

ヒッグス粒子研究のまとめ

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(ICEPP)

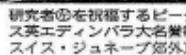
先端加速器LHCが切り拓くテラスケールの素粒子物理学
研究会@名古屋大学 東山キャンパス



【ジュネー
新粒子を発見
んばかりに
核研究機構

申の粒子

「ヒューダフ粒子」発見



益川さ

CERNでの実験概要(イメージ)
陽子と陽子を衝突させて衝突



加速器本体	古河電工	加速器の心臓部に当たる超電導導材
	I H I	超電導状態を作るのに必要な冷却装置
	J F E エスチール	超電導磁石に使う銅材



新素粒子検出 年内に結論

日米欧2千-L

ヒッグス粒子発見か

歐洲原子核機關

質量与える役割

[illegible]

ヒッグス粒子存在確定

重さの起源 新粒子を発見

國際チーム

日本

ケールの素粒子物理学

A Higgs Boson (not Higgs-“like”)

New results indicate that particle discovered at CERN is
a Higgs boson

Geneva, 14 March 2013.

At the Moriond Conference today, the ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year.

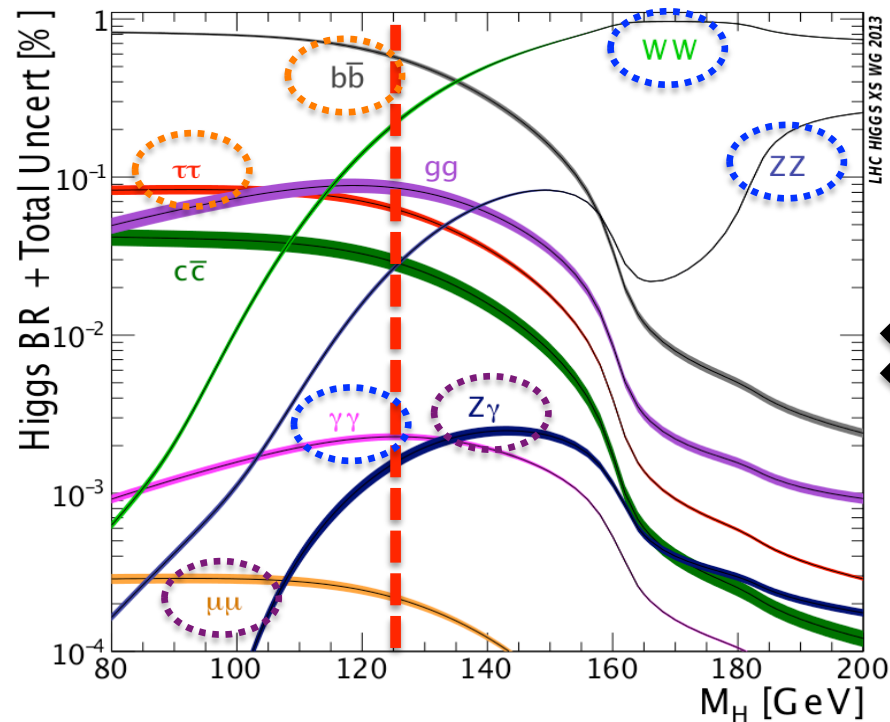
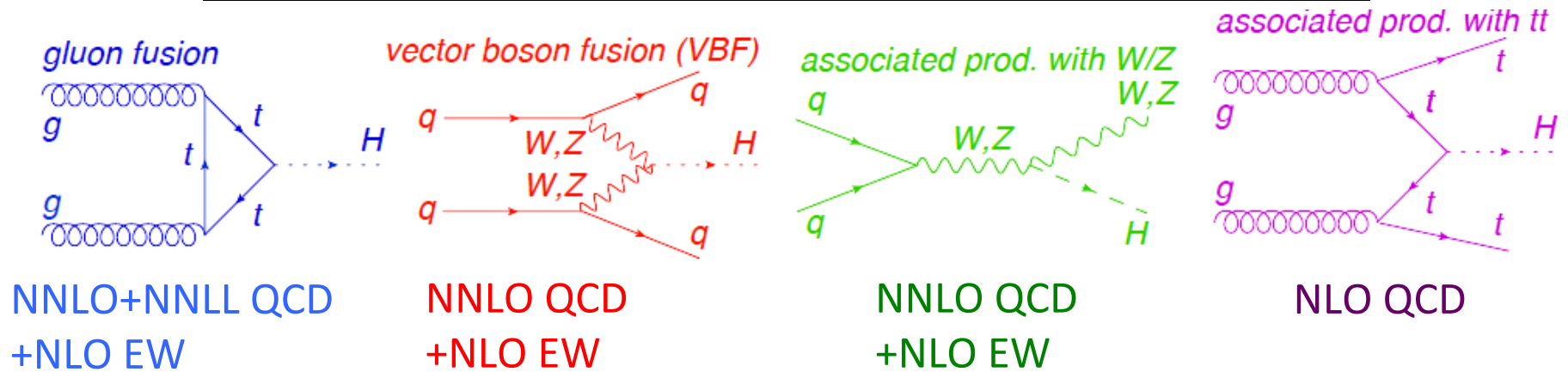
Having analysed two and a half times more data than was available for the discovery announcement in July, they find that
the new particle is looking more and more like a Higgs boson,
the particle linked to the mechanism that gives mass to elementary particles...

アウトライン

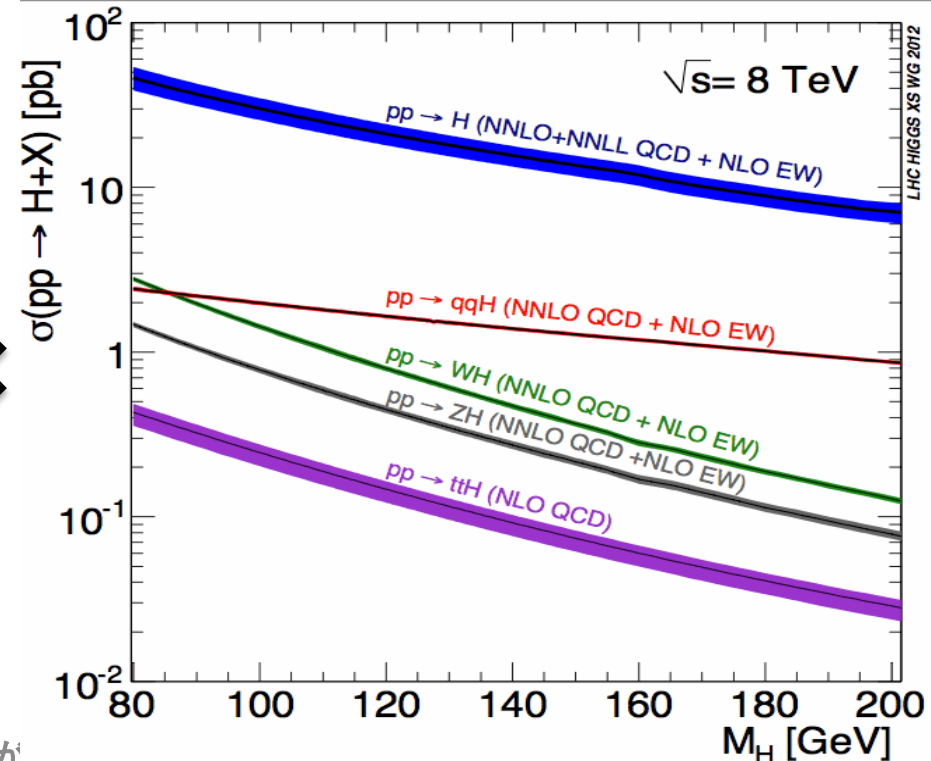
- イン트로ダクション
- 簡単に各論(ATLAS & CMS)
 - $H \rightarrow \gamma\gamma$, $ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$
 - $H \rightarrow b\bar{b}$, $H \rightarrow \tau\tau$
- ヒッグス粒子の性質測定と全体像(ATLAS & CMS)
 - 質量測定
 - カップリング測定
 - スピン/パリティ測定
- まとめ

何がどこまで測れているか？
SMとのズレは？

Higgs Production and Decay



×



簡単に各論

・現在の解析状況(ATLAS)

チャンネル	7 TeV (4.7-4.9fb ⁻¹)	8 TeV (21.0 fb ⁻¹)
H→γγ	4.9fb ⁻¹	21fb ⁻¹
H→ZZ→4l	4.8fb ⁻¹	21fb ⁻¹
H→WW→lvlv	4.7fb ⁻¹	21fb ⁻¹
H→ττ	4.7fb ⁻¹	13.0fb ⁻¹
H→bb	4.7fb ⁻¹	13.0fb ⁻¹

LHC Run I Full data!!

HCPまでのデータを解析
Full dataはL&Pに向けて鋭意
アップデート中

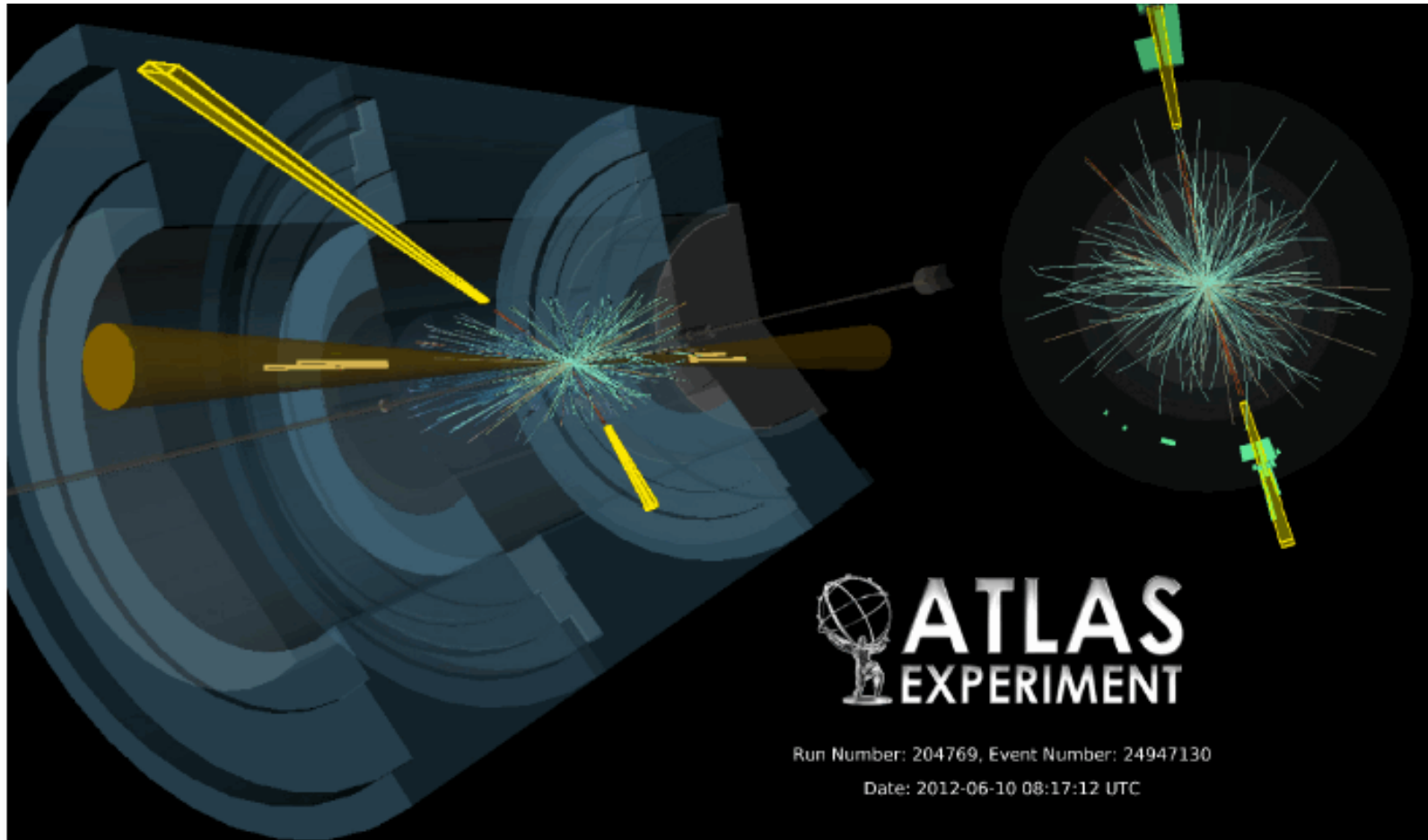
チャンネル	7 TeV (4.7-4.9fb ⁻¹)	8 TeV (21.0 fb ⁻¹)
H→Zgam	4.9fb ⁻¹	21fb ⁻¹
H→μμ	-	21fb ⁻¹
ttH→bb	4.7fb ⁻¹	-
H→invisible	4.7fb ⁻¹	13.0fb ⁻¹

比較的新しいDecay
mode, production mode
を解析し始めている

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

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG>

$$\underline{H \rightarrow \gamma\gamma}$$



VBF $H \rightarrow \gamma\gamma$ Candidate

$H \rightarrow \gamma\gamma$

• 事象選択

- di-photon trigger (99% efficiency w.r.t. offline photons)
- $E_T(\gamma 1) > 40 \text{ GeV}$, $E_T(\gamma 2) > 30 \text{ GeV}$ ($|\eta_\gamma| < 2.37$)
- Photon ID based on shower shape (NN particle ID in 7 TeV)

• カテゴリー分け(9+2+3)

lepton category(VH)

- Require 1 lepton or $60 < M_{jj} < 110 \text{ GeV}$
- High MET significance

VBF Category(VBF)

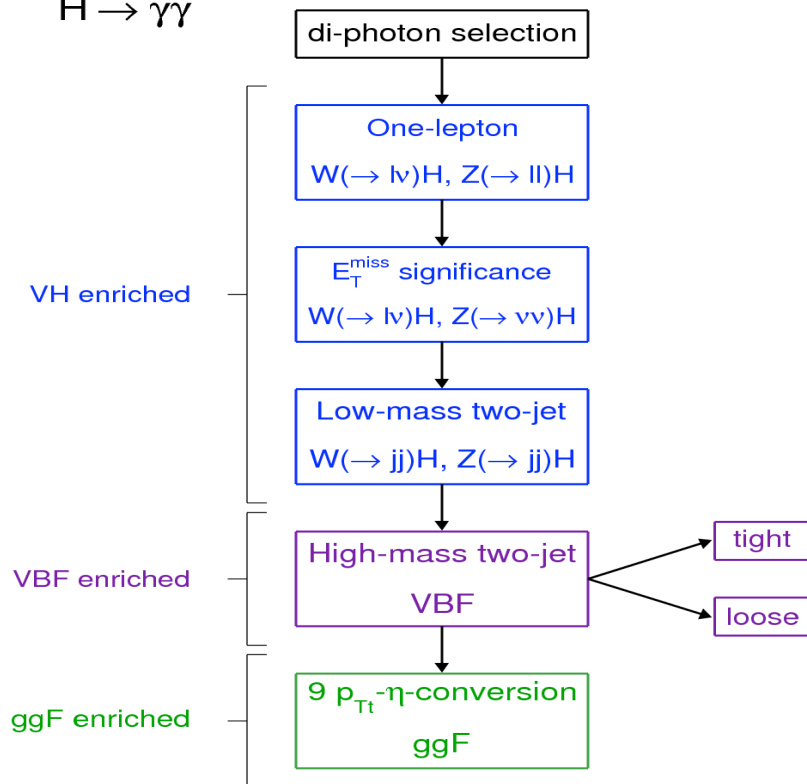
- ≥ 2 jets high M_{jj} with MVA analysis
- High BDT score, low BDT score

Other 9 categories(ggF)

- conversion or unconversion
- Photon η
- p_{Tt} (>60 or $<60 \text{ GeV}$)

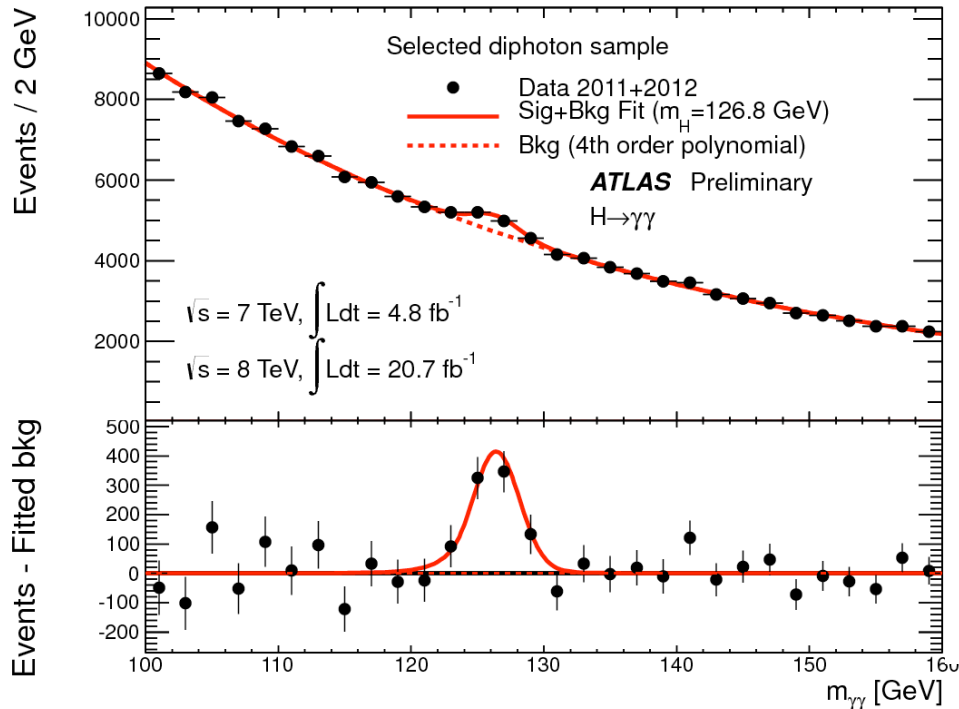
ATLAS
 $H \rightarrow \gamma\gamma$

Preliminary



$H \rightarrow \gamma\gamma$

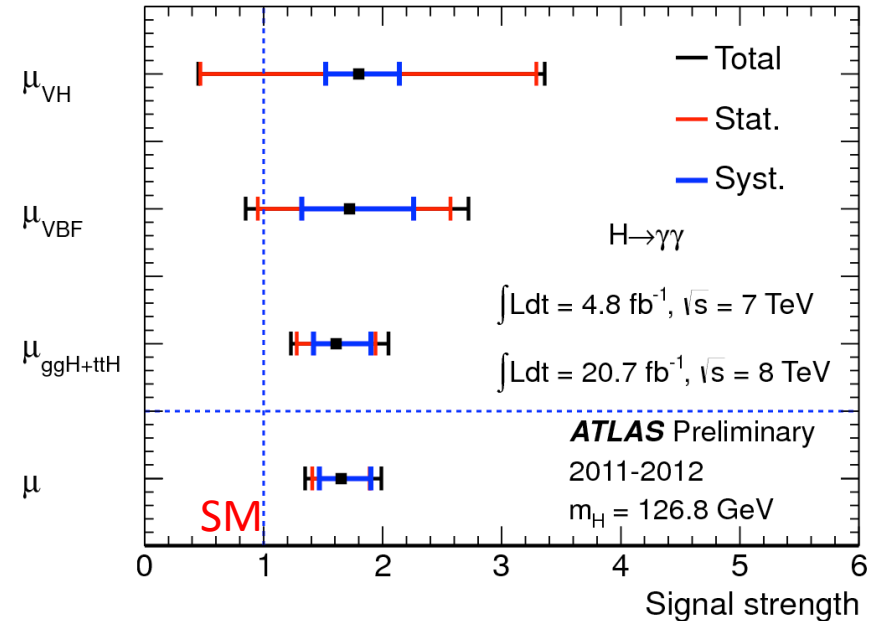
- $m_{\gamma\gamma}$ mass distribution (inclusive)
 - 23788 events (7 TeV), 118893 (8 TeV)



Local p_0 (背景事象のふらつきでデータが説明できる確率) @ 126.5 GeV

Exclusive analysis

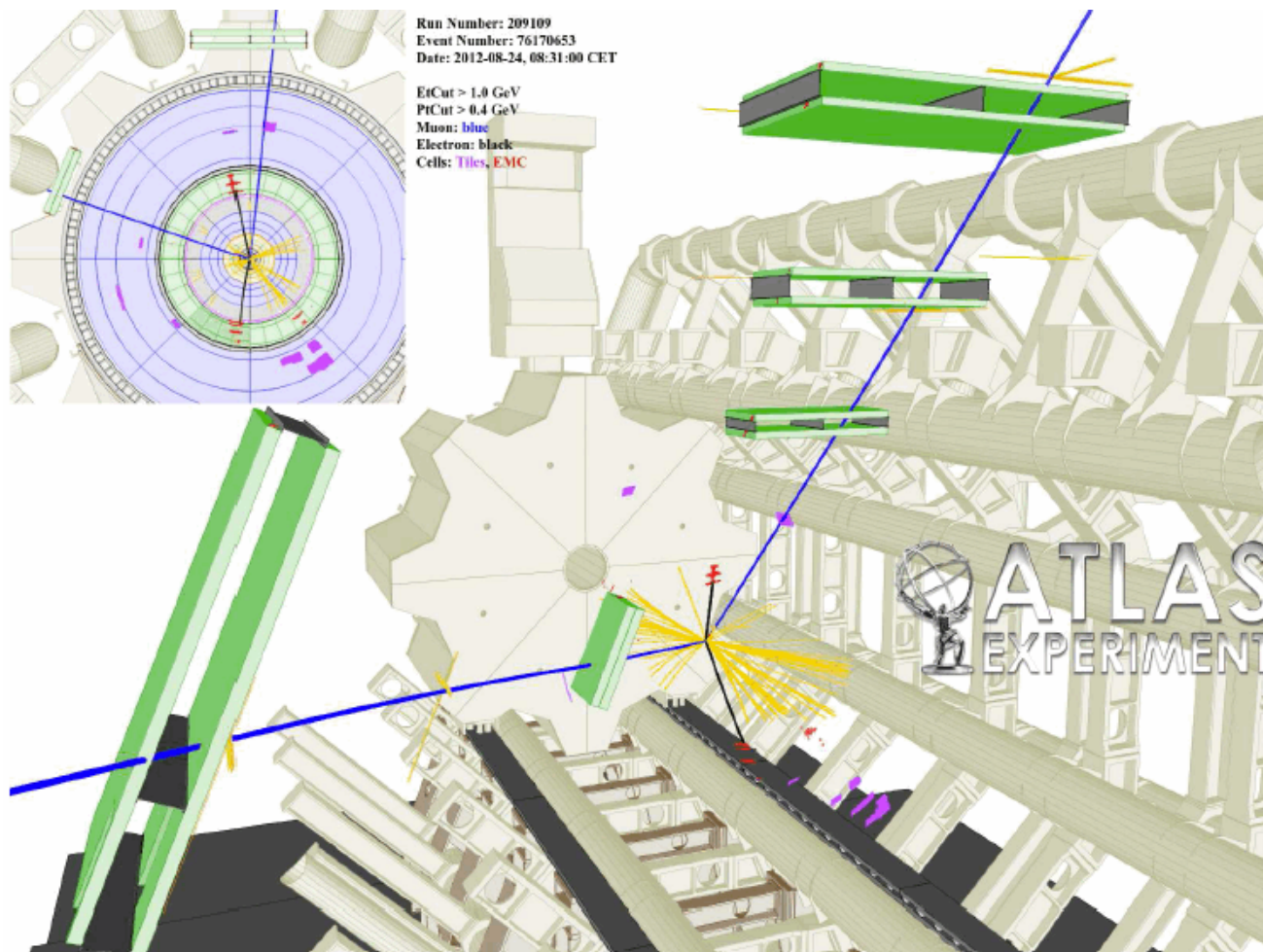
7.4 σ (Observed), 4.1 σ (Expected)



Signal strength (SM : $\mu=1$)

- $\mu_{\text{global}} : 1.65^{+0.34}_{-0.30}$ (SMから2.3 σ のズレ)
- $\mu_{\text{ggF+ttH}} * B/B_{\text{SM}} : 1.6 \pm 0.3(\text{stat.})^{+0.3}_{-0.2}(\text{sys})$
- $\mu_{\text{VBF}} * B/B_{\text{SM}} : 1.7 \pm 0.8(\text{stat.})^{+0.5}_{-0.4}(\text{sys})$
- $\mu_{\text{VH}} * B/B_{\text{SM}} : 1.8^{+1.5}_{-1.3}(\text{stat.}) \pm 0.3(\text{sys})$

$$\underline{H \rightarrow ZZ^{(*)} \rightarrow 4l}$$



**VBF 2e2μ
Candidate**

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

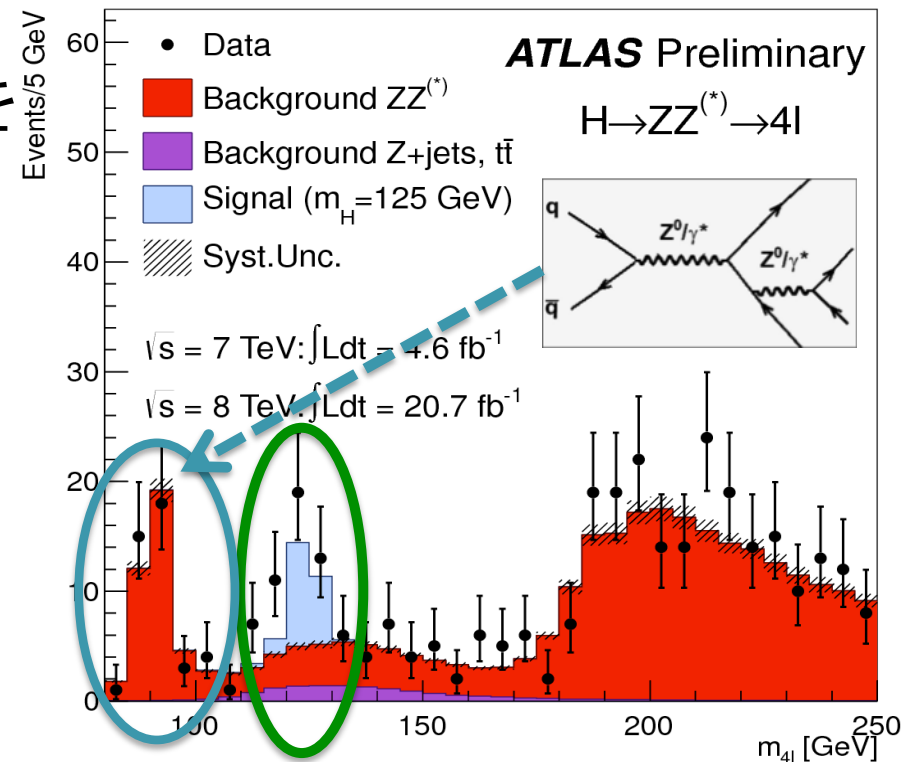
- Golden-channel
 - 終状態に4レプトン($4e, 4\mu, 2e2\mu$)を含む (Good S/B = $\sim 0.6-1.7$)
 - Narrow signal mass peak ($\Delta m_{4l} \sim 1.6-2.4$ GeV @ $m_H = 125$ GeV)
- 事象選択
 - 4 isolated lepton ($p_T > 20$ GeV, 15 GeV, 10 GeV, 7(e) or 6(μ) GeV)
 - 2 same-flavor and opposite-sign lepton pairs
 $50 < m_{12} < 106$ GeV, $m_{\min} < m_{34} < 115$ GeV ($m_{\min}$ は m_{4l} に依存して最適化
 e.g. $m_{\min} = 12$ GeV at $m_{4l} = 125$ GeV)
 - selection efficiency ($m_H = 125$ GeV) : 39% for 4μ , 26% for $2e2\mu/2\mu2e$, 19% for $4e$
 - Categorization : $\Delta\eta_{jj} > 3.0$, $M_{jj} > 350$ (VBF category)
 Additional 1 lepton with $p_T > 8$ GeV (VH category)
- 背景事象
 - continuum ZZ (MCから評価)
 - Z+jets, $t\bar{t}$ (MCとdataを用いて評価)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

- m_{4l} 分布 (7TeV+8TeV)
 - 125GeV付近にデータの超過を観測
 - 高い質量領域はSM ZZ背景事象と良い一致
 - Local p_0 at 124.3 GeV
- 7+8 TeV : **6.6 σ** (exp. 4.4 σ)

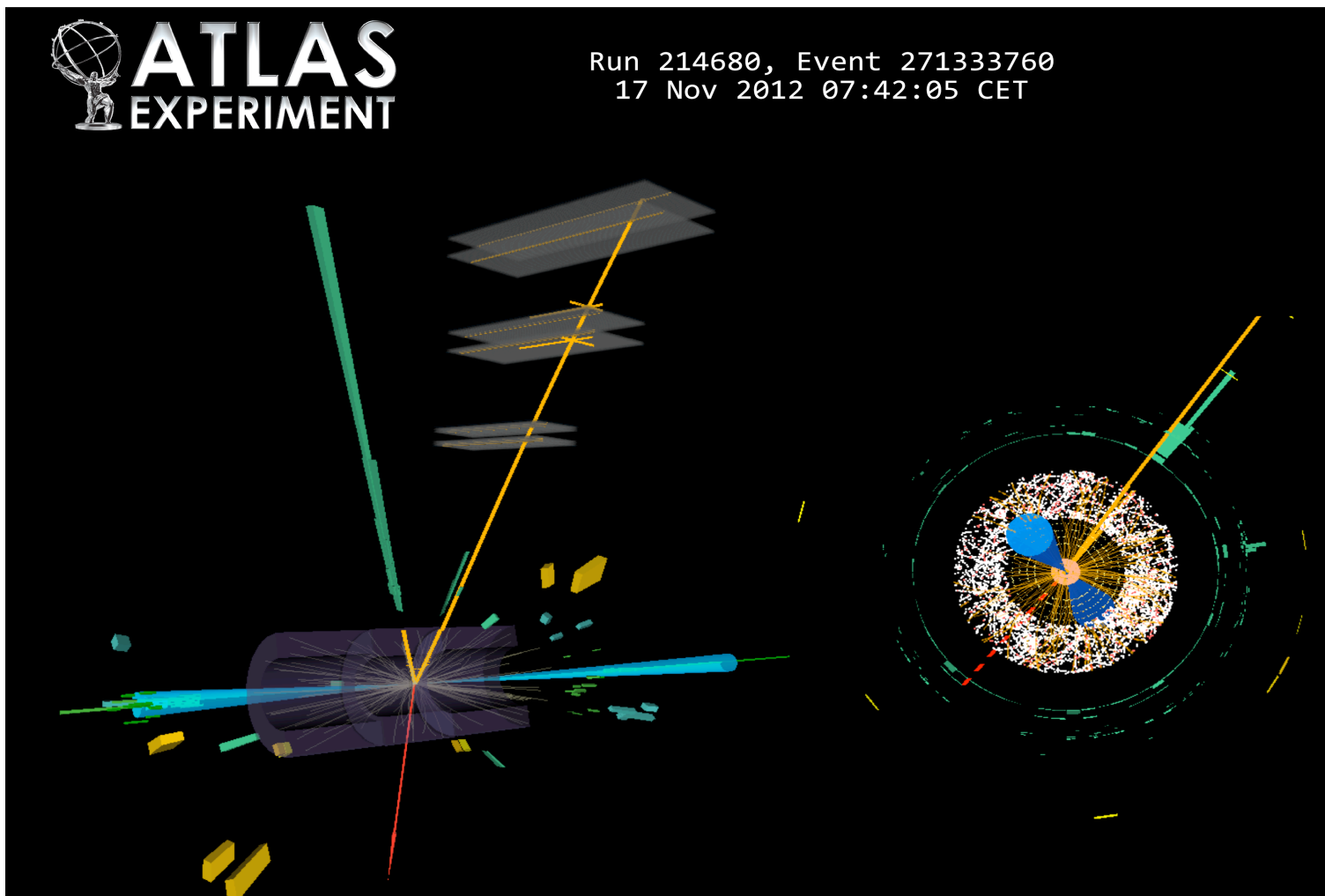
signal strength

$$\mu = 1.7^{+0.5}_{-0.4} @ 124.3 \text{ GeV}$$



$120 < m_{4l} < 130 \text{ GeV}$	Signal (125 GeV)	ZZ	Z+jets, $t\bar{t}$	Signal+Bkg	Observed
4 μ	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	9.6 ± 1.0	13
2 μ 2e	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	6.0 ± 0.8	5
2e2 μ	4.0 ± 0.5	2.1 ± 0.1	1.55 ± 0.17	6.6 ± 0.8	8
4e	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	4.9 ± 0.8	6

$$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$$

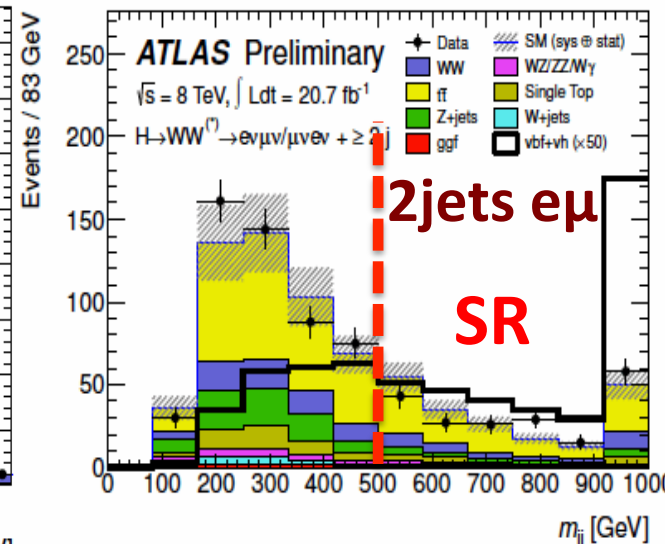
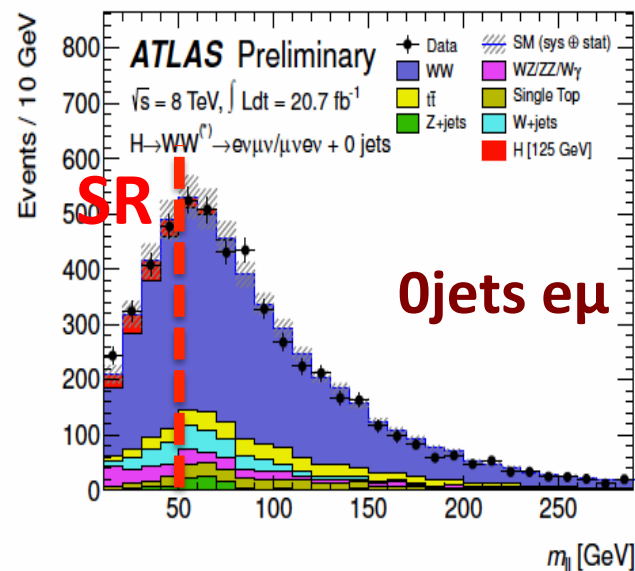
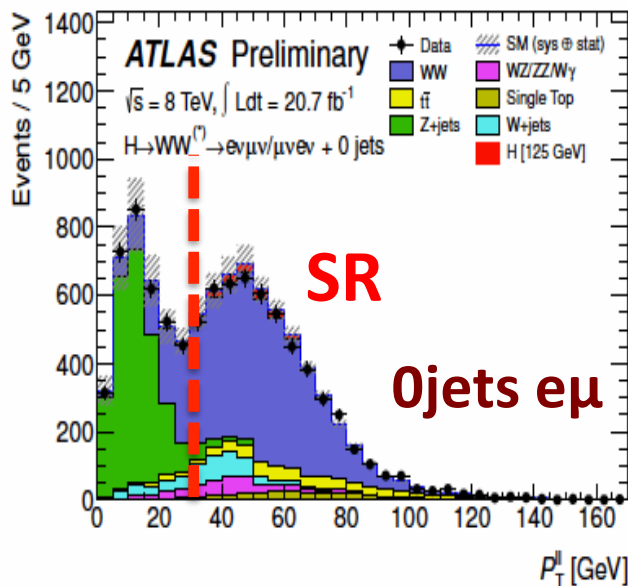
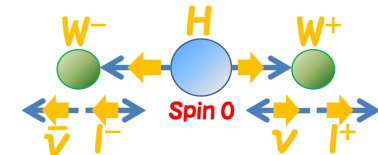


VBF Candidate ($e\mu$ +MET+ forward jets)

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

- 2 leptons+high MET+jets(ggF for 0/1j, VBF for 2j)
 - 終状態に2つのニュートリノを含むため質量再構成が困難
 $\Delta m(\gamma\gamma, ZZ \rightarrow 4l) \sim 1\text{-}2\text{ GeV}$, $\Delta m(WW) \sim 20\text{ GeV}$
→ 背景事象と区別が付きにくい
 - それぞれのカテゴリで最適な事象選択を行っている
- 主な背景事象
WW, W+jets, Z+jets, top, non-WW diboson
- Z+jets rejection, top rejection (1,2jets), WW rejection

	0jet	1jet	>=2jets
ee-ch	○	○	○
$\mu\mu$ -ch	○	○	○
$e\mu, \mu e$ -ch	○	○	○

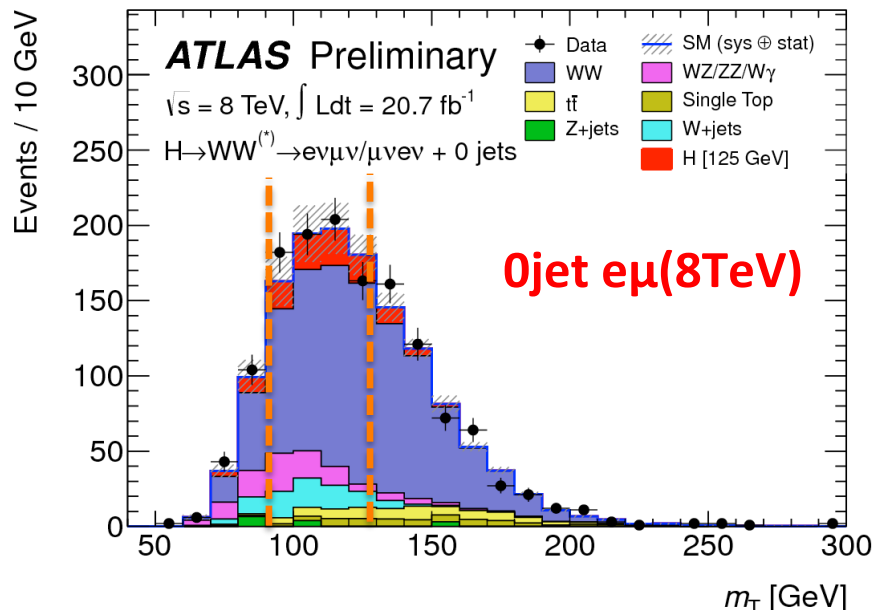


$H \rightarrow WW \rightarrow l\nu l\nu$

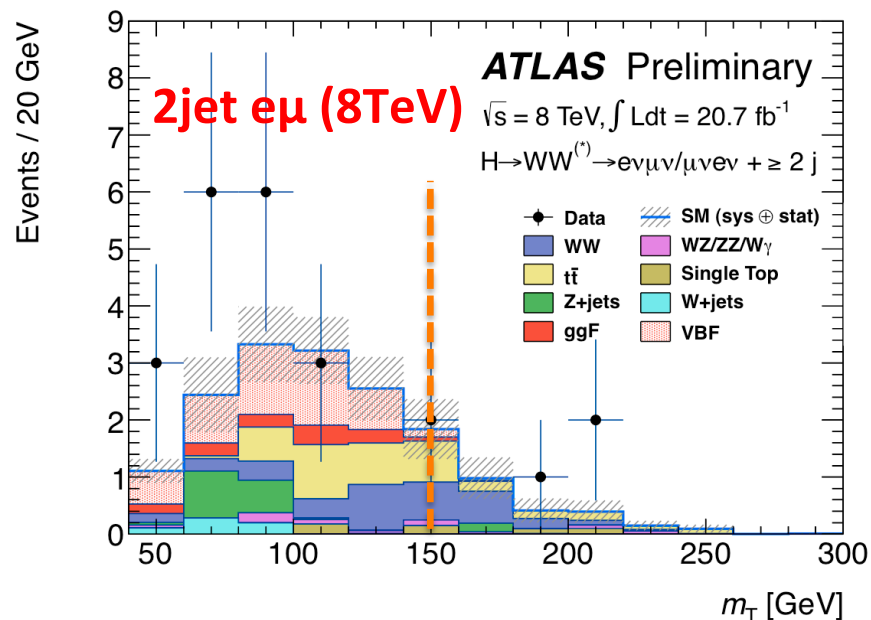
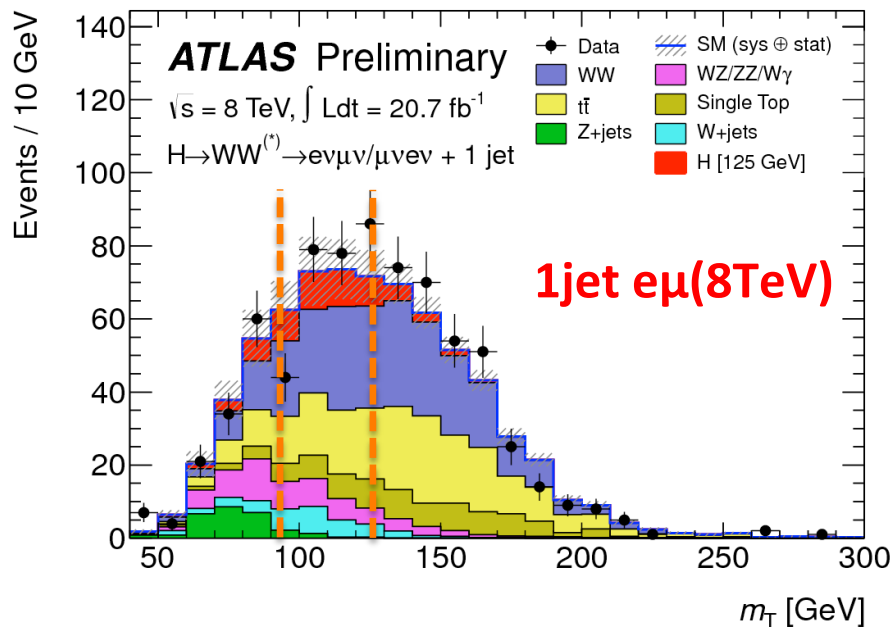
$$E_T^{ll} = \sqrt{(P_T^{ll})^2 + m_{ll}^2}$$

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (\mathbf{P}_T^{ll} + \mathbf{E}_T^{miss})^2}$$

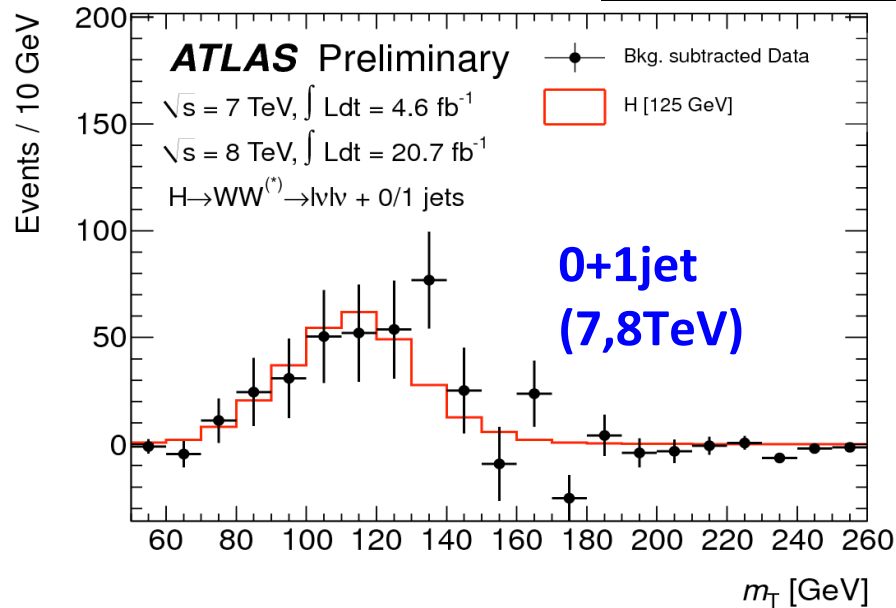
- m_T 分布 fit から最終結果を計算
- 信号領域で超過が観測



Njet(ee+μμ+eμ)	Nobs	Nbkg	Nsig
0jet	831	739±39	97±20
1jet	309	261±28	40±13
≥2jets	55	36±4	10.6±1.4



$H \rightarrow WW \rightarrow l\nu l\nu$

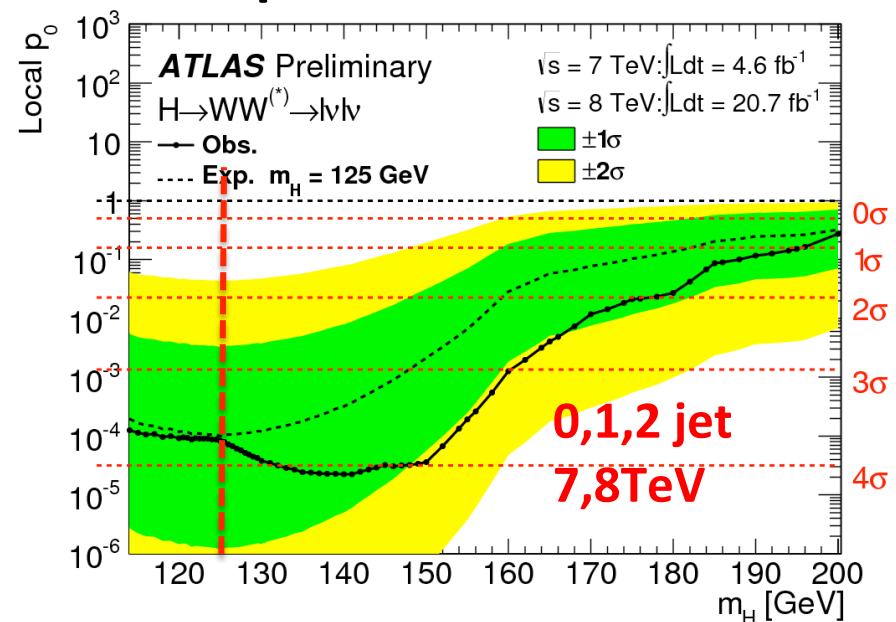
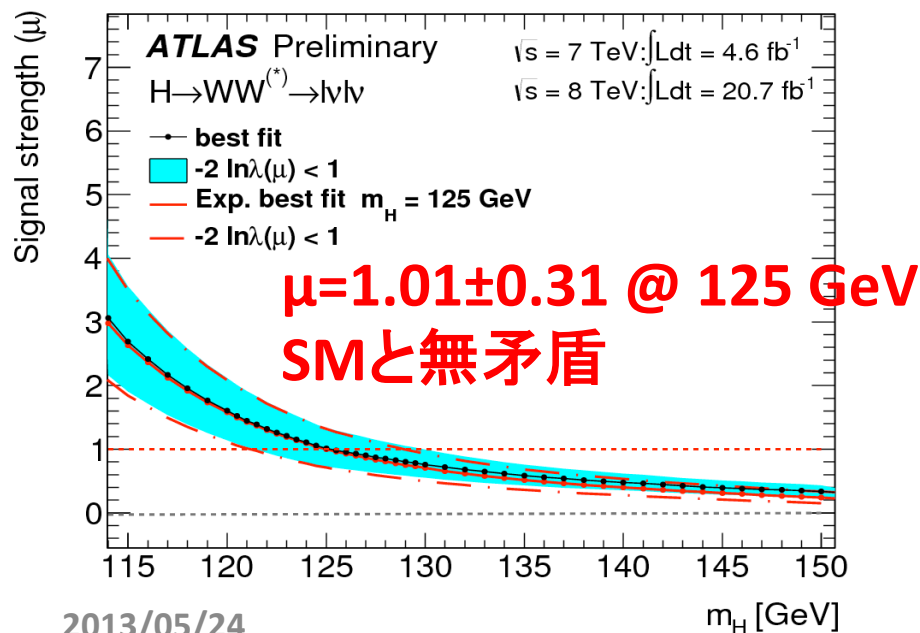


- データから背景事象を差し引いた m_T 分布

- Local p_0 @ 125 GeV

Observed : 3.8σ

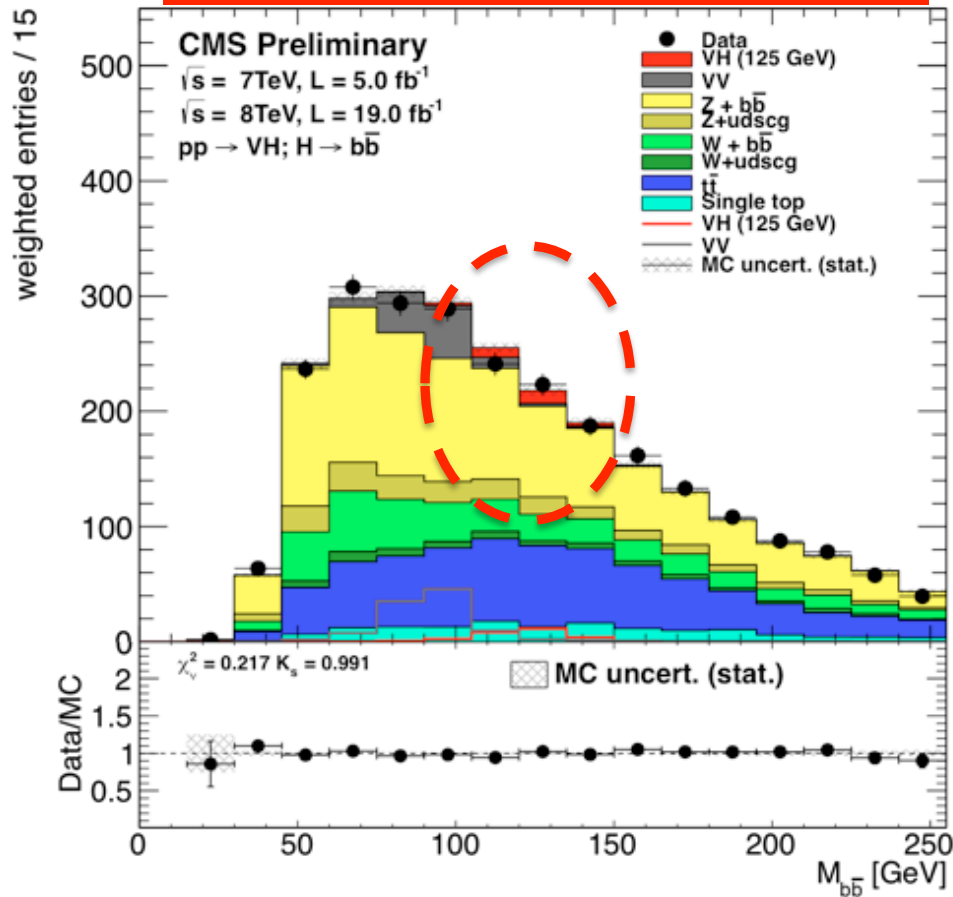
Expected : 3.7σ



$H \rightarrow b\bar{b}, H \rightarrow \tau\tau$ (CMS)

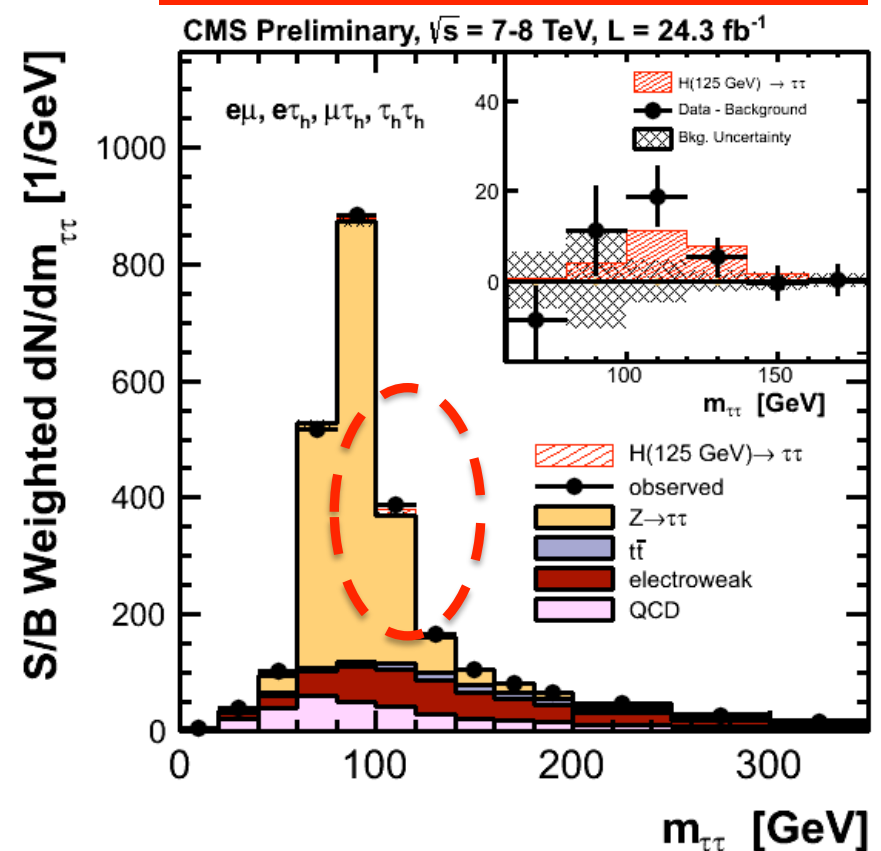
- $H \rightarrow b\bar{b}, H \rightarrow \tau\tau$ も見え始めている。。。

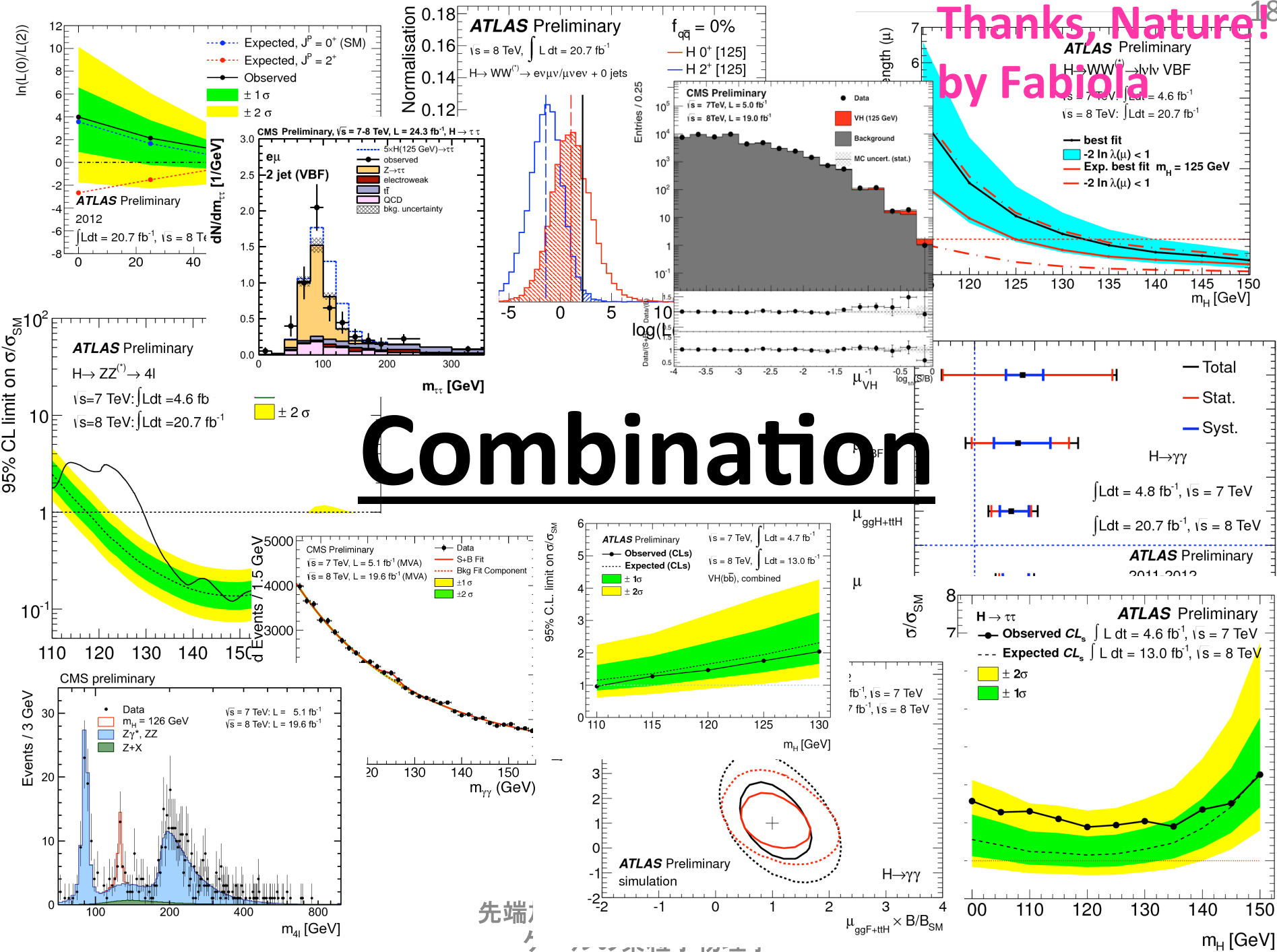
$VH \rightarrow b\bar{b}$ combine (Weighted)



実際の解析はMVAで。。。

$H \rightarrow \tau\tau$ combine (Weighted)





Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L dt$ [fb ⁻¹]	Ref.
2011 $\sqrt{s}=7$ TeV				
$H \rightarrow ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, 2\text{-jet VBF}, \ell\text{-tag}\}$	4.6	[8]
$H \rightarrow \gamma\gamma$	–	10 categories $\{p_{Tl} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{2\text{-jet VBF}\}$	4.8	[7]
$H \rightarrow WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{0\text{-jet}, 1\text{-jet}, 2\text{-jet VBF}\}$	4.6	[9]
$H \rightarrow \tau\tau$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{e\mu\} \otimes \{0\text{-jet}\} \oplus \{\ell\ell\} \otimes \{1\text{-jet}, 2\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, VH\}$	4.6	[10]
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{0\text{-jet}, 1\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, 2\text{-jet}\}$	4.6	
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{1\text{-jet}, 2\text{-jet}\}$	4.6	
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_T^{\text{miss}} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet}, 3\text{-jet}\}$	4.6	[11]
	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	4.7	
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	4.7	
2012 $\sqrt{s}=8$ TeV				
$H \rightarrow ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, 2\text{-jet VBF}, \ell\text{-tag}\}$	20.7	[8]
$H \rightarrow \gamma\gamma$	–	14 categories $\{p_{Tl} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{2\text{-jet VBF}\} \oplus \{\ell\text{-tag}, E_T^{\text{miss}}\text{-tag}, 2\text{-jet VBF}\}$	20.7	[7]
$H \rightarrow WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{0\text{-jet}, 1\text{-jet}, 2\text{-jet VBF}\}$	20.7	[9]
$H \rightarrow \tau\tau$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{\ell\ell\} \otimes \{1\text{-jet}, 2\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, VH\}$	13	[10]
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{0\text{-jet}, 1\text{-jet}, p_{T,\tau\tau} > 100 \text{ GeV}, 2\text{-jet}\}$	13	
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{1\text{-jet}, 2\text{-jet}\}$	13	
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_T^{\text{miss}} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet}, 3\text{-jet}\}$	13	[11]
	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13	
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13	

ATLAS

$H \rightarrow \gamma\gamma, ZZ \rightarrow 4\ell, WW \rightarrow \ell\nu\ell\nu$

→ full-data

$H \rightarrow bb, \tau\tau$

→ HCP data(13fb⁻¹)

CMS

$H \rightarrow \gamma\gamma, ZZ \rightarrow 4\ell, WW \rightarrow \ell\nu\ell\nu, H \rightarrow \tau\tau$

→ full-data

$H \rightarrow bb$

→ HCP data(12fb⁻¹)

H decay	Prod. tag	Analyses	No. of channels	m_H resolution	Lumi (fb ⁻¹)		Ref.
		Exclusive final states			7 TeV	8 TeV	
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4 + 4	1-2%	5.1	19.6	[63]
	VBF-tag	$\gamma\gamma + (jj)_{\text{VBF}}$ (two dijet classes for 8 TeV)	1 + 2	<1.5%	5.1	19.6	
	VH-tag	$\gamma\gamma + (e, \mu, \text{MET})$	3	<1.5%		19.6	
$ZZ \rightarrow 4\ell$	$N_{\text{jet}} < 2$	$4e, 4\mu, 2e2\mu$	3 + 3	1-2%	5.1	19.6	[64]
	$N_{\text{jet}} \geq 2$		3 + 3				
$WW \rightarrow \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4 + 4	20%	4.9	19.5	[65]
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\text{VBF}}$ (DF or SF dileptons for 8 TeV)	1 + 2	20%	4.9	12.1	[66]
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2 + 2		4.9	19.5	[67]
$\tau\tau$	0/1-jet	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu) \times (\text{low or high } p_T^l)$	16 + 16	15%	4.9	19.6	[68]
	1-jet	$\tau_h\tau_h$	1 + 1				
	VBF-tag	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\text{VBF}}$	5 + 5				
	ZH-tag	$(ee, \mu\mu) \times (\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu)$	8 + 8	5.0	19.5	[69]	
	WH-tag	$\tau_h\mu\mu, \tau_h e\mu, e\tau_h\tau_h, \mu\tau_h\tau_h$	4 + 4				
bb	VH-tag	$(\nu\nu, ee, \mu\mu, e\nu, \mu\nu \text{ with 2 b-jets}) \times (\text{low or high } p_T(V) \text{ or loose b-tag})$	10 + 13	10%	5.0	12.1	[70]
	ttH-tag	$(\ell \text{ with 4, 5 or } \geq 6 \text{ jets}) \times (3 \text{ or } \geq 4 \text{ b-tags});$ $(\ell\ell \text{ with 6 jets with 2 b-tags}); (\ell\ell \text{ with 2 or } \geq 3 \text{ b-tagged jets})$	6 + 6 3 + 3		5.0	5.1	[71]

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L dt$ [fb ⁻¹]	Ref.
2011 $\sqrt{s}=7$ TeV				
$H \rightarrow ZZ^{(*)}$	4ℓ	{ $4e, 2e2\mu, 2\mu2e, 4\mu, 2$ -jet VBF, ℓ -tag}	4.6	[8]
$H \rightarrow \gamma\gamma$	$m_H=125.5$ GeV			[7]
$H \rightarrow WW^{(*)}$				[9]
$H \rightarrow \tau\tau$				[10]
$VH \rightarrow Vbb$				[11]
$H \rightarrow ZZ^{(*)}$	ZZ	4.4	6.6	
$H \rightarrow \gamma\gamma$	$\gamma\gamma$	4.1	7.4	
$H \rightarrow WW^{(*)}$	WW	3.7	3.8	
$H \rightarrow \gamma\gamma$	bb(HCP data)	$\sim 1\sigma$	$< 1\sigma$	
$H \rightarrow WW^{(*)}$	$\tau\tau$(HCP data)	1.7	1.1	
$H \rightarrow \tau\tau$	$Z \rightarrow \nu\nu$	$E_T^{\text{miss}} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet}, 3\text{-jet}\}$	13	
$VH \rightarrow Vbb$	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13	[11]
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13	

ATLAS

$H \rightarrow \gamma\gamma, ZZ \rightarrow 4\ell, WW \rightarrow \ell\nu\ell\nu$

→ full-data

$H \rightarrow bb, \tau\tau$

→ HCP data(13fb⁻¹)

CMS

$H \rightarrow \gamma\gamma, ZZ \rightarrow 4\ell, WW \rightarrow \ell\nu\ell\nu, H \rightarrow \tau\tau$

→ full-data

$H \rightarrow bb$

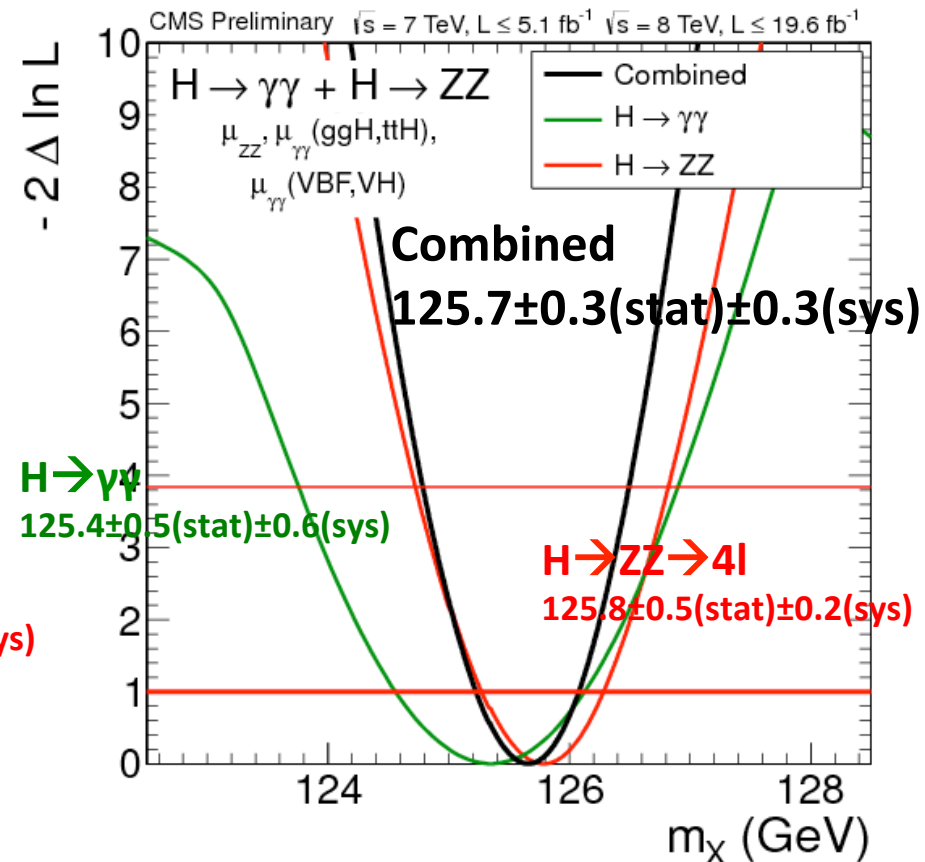
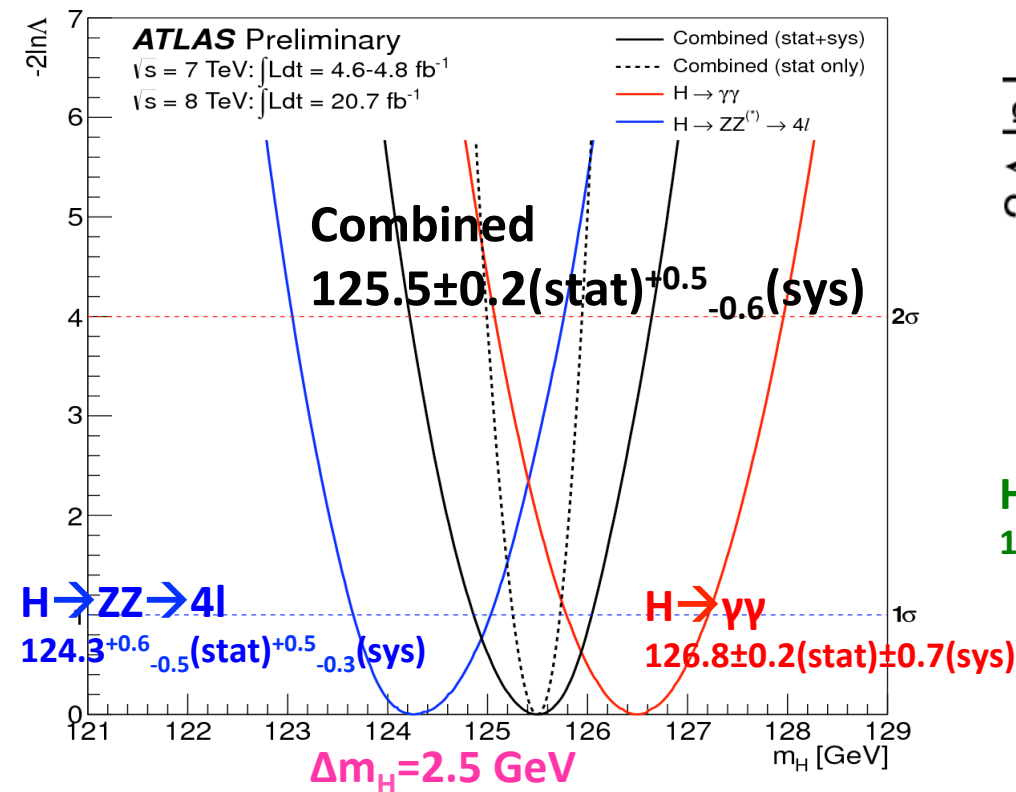
→ HCP data(12fb⁻¹)

			$m_H=125.7$ GeV			m_H resolution	Lumi (fb ⁻¹)		Ref.
H decay	Prod. tag	Exc	Decay mode	Expected (σ)	Observed (σ)		7 TeV	8 TeV	
$\gamma\gamma$	untagged	$\gamma\gamma$	ZZ	7.1	6.7	1-2%	5.1	19.6	[63]
	VBF-tag	$\gamma\gamma$				<1.5%	5.1	19.6	
	VH-tag	$\gamma\gamma$				<1.5%		19.6	
$ZZ \rightarrow 4\ell$	$N_{\text{jet}} < 2$	$4e, 4\mu$	ZZ	7.1	6.7	1-2%	5.1	19.6	[64]
	$N_{\text{jet}} \geq 2$								
$WW \rightarrow \ell\nu\ell\nu$	0/1-jets	(DF)	$\gamma\gamma$	3.9	3.2	20%	4.9	19.5	[65]
	VBF-tag	$\ell\nu\ell\nu$				20%	4.9	12.1	
	WH-tag	$3\ell 3\nu$					4.9	19.5	
$\tau\tau$	0/1-jet	($e\tau$)	WW	5.3	3.9	15%	4.9	19.6	[68]
	1-jet	$\bar{q}q\tau$							
	VBF-tag	($e\tau$)							
bb	ZH-tag	(ee)	bb(HCP data)	2.2	2.0	10%	5.0	19.5	[69]
	WH-tag	$\bar{q}q\mu$							
	VH-tag	($\nu\nu$)							
bb	ttH-tag	($\ell\ell$)	$\tau\tau$	2.6	2.8	10%	5.0	12.1	[70]
		($\ell\ell$)							
							5.0	5.1	[71]

質量測定

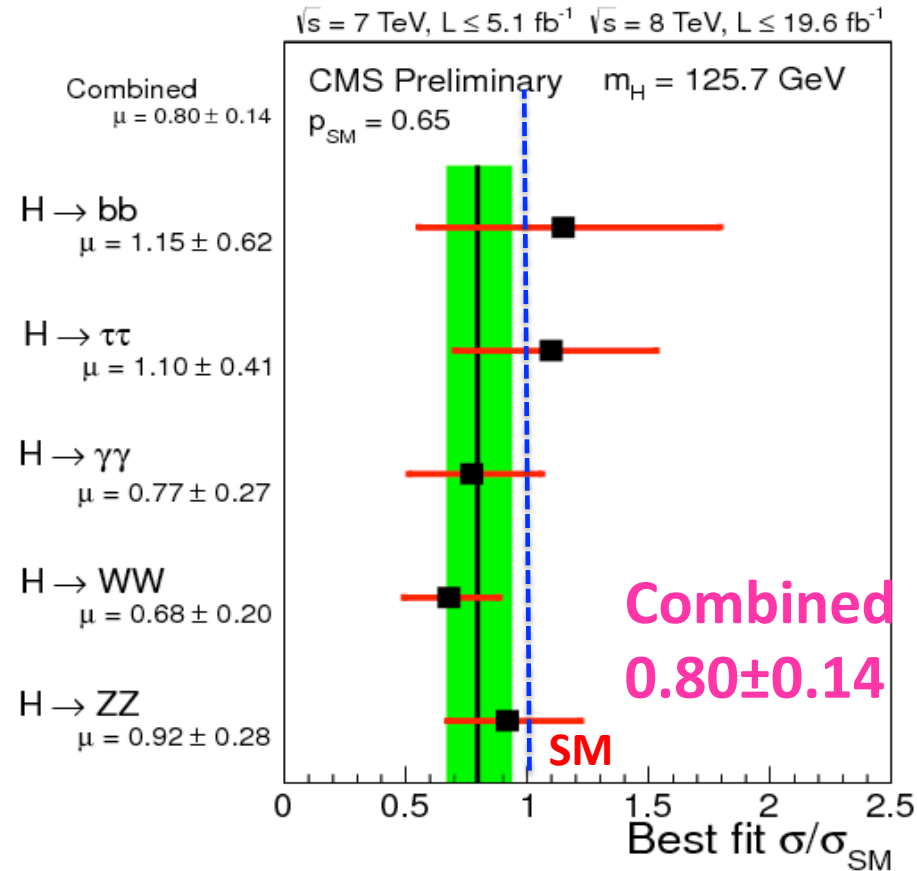
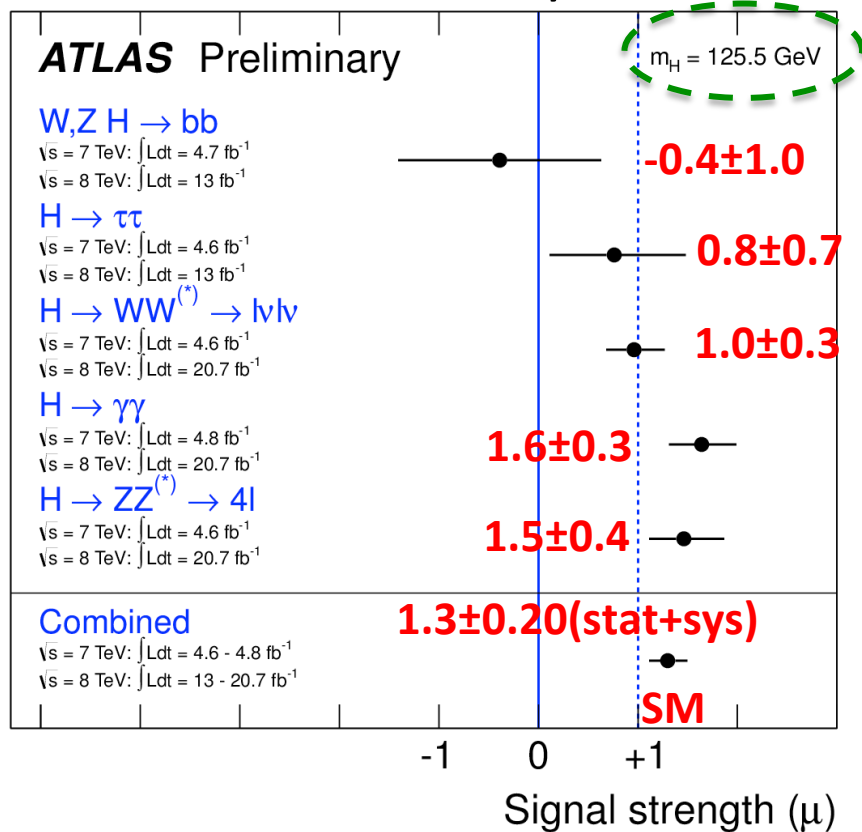
- 2つの質量解像度が良いチャンネル $H \rightarrow \gamma\gamma$ vs $H \rightarrow ZZ \rightarrow 4l$
 - $H \rightarrow \gamma\gamma$ の系統誤差 : γ energy scale/resolution
 - $H \rightarrow ZZ \rightarrow 4l$ の主な系統誤差 : μ momentum scale/resolution
- 2つの測定の相関は少ない

* electron energy scale/
resolution は γ と相関あり



Combined Signal Strength

- Combined signal strength (SMに規格したときの観測された信号の量)



ATLAS : $\gamma\gamma, ZZ$ は高め

CMS : $\gamma\gamma, WW, ZZ$ は低め

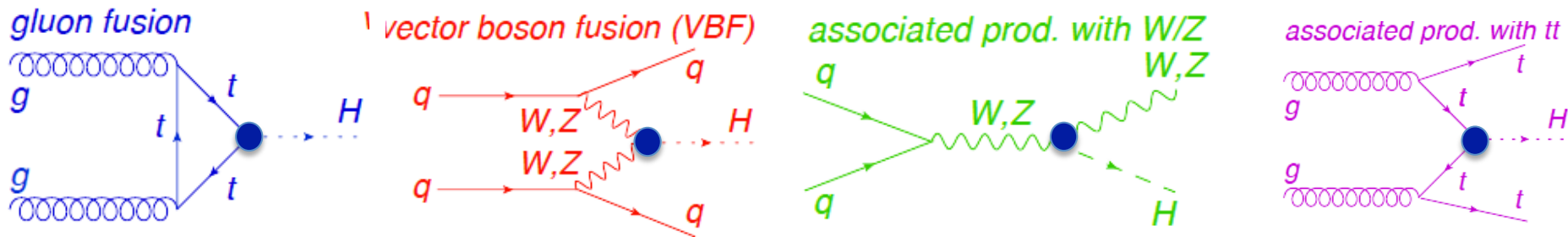
それぞれの実験はSMと無矛盾 ($< 2\sigma$)

$\tau, b\bar{b}$ はまだ感度低い

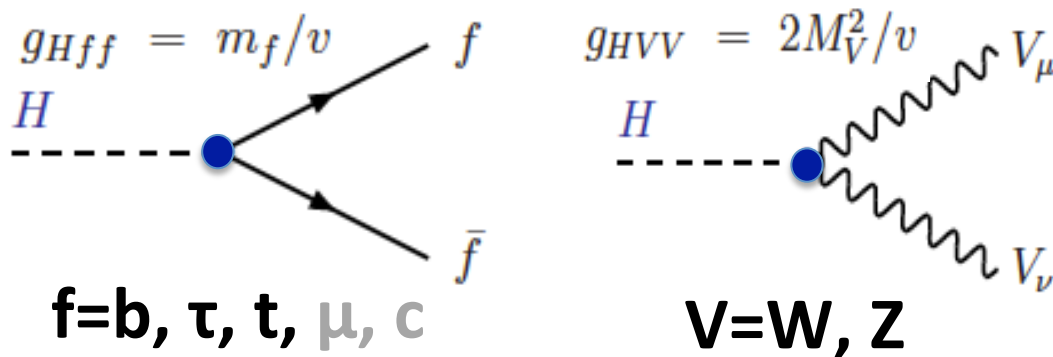
先端加速器LHCが切り拓くテラス
ケールの素粒子物理学

カップリングの測定

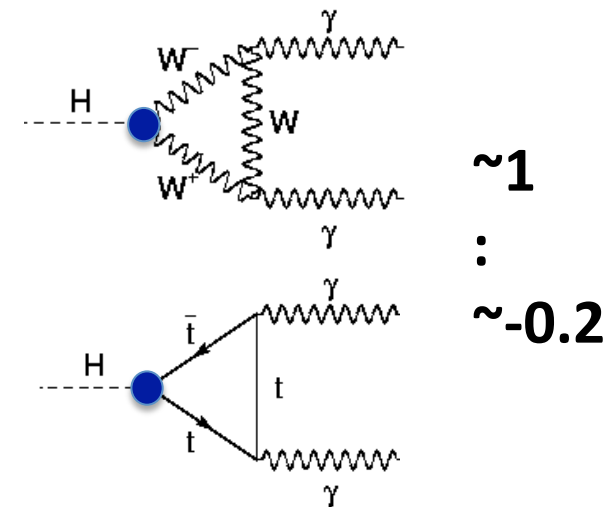
生成過程でのヒッグスとの結合



崩壊過程でのヒッグスとの結合

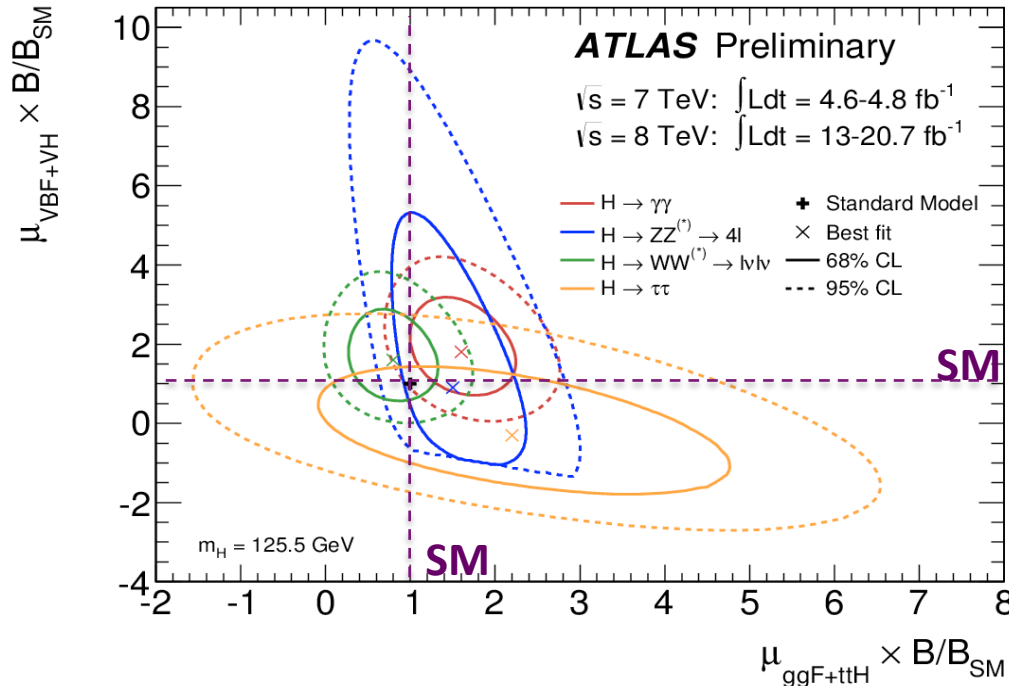


$H \rightarrow \gamma\gamma$ は両方の
カップリングが寄与



ggF vs. VBF Production

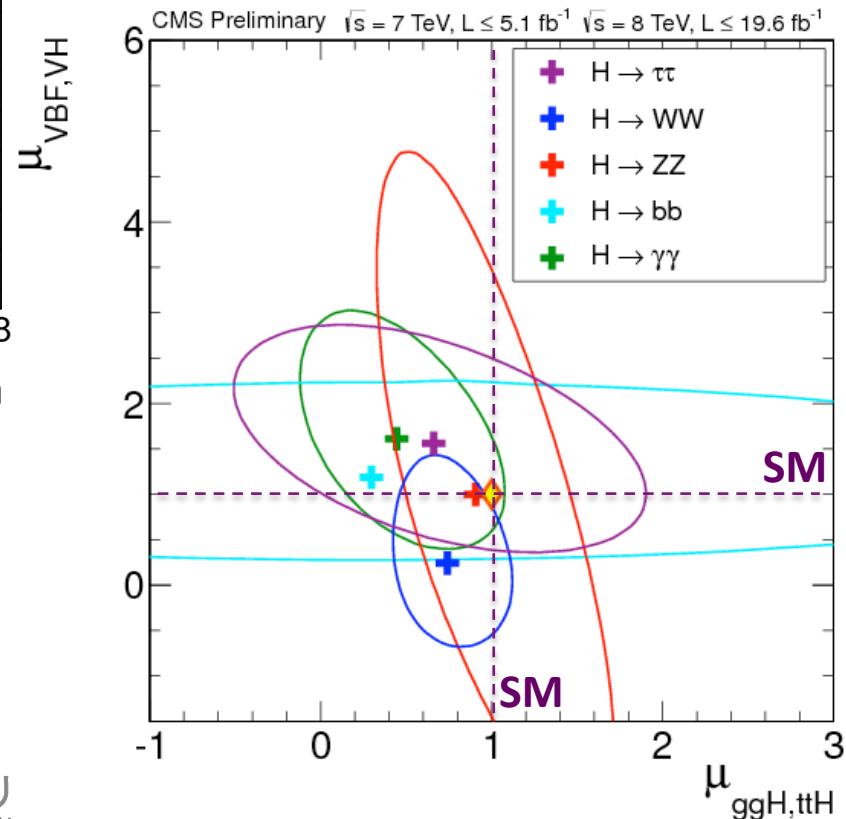
- 同じ崩壊チャンネルを見る事での崩壊からの不定性はキャンセル
(生成過程に対する μ のズレを見る事が可能)



$H \rightarrow \gamma\gamma$ はggF/VBF共に高めに出現している(<2 σ)
 他のチャンネルも大きくSMとずれているもの
 はない

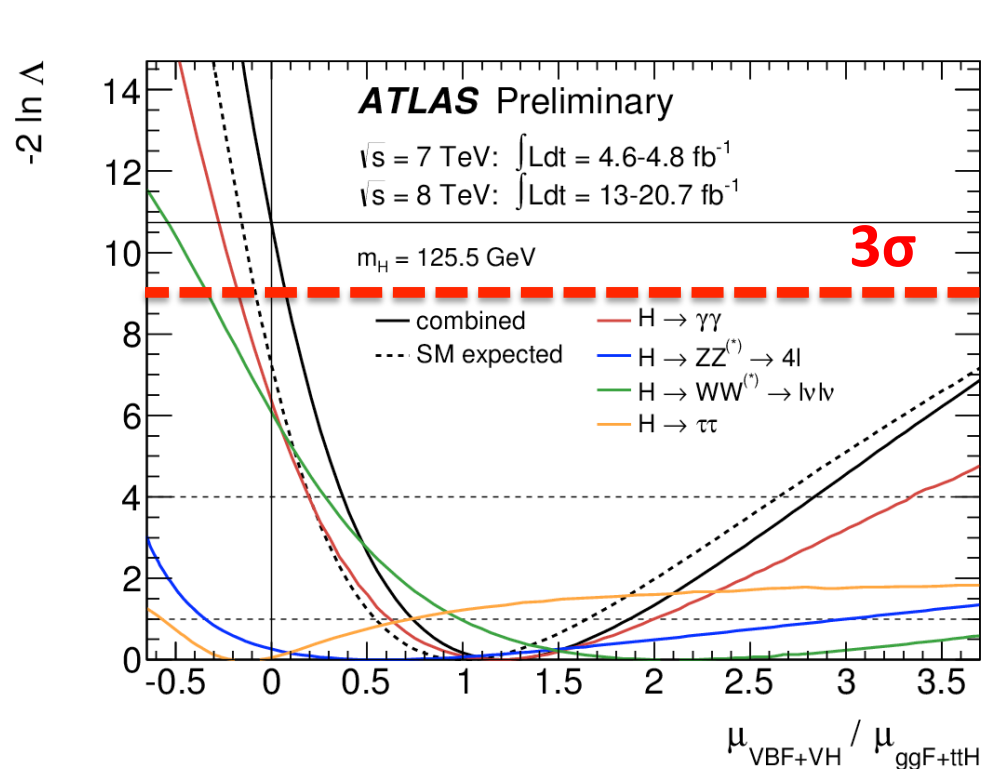
- * $H \rightarrow \tau\tau$: ggFの感度なし
- * $H \rightarrow ZZ \rightarrow 4l$: VBFの感度なし

$H \rightarrow WW$ はggF低めに出ている
 $H \rightarrow \gamma\gamma$ はggF低め、VBF高め



ggF vs VBF Production

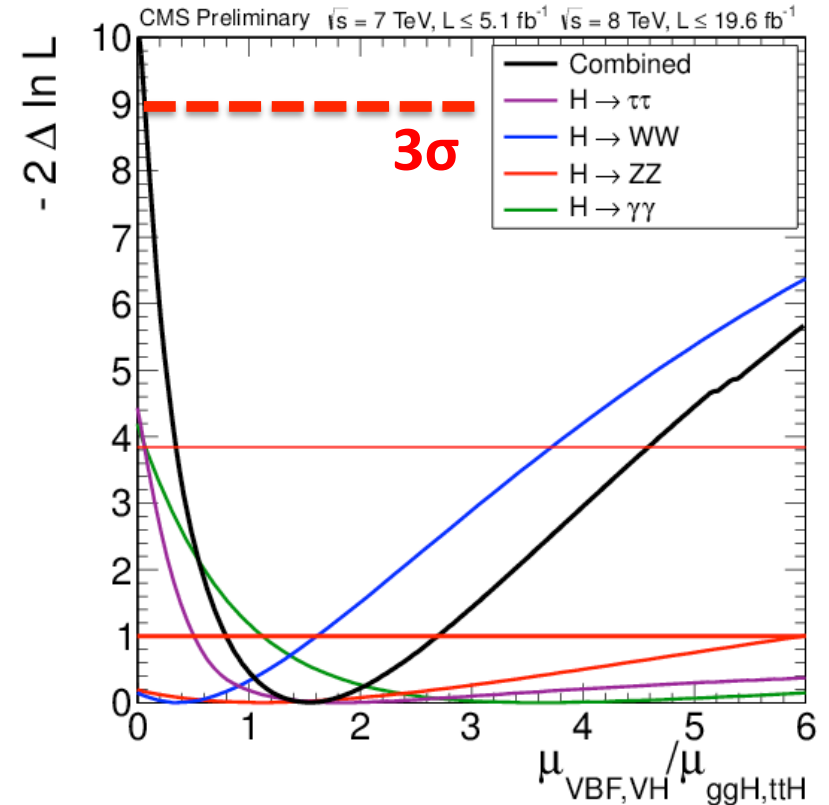
- 比($\mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}}$)をとることでそれぞれの崩壊モードを同じ変数として比較可能(コンバインも可能)



$\mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}} = 1.2^{+0.7}_{-0.5}$ (SMと無矛盾)

$\mu_{\text{VBF+VH}} = 0$ を3.3σで棄却

→ 有意にVBF productionが見えている



$\mu_{\text{VBF+VH}} > 0$ を強く示唆(>3σ)

カップリングの測定

一例

- 125.5 GeVのSM Higgs boson (spin 0 CP-even scalar)を仮定

$$\sigma \times BR(gg \rightarrow H \rightarrow \gamma\gamma)$$

$$\sigma \times BR(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

$$= \sigma_{SM} \cdot BR_{SM} \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Coupling scale factor ($\kappa^{SM}=1$)

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \left\{ \begin{array}{l} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{array} \right.$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \left\{ \begin{array}{l} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{array} \right.$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \left\{ \begin{array}{l} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{array} \right.$$

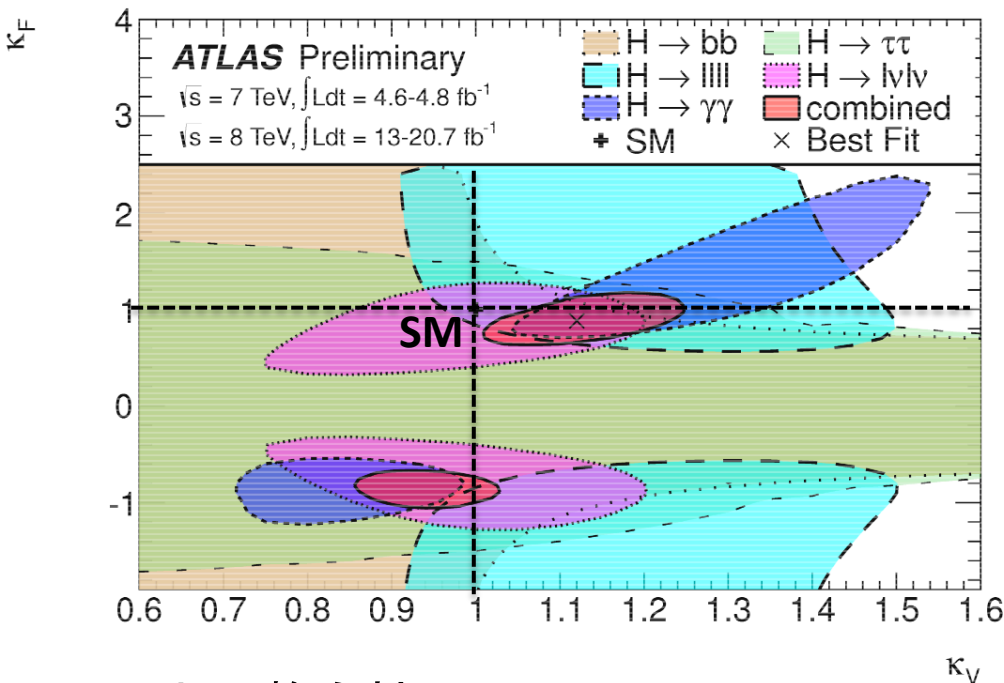
カップリング測定

- フェルミオン($\kappa_t, \kappa_b, \kappa_\tau, \kappa_g$)とボソン(κ_W, κ_Z)の
カップリングをパラメータとしてフィット

$$* \kappa_V^2(\kappa_F, \kappa_V) \propto |1.261\kappa_V - 0.265\kappa_F|^2$$

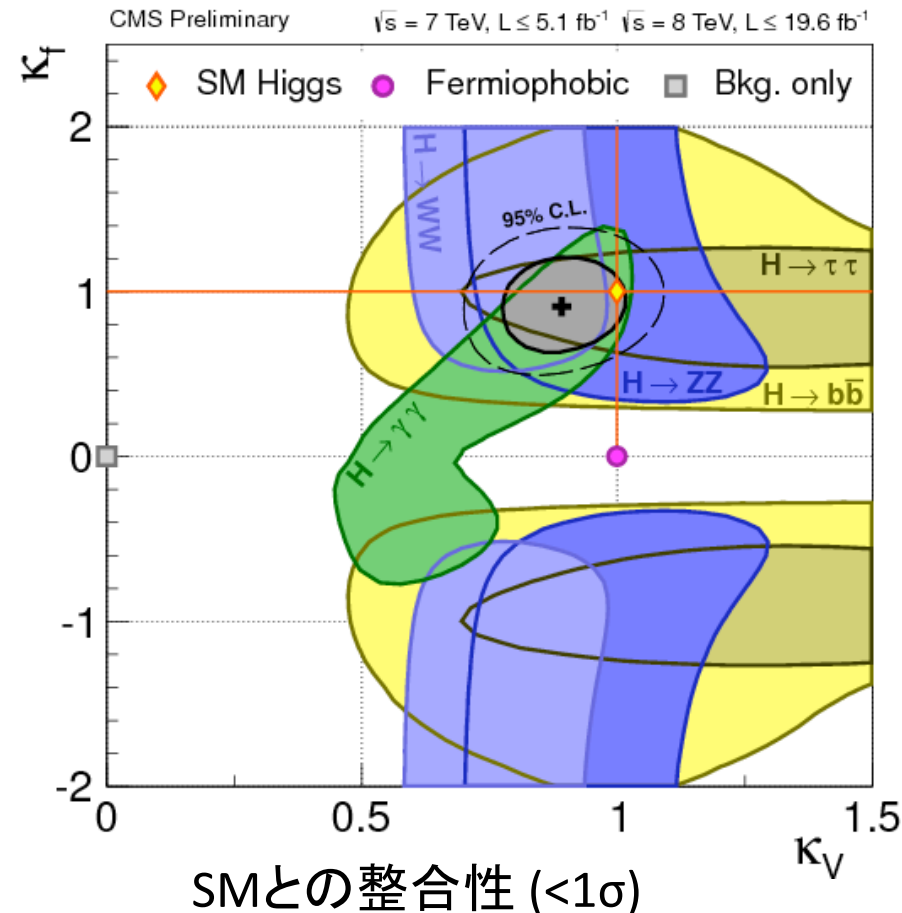
$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$



SMとの整合性 $\sim 8\%$ ($< 2\sigma$)

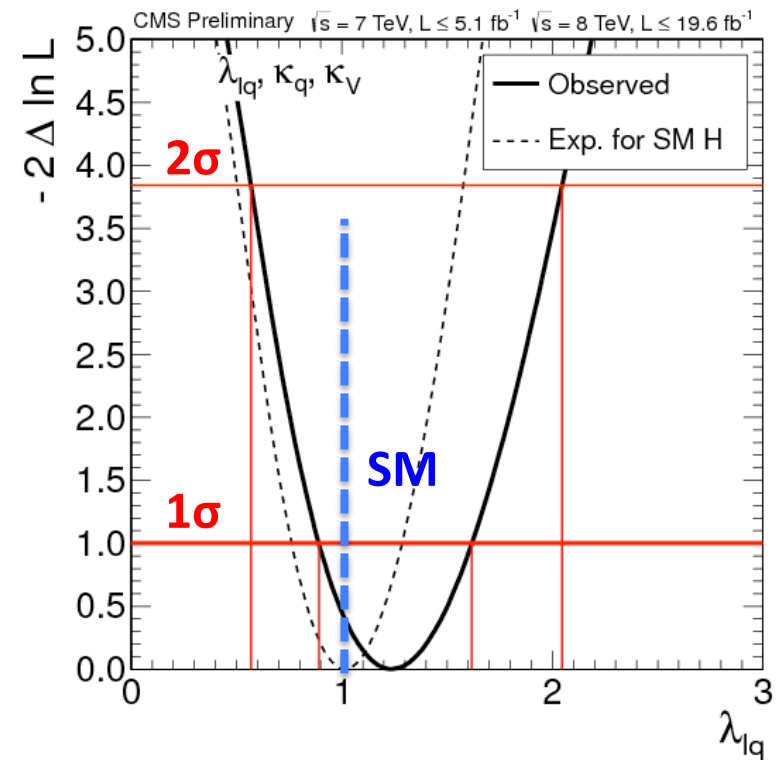
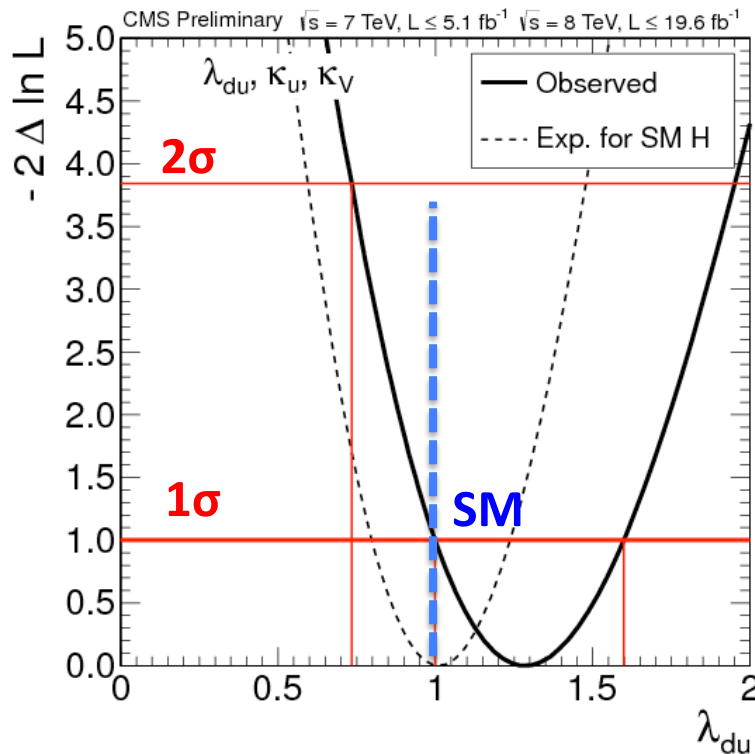
$\kappa_V > 0$ のみ: 非対称性は $H \rightarrow \gamma\gamma$ のloopから



SMとの整合性 ($< 1\sigma$)

カップリング測定(CMS)

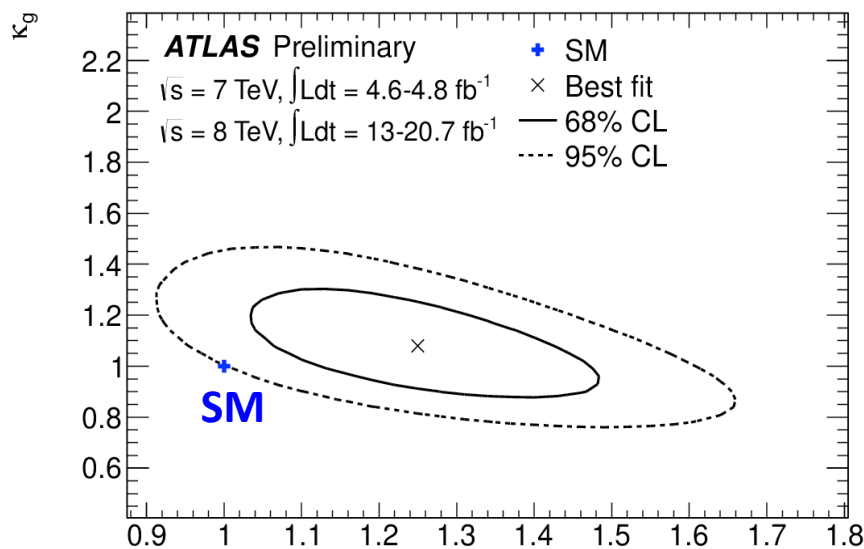
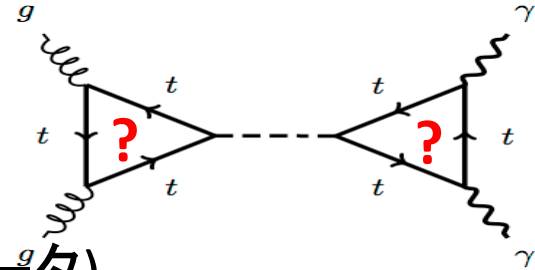
- down typeとup typeのカップリング比($\lambda_{du} = \kappa_d / \kappa_u$)測定
 → MSSMなどではdown typeがenhanceされる可能性
- leptonとquarkのカップリング比($\lambda_{lq} = \kappa_l / \kappa_q$)測定
 → 2HDMではleptonとカップルしないシナリオも



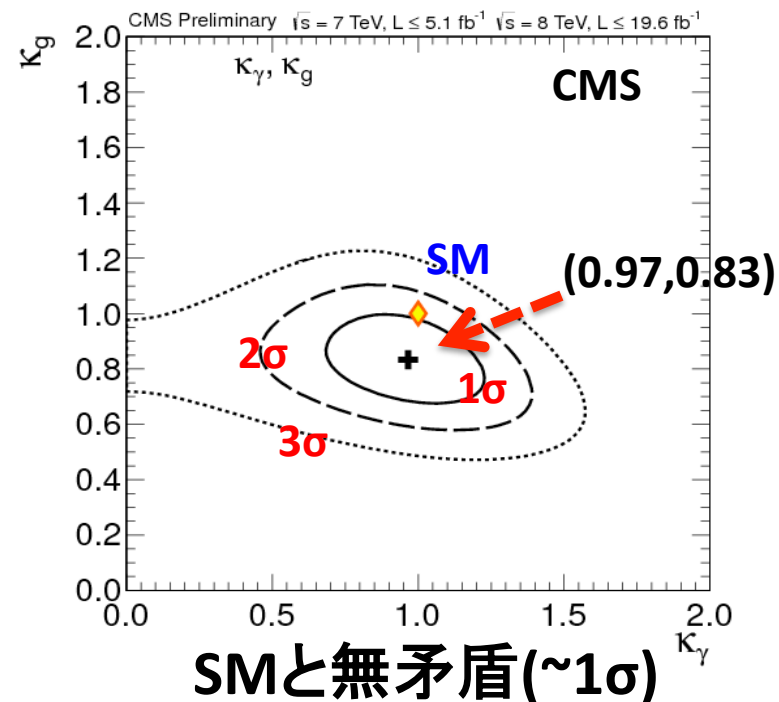
SMからの大きなズレは観測されず

カップリング測定

- $gg \rightarrow H, H \rightarrow \gamma\gamma$ のloopにnon-SM粒子の寄与がある場合 $\rightarrow \kappa_g, \kappa_\gamma$ のズレが見える可能性
 - 全崩壊幅はSMと同じと仮定 (κ_g, κ_γ がパラメータ)



SMとの整合性は5% ($\sim 2\sigma$)



- non-SM粒子が全崩壊幅に寄与する場合 (non-SM粒子は観測されない)

BR(invisible) < 0.6(0.52) @95% CL in ATLAS(CMS)

スピン・パリティ測定

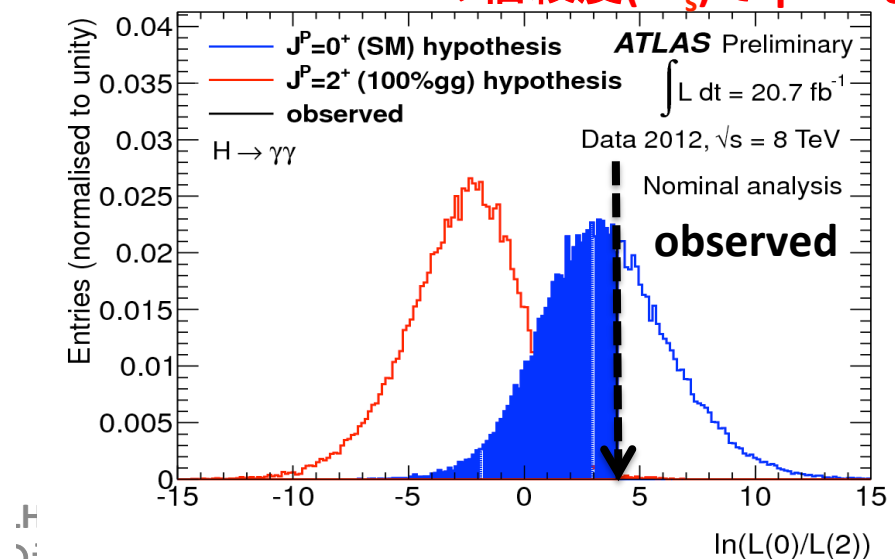
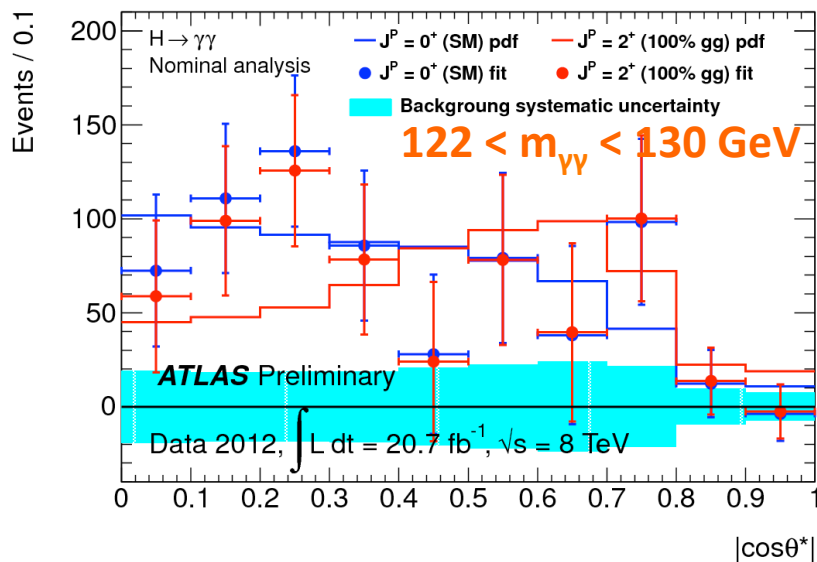
- $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4l$ チャンネルでスピン測定
 - Spin 0^+ vs 2^+ : 最もシンプルなgraviton-likeモデルをspin 2^+ のベンチマークとして使用 (Spin $1^{+/-}$ はLandau-Yang定理で禁止されている)
 - $ZZ \rightarrow 4l$ は $0^-, 1^+, 1^-, 2^-$ との識別にも感度がある

[Phys. Rev. D 16, 2219–2225 \(1977\)](#)

❖ $H \rightarrow \gamma\gamma$: Z-軸と光子の放出角度 $|\cos\theta^*|$ のみをもちいてスピンを測定

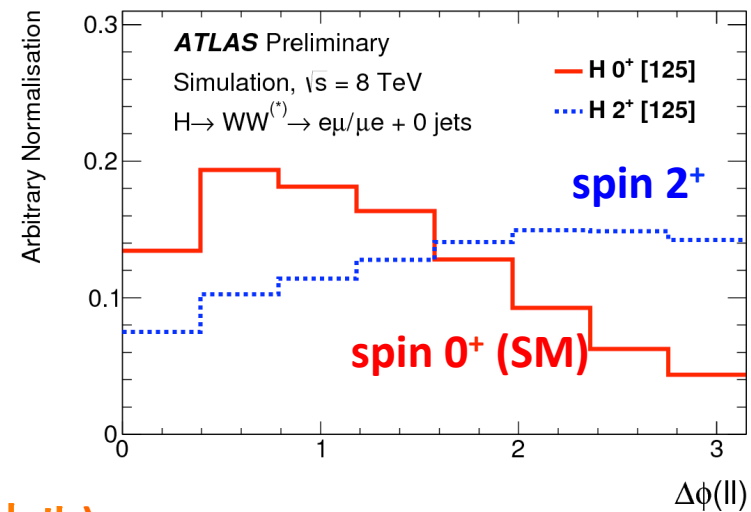
– $|\cos\theta^*|$ と $m_{\gamma\gamma}$ (bkg normalization in side band)をフィットする

99.3%の信頼度(CL_s)でspin 2^+ を棄却

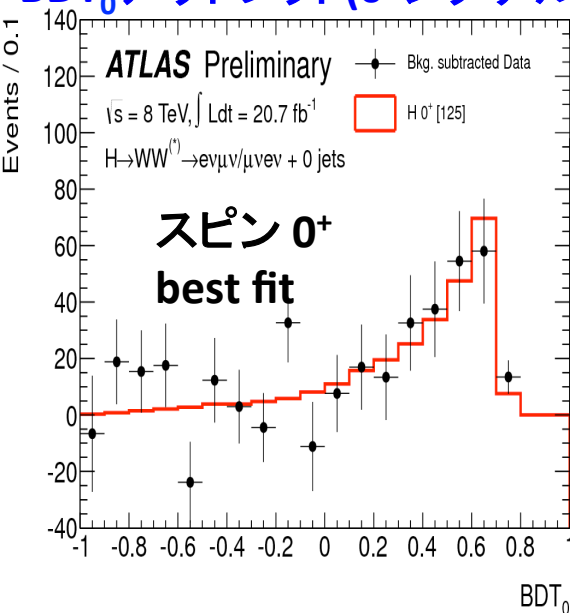


スピン・パリティ測定

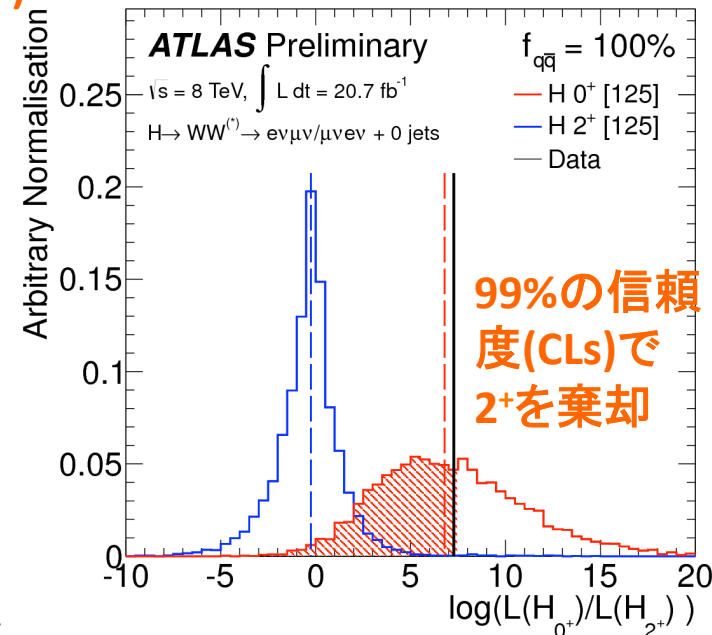
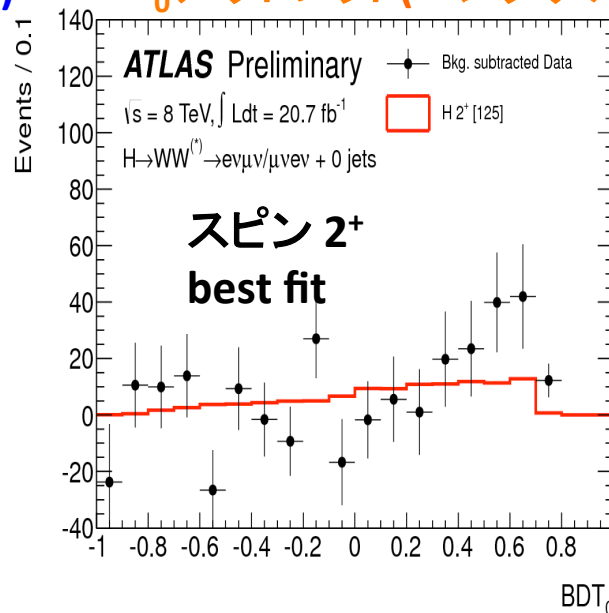
- ❖ $H \rightarrow WW \rightarrow l\nu l\nu : \Delta\phi_{ll}, p_T^{ll}$ 等のスピンに感度がある変数をMVAで解析
- μ 測定よりセレクションを緩くしてspin $0^+, 2^+$ を選択
- 2つのBDT₀(spin 0^+ vs bkg), BDT₂(spin 2^+ vs bkg)を2Dフィット



BDT₀アウトプット(0^+ シグナル)



BDT₀アウトプット(2^+ シグナル)



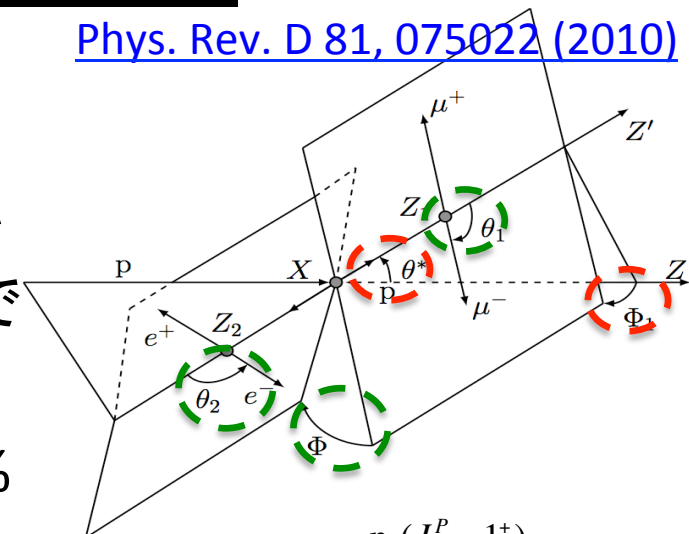
スピン・パリティ測定

[Phys. Rev. D 81, 075022 \(2010\)](#)

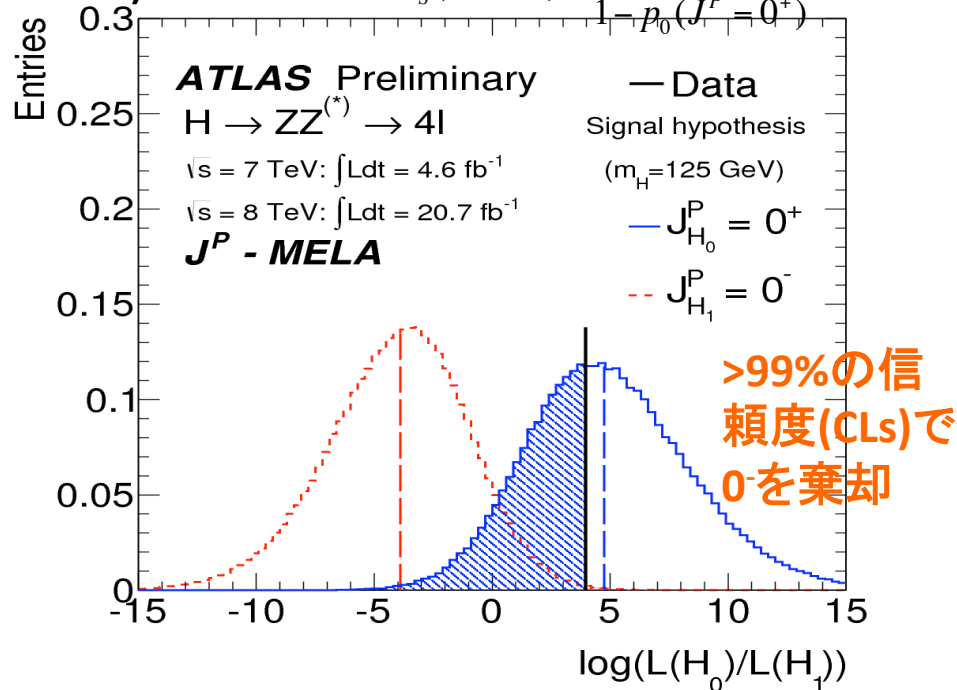
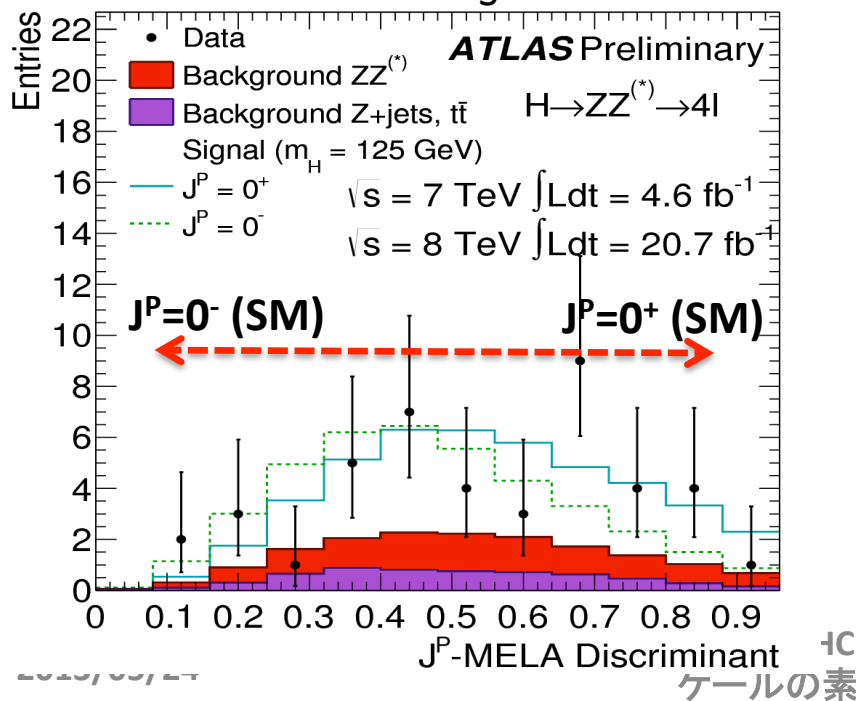
❖ $H \rightarrow ZZ \rightarrow 4l$: ME LA (Matrix Element Likelihood Analysis)

– 4-leptonを用いた角度変数と m_{12}, m_{34} をlikelihoodにいれてME LA discriminantで評価

– $0^+ \text{ vs } 0^-, 1^+, 1^-, 2^+, 2^- \rightarrow 0^-, 1^+, 1^-$ は97-99%
%の信頼度(CL_s)で棄却 (2-は~90%)



$$CL_s(J^P = 1^+) = \frac{p_0(J^P = 1^+)}{1 - p_0(J^P = 0^+)} = 0.004$$



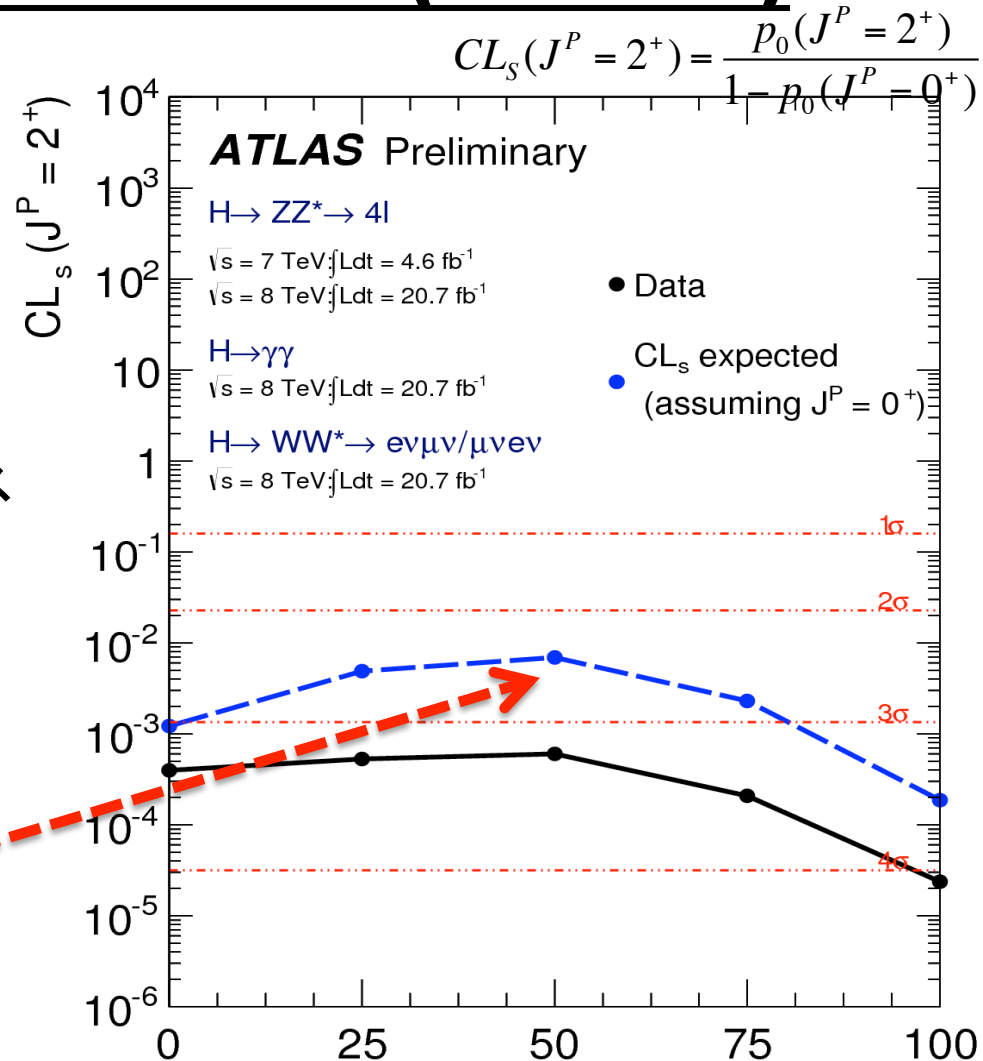
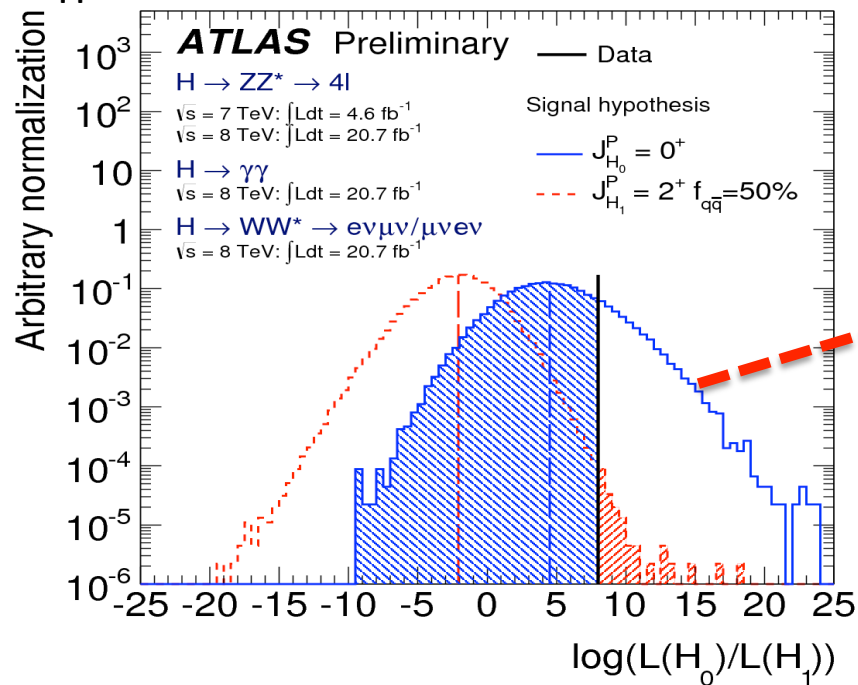
スピン測定コンビネーション(0^+ vs 2^+)

$H \rightarrow WW, \gamma\gamma, ZZ$ コンバイン

- Spin 2^+ で $f_{q\bar{q}}$ を0%-100%まで変化させてチェック

→ 全てのケースで99%以上の信頼度でSpin 2^+ のモデルを排除

$f_{q\bar{q}}(\text{Spin}2^+) = 50\%$: 最も区別が難しいケース



CMSもWW,ZZでほぼ同様の結果を得ている

まとめ

- ヒッグス(like)粒子の発見以来, 順調にデータ取得&解析が進行中
質量測定

ATLAS : $125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$

CMS : $125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{sys})$

スピン/パリティ測定

- $0^+ \text{ vs } 2^+ \rightarrow 0^+ \text{を強く示唆}$ (99%以上の信頼度で 2^+ を棄却)
- $0^+ \text{ vs } 0^-, 1^+, 1^- \rightarrow 0^+ \text{を強く示唆}$ (~99%の信頼度で $0^-, 1^+, 1^-$ を棄却)

カップリング測定

- SMとの大きなズレは観測されていない
- フェルミオンとのカップリングは $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$ の解析のアップデートに期待 $\rightarrow$ **近日公開(ATLAS)**

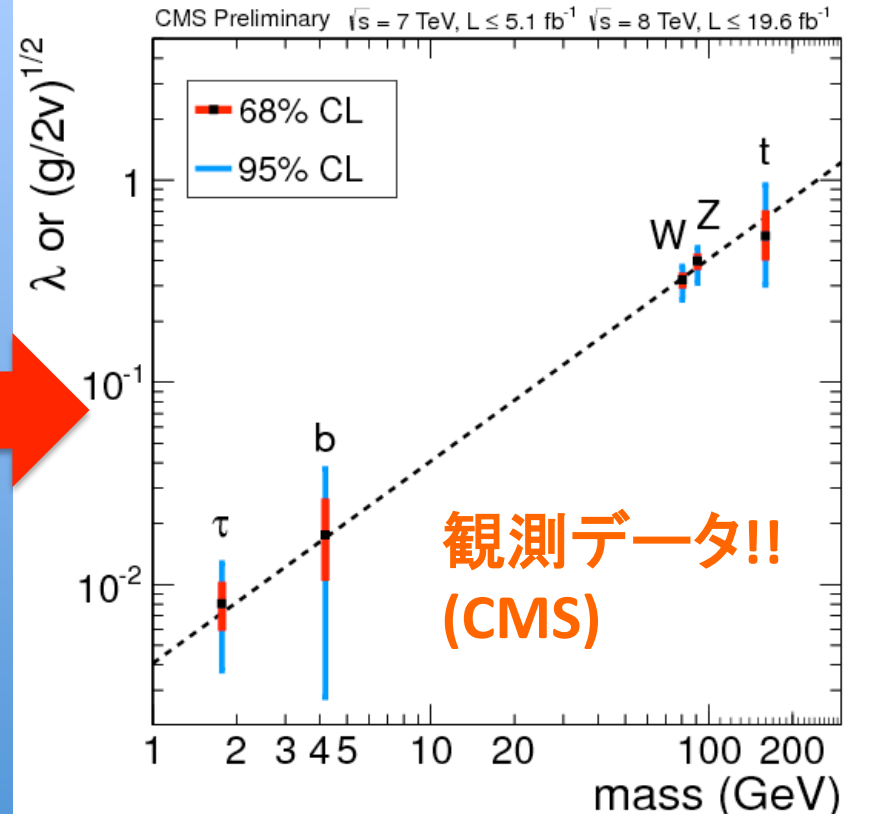
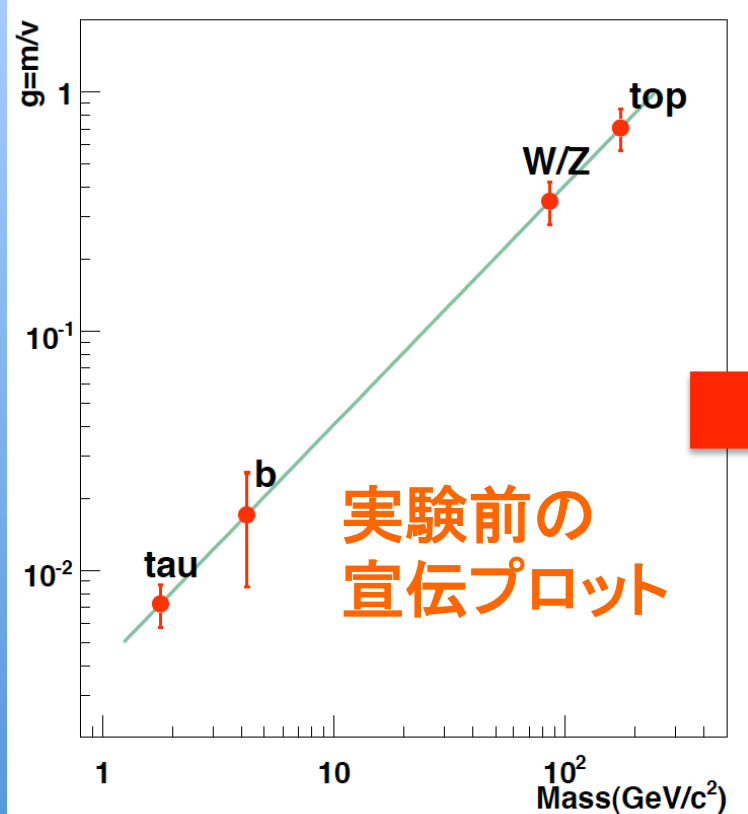
“A Higgs boson”を発見

他のヒッグスがある
可能性は明日のトークで

- 今後, より低い生成断面積のプロセス($t\bar{t}H$, VBF, VH), 崩壊モード($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$)の研究でヒッグス粒子の性質の精密測定が可能に

まとめ

- ヒッグス(like)粒子の発見以来, 順調にデータ取得&解析が進行中
質量測定

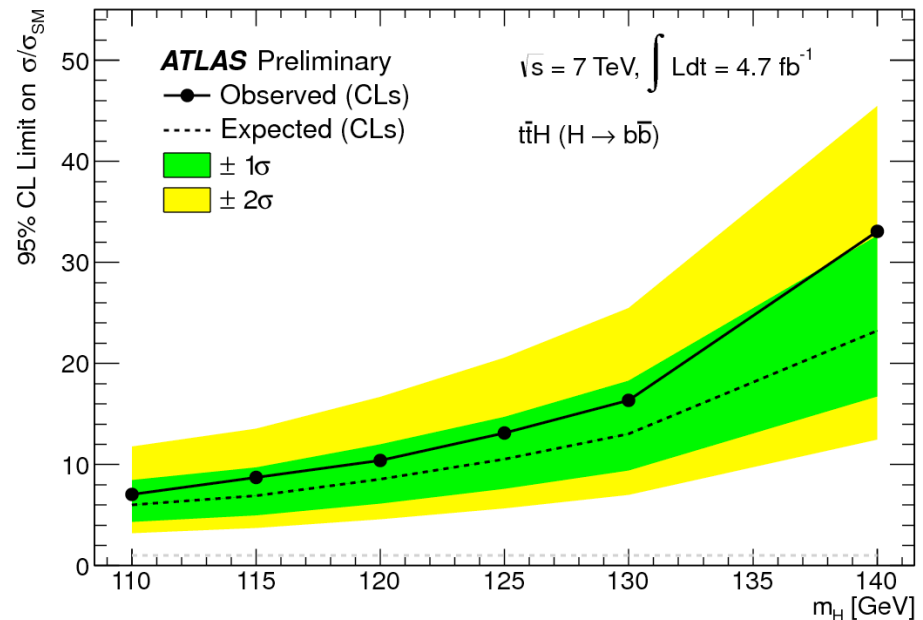
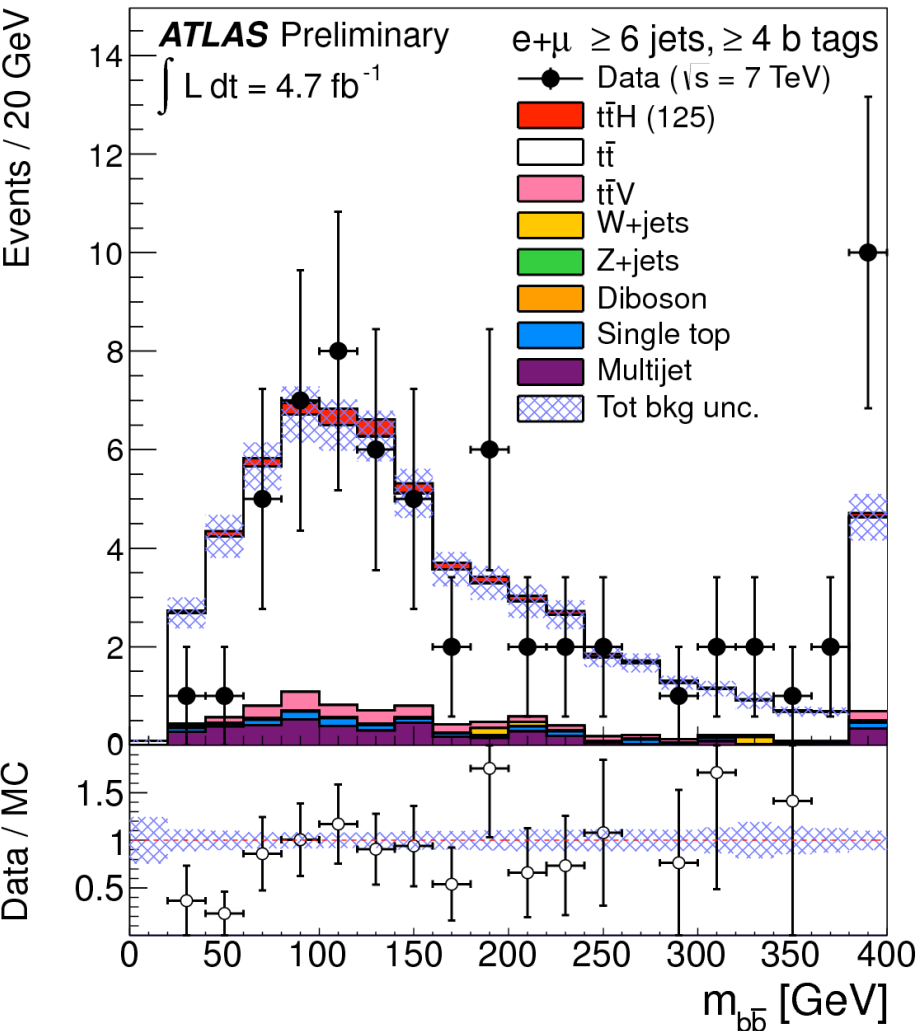


- 今後, より低い生成断面積のプロセス (ttH, VBF, VH), 崩壊モード ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$) の研究で性質の精密測定が可能に

2013/05/24

Rare-Production mode

- $t\bar{t}H \rightarrow b\bar{b}$ (direct $Y_{t\bar{t}b\bar{b}}$ Search)



7TeV 4.7fb⁻¹のみ

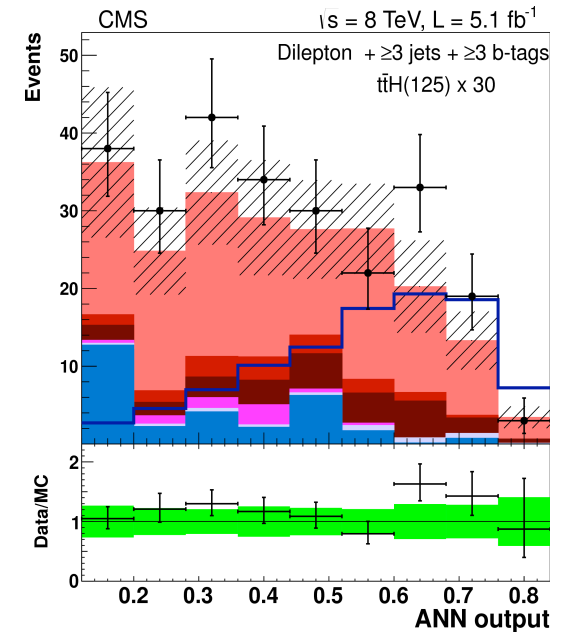
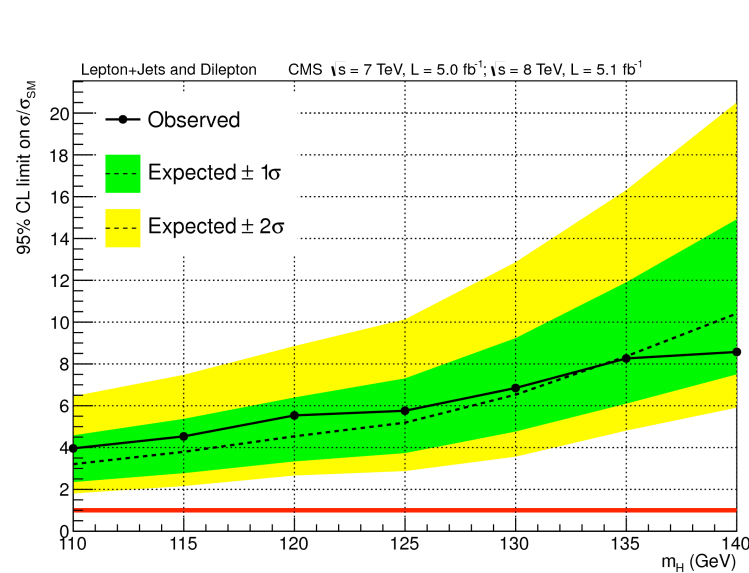
Observed : SM×13.1

Expected : SM×10.5

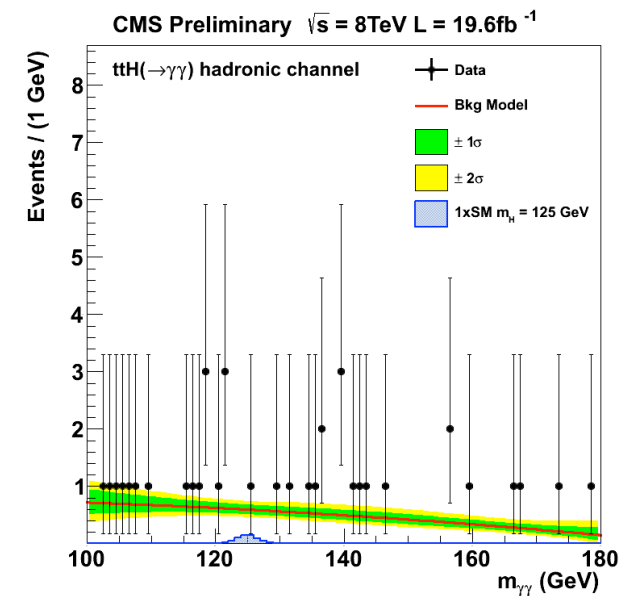
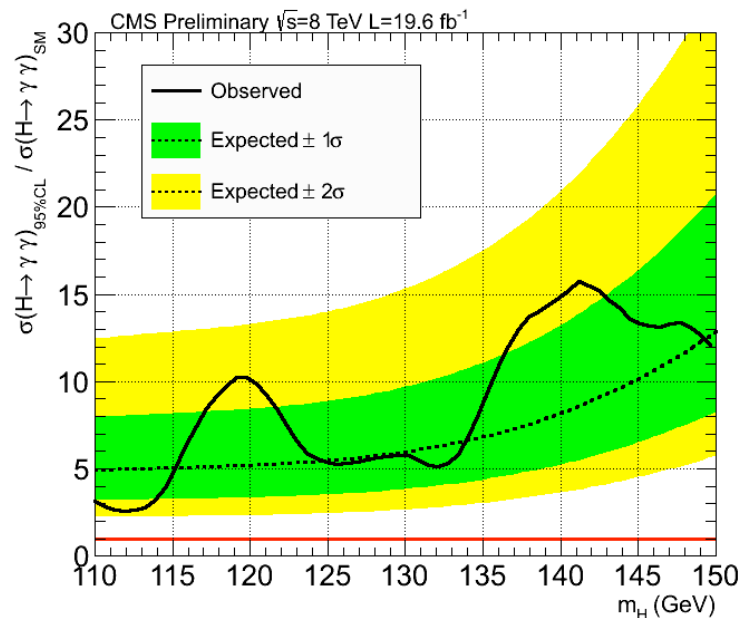
➡ +8TeVで~SM×4は到達可能

Rare-Production Mode (CMS)

• $ttH \rightarrow bb$

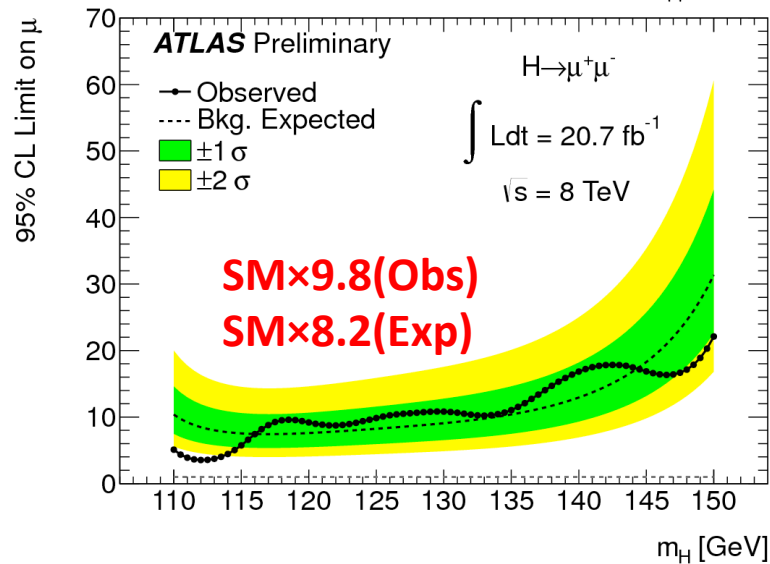
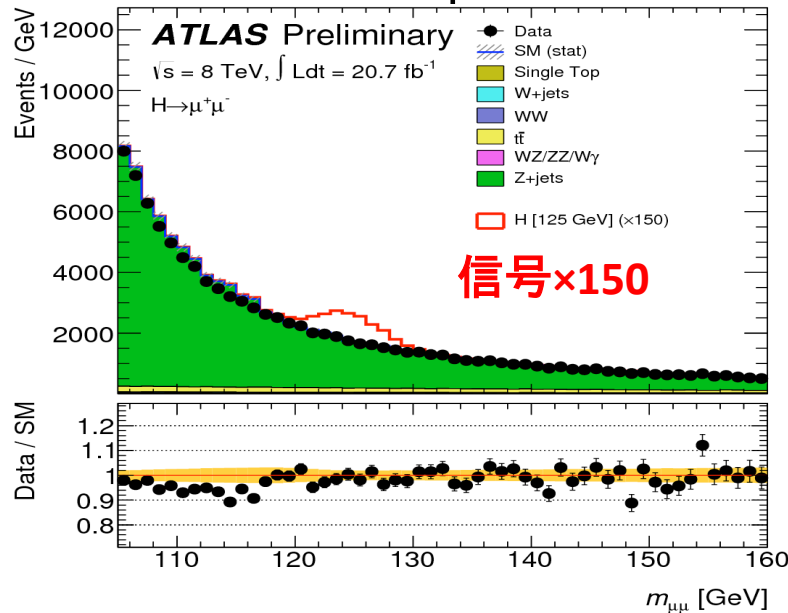


• $ttH \rightarrow \gamma\gamma$

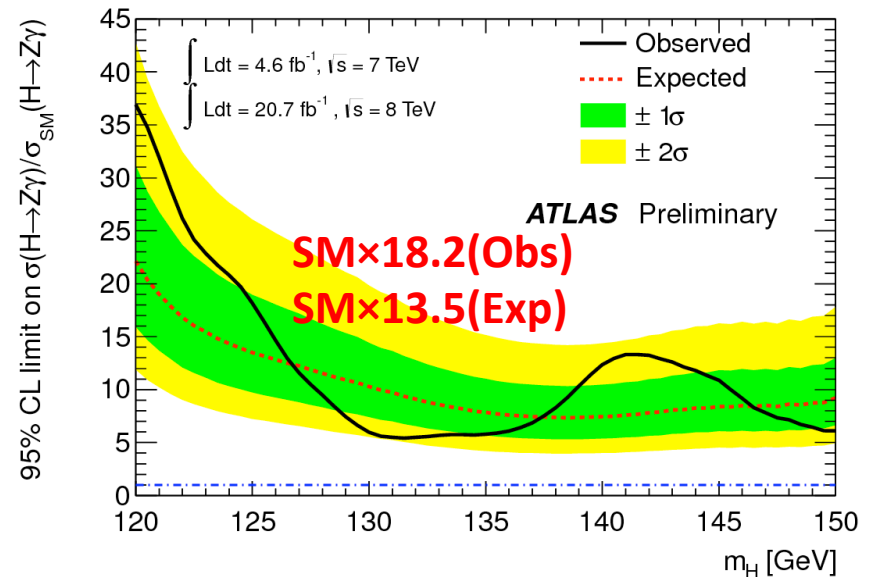
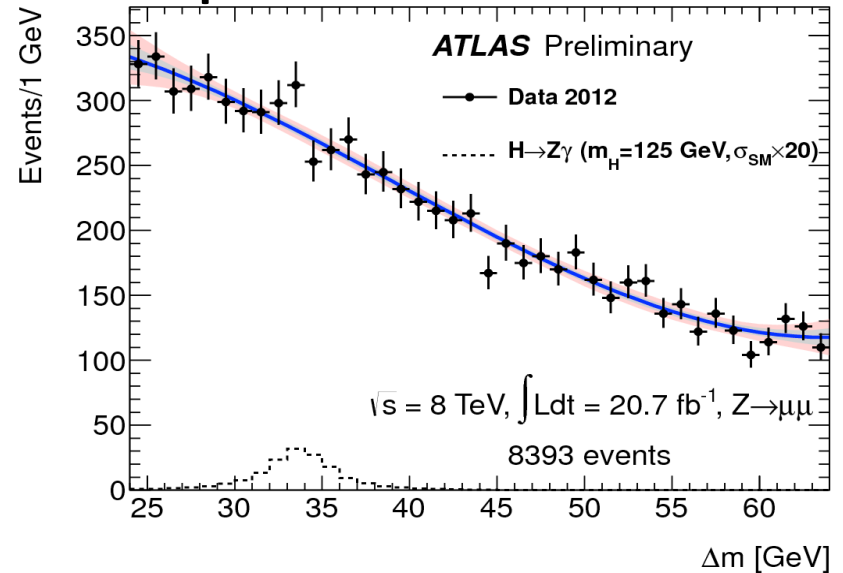


Rare-decay mode

• $H \rightarrow \mu\mu$ (γ_μ)

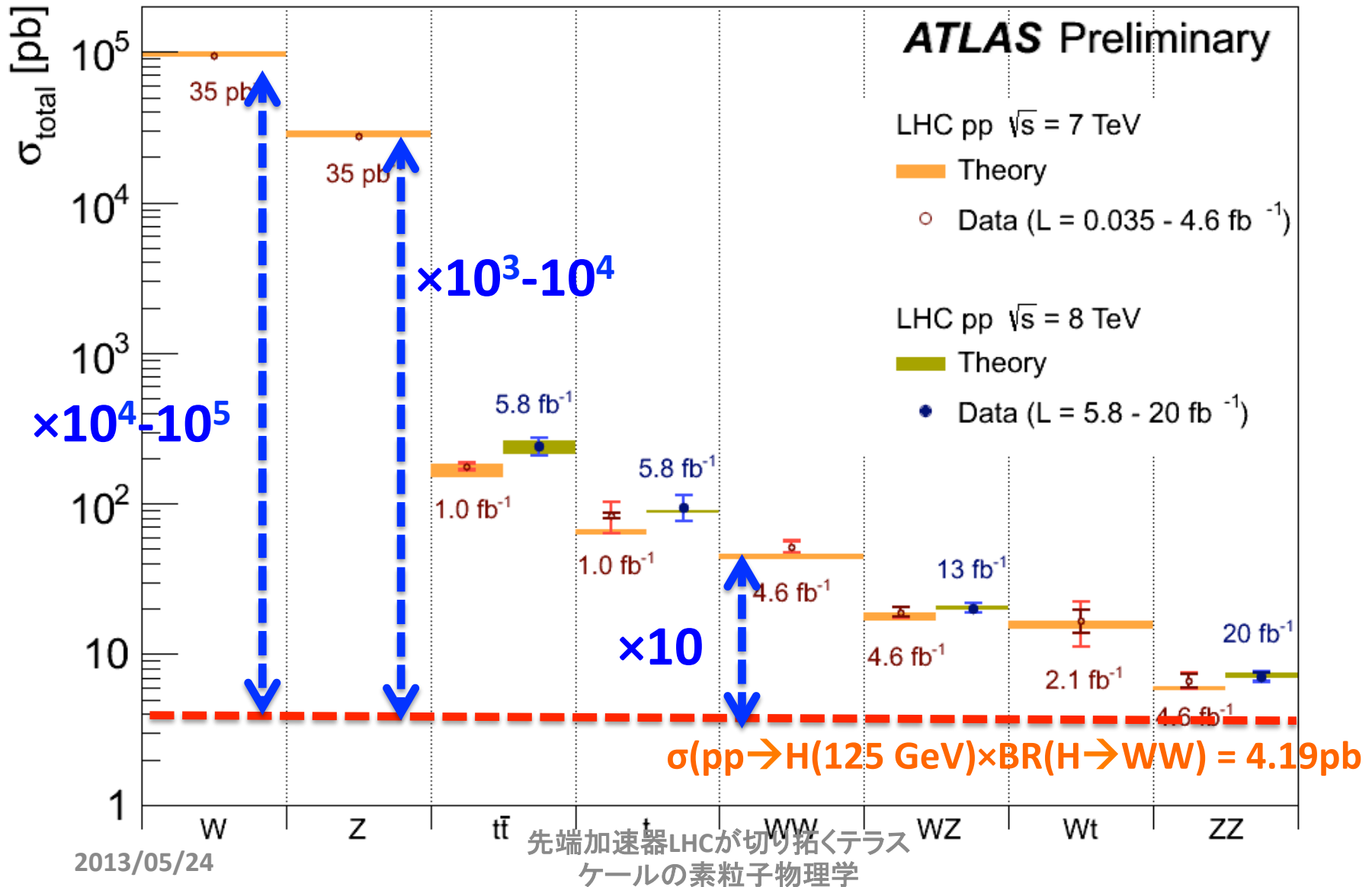


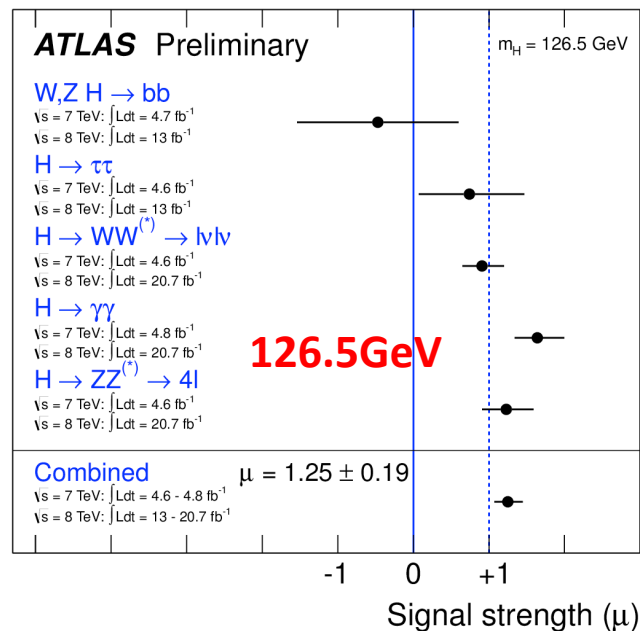
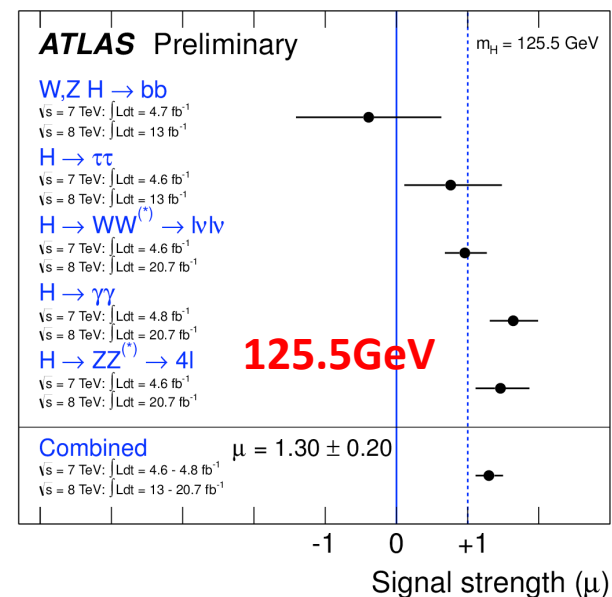
• $H \rightarrow Z\gamma$



SM背景事象

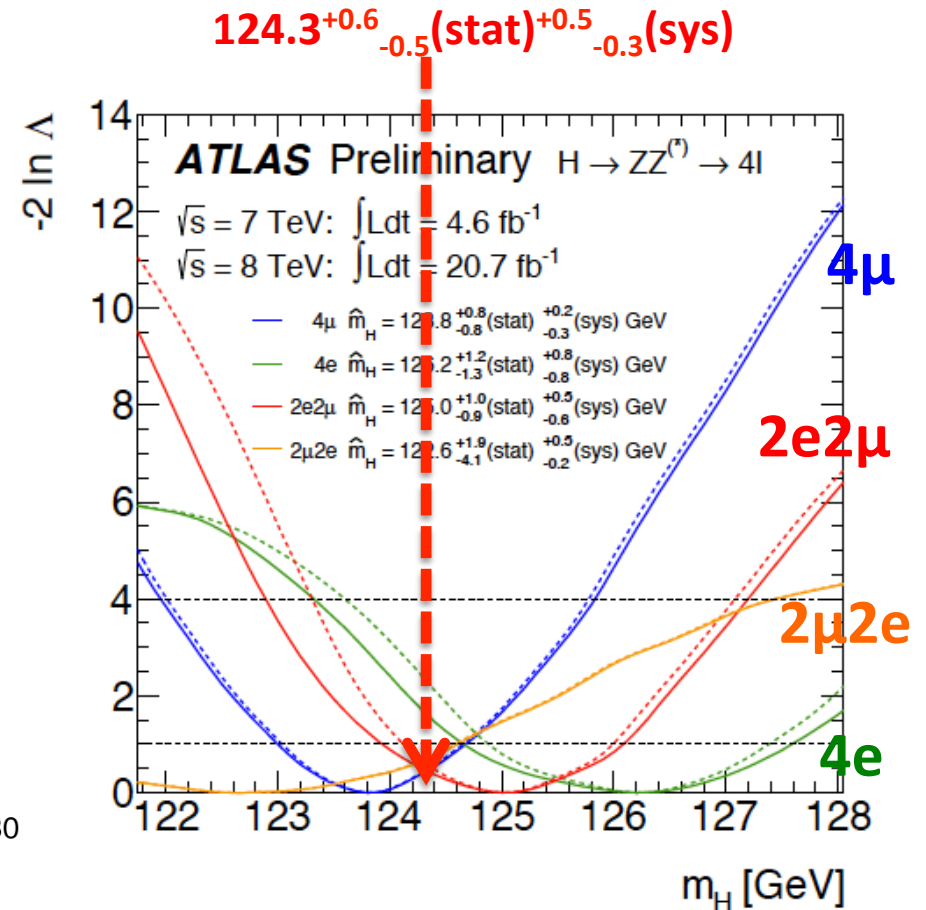
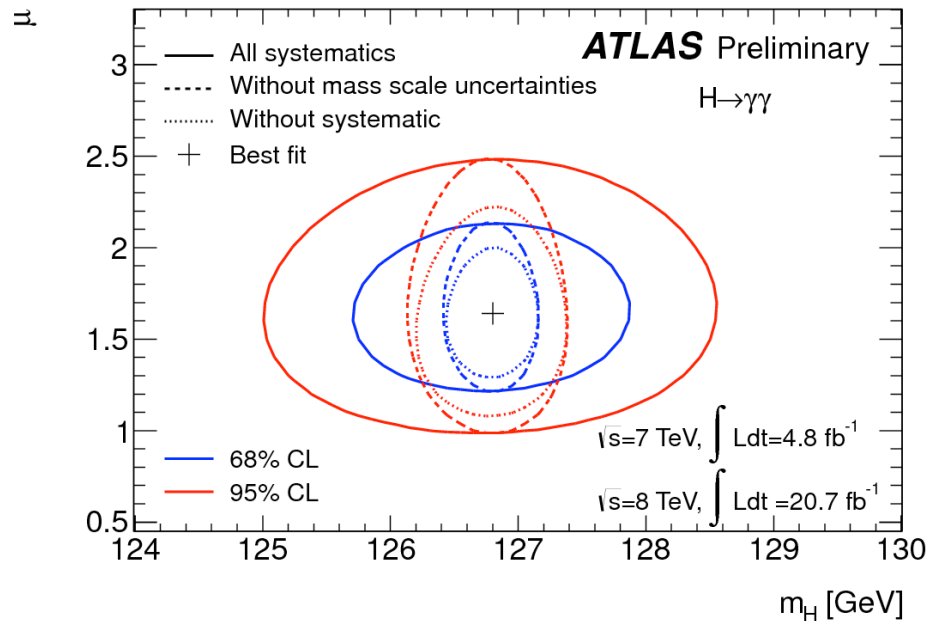
- 背景事象の見積もりと事象選択が重要



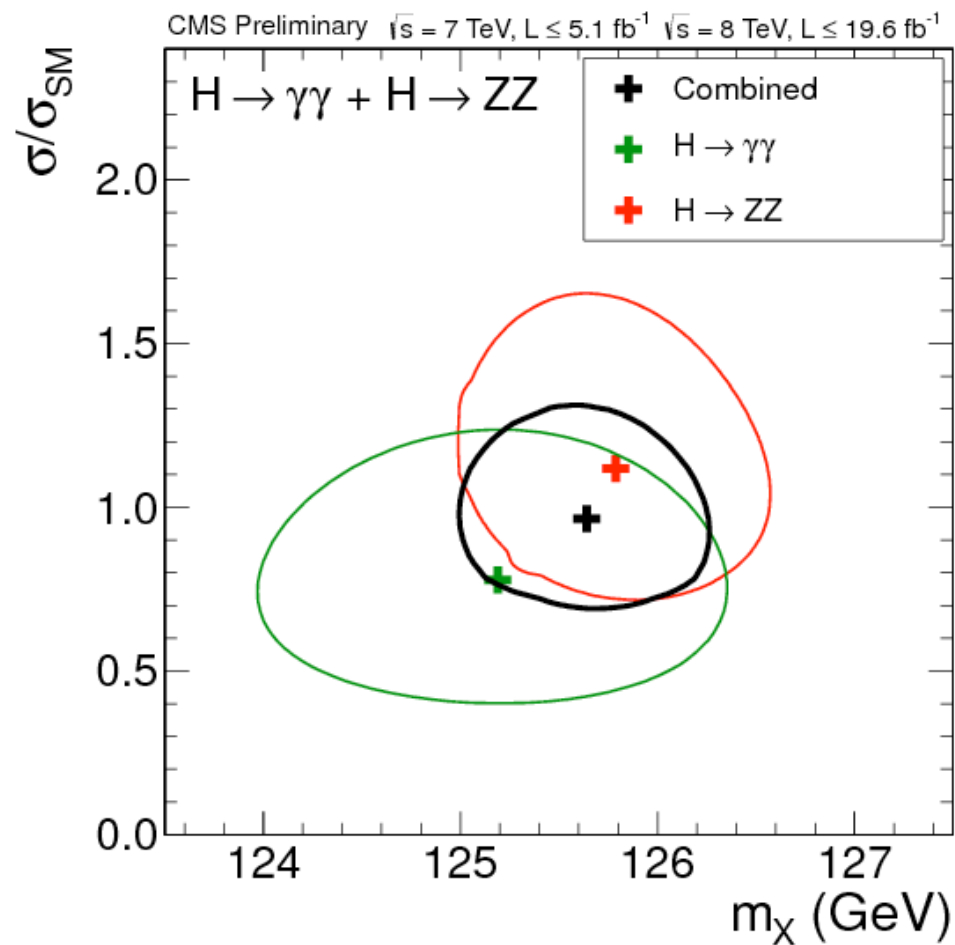
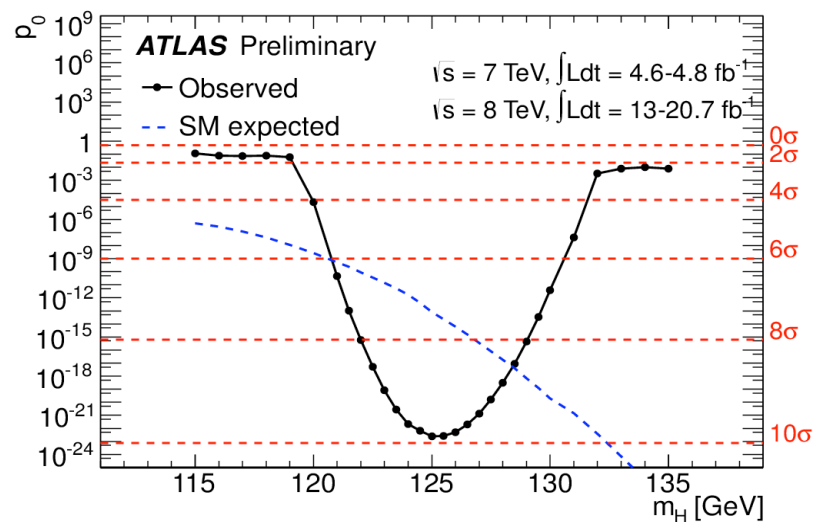
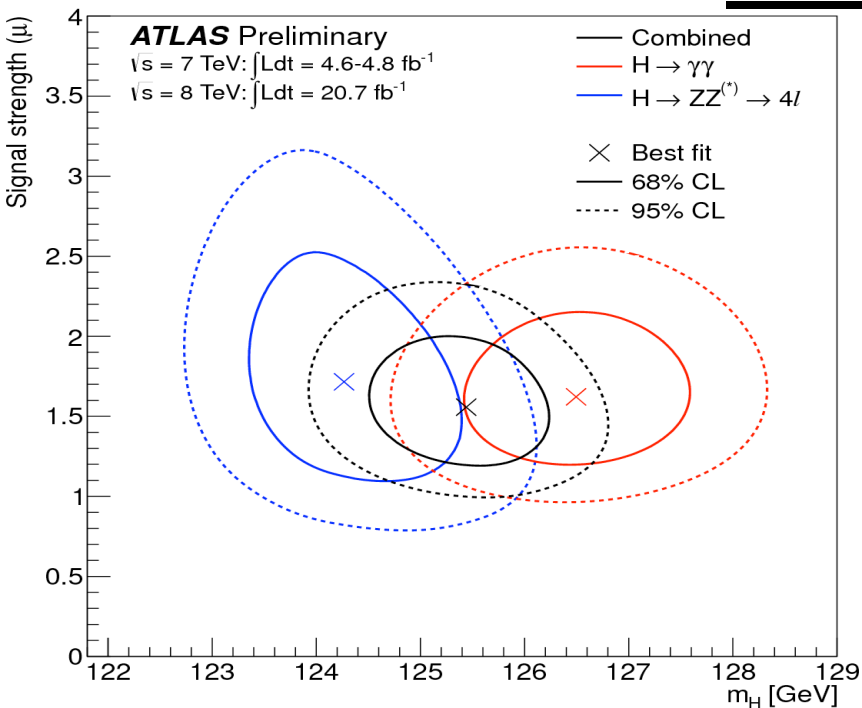


質量測定

- $\gamma\gamma$ vs ZZ



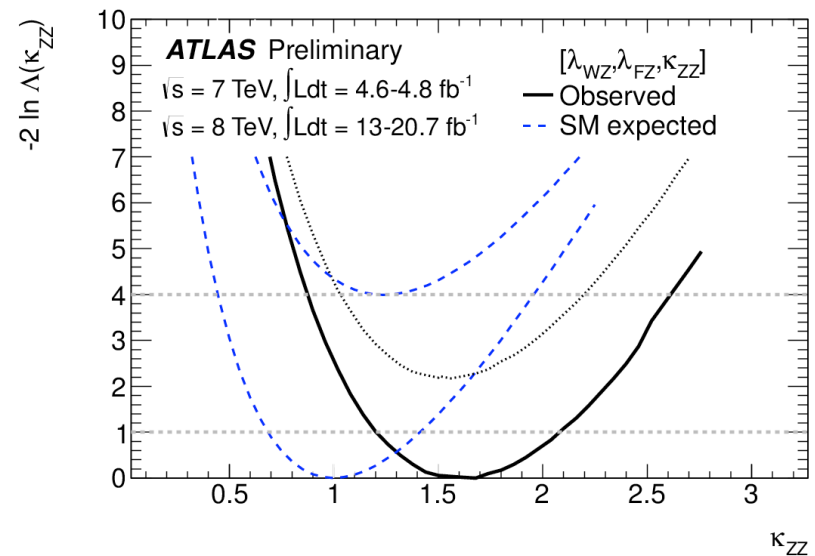
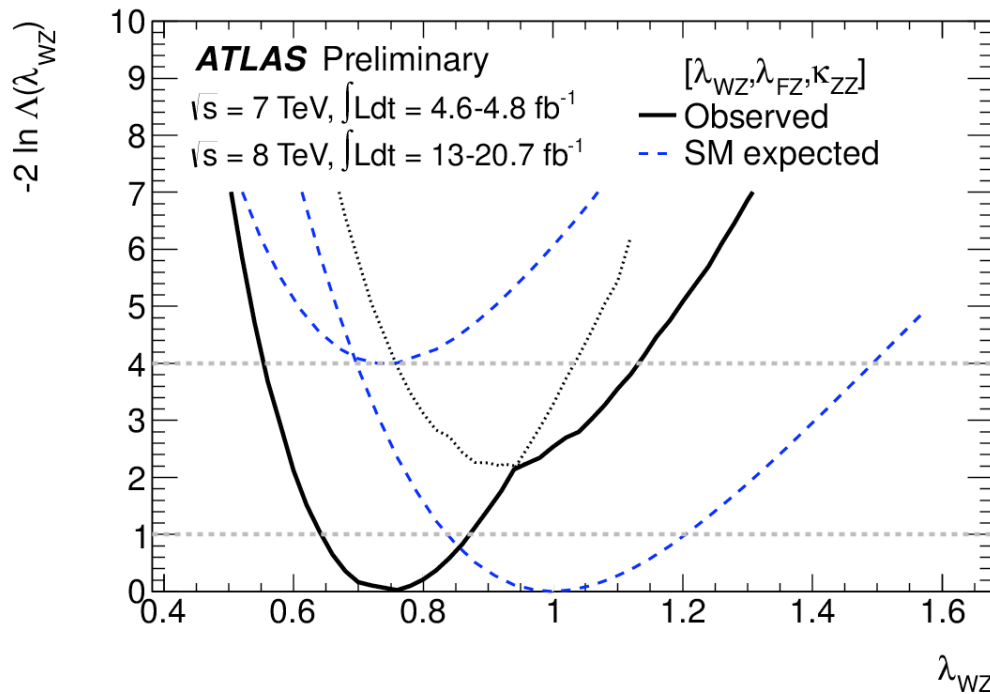
質量測定



器LHCが切り拓くテラス
 の素粒子物理学

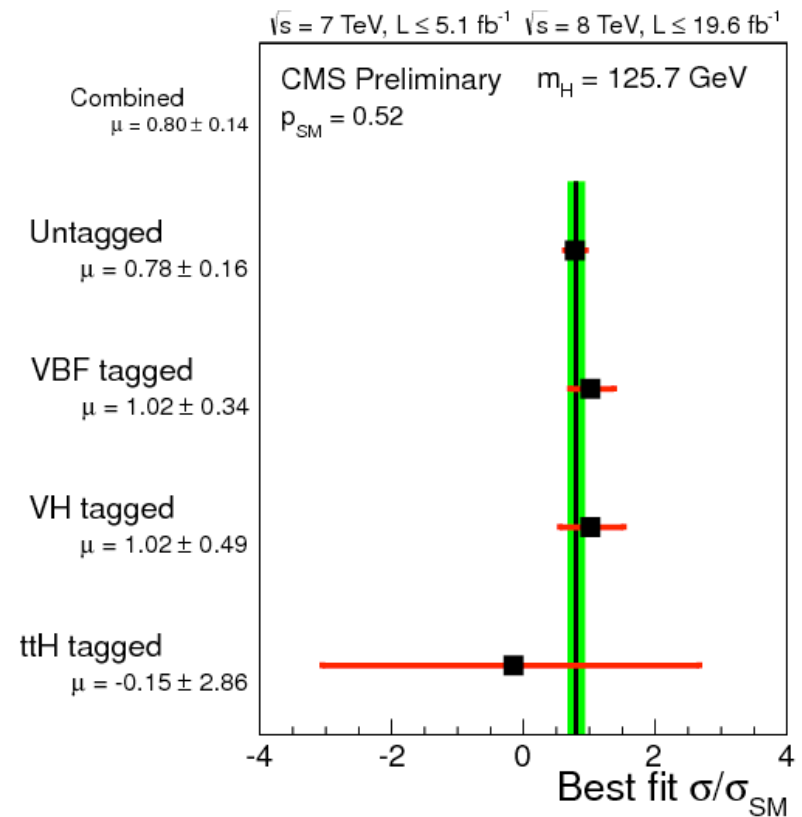
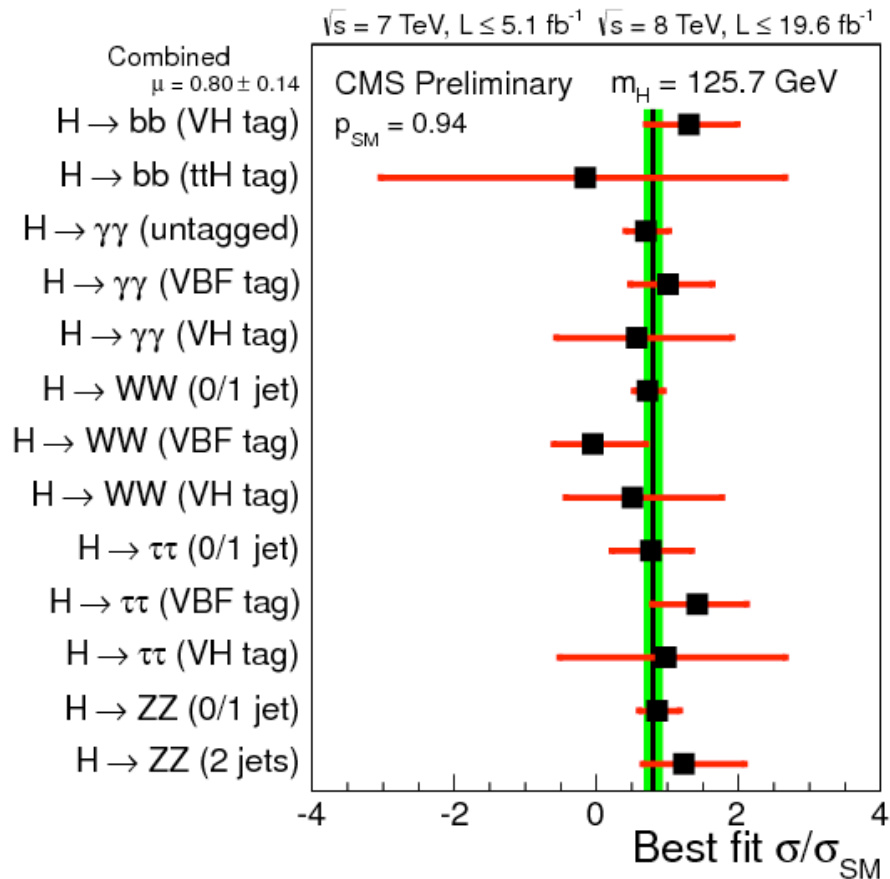
カップリング測定

- i. W,Z couplingの比($\lambda_{WZ} = \kappa_W / \kappa_Z$)を直接測定 : $SU(2)_V$ custodial symmetryと ρ パラメータの測定から $\lambda_{WZ} \sim 1$
- $H \rightarrow ZZ \rightarrow 4l : \kappa_Z$
 - $H \rightarrow \gamma\gamma, H \rightarrow WW \rightarrow l\nu l\nu : \kappa_W$



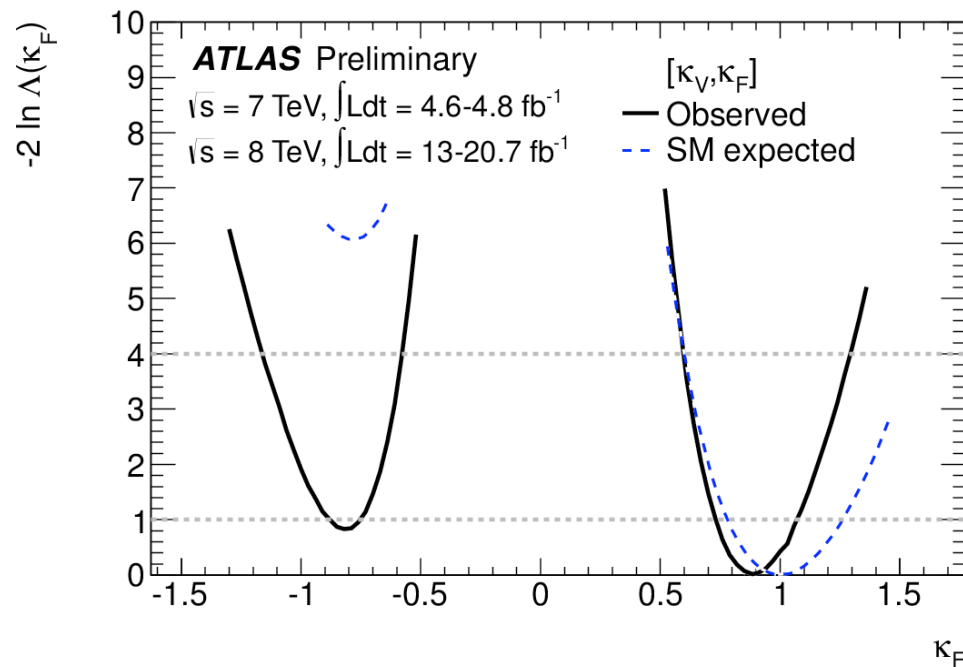
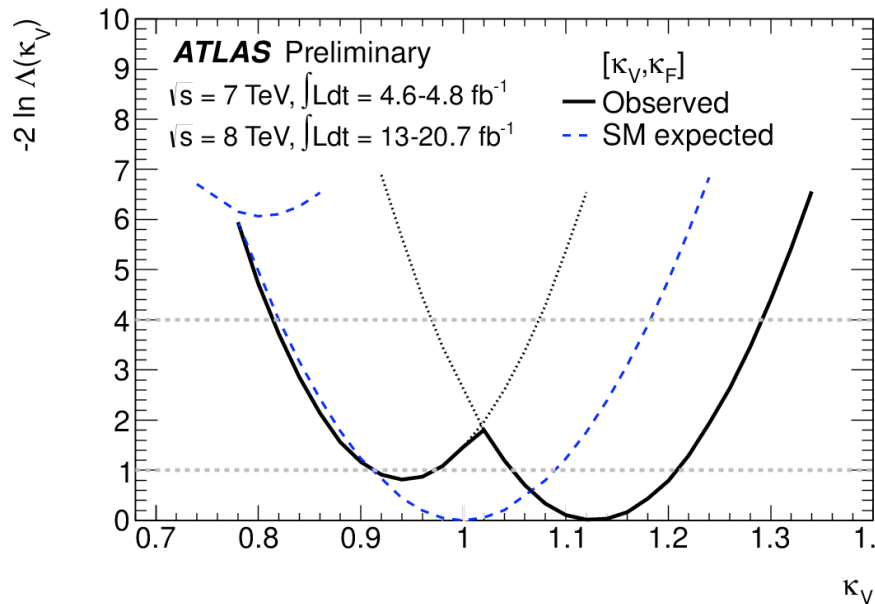
$\mu_{H \rightarrow ZZ \rightarrow 4l} (\sim 1.5) > \mu_{H \rightarrow WW \rightarrow l\nu l\nu} (\sim 1.0)$
 を反映

CMS



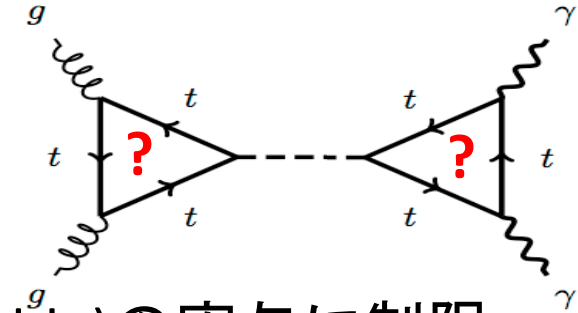
カップリング測定

- κ_V, κ_F 1D

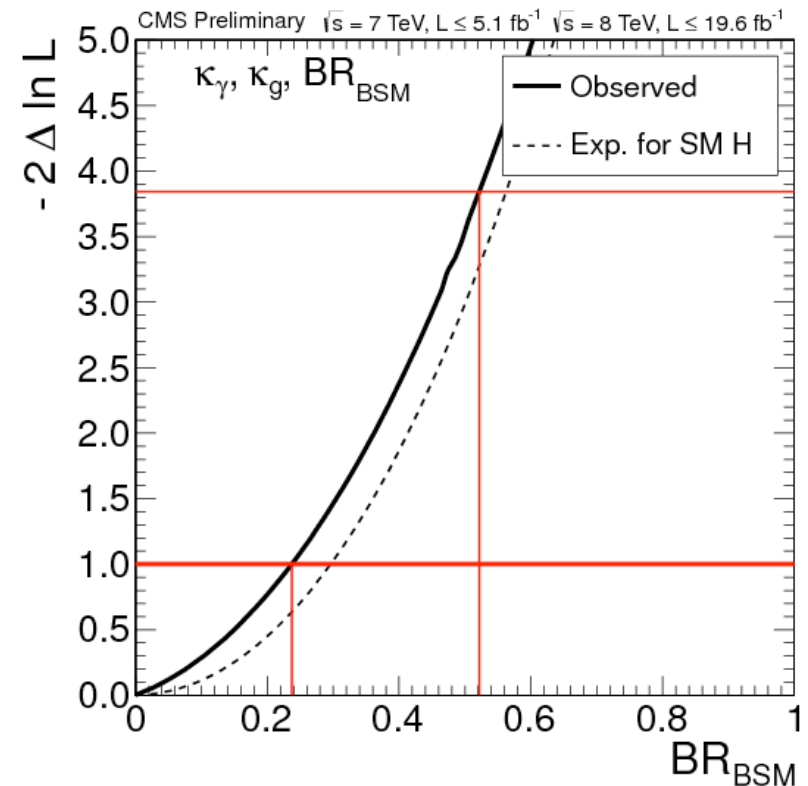
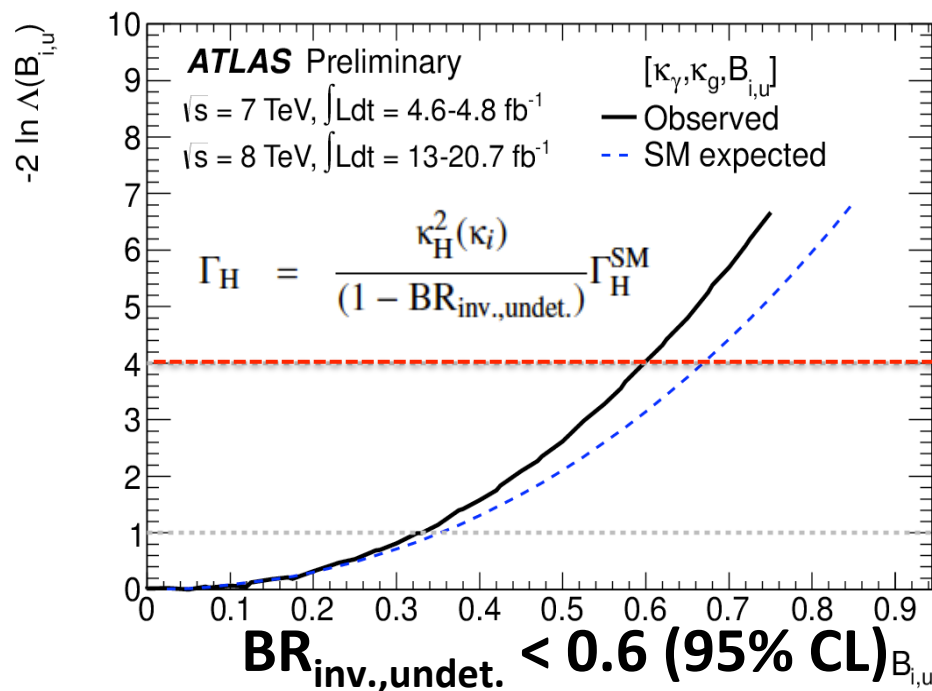


カップリング測定

- $gg \rightarrow H, H \rightarrow \gamma\gamma$ のloopにnon-SM粒子の寄与がある場合 $\rightarrow \kappa_g, \kappa_\gamma$ のズレが見える可能性



– 全崩壊幅もパラメータ (invisible, undetectable) の寄与に制限



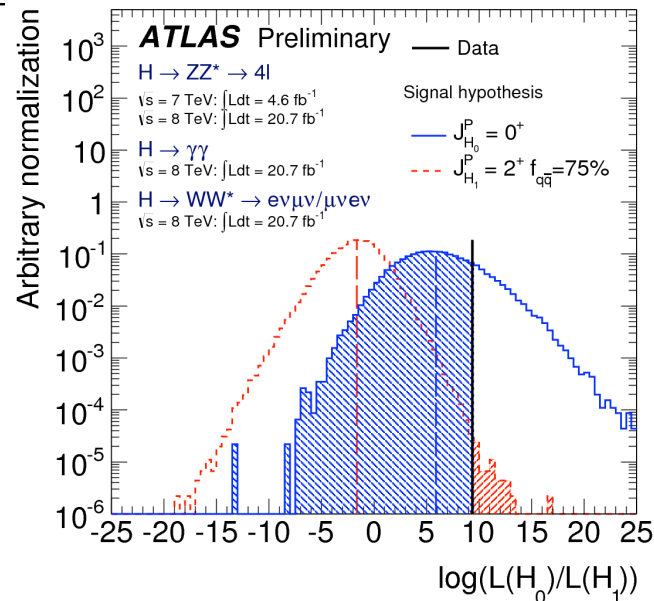
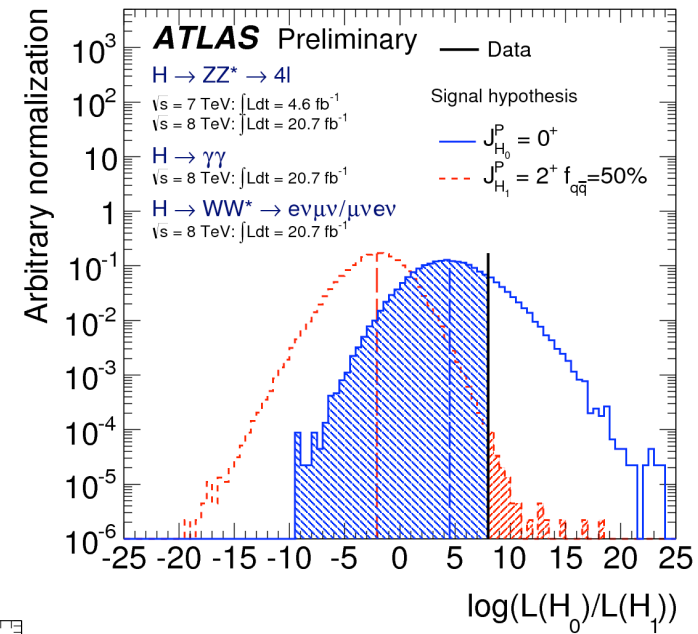
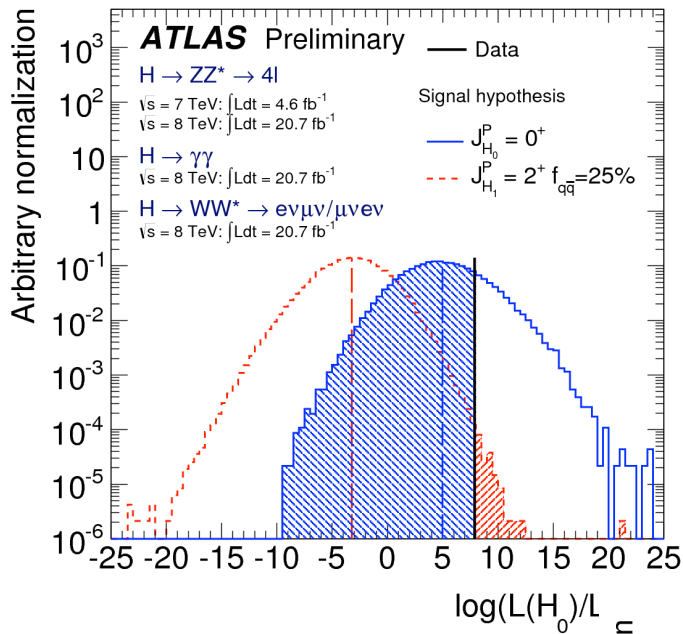
スピン2モデル

- graviton-like tensor(pseudo-tensor)

$$\begin{aligned}
 A(H \rightarrow VV) = \Lambda^{-1} & \left[2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \right. \\
 & + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f_{\mu\alpha}^{*2} + f^{*2,\mu\nu} f_{\mu\alpha}^{*1}) + g_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f_{\alpha\beta}^{*(2)} \\
 & + m_V^2 \left(2g_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
 & + g_8 \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + g_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\
 & \left. + \frac{g_{10} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)) \right],
 \end{aligned}$$

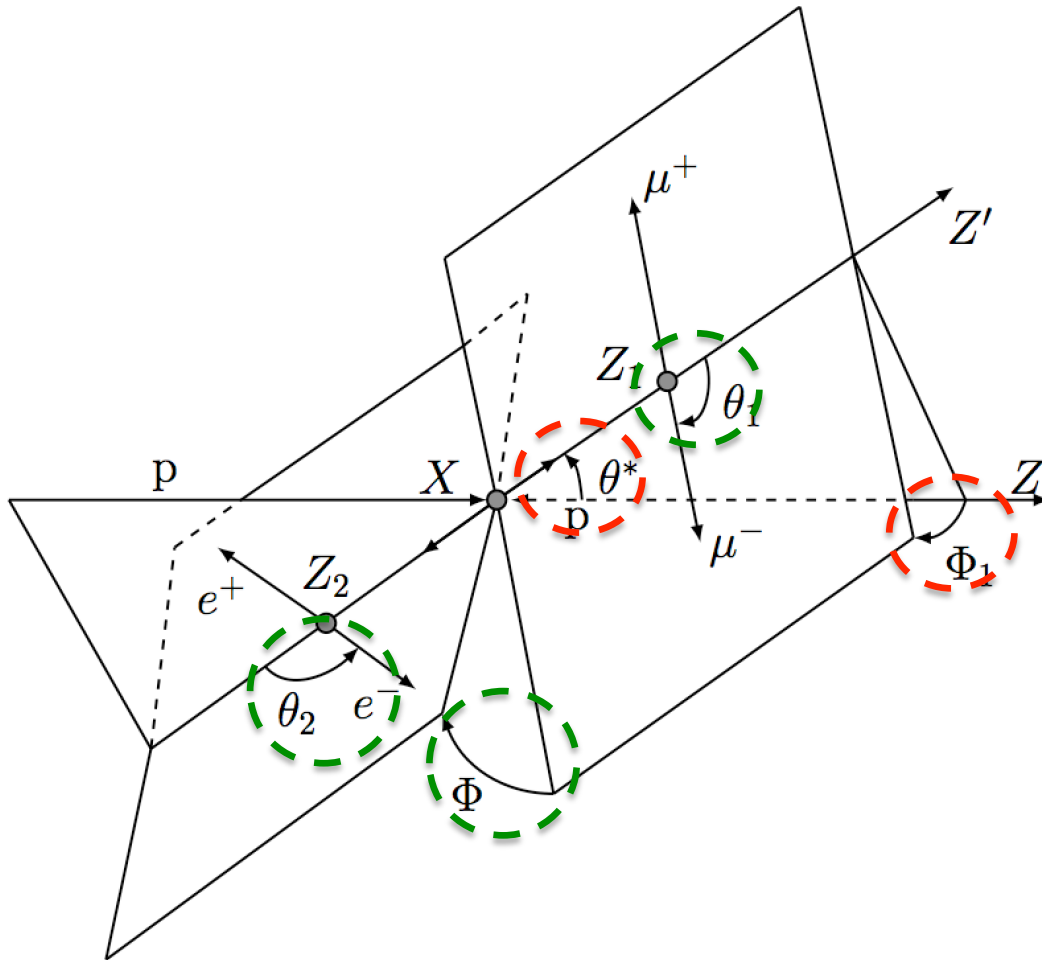
パラメータ g_1 - g_{10} を変えて spin 2^- , 2^+ をモデルする
 gluon-gluon fusion と qqbar annihilation が混在可能
 production の割合 (qq/qqbar) は スキャンする

スピン測定



スピン測定(ZZ→4l)

- 終状態が全て測定可能なZZ→4lは強力



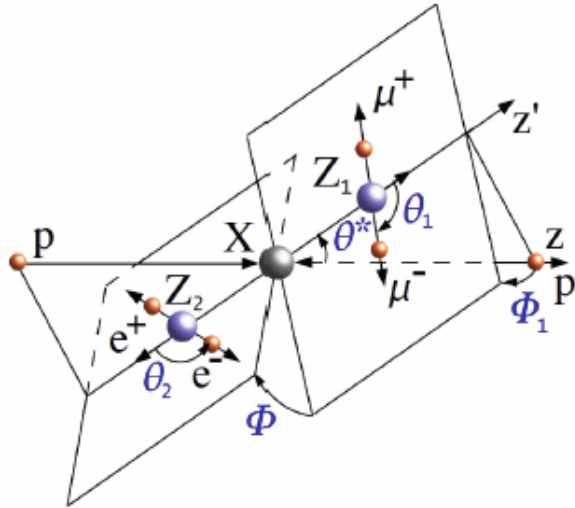
- θ_1, θ_2, Φ はパリティをを区別するとき有用
- これらの角度変数の他に m_{12}, m_{34} も用いる
- 一つ一つの変数は非力だがMVAで識別可能

$H \rightarrow ZZ \rightarrow 4l$ (CMS)

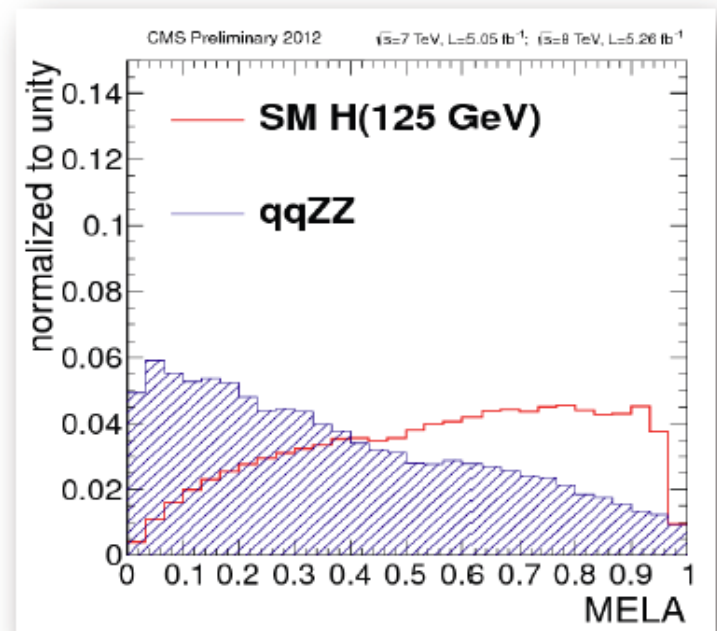
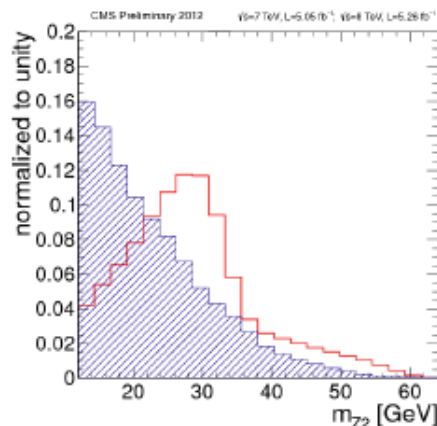
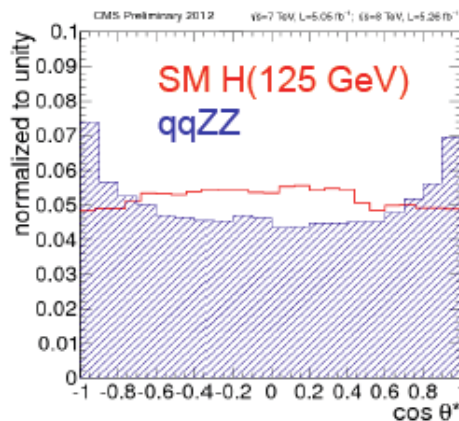
Matrix **E**lement **L**ikelihood **A**nalysis:
uses kinematic inputs for
signal to background discrimination

$$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$$

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4l})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4l})} \right]^{-1}$$

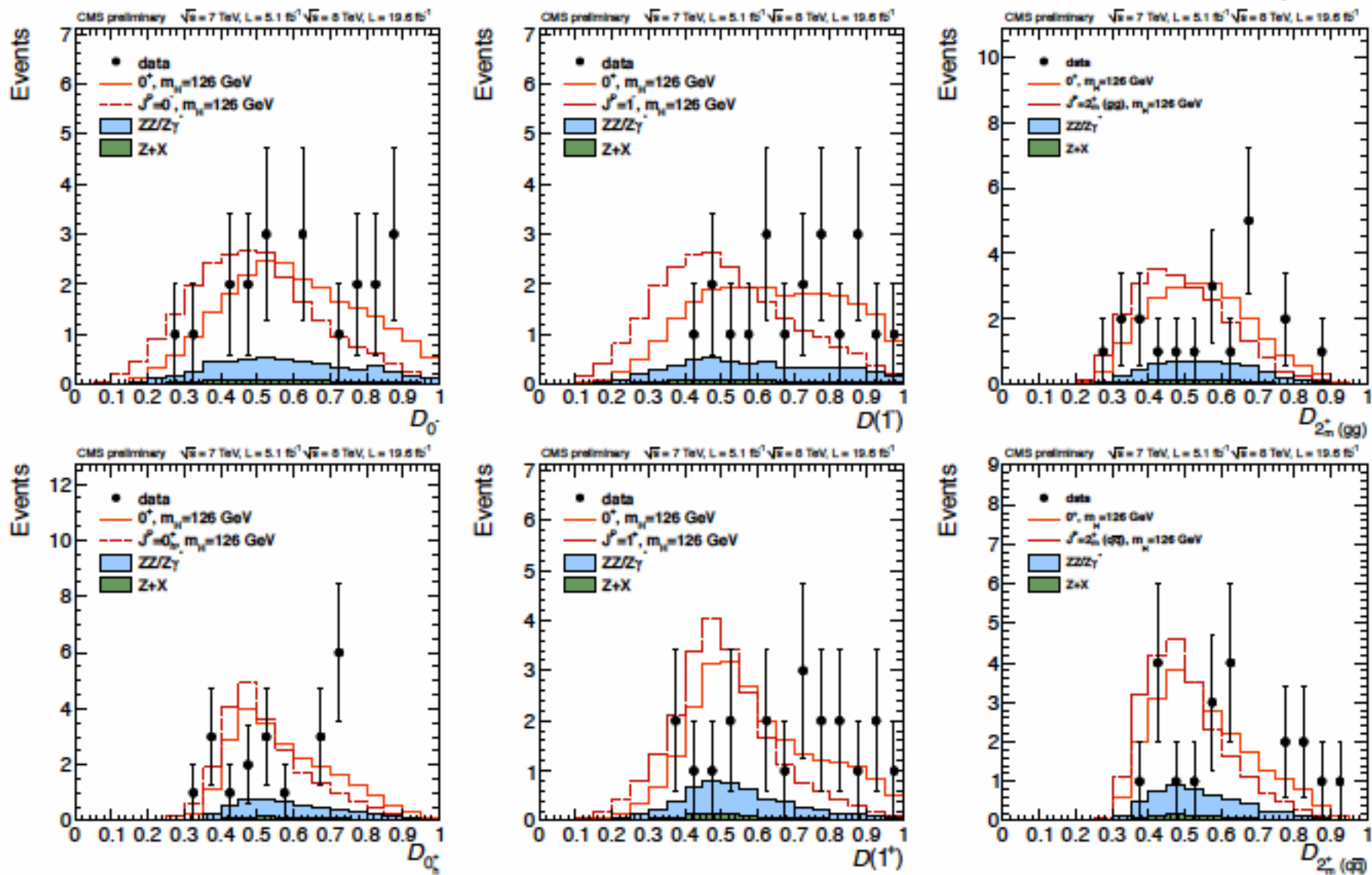


PRD81,075022(2010) <http://arxiv.org/abs/1001.3396>
PRD82,013003(2010) <http://arxiv.org/abs/1001.5300>



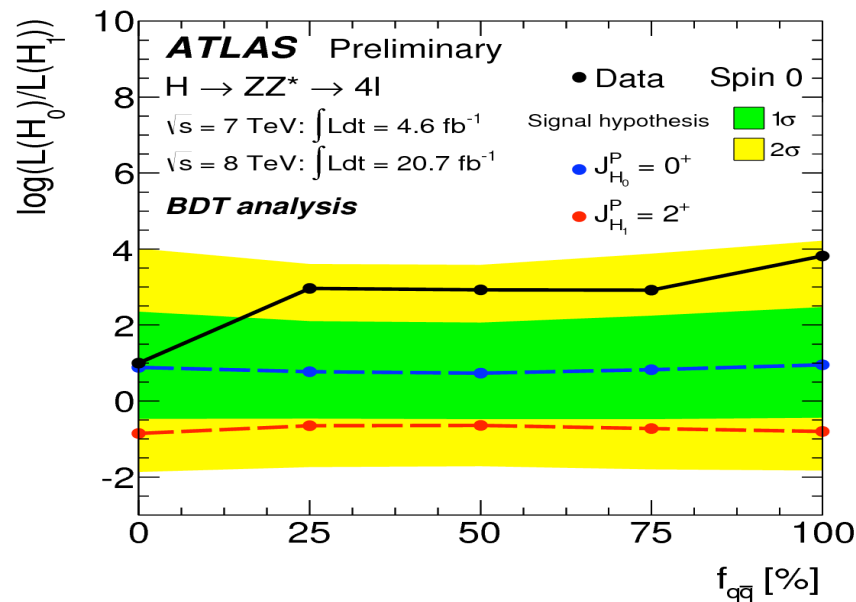
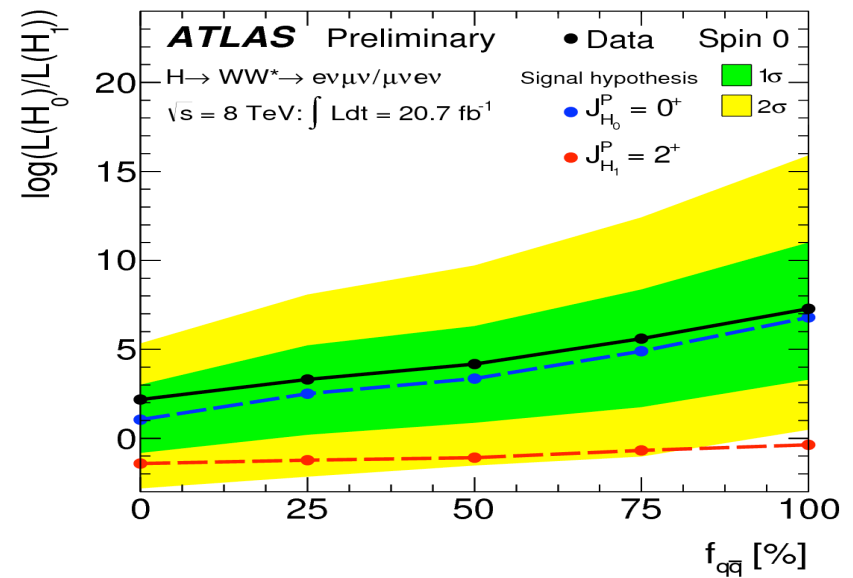
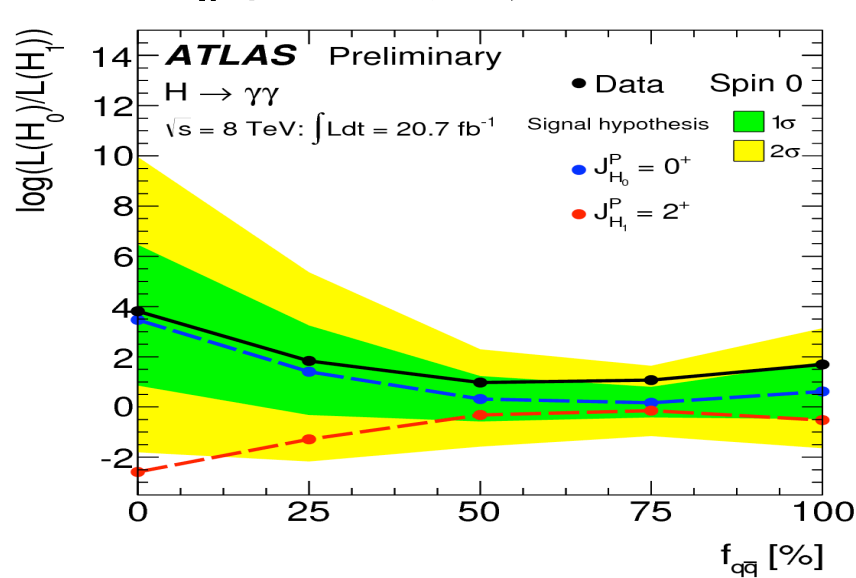
Discrimination with $m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1$

H $\rightarrow$ ZZ $\rightarrow$ 4l スピン/パリティ測定



スピン測定(0^+ vs 2^+)

個々のチャンネル



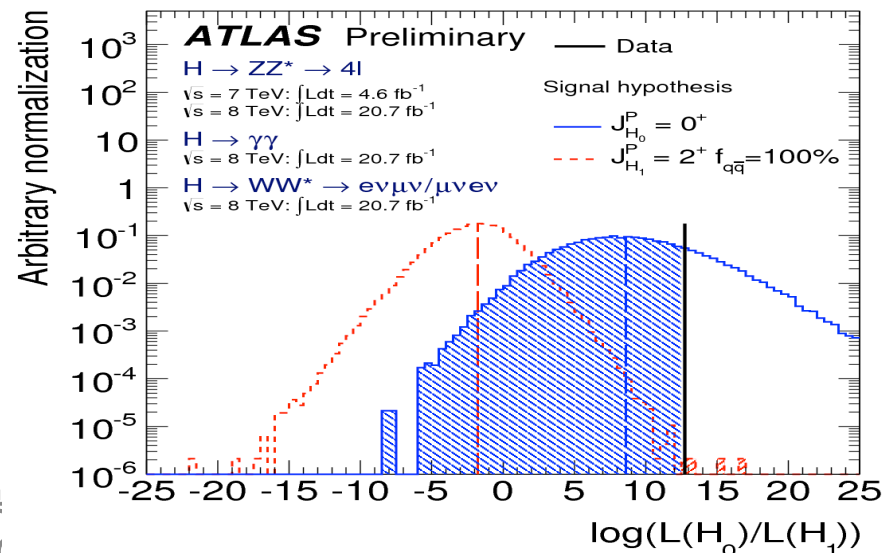
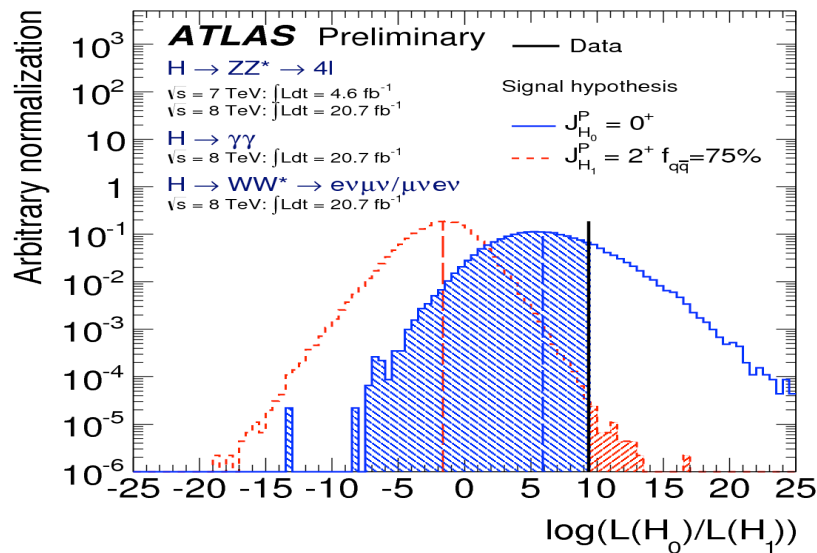
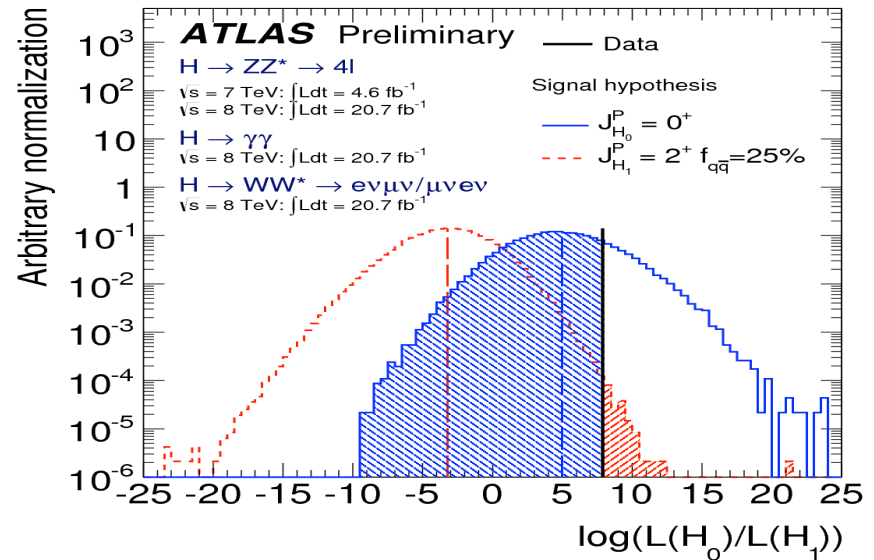
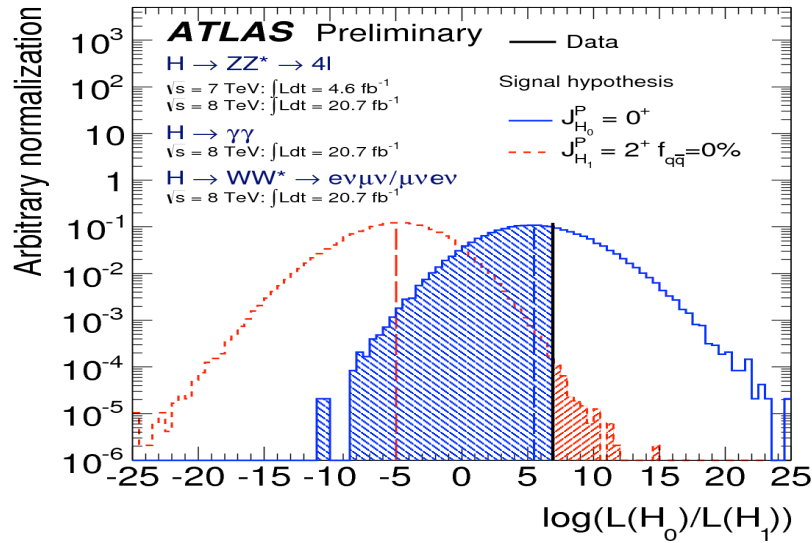
$H \rightarrow \gamma\gamma$: qq の割合が少ないときに分離能力が高い

$H \rightarrow WW \rightarrow l\nu l\nu$: qq の割合が多いときに分離能力が高い

$H \rightarrow ZZ \rightarrow 4l$: qq の割合によらない

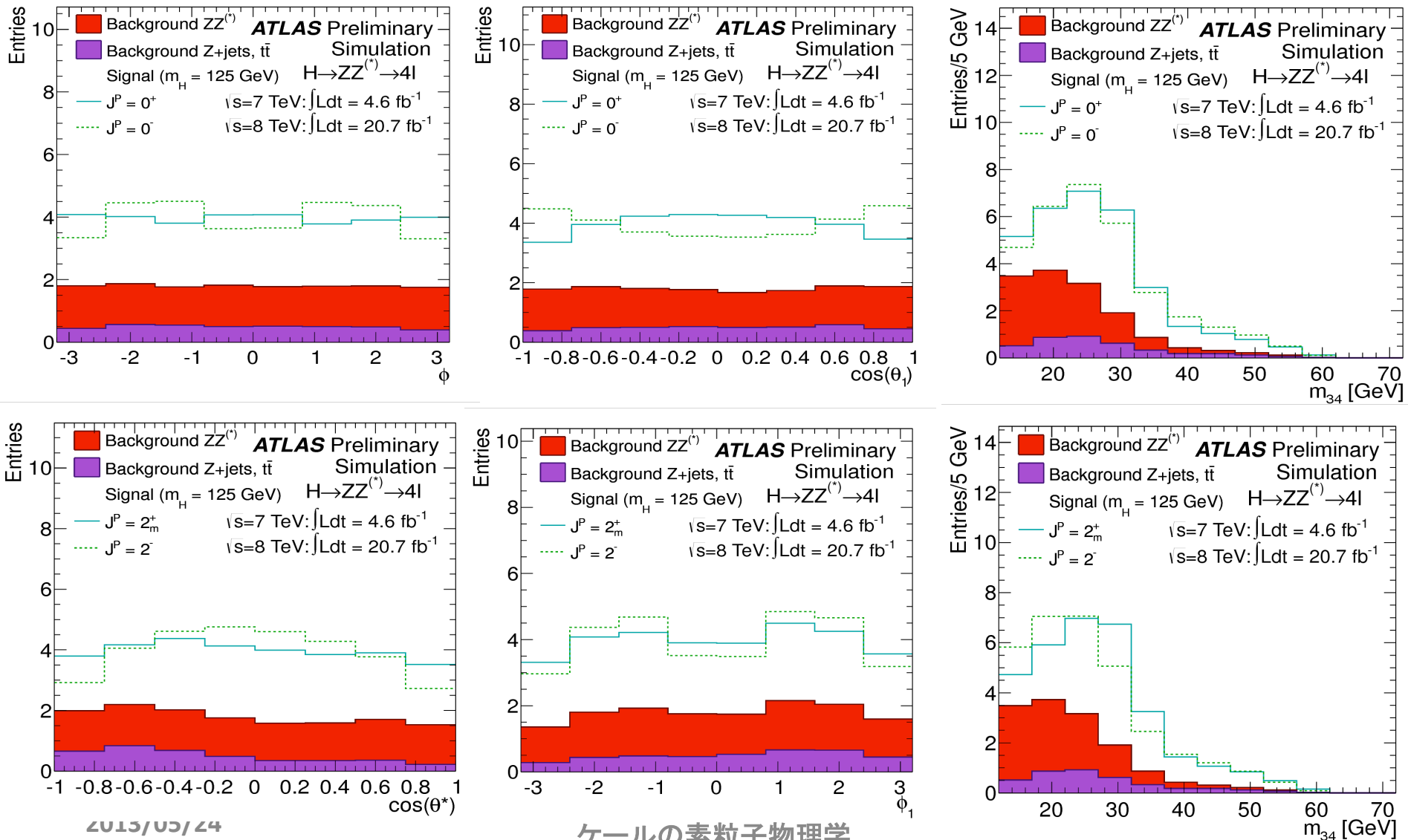
スピン測定(0^+ vs 2^+)

- $H \rightarrow \nu\nu$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4l$ コンビネーション



スピン測定($ZZ \rightarrow 4l$)

- 終状態が全て測定可能な $ZZ \rightarrow 4l$ は強力



ヒッグス!?を見つけた

ATLAS実験

“Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”

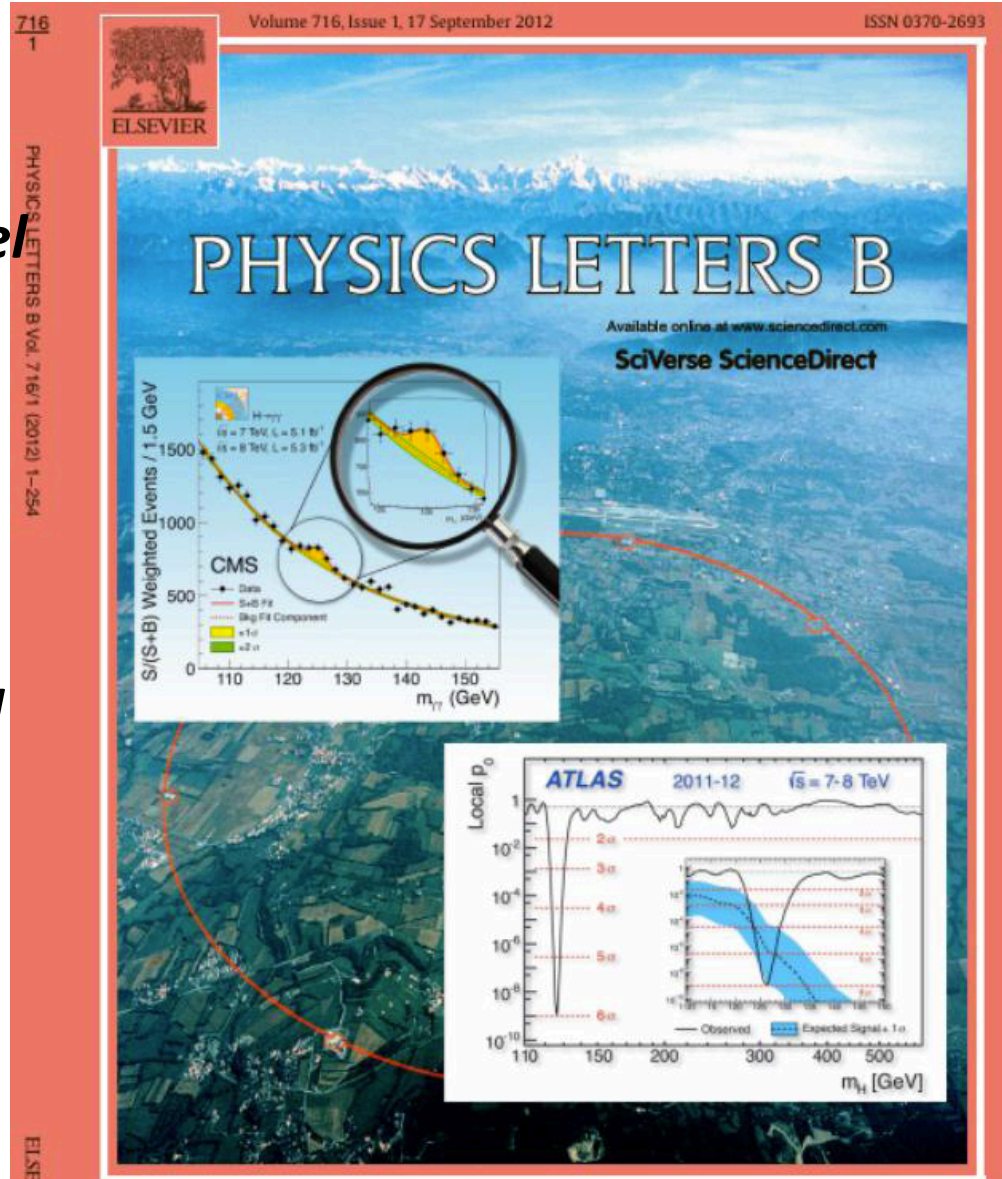
Physics Letters B 716 (2012) 1-29

CMS実験

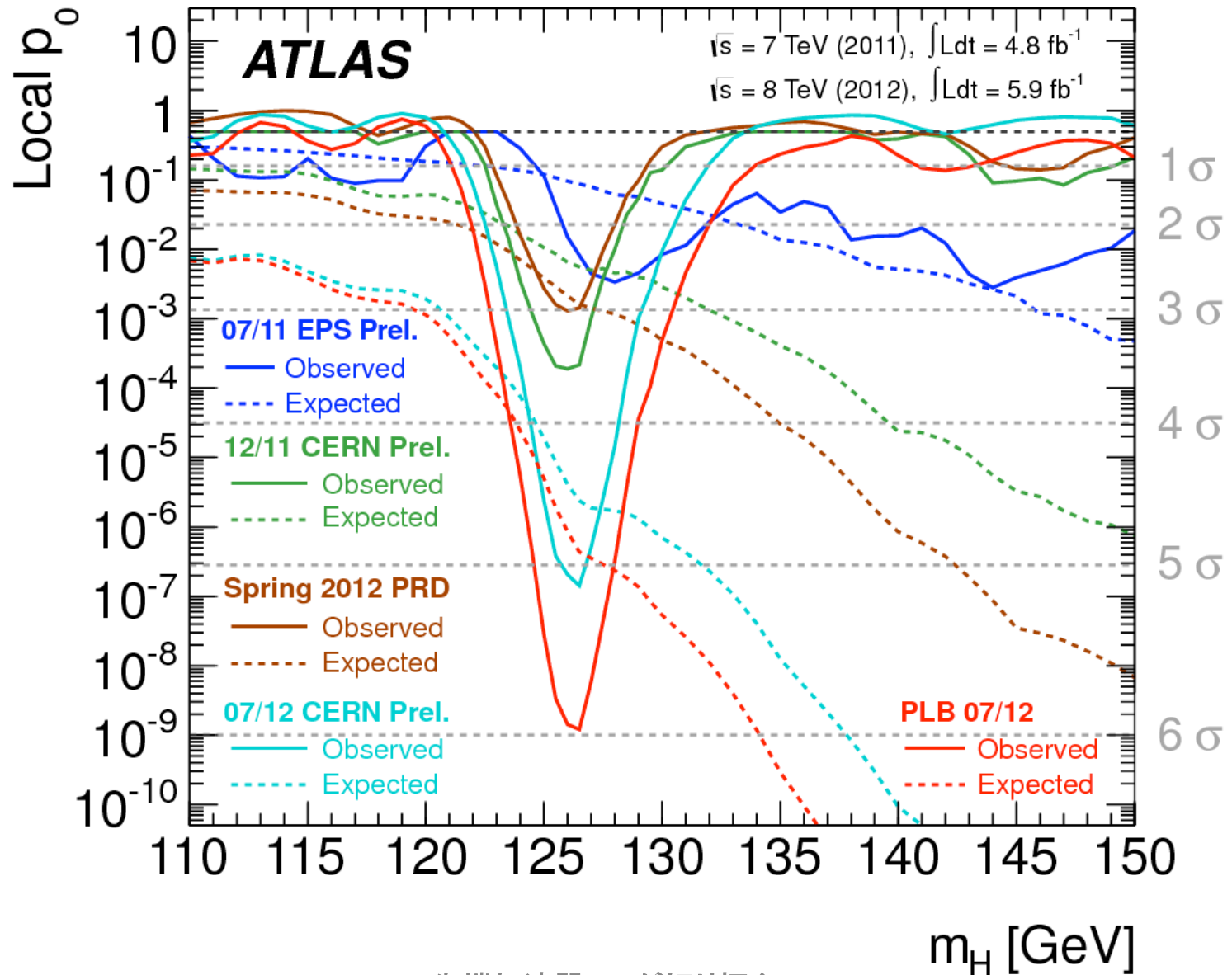
“Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”

Physics Letters B 716 (2012) 30-61

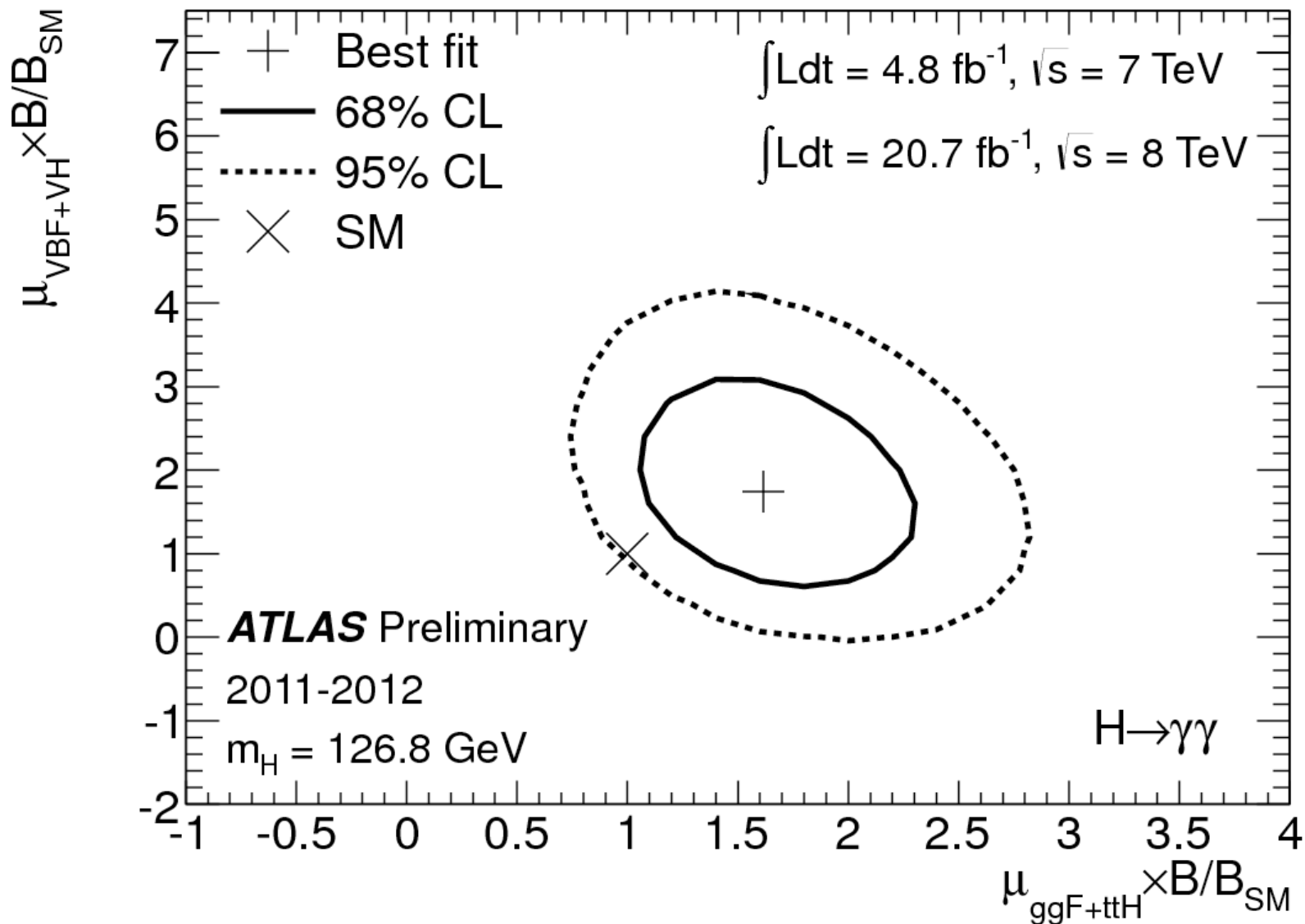
“Search for the Standard Model Higgs boson in the $H \rightarrow WW \rightarrow l\nu l\nu$ decay mode with 4.7fb^{-1} ATLAS data at $\sqrt{s}=7\text{TeV}$ ”
Physics Letters B 716 (2012) 62-81



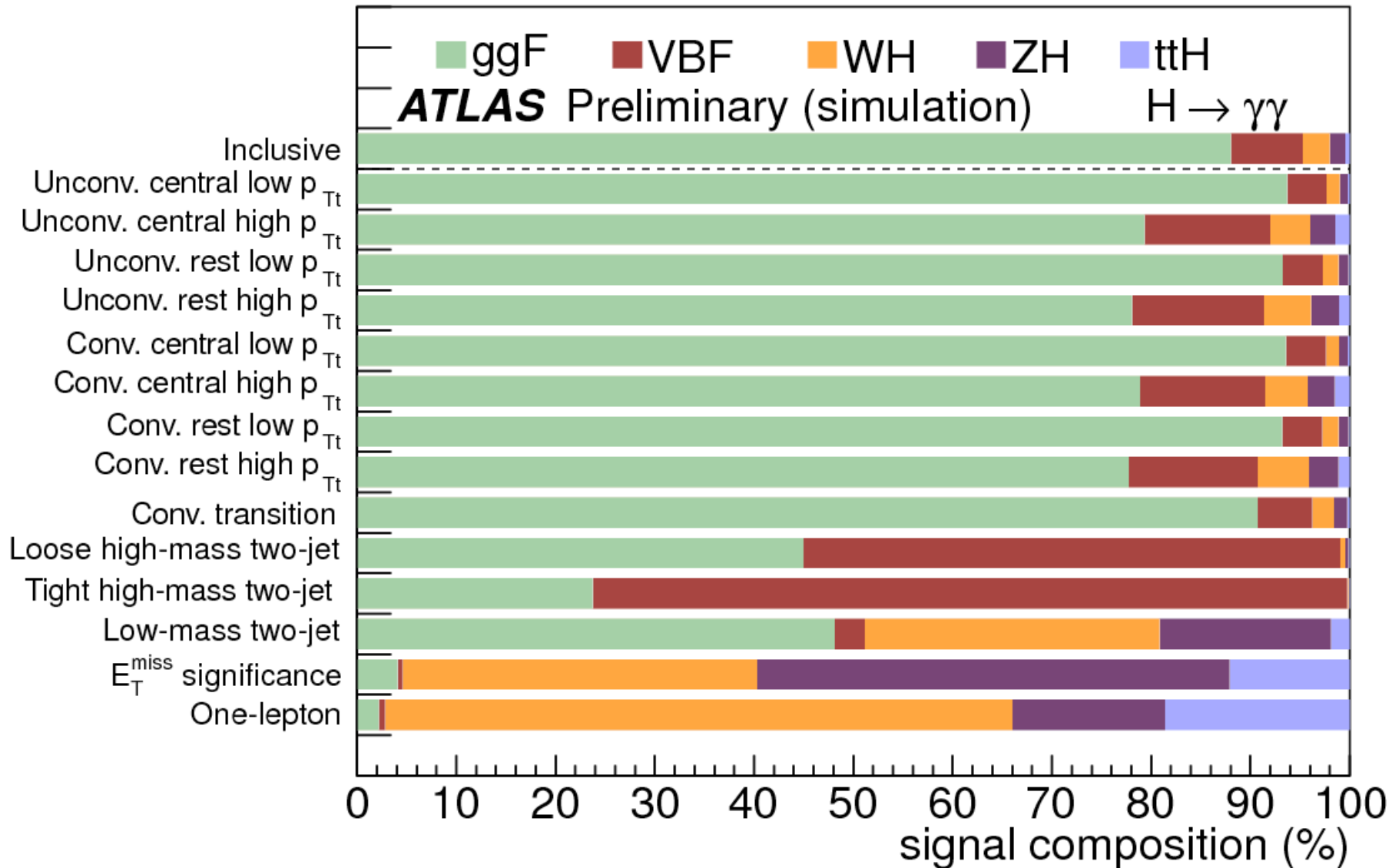
ヒッグス探索の歴史



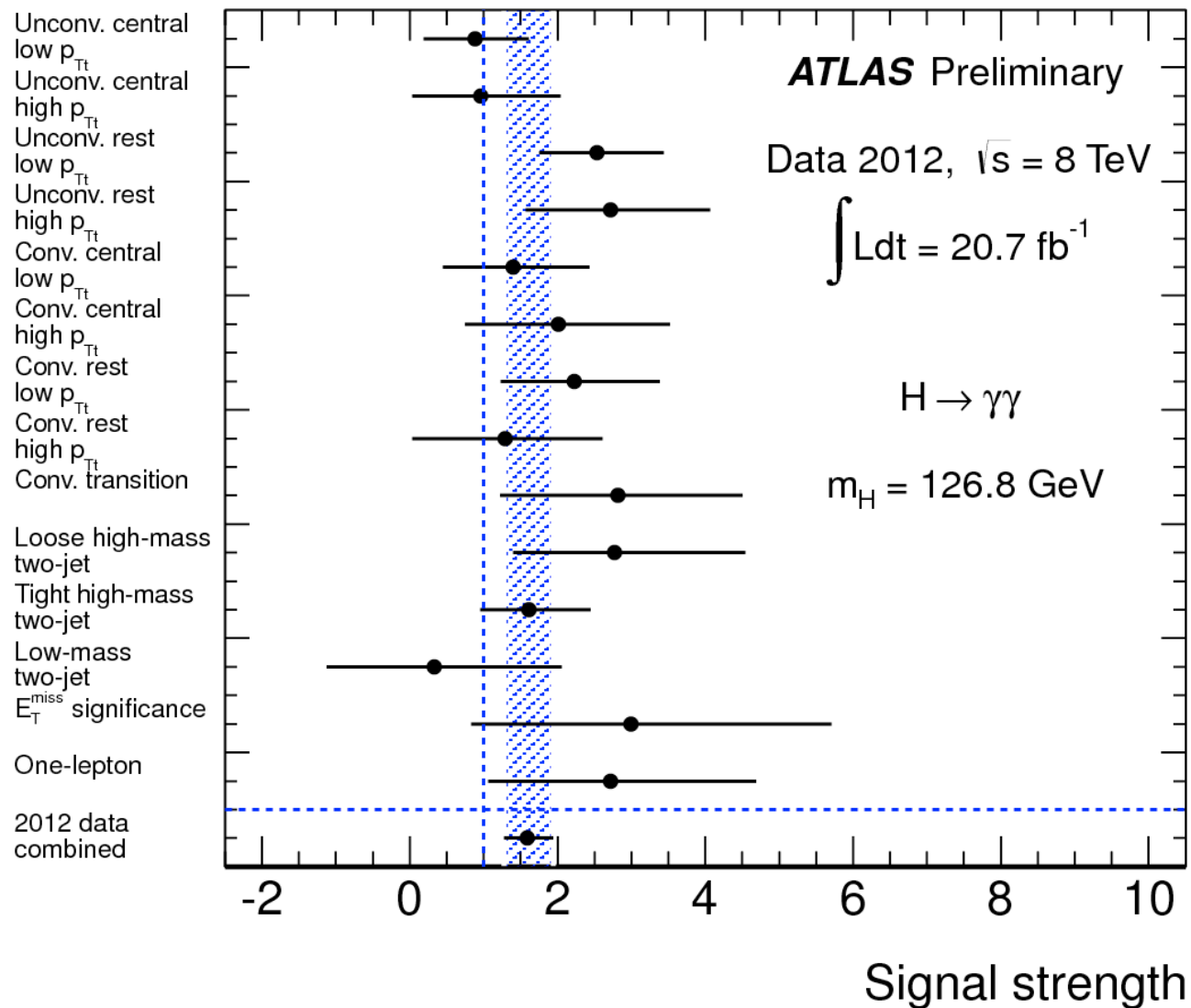
ggF vs VBF



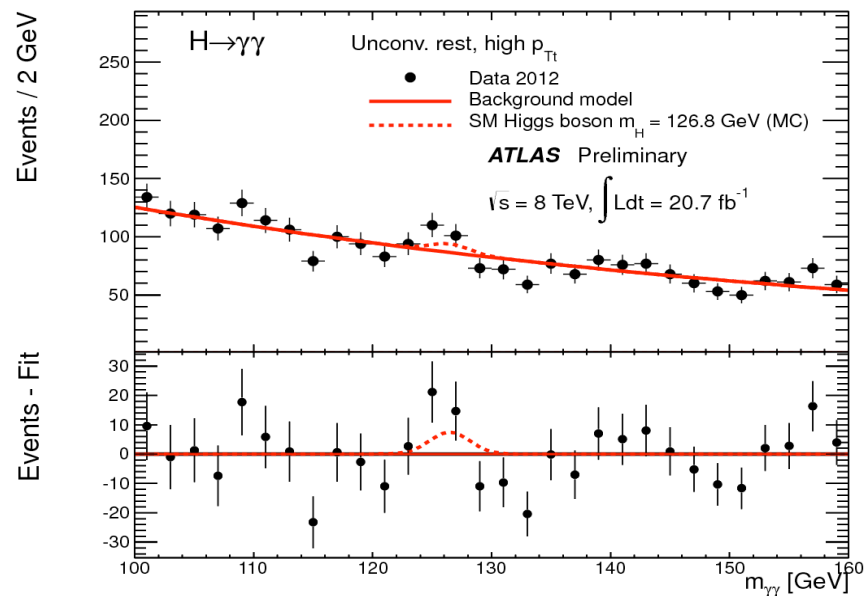
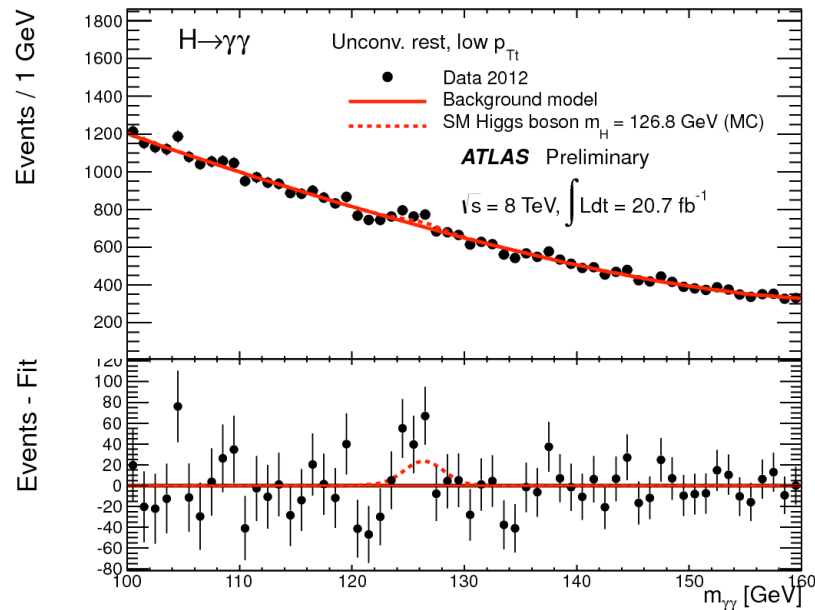
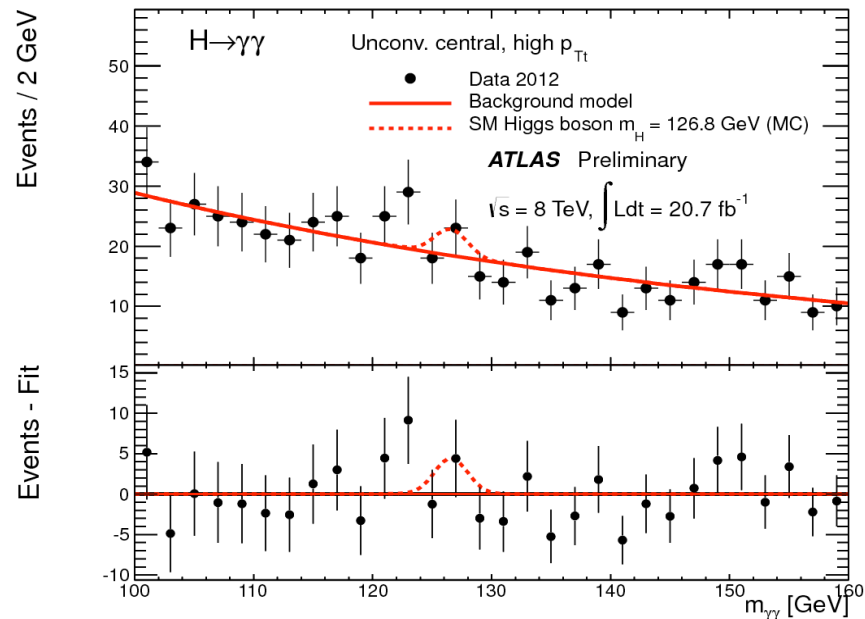
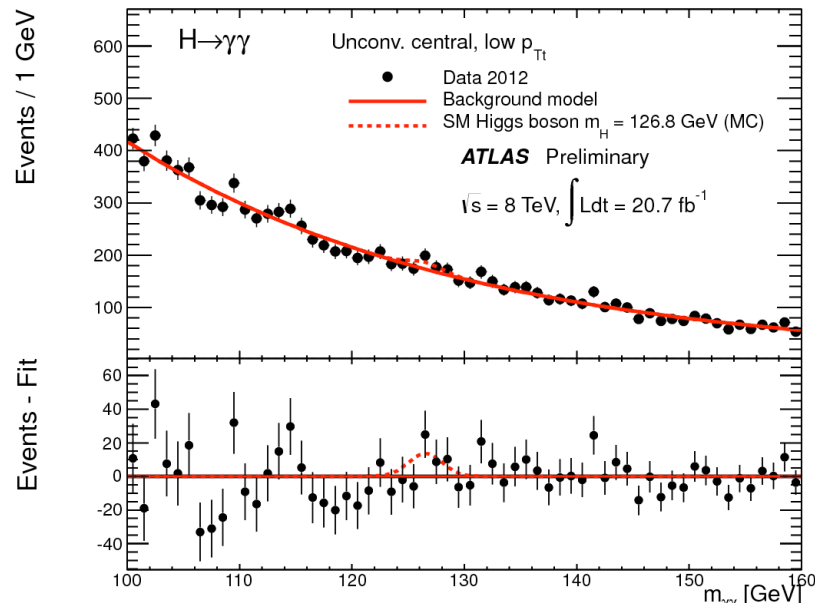
$H \rightarrow \gamma\gamma$ (カテゴリー別)



$H \rightarrow \gamma\gamma$ (カテゴリー別)

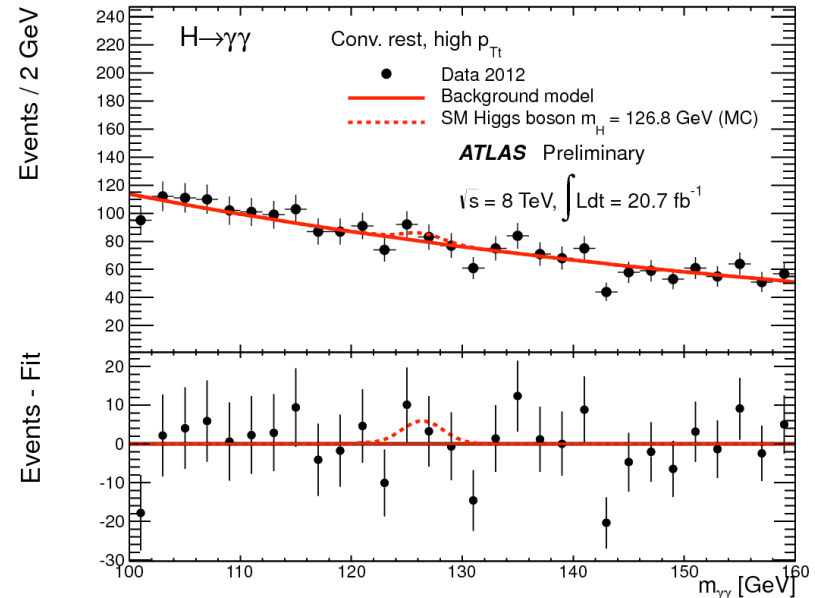
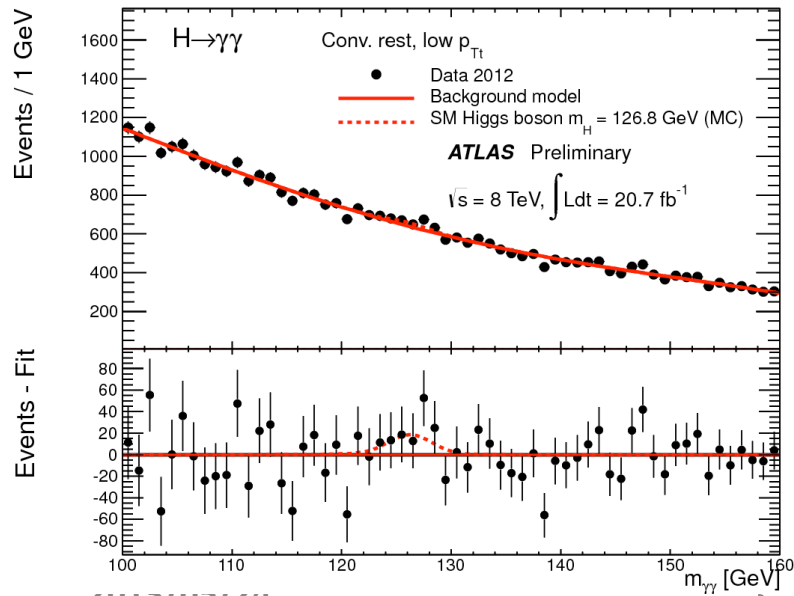
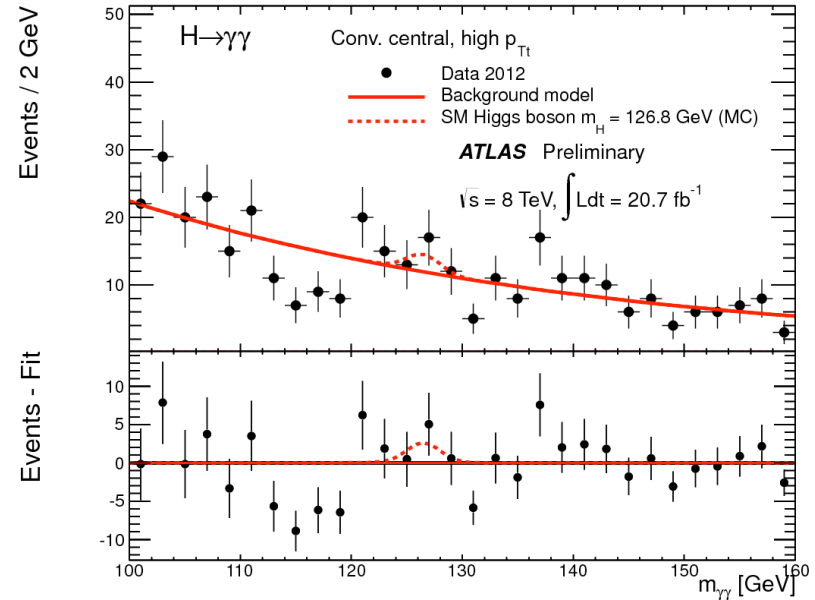
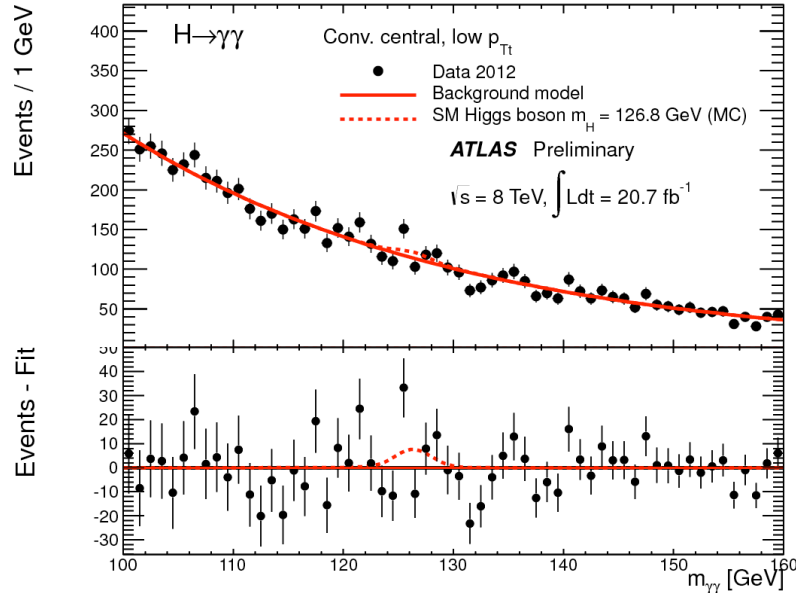


$H \rightarrow \gamma\gamma$ (ggFカテゴリー)

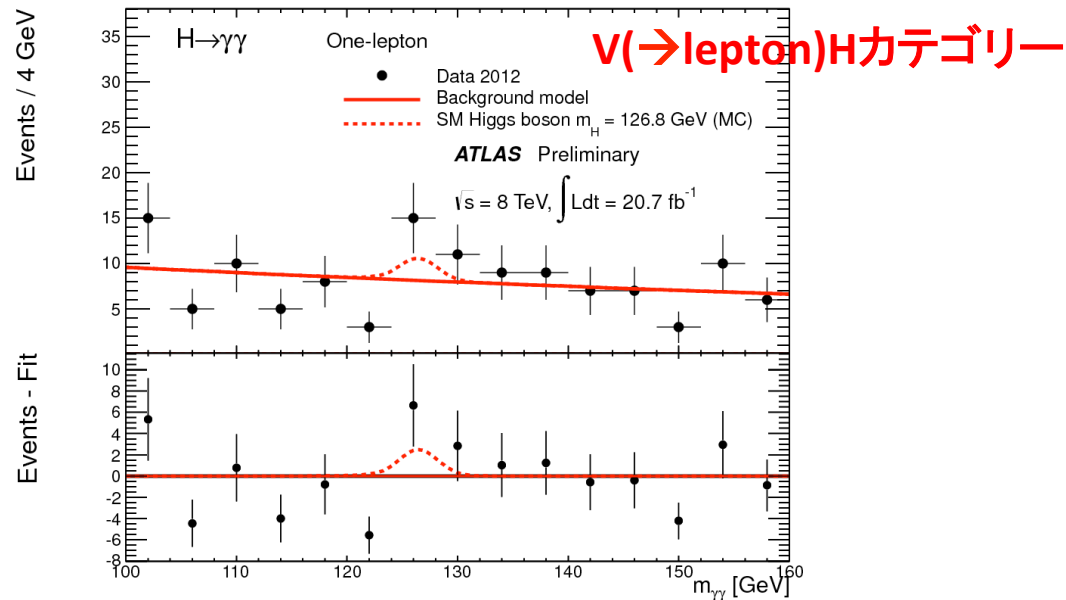
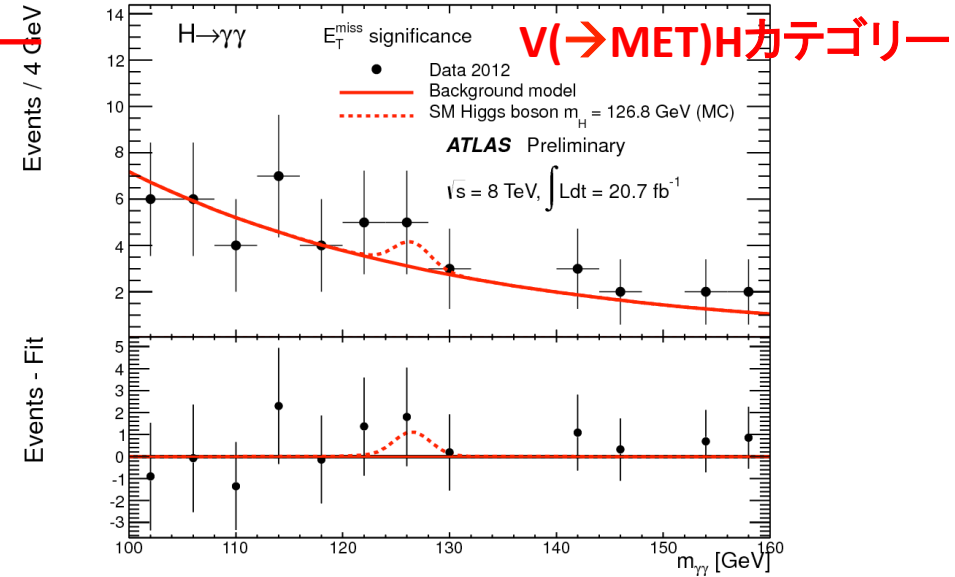
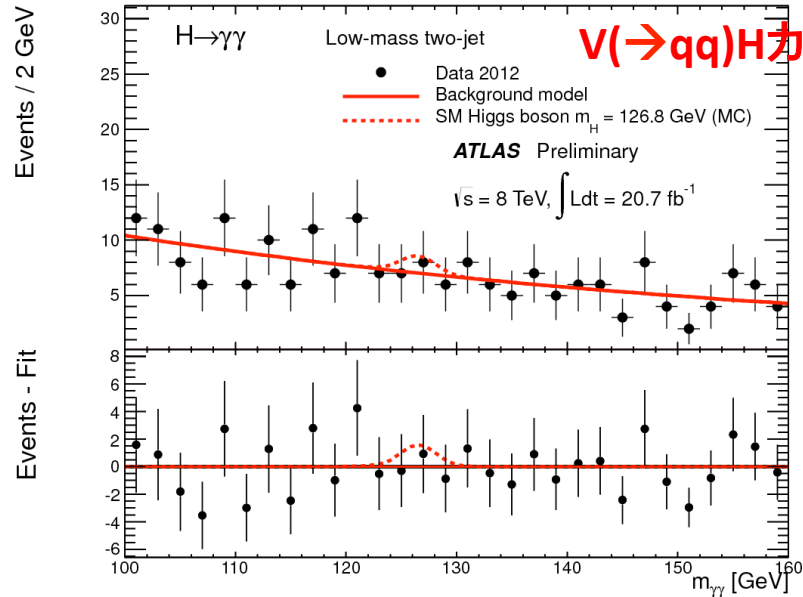


2015/05/24

$H \rightarrow \gamma\gamma$ (ggFカテゴリー)

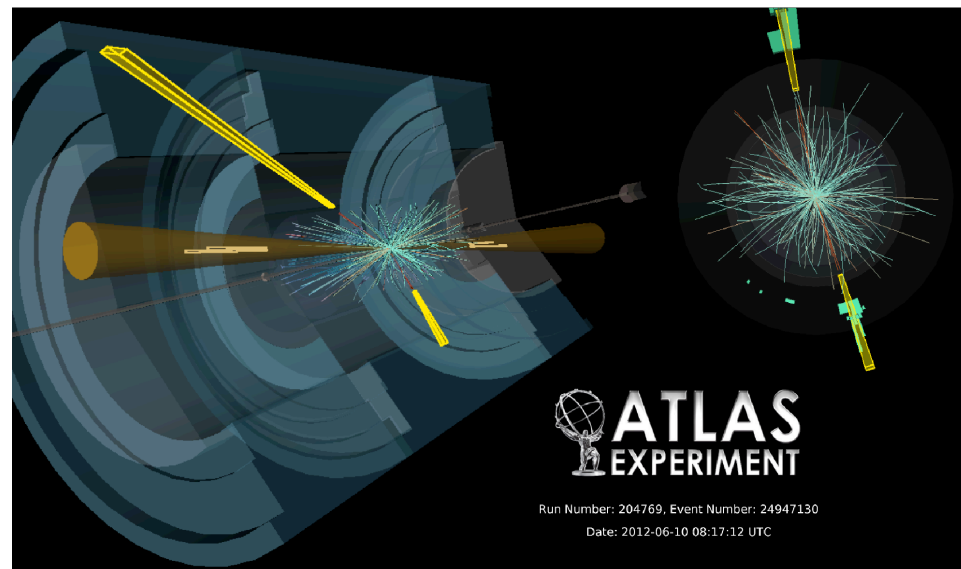
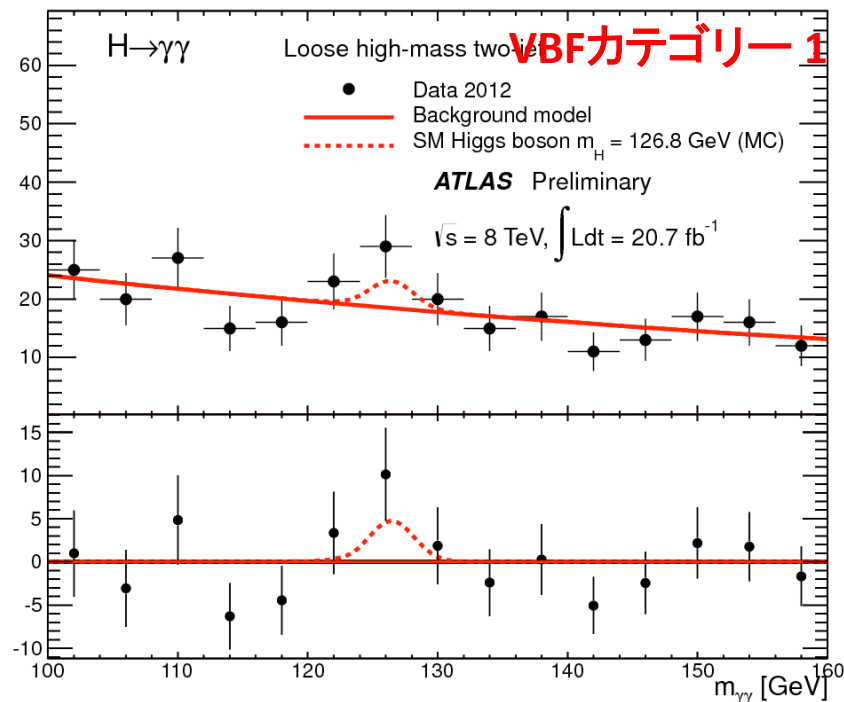


$H \rightarrow \gamma\gamma$ (VHカテゴリー)



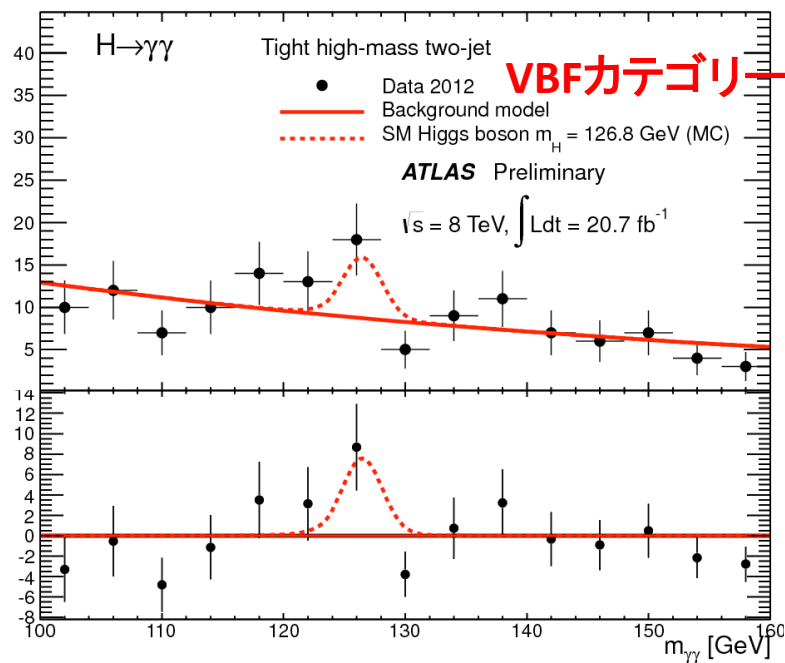
$H \rightarrow \gamma\gamma$ (VBFカテゴリー)

Events / 4 GeV



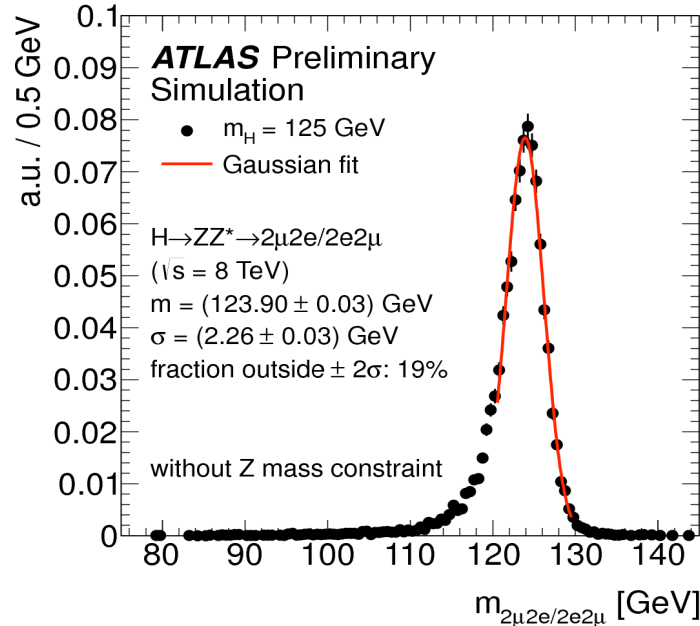
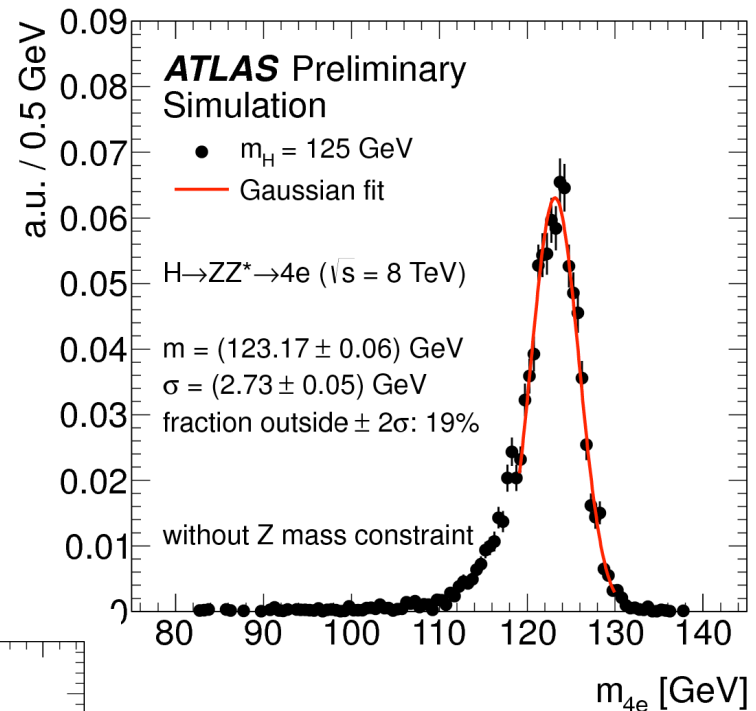
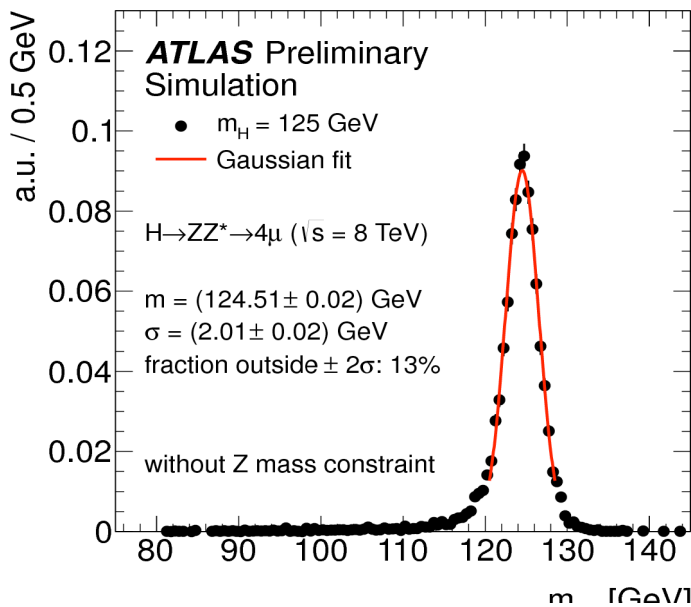
Events / 4 GeV

Events - Fit



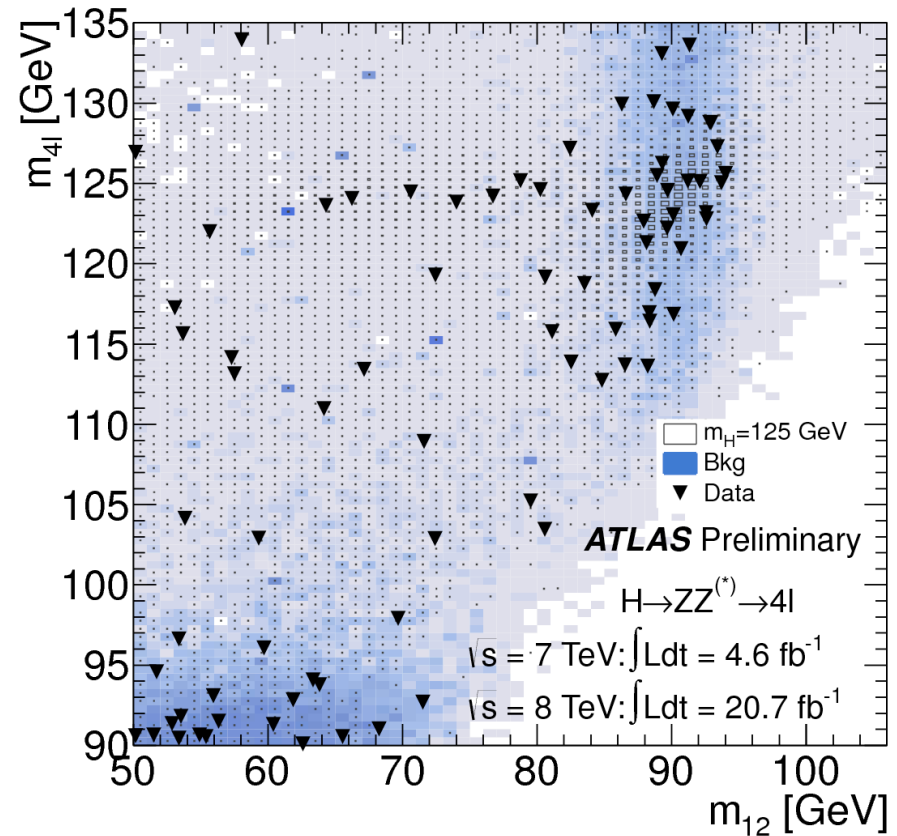
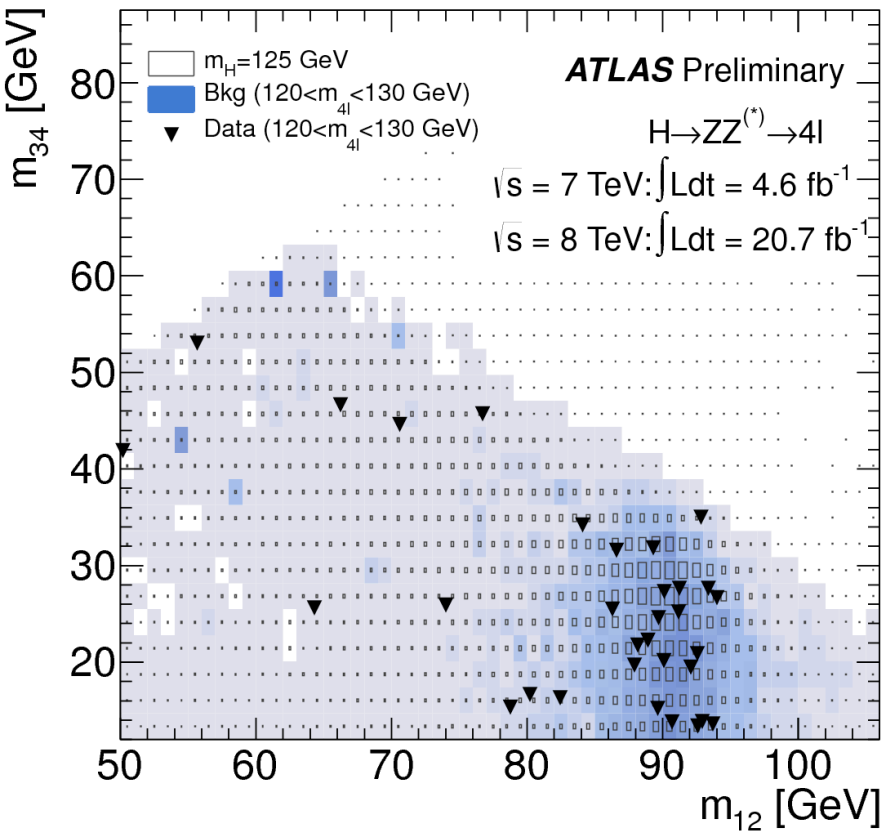
• a

$H \rightarrow ZZ \rightarrow 4l$ Signal Mass Shape



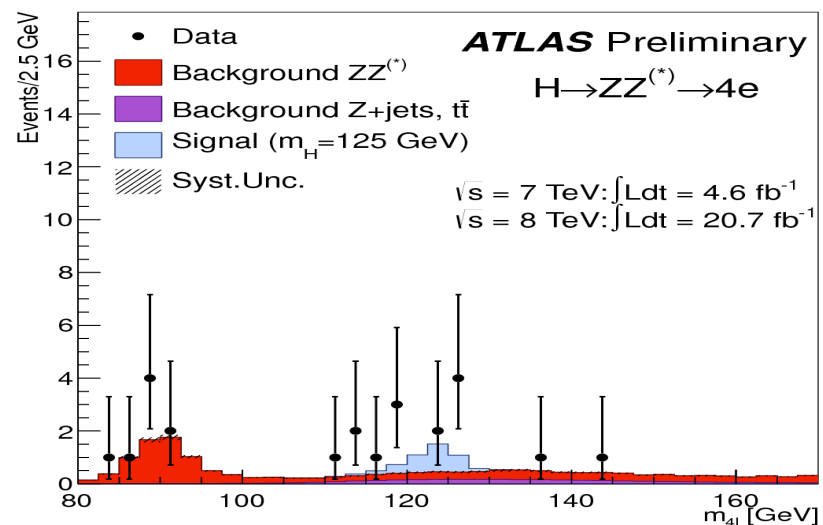
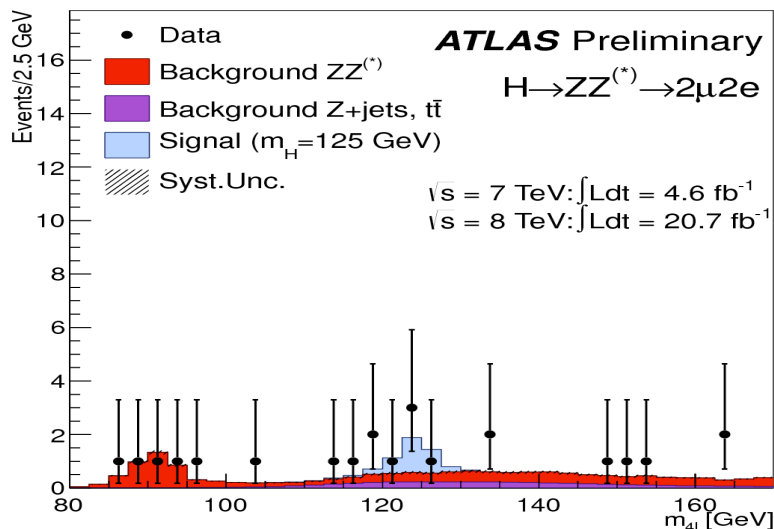
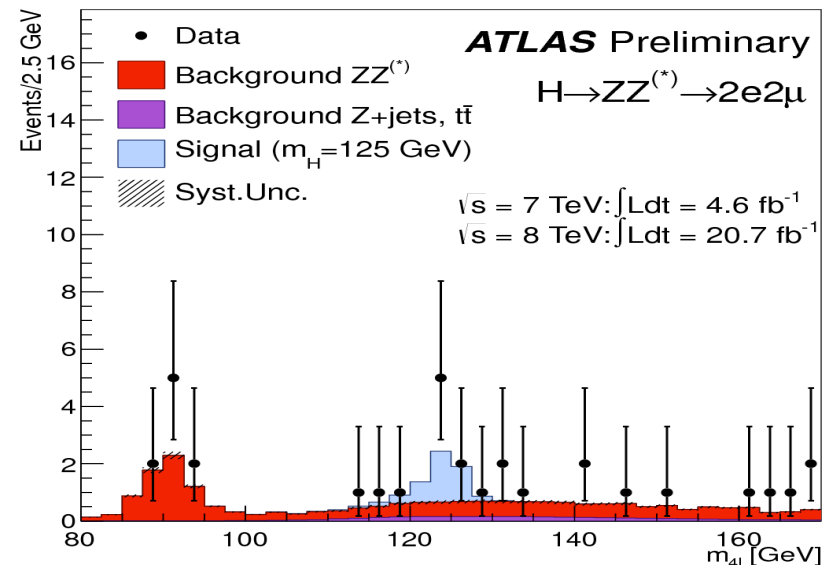
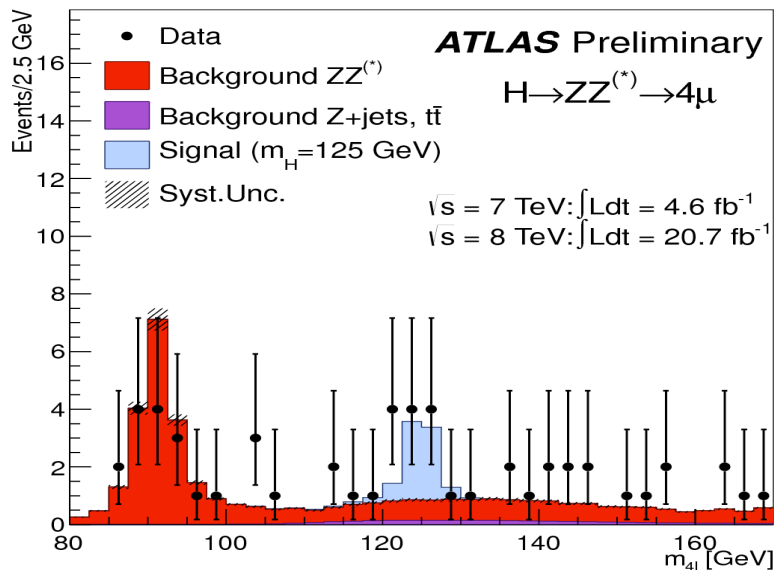
$H \rightarrow ZZ$ material

- m_{4l} (7 TeV and 8 TeV)



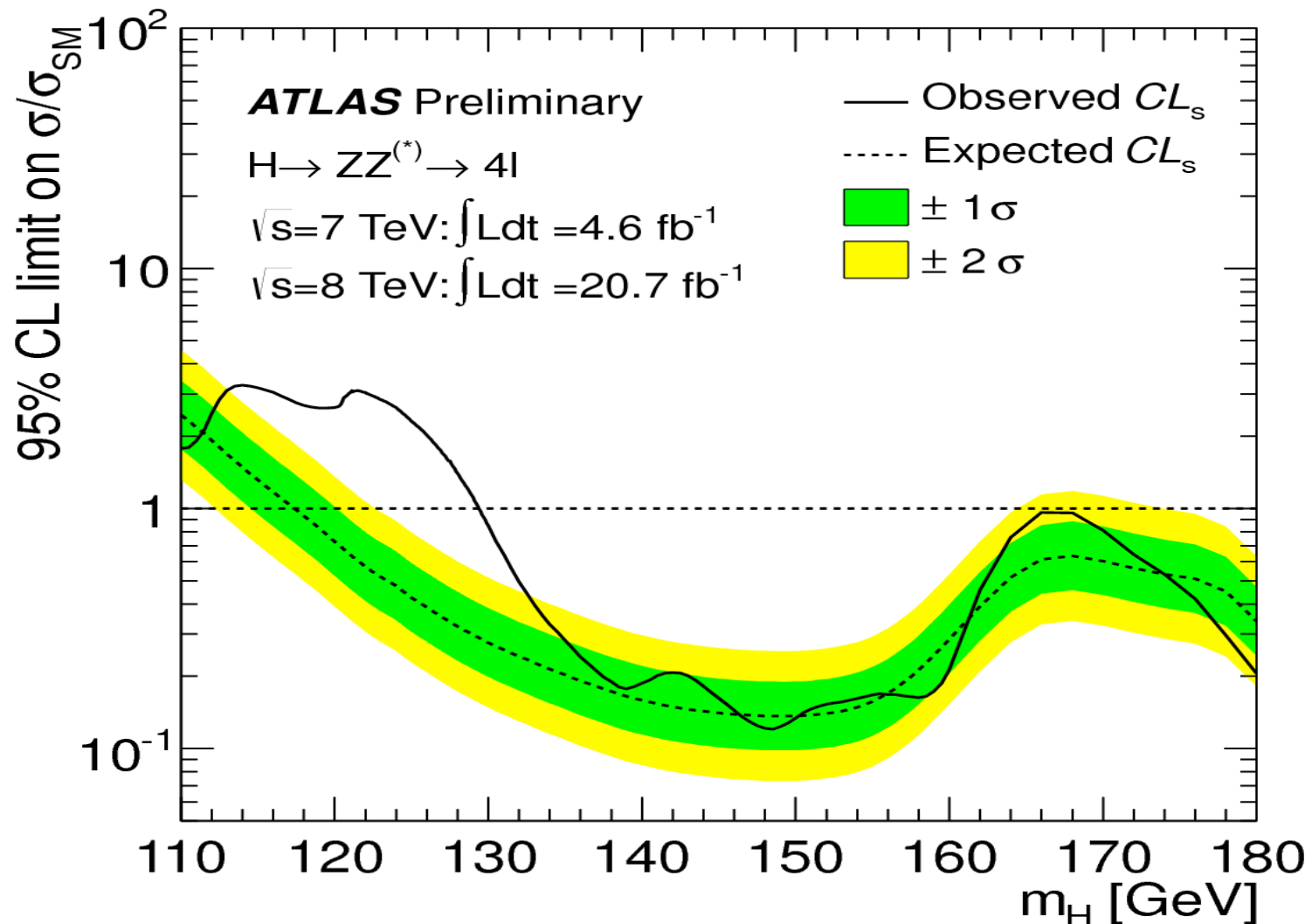
$H \rightarrow ZZ$ material

- $m_{\ell\ell}$ (4e, 4 μ , 2e2 μ)



$H \rightarrow ZZ \rightarrow 4l$

- Exclusion



質量測定 of 系統誤差

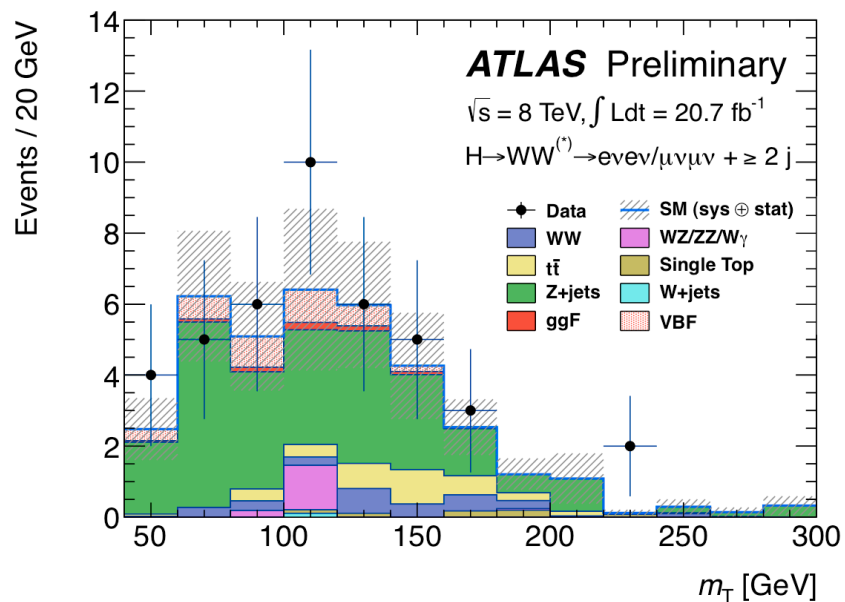
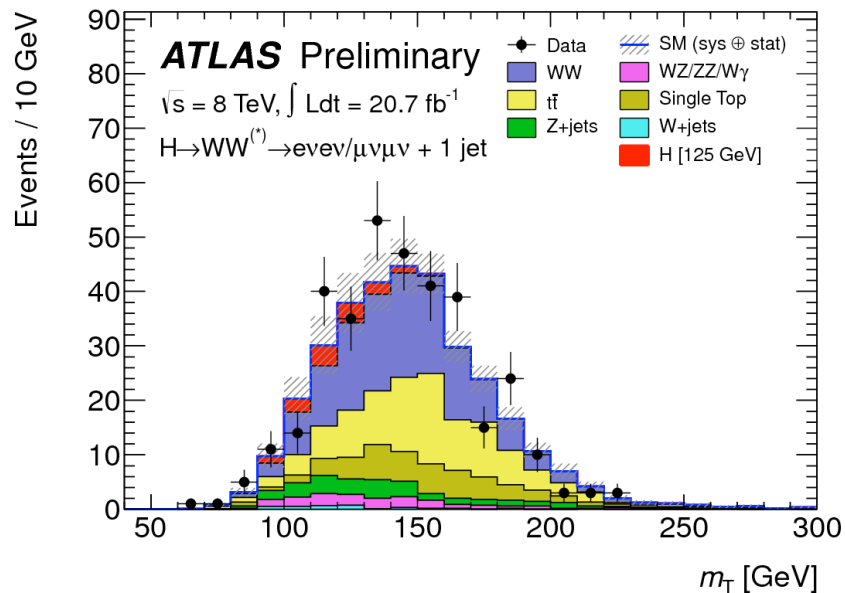
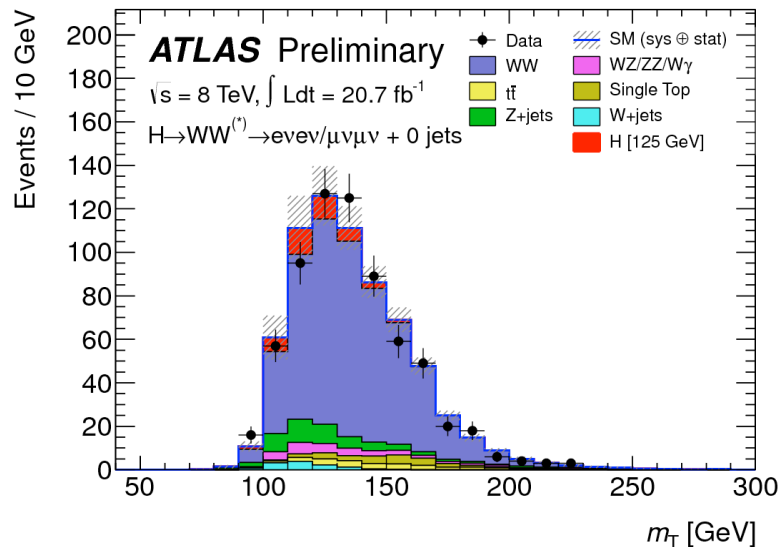
- photon
 - absolute energy scale calibration factor : $\pm 0.3\%$
 - imperfect material before calorimeter : $\pm 0.3\%$
 - 各EM calorimeter layerのrelative calibration : $\pm 0.1\%$, $\pm 0.2\%$
 - eと γ のshower発展の違い : $\pm 0.1\%$
 - $H \rightarrow \gamma\gamma$ photonと $Z \rightarrow ee$ electronの違い : $\pm 0.15\%$
 - pile up impact $< \pm 0.1\%$
 - conversion photonのperformanceのdataとMCの違い : $\pm 0.13\%$
 - background modelの違い : $\pm 0.1\%$
 - mass resolutionのstability : $\pm 0.15\%$
 - photonのangleから起因するbias : $\pm 0.03\%$
 - ➔ Total systematic uncertainty ± 0.7 GeV for $H \rightarrow \gamma\gamma$
 - ➔ $Z \rightarrow ll\gamma$ を用いてcross check

質量測定 of 系統誤差

- muon
 - muon momentum scale/resolution with $J/\psi \rightarrow \mu\mu$, $Z \rightarrow \mu\mu < \pm 0.1\%$
 - charge-symmetric scale biases and local charge-asymmetric scale biases...
 - total uncertainty $\pm 0.2\%$ for 4μ
- electron
 - Sourceはphotonと同じ
 - electron energy scale/resolution $\pm 0.4\%$
 - final-state QED radiation modeling $< \pm 0.1\%$
- Total systematic uncertainty ± 0.3 GeV for $H \rightarrow ZZ \rightarrow 4l$
- Stat ± 0.9 GeV

$H \rightarrow WW \rightarrow l\nu l\nu$

- $ee + \mu\mu$



$H \rightarrow WW \rightarrow l\nu l\nu$

- Signal Strength (μ)

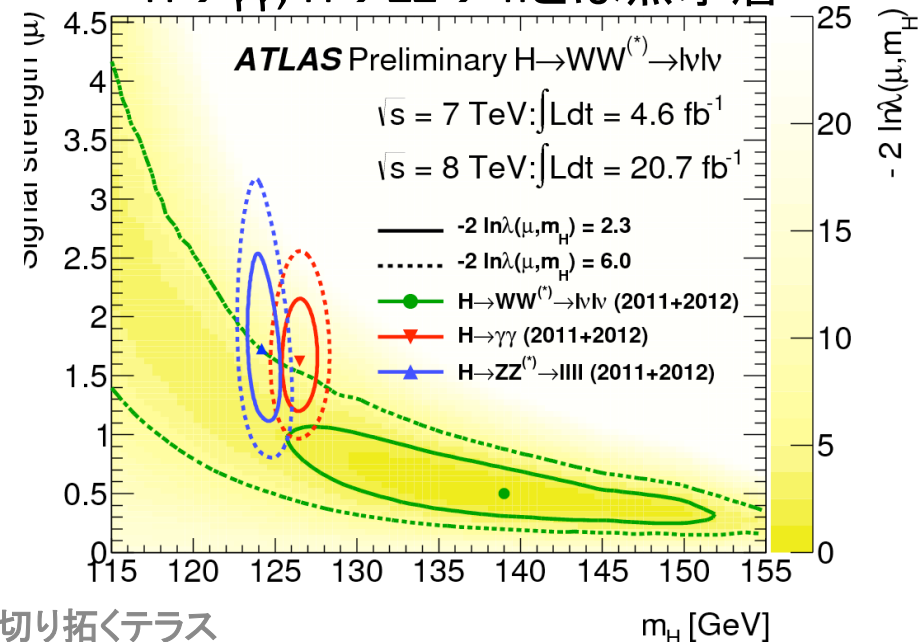
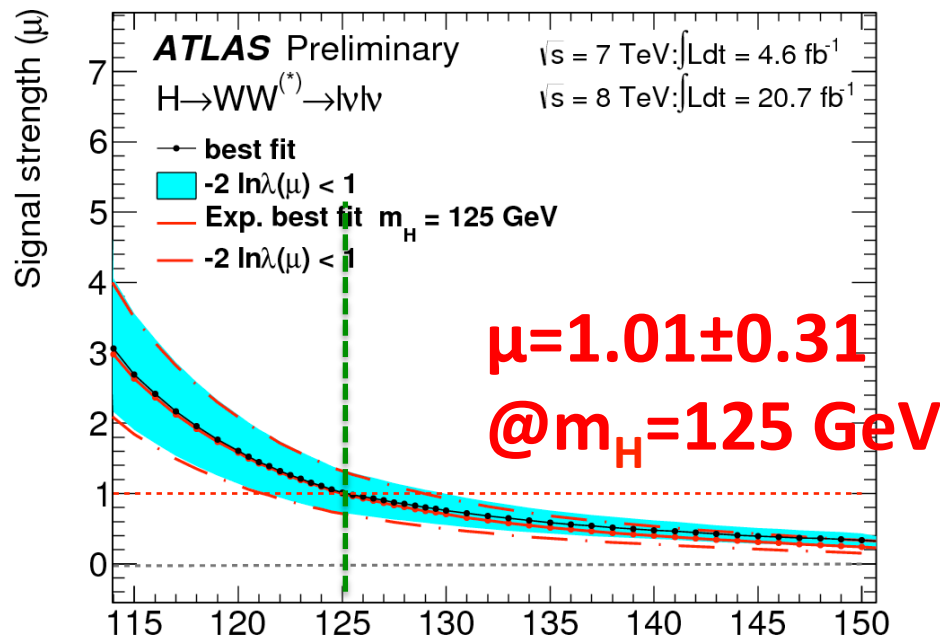
$$1.01 \pm 0.21 \text{ (stat.)} \pm 0.19 \text{ (theo. syst.)} \pm 0.12 \text{ (expt. syst.)} \pm 0.04 \text{ (lumi.)}$$

- $\sigma(pp \rightarrow H) * BR(H \rightarrow WW) @ 8\text{TeV}$

$$6.0 \pm 1.1 \text{ (stat.)} \pm 0.8 \text{ (theo. syst.)} \pm 0.7 \text{ (expt. syst.)} \pm 0.3 \text{ (lumi.) pb}$$

理論値: $4.77^{+0.64}_{-0.64} \text{ (cross section)}^{+0.20}_{-0.20} \text{ (branching fraction) pb}$

質量分解能はほぼない。
 $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ とは無矛盾

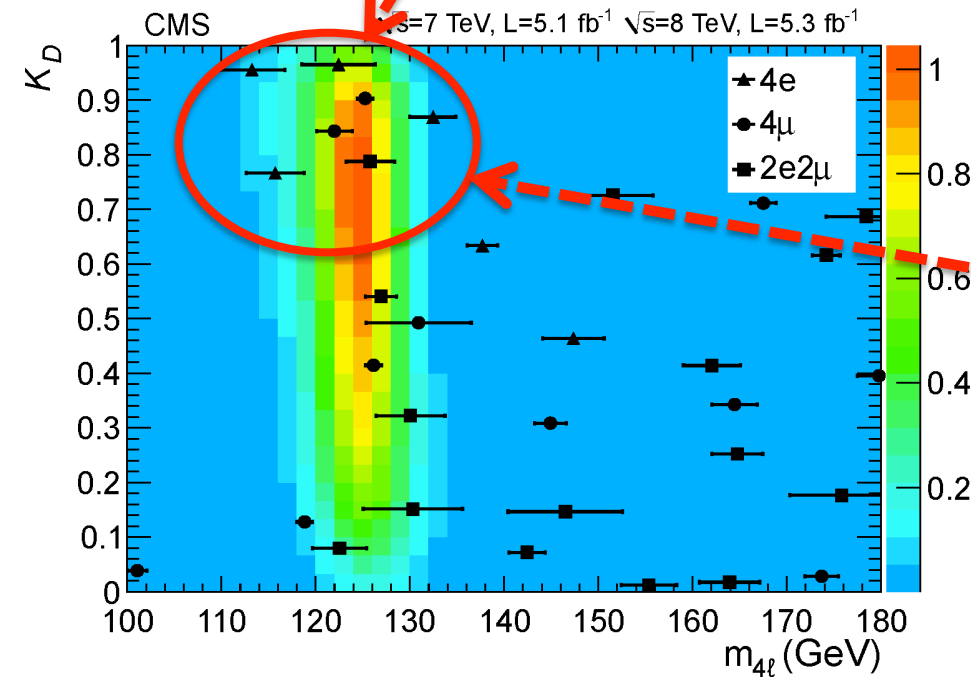
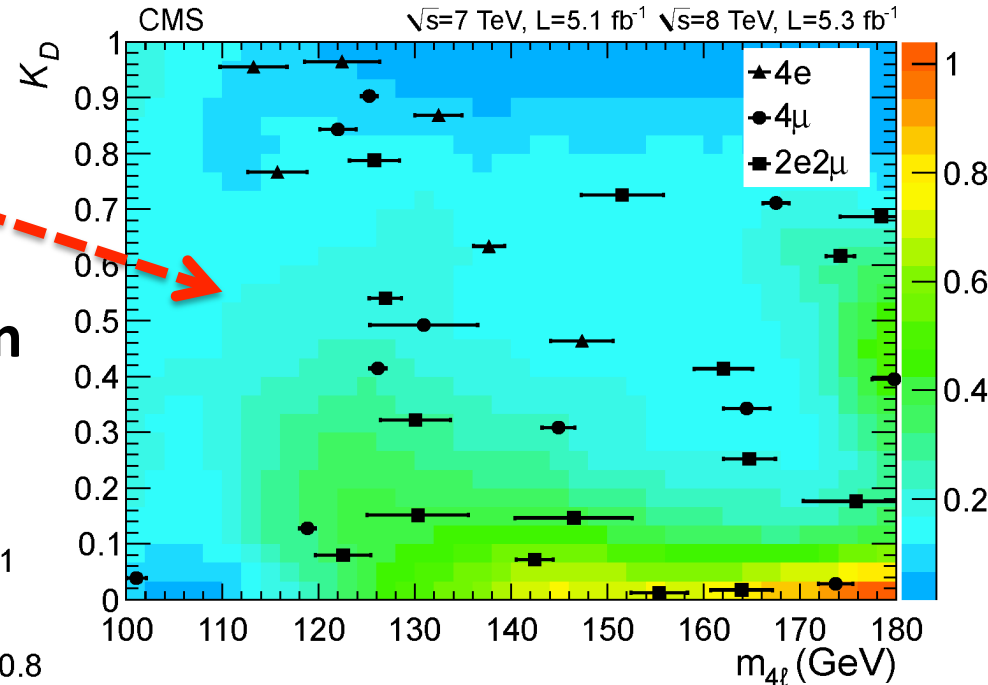


$H \rightarrow ZZ \rightarrow 4\ell$ (CMS)

- $K_D = P_{\text{sig}} / (P_{\text{sig}} + P_{\text{bkg}})$

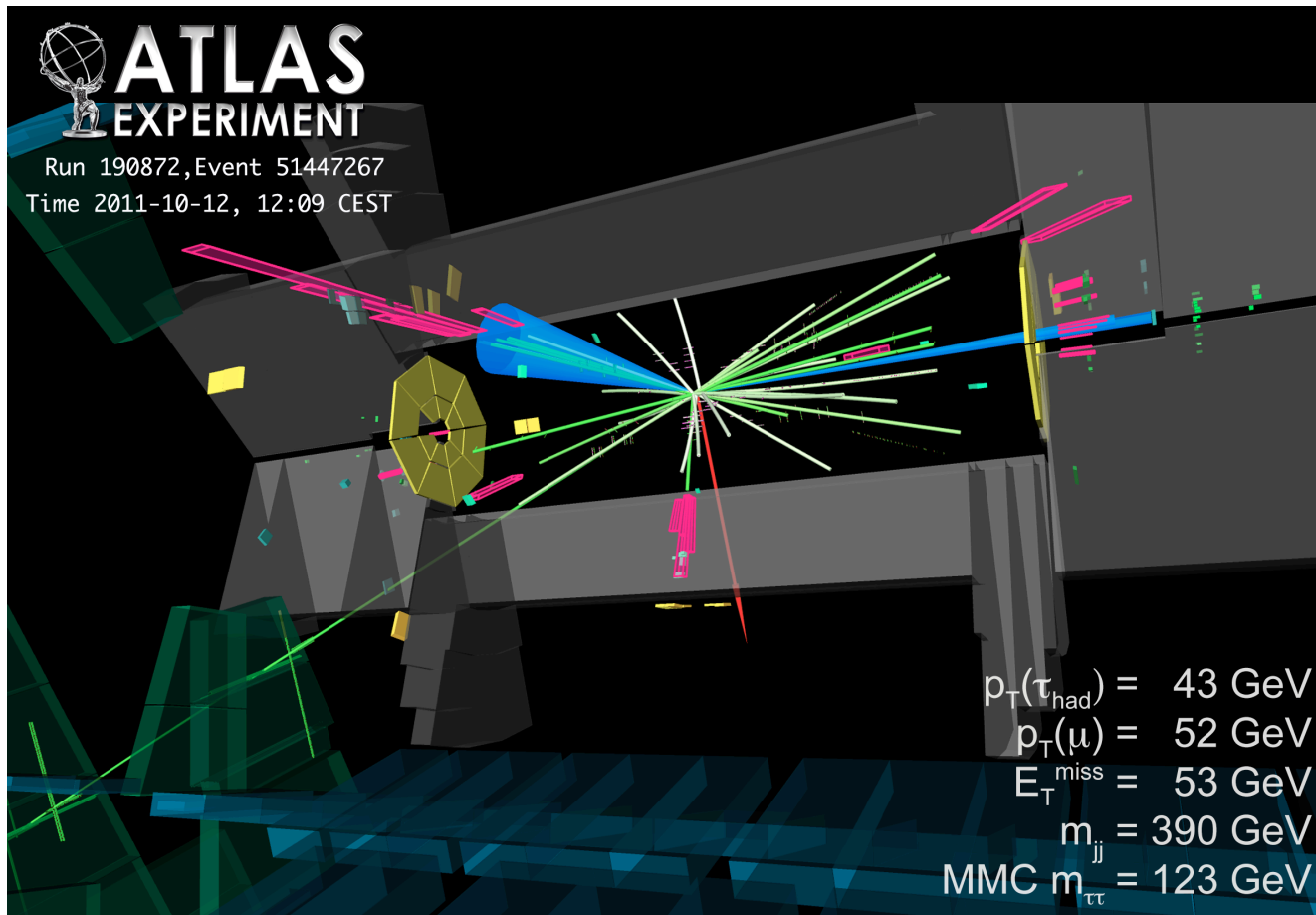
Background distribution

Signal (125 GeV) distribution



信号領域にデータが集まっている

$$\underline{H \rightarrow \tau\tau}$$



$H \rightarrow \tau\tau$ ($\tau_{\text{lep}}\tau_{\text{lep}}, \tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$)

- 3つのチャンネル($\tau_{\text{lep}}\tau_{\text{lep}}$ (2leps), $\tau_{\text{lep}}\tau_{\text{had}}$ (1lep), $\tau_{\text{had}}\tau_{\text{had}}$ (0lep))を解析
- e/μ の数でexclusiveに解析を分けている
- それぞれのチャンネルはさらにカテゴリーを分けて解析を最適化

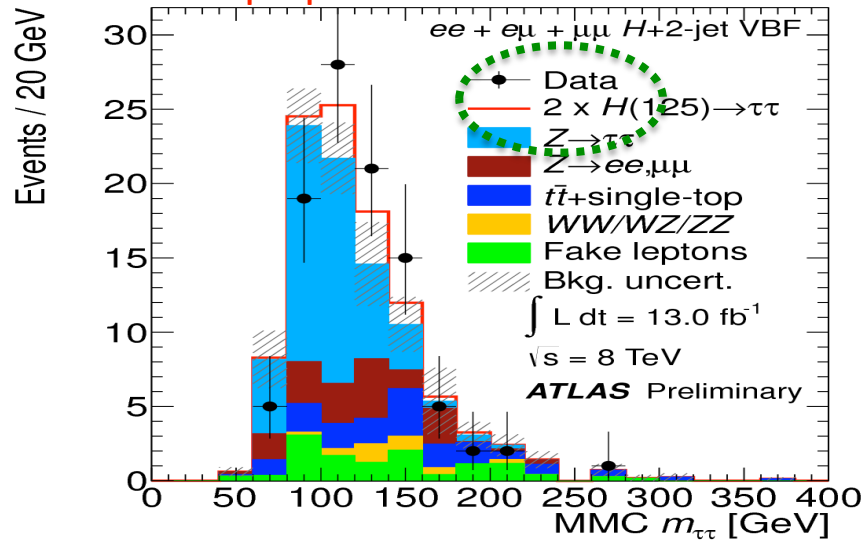
category($\tau_{\text{lep}}\tau_{\text{lep}}$)	2 jet VBF	Boosted	2-jet VH	1 jet
主なセクション	$m_{jj} > 400 \text{ GeV}$ $\Delta\eta_{jj} > 3.0$	$p_T^{\tau\tau} = p_T^{l1} + p_T^{l2} + p_T^{\text{miss}} > 100 \text{ GeV}$	$30 < m_{jj} < 100$ $\Delta\eta_{jj} < 2.0$	$m_{\tau\tau} > 225 \text{ GeV}$
主な信号	VBF	ggF	VH	ggF

category($\tau_{\text{lep}}\tau_{\text{had}}$)	2 jet VBF	Boosted	1 jet	0 jet
主なセクション	$m_{jj} > 500 \text{ GeV}$ $\Delta\eta_{jj} > 3.0$	$p_T^H = p_T^l + p_T^{\tau\text{had}} + E_T^{\text{miss}} > 100 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$, at least 1 jet	$E_T^{\text{miss}} > 20 \text{ GeV}$, 0jet
主な信号	VBF	ggF	ggF	ggF

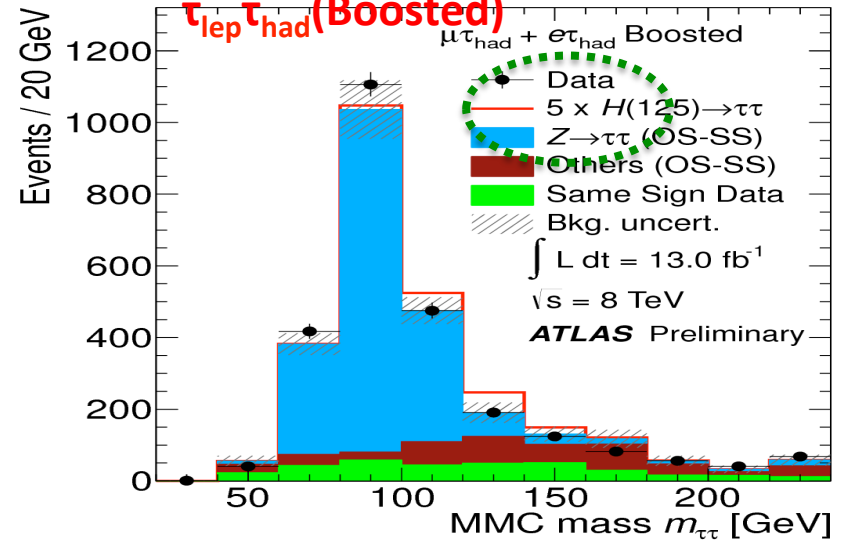
category($\tau_{\text{had}}\tau_{\text{had}}$)	2 jet VBF	Boosted
主なセクション	$m_{jj} > 350 \text{ GeV}$ $\Delta\eta_{jj} > 2.6$	1jet $p_T > 70 \text{ GeV}$ $\Delta R(\tau_1, \tau_2) < 1.9$, $\min\{\Delta\phi(E_T^{\text{miss}}, \tau_1), \Delta\phi(E_T^{\text{miss}}, \tau_2)\} < 0.1\pi$
主な信号	VBF	ggF

$H \rightarrow \tau\tau$ ($\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$)

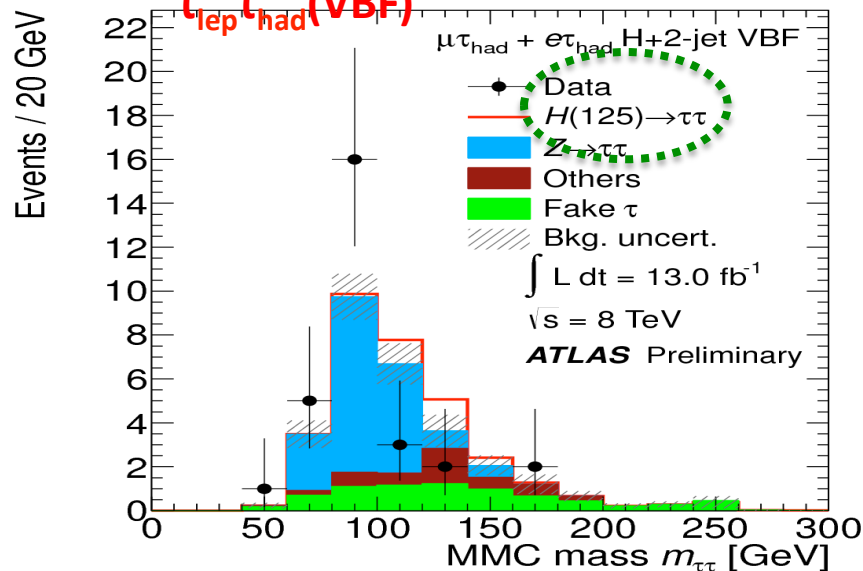
$\tau_{\text{lep}}\tau_{\text{lep}}$ (VBF)



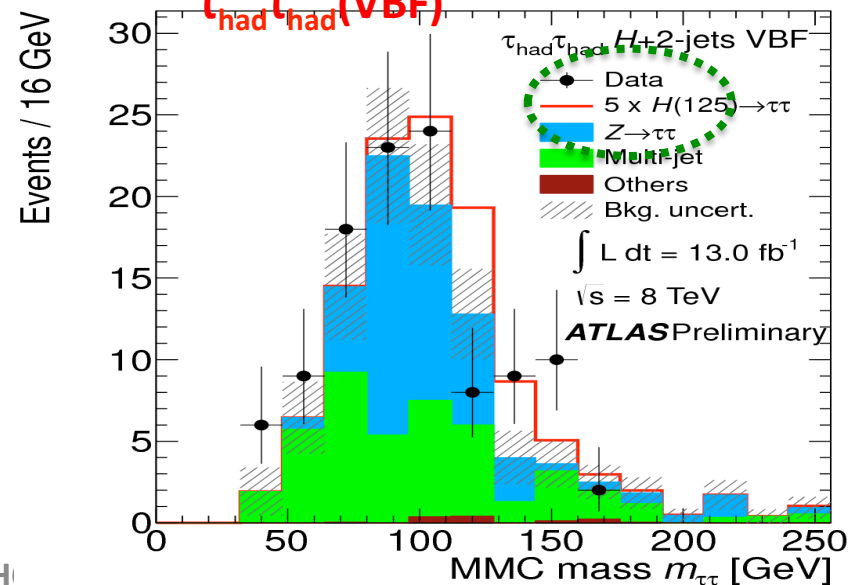
$\tau_{\text{lep}}\tau_{\text{had}}$ (Boosted)



$\tau_{\text{lep}}\tau_{\text{had}}$ (VBF)

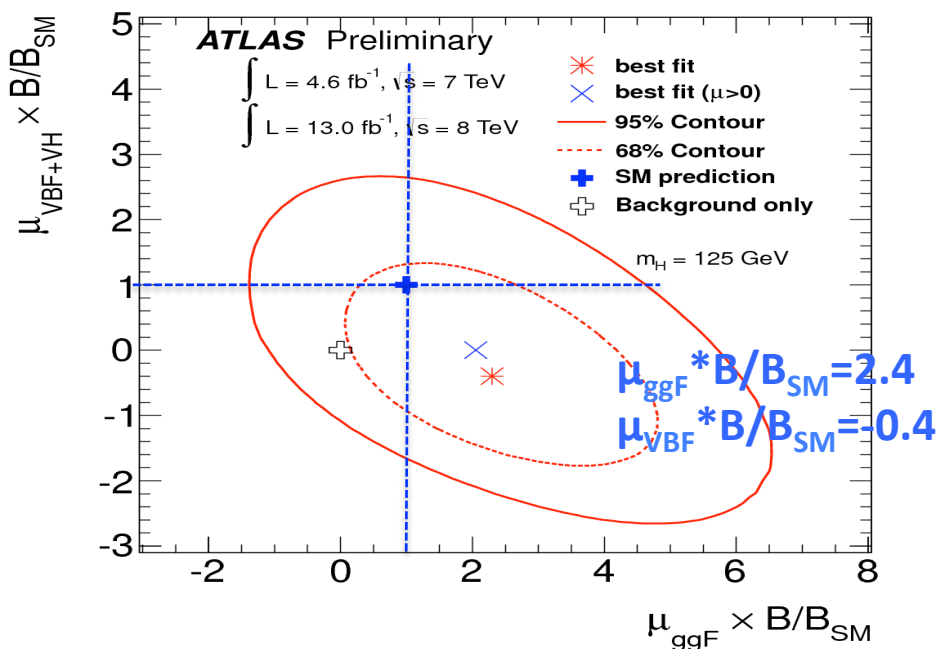
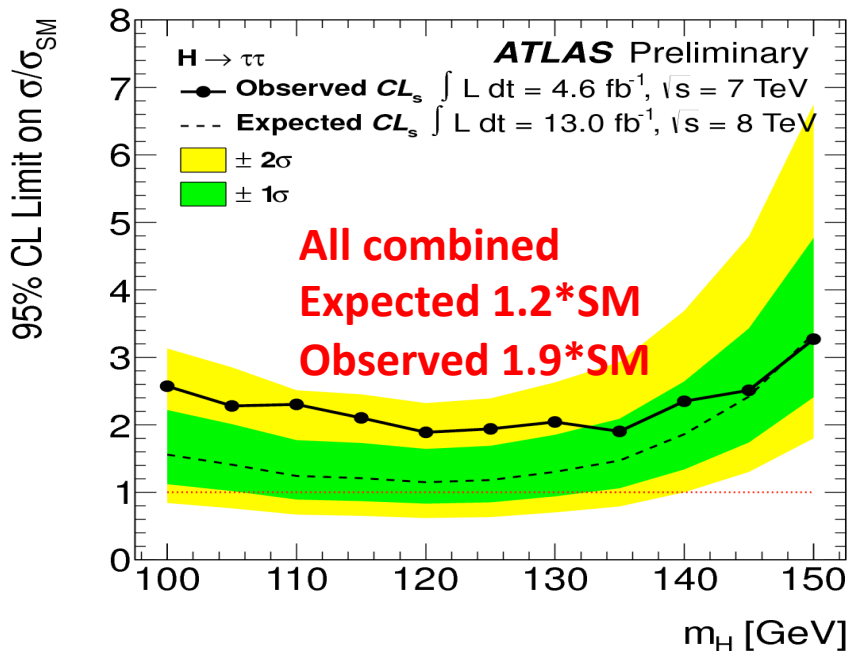
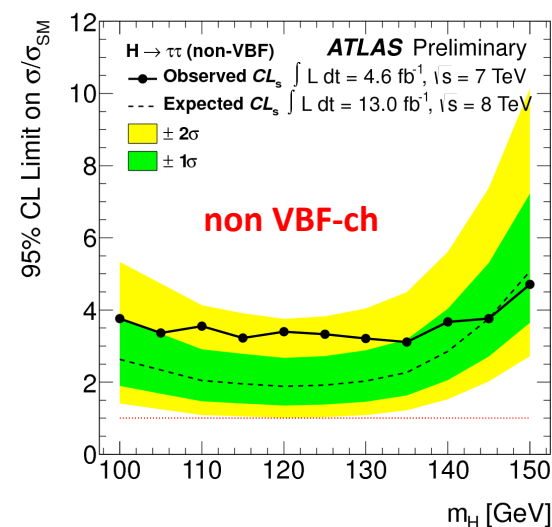
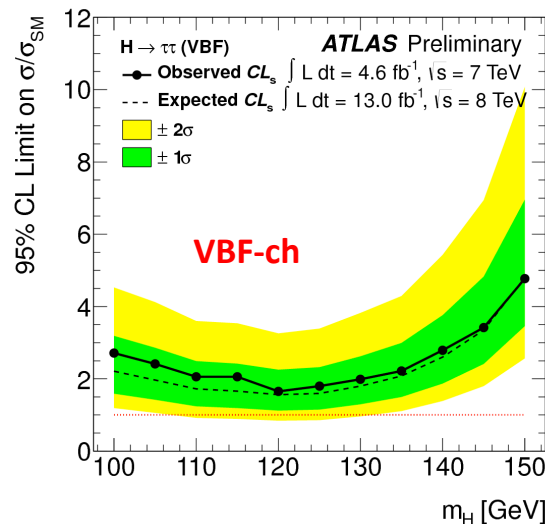


$\tau_{\text{had}}\tau_{\text{had}}$ (VBF)



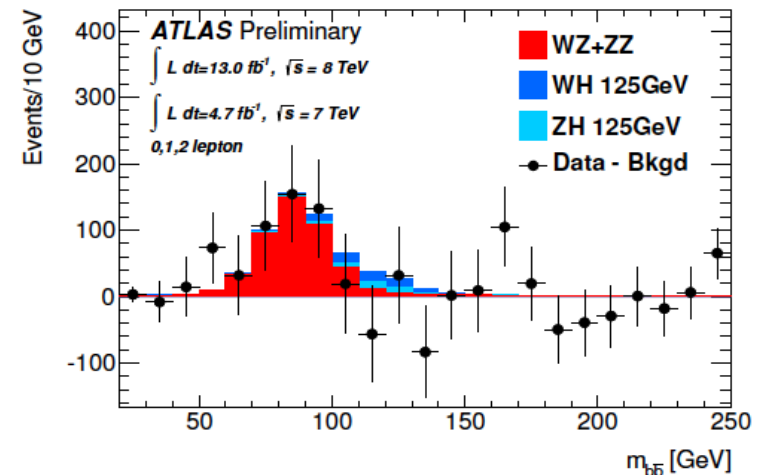
$H \rightarrow \tau\tau$ ($\tau_{\text{lep}}\tau_{\text{lep}}, \tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$)

- $m_{\tau\tau}$ 分布でヒッグス粒子の兆候を探索
- $H \rightarrow \tau\tau$ channelはVBFカテゴリーも感度がある
→まだ発見には至らず



W/ZH($\rightarrow$ b $\bar{b}$)

- H $\rightarrow$ bb探索で有望チャンネル
 - WH,ZH : 終状態にレプトンorMETを含む(lepton or MET trigger)
 - pT(W/Z)でカテゴリー分け
 - 主な背景事象はW/Z+jets, ttbar, QCD, Diboson (WZ,ZZ)



$\mu_D = 1.09 \pm 0.22(\text{stat.}) \pm 0.22(\text{sys})$
 significance 4.0σ

WH $\rightarrow$ lvbb	ZH $\rightarrow$ llbb	ZH $\rightarrow$ vvbb
one lepton (e, μ)	two leptons (ee, $\mu\mu$)	$E_T^{\text{miss}} > 120 \text{ GeV}$
$E_T^{\text{miss}} > 25(50), \text{ GeV},$ (40 <) $m_T < 120 \text{ GeV}$	$83 \text{ GeV} < m_{ll} < 99 \text{ GeV},$ $E_T^{\text{miss}} < 60 \text{ GeV}$	$p_T^{\text{miss}} > 30 \text{ GeV}, \Delta\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < \pi/2,$ $ \Delta\phi(E_T^{\text{miss}}, \text{jet}) > 1.5, \Delta\phi(E_T^{\text{miss}}, b\bar{b}) > 2.8$
Two b-jets (45,25 GeV) b-tag efficiency 70% (c mistag 20%, light mistag 0.07%)		
Categorize events depending on vector boson p_T (p_{TV}) or MET (Boost VH Events)		
$p_{TV} < 50, 50 < p_{TV} < 100, 100 < p_{TV} < 150, 150 < p_{TV} < 200,$ $p_{TV} > 200 \text{ GeV}$	$120 < E_T^{\text{miss}} < 160, 160 < E_T^{\text{miss}} < 200, E_T^{\text{miss}} > 200 \text{ GeV}$	

W/ZH($\rightarrow$ b $\bar{b}$)

- 単純な $m_{b\bar{b}}$ のfittingでヒッグス粒子探索

