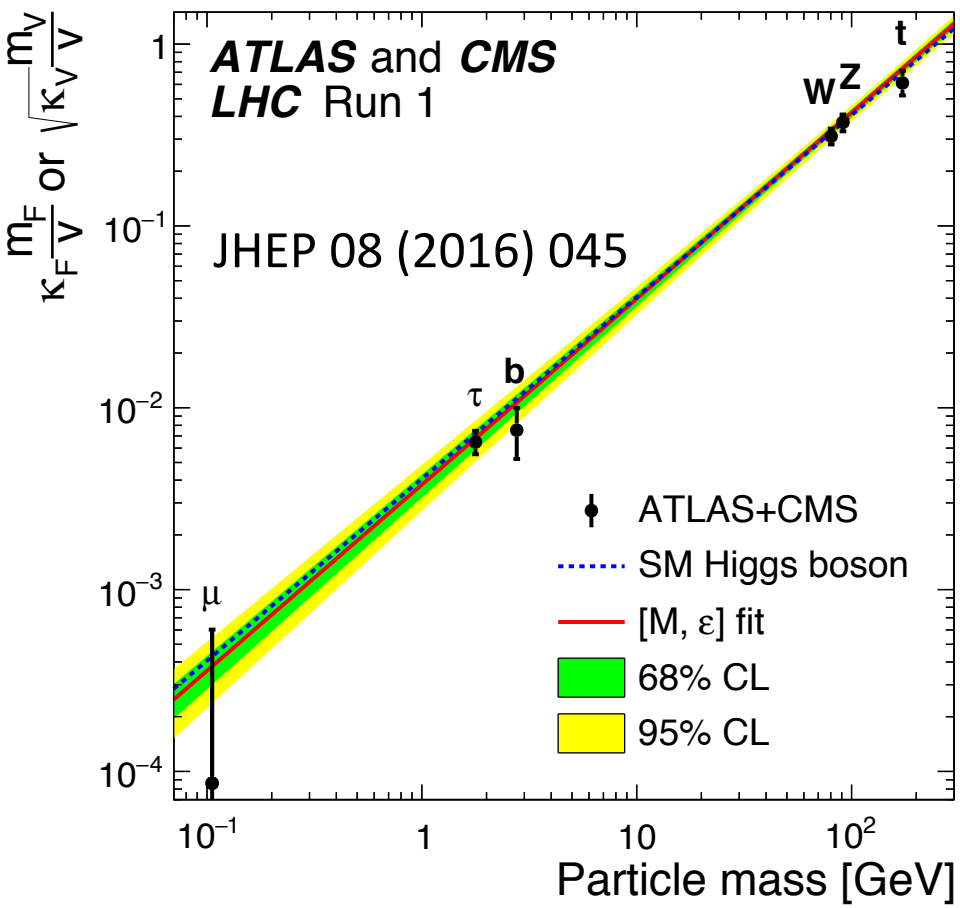
2017

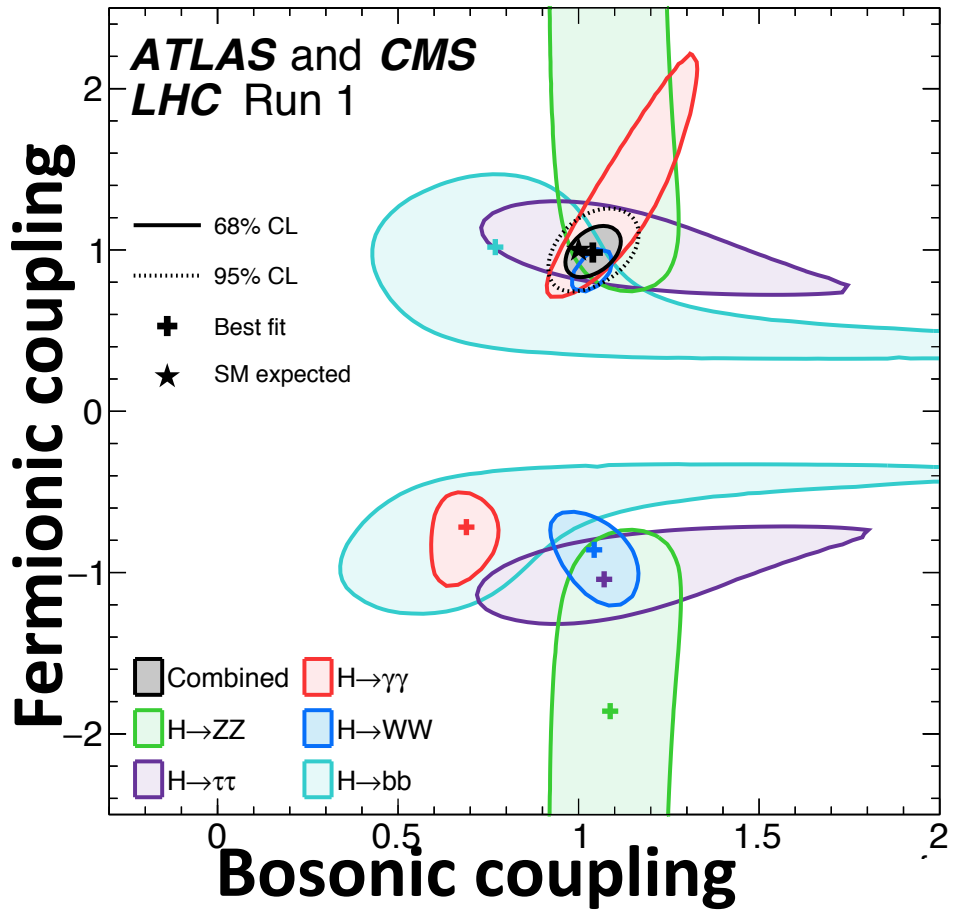


2016

Higgs couplings (LHC Run 1)

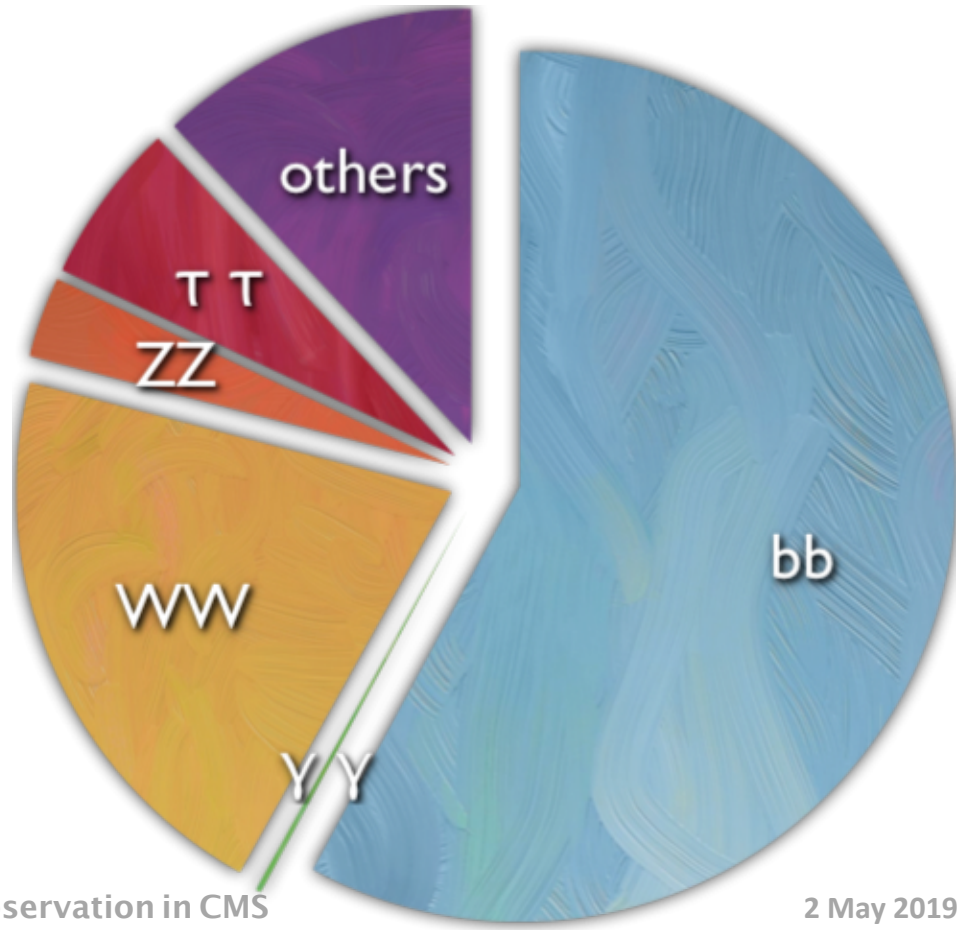
- Each particle's coupling is proportional to its mass.
  - Gauge/Yukawa for bosons/fermions
- Combination of big five (+μμ) yields bosonic and fermionic Higgs boson couplings within 1σ of SM expectations.



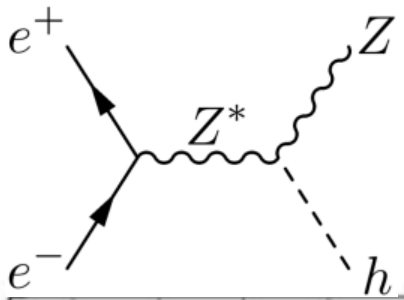


Higgs boson summary

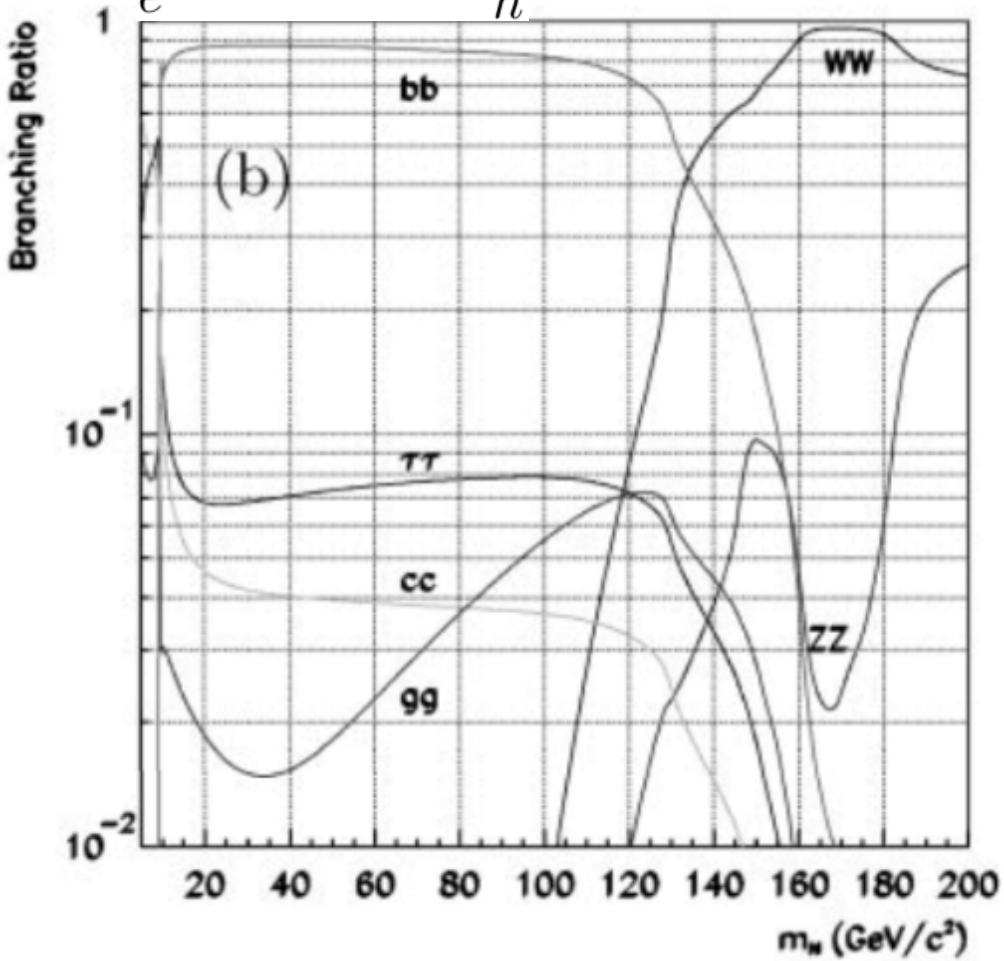
- Properties
  - Spin 0 / parity + (SM)
  - Signal strength near SM expectations (1.09±0.11)
  - SM compatible couplings
  - Mass precision of 0.2%
- Established Higgs production
  - Gluon fusion
  - Vector boson fusion
  - VH (2018!)
  - ttH (2018!)
- Established Higgs decays
  - ZZ, γγ, WW (Run 1)
  - ττ (2017)
  - bb (2018!)



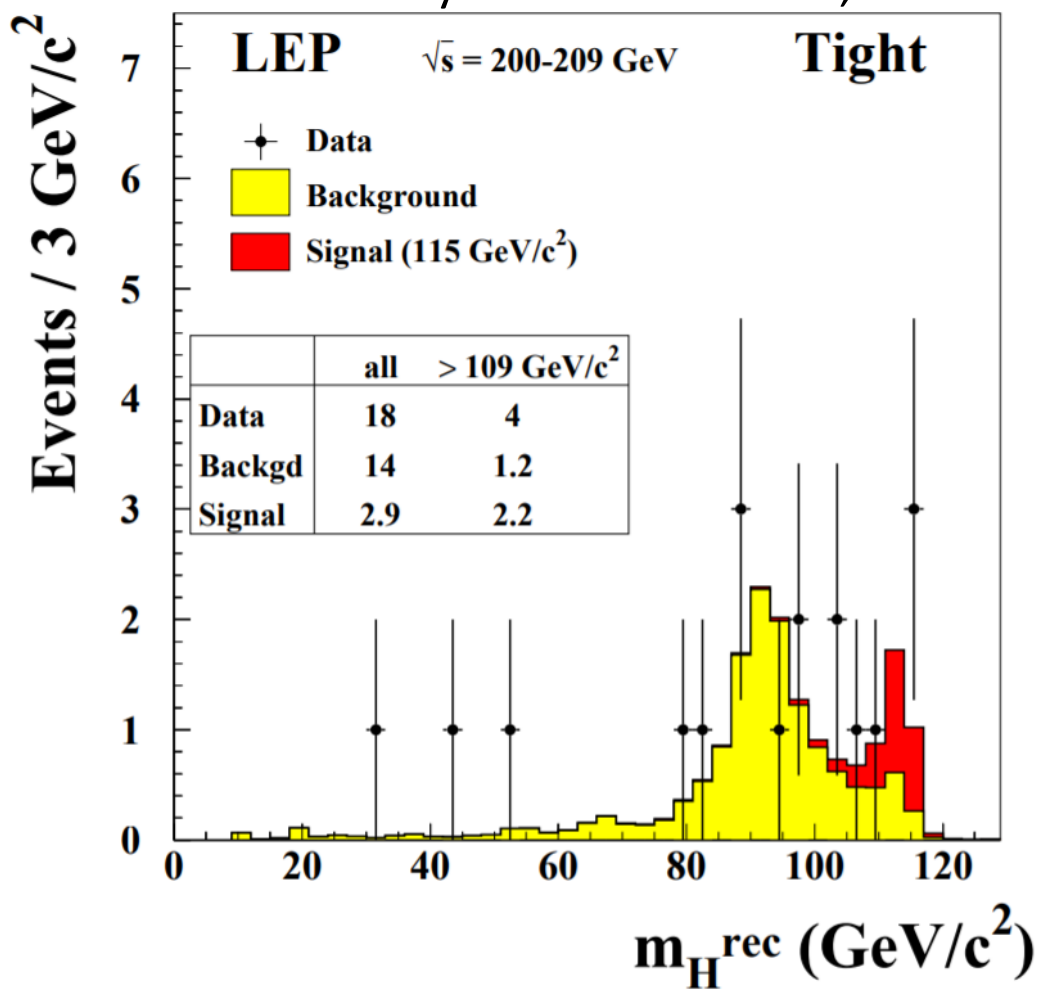
(Z)Hbb at LEP



- For low Higgs masses bb is the dominant decay channel.



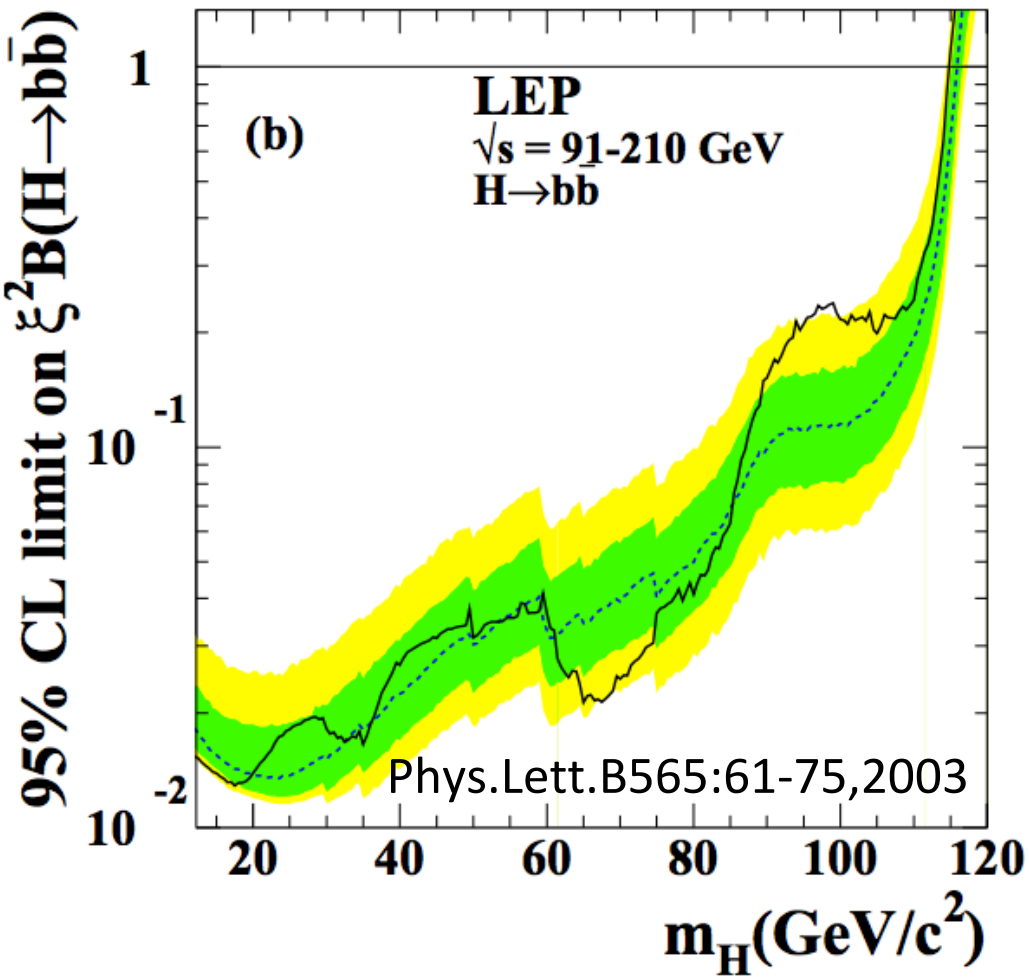
Phys.Lett.B565:61-75,2003

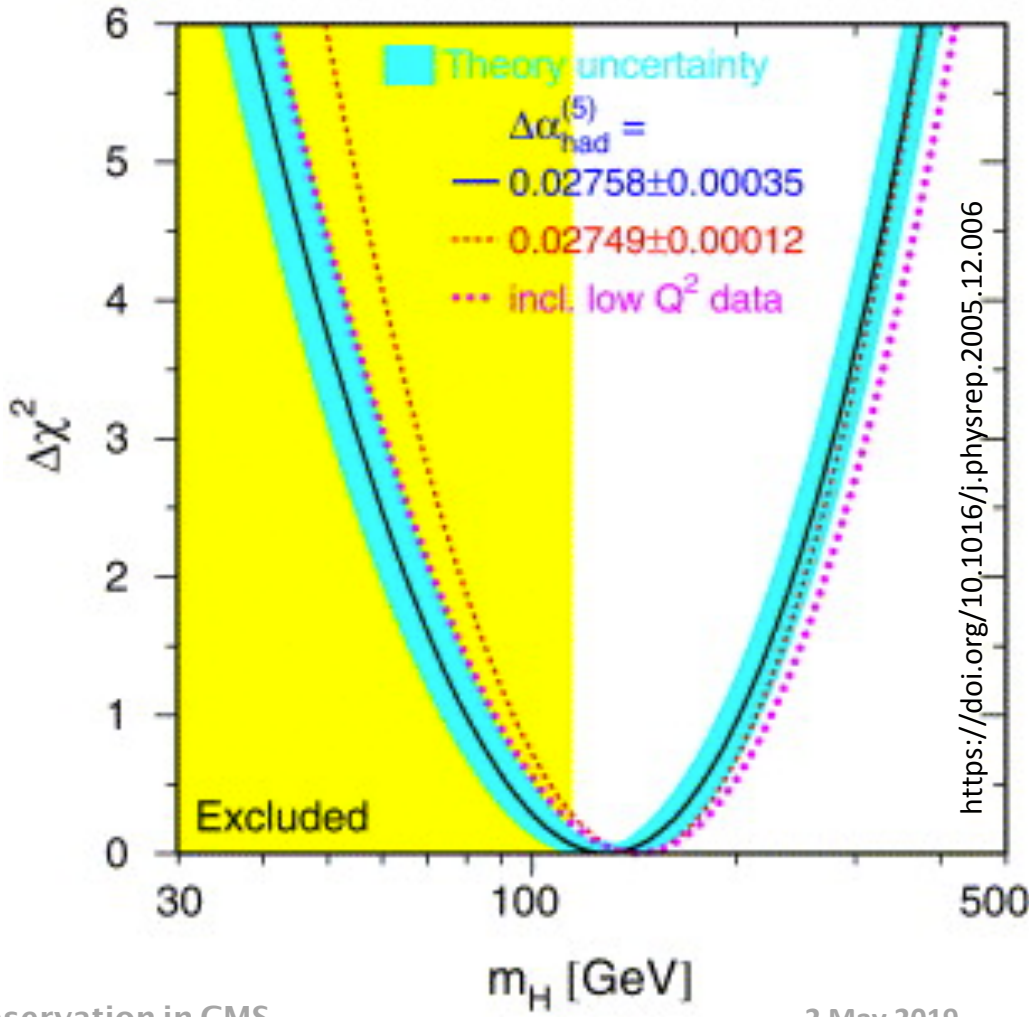


	all	> 109 GeV/c²
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

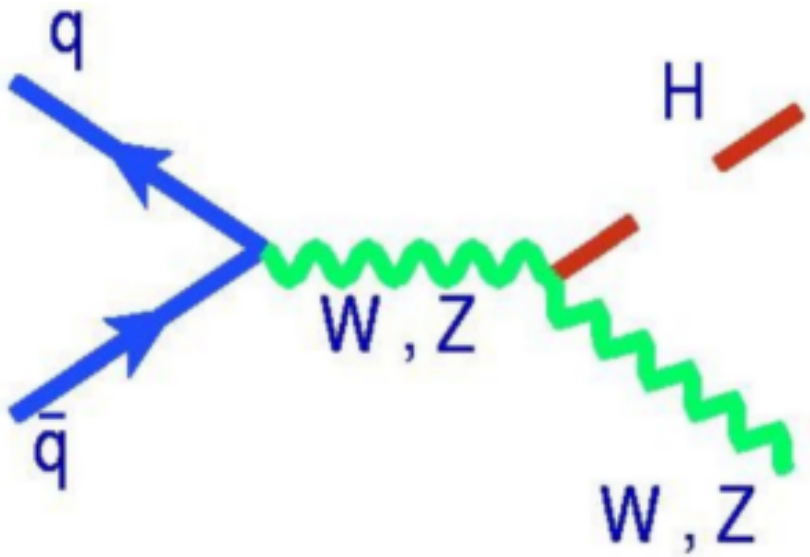
(Z)Hbb at LEP

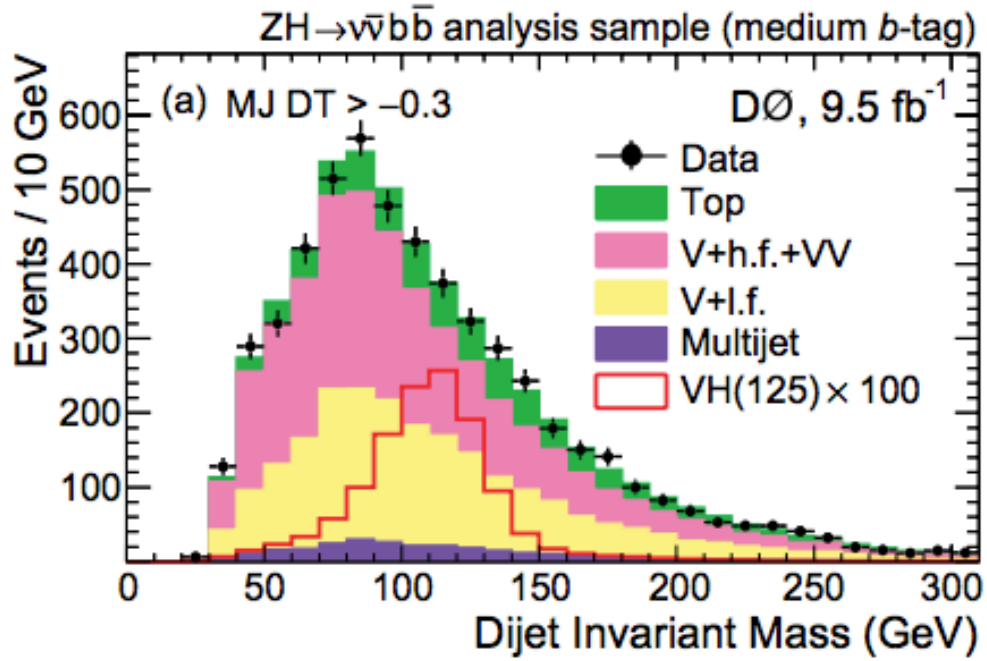
- Combined with ττ and WW channels, the mass of the Higgs boson was excluded less than 114.4 GeV at 95% confidence level.



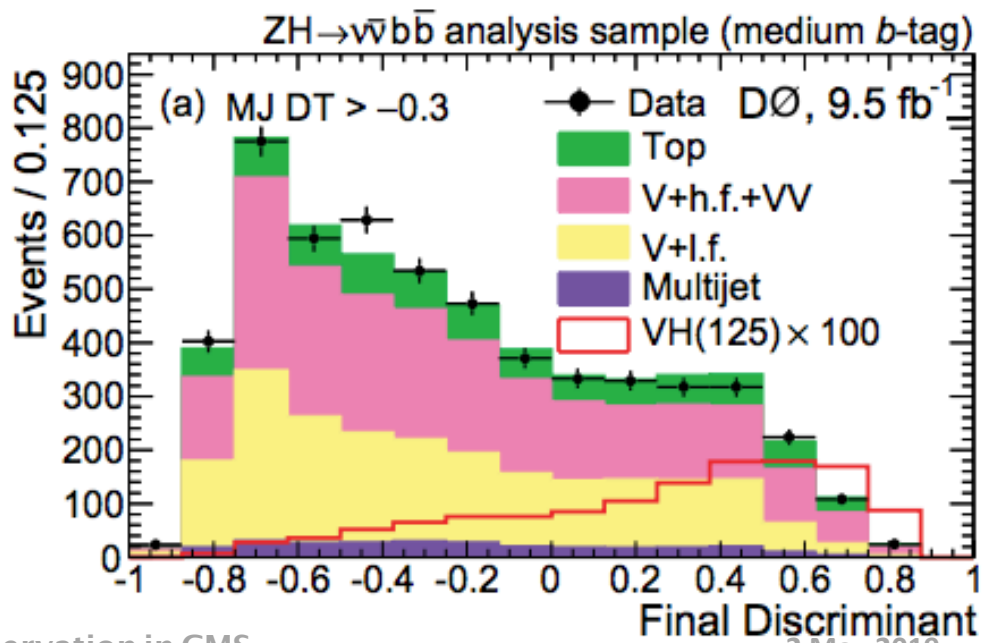


(V)Hbb at Tevatron



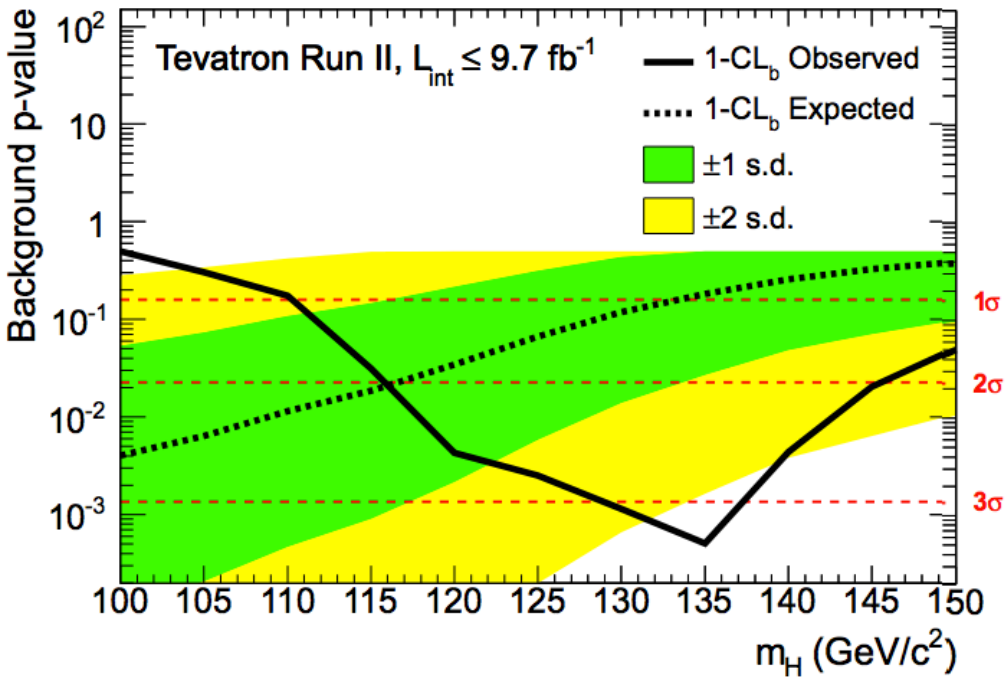


- D0 and CDF combined analyses very similar to those performed at LHC to provide the first hints of this process.
  - Sharpen the mass resolution
  - Multi-variate discriminant



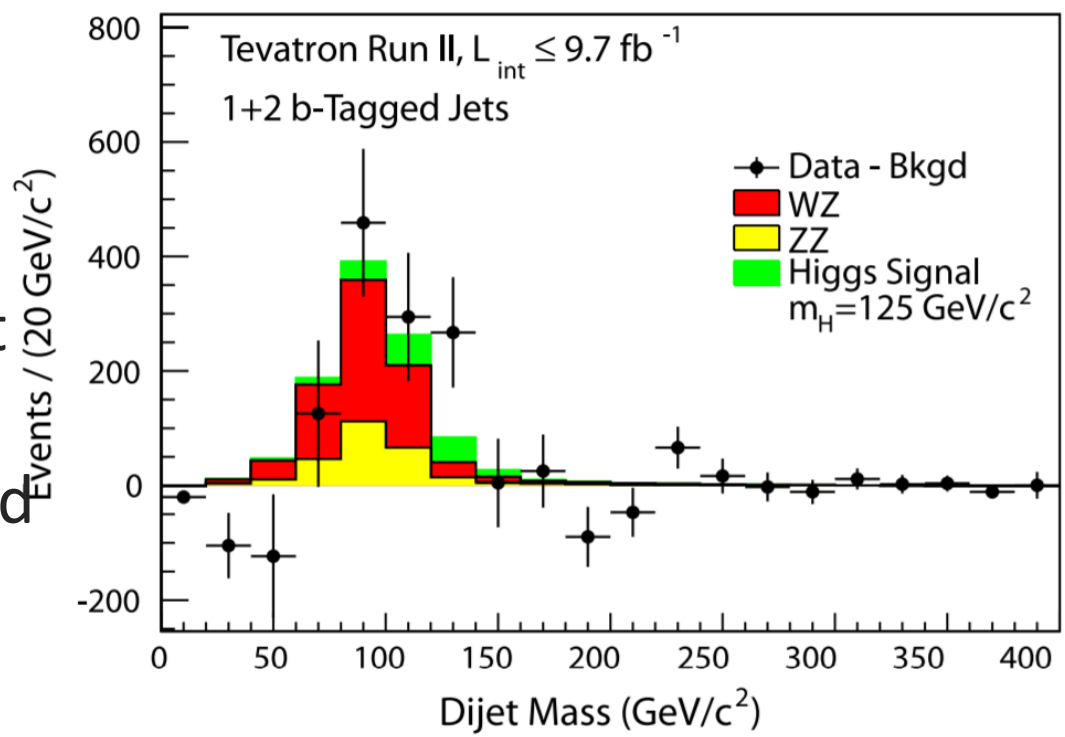
Phys. Rev. Lett. 109, 071804 (2012)

(V)Hbb at Tevatron



Significance

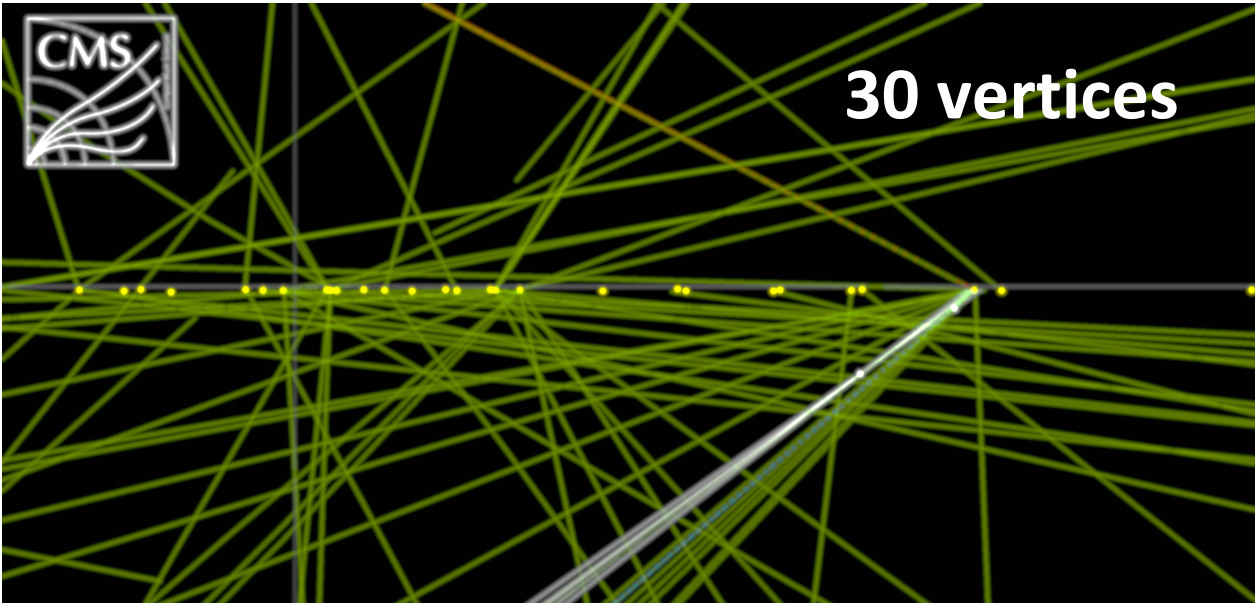
2.8σ observed @ 125 GeV



- The hbb searches are the most significant components of the final combination with WW and ττ.

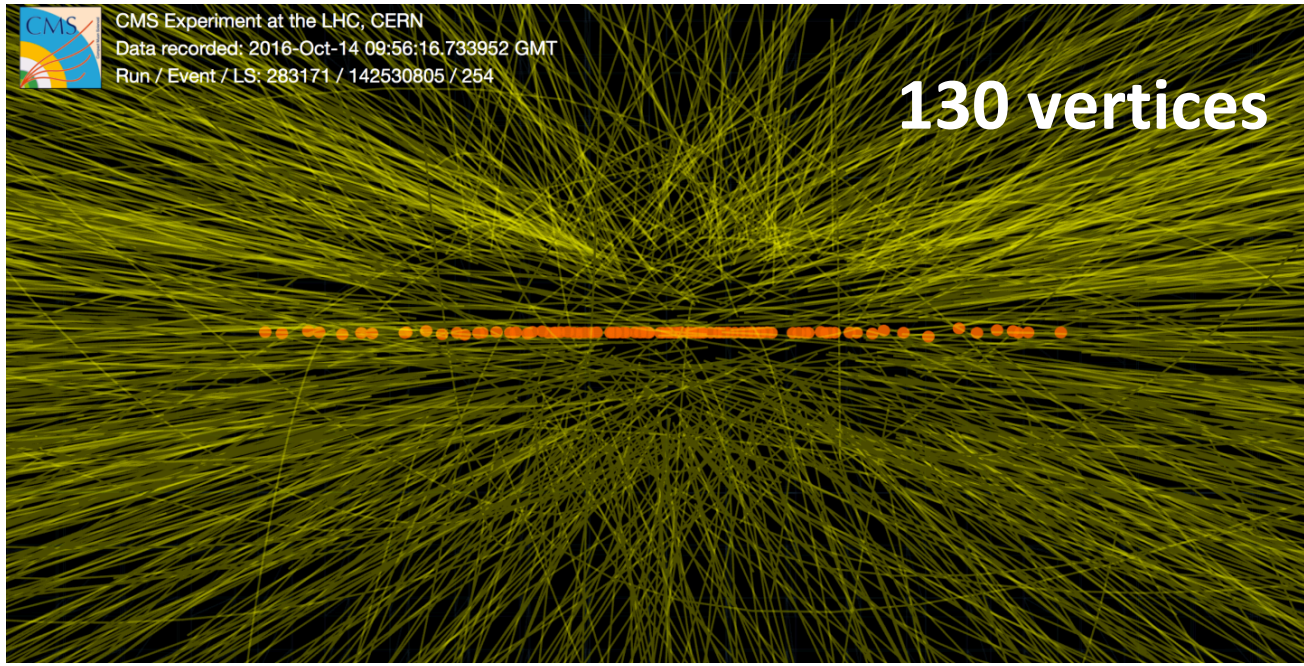
Phys. Rev. Lett. 109, 071804 (2012)

More proton-proton collisions



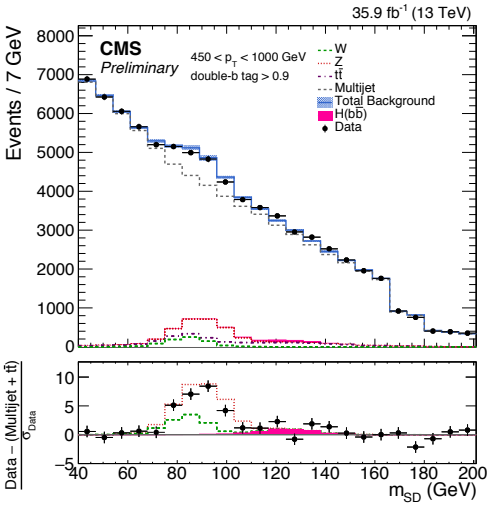
- More instantaneous luminosity means more collisions per crossing
- Run 2 and Run 3 have between 20-50 simultaneous pp collisions
  - Like top left

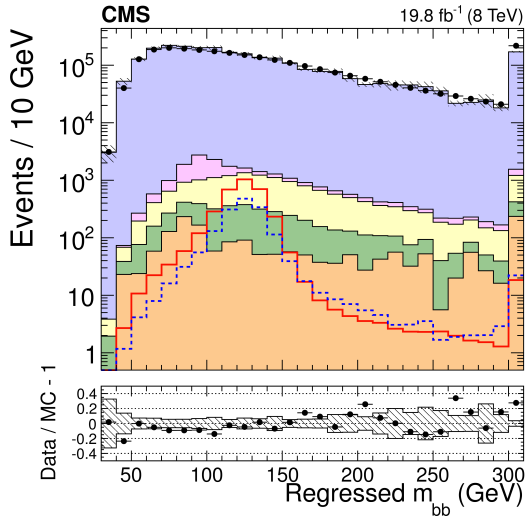
- At HL-LHC it will be more like 100-200.
- The right plot is from a special high “pile-up” fill with luminosity more like HL-LHC.

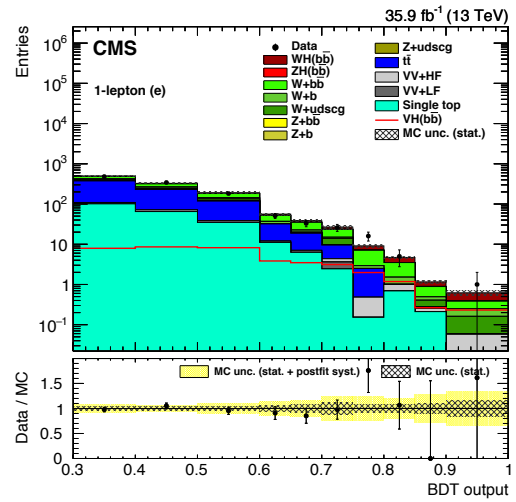


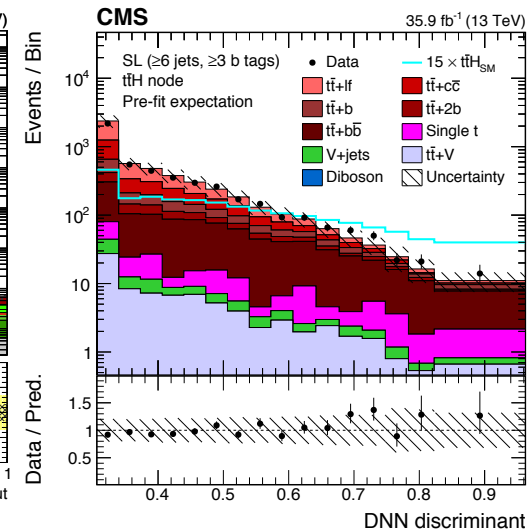
Further CMS Hbb Searches

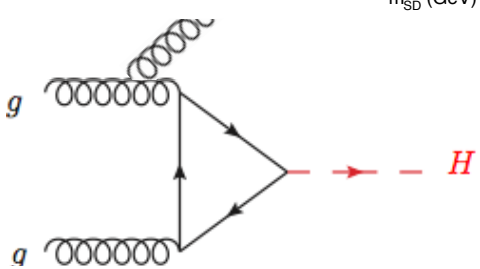
- Trigger strategies based on two b-jets are overwhelmed by QCD and ttbar backgrounds at LHC.
- All Hbb analyses in CMS are based (at least in part) on other decay products recoiling against the Higgs boson.



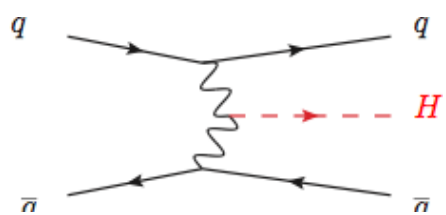




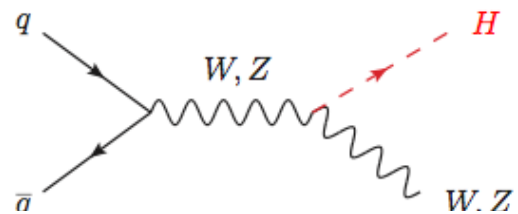




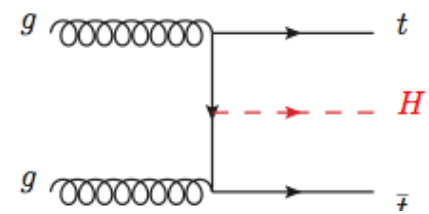
PRL 120, 071802 (2018)
2016 data



PRD 92 (2015) 032008
Run 1 data

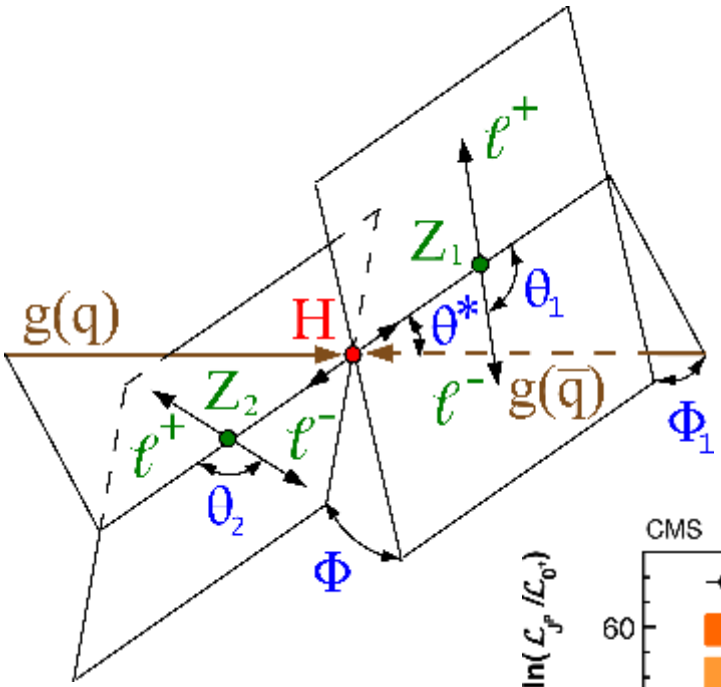


Phys. Lett. B 780 (2018) 501
2016 data

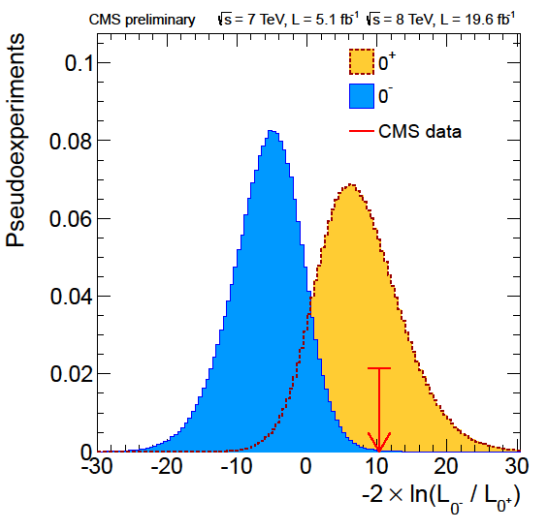


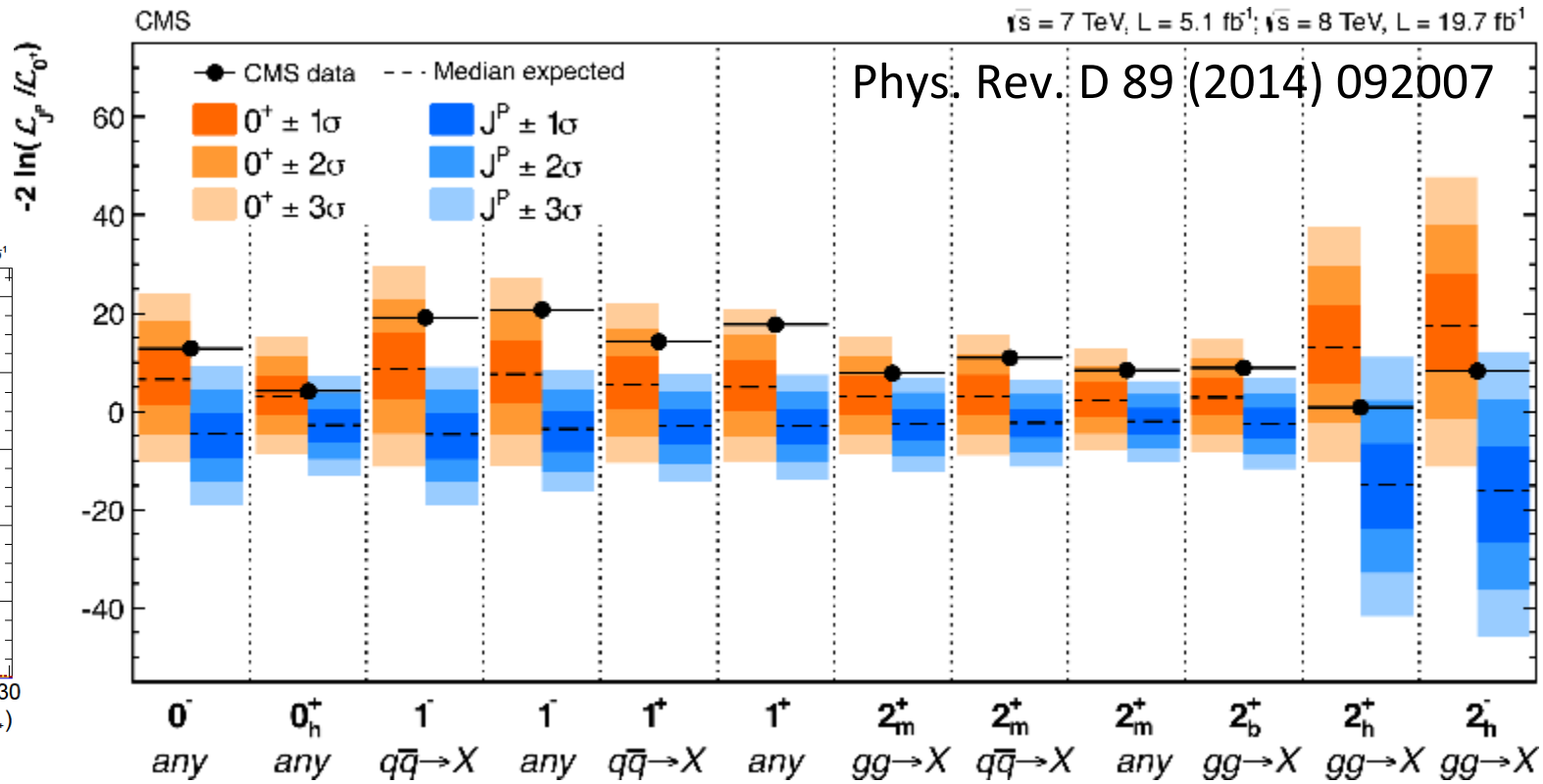
arXiv:1804.03682
(JHEP 1806 (2018) 101)
2016 data

Higgs properties measurements



- How SM is this Higgs boson?
- Using only 4-lepton events with full Run 1 dataset, the favored spin-parity was clear.
  - SM: 0^+

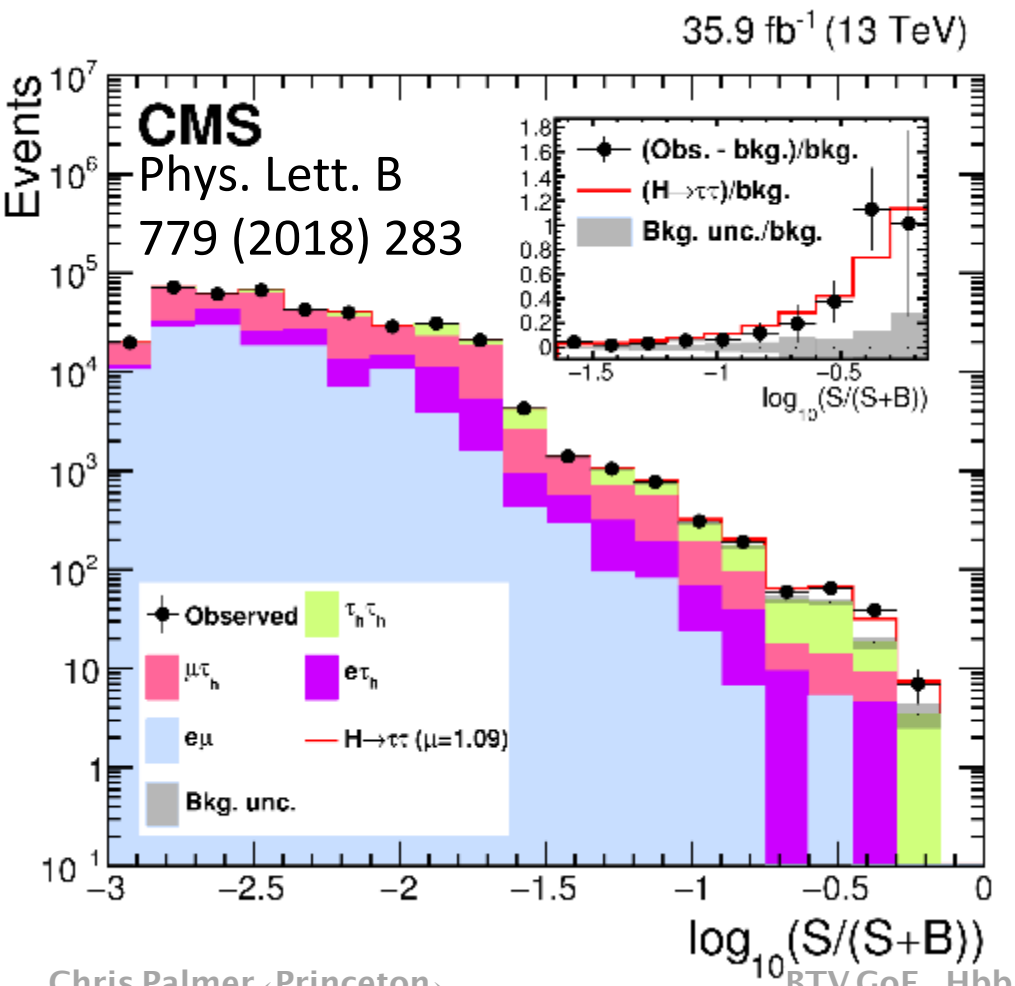


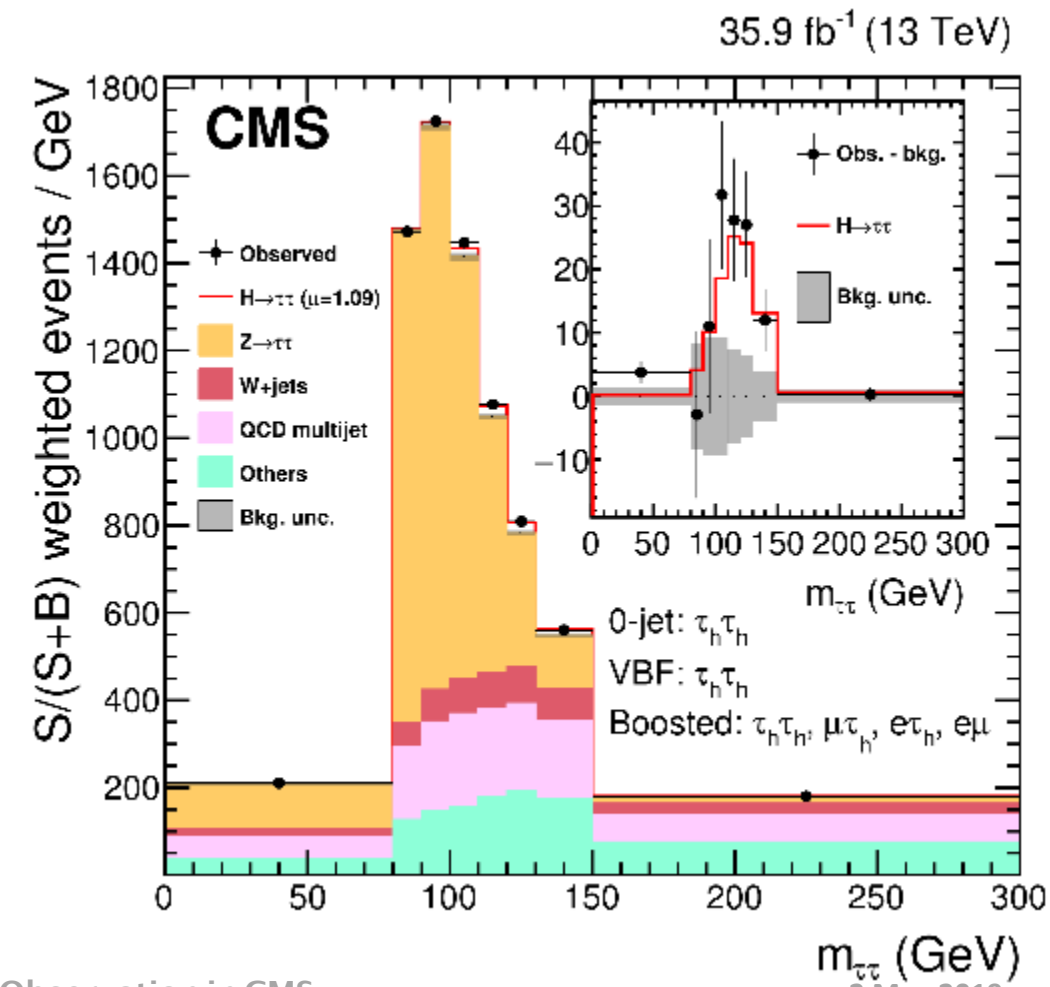


Phys. Rev. D 89 (2014) 092007

Observations of lepton coupling

- Tree-level lepton coupling to Higgs boson observed in CMS with Higgs to ττ search!
  - 2016 data plus Run 1 combination: 5.9σ observed

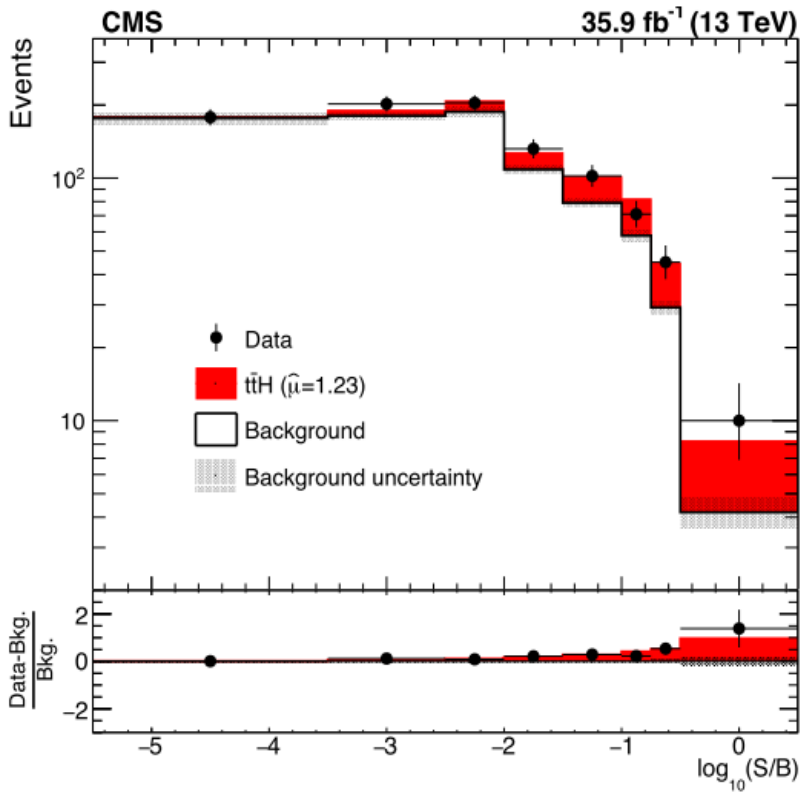




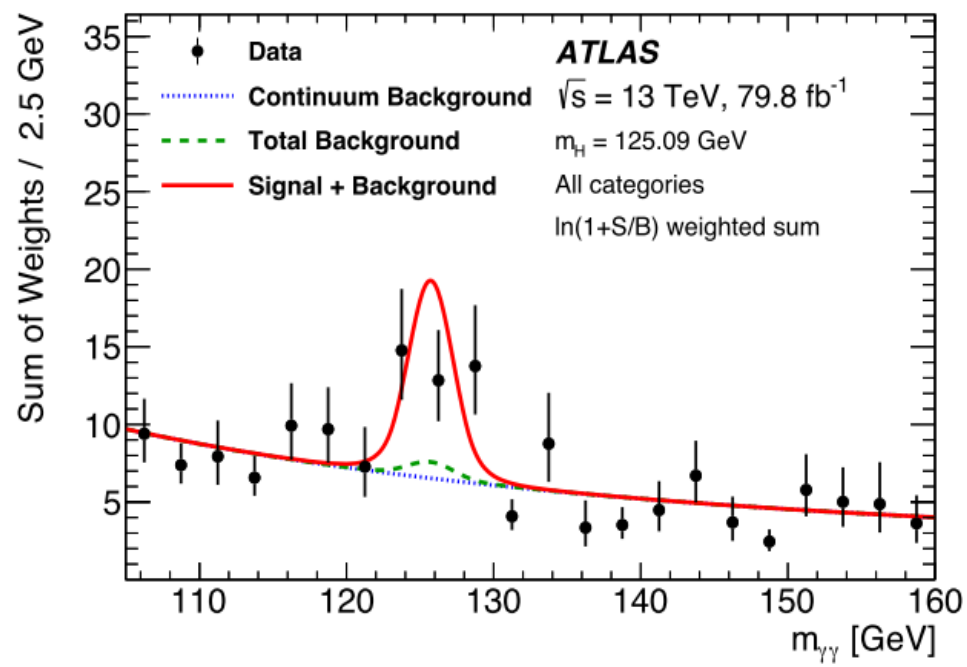
ttH Production Observed!

the news of the past 12 months

A few weeks ago:
CMS >5-sigma ttH

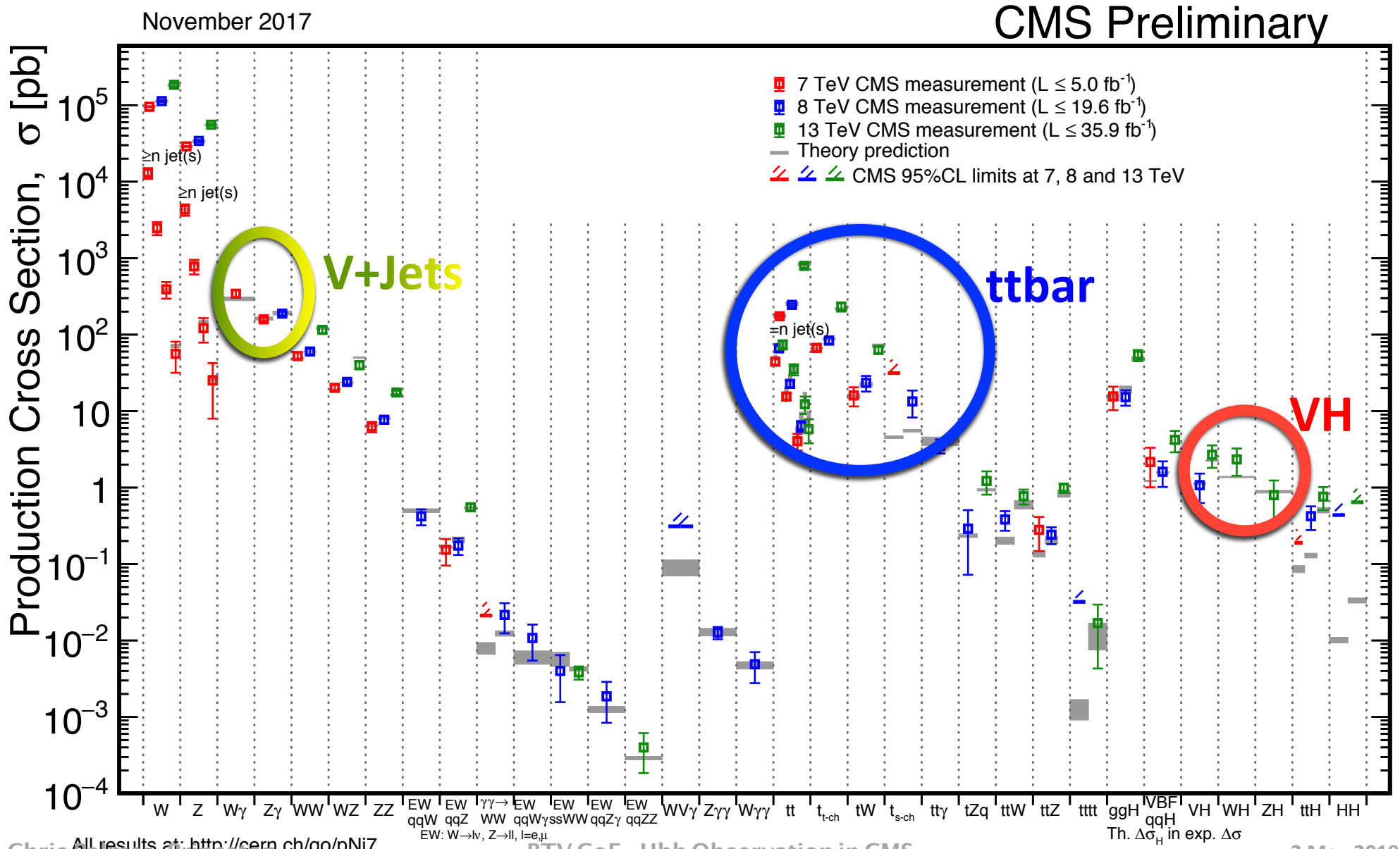


This week:
ATLAS >5-sigma ttH



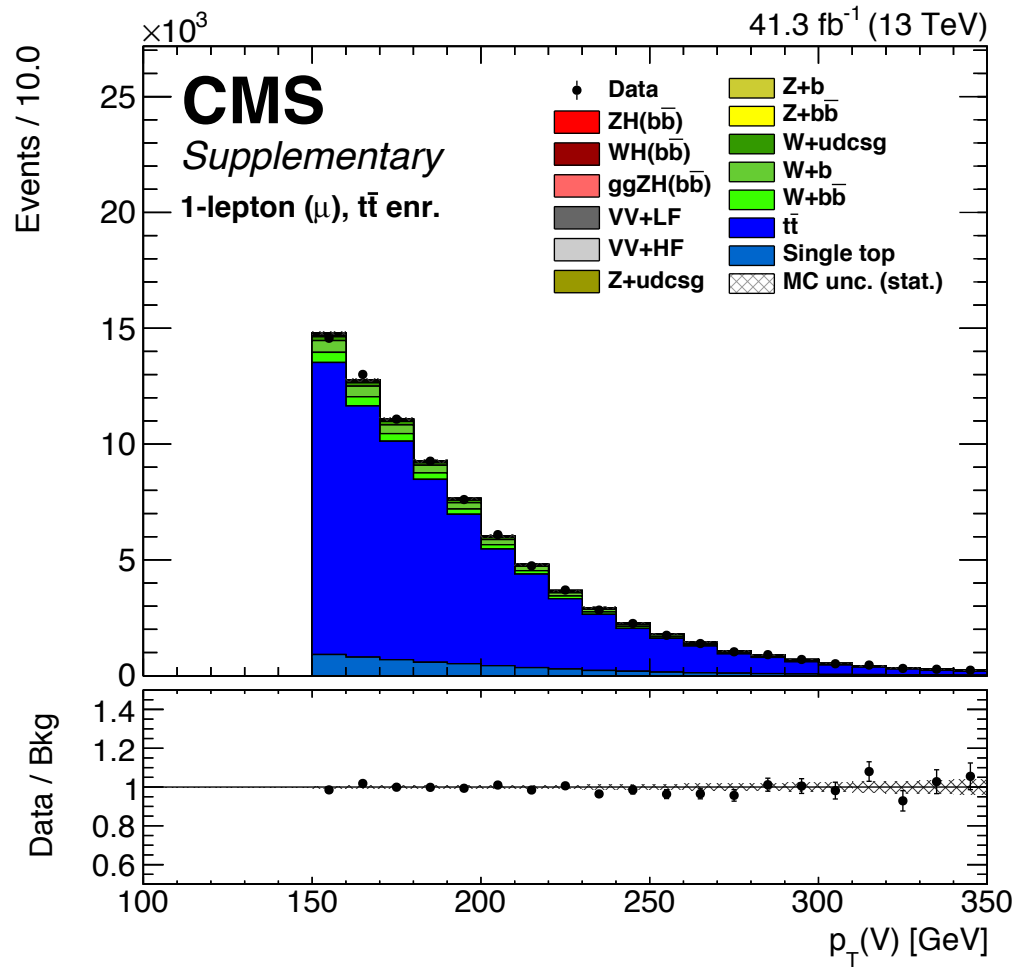
VHbb at LHC?

- The volume of background events is a bit staggering.



Treating $P_{T,V}$ with care

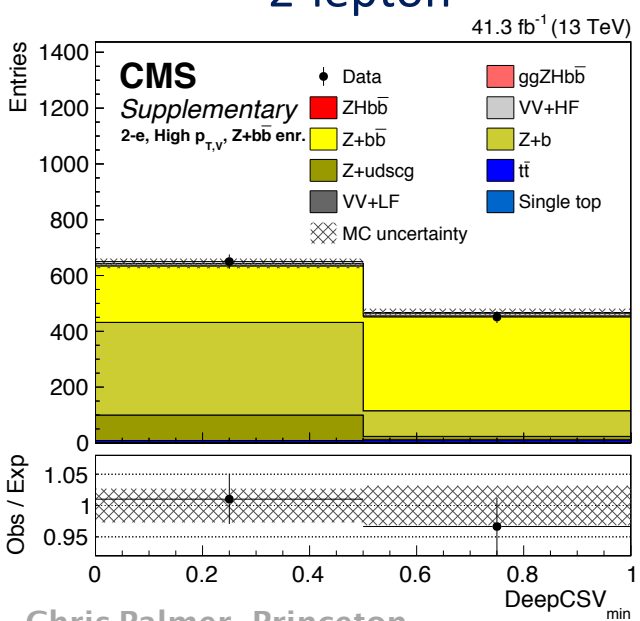
- The transverse momentum of the vector boson is one of the more important variables in this analysis.
- $P_{T,V}$-dependent electroweak correction uncertainties on signal and background
- In W+Jets (Madgraph) and ttbar (Powheg) $P_{T,W}$ must be corrected.
  - Empirical approaching: derive correction by fitting data/MC in control regions.
- The size of V+Jets samples in the highest $P_{T,V}$ bins are limited.
  - Normalization uncertainties impacted.



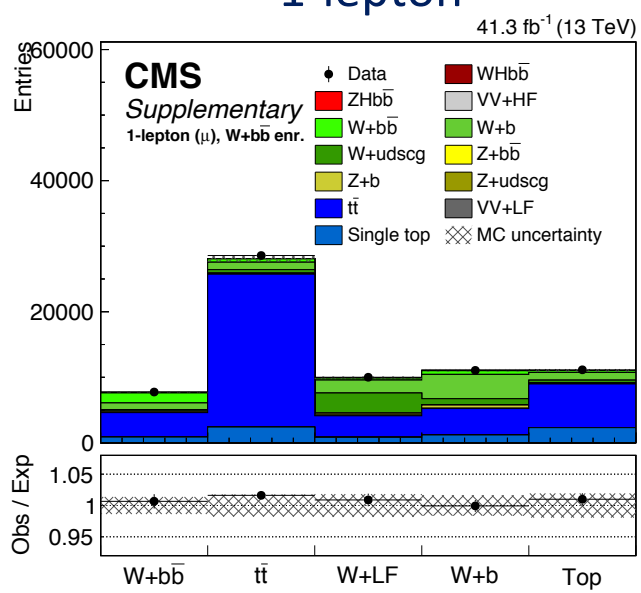
Heavy Flavor control region discriminators

- Reminder: leading systematic uncertainty from normalization of V+(b)b
- 2-lepton channel control region very pure
  - Fit b-tag shape (DeepCSV) to discriminate processes
- 0- and 1-lepton channel control regions less pure
  - Fit DNN multi-categorizer to distinguish among background components
    - Use same input variables as Signal vs Background discriminator

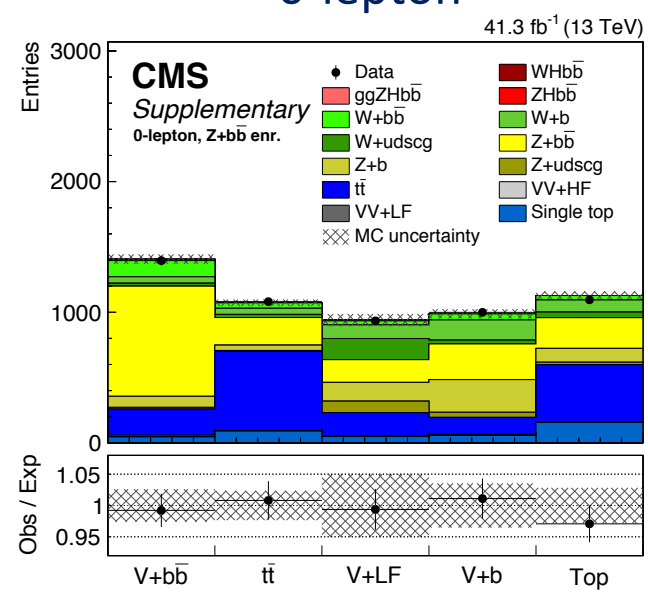
2-lepton



1-lepton



0-lepton



Trigger and basic categorization

- For the triggers focus on the vector boson decay products
- 0-lepton (targeting Z→νν)
  - Large missing transverse energy or missing hadronic energy (only jets)
- 1-lepton (targeting W→lν)
  - Single lepton triggers
- 2-lepton (targeting Z→ll)
  - Double lepton triggers
- Offline selection mirrors online

Channel	Online	Offline
0-lepton (MET)	120 GeV	170 GeV
1-muon	22 GeV	25 GeV
1-electron	32 GeV	30 GeV
2-muons	17,8	20,20
2-electrons	23,12	25,20

Background normalizations

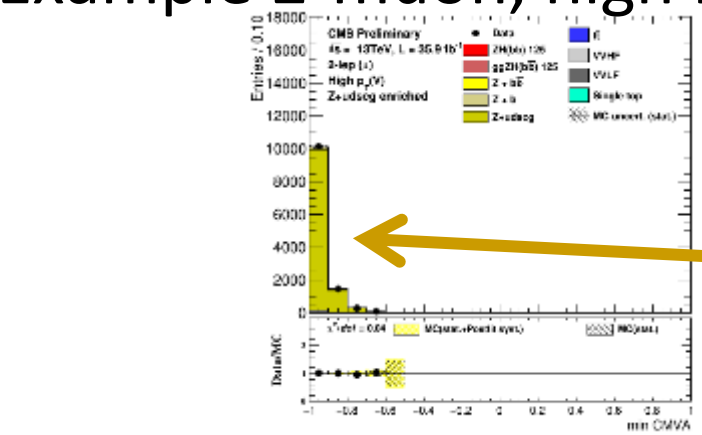
- After fitting control regions and signal regions the following scale factors are derived per process per channel.
- Fitting control regions only yield very similar results.
- Note: TTbar and V+light flavor control regions are fit to yield only

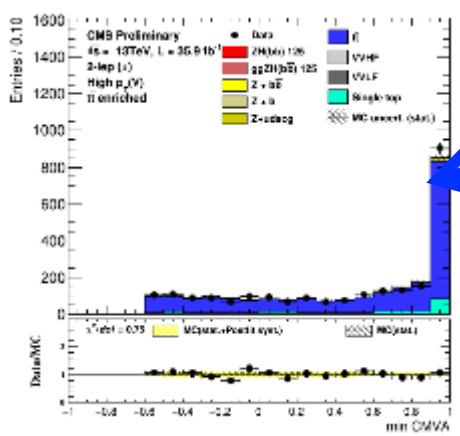
Process	$Z(\nu\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$ low-p_T	$Z(\ell\ell)H$ high-p_T
$W + udscg$	1.04 ± 0.07	1.04 ± 0.07	–	–
$W + b$	2.09 ± 0.16	2.09 ± 0.16	–	–
$W + b\bar{b}$	1.74 ± 0.21	1.74 ± 0.21	–	–
$Z + udscg$	0.95 ± 0.09	–	0.89 ± 0.06	0.81 ± 0.05
$Z + b$	1.02 ± 0.17	–	0.94 ± 0.12	1.17 ± 0.10
$Z + b\bar{b}$	1.20 ± 0.11	–	0.81 ± 0.07	0.88 ± 0.08
$t\bar{t}$	0.99 ± 0.07	0.93 ± 0.07	0.89 ± 0.07	0.91 ± 0.07

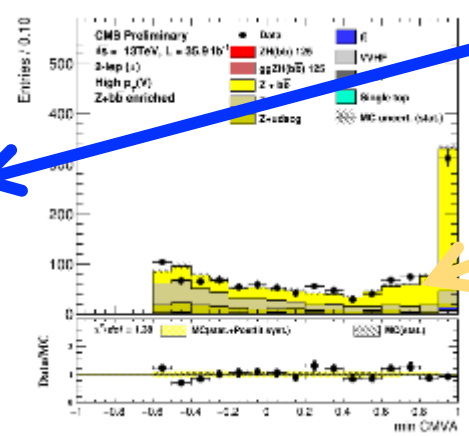
2016 Signal extraction

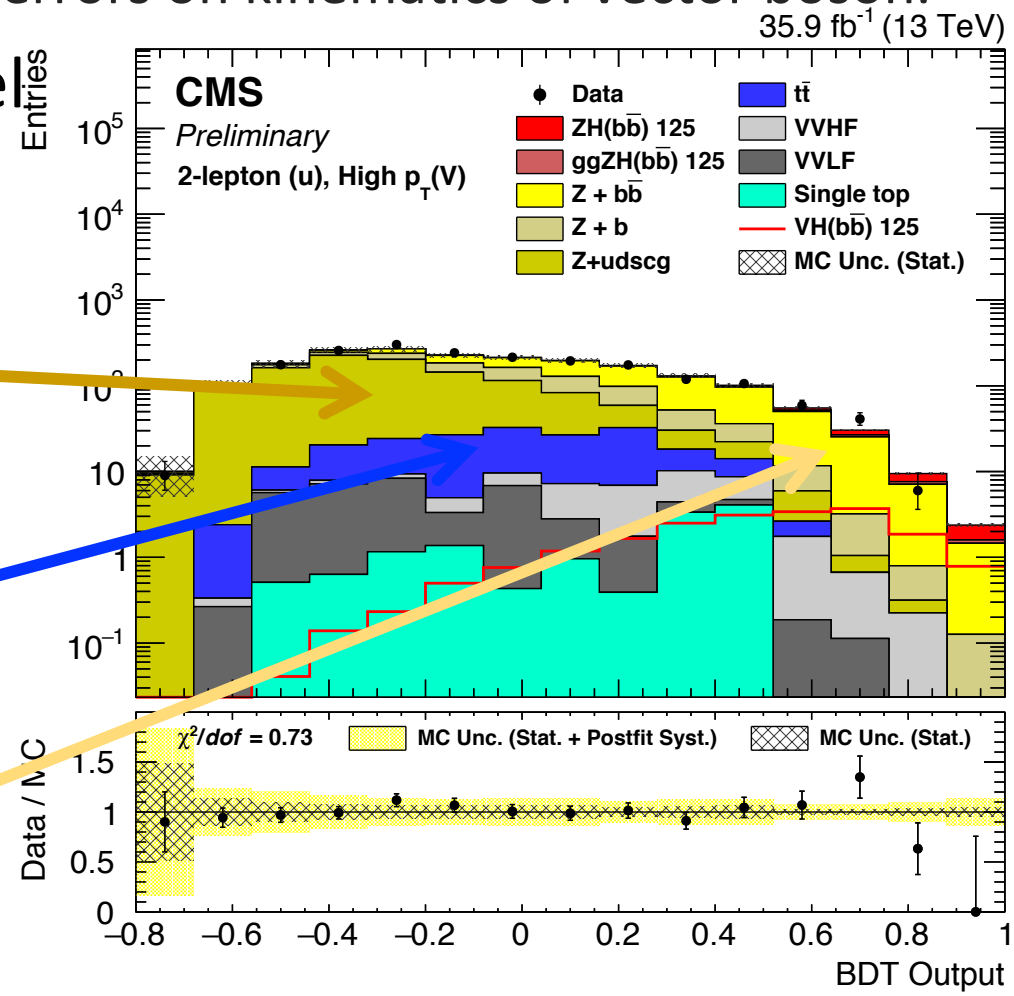
- Normalizations factors are generally independent per channel
  - They float freely just like the signal strength.
- Uncertainties on the heavy flavor components come both from the size of the V+Jets samples and from systematic errors on kinematics of vector boson.

Example 2-muon, high $P_{T,V}$ channel







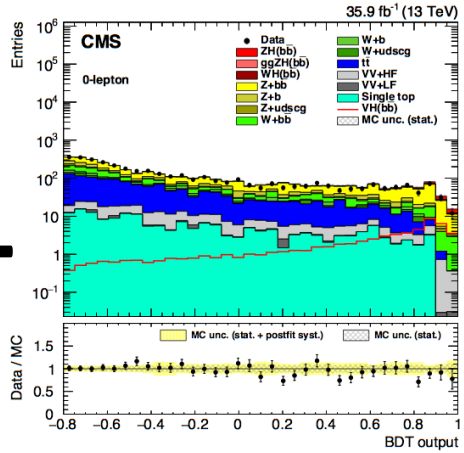


Putting all 2016 channels together

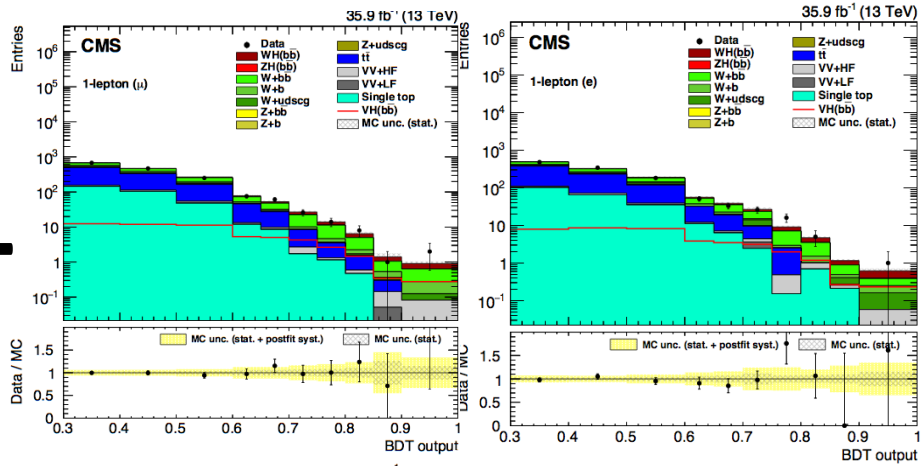
- Discriminator (BDT) distributions that are fit with control regions.
- Coarsely one can see that the data to simulation agreement is very good after the fitting with shape systematics.

Channel	# Signal Regions	# Control Regions
0-lep	1	3
1-lep	2	8
2-lep	4	12
Total	7	23

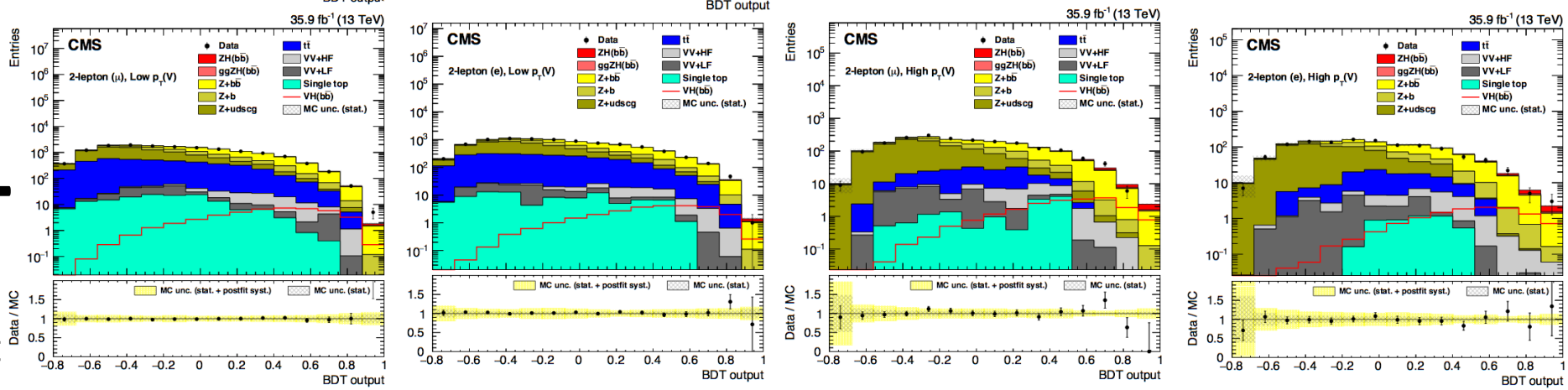
0-lepton



1-lepton



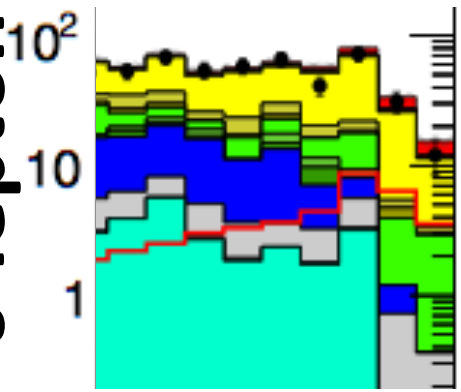
2-lepton



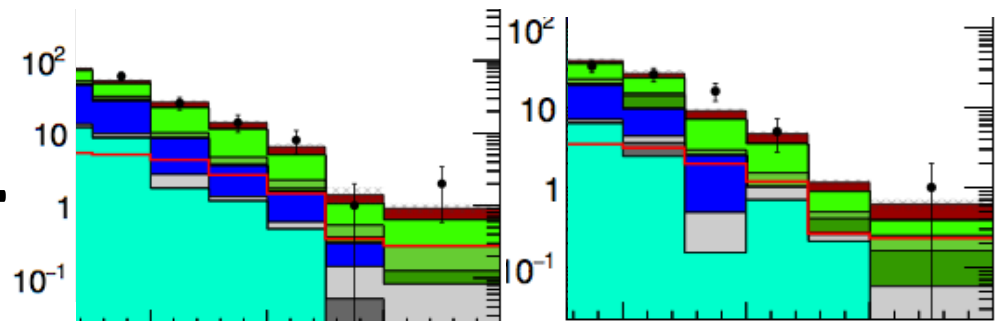
Putting all 2016 channels together

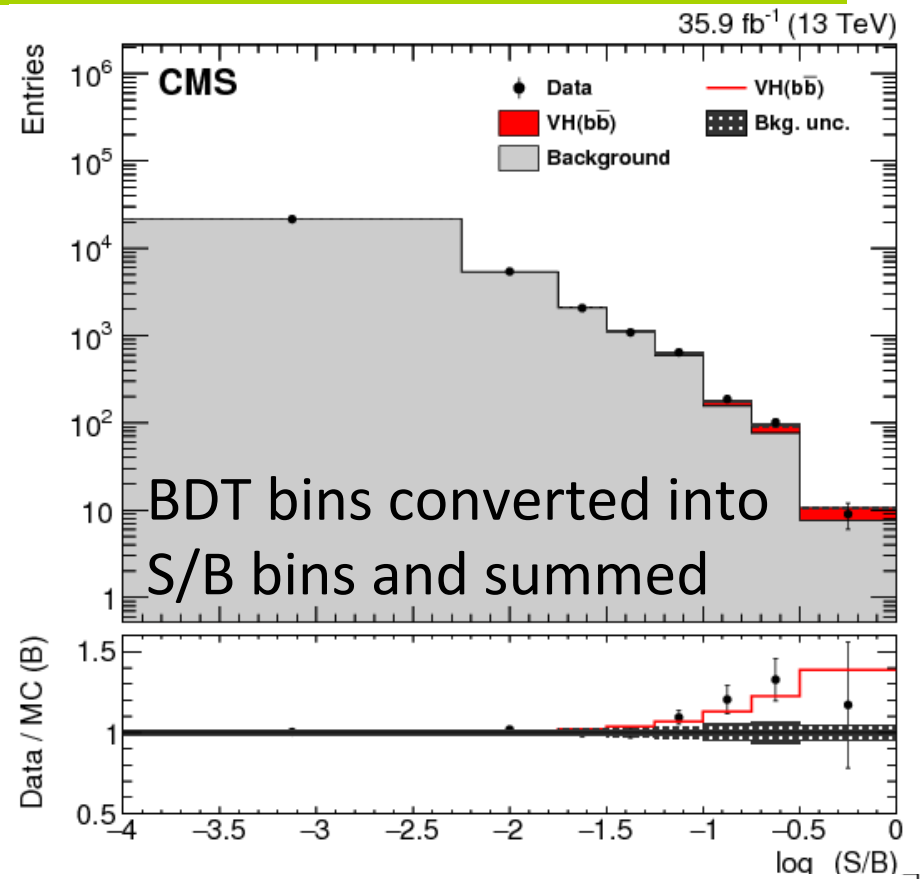
- Zooming into high sensitivity region.
- Overall visually compatible with S+B hypothesis.

0-lepton

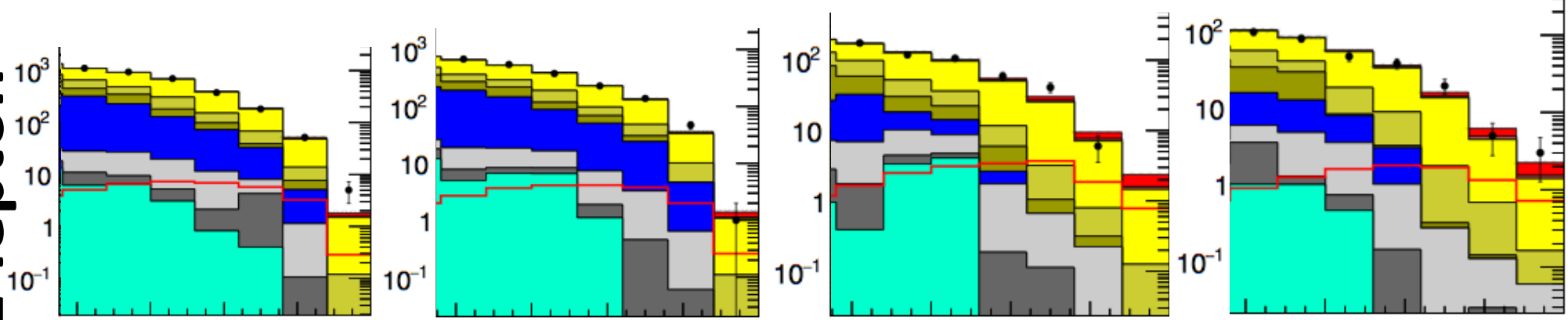


1-lepton

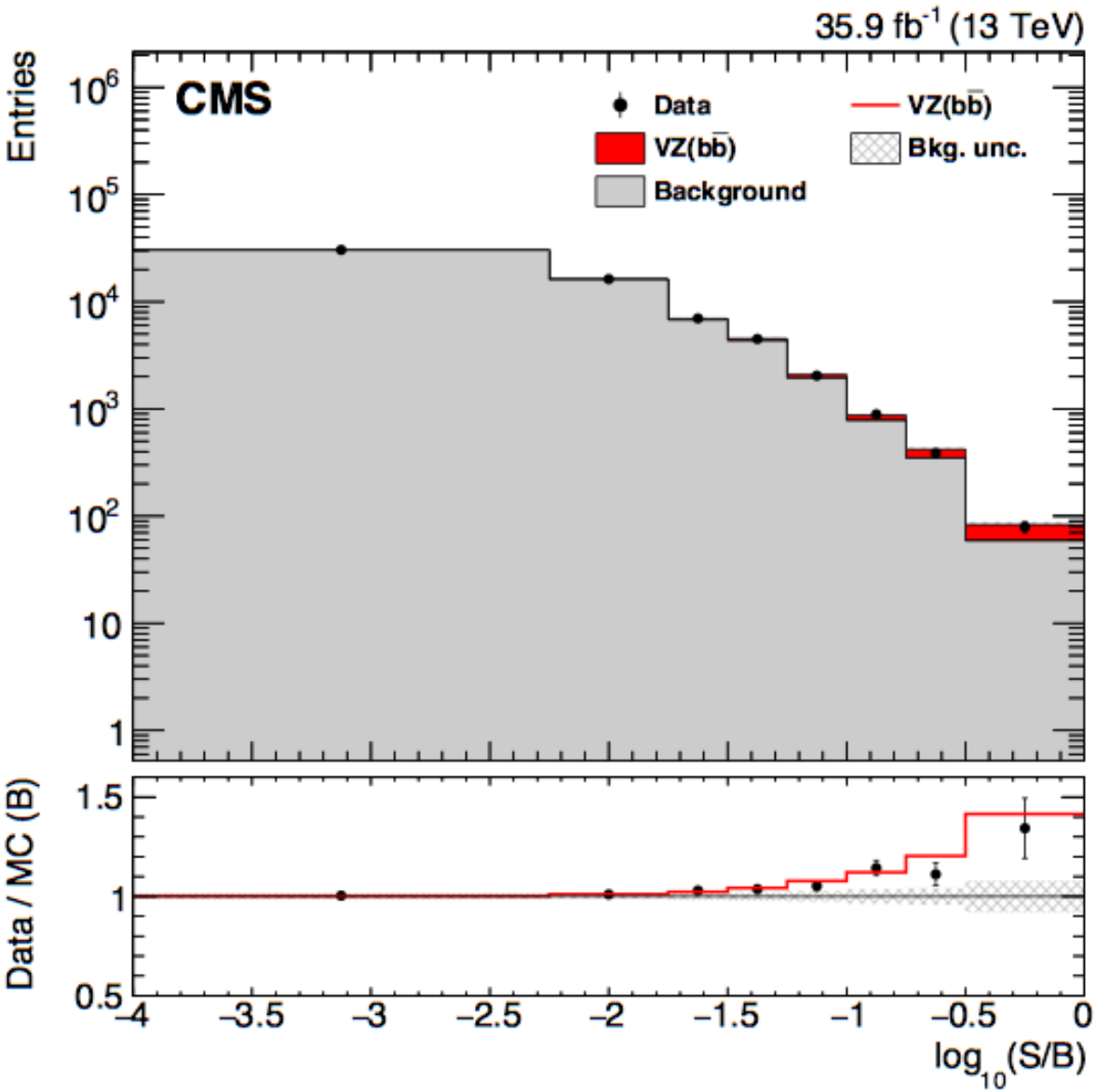




2-lepton



Validating with VZbb in 2016



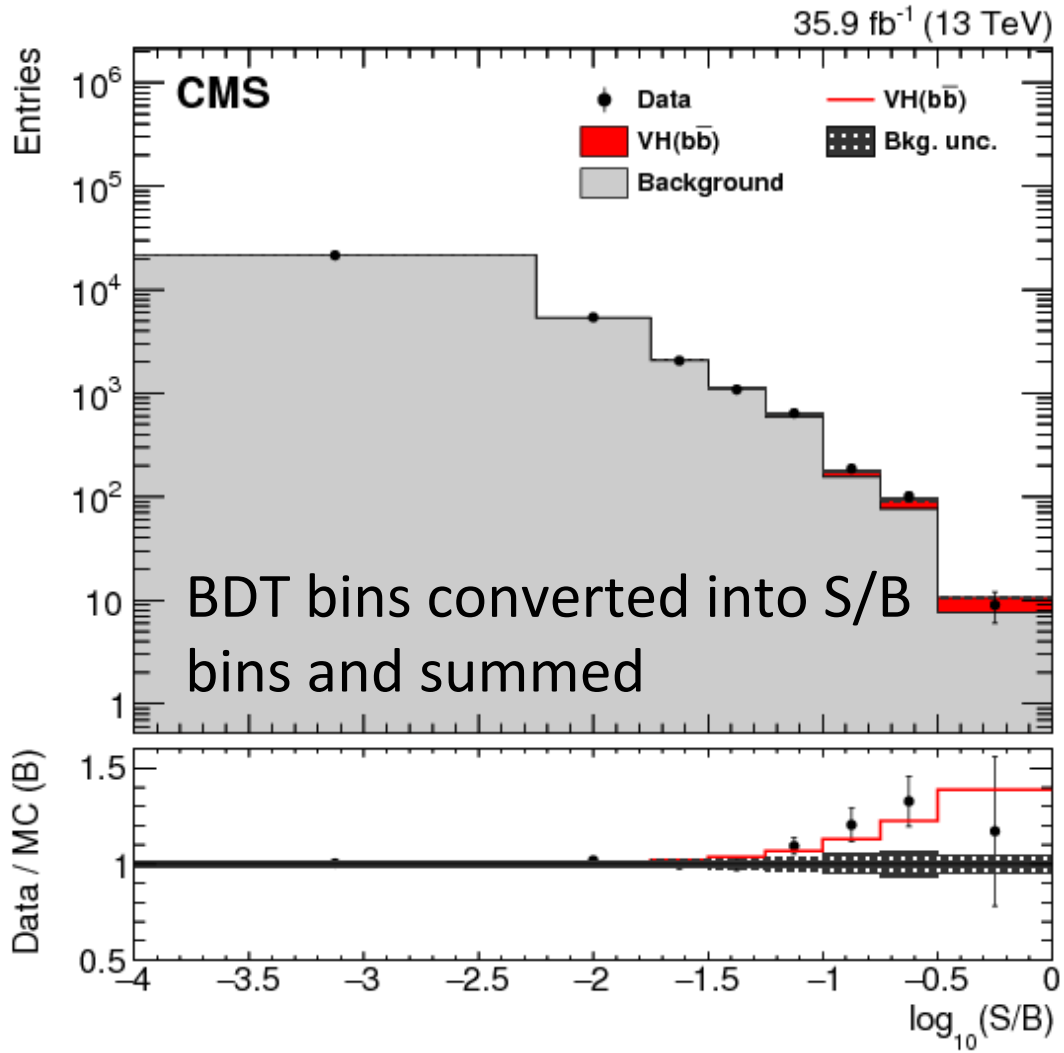
- Take advantage of similar process with much larger cross section.
  - Shift mass window down to Z
- Strikingly consistent!

Channels	Signal strength observed
0-lepton	0.57 ± 0.32
1-lepton	1.67 ± 0.47
2-lepton	1.33 ± 0.34
Combined	1.02 ± 0.22

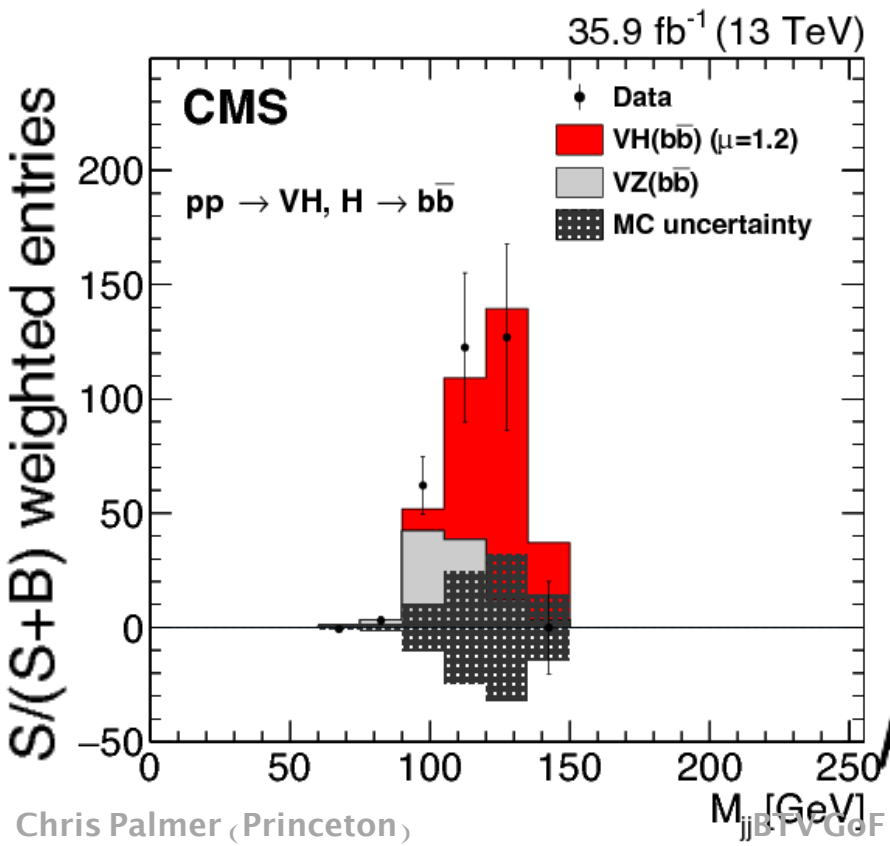
Channels	Significance expected	Significance observed
0-lepton	3.1	2.0
1-lepton	2.6	3.7
2-lepton	3.2	4.5
Combined	4.9	5.0

2016 VHbb Results

Significance
2.8σ expected
3.3σ observed !



BDT bins converted into S/B bins and summed



Signal strength relative to SM

$$\mu = 1.19^{+0.21}_{-0.20}(stat)^{+0.34}_{-0.32}(syst)$$

Compatibility among channels (2016)

- Fair compatibility between channels in the VH fits
  - the 3 channels are contributing almost equally to sensitivity

Channels	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
Combined	2.8	3.3

- The probability for these channels to be compatible with the combined μ is 6%.