

# Higgs-like to Higgs and Prospects

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For the ATLAS collaboration

# ヒッグス探索の歴史

## ❖ 1980年代

▶ 1984年 : Crystal Ball at Doris

●  $\Upsilon \rightarrow H \gamma$

▶ CUSB at CESR

●  $\Upsilon \rightarrow H \gamma$

▶ SINDRUM

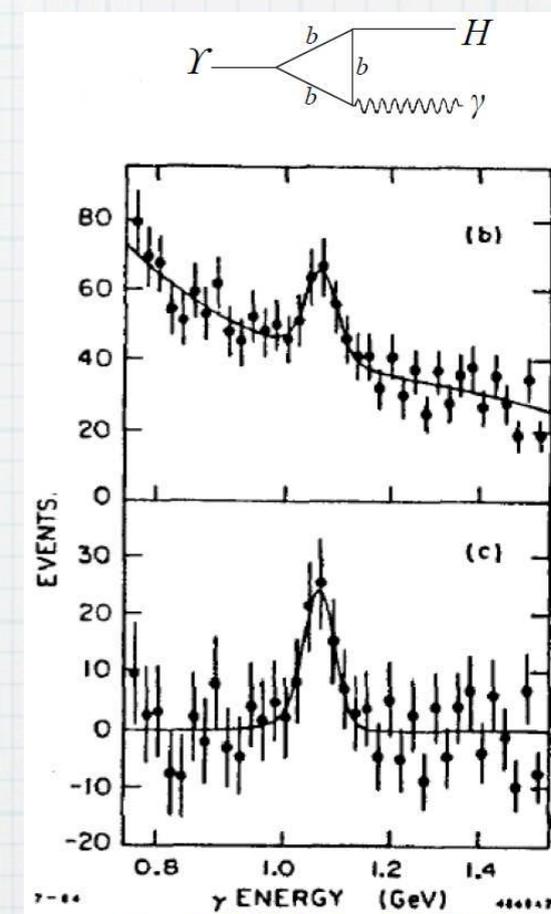
●  $\pi \rightarrow e \nu H (\rightarrow ee)$

▶ CELO at CESR

●  $B \rightarrow KH (\rightarrow \mu \mu, \pi \pi, KK)$

▶  $m_H > 8$  or  $9$  GeV

Crystal Ball signal

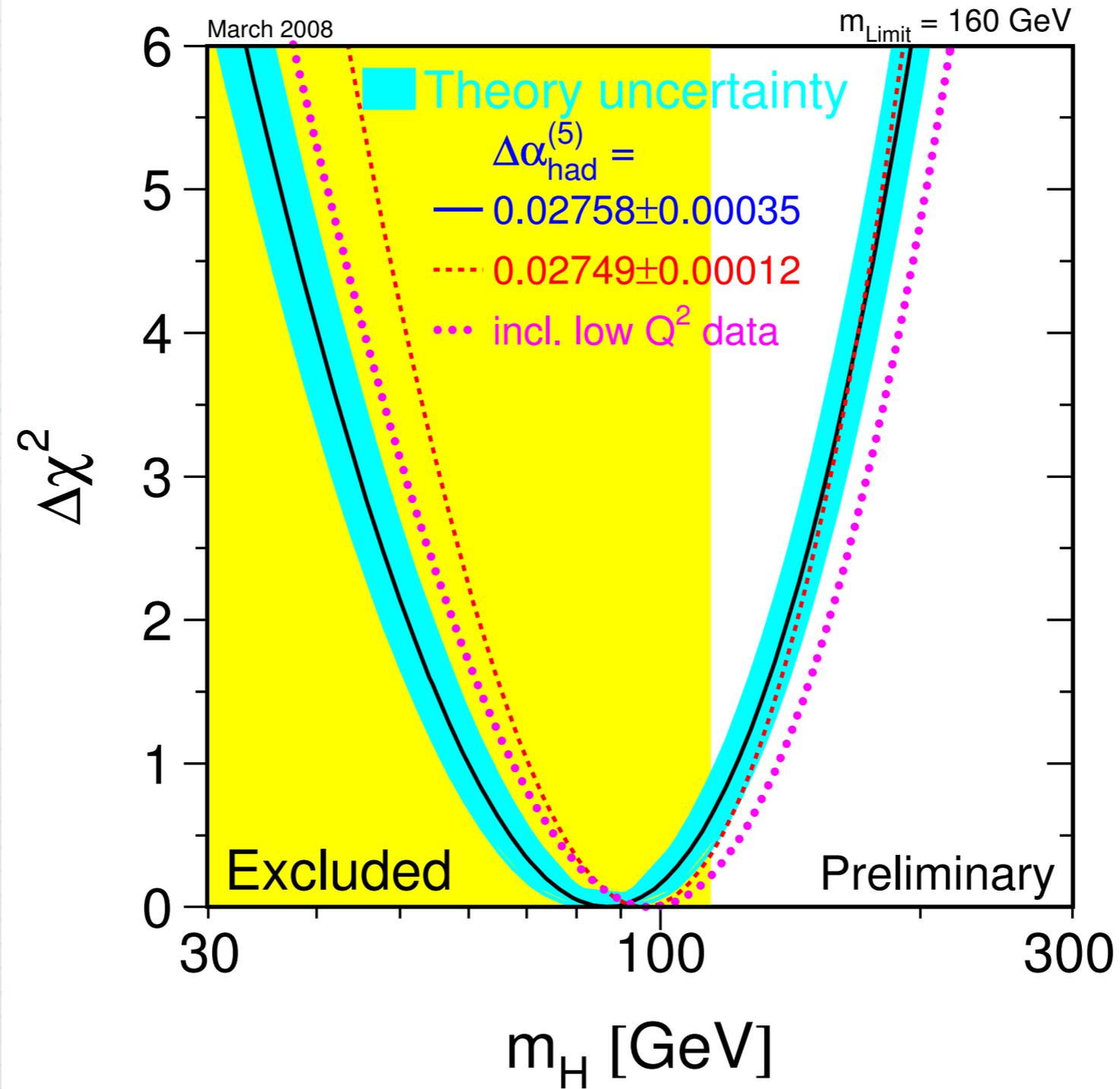


# ヒッグス探索の歴史

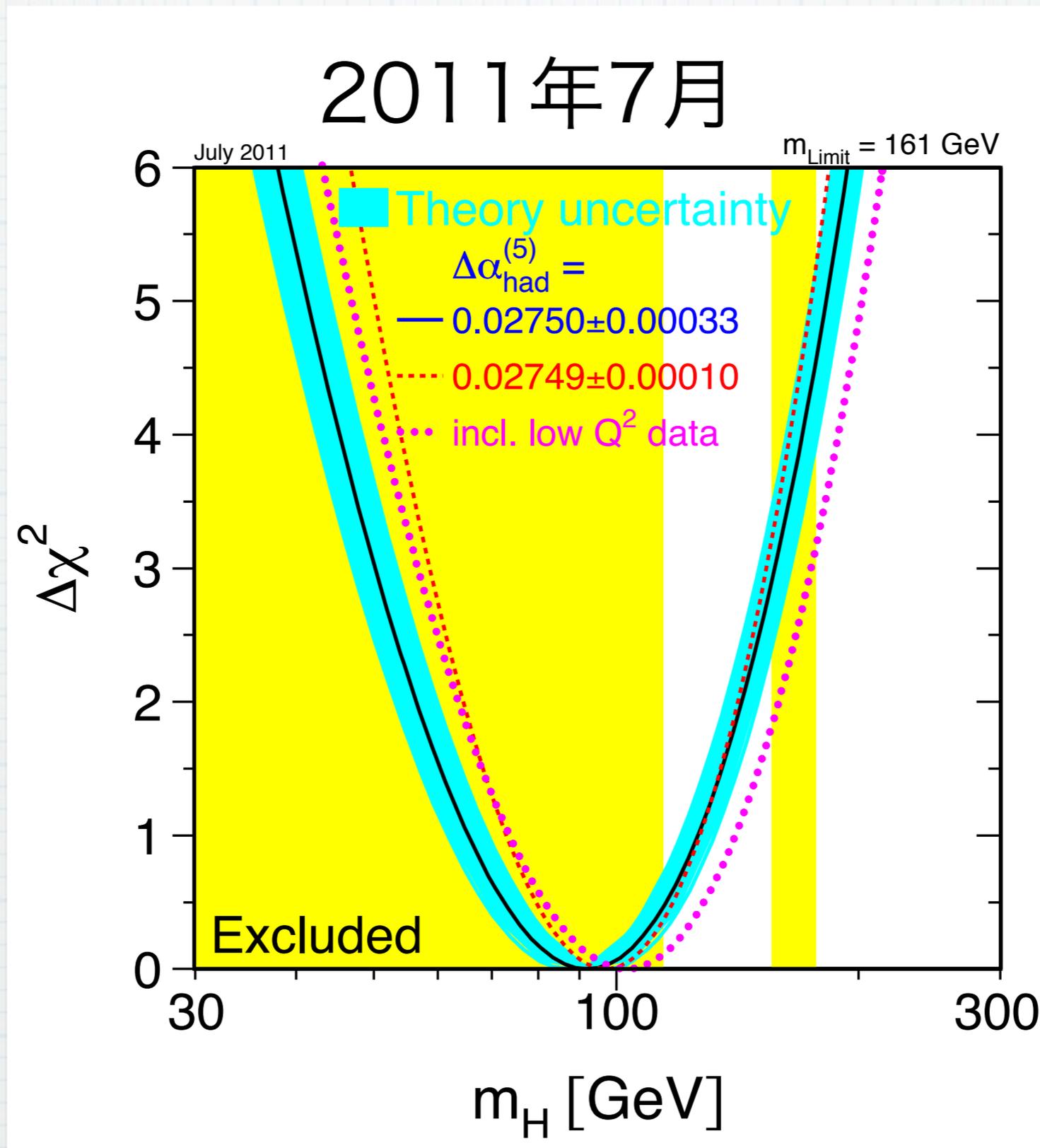
- ❖ LEP 1 (1989-1995)
- ❖ LEP 2 (1995-2000)
  - ▶ hint of 114 GeV Higgs
- ❖ Tevatron (1987-2011)
  - ▶ actual search in run 2 (2001-2011)

# ヒッグス探索の歴史

2008年3月

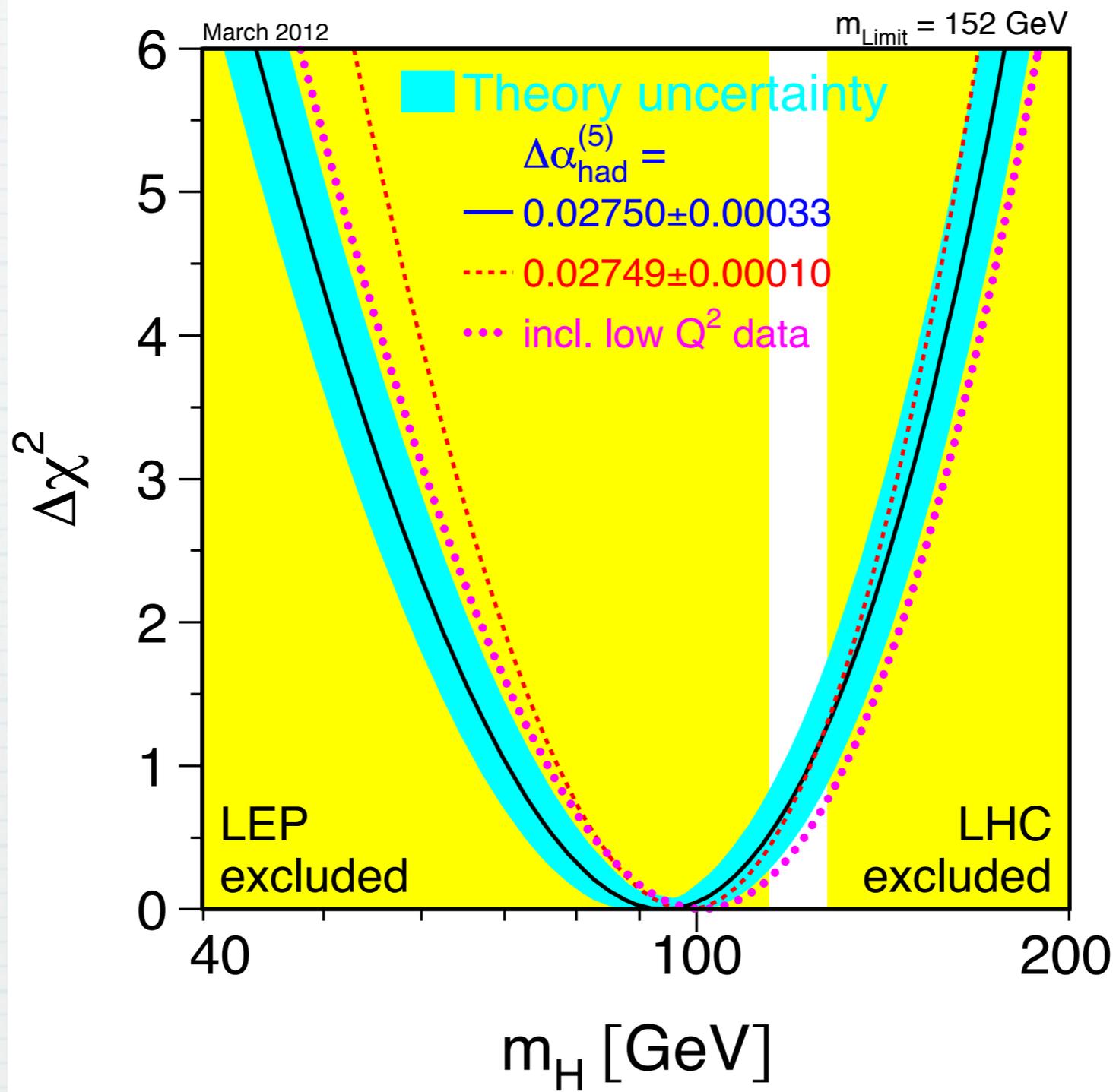


# ヒッグス探索の歴史

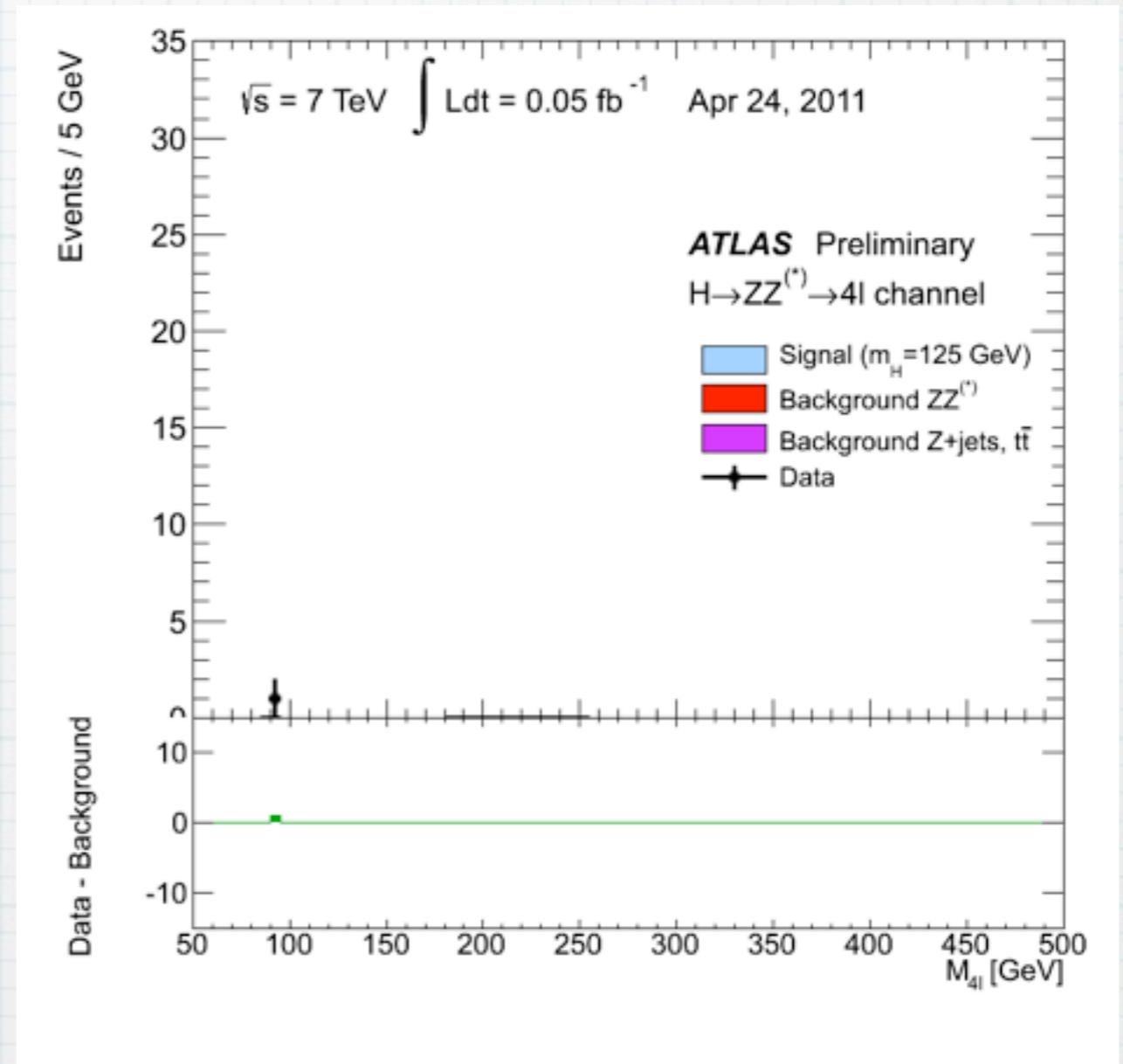
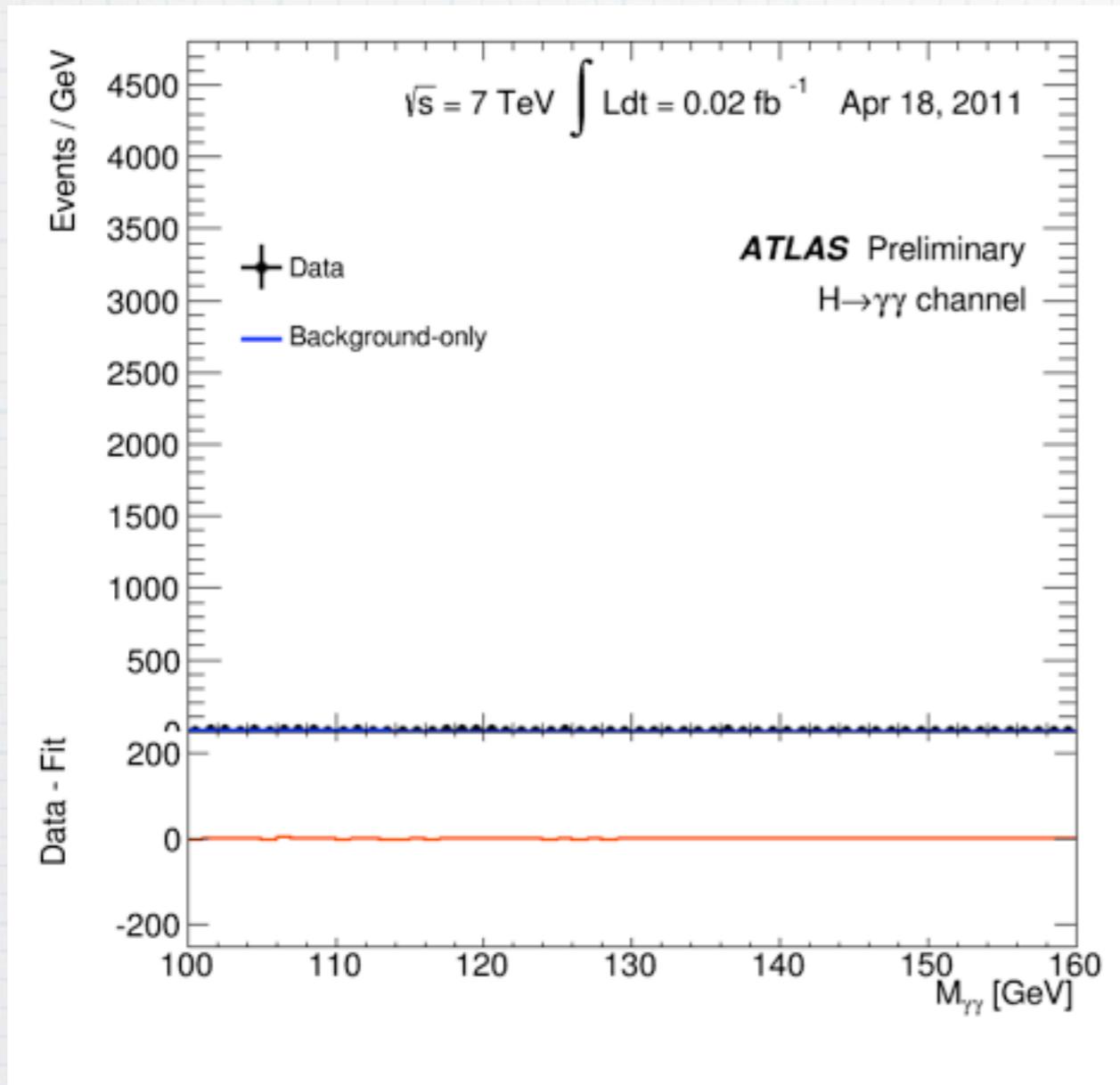


# ヒッグス探索の歴史

2012年3月



# Higgs-like boson 発見



# ヒッグスセクター

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_H^2\phi^2) && \leftarrow \text{スカラーボソン} \\ &+ \frac{vg^2}{2}\phi W_\mu^+ W^{-\mu} + \frac{v(g^2 + g'^2)}{4}\phi Z_\mu Z^\mu && \leftarrow \text{ゲージ結合} \\ &- \sum_f Y_f \phi \bar{f} f && \leftarrow \text{湯川結合} \\ &- \lambda v \phi^3 - \lambda \frac{\phi^4}{4} && \leftarrow \text{自己結合} \\ &+ \frac{g^2}{2}\phi^2 W_\mu^+ W^{-\mu} + \frac{(g^2 + g'^2)}{4}\phi^2 Z_\mu Z^\mu\end{aligned}$$

# 気になるところ

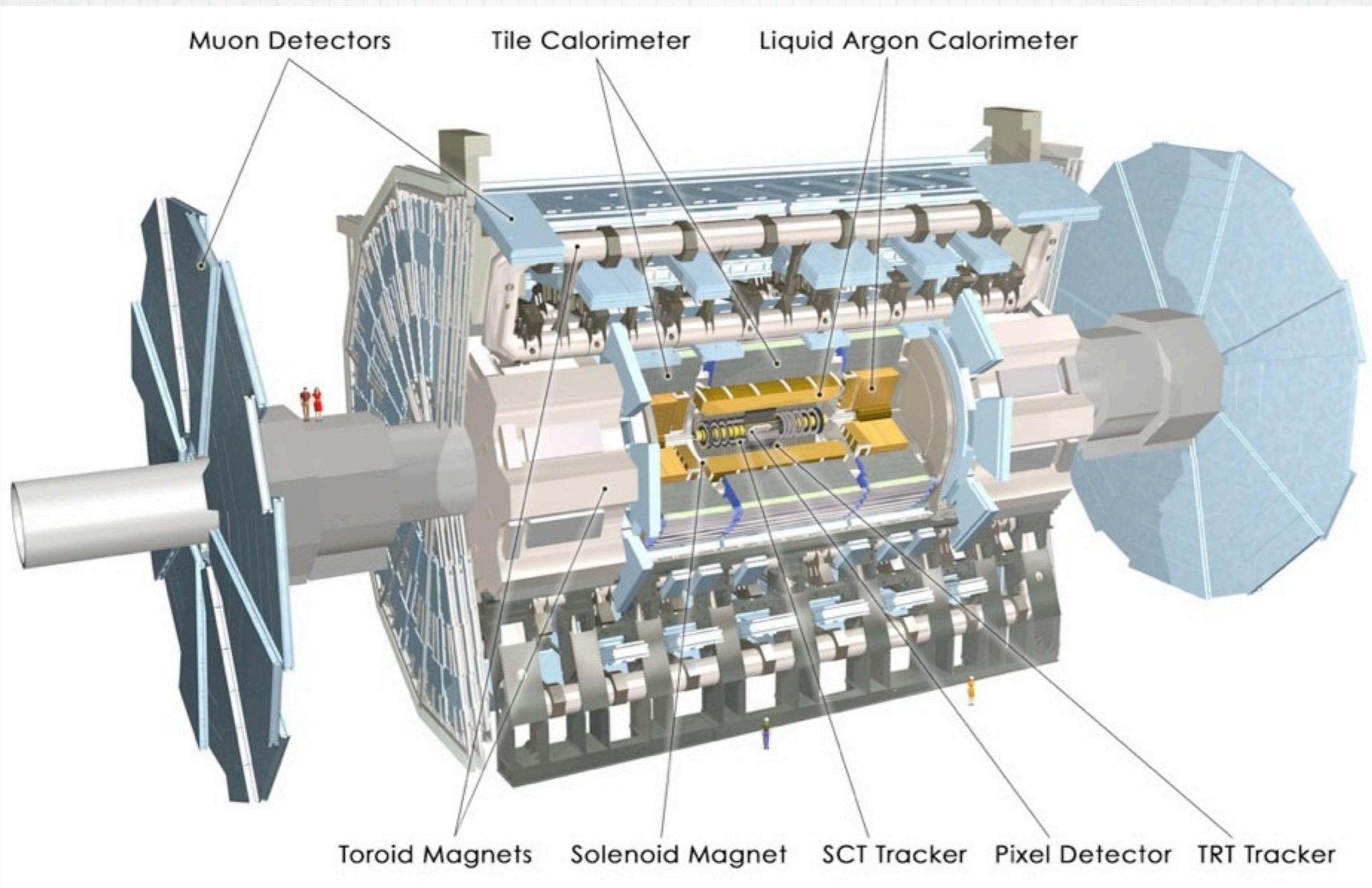
- ❖ スカラーボソン
- ❖ 指導原理の欠如
  - ▶ 湯川結合の導入
    - ヒッグスが素粒子のidentifyを決める？
- ❖ 謎の質量パラメータ  $\mu$  ( $m_H^2 = -2\mu^2$ )
- ❖ Gauge cancellation

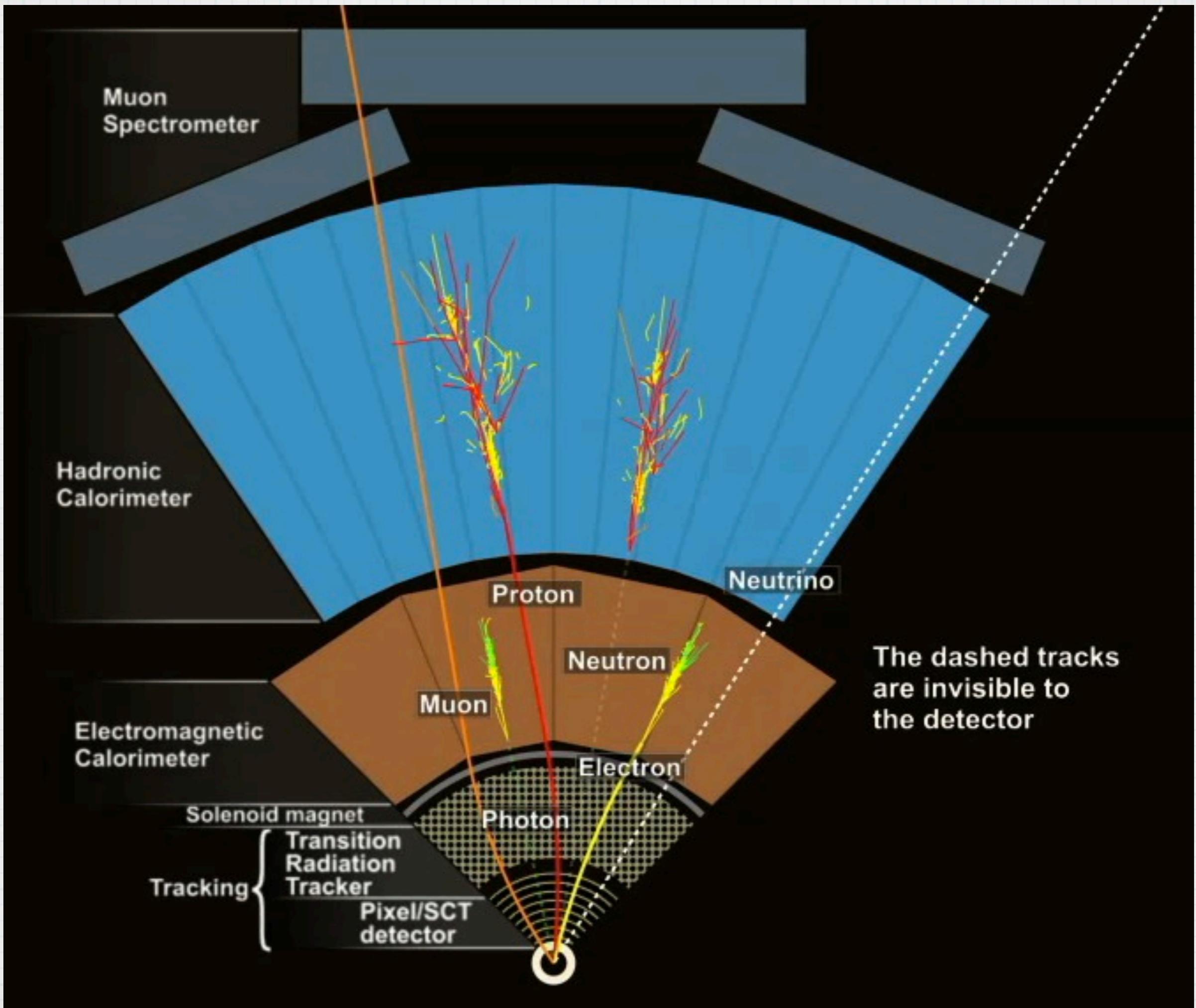
## 実験からの知見

ILCが走るまではLHCが  
ヒッグスを直接研究できる唯一の施設

LHC / ATLAS 実験

# ATLAS 検出器

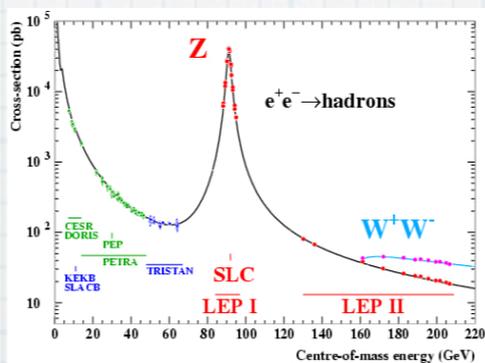
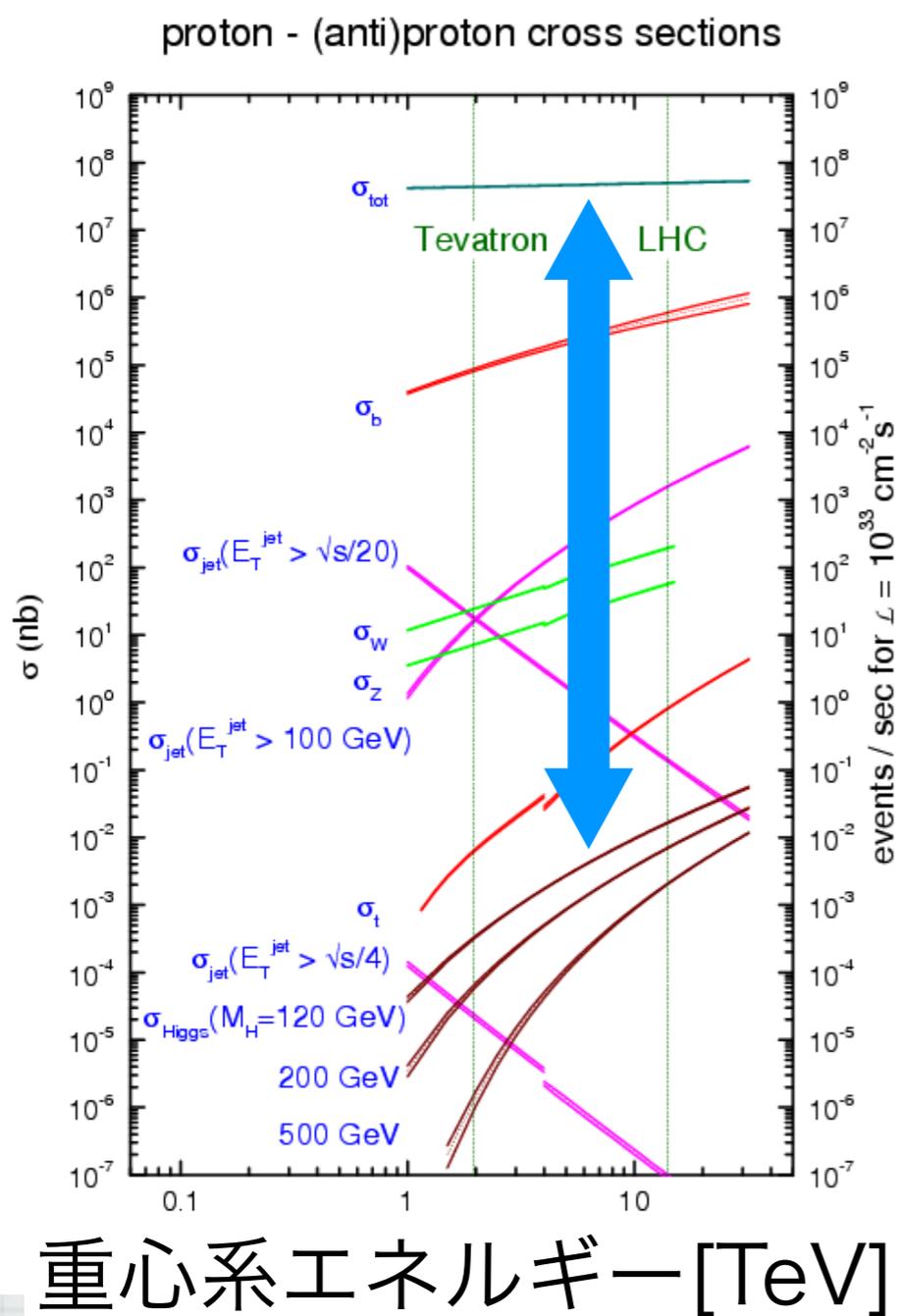
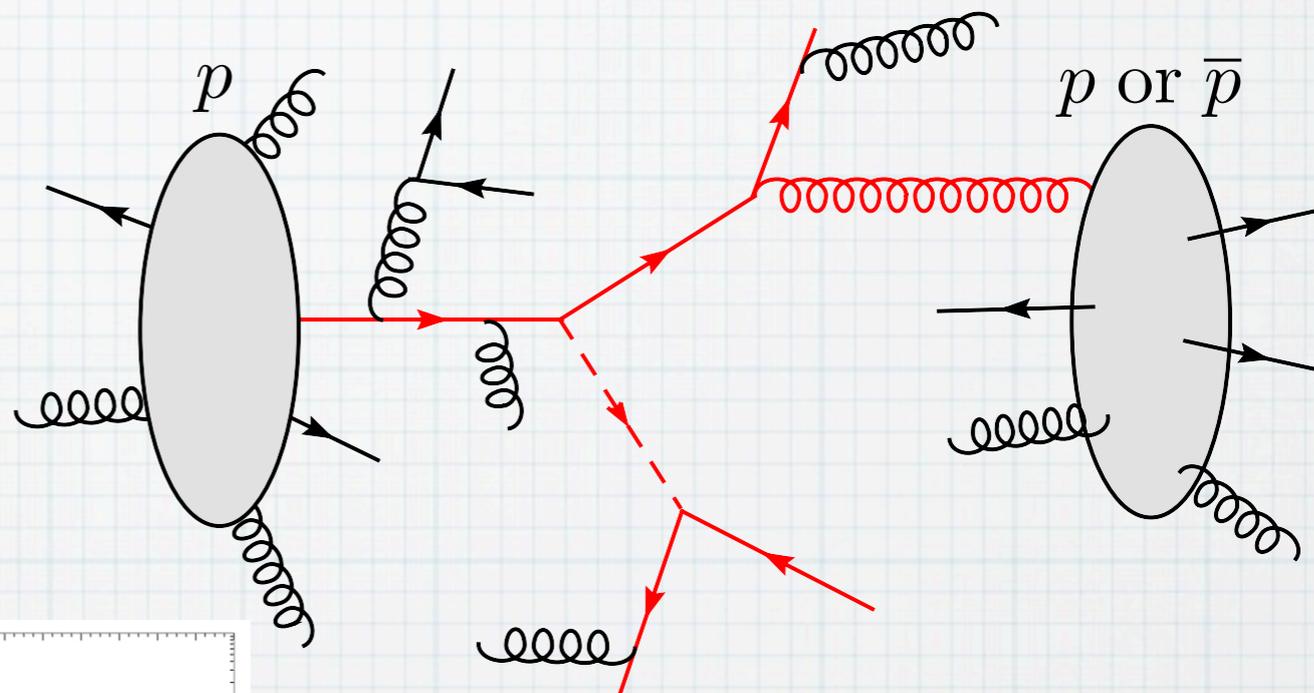




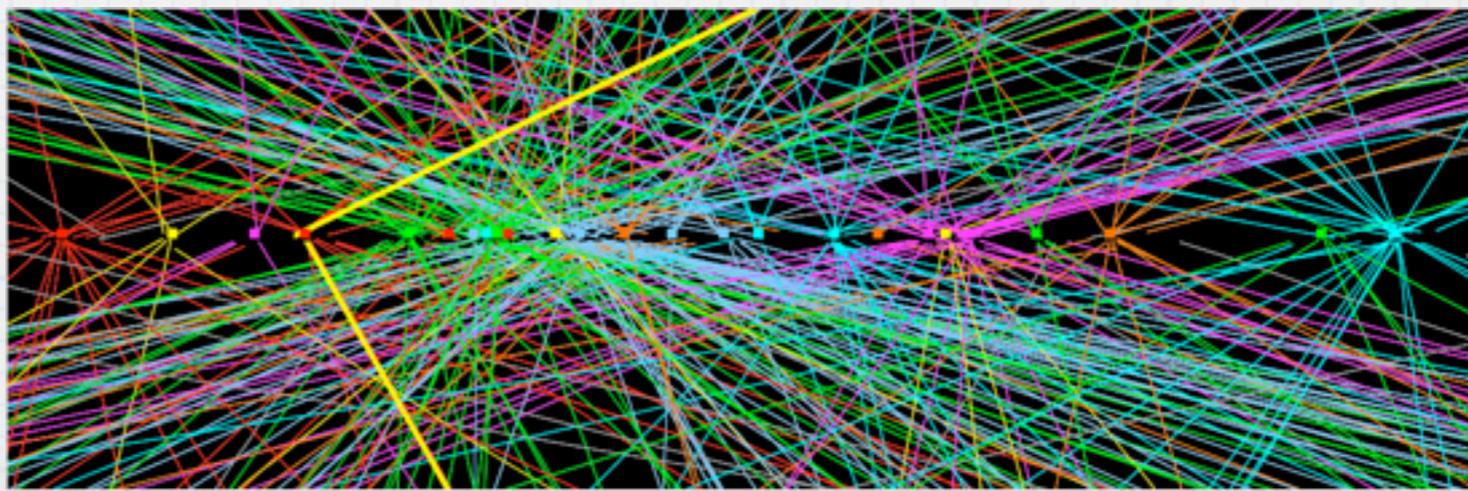
# ハドロンコライダーの難しさ

## ❖ S/Nが小さい

## ❖ Underlying Event

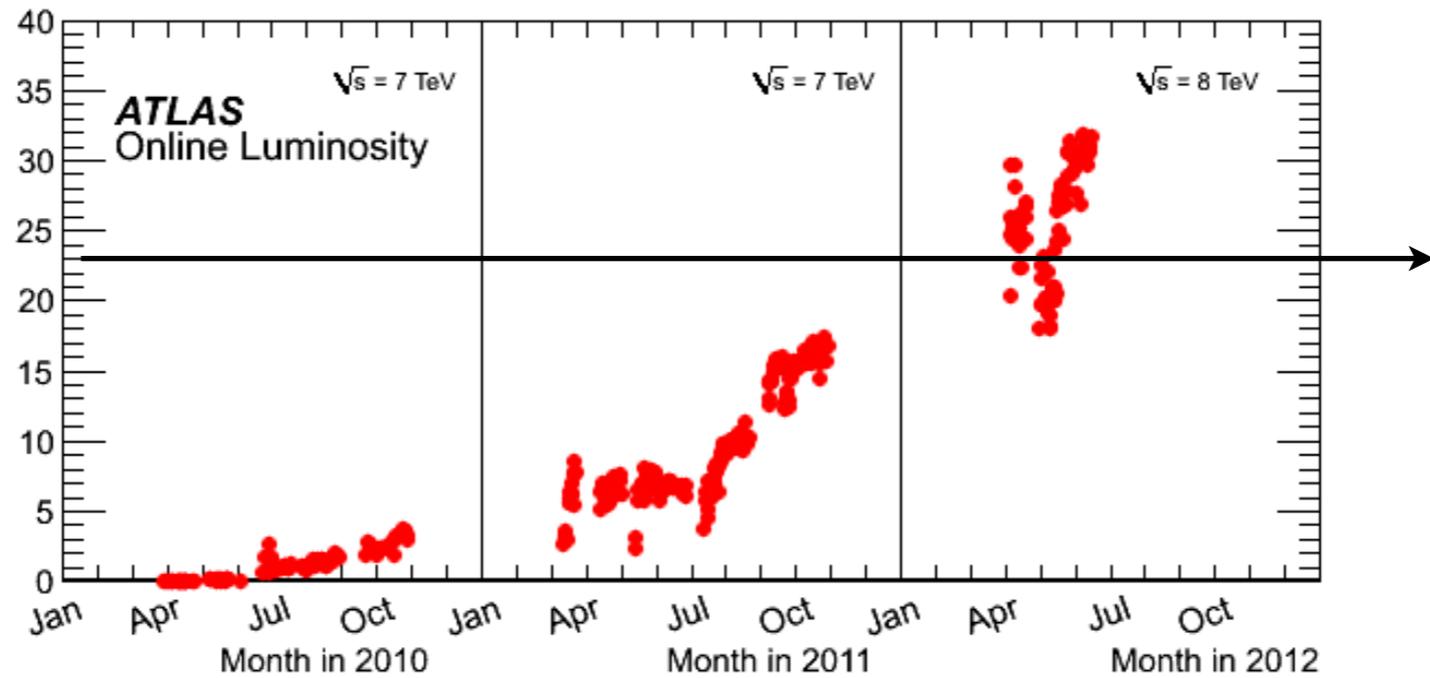


## ❖ 多重衝突



# 多重衝突 (ルミノシティに依存)

バンチ交差あたりの  
最高衝突数



現行での  
設計値

## ❖ 衝突数/bunch crossing

= ルミノシティ × 断面積 × bunch spacing

=  $7E33 \text{ [cm}^{-2}\text{s}^{-1}] \times 80\text{mb} \times 50\text{n [s]} \sim 28$  (現行)

=  $5E34 \text{ [cm}^{-2}\text{s}^{-1}] \times 80\text{mb} \times 25\text{n [s]} \sim 100$

→ 最大140

(HL-LHC)

# Efficiencyの理解

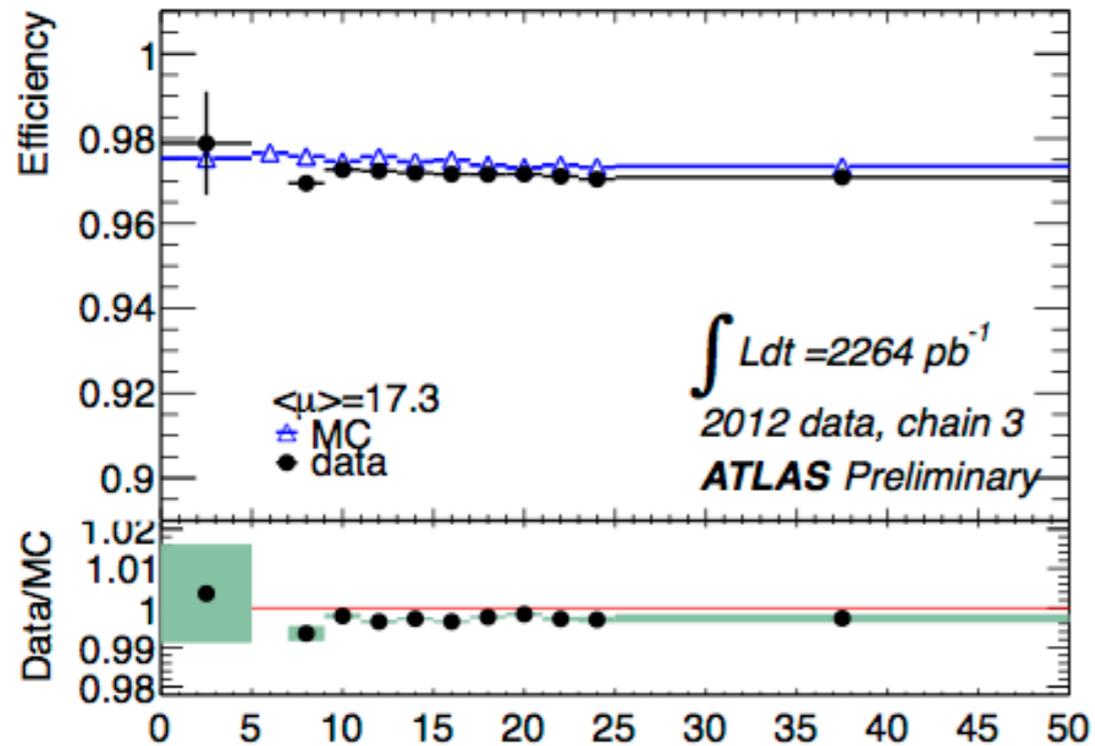
$$N = \sigma \times \mathcal{L} \times BR \times \mathcal{A} \times \epsilon$$

❖  $\sigma \times BR$ を測るにはefficiency  $\epsilon$ の理解が重要

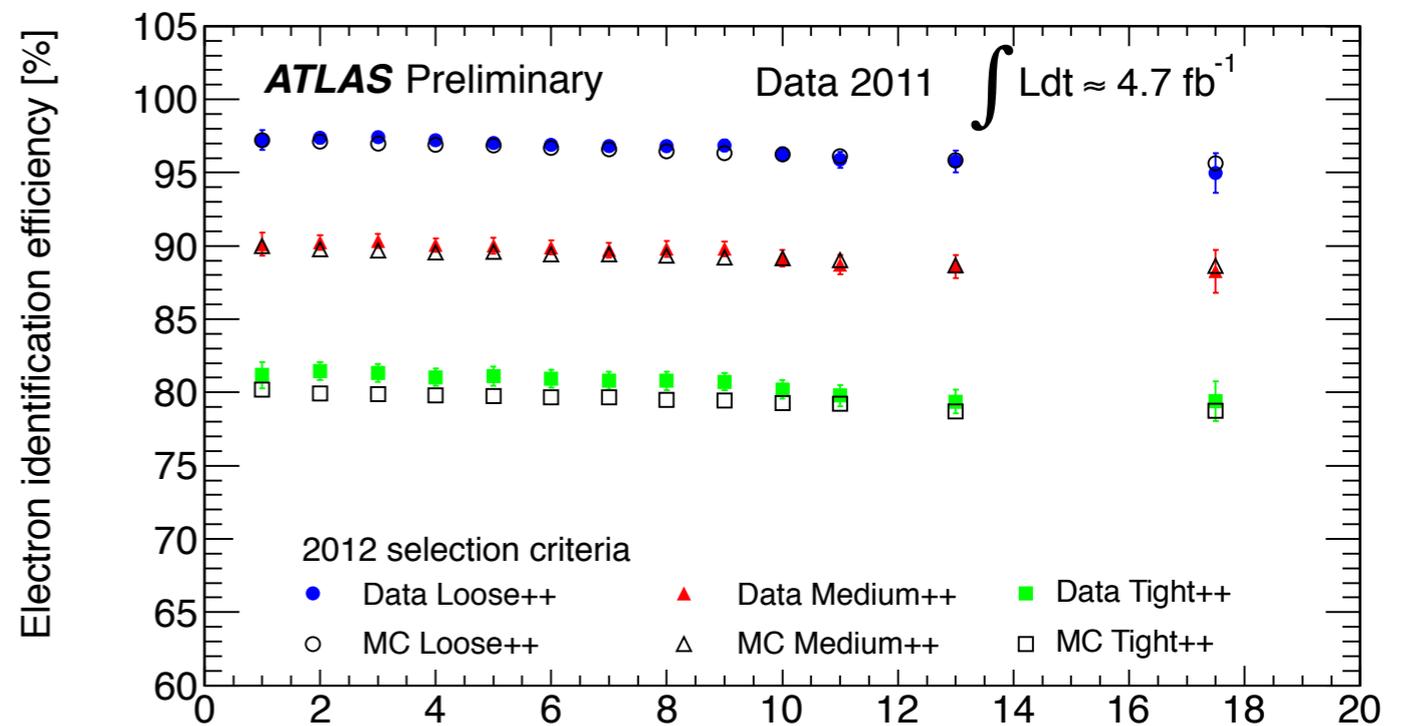
efficiencyのバンチあたり衝突数への依存性

ミューオン

電子



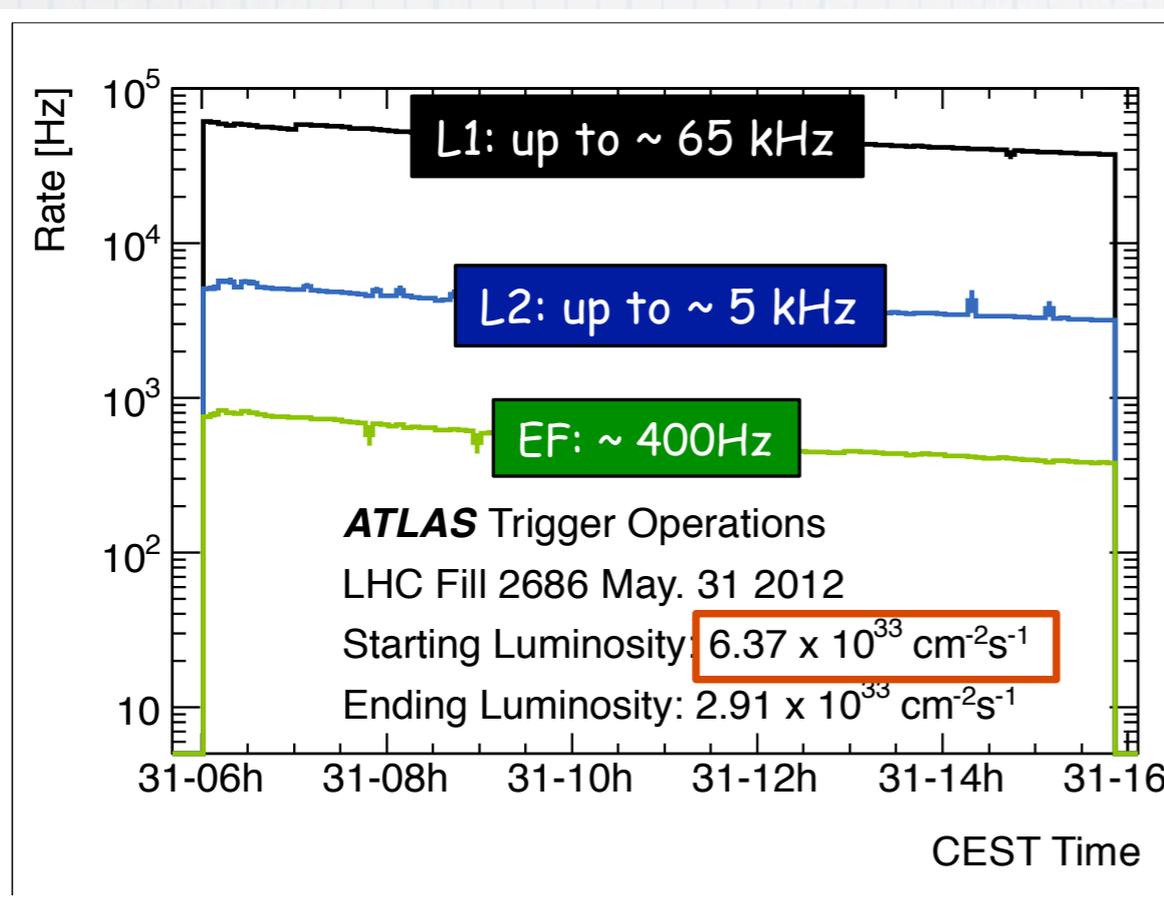
バンチあたり衝突数



再構成されたpp衝突地点数

# Trigger

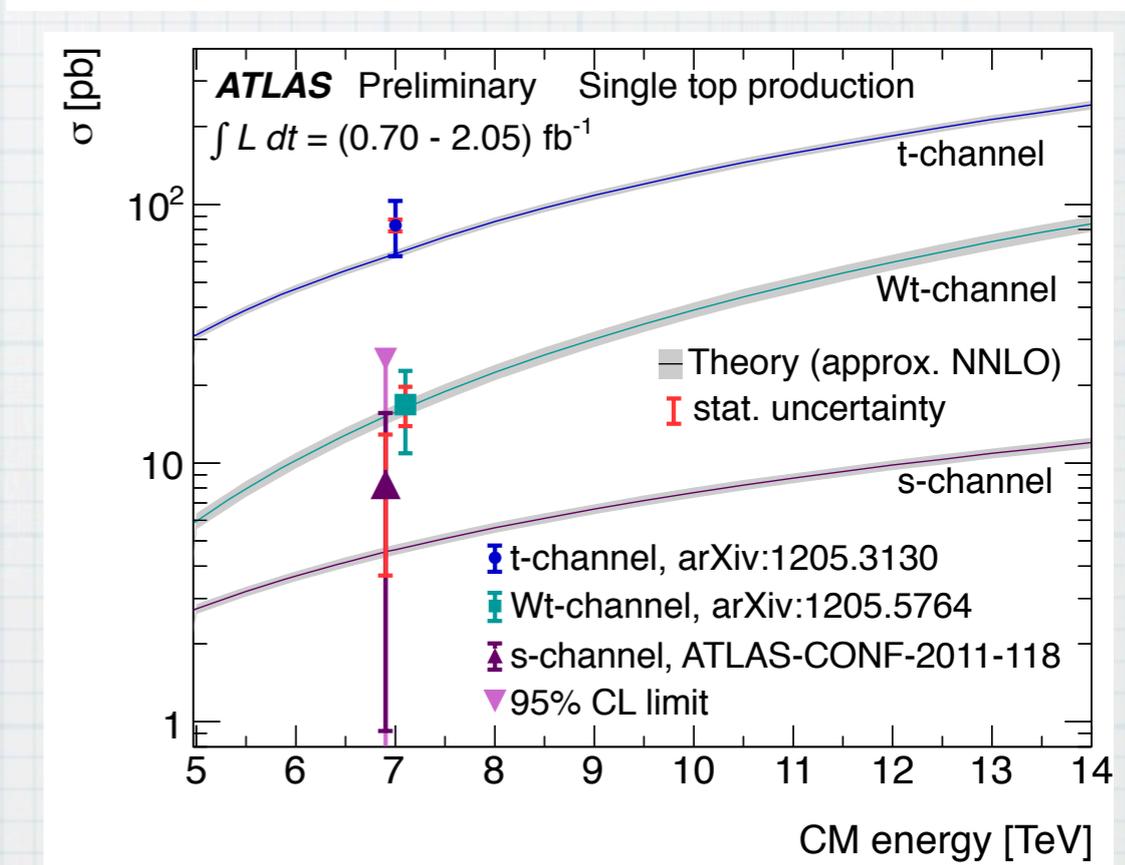
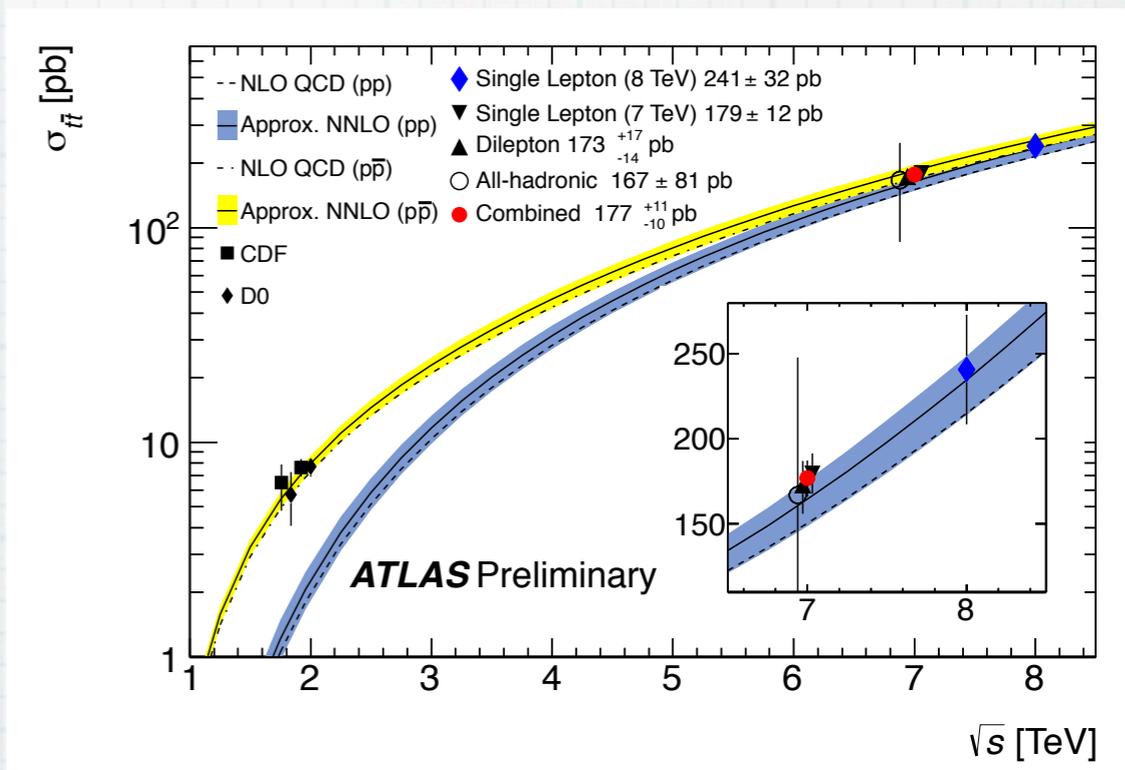
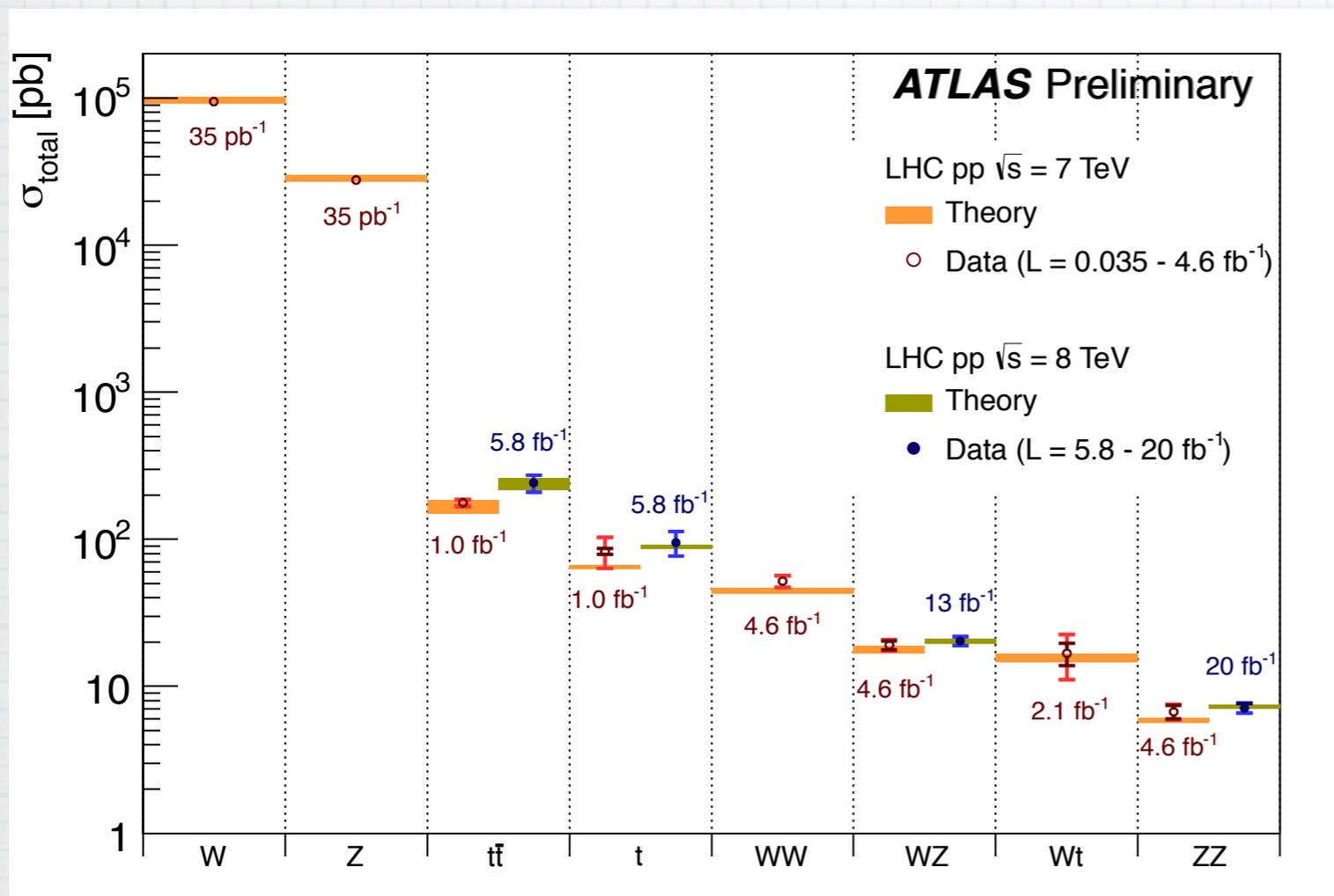
- ❖ Raw rate  $\sim 80\text{mb} \times 6 \times 10^{33} = 500\text{M Hz}$
- ❖ Rate to tape  $\sim 400\text{ Hz}$
- ❖ Factor of 1,000,000 reduction



## Non-prescaled triggers

| Item                | $p_T$ threshold (GeV) | Rate (Hz)<br>5x10 <sup>33</sup> |
|---------------------|-----------------------|---------------------------------|
| Incl. e             | 24                    | 70                              |
| Incl. $\mu$         | 24                    | 45                              |
| ee                  | 12                    | 8                               |
| $\mu\mu$            | 13                    | 5                               |
| $\tau\tau$          | 29,20                 | 12                              |
| $\gamma\gamma$      | 35,25                 | 10                              |
| $E_T^{\text{miss}}$ | 80                    | 17                              |
| 5j                  | 55                    | 8                               |

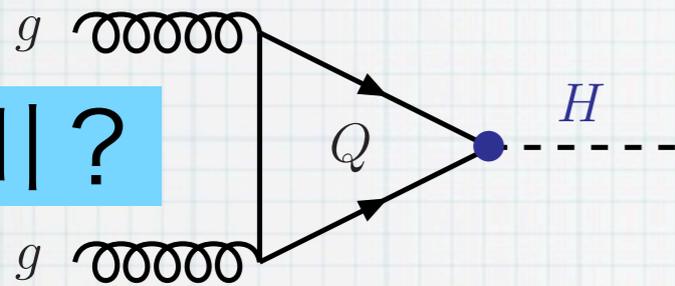
# 標準模型の確認



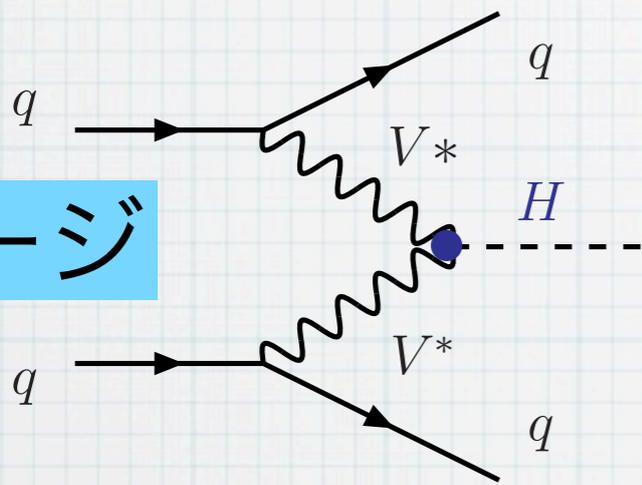
# ヒッグスの生成と崩壊

# LHCでのSMヒッグスの生成 (125GeV)

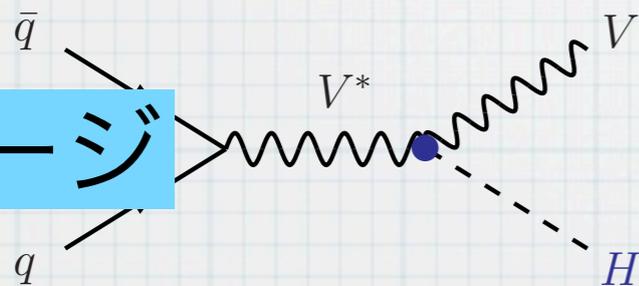
湯川?



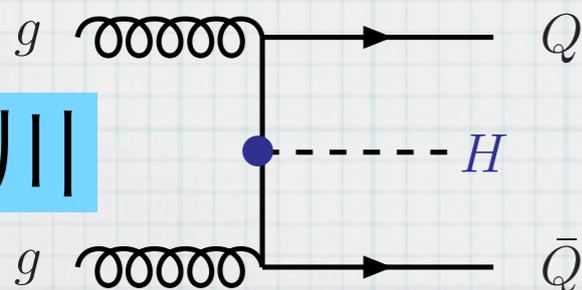
ゲージ



ゲージ

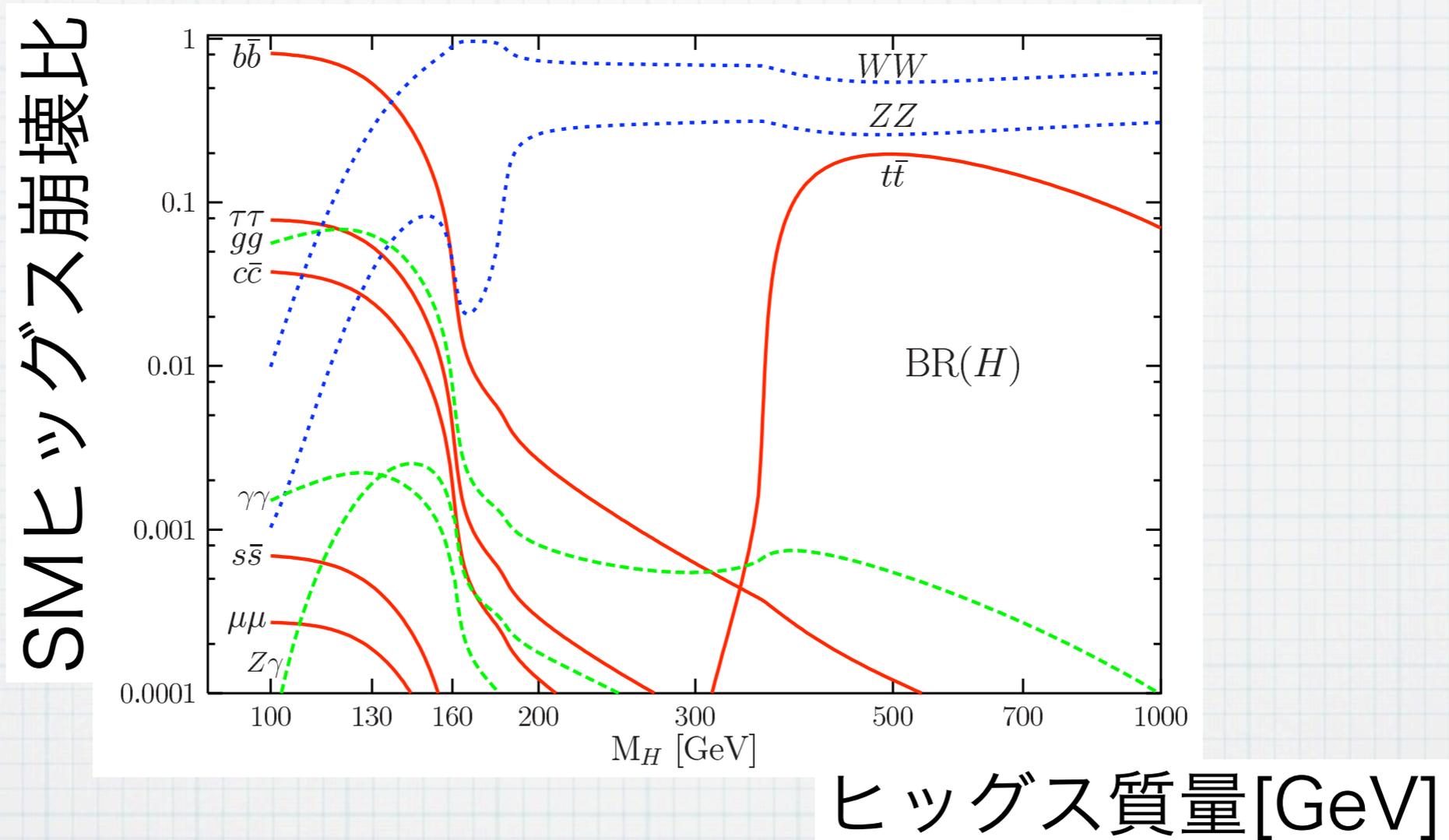


湯川



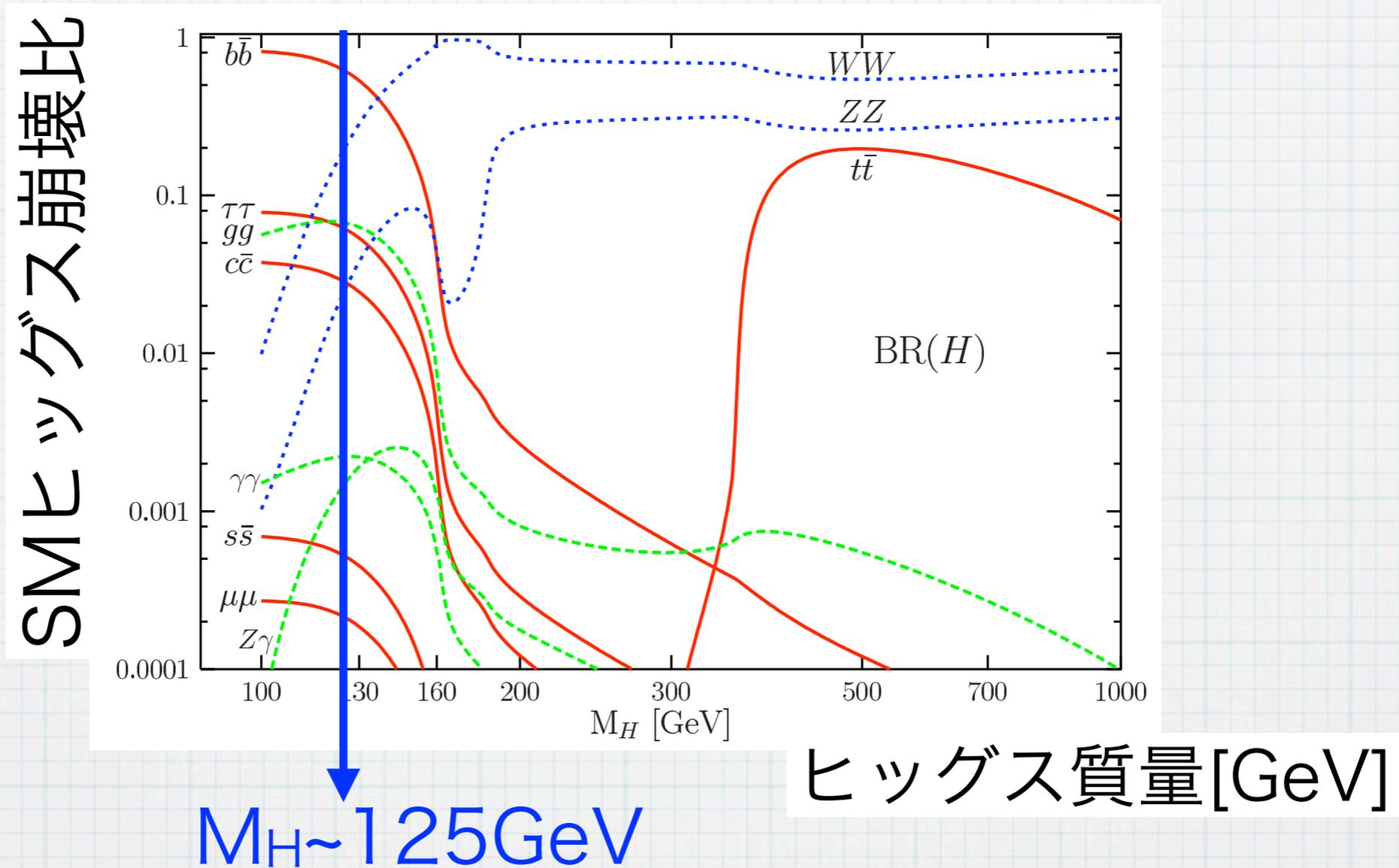
|                              | $\sigma$ (pb)<br>@7TeV | $\sigma$ (pb)<br>@14TeV | 14TeV<br>/ 7TeV |
|------------------------------|------------------------|-------------------------|-----------------|
| Gluon Fusion<br>(ggF)        | 15.3                   | 50.0                    | 3.3             |
| Vector Boson<br>Fusion (VBF) | 1.2                    | 4.2                     | 3.5             |
| WH                           | 0.6                    | 1.5                     | 2.5             |
| ZH                           | 0.3                    | 0.9                     | 3.0             |
| ttH                          | 0.1                    | 0.6                     | 6.0             |
| ttbar                        | 170                    | 830                     | 4.9             |

# ヒッグスの崩壊



- ❖  $\Gamma$  (vector boson)  $\propto m_H^3$
- ❖  $\Gamma$  (fermion)  $\propto m_H$

# ヒッグスの崩壊



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- ❖  $\Gamma$  (fermion)  $\propto m_H$

# ヒッグスの崩壊

## ❖ SM 125GeV 崩壊比 (%)

|                          |       |                              |      |
|--------------------------|-------|------------------------------|------|
| $H \rightarrow b\bar{b}$ | 58    | $H \rightarrow \gamma\gamma$ | 0.23 |
| $H \rightarrow \tau\tau$ | 6.3   | $H \rightarrow WW$           | 22   |
| $H \rightarrow \mu\mu$   | 0.022 | $H \rightarrow ZZ$           | 2.7  |
| $H \rightarrow c\bar{c}$ | 2.7   | $H \rightarrow Z\gamma$      | 0.16 |
| $H \rightarrow s\bar{s}$ | 0.044 | $H \rightarrow gg$           | 8.6  |

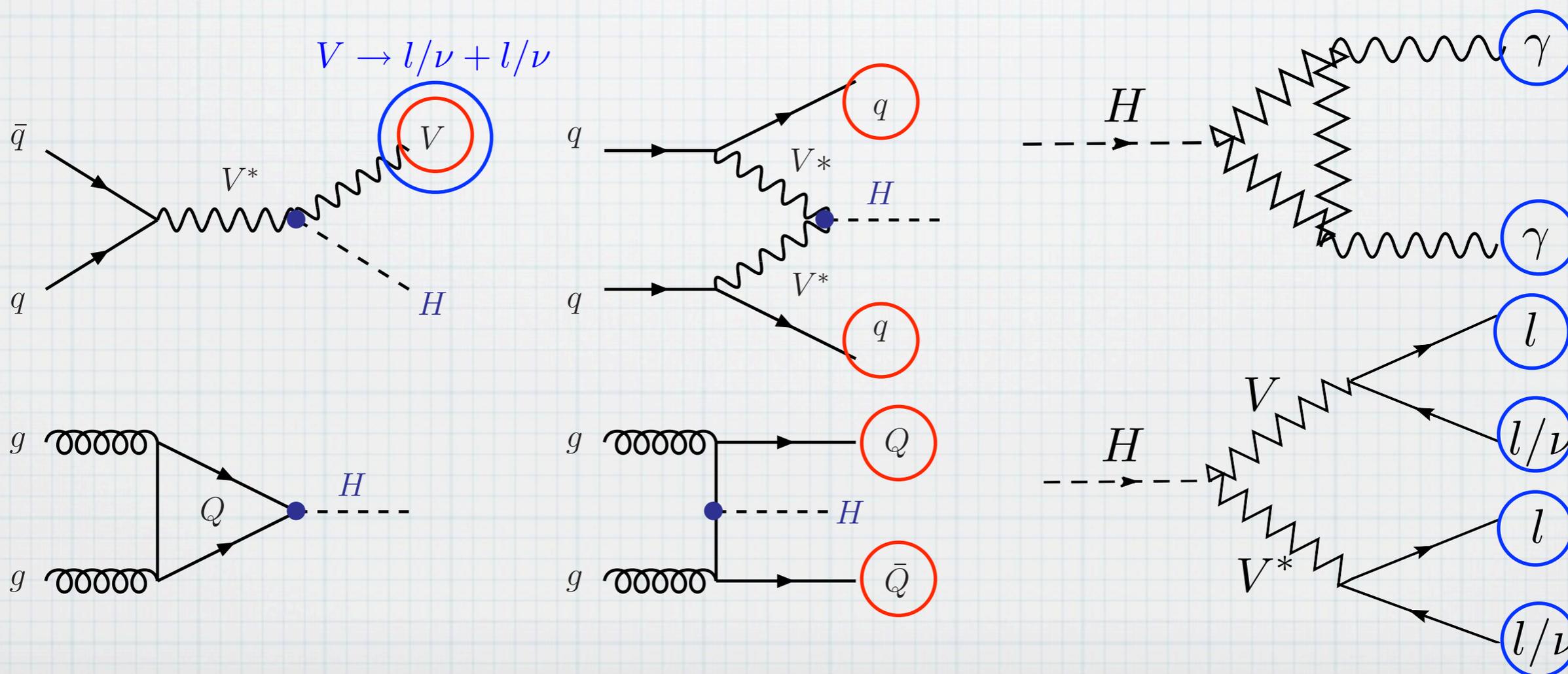
全幅は 4 MeV

# 信号の手がかり

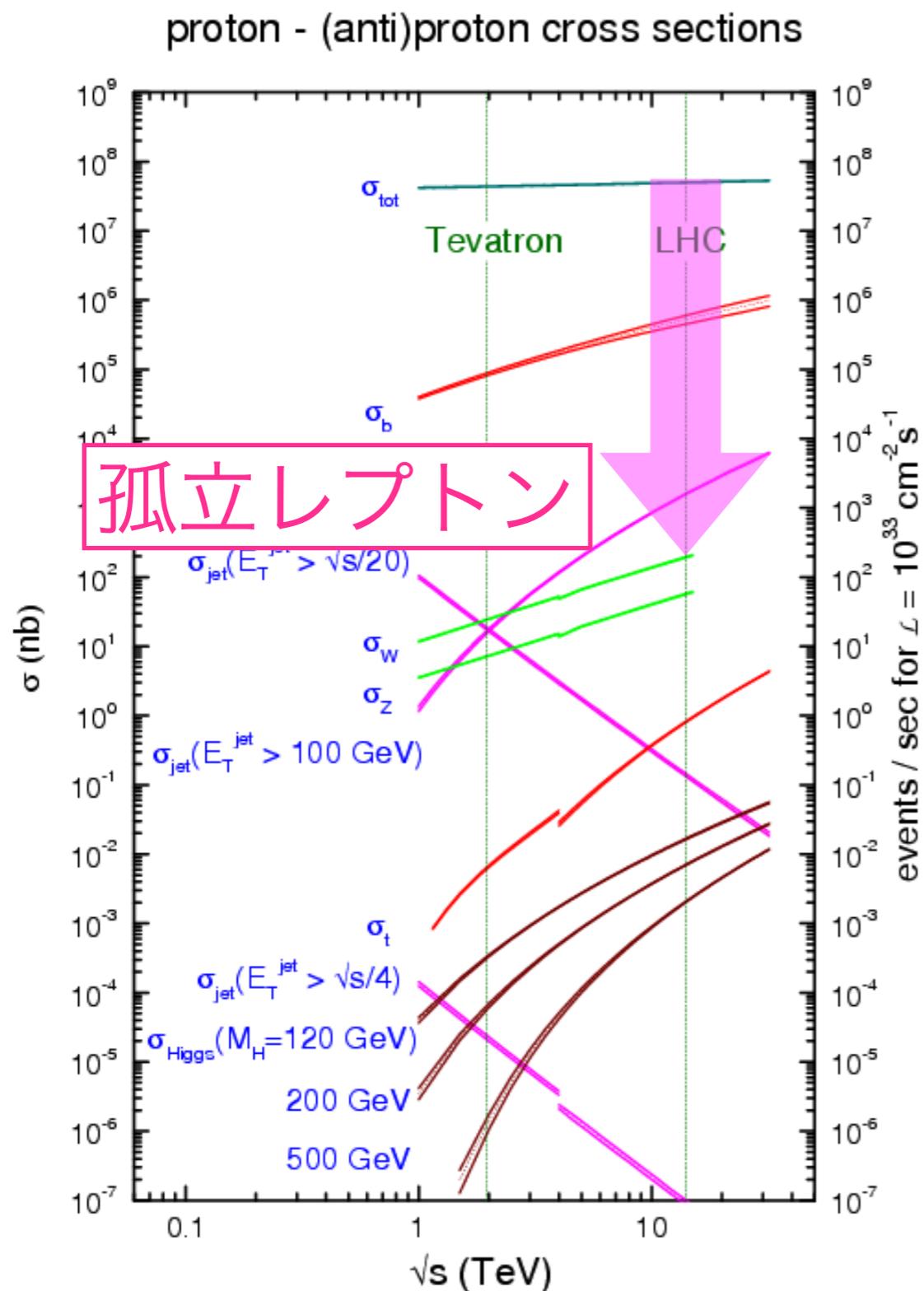
❖ 背景事象の多くはクォーク/グルーオン  
 (=ジェット)生成 [強い相互作用は強い...]

⇒ ジェット以外の何かが必要

▶ 運動学的な特徴あるいは孤立レプトン



# たとえば孤立レプトン



❖ 孤立した（周囲に他の粒子のいない）レプトン

▶ 重い粒子（W, Z）の崩壊によるレプトン

❖ ジェット近傍のレプトン

▶ b/cからの崩壊

▶  $\pi$  / Kの崩壊

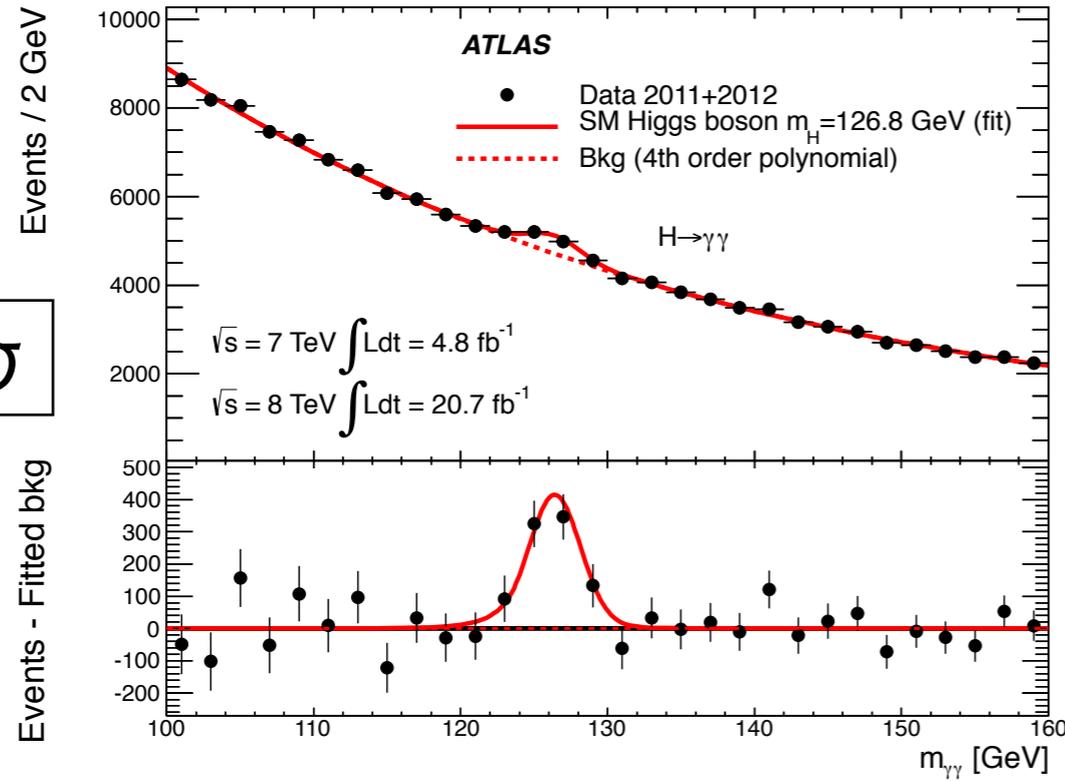
Higgs-like to Higgs

# Data & Event Selection

- ❖  $H \rightarrow \gamma \gamma$  : 4.8 (7TeV) + 20.7 (8TeV) fb<sup>-1</sup>
  - ▶ two **isolated** photons w/  $p_T > 40, 30$  GeV
- ❖  $H \rightarrow ZZ \rightarrow 4l$  : 4.6 + 20.7 fb<sup>-1</sup>
  - ▶ **isolated** lep.  $p_T > 20, 15, 10, 7(e)/6(\mu)$  GeV
  - ▶  $50 < m_{12} < 106$  GeV,  $12-50 < m_{34} < 115$  GeV
- ❖  $H \rightarrow WW \rightarrow l \nu l \nu$  : 4.6 + 20.7 fb<sup>-1</sup>
  - ▶ **isolated** lepton  $p_T > 25, 15$  GeV
  - ▶ missing  $E_T$ ,  $M_z$  veto
  - ▶  $m_{ll} < 50-60$  GeV,  $\Delta \Phi_{ll} < 1.8$

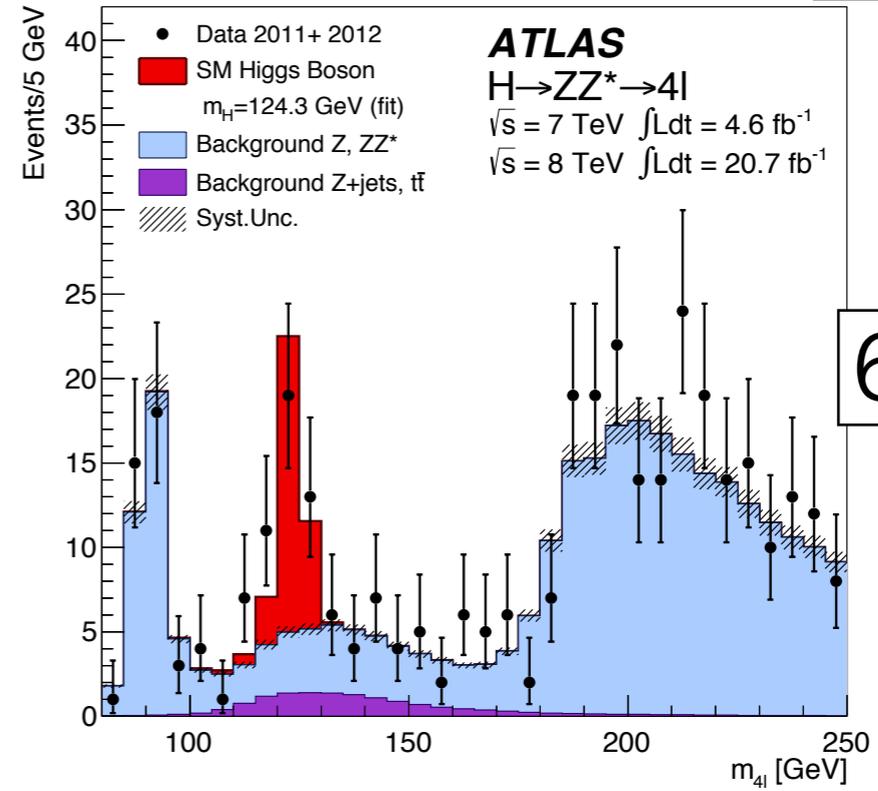
# Signal Yield

$H \rightarrow \gamma\gamma$



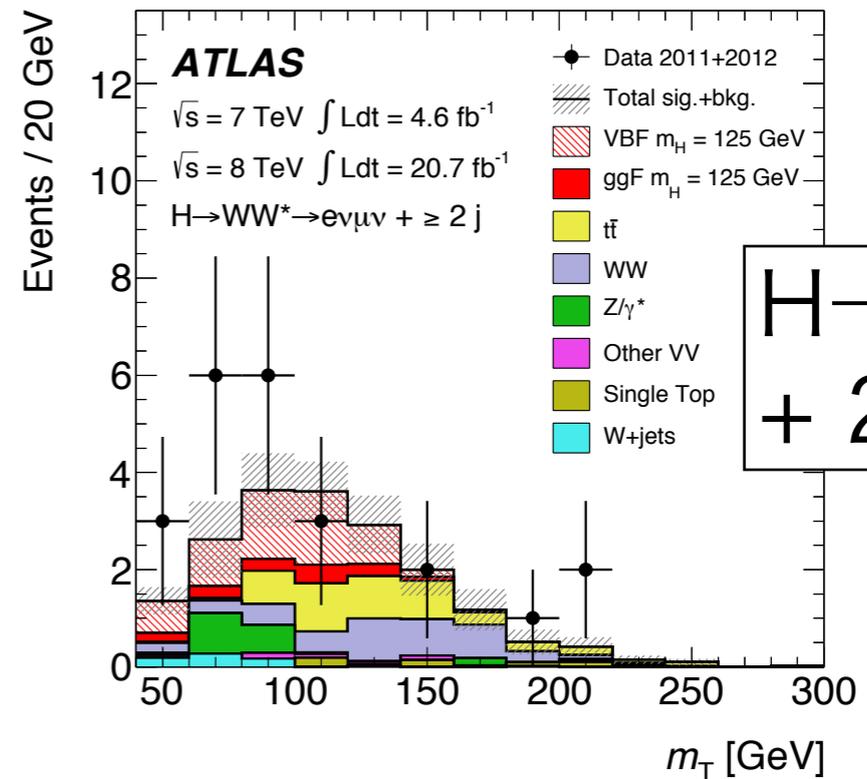
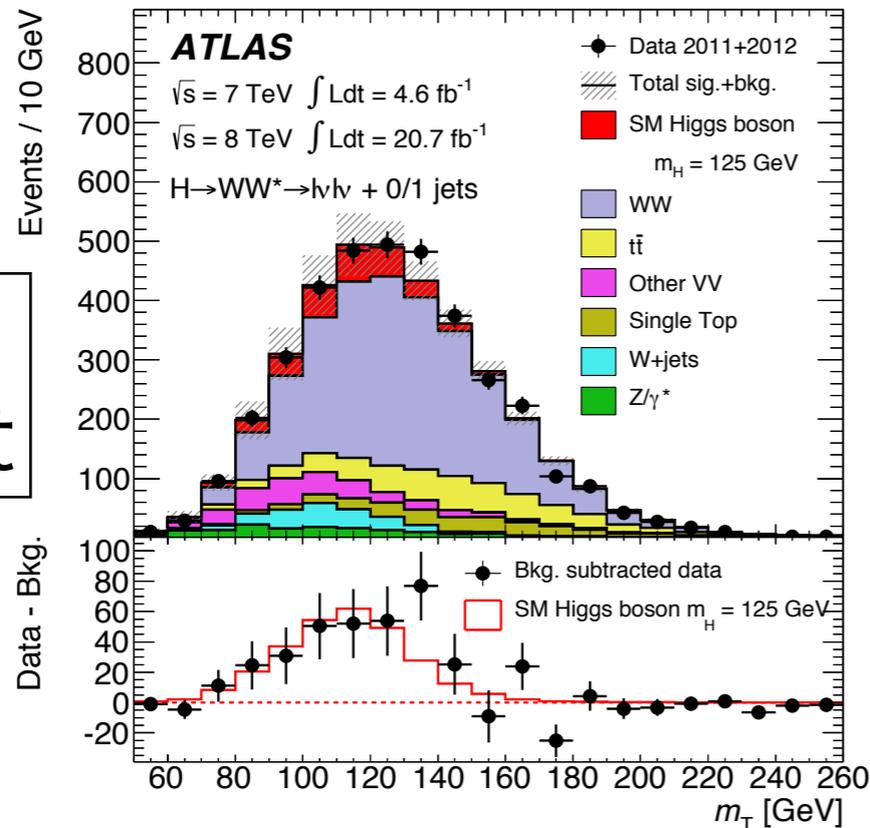
$7.4\sigma$

$H \rightarrow ZZ$



$6.6\sigma$

$H \rightarrow WW$   
 + 0, 1 jet



$H \rightarrow WW$   
 + 2 jets

# Statistical Method

## ❖ Maximum likelihood ratio

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

conditional  
estimate

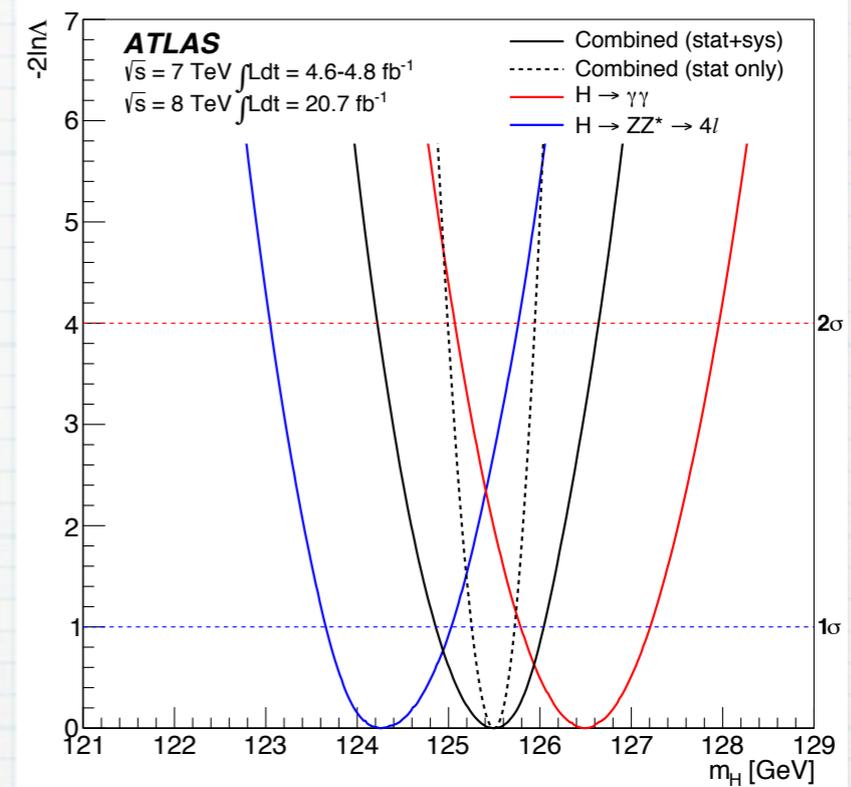
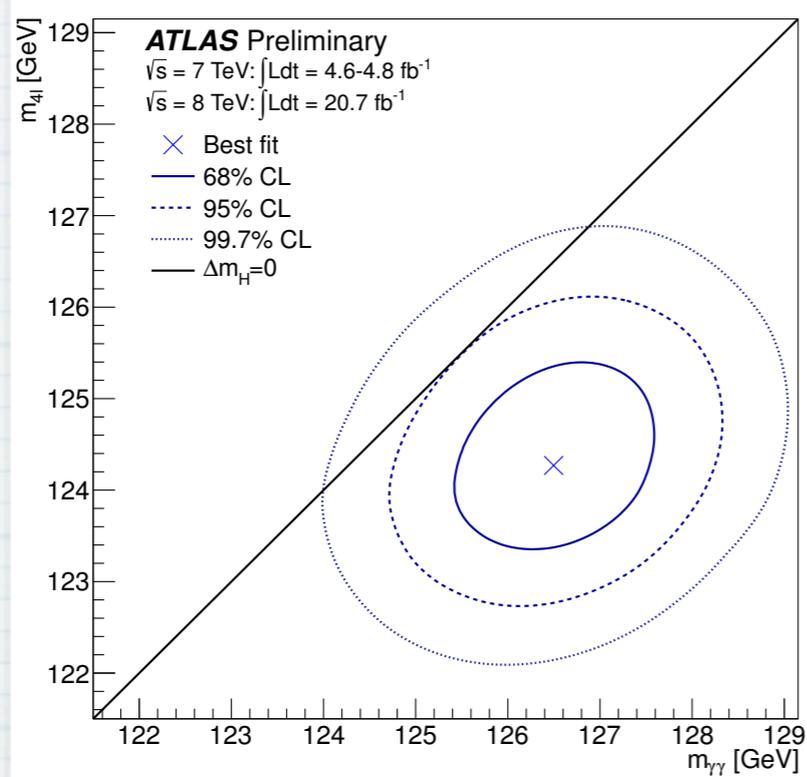
## ❖ $\alpha$ : 測定したいパラメータ

- ▶ signal strength  $\mu$ , 質量  $m_H$ ,  
結合定数のSM予言値に対する比, 等々

## ❖ $\theta$ : nuisance parameters

unconditional  
estimate

# 質量



$\gamma\gamma$

$$m_H = 126.8 \pm 0.2 \pm 0.7 \text{ GeV}$$

4 lepton

$$m_H = 124.3^{+0.6}_{-0.5} \text{ } ^{+0.5}_{-0.3} \text{ GeV}$$

$\gamma\gamma + 4 \text{ lepton}$

$$m_H = 125.5 \pm 0.2 \text{ } ^{+0.5}_{-0.6} \text{ GeV}$$

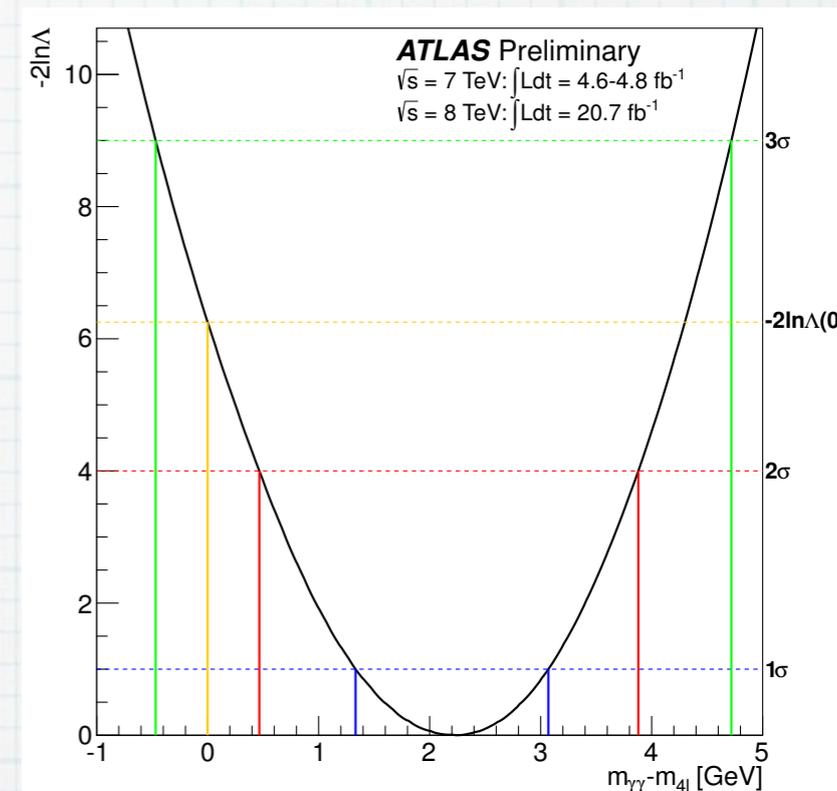
# 質量測定 of 精度

$$m_H^{\gamma\gamma} - m_H^{4l} = 2.3_{-0.7}^{+0.6}(\text{stat}) \pm 0.6(\text{syst}) \text{ GeV}$$

本当は差がないにもかかわらず

2.3GeV以上の差を観測する確率：1.2~1.5%

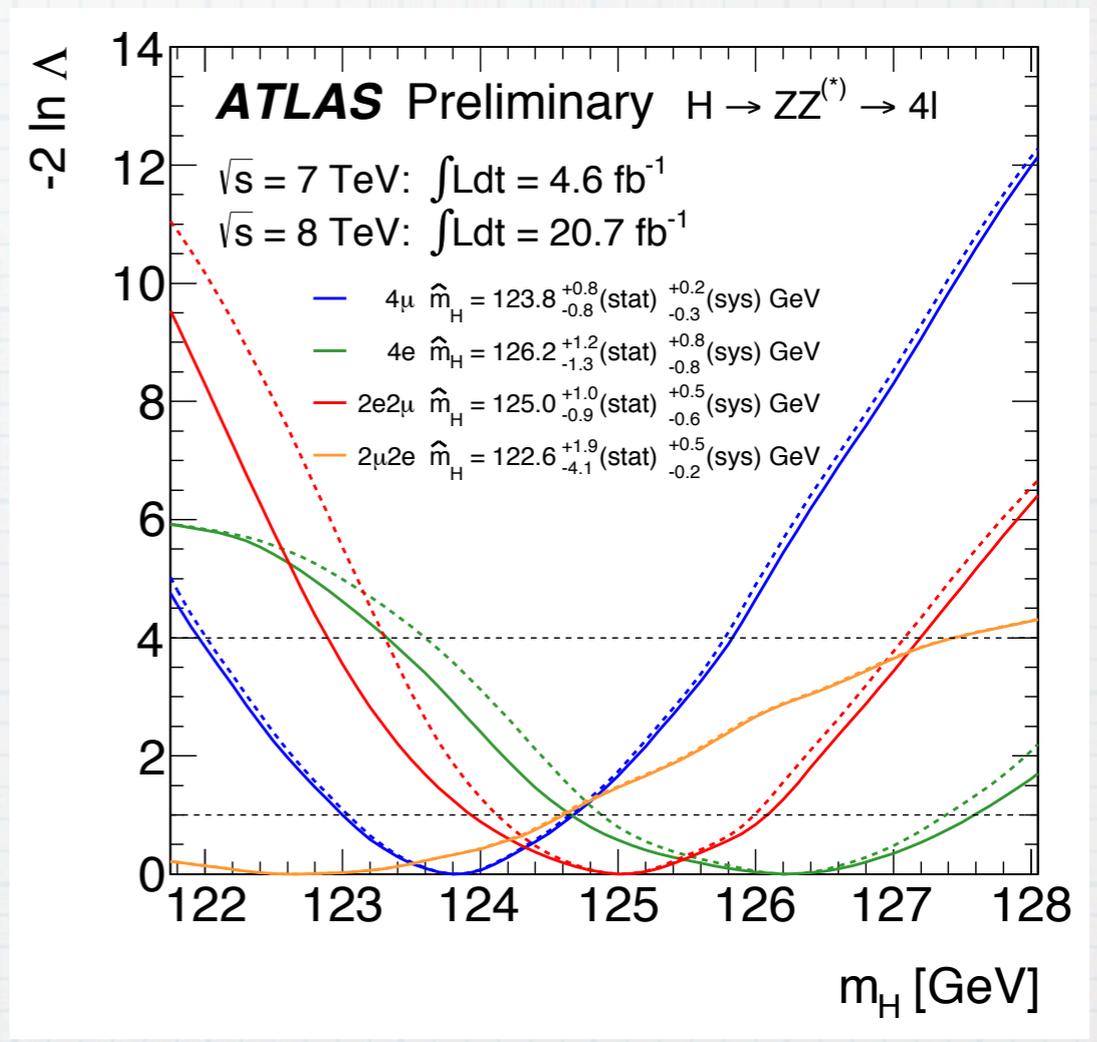
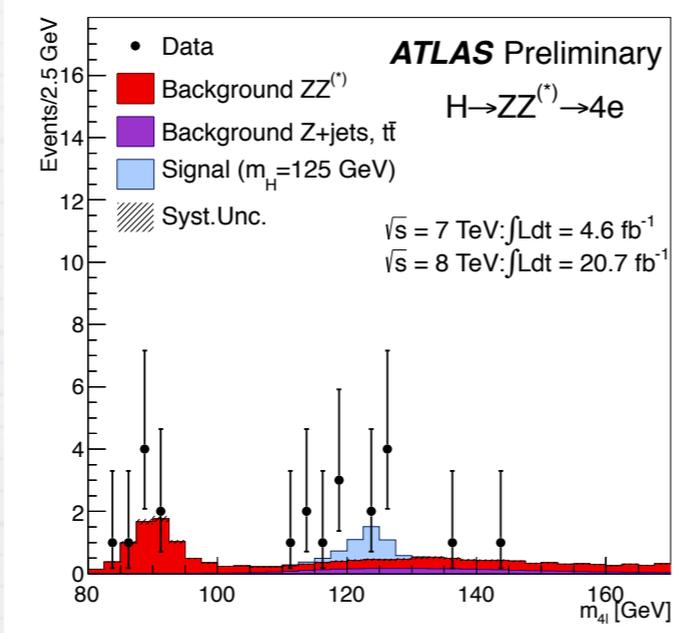
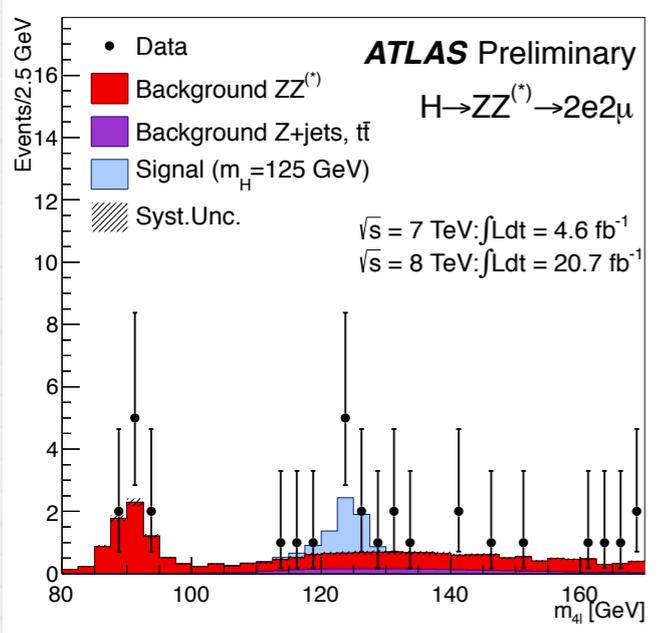
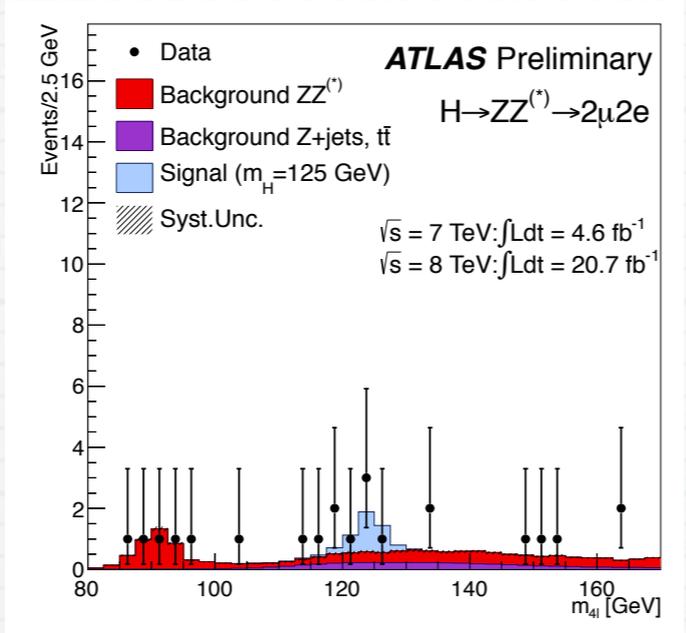
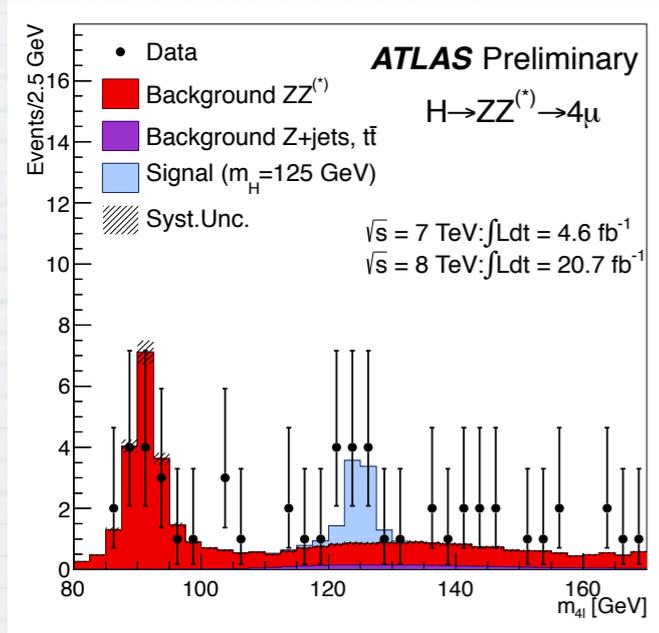
conservativeにやると8%



## ❖ $H \rightarrow \gamma\gamma$

- ▶ systematics : 0.7GeV in total
  - 0.4GeV :  $Z \rightarrow ee$  calibration
  - 0.4GeV : material estimates
  - 0.2GeV : preshower energy scale
- ▶ resolution : 1.4 - 2.5 GeV
  - extrapolation from e to  $\gamma$

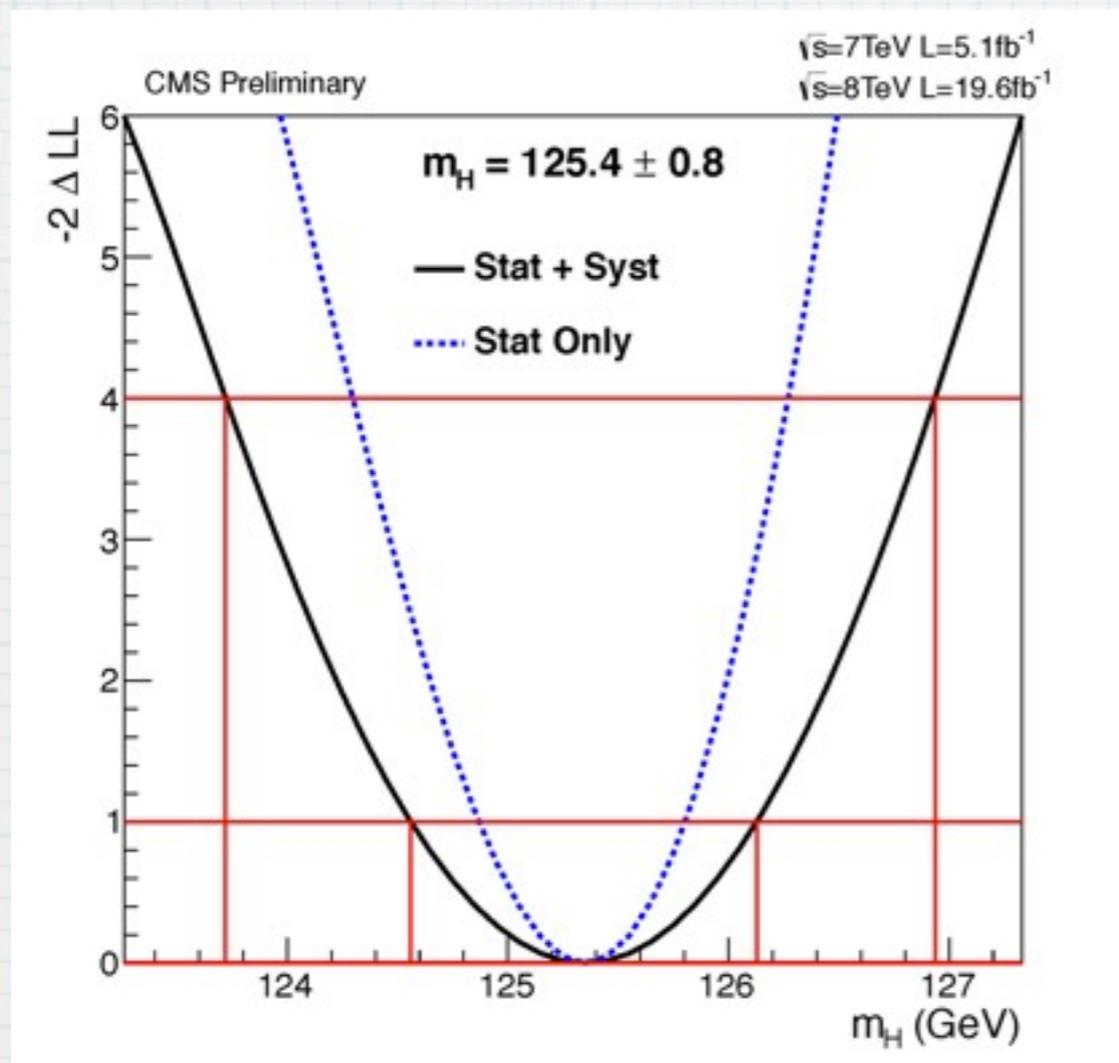
# Mass in $H \rightarrow ZZ$



❖ Resolution : 1.6( $4\mu$ ), 1.9( $2e2\mu$ ), 2.4( $4e$ ) GeV

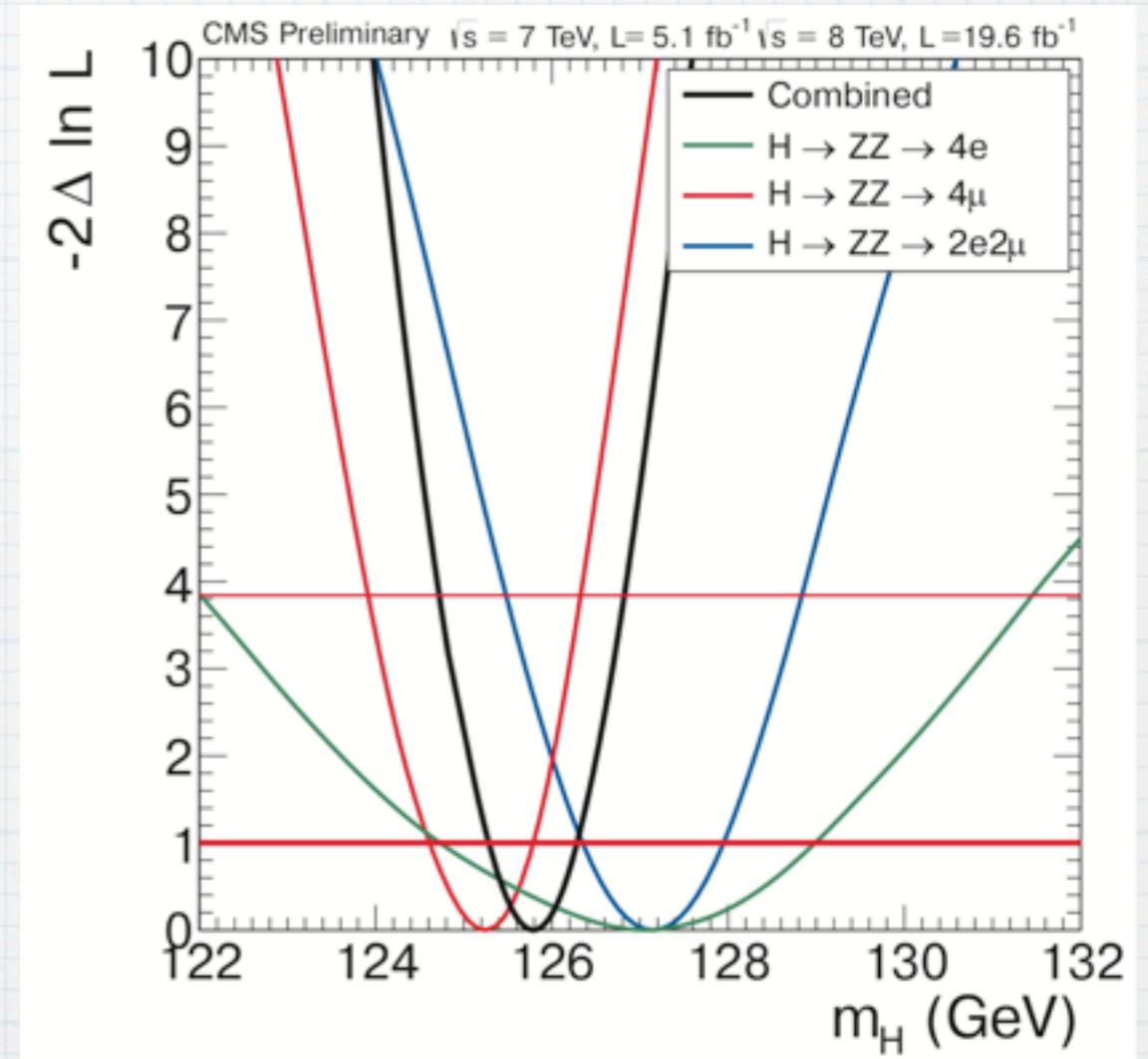
# Mass measurement at CMS

$$H \rightarrow \gamma \gamma$$



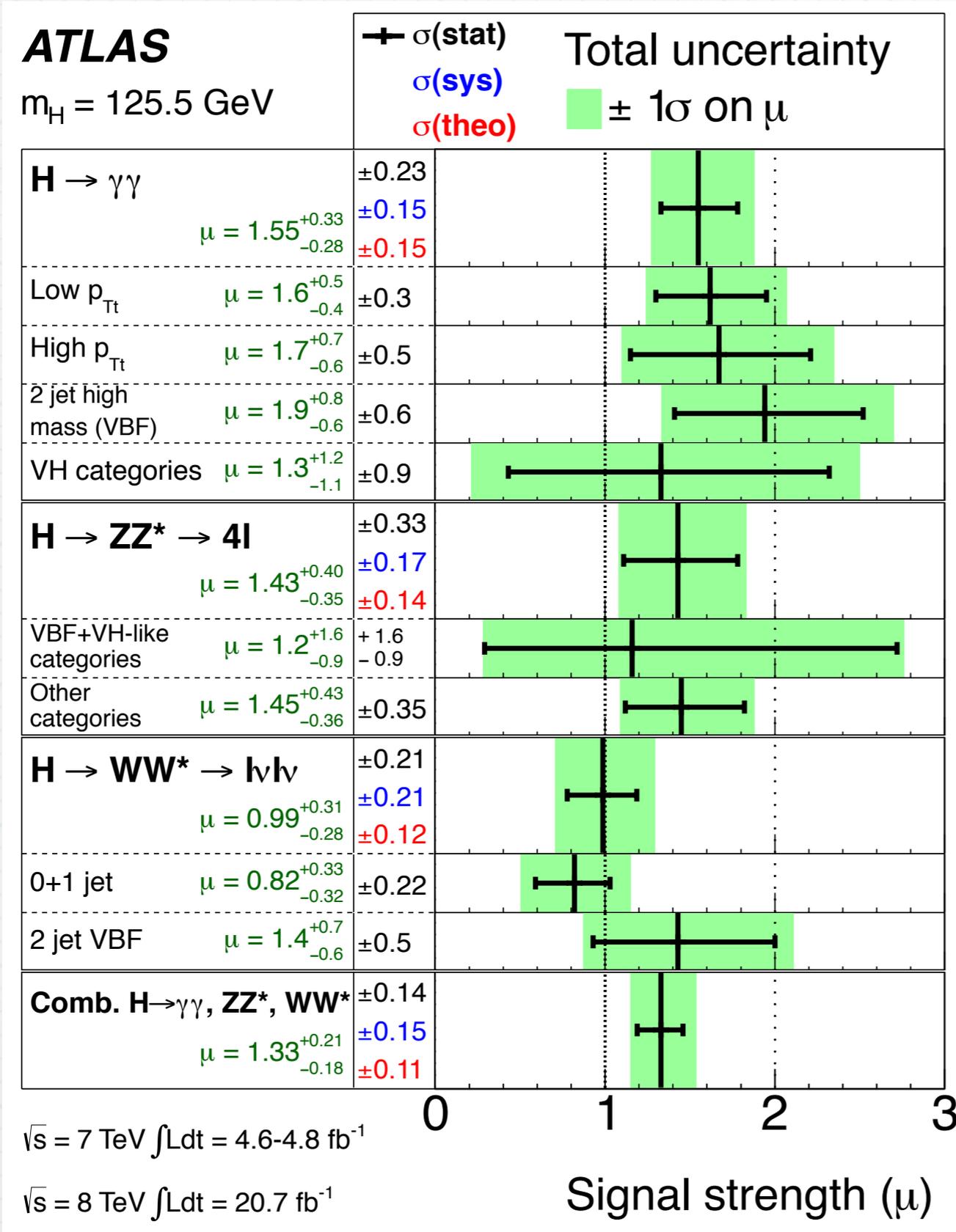
$125.4 \pm 0.5 \pm 0.6$  GeV

$$H \rightarrow ZZ$$

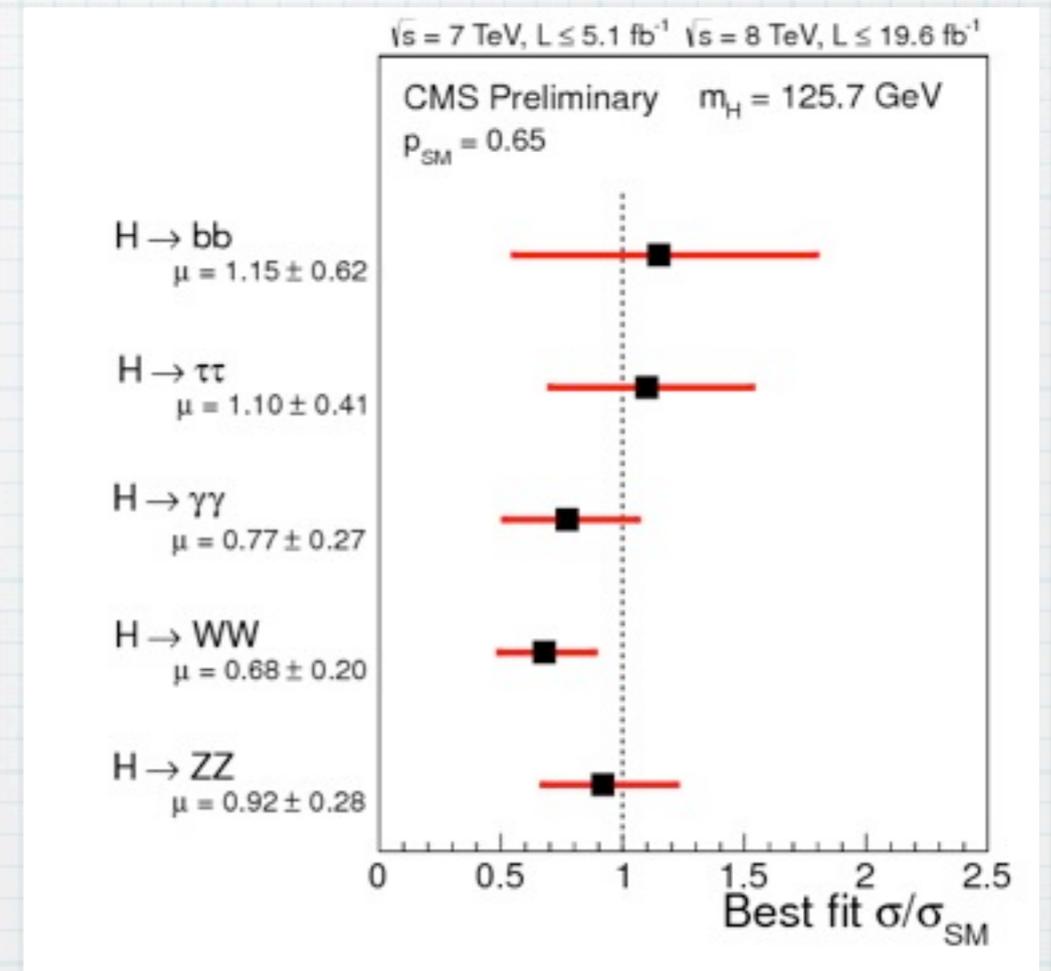


$125.8 \pm 0.5 \pm 0.2$  GeV

# Signal strength w.r.t. SM expectation



$$\mu \equiv \frac{(\# \text{events})_{\text{observed}}}{(\# \text{events})_{\text{SM}}}$$



# 結合定数

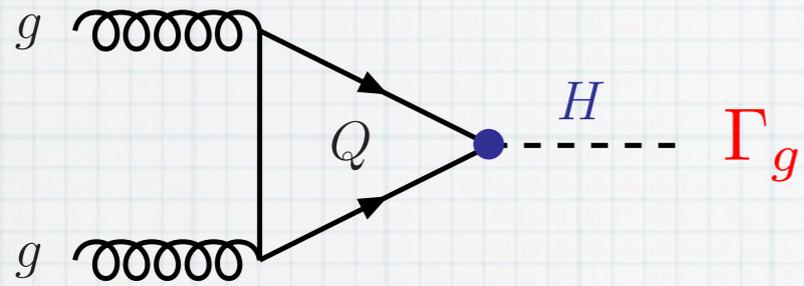
$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_H^2\phi^2) \\ &+ \frac{vg^2}{2}\phi W_\mu^+ W^{-\mu} + \frac{v(g^2 + g'^2)}{4}\phi Z_\mu Z^\mu \\ &- \sum_f Y_f \phi \bar{f} f \\ &- \lambda v \phi^3 - \lambda \frac{\phi^4}{4} \\ &+ \frac{g^2}{2}\phi^2 W_\mu^+ W^{-\mu} + \frac{(g^2 + g'^2)}{4}\phi^2 Z_\mu Z^\mu\end{aligned}$$

←ゲージ結合

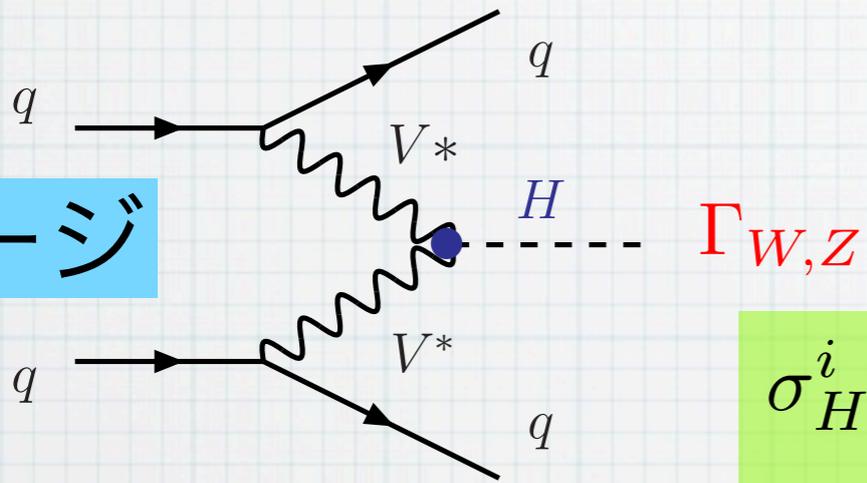
←湯川結合

# 生成と崩壊に寄与する結合

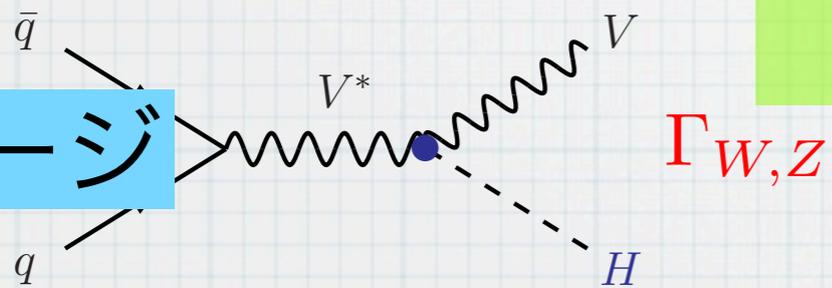
?



ゲージ

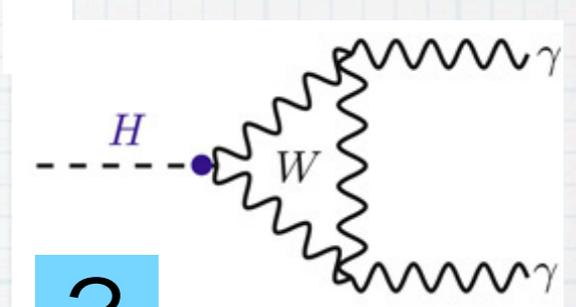
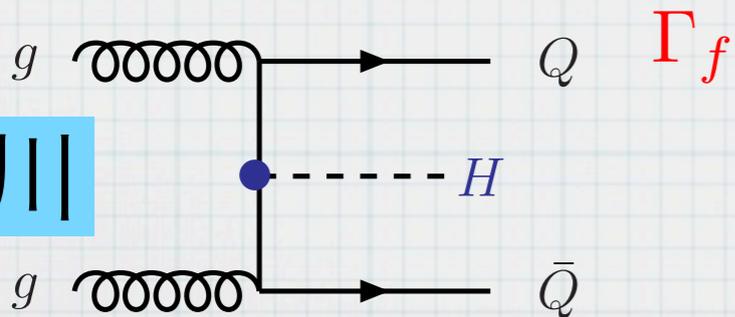


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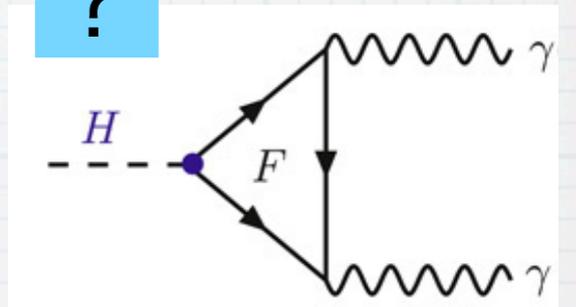


$$\sigma_H^i \times BR(H \rightarrow jj) = \frac{\sigma_H^{SM}}{\Gamma_i^{SM}} \times \frac{\Gamma_i \Gamma_j}{\Gamma_H}$$

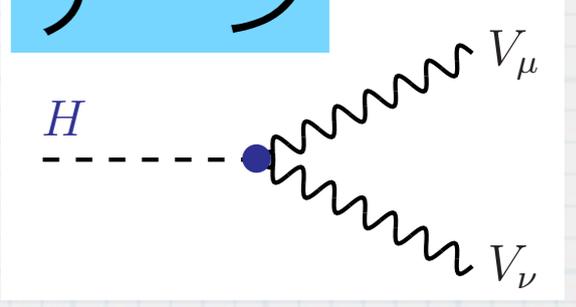
湯川



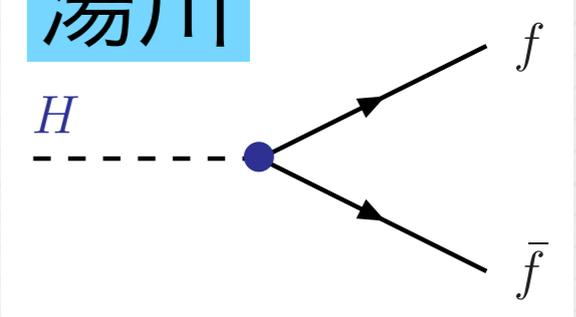
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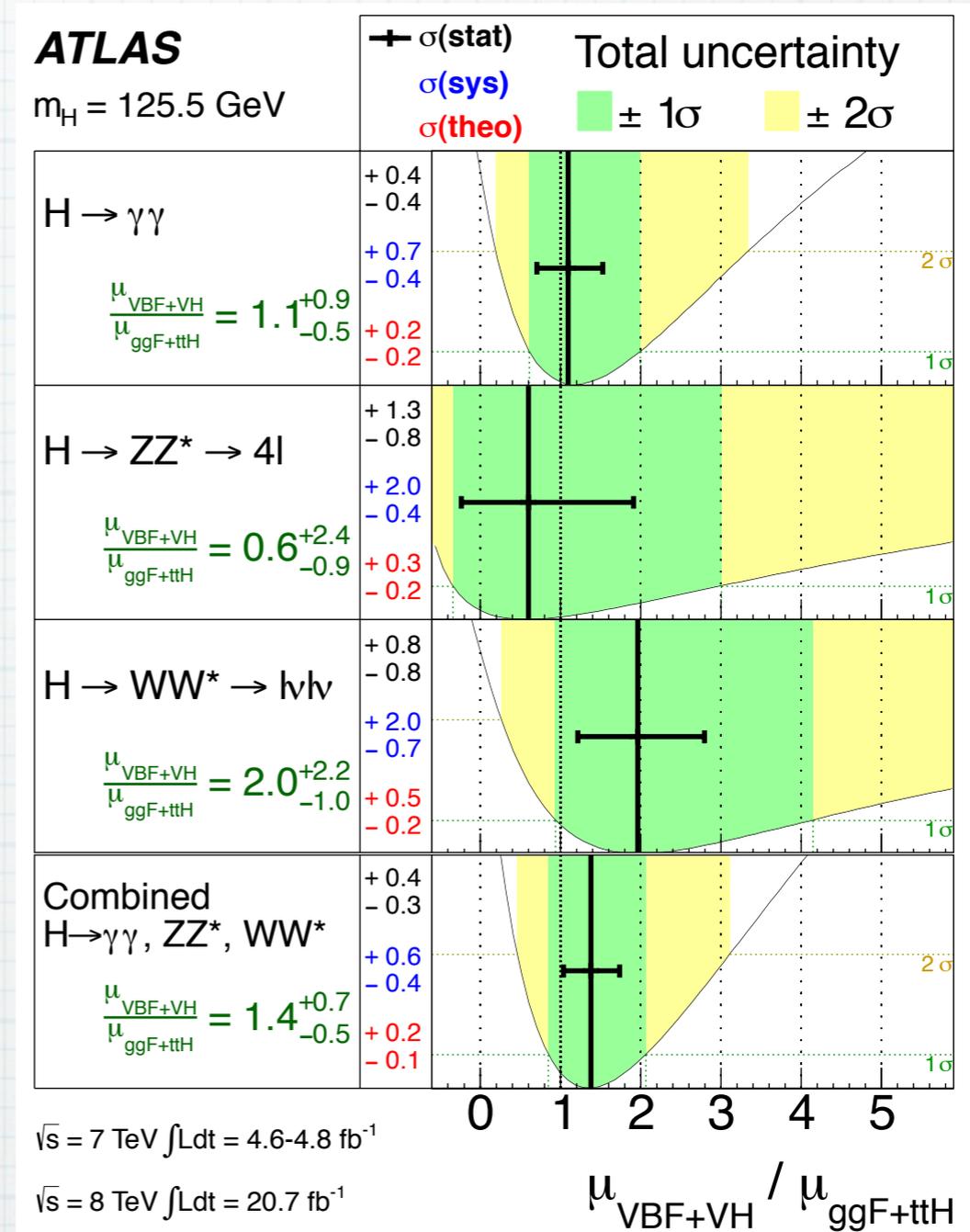
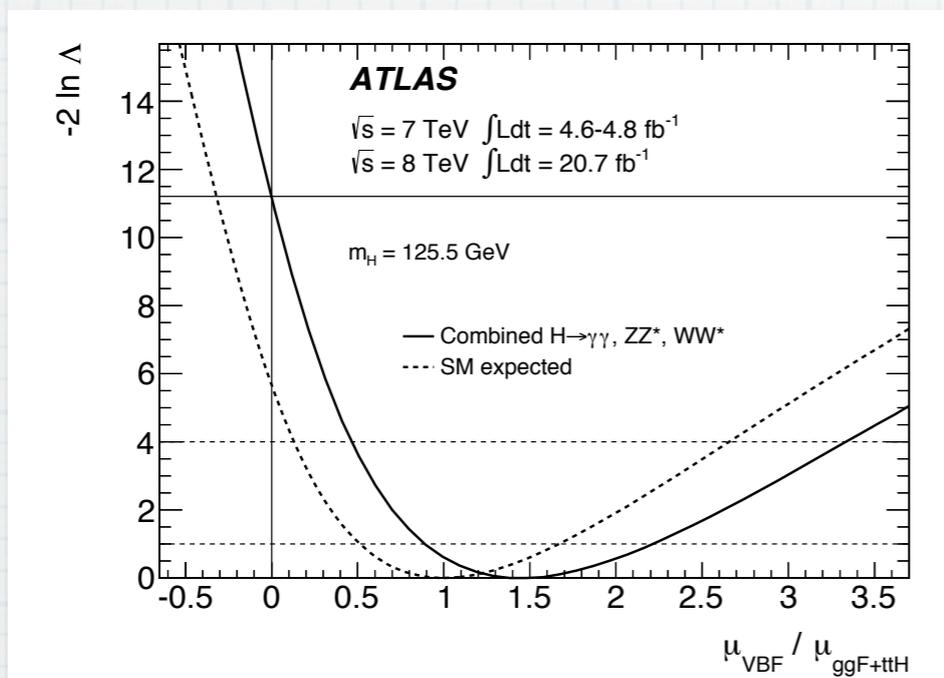
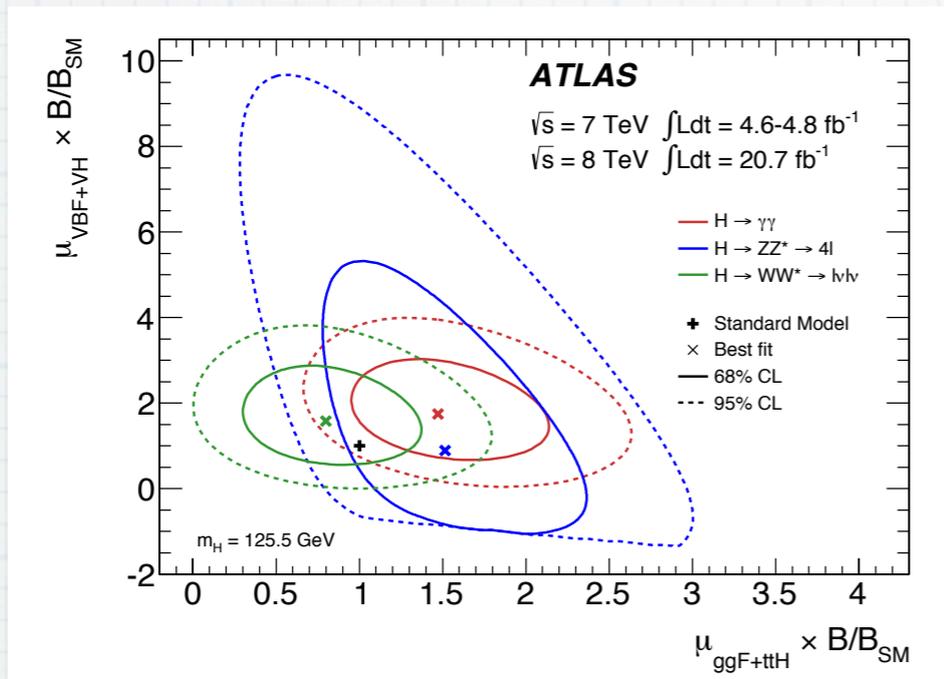
ゲージ



湯川



# ゲージ vs 湯川



- ❖ Yukawa indirectly confirmed
- ❖ VBF confirmed at  $3.3\sigma$

# 結合定数測定

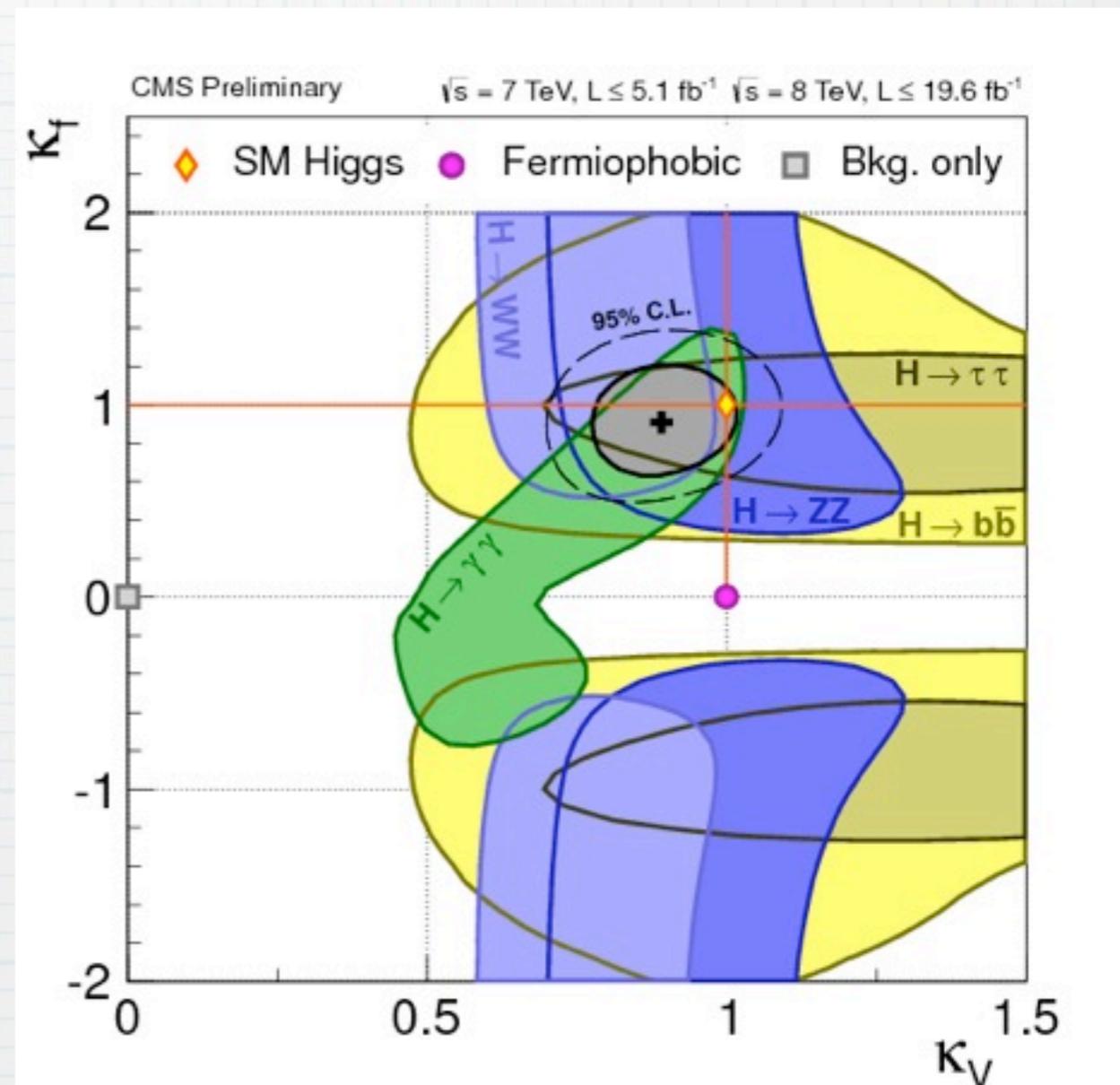
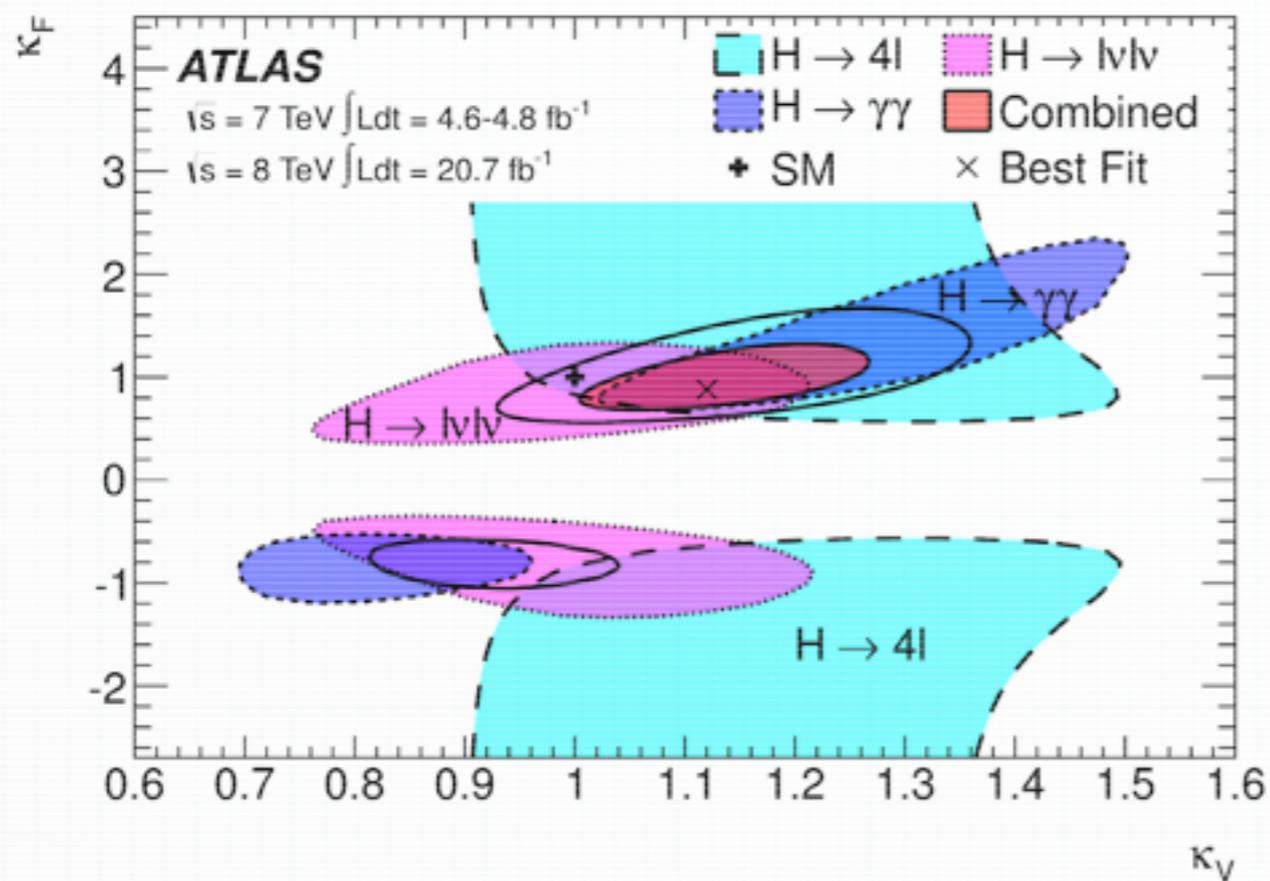
❖  $\kappa$  : scaling factor to SM value

$$\text{例) } \frac{\sigma \cdot \text{B} (gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(gg \rightarrow H) \cdot \text{B}_{\text{SM}}(H \rightarrow \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

| Source (experimental) | Uncertainty (%)  |
|-----------------------|--|
| Luminosity            | $\pm 1.8$ (2011), $\pm 3.6$ (2012)                     |
| Electron efficiency   | $\pm 2-5$  |
| Jet energy scale      | $\pm 1-5$  |
| Jet energy resolution | $\pm 2-40$   |
| Source (theory)       | Uncertainty (%)  |
| QCD scale             | $\pm 8$ (ggF), $\pm 1$ (VBF, VH), ${}_{-9}^{+4}$ (ttH) |
| PDFs + $\alpha_s$     | $\pm 8$ (ggF, ttH), $\pm 4$ (VBF, VH)                  |

# 結合定数測定結果

- ❖ No Beyond SM contributions assumed
- ❖  $\mathcal{K}_f \equiv \mathcal{K}_t = \mathcal{K}_b = \mathcal{K}_\tau$ ,  $\mathcal{K}_v \equiv \mathcal{K}_W = \mathcal{K}_Z$



# 結合定数測定結果 (別の仮定)

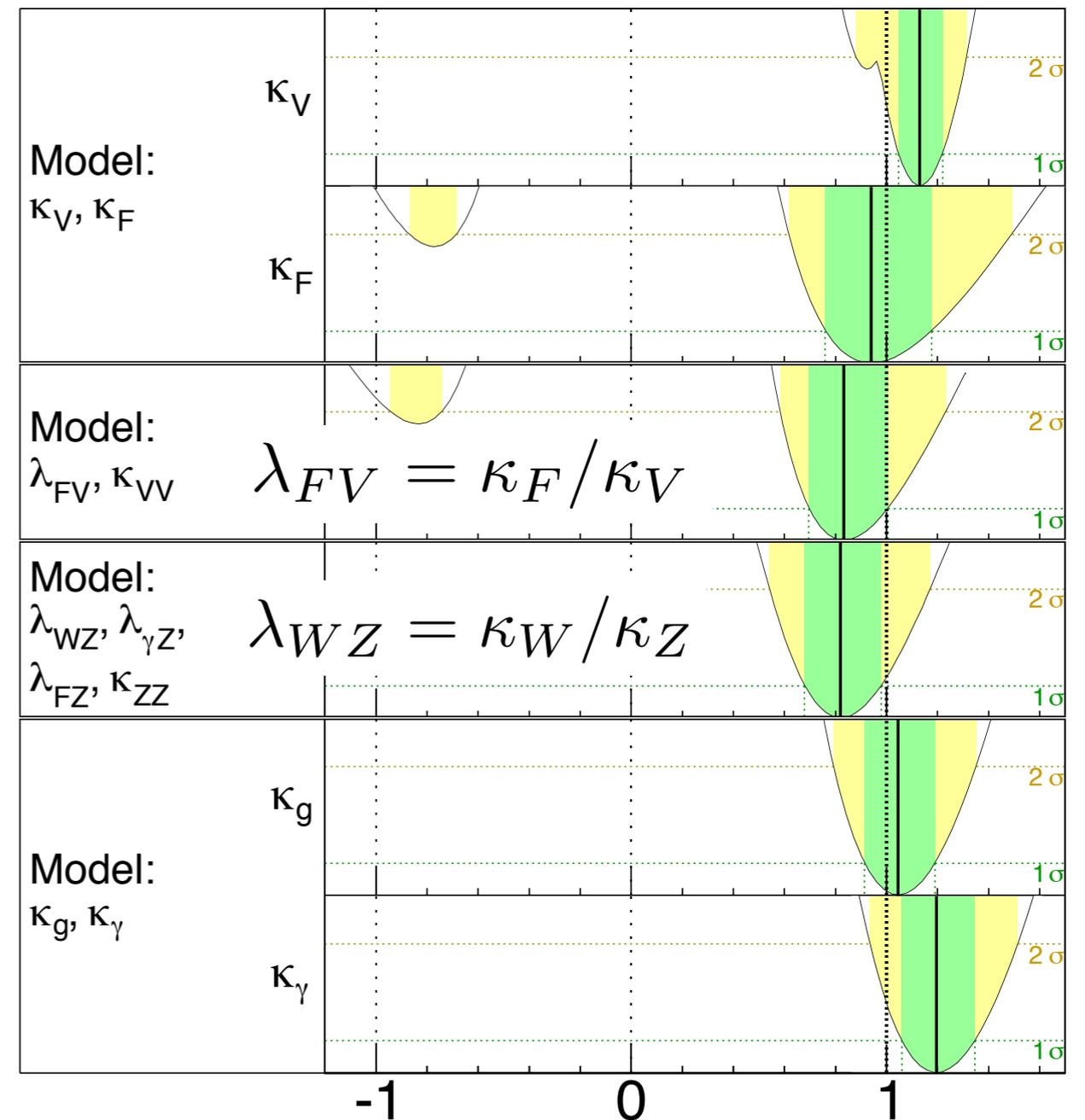
| Model | Probed couplings                 | Parameters of interest  | Functional assumptions |            |            |                 |            |
|-------|----------------------------------|---|------------------------|------------|------------|-----------------|------------|
|       |                                  |   | $\kappa_V$             | $\kappa_F$ | $\kappa_g$ | $\kappa_\gamma$ | $\kappa_H$ |
| 1     | Couplings to fermions and bosons | $\kappa_V, \kappa_F$  | ✓                      | ✓          | ✓          | ✓               | ✓          |
| 2     |                                  | $\lambda_{FV}, \kappa_{VV}$                                   | ✓                      | ✓          | ✓          | ✓               | -          |
| 3     | Custodial symmetry               | $\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$                     | -                      | ✓          | ✓          | ✓               | -          |
| 4     |                                  | $\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$ | -                      | ✓          | ✓          | -               | -          |
| 5     | Vertex loops                     | $\kappa_g, \kappa_\gamma$                                     | =1                     | =1         | -          | -               | ✓          |

**ATLAS**

$m_H = 125.5$  GeV

Total uncertainty

■  $\pm 1\sigma$     ■  $\pm 2\sigma$



$\sqrt{s} = 7$  TeV  $\int L dt = 4.6-4.8$  fb $^{-1}$

$\sqrt{s} = 8$  TeV  $\int L dt = 20.7$  fb $^{-1}$

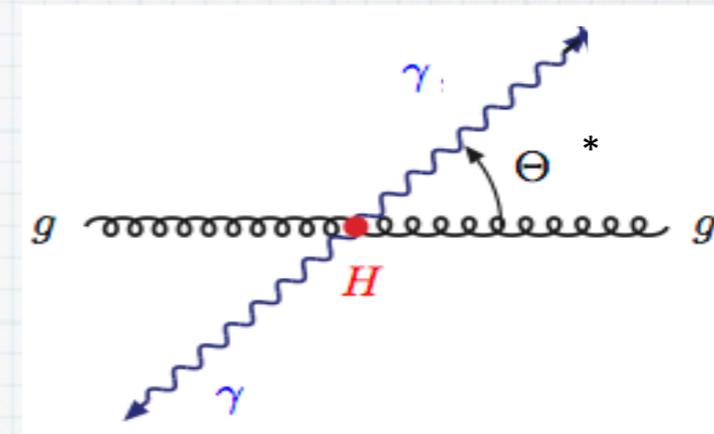
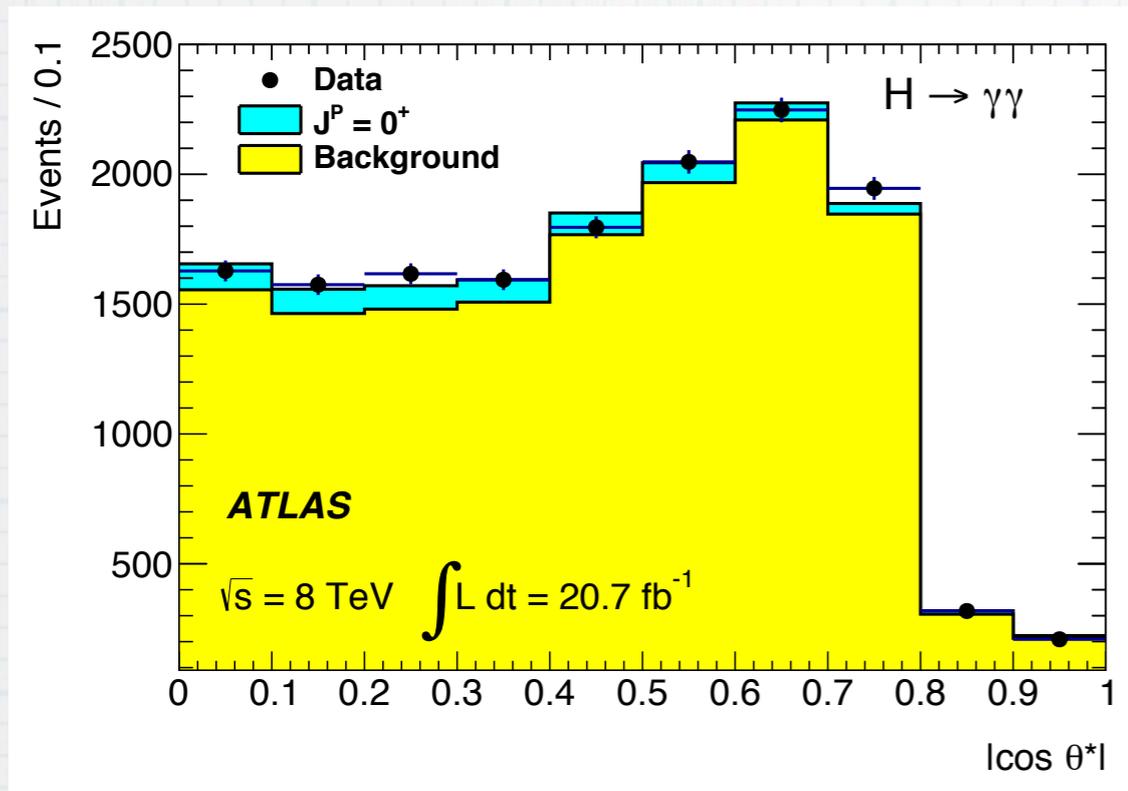
Parameter value

Combined  $H \rightarrow \gamma\gamma, ZZ^*, WW^*$

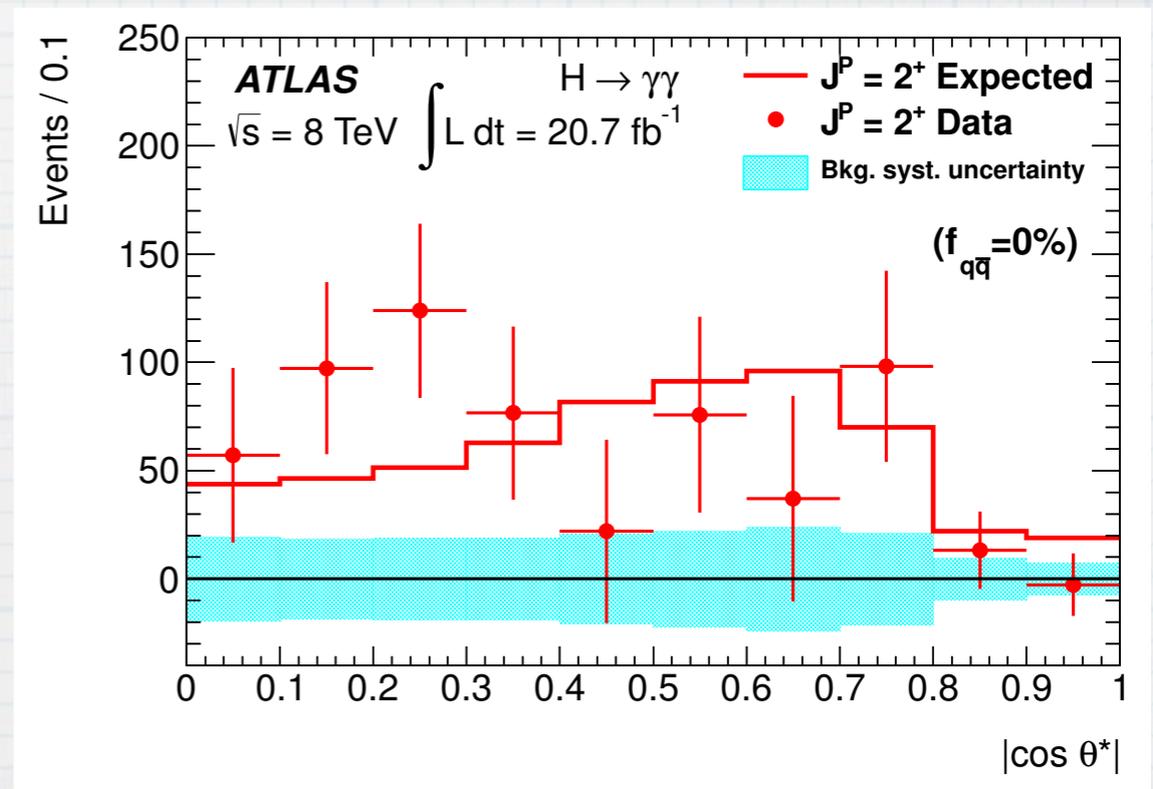
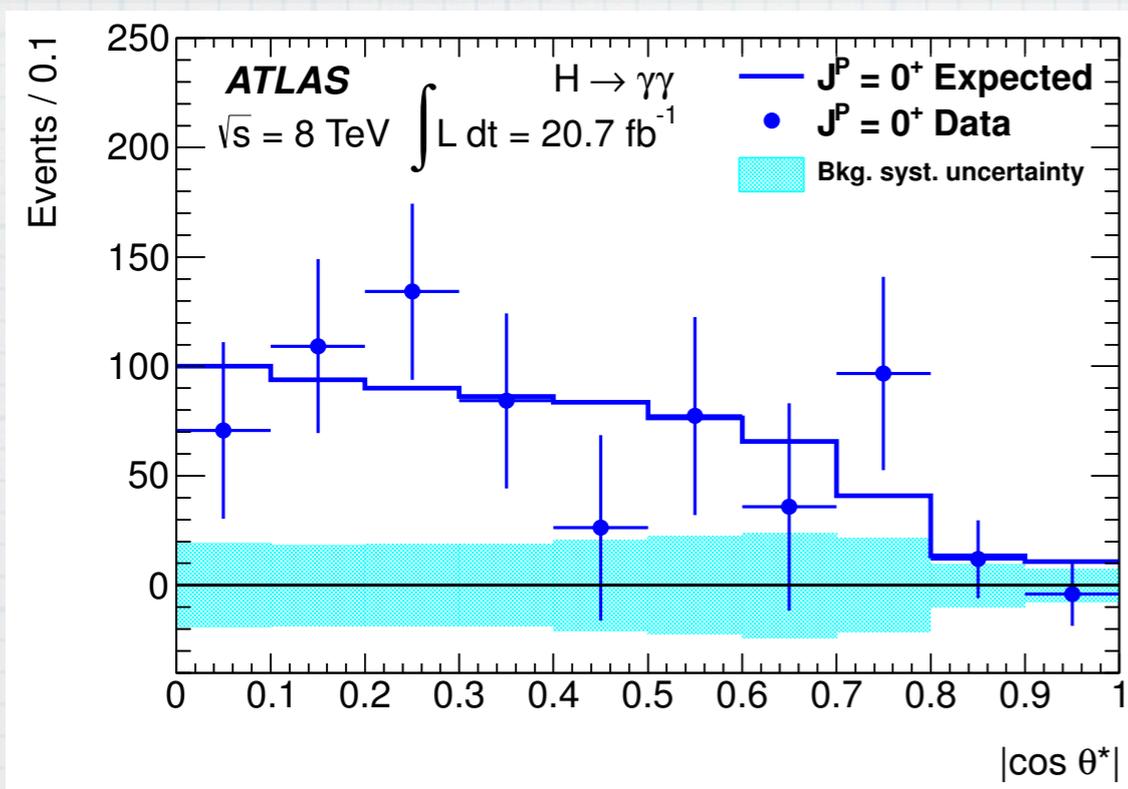
# スピン・パリティ測定

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_H^2\phi^2) && \leftarrow \text{スカラーボソン} \\ &+ \frac{vg^2}{2}\phi W_\mu^+ W^{-\mu} + \frac{v(g^2 + g'^2)}{4}\phi Z_\mu Z^\mu \\ &- \sum_f Y_f \phi \bar{f} f \\ &- \lambda v \phi^3 - \lambda \frac{\phi^4}{4} \\ &+ \frac{g^2}{2}\phi^2 W_\mu^+ W^{-\mu} + \frac{(g^2 + g'^2)}{4}\phi^2 Z_\mu Z^\mu\end{aligned}$$

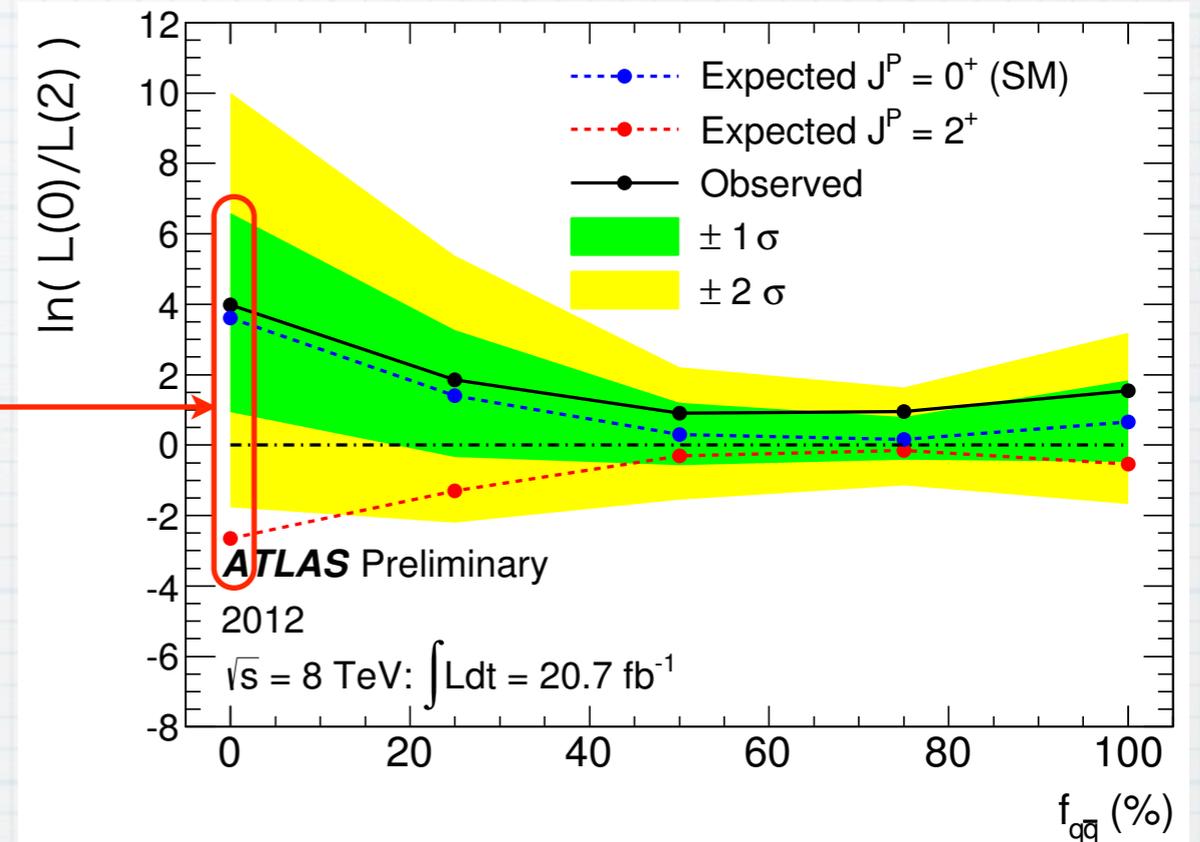
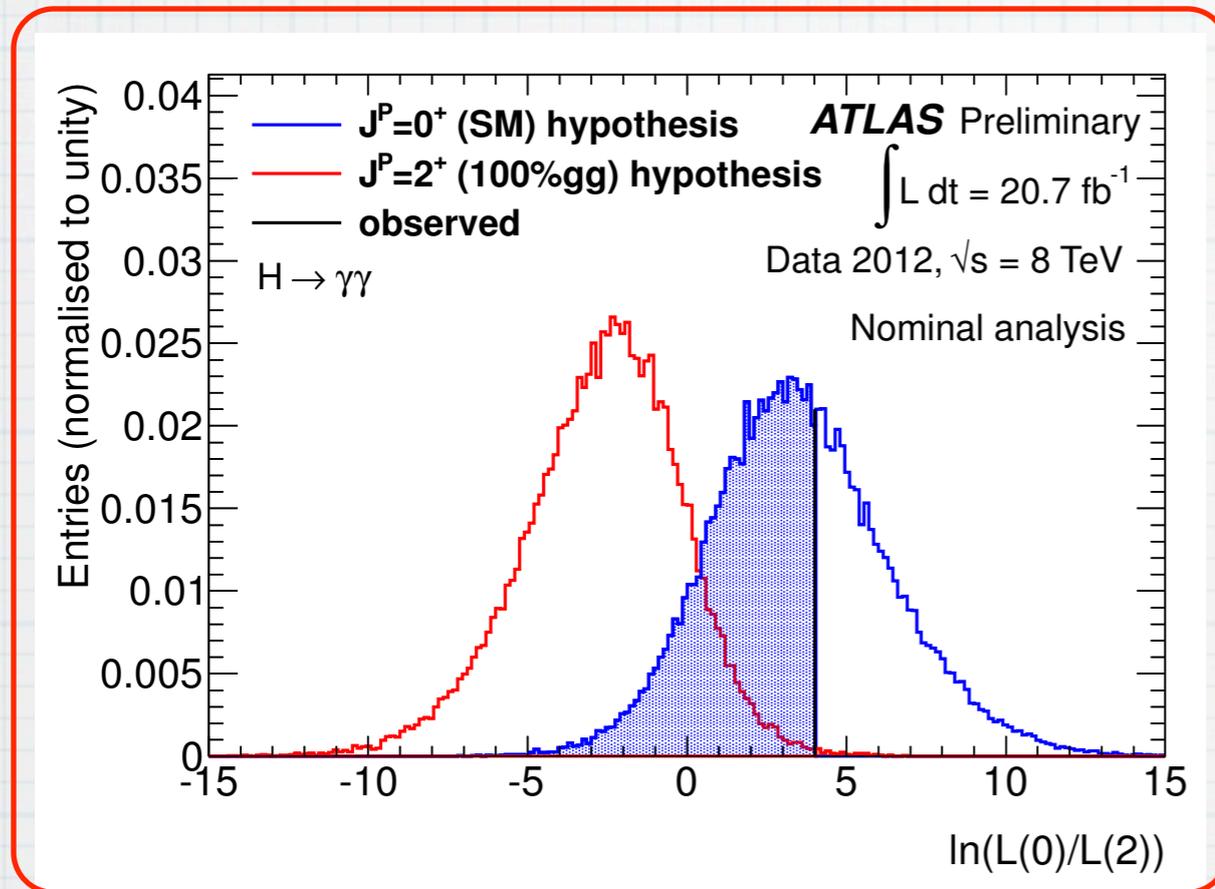
# $H \rightarrow \gamma \gamma$ ( $0^+$ vs $2^+$ )



$$|\cos \theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1 + (p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



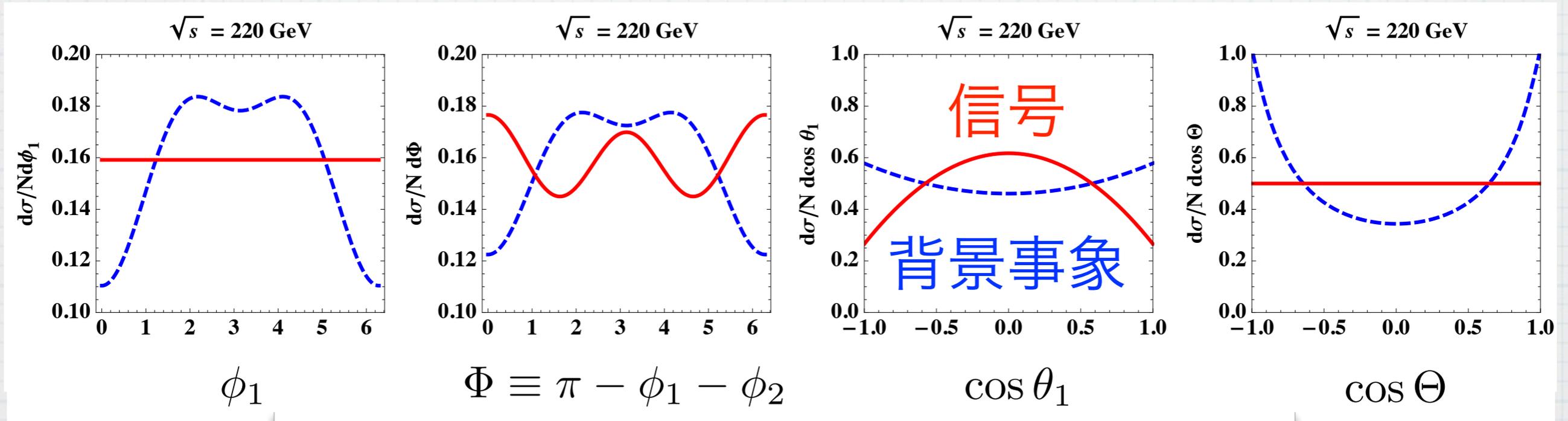
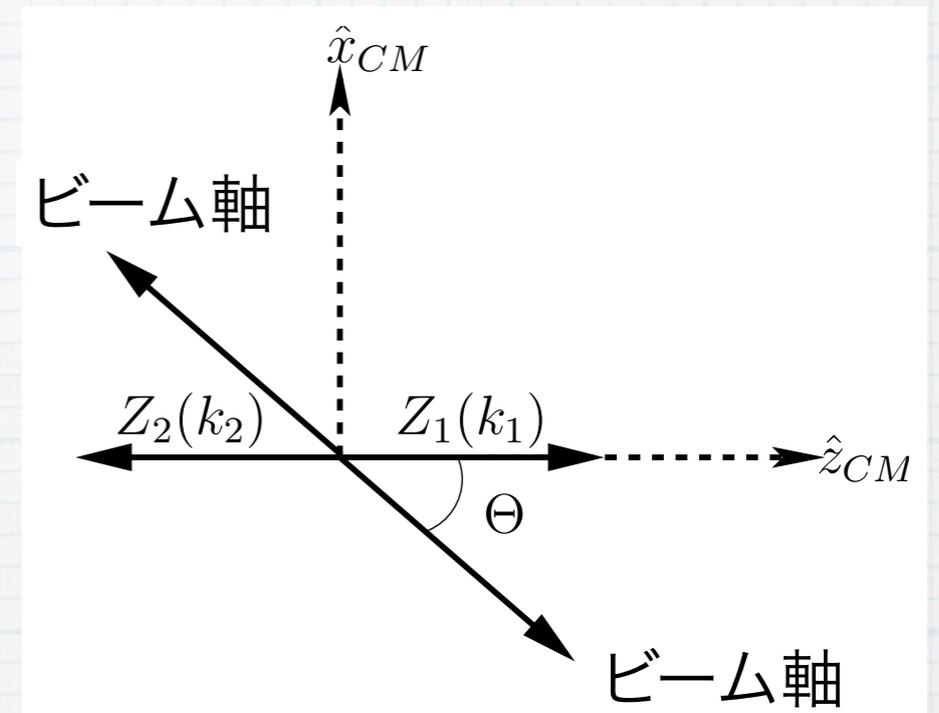
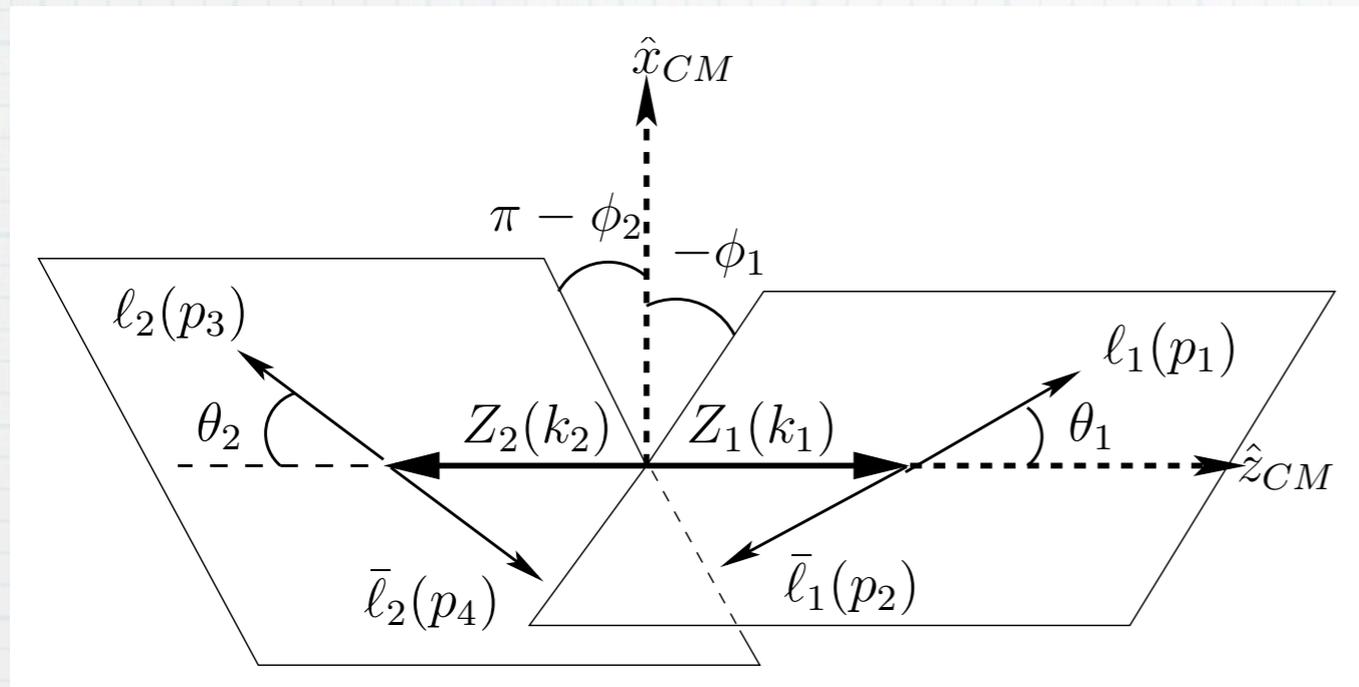
# H → $\gamma\gamma$ 結果



❖  $2\sigma$  ちよっとから  $1\sigma$  程度 ( $qq$  の割合に依存) で  $0^+$  を favor

# H → ZZ での Spin/Parity 測定

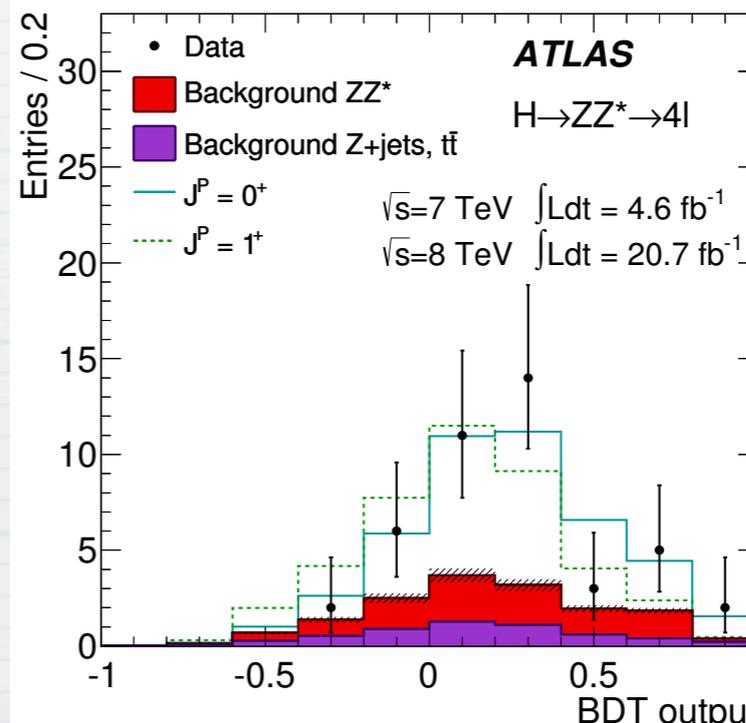
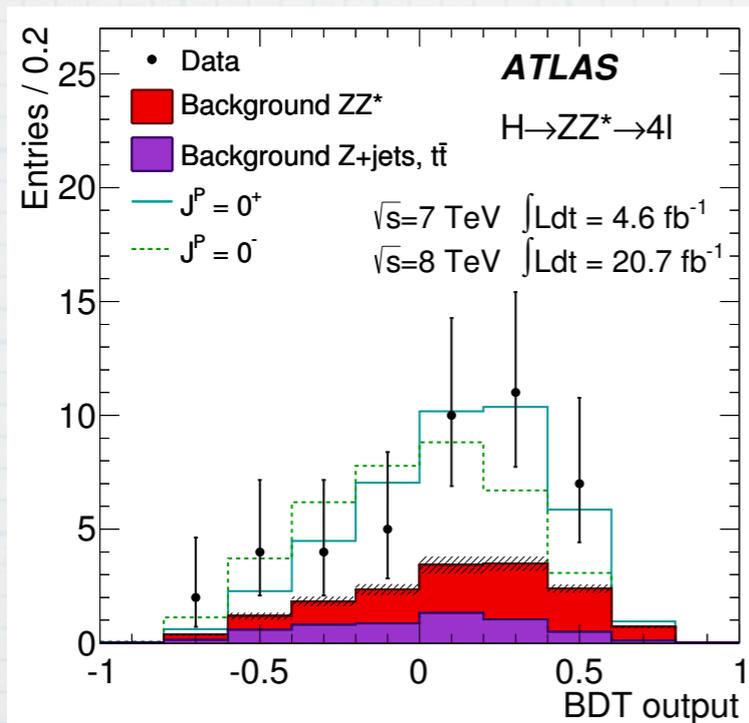
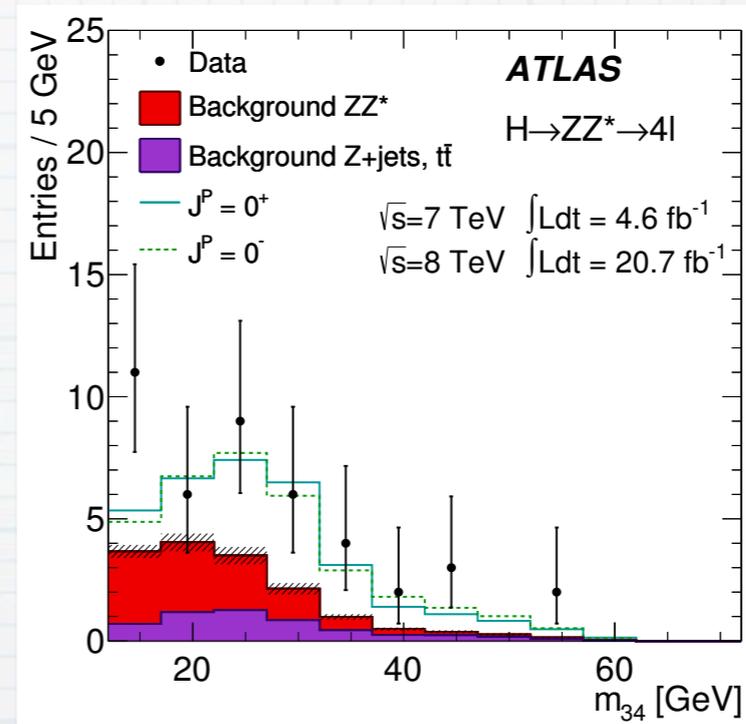
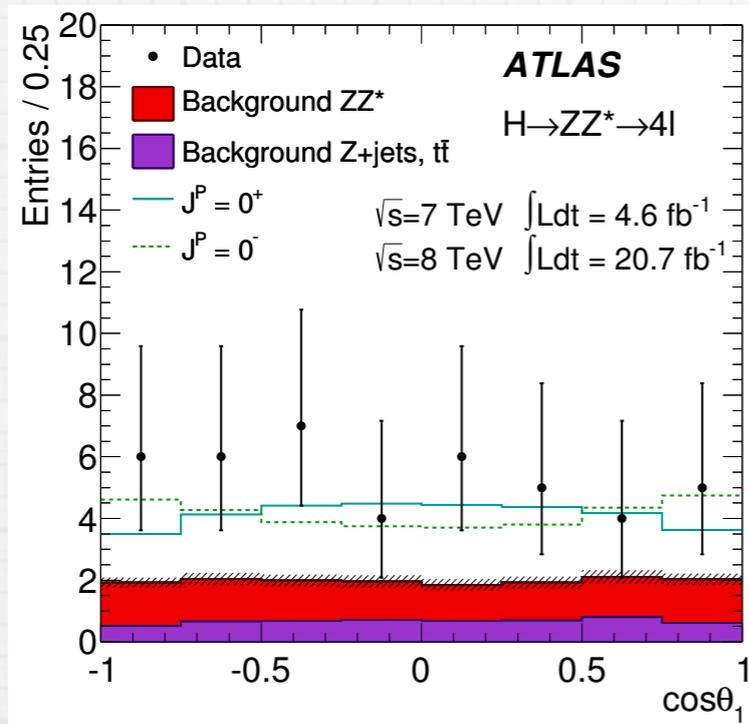
arXiv:1108.2274v2 [hep-ph]



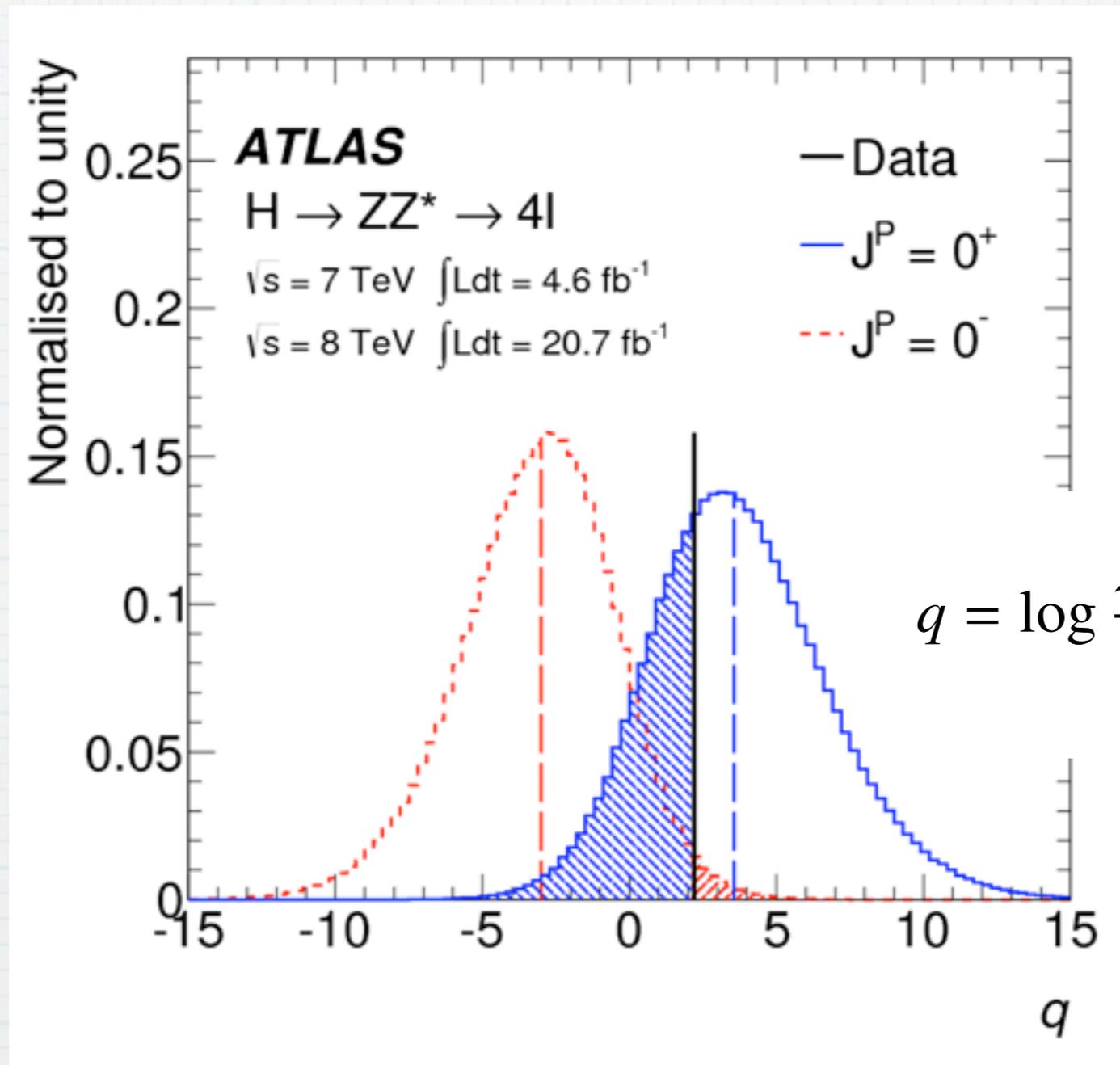
これらの分布が spin/parity に依存

# H → ZZ

## ❖ 5個のdecay angleと $m_{12}$ , $m_{34}$ からBDT



# $0^+$ vs $0^-$ by $H \rightarrow ZZ$



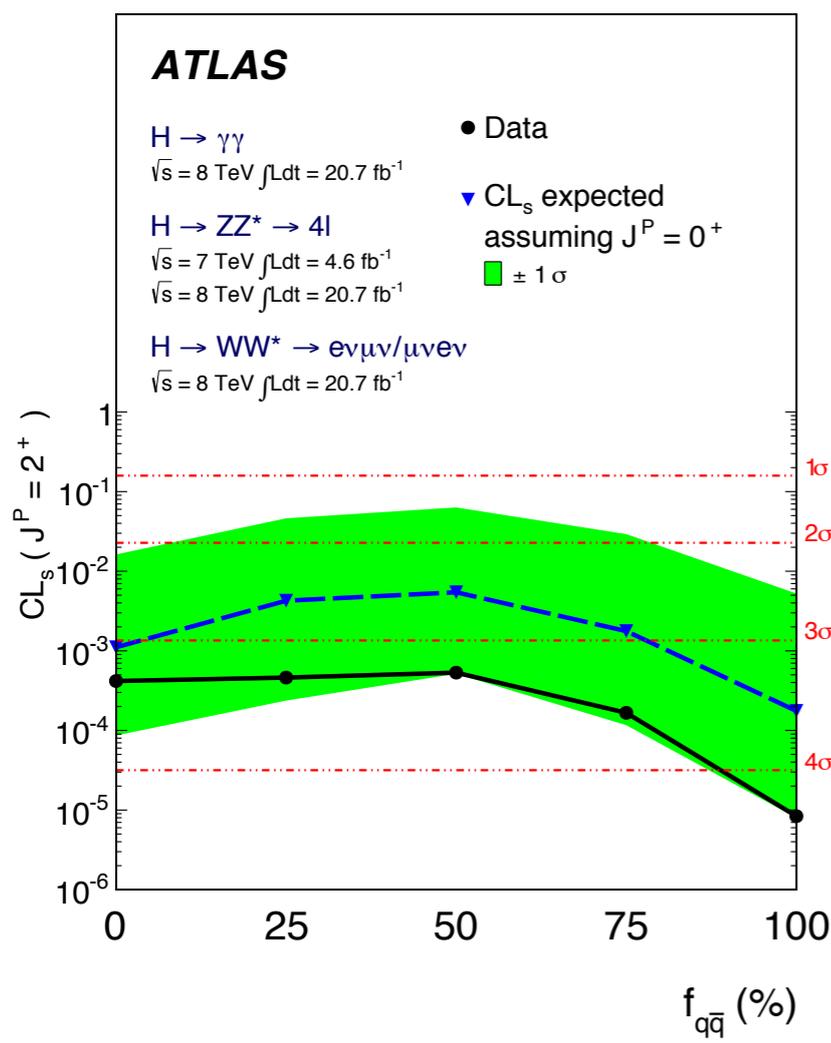
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\mu}_{0^+}, \hat{\theta}_{0^+})}{\mathcal{L}(J_{\text{alt}}^P, \hat{\mu}_{J_{\text{alt}}^P}, \hat{\theta}_{J_{\text{alt}}^P})}$$

❖  $0^-$  is excluded at 97.8% CL

# 0<sup>+</sup>以外の棄却

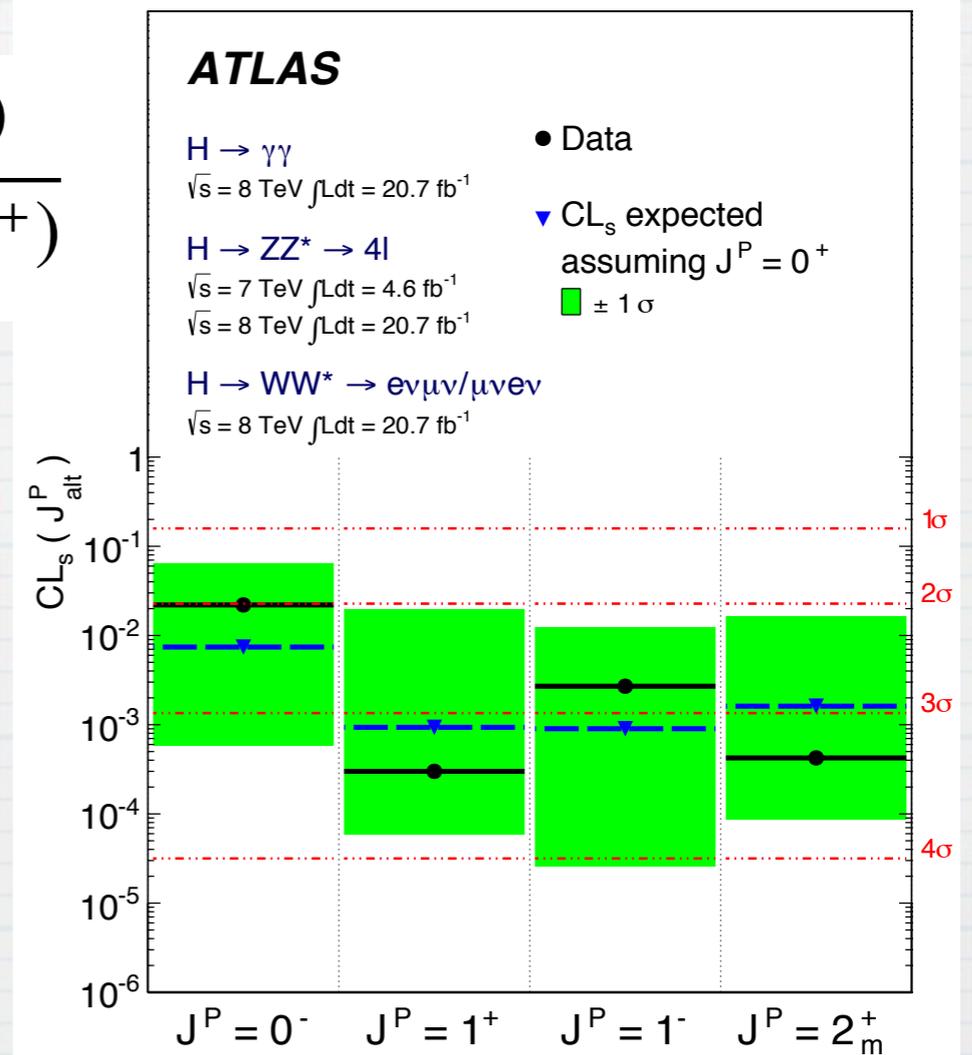
- ❖ 0<sup>+</sup> vs 1<sup>±</sup> : H → ZZ, WW
- ❖ 0<sup>+</sup> vs 2<sup>+</sup> : H → γγ, ZZ, WW

0<sup>+</sup> vs 2<sup>+</sup>



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

0<sup>+</sup> vs 0<sup>+</sup>以外

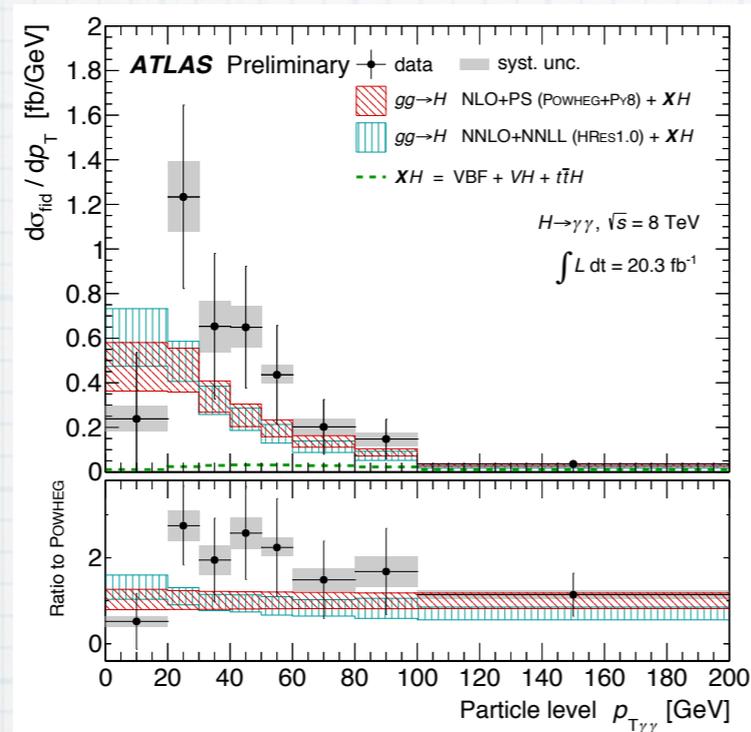


# Higgs boson ^

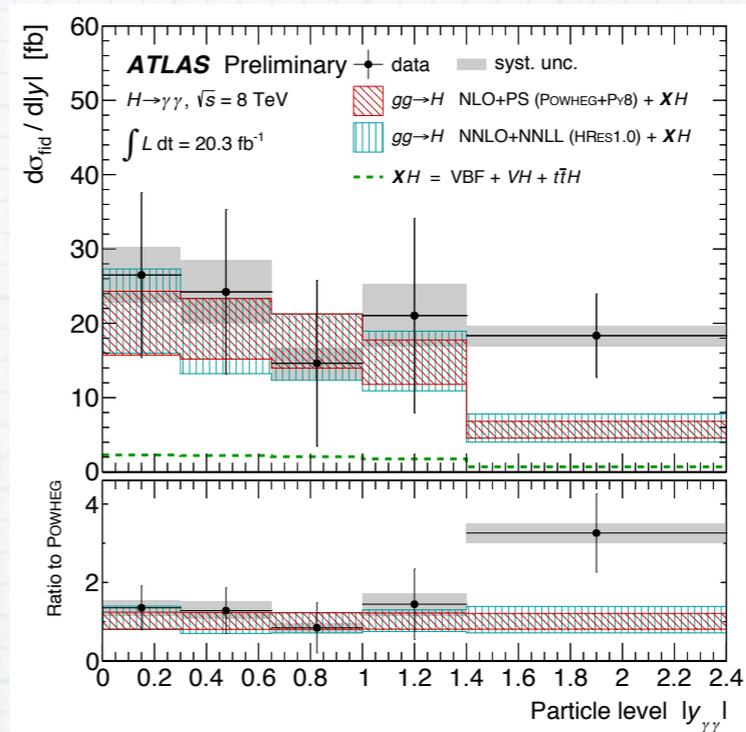
- ❖ ゲージセクターと結合してる
- ❖ 湯川もありそう
- ❖  $0^+$ っぽい
  
- ❖ Lepton universality を破ってそう

# Some new results from ATLAS

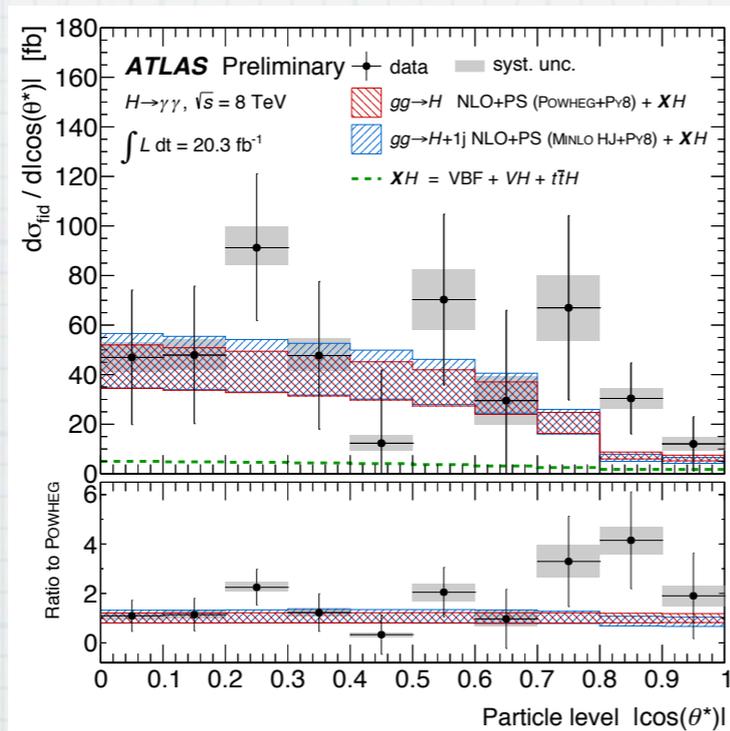
# Differential cross section in $H \rightarrow \gamma \gamma$



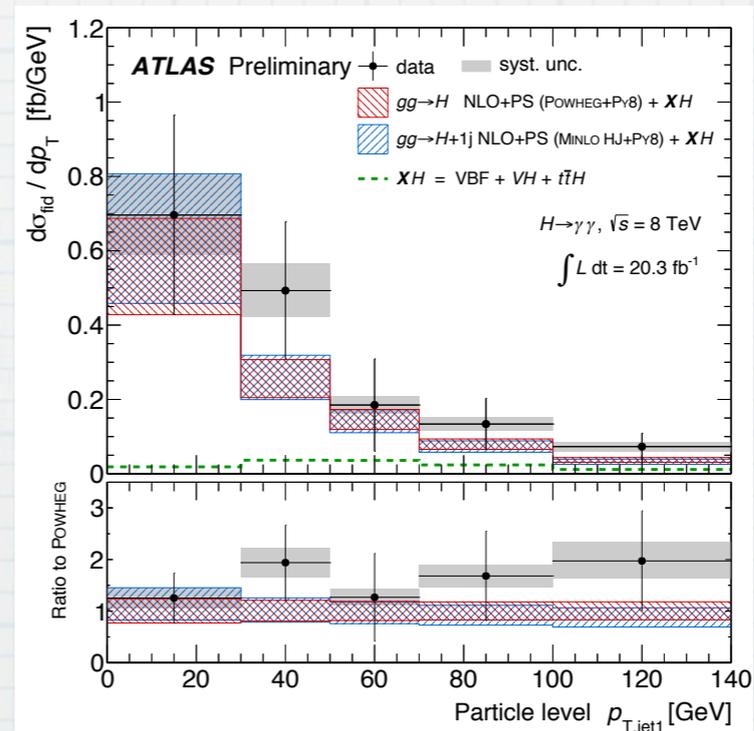
(a)  $p_T^{\gamma\gamma}$



(b)  $|y^{\gamma\gamma}|$

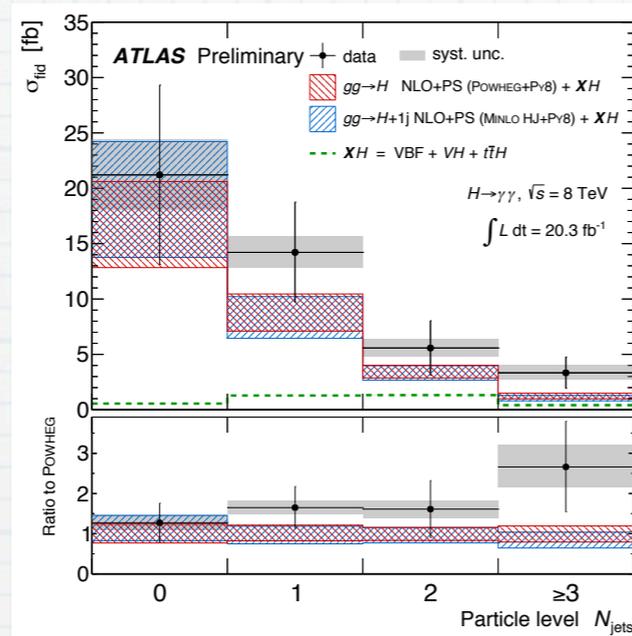


(c)  $|\cos \theta^*|$

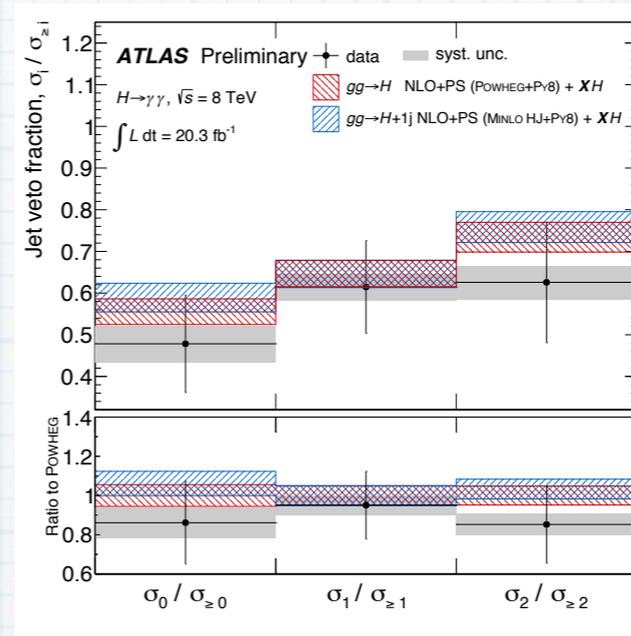


(d)  $p_T^{\text{jet}1}$

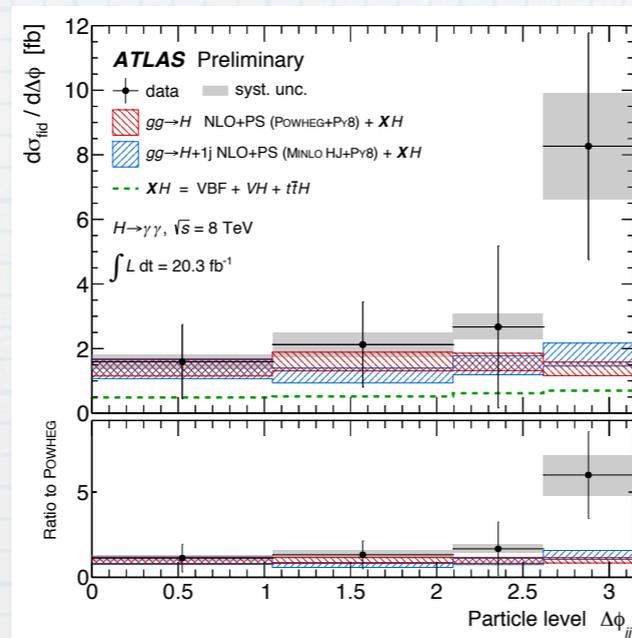
# Jet in $H \rightarrow \gamma\gamma$



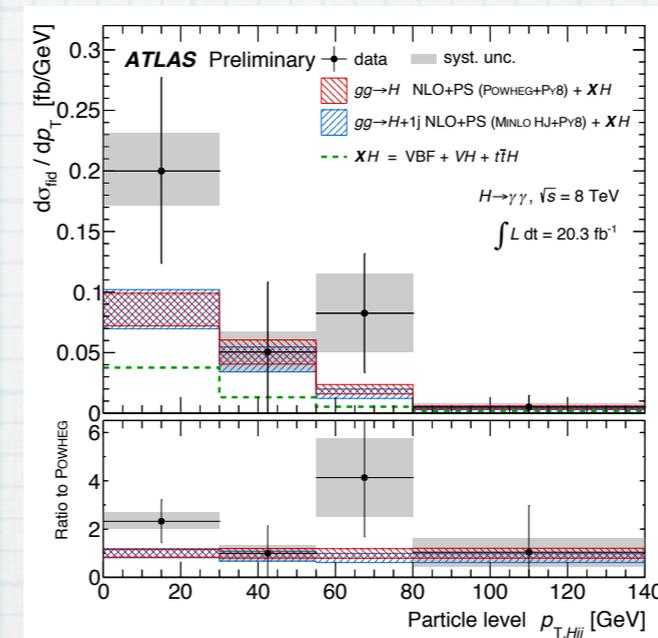
(a)  $N_{\text{jets}}$



(b)  $\sigma_{N_{\text{jets}}=i} / \sigma_{N_{\text{jets}} \geq i}$



(c)  $\Delta\phi_{jj}$



(d)  $p_T^{\gamma jj}$

- ❖ 言い訳：2本目のジェットは parton shower
- ▶ 誤差も過小評価

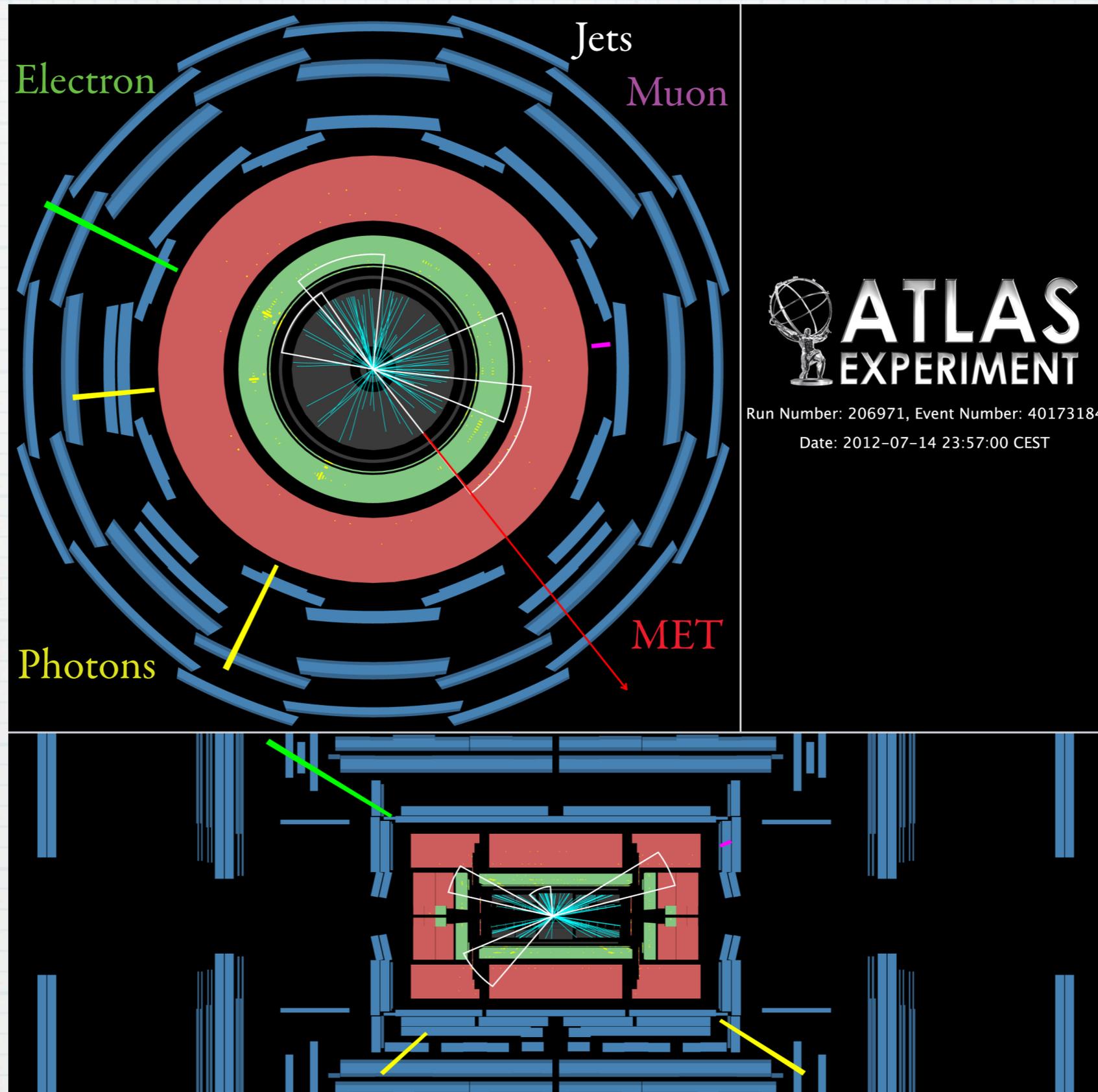
# $ttH (\rightarrow \gamma \gamma)$

- ❖ Event selection 1 (leptonic channel)
  - ▶ two photons, at least one lepton, at least one b-tagged jet, missing  $E_T > 20 \text{ GeV}$ , veto  $84 < M_{e\gamma} < 94 \text{ GeV}$
- ❖ Event selection 2 (hadronic channel)
  - ▶ two photons, no leptons, at least 6 jets, at least two b-tagged jets

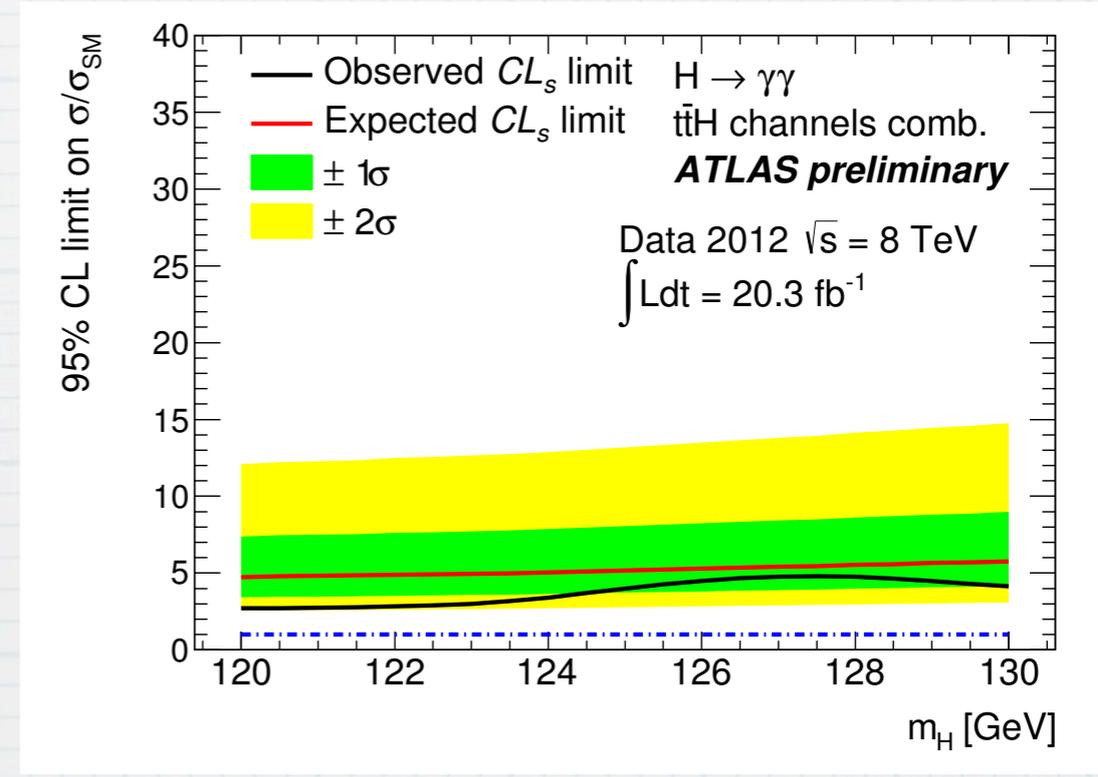
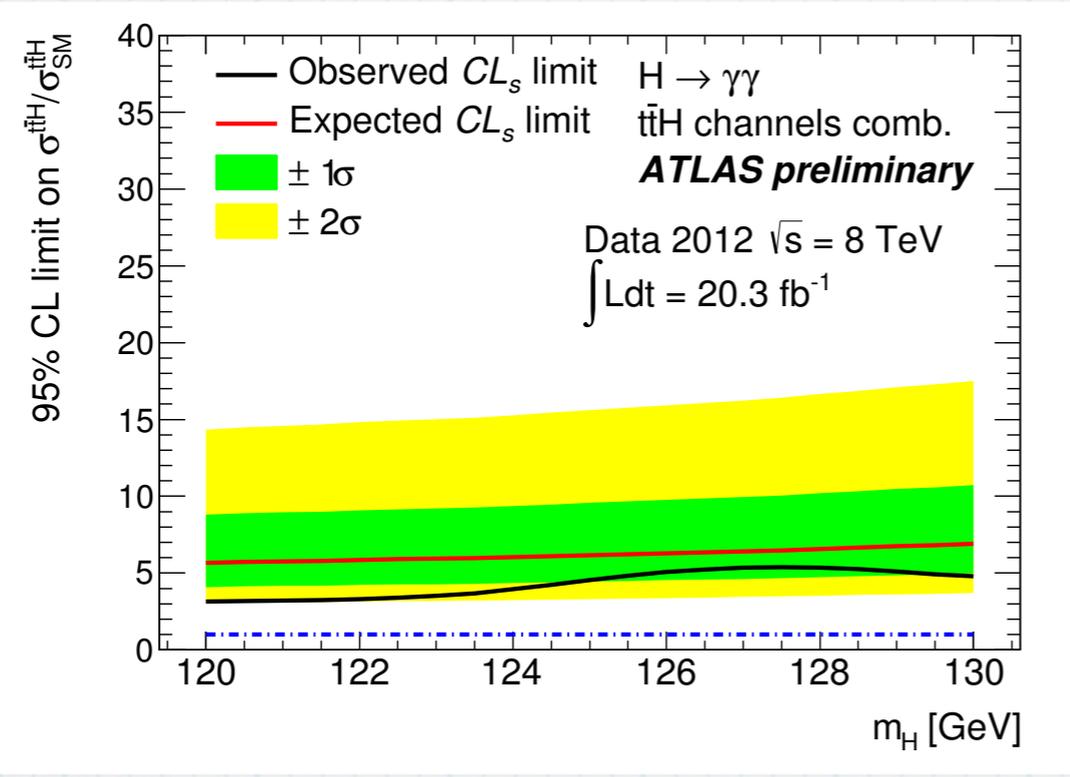
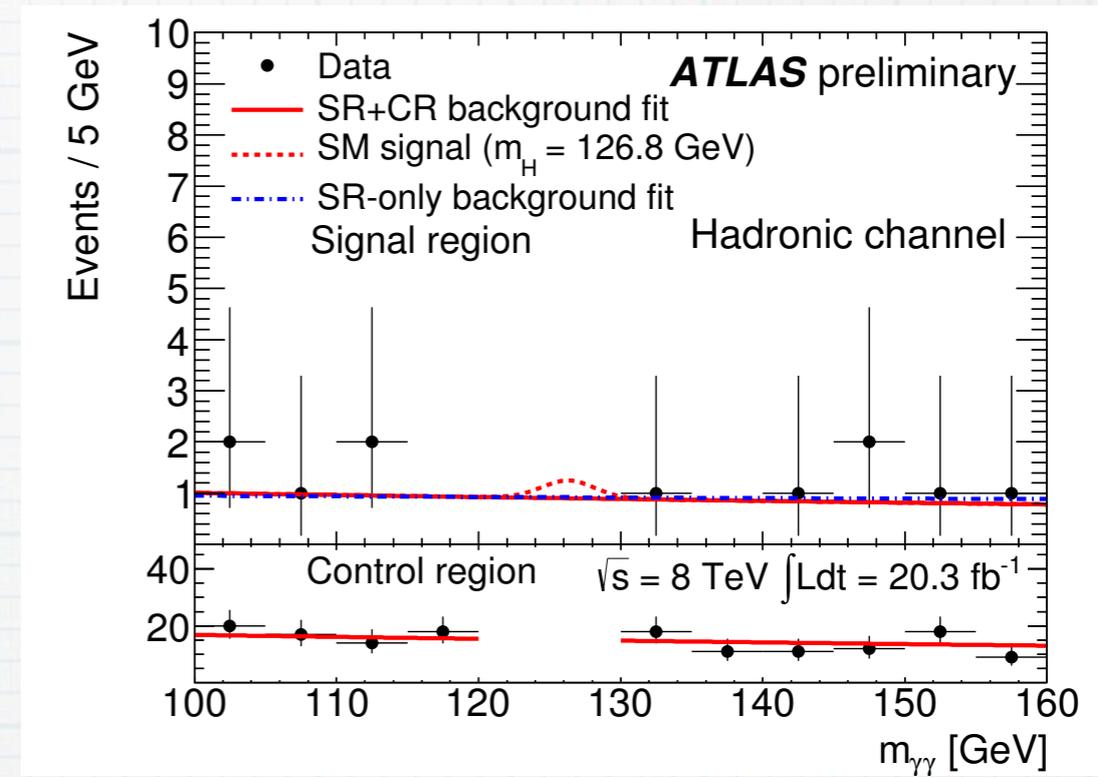
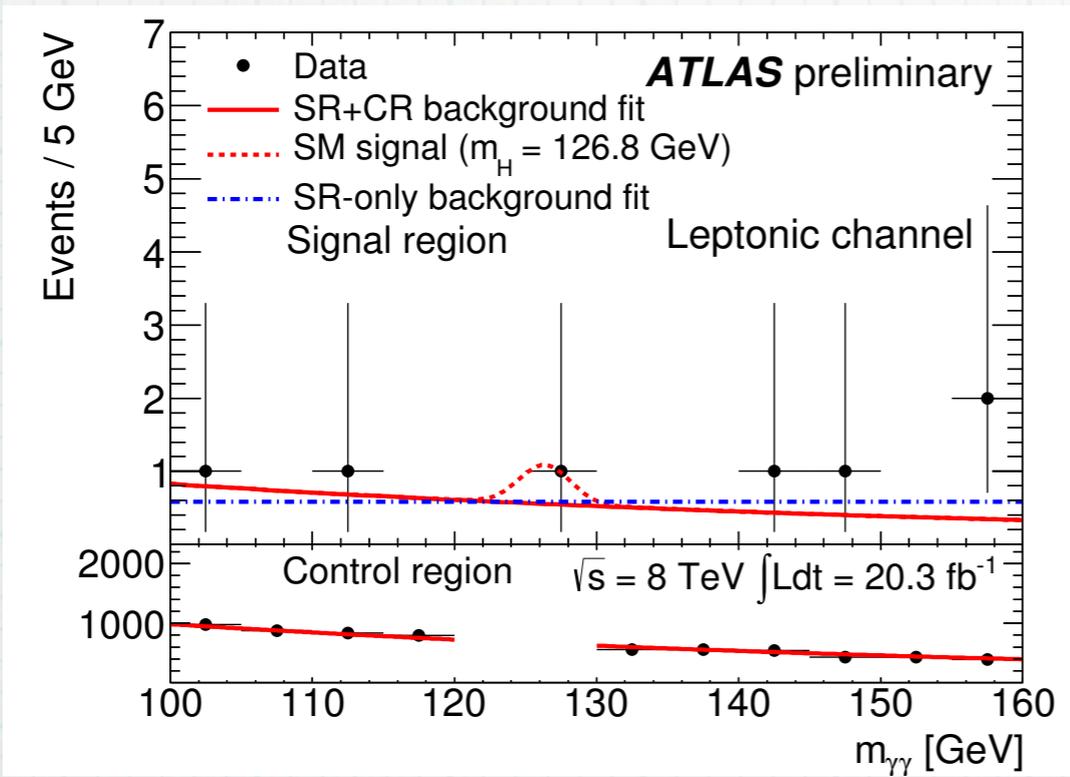
expectation for  $20.3 \text{ fb}^{-1}$

| Channel  | $N_S$ | $ggF(\%)$           | $VBF(\%)$   | $WH(\%)$ | $ZH(\%)$ | $tH(\%)$ | $t\bar{t}H(\%)$ |
|----------|-------|---------------------|-------------|----------|----------|----------|-----------------|
| Leptonic | 0.55  | 0.6                 | 0.3         | 7.7      | 2.4      | 6.1      | 82.8            |
| Hadronic | 0.36  | 5.3                 | 1.1         | 1.1      | 1.3      | —        | 91.2            |
| Channel  | $N_S$ | $N_B$               | $N_S / N_B$ |          |          |          |                 |
| Leptonic | 0.55  | $1.2^{+0.6}_{-0.5}$ | 0.45        |          |          |          |                 |
| Hadronic | 0.36  | $1.9^{+0.7}_{-0.5}$ | 0.19        |          |          |          |                 |

# $ttH(\rightarrow \gamma \gamma)$ Event Display



# $t\bar{t}H(\rightarrow \gamma\gamma)$ 結果

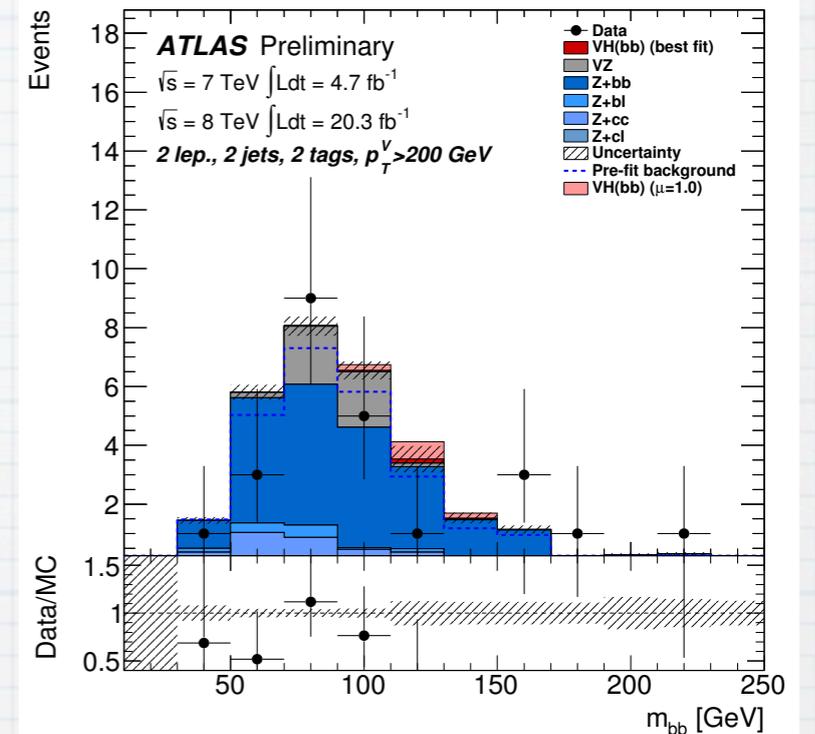
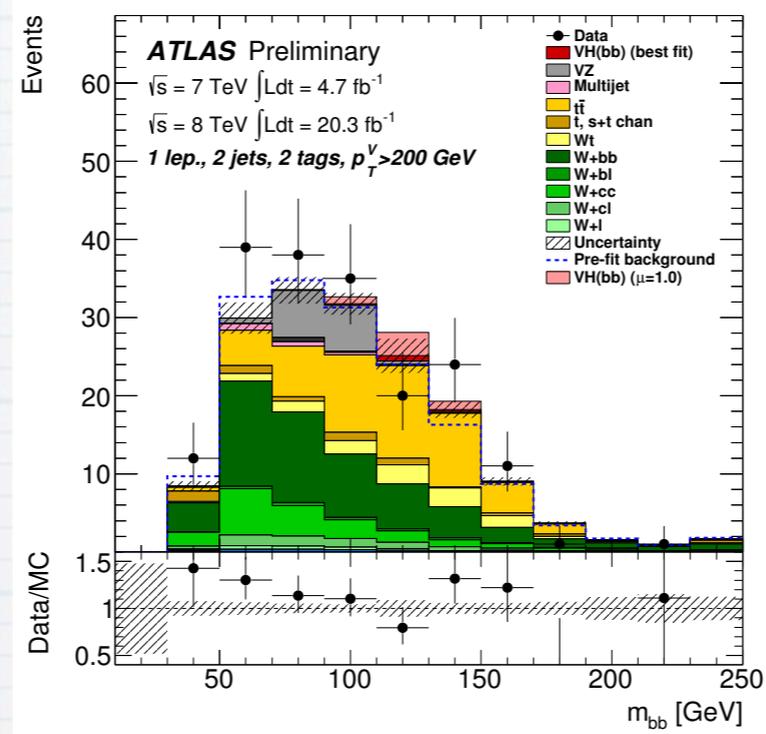
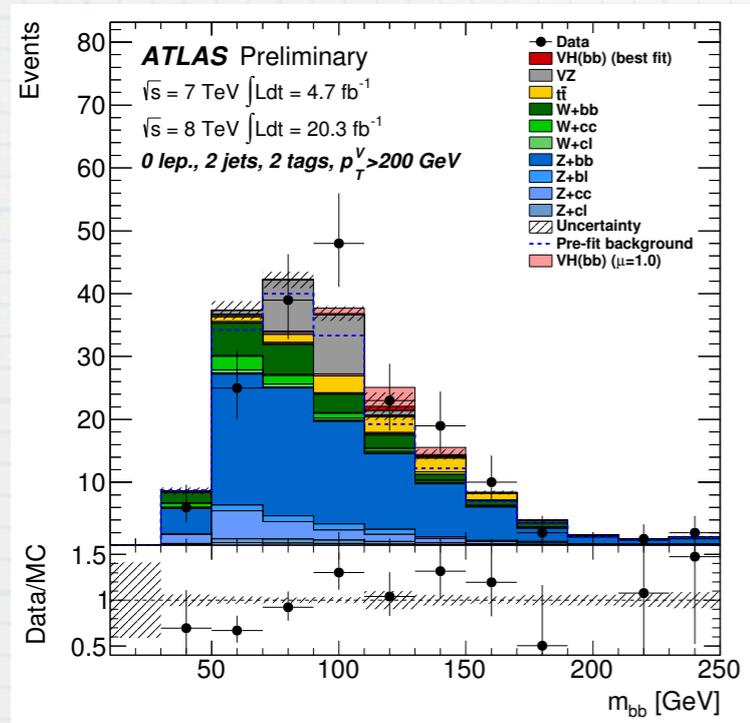


# VH( $\rightarrow$ bb)

| Object        | 0-lepton  | 1-lepton  | 2-lepton                             |
|---------------|---|---|--------------------------------------|
| Leptons       | 0 loose leptons   | 1 tight lepton<br>+ 0 loose leptons   | 1 medium lepton<br>+ 1 loose lepton  |
| Jets          |   | 2 <i>b</i> -tags<br>$p_T^{\text{jet}_1} > 45 \text{ GeV}$<br>$p_T^{\text{jet}_2} > 20 \text{ GeV}$<br>+ $\leq 1$ extra jets |                                      |
| Missing $E_T$ | $E_T^{\text{miss}} > 120 \text{ GeV}$<br>$p_T^{\text{miss}} > 30 \text{ GeV}$<br>$\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^{\text{miss}}) < \pi/2$<br>$\min[\Delta\phi(\mathbf{E}_T^{\text{miss}}, \text{jet})] > 1.5$<br>$\Delta\phi(\mathbf{E}_T^{\text{miss}}, b\bar{b}) > 2.8$ | $E_T^{\text{miss}} > 25 \text{ GeV}$  | $E_T^{\text{miss}} < 60 \text{ GeV}$ |
| Vector Boson  | -   | $m_T^W < 120 \text{ GeV}$   | $83 < m_{\ell\ell} < 99 \text{ GeV}$ |

❖ Vector bosonの $p_T$ , *b*-tagのありなし,  
 ジェットの数でbinning

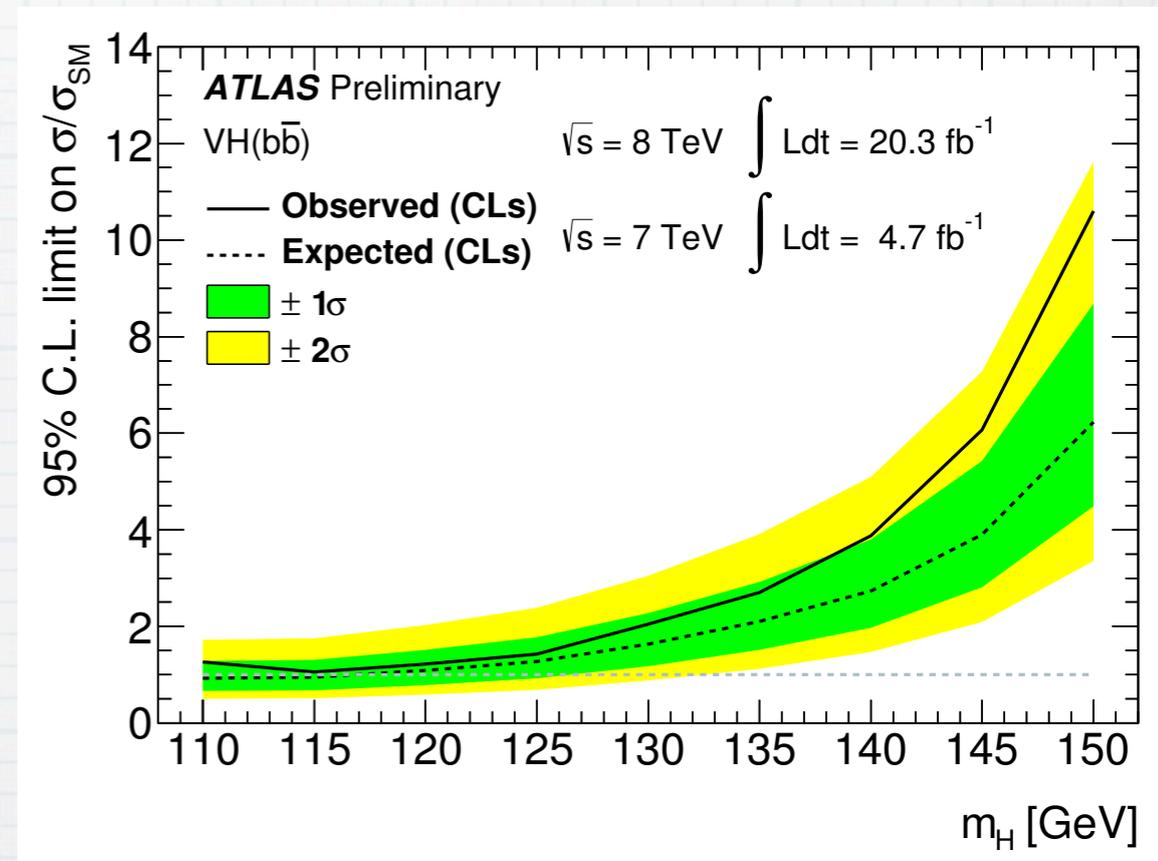
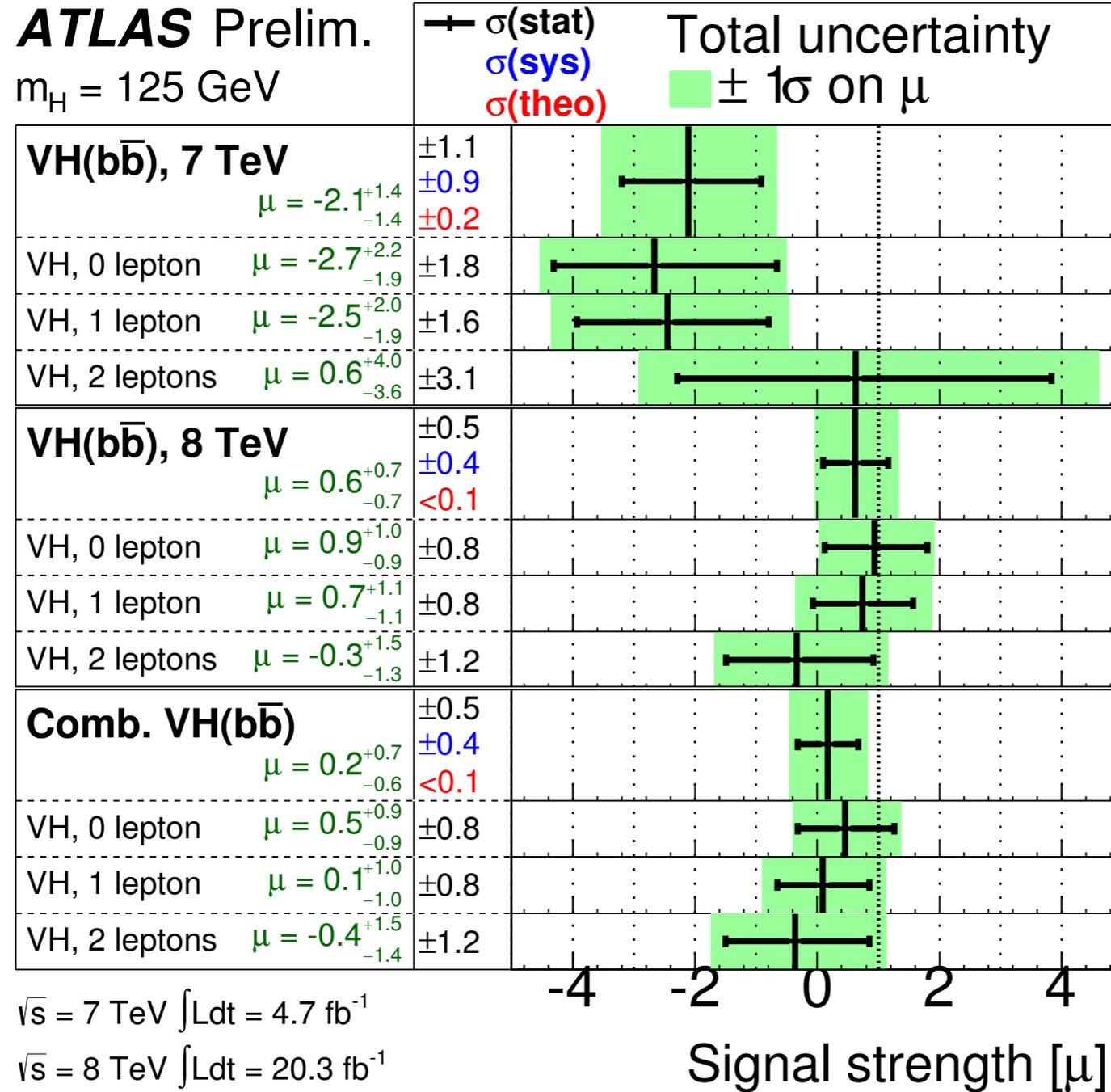
# VH( $\rightarrow$ bb) ...continued



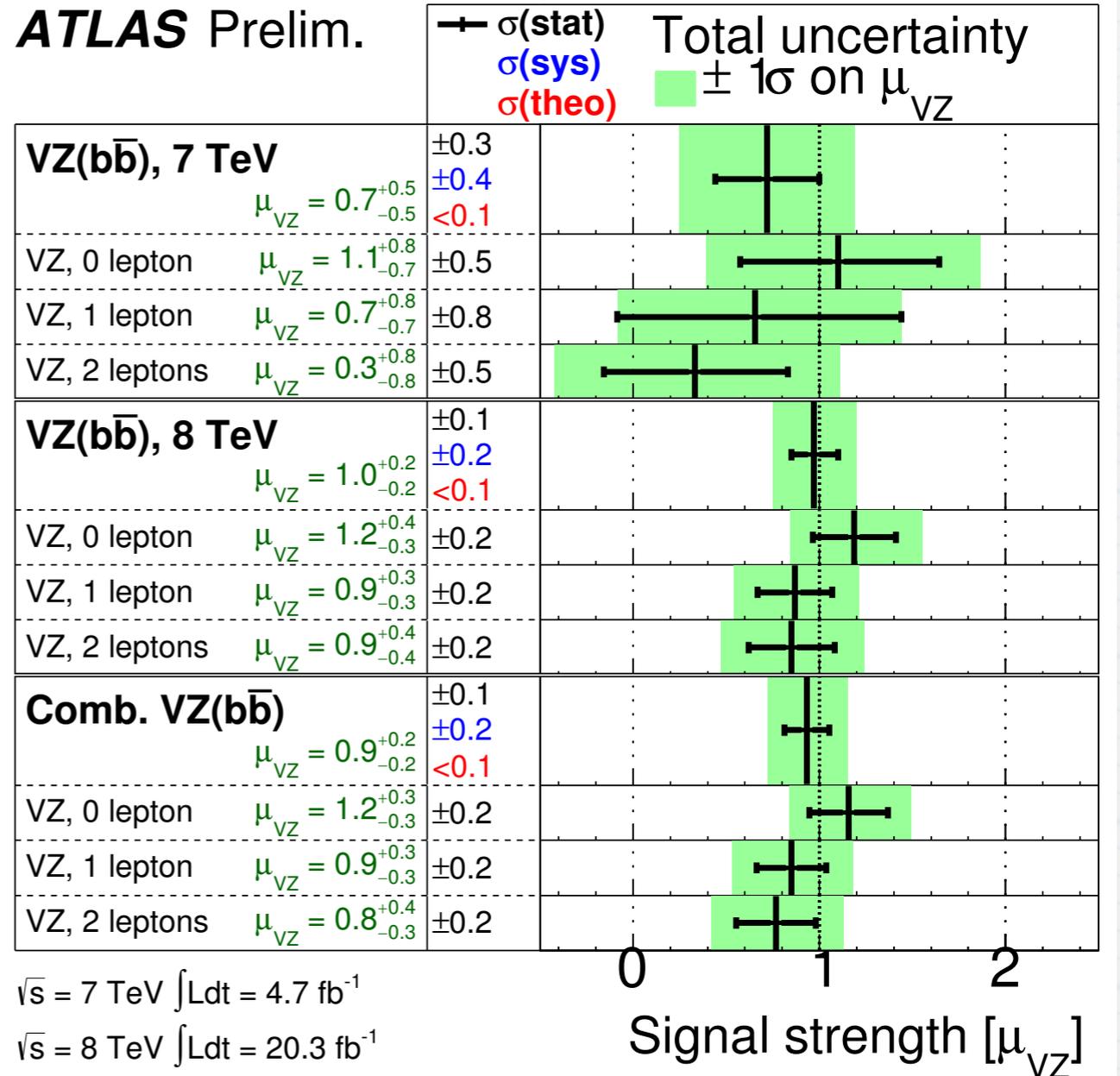
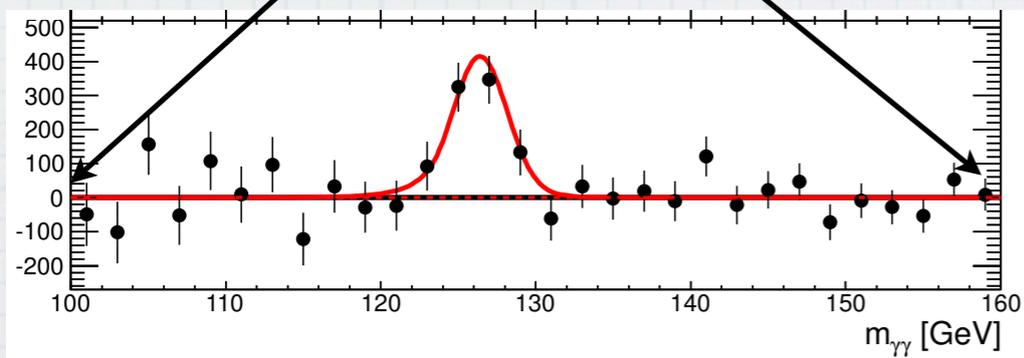
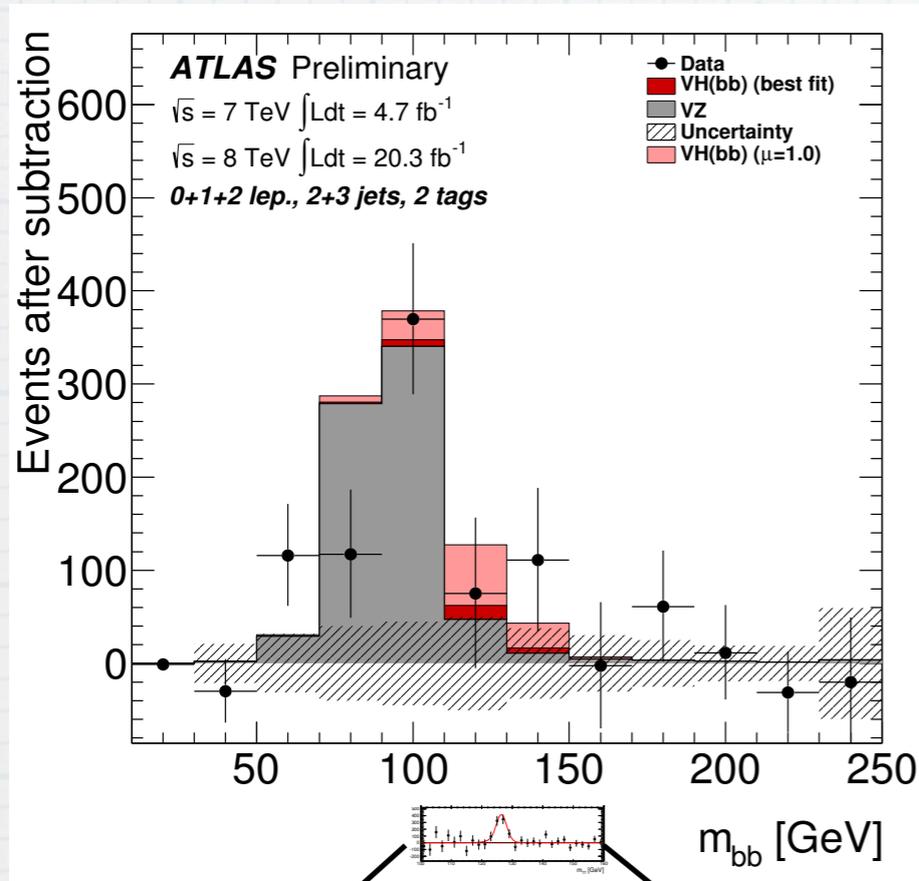
❖ Bin分けされたサンプル  
を同時フィット

| Process    | Scale factor    |
|------------|-----------------|
| $t\bar{t}$ | $1.13 \pm 0.05$ |
| $Wb$       | $0.89 \pm 0.15$ |
| $Wcl$      | $1.05 \pm 0.14$ |
| $Zb$       | $1.30 \pm 0.07$ |
| $Zcl$      | $0.89 \pm 0.48$ |

# VH( $\rightarrow$ bb) 結果



# VZ( $\rightarrow$ bb) as a Validation



resolutionの違い...

将来展望

# スケジュール

|                |   |
|----------------|---|
| 2013-14        | Long Shutdown 1 (LS1) (ATLAS pixelの追加)                                  |
| 2015-17        | $\sqrt{s} = 13-14 \text{ TeV}$ , $L = 10^{34}$ , $50-100\text{fb}^{-1}$ |
| 2018           | LS2 (ATLAS Phase-I Upgrade)   |
| 2019-21        | $L = 2-3 \times 10^{34}$ , $300-400\text{fb}^{-1}$                      |
| 2022           | LS3 (ATLAS Phase-II Upgrade)  |
| 202X<br>HL-LHC | $L = 5 \times 10^{34}$ , luminosity leveling, $\sim 3000\text{fb}^{-1}$ |

# 解析方法 (ATLAS)

- ❖ Geantによるdetector simulationはやらない  
Generator からの4元ベクトルをsmear
  - ▶ Efficiency/Fake/Resolution は7TeVの解析を再現
    - luminosityが上がっても変わらないと仮定
    - Missing  $E_T$ の分解能はbunchあたりの衝突数に対する依存性を外挿
- ❖ 系統誤差は7TeVと同じと仮定
- ❖ MCの断面積はNLOにスケール

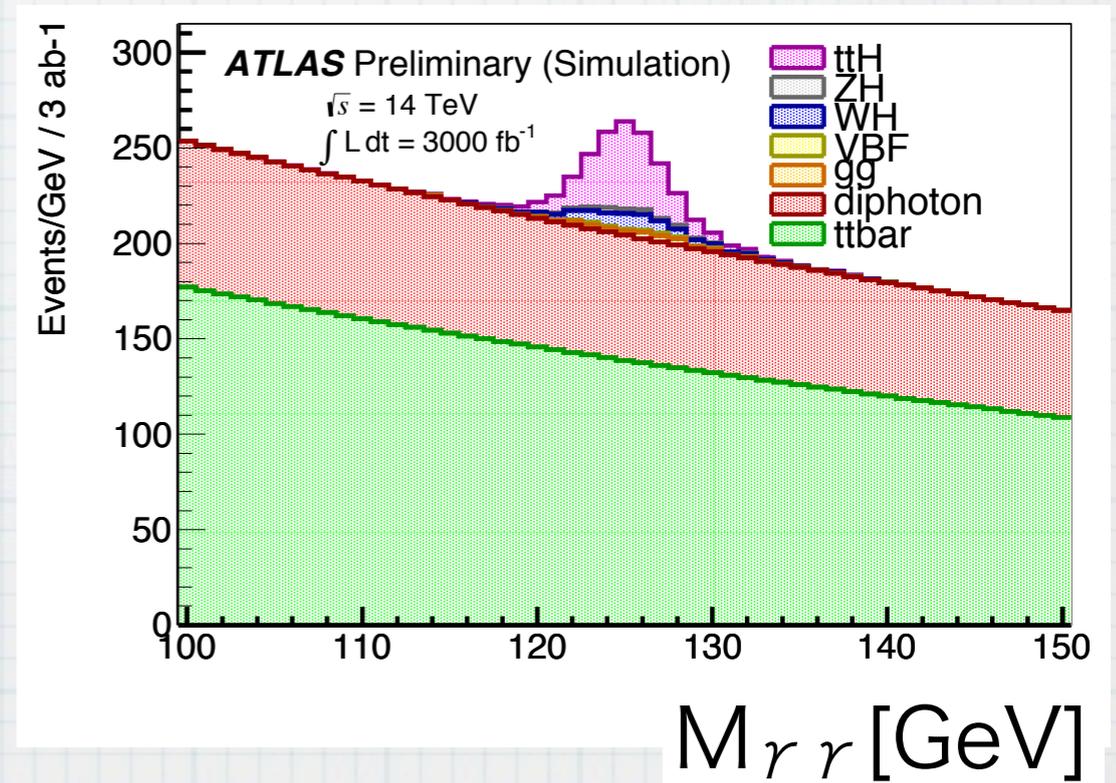
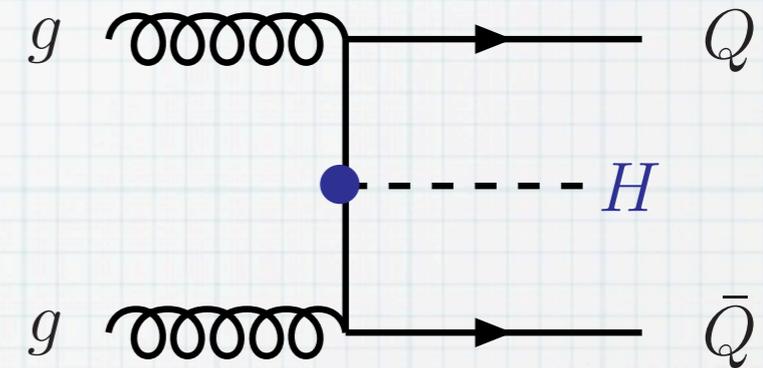
# 使った過程

|                                     | ggF       | VBF   | VH              | ttH                 |
|-------------------------------------|-----------|-------|-----------------|---------------------|
| $H \rightarrow \gamma \gamma$       | 0-jet     | 2-jet | 1 and 2 leptons | leptonic & hadronic |
| $H \rightarrow ZZ^* \rightarrow 4l$ | inclusive |       |                 |                     |
| $H \rightarrow WW$                  | 0-jet     | 2-jet | —               | —                   |
| $H \rightarrow \tau \tau$           | —         | 2-jet | —               | —                   |
| $H \rightarrow \mu \mu$             | inclusive |       |                 | added               |

$$WW \rightarrow |\nu \nu|, \quad \tau \tau \rightarrow ll + X$$

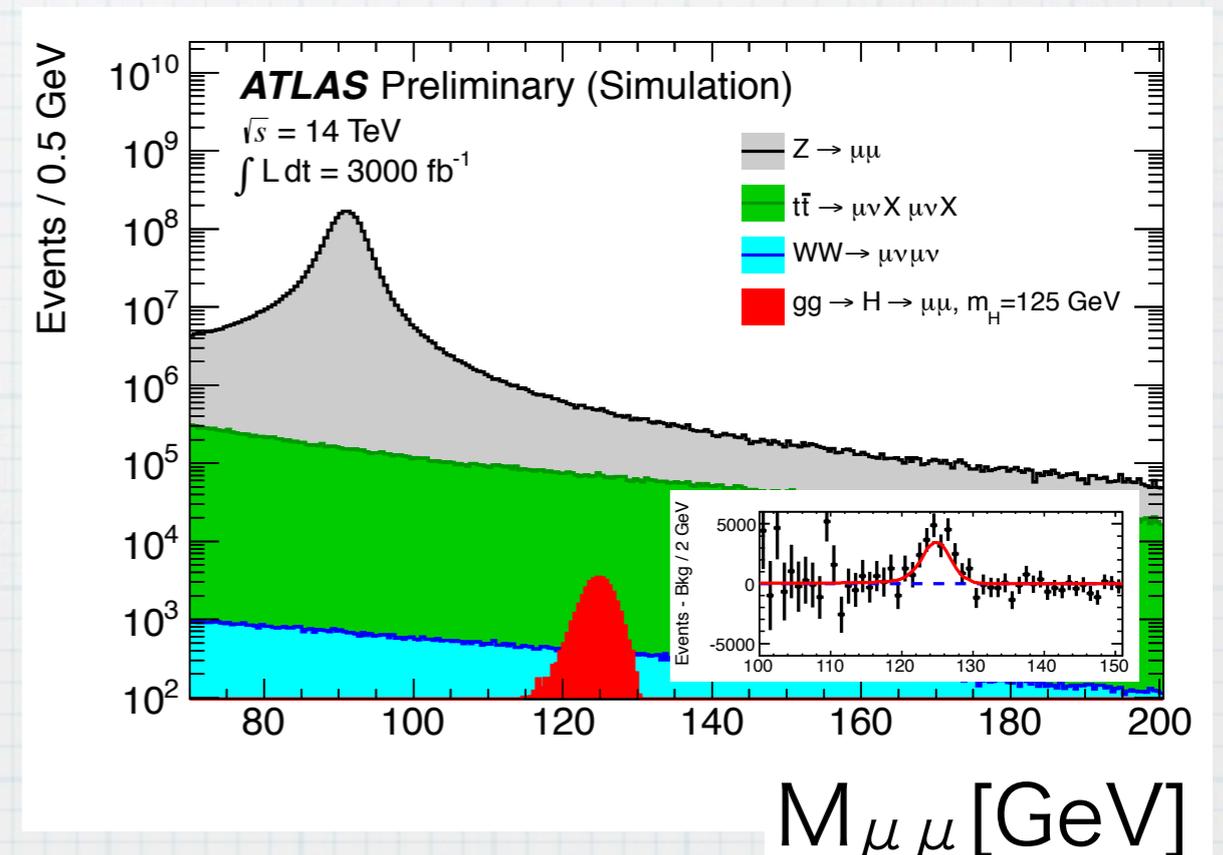
# ttH ( $\rightarrow \gamma \gamma$ )

- ❖ トップ湯川へのアクセス
- ❖  $3000\text{fb}^{-1}$
- ❖  $122 < M_{\gamma\gamma} < 128 \text{ GeV}$ 
  - ▶ 1lepton,  $H_T > 300\text{GeV}$ 
    - S~200, B~1300
  - ▶ 2lepton, no  $H_T$ ,  
Z veto
    - S~30, B~110



$$H \rightarrow \mu \mu$$

- ❖  $\mu$  の高い運動量分解能  $\rightarrow$  高い質量分解能
  - ▶ S/Nは~0.2%程度
- ❖  $\mu$  の  $p_T > 20, 15$  GeV
- ❖ 背景事象は  $Z \rightarrow \mu \mu$ ,  $t\bar{t}$  など
  - ▶ Resonance search
- ❖  $3000\text{fb}^{-1}$  で  $S/\sqrt{B} > 6$

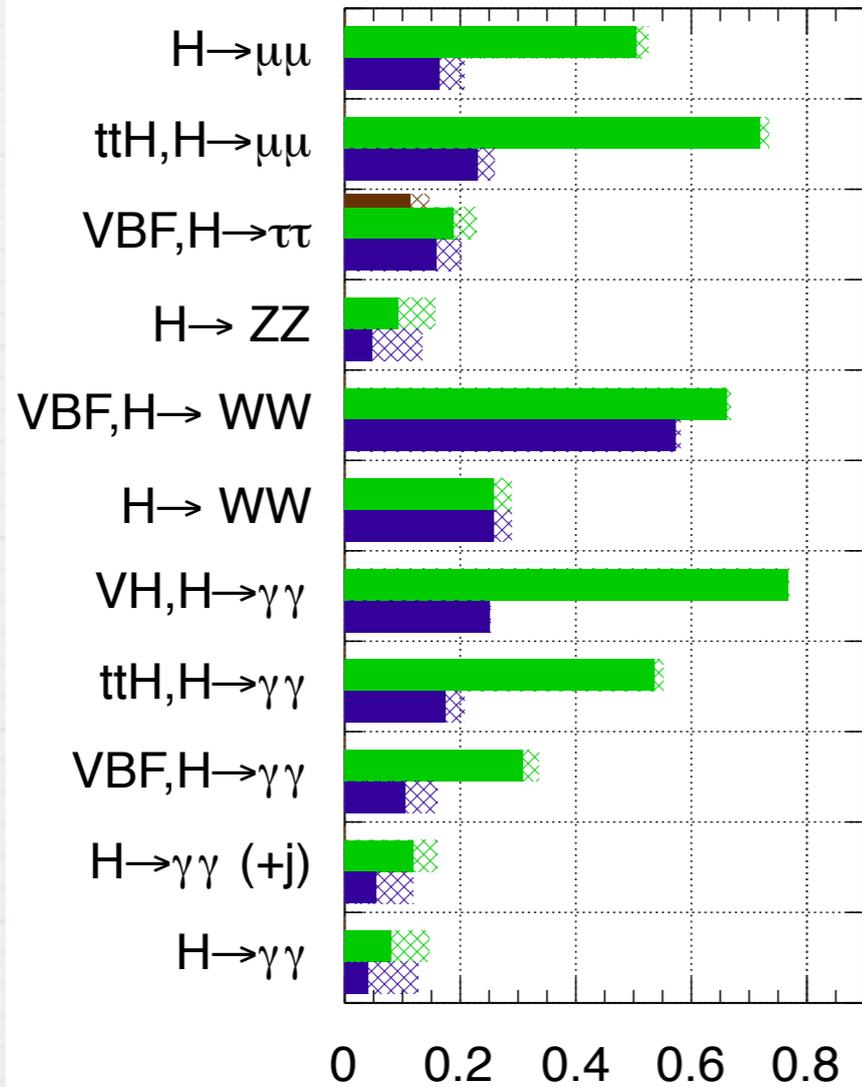


# 結合定数測定

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

$\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV

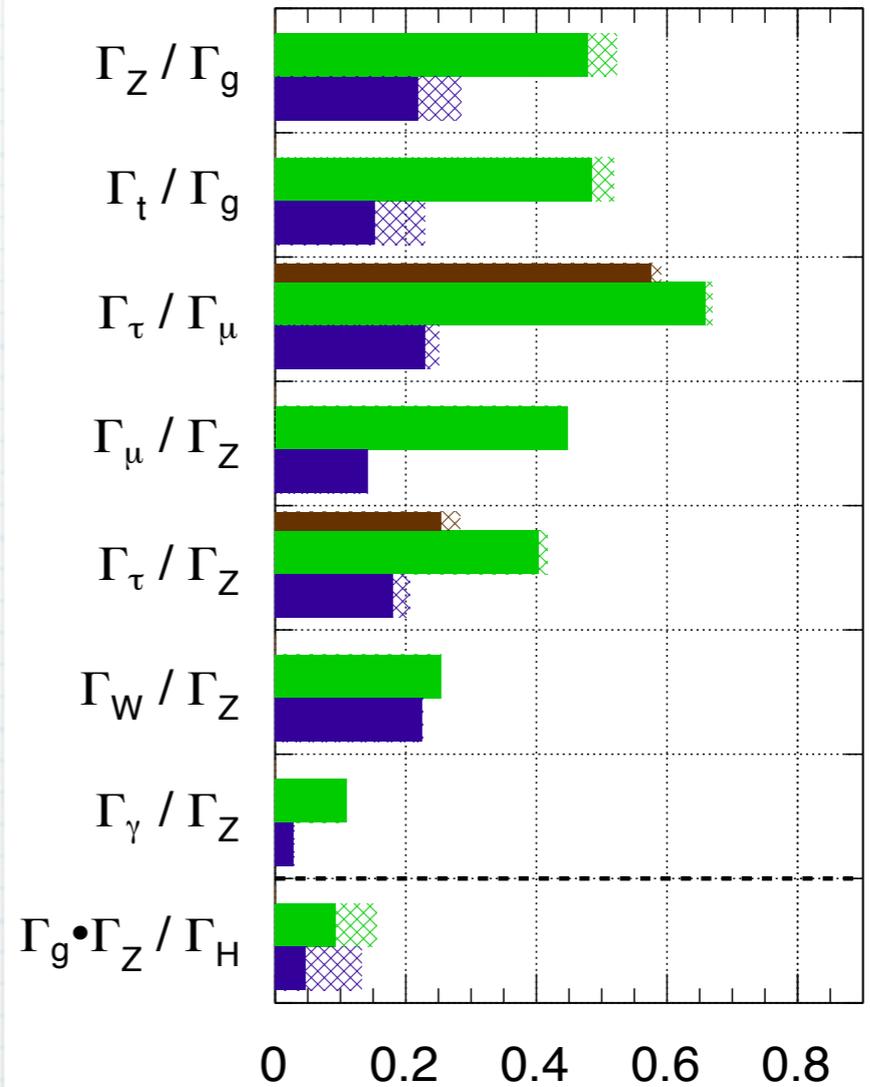


$\frac{\Delta\mu}{\mu}$

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

$\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



$$\frac{\Delta(\Gamma_x/\Gamma_y)}{\Gamma_x/\Gamma_y} \sim 2 \frac{\Delta(\kappa_x/\kappa_y)}{\kappa_x/\kappa_y}$$

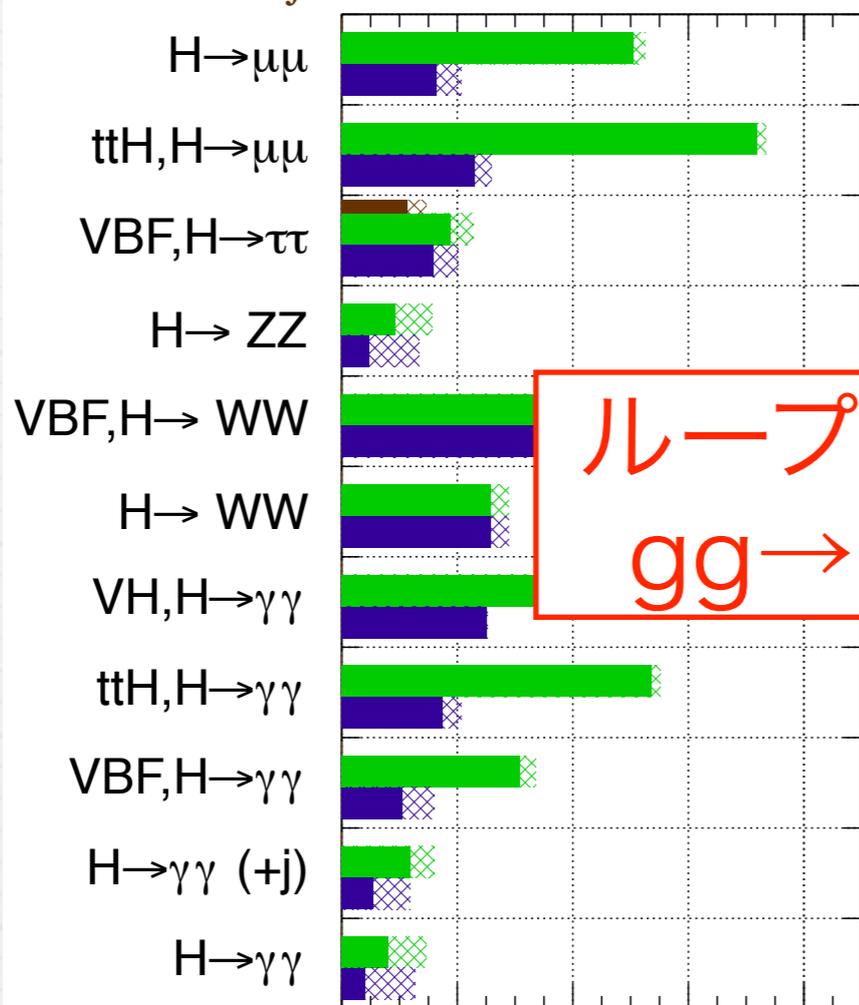
❖ Loopの中身, 崩壊全幅への仮定なし ⇒ only ratio

# 結合定数測定

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int Ldt=300 \text{ fb}^{-1}$ ;  $\int Ldt=3000 \text{ fb}^{-1}$

$\int Ldt=300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV

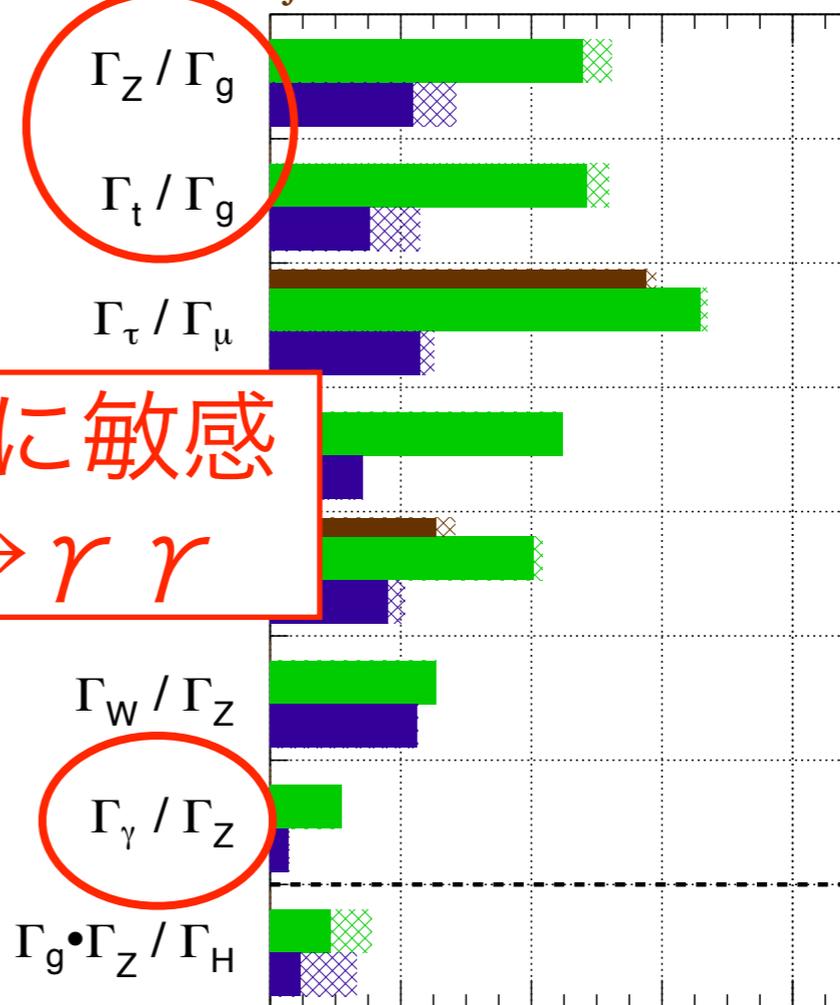


ループの効果に敏感  
 $gg \rightarrow H, H \rightarrow \gamma\gamma$

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int Ldt=300 \text{ fb}^{-1}$ ;  $\int Ldt=3000 \text{ fb}^{-1}$

$\int Ldt=300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



$$\frac{\Delta(\Gamma_x/\Gamma_y)}{\Gamma_x/\Gamma_y} \sim 2 \frac{\Delta(\kappa_x/\kappa_y)}{\kappa_x/\kappa_y}$$

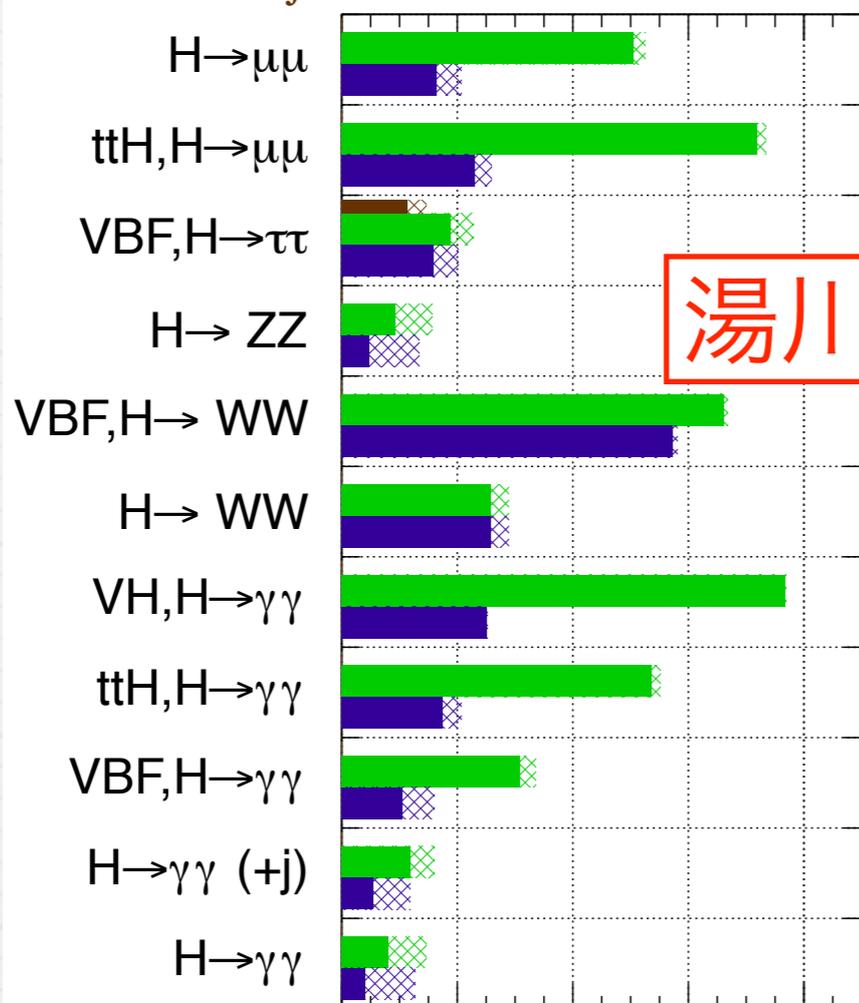
❖ Loopの中身, 崩壊全幅への仮定なし ⇒ only ratio

# 結合定数測定

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

$\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV

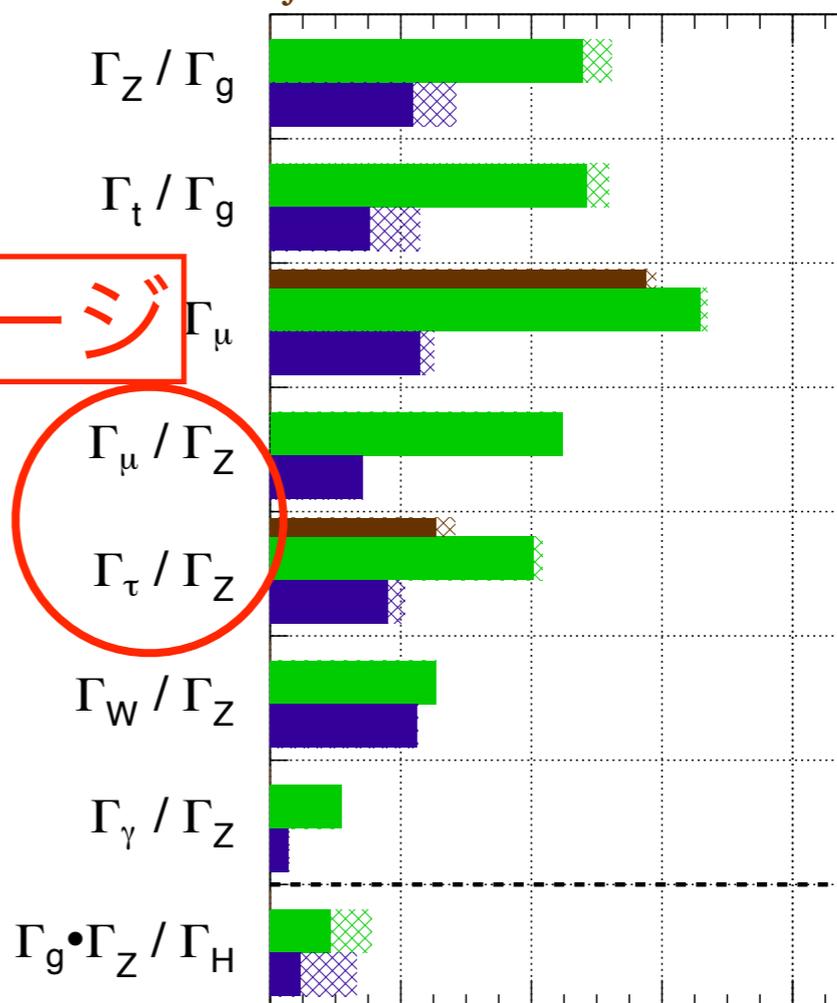


湯川 vs ゲージ

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

$\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



$$\frac{\Delta(\Gamma_x/\Gamma_y)}{\Gamma_x/\Gamma_y} \sim 2 \frac{\Delta(\kappa_x/\kappa_y)}{\kappa_x/\kappa_y}$$

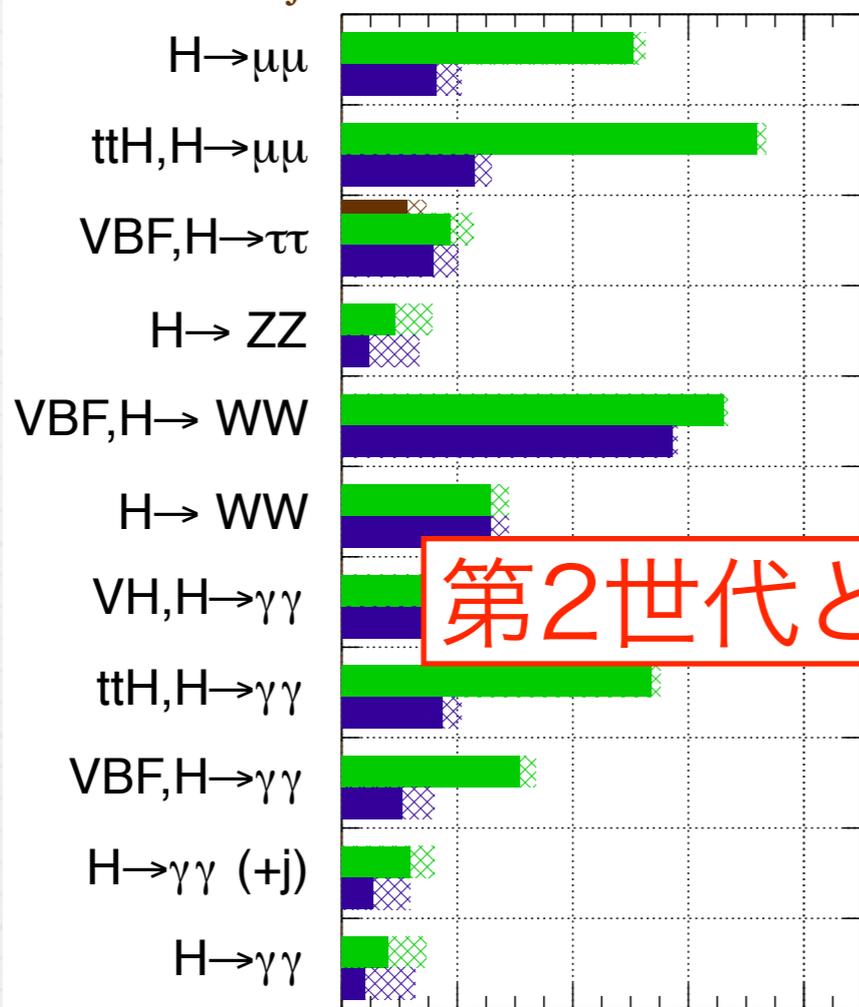
❖ Loopの中身, 崩壊全幅への仮定なし ⇒ only ratio

# 結合定数測定

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

$\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



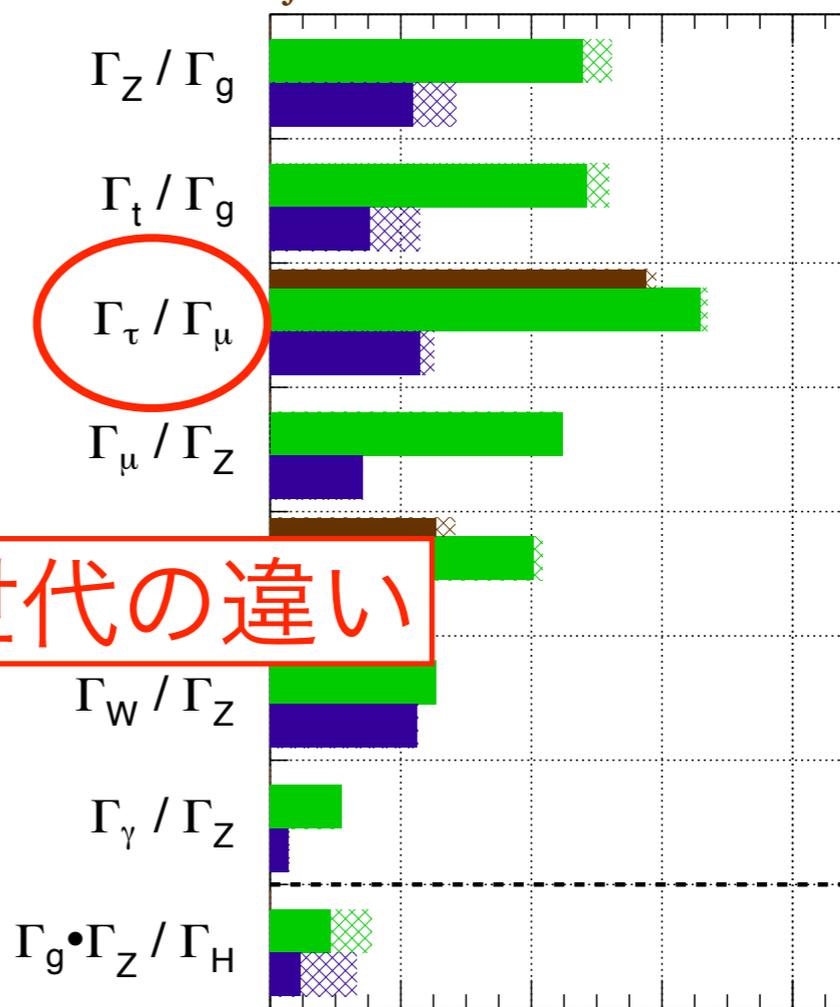
第2世代と第3世代の違い

$\frac{\Delta\mu}{\mu}$

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

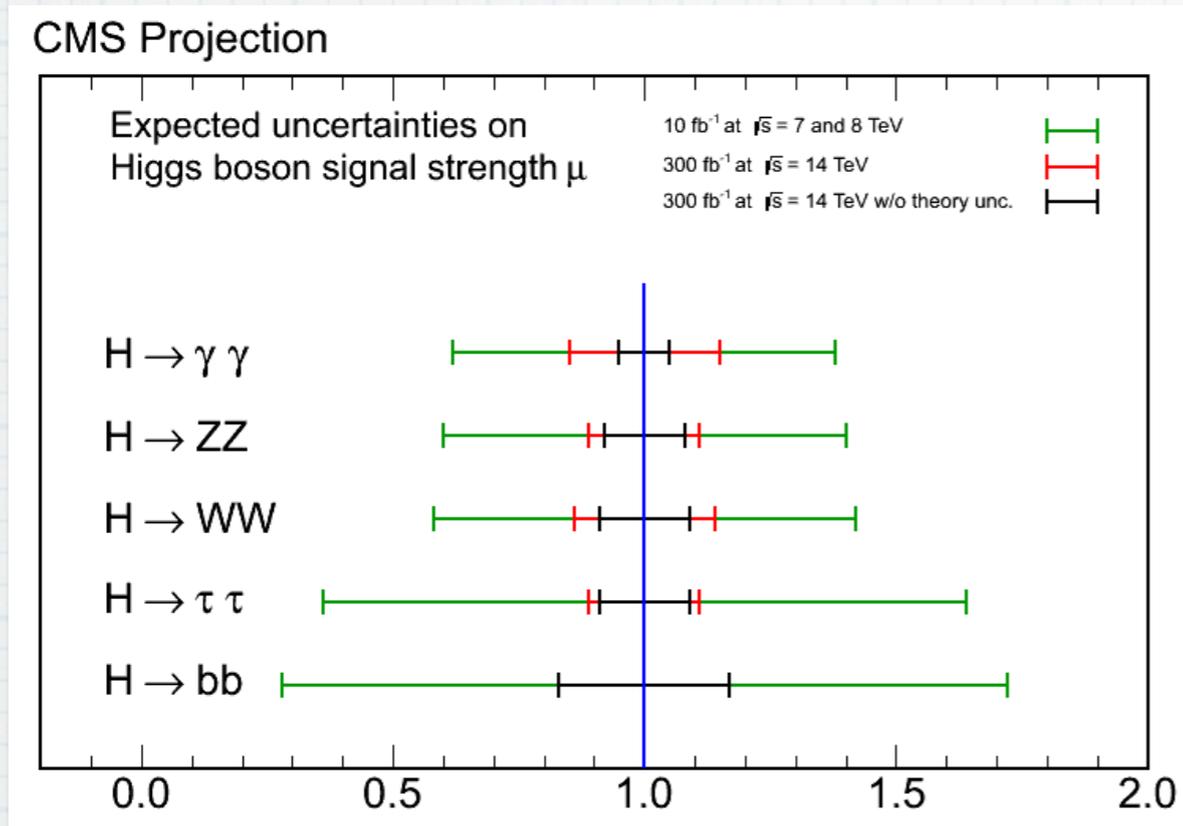
$\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2 \frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$

❖ Loopの中身, 崩壊全幅への仮定なし ⇒ only ratio

# ATLAS vs CMS 300fb<sup>-1</sup>での比較



CMSの予想精度

| 精度                 | ATLAS    | CMS |
|--------------------|----------|-----|
| H → $\gamma\gamma$ | 20%      | 15% |
| H → ZZ             | 15%      | 11% |
| H → $\tau\tau$     | 40%      | 10% |
| H → bb             | not done | 18% |

理論の不定性も含む

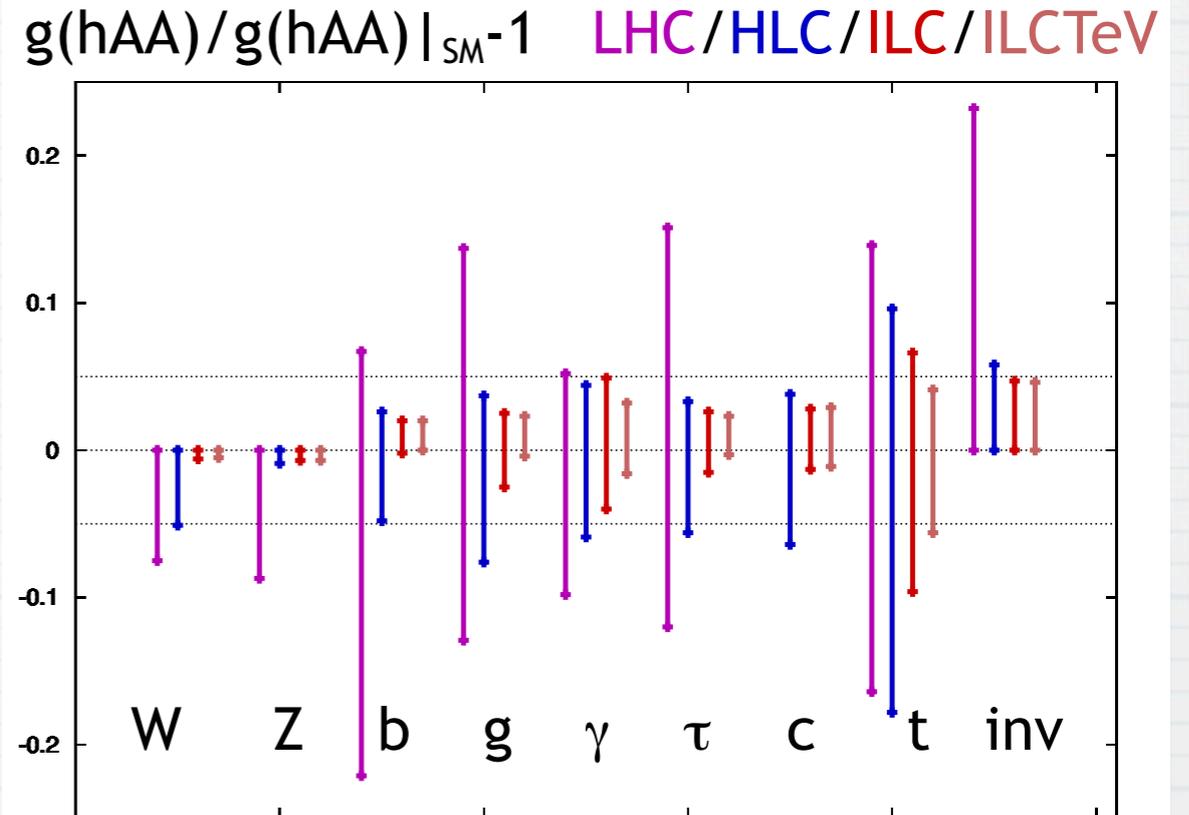
- ❖ CMSの解析手法もATLASと同様
  - ▶ 現在の検出器のefficiency/resolutionを仮定
- ❖ CMSの方がaggressive(?)

# Peskin/Duhrssen との比較

LHC 300fb<sup>-1</sup>

arXiv:1207.2516/ATL-PHYS-2003-030

| 精度                            | ATLAS    | Peskin          |
|-------------------------------|----------|-----------------|
| $H \rightarrow \gamma \gamma$ | 20%      | 20 $\oplus$ 15% |
| $H \rightarrow ZZ$            | 15%      | 21 $\oplus$ 15% |
| $H \rightarrow \tau \tau$     | 40%      | N/A             |
| $H \rightarrow bb$            | not done | 25 $\oplus$ 15% |



(注1) Peskinの $H \rightarrow bb$ は単独のチャンネル

(注2) Peskinでは $g(hAA)$ の導出に緩い仮定

❖ 孤立レプトンの評価は結構あった

▶  $H \rightarrow bb$ は楽観的→悲観的→現在はその中間

# ヒッグスセクター

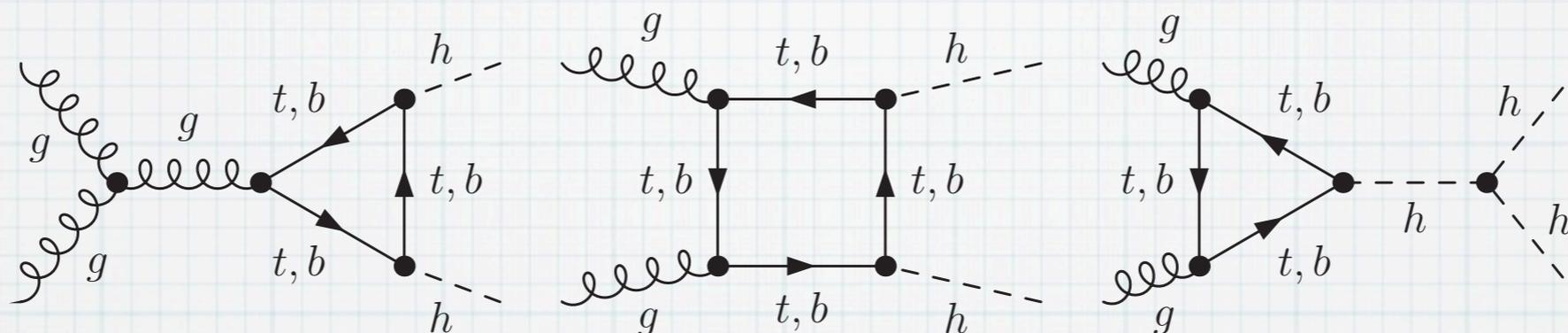
$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_H^2\phi^2) \\ &+ \frac{vg^2}{2}\phi W_\mu^+ W^{-\mu} + \frac{v(g^2 + g'^2)}{4}\phi Z_\mu Z^\mu \\ &- \sum_f Y_f \phi \bar{f} f \\ &- \lambda v \phi^3 - \lambda \frac{\phi^4}{4} \\ &+ \frac{g^2}{2}\phi^2 W_\mu^+ W^{-\mu} + \frac{(g^2 + g'^2)}{4}\phi^2 Z_\mu Z^\mu\end{aligned}$$

←自己結合

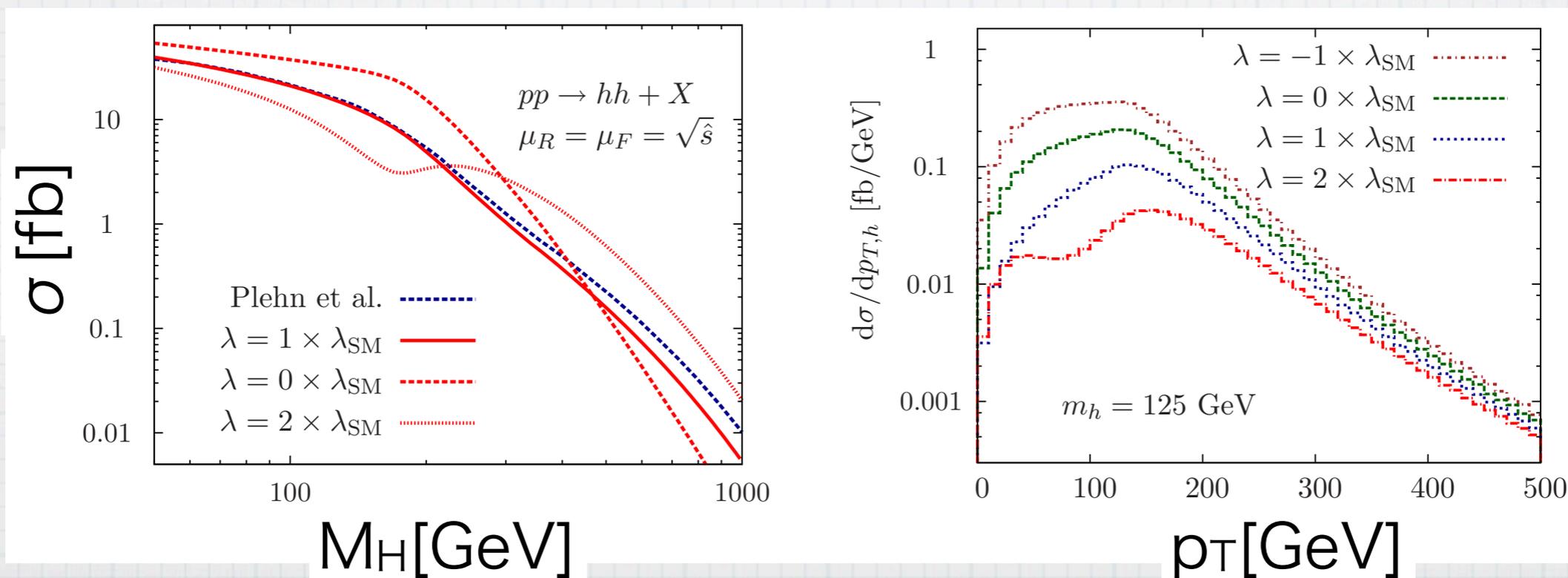
# 自己結合定数

❖ ヒッグス機構理解の鍵

❖ まずはHH生成の検出



❖ 自己結合定数  $\lambda$  の抽出



arXiv:1206.5001 [hep-ph]

# ヒッグス崩壊の組み合わせ

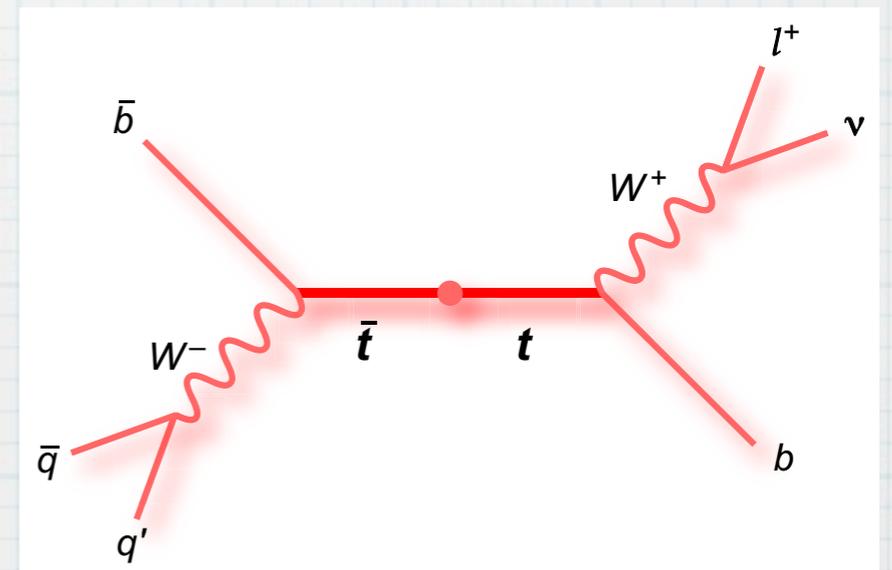
|   | $H \rightarrow \gamma \gamma$ | $H \rightarrow b\bar{b}$ | $H \rightarrow \tau \tau$ | $H \rightarrow WW$<br>$\rightarrow  \nu \nu $ | $H \rightarrow ZZ$<br>$\rightarrow \mu\mu$ | $H \rightarrow ZZ$<br>$\rightarrow llqq$ |
|---|-------------------------------|--------------------------|---------------------------|---|--|--|
| $H \rightarrow \gamma \gamma$                 | x                             | ○                        | x                         | ?   | ?  | ?  |
| $H \rightarrow b\bar{b}$                      |                               | x                        | $\Delta \circ ?$          | $\Delta$                                      | ?  | ?  |
| $H \rightarrow \tau \tau$                     |                               |                          | x?                        | ?   | ?  | ?  |
| $H \rightarrow WW$<br>$\rightarrow  \nu \nu $ |                               |                          |                           | x?  | x?   | x?                                       |
| $H \rightarrow ZZ$<br>$\rightarrow \mu\mu$    |                               |                          |                           |   | x  | x  |
| $H \rightarrow ZZ$<br>$\rightarrow llqq$      |                               |                          |                           |   |  | x  |

# HH→bbWW

- ❖ BR(HH→bbWW→bbllνqq) ~ 10% ⇒ 10k @3000fb<sup>-1</sup>
- ❖ one lepton + missingE<sub>T</sub> + two jets (at least one b-tagged)
  - ▶ W質量を仮定してνのpz

$$\chi^2 = \left(\frac{M_{bb} - m_H}{\sigma_{M_{bb}}}\right)^2 + \left(\frac{M_{WW} - m_H}{\sigma_{M_{WW}}}\right)^2$$

- ❖ ttbar が莫大
  - ▶ S/B ~ 10<sup>-5</sup>...



# HH→bb $\gamma$ $\gamma$

- ❖ 3000fb<sup>-1</sup>で260事象生成
- ❖  $p_T(\gamma) > 25\text{GeV}$ ,  
 $p_T(b) > 40/25\text{ GeV}$
- ❖ 2 isolated photons  
&& 2 b-tagged jets
- ❖ 角度分布
- ❖  $50 < M_{bb} < 130\text{ GeV}$   
&&  $120 < M_{\gamma\gamma} < 130\text{ GeV}$

選別後事象数

|               |    |
|---------------|----|
| $\lambda = 0$ | 26 |
| $\lambda = 1$ | 15 |
| $\lambda = 2$ | 8  |
| BG            | 24 |

観測はできそうだが単独での $\lambda$ の測定は...

$$HH \rightarrow bb \tau \tau, bb \mu \mu$$

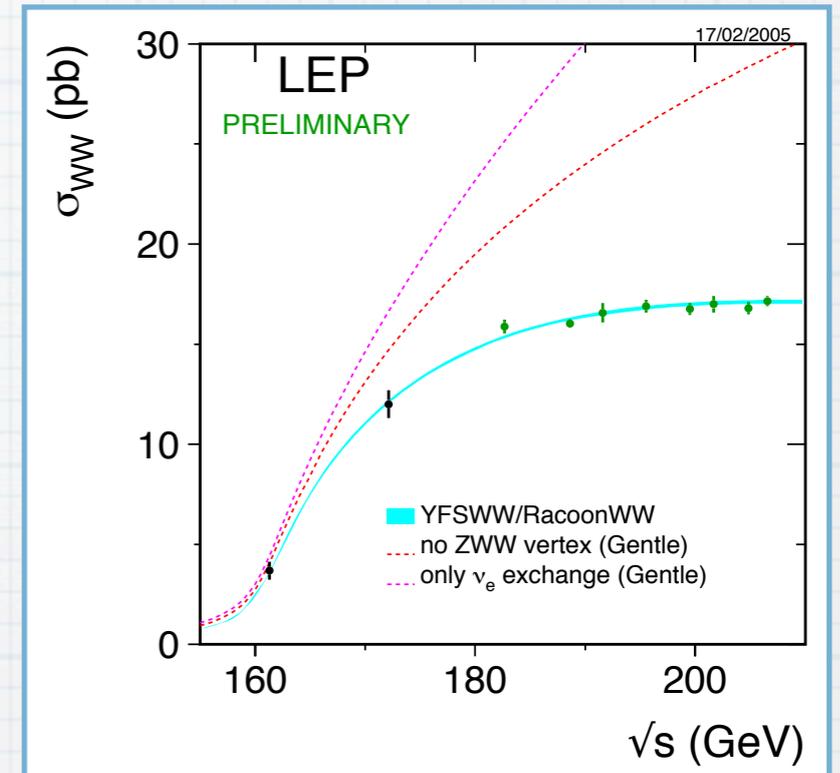
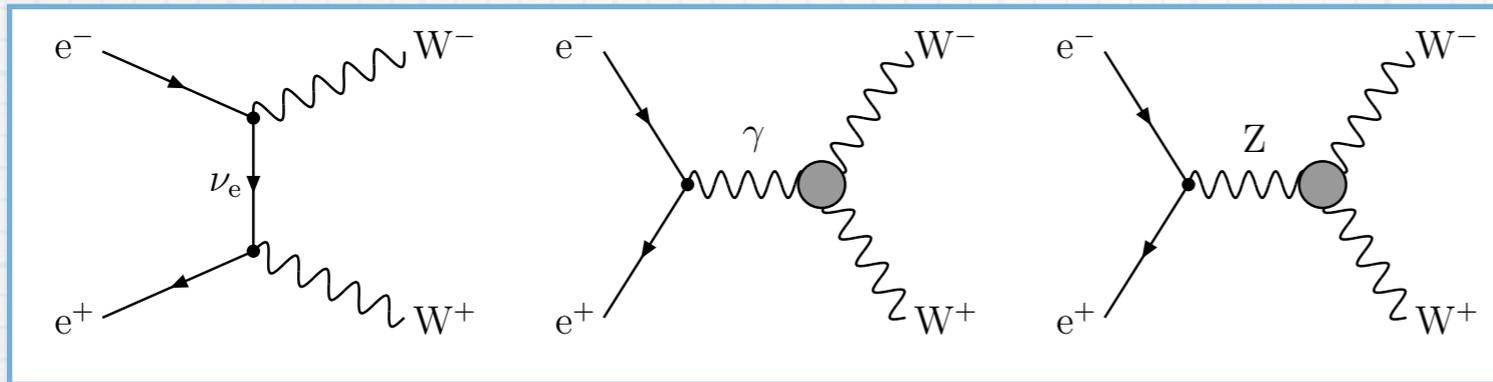
❖  $bb \tau \tau$  : ATLASの解析は終わっていないが  
arXiv:1206.5001 [hep-ph]によると有望

▶ parton level study

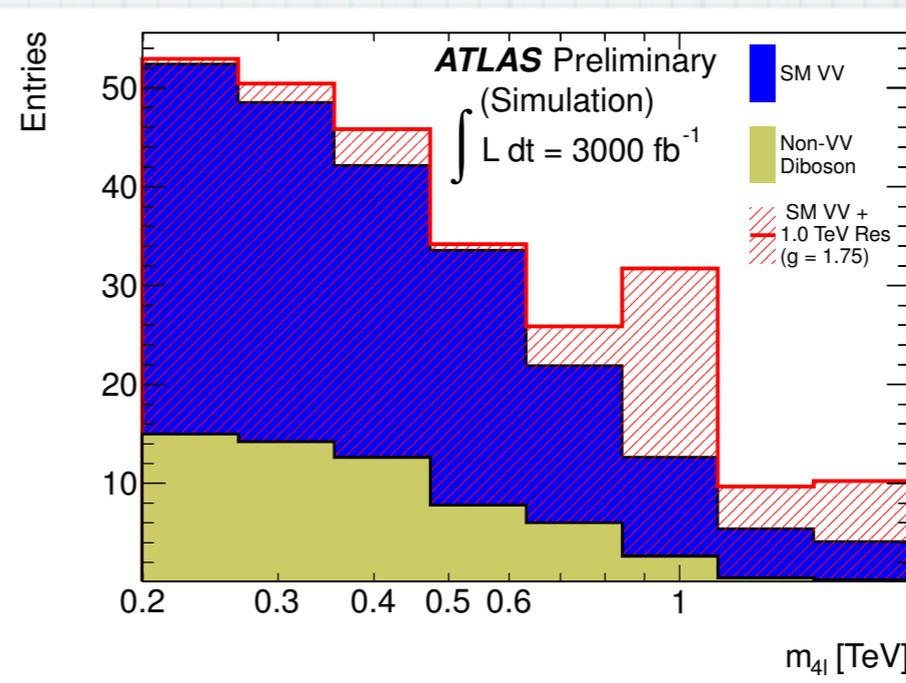
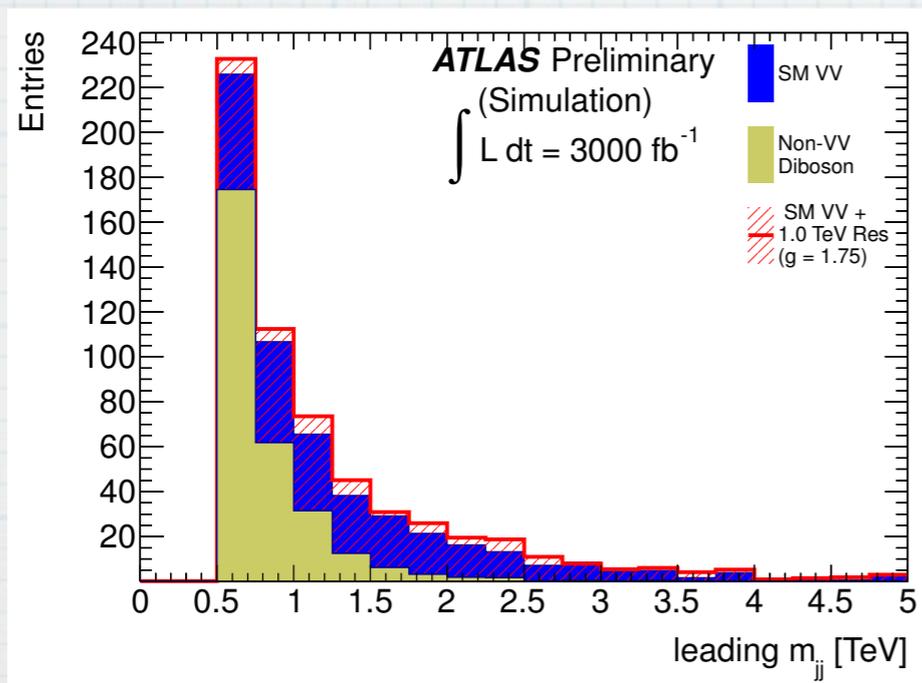
| 単位は $[\text{fb}^{-1}]$                            | $\xi = 0$ | $\xi = 1$ | $\xi = 2$ | $b\bar{b}\tau\tau$ | $b\bar{b}\tau\tau$ [ELW] | $b\bar{b}W^+W^-$ | S/N ratio           |
|---|-----------|-----------|-----------|--------------------|--------------------------|------------------|---------------------|
| cross section before cuts                         | 59.48     | 28.34     | 13.36     | 67.48              | 8.73                     | 873000           | $3.2 \cdot 10^{-5}$ |
| reconstructed Higgs from $\tau$ s                 | 4.05      | 1.94      | 0.91      | 2.51               | 1.10                     | 1507.99          | $1.9 \cdot 10^{-3}$ |
| fatjet cuts                                       | 2.27      | 1.09      | 0.65      | 1.29               | 0.84                     | 223.21           | $4.8 \cdot 10^{-3}$ |
| kinematic Higgs reconstruction ( $m_{b\bar{b}}$ ) | 0.41      | 0.26      | 0.15      | 0.104              | 0.047                    | 9.50             | $2.3 \cdot 10^{-2}$ |
| Higgs with double $b$ -tag                        | 0.148     | 0.095     | 0.053     | 0.028              | 0.020                    | 0.15             | 0.48                |

❖  $bb \mu \mu$  : HE-LHCなら可能性ありか

# おまけ WW散乱



- ❖ Spin 0 component cancelled by Scalar (=Higgs?)
- ❖ VV scattering needs to be checked



jj+ZZ

# 展望のまとめ

- ❖ Spin/Parityの決定
  - ▶  $300\text{fb}^{-1}$  あれば  $5\sigma$  以上の分離
- ❖ ゲージ/湯川結合定数  $\leftarrow$  比の測定
  - ▶  $300\text{fb}^{-1}$  で 10-20%程度
- ❖ 自己結合定数
  - ▶  $3000\text{fb}^{-1}$  で HH生成を検出できるかも

# 結論

- ❖ 2012年に発見した粒子はヒッグスっぽい
- ❖ LHCは世界で唯一のヒッグス製造工場
  - ▶ 実験からの知見が不可欠
- ❖ 自然がどんな構造をしているかわからない
  - ▶ 虚心坦懐に様々な角度から検証
    - ◎ SMで除外された過程も大切

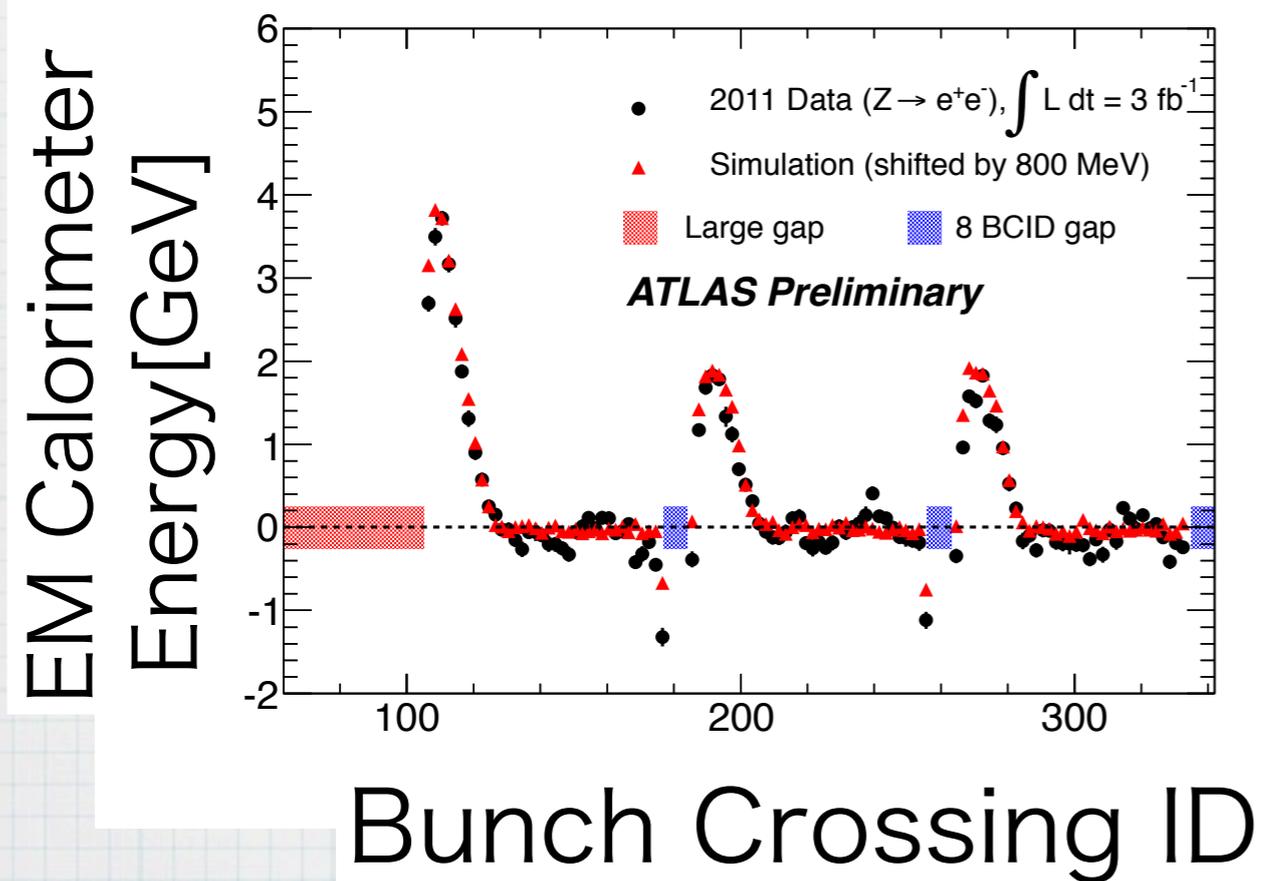
backup

# Efficiencyの理解

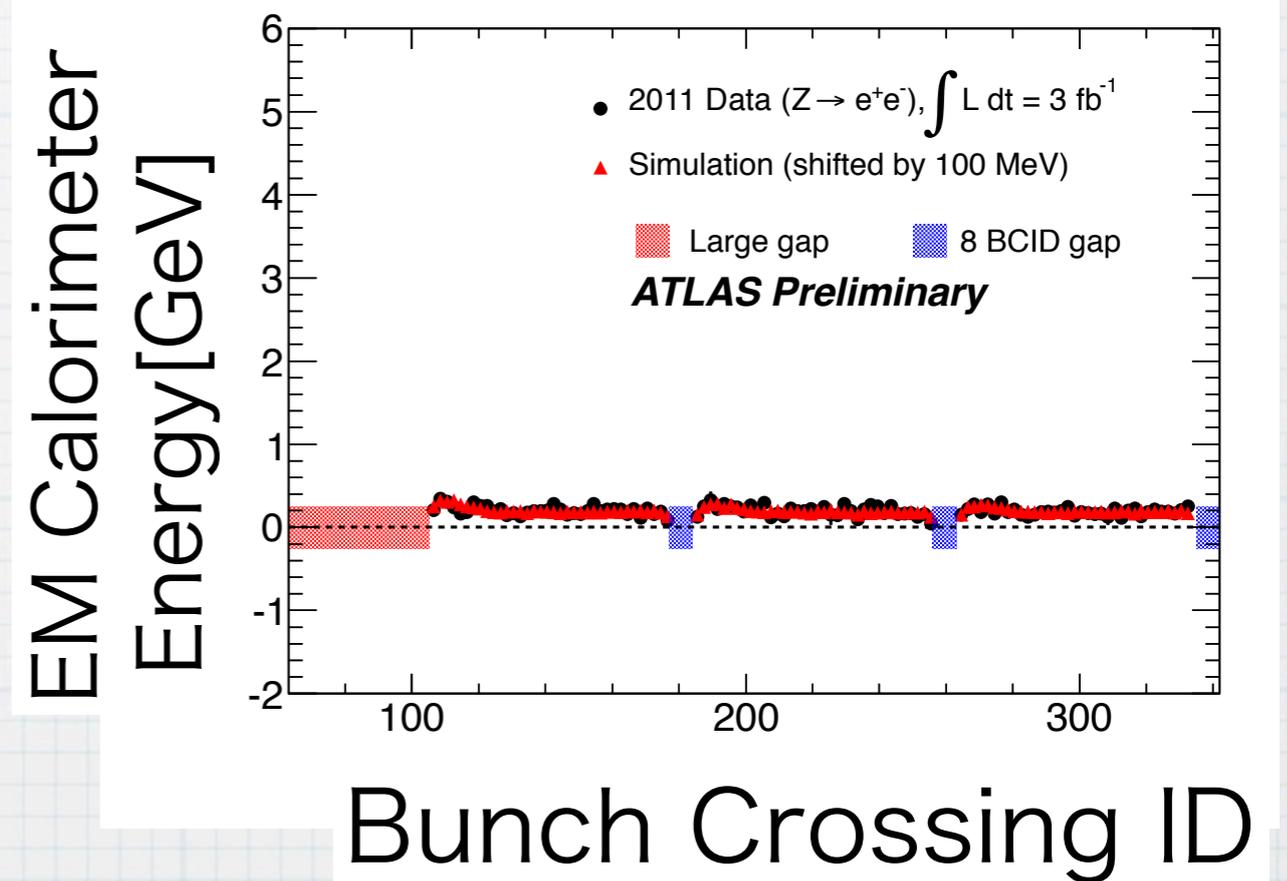
$$N = \sigma \times \mathcal{L} \times BR \times \mathcal{A} \times \epsilon$$

❖  $\sigma \times BR$ を測るにはefficiency  $\epsilon$  の理解が重要

補正前



補正後



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

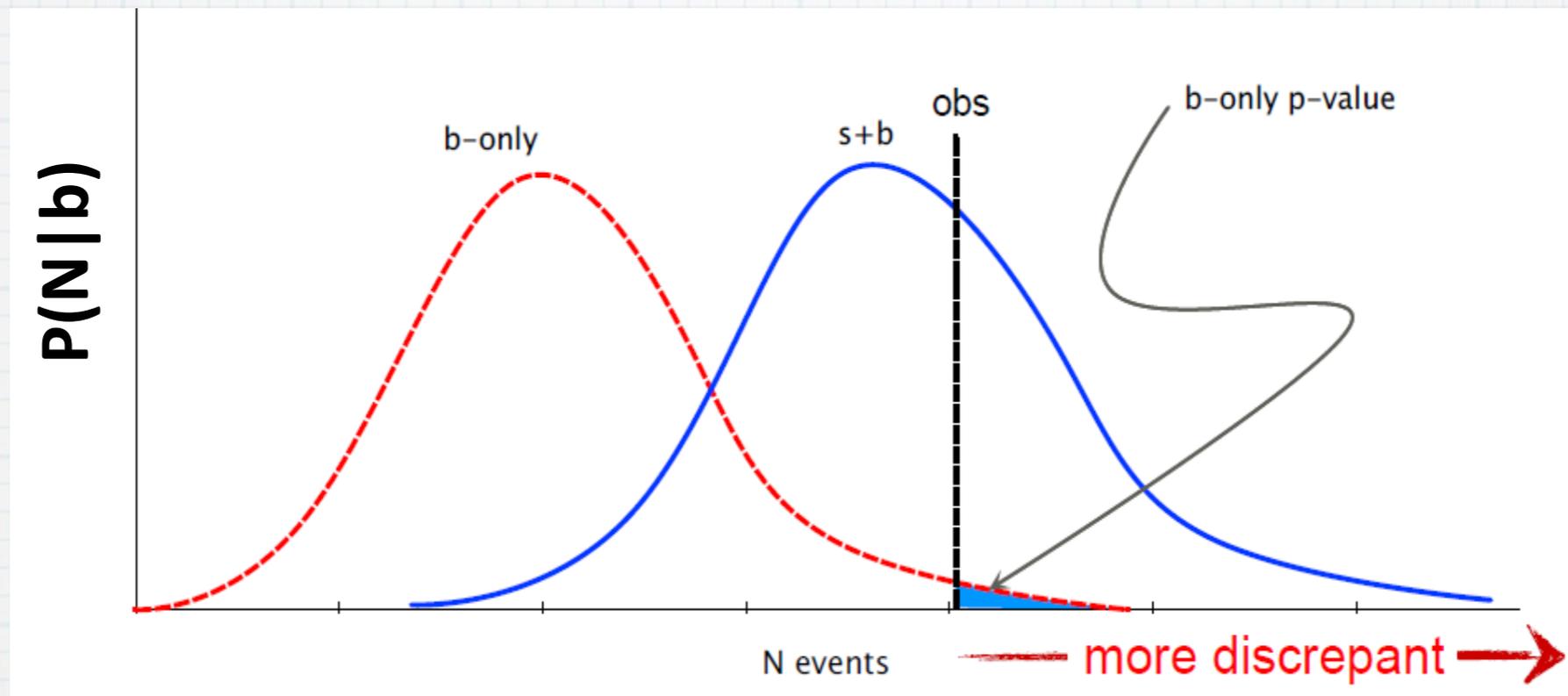
| $J^P$   | Production configuration           | Decay configuration             | Comments                                    |
|---------|------------------------------------|---------------------------------|---|
| $0^+$   | $gg \rightarrow X :$               | $g_1 = 1 \ g_2 = g_3 = g_4 = 0$ |   |
| $0^-$   | $gg \rightarrow X :$               | $g_4 = 1 \ g_1 = g_2 = g_3 = 0$ |   |
| $1^+$   | $q\bar{q} \rightarrow X :$         | $g_1 = 0 \ g_2 = 1$             |   |
| $1^-$   | $q\bar{q} \rightarrow X :$         | $g_1 = 1 \ g_2 = 0$             |   |
| $2_m^+$ | $gg \rightarrow X : g_1 = 1$       | $g_1 = g_5 = 1$                 | Graviton-like tensor with minimal couplings |
| $2_m^+$ | $q\bar{q} \rightarrow X : g_1 = 1$ | $g_1 = g_5 = 1$                 | Graviton-like tensor with minimal couplings |
| $2^-$   | $gg \rightarrow X : g_1 = 1$       | $g_8 = g_9 = 1$                 | “Pseudo-tensor”                             |

# Possible channels for future Higgs selfcouplings studies for ES

$\sigma_{HH}$  (14 TeV) = 33.71 fb (M. Spira, July 2012, HPAIR)

| Decay channel   | Branching ratio (%)                     | Cross Section                            | Events in 3 ab <sup>-1</sup>            |
|---|---|--|---|
| bb + WW   | 24.81                                   | 8.36                                     | 25K                                     |
| bb $\gamma\gamma$   | 0.263                                   | 0.0887                                   | 266                                     |
|   |   |  |   |
| ZZbb $\rightarrow$ 4l bb  | 3.05 $\rightarrow$ 0.0137               | 1.03 $\rightarrow$ 0.0046                | 3084 $\rightarrow$ 13.9                 |
| ZZbb $\rightarrow$ 2l2b bb  | 3.05 $\rightarrow$ 0.061                | 1.03 $\rightarrow$ 0.0205                | 3084 $\rightarrow$ 62                   |
| ZZ $\gamma\gamma$   | 0.01204                                 | 0.004                                    | 12.2                                    |
| WW $\tau\tau\rightarrow$ lvqq $\tau_l\tau_h$                          | 2.72 $\rightarrow$ 0.181                | 0.917 $\rightarrow$ 0.061                | 2751 $\rightarrow$ 183                  |
| WW $\tau\tau\rightarrow$ lvlv $\tau_l\tau_h$                          | 2.72 $\rightarrow$ 0.029                | 0.917 $\rightarrow$ 0.0098               | 2751 $\rightarrow$ 29                   |
| <b>bb<math>\tau\tau\rightarrow</math>bb <math>\tau_l\tau_h</math></b> | <b>7.29<math>\rightarrow</math>1.66</b> | <b>2.46<math>\rightarrow</math>0.559</b> | <b>7376<math>\rightarrow</math>1678</b> |
|   |   |  |   |

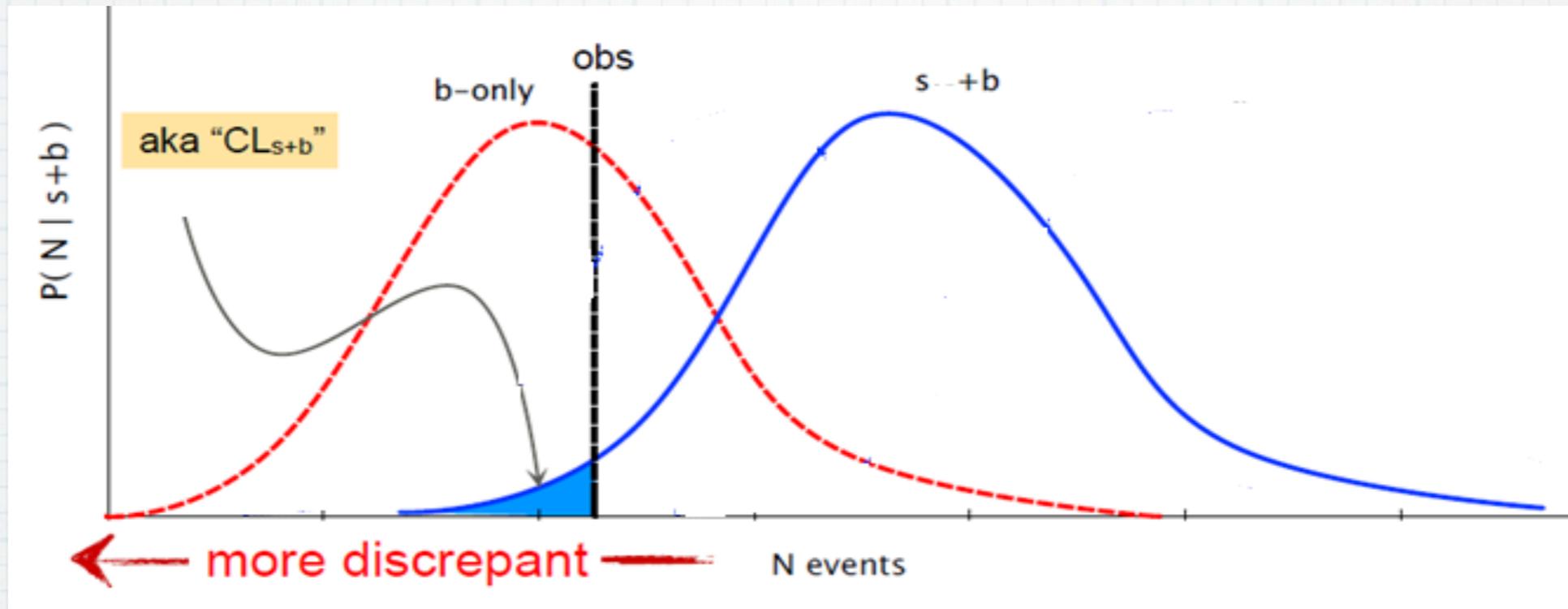
# p-value



$$p\text{-value} = P(N > N_{obs} | b)$$

- ❖ 検定量は色々ある
  - ▶ 観測事象数, likelihood ratio, etc..
- ❖ (今回の) Significanceはp-valueから算出

# Confidence Level

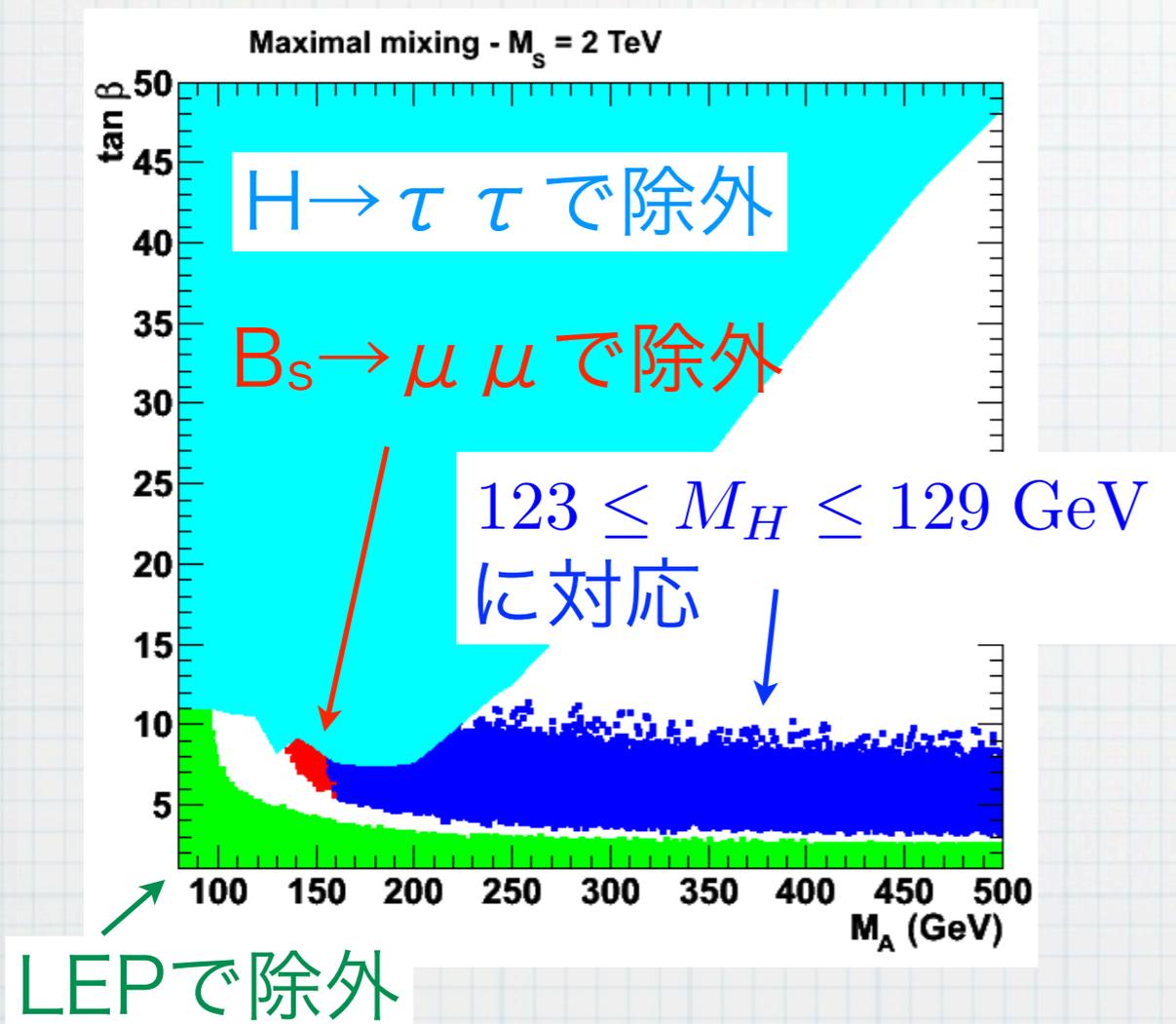


$$CL_{s+b} = P( N < N_{obs} | s+b )$$

- ❖  $CL_{s+b} < 5\%$  なら95%CLで棄却
- ❖  $CL_{s+b}(\mu) = P( N < N_{obs} | \mu s+b ) = 5\%$   
となる  $\mu$  を95%CLで棄却した, と言う

# Beyond SM (SUSY)

## MSSM parameter scan



arXiv:1207.1348

### ❖ 様々なシナリオ

- ▶ 126GeVが2番目に軽いヒッグス
- ▶  $H \rightarrow \gamma \gamma$  をenhance &&  $H \rightarrow bb / \tau \tau$  を suppress
- ▶ 他たくさん

### ❖ SMで除外された

モードの探索も重要