

LHCでのヒッグス研究の最新 結果

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東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo

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2017/12/14-15

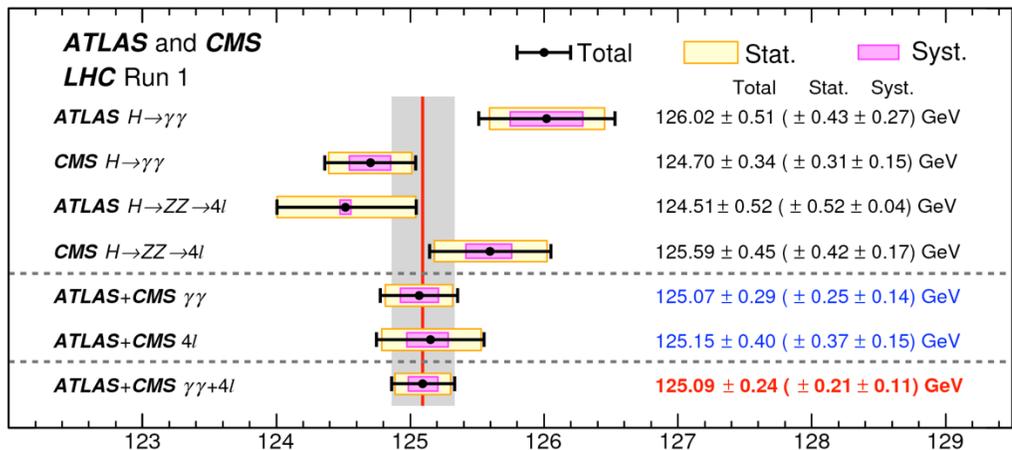


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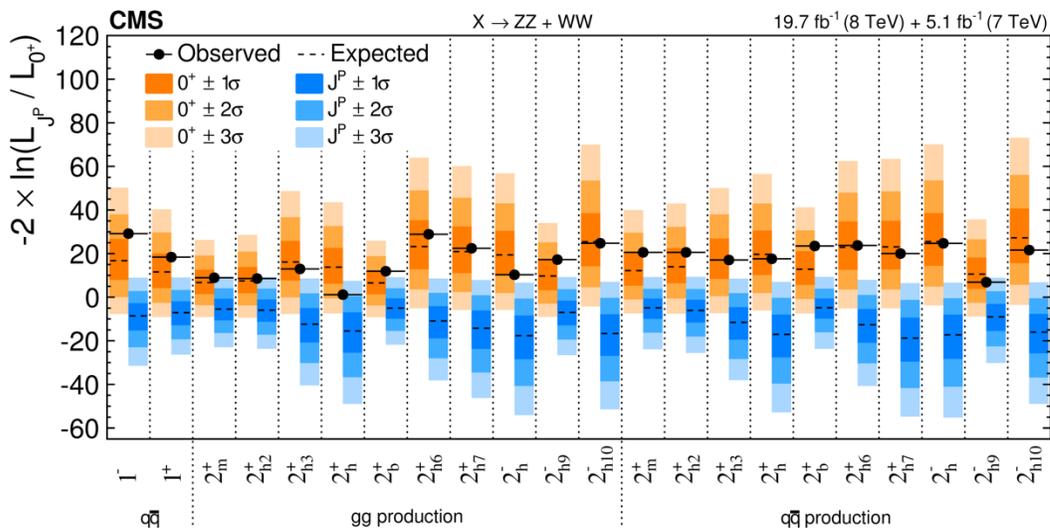
- イントロ
- LHCの状況
- ボソニック崩壊チャンネル(精密測定)
 - 質量測定
 - Coupling
 - Differential cross section measurement
- フェルミオン崩壊/生成(探索)
 - π /bb decay
 - ttH production
- Rare decay, BSM Higgs Search

LHC Higgs Run1 Achievement

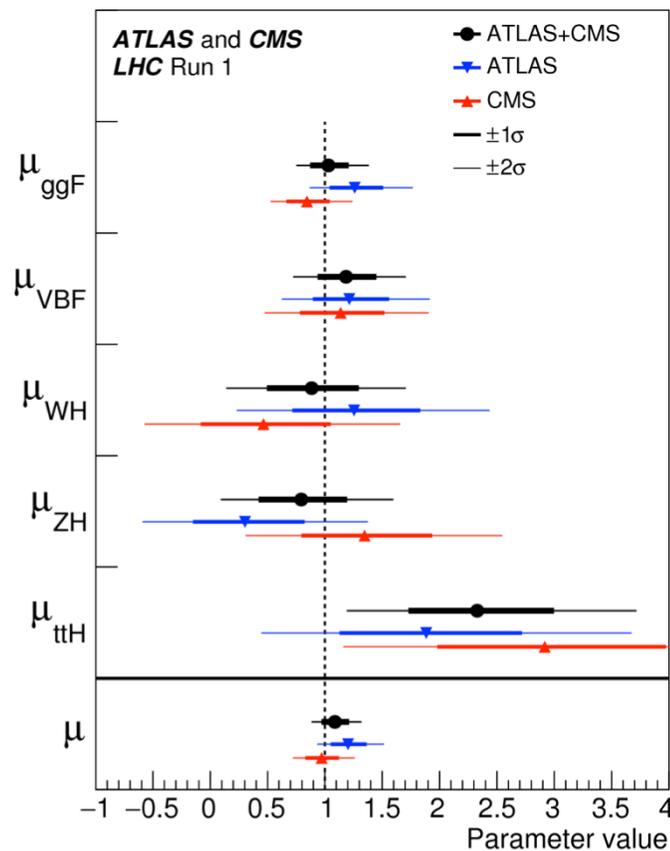
発見から精密測定へ



質量測定精度 $\sim 0.2\%$ (統計誤差が支配的) m_H [GeV]



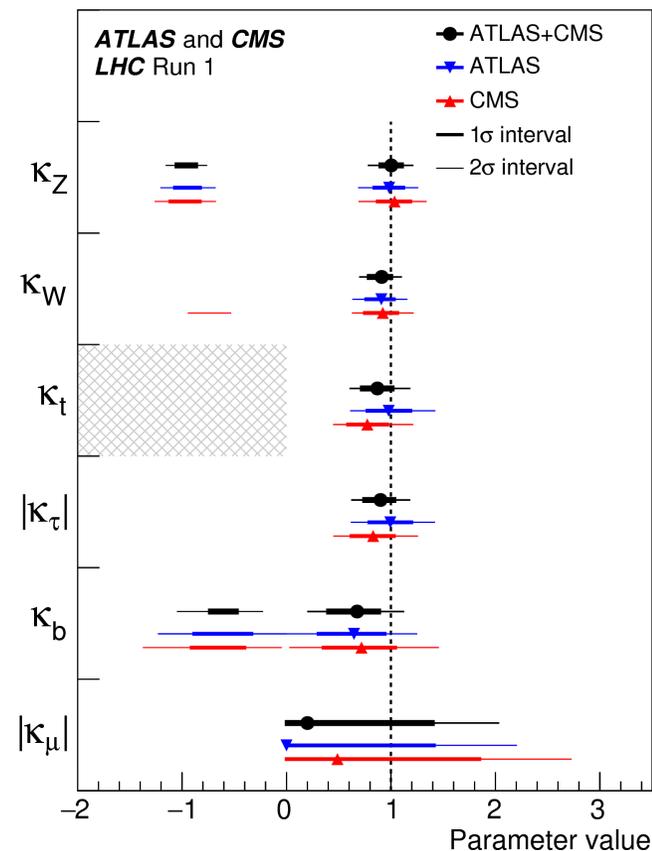
Spin/Parity : SM 0^+ と無矛盾



ATLAS : $\mu = 1.20^{+0.15}_{-0.14}$

CMS : $\mu = 0.97^{+0.14}_{-0.13}$

ATLAS+CMS $\mu = 1.09^{+0.11}_{-0.10}$



VBF 5.4σ (Exp. 4.6σ)

VH 3.5σ (Exp. 4.2σ)

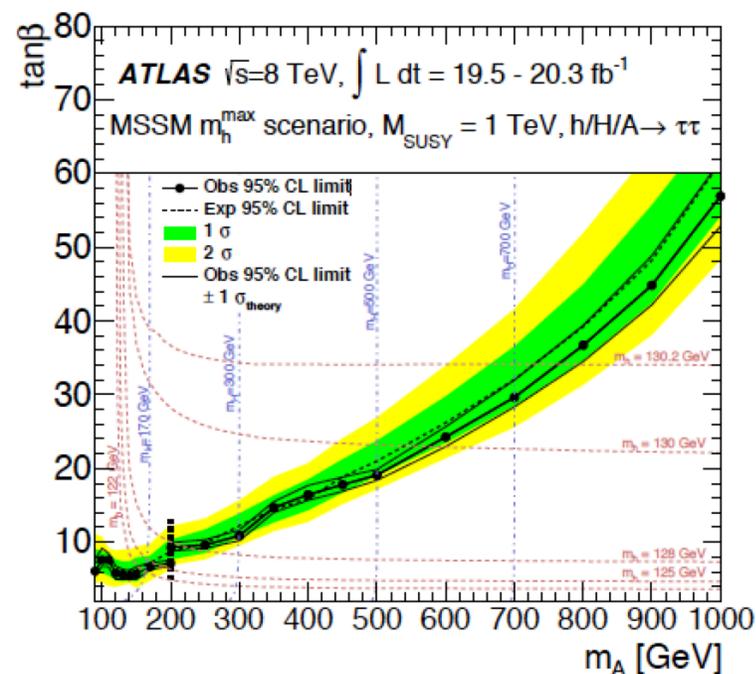
ttH 4.4σ (Exp. 2.0σ)

$H \rightarrow \tau\tau$ 5.5σ (Exp. 5.0σ)

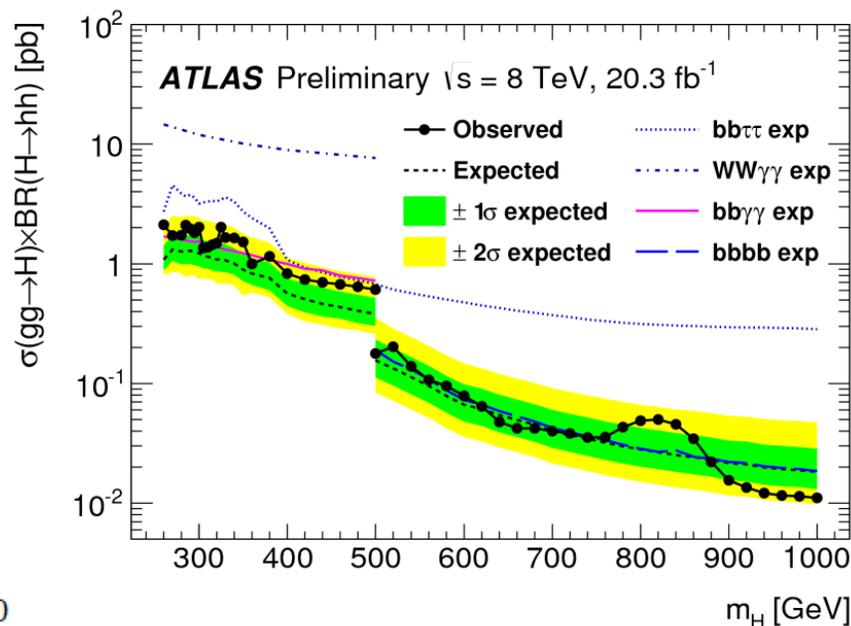
$H \rightarrow bb$ 2.6σ (Exp. 3.7σ)

LHC Higgs Run1 Achievement

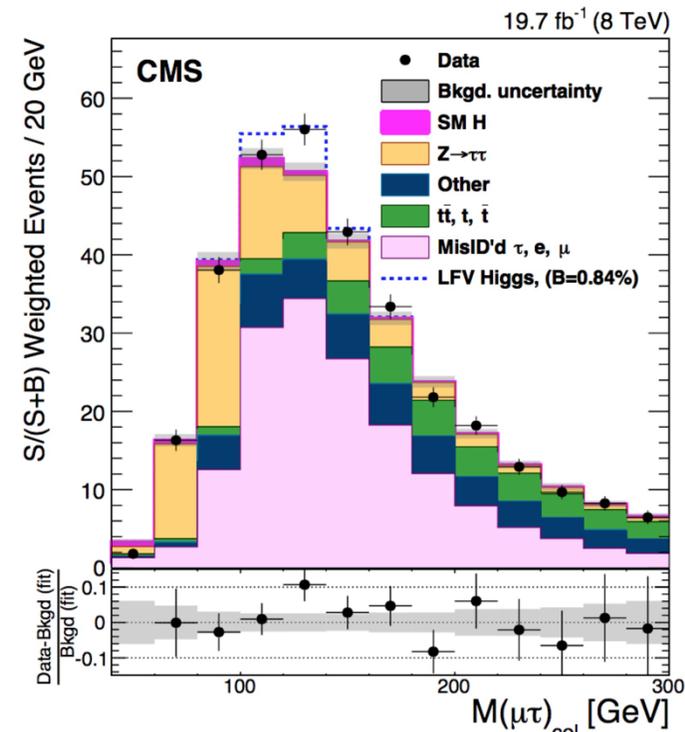
- 重いヒッグスの直接探索, Anomalous coupling



A $\rightarrow\tau\tau$ (high $\tan\beta$ に感度)
 $m_A > 800$ GeV ($\tan\beta \sim 40$)
 $m_A > 500$ GeV ($\tan\beta \sim 20$)



hh resonance探索

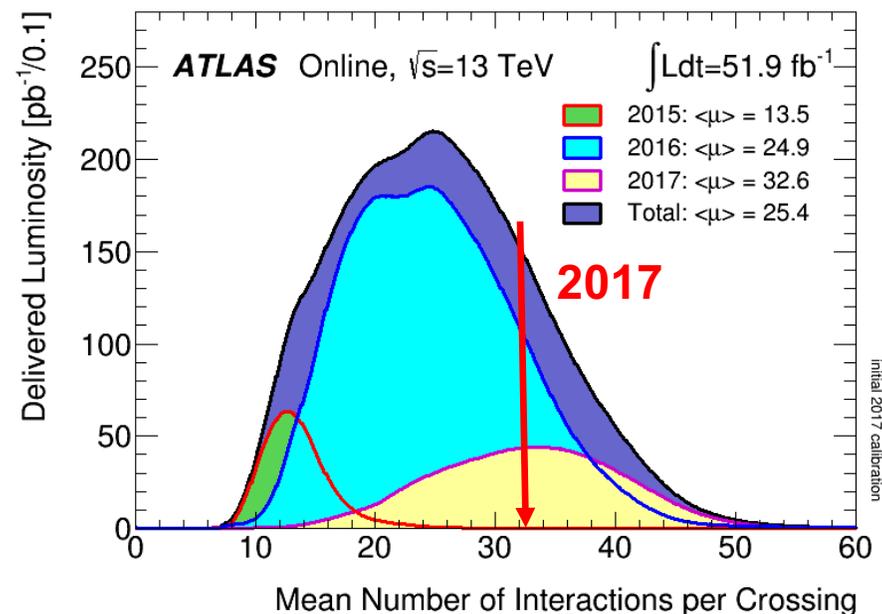
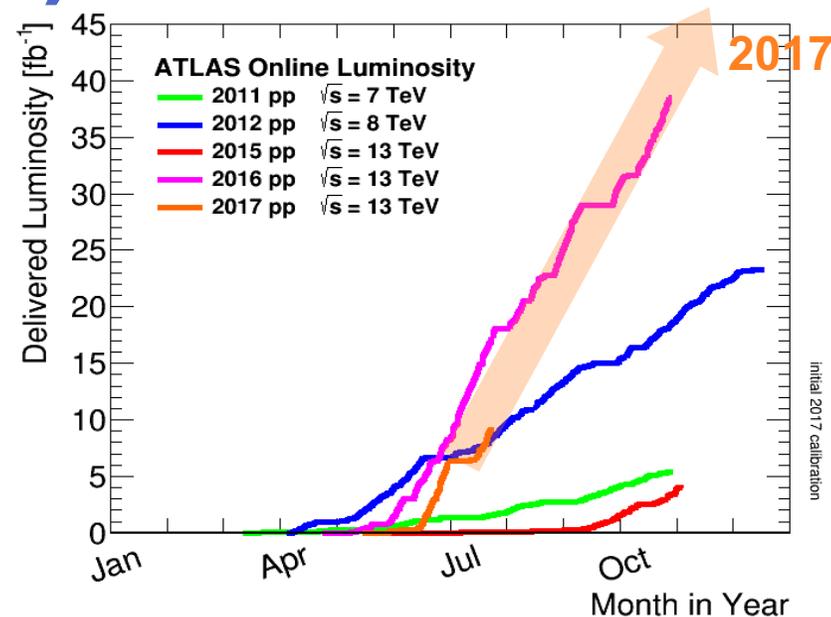


LFV Higgs探索
 $H \rightarrow \mu\tau : 2.4\sigma$
 $BR(H \rightarrow \mu\tau) 0.84^{+0.39}_{-0.37}\%$

Run1でBSMヒッグスの有意な証拠は見つからず。。。

LHC Run2 (2015-2017) Status

- Run2 2015+2016ラン : 13TeVで約43fb⁻¹のデータを取得(**Good Run ~36fb⁻¹**)
- 2017ランは順調にスタート
13TeVデータを取得中(~9.2fb⁻¹)
- 最高瞬間ルミノシティ : $1.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (すでに2016年から20%向上)
- 実験的には大きなアップグレード前の2018年までが1つの正念場
 - すでに瞬間ルミノシティは設計値($1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$)を大きく超えている
 - 2016 : Pile up $\langle \mu \rangle = \sim 25$
 - 2017 : Pile up $\langle \mu \rangle \sim 33$ (現在) , $\mu_{\text{max}} = 51$
- トリガー、Particle-ID/tagに厳しい環境だが、ATLASは順調にデータを取得
 - 2016 : 93-95%
 - 2017 : ~91%

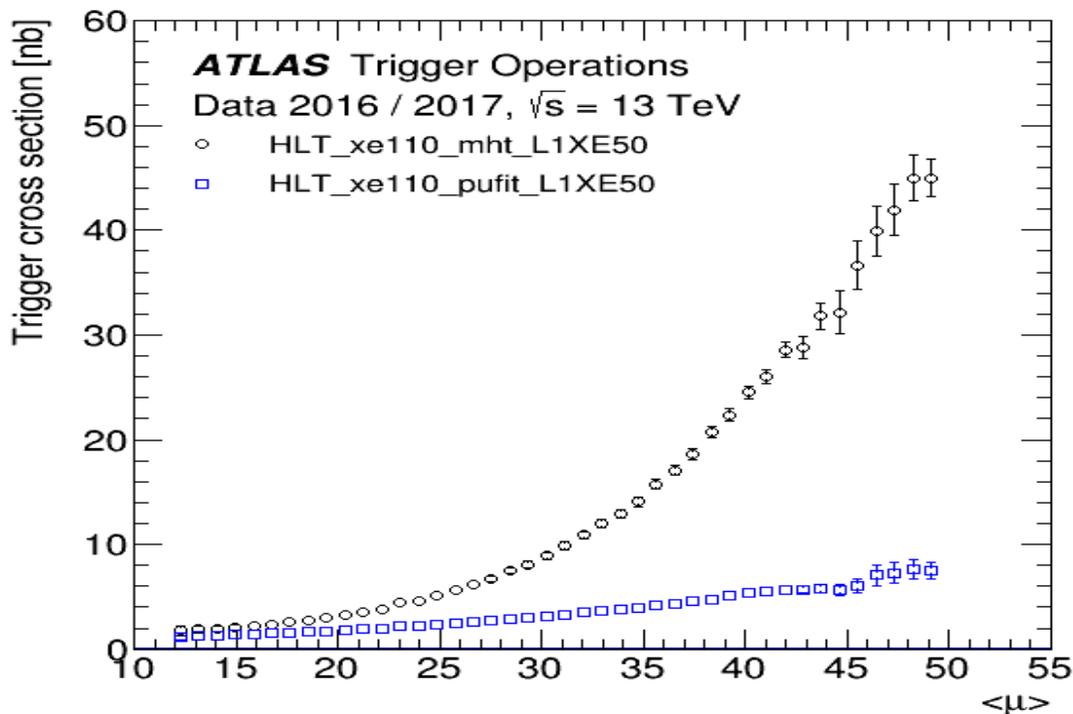


Key Performances for Higgs analysis

MET trigger algorithmをPile-upに強く

2016 : Calibrateしたhadronic jet (missing HT)+pile-up subtractionから計算

2017 : pile-upとhard scatterのカロリメータタワーからpile-up由来のタワーを”推定”してMETを補正

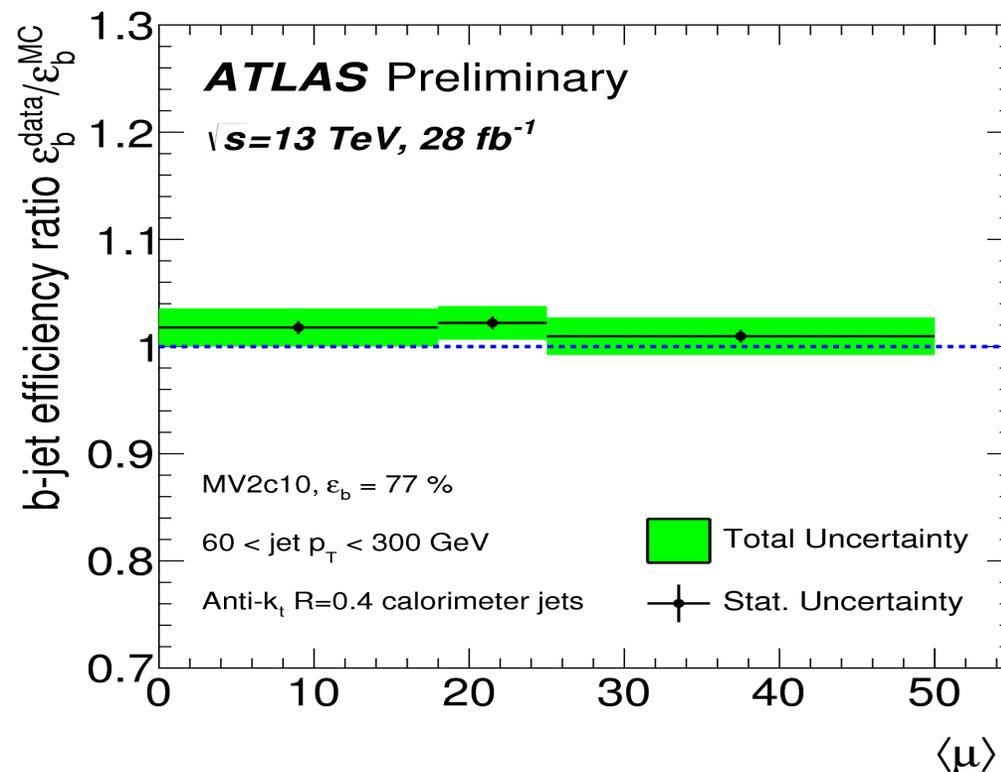


→Pile-up依存性を低減(なるべく低い閾値を保つ)

b-tagging efficiency scale factor

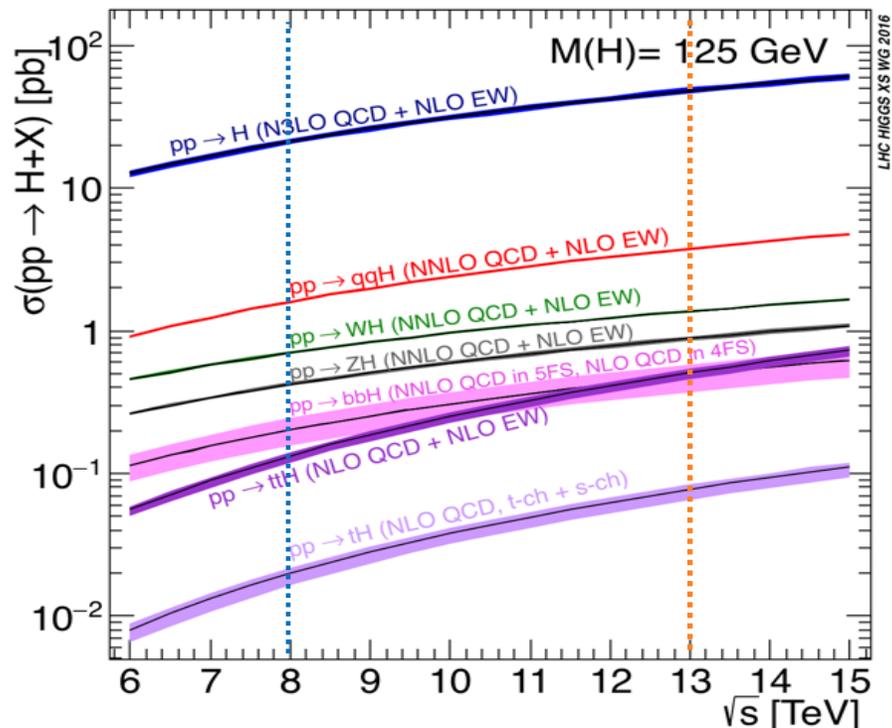
ttbarを使ってefficiencyを較正

data/MC, pile-up依存性をよく理解出来ている
ttH, VH→bbの解析に重要

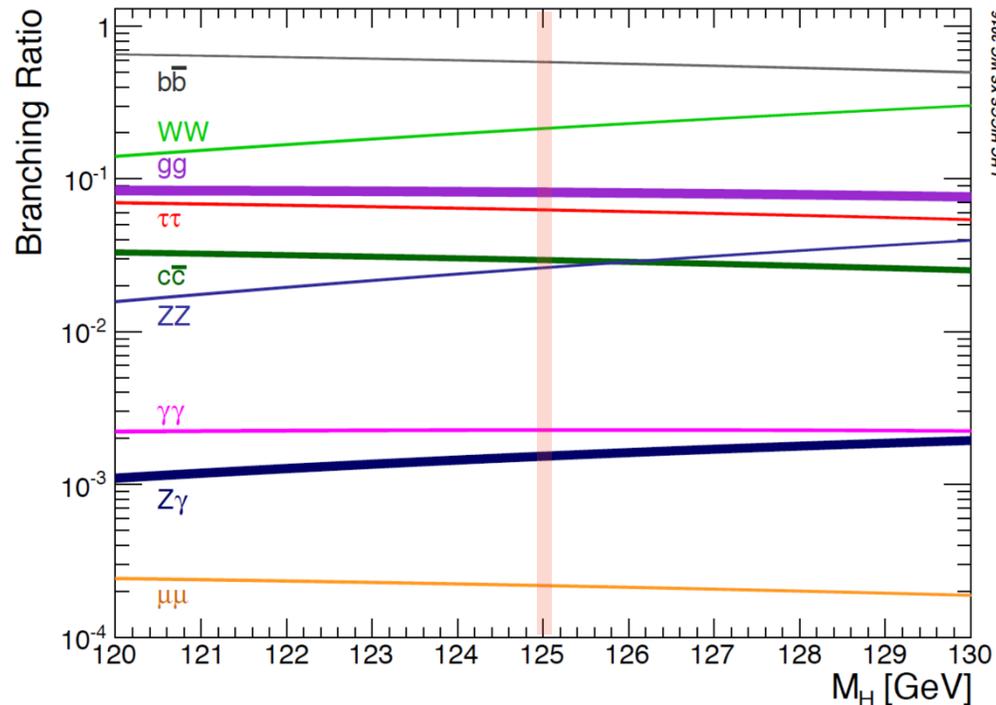


Run2 Higgs Physics Strategy

- LHCでのヒッグス生成断面積



- ヒッグスの崩壊分岐比



Process	ggF	VBF	WH	ZH	ttH
X-sec(pb)	49pb	3.8pb	1.34pb	0.88pb	0.51pb

ggF : N³LO QCD+NLO EW

X-sec(13TeV/8TeV) ~2-2.5

ttH ~4 higher → Run2 13TeVで感度向上

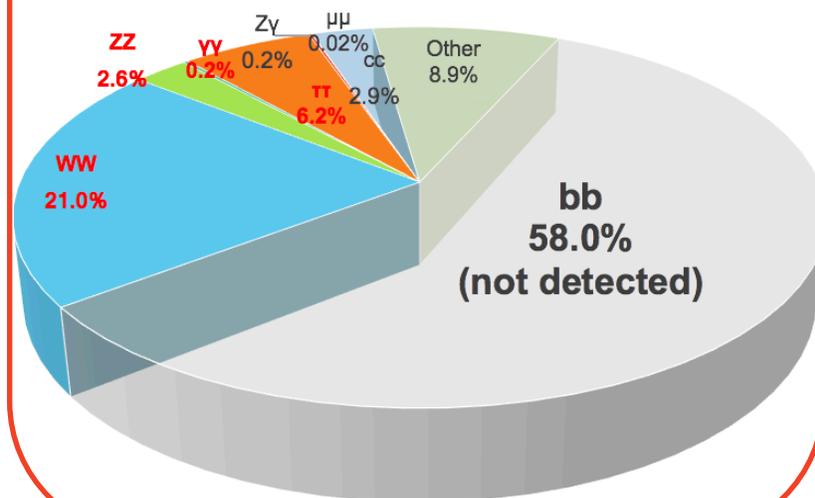
Decay	bb	WW	ττ	ZZ
BR	58%	21%	6.2%	2.6%
	γγ	Zγ	μμ	cc
	0.23%	0.15%	0.022%	2.9%

Run2 Higgs Physics Strategy

- I. Higgsの物理は精密測定の時へ
 - 発見したヒッグスボソン($m_h \sim 125$ GeV)の精密測定から新物理を探る
- II. 次のスカラー粒子・新物理を直接探索

Property Measurement

- Mass, Width
- Spin/Parity
- Coupling
- Rare Decay/Production Search



Higgs Sector

“A” Higgs boson (125 GeV)
5歳

BSM direct search

- Heavy Higgs search
- Light Higgs search
- Invisible higgs
- Anomalous coupling
-

主にRun2, 2016年までのフルデータ
($\sim 35\text{fb}^{-1}$)を使った
精密測定・探索結果にフォーカスして報告する

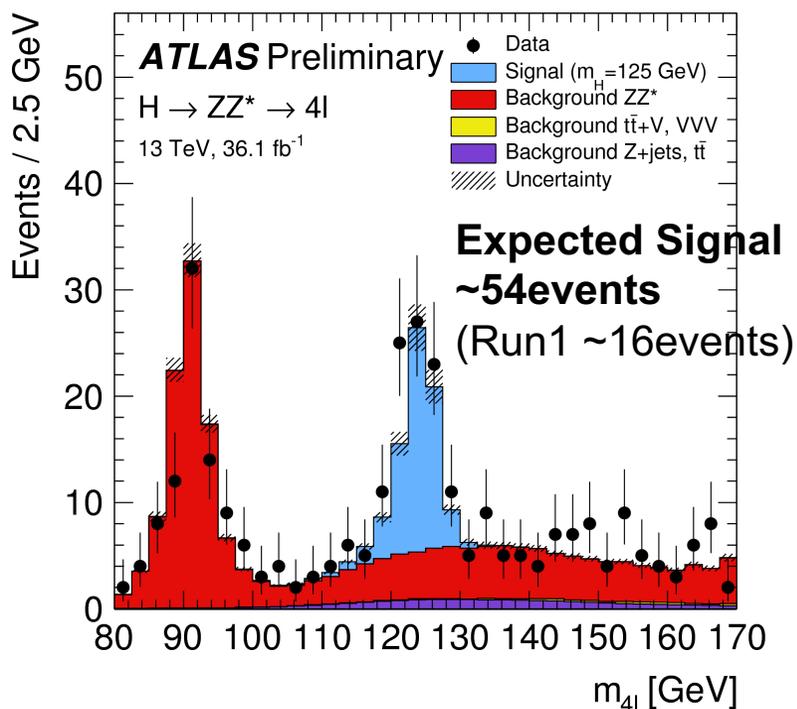
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Higgs Bosonic Decay mode

H \rightarrow ZZ \rightarrow 4l analysis Overview

- ヒッグス粒子精密測定のためのGolden Channel：終状態に4つのレプトン
 - 背景事象がかなり少ない S/B > 2
 - 高分解能($\sigma(m_H) \sim 1-2\%$)でヒッグスの質量再構成が可能, ヒッグスの崩壊生成物がすべて観測可能
 - 統計が少ない BR(H \rightarrow ZZ \rightarrow 4l) $\sim 0.01\%$



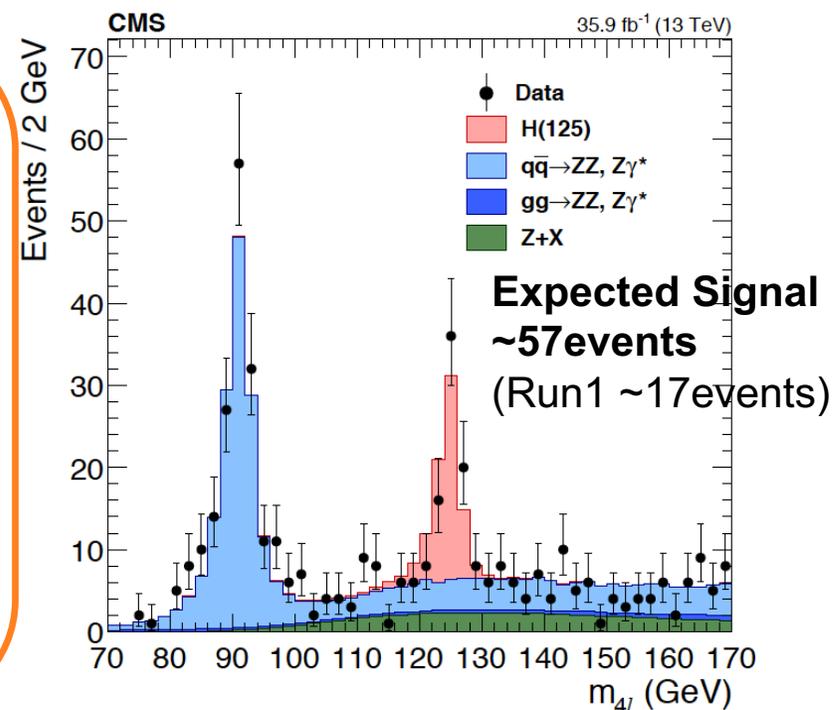
Event Selection

- 4l (4e, 4 μ , 2e2 μ)
- Z/Z* mass selection

生成過程で分類分け

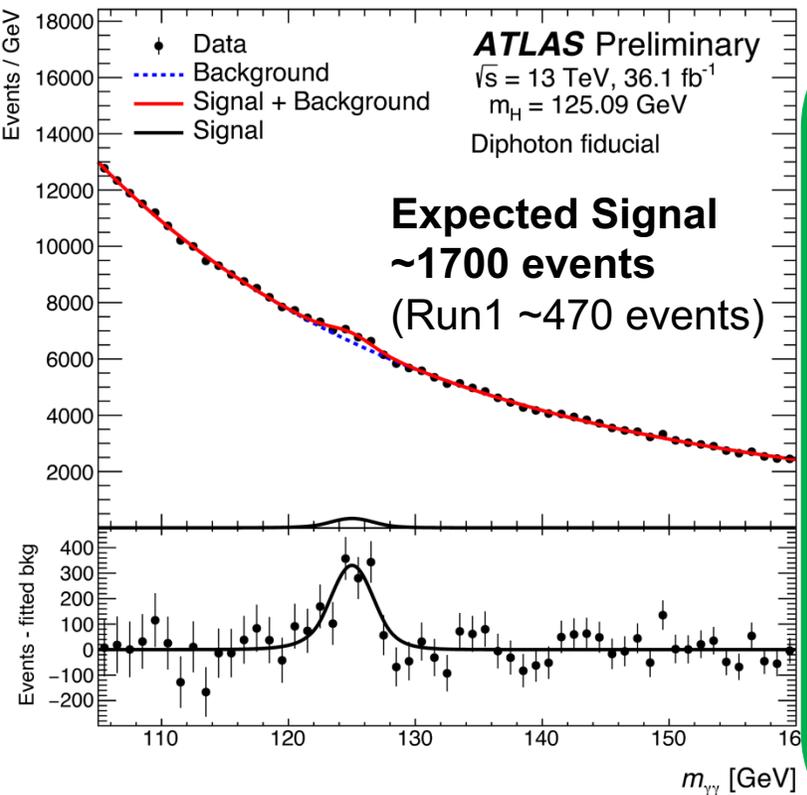
- ttH (b-jetを要求)
- VH (leptonを要求)
- VBF (高い m_{jj} を要求)
- ggF(0,1 jet)

各カテゴリーごとにBDT, MED
で背景事象を分離



H $\rightarrow\gamma\gamma$ analysis Overview

- 2光子の質量ピークが観測可能
 - 高い質量分解能 (1-2%)
 - 背景事象は質量のside-bandから外挿(MCに依存しない)
 - 信号の統計は比較的多い BR(H $\rightarrow\gamma\gamma$) \sim 0.2%



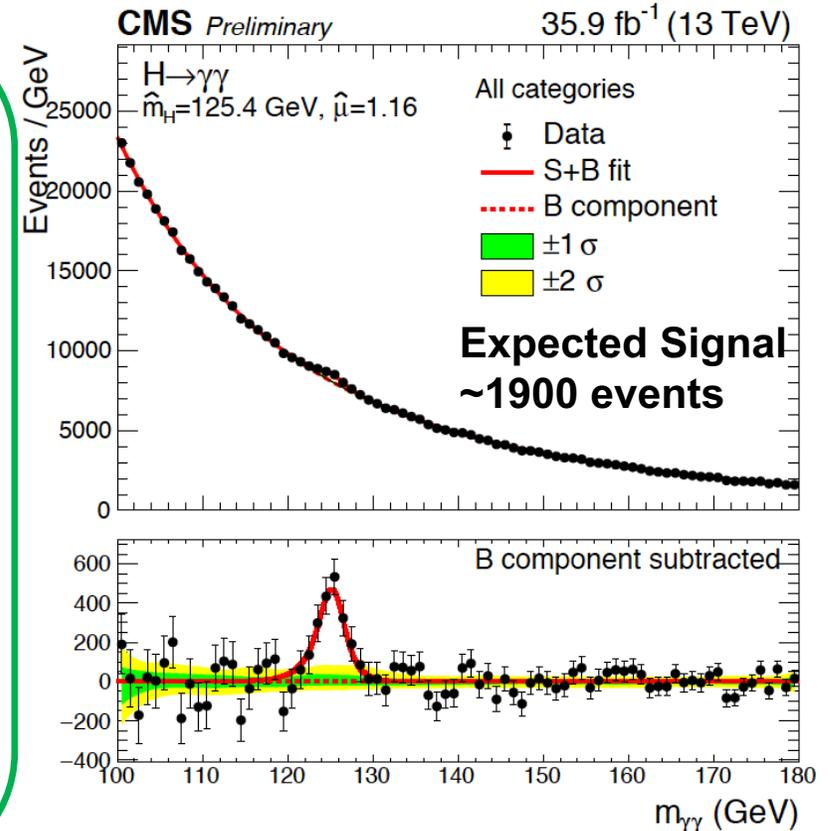
Event Selection

- 2 photon
- $E_T/m_{\gamma\gamma} > 0.35(0.25)$
- NN-base primary vertex selection

生成過程で分類分け

- tH, ttH (b-jetを要求)
- VH (lepton, METを要求)
- VBF (高い m_{jj} を要求)
- ggF(0, 1 jet, 2jets), $p_T^{\gamma\gamma}$ で場合分け

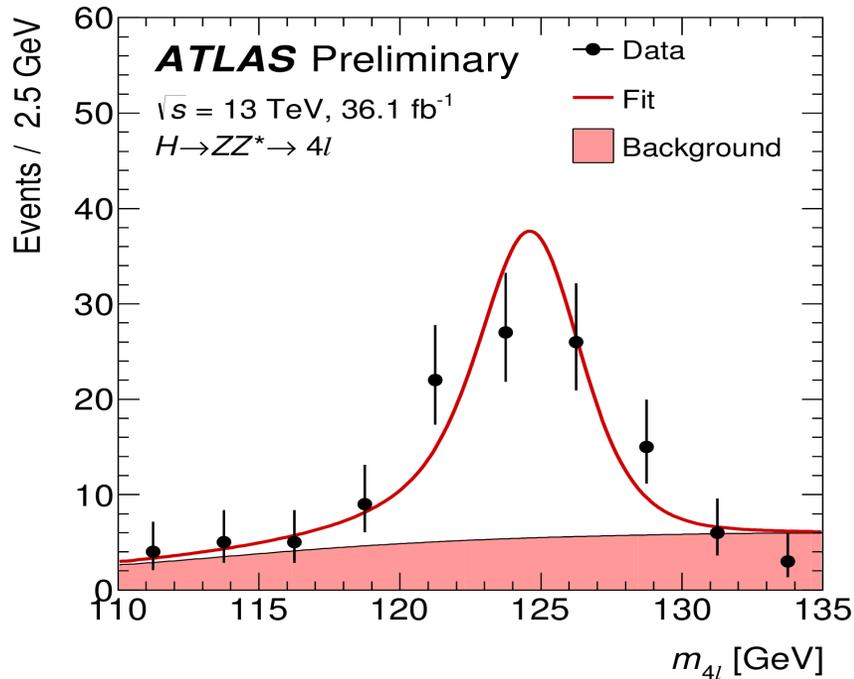
BDTで背景事象を分離(VBF, ttH)



Higgs 質量精密測定

- 質量分解能が良い $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow \gamma\gamma$ チャンネルで質量測定

$H \rightarrow ZZ \rightarrow 4l$



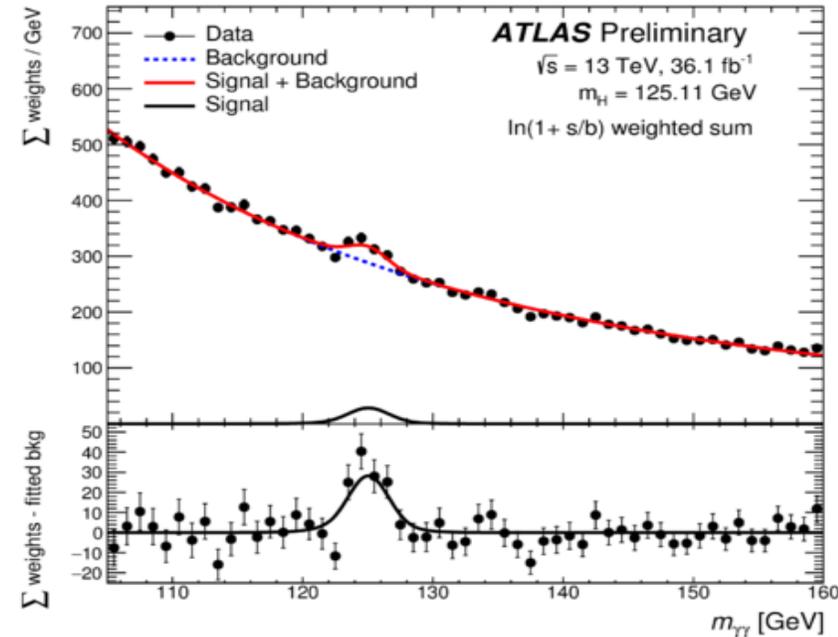
$$m_H^{ZZ^*} = 124.88 \pm 0.37(stat) \pm 0.05(syst) GeV$$

Leading systematic source :

Muon momentum scale (40 MeV)

まだ統計誤差が支配的

$H \rightarrow \gamma\gamma$



$$m_H^{\gamma\gamma} = 125.11 \pm 0.21(stat) \pm 0.36(syst) GeV$$

Leading systematic source :

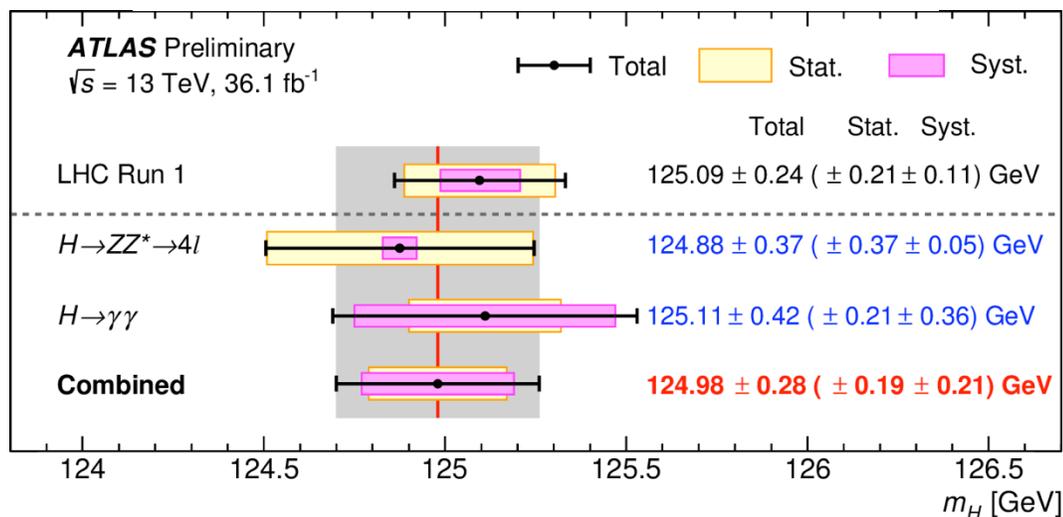
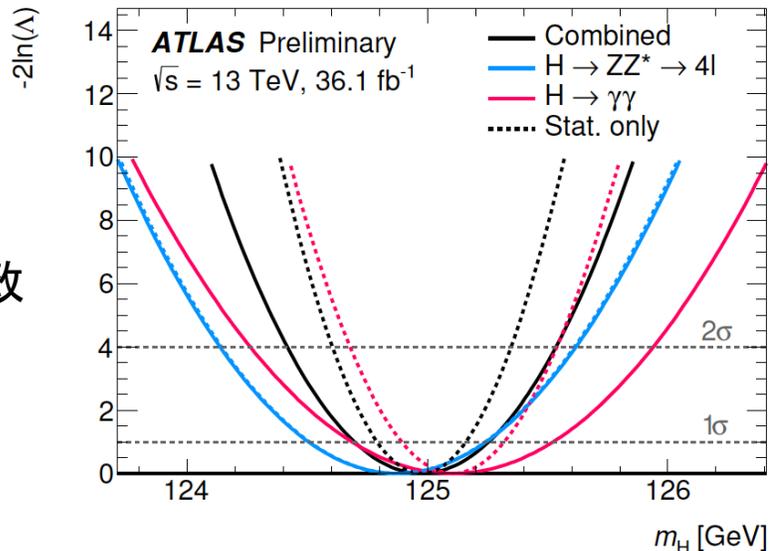
LAr cell non-linearly, layer calibration (~200 MeV)

すでに系統誤差が支配的

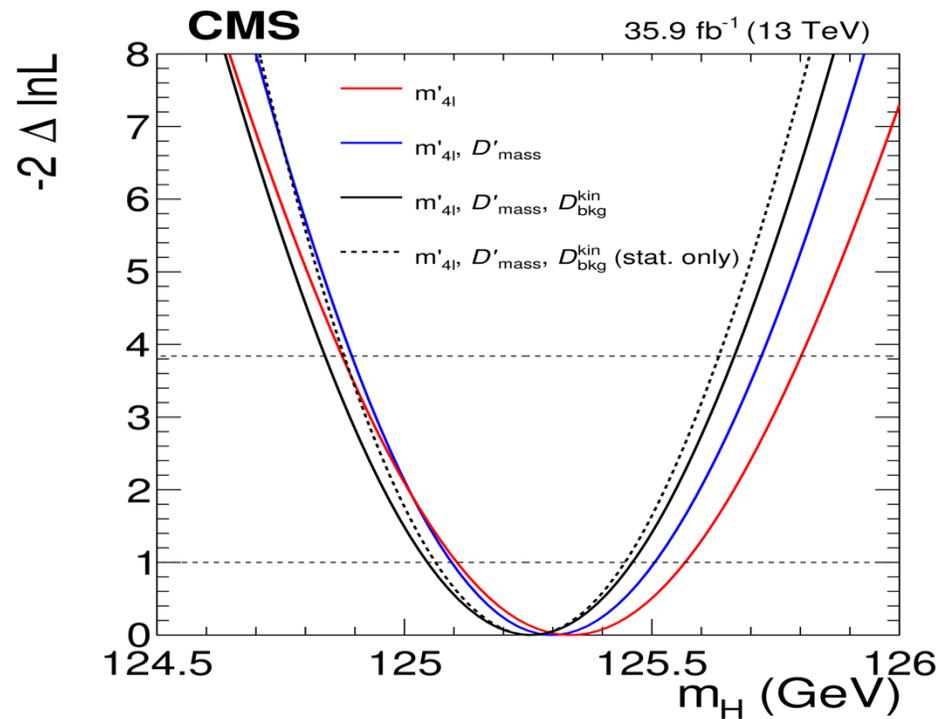
Higgs 質量精密測定

- $ZZ \rightarrow 4l, \gamma\gamma$ でコンビネーション

0.4 σ で
 $m_{ZZ}, m_{\gamma\gamma}$ 一致



124.98 ± 0.28 GeV (Run1 ATLAS 125.36 ± 0.41 GeV)



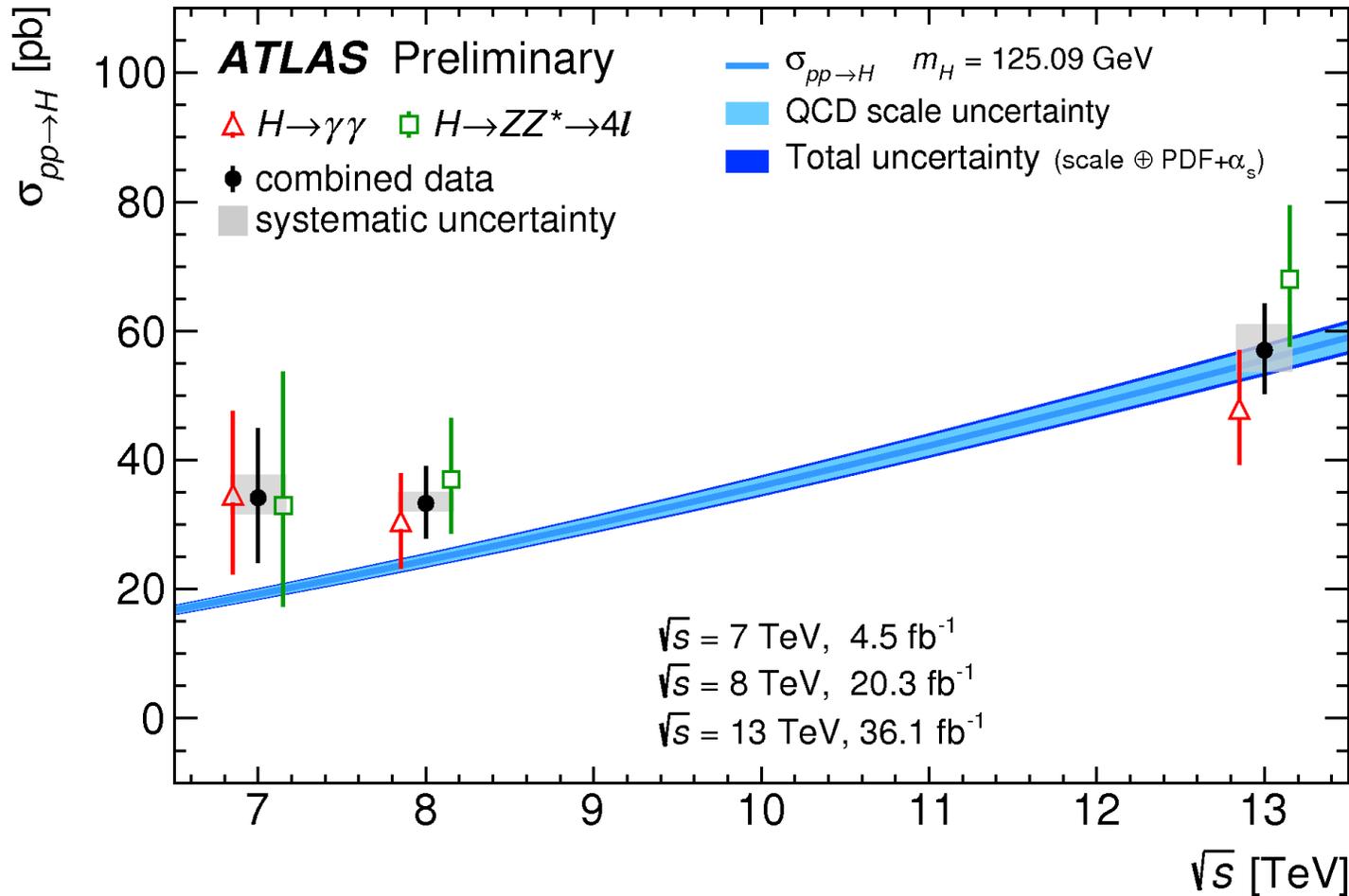
CMS ($ZZ \rightarrow 4l$ のみ)

3D fit : 21%分解能を改善

125.26 ± 0.20(stat) ± 0.08(syst) GeV
± 0.21(tot) GeV (World best)

Total Cross Section Measurement

- Inclusive $m_{\gamma\gamma}$, m_{4l} distributionから計算



$H \rightarrow ZZ$

$68.0^{+11.4}_{-10.4}$ pb

$H \rightarrow \gamma\gamma$

$47.9^{+9.1}_{-8.6}$ pb

Combined (ZZ, $\gamma\gamma$)

$57.0^{+6.0}_{-5.9}(\text{stat})^{+4.0}_{-3.3}(\text{syst})$ pb

SM Prediction

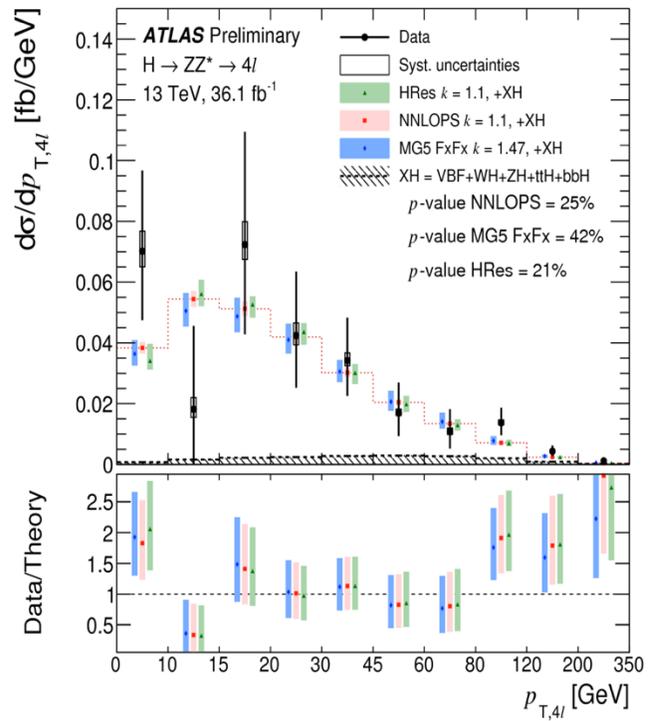
$55.6^{+2.4}_{-3.4}$ pb

Differential Cross Section($ZZ \rightarrow 4l, \gamma\gamma$)

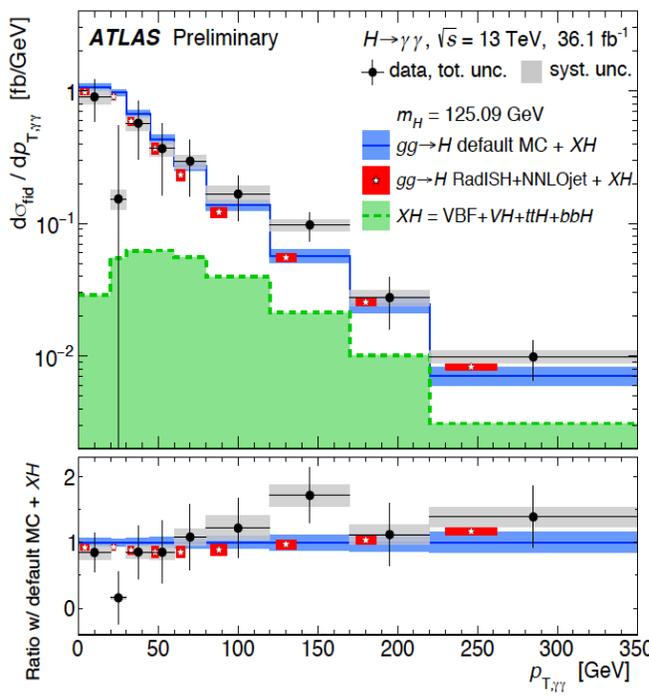
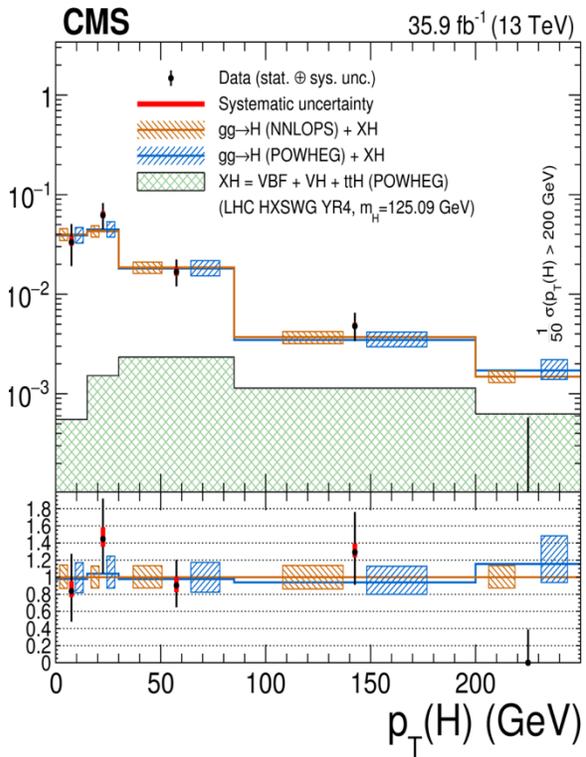
- $p_T^H(4l \text{ or } \gamma\gamma)$: 摂動QCD計算に感度
 - 重い新粒子がloopに入る寄与 \rightarrow high p_T で分布がズれる
 - bottom/charmの寄与 \rightarrow low p_T にズレ

$ZZ \rightarrow 4l$

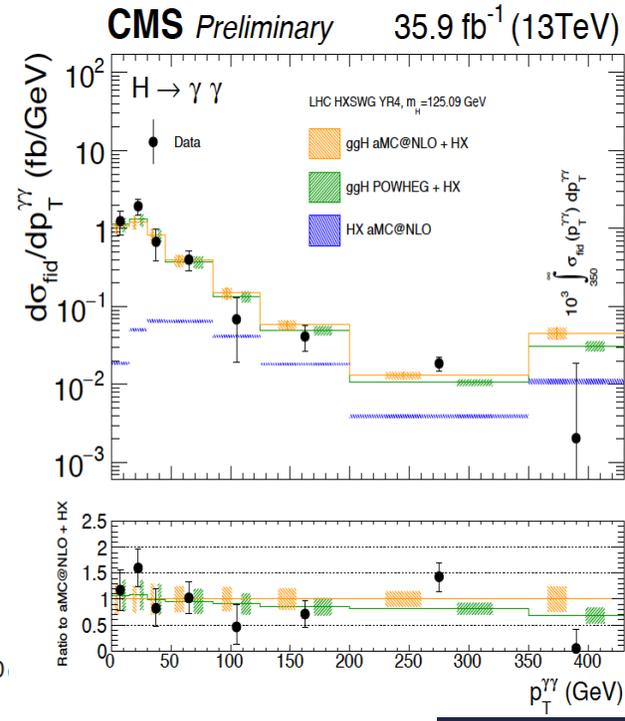
$H \rightarrow \gamma\gamma$



p-value 25%

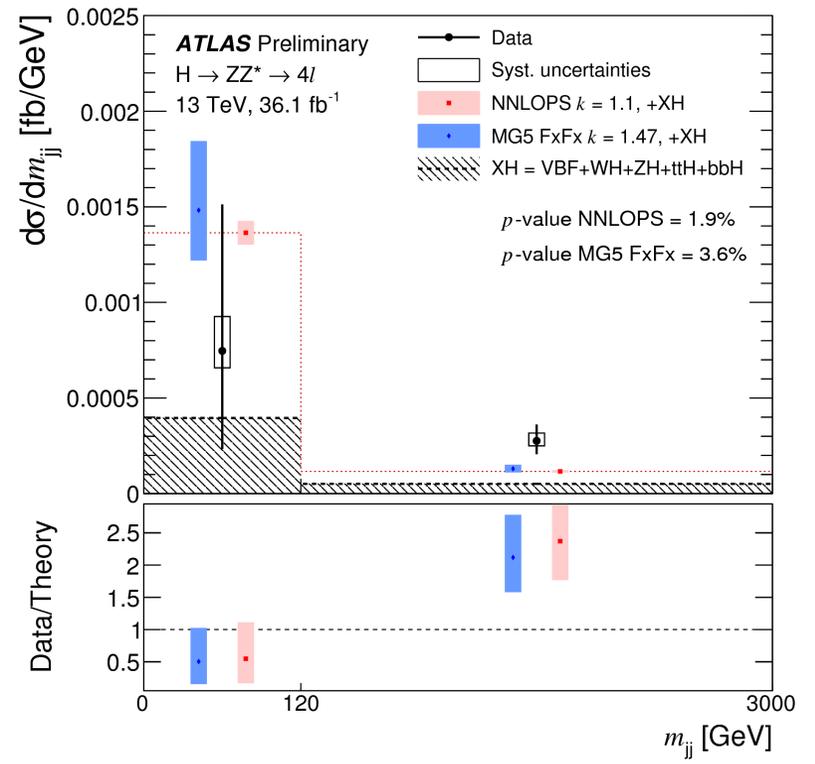
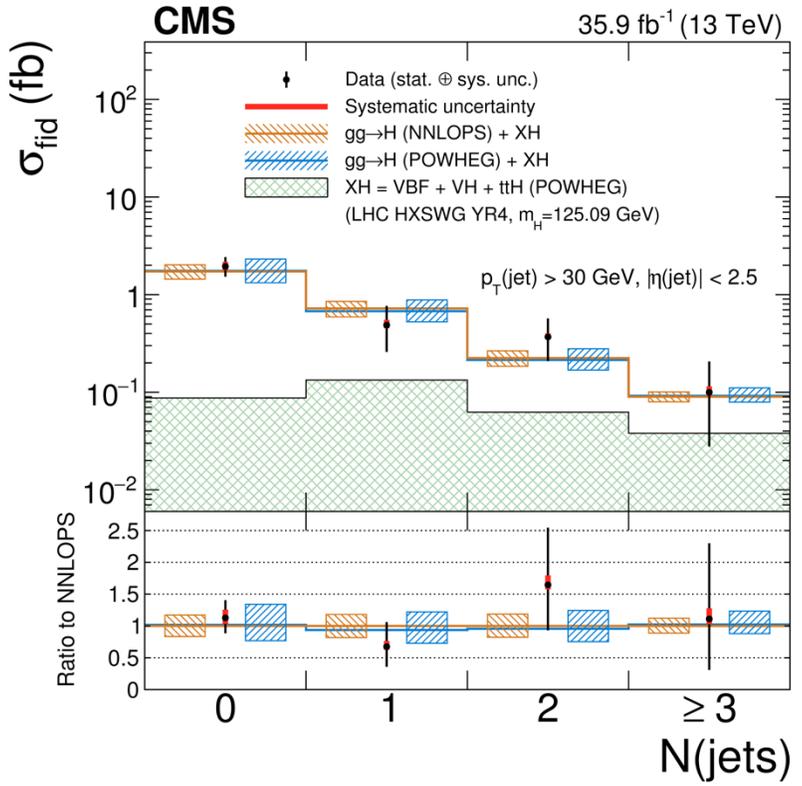
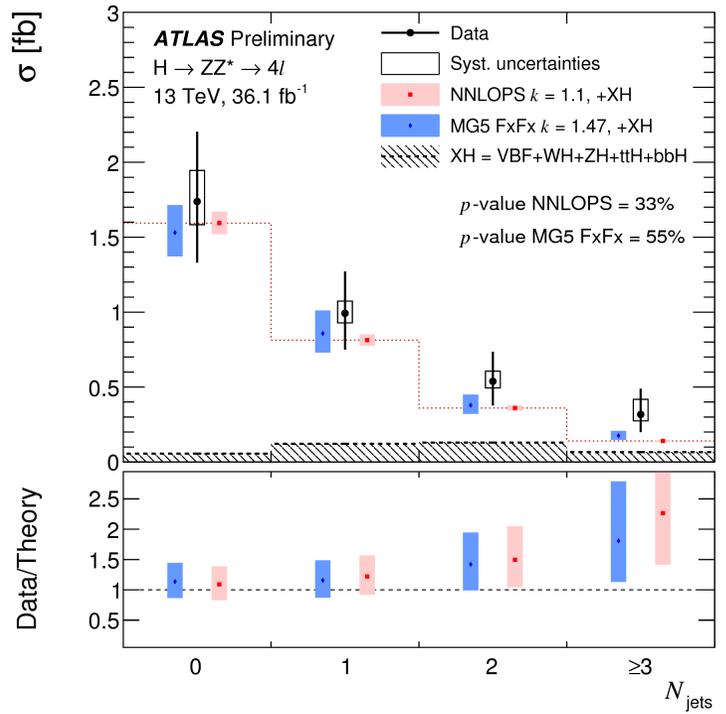


p-value 51%



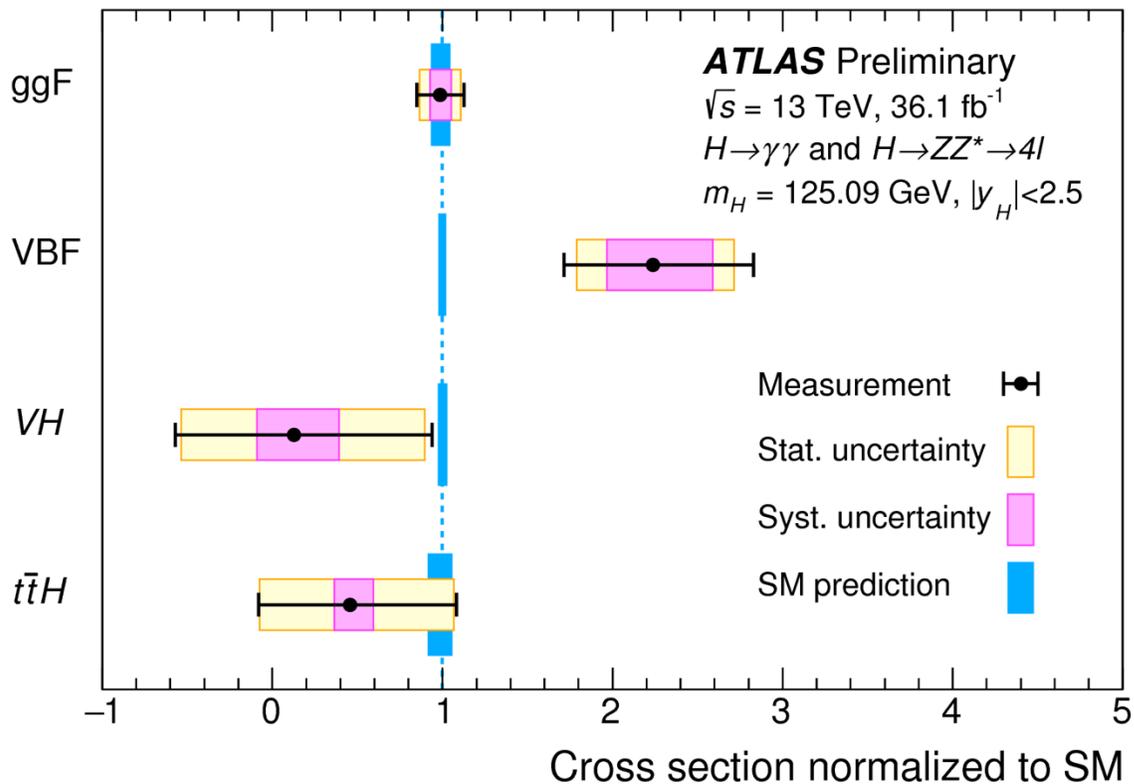
Differential Cross Section($ZZ \rightarrow 4l, \gamma\gamma$)

- Number of jets : 生成過程の組成, Gluon emissionに感度
- m_{jj} : VBF生成過程に感度 (p-value 1.9-3.6%)

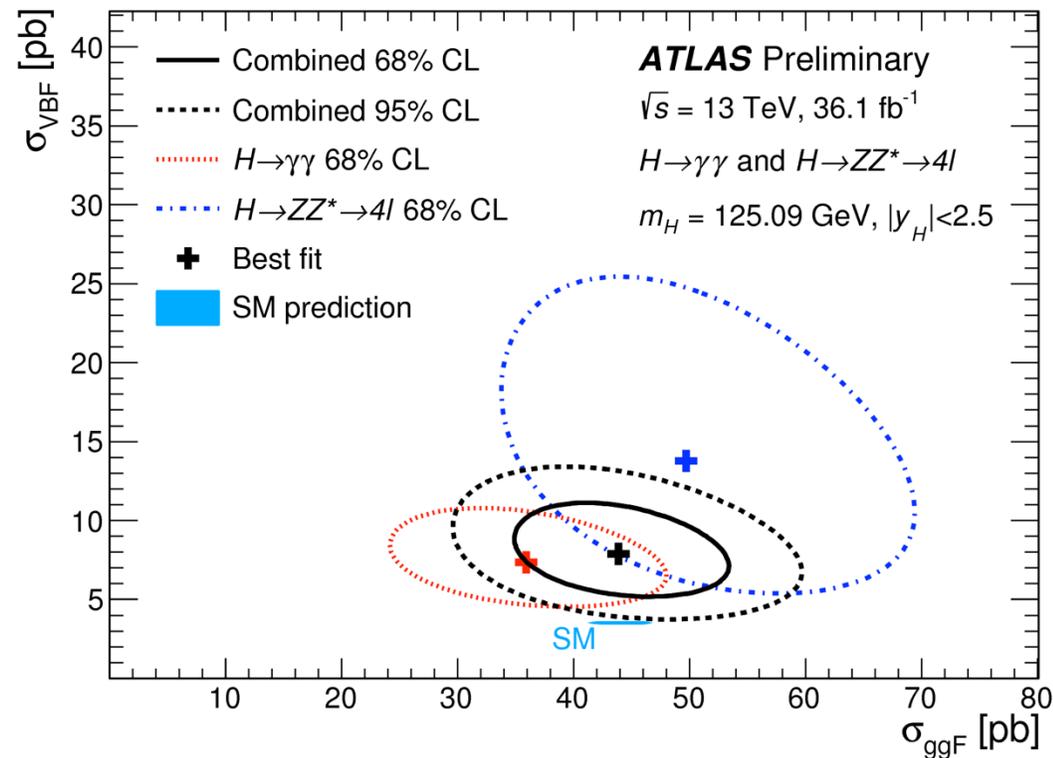


Cross Section Measurement($\gamma\gamma, ZZ\rightarrow 4l$)

- $H\rightarrow\gamma\gamma, H\rightarrow ZZ\rightarrow 4l$ 事象を生成過程のkinematicsでカテゴリ分け
 - 統計が少ないのでVH, ttHは感度なし



VBFがSM予想よりも高め, ggFはドンピシャ

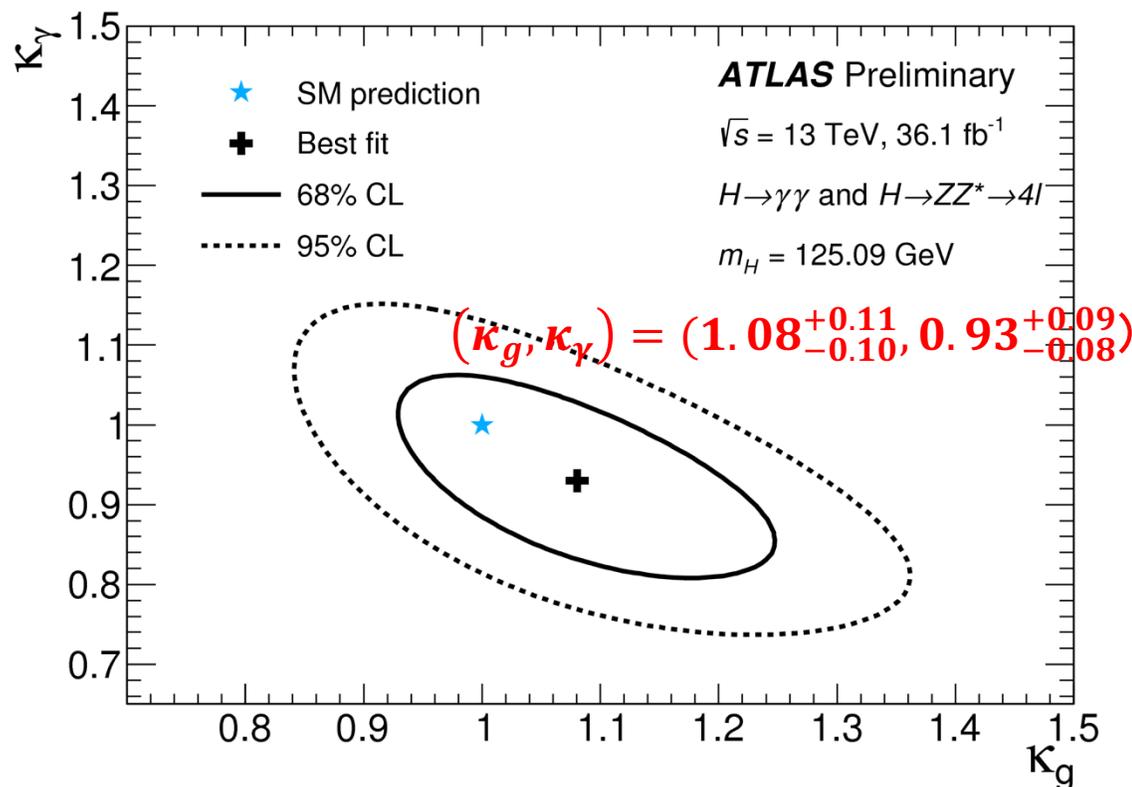
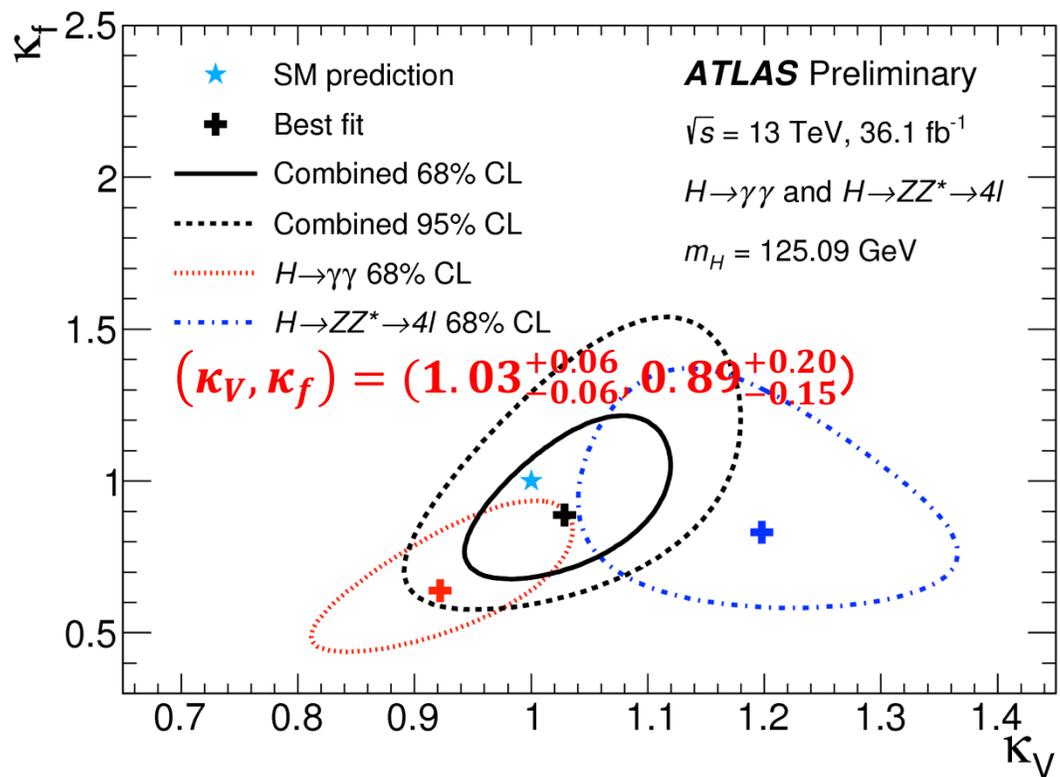
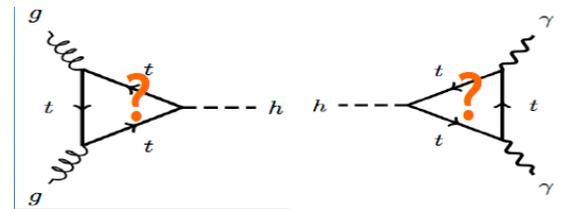


VBFは $\gamma\gamma, ZZ$ ともに高め (p-value 3%)
→ 今後高統計で精度が向上する

Coupling Measurement ($\gamma\gamma, ZZ \rightarrow 4l$)

- κ framework

$$\sigma(i \rightarrow H \rightarrow f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$



$H \rightarrow \gamma\gamma, H \rightarrow ZZ$ Combinationでは有意なズレは観測されていない
 →他のチャンネルもすべてコンバイン (秋-冬に公表予定)

Higgs Fermionic Decay/production mode

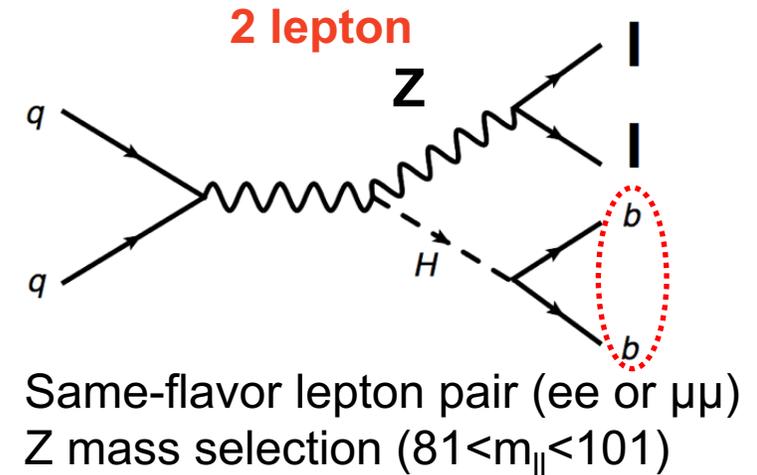
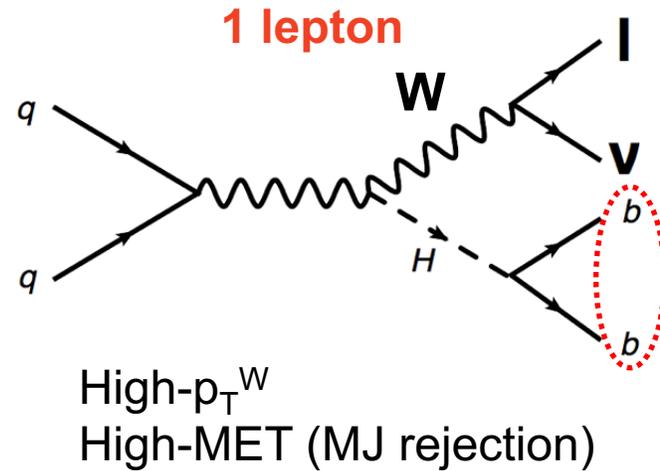
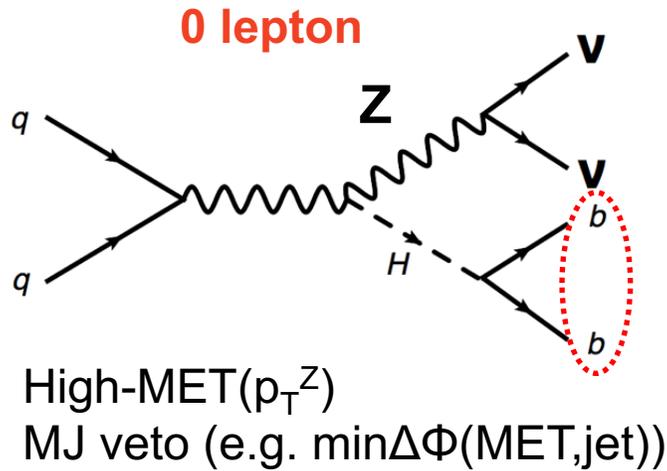
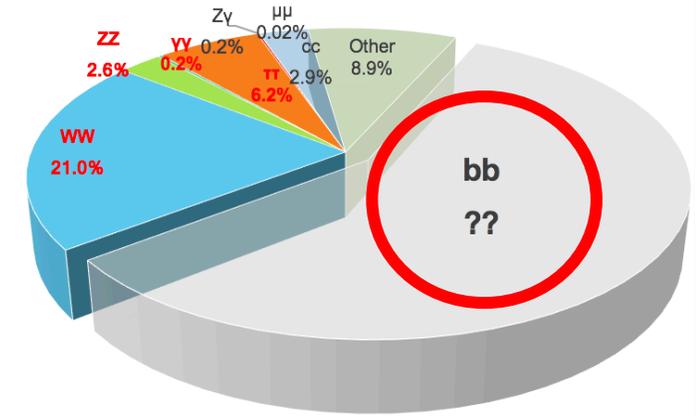
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Event#: 990753168

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H → bb 探索

- Run1 ATLAS+CMS : 2.6σ (exp. 3.7σ)
- Run2 2016年までのデータ(36.1fb⁻¹)でH → bb崩壊モードの探索
- QCD(Multi-Jet)の背景事情が膨大 (ggF, VBFは困難) → VHが有望
 - Vの崩壊モードによって0,1,2 leptonに分類して最適化



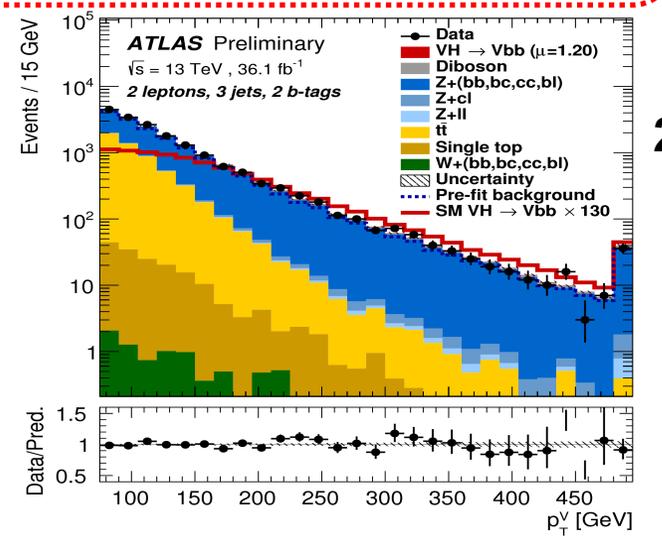
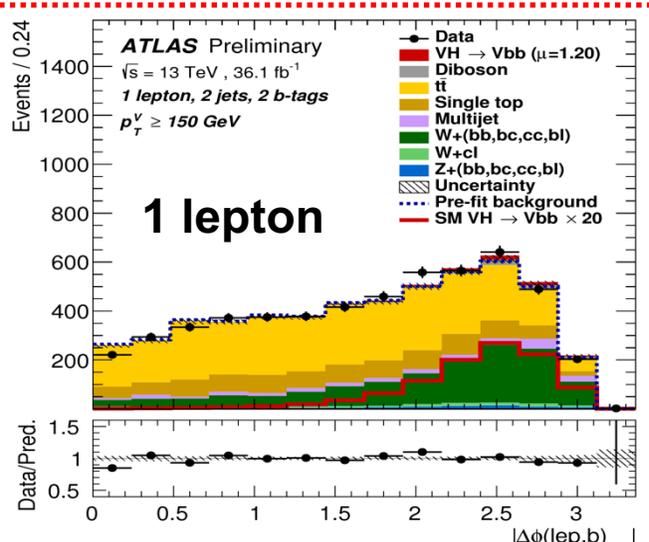
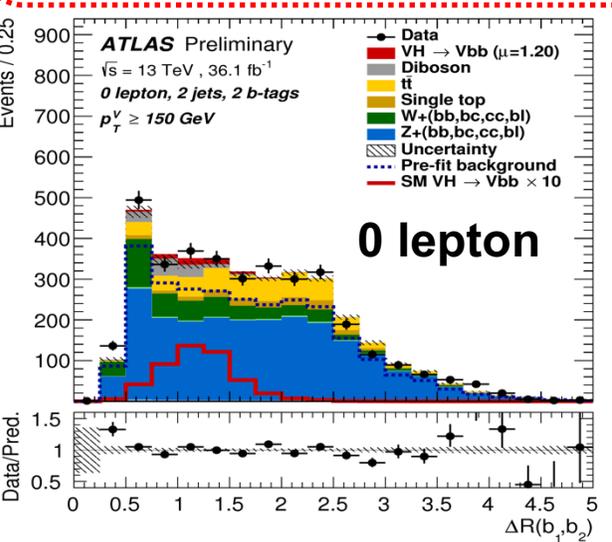
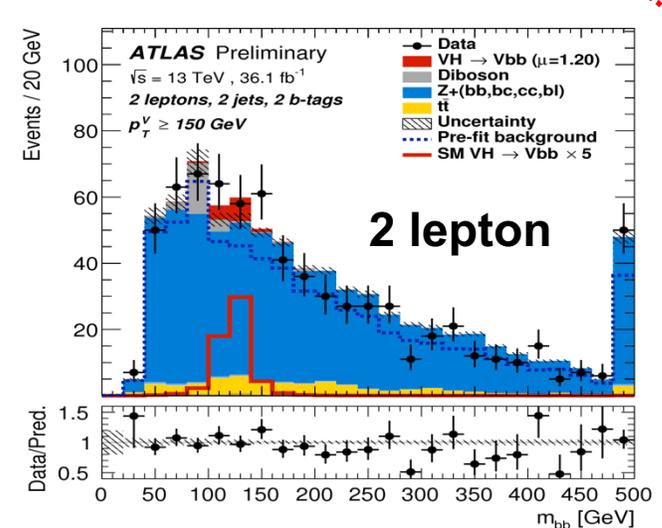
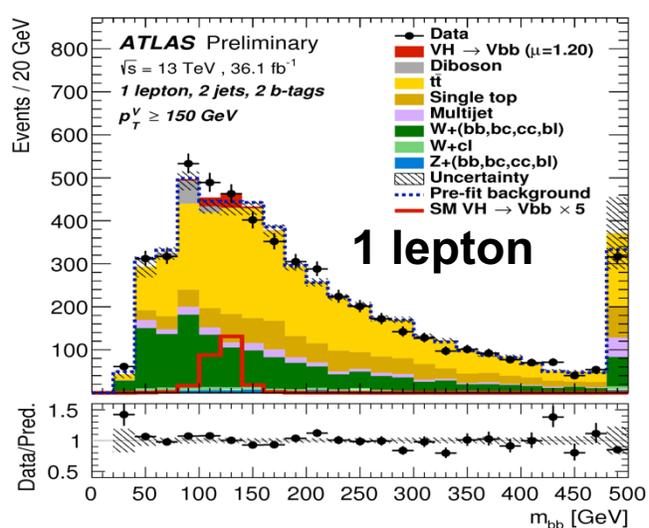
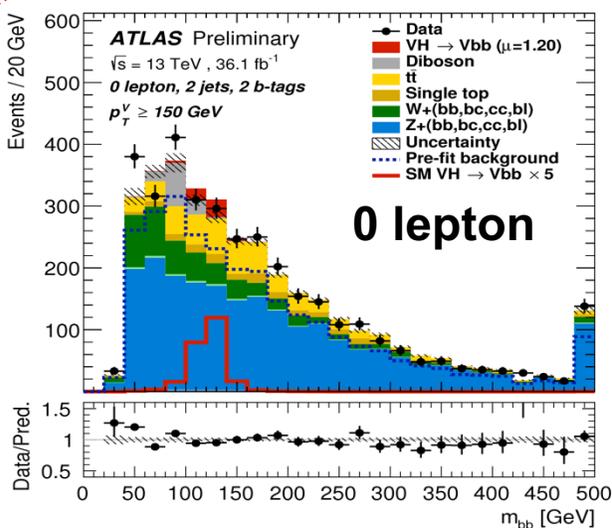
Categorization	0lepton	1lepton	2lepton
$N_{b\text{-jet}}$	2 b-tagged jets		
p_T^V	$p_T^Z > 150$ GeV	$p_T^W > 150$ GeV	$75 < p_T^Z < 150, p_T^Z > 150$ GeV
N_{jets}	2,3jets	2,3jets	2, ≥ 3 jets

Main Background

- **W+jets, Z+jets**
- **top (ttbar, single top)**
- **multi-jet**
- **diboson**

H → bb探索

- 背景事象との分離能力を高めるためにMulti-variate analysis(BDT)を使う



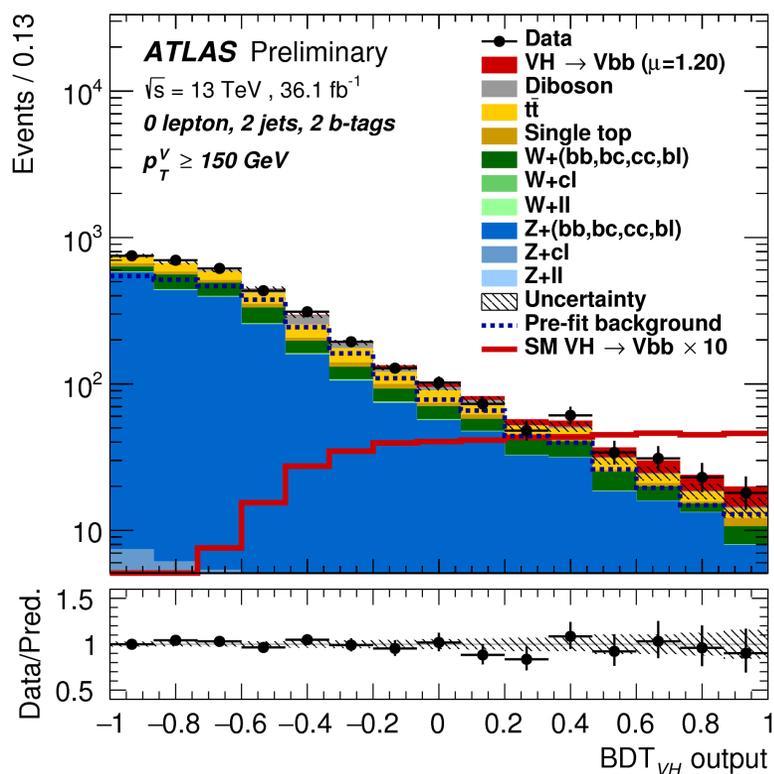
Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$ \Delta\eta(b_1, b_2) $	×		
$\Delta\phi(V, bb)$	×	×	×
$ \Delta\eta(V, bb) $			×
m_{eff}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}		×	
$ \Delta Y(V, bb) $		×	
Only in 3-jet events			
$p_T^{\text{jet}_3}$	×	×	×
m_{bbj}	×	×	×

2 lepton

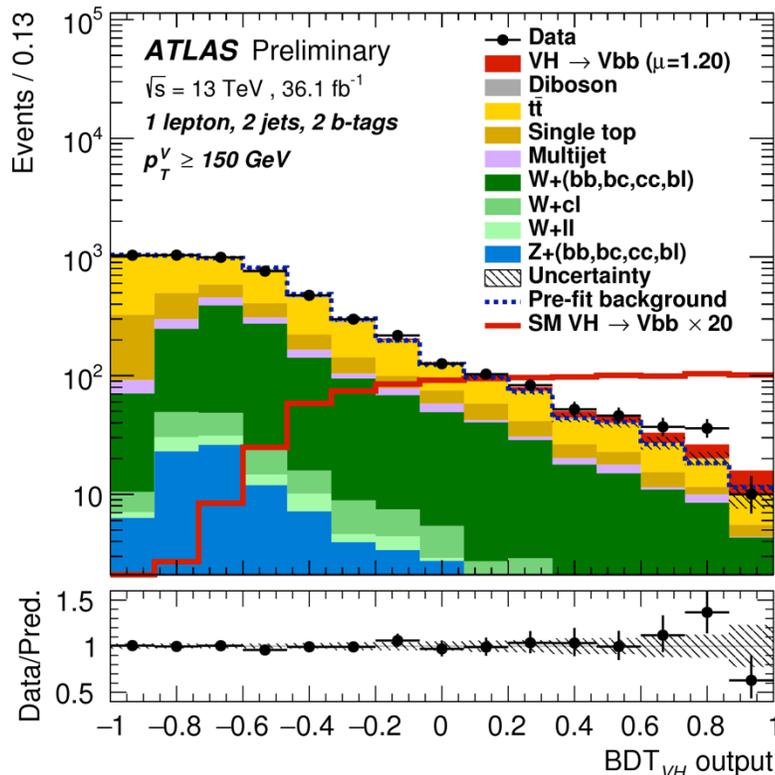
H \rightarrow bb探索

- 統計解析後のBDT分布 (最も発見感度が高い, $p_T^V > 150$ GeV, 2 b-tag信号領域)
 - 8信号領域と背景事象を見積もるための6コントロール領域(W+jets, top)を同時フィットする
 - BDTを使うことで m_{bb} のみよりも感度が10-20%向上

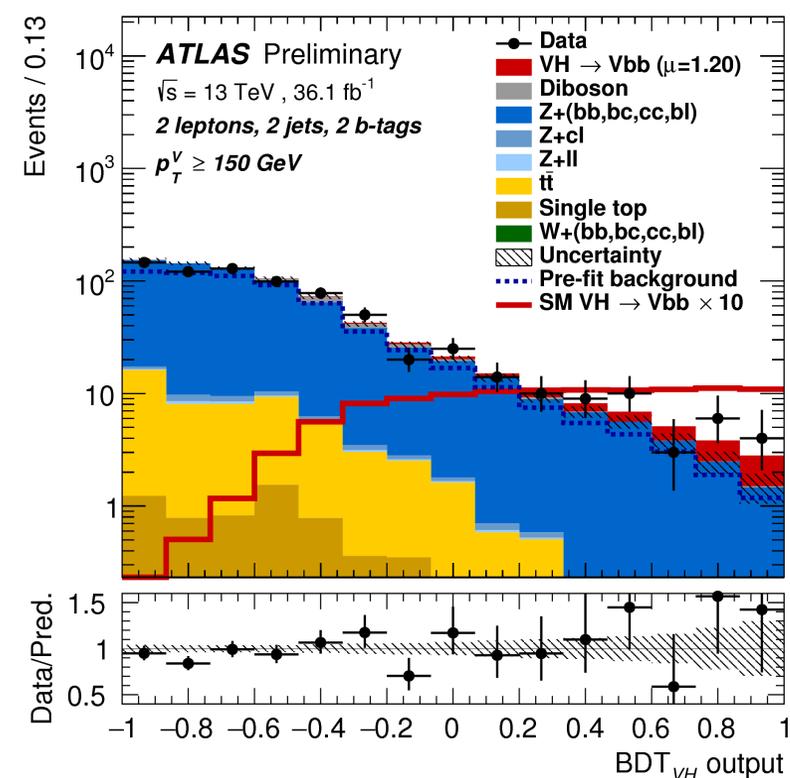
0 lepton



1 lepton



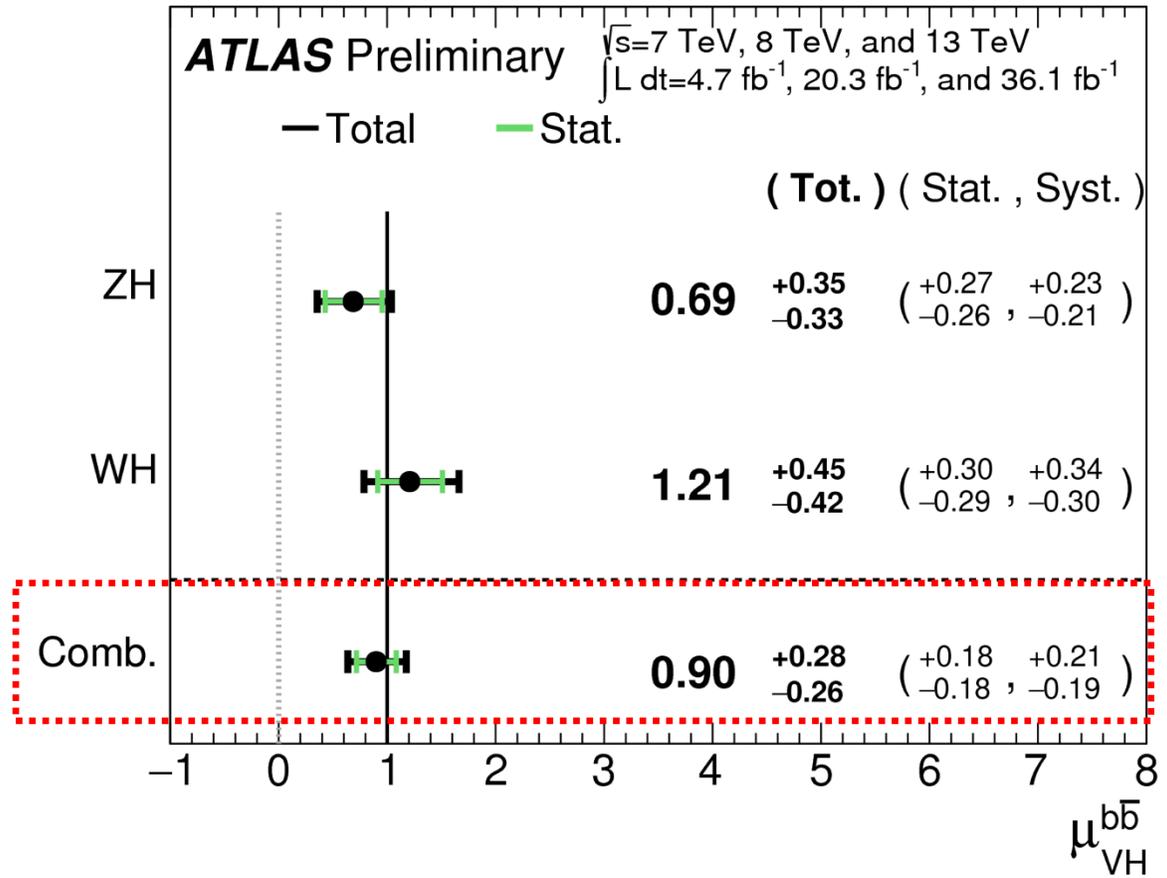
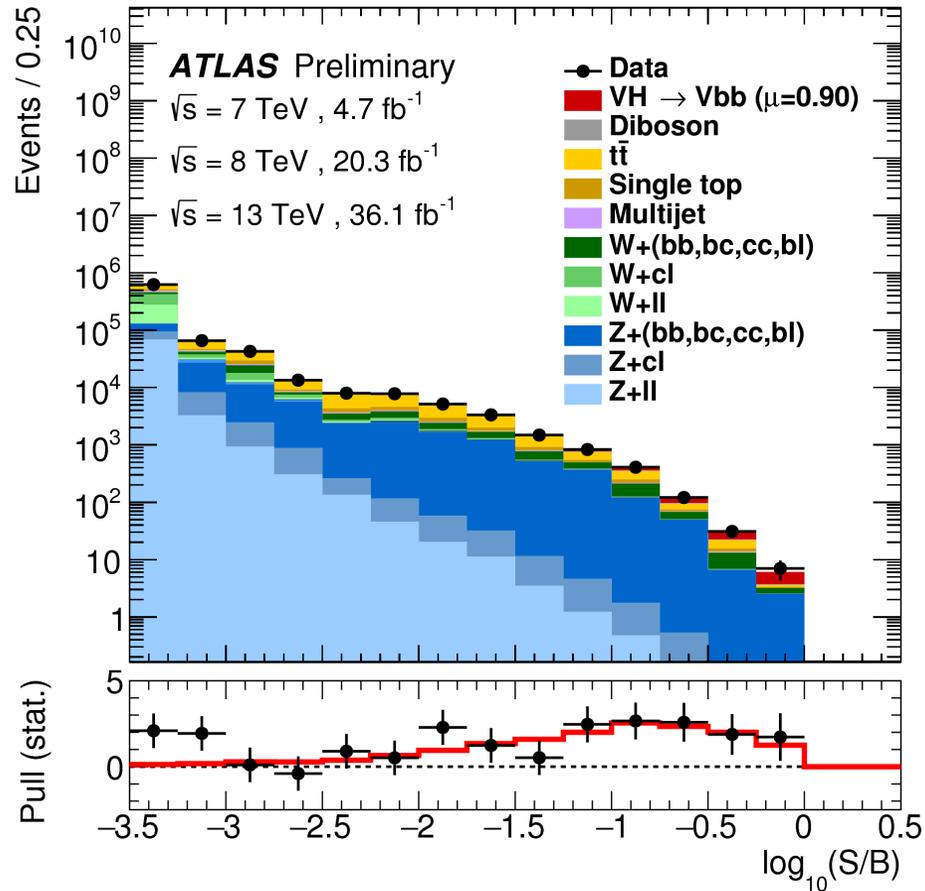
2 lepton



信号領域に有意なデータの超過を観測

“First” Evidence for $H \rightarrow b\bar{b}$

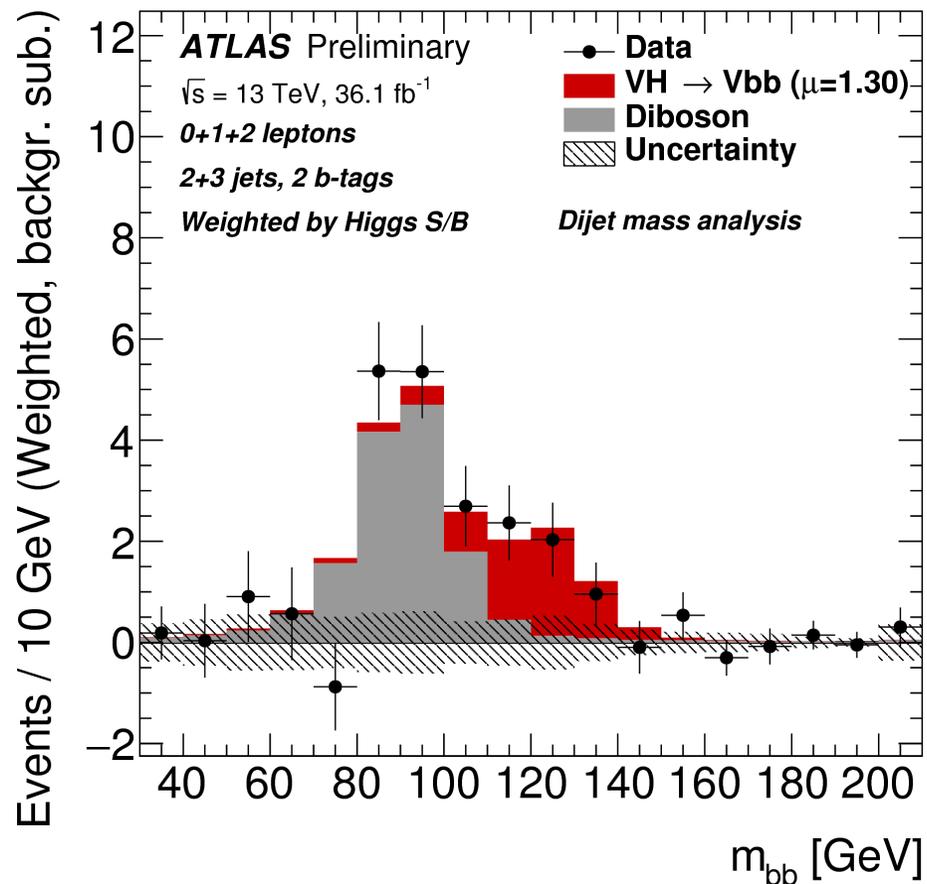
- Run1(4.7fb⁻¹+20.3fb⁻¹)+Run2(36.1fb⁻¹) combination



Observed significance 3.6 σ
(Expected 4.0 σ)

Evidence for $H \rightarrow bb$

- BDTは m_{bb} もインプットに使っているため m_{bb} を直接観測できない
- m_{bb} をフィットする解析で $H \rightarrow bb$ の信号も観測



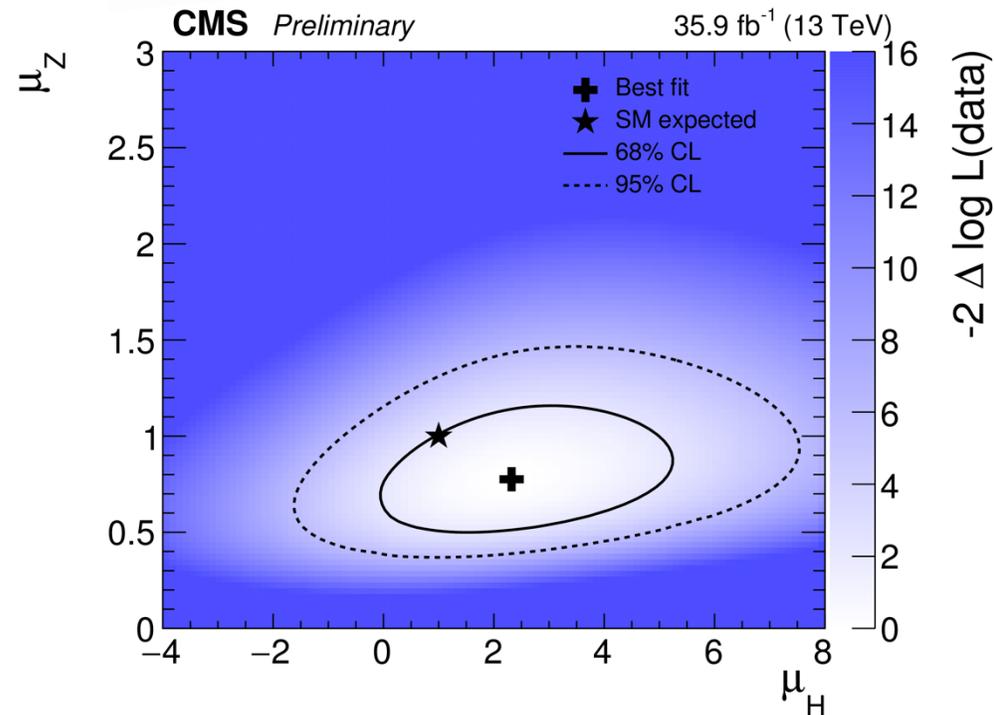
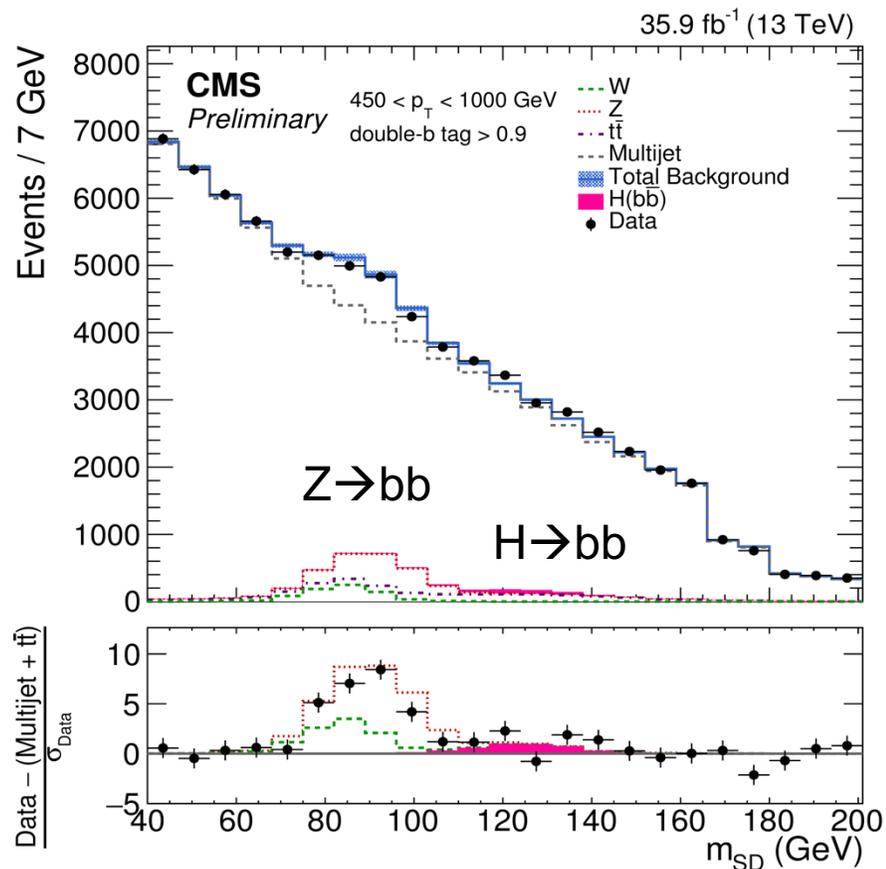
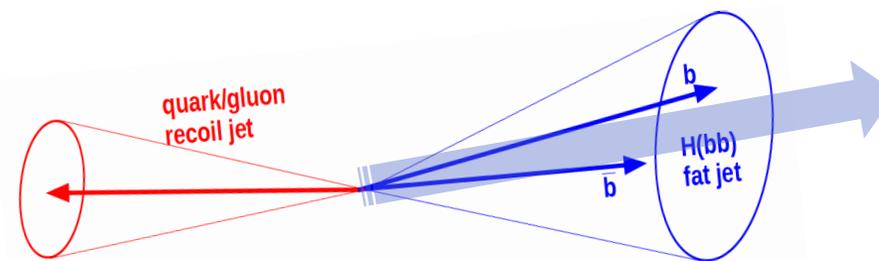
Run2 only

$$\mu_{VH}(m_{bb}) = 1.30_{-0.27}^{+0.28}(\text{stat})_{-0.29}^{+0.37}(\text{syst})$$
$$\mu_{VH}(MVA) = 1.20_{-0.23}^{+0.24}(\text{stat})_{-0.28}^{+0.34}(\text{syst})$$

Observed significance 3.5σ
(Expected 2.8σ)

Inclusive $H \rightarrow bb$ 探索

- boosted $H \rightarrow bb$ を使った inclusive 探索
 - High- $p_T^{(H)} > 450$ GeV
 - fat-jet の中に 2 つの b-hadron がいることを要求 ($H \rightarrow bb$ eff 33%, QCD jet rejection 1/100)



Z → bb results
 observed significance 5.1σ (exp. 5.8σ)

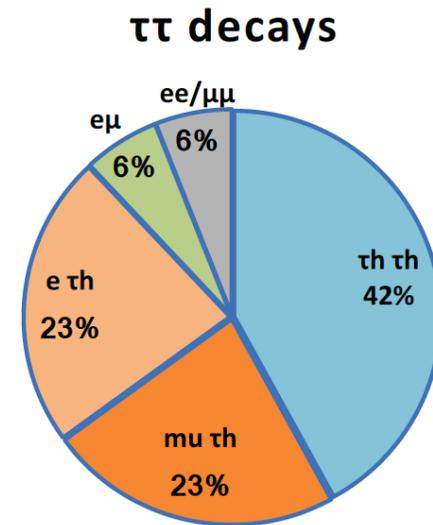
$$\mu_Z = 0.78^{+0.23}_{-0.19}$$

H → bb results
 observed significance 1.5σ (exp. 0.7σ)

$$\mu_H = 2.3^{+1.8}_{-1.6}$$

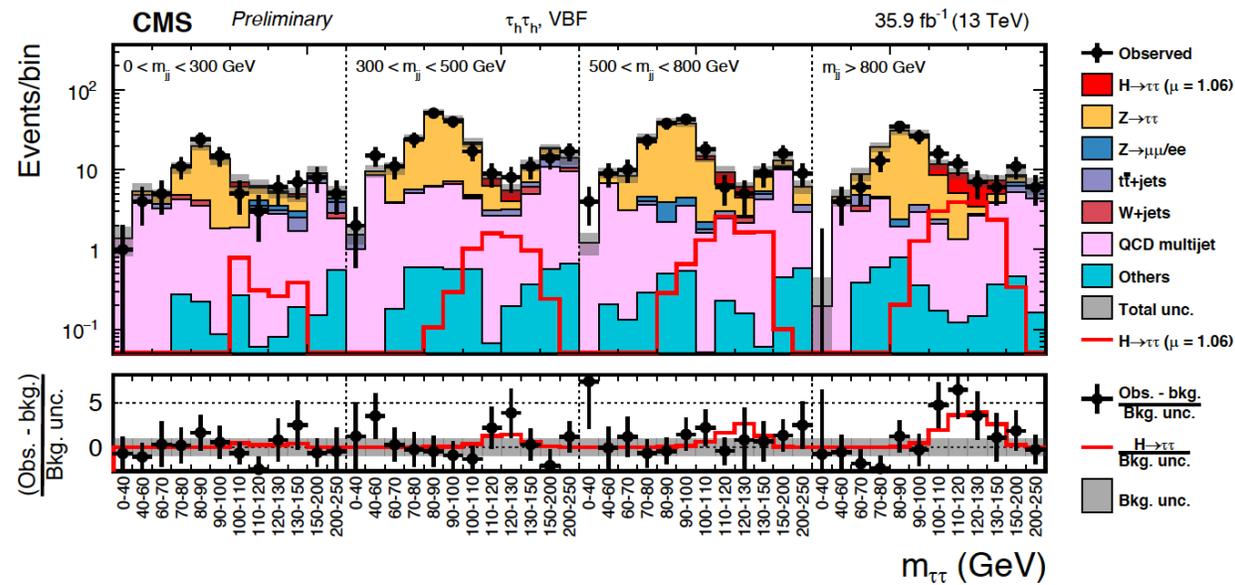
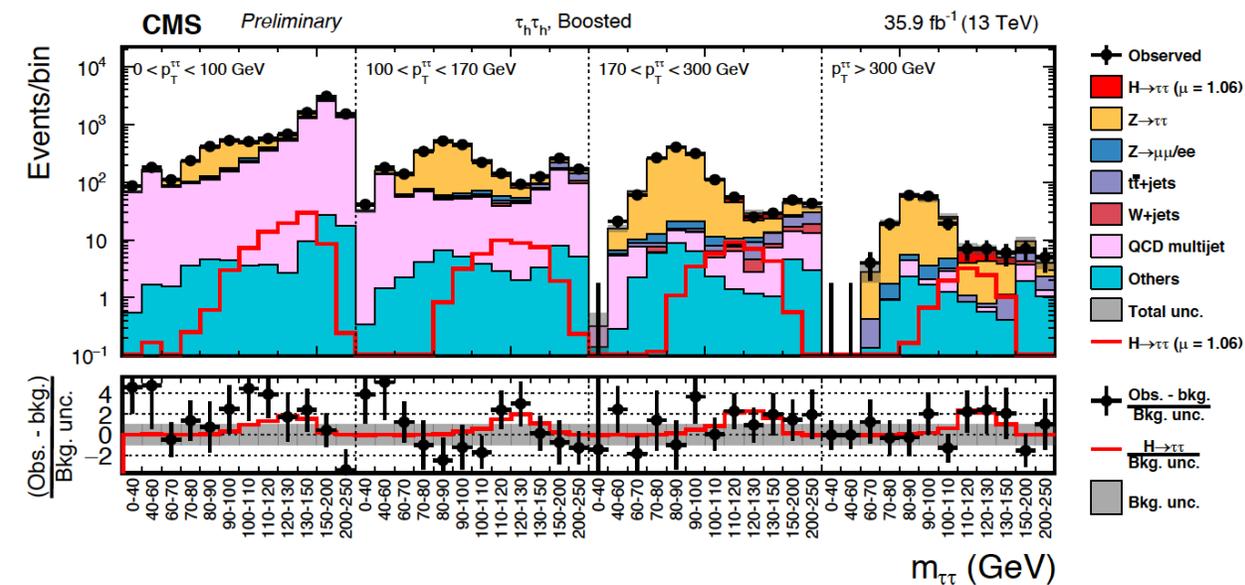
H → ττ Observation (Run2)

- Y_τの直接測定
- Categorization
 - (eτ_h, μτ_h, τ_hτ_h, eμ) × (0jet, boosted p_T(ττ), VBF)



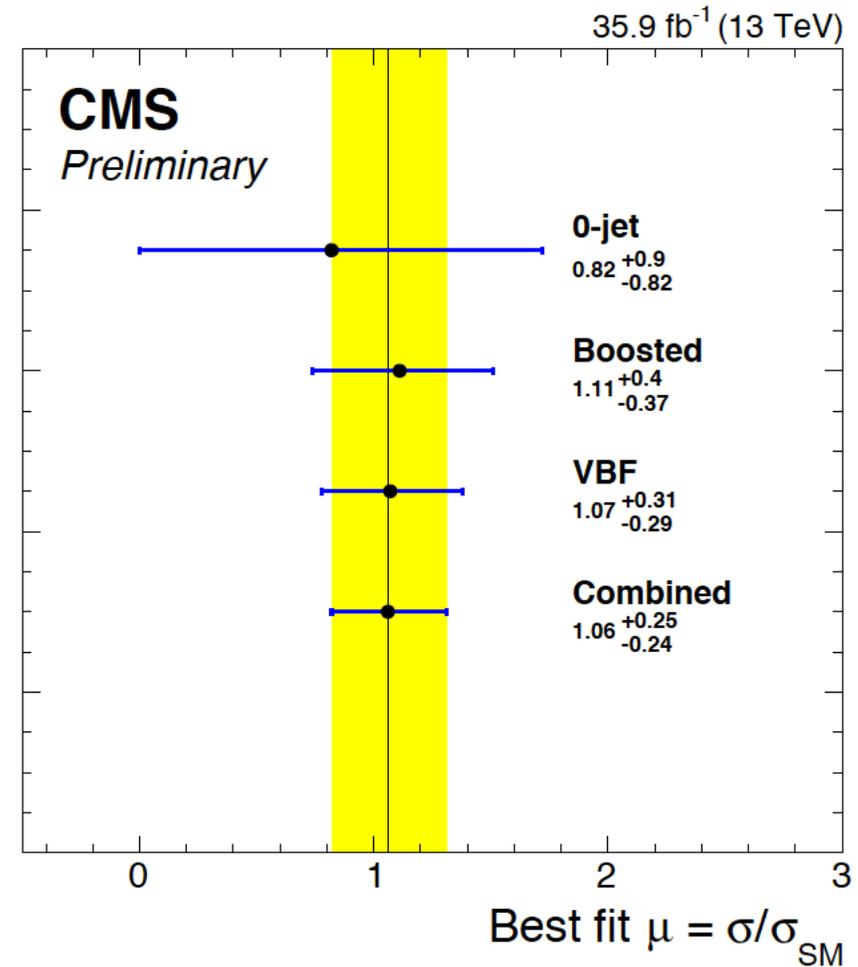
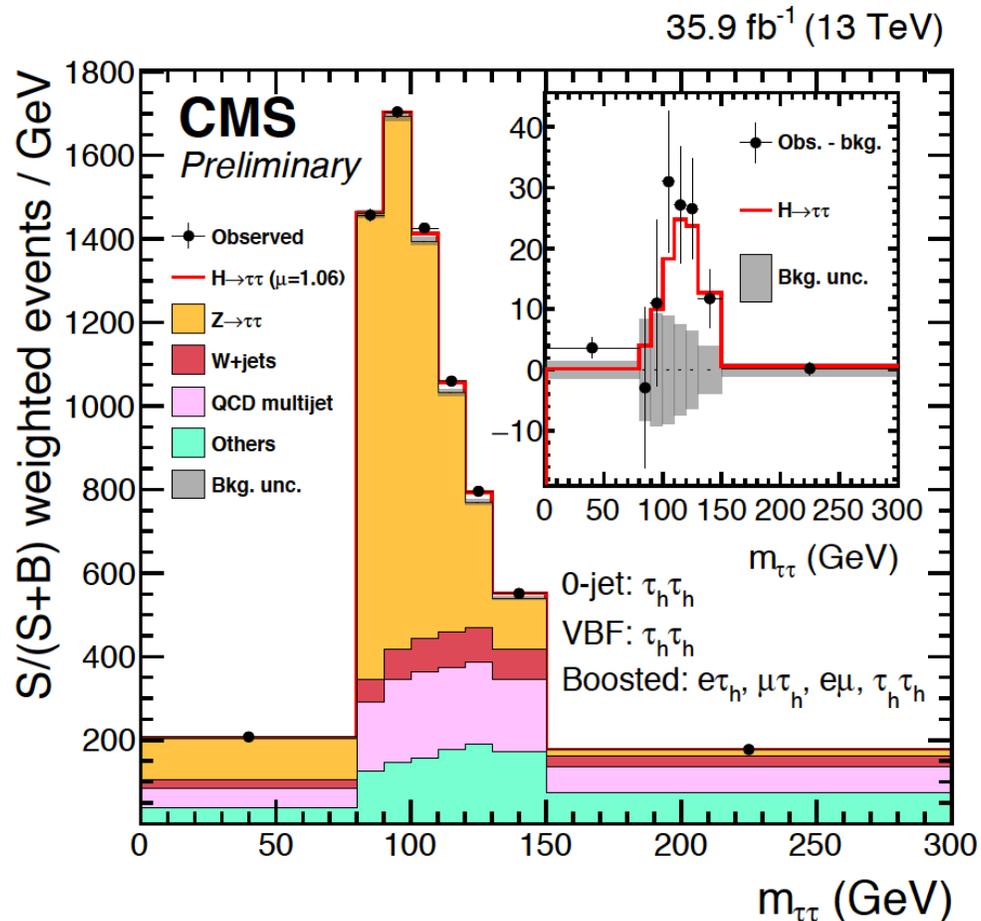
Boosted category (τ_hτ_h)
m_{ττ} vs p_T(ττ)

VBF category (τ_hτ_h): 最高感度
m_{ττ} vs m_{jj}



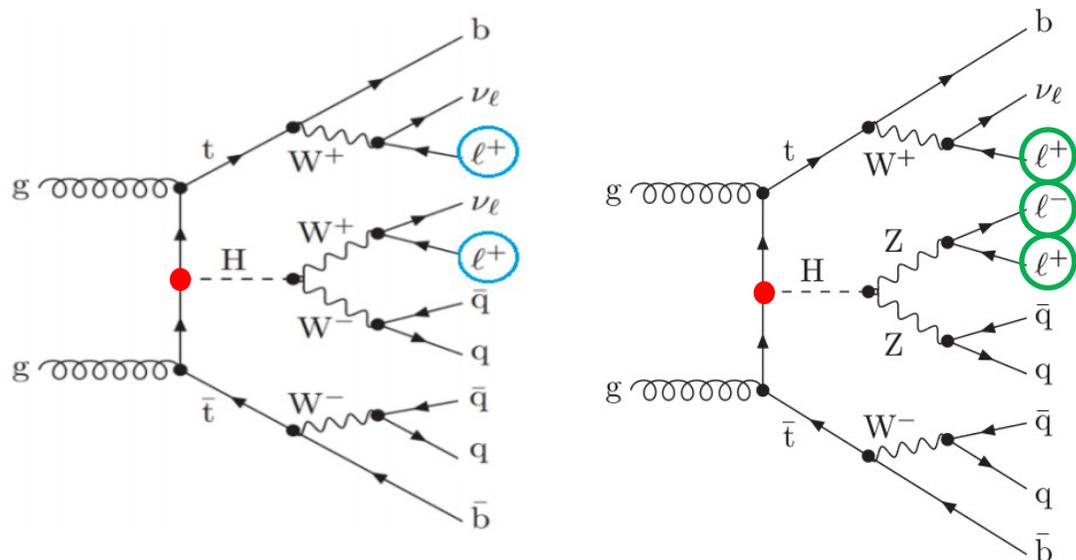
H → ττ Observation

- Observed significance 4.9σ (5.9σ with Run1)
- $\mu = 1.06^{+0.25}_{-0.24}$ (Run2)



Search for ttH (multi-lepton)

- Y_t の**直接探索**が可能
- 13TeVでttHの断面積は4倍!!
- 終状態にleptonを含む(WW, ZZのdecay)



Dominant backgrounds

- **ttW/ttZ : MC**
- **non-prompt (ttbar) : data-driven**
- **Diboson : MC**

Same-sign 2 lepton channel

- 2つのleptonが同電荷を持つ (ee, $\mu\mu$, e μ)
- 4本以上のジェット
- 2 b-tagged jets (tight or loose)

3 lepton channel

- 3つのlepton
- 2本以上のジェット
- 2 b-tagged jets (tight or loose)

4 lepton channel

- 4つのlepton
- 2本以上のジェット
- 2 b-tagged jets

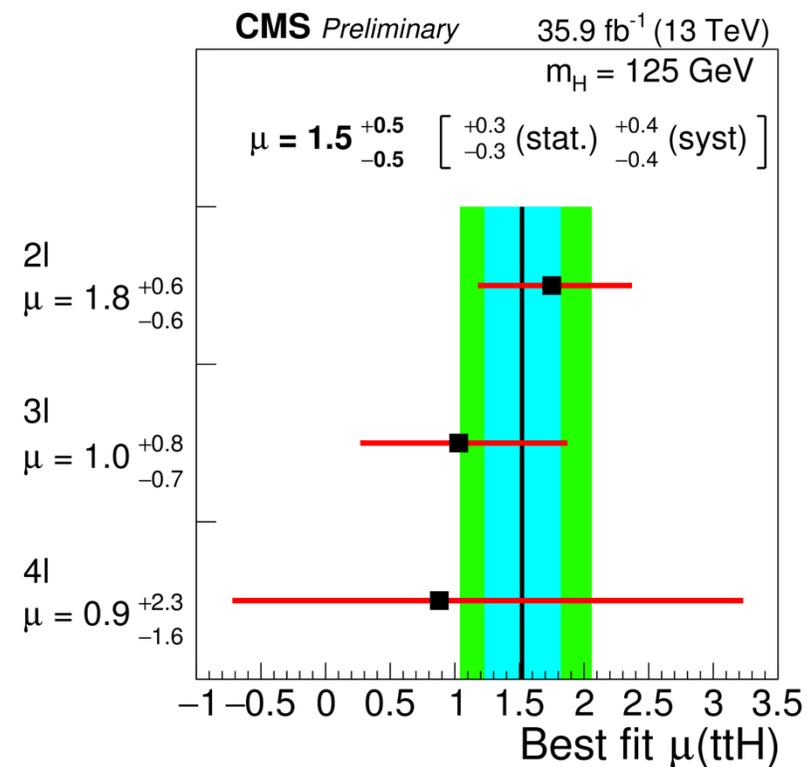
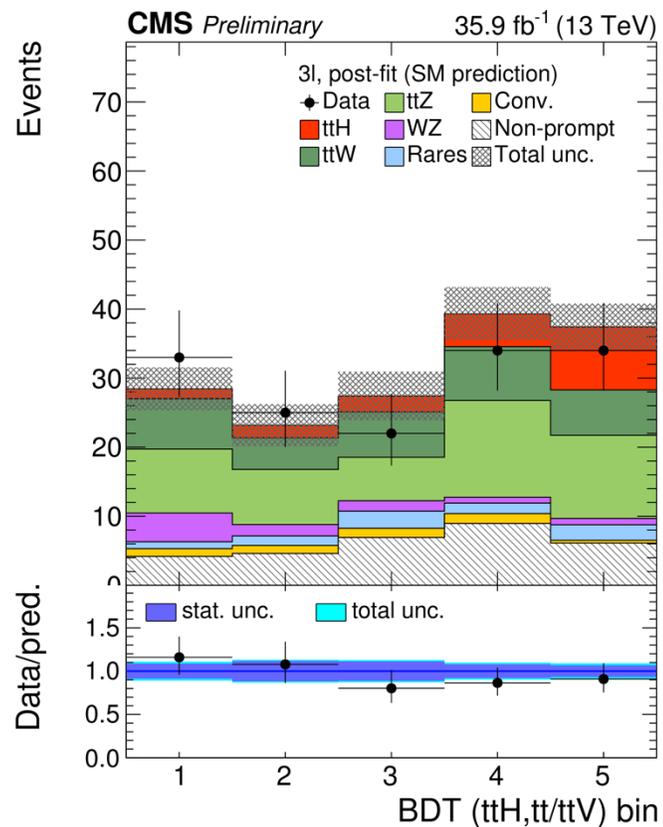
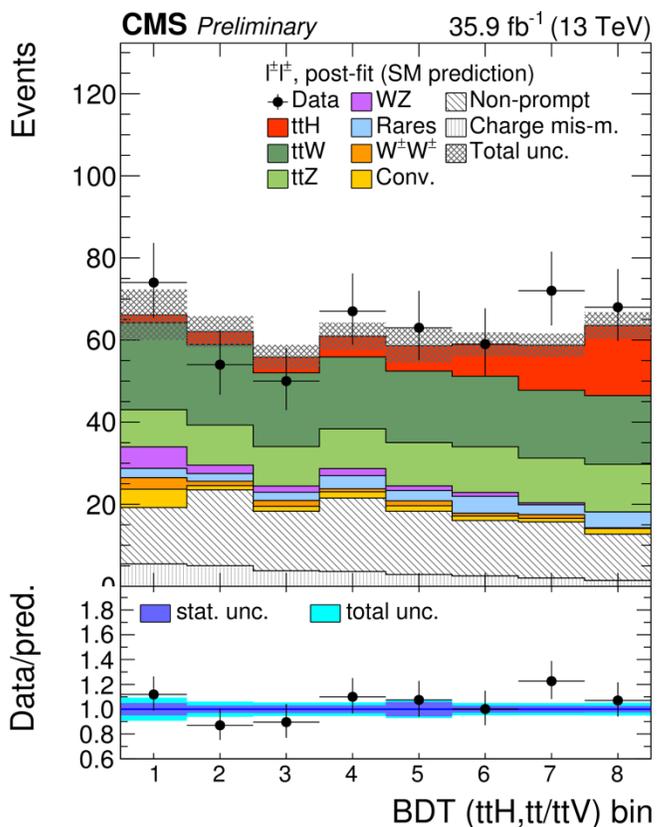
2つのBDT (ttH vs ttbar, ttW/Z)
 として主要背景事象を分ける

Search for ttH (multi-lepton)

- Run1+Run2 combination

- $\mu = 1.5^{+0.5}_{-0.5} (tot) = 1.5^{+0.3}_{-0.3} (stat)^{+0.4}_{-0.4} (syst) \leftarrow$
 すでに系統誤差が支配的

Observed significance 3.3σ (exp. 2.5σ)



Summary of ttH search

- Y_t の直接探索は難しい。。。(実験屋の腕の見せ所)

ttH CMS	Data	sensitivity	μ
bb	12.9fb ⁻¹	-	-0.19±0.8
multi-lepton	Full 2015+2016+Run1	3.3σ (exp. 2.5σ)	1.5±0.5
$\tau\tau$	Full 2015+2016	1.4 σ (exp. 1.8 σ)	0.72 ^{+0.62} _{-0.53}
$\gamma\gamma$	Full 2015+2016	3.3σ (exp. 1.5σ)	2.2 ^{+0.9} _{-0.8}

ttH ATLAS	Data	sensitivity	μ
bb	13.2fb ⁻¹	-	2.1 ^{+1.0} _{-0.9}
multi-lepton, $\tau\tau$	13.2fb ⁻¹	2.2 σ (exp. 1.3 σ)	2.5±0.7 ^{+1.1} _{-0.9}
$\gamma\gamma$	Full 2015+2016	1.0 σ (exp. 1.8 σ)	0.5 ^{+0.6} _{-0.6}

全体的に μ が高めに出ている(系統誤差が大きい)

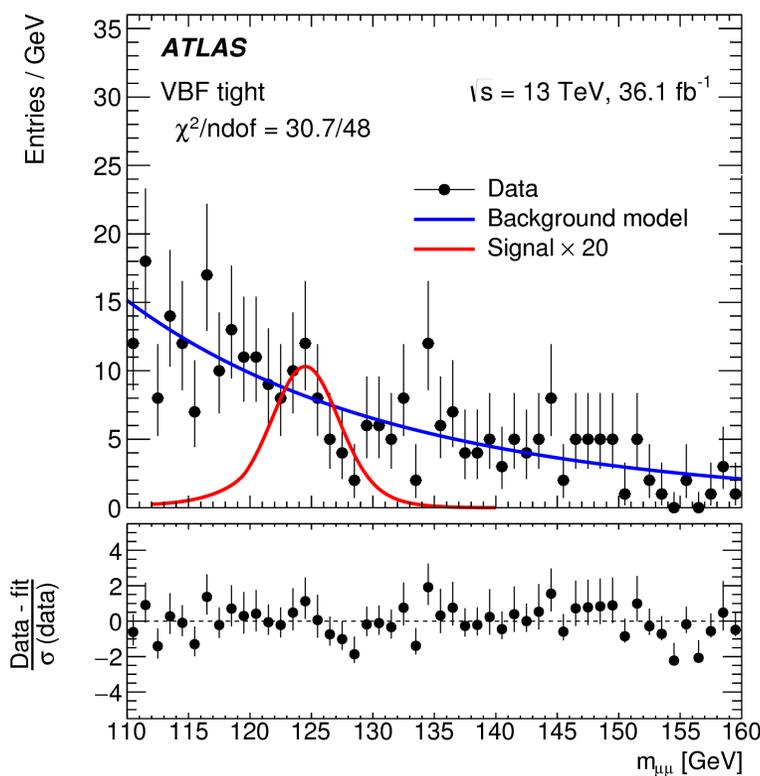
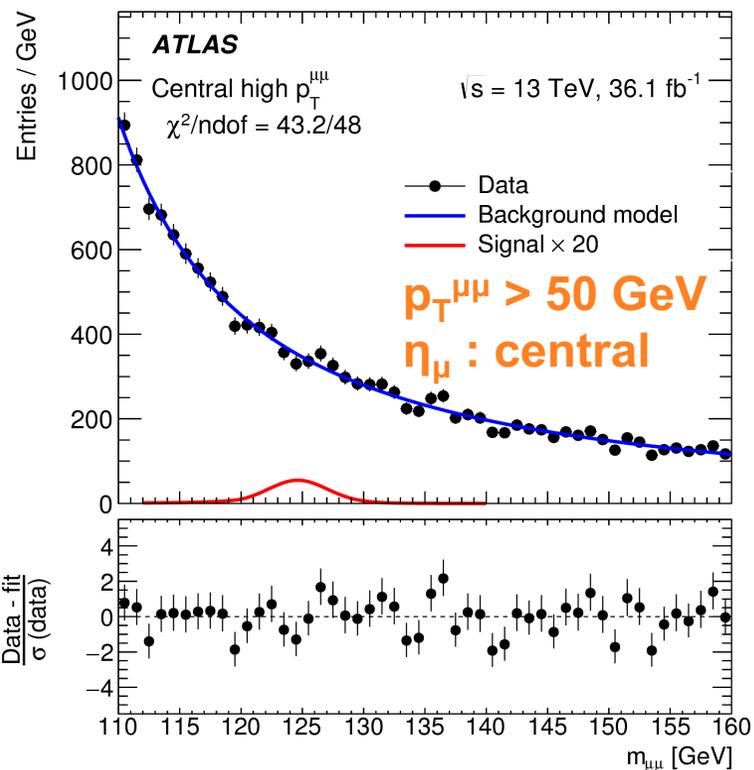
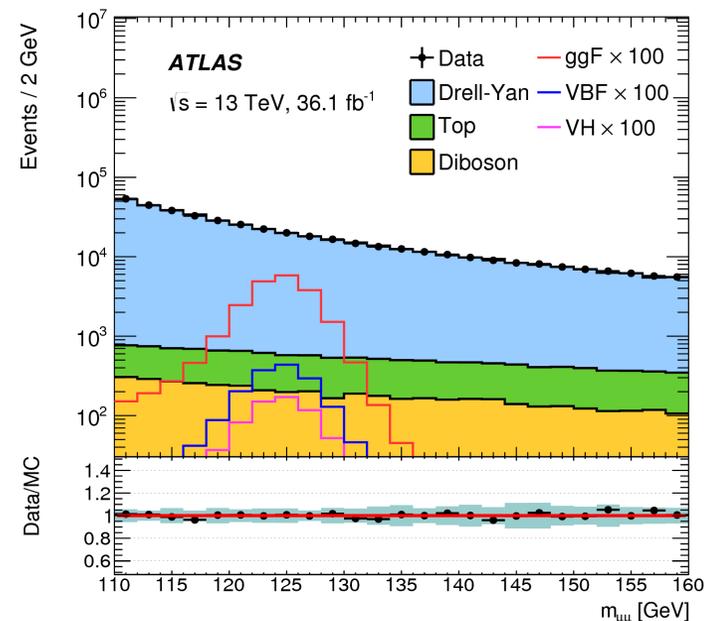
2015+2016のFull dataの結果がもうすぐ出揃う

- 全チャンネルをコンバインしてATLAS,CMSともに(Expected) 3 σ は超えるはず
- 5 σ に到達するためには系統誤差を抑える必要あり(主にbackground由来)

Higgs rare decay Di-Higgs, BSM Higgs search

Search for $H \rightarrow \mu\mu$

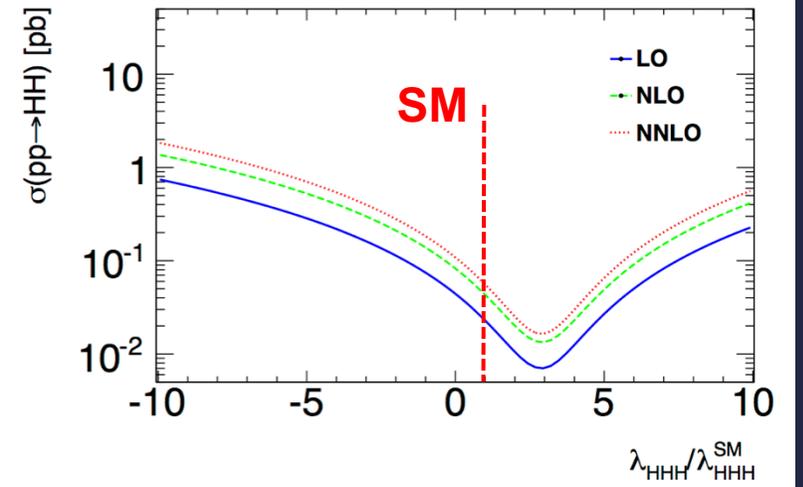
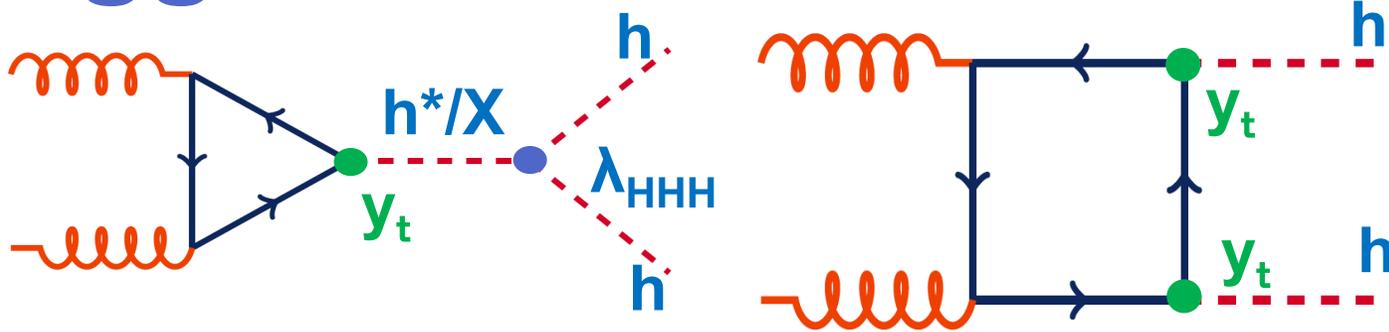
- Y_μ (2nd generation)の直接探索
 - $BR(H \rightarrow \mu\mu) \sim 0.02\%$: 信号はかなり少ない
 - $m_{\mu\mu}$ 質量ピーク ($\sigma(m_H) \sim 2-3\%$) をとして観測
- VBF (BDT high/low score), ggF ($p_T^{\mu\mu}, \eta_\mu$) でカテゴリー分け



Run1+Run2 combination
 95% C.L. upper limit
Observed $2.8 \times \text{SM}$
 (Expected $2.9 \times \text{SM}$)

統計のみの改善で
 Run3($\sim 300 \text{ fb}^{-1}$)までに 3σ い
 けるか。。。 (ATLAS+CMS)

Higgs対生成探索



- Non-resonant (anomalous couplings), resonant HH探索

Non-resonant HH探索 : ggF box, triangleの干渉でBSMだと
 $(\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM} \neq 1)$ cross sectionが増減

Resonant HH探索 : 2HDM, WED...

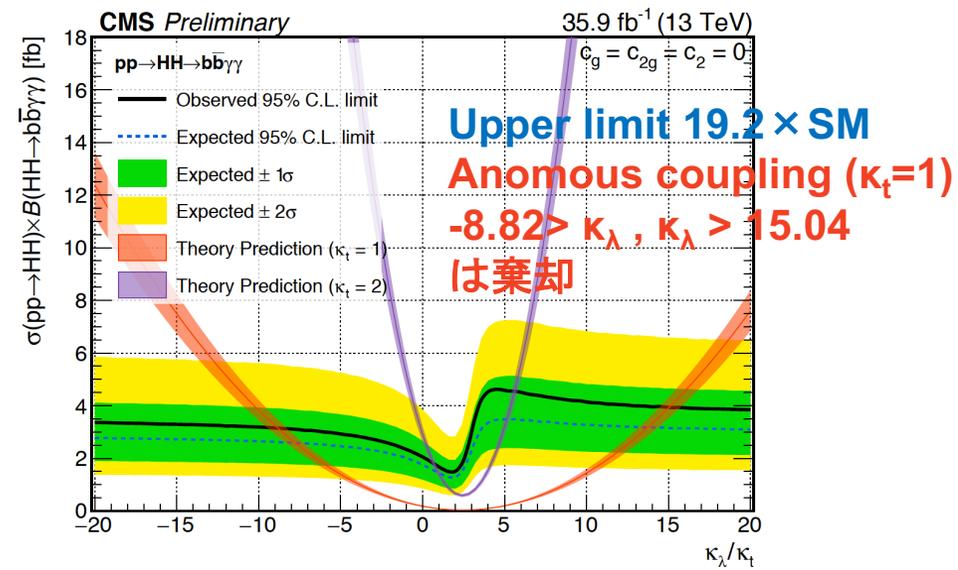
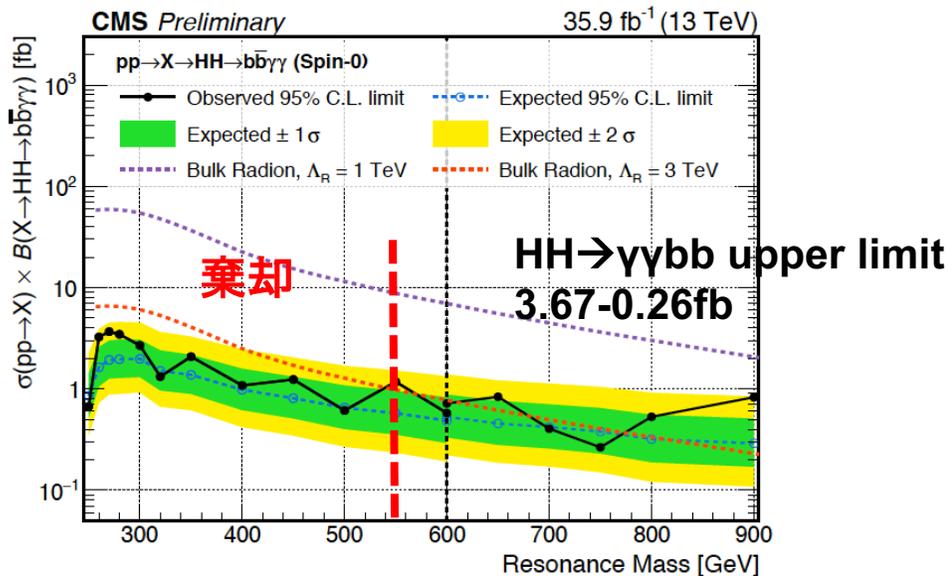
- SM $\sigma(\text{ggF} \rightarrow \text{HH}) = 33\text{fb}$ (NNLO+NNLL) @13 TeV

- 生成断面積はかなり低い
 - ✓ bb (BR=58%)で断面積を稼ぐ
 - ✓ $\gamma\gamma, \tau\tau$ (bb, WW)で背景事象を落とす → 王道

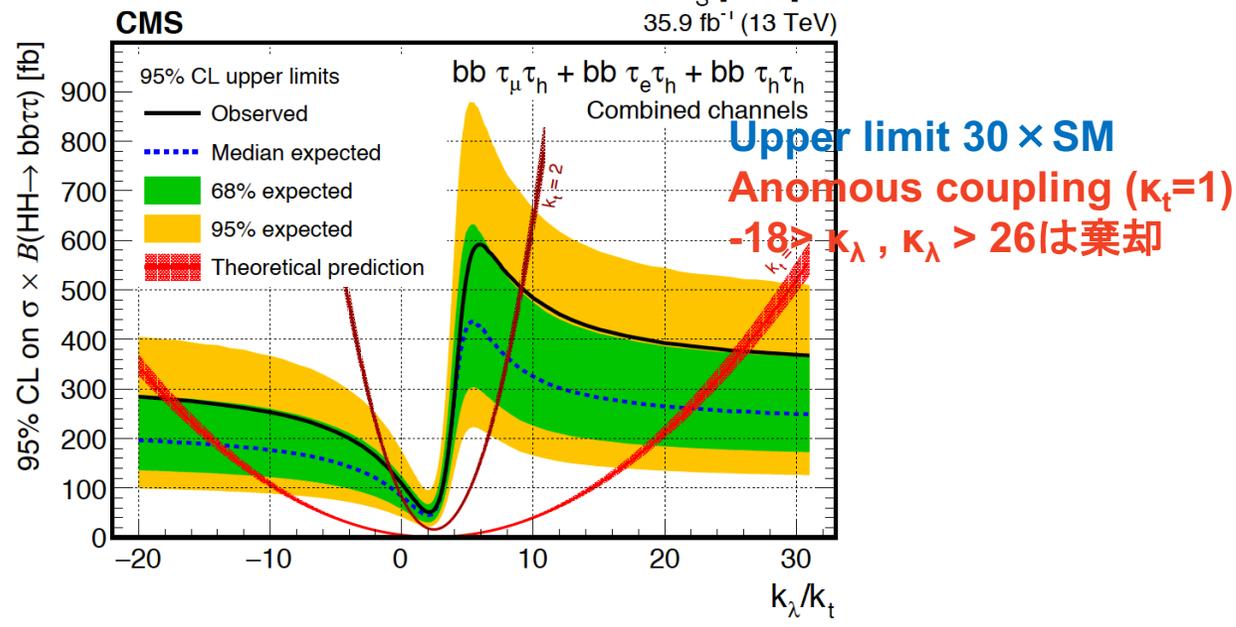
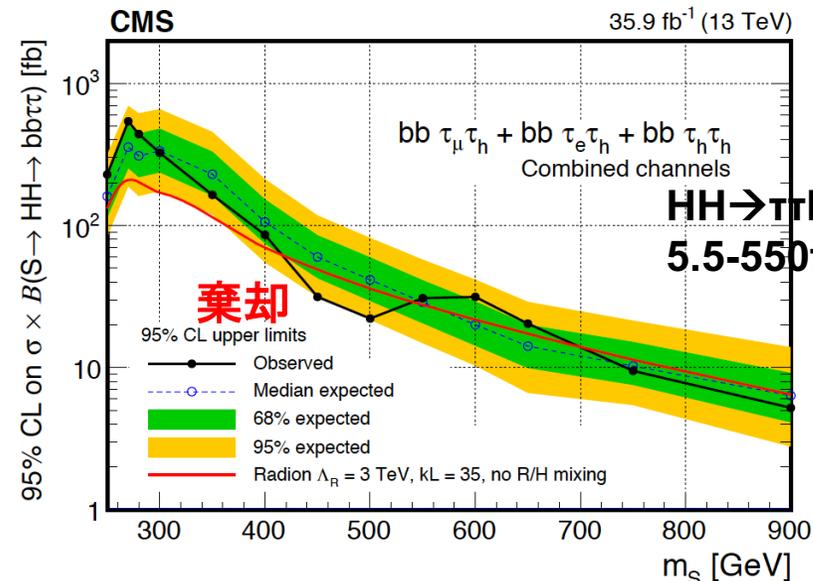
Decay	bb	$\gamma\gamma$	$\tau\tau$	WW
bb	4b (34%)			
$\gamma\gamma$	bb $\gamma\gamma$ (0.27%)	4 γ (0.0005%)		
$\tau\tau$	bb $\tau\tau$ (7.2%)	$\tau\tau\gamma\gamma$ (2.9%)	4 $\tau\tau$ (0.4%)	
WW	bbWW (24%)	$\gamma\gamma$ WW(0.1%)	$\tau\tau$ WW(2.6%)	4W(4.4%)

Higgs対生成探索

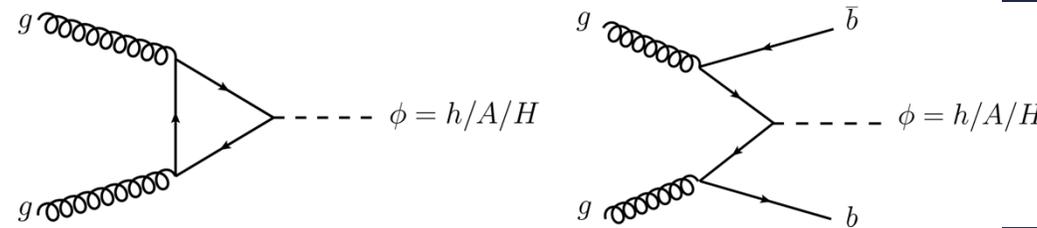
• HH→γγbb (現在最高感度)



• HH→bbττ

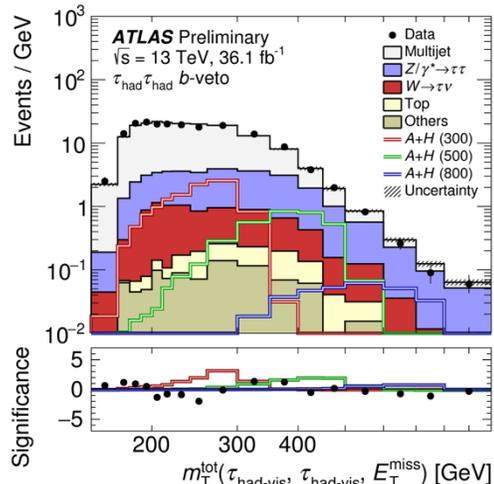
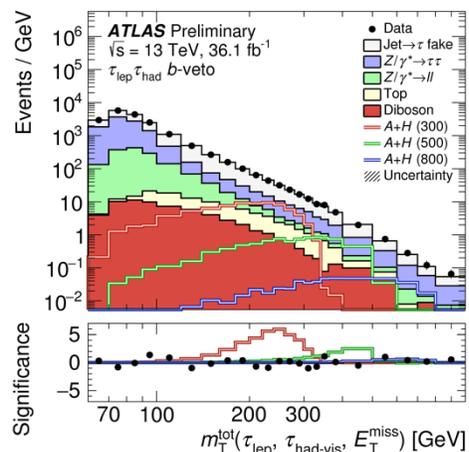


A/H → ττ BSM Search

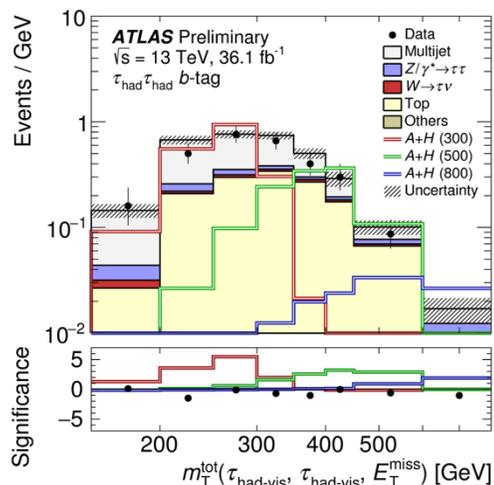
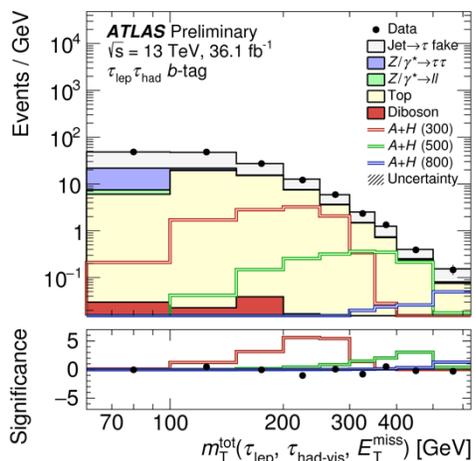


- hMSSM scinaro (gluon fusion+b-associated production)
- Decay mode ($\tau_{lep}T_{had}, T_{had}T_{had}$) × Number of b-tag (≥ 1 b-tag, 0 b-tag)

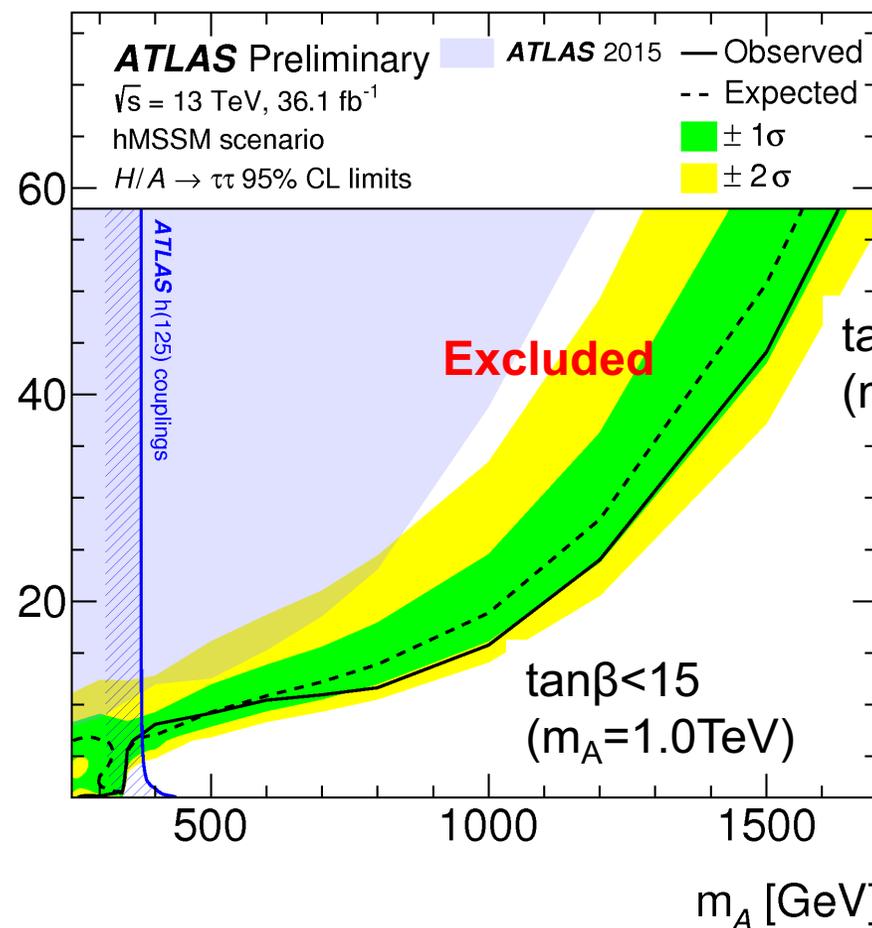
b-veto
(ggF)



b-tag
(bbPhi)



$\tan\beta$

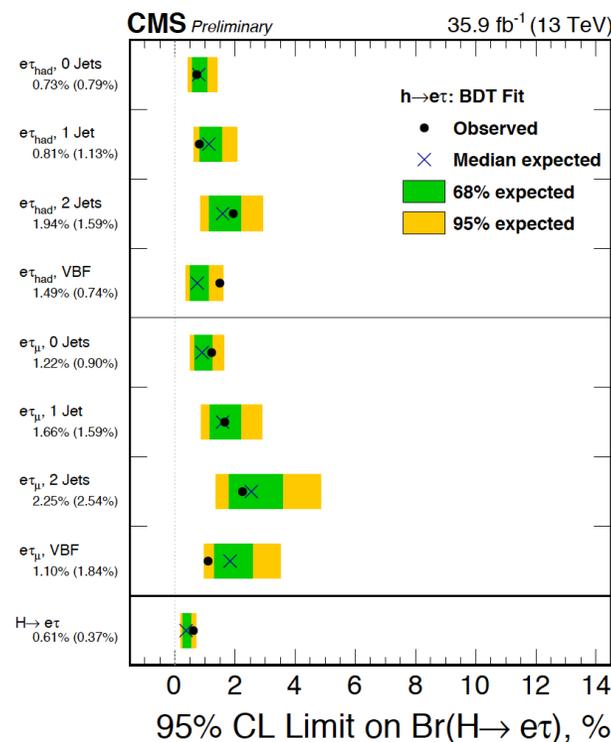
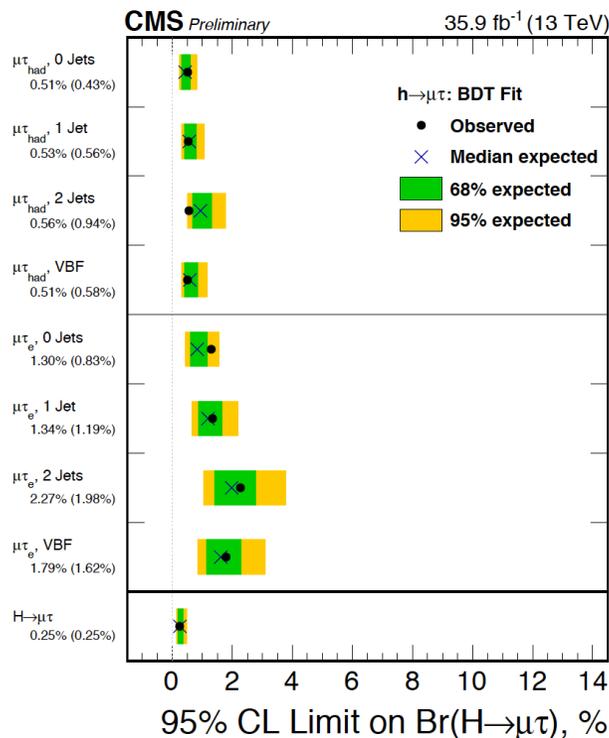


$\tan\beta < 45$
($m_A = 1.5 \text{ TeV}$)

$\tan\beta < 15$
($m_A = 1.0 \text{ TeV}$)

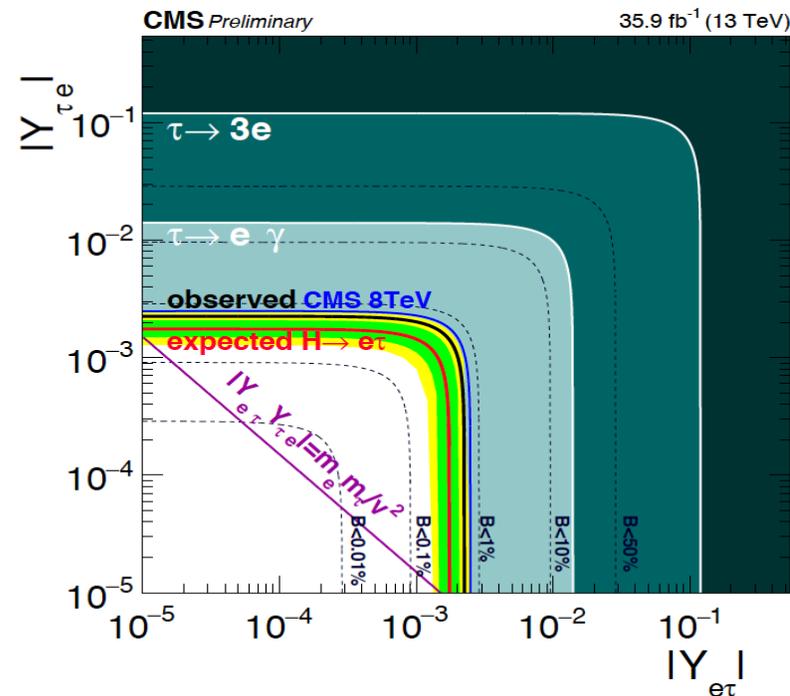
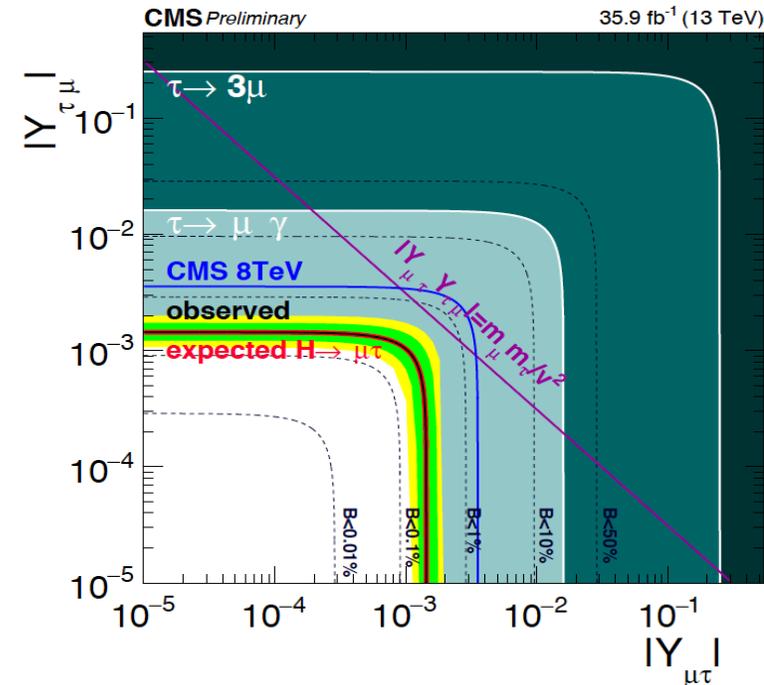
LFV Higgs探索

- Run1に観測されたExcess $\text{Br}(H \rightarrow \mu\tau) = 0.84\%$ をRun2でチェック
- BDTを使って解析感度を改善



	Obs limit(%)	Best fit BR (%)	Limit on Yukawa
$H \rightarrow \mu\tau$	<0.25%	$0.00 \pm 0.12\%$	$<1.43 \times 10^{-3}$
$H \rightarrow e\tau$	0.61%	$0.30 \pm 0.18\%$	$<2.26 \times 10^{-3}$

Run1のExcessは確認されず0と無矛盾



Summary

- $H \rightarrow \gamma\gamma$, $ZZ \rightarrow 4l$ 精密測定
 - SMからの有意なズレはまだ観測できず → 微分断面積などさらに高統計が必要
- $H \rightarrow bb$, $\tau\tau$, ttH
 - $H \rightarrow bb$ がATLASで初観測 3.6σ
 - $ttH(\text{multi-lepton}) : 3.3\sigma$
 - → 今後Cross sectionやCouplingの精密測定の時代へ
- BSM直接探索
 - 新物理の兆候は見えず。。。 (Diboson, $\gamma\gamma$, Invisible 探索)は寺師さんのトーク
- Run2(2018)で $>120\text{fb}^{-1}$ の物理データが貯まる予定

ATLAS : <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults>

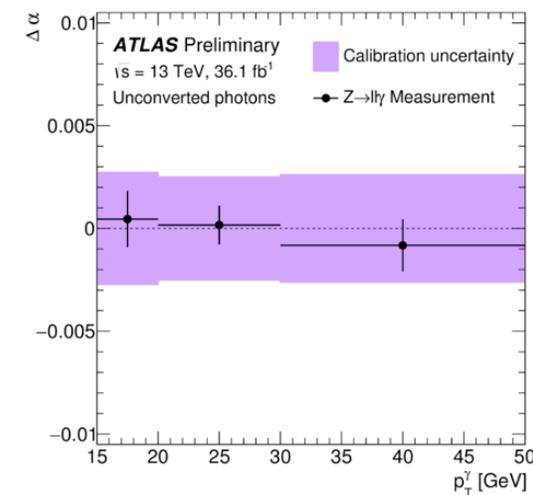
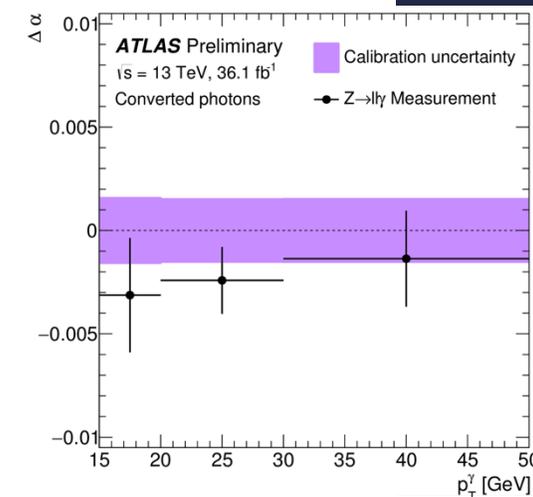
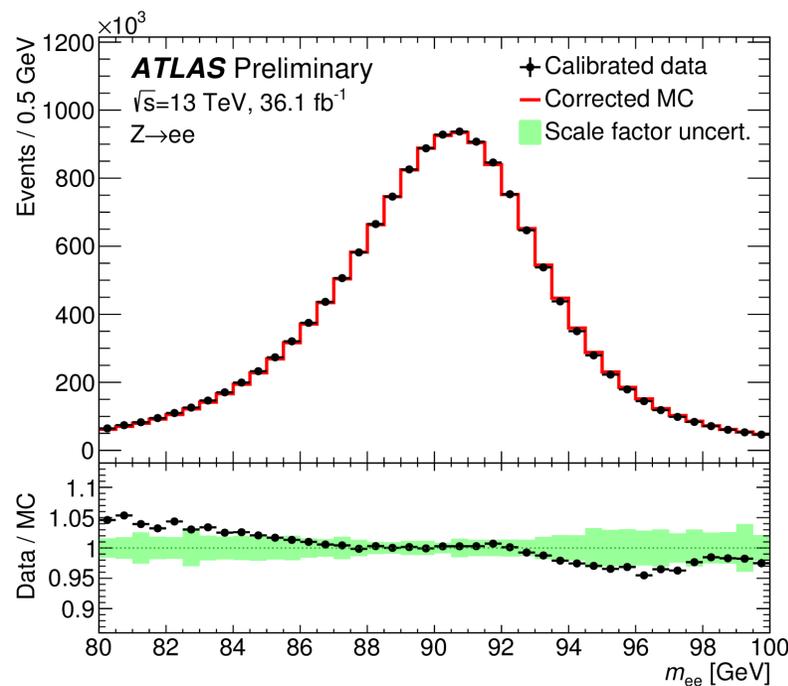
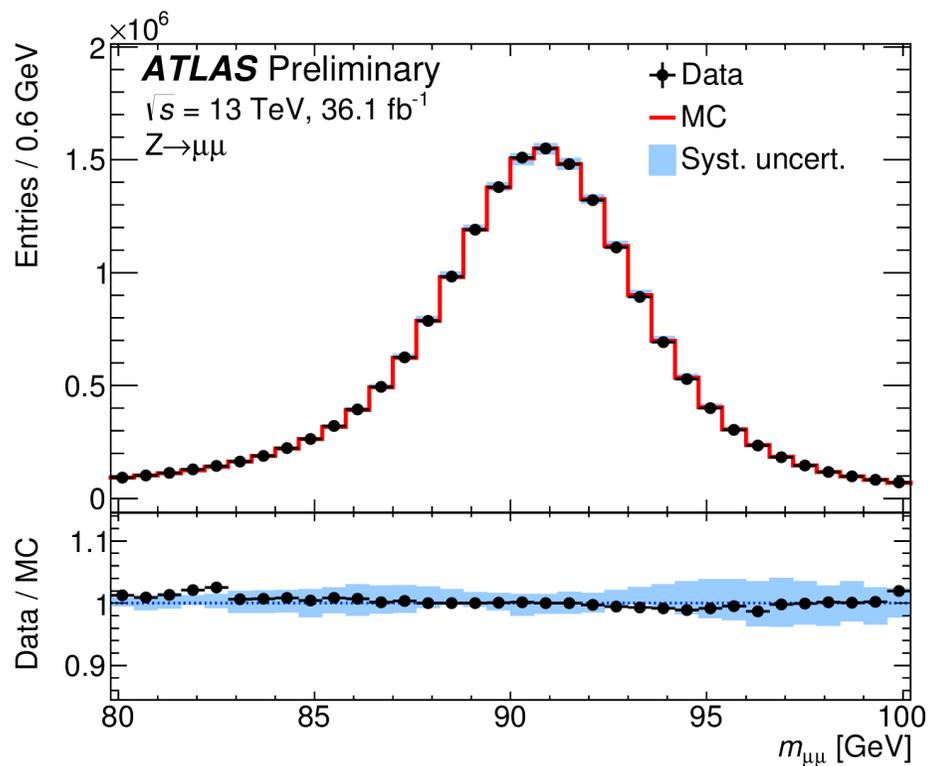
CMS : <http://cms-results.web.cern.ch/cms-results/public-results/publications/>

Back up

Run: 303499
Event: 2810362531
2016-07-08 03:06:16.000

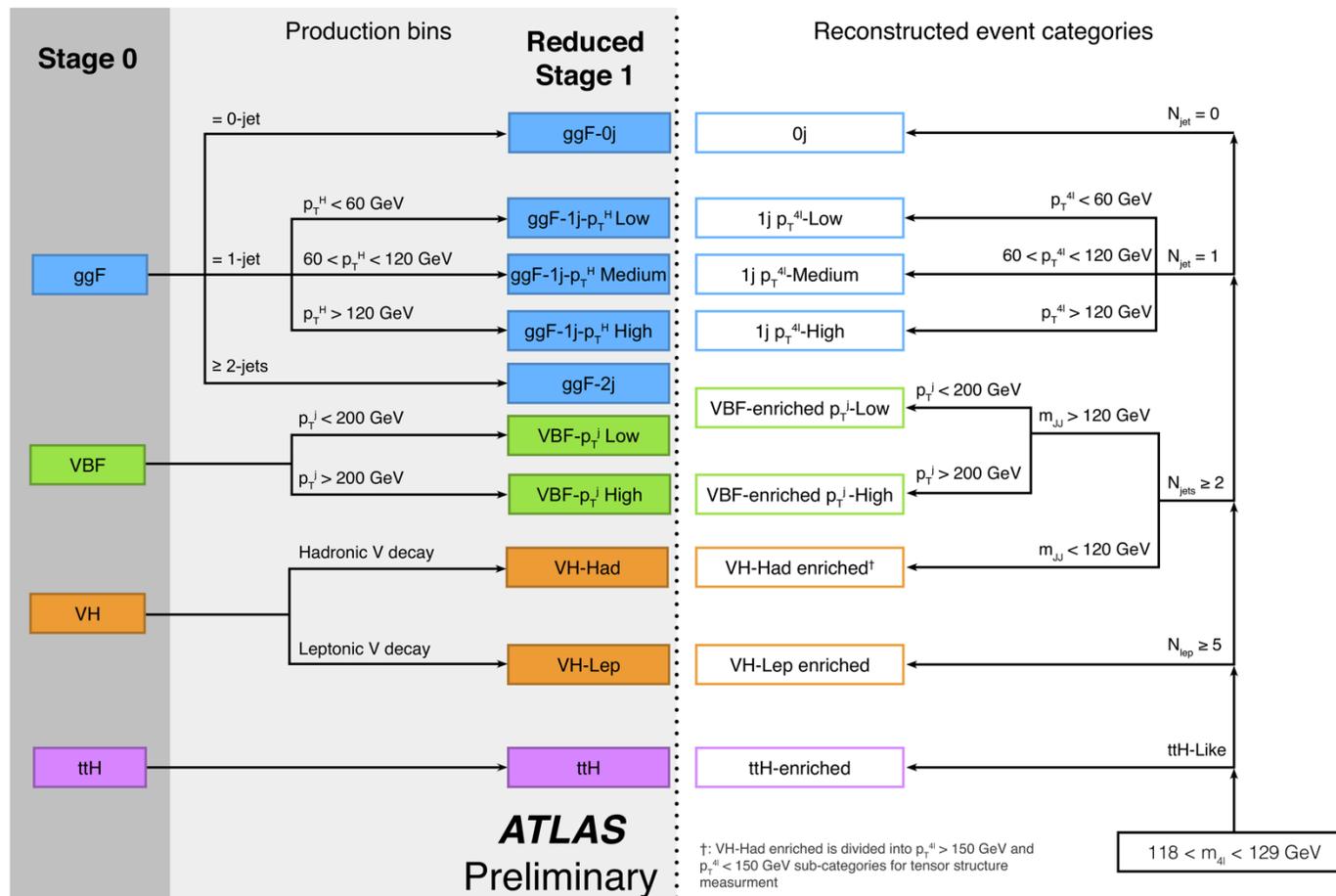
Photon(electron) and muon calibration

- Muon momentum scale/resolution
 - Calibrate with $Z(J/\psi) \rightarrow \mu\mu$
 - momentum scale 0.1-0.5%
 - momentum resolution 1-2% (barrel), 10%(foward)
 - Total uncertainty $\sim 20\text{MeV}$ for $Z \rightarrow \mu\mu$
- Photon energy scale/resolution
 - Calibrate with $Z \rightarrow ee$
 - Validate with $J/\psi, Z \rightarrow ll\gamma$
 - energy scale : 0.4-0.8%
 - energy resolution : 10-20%

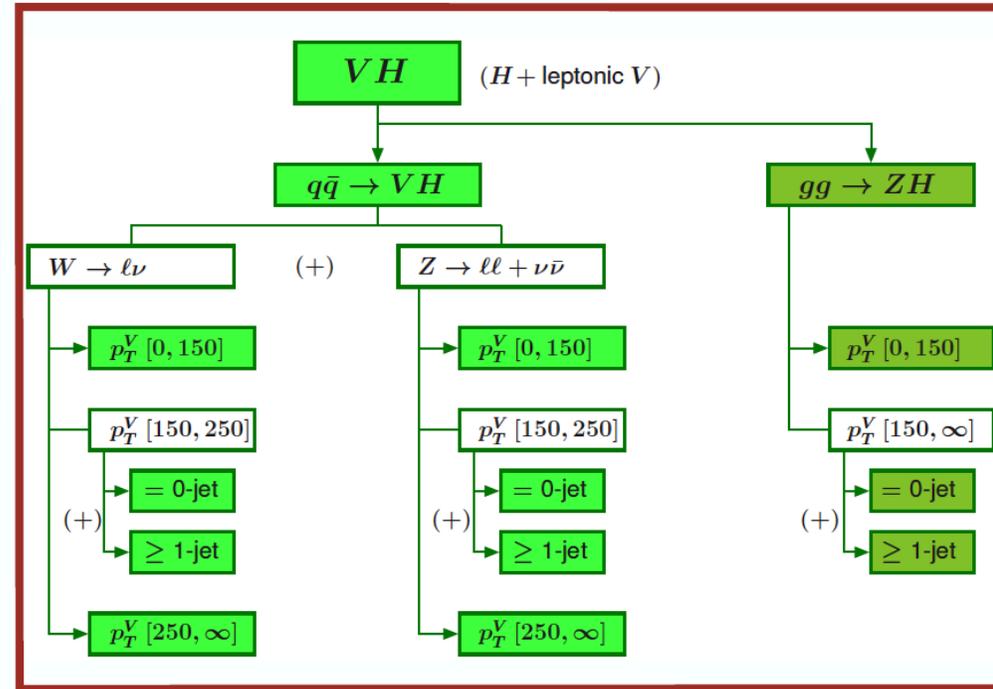
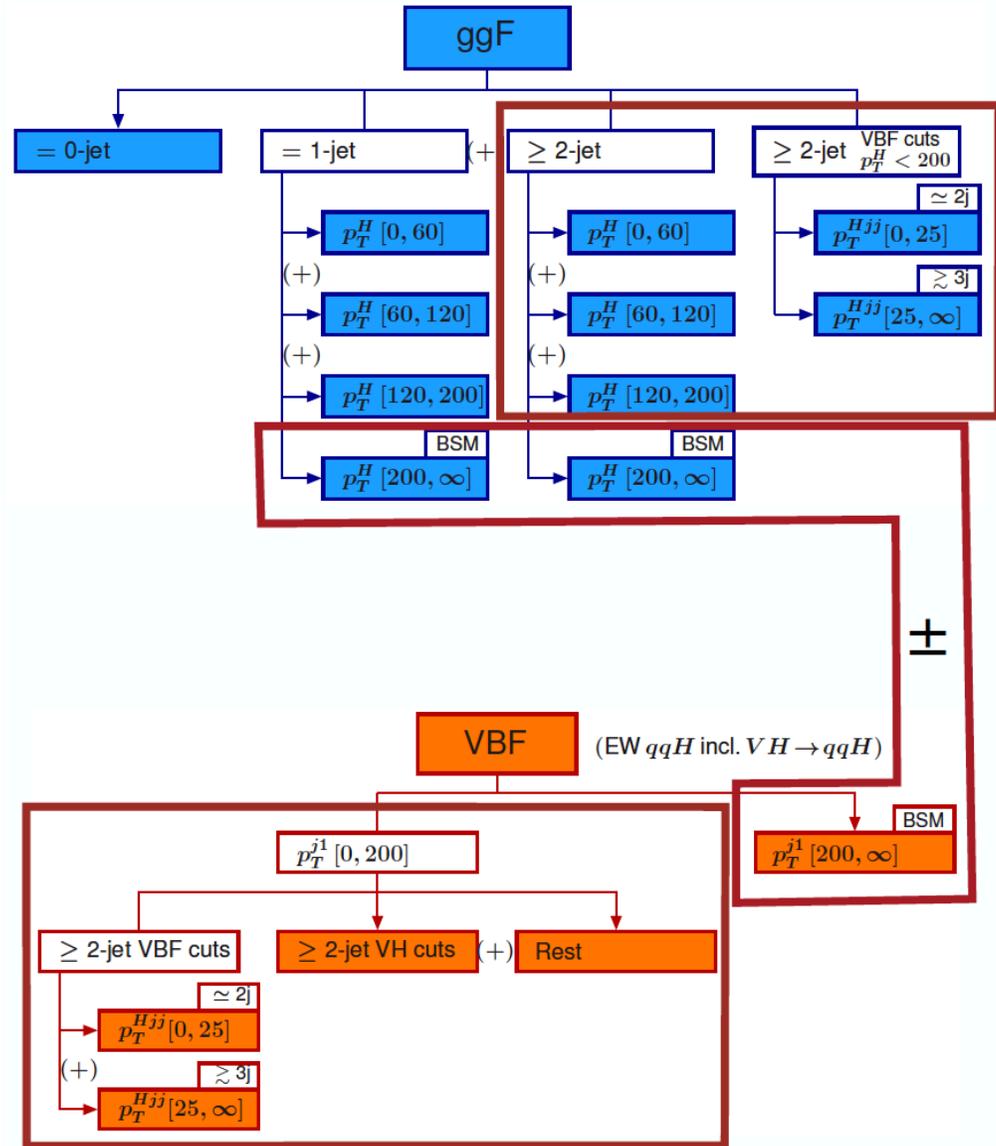


ATLAS ZZ→4l

• S



Simplified Template X-Sections Framework



H → ZZ, H → γγ Categorization

$H \rightarrow \gamma\gamma$

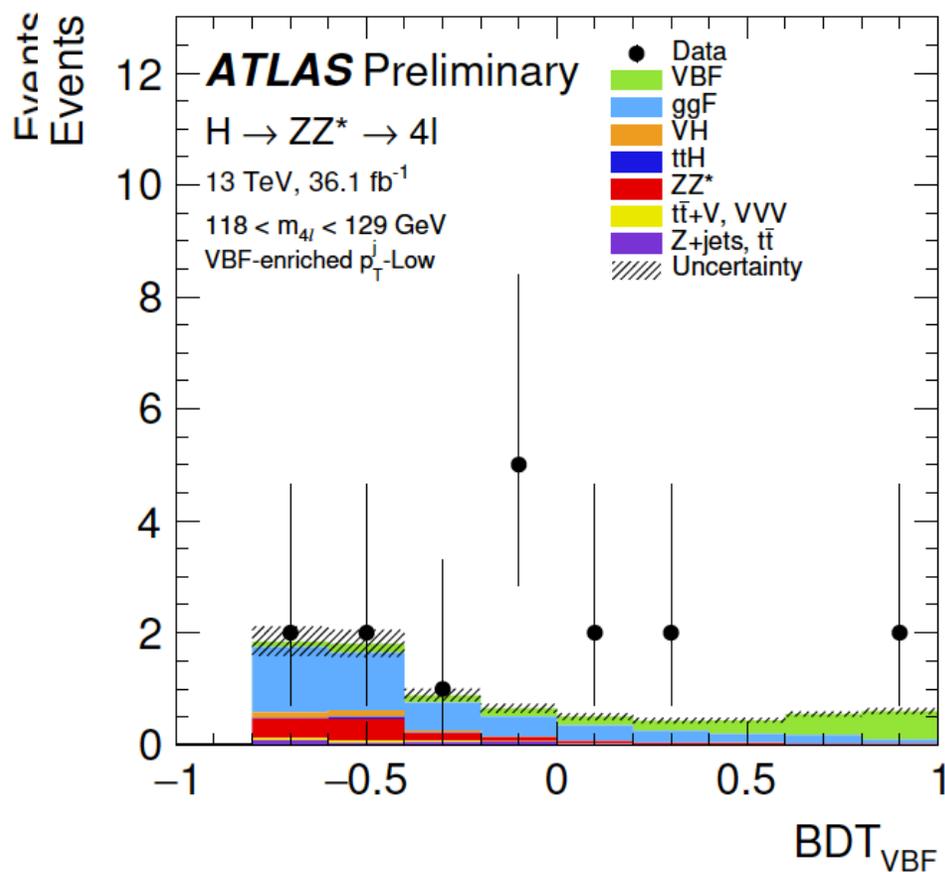
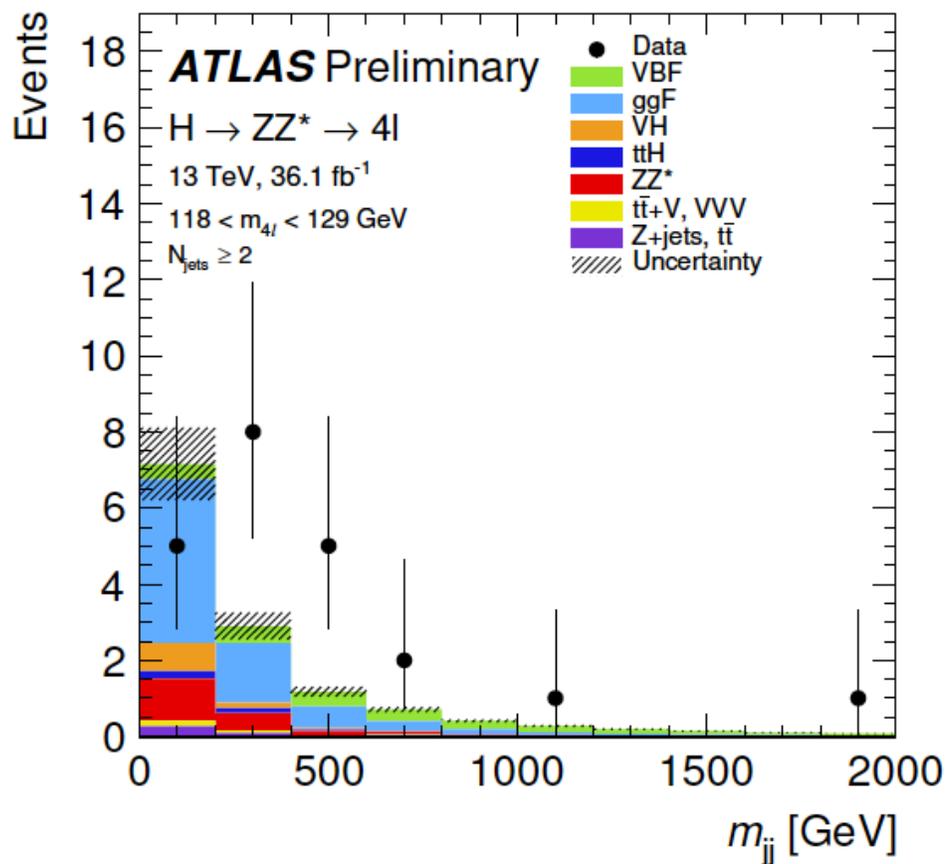
- $t\bar{t}H+tH$ leptonic (two tHX and one $t\bar{t}H$ categories)
 - $t\bar{t}H+tH$ hadronic (two tHX and four BDT $t\bar{t}H$ categories)
 - VH dilepton
 - VH one-lepton, $p_T^{\ell+MET} \geq 150$ GeV
 - VH one-lepton, $p_T^{\ell+MET} \leq 150$ GeV
 - VH $E_T^{miss}, E_T^{miss} \geq 150$ GeV
 - VH $E_T^{miss}, E_T^{miss} \leq 150$ GeV
 - $VH+VBF$ $p_T^{j1} \geq 200$ GeV
 - VH hadronic (BDT tight and loose categories)
 - VBF, $p_T^{\gamma\gamma jj} \geq 25$ GeV (BDT tight and loose categories)
 - VBF, $p_T^{\gamma\gamma jj} \leq 25$ GeV (BDT tight and loose categories)
 - ggF 2-jet, $p_T^{\gamma\gamma} \geq 200$ GeV
 - ggF 2-jet, 120 GeV $\leq p_T^{\gamma\gamma} \leq 200$ GeV
 - ggF 2-jet, 60 GeV $\leq p_T^{\gamma\gamma} \leq 120$ GeV
 - ggF 2-jet, $p_T^{\gamma\gamma} < 60$ GeV
 - ggF 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV
 - ggF 1-jet, 120 GeV $\leq p_T^{\gamma\gamma} \leq 200$ GeV
 - ggF 1-jet, 60 GeV $\leq p_T^{\gamma\gamma} \leq 120$ GeV
 - ggF 1-jet, $p_T^{\gamma\gamma} \leq 60$ GeV
 - ggF 0-jet (central and forward categories)
-
-

$H \rightarrow ZZ^* \rightarrow 4\ell$

- $t\bar{t}H$
- VH leptonic
- 2-jet VH
- 2-jet VBF, $p_T^{j1} \geq 200$ GeV
- 2-jet VBF, $p_T^{j1} \leq 200$ GeV
- 1-jet ggF, $p_T^{4\ell} \geq 120$ GeV
- 1-jet ggF, 60 GeV $\leq p_T^{4\ell} \leq 120$ GeV
- 1-jet ggF, $p_T^{4\ell} \leq 60$ GeV
- 0-jet ggF

基本的にSTXS frameworkをベースに
統計が少ない場合は適宜カテゴリーをま
とめる

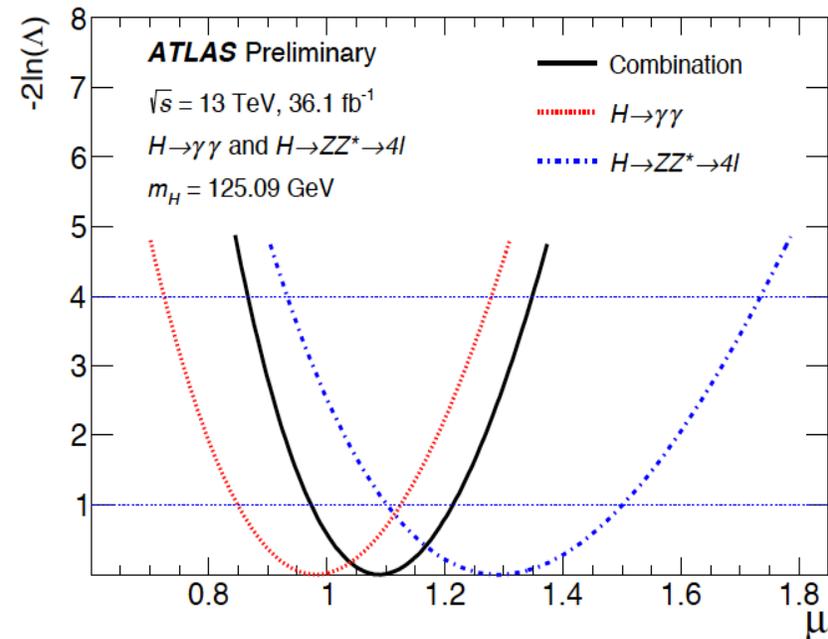
H → ZZ → 4l VBF channel



Global Signal Strength

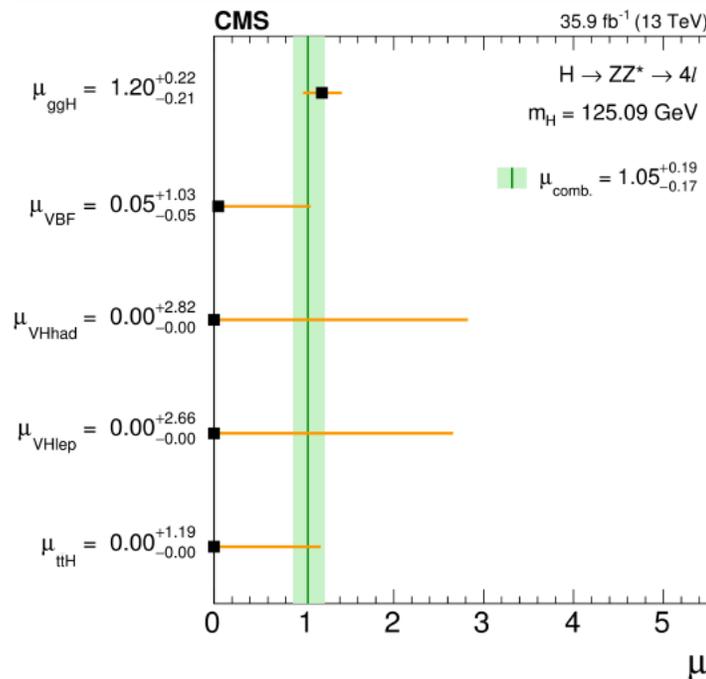
- $\gamma\gamma+ZZ\rightarrow 4l$

$$\mu = 1.16_{-0.10}^{+0.11}(\text{stat.})_{-0.08}^{+0.09}(\text{sys.})_{-0.05}^{+0.06}(\text{theo.})$$

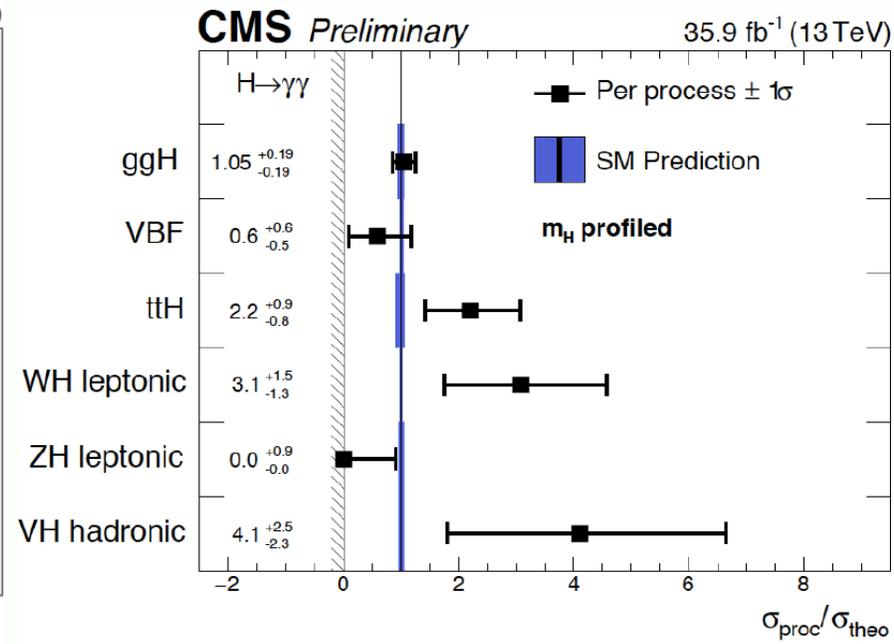


$$\mu = 1.09 \pm 0.12$$

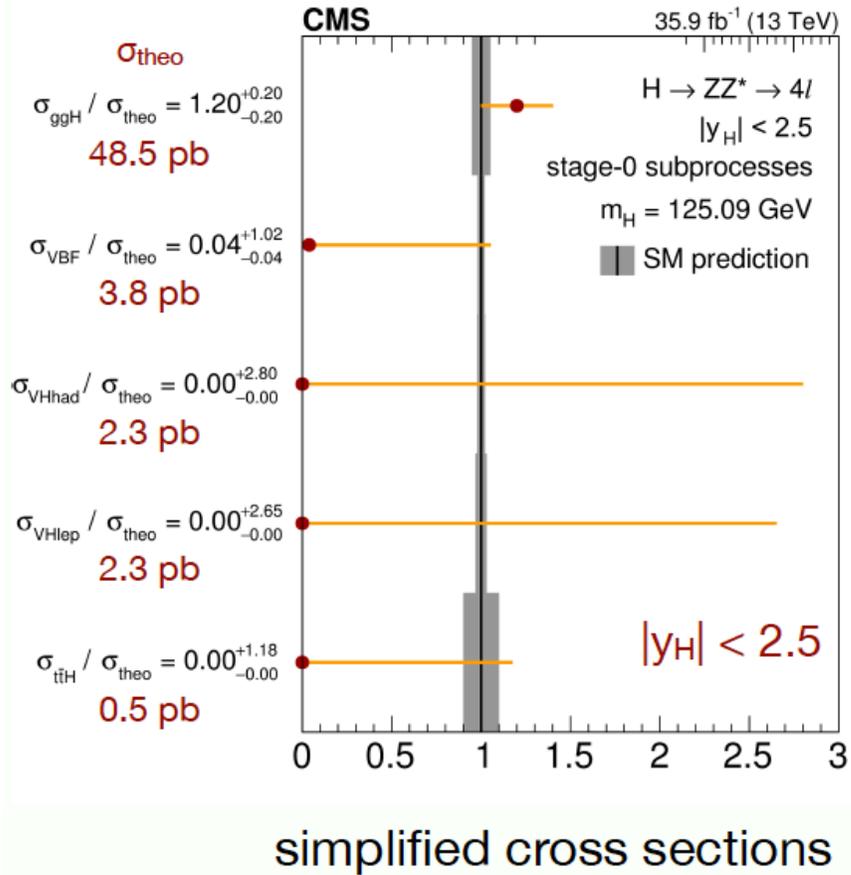
$$= 1.09 \pm 0.09(\text{stat})_{-0.05}^{+0.06}(\text{exp.})_{-0.05}^{+0.06}(\text{th.})$$



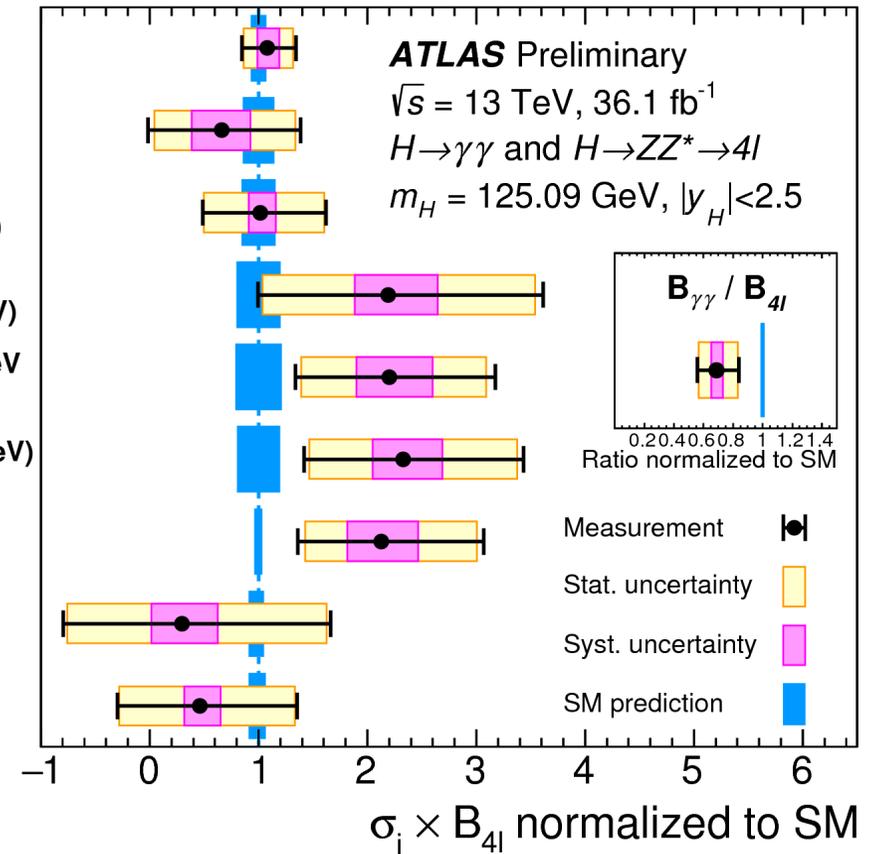
$$\mu = 1.05_{-0.14}^{+0.15}(\text{stat.})_{-0.09}^{+0.11}(\text{syst.})$$



STXS Cross Section Measurement



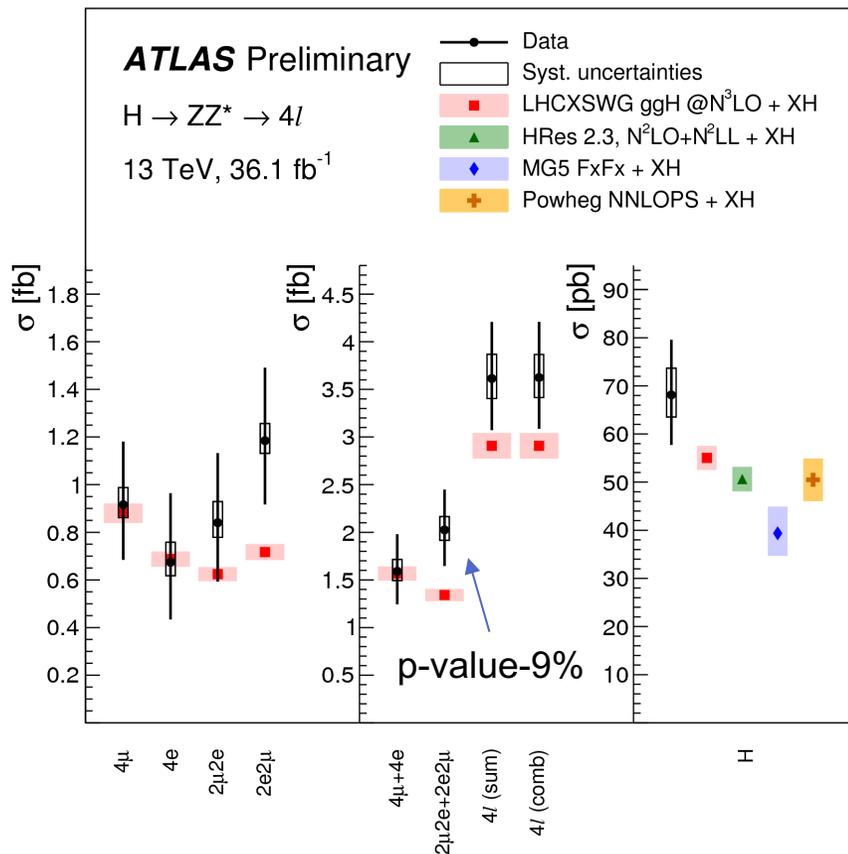
- $gg \rightarrow H$ (0-jet)
- $gg \rightarrow H$ (1-jet, $p_T^H < 60 \text{ GeV}$)
- $gg \rightarrow H$ (1-jet, $60 \leq p_T^H < 120 \text{ GeV}$)
- $gg \rightarrow H$ (1-jet, $120 \leq p_T^H < 200 \text{ GeV}$)
- $gg \rightarrow H$ (≥ 2 -jet, $p_T^H < 200 \text{ GeV}$ or VBF-like)
- $gg \rightarrow H$ (≥ 1 -jet, $p_T^H \geq 200 \text{ GeV}$) + $qq \rightarrow Hqq$ ($p_T^j \geq 200 \text{ GeV}$)
- $qq \rightarrow Hqq$ ($p_T^j < 200 \text{ GeV}$)
- $gg/qq \rightarrow Hll/Hl\nu$
- $gg/qq \rightarrow ttH$



Fiducial cross section

- $H \rightarrow ZZ \rightarrow 4l$ (Fiducial, total cross section)

Fiducial Volume

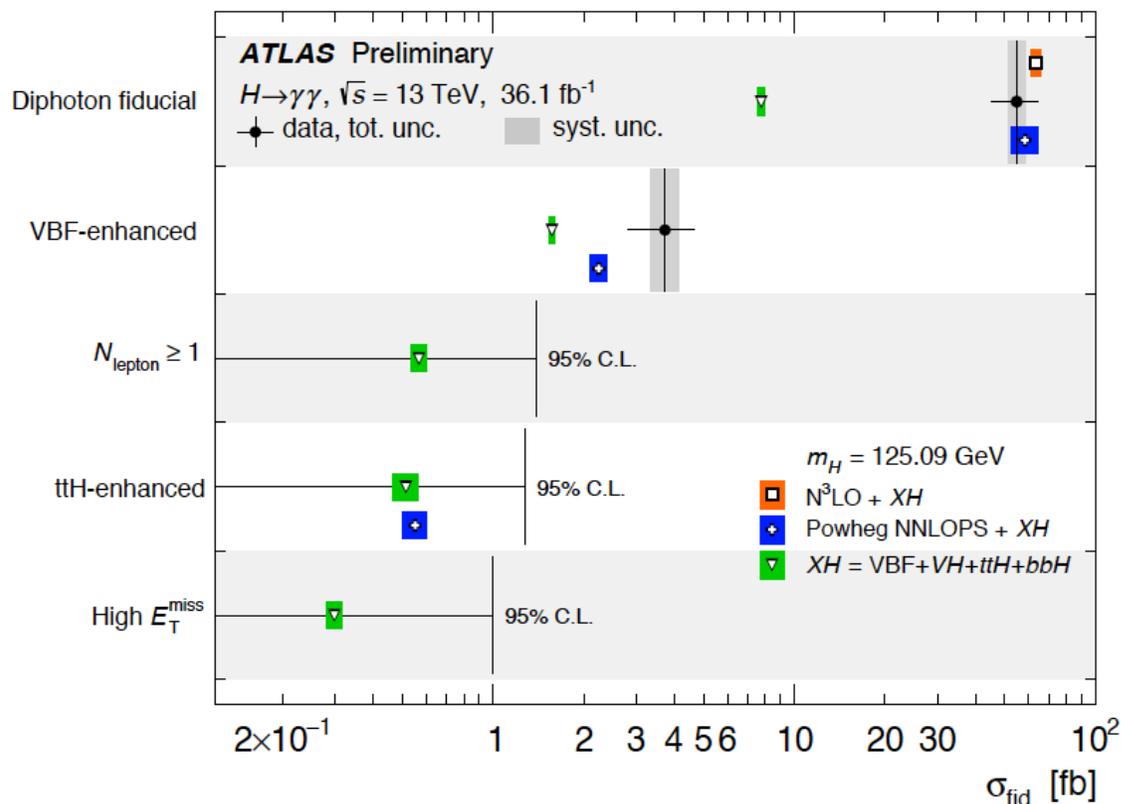


muon	$p_T > 5 \text{ GeV}, \eta < 2.7$
electron	$p_T > 7 \text{ GeV}, \eta < 2.47$
jets	$p_T > 30 \text{ GeV}, y < 4.4$
lepton p_T	$p_T > 20, 15, 10$
m_{12}	$50 < m_{12} < 106$
m_{34}	$12 < m_{34} < 115$
m_{ll}	$m_{ll} > 5 \text{ GeV}$ (all SFOS lepton pair)
m_{4l}	$115 \text{ GeV} < m_{4l} < 130$

Fiducial selectionのAcceptance 42% @ $m_H = 125 \text{ GeV}$
 detector level/particle level 40-60% (lepton flavor依存)

Fiducial cross section

- $\gamma\gamma$ Fiducial cross section

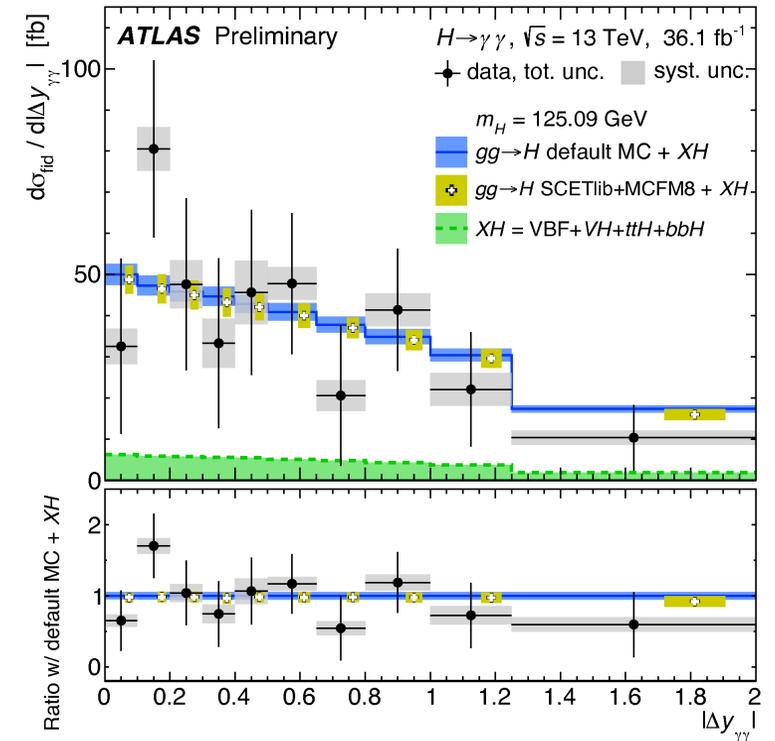
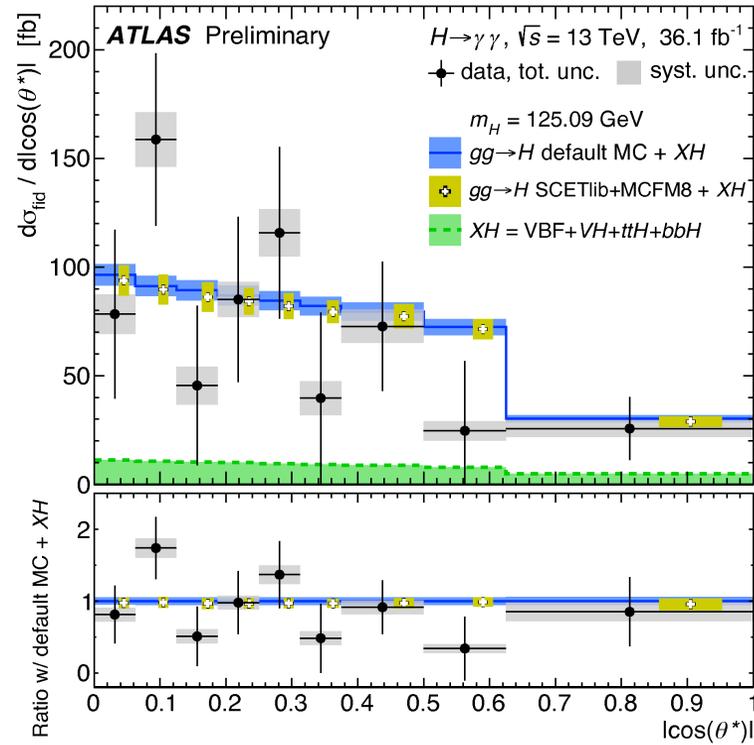
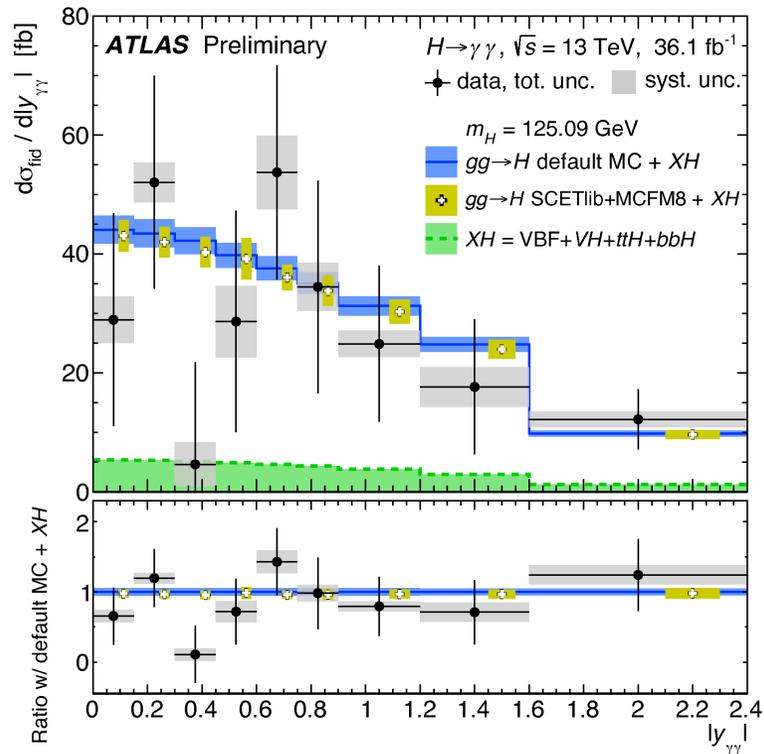


Fiducial Volume

Objects	Definition
Photons	$ \eta < 1.37$ OR $1.52 < \eta < 2.37$, $p_T^{\text{iso},0.2} / p_T^\gamma < 0.05$
Jets	anti- k_t , $R = 0.4$, $p_T > 30$ GeV, $ y < 4.4$
Leptons, ℓ	e or μ , $p_T > 15$ GeV, $ \eta < 2.47$ (excluding $1.37 < \eta < 1.52$ for $\ell = e$)
Fiducial region	Definition
Diphoton fiducial	$N_\gamma \geq 2$, $p_T^{\gamma 1} > 0.35 m_{\gamma\gamma}$, $p_T^{\gamma 2} > 0.25 m_{\gamma\gamma}$
VBF-enhanced	Diphoton fiducial, $N_j \geq 2$, $m_{jj} > 400$ GeV, $ \Delta y_{jj} > 2.8$, $ \Delta\phi_{\gamma\gamma, jj} > 2.6$
$N_{\text{lepton}} \geq 1$	Diphoton fiducial, $N_\ell \geq 1$
High E_T^{miss}	Diphoton fiducial, $E_T^{\text{miss}} > 80$ GeV, $p_T^{\gamma\gamma} > 80$ GeV
$t\bar{t}H$ -enhanced	Diphoton fiducial, $(N_j \geq 4, N_{\text{b-jets}} \geq 1)$ OR $(N_j \geq 3, N_{\text{b-jets}} \geq 1, N_\ell \geq 1)$

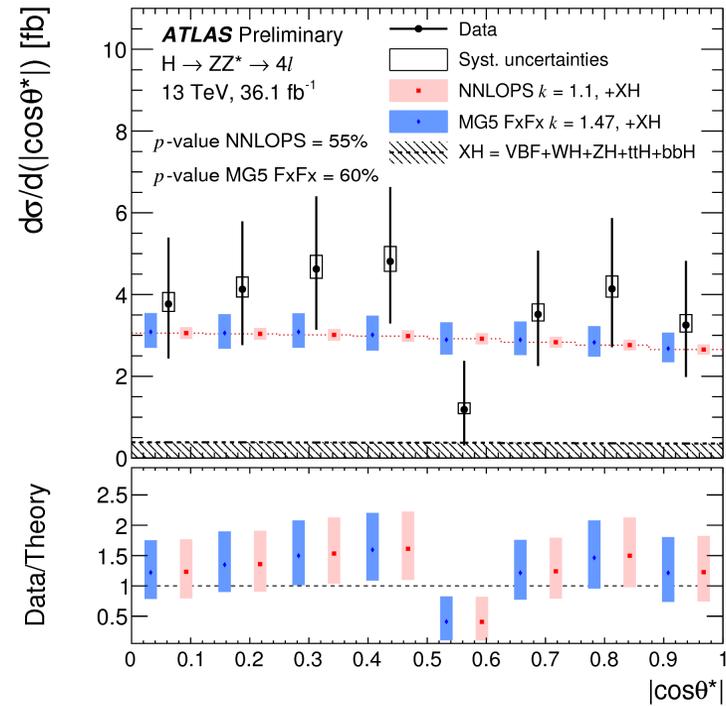
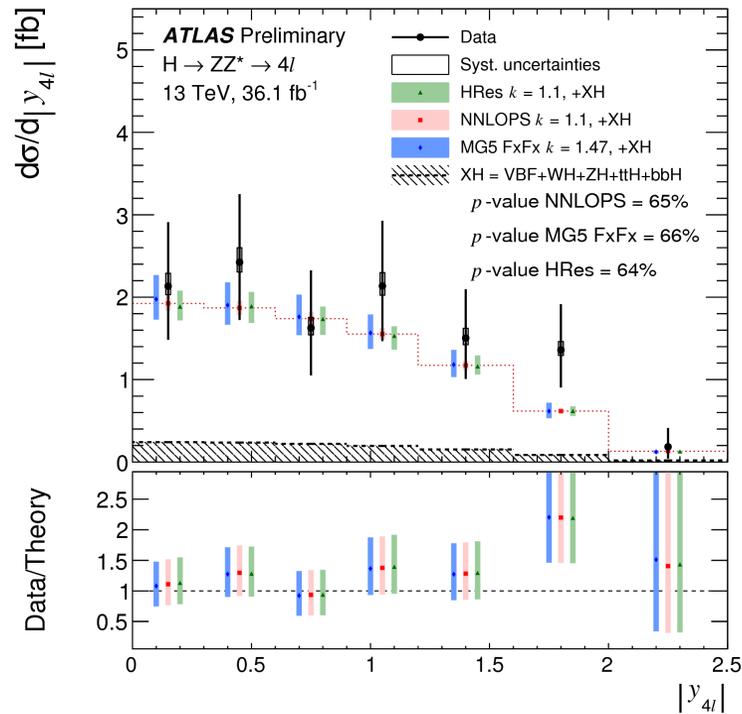
Differential Distribution

- $y_{\gamma\gamma}$: 生成過程のPDFに感度を持つ
- $|\cos(\theta^*)|$ (CS frame) : Spinに感度
- $|\Delta y_{\gamma\gamma}|$: Spinに感度

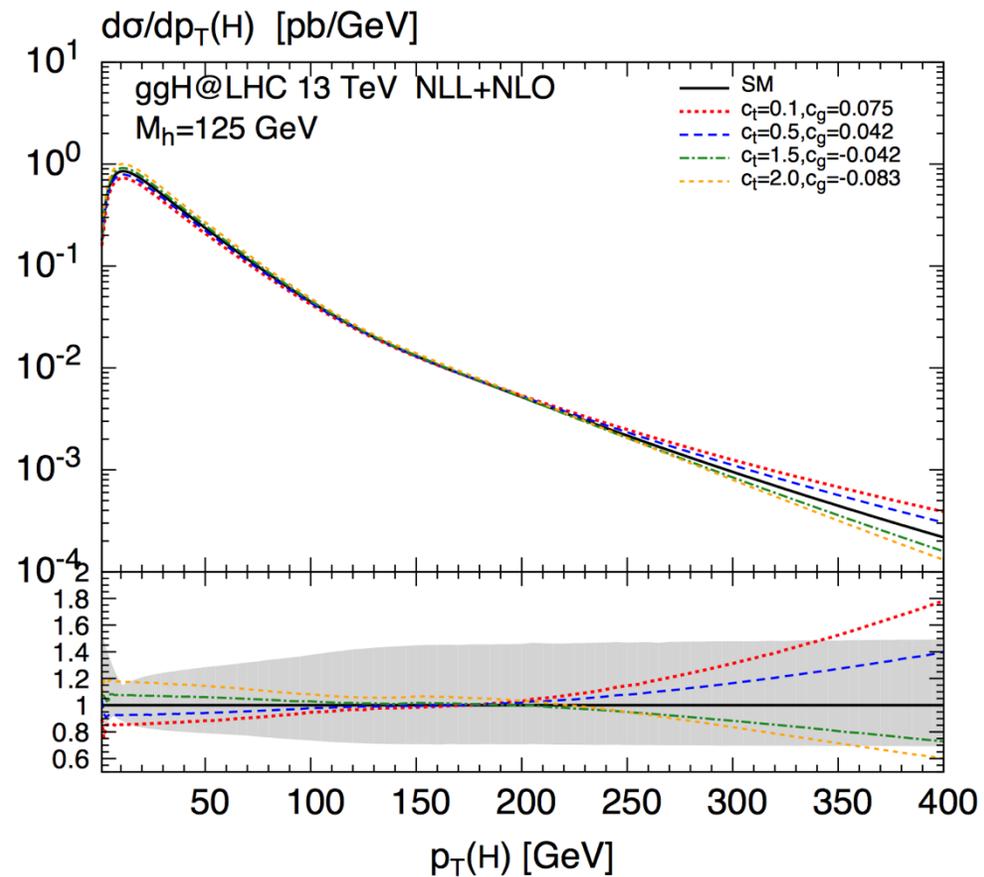


Differential Distribution

- y_{4l} : 生成過程のPDFに感度を持つ
- $|\cos(\theta^*)|$ (CS frame) : Spinに感度



BMS in high $p_T(H)$



Tensor Structure Measurement (ZZ→4l)

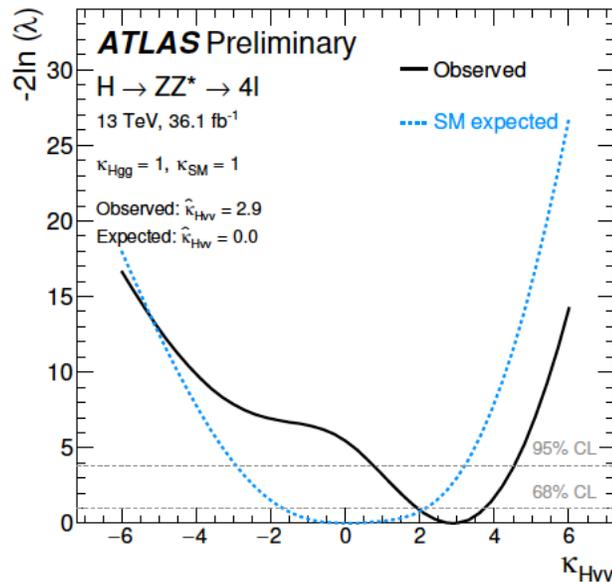
- Check tensor structure of Higgs boson coupling

Spin0 : EFT (An example in ATLAS H→ZZ→4l)

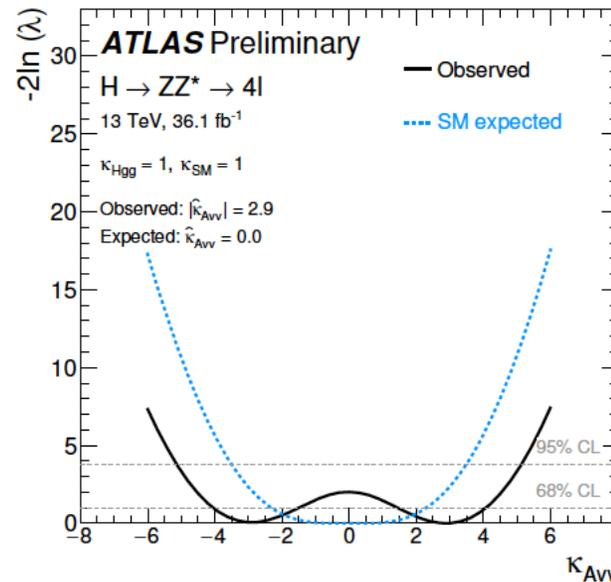
$$L_0^V = [c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu \right] - \frac{1}{4} \frac{1}{\Lambda} [c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}]] X_0$$

SM Higgs
BSM CP-even coupling
CP-odd coupling

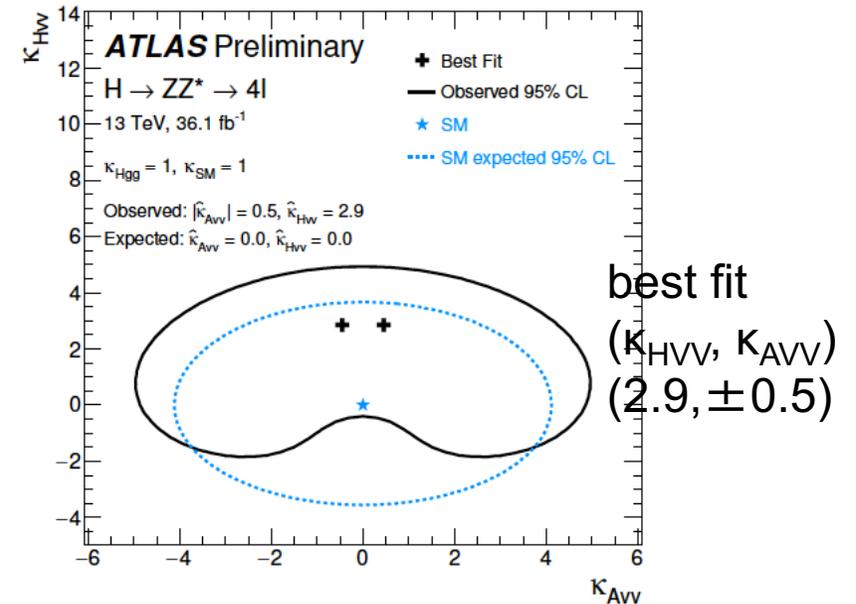
Λ : cut-off scale, α : Mixing angle,
 $c_\alpha = \cos \alpha$, $s_\alpha = \sin \alpha$



$0.8 < \kappa_{HVV} < 4.5$ @ 95% CL
 Best fit $\kappa_{HVV} = 2.9$



$-5.2 < \kappa_{AVV} < 5.2$ @ 95% CL
 Best fit $\kappa_{AVV} = \pm 2.9$



1.9σ from SM expectation

Spin/CP Measurement

- Anomalous coupling measurement

$$A(HVV) \sim \left[\boxed{a_1^{VV}} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \boxed{a_2^{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \boxed{a_3^{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

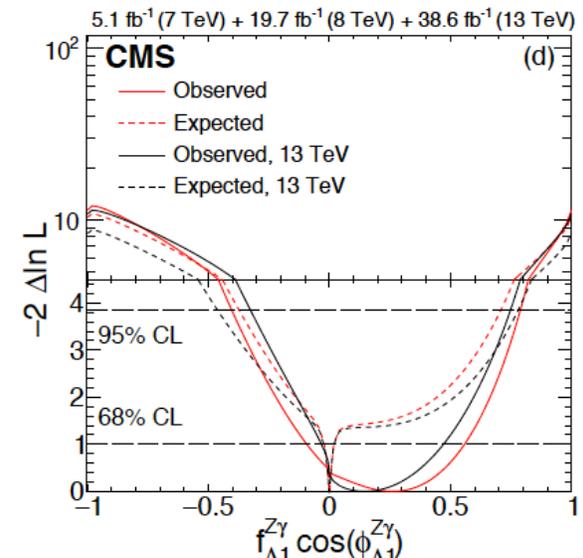
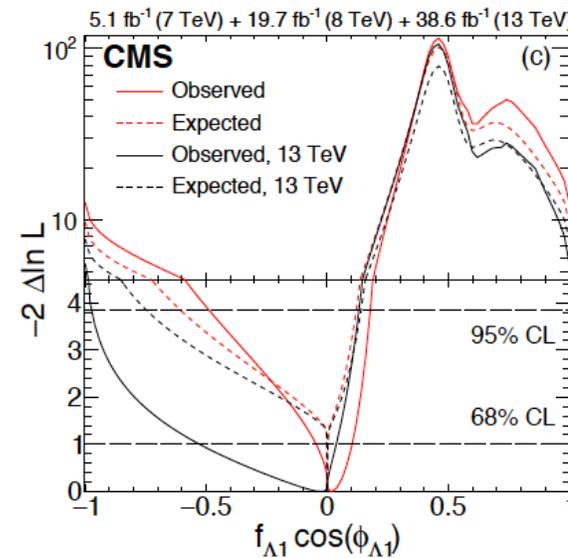
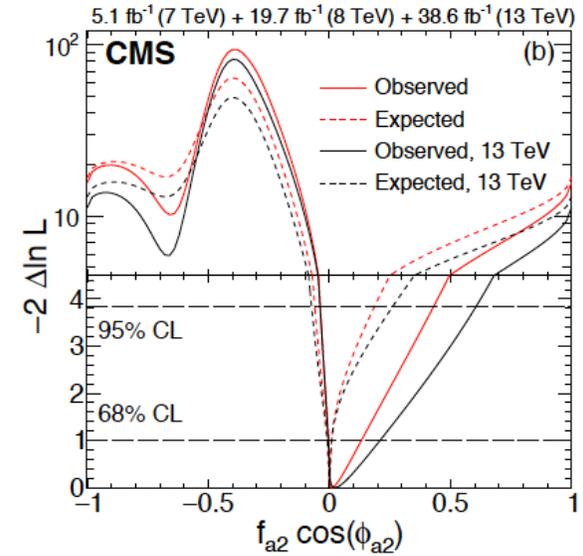
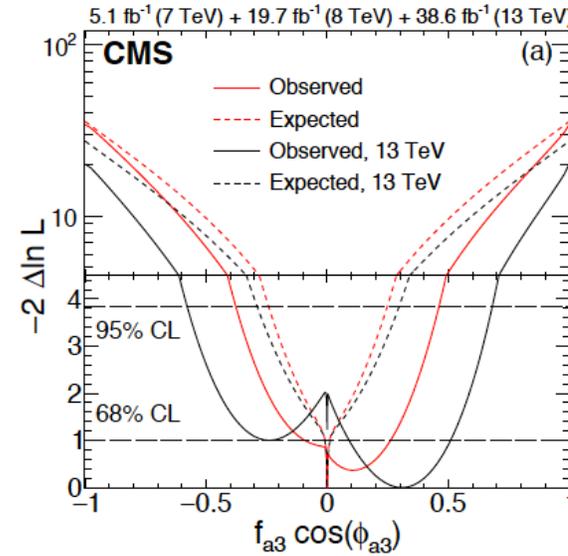
SM
BSM CP-even
BSM CP-odd

- effective cross sectionの割合 f_i と phase を測定

$$f_{ai} = |a_i|^2 \sigma_i / \sum |a_j|^2 \sigma_j,$$

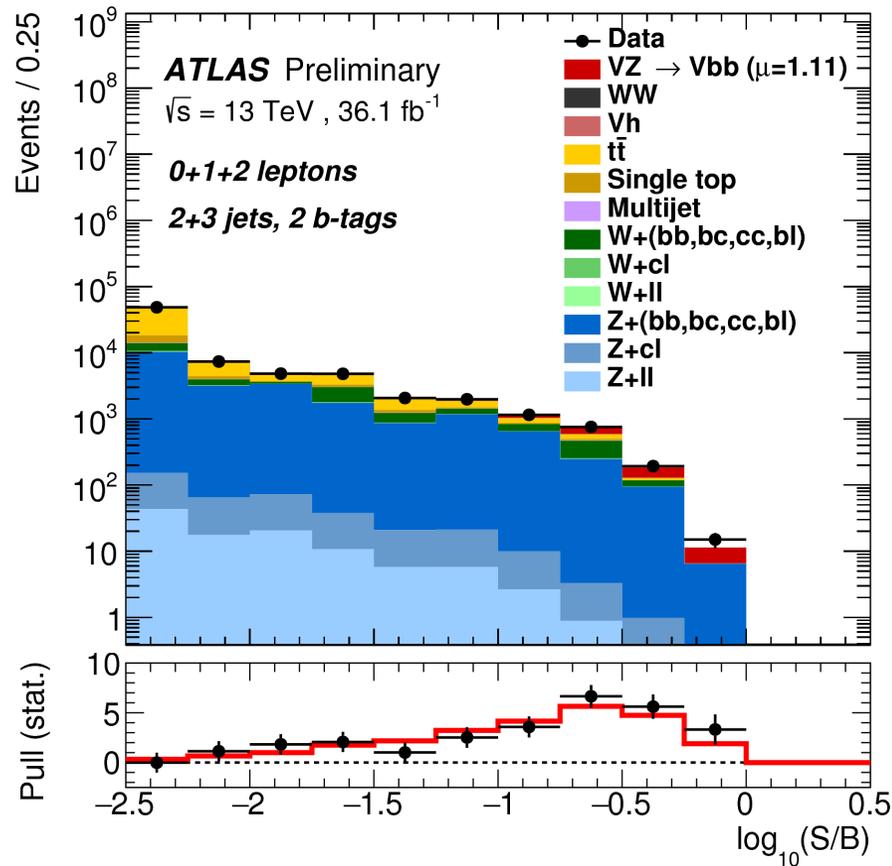
$$\phi_{ai} = \arg(a_i/a_1)$$

- H → ZZ → 4l の崩壊だけでなく, VBF, VH の生成の情報も用いて感度向上
- SM から有意なズレはなし (Run2 full で統計4倍で感度良くなる)



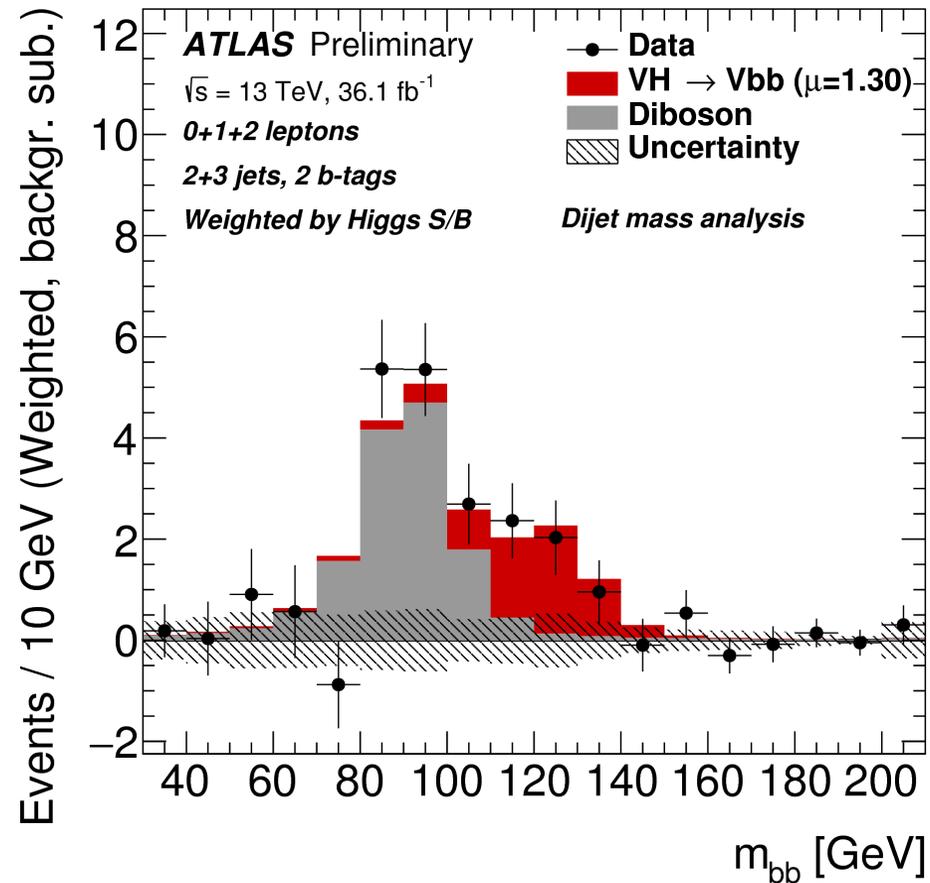
Evidence for $H \rightarrow b\bar{b}$ decay mode

- Validation with VZ diboson and $m_{b\bar{b}}$ analysis in Run2 analysis



$$\mu_{VZ}^{b\bar{b}} = 1.11^{+0.25}_{-0.22}$$

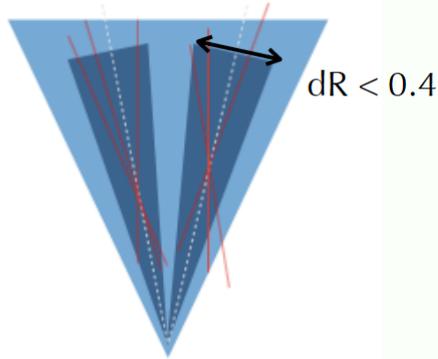
Observed significance 5.8σ (exp. 5.3σ)



$$\mu_{VH}(m_{bb}) = 1.30^{+0.28}_{-0.27}(\text{stat})^{+0.37}_{-0.29}(\text{syst})$$

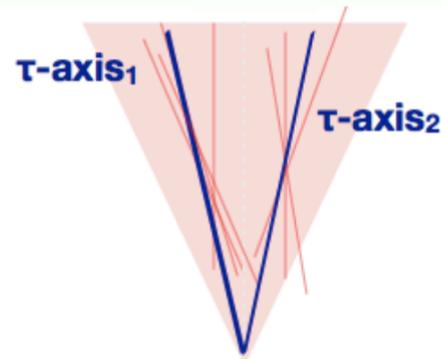
$$\mu_{VH}(MVA) = 1.20^{+0.24}_{-0.23}(\text{stat})^{+0.34}_{-0.28}(\text{syst})$$

Boosted $H \rightarrow bb$ double b-tagging



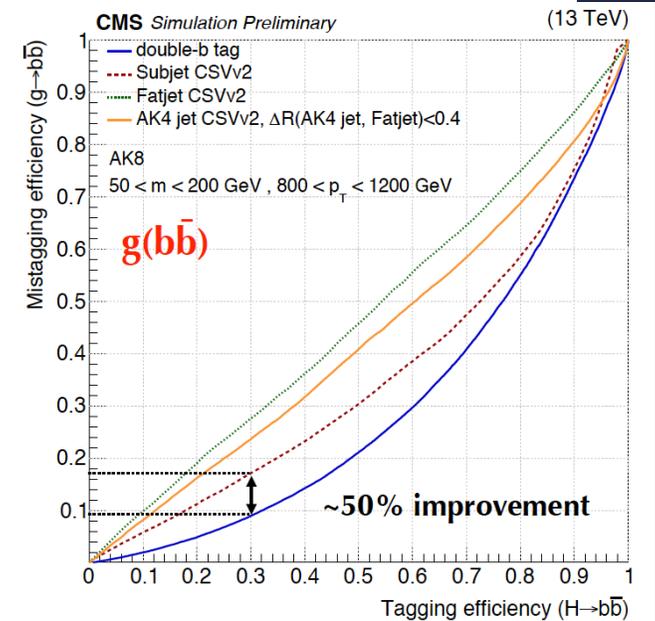
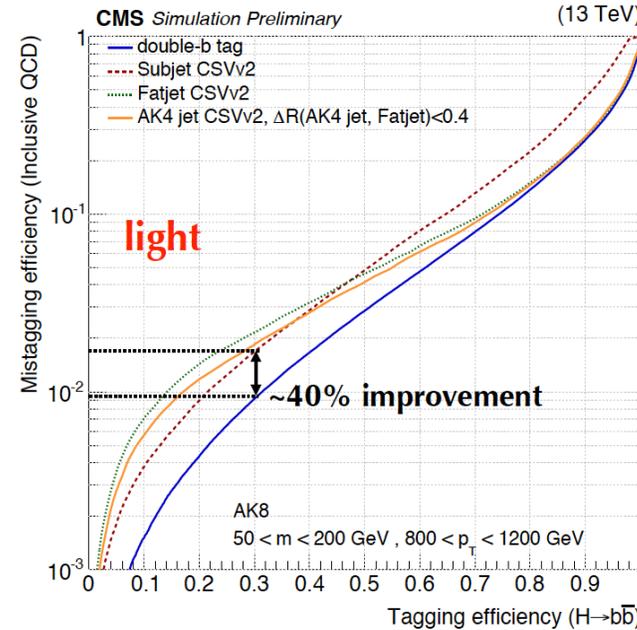
sub-jet b-tagging

- Defines sub-jets
- Standard b-tagging algorithm applied to each subjet



double-b tagger

- Identifies the two B hadron decay chains from b and \bar{b} within the same fat jet.
- It does not define sub-jet but uses N-jettiness axes



- The measured cross sections for Z+jets and Higgs for jet $p_T > 450 \text{ GeV}$ are:

$$\sigma_Z = 849 +257/-209 \text{ fb}$$

$$\sigma_H = 74 +51/-49 \text{ fb}$$

- Broken down into:

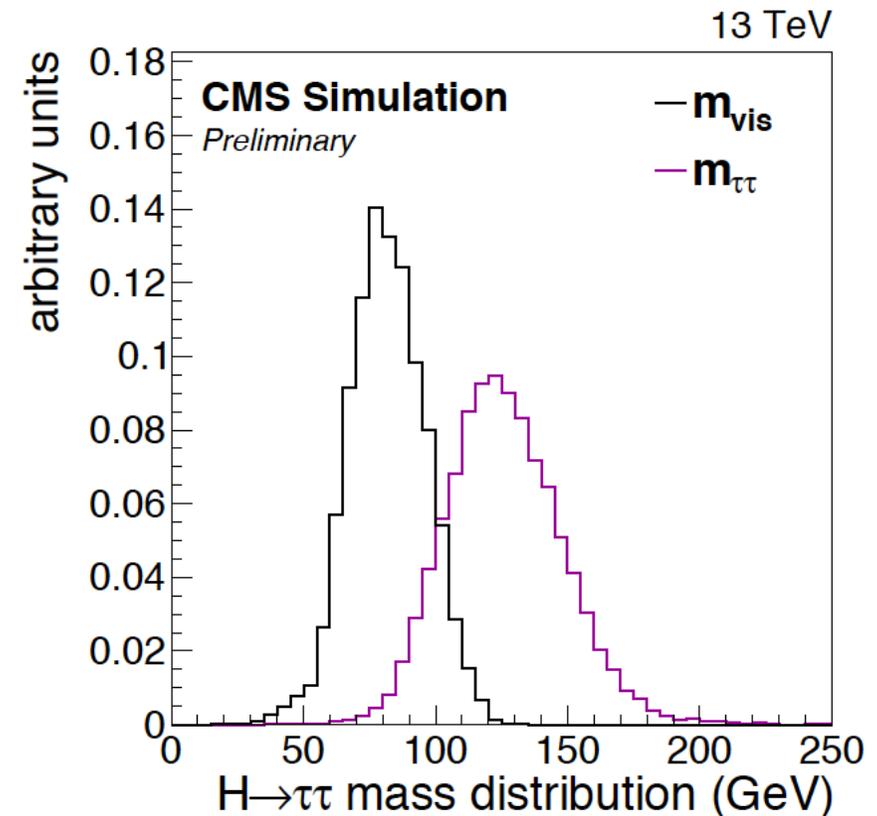
$$\sigma_Z = 849 +155/-155 \text{ (stat.)} +140/-205 \text{ (syst.)}$$

$$\sigma_H = 74 +48/-48 \text{ (stat.)} +10/-17 \text{ (syst.)}$$

H \rightarrow $\tau\tau$

- $m_{\tau\tau}$ mass reconstruction
 - dynamic likelihood algorithmで再構成
- インプット
 - $p_T(\tau_1)$, $p_T(\tau_2)$, Missing p_T , $\text{cov}(\text{MPT})$
 - Maximum Likelihood Method :
 $L = (\tau \text{ decay matrix elements, angle})^*$
(experimental resolution)

Higgs massを125 GeVに再構成可能
分解能 : 15-20%

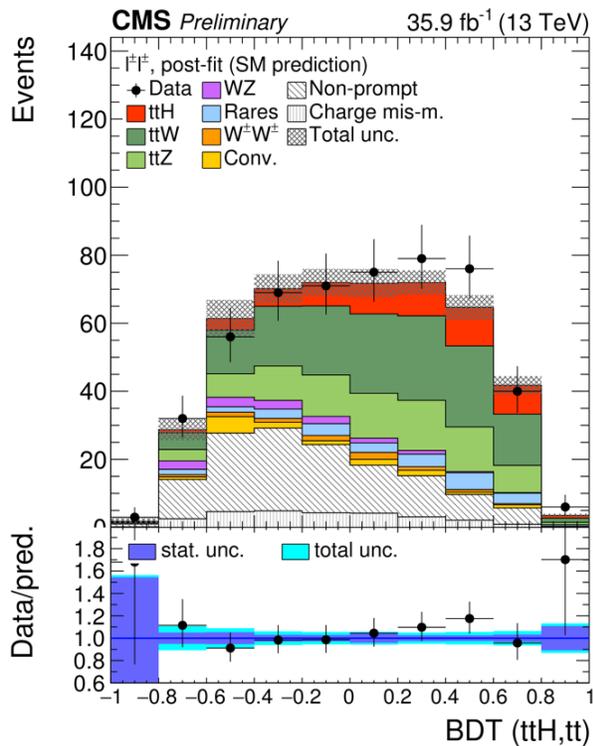


ttH Multi-lepton analysis

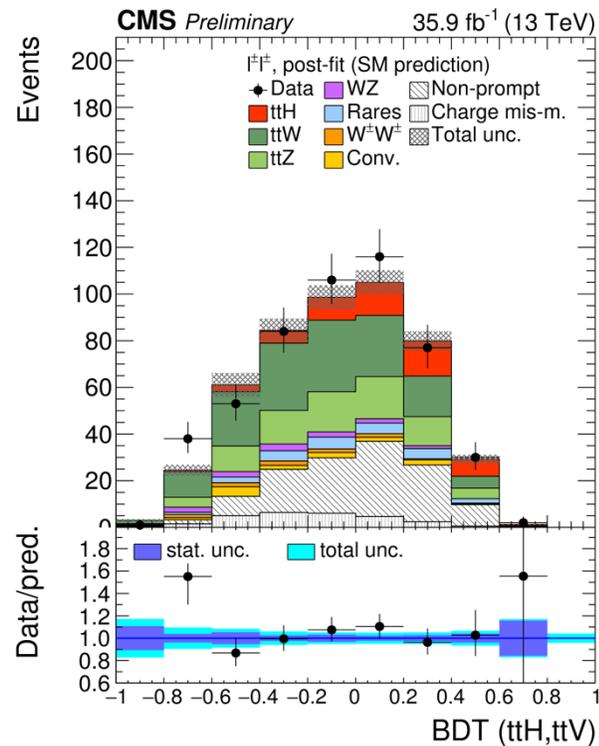
- Kinematic discrimination

2lepton SS

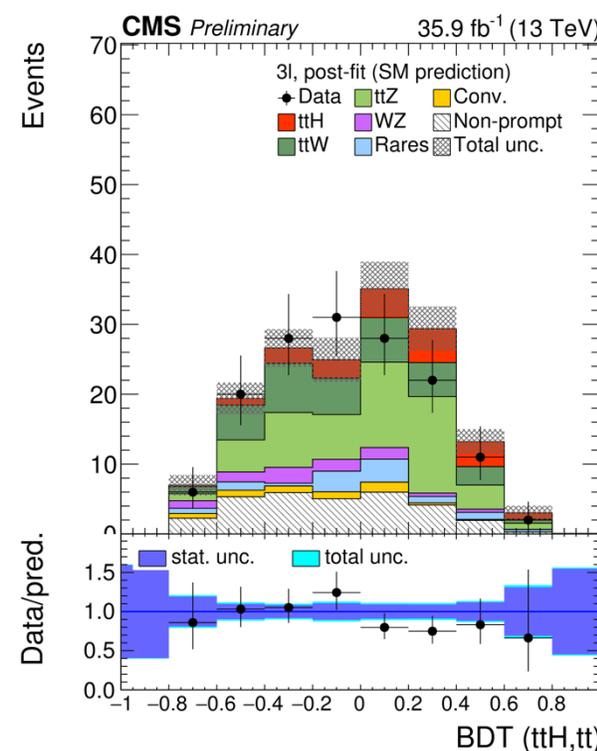
3 lepton



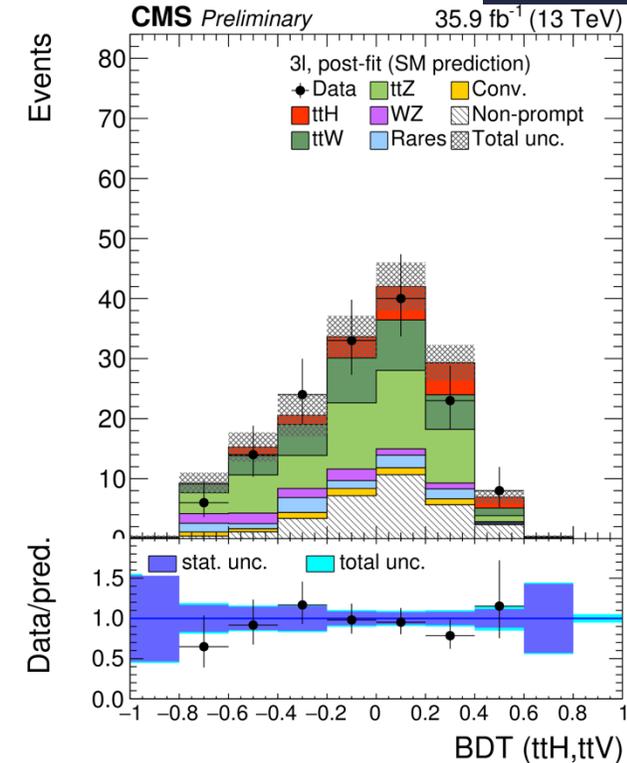
ttH vs ttbar



ttH vs ttV

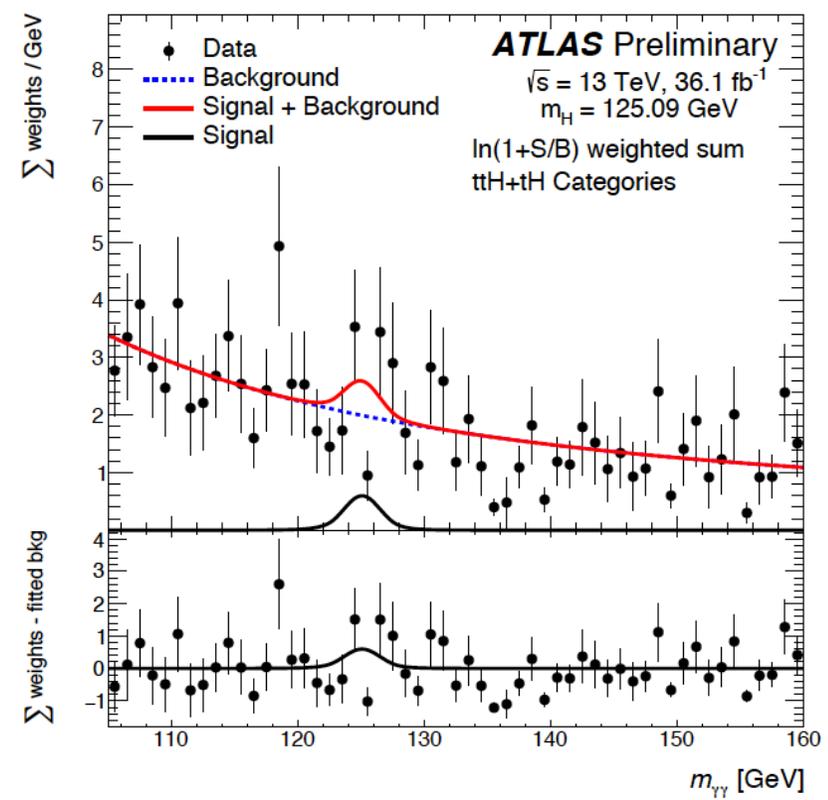
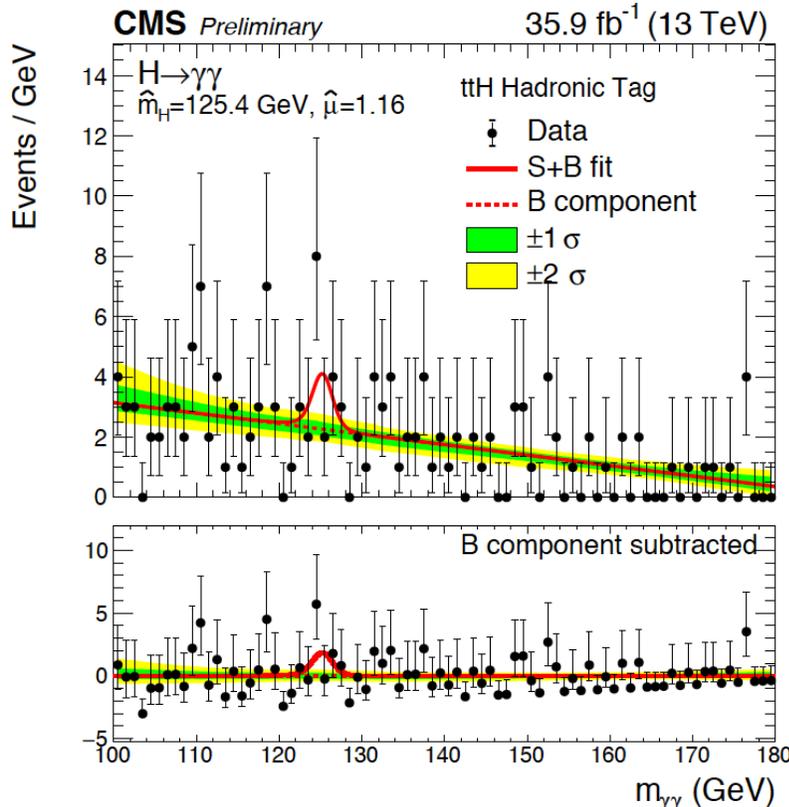
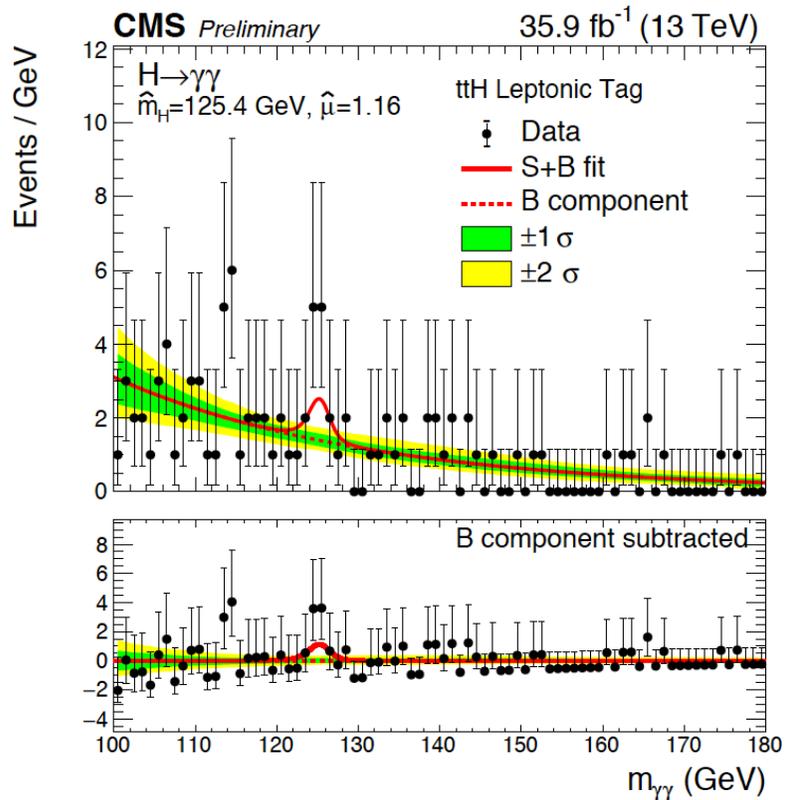


ttH vs ttbar



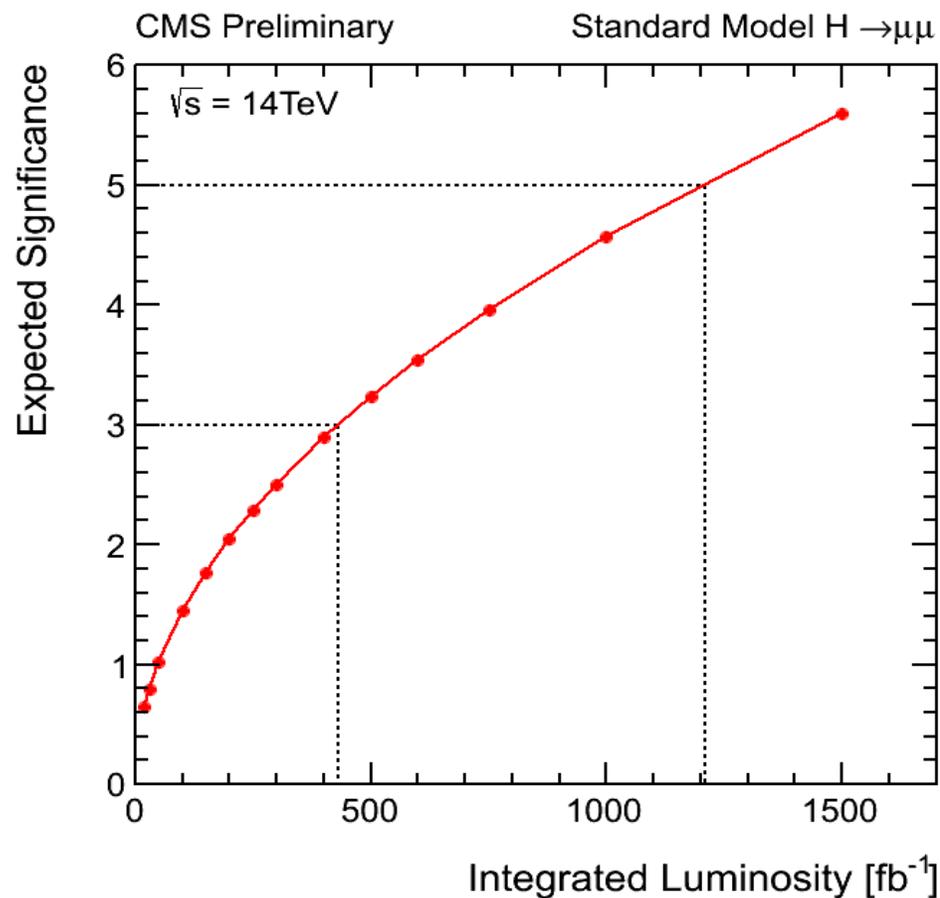
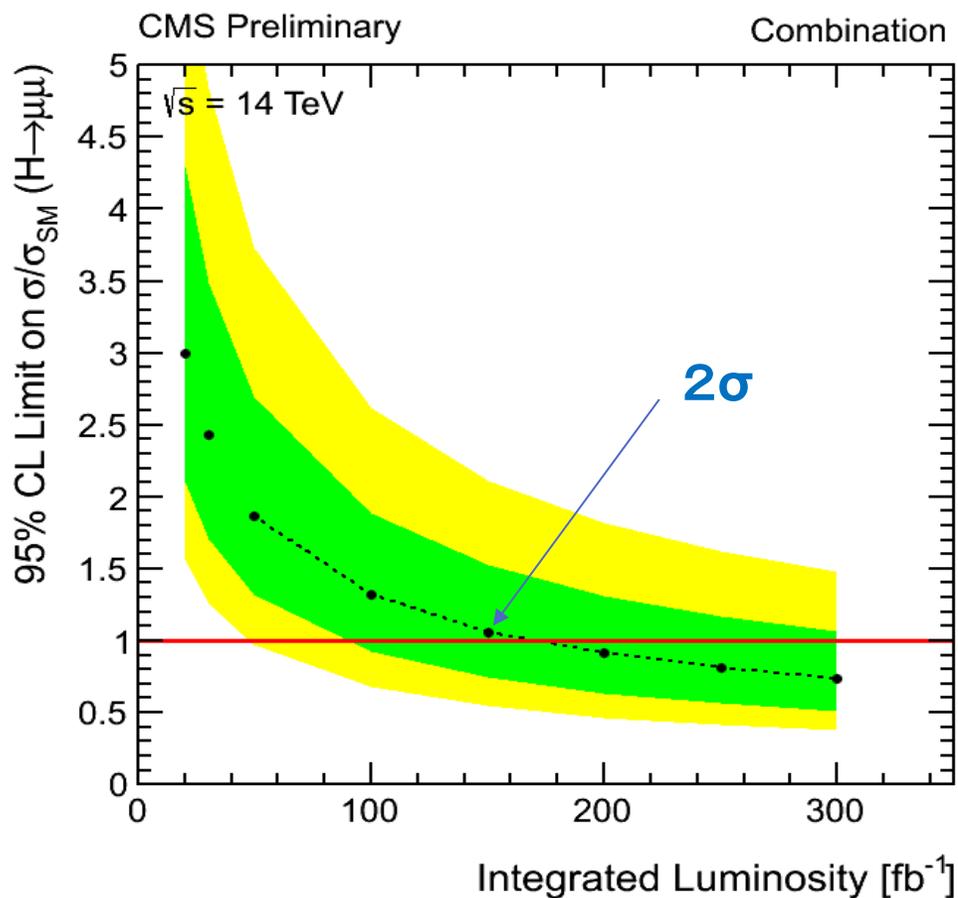
ttH vs ttV

$ttH \rightarrow \gamma\gamma$



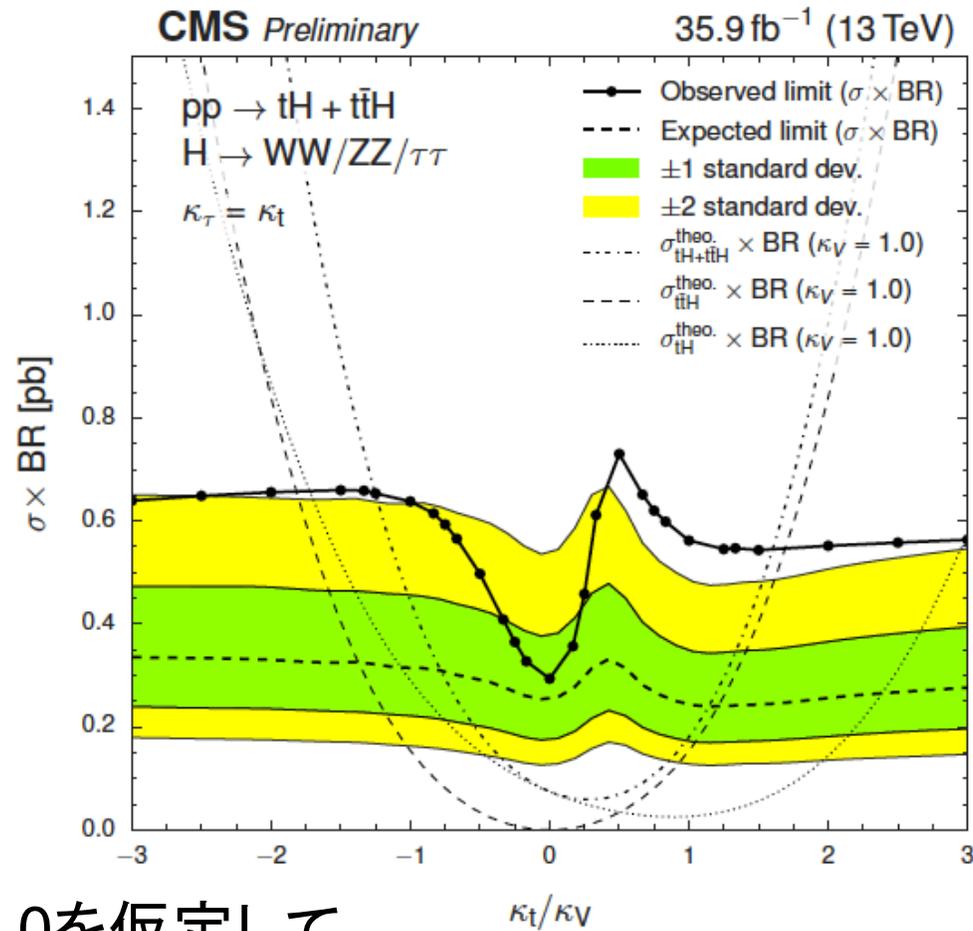
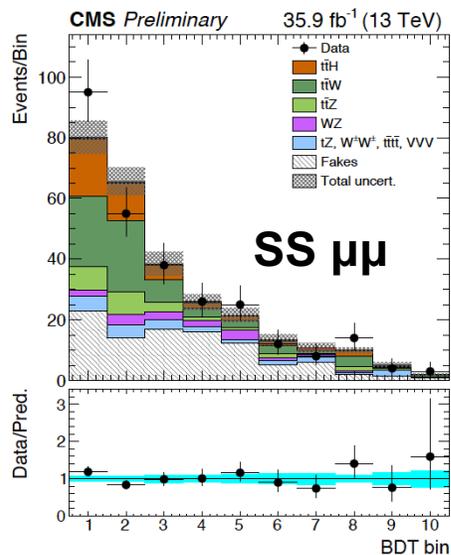
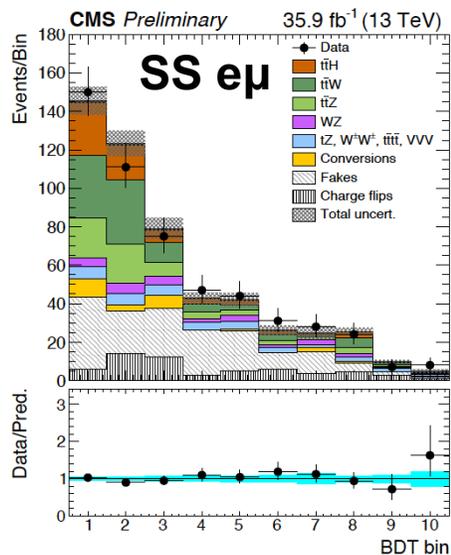
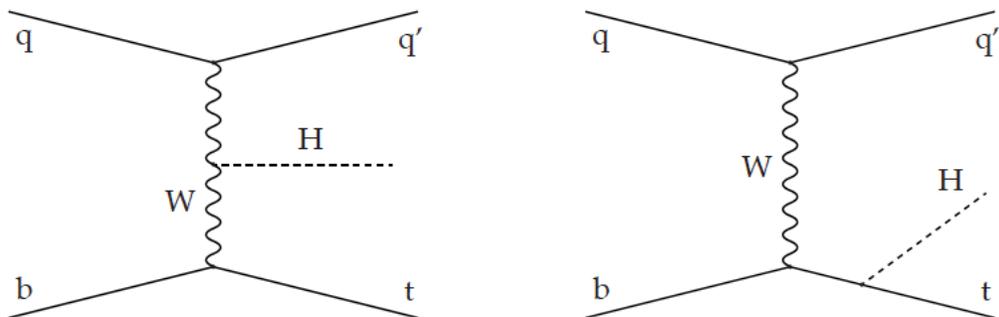
H $\rightarrow\mu\mu$ projection (CMS)

- Run3 $\sim 300\text{fb}^{-1}$ で 3σ 近くまで感度伸びる
 - 感度向上でRun3で見える可能性 (ATLAS+CMS)
- HL-LHC 1200fb^{-1} 5σ



tHq Measurement (multi-lepton analysis)

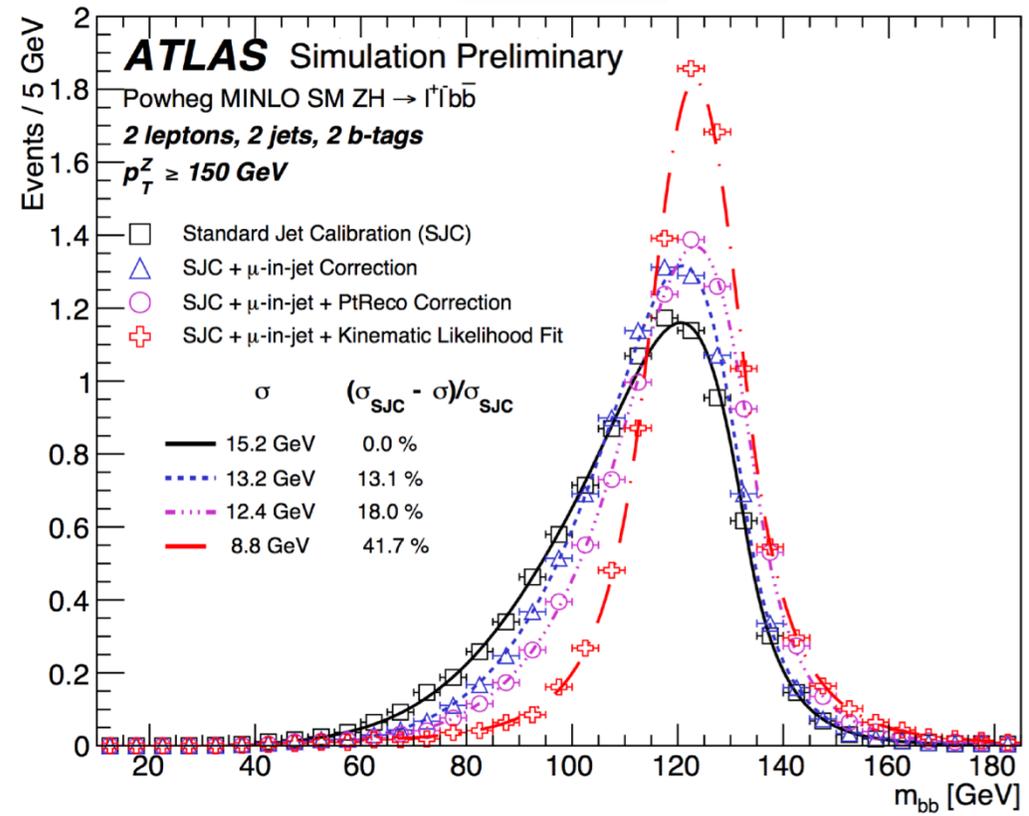
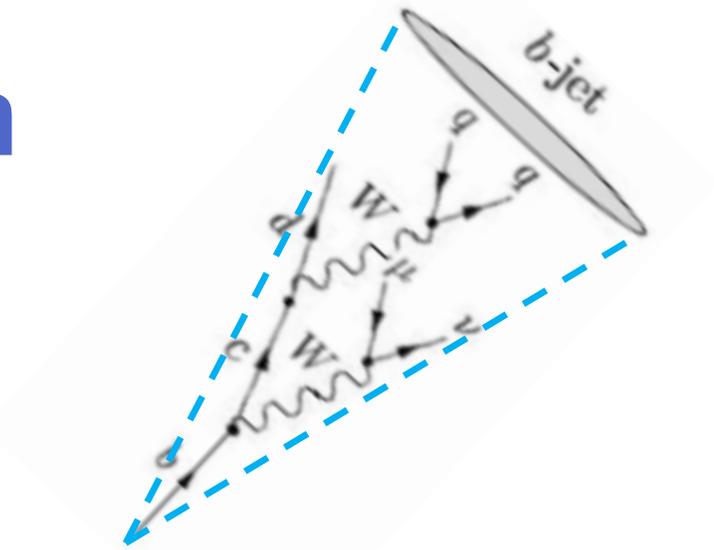
- 2つのdiagramの干渉で κ_t , κ_V の正負に感度
- $H \rightarrow WW/ZZ/\tau\tau$ のmulti-leptonを使う (SS 2lep or 3lep)



$\kappa_V=1.0$ を仮定して
 $-1.25 < \kappa_t < +1.60$ (95% CL)

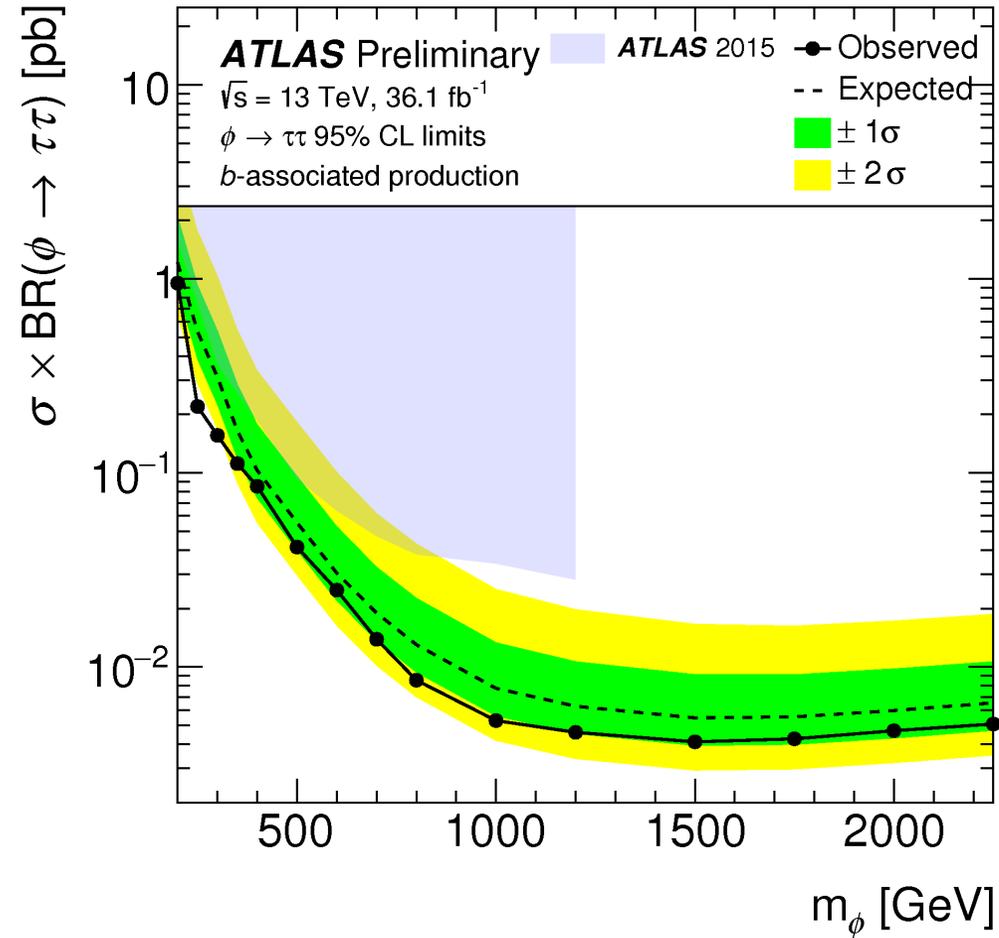
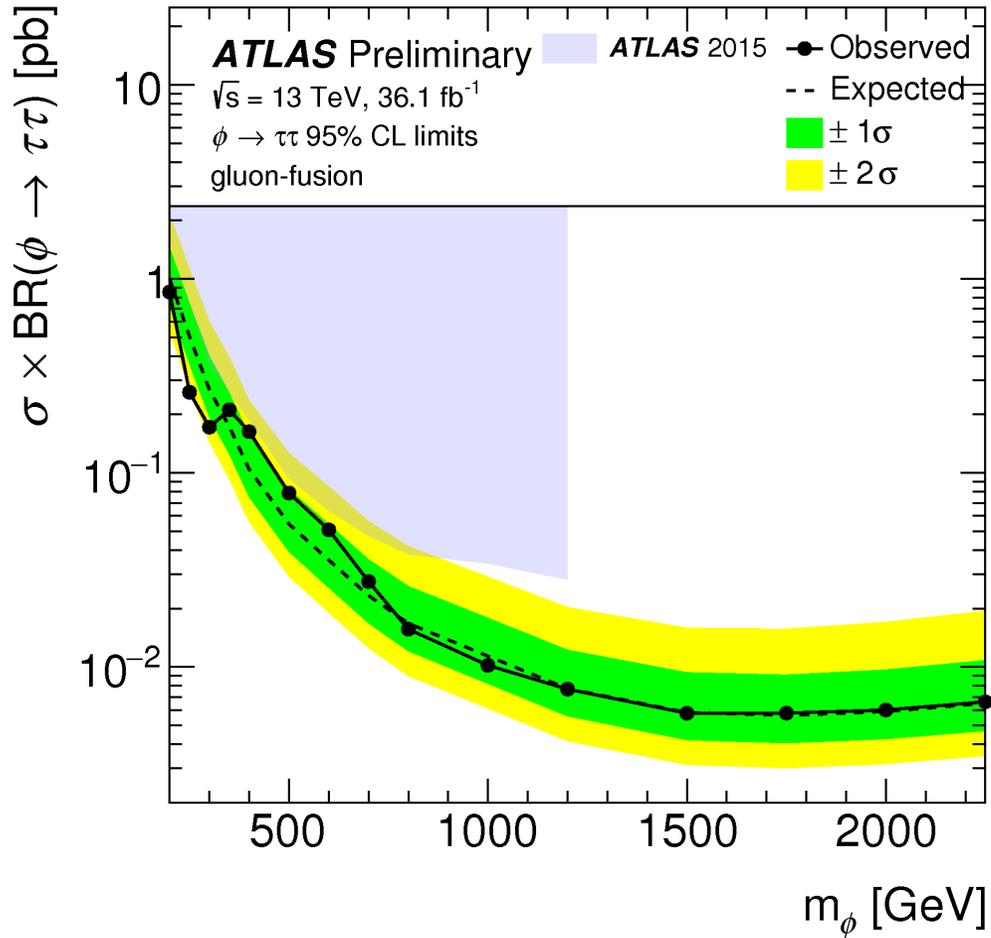
VH→bb Mass Resolution Improvement

- b-jet specific correction is important to improve m_{bb} resolution
 - Standard jet is calibrated for light jet
 - b-jet specific future (semileptonic decay) is not taken into account
- Specific correction is applied
 - Muon-in-jet correction
 - PtReco Correction (0/1 lep only)
 - Kinematic likelihood fit (2lepton only)
- Final m_{bb} resolution
 - ~10% for 0/1 lepton
 - ~7% for 2lepton



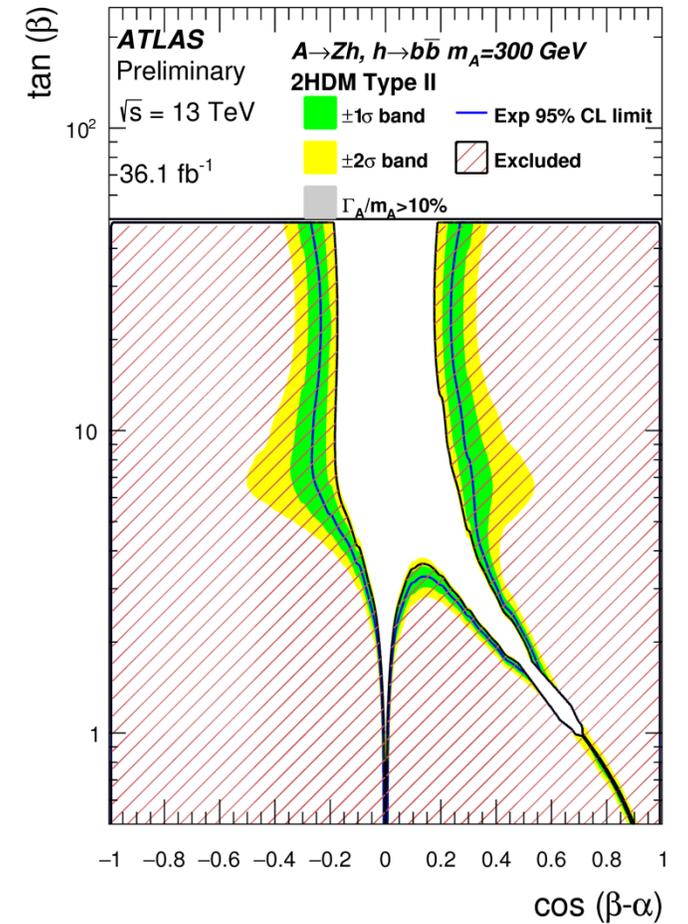
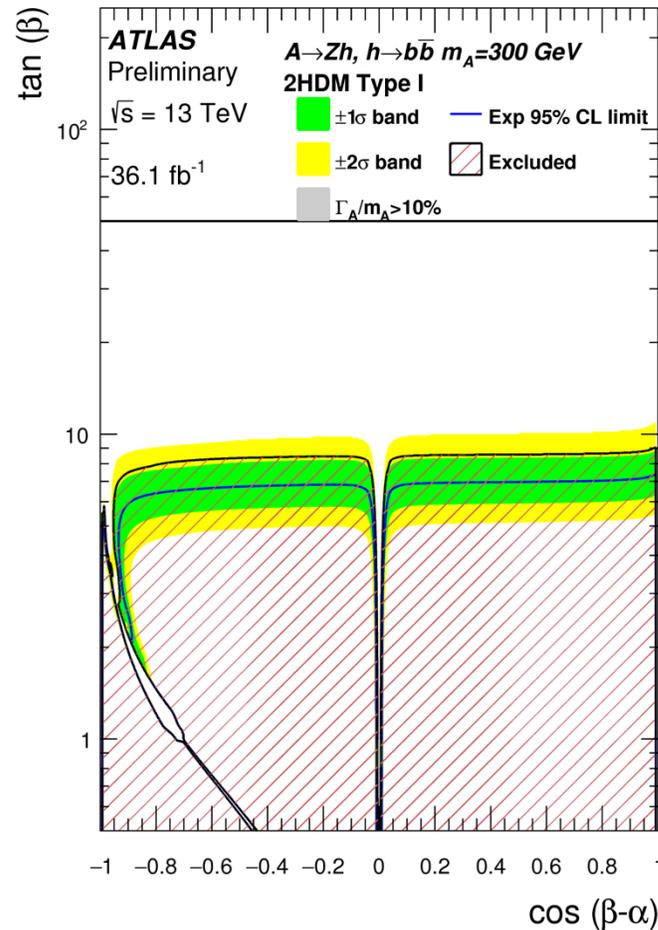
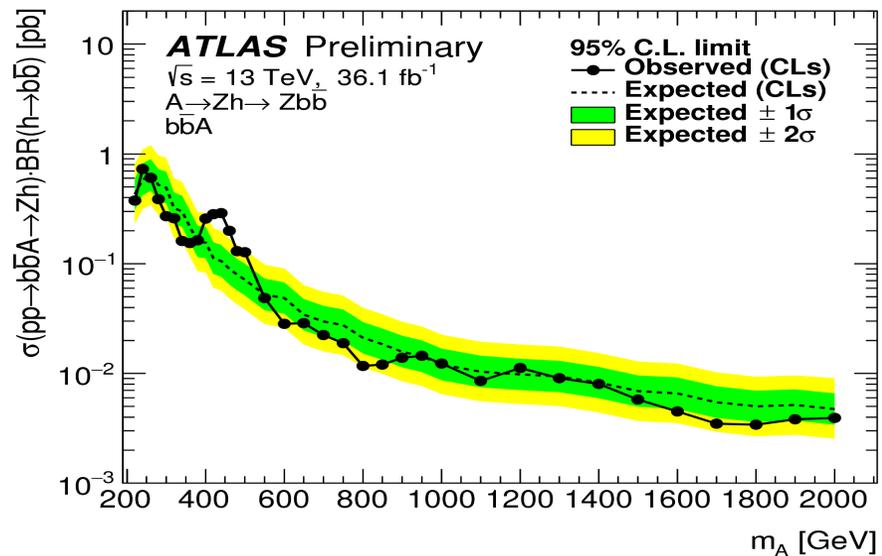
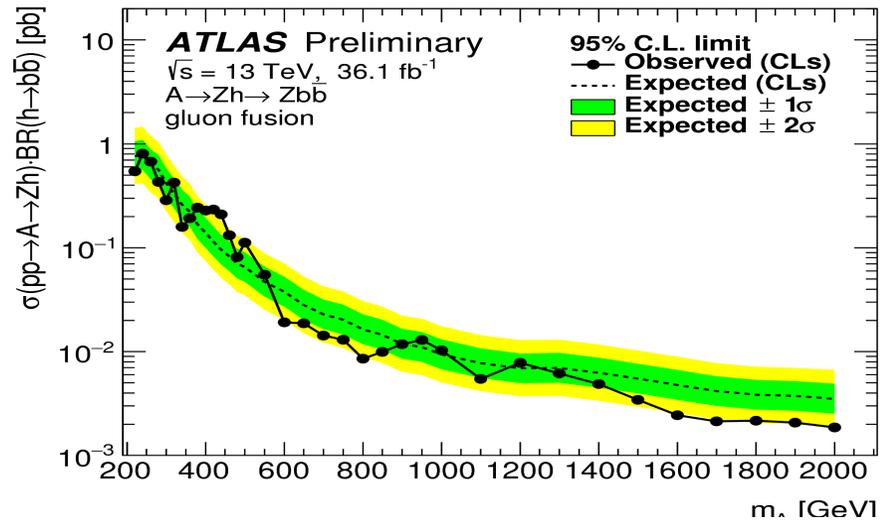
$\Phi \rightarrow \tau\tau$ BSM Search

- Model independent cross section limit



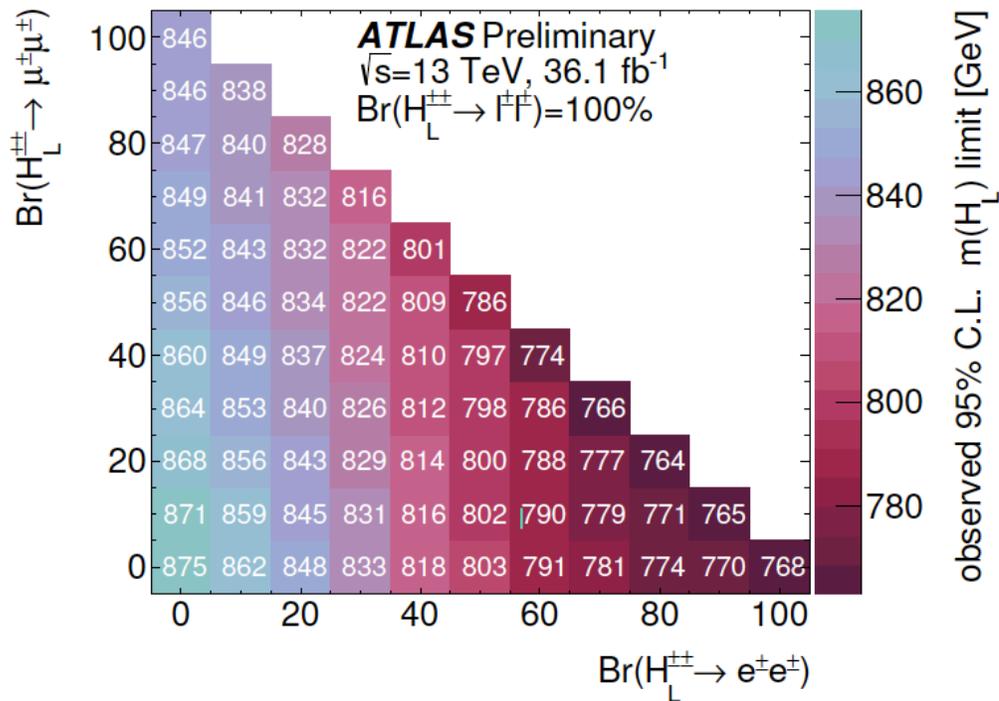
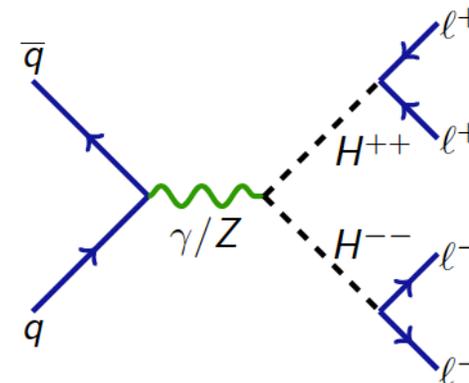
$A \rightarrow Zh(\rightarrow bb)$

- High branching ratio in low $\tan\beta$

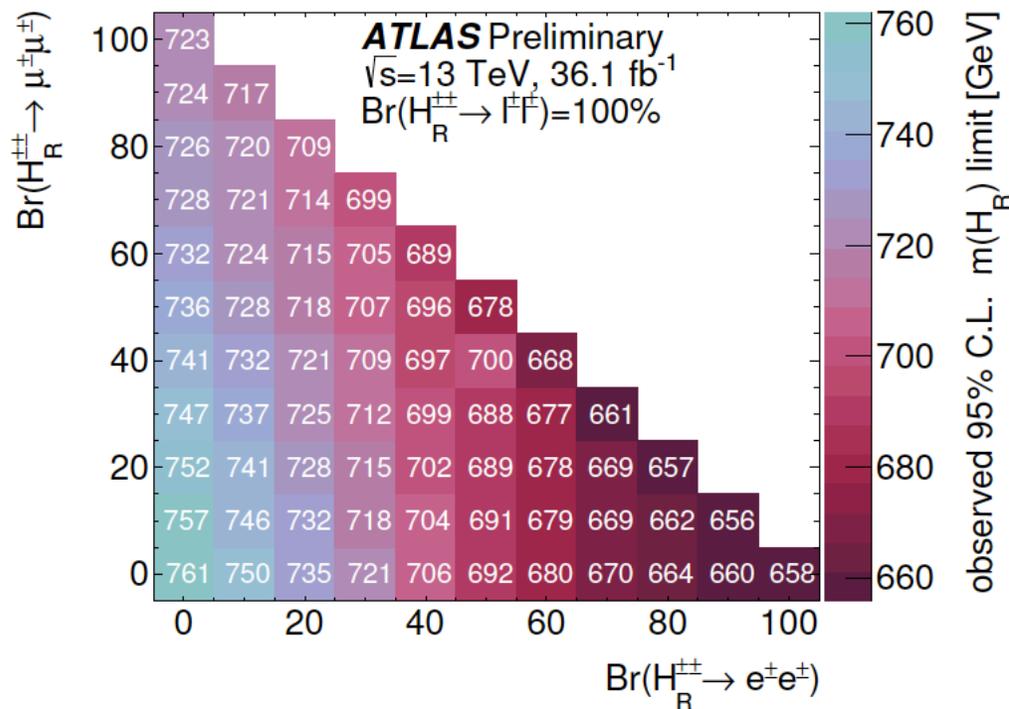


Doubly Charged Higgs

- Several BSMで予言されている (Higgs triplet, little Higgs, Type II seesaw...)
- $m(H^{++})$ 分布で信号のExcessを探索 (same-sign dilepton mass, good mass resolution)
- $BR(H^{++} \rightarrow l^\pm l^\pm) = 100\%$ として $m(H^{++}_{L/R})$ に対するリミット

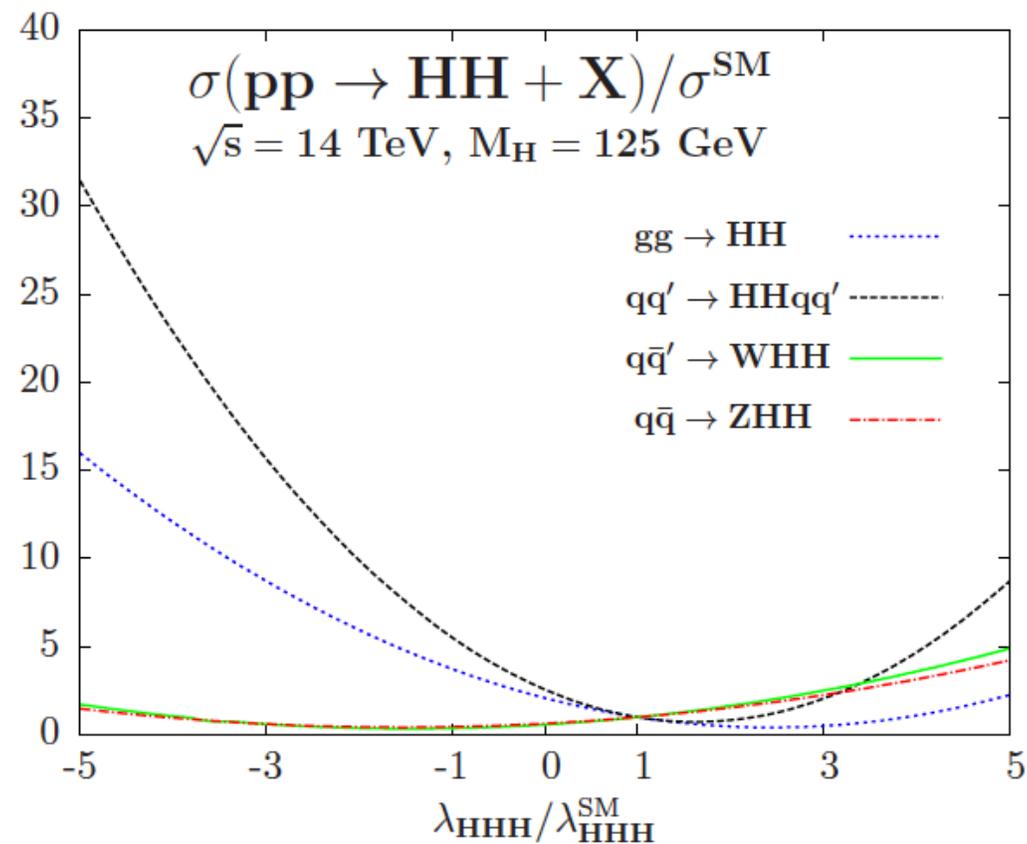
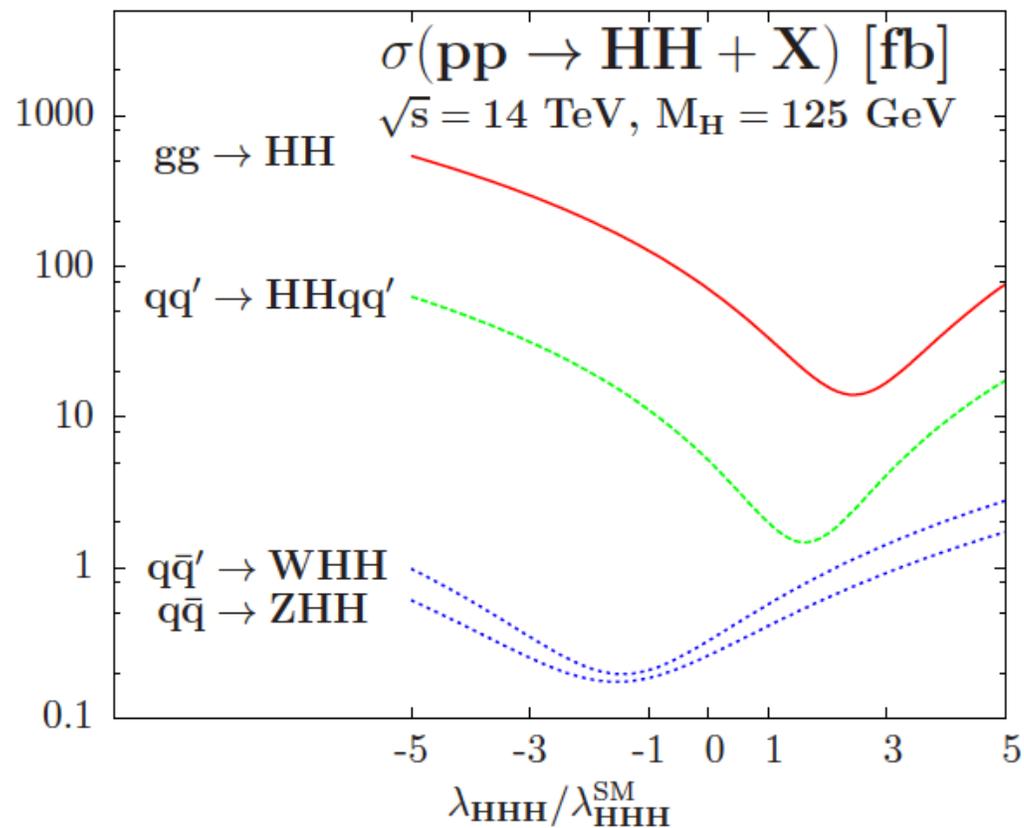


$m(H^{++}_L) > 770\text{-}875 \text{ GeV @}95\% \text{ CL}$

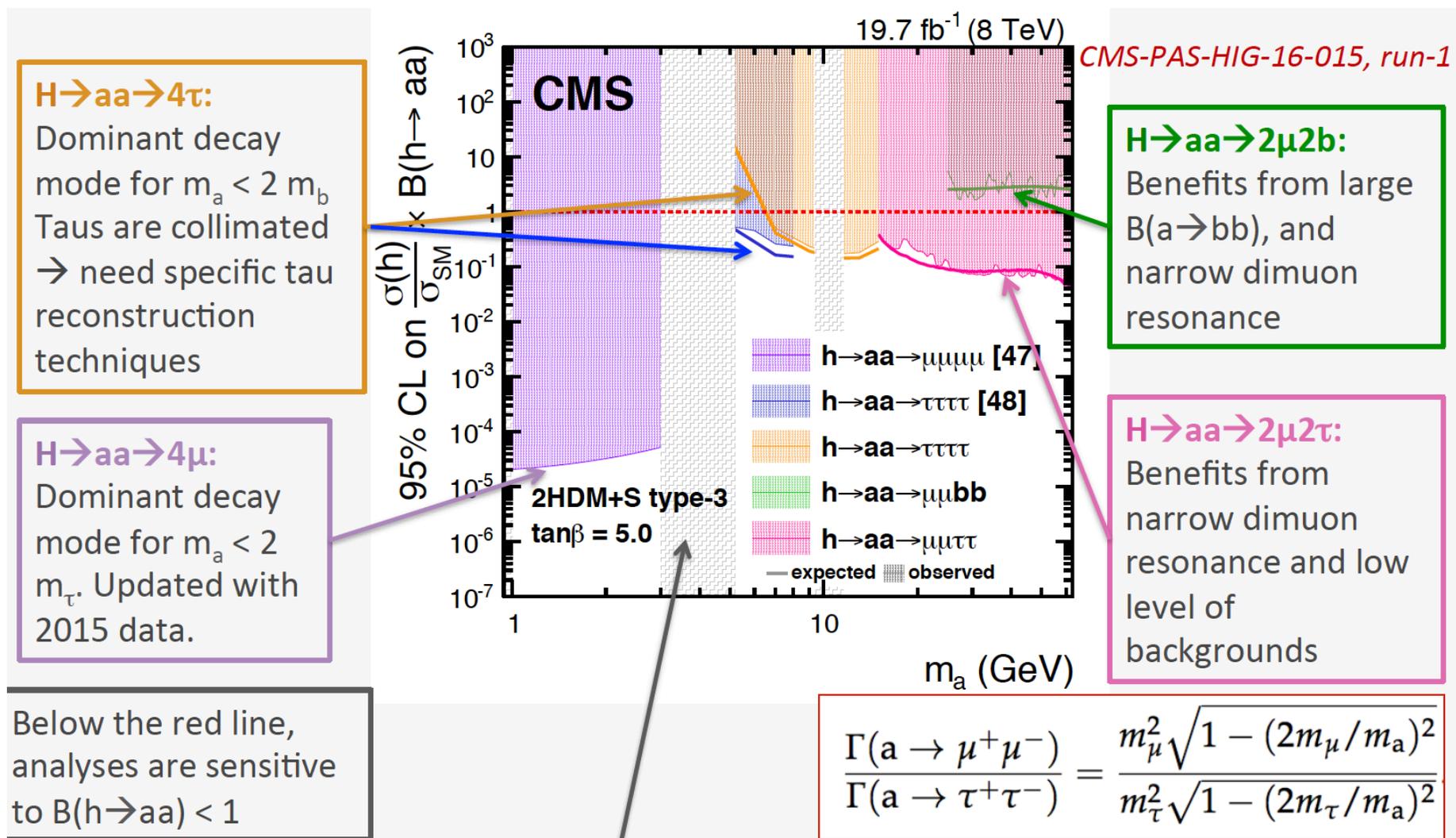


$m(H^{++}_R) > 660\text{-}760 \text{ GeV @}95\% \text{ CL}$

Di-Higgs Cross Section



NMSSM探索



$H \rightarrow aa \rightarrow 4\tau$:
 Dominant decay mode for $m_a < 2 m_b$
 Taus are collimated
 \rightarrow need specific tau reconstruction techniques

$H \rightarrow aa \rightarrow 4\mu$:
 Dominant decay mode for $m_a < 2 m_\tau$. Updated with 2015 data.

$H \rightarrow aa \rightarrow 2\mu 2b$:
 Benefits from large $B(a \rightarrow bb)$, and narrow dimuon resonance

$H \rightarrow aa \rightarrow 2\mu 2\tau$:
 Benefits from narrow dimuon resonance and low level of backgrounds

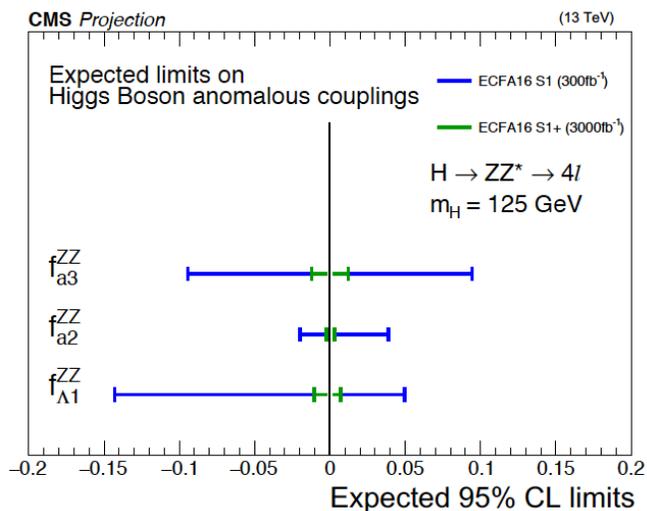
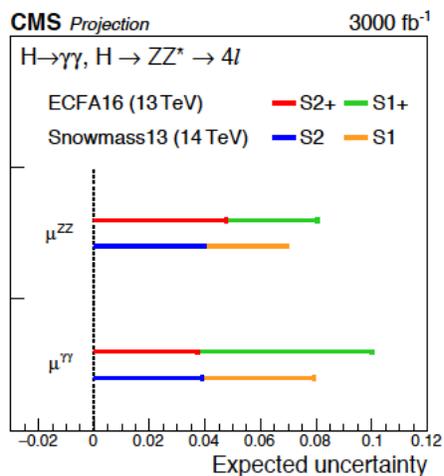
Below the red line, analyses are sensitive to $B(h \rightarrow aa) < 1$

$$\frac{\Gamma(a \rightarrow \mu^+ \mu^-)}{\Gamma(a \rightarrow \tau^+ \tau^-)} = \frac{m_\mu^2 \sqrt{1 - (2m_\mu/m_a)^2}}{m_\tau^2 \sqrt{1 - (2m_\tau/m_a)^2}}$$

In 2HDM+S type-3 with high $\tan \beta$, decays to leptons are enhanced over decays to quarks

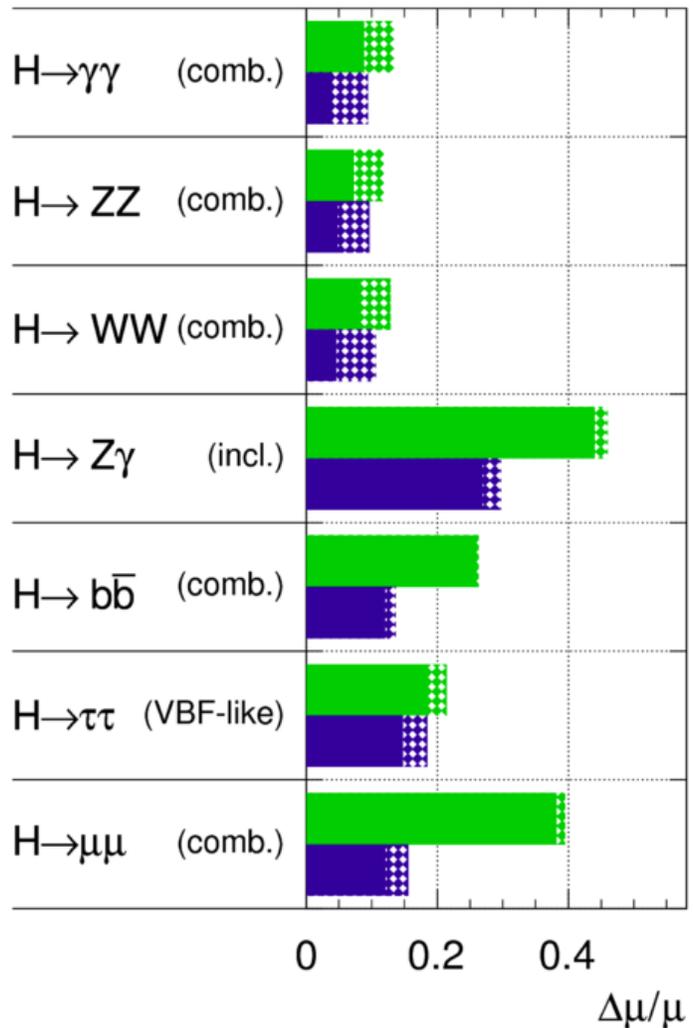
Prospect (Measurement)

- Coupling



ATLAS Simulation Preliminary

√s = 14 TeV: ∫Ldt=300 fb⁻¹ ; ∫Ldt=3000 fb⁻¹



HH Prospect

