

中国科学院高能物理研究所

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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



History of Higgs discovery (2)

As a layman, we have it, but as a scientist, we have to find out what sort of Higgs boson it is.

lulv 4-20

Standard Model Lagrangian



Yukawa coupling with new scalar (completely new interaction type) ttH, $H \rightarrow bb$ and $H \rightarrow \tau\tau$ 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!



Higgs bosons produced in Run 2 (2015-2017)

~300k

~200k

~40k

Higgs Decay

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



bb, **TT**: 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 during construction



46 m long, Overall weight: 7000 Tons

~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

9 350

P250

÷200

150E

100

- largest branching ratio (~58%), not confirmed yet
 - VHbb ATLAS (3.5σ), CMS (3.8σ).



proton - (anti)proton cross sections

Tevatro

σH ~10-11 σtot

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

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

$H \rightarrow bb$ observation in ICHEP2018

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



我国每万人口拥有10.6件发明专利

A 新史第7月 45 日前(纪世家美)小大,王 FERPERAD 201 中国日本世界内学校 *** **国家**和利用市業業務和10月前日本中部日本

4. 我上到十年。月末,我里里八张树中州 國家重点社會主 20%。我计量中,言任景切这声 在世界的小的 另个孩子都能小,望大家田中村 N10个,但在大学,医学说术,发行机和优先等 2个物质和国内学生系统。228里上第二国内状 TOTAL COLOR AND DE

上也从此来,"每些个吧,在时常着我来好学时

中、重片橡皮 以中以上的有效实现中的在上述

末,定物,计算机技术等+个物理,算内外差统 H里、出此、美国市由く在木物県上市市市市 8.28981.85年4月4.78%(至古法 中国家名言書法《中午》代表。

34个秘密中、34个技术物能必要量少于留外

国家におやお見たら夏を伝説文明の何 2014年上ヤ年、天営と学行びござれたかどだおうみ #4. 100 Rafe ##4. ## 1018 W + F.H. # 第二人に不会構成な 決計中に決定量あけ いちん NR. BAARDARE CRIMER, BAR, BARRARE CONTRACTOR BELLEN, MELECON, XO.14 THE 自営人、間も考えていた。

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

約時間会区上, 前井田子小心大型場子対量化之的 LAL 白白田 至大田田 7 ● 田田田 7 4 ● 1 甲田田 1 PLOANER.

物理学家认为、参考新说色子教子基本发子以 新聞·希可以東京成不開始于·法也正希中电影团也 了根来为"上帝电子"的第三、之前称乎来自然地说 色子板 + 每子时要记程,这些已经是要判的要定量 81日日日, 你们没有你的现在了我们会认识的。 No. 46825/828 1046646825/8 充成一时里春光, 也是希腊新说出了最新重大生的 我觉过程。我最利达一天觉过程将真计时中的影响 于以另约一天空白、所用是一步位发展新导先表量

由于操作时最优上的子安集举的的高级节约 1000 THULL FURRER-RESERVED. R. RATIALS服用会了并个考虑影响而于产生记程的 OF WE TO SHOP FRANCE SERATRAL 稿,发生装色于树树植"生过楼,没有充时树植"生过

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

●小工业建立化业研究加速点不多的保证(100)100

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にましの形式和田田田田市の.小田 ATLAS 日 NANET AND THEM. ROOMS 与教子教会过每约正式发展争先为武变分钟。被 AT-LAS会行地位会大学公式の大学人、世外成大学区 41.4.2度、同意,要求出意保分析的信号和安全产。 留景和合与信号情导着方面作出主导实际,并在 ATLAS BORDON TERMS.

ARE/0488168X THEY X244 BOOMER 共国 TROUTPHS. NOOP SATERIANS, TRUESD & 的复数指示器体力关系4位,紧张器,小器和体育学校的中央企会。 推 和信息新闻法会、非常事故的合作协议、关闭性老牛头企业和信 ()》、算术委主任,更多数法公由空文,小算和公式的条化,更多 教法者,书记处着一书记师老鹅已老开设地,望供委先委委员,教 10.0401.000. da.

我总产业年期不能优化。1月后的代表社会发展,其外带会富力约出了 ▲+方副、生然和改革由**主要由米定甲基要利用-技术发展工业内 REXT/FARMINT/. #PERMAINFORD#++-他们国人外的日期人才和武勇、和男子央企业日期代本和人才的"事 na'.emi.hoes@towshart.rneesete.t #i422#or#2#480.g #tokdomexites 約4-2011年、25年、76月4日中小学、78里日丁製的市场工具 KA.#0-107**** CE2#311.50"-*-#"##.

来至天我出,小井上上作为国地吃养的老个力量和建设主新 S国家の業業/量、業業業以降の決定会社長を継ば業業業業 我这些决立会就算重发展,这里其常会想要争力的性质一类会 2、由空文明小学和办法教训者的小头上会称我自家的文神条件 ##·##7-步梦21展与3全形论也形式会们,标果产生融合 新建市,成人民的中央企业平等,出现,合作,在中国和各利工作 Y. WASTER, NO ADDRESS CREATING & 这个决立业空影成是不影响现。它们人才已确成长。

会上,現古臺灣(國東委 小園和市共開建市中央企業和成型 第18時合作的53、株量的2、國東會和小園和市場合作用業業者 建设,引导中央企业和供加家,党进国际产学业作,指表"一考一 時"農业、保化引引着考察者、进大产业包裹人才队员。加强中央 心会和论理新聞後,用書作学書含其屬於影,與人共興企会科書 T-作用自由非常不可能的。

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THERE LANS LARS LARANS LA STOPPHE ENSING PRAN ENANG SATERDAR LOWALDRADAR LWA S BERRAR BERR BIR BERTRING

(2) 他们来来不会问题点、大学会的小学家的时间来来。 我呆了最近天事, 不非教授小心的包括主要从天多中 EDINFURCT. PREMIPORAL AND WATED TRACKING STEATINGS 2884FAR.AUS/#22334KE.#2888 S. CHEVESAR METER &M"SROOM ADATERATION 12. 第四十四日の中国第四十四日、

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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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) $+\gamma$



Event display for VBF H(bb)

Photon



VBF jets

b-jets

Analysis strategy

Event pre-selection

Boosted decision tree

Trigger

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)



Event Selection

Two to Chan	Central F nel (1fj+2b) VBF	VBF b VBF our central Channel (2b+2j)	q' W W H W H b b b b b b b b b b
	Two central	Four central	Photon
2 b-jet	p _, >95GeV p _, >70GeV	p _, >55GeV	p _, >40GeV
2 VBF jets	p _, >60GeV, 3.2< η <4.4 p _, >20GeV, η <4.4	p_>55 GeV, η <4.4 Veto event with jet p_ >60GeV, 3.2< η <4.4	p _, >40GeV η < 4.4
Photon			E _, >30GeV
Event topology	p _, (bb)>160GeV	p _, (bb)>150GeV	p _, (bb)>80GeV M(jj) >800GeV

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

Boost decision tree analysis



MVA Input variable: photon centrality



No color connection between VBF jets and b jets in signal



Analysis strategy

Event pre-selection

Boosted decision tree

Trigger

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.



CERN-EP-2018-140

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ATLAS-CONF-2018-036

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Z,

0-lepton

l-lepton

2-lepton

VH, $H \rightarrow bb$

- VH production most sensitive mode for $H \rightarrow bb$ at the LHC
- 3 channels (0-, I-, 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 ΔR(bb) (combined into a Boosted Decision Tree)



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



VH(→bb) sensitivity

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



$H \rightarrow bb$ combination

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

Run-I+Run-2

• VH, $H \rightarrow bb$

• $ttH, H \rightarrow bb$

- $H \rightarrow bb$ combination NEW Significance: ATLAS Preliminary Is= 7 TeV, 8 TeV, and 13 TeV 4.7 fb⁻¹, 20.3 fb⁻¹, and 24.5-79.8 fb⁻¹ -Stat. —Total 5.4 σ observed (Tot.) (Stat., Syst.) VBF+ggF 1.68 +1.16 (+1.01 +0.57 -1.00 + -0.51 $(5.5\sigma \text{ expected})$ VBF(+ggF), H → bb +0.56 +0.28 +0.48 ttH 1.00 -0.27 + -0.46 (+0.14 +0.17 -0.14 -0.16 +0.22VH 0.21 **Observation of** (+0.12 +0.16 -0.12 , -0.15) +0.20 $H \rightarrow bb!!$ Comb. 1.01 HÓH -0.20 2 3 0 4 5 6 $\mu_{H \rightarrow bb}$
 - **VH** combination

NEW

- Run-2
 - VH, H → bb
 - VH, $H \rightarrow \gamma\gamma$
 - VH. H \rightarrow ZZ*

Significance:	
5.3 σ observed (4.8 σ expected)	

Observation of VH production!!

ATLAS-CONF-2018-036

N. Morange N. Wardle Higgs production modes





- 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)
1	* 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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- 31 Giacinto Piacquadio ICHEP 2018



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	* including VH	, H → bb (80 fb ⁻¹)

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