Highlights of Higgs Results from ATLAS

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山东大学

第十五届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

丹东，2018年8月21日-27日

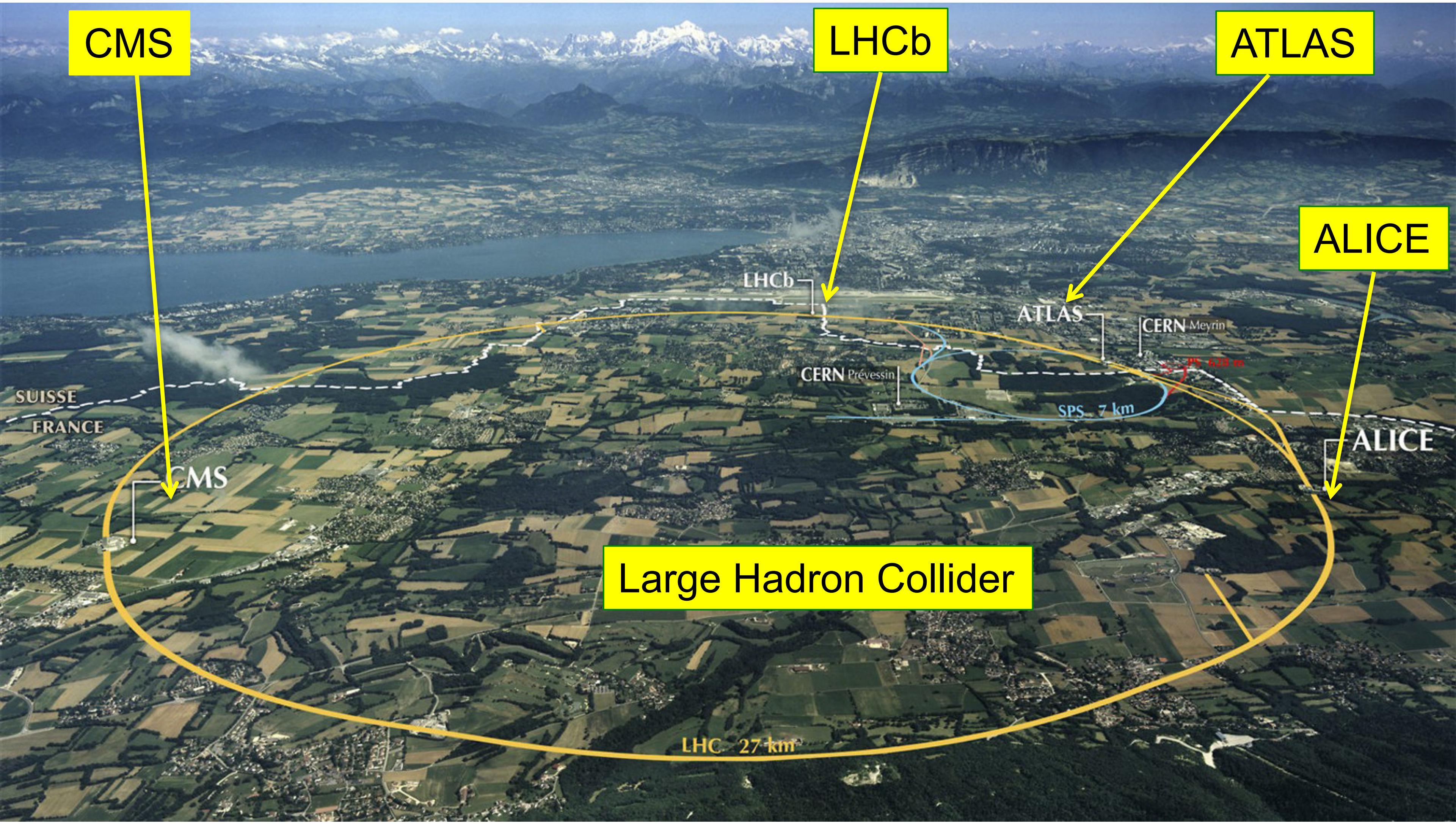
希格斯物理现状

- LHC在2012年发现了一个约125GeV的标量粒子。随后的实验结果显示，这个粒子很像标准模型预言的希格斯粒子
- 做为唯一的TeV对撞机，在LHC上直接寻找新物理仍然意义重大
- 对于Higgs物理，需要尽可能精确地测量Higgs的性质
- 并且对Higgs的所有可能的衰变末态进行测量

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

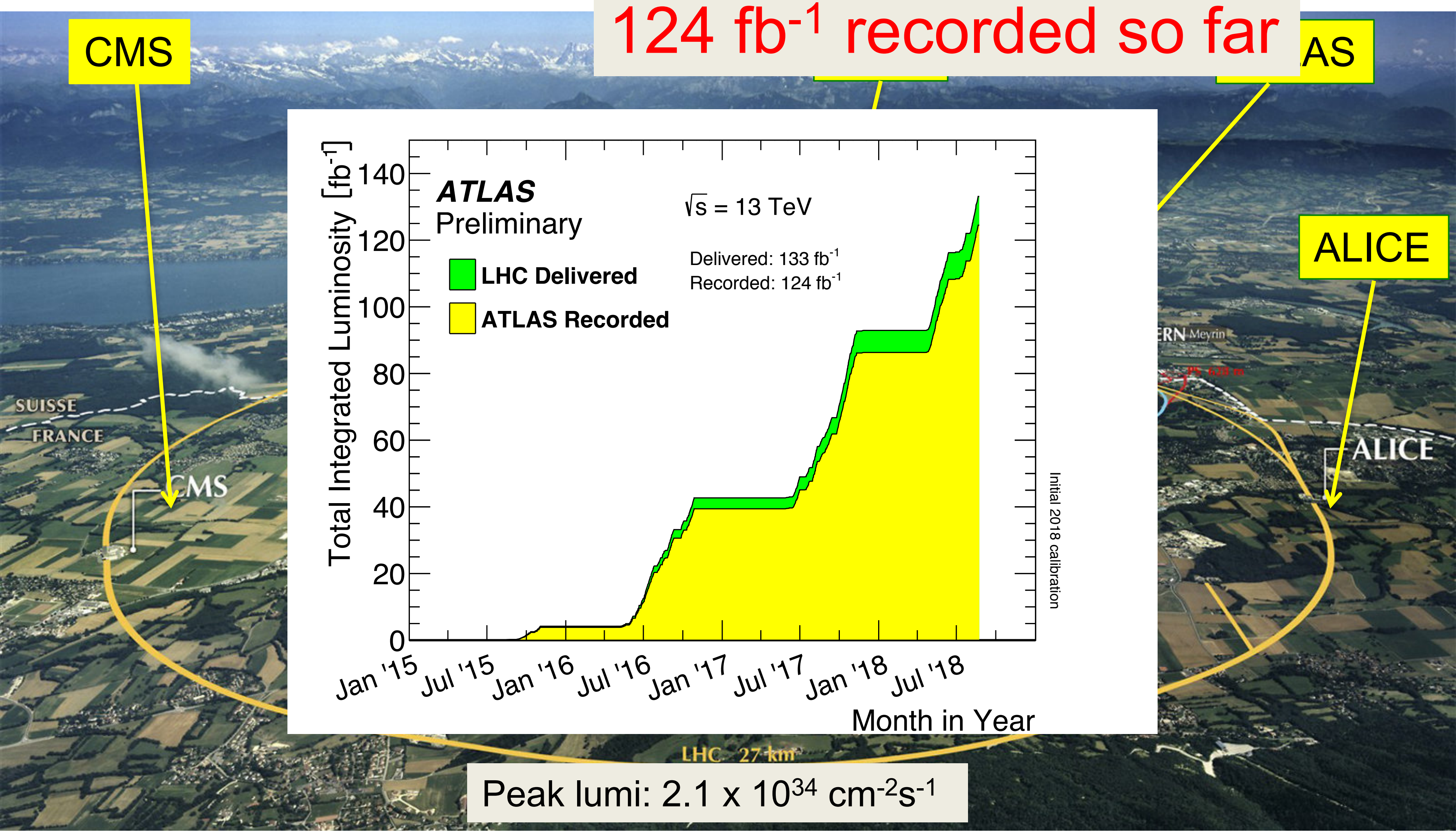
Snowmass 2013
arXiv:1310.8361

Status of LHC Data Taking



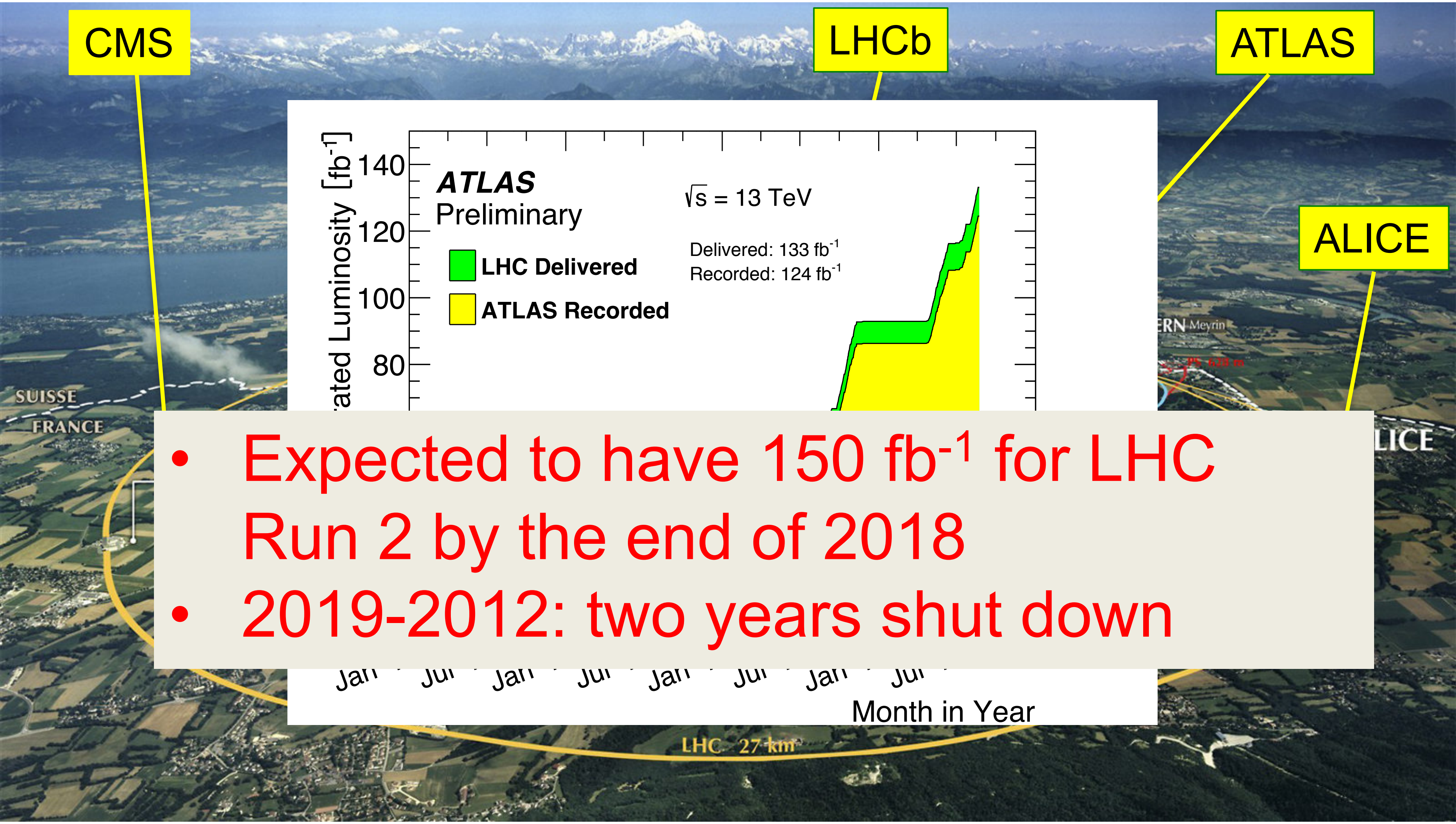
Status of LHC Data Taking

124 fb^{-1} recorded so far

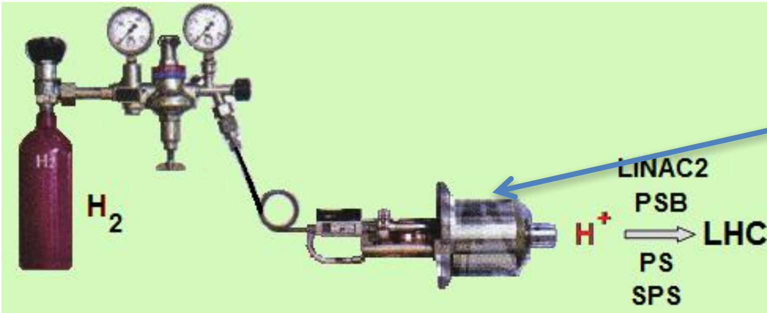


Peak lumi: 2.1 x 10^{34} cm^{-2}s^{-1}

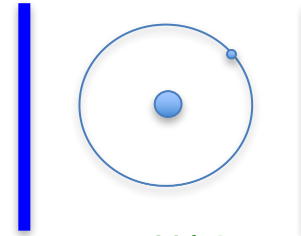
Status of LHC Data Taking



- Expected to have 150 fb^{-1} for LHC Run 2 by the end of 2018
- 2019-2012: two years shut down

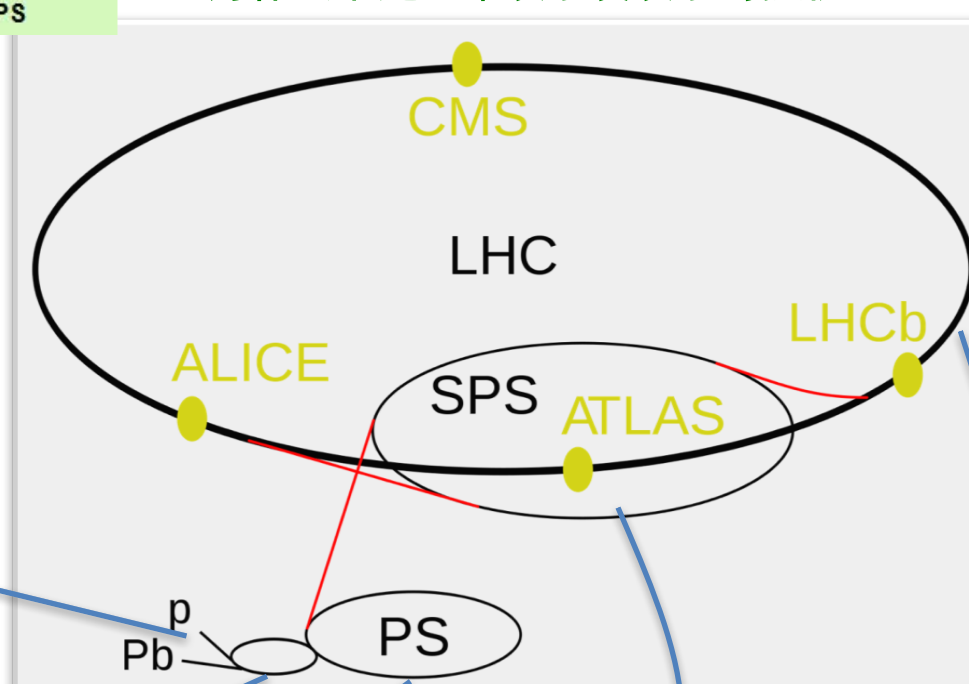


高电压



为什么不建一个质子反质子对撞机？

质子束流的制备



Linac2: 50 MeV

PS Booster: 1.4 GeV

PS: 25 GeV

CERN的第一个同步加速器

SPS: 450 GeV

W, Z Discovery

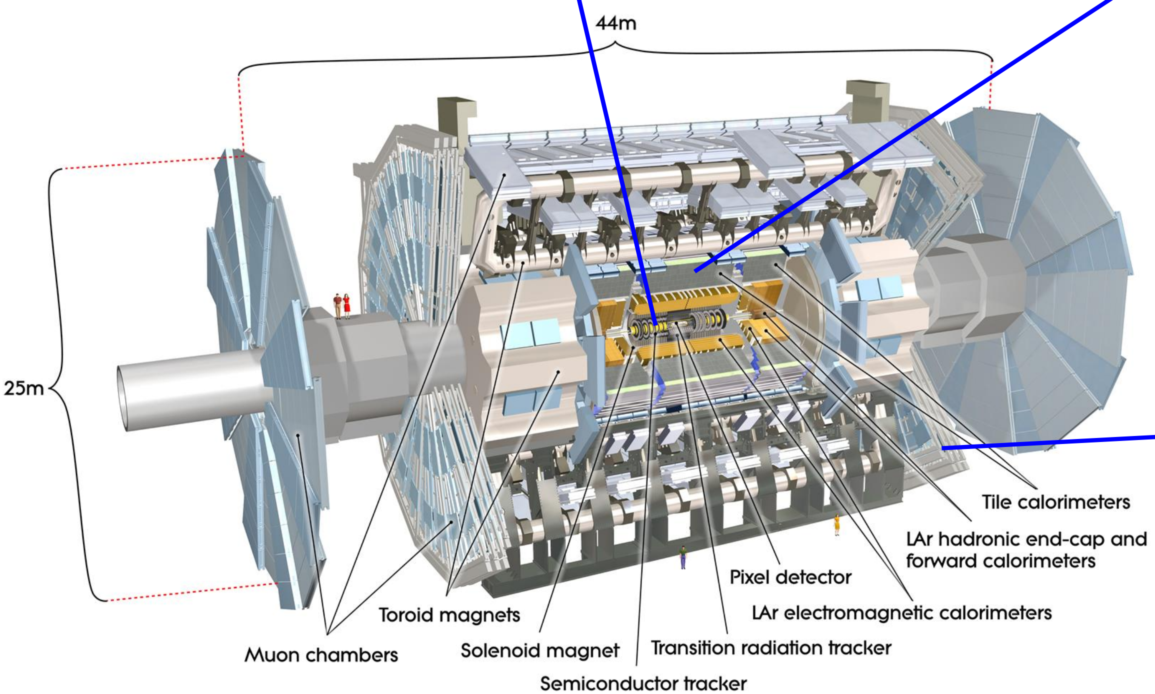
LHC: 6.5 TeV

Higgs Discovery

ATLAS 探测器

Inner Detector;
$|\eta| < 2.5$
Solenoid 2 T
Tracking and vertexing
$\sigma/p_T \sim 0.05\% \cdot p_T \oplus 1\%$

Calorimeter;
$|\eta| < 4.9$
EM : Pb-LAr; $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$
Had : Fe-Scint.; $\sigma/E \sim 50\%/\sqrt{E} \oplus 4\%$

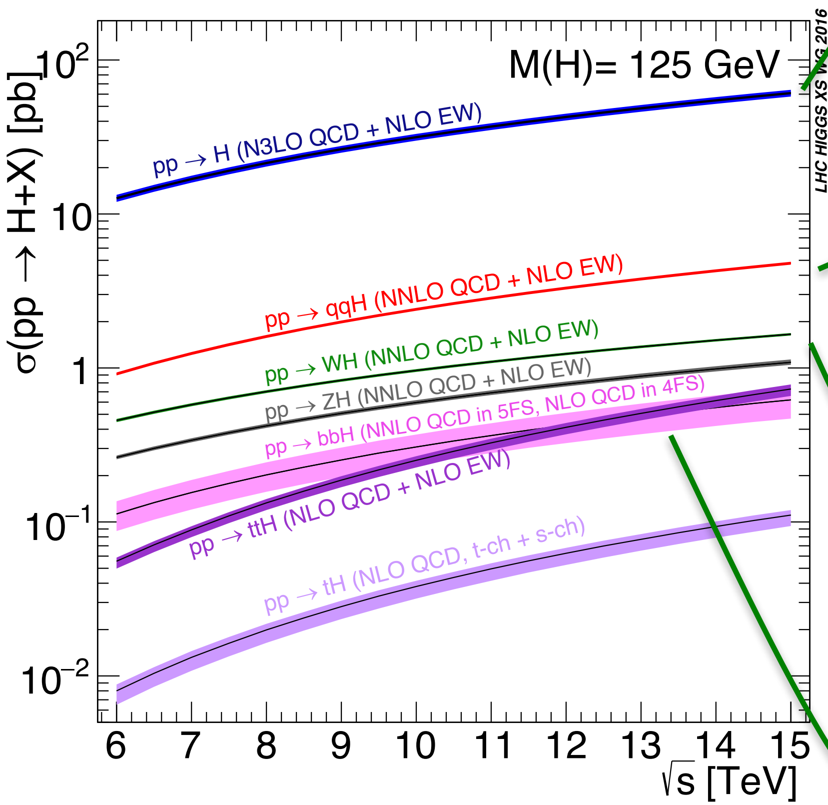


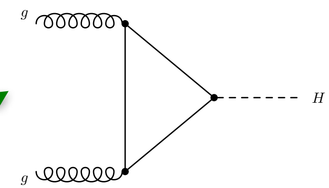
Muon Spectrometer;
$|\eta| < 2.7$
Air-core toroidal & gas chambers
$\sigma/p_T \sim 2\%$ @ 50 GeV
$\sigma/p_T \sim 10\%$ @ 1 TeV

40 m long, 25 m high. 100 M read-out channels

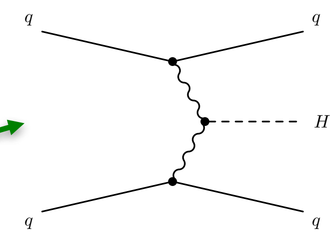
LHC上希格斯玻色子的产生

LHC Higgs Cross Section Working Group

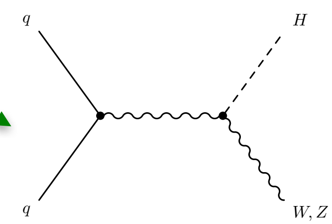




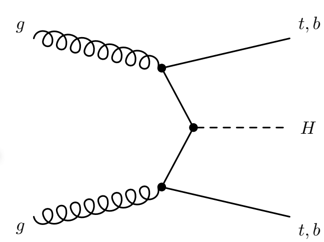
ggF: dominant, larger initial state radiation from gluons



VBF: two forward jets with high mass and large rapidity gap



VH: vector boson (lv, ll', qq')

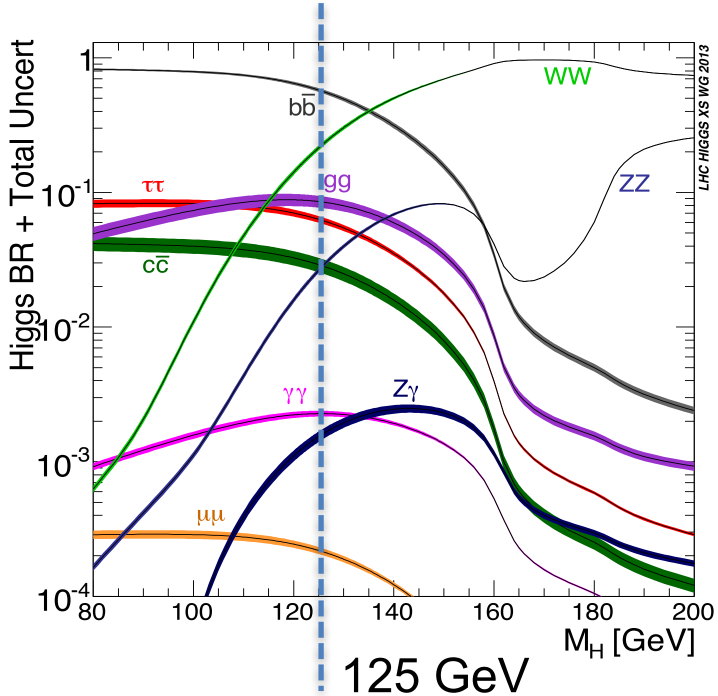


ttH: many b-jets, leptons, E_T^{miss}

With 80 fb-1, about 4M ggF events, 300K VBF, 200K VH and 40K ttH events

希格斯玻色子的衰变

LHC Higgs Cross Section Working Group



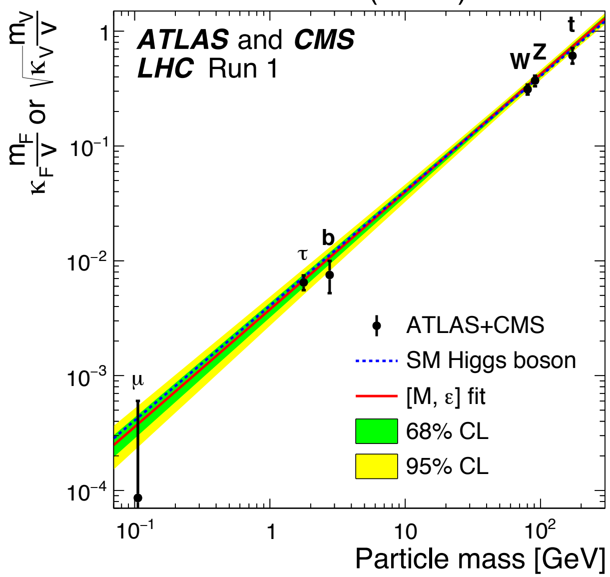
m_H=125 GeV

Higgs decays	**BR [%]**
$H \to bb$	57.8
$H \to WW$	21.4
$H \to gg$	8.19
$H \to \tau\tau$	6.27
$H \to ZZ$	2.62
$H \to cc$	2.89
$H \to \gamma\gamma$	0.227
$H \to Z\gamma$	0.153
$H \to \mu\mu$	0.022

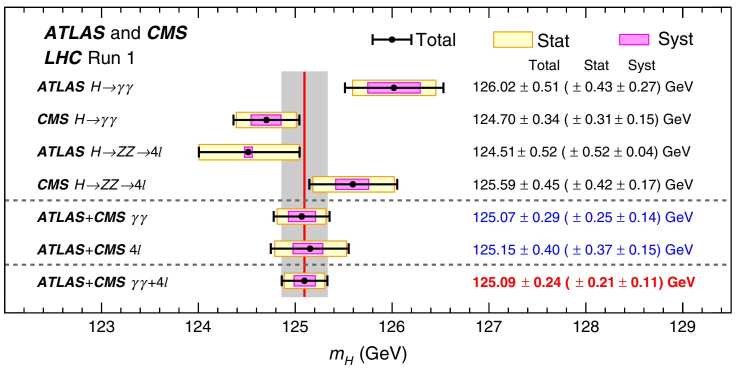
- Observations: low BR channels (ZZ→4l, γγ, Zγ and μμ) have better mass resolutions but small rate. Channels with higher BRs (the rest) are challenging experimentally

LHC Run 1 Legacy

JHEP 08 (2016) 045



PRL 114, 191803 (2015)



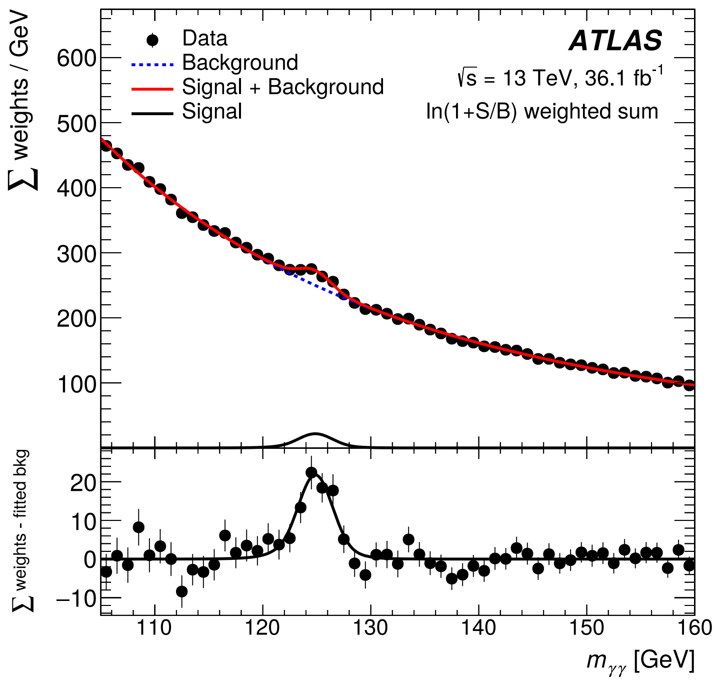
Higgs Mass

Higgs Boson Mass

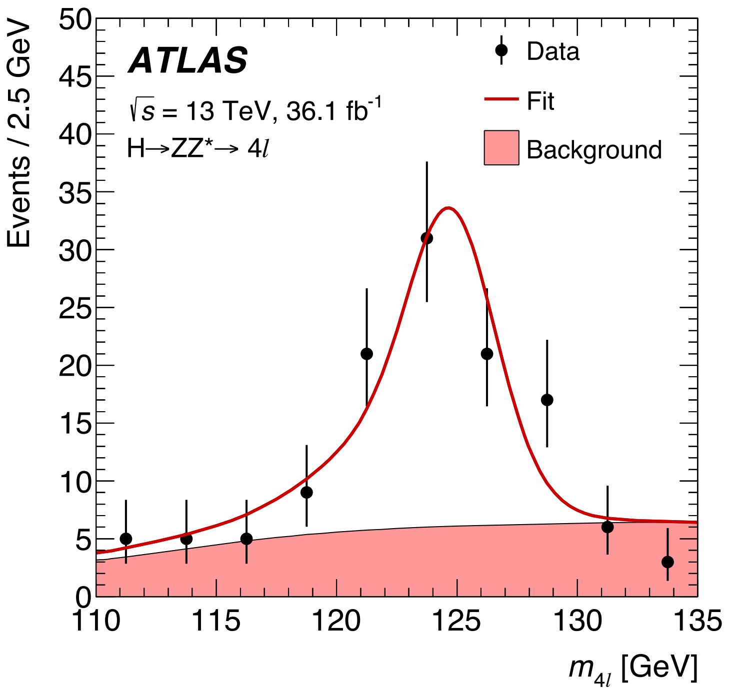
arXiv: 1806.00242

- Higgs mass is the only free parameter in BEH mechanism
- Use 36 fb^{-1} LHC Run 2 data, with $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$

$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ \rightarrow 4l$

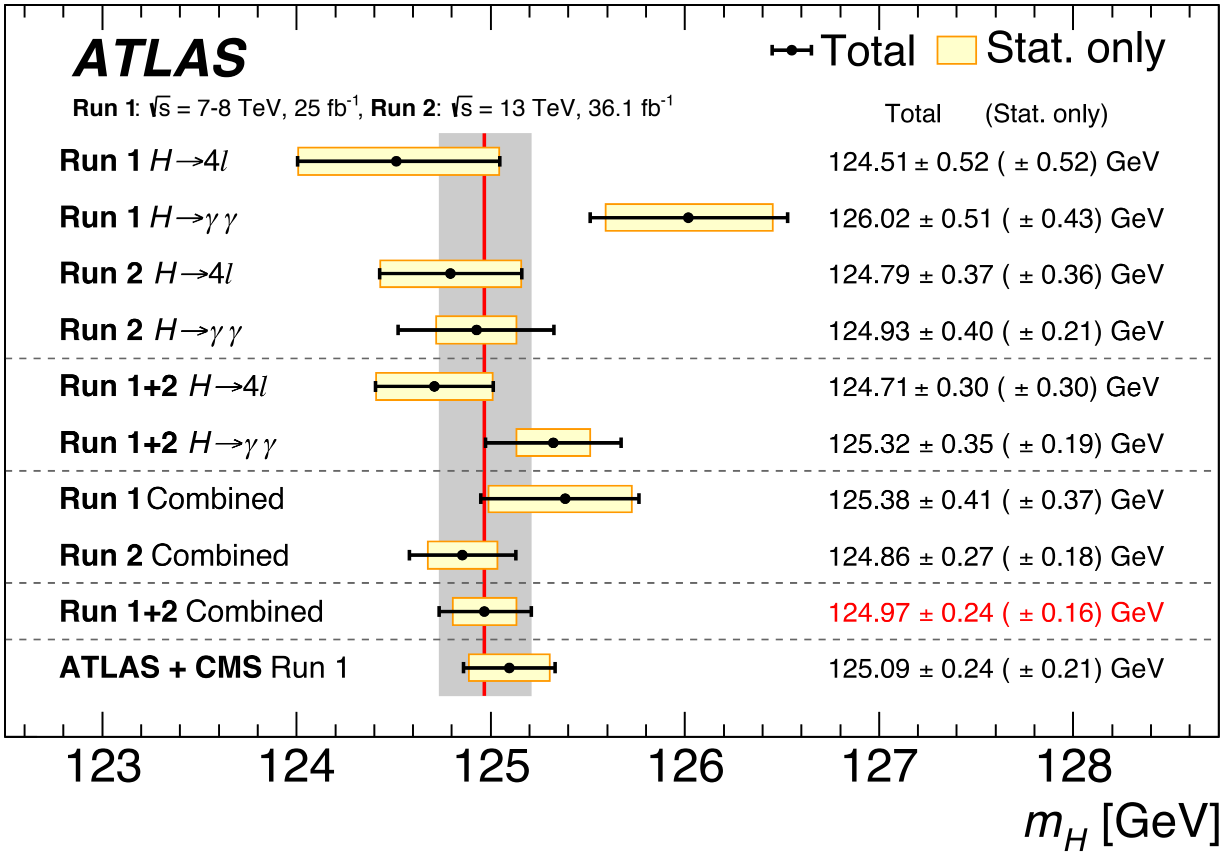


$$m_H = 124.93 \pm 0.40 \text{ GeV}$$

$$m_H = 124.79 \pm 0.37 \text{ GeV}$$

Higgs Boson Mass

arXiv: 1806.00242



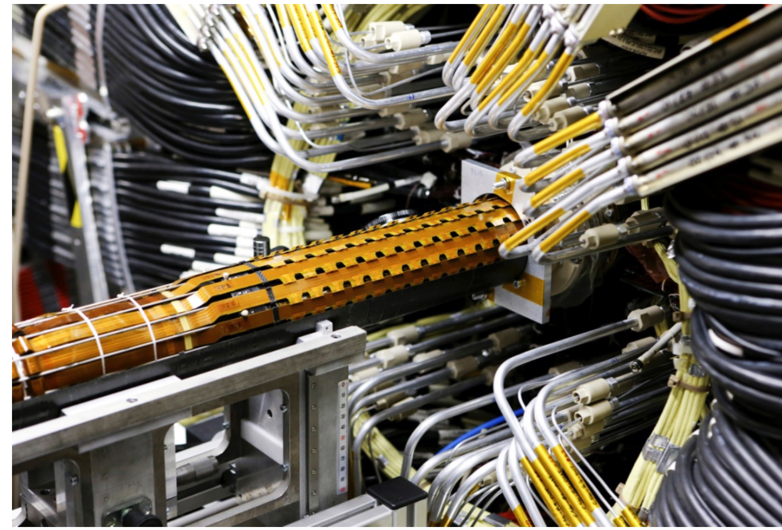
ATLAS Run1+2 combined: $m_H = 124.97 \pm 0.24$ GeV

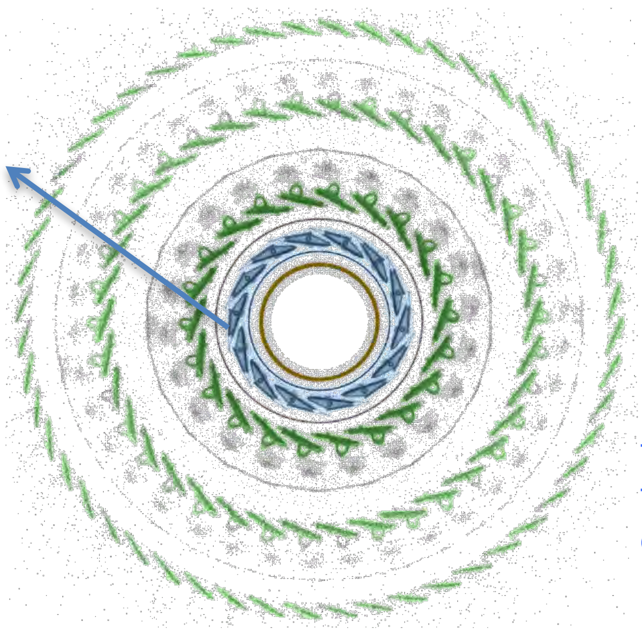
- Precise object reconstruction is important for this measurement
- H→ZZ is still statistics limited; $H\to\gamma\gamma$ is systematics limited (photon energy scale)

ttH

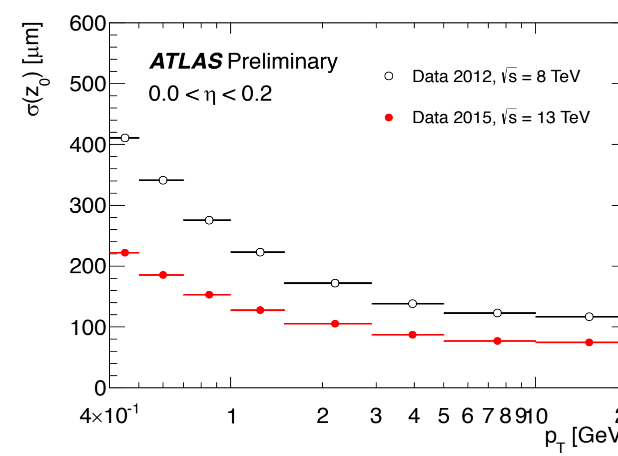
ATLAS Upgrade Phase-0

- Innermost silicon pixel detector layer (IBL)
- 33 mm from beam
- Improve tracking and bjet tagging (~4 times better for light flavor jet rejection)



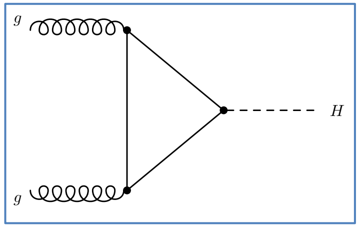


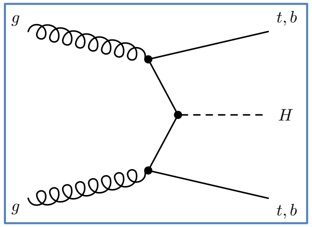
B hadron with p_T=50 GeV will travel 3 mm in the transverse direction



ttH

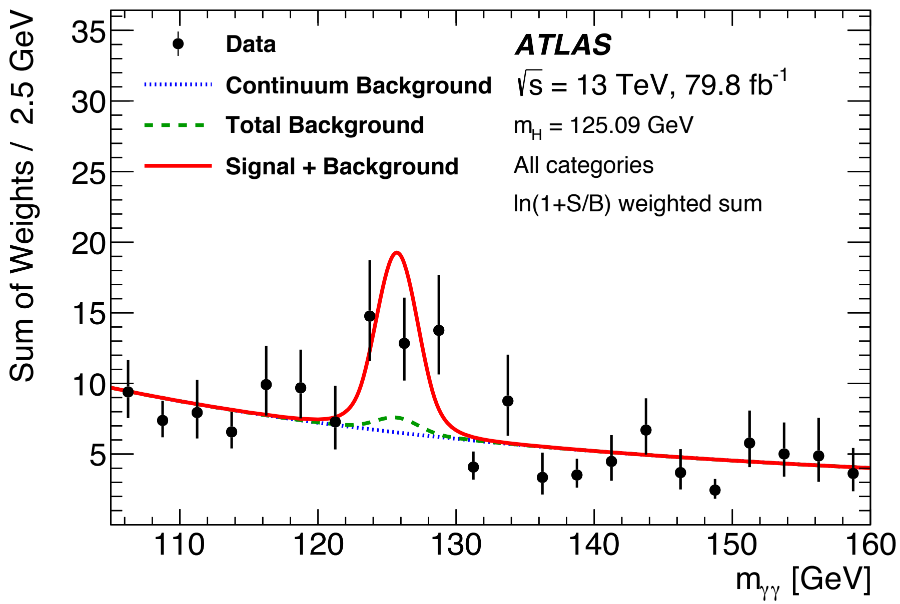
arXiv:1806.00425

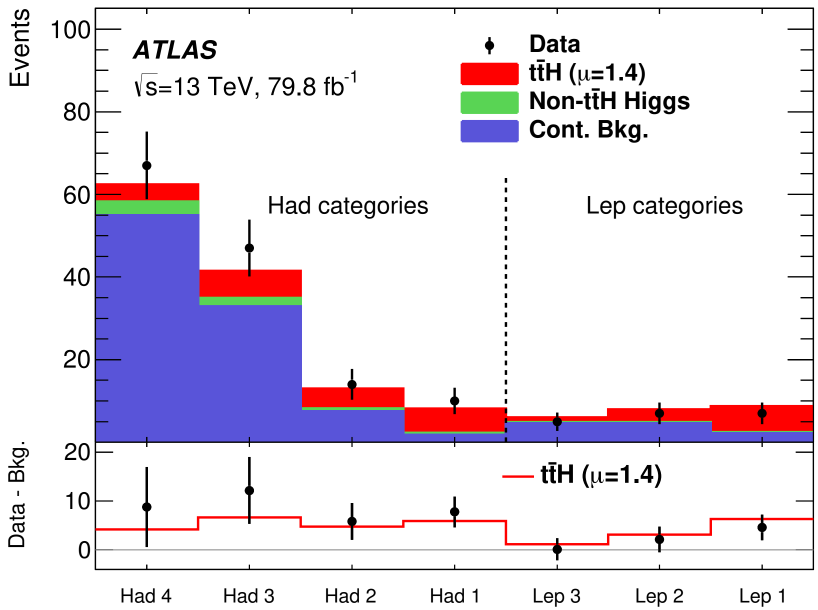




ttH allows direct probe of top Higgs Yukawa coupling

ttH, H→$\gamma\gamma$

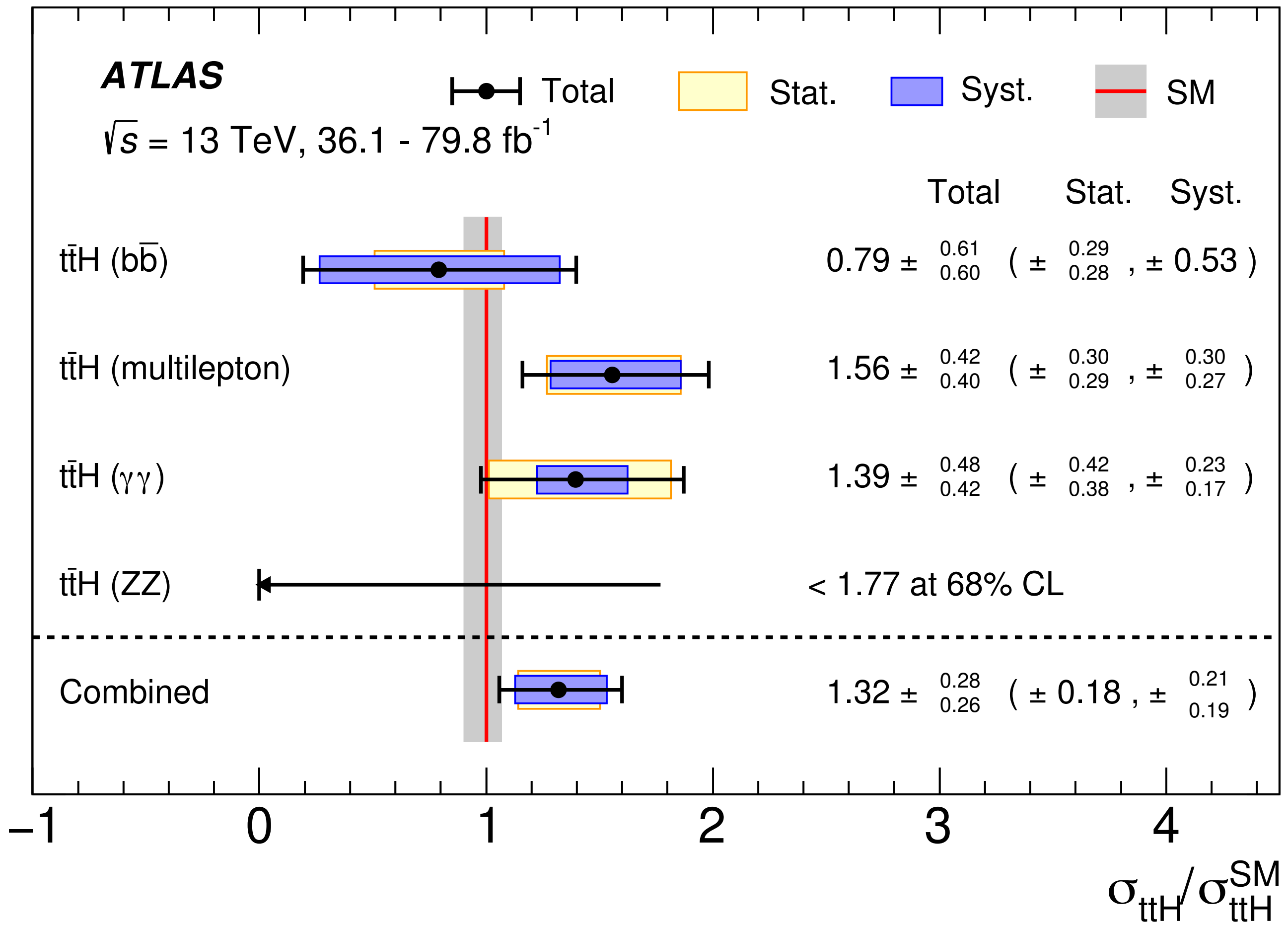




Significance: 4.1σ (3.7σ exp.)

ttH

arXiv:1806.00425



Combined with Run 1 data, Significance: 6.3σ (5.1σ exp.)

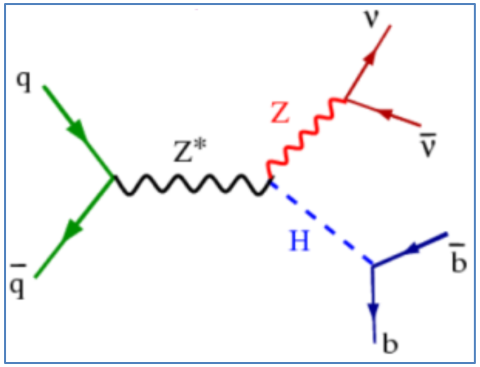
Observation of ttH production mode

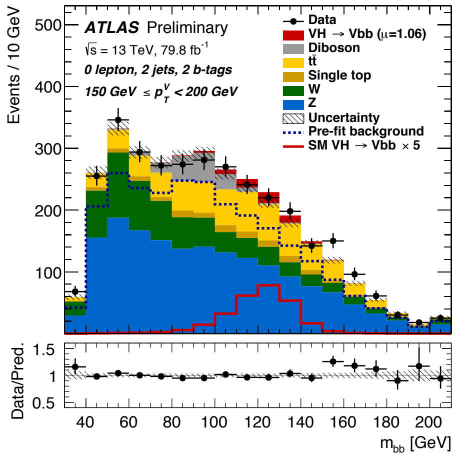
$H \rightarrow bb$

H→bb

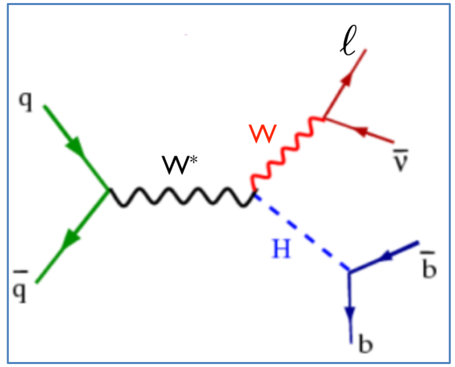
- About 58% of Higgs decay to bb

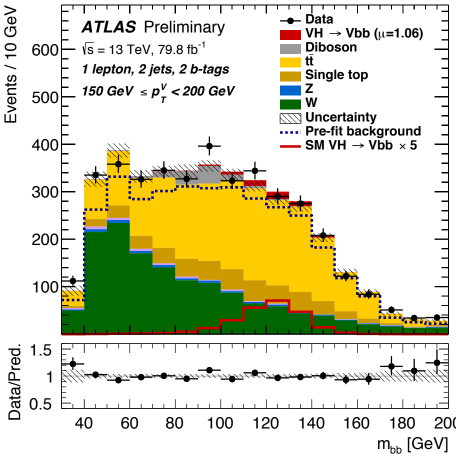
0-lepton



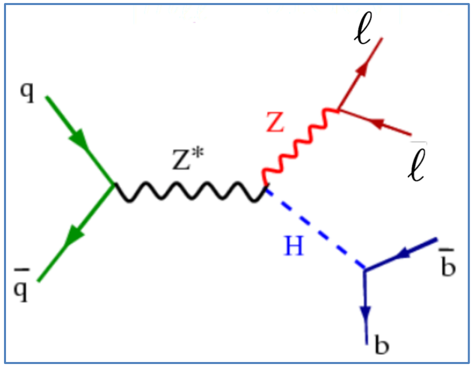


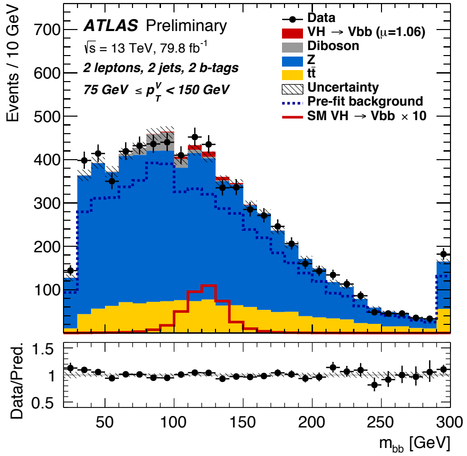
1-lepton





2-lepton





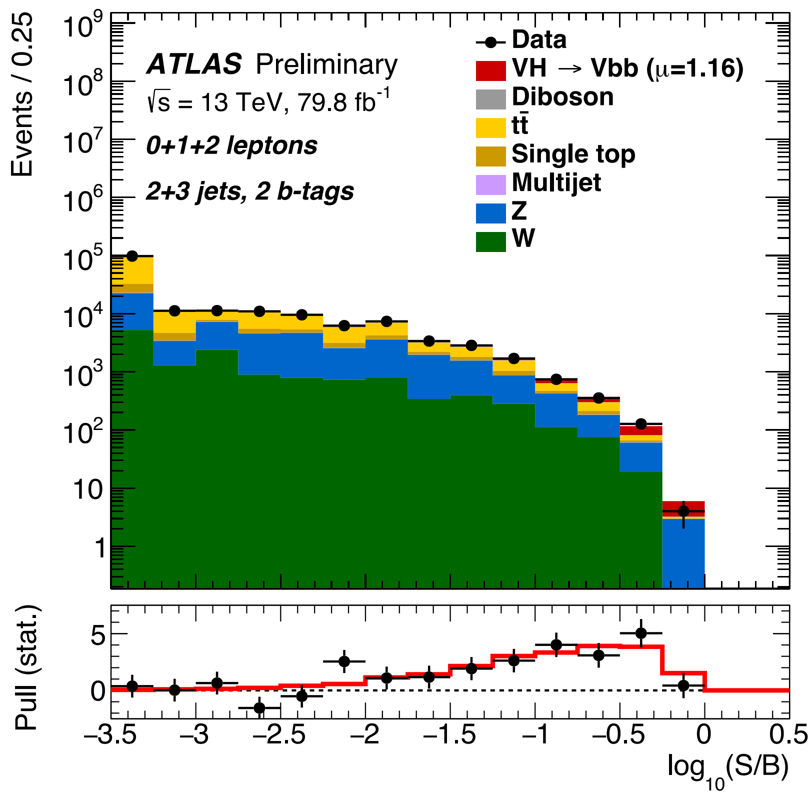
Select 2 b-tagged jets and pT(V) > 75 GeV or 150 GeV

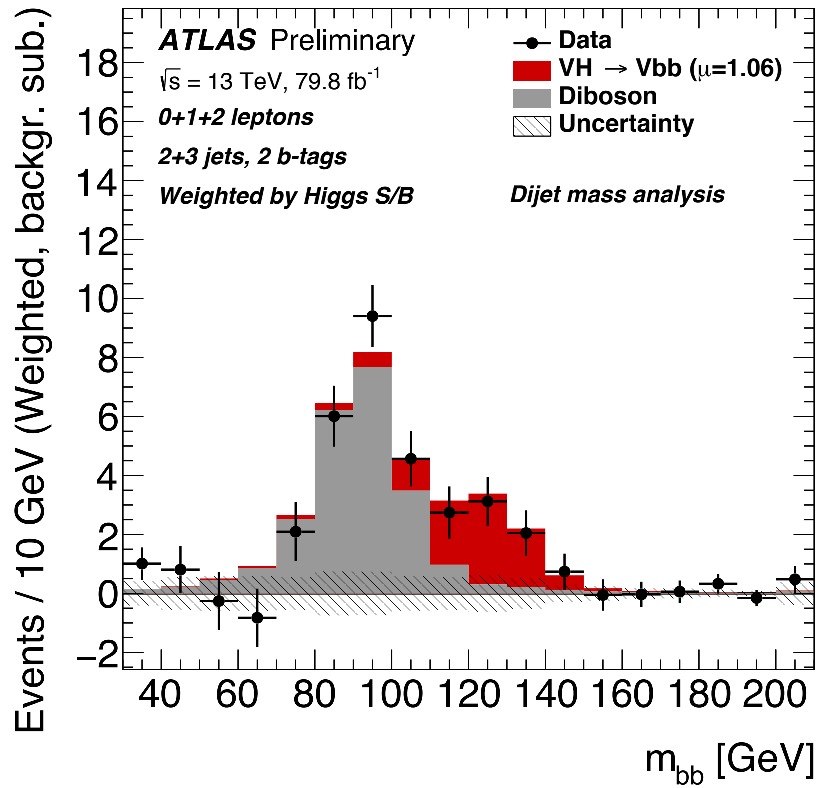
H→bb

ATLAS-CONF-2018-036

- Combine several variables with BDT (m_{bb}, p_T^V, ΔR_{bb} etc.)

Event yields





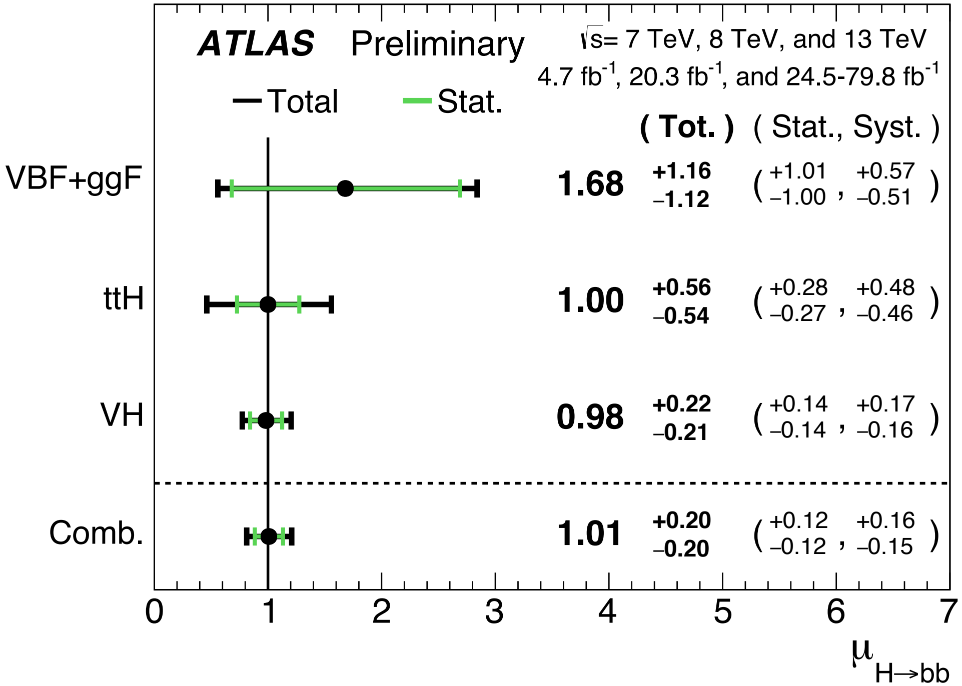
Combined with Run 1 data,
Significance: 4.9σ (5.1σ exp.)

$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.}),$$

(Run 2 data)

H→bb

ATLAS-CONF-2018-036



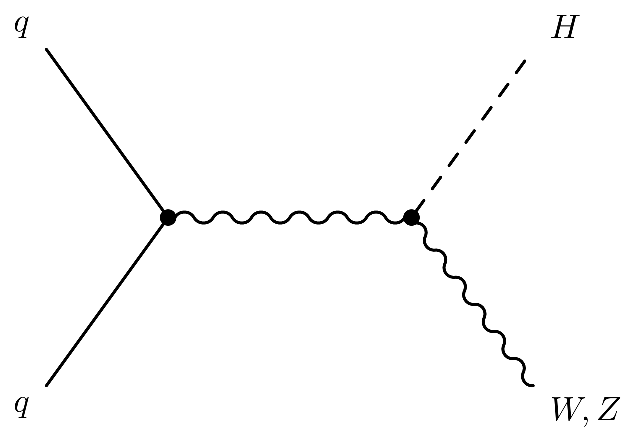
- Combined Run 1 and Run 2 data
- Include VH, H→bb; VBF+ggF, H→bb; ttH, H→bb

Significance: 5.4σ (5.5σ exp.)

Observation of H→bb

VH

ATLAS-CONF-2018-036



Include VH, H→bb;
VH, H→$\gamma\gamma$;
VH, H→ZZ

Significance: 5.3σ (4.8σ exp.)

Observation of VH production mode

CERN-LHC Seminar

CERN-LHC Seminar on **Tuesday 28 August** in Filtration Plant (222-R-001) at 11h00:

Observation of the H->b bbar decay at ATLAS and CMS

https://indico.cern.ch/event/750541/

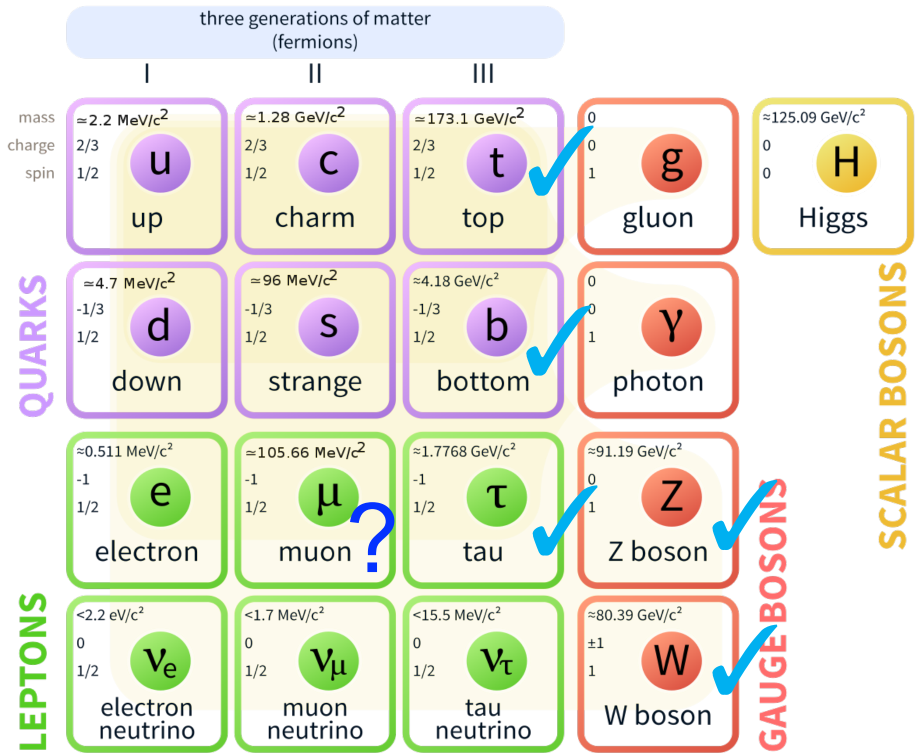
Abstract:

This seminar presents the observation of the Higgs boson decay to a bottom quark-antiquark pair by the ATLAS and CMS experiments. The results presented use all available datasets from the LHC Run 1 and Run 2 including the most recent 13 TeV dataset that corresponds to an integrated luminosity of ~80 fb^-1. The analysis strategy and the background estimation techniques are discussed and a comprehensive set of measurements are presented.

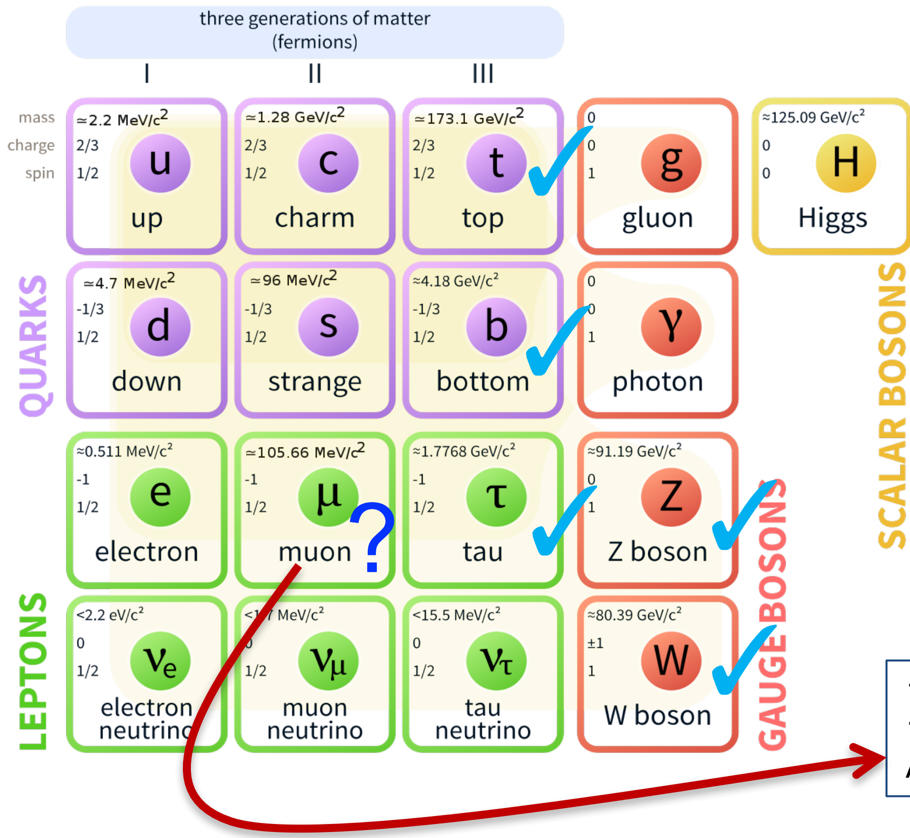
$H \longrightarrow \mu\mu$

BR=0.02%

Higgs Couplings to Massive Elementary Particles



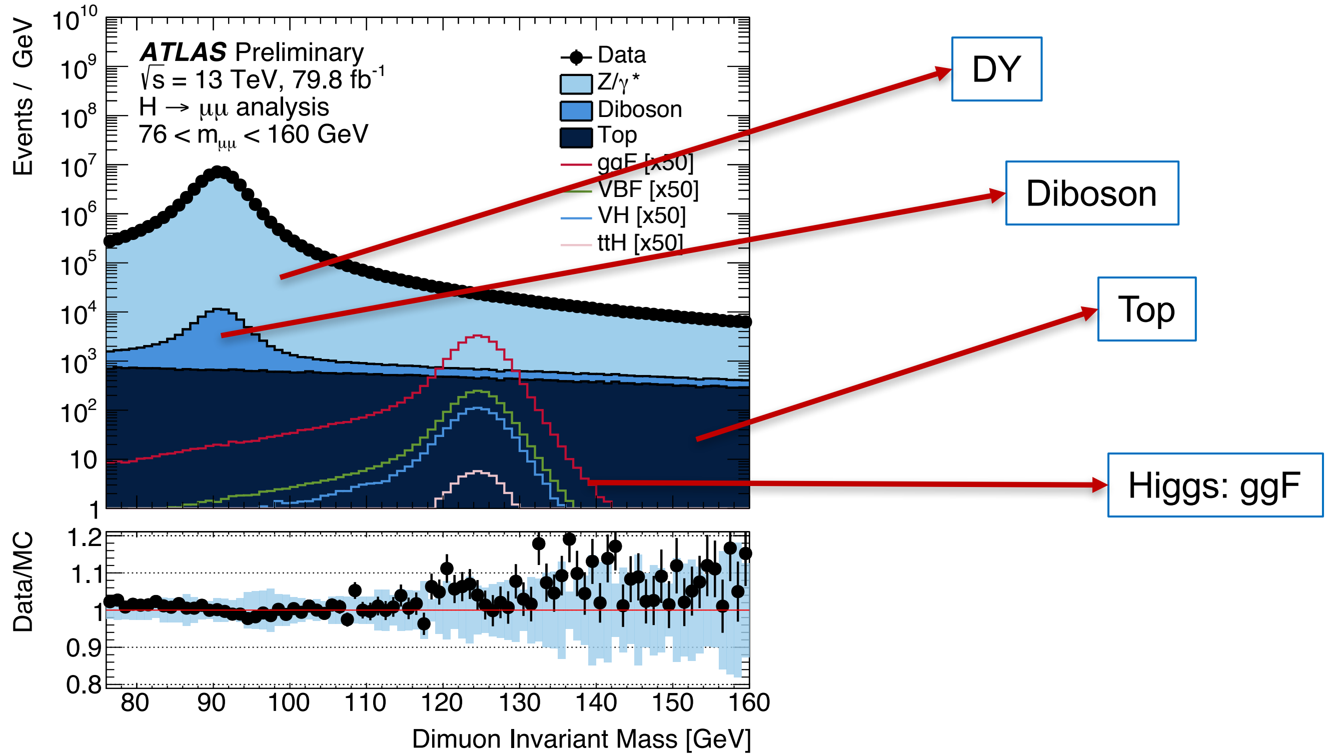
Higgs Couplings to Massive Elementary Particles



106 MeV particle
1937, S.H. Neddermeyer, C.D. Anderson

H→$\mu\mu$

- Dominant background is Drell-Yan process
- Dedicated categories for ggF abd VBF
- Use analytic functions to model signal and backgrounds



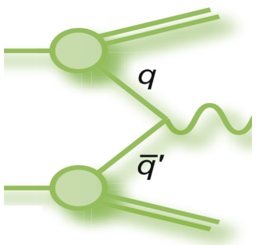
ATLAS-CONF-2018-026

H→$\mu\mu$ ggF

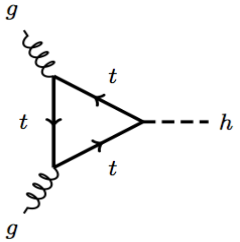
- Signal has more ISR than background. Signal tends to have large $p_T^{\mu\mu}$ than background

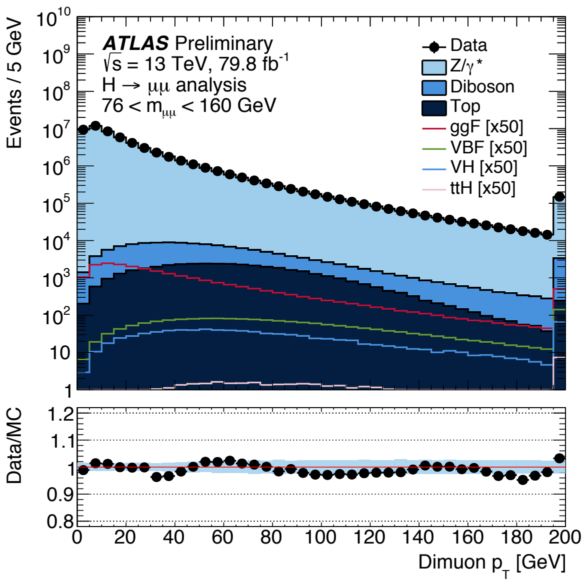
ATLAS-CONF-2018-026

Background



Signal





$H \rightarrow \mu\mu$ VBF

ATLAS

- Multivariate analysis method is used for VBF category to get better sensitivity
- 14 variables are used to train a BDT (most sensitive ones: m_{jj}, $\Delta\eta_{jj}$, $p_T^{\mu\mu}$, ΔR_{jj})
- Cut on BDT score to have `VBF Tight` (BDT $>$ 0.885) and `VBF Loose` (0.685$<$ BDT $<$ 0.885) [1]
- Events with BDT $<$ 0.685 are classified as ggF-like events

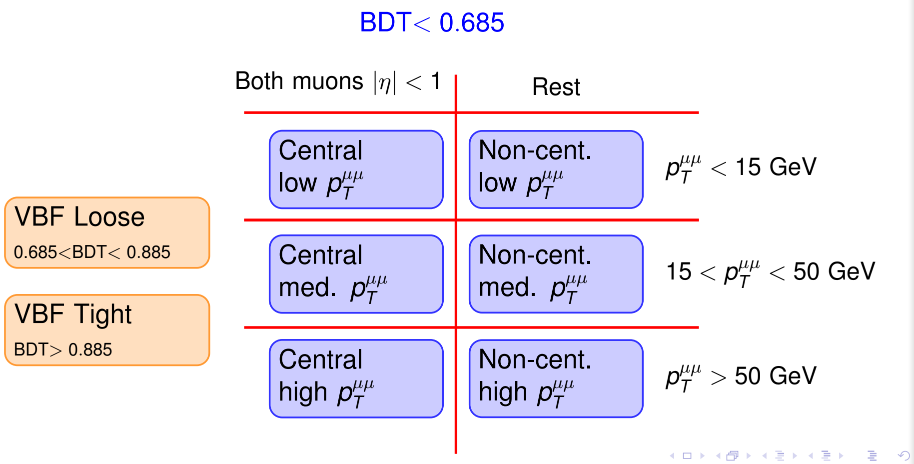
CMS

Trained a BDT

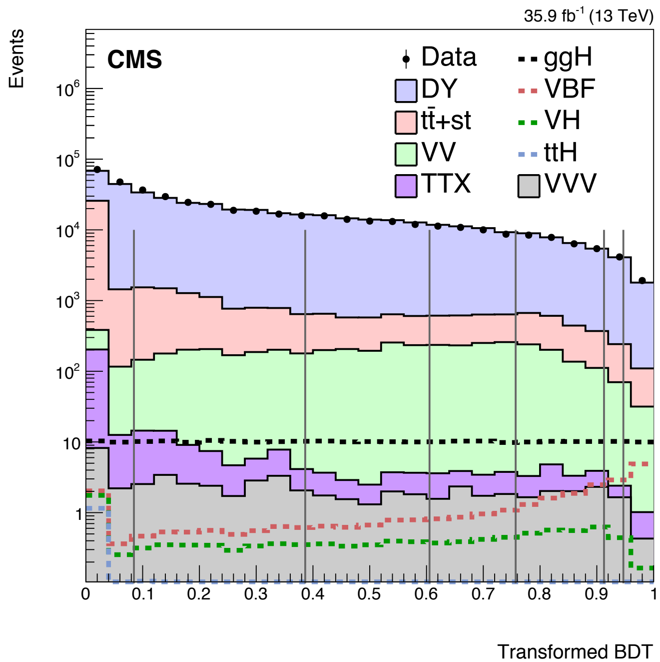
- pT, eta of dimuon system
- Δη, Δφ between the muons
- η of the two highest pT jets
- mass and Δη between the jets
- N. jets; N. btagged jets

H→$\mu\mu$ Categorization

ATLAS



CMS

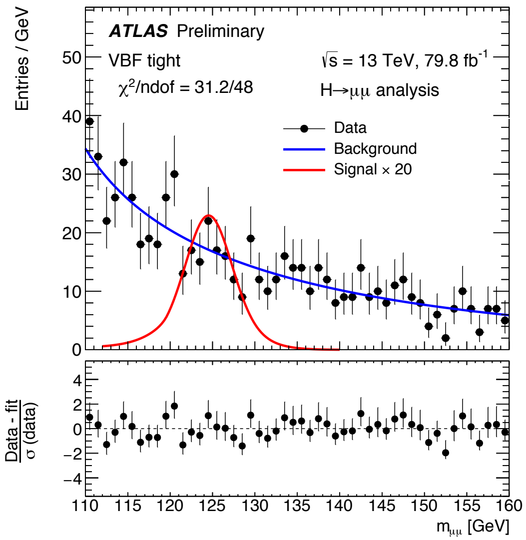


H→μμ Results

ATLAS

ATLAS-CONF-2018-026

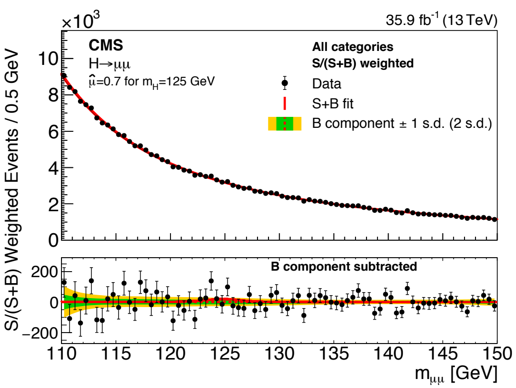
VBF tight

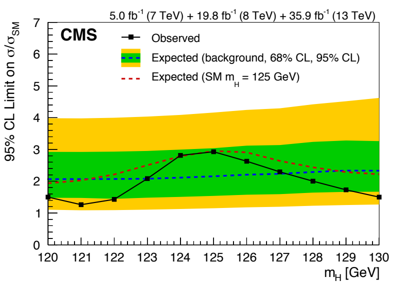


Upper limits on signal strength: 2.1 (2.0 exp.)
Significance: 0σ (0.9σ)

CMS

arXiv: 1807.06325



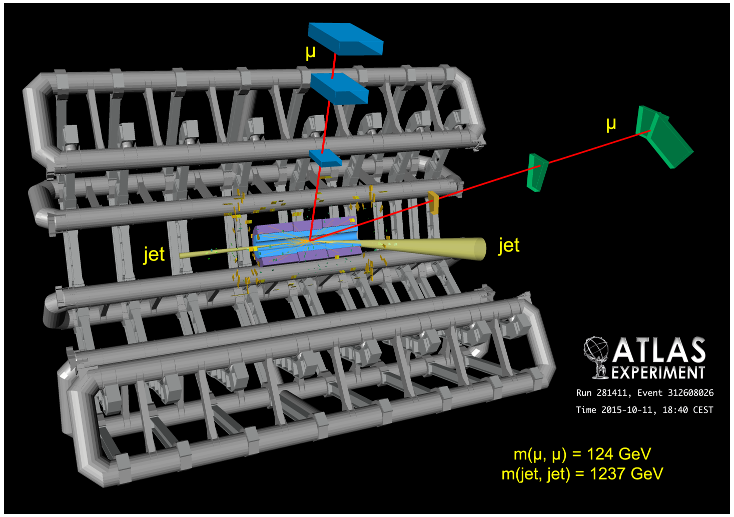


Upper limits on signal strength: 2.92 (2.16 exp.)
Significance: 0.9σ

$H \to \mu\mu$ Results from Last Publication

Data: 2015+2016 LHC *pp* collisions data. Integrated luminosity: 36.1 fb^{-1}

Phys. Rev. Lett. 119, 051802 (2017)
PRL Editors' Suggestion



Upper limit on signal strength

	Observed	Expected
Run-2	3.0	3.1
Run-1&Run-2	2.8	2.9

Measurement of signal strength

	$\hat{\mu}$
Run-2	-0.1 ± 1.5
Run-1&Run-2	-0.1 ± 1.4

Some recent theory papers citing H $\rightarrow \mu\mu$ paper

To 理论家：

PHYSICAL REVIEW LETTERS **121,** 021801 (2018)

Higgs Pair Production as a Signal of Enhanced Yukawa Couplings

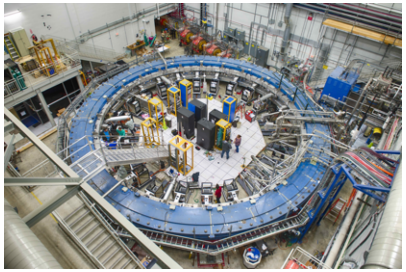
Martin Bauer,[1] Marcela Carena,[2,3,4] and Adrián Carmona[5]
[1]*Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[2]*Fermilab, Post Office Box 500, Batavia, Illinois 60510, USA*
[3]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[4]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois 60637, USA*
[5]*PRISMA Cluster of Excellence & Mainz Institute for Theoretical Physics, Johannes Gutenberg University, 55099 Mainz, Germany*

FNAL Muon g-2 Experimental Hall

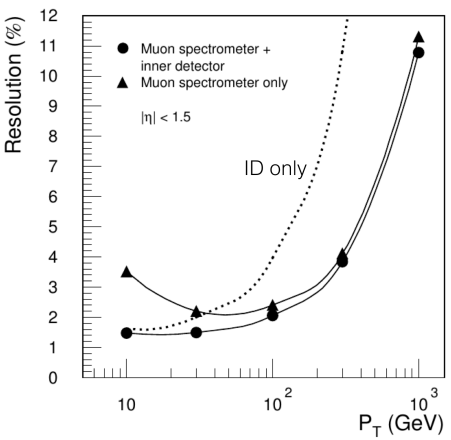
arXiv: 1807.11484

Combined explanations of $(g-2)_{\mu,e}$ and implications for a large muon EDM

Andreas Crivellin,[1] Martin Hoferichter,[2] and Philipp Schmidt-Wellenburg[1]
[1]*Paul Scherrer Institut, CH–5232 Villigen PSI, Switzerland*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*



To 实验家：



- Most $H \to \mu\mu$ signal have muon pT between 50 GeV and 100 GeV.
- Sensitivity to signal is proportional to the $1/\sqrt{\sigma}$

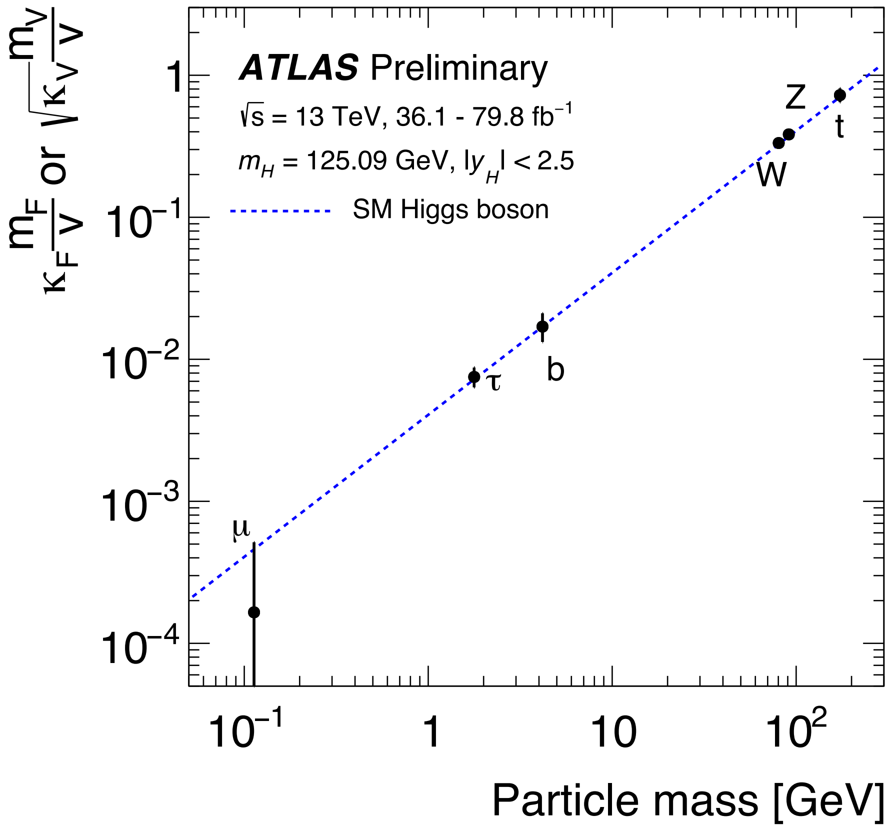
$$\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma}}$$

Improving the dimuon mass resolution is the key to find $H \to \mu\mu$ signal at LHC

A good inner tracking detector is so important for hadron collider experiments

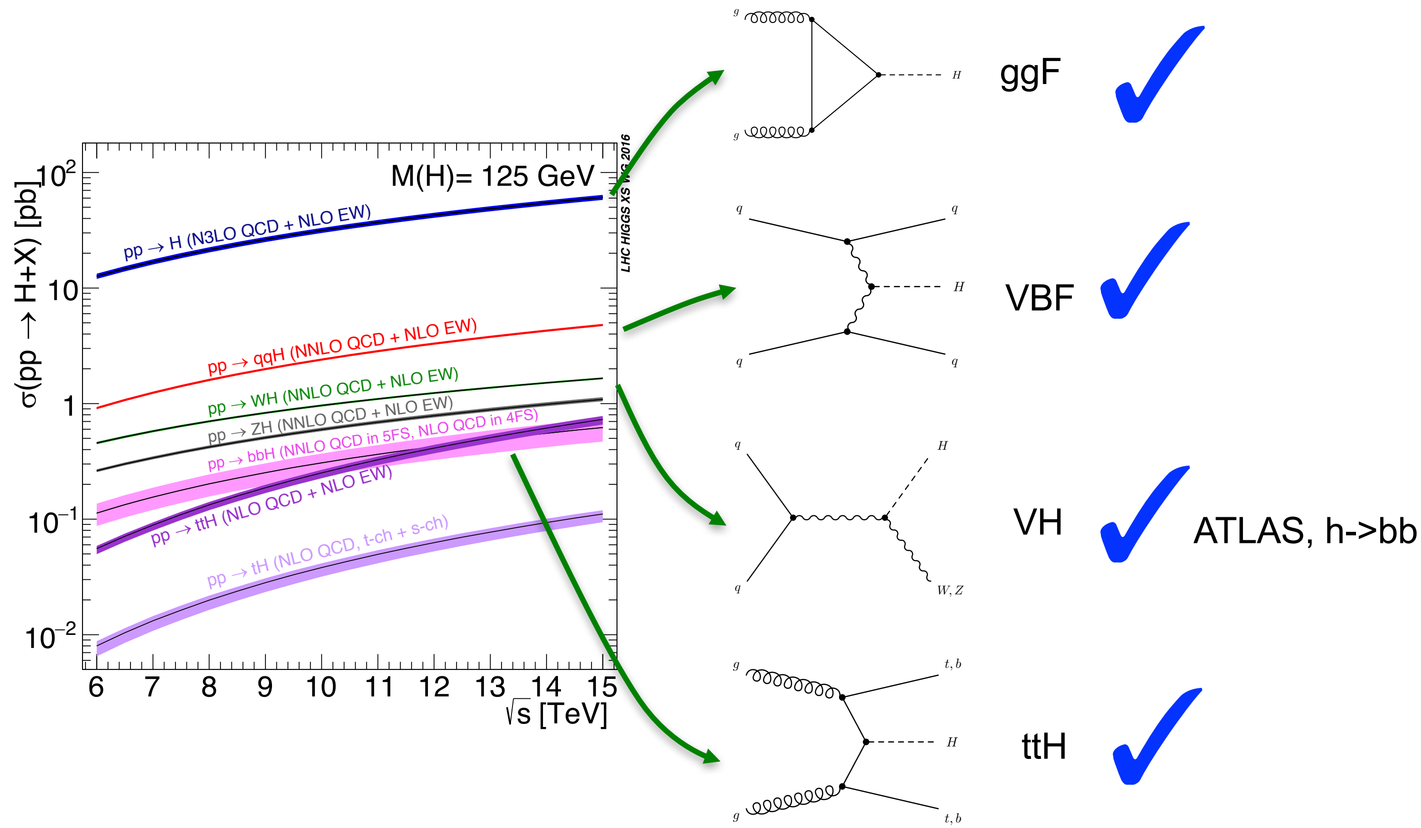
Combined measurement of Higgs couplings

ATLAS-CONF-2018-031



Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	36.1
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1

LHC观测到了Higgs四个主要产生道



Higgs粒子的衰变

m_H=125 GeV

	Higgs decays	BR [%]
✓	$H \to bb$	57.8
✓	$H \to WW$	21.4
	$H \to gg$	8.19
✓	$H \to \tau\tau$	6.27
✓	$H \to ZZ$	2.62
	$H \to cc$	2.89
✓	$H \to \gamma\gamma$	0.227
?	$H \to Z\gamma$	0.153
?	$H \to \mu\mu$	0.022

H->cc: LHC上不可能. Future e+e- collider

? + H -> unknown particles.

Summary

- ATLAS has performed Higgs measurements using 80 fb^{-1} LHC Run 2 data
- Observed ttH and VH production modes
- Observed $H \rightarrow bb$ decay mode
- For $H \rightarrow \mu\mu$, upper limit is 2.1 times SM prediction at 95% CL

- No obvious deviation from SM is found at Higgs sector at LHC

新版瑞士法郎纸币使用了LHC实验上的对撞事例图案

Backup

Higgs mass measurement systematics

Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10