

LHCでのHiggs研究

東大ICEPP

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基研研究会 素粒子物理学の進展2016

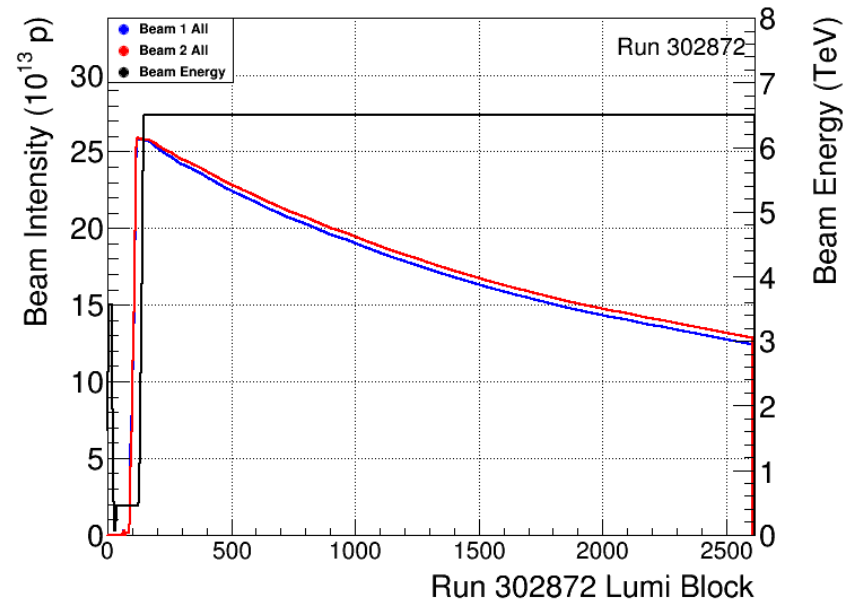
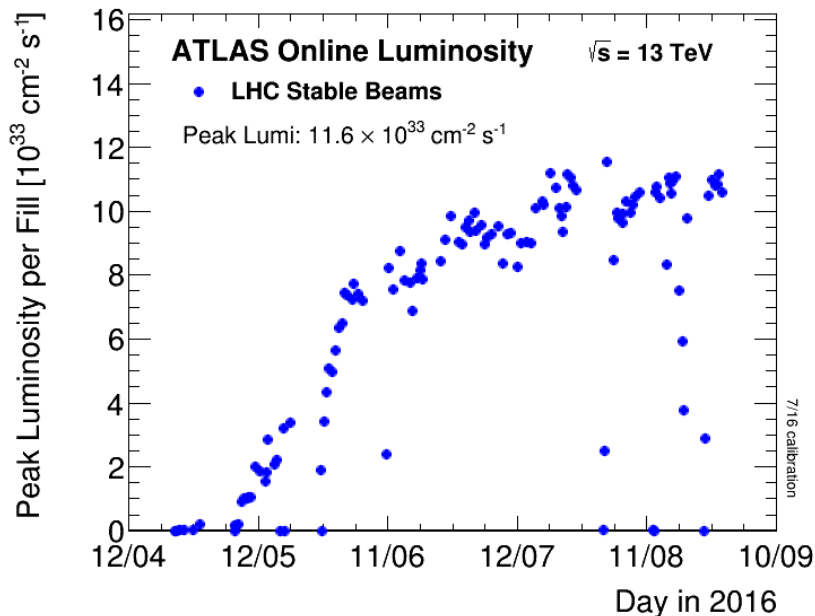
2016年9月5日－9月9日
於 京都大学 基礎物理学研究所

目次

- イントロ
 - LHCとATLASの運転状況
- SM Higgsの最新結果
 - Bosonic channel : $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$
 - Fermionic channel : $H \rightarrow bb$, ttH
- VV/VH resonance search
- まとめ

LHC 13 TeV run (2015-)

- ICHEP前はまさに絶好調！
 - ICHEPのデータセットは最大15 fb⁻¹
 - 現在までの積分ルミノシティは23 fb⁻¹.
 - 瞬間ルミノシティは $1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - 一回のFillで700 pb⁻¹を貯めた。
- 今年は落雷などによる停電もなく、素晴らしいパフォーマンス。



LHC加速器

	2015年(11月)	2016年(8月)	LHCの設計値
エネルギー [TeV]	6.5	6.5	7
バンチ間隔 [ns]	25	25	25
陽子数 [10^{14}]	~2.5	~2.5	1.15
衝突バンチ数	2232 (18トレイン)	2160 (23トレイン)	2736
beta* [cm]	80	40	50
ピークルミノシティ [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	~0.5	~1.2	1



- 設計値を越えつつある。
- ピークルミノシティはまだ伸びる予定。
- 実験側は。。

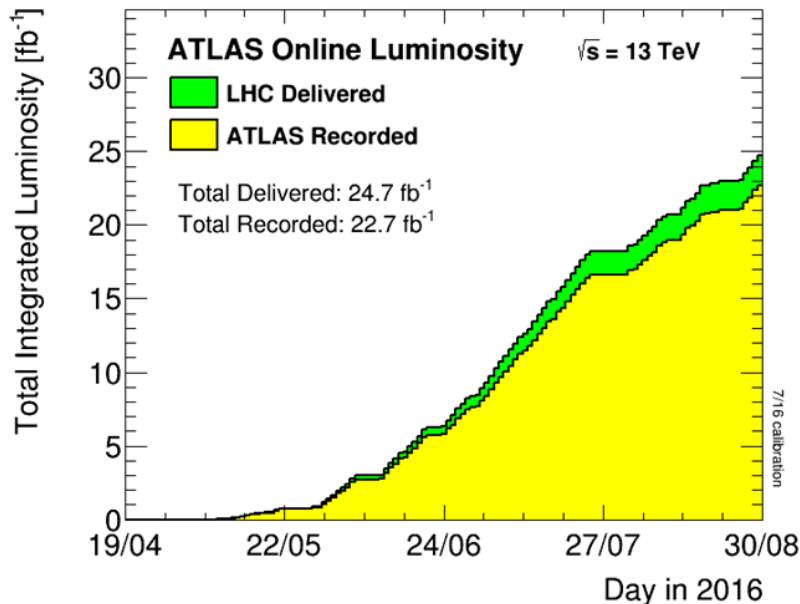
ATLASの運転状況

ATLAS pp 25ns run: April-July 2016

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
98.9	99.9	100	99.8	100	99.6	99.8	99.8	99.8	99.7	93.5

Good for physics: 91-98% ($10.1-10.7 \text{ fb}^{-1}$)

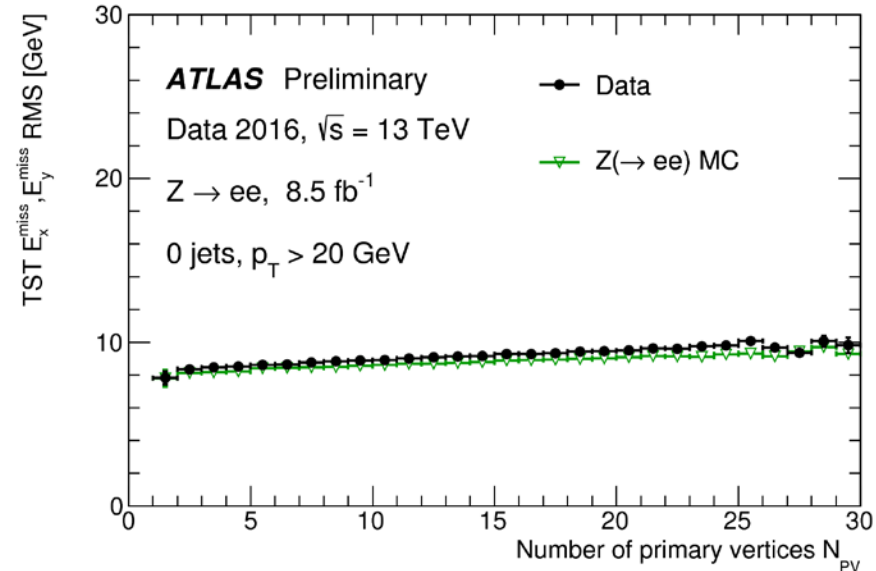
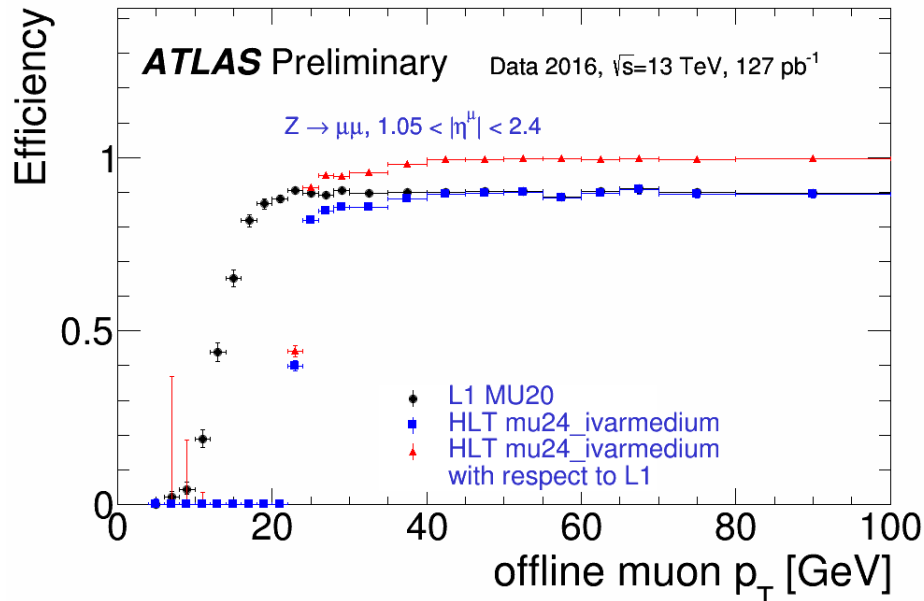
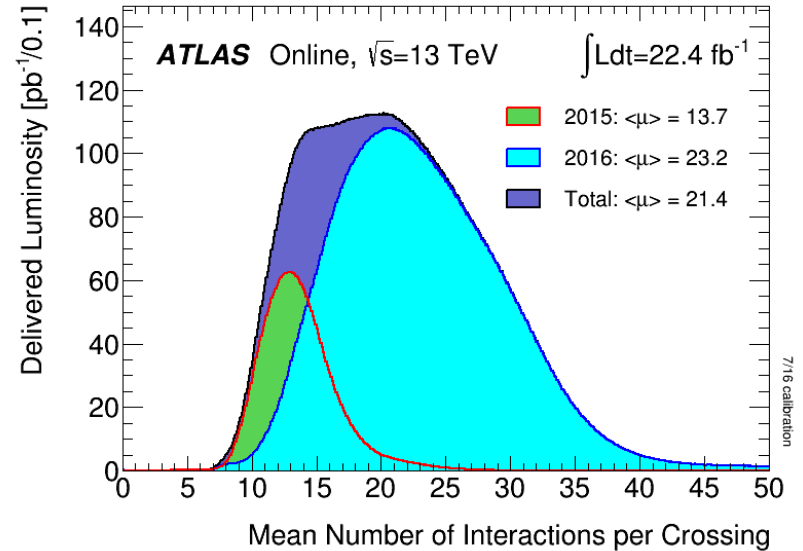
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at $\sqrt{s}=13 \text{ TeV}$ between 28th April and 10th July 2016, corresponding to an integrated luminosity of 11.0 fb^{-1} . The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1} . Analyses that don't require the toroid magnet can use that data.



- これまで 22.7 fb^{-1} のデータを取得済み
- 検出器側も大きなトラブルはなく、好調と言える。

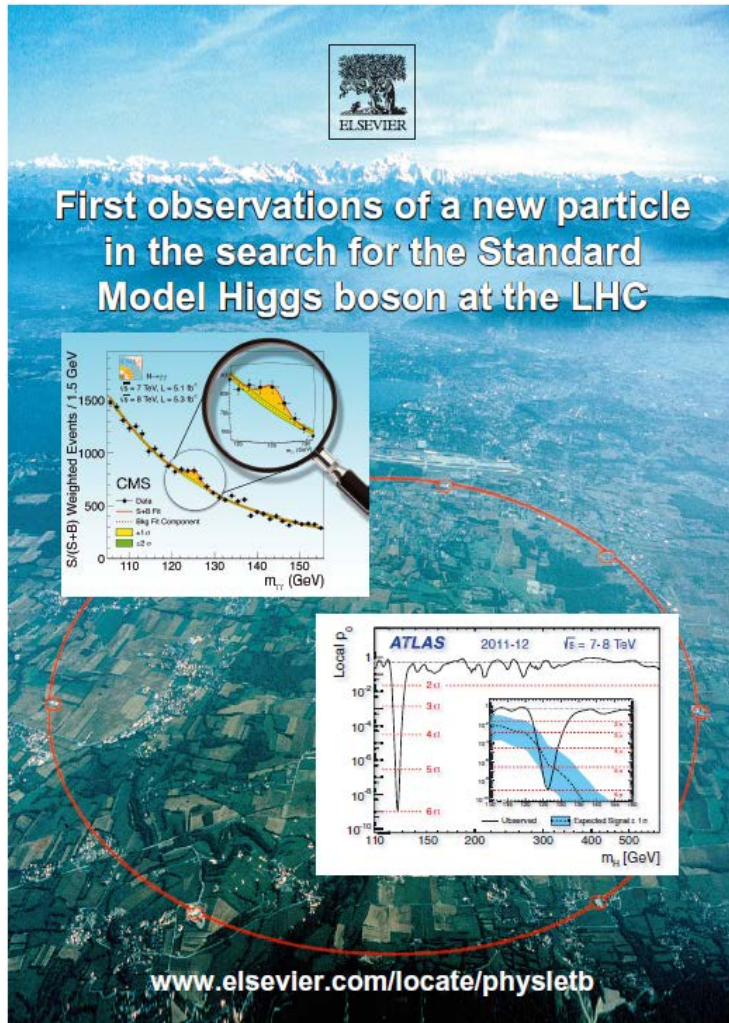
物理解析への影響

- 沢山データが貯まるのはうれしいのですが、
- 実験側は戦い。
 - トリガー
 - MET
- 今のところ大丈夫。
 - まだ50%程上がる可能性があり、準備を進めている。



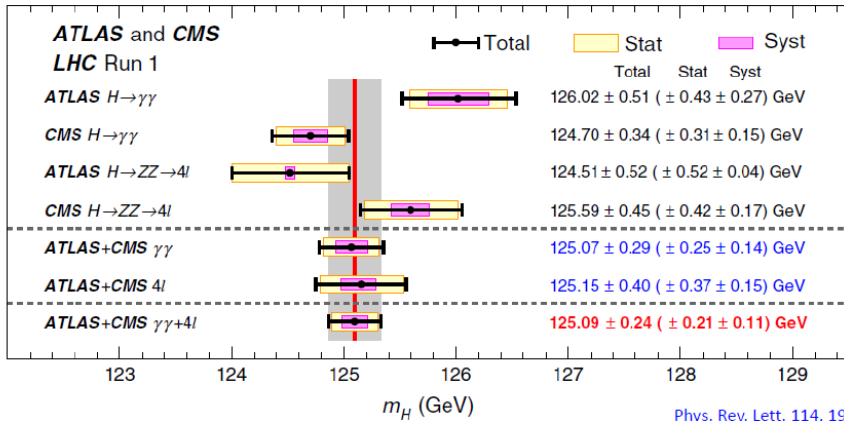
- SM Higgsの詳細測定
 - プロパティ
 - 結合定数
- BSM Higgs
 - MSSM: $H \rightarrow \tau\tau$, charged Higgs
- VV/VH/HH resonance
 - 2HDM
 - Heavy Vector Triplet

Discovery to measurement



- 2012 July : discovery
 - 7 TeV(5 fb⁻¹)+ 8 TeV (5.8 fb⁻¹)
 - H → $\gamma\gamma$ and H → ZZ
- Run 1
 - 7 TeV 5 fb⁻¹
 - 8 TeV 20 fb⁻¹
- Run-2 has started at 13 TeV!
 - 2015: 3.2 fb⁻¹
 - 2016: 13.2 fb⁻¹ + α (~ 1.5 fb⁻¹).

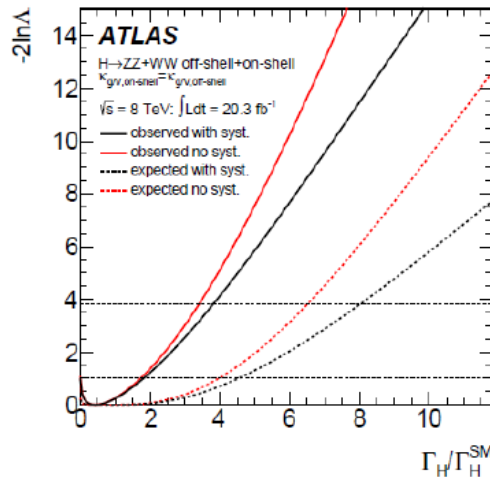
From Run-1



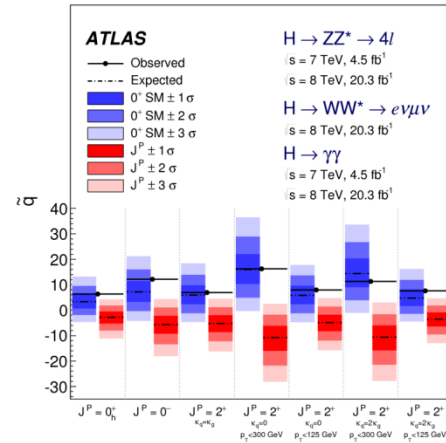
Phys. Rev. Lett. 114, 191803

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

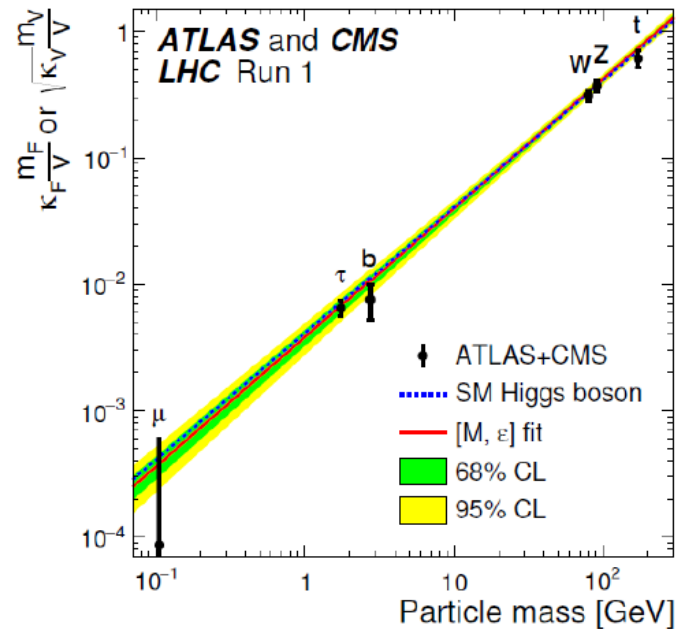
$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$



95% CL. Upper limit on Higgs width = 22.7 MeV
(expect = 33.0 MeV)



Spin 0
Parity Even



Coupling as expected with SM!

Run-1 to Run-2

- Run-2 at 13 TeV!

Production cross section

@ $m_H=125$ GeV

19.3 pb @7 TeV

24.5 pb @8 TeV

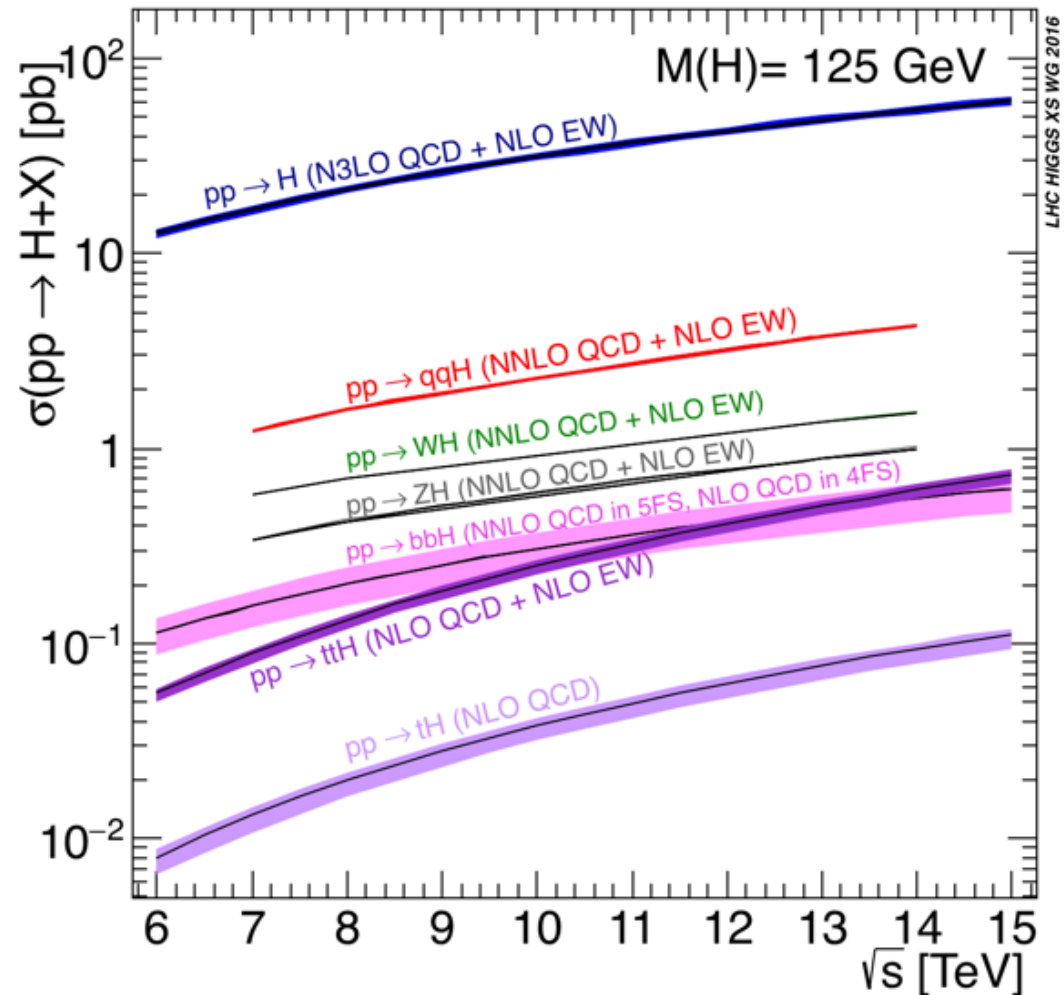
55.7 pb @13 TeV

62.7 pb @14 TeV

8 → 13 TeV:

ggF: × 2.3

ttH: × 3.9



H → VV at Run-2

• Run-2 at 13 TeV!

– H → $\gamma\gamma$

– H → ZZ → 4l

Production cross section

@m_H=125 GeV

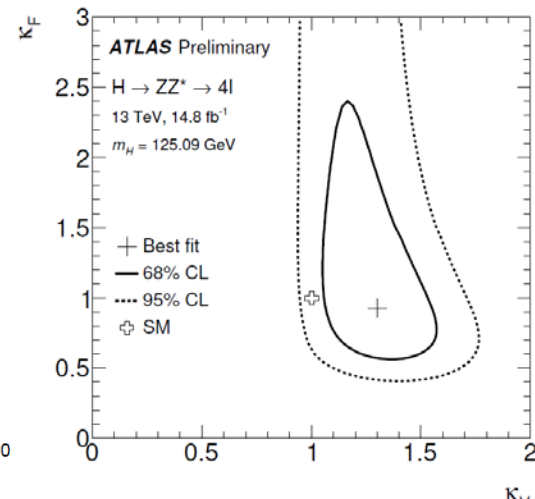
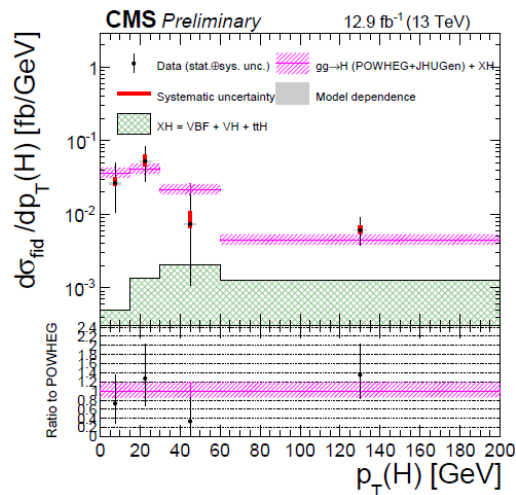
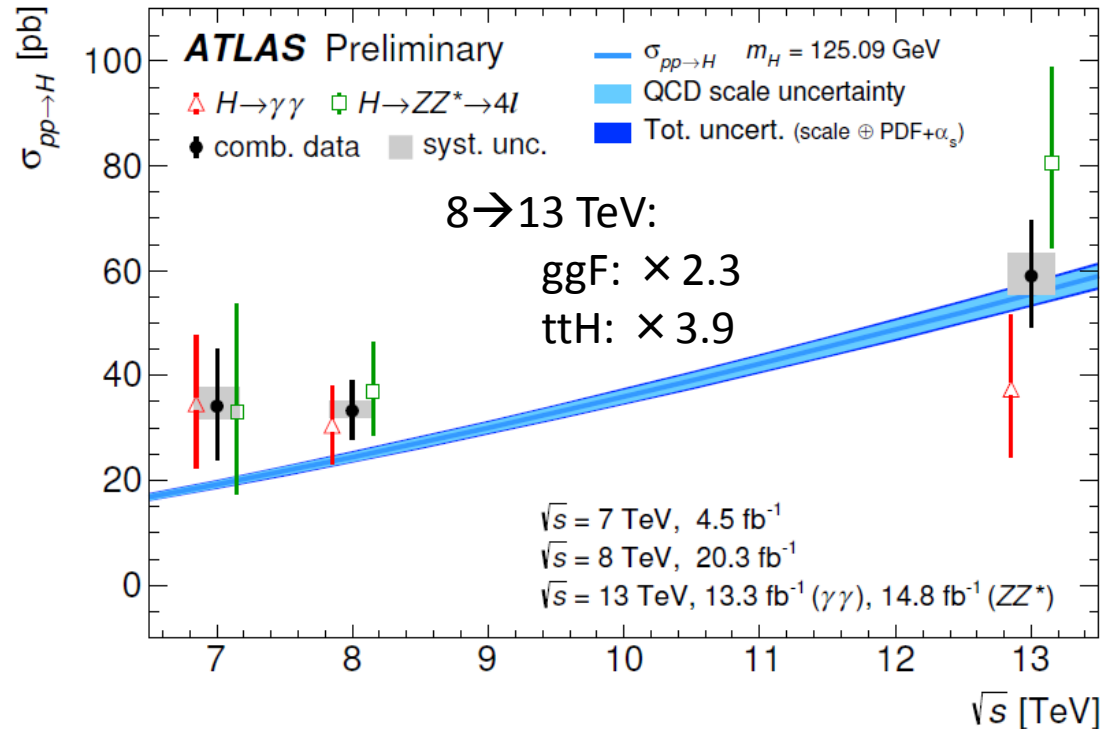
19.3 pb @7 TeV

24.5 pb @8 TeV

55.7 pb @13 TeV

62.7 pb @14 TeV

- 結合測定にむけた生成プロセスを特定できるカテゴリ別の解析
- S/BはRun-1より10-50%良い。
- 実際に検出された事象数もRun-1を越えた!



H → VV at Run-2

- Run-2 at 13 TeV!

- H → γγ

- H → ZZ* → 4l

Pro

Fermionとの結合は？

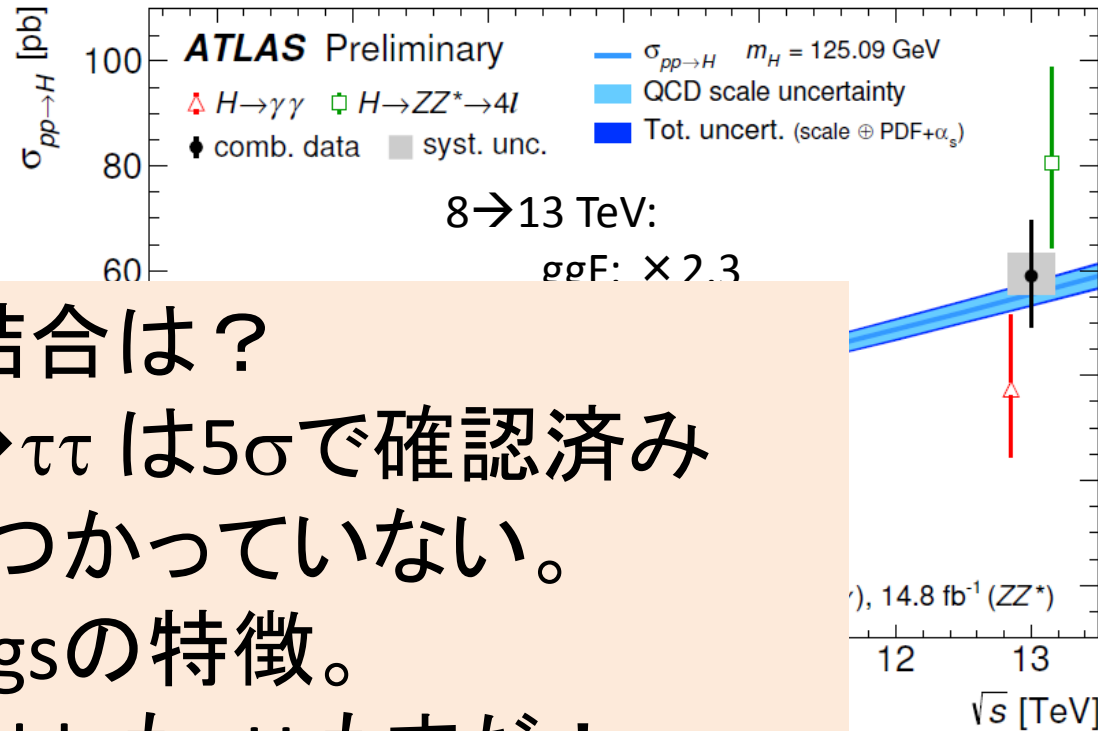
Run-1でH → ττ は5σで確認済み

Muonは見つかっていない。

→ Higgsの特徴。

しかし、H → bb も ttH もまだ！

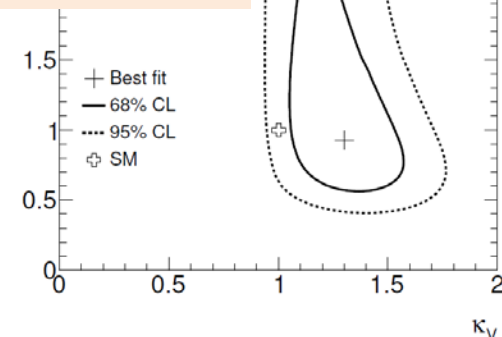
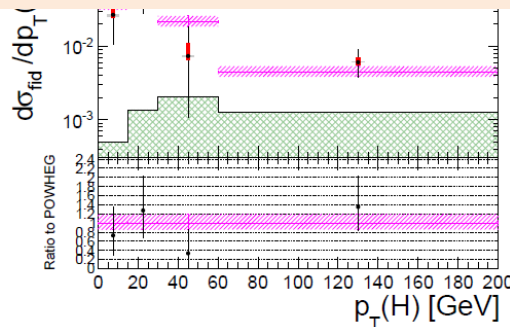
Run-2では見える？



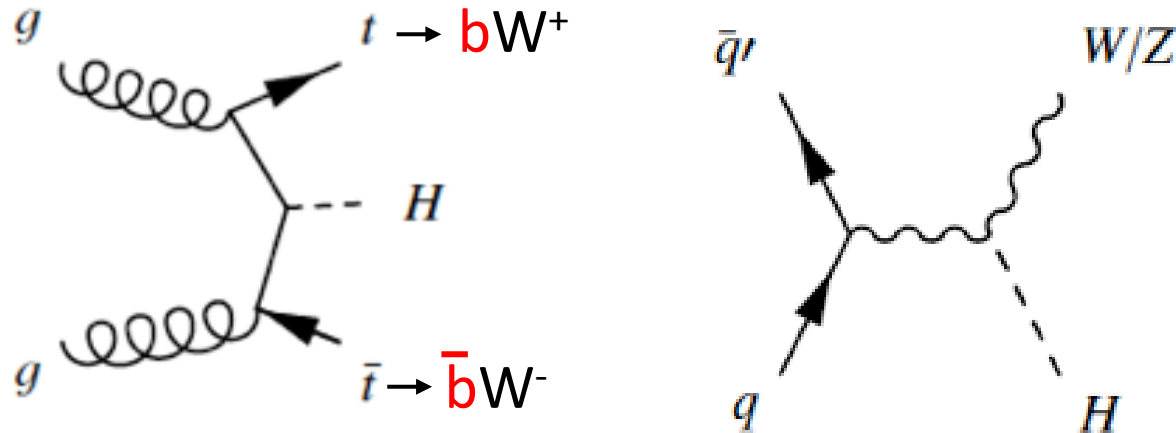
($\sigma_{pp \rightarrow H}$), 14.8 fb⁻¹ (ZZ*)

\sqrt{s} [TeV]

- 結合測定
特定できるカテゴリー別の解析
- S/BはRun-1より10-50%良い。
- 実際に検出された事象数もRun-1を越えた！



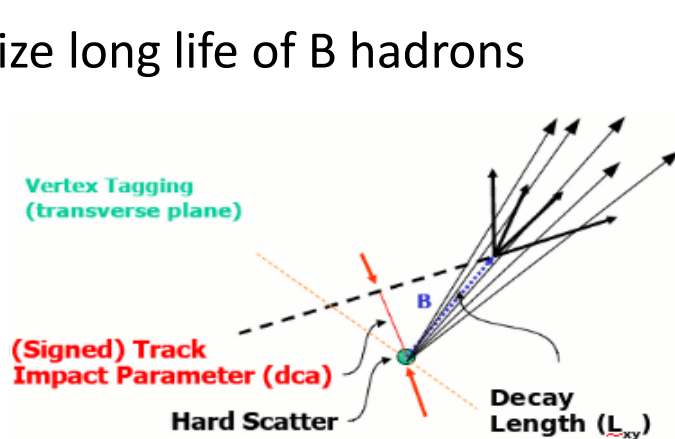
ttH and VH



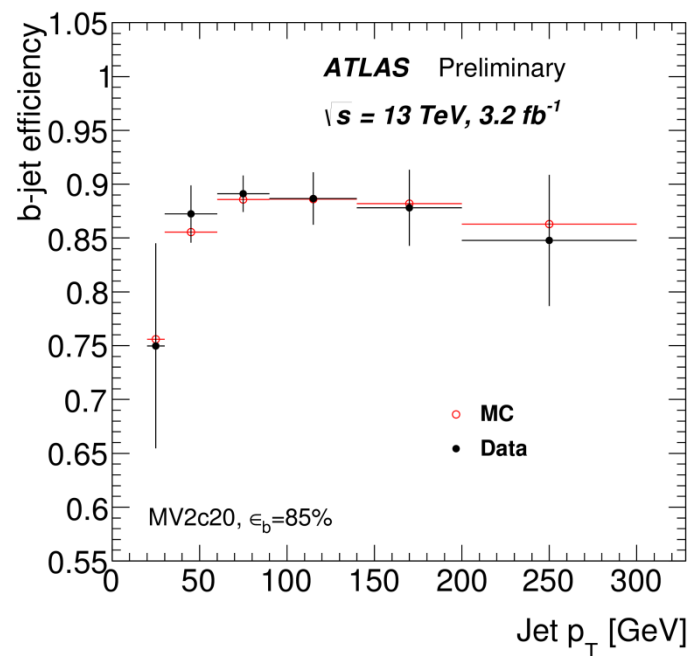
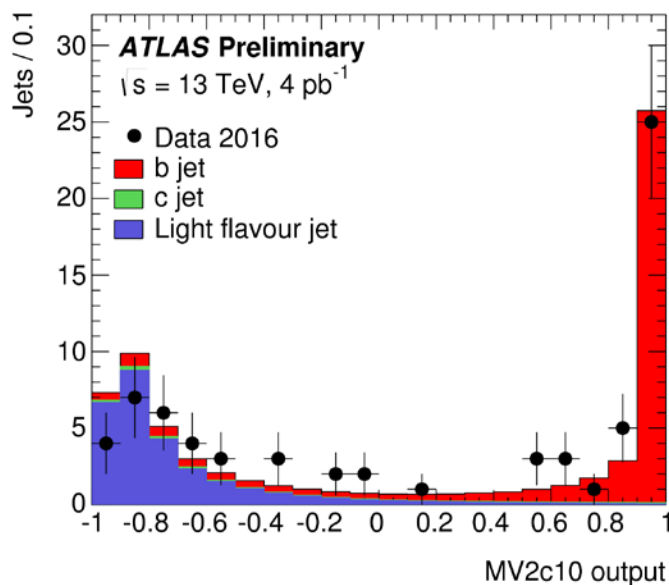
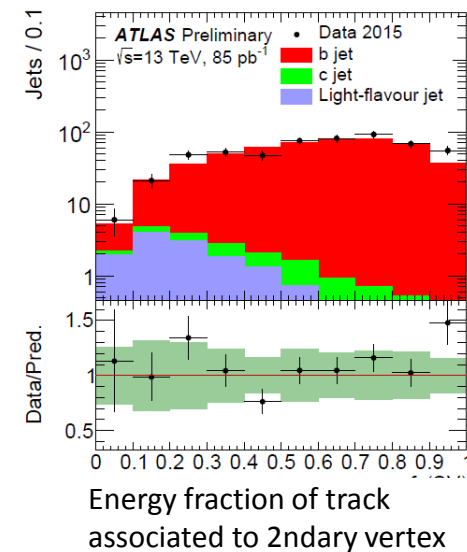
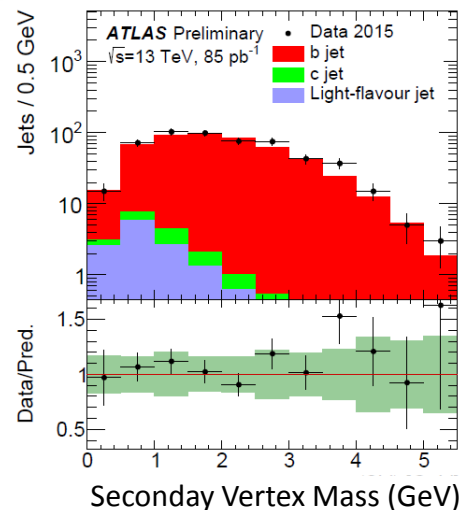
- Due to multi-jet background, Leptons (e, μ or $\nu\nu$) need to be final state.
- For $H \rightarrow bb$, VH production is most sensitive
 - $W \rightarrow e\nu, \mu\nu$. $Z \rightarrow ee, \mu\mu, \nu\nu$
- For ttH, we try to use all mode
 - $H \rightarrow bb$ is the main analysis
- Backgrounds
 - Common: **W+jets, Z+jets**, s-top, **ttbar**, **Multi-jets**
 - VH case: **Diboson**
 - ttH case: **ttbar+heavy flavor (bb/cc)**, **ttbar+vector boson(s)**
- b-jet identification and reconstruction is the key for these analysis.

b-Jet tagging

- Utilize long life of B hadrons

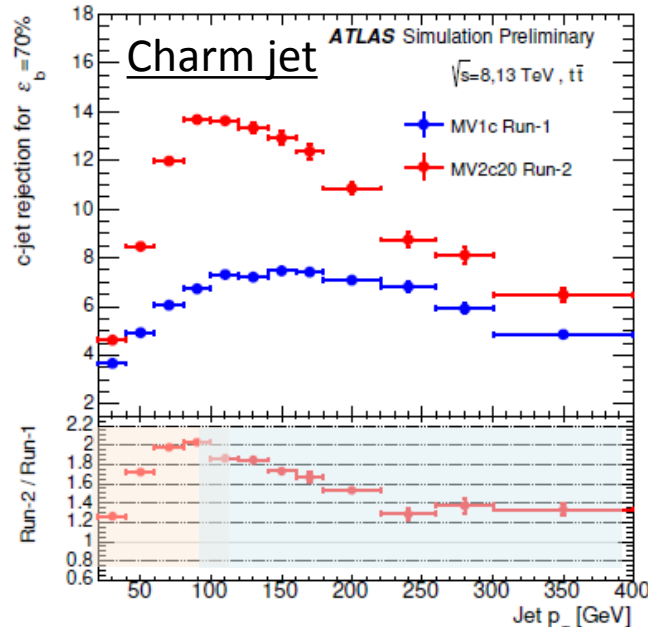
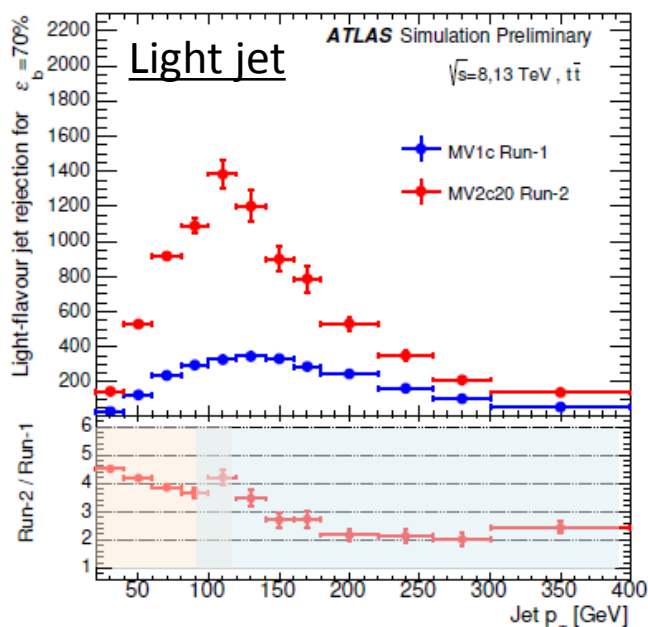
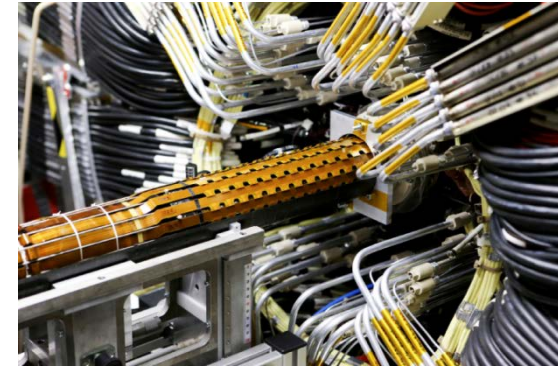
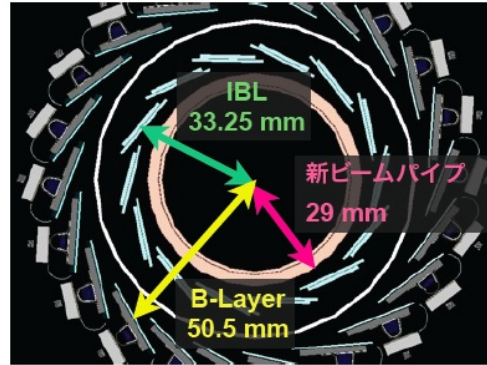


- MVA is used to maximize separation between light and charm jets from b-jets



Improvement on b-tagging at Run-2

- IBL
 - Additional Pixel layer
 - Resolution of impact param. for track p_T range of 5-10 GeV
→ 30-60% improvement
- MVA training scheme
 - Run-1 training: b-jet vs light jet
→ Run-2: b-jets vs (80% light + 20% charm)

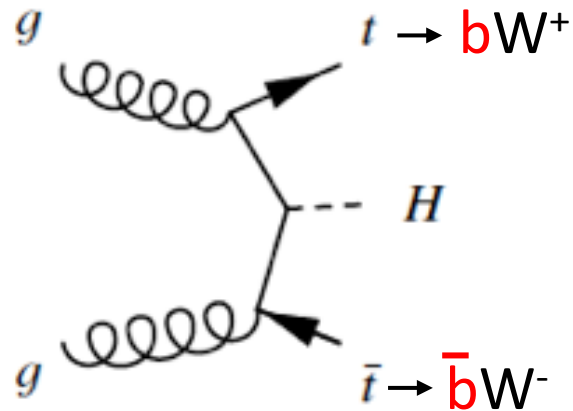


Improvements on rejection factor

Low jet p_T
→ **IBL** + **algorithm**

High jet p_T
→ mainly **algorithm**

ttH analysis



- $H \rightarrow b\bar{b}$
 - 1-lepton, 2-lepton
- $H \rightarrow \gamma\gamma$
- $H \rightarrow WW, ZZ$
 - Same sign 2-lepton, 3-lepton, 4-lepton
 - Channel with tau.

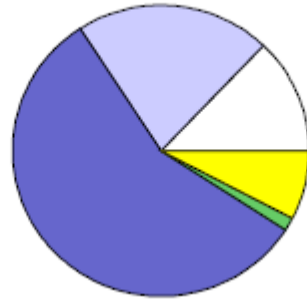
b-Jet tagging

- In the analysis ATLAS Run2 b-tag : btag eff: b: 70%, c: 1/12, light: 1/380
 - Categorize event with number b-jet (i.e. 70% OP)

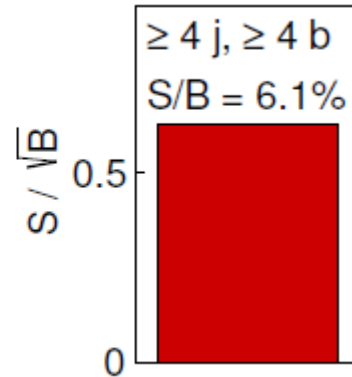
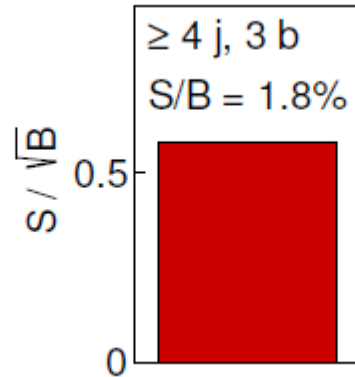
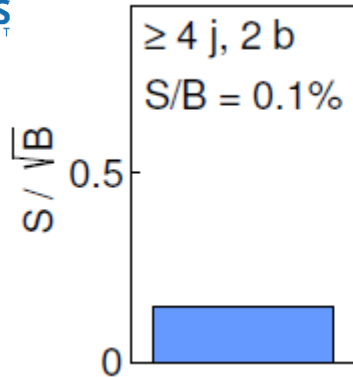
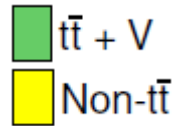
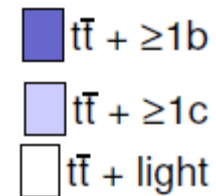
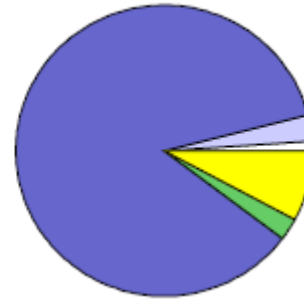
$\geq 4 j, 2 b$



$\geq 4 j, 3 b$



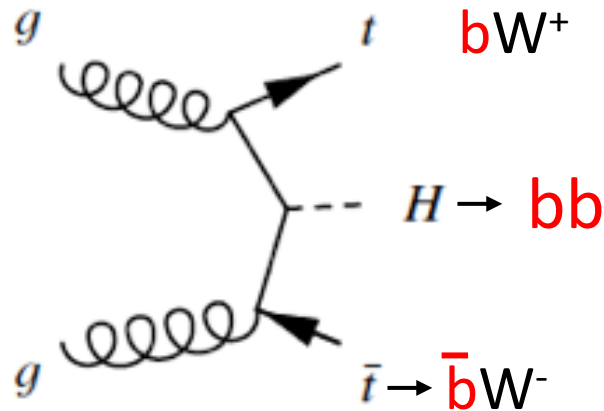
$\geq 4 j, \geq 4 b$



Example case for ATLAS $t\bar{t}H$ $H \rightarrow bb$, dilepton

$ttH, H \rightarrow bb$

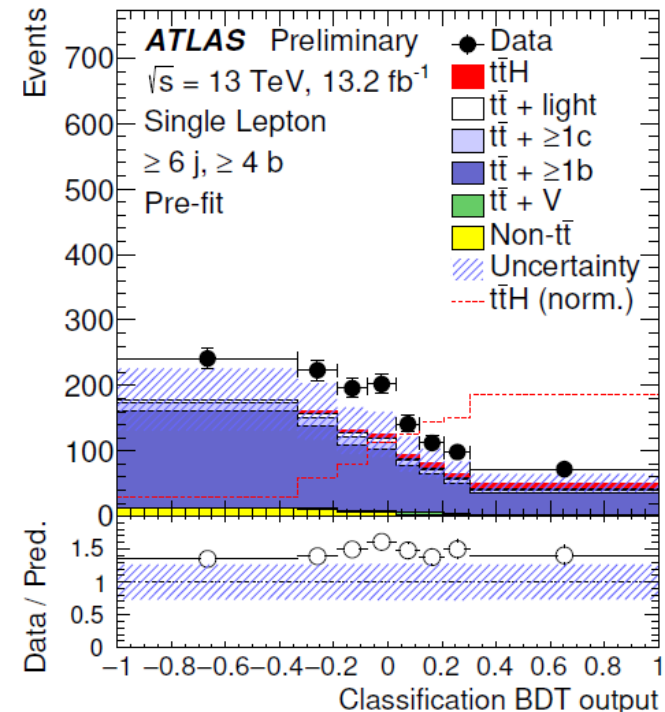
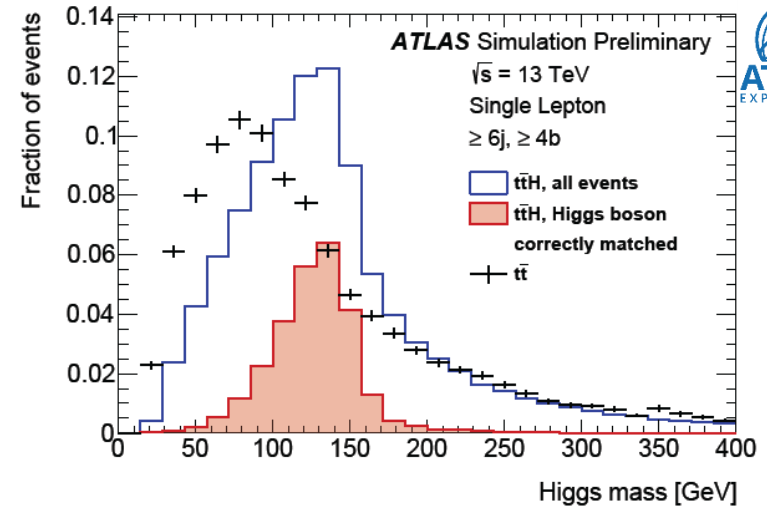
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1-lepton: 6 jets with 4 b-jets

2-lepton: 4 jets with 4 b-jets

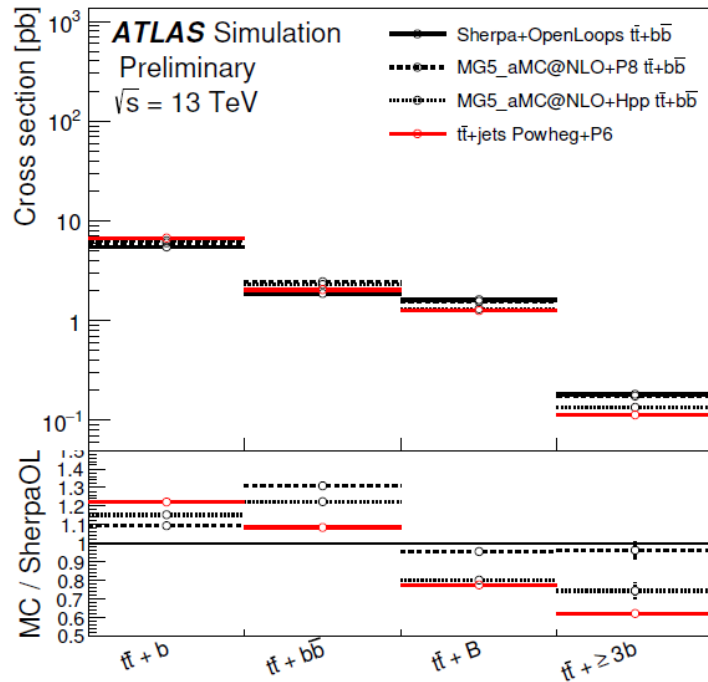
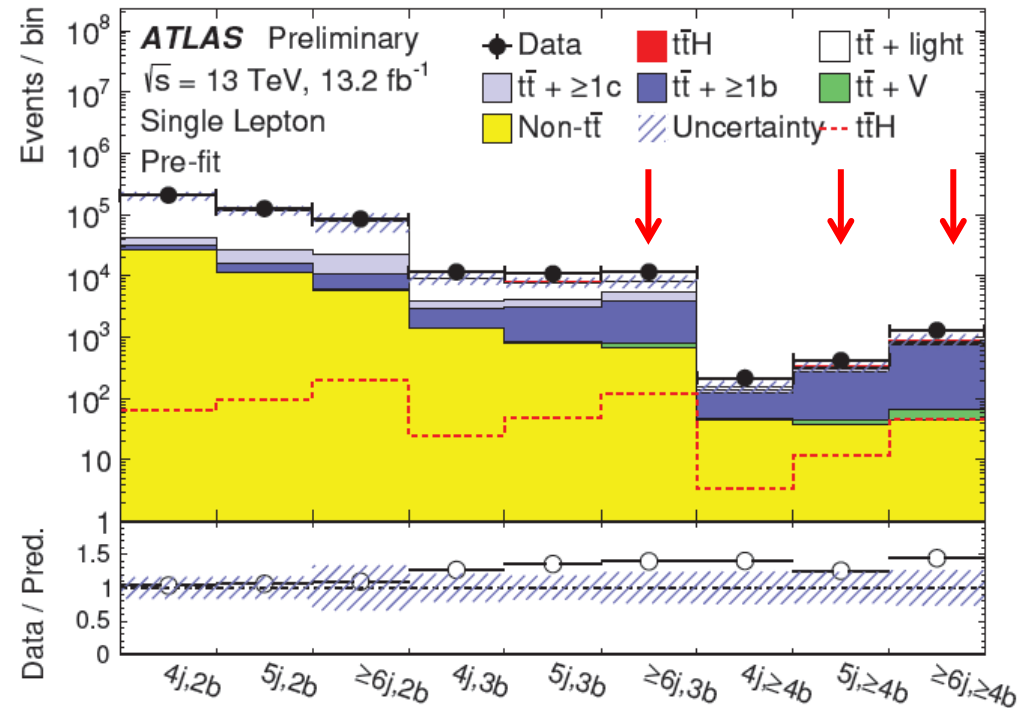
- There are four true b-jets in a ttH event.
 - With reconstruction BDT
 - Correct assignment can be achieved only 12% (42%) for 1-lepton (2-lepton)
 - BDT is also use for signal extraction as final discriminant.
- Background is tt +light, tt +cc, tt +bb



ttH Hbb fit model

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- In order to estimate BG, perform simultaneous fit with control regions (CR)
 - 6 CRs : HT is used.
 - 3 SRs: MVA is used.
- Normalization and systematic variations are constrained by the fit.



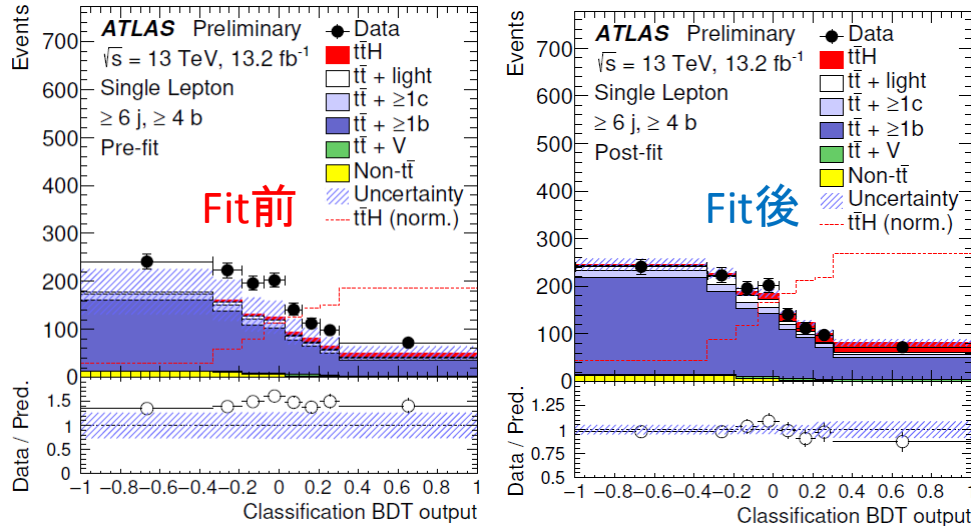
ME gen.	MG5_aMC	MG5_aMC	SherpaOL
PS/UE gen.	Herwig++ 2.7.1	Pythia 8.210	Sherpa
Renorm. scale	μ_{CMMPs}	μ_{CMMPs}	μ_{CMMPs}
Fact. scale	$H_T/2$	$H_T/2$	$H_T/2$
Resumm. scale	$f_Q\sqrt{\hat{s}}$	$f_Q\sqrt{\hat{s}}$	$H_T/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune

Systematic variations for $t\bar{t} + b\bar{b}$

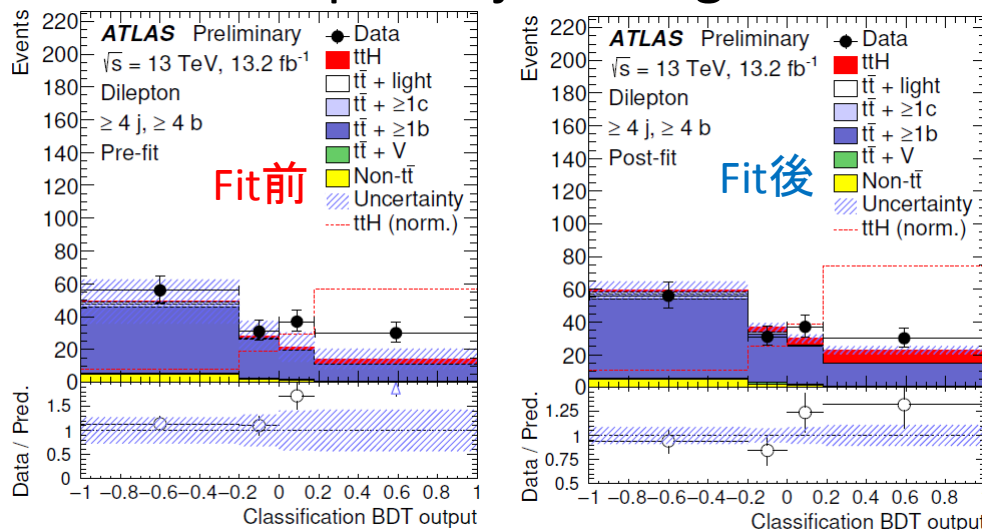
ttH, Hbb effect on systematics



1 lepton 6jet 4 btag

[ATLAS-CONF-2016-080](#)


2 lepton 4jet 4btag

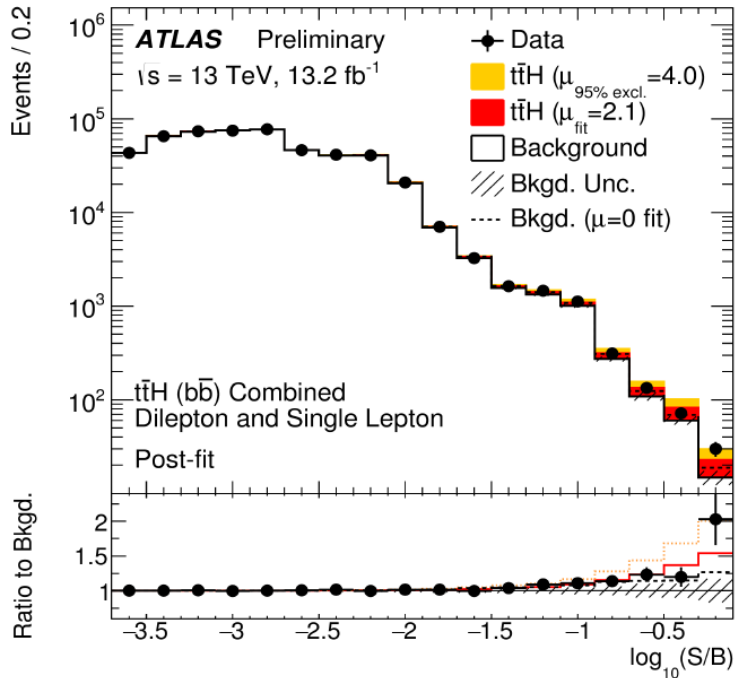


Uncertainty source	$\Delta\mu$	
<u>$t\bar{t} + \geq 1b$ modelling</u>	+0.53	-0.53
Jet flavour tagging	+0.26	-0.26
$t\bar{t}H$ modelling	+0.32	-0.20
Background model statistics	+0.25	-0.25
$t\bar{t} + \geq 1c$ modelling	+0.24	-0.23
Jet energy scale and resolution	+0.19	-0.19
$t\bar{t}$ +light modelling	+0.19	-0.18
Other background modelling	+0.18	-0.18
Jet-vertex association, pileup modelling	+0.12	-0.12
Luminosity	+0.12	-0.12
$t\bar{t}Z$ modelling	+0.06	-0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	-0.05
Total systematic uncertainty	+0.90	-0.75
<u>$t\bar{t} + \geq 1b$ normalisation</u>	+0.34	-0.34
$t\bar{t} + \geq 1c$ normalisation	+0.14	-0.14
Statistical uncertainty	+0.49	-0.49
Total uncertainty	+1.02	-0.89

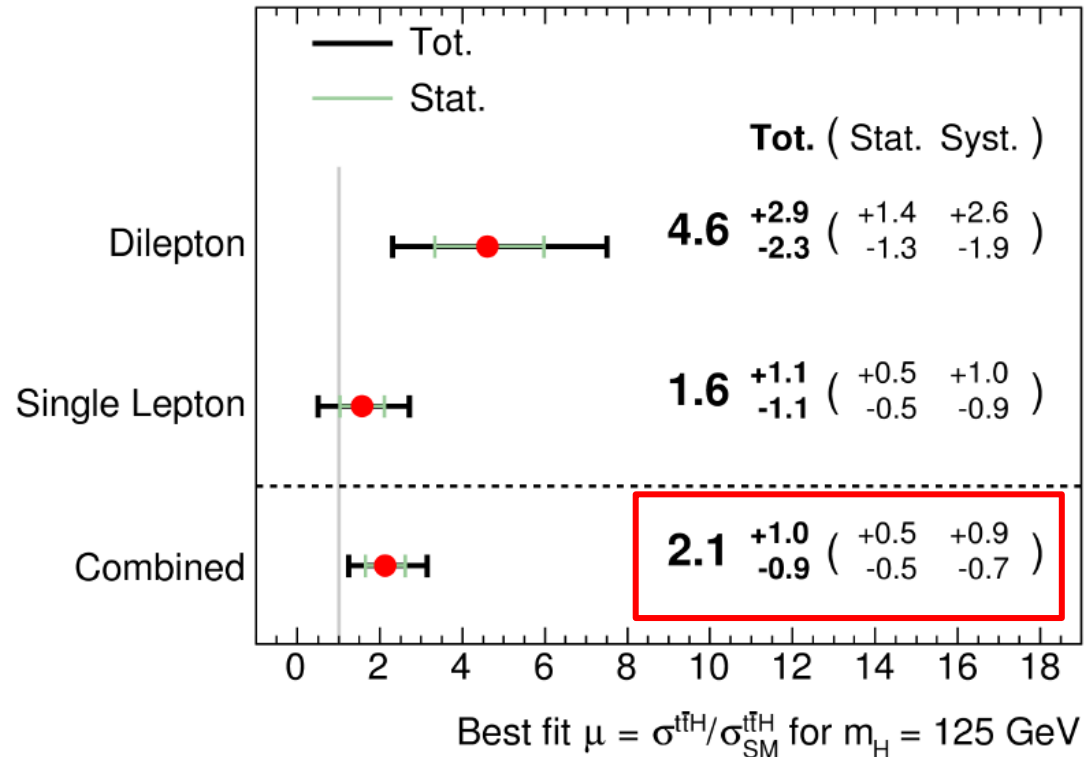
- $t\bar{t}$ + bb modeling is dominant systematic.

ttH, Hbb result

ATLAS-CONF-2016-080



ATLAS Preliminary $t\bar{t}H$ ($b\bar{b}$), $\sqrt{s} = 13 \text{ TeV}, 13.2 \text{ fb}^{-1}$



CMS has 13 TeV analysis with 2.7 fb^{-1} .

observed $\mu = -2.0 \pm 1.8$.

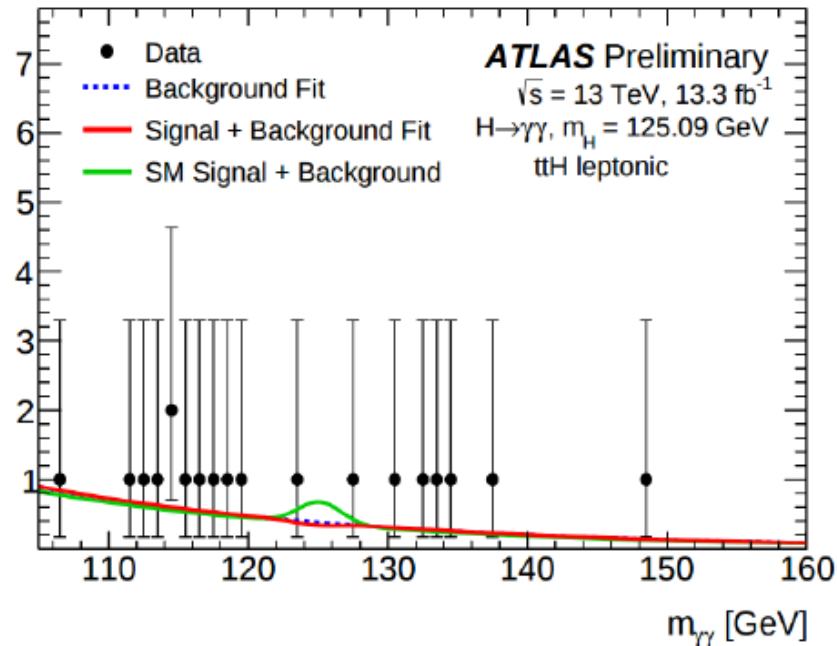
$ttH \text{ } H \rightarrow \gamma\gamma$

- Leptonic and Hadronic categories for $t\bar{t}$ reconstruction

Channel	Region	$t\bar{t}H$ (S)	Bkgd (B)	$tHj\bar{b} + WtH$	S/B	N_{Data}
$H \rightarrow \gamma\gamma$	all-hadronic	1.58	8.27	0.10	0.19	9
	leptonic	1.16	2.42	0.10	<u>0.48</u>	2

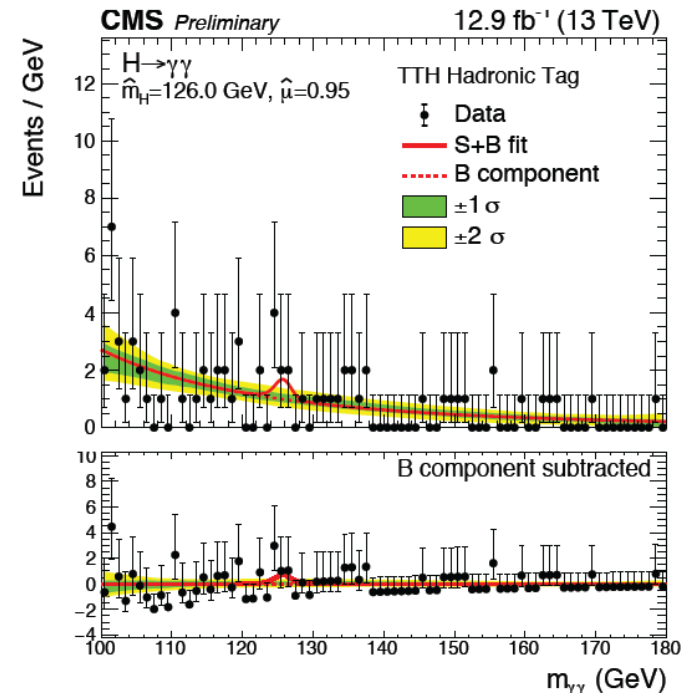


Events / GeV



Observed $\mu = -0.3^{+1.2}_{-1.0}$
 @ $M_H = 125.1 \text{ GeV}$

ATLAS-CONF-2016-067

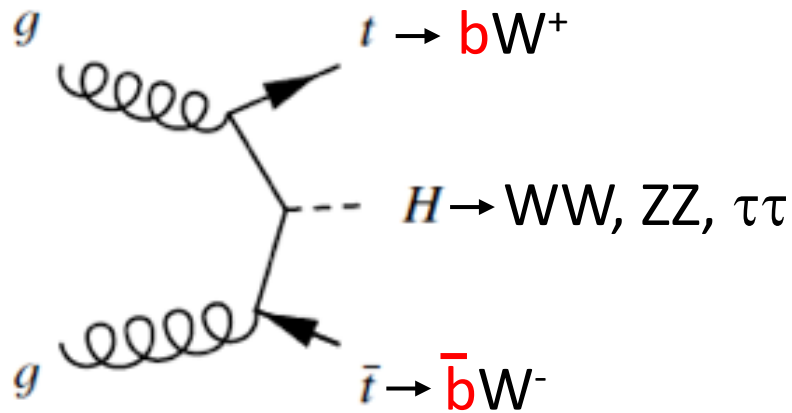


Observed $\mu = 1.9^{+1.5}_{-1.2}$
 @ $M_H = 125 \text{ GeV}$

CMS-PAS-HIG-16-020

ttH multi leptons

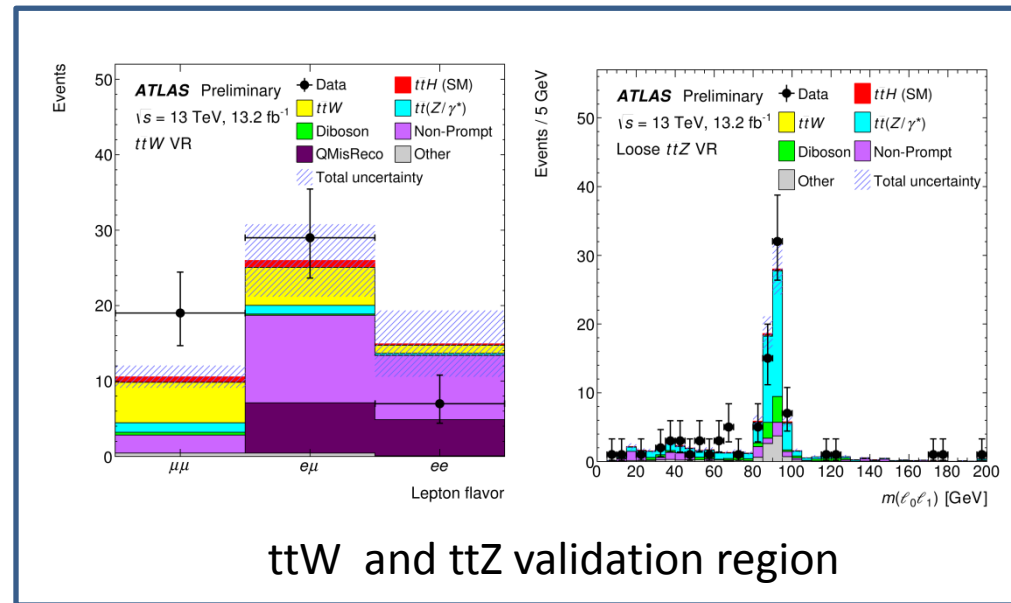
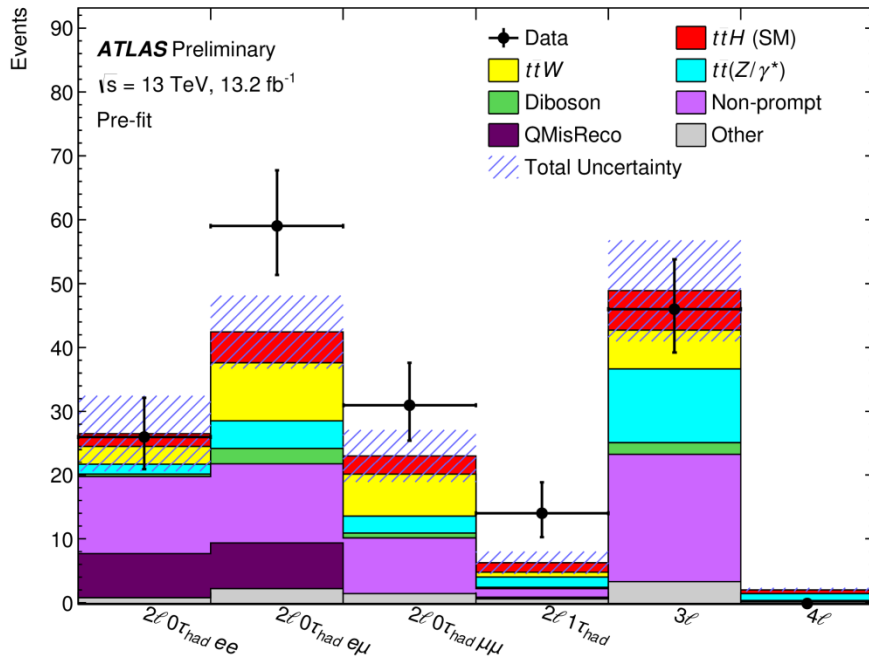
ATLAS-CONF-2016-058



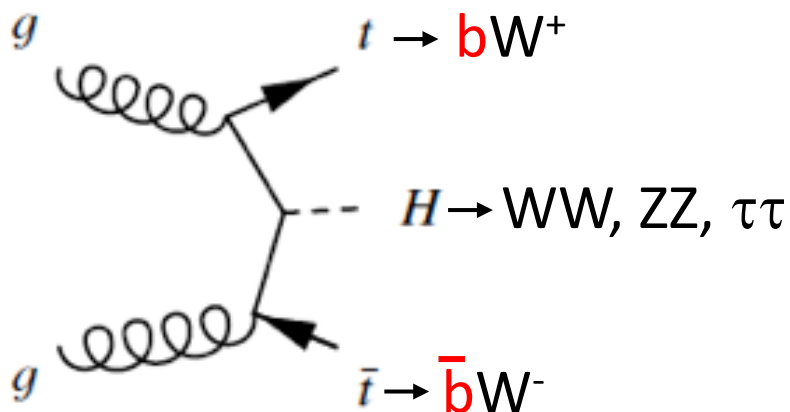
- $H \rightarrow WW, ZZ, \tau\tau$

Category	Higgs boson decay mode				$A \times \epsilon$ ($\times 10^{-4}$)
	WW^*	$\tau\tau$	ZZ^*	Other	
$2\ell 0\tau_{\text{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\text{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

Dominant background are with:
Electron charge flip, Fake lepton BG

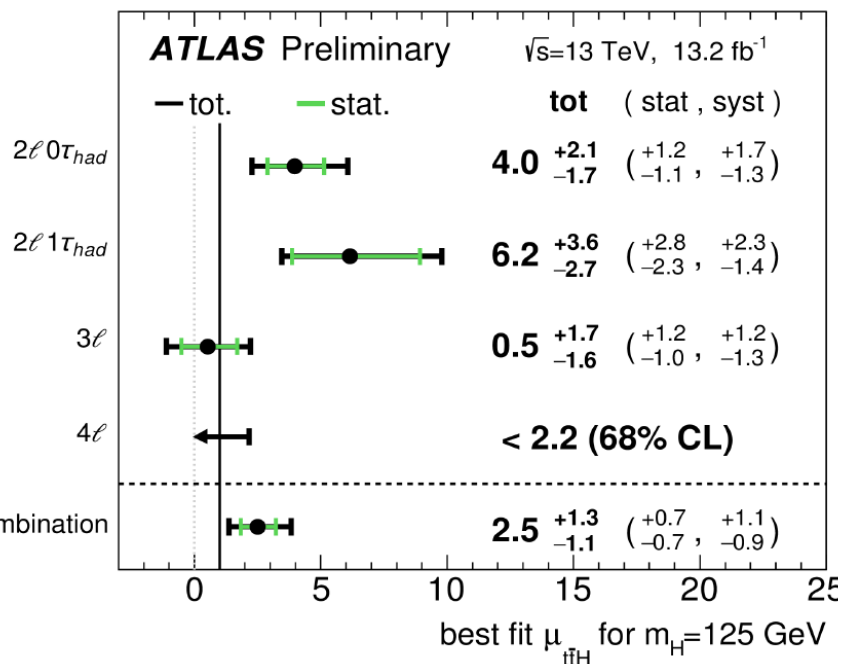


ttH multi leptons



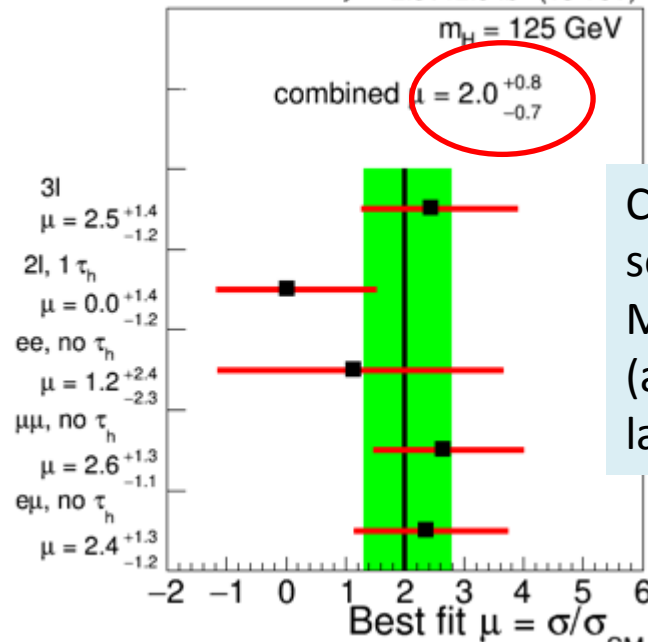
- $H \rightarrow WW, ZZ, \tau\tau$

Category	Higgs boson decay mode				$A \times \epsilon$ ($\times 10^{-4}$)
	WW^*	$\tau\tau$	ZZ^*	Other	
$2\ell 0\tau_{had}$	77%	17%	3%	3%	14
$2\ell 1\tau_{had}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88



[ATLAS-CONF-2016-058](#)

CMS Preliminary $2.3+12.9$ fb $^{-1}$ (13 TeV)



CMS has better sensitivity with MVA analysis (and slightly larger dataset.)

[CMS-PAS-HIG-16-022](#)

Summary on ttH analyses ($\sigma_{\text{obs}}/\sigma_{\text{SM}}$)



CMS

ttH Channel	$\mu = \sigma/\sigma_{\text{SM}}$ ($m_H = 125.7 \text{ GeV}$)
$\gamma\gamma$	$1.9^{+1.5}_{-1.2}$
$b\bar{b}$	-2.0 ± 1.8 (2.7 fb ⁻¹)
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$ (Run1)
4l	} $2.0^{+0.8}_{-0.7}$
3l	
Same-sign 2l	---
Combined	$+2.5^{+1.1}_{-1.0}$ (Run1)

Combination for run2 is not yet done.

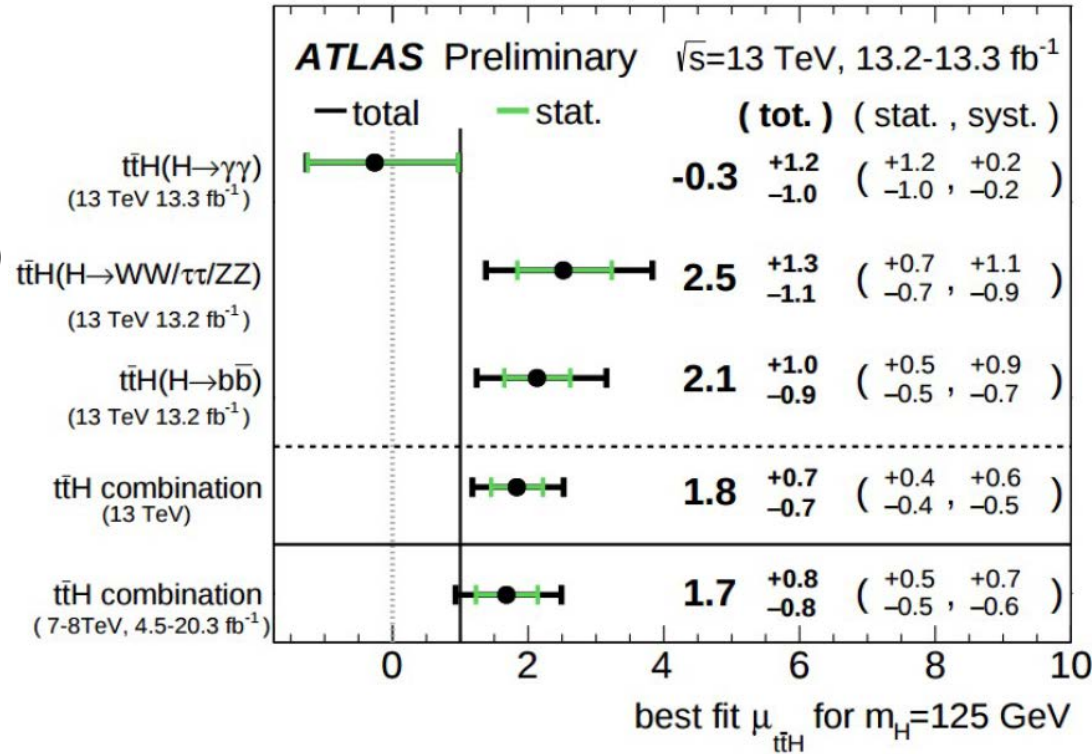
[CMS-PAS-HIG-16-022](#)

[CMS-PAS-HIG-16-020](#)

[CMS-PAS-HIG-15-008](#)



ATLAS (Run-2)



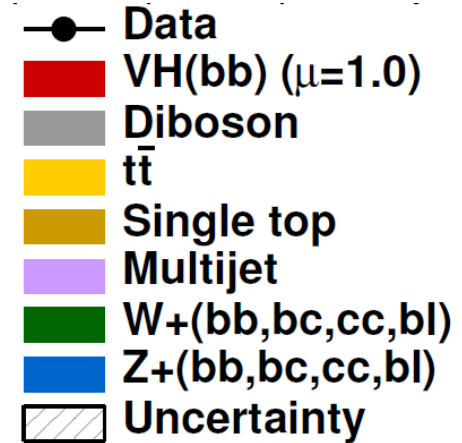
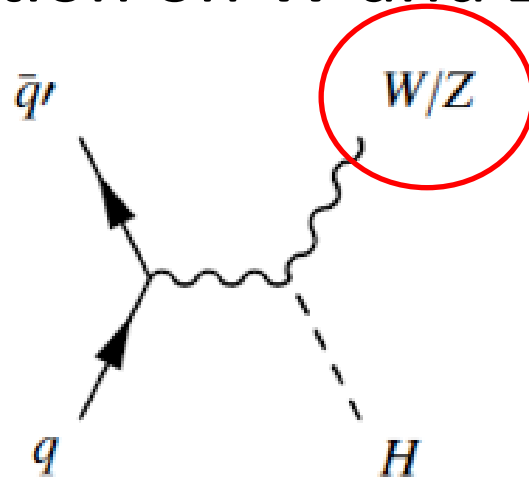
[ATLAS-CONF-2016-068](#)

Run-1の感度を超えている。2016年の全データを使えば見えるか。

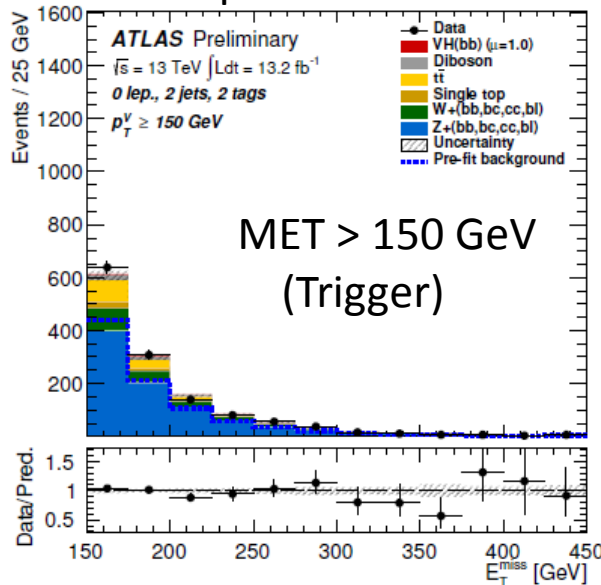
VH, $H \rightarrow bb$ analysis

ATLAS-CONF-2016-091

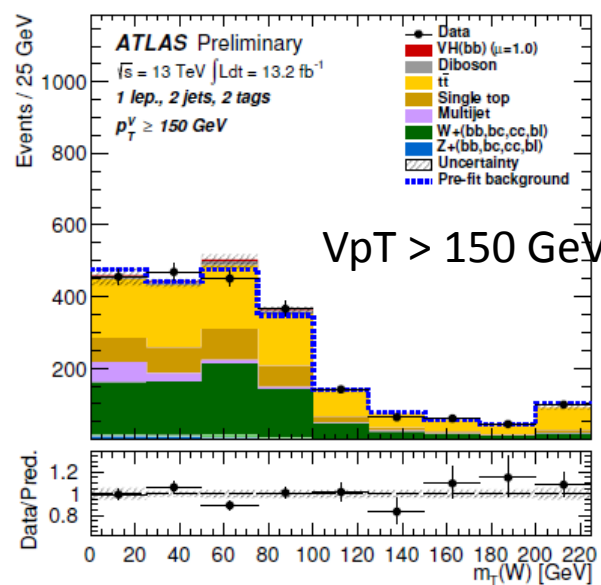
- Reconstruction on W and Z



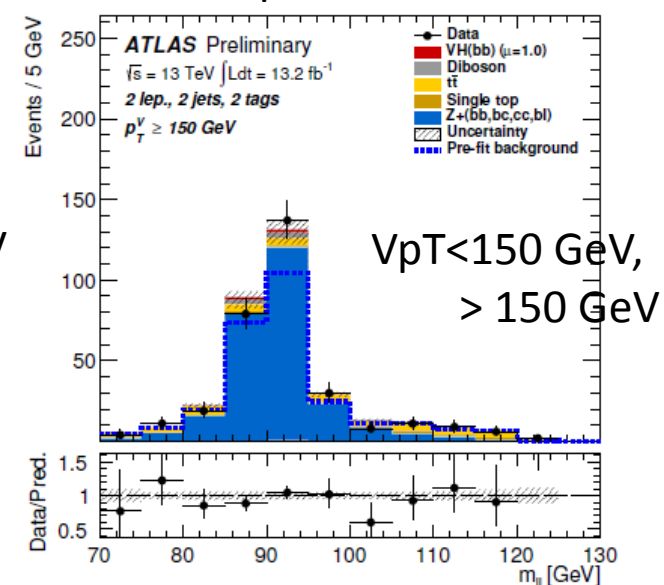
0-lepton: $Z \rightarrow \nu\nu$



1-lepton: $W \rightarrow l\nu$



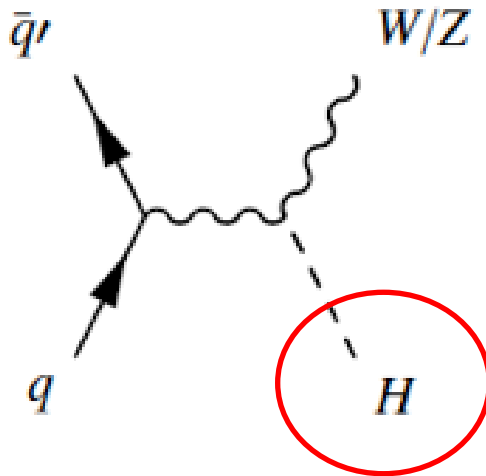
2-lepton: $Z \rightarrow ll$



VH, $H \rightarrow bb$ analysis

ATLAS-CONF-2016-091

• Reconstruction on $H \rightarrow bb$



Main BG is $Z+bb$ and $t\bar{t}$

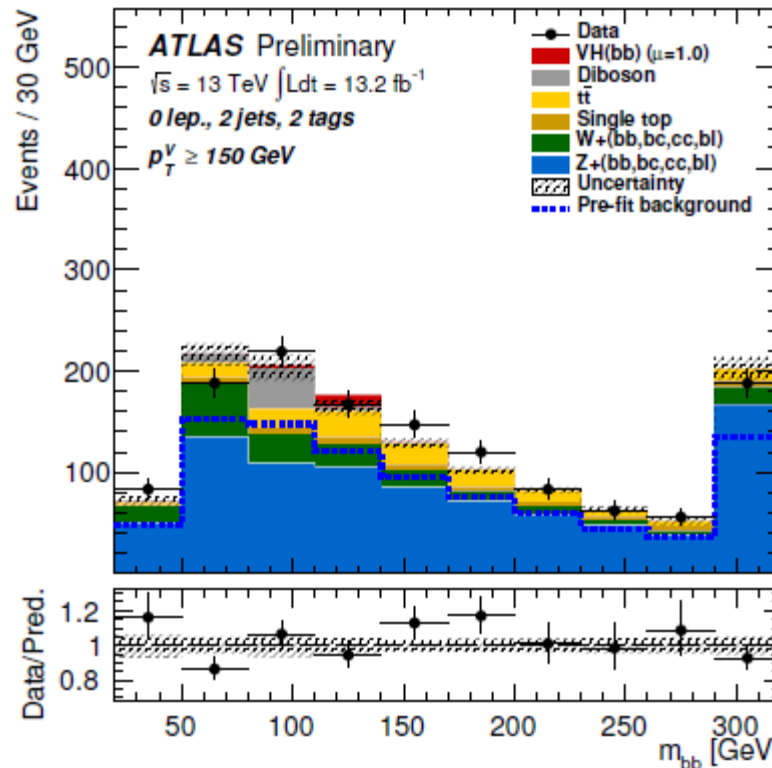
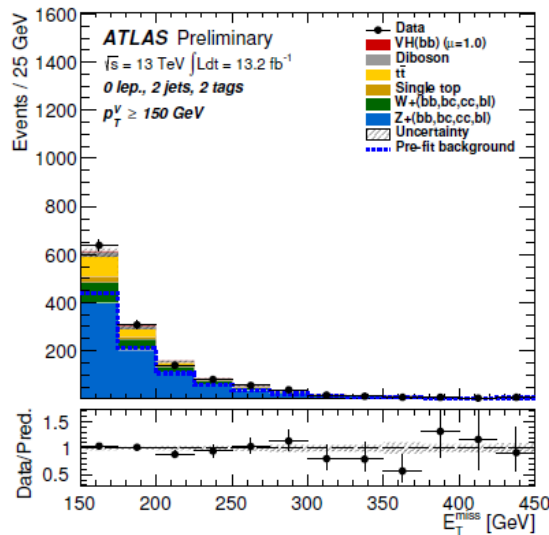
($t\bar{t}$ for 1-lepton is largest)

On the side of $H \rightarrow bb$ at 125 GeV, VZ , $Z \rightarrow bb$.

→ Use this process as cross check.



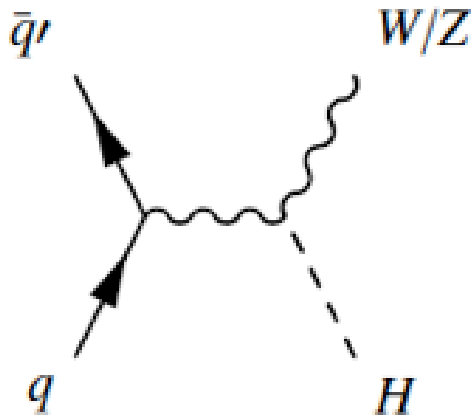
For 0-lepton case



VH, H → bb analysis

[ATLAS-CONF-2016-091](#)

- In order to maximize sensitivity, MVA is used.

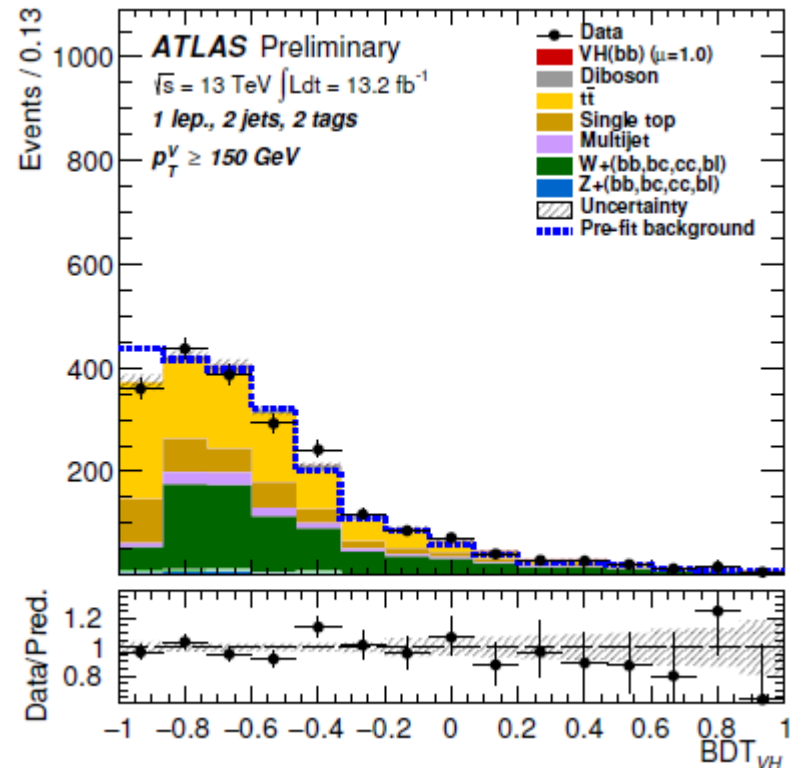
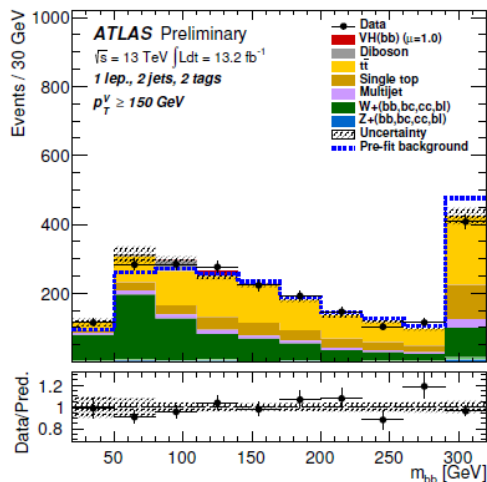


Input variables:

- Most sensitive variable is M_{bb}
- M_{top} , scalar sum of jets
- Angles between objects.

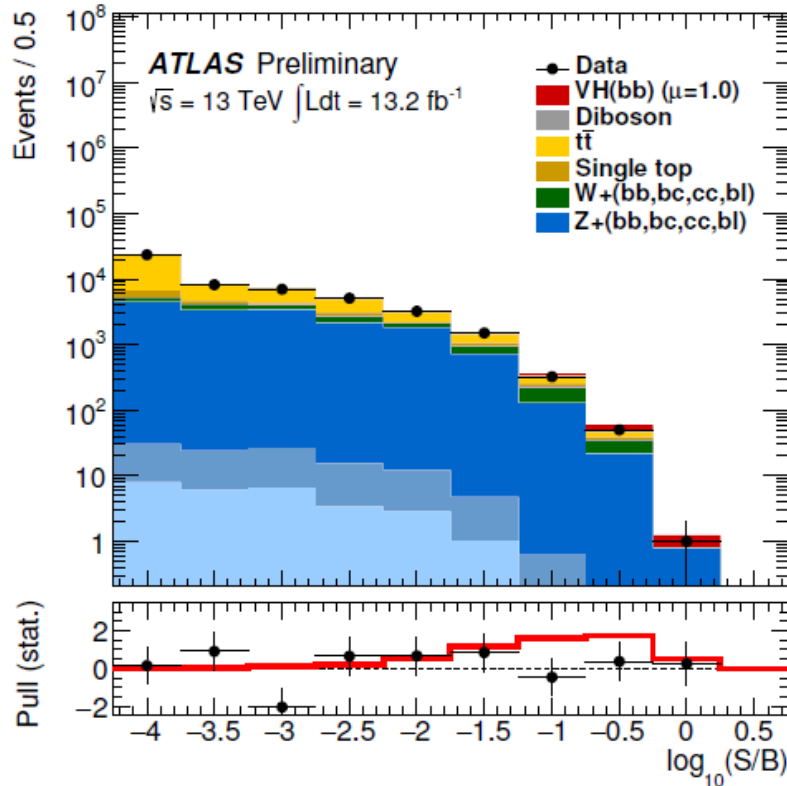


For 1-lepton case

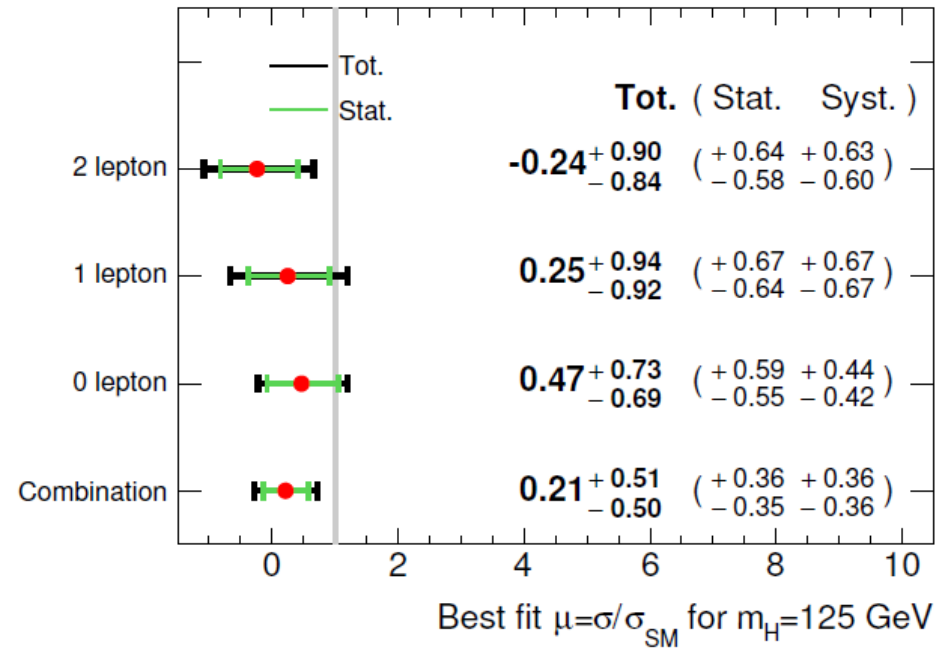


Result: ATLAS VH Hbb 13 TeV (13.2 fb^{-1})

ATLAS-CONF-2016-091



ATLAS Preliminary $\sqrt{s}=13 \text{ TeV}, \int \mathcal{L} dt= 13.2 \text{ fb}^{-1}$



Cross check on VZ cross section measurement

$$\mu_{VZ} = 0.91 \pm 0.17 \text{ (stat)}^{+0.32}_{-0.23} \text{ (sys)}$$

→ Observed significance: 3.2σ

- Expected sensitivity is 1.9σ
- **Low mu value was observed (again)**
 - Run1: $\mu = 0.52 \pm 0.40$
- CMS result is not released yet.
- Systematic uncertainty is comparable with stat uncertainty.

Systematic on VH Hbb

- Major contributions are

- Related B-tagging

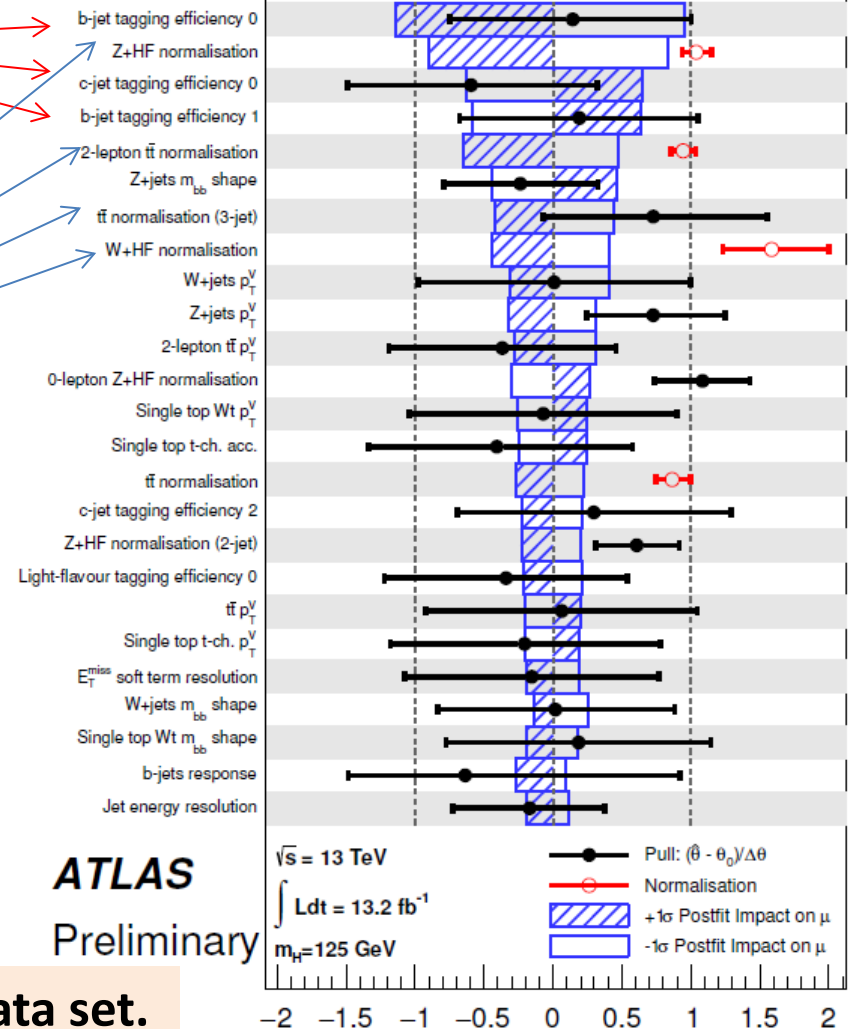
- Only preliminary efficiency measurement is performed. Expect to be reduced with amount of data

- Normalization

→ Shrink with amount of data. Control region can be used.

- Shape on BGs

- Dijet mass modeling
- VpT modeling



**Aim for Hbb observation with full 2016 data set.
 (after combination with Run-1)**

Systematic on VH Hbb

- Major contributions are

- Rejected Backgrounds

- $H \rightarrow bb$ は

- VBF, $H \rightarrow bb$

- VBF+ γ , $H \rightarrow bb$ の解析も進行中。

- No

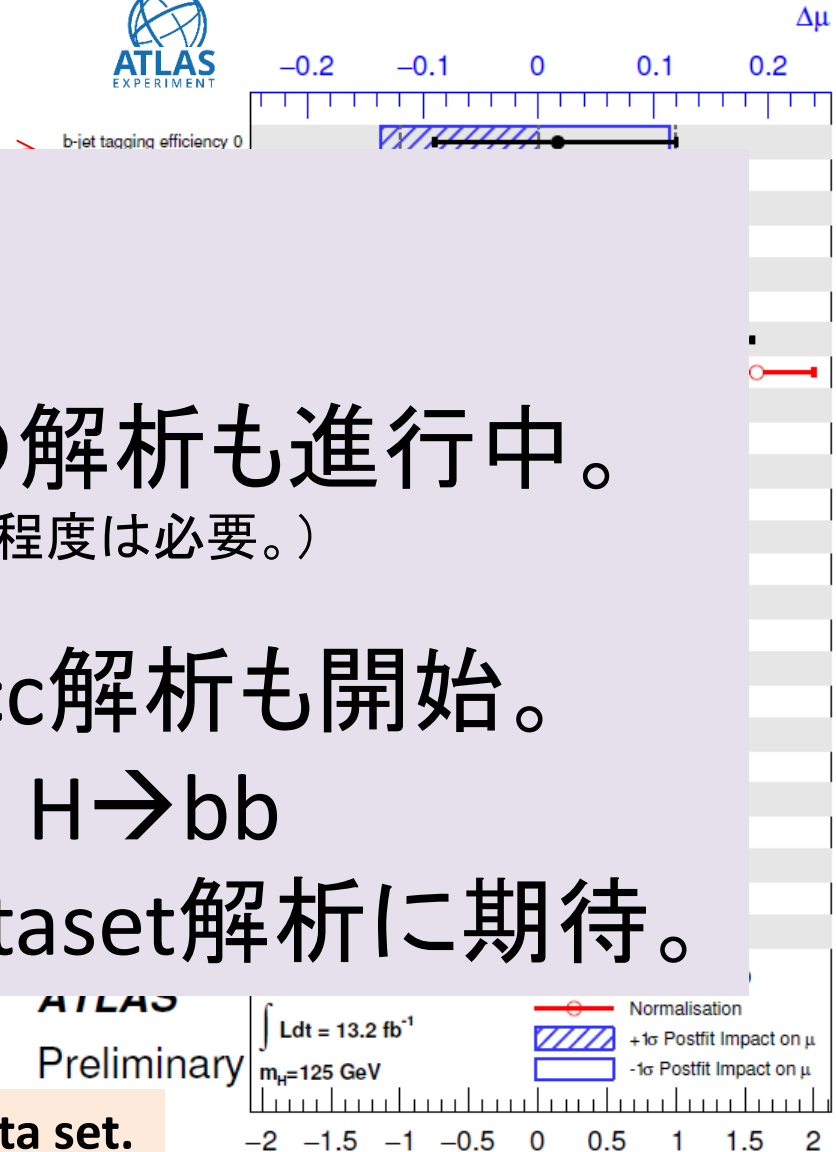
(Sensitivityは低く、50 fb⁻¹程度は必要。)

本格的なVH, $H \rightarrow cc$ 解析も開始。

- Signal

メインはやはりVH, $H \rightarrow bb$

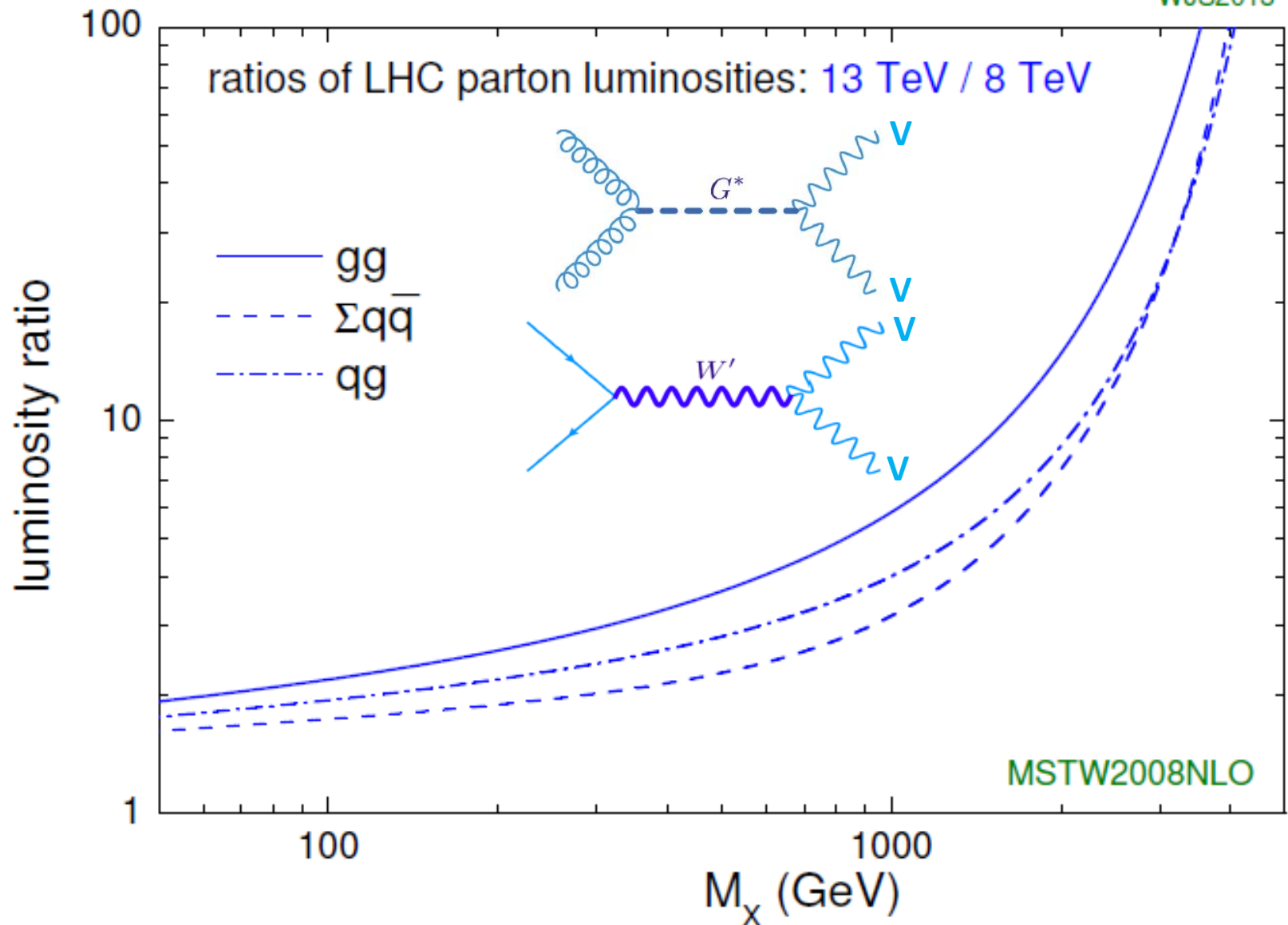
2016年のFull dataset解析に期待。



Aim for Hbb observation with full 2016 data set.
(after combination with Run-1)

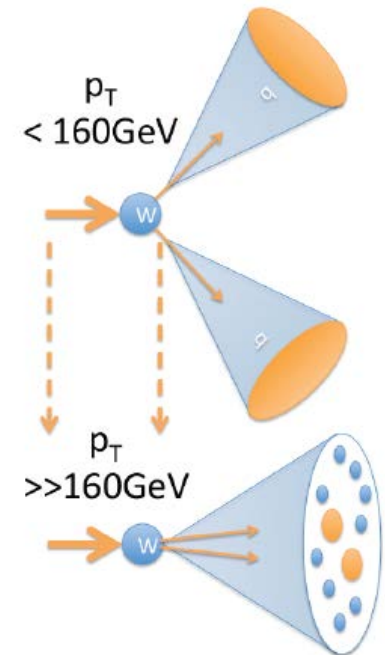
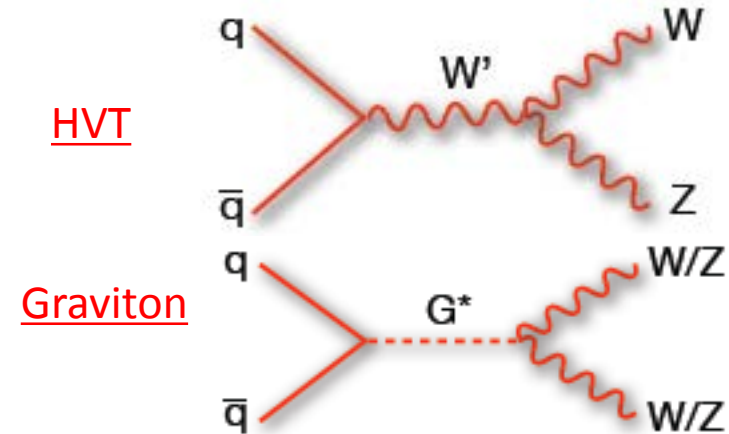
High mass resonance search!

WJS2013



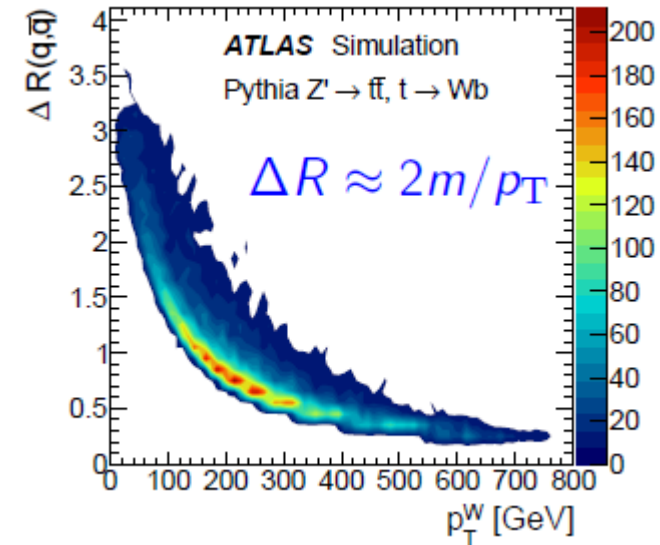
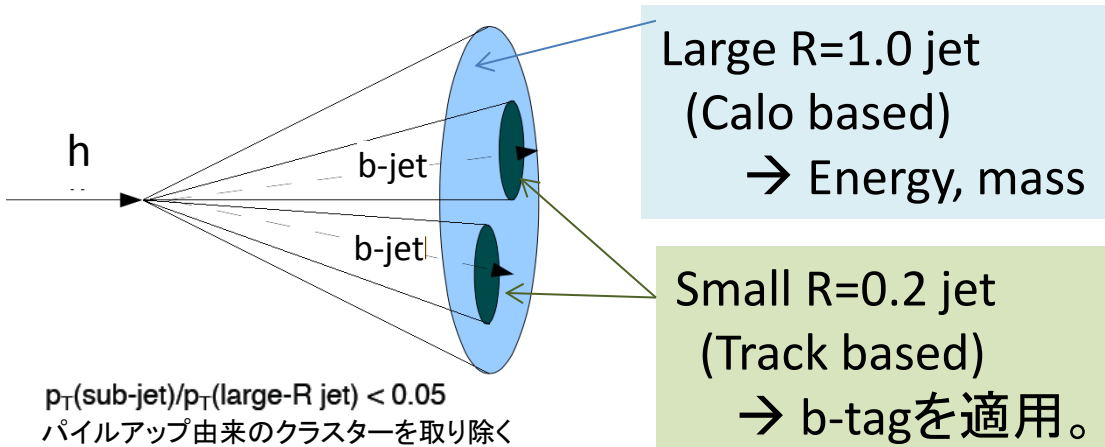
VV / VH searches

- 2HDM, HVT, Graviton
 - VV : WW, WZ, ZZ (and $\gamma\gamma$, $Z\gamma$)
 - VH : WH, ZH
 - W: lv or qq'
 - Z: vv, ll or qq
 - H: $H \rightarrow bb$
- Decay from heavy particle carry large p_T .
 - Use Large-R jet to reconstruct.
 - ATLAS: $R=1.0$ is chosen.

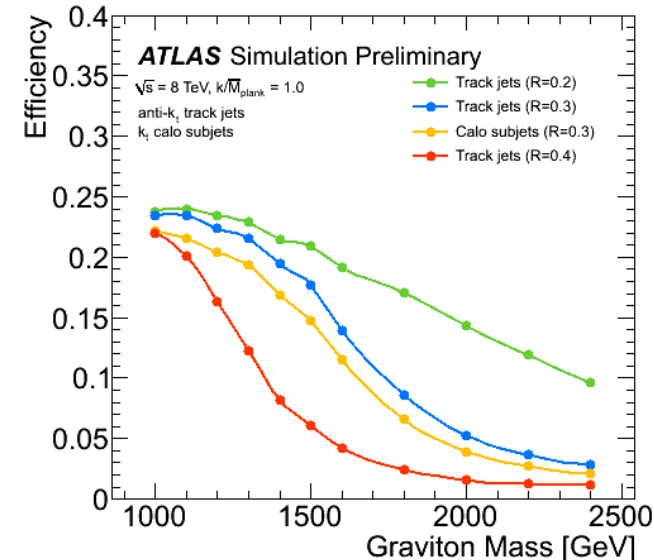


Boson tagging

- Higgsの p_T が高くなると...

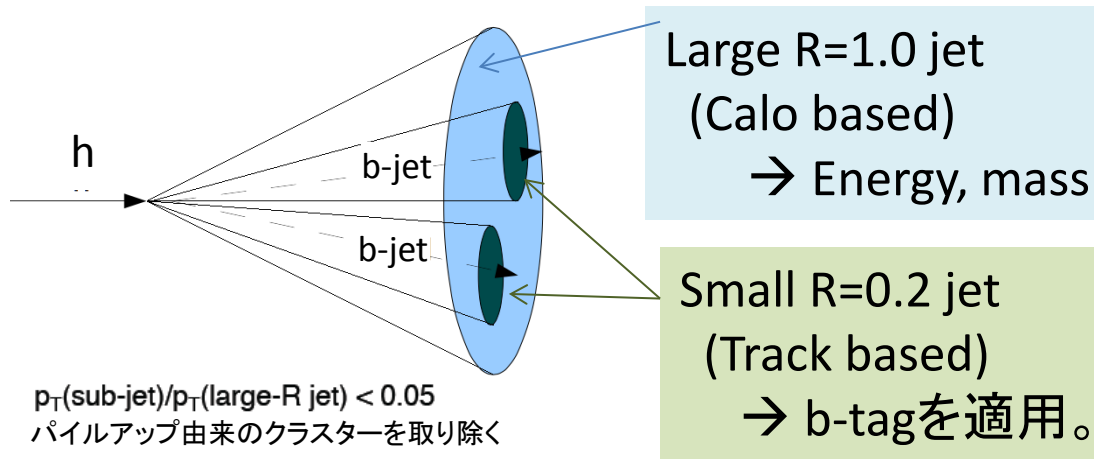


- カロリメータベースのジェットでEnergy, Massを測定
 - Grooming後のクラスターから。
- トラックベースのジェットでb-タグする。
 - 小さいサイズのJetを再構成出来る。
 - B-hadronの方向とjet軸が近くなり、性能向上。
- Resonance searchに非常に有効。

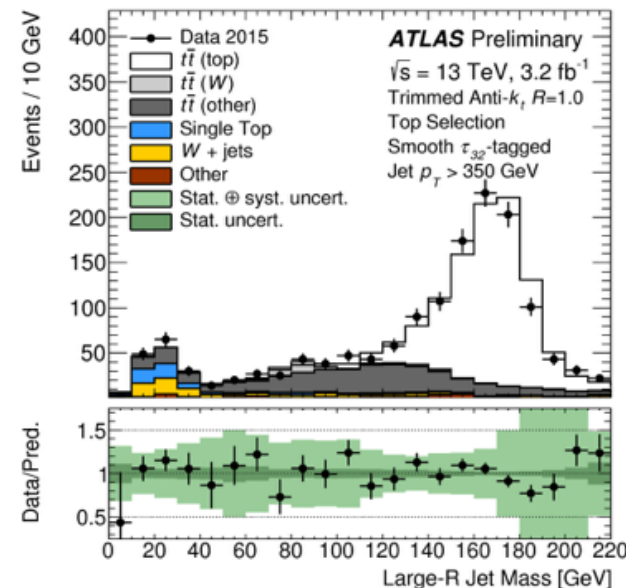
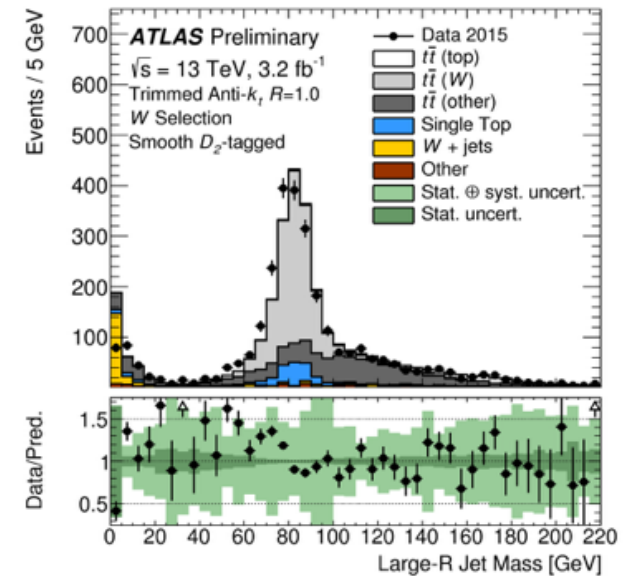


Boson tagging

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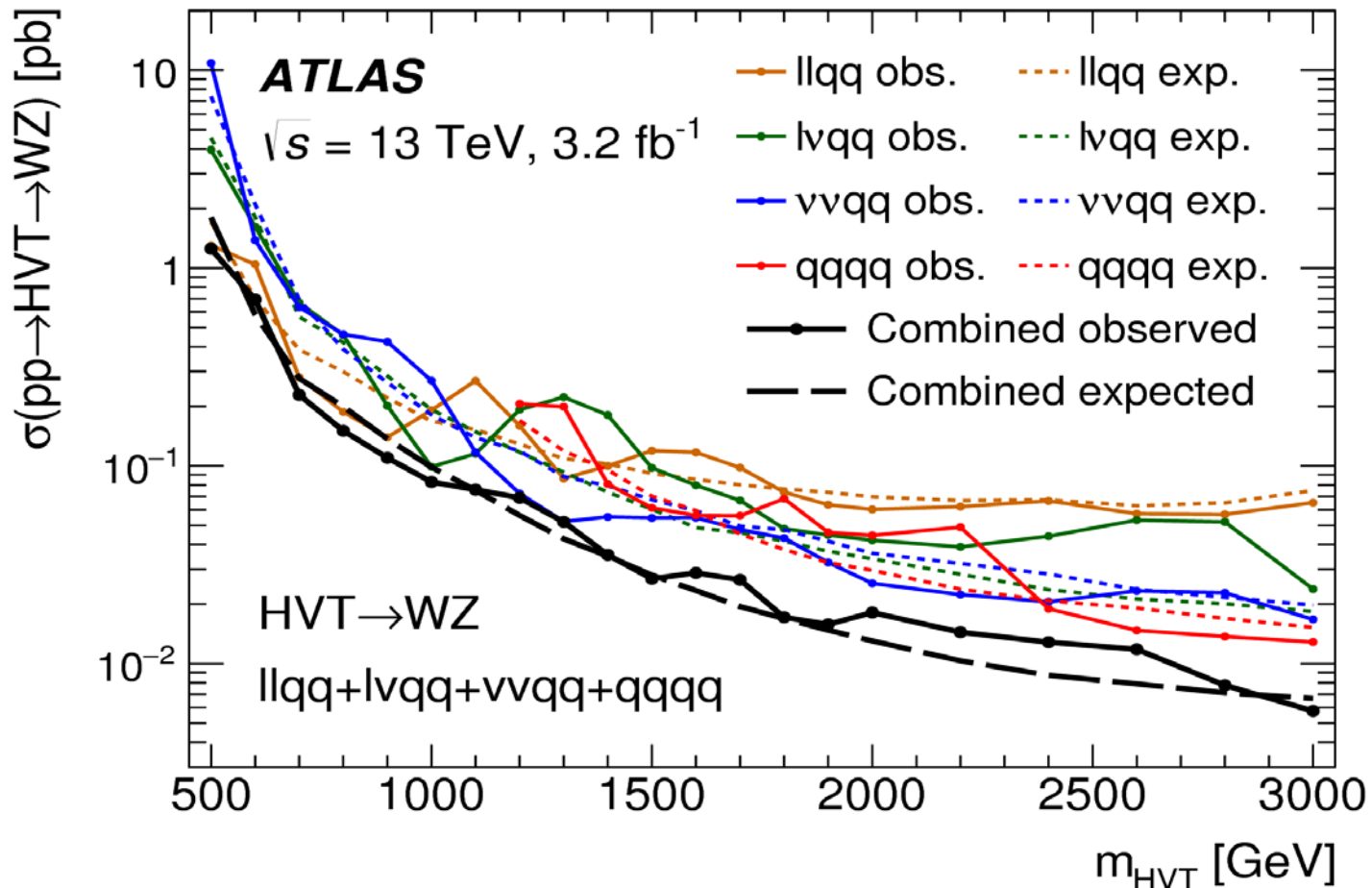
- カロリメータベースのジェットでEnergy, Massを測定
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- トラックベースのジェットでb-タグする。
 - 小さいサイズのJetを再構成出来る。
 - B-hadronの方向とjet軸が近くなり、性能向上。
- Resonance searchに非常に有効。



2015 result

$Z\gamma$, **2-lepton**, **1-lepton**, 0-lepton (**vv+jet**, **JJ**)

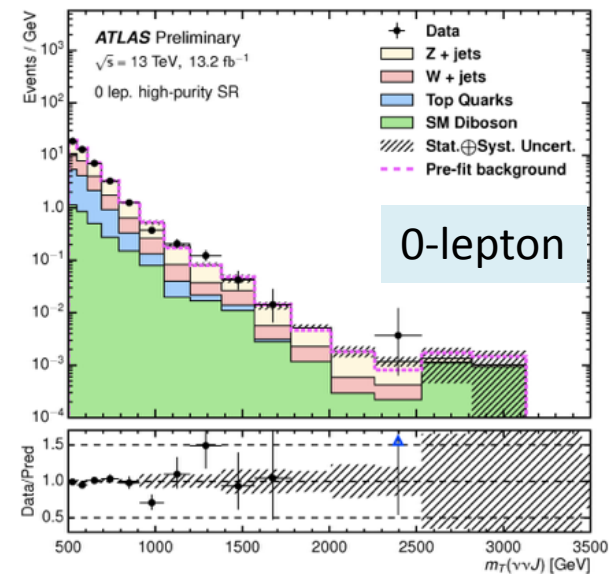
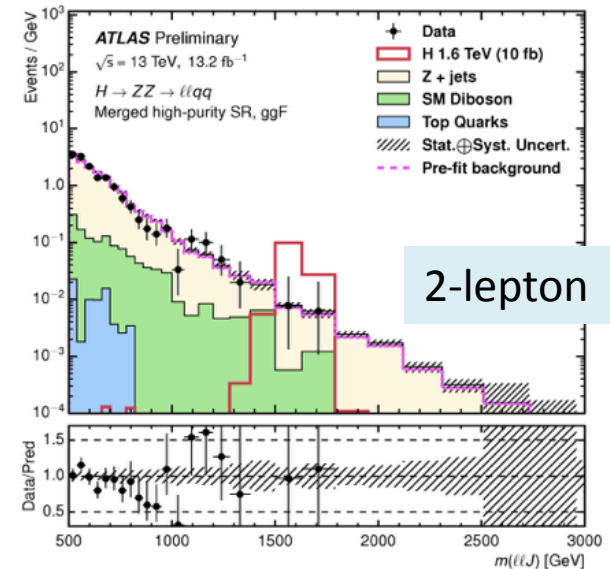
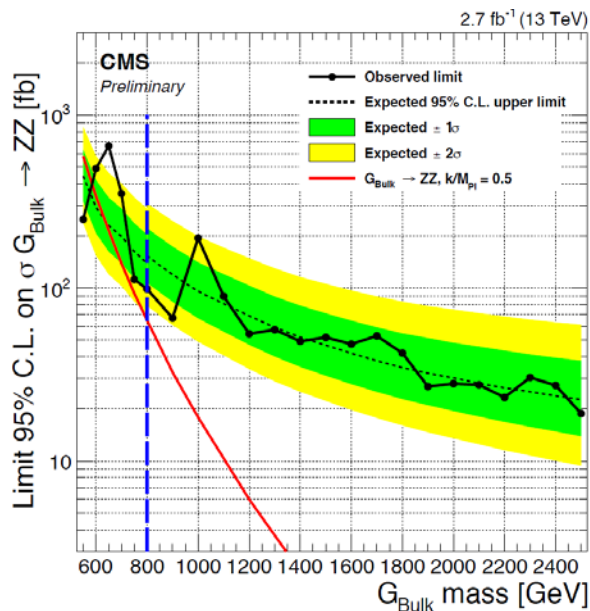
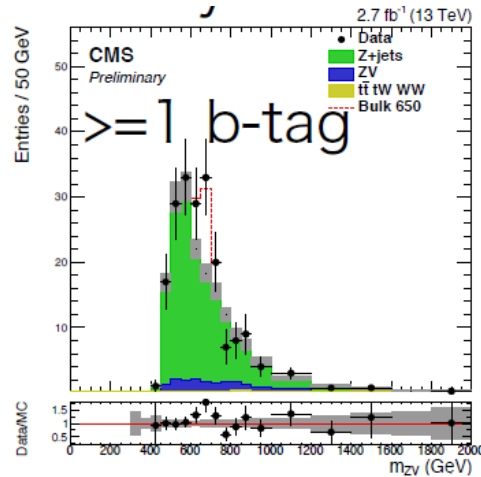
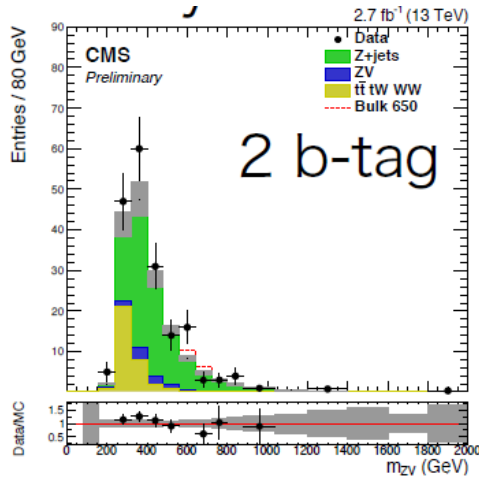
Low mass \longrightarrow High mass
 Good mass resolution good in trigger High signal yield



VV reso search : 2-lepton

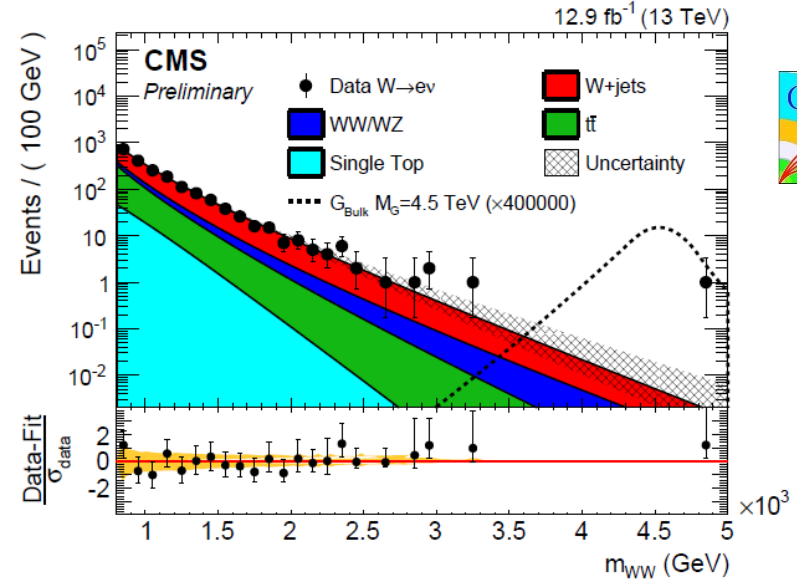
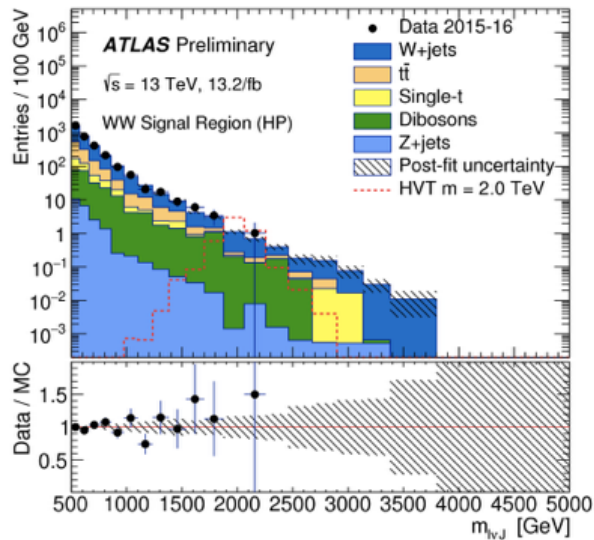


CMSは 2.7 fb^{-1} で 650 GeV に 3σ 強
のExcessを報告

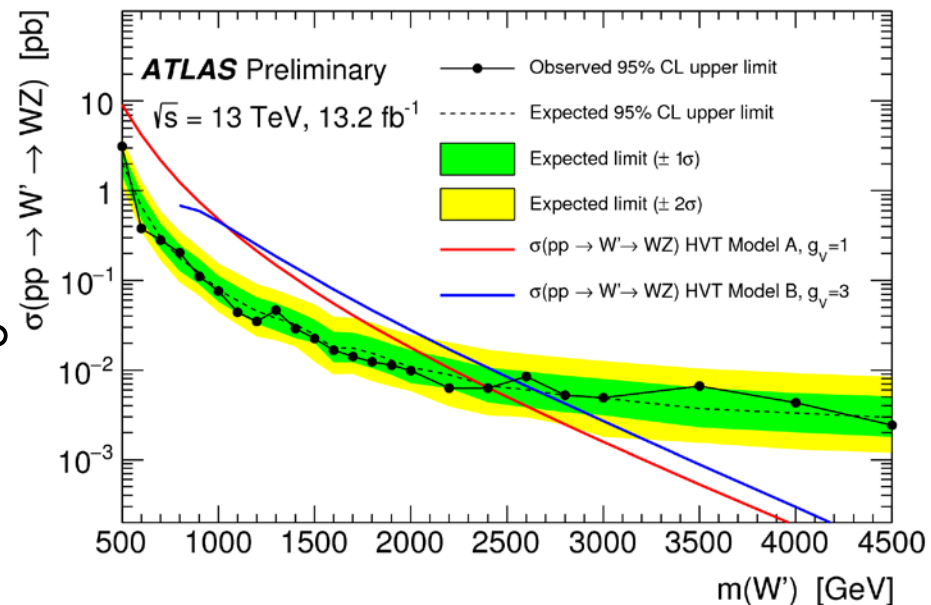


ATLASの 13.2 fb^{-1} には見えず。

VV reso search : 1-lepton

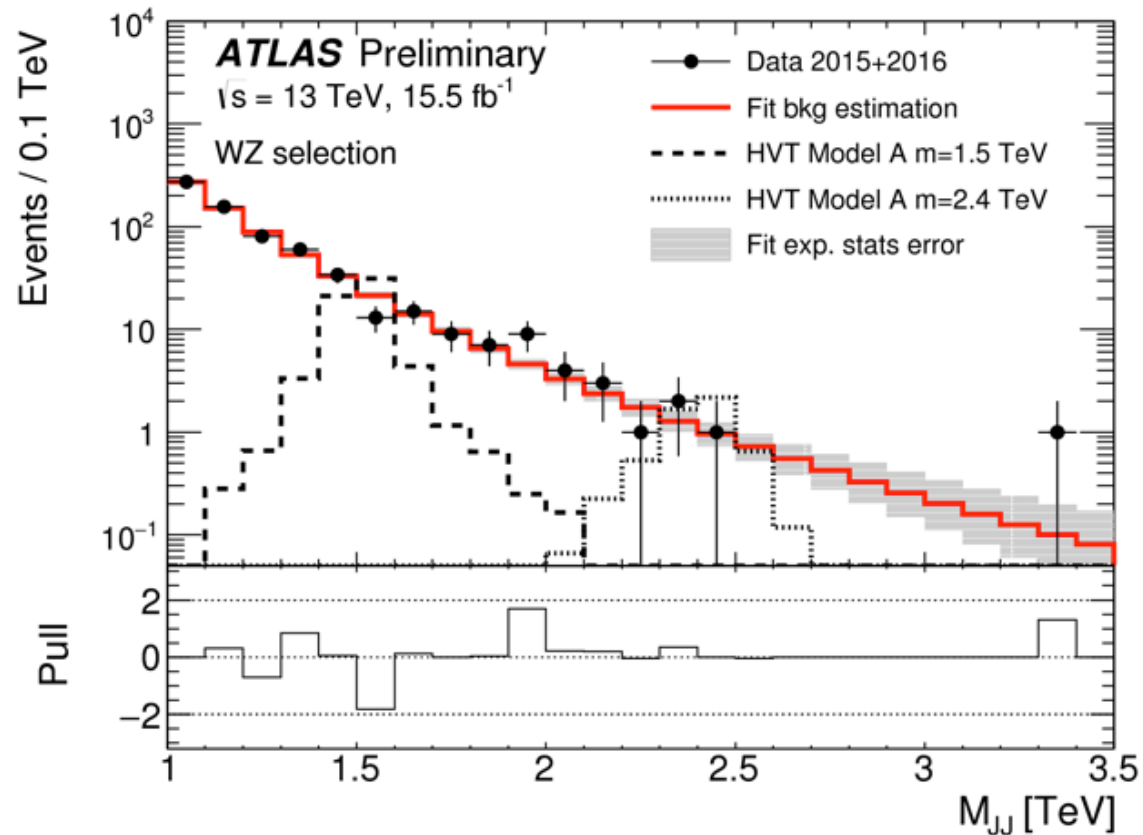
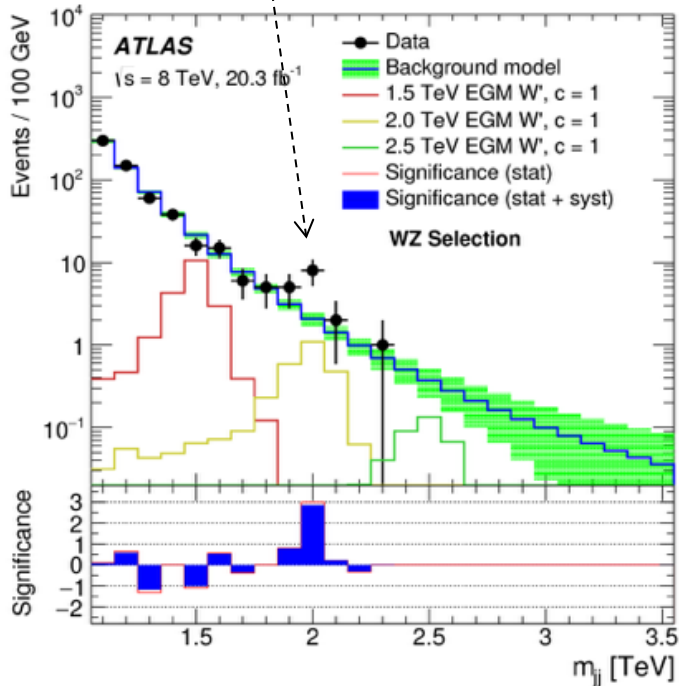


- ATLAS, CMSともに 13 fb^{-1} の解析。
- BG予想と良く一致
- 2.2 TeV以下はExcessなし。
 - Modelによっては $tt\bar{t}$ threshold 以下は可能性はある。



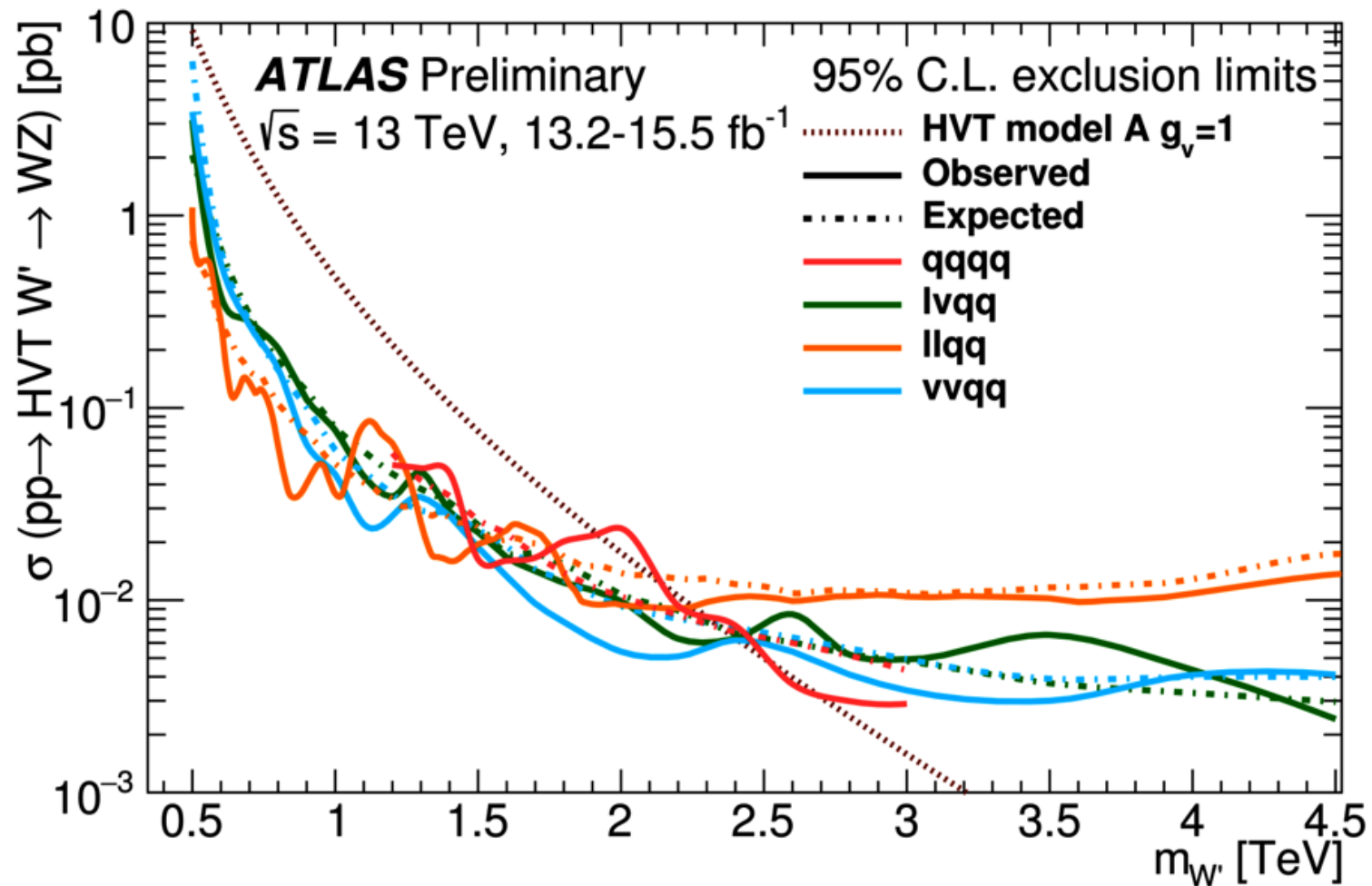
VV reso search : 0-lepton (JJ)

- 8 TeVの解析では2TeVに3 σ のExcess。



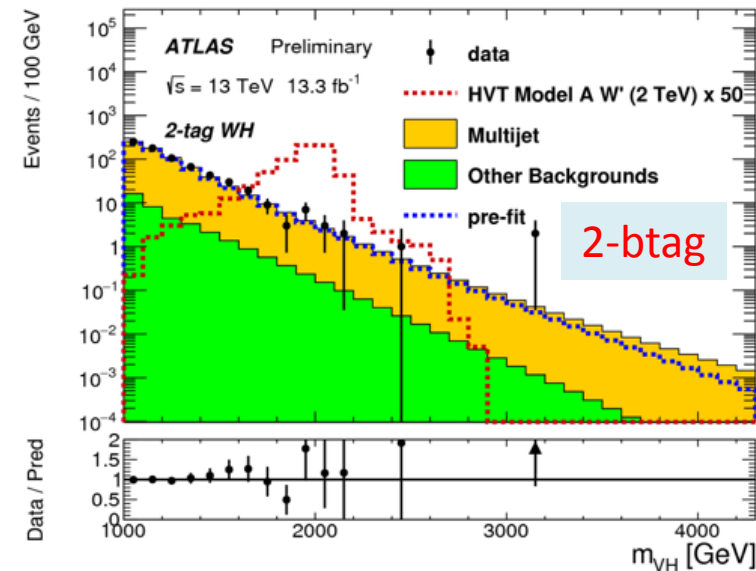
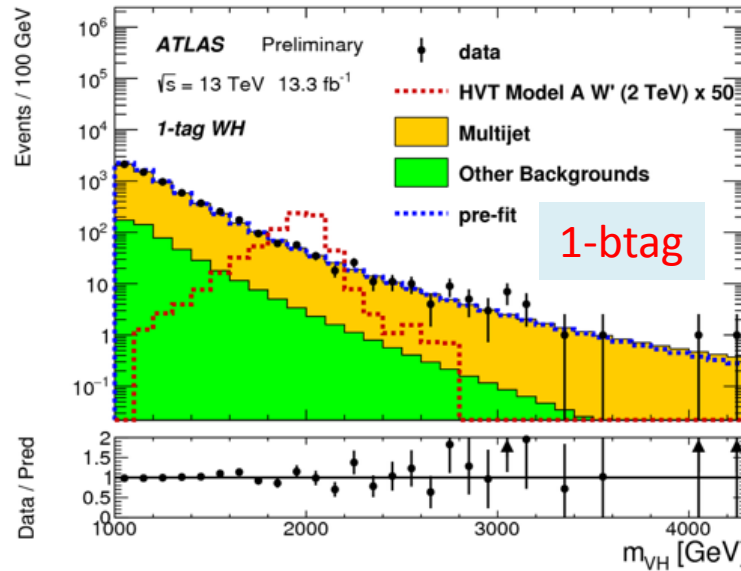
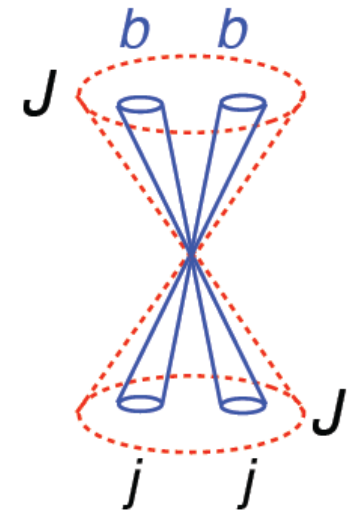
- 13 TeVは2 σ 以下

VV resonance search with 13-15 fb⁻¹

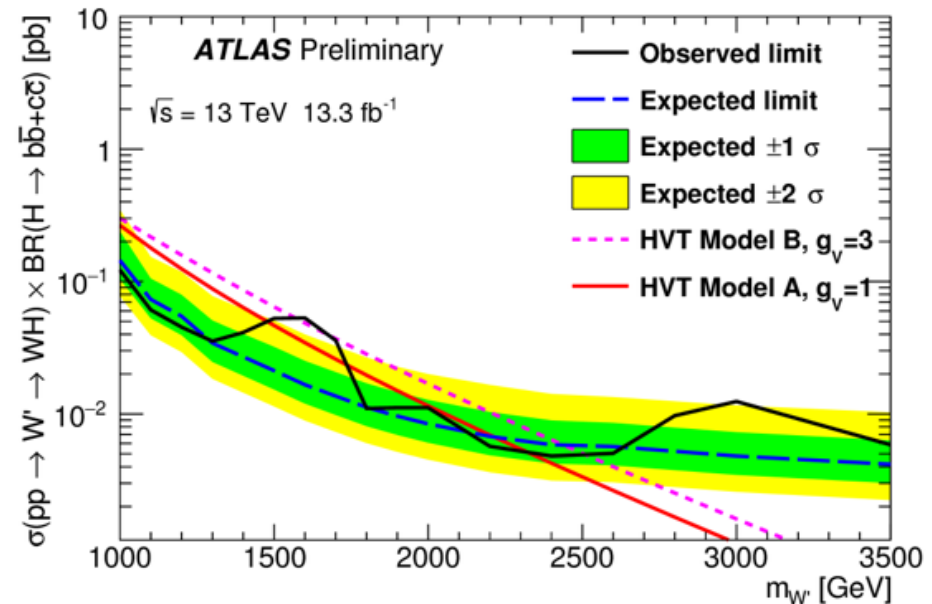


- 残念ながら、2.3 TeVまではExcess無し。

$Z' \rightarrow ZH, W' \rightarrow WH$ with JJ



- All HadでのVH reso最初の解析。
- 1.6 TeVと3 TeVに2 σ 強のExcess.
- Leptonicチャンネルを鋭意解析中



まとめ

- ヒッグス粒子発見後、舞台は測定に。
- クォークとの結合の直接測定はもう少しデータが必要。
 - HbbはRun-1とのCombinedで
 - ttHはすべてのFinal stateを足すことで
2016年のデータで「発見」可能か？
- Run-2で観測されたHiggsの数がRun-1を越えた。
 - 最初の結合測定もICHEPで発表された
 - ATLASとCMSで共通のFrameworkを決め、Fiducial cross section, Differential cross sectionを測定していく。
- VV/VH resonance searchが進行中
 - BGモデルはHiggsの解析からの影響大
 - 今のところ、Excess無し(2.2 TeVくらいまで)。
- 2018年終わりまでに今の10倍のデータが手に入る