中国科学院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences

Dominant Decay Channel of Higgs Particle Observed at ATLAS

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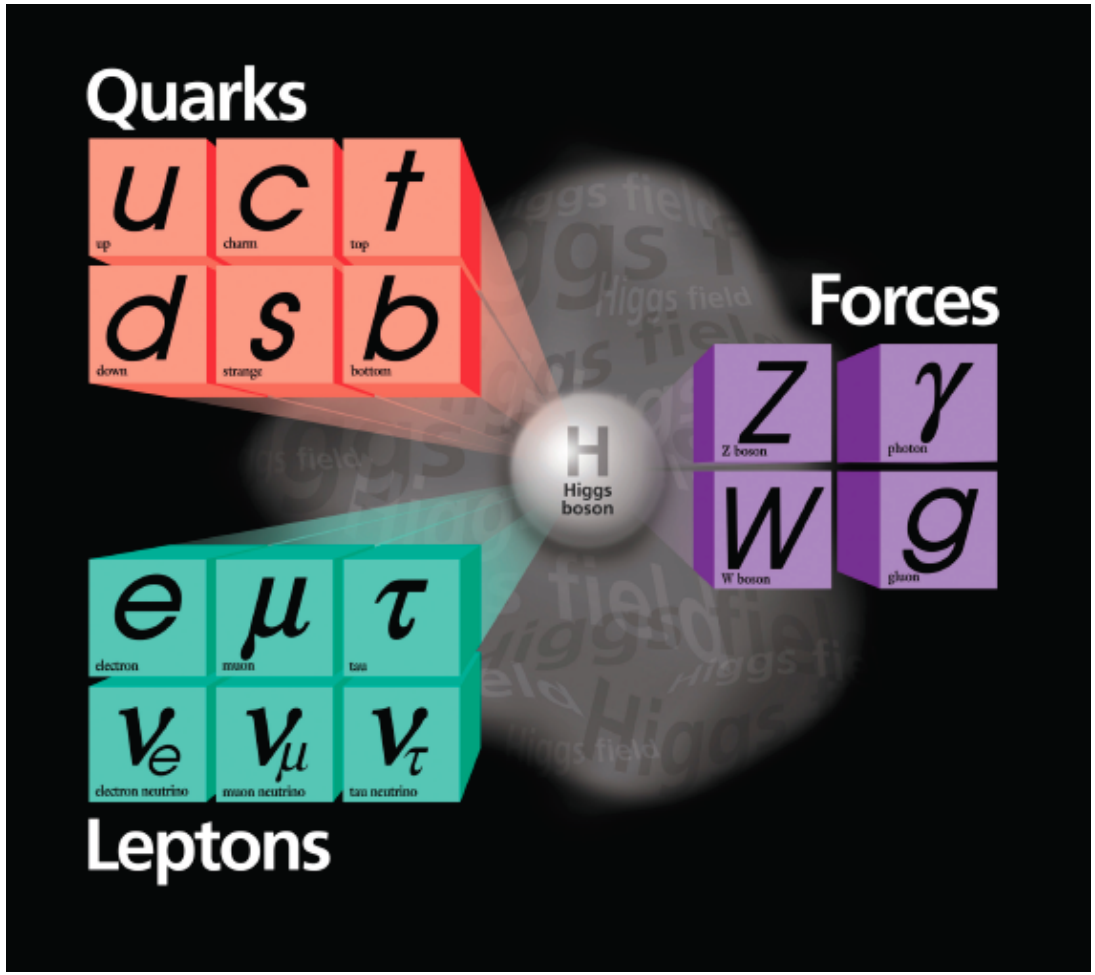
Outline

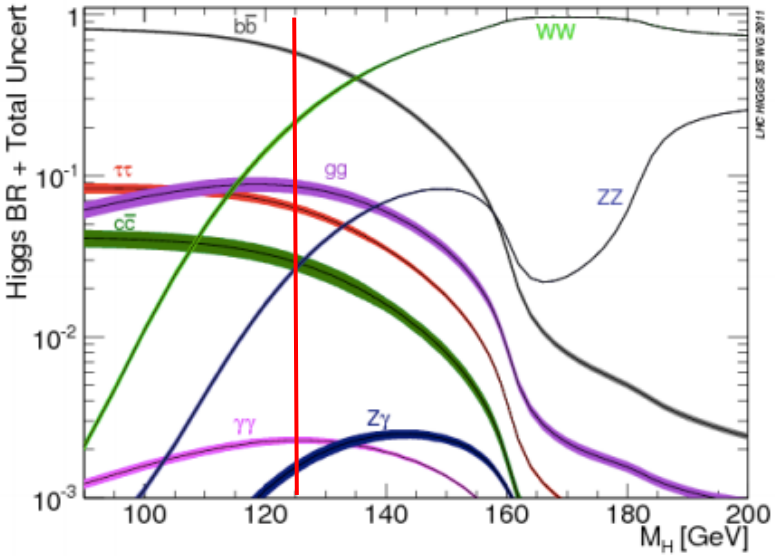
- Introduction to Higgs physics
- Introduction to ATLAS experiment
- Search for H→bb mode (Dominant Decay Channel)
  - VBF H→bb analysis
  - VH(→bb)
  - H→bb Comination

Introduction

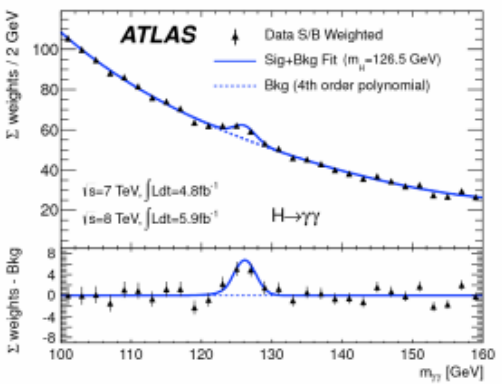
- Previously known: quarks, leptons, and vector bosons
- SM Higgs Mechanism solves two separate problems.
  - Electroweak symmetry breaking
  - Fermion masses

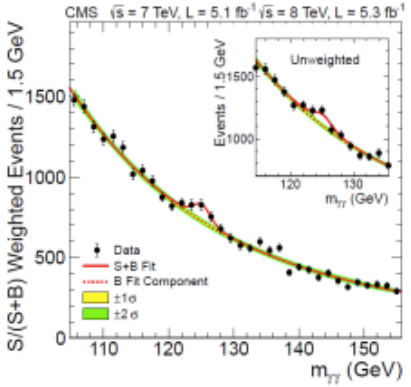


History of Higgs discovery

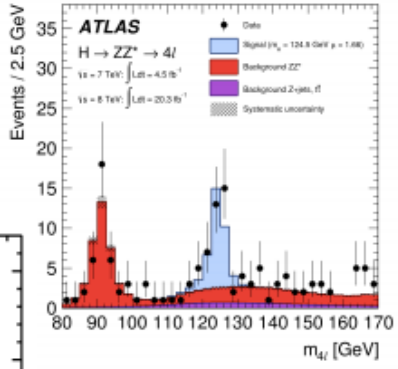


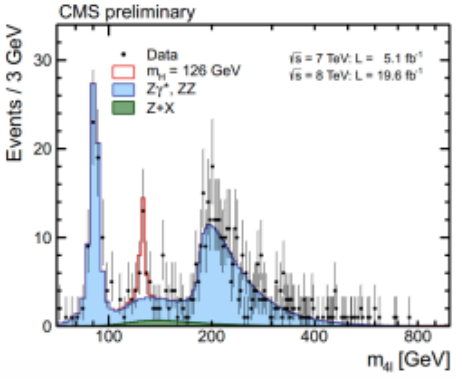
$H \to \gamma\gamma$



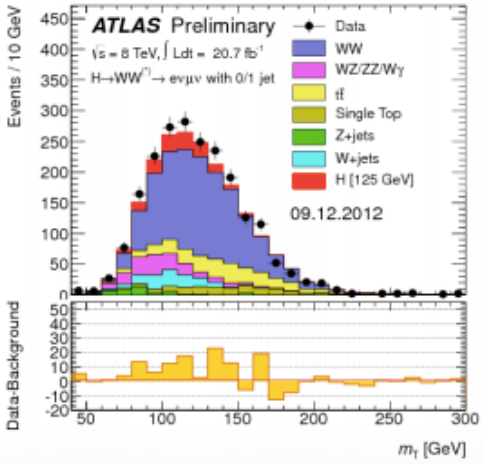


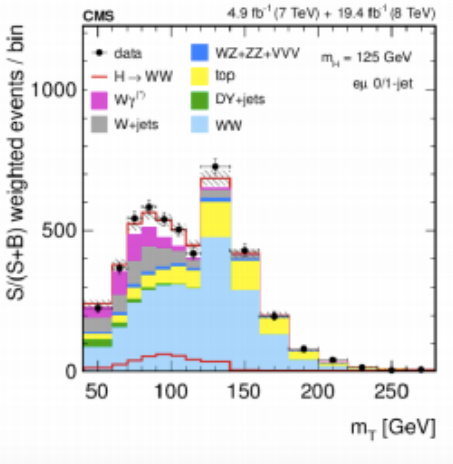
$H \to ZZ$





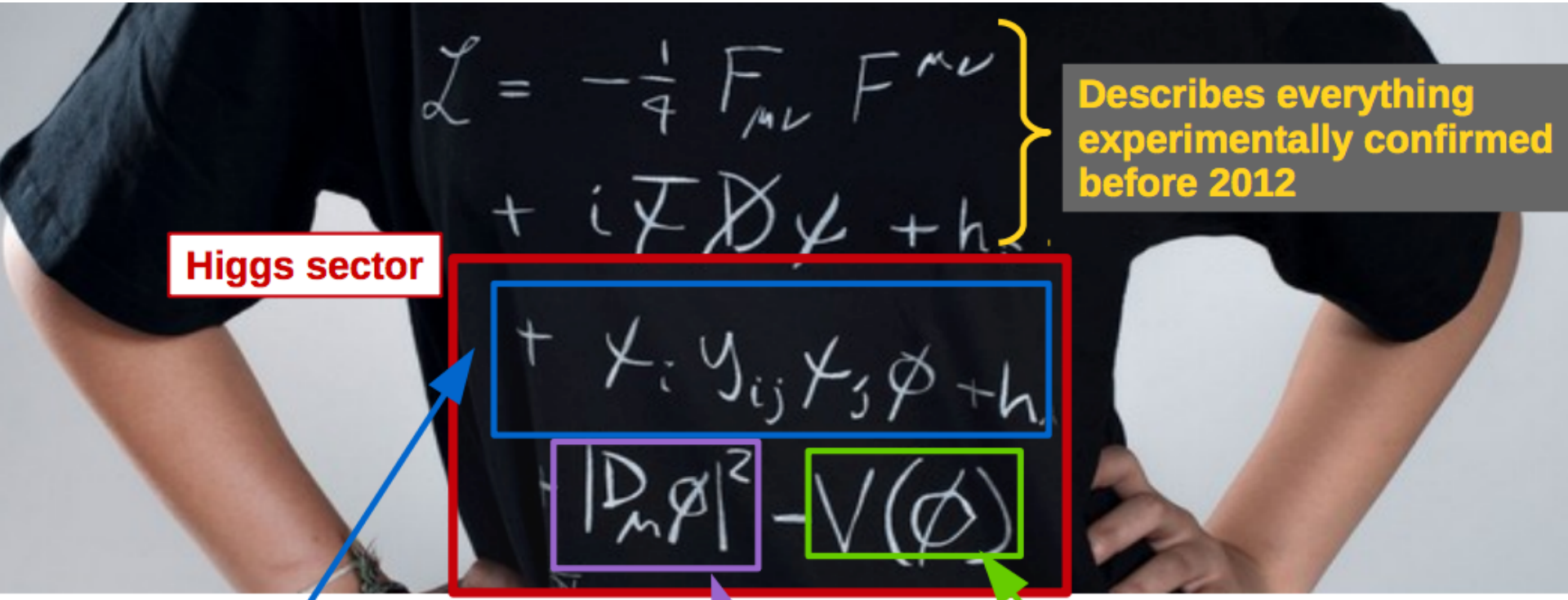
$H \to W^+W^-$





History of Higgs discovery (2)

Standard Model Lagrangian



Describes everything experimentally confirmed before 2012

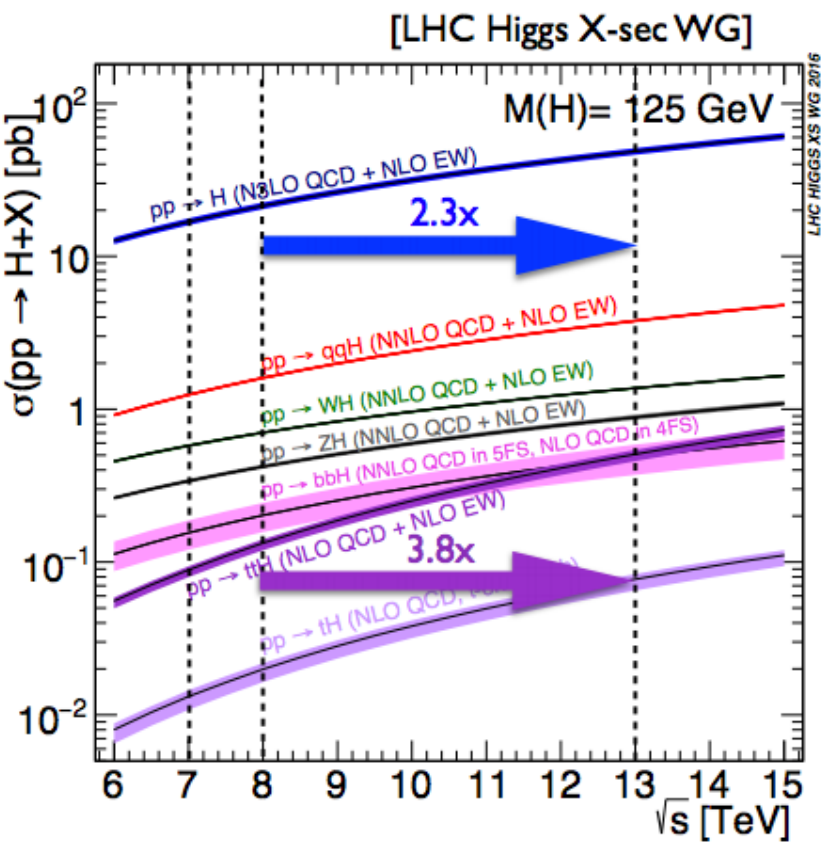
Higgs sector

Yukawa coupling with new scalar
(completely new interaction type)
ttH, H→bb and H→ ττ are important !

Higgs potential ($\mu^2 \phi^2 + \lambda \phi^4$)
(to be explored by High Lumi-LHC)

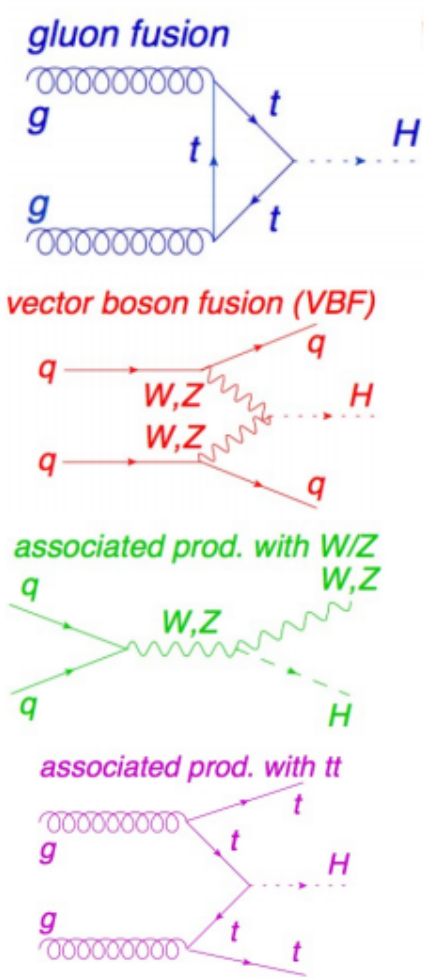
Gauge boson interaction with new scalar
(new for scalar, but known for fermions)

Higgs Production



- Significant increase in production rate due to higher center-of-mass energy from LHC Run-1 to Run-2!

Production modes



Higgs bosons produced in Run 2 (2015-2017)

~4M

~300k

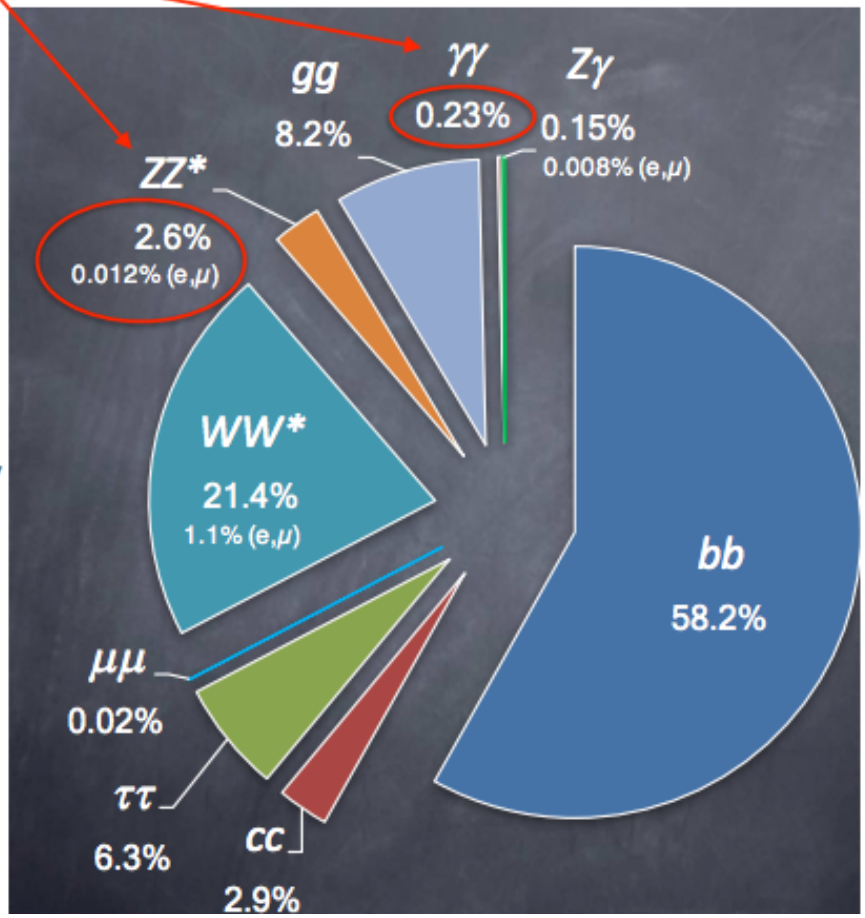
~200k

~40k

Higgs Decay

- H→bb is the Dominant Decay mode of Higgs Boson(58%)

ZZ, γγ: high mass resolution channels mass and precise differential measurements

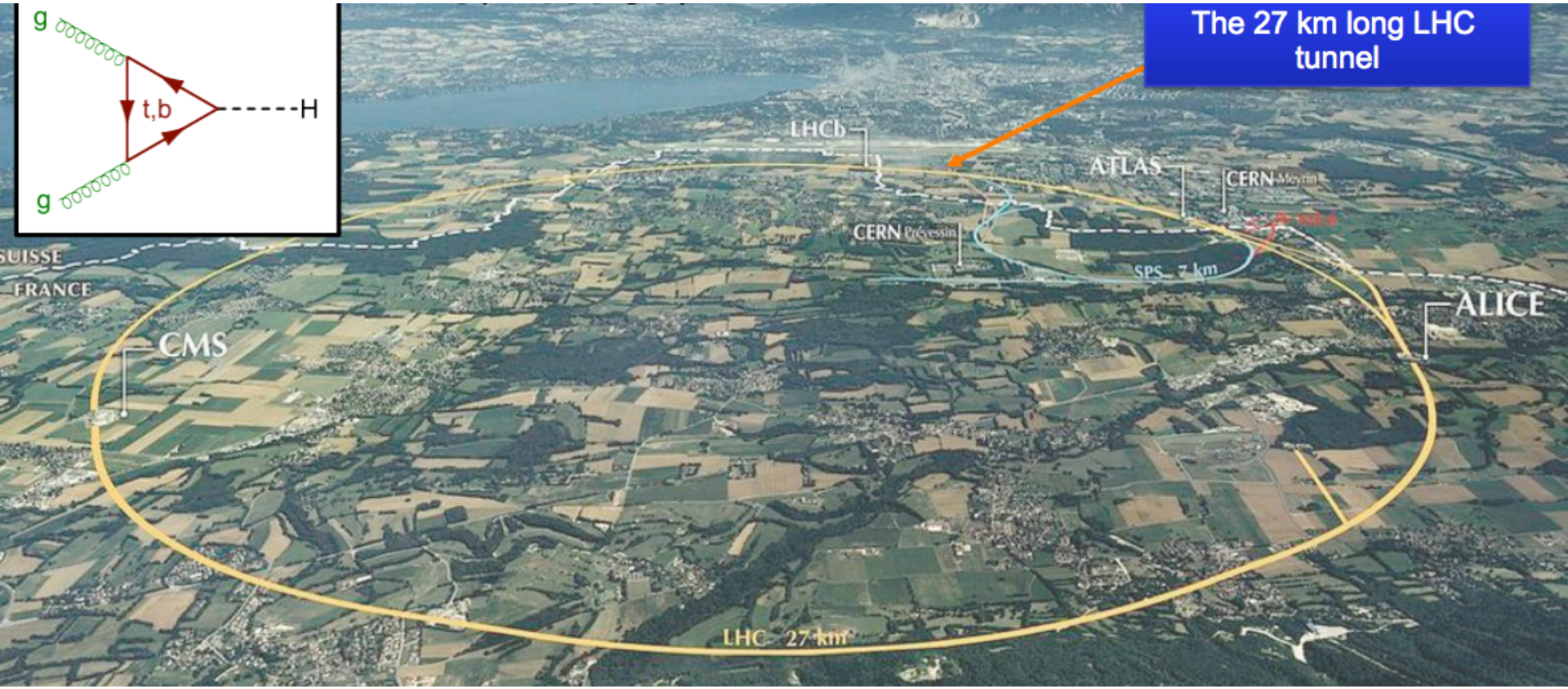


WW: High BR, but low mass resolution

μμ: very small BR, but access to coupling to 2nd generation fermions

bb, ττ: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions

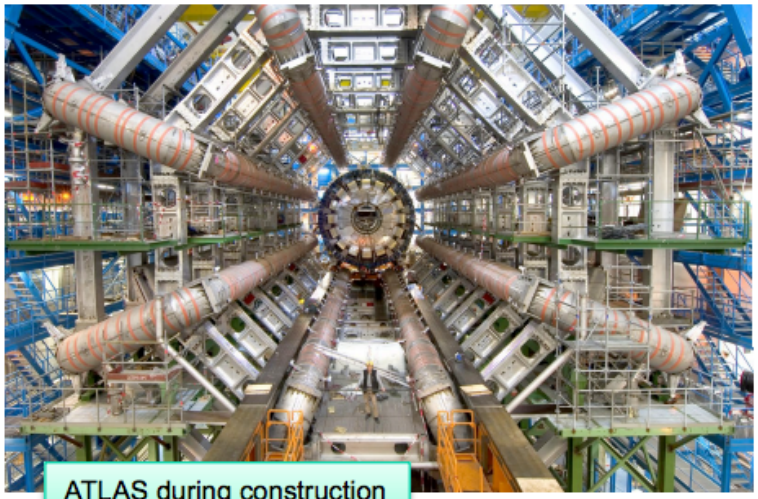
Large Hadron Collider



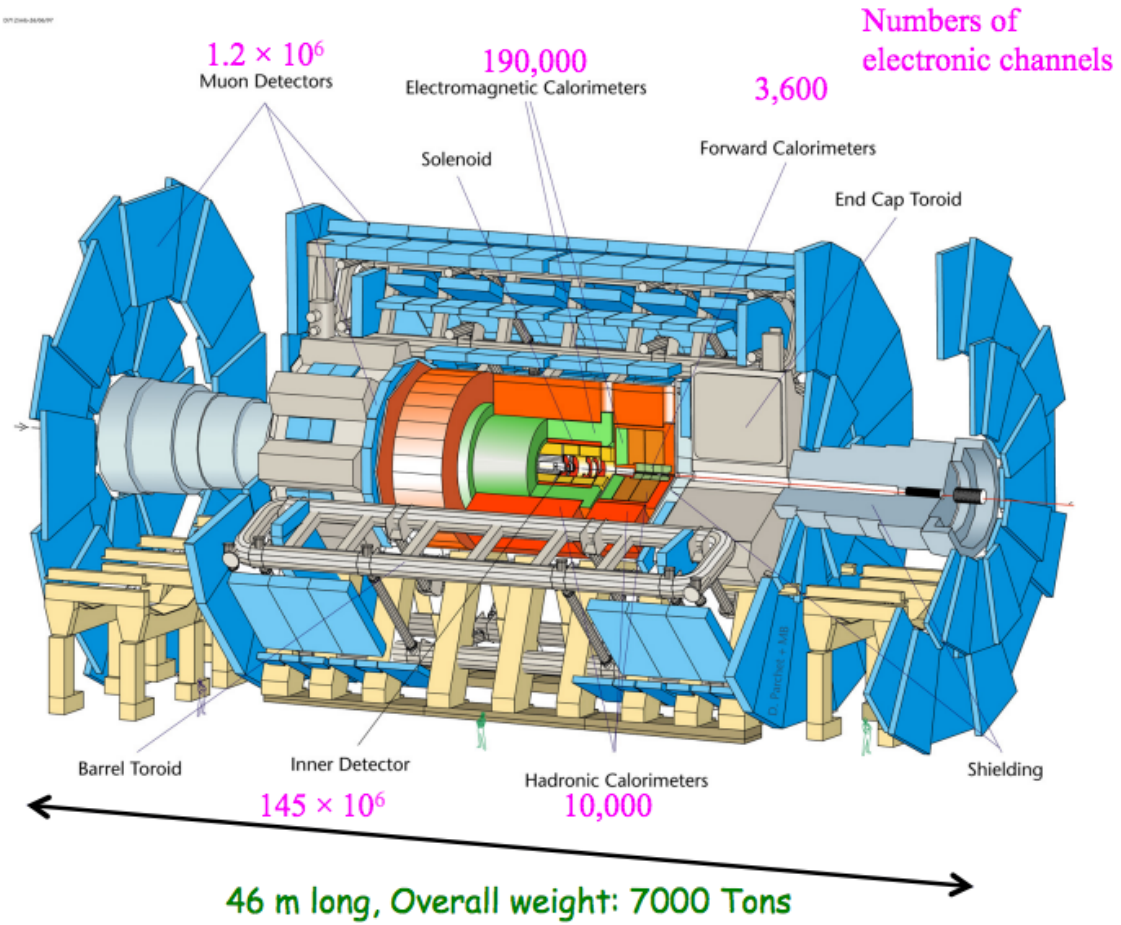
ATLAS experiment

Designed & Built with cutting edge/innovative technologies by HEP physicists

ATLAS superimposed on the 5 story building



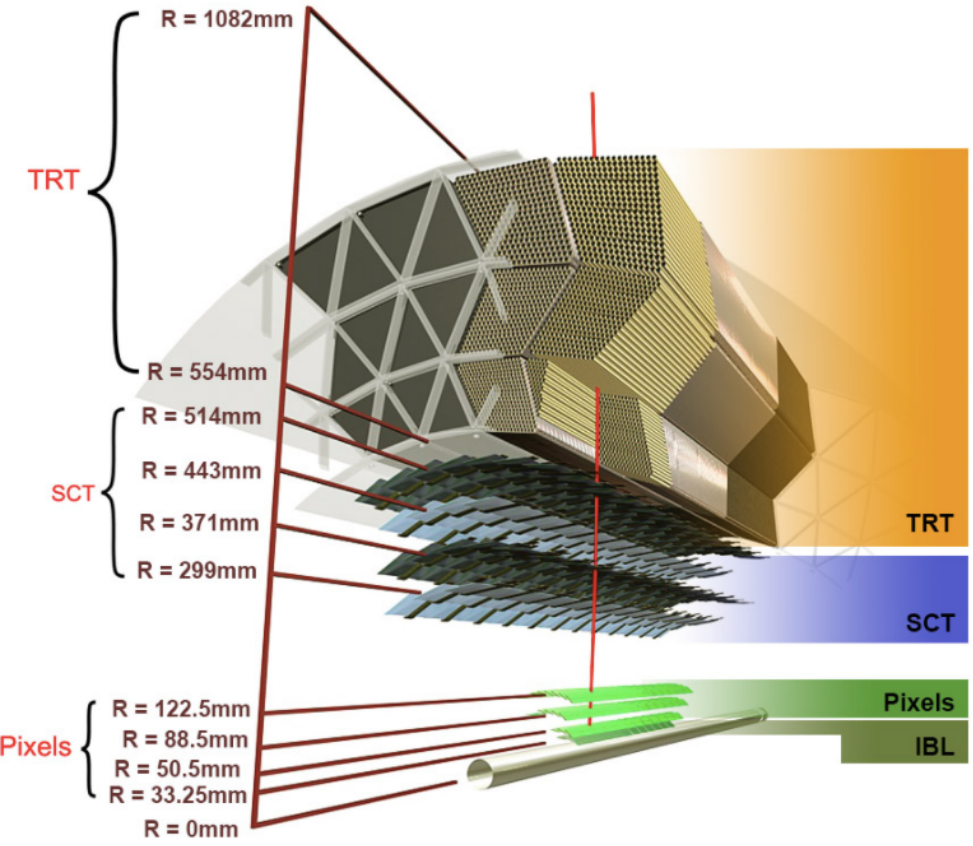
ATLAS during construction

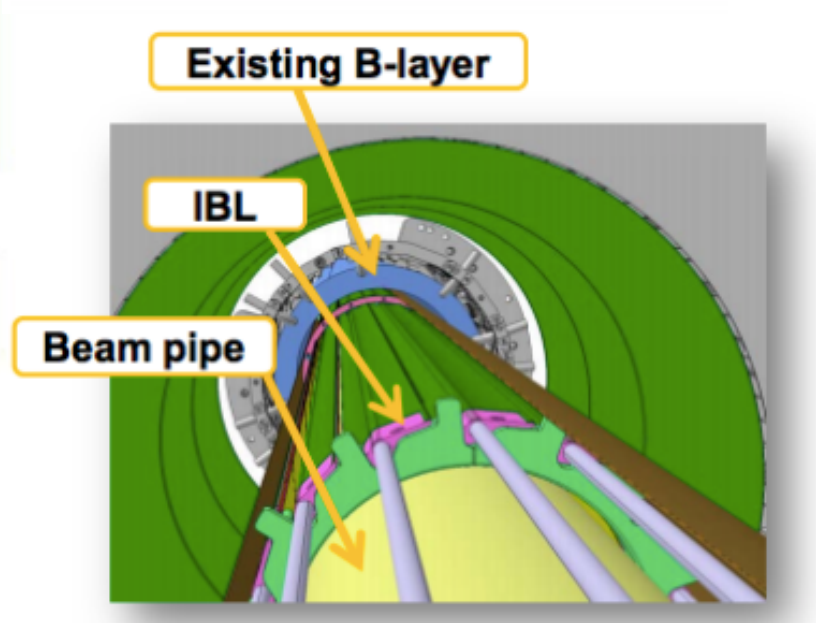


~3000 scientists from 174 Institutions and 38 Countries

ATLAS Detector phase 0 upgrade from run 1 to run 2

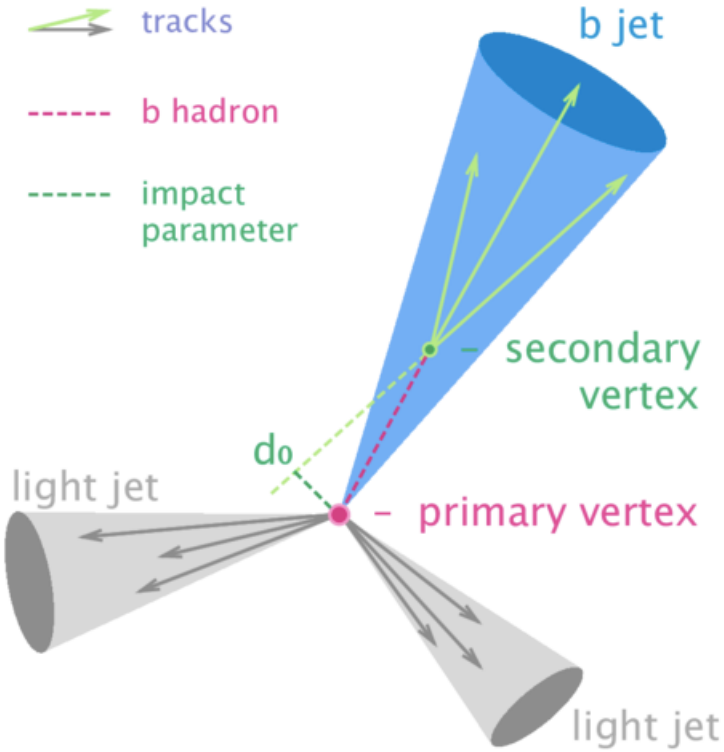
- IBL = New Insertable pixel B-Layer at R=33 mm

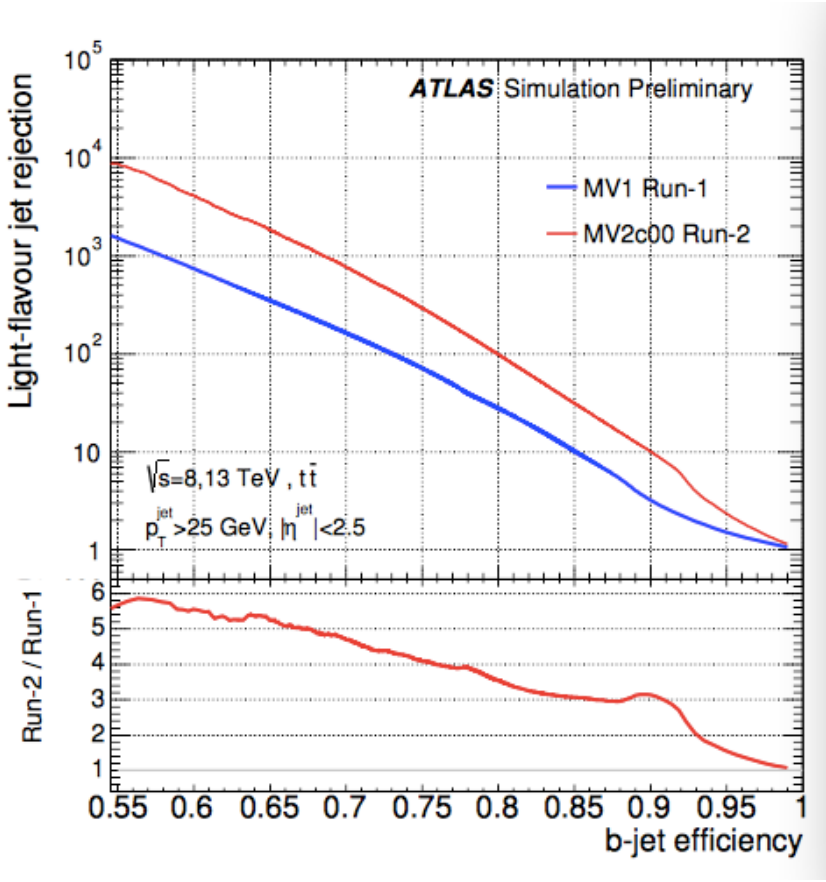




b quark jets in ATLAS

- Light jet rejection power increases by a factor of 10 in run 2
- Two ways to Identify b jets
  - impact parameters
  - secondary vertex from B decay





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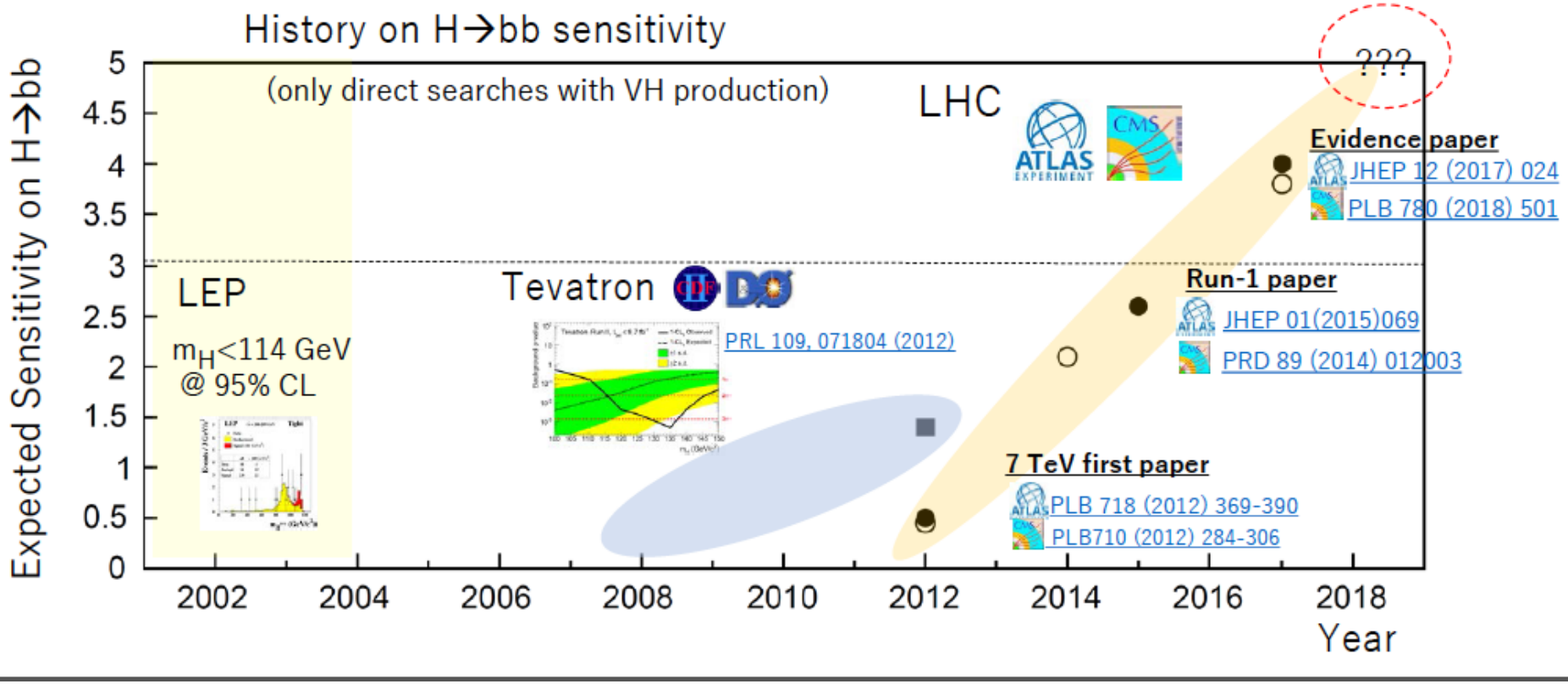
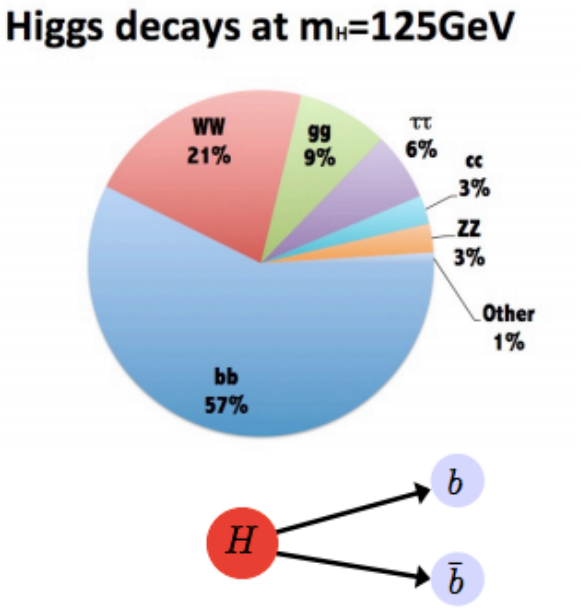
The history of H→bb search

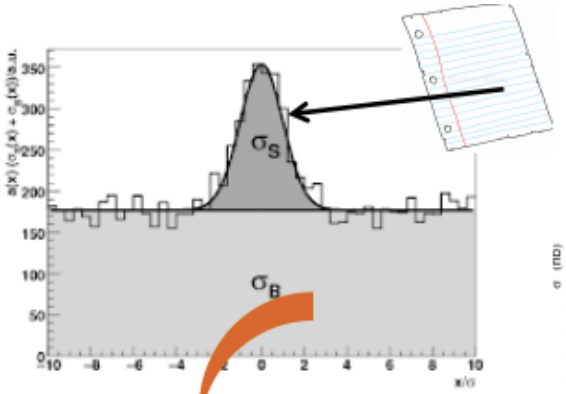
- Started in LEP, developed in Tevatron, then LHC.

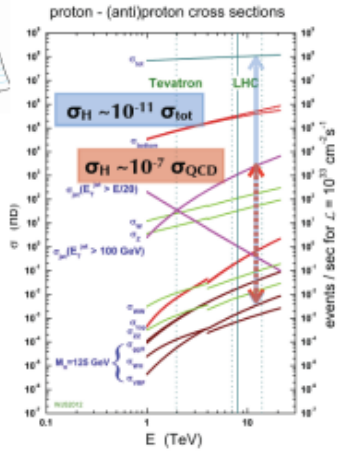


Search for SM VBF H(bb)+γ

- Motivation: Search H→bb decay mode
  - largest branching ratio (~58%), not confirmed yet
    - VHbb ATLAS (3.5**σ**), **CMS** (3.8**σ**).







$$m_H = \sqrt{(p_b + p_{\bar{b}})^2}$$

Need to reconstruct an individual quark
Need to identify the flavor of the quark
SM background is 10 orders of magnitude higher

H→bb observation in ICHEP2018

- ATLAS collaboration presented H→bb observation result in ICHEP2018 at July 9th
- China Science Daily reported this in its front page

中国科学报

CHINA SCIENCE DAILY

总第7082期 2018年7月11日 星期三 今日8版

我国每万人口拥有10.6件发明专利

ATLAS首次发现希格斯粒子最主要衰变过程

中国科学家作出关键贡献

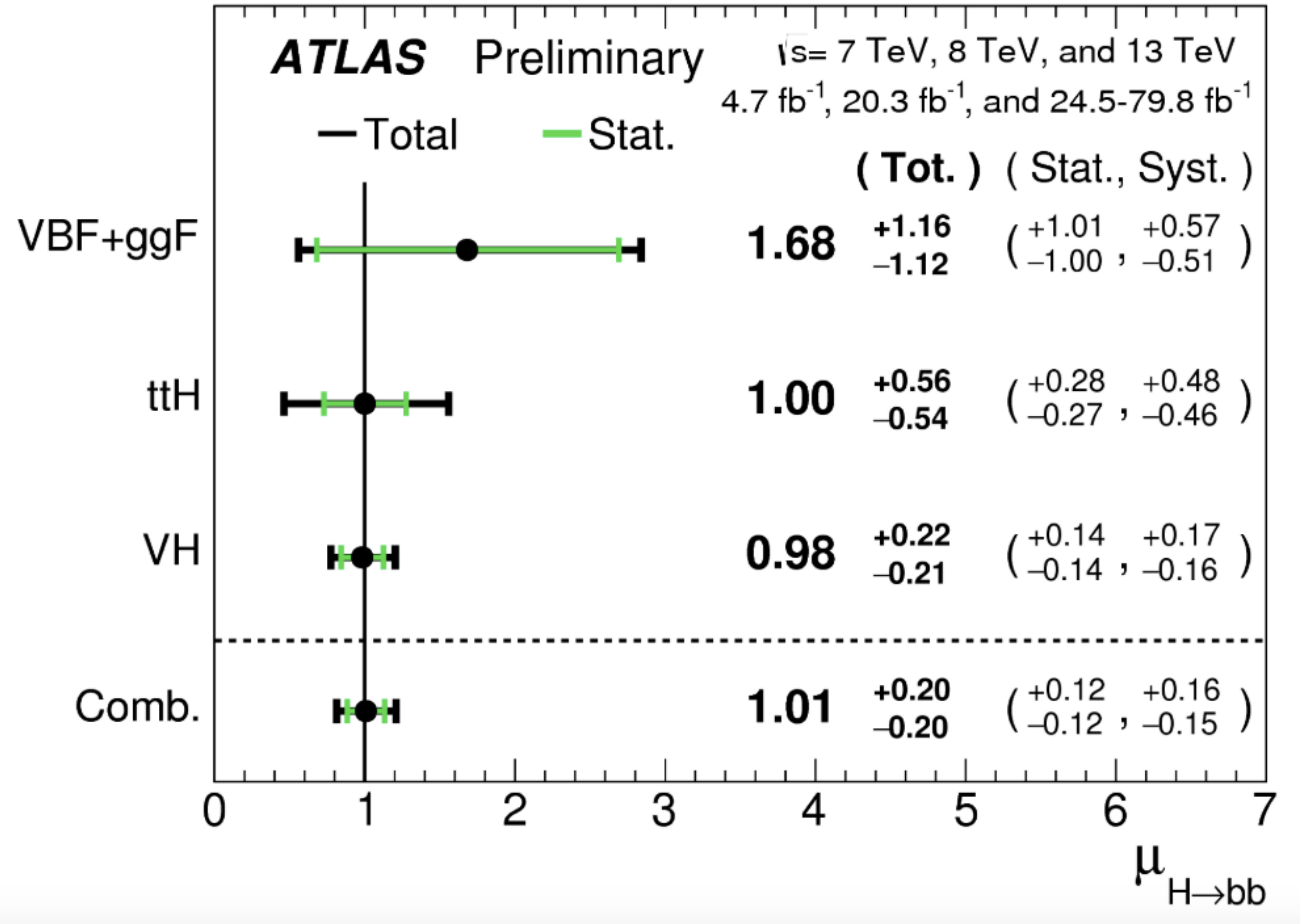
我国最大盐湖资源环境信息数据库建成

含有我国近千个盐湖基本数据

国资委与中国科协合作 共推中央企业科技创新

IHEP contribution to H->bb observation

- Three channel contributed to H->bb observation
  - VBF+ggF , VH , ttH ,
- IHEP ATLAS team led the VBF+ggF analysis



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  - VH(→bb)
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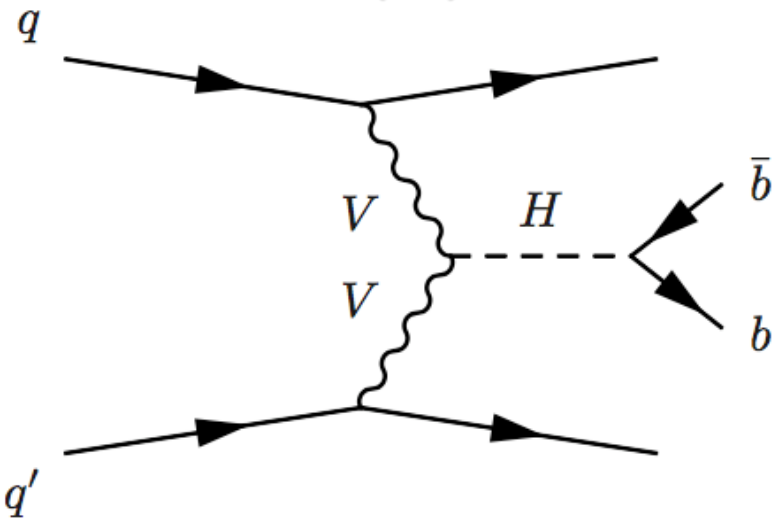
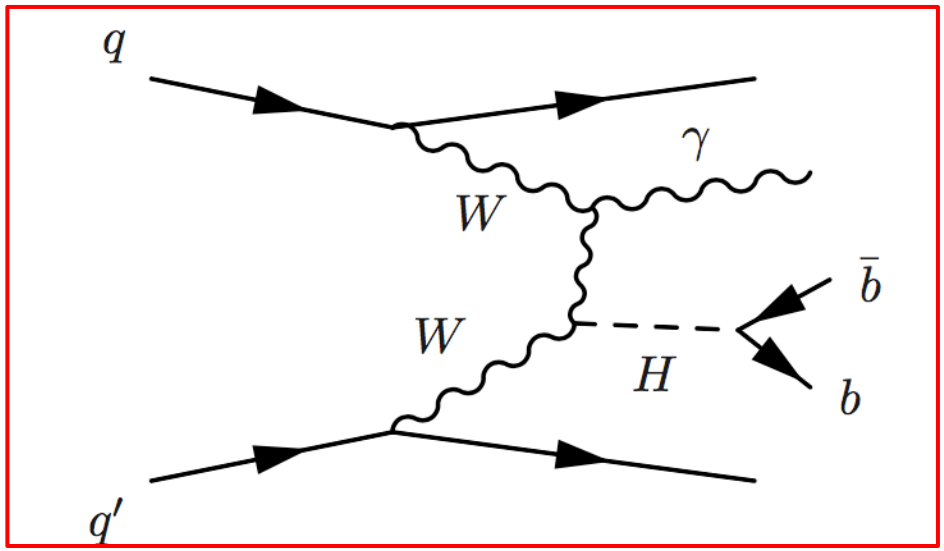
VBF H(bb) analysis

- IHEP team propose Search for H->bb in VBF events containing a central photon
- Advantages of requiring a photon
  - extra handle for trigger
  - suppresses QCD background
  - Sensitive to WWH VBF production
  - not sensitive to ZZH VBF

VBF H(bb)



VBF H(bb) +γ

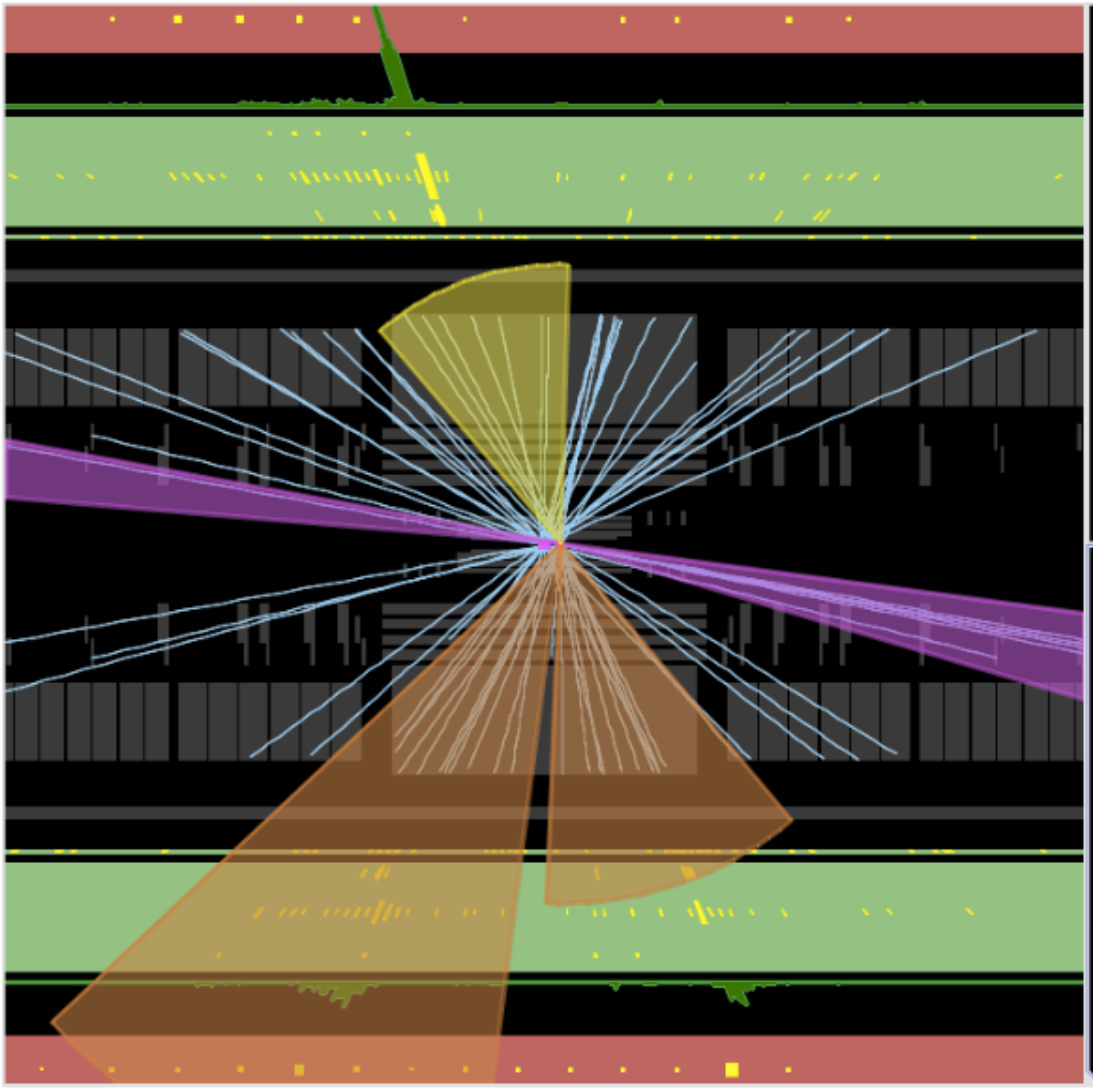


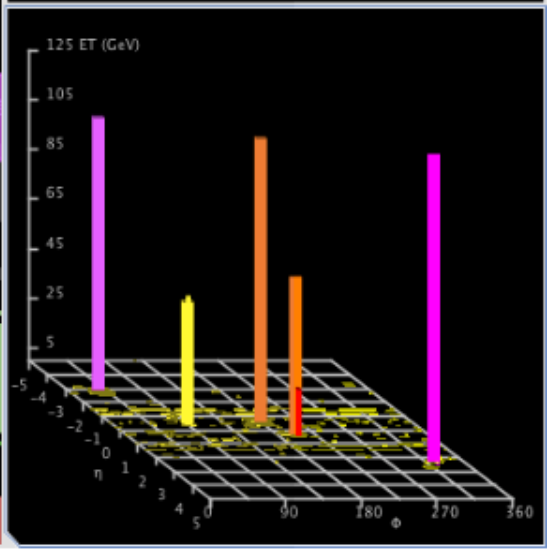
Event display for VBF H(bb)

Photon

VBF jets

b-jets





Analysis strategy

Trigger

Event pre-selection

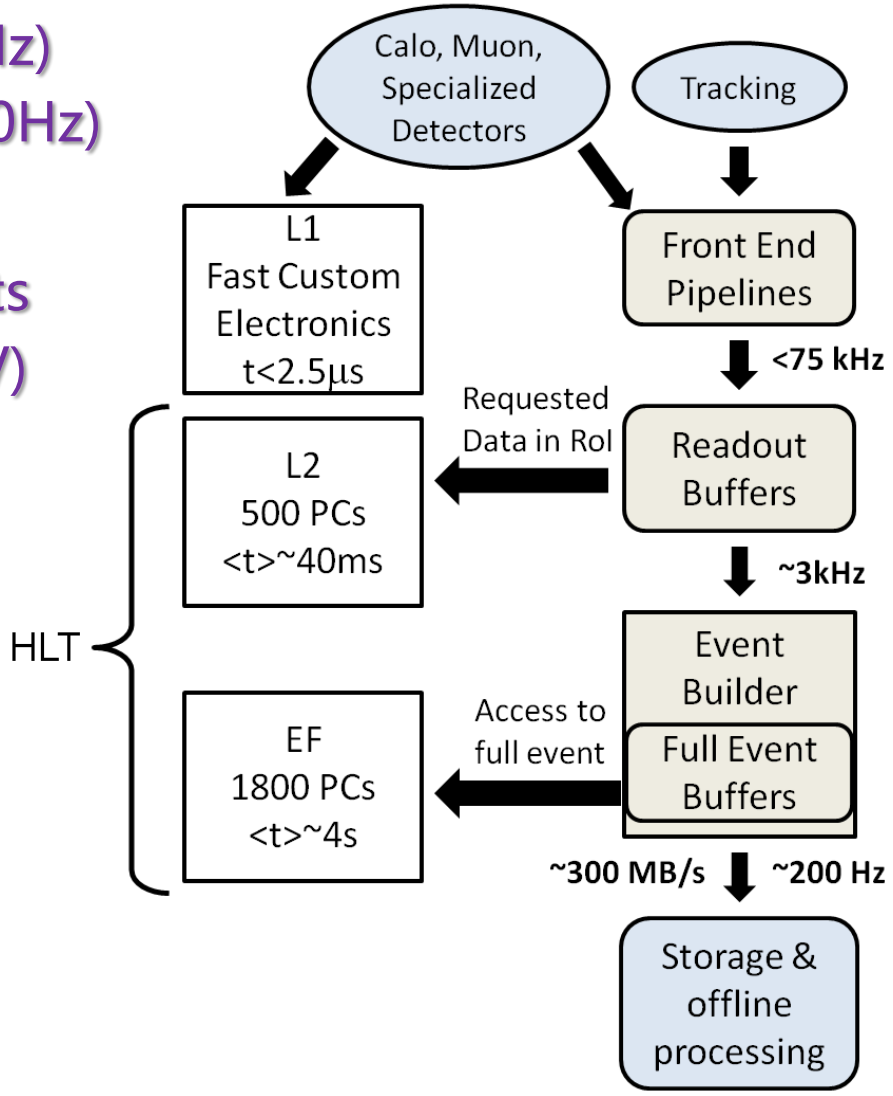
Boosted decision tree

Divide into different categories based on BDT weight

Simultaneous M(bb) Fit on all categories

ATLAS trigger system

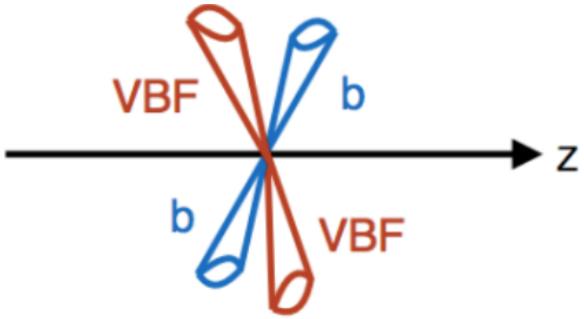
- Three level trigger system
  - L1 trigger: Calo / Muon (75kHz)
  - L3/Event filter: PC based (~200Hz)
- Difficulty
  - Hard to lower threshold for jets
  - Typical 4jet trigger (pT>80GeV)
  - Higgs need lower thresholds
    - Eg: pT>35GeV



Trigger

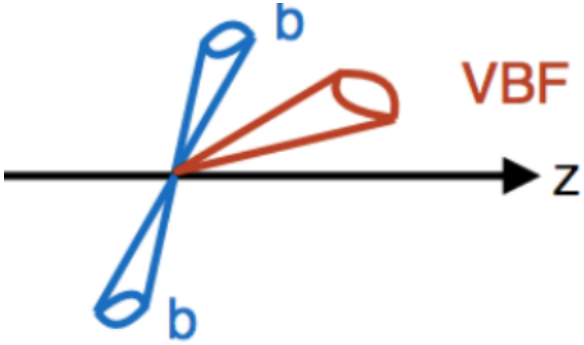
- divided into 3 channels based on triggers:
  - VBF inclusive
    - Two central : 4 central jets with 2 bjet(2b+2j)
    - Four central: 2 central + 1 forward trigger jet (1fj+2b)
  - VBF+photon
    - Photon: photon + 2bjet+2 forward jets (γ+2b+2fj)

L1 trigger: 4 central Jet



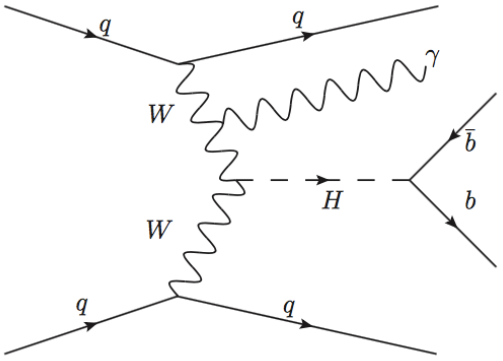
Four central
Channel (2b+2j)

L1: 1 forward jet
+2 central jets



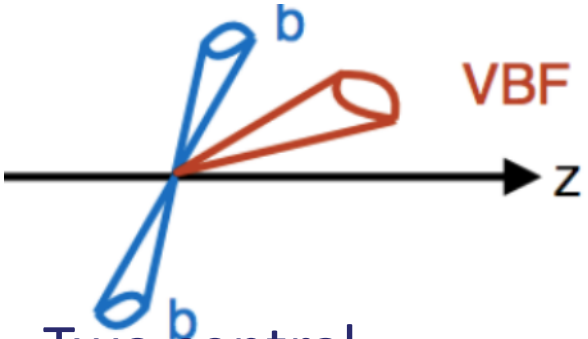
Two central
Channel (1fj+2b)

L1: 1 EM object

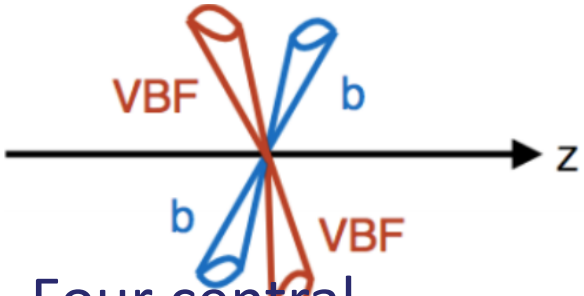


Photon channel
γ+2b+2fj

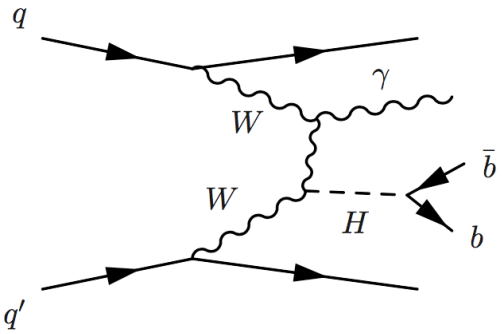
Event Selection



Two central
Channel (1fj+2b)



Four central
Channel (2b+2j)



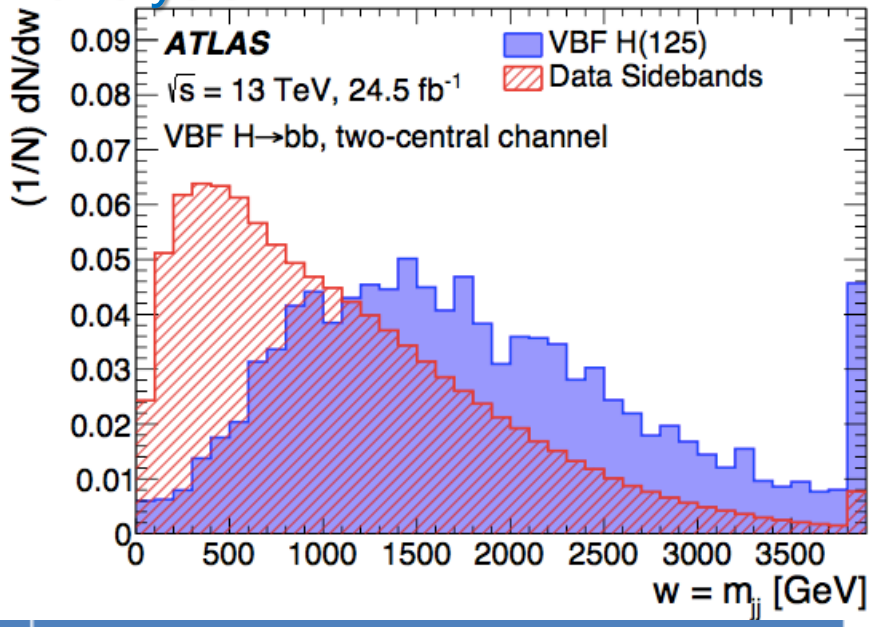
Photon channel
γ+2b+2fj

	Two central	Four central	Photon
2 b-jet	p_T>95GeV p_T>70GeV	p_T>55GeV	p_T>40GeV
2 VBF jets	p_T>60GeV, 3.2<|η|<4.4 p_T>20GeV, |η|<4.4	p_T>55 GeV,|η|<4.4 Veto event with jet p_T >60GeV, 3.2<|η|<4.4	p_T>40GeV |η|< 4.4
Photon			E_T>30GeV
Event topology	p_T(bb)>160GeV	p_T(bb)>150GeV	p_T(bb)>80GeV M(jj) >800GeV

Inclusive analysis veto data events in photon channel
orthogonality between different channels

Boost decision tree analysis

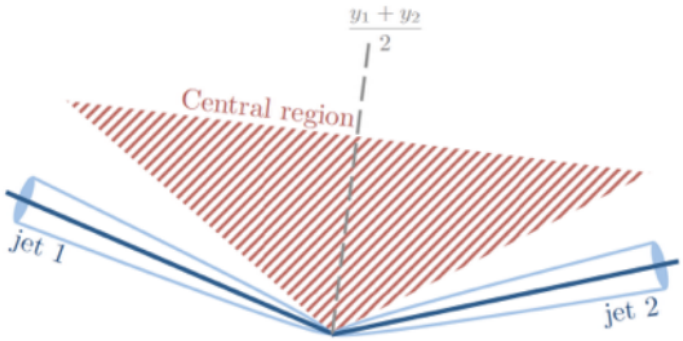
- More than 10 variable used in BDT analysis



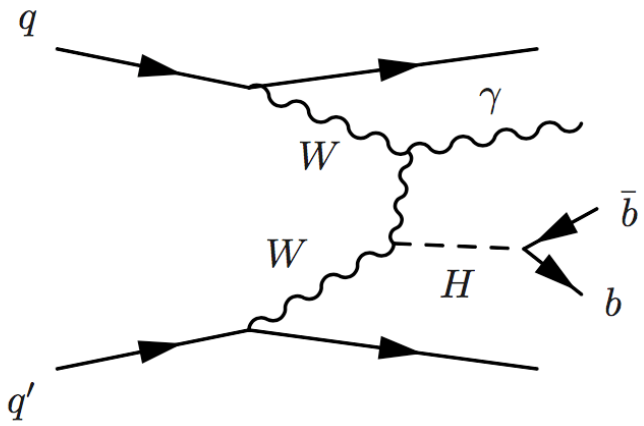
	VBF H(bb) Inclusive	VBF H(bb)+Photon
g/q seperation	Ntrk(j1),Ntrk(j2) minΔR(J1),minΔR(J2)	Ntrk(j1),Ntrk(j2)
VBF jets	p_T(JJ), M(JJ),ΔM(JJ) Max(η(J1), η(J2))	p_T(JJ), M(JJ), Δη(JJ)
Color connection	p balance η^{*J} (Higgs centrality)	p balance p_T Photon Centrality
Angular	cos θ(bb,jj)	ΔR(b1,γ),ΔR(b2,γ),Δϕ(bb,jj),cos θ

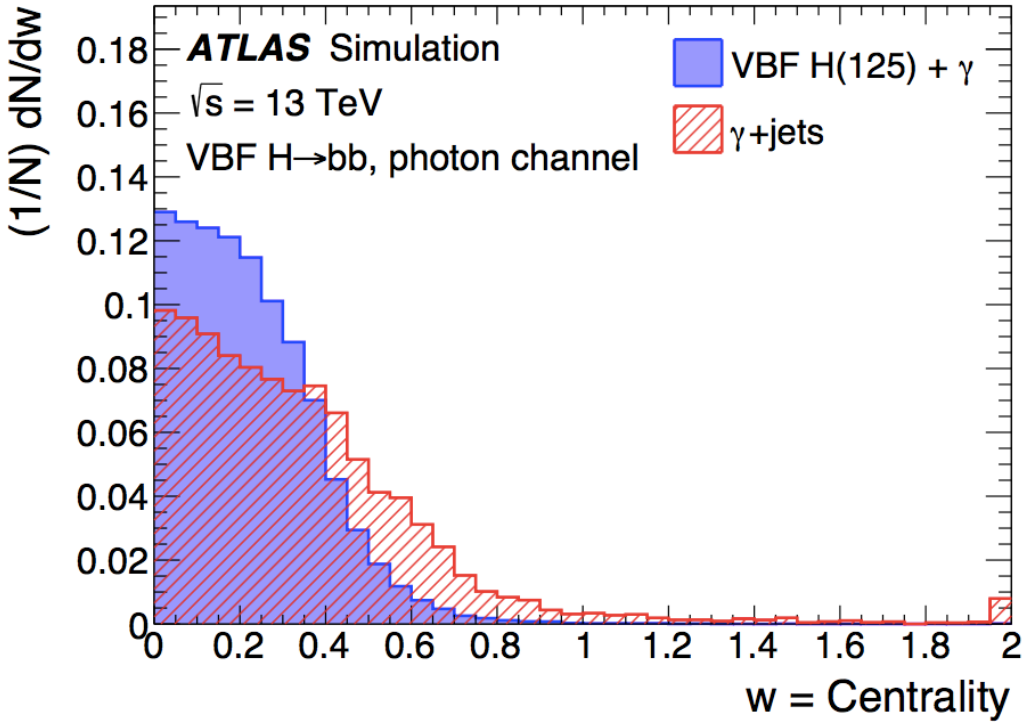
MVA Input variable: photon centrality

$$centrality(\gamma) = \left| \frac{y_\gamma - \frac{y_{j_1} + y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right|$$



No color connection between VBF jets and b jets in signal





Analysis strategy

Trigger

Event pre-selection

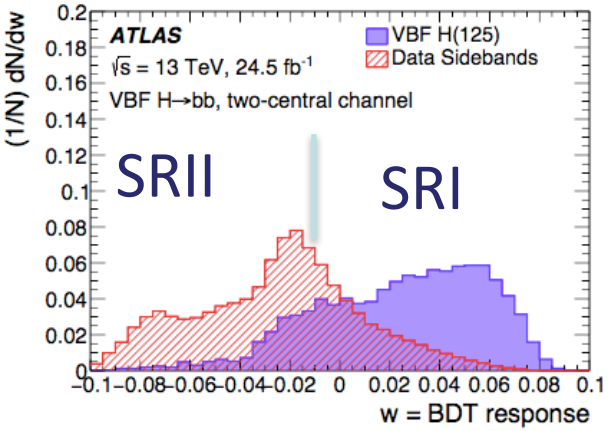
Boosted decision tree

Divide into different categories based on BDT weight

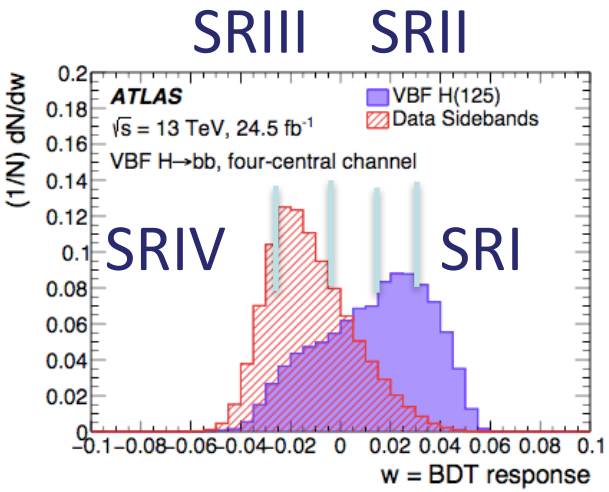
Simultaneous M(bb) Fit on all categories

BDT response

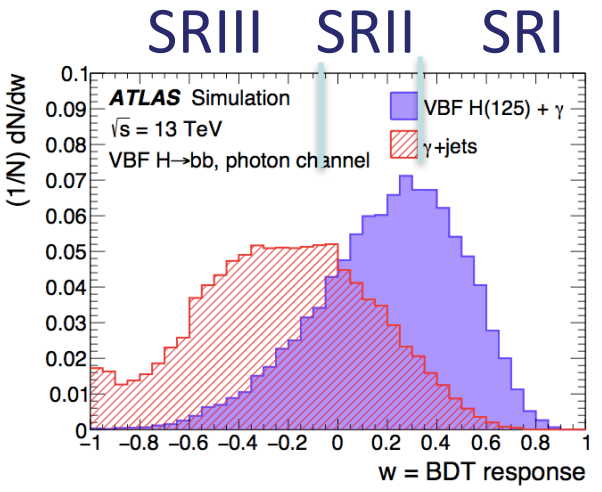
- Divide into 9 categories based on BDT weight
  - Expected Higgs and Z events in 100GeV<m(bb)<140GeV



Two central



Four central

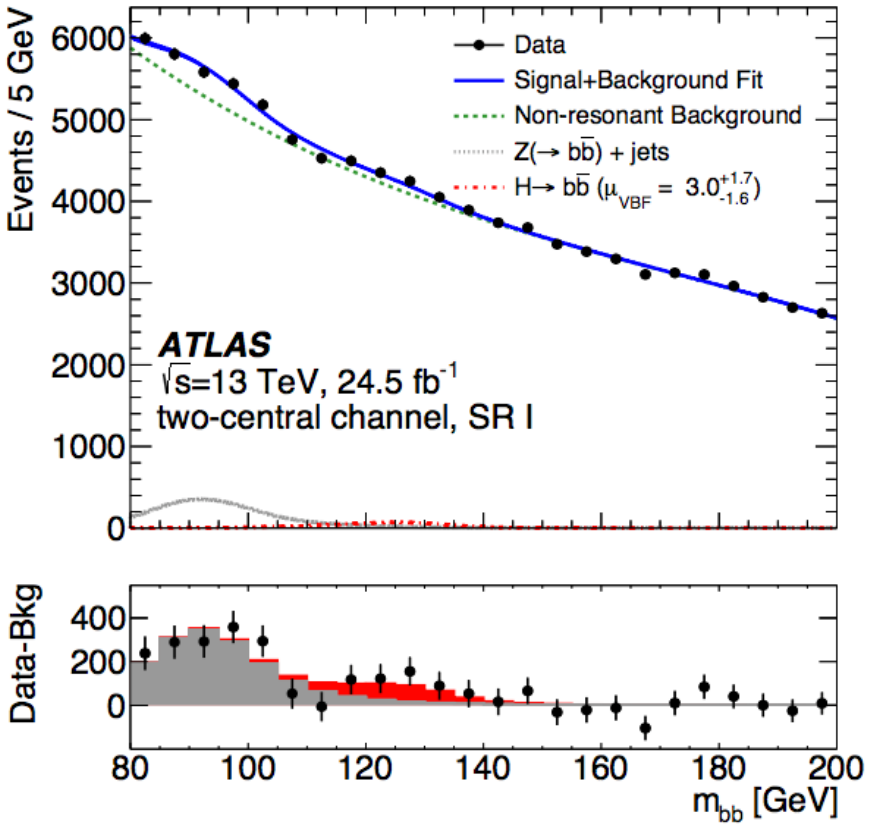


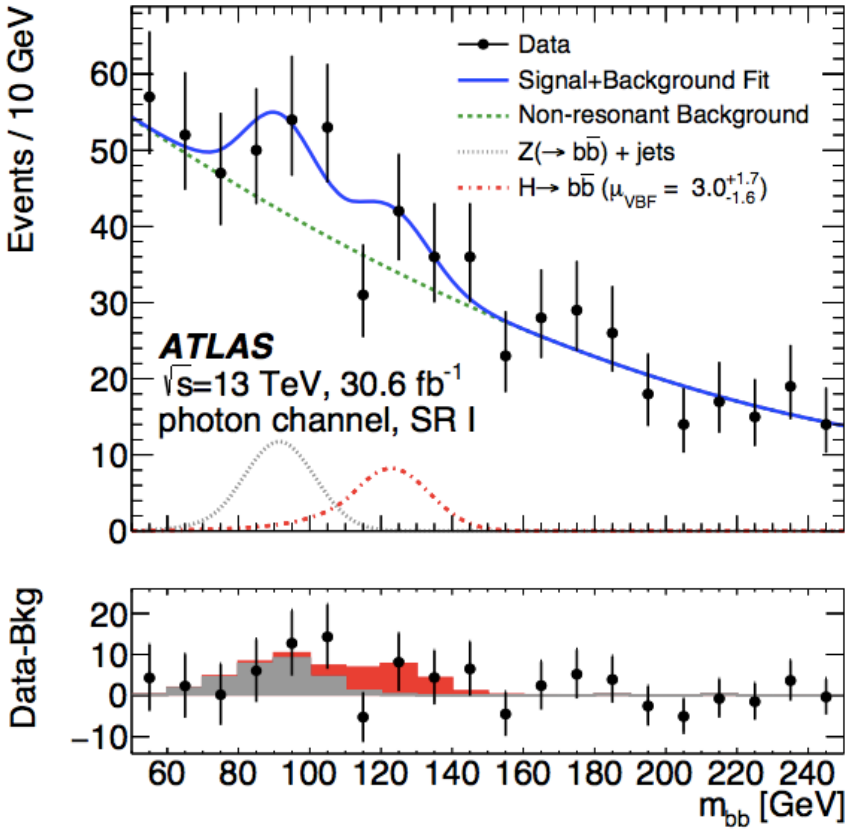
Photon channel

Channel	*two-central*		*four-central*				*photon*		
Region	SR I	SR II	SR I	SR II	SR III	SR IV	SR I	SR II	SR III
Higgs									
VBF	101.2±2.0	22.2±0.9	51.6±1.1	28.4±0.9	43.1±1.0	41.9±1.1	6.2±0.1	5.5±0.1	2.3±0.1
ggF	23.8±2.6	75.7±6.1	11.3±2.2	13.2±1.5	43.4±3.8	127.0±6.5	0.5±0.2	0.3±0.1	0.8±0.3
VH	0.2±0.2	6.0±1.2	1.2±0.9	0.7±0.3	3.9±0.8	28.9±2.6	<0.1	<0.1	<0.1
ttH	2.0±0.2	14.6±0.7	0.3±0.1	1.0±0.1	5.7±0.3	20.2±0.5	<0.1	<0.1	0.4±0.1
Z + jets ($Z\gamma$)	183.1±50.6	515.1±73.4	76.42±14.8	119.4±21.9	385.4±48.5	1224.6±97.9	2.4±0.1	6.9±0.1	13.0±0.1

Simultaneous m(bb) Fit

- Simultaneous m(bb) Fit to all 9 regions





Results of VBF H(bb)

- Observed significance: **1.9σ (μ= 3.0+-1.7)**
  - **Analysis sensitivity dominated by the photon channel.**
- **Dominant uncertainty from data statistics**
  - **Expect significant improvement with full run-2 data.**

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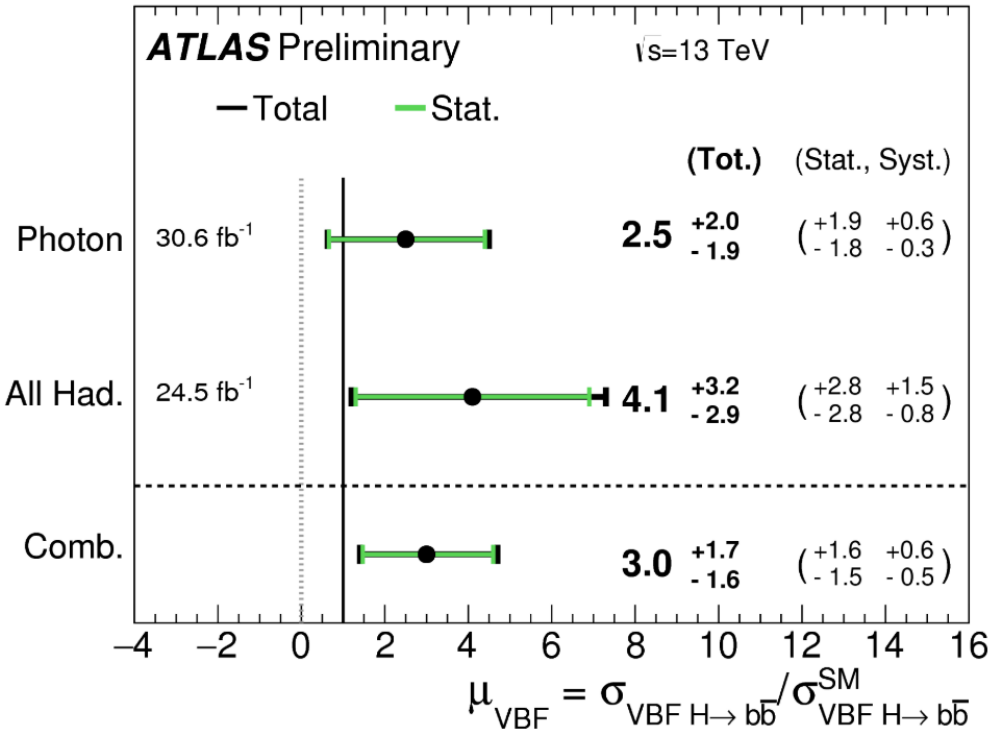

- Introduction to Higgs physics
- Introduction to ATLAS experiment
- Search for H→bb mode (Dominant Decay Channel)
  - VBF H→bb analysis
  - VH(→bb)
  - H→bb Comination

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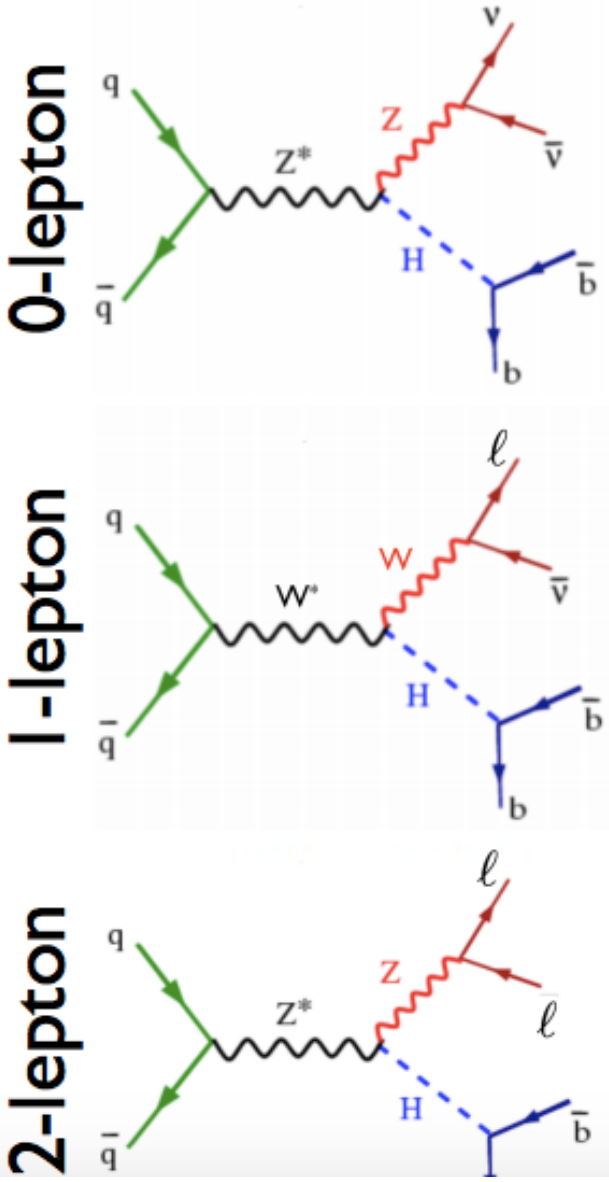
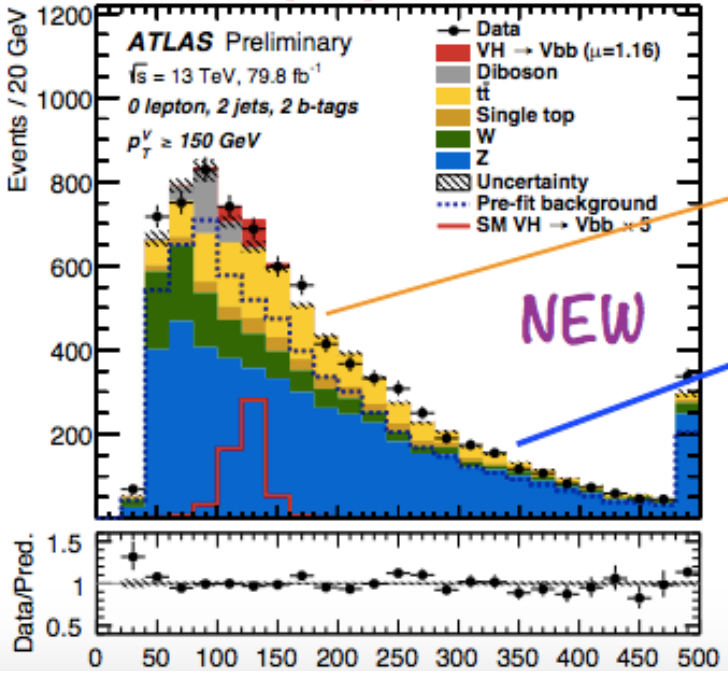
VH, H → bb



- VH production most sensitive mode for H → bb at the LHC
- 3 channels (0-, 1-, 2 charged leptons from V= W/Z boson)
- Select 2 b-tagged jets and $p_T(V) > 75$ or 150 GeV
- Main discriminant variables m(bb), $p_T(V)$ and $\Delta R(bb)$ (combined into a Boosted Decision Tree)

m(bb)



Non-resonant backgrounds:

ttbar, single top

(NLO, PowHeg)

W+jets

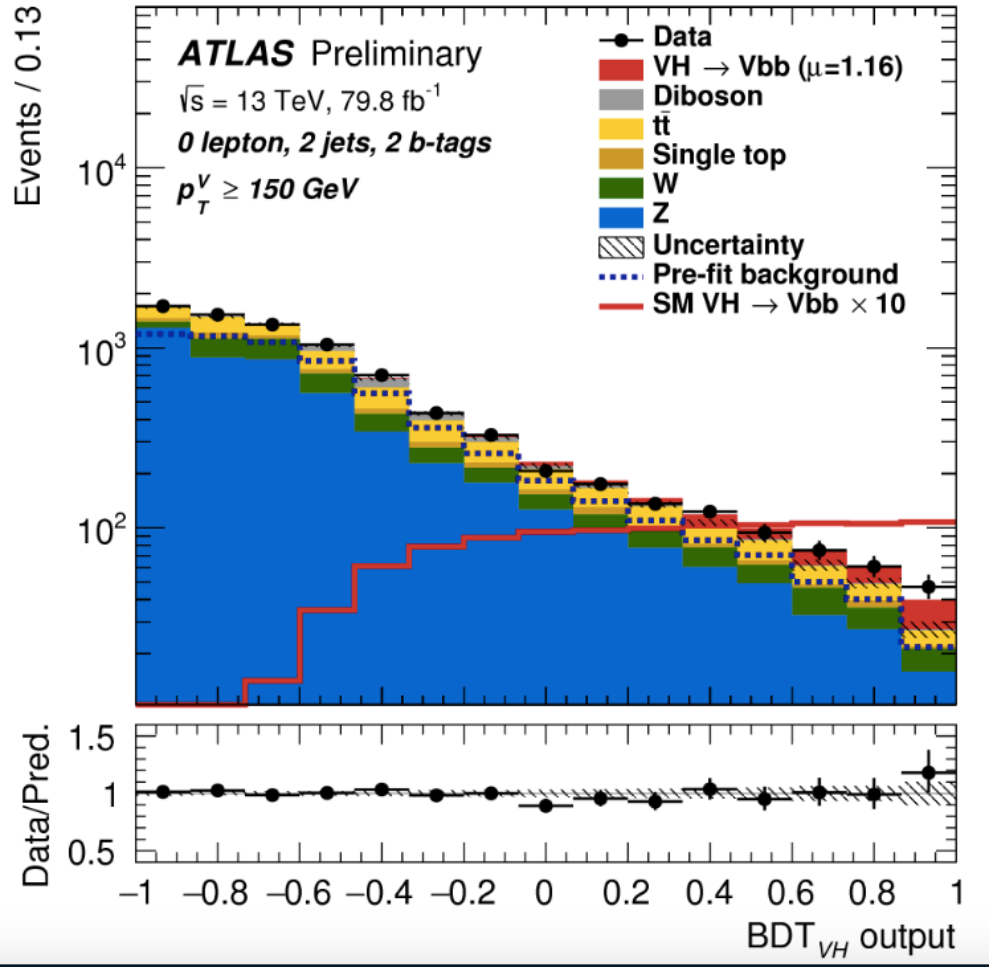
Z+jets

(NLO for up to 2 extra jets, Sherpa 2.2.1)

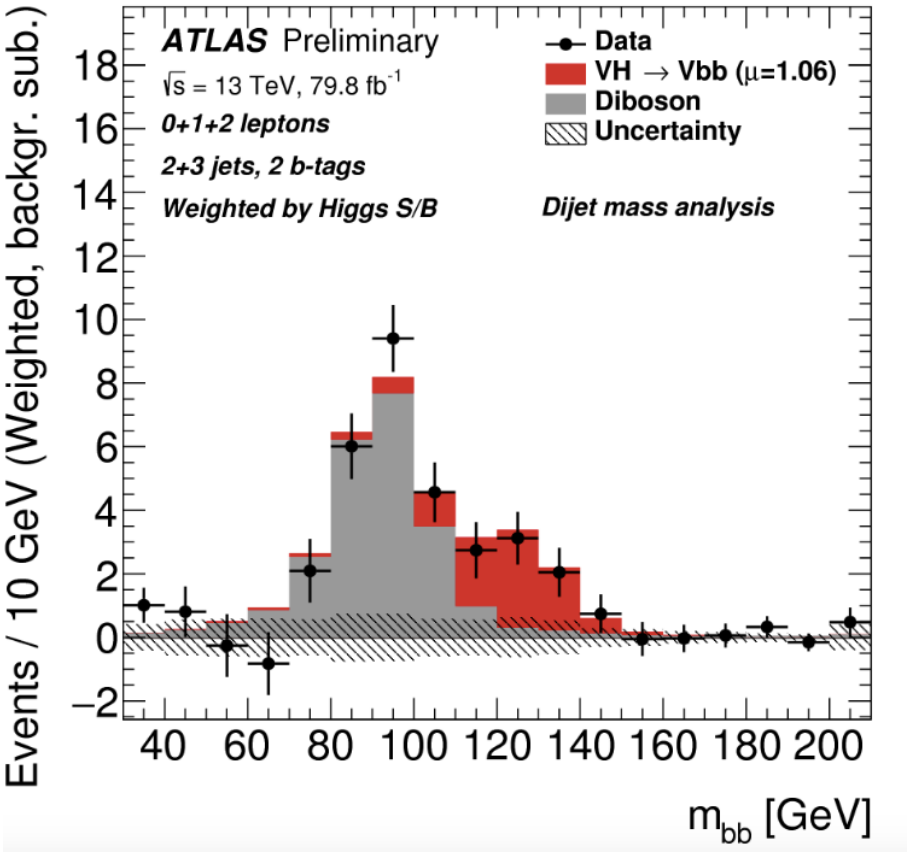
Overall strategy: normalization from

VH(→bb)

- Two methods: Boost decision base (nominal) and cut based

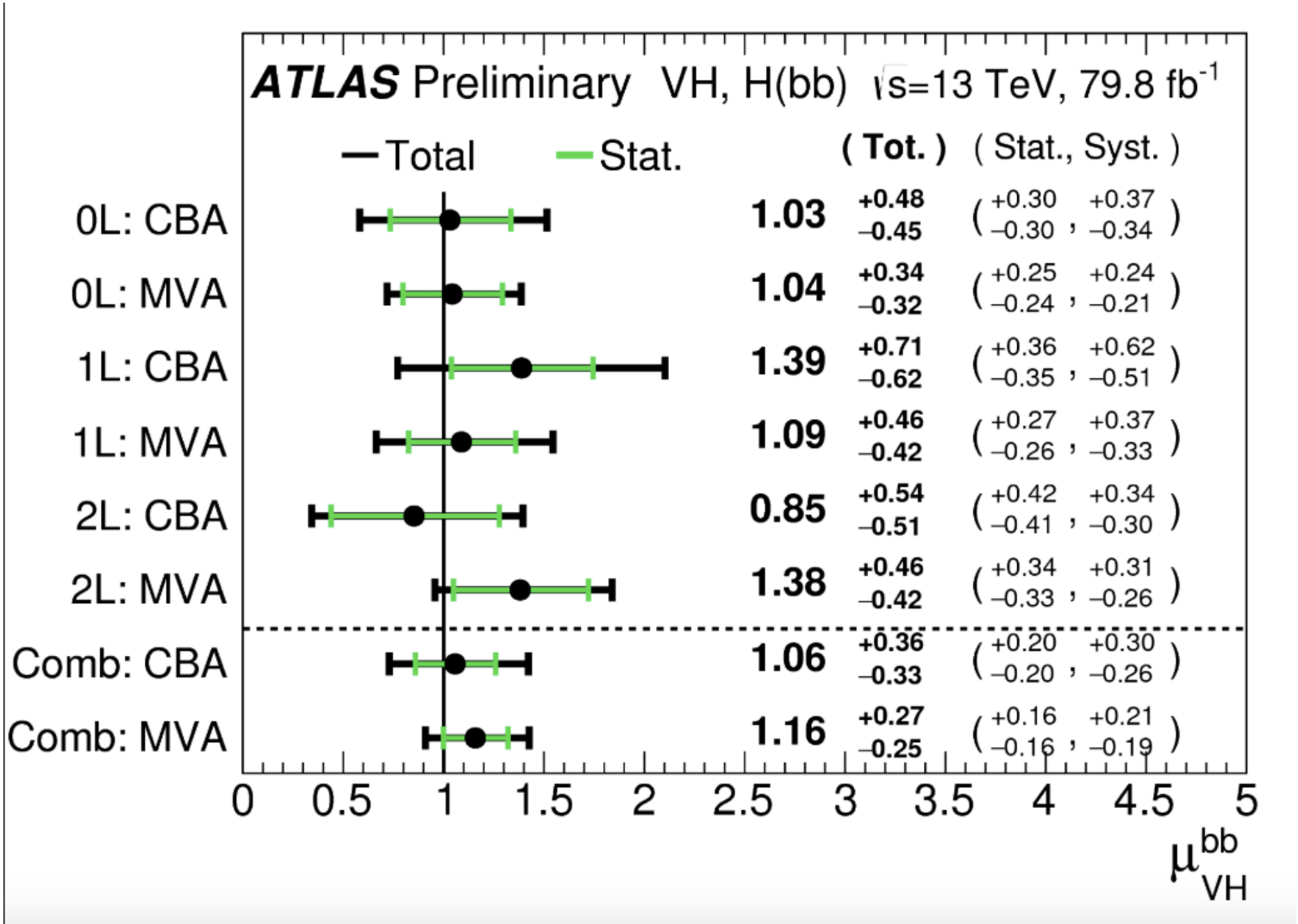


- Detailed validation of analysis:
  - Fit to diboson VZ, Z → bb: $\mu = 1.20^{+0.20}_{-0.18}$ **(9.6σ)**
  - m(bb) fit for VH, H → bb: $\mu = 1.06^{+0.36}_{-0.33}$ **(3.6σ)**



VH(→bb) sensitivity

- Each channel contributes 2σ ~3σ significance
  - Multi-variable (MVA) analysis is better than Cut based (CBA)



H→bb combination

- First observation of H->bb decay mode
- First observation

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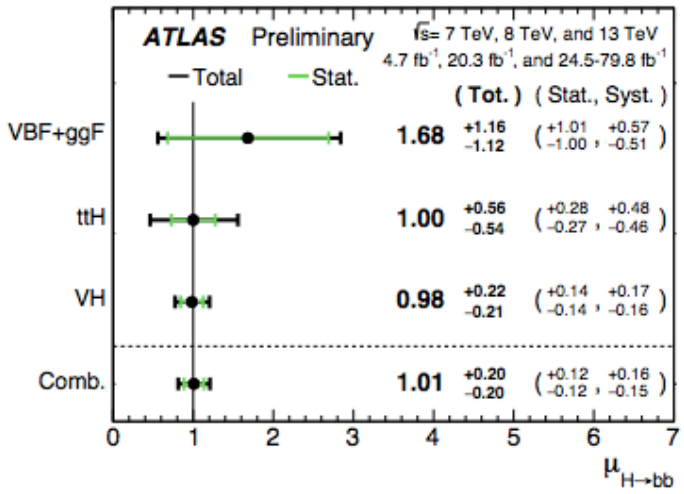
H → bb combination

NEW

- Run-1+Run-2
  - VH, H → bb
  - VBF(+ggF), H → bb
  - ttH, H → bb



Significance:
5.4σ observed
(5.5σ expected)

Observation of H → bb!!

VH combination

NEW

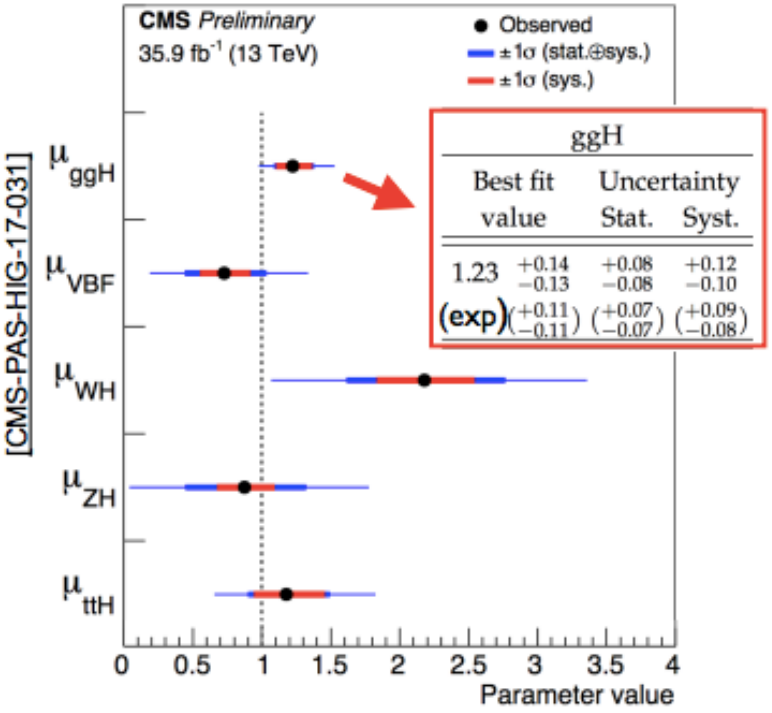
- Run-2
  - VH, H → bb
  - VH, H → γγ
  - VH, H → ZZ*

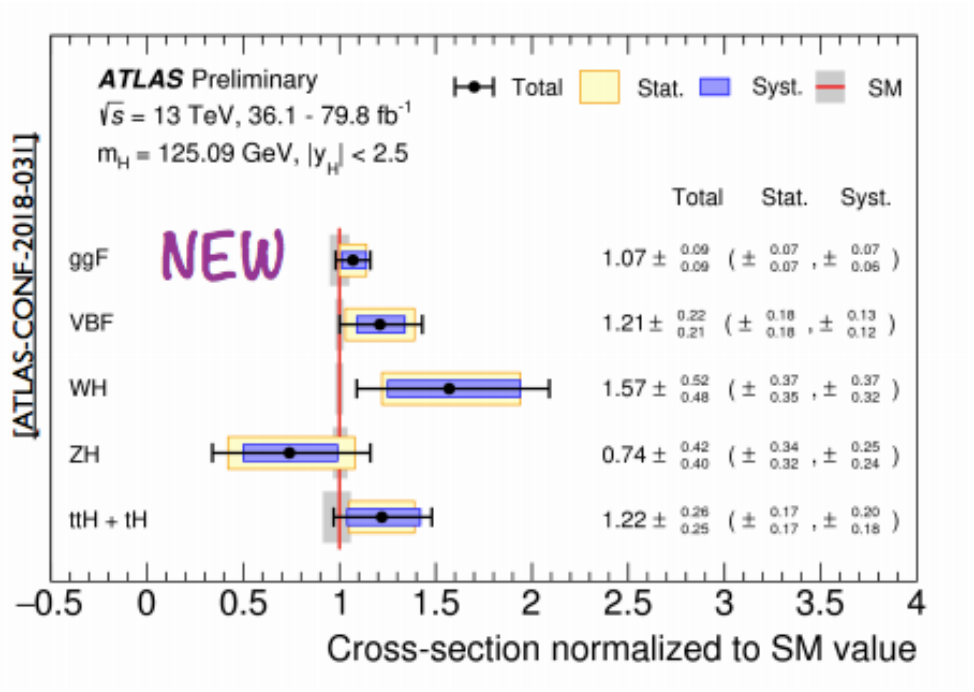
Significance:
5.3σ observed (4.8σ expected)

Observation of VH production!!

N. Morange N. Wardle

Higgs production modes



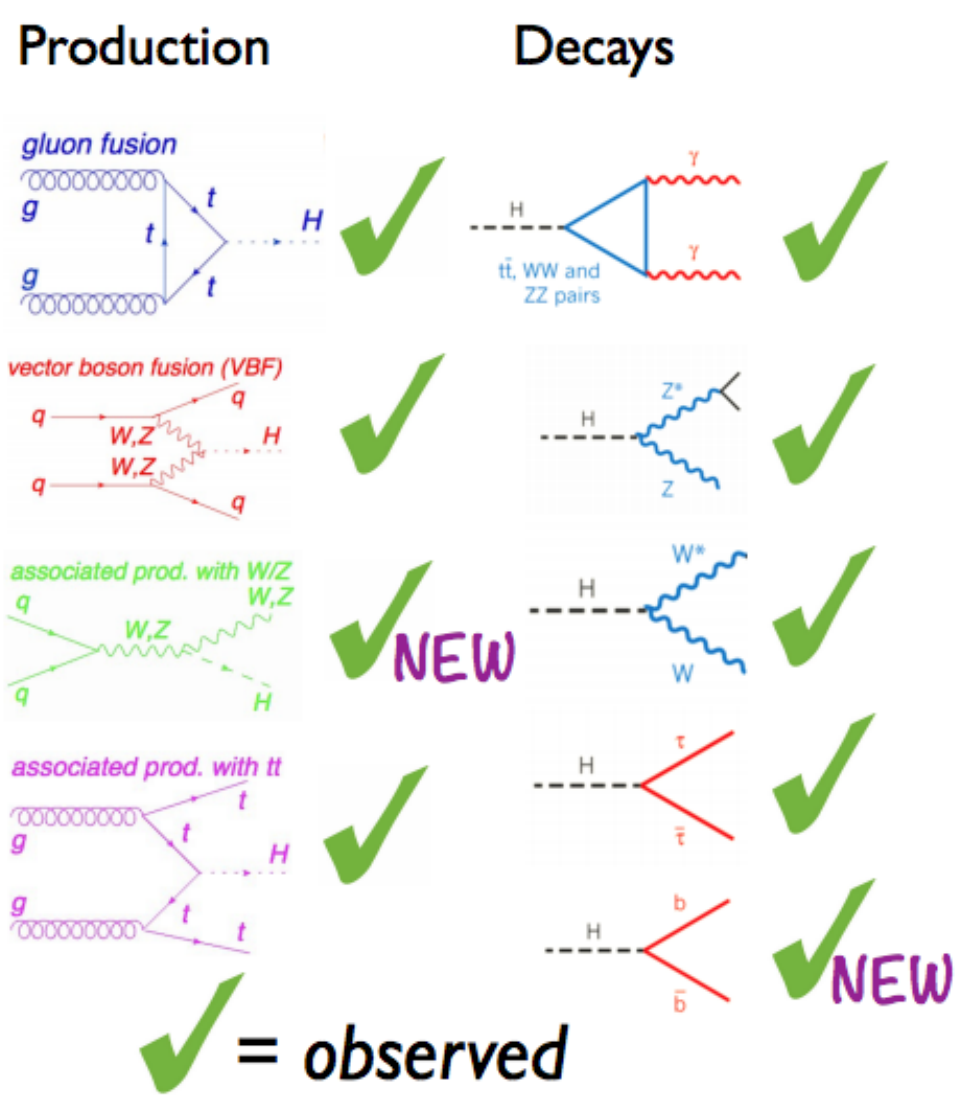


- **9-11% precision on** ggF cross section by each experiment, compatible with SM
- State-of-the-art theory prediction (N3LO QCD+NLO EW [JHEP **1605** (2016) 058]), which has **~5% uncertainty.**
- All main production modes, **ggF**, **VBF**, **VH** and **ttH** have now been observed!!

Significance obs (exp.)	ATLAS+CMS Run-I	ATLAS (single exp)
VBF	**5.4σ** (4.6σ)	**6.5σ** (5.3σ)
VH	**3.5σ** (4.2σ)	**5.3σ*** (4.8σ)
ttH	**4.4σ** (2.0σ)	**5.8σ** (5.3σ)

* including VH, H → bb (80 fb-1)

Higgs result summary in ICHEP



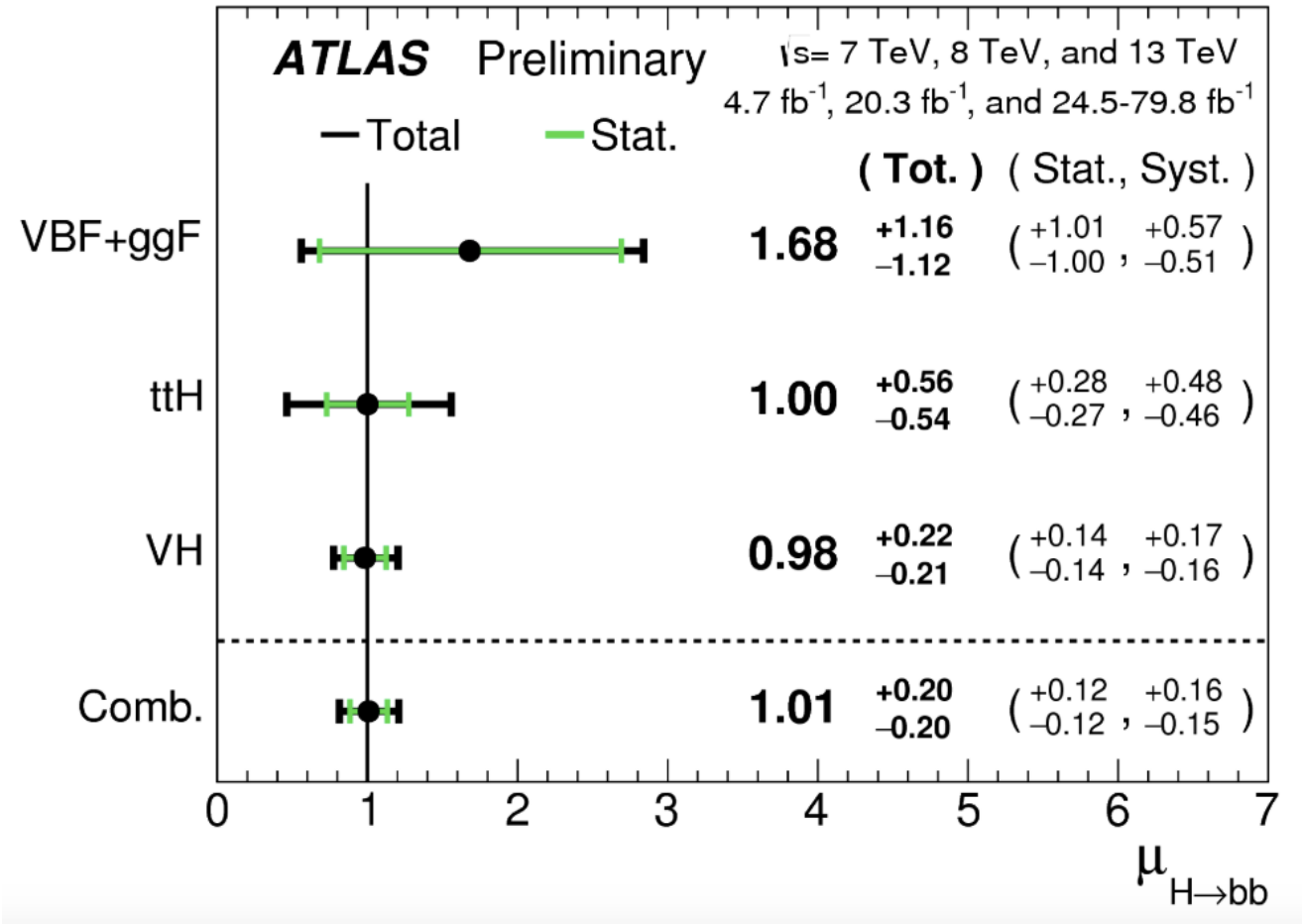
- Thanks to the first 36-80 fb^{-1} of Run-2 data:
  - The bosonic decay channels entered a precision era (~3x improvement w.r.t. Run-1)
  - Direct observation achieved for all main production and decay modes!
  - Direct confirmation of coupling to all 3rd generation fermions (top-quark, **bottom-quark**, taus)
  - Sensitivity to double Higgs production approaching 10 x SM
- Higgs physics an important indirect probe for New Physics: so far no deviations from SM…
- But still at the beginning of a long journey! Only analyzed <3% of the final LHC luminosity.

Summary

- First observation of H->bb decay mode
  - IHEP ATLAS group made major contribution
  - lead ggF+VBF channel
- First observation of VH production mode
  - Main Higgs production mode in CEPC
  - Current precision of H->bb coupling about 20%
  - CEPC can reach precision with 1%

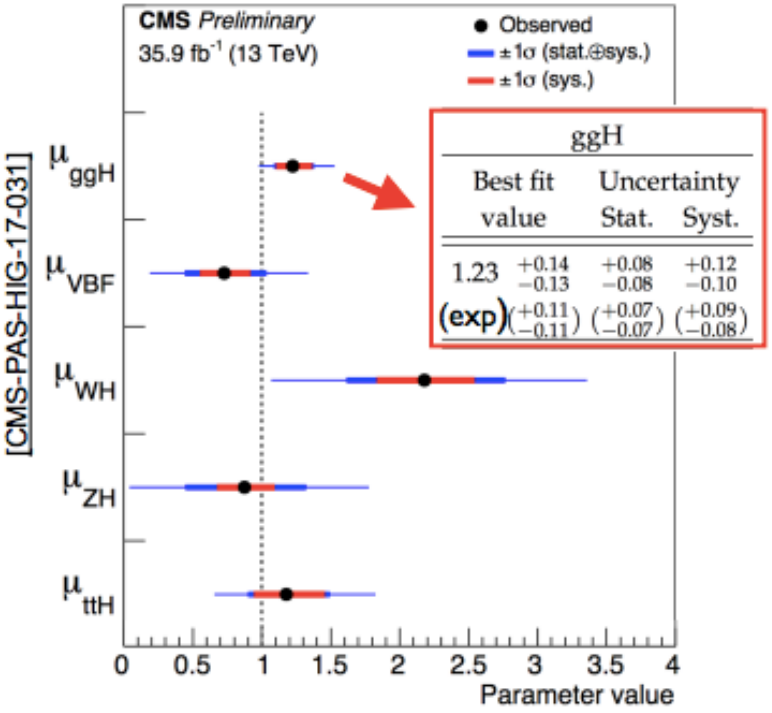
IHEP contribution to H->bb observation

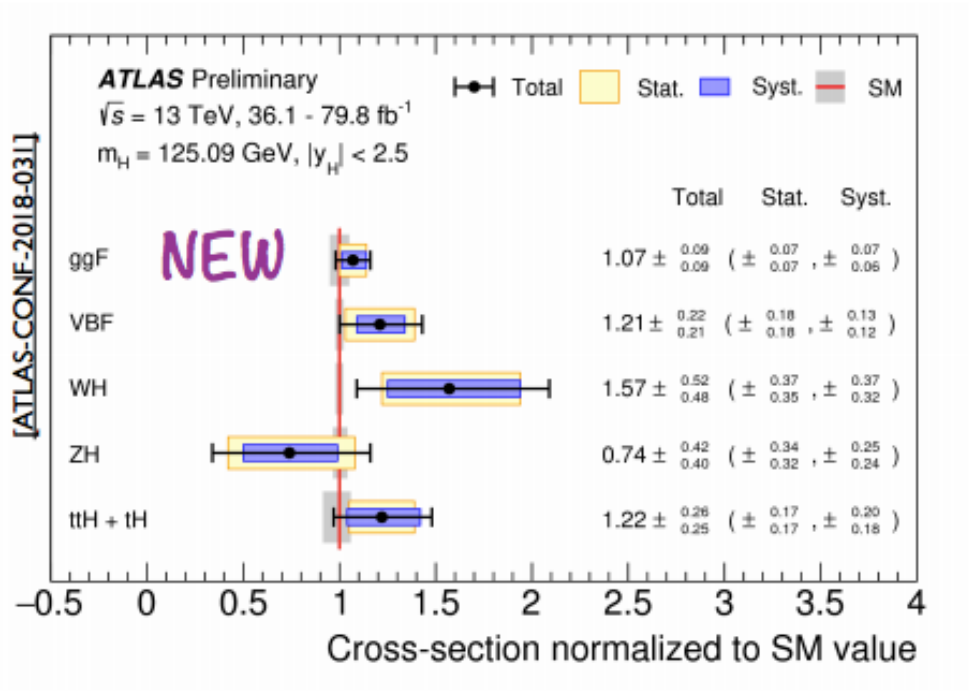
- IHEP ATLAS team led the VBF+ggF analysis



N. Morange N. Wardle

Higgs production modes





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* including VH, H → bb (80 fb-1)

H→bb observation in ICHEP2018

- ATLAS collaboration presented H→bb observation result in ICHEP2018 at July 9th