



# LHC最新結果

高エネルギー物理学将来計画検討小委員会タウンミーティング  
『コライダー加速器による高エネルギー物理学の将来展望』  
名古屋大学

田中 純一  
東京大学 素粒子物理国際研究センター



2011年9月10日



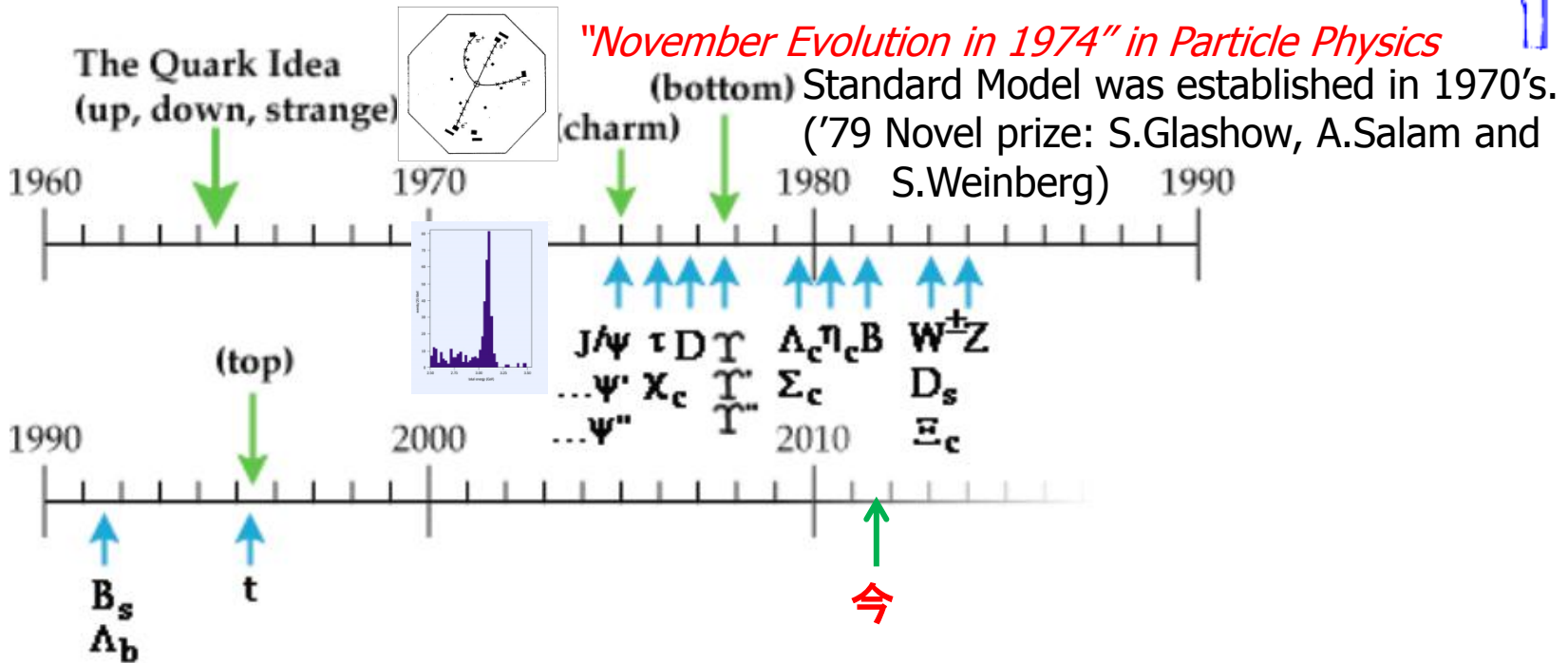
# 内容

- インTRODクシヨN (LHC実験)
- ヒツグス粒子探索
- SUSY探索
- Other BSM探索
- まとめ

ATLASの結果が多いです。  
Higgsが多いです。



# Toward "New Evolution"



- Involving in very exciting research at CERN in Switzerland.
  - We have the highest energy accelerator "LHC" in the world and excellent detectors "ATLAS and CMS".
  - Our experiment has started at 30<sup>th</sup>, March 2010 with  $\sqrt{s}=7\text{TeV}$ .  
-> We have almost caught up with Tevatron (closed at the end of FY2011).
- Expect a "NEW EVOLUTION" in particle physics.
  - New particles/phenomenology -> Close SM and move to BSM (Supersymmetry, Extra-dimension, ...)



# Large Hadron Collider (LHC)

Jura mountain



ATLAS

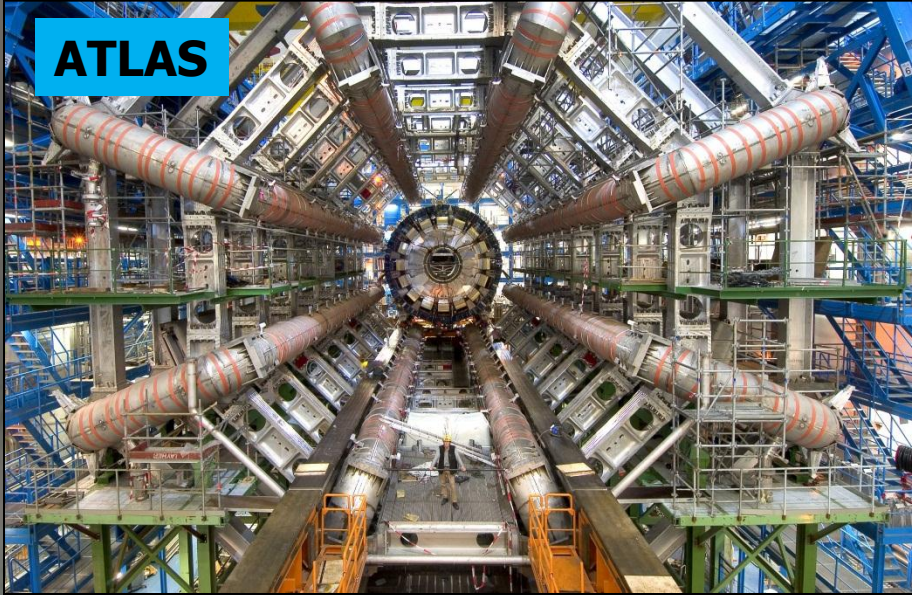
CERN

CMS

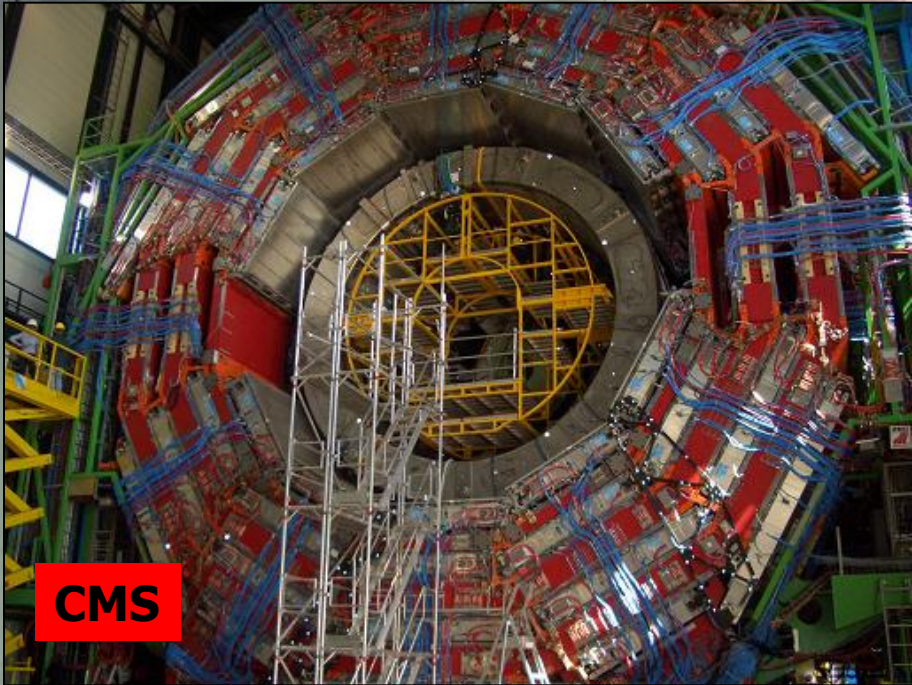
Geneva international airport



LHC tunnel  
- ~27km circumference  
- ~100m below the ground



**ATLAS**



**CMS**

## LHC tunnel

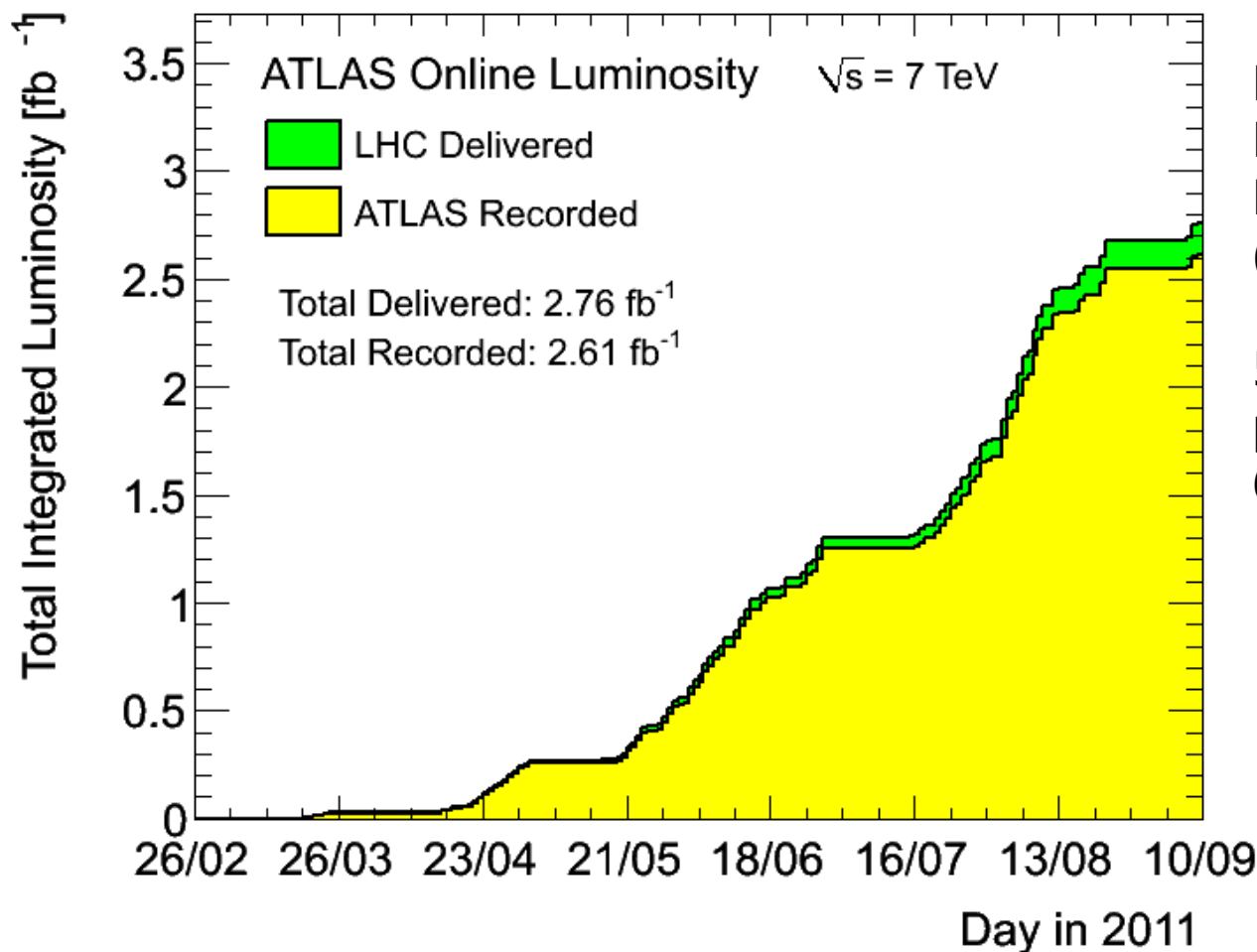
- $\sim 100\text{m}$  below the ground
- 1232 x Dipole magnet
  - operate at 1.9K
  - $B=8.3\text{Tesla}$  for  $\sqrt{s}=14\text{TeV}$
  - $\rightarrow 4.1\text{Tesla}$  for  $\sqrt{s}=7\text{TeV}$





# LHC in 2011

LHC =  $\sqrt{s}=7\text{TeV}$ で順調にデータを供給

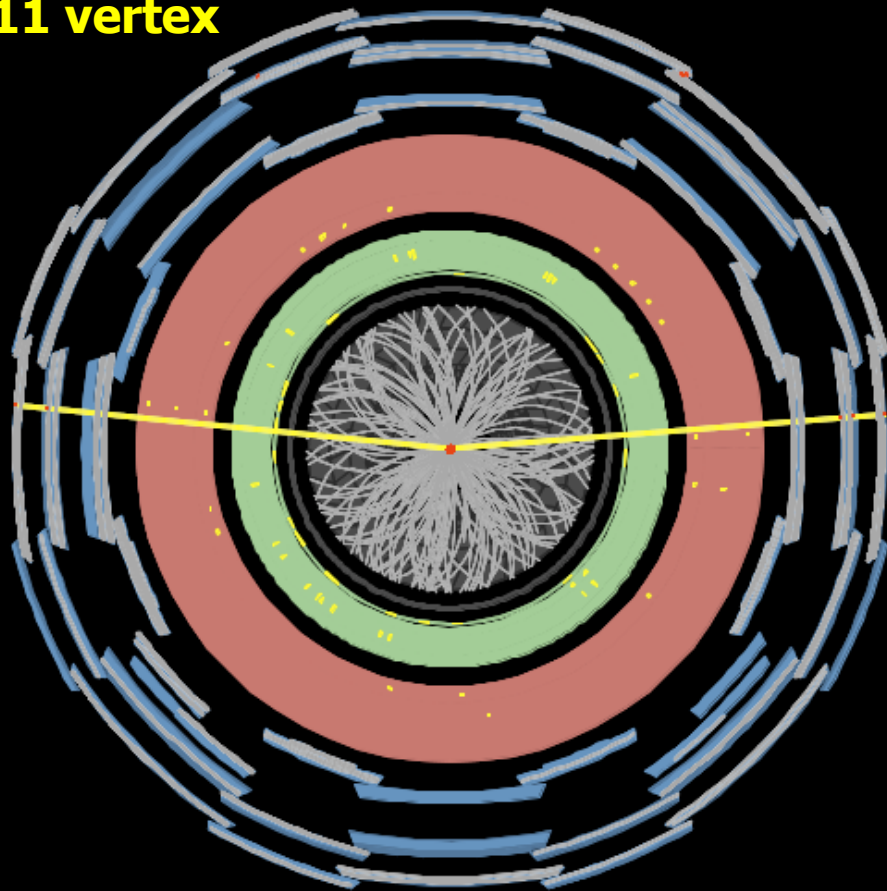


Peak  $\sim 2.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$   
Max  $\sim 90 \text{ pb}^{-1} / \text{day}$   
L  $\sim 2.8 \text{ fb}^{-1}$  delivered  
(昨年の約70倍)

50ns bunch spacing  
pileup =  
6 collision / crossing (ave.)



11 vertex

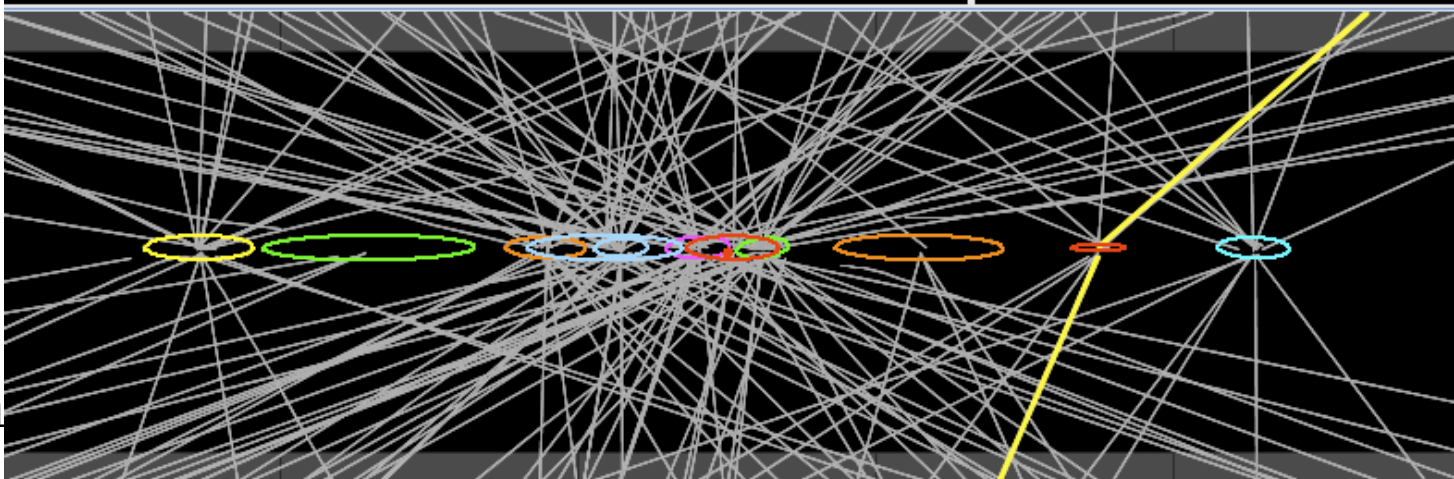
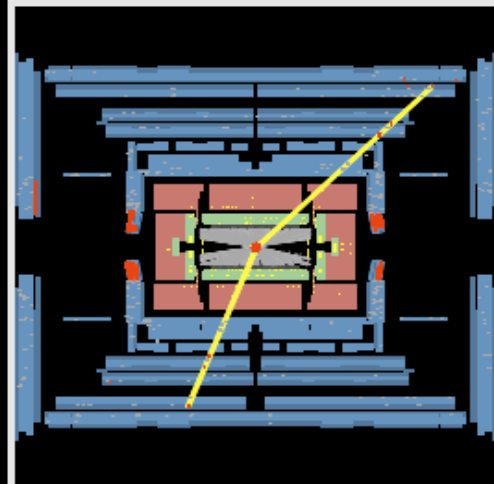


Z-> $\mu\mu$  (93.4GeV)



Run Number: 180164, Event Number: 146351094

Date: 2011-04-24 01:43:39 CEST



2011



# Standard Model



2011年9月10日

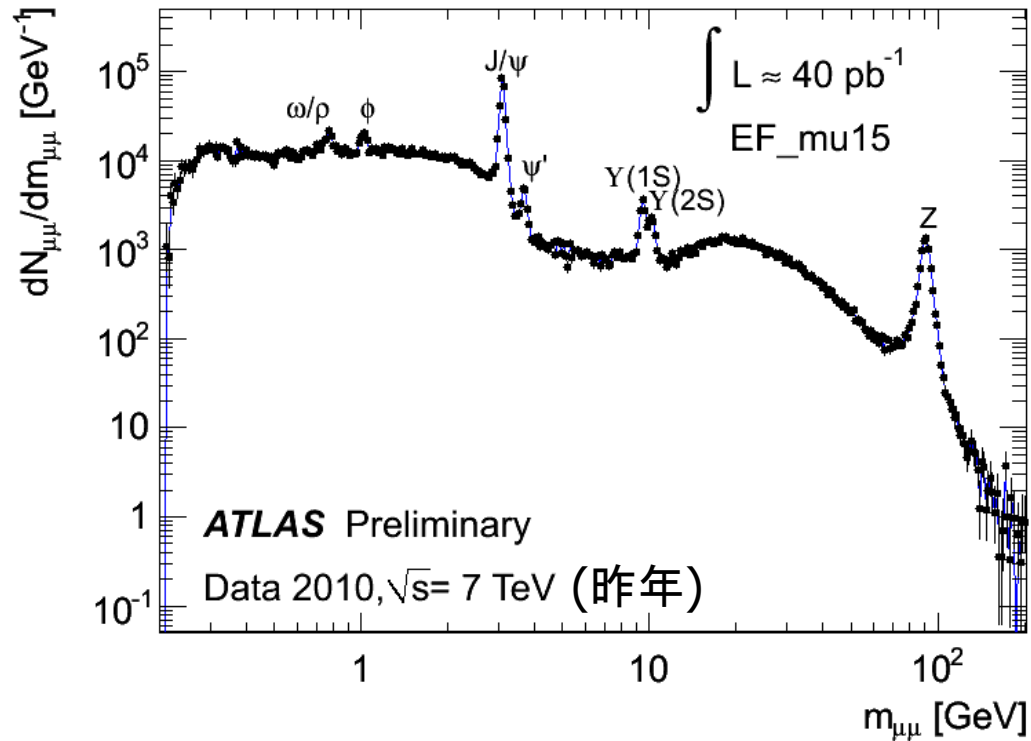
コライダー加速器による高エネルギー物理学の将来展望



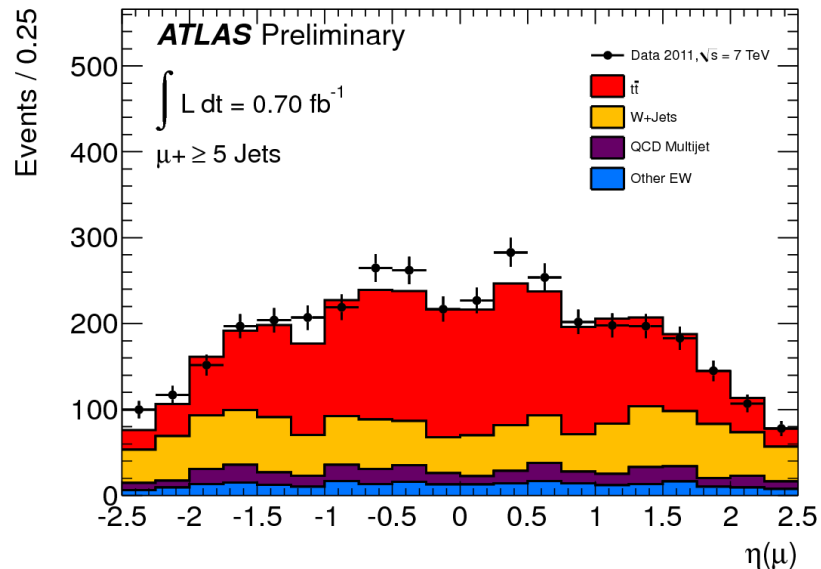
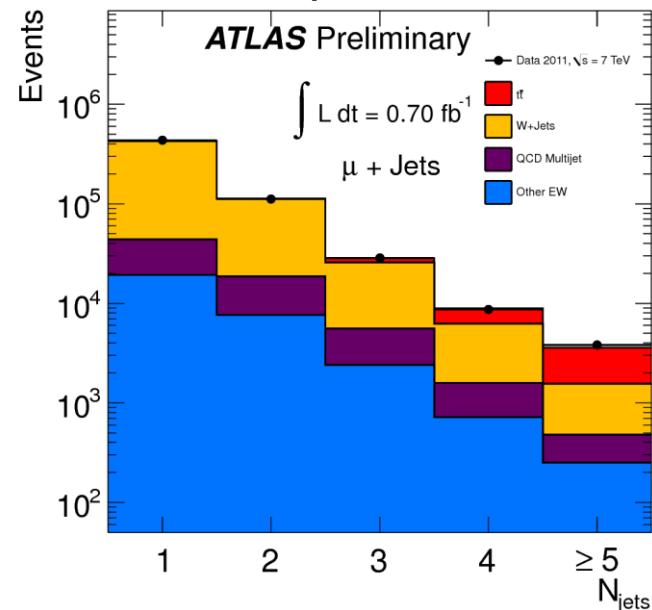
# Re-discovery



OS di-muon invariant mass

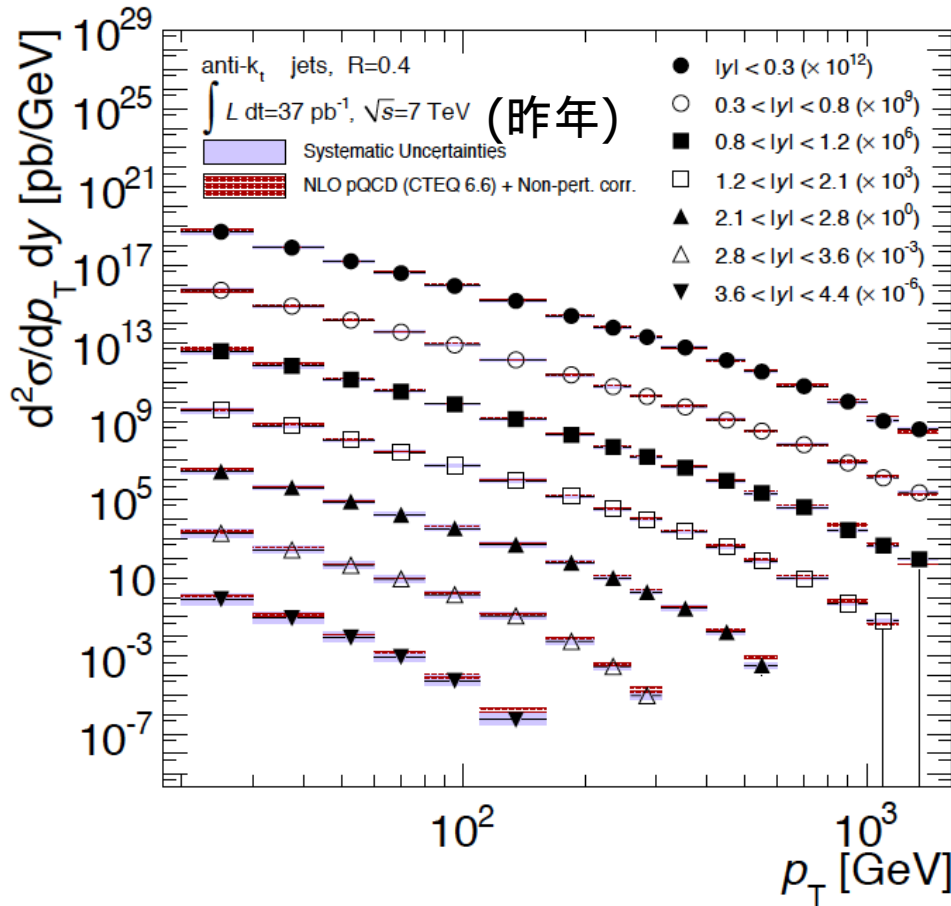


Top Quark





# QCD jet



「Hadron colliderで  
MC simulationなんて  
、、、」という常識は古くなった。

- Our MC prediction, NLO pQCD, has a good agreement!!!
  - Up to  $y=4.4$
  - Up to  $p_T=2\text{TeV}$





# ヒッグス粒子探索

ヒッグスが話題になった会合と時期  
EPS ... 7月のヨーロッパの大きな会議  
LP ... 8月 Lepton Photon 2011



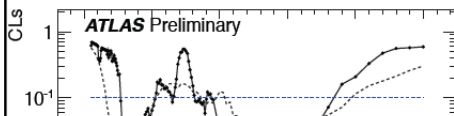
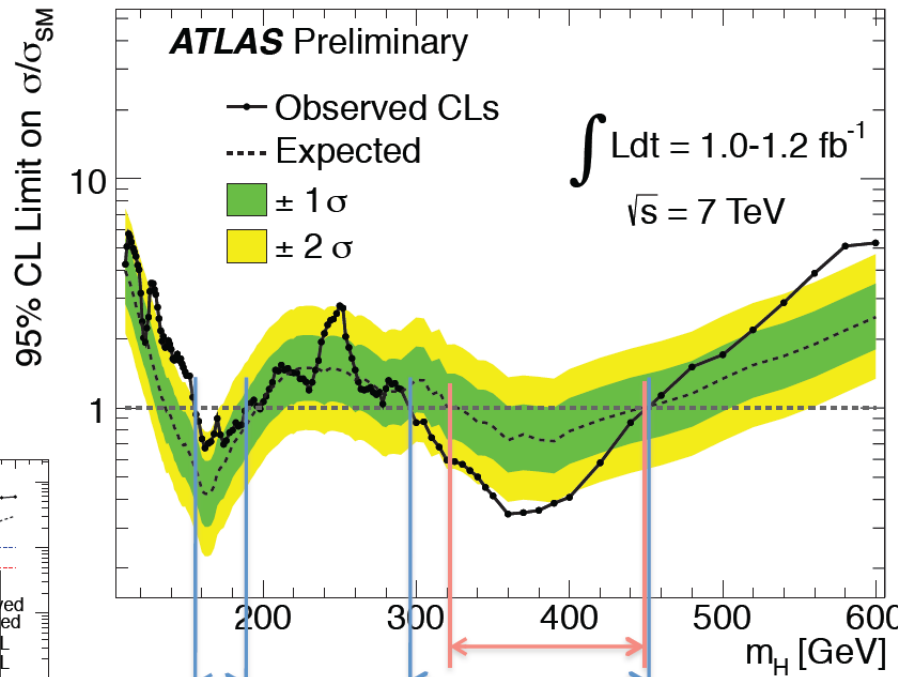


EPSでの結果  
-> 期待感 ↗

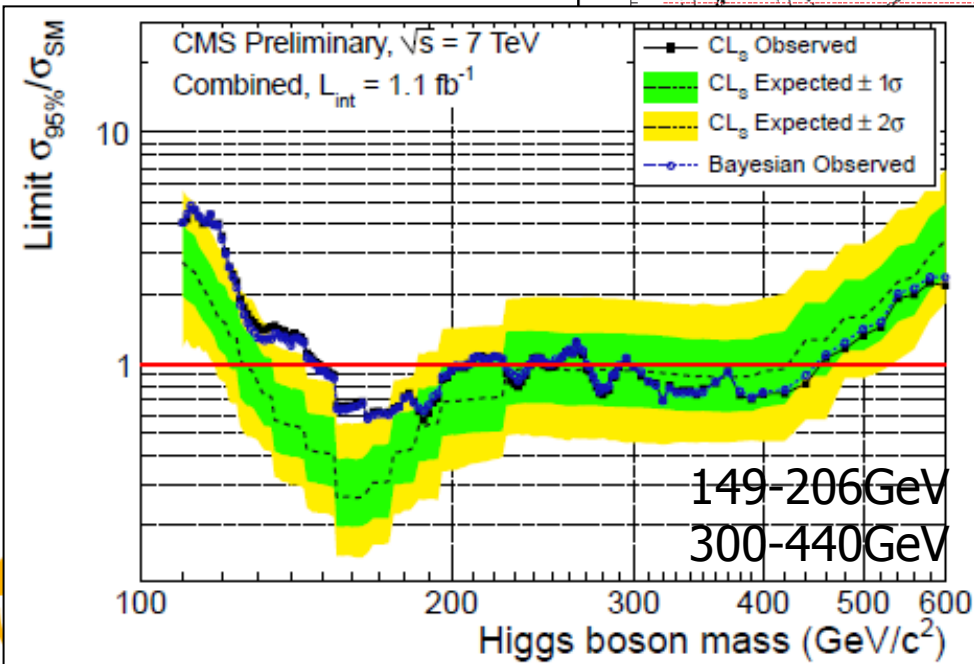
Limits full mass range

Additional High-mass channels extend the  $H \rightarrow ZZ \rightarrow 4l\nu\nu$  exclusion

Noticeable excess around 250 GeV from  $H \rightarrow ZZ \rightarrow 4l$  candidates



EPSで見たCMSの結果

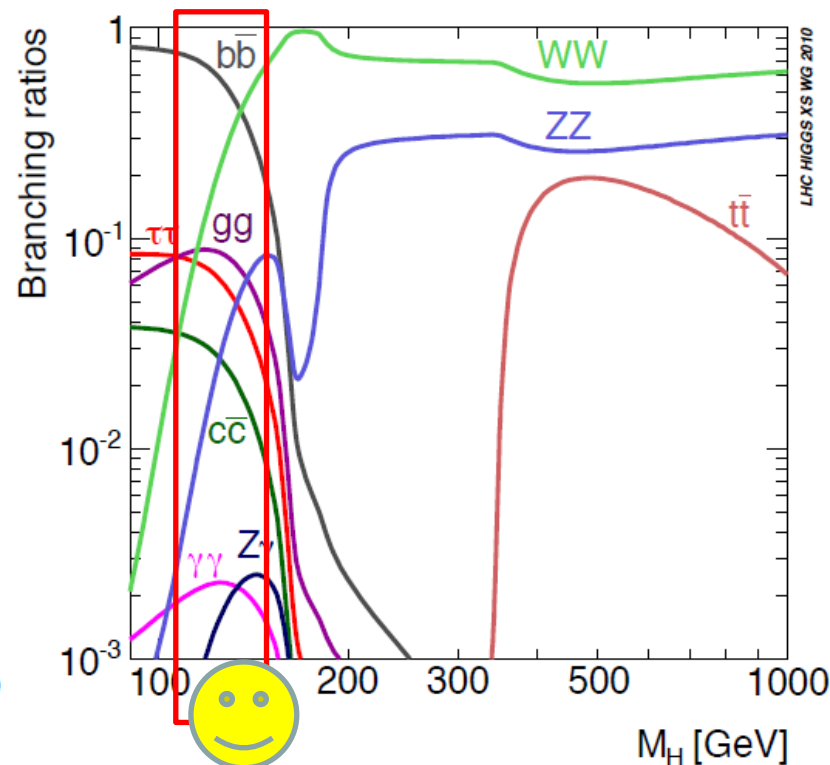
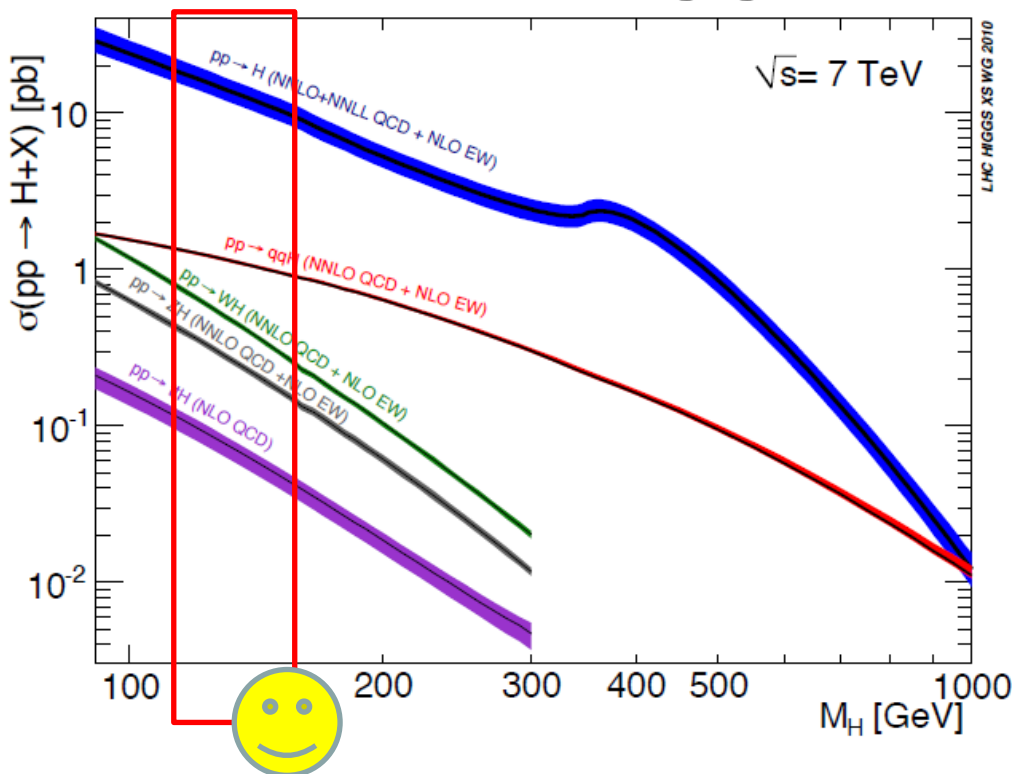


H->WW->lnlnの解析結果において  
両実験において150GeV以下に  
何らかのexcessを見た。

- 統計のふらつき(偶然)?
- お互いが共通の何かを見逃している?
- 本物?



# SM Higgs 生成断面積とBR



- SM Higgsに残された領域@EPS
  - 150GeV以下、450GeV以上
  - 200-300GeV
    - ATLASにのみ240-260GeVにExcess。CMSはほぼすべてexcludeしたが、3つのスパイクがある。
- 150GeV以下に大きな注目 -> ここに存在すれば、SM HiggsのYukawaも測定可能。  
SUSY -> “<135GeV”を切望





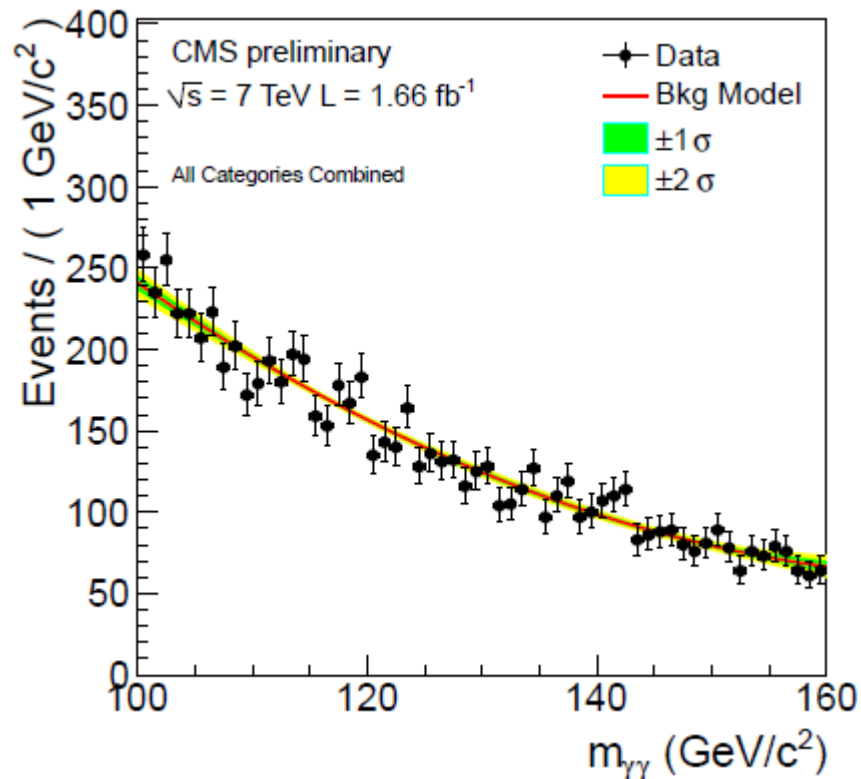
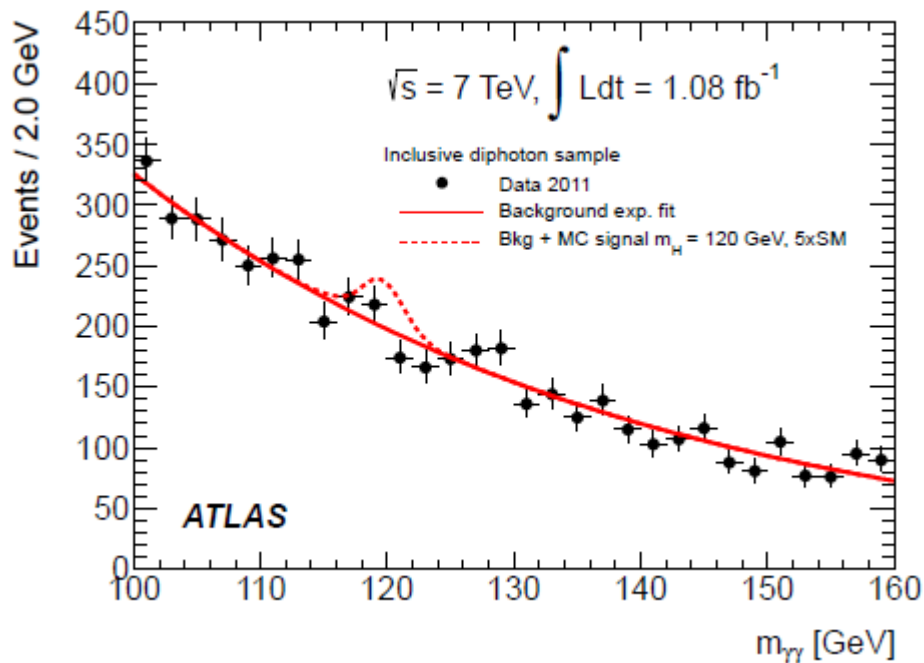
# H- $\rightarrow\gamma\gamma$

New Resonanceを見つけるには最もよいチャンネル  $\rightarrow$  res  $\sim$  a few GeV for  $m_{\gamma\gamma} \sim 120$  GeV

[Selection]

Two isolated photons  $p_T > 40$  GeV, 25 GeV(ATLAS), 40 GeV, 30 GeV(CMS)

$\rightarrow$  Reconstruct  $m_{\gamma\gamma}$

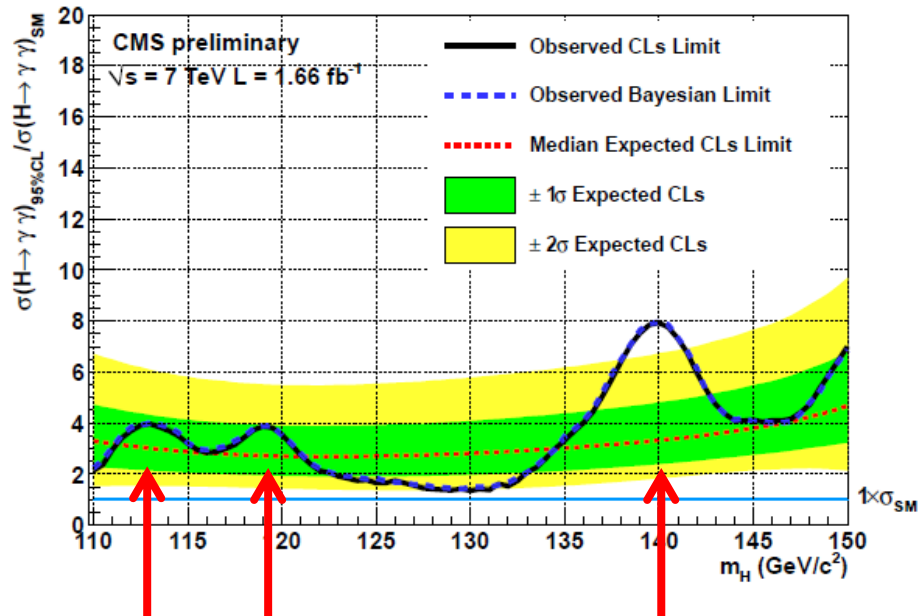
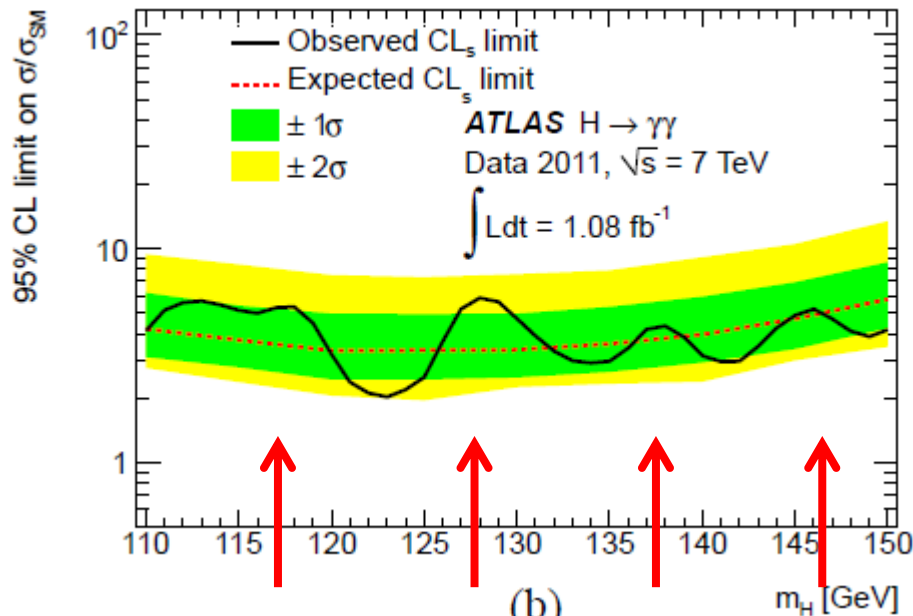




# Limit with $H \rightarrow \gamma\gamma$

ATLAS(1.08 fb<sup>-1</sup>)

CMS(1.66 fb<sup>-1</sup>)



- ~1.5-4xSM程度を棄却した。
- 上に振れている領域
  - ATLAS : <120GeV, 128GeV, 138GeV, 147GeV
  - CMS : 113GeV, 119GeV, 140GeV
- まだ統計のふらつきをみている。
  - Look elsewhere effect





# H → WW → lνlν

[Selection] ( $m_H < 220 \text{ GeV}$ )

(1) Two isolated leptons (electron or muon)

$p_T > 25 \text{ GeV}$ ,  $p_T > 15 \text{ GeV}$

(2) MET > 30 GeV

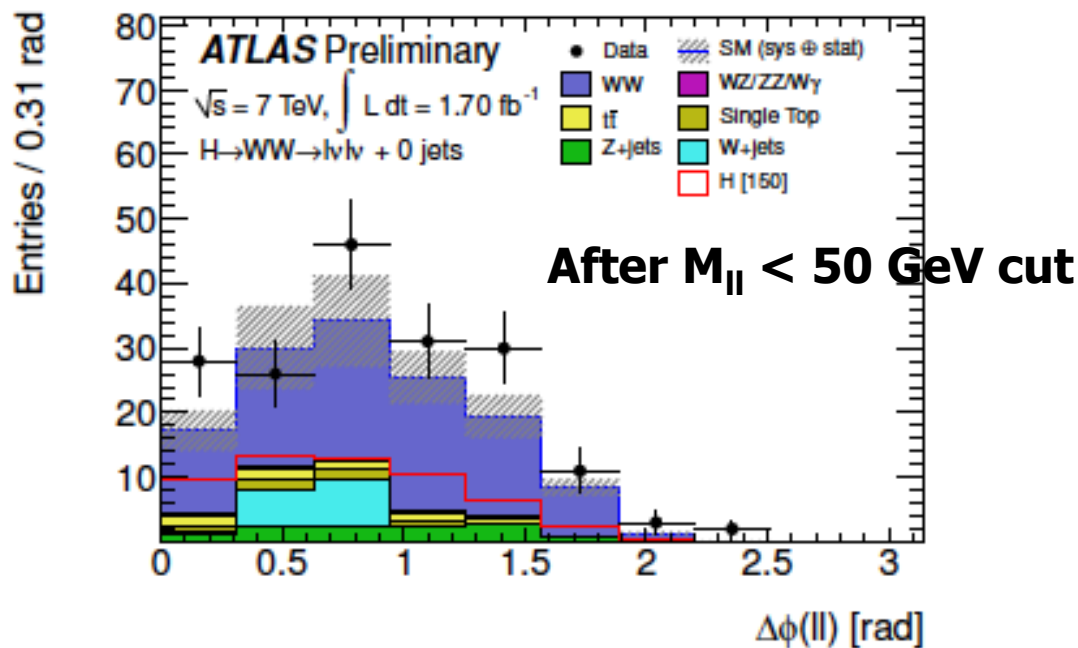
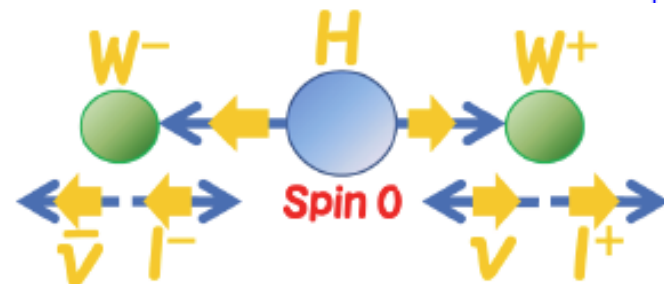
(3)  $M_{ll} < 50$  ( $m_H < 170$ ) or 65 GeV ( $m_H \geq 170$ )

(4) Angle  $\phi_{ll} < 1.3$  or 1.8

etc

-> Reconstruct  $m_T$

$$M_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}})^2}$$





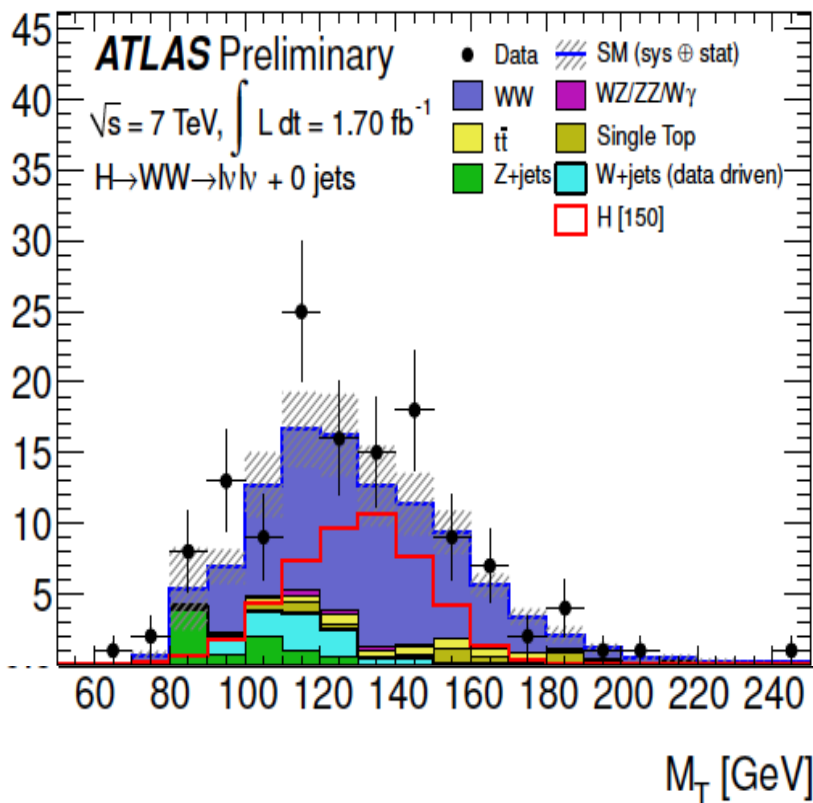


# H -> WW -> lνlν

0 jet

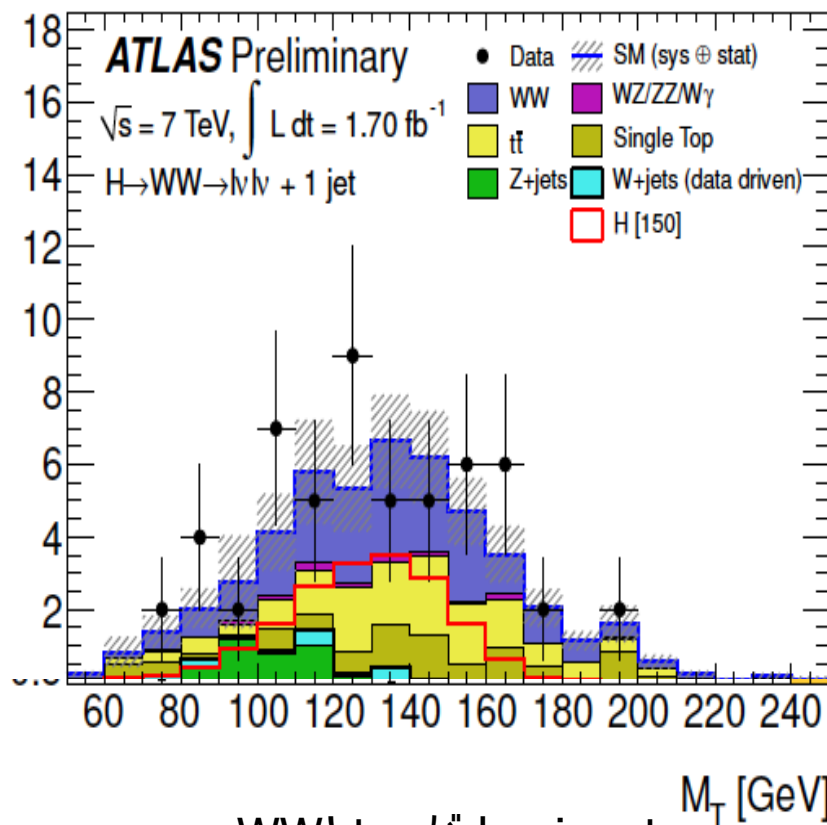
1 jet

Entries / 10 GeV



WWがdominant

Entries / 10 GeV



WWとtopがdominant

150GeV Higgsの存在は明らかにサポートしない

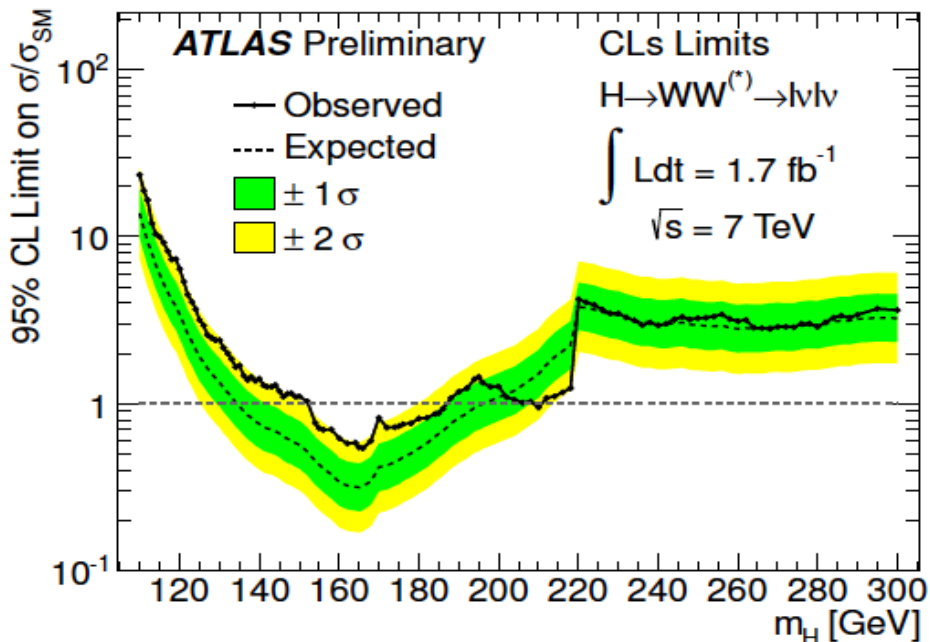
$M_T$ 分布はbroad -> 明確なシグナルの存在の印象を与える -> 数で勝負。





# Limit with $H \rightarrow WW \rightarrow l\nu l\nu$

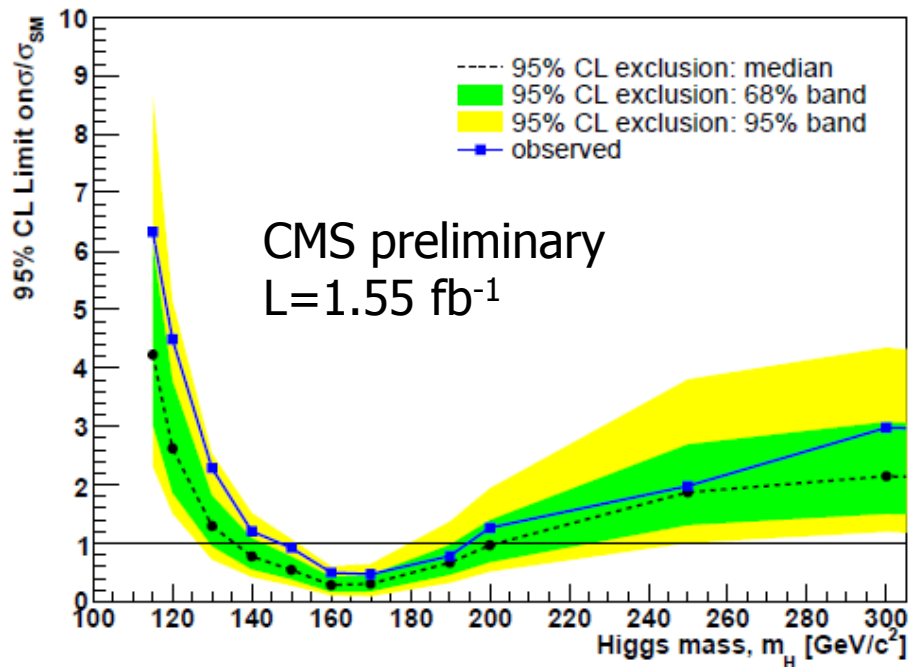
ATLAS



Observed  $154 < m_H < 186 \text{ GeV}$   
 Expected  $135 < m_H < 196 \text{ GeV}$

CMS

$H \rightarrow WW \rightarrow 2l2\nu + 0/1/2 \text{ jets (CLs)}$



Observed  $147 < m_H < 194 \text{ GeV}$   
 Expected  $136 < m_H < 200 \text{ GeV}$

依然として軽い側にマイルドな Excess





# H->ZZ->4l

[Selection] (ATLAS)

(1) Four isolated leptons (electron or muon)

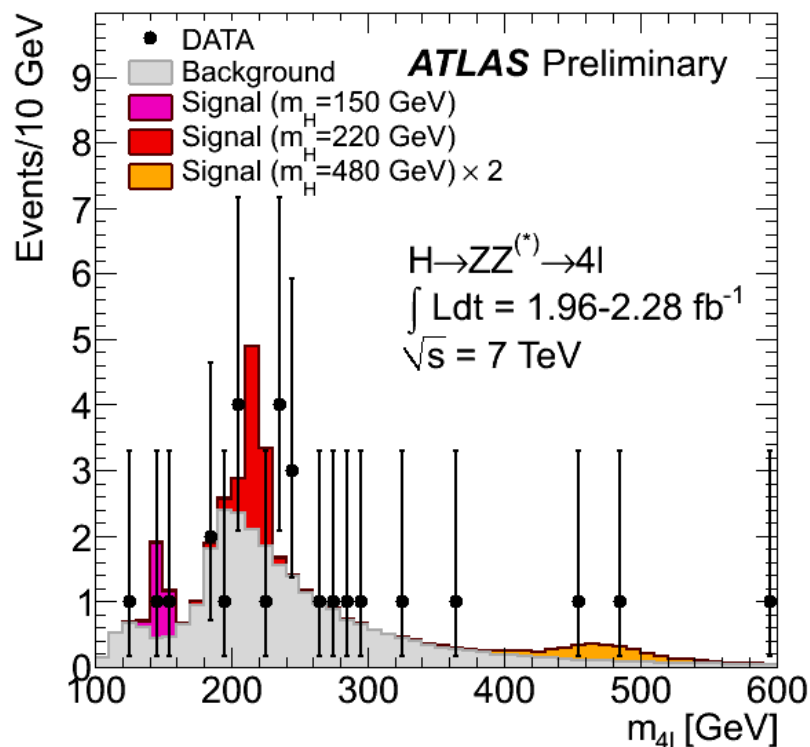
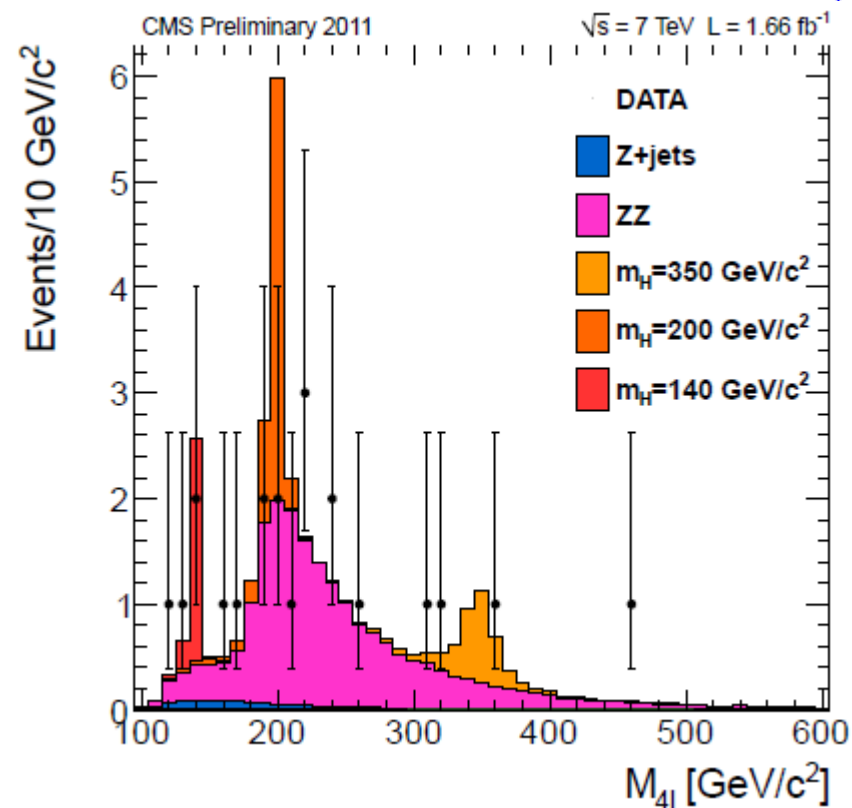
pT > 20, 20 GeV (for trigger)

pT > 15 GeV (elec) or 7 GeV (muon)

(2)  $M_{ll} \sim Z$  mass ( $\pm 12 \sim 15$  GeV)

etc

-> Reconstruct  $m_{llll}$



棄却

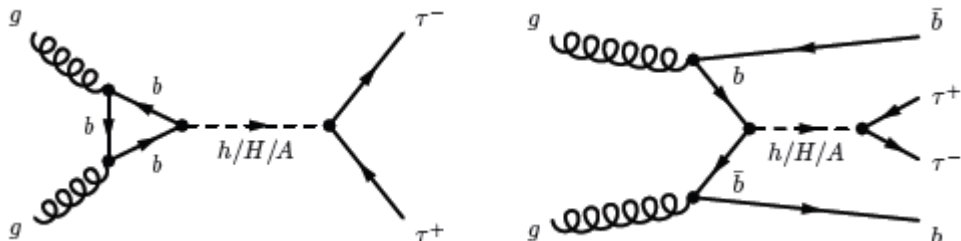
ATLAS  $192 < m_H < 196, 214 < m_H < 222 \text{ GeV}$

CMS ほぼ "185-300 GeV" (1を前後)





# (MS)SM $H \rightarrow \tau\tau \rightarrow ll\nu\nu\dots, lh_\tau\nu\nu\dots$



Higgs sector in MSSM

-> 5 Higgs particles;

3 h/H/A and 2 charged Higgs

Higgs coupling to b,  $\tau$  (down type fermions) is enhanced in larger  $\tan\beta$ .

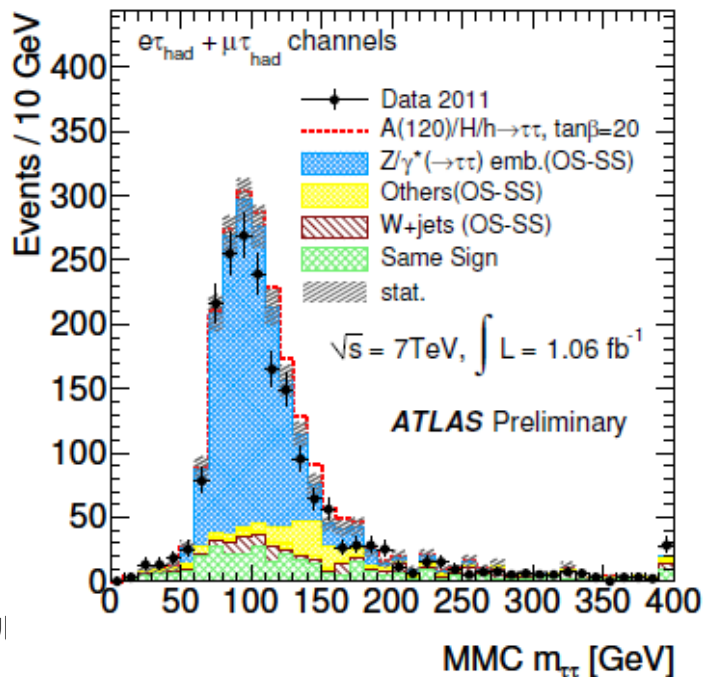
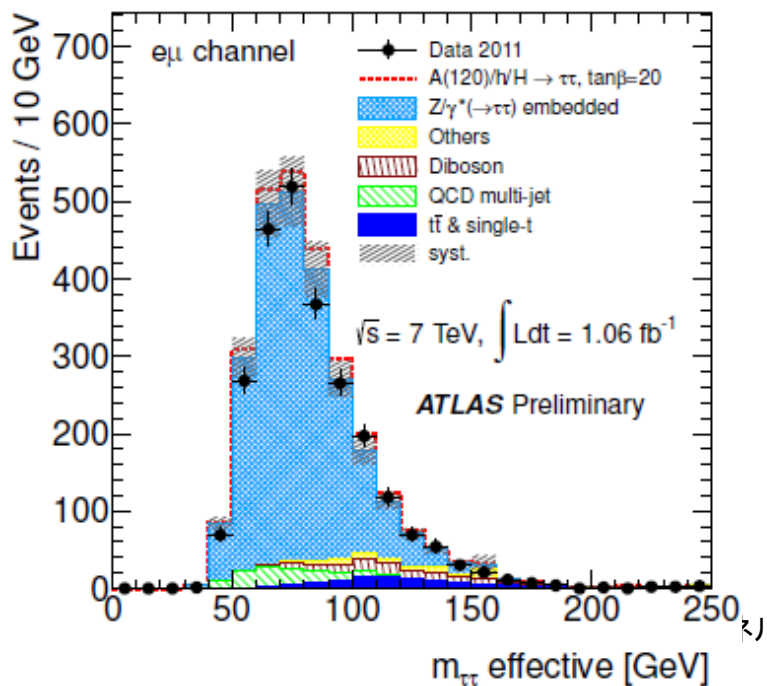
[Selection for  $lh$  channel]

(1) One isolated lepton  $p_T > 22(e)/20(\mu)\text{GeV}$

(2) One hadronic tau  $p_T > 20\text{GeV}$

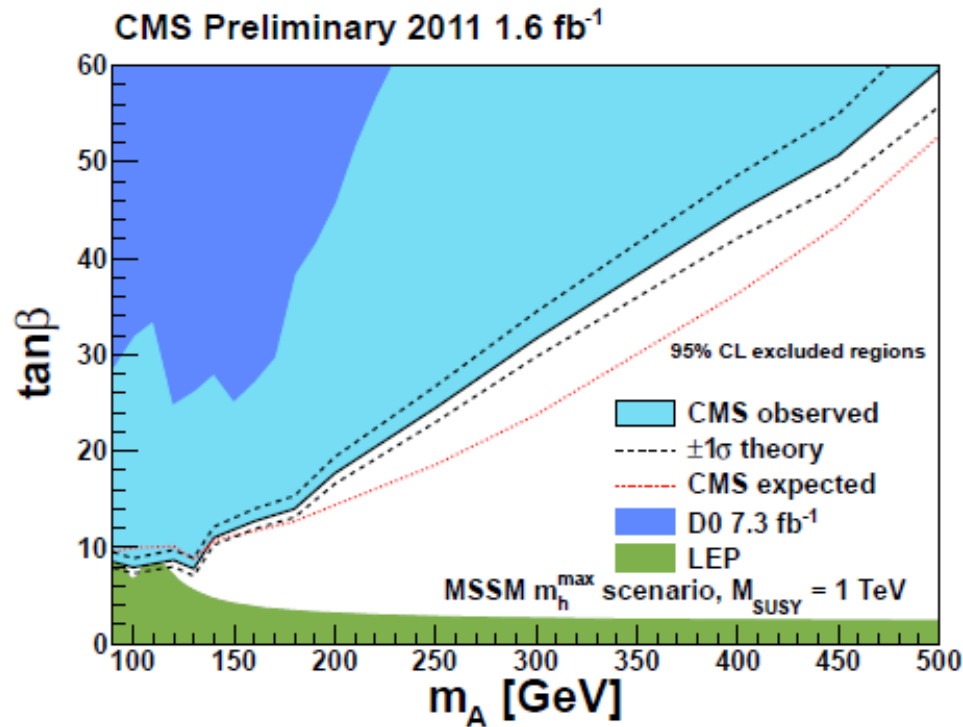
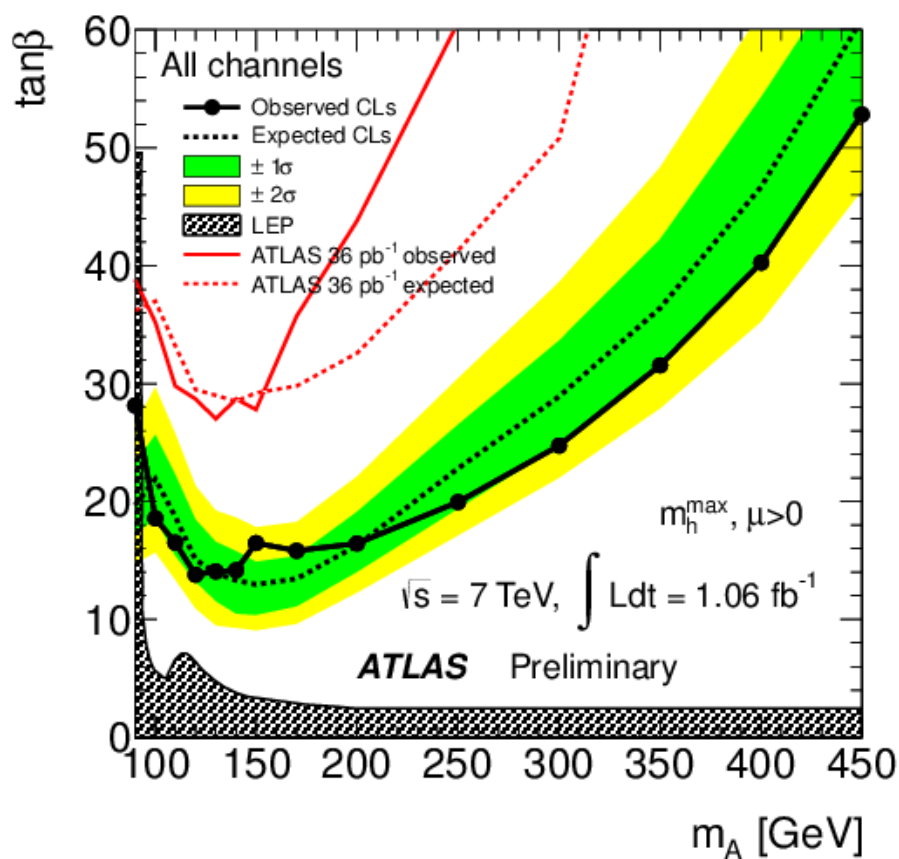
(3) MET > 20GeV

etc





# MSSM limit with $\tau\tau$

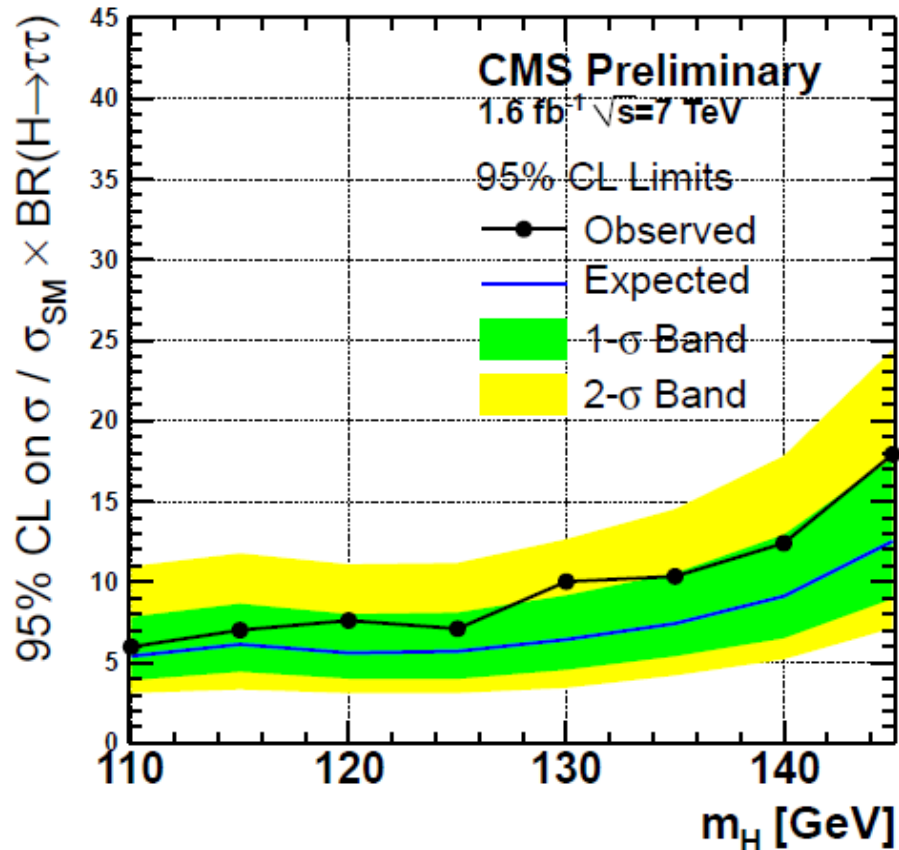
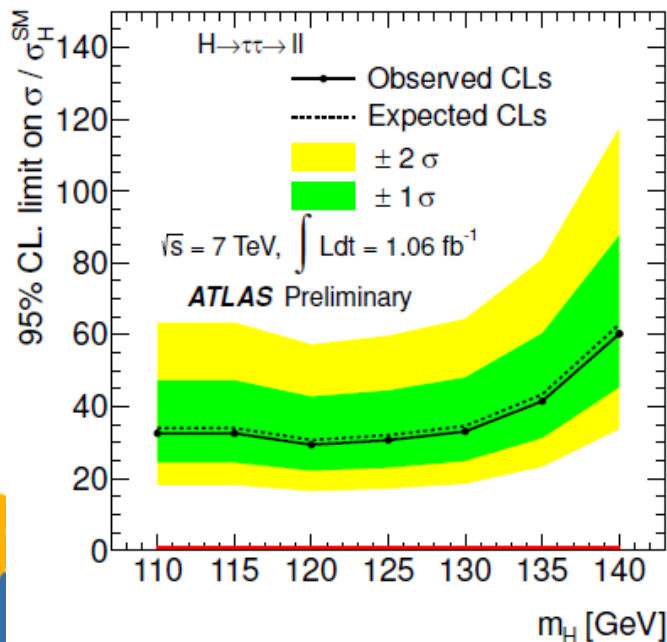
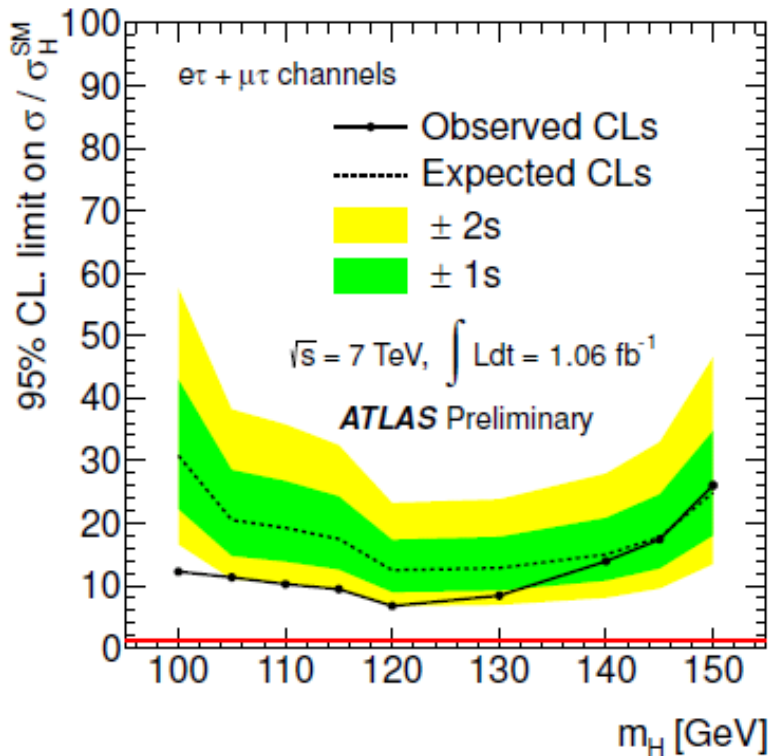


Tevatronの結果は昨年データを超えた。  
 $M_A$ の小さい部分はLEP Limitと重なり始めた。





# SM limit with $\tau\tau$



$m_h = 120 \text{ GeV}$   
 $\sim 7$ 倍 @ ATLAS (expected  $\sim 12$ 倍)  
 $\sim 7$ 倍 @ CMS (expected  $\sim 6$ 倍)

**軽い領域で活躍開始！**





# Combination

Channel	ATLAS	CMS
$\gamma\gamma$	Inclusive, with 5 category	Inclusive, with 8 category
$\tau\tau \rightarrow ll$	$\geq 1$ jet (ee, $\mu\mu$ , e $\mu$ )	VBF + non VBF ( $\mu\mu$ , e $\mu$ )
$\tau\tau \rightarrow lh$	Inclusive	VBF + non VBF
bb	WH/ZH inclusive	Boosted WH/ZH
WW $\rightarrow l\nu l\nu$	0, 1 jet	0, 1 jet and VBF(2 jets)
ZZ $\rightarrow ll ll$	Inclusive	Inclusive
ZZ $\rightarrow ll \tau\tau$	-	Inclusive
ZZ $\rightarrow ll qq$	Btag or not	Inclusive
ZZ $\rightarrow ll \nu\nu$	Jet veto	Bjet veto

$l = e$  or  $\mu$





# CLs

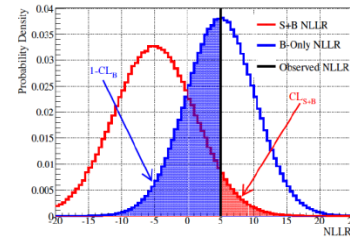
統計処理 based on frequent approach (Bayesian approachはチェック用)  
 - 統計誤差まで記述したLikelihoodをProfilingして最大値を求める。。。云々

[test statistic]

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}, \quad \text{with a constraint } 0 \leq \hat{\mu} \leq \mu$$

$\mu$  ... SM predictionの何倍か? というファクター  
 $q_\mu$ はHypothesisからズれていると大きくなる。

昔はよかった...



$$p_\mu = P \left( q_\mu \geq q_\mu^{obs} \mid \mu_S(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs}) \right)$$

$$p_0 = P \left( q_\mu \geq q_\mu^{obs} \mid b(\hat{\theta}_0^{obs}) \right),$$

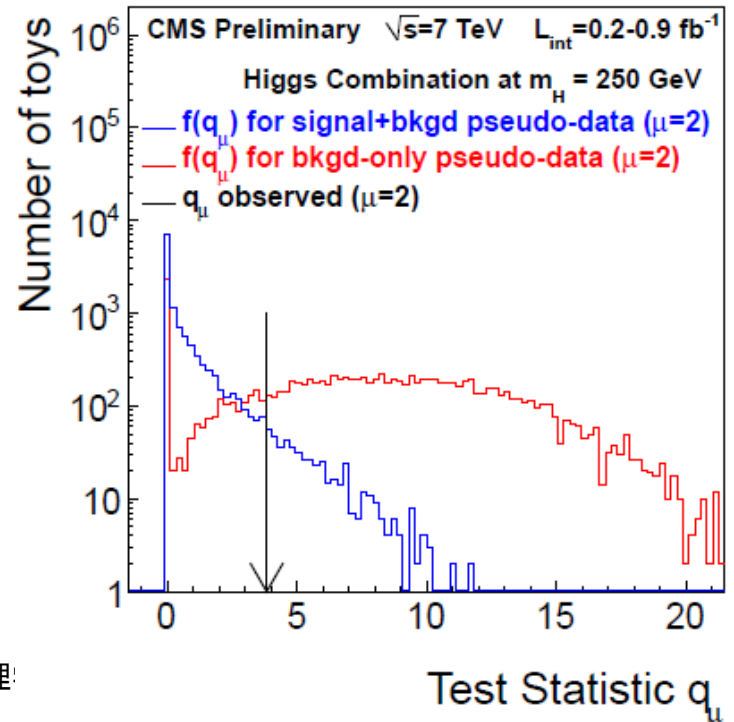
調べたい $\mu$ に対して、

$p_\mu$  ...  $\mu$ で決めた分布に対する相度合

$p_0$ ... 0で決めた(BG-only)分布に対する相度合

$$CL_s(\mu) = \frac{p_\mu}{p_0}$$

これが0.05を下回ったら棄却







# p-value or $p_0$

- p-value, local p-value,  $p_0$  (たくさん言い方あります)

$$p_0 = P \left( q_0 \geq q_0^{obs} \mid b(\hat{\theta}_0^{obs}) \right)$$

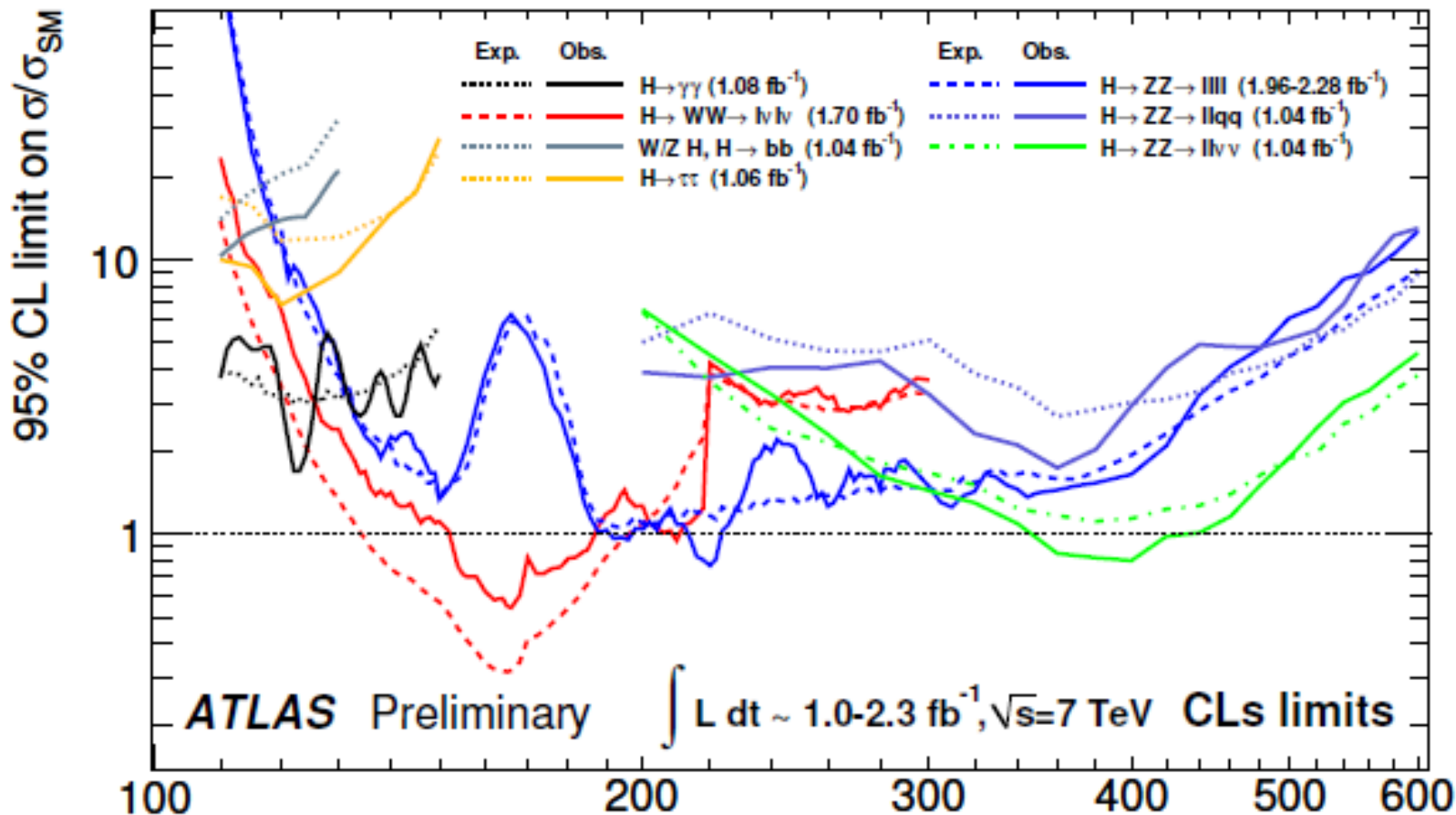
前ページとの違いは、テストする $\mu$ が0になった。

BG-onlyで決めた分布を、BG-onlyと考えて評価したときの相度合。  
小さいと相度合が悪い。BG-onlyつまりSMから離れている。





# Summary of ATLAS Limit



軽い領域

$H \rightarrow \gamma\gamma$

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

$H \rightarrow ZZ \rightarrow ll ll$

重い領域

$m_H$  [GeV]

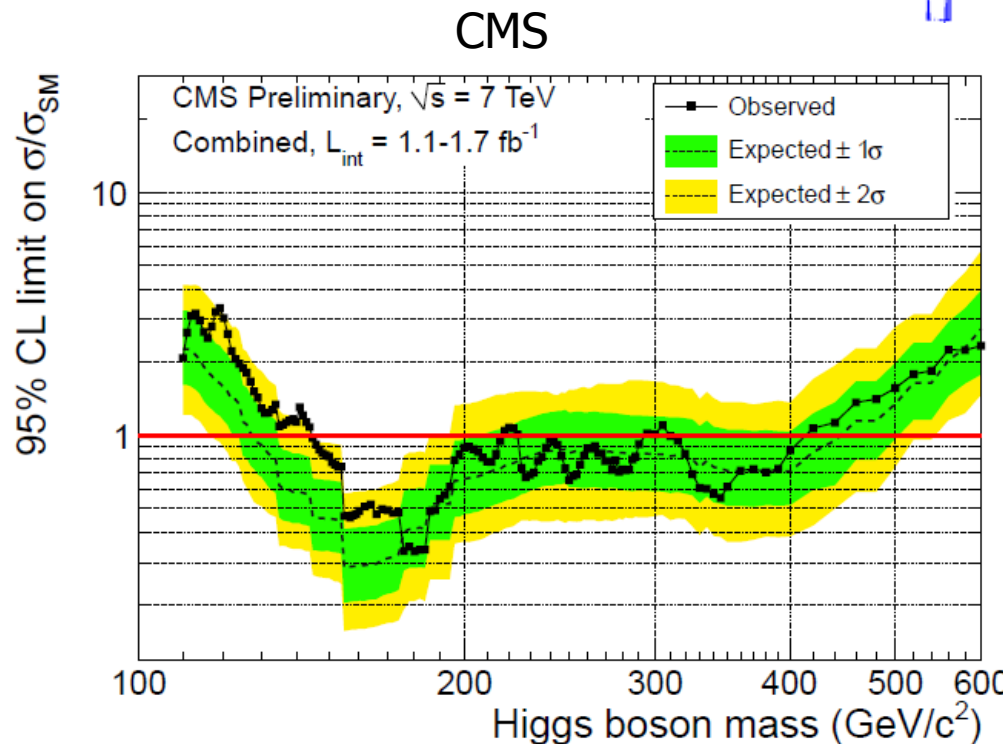
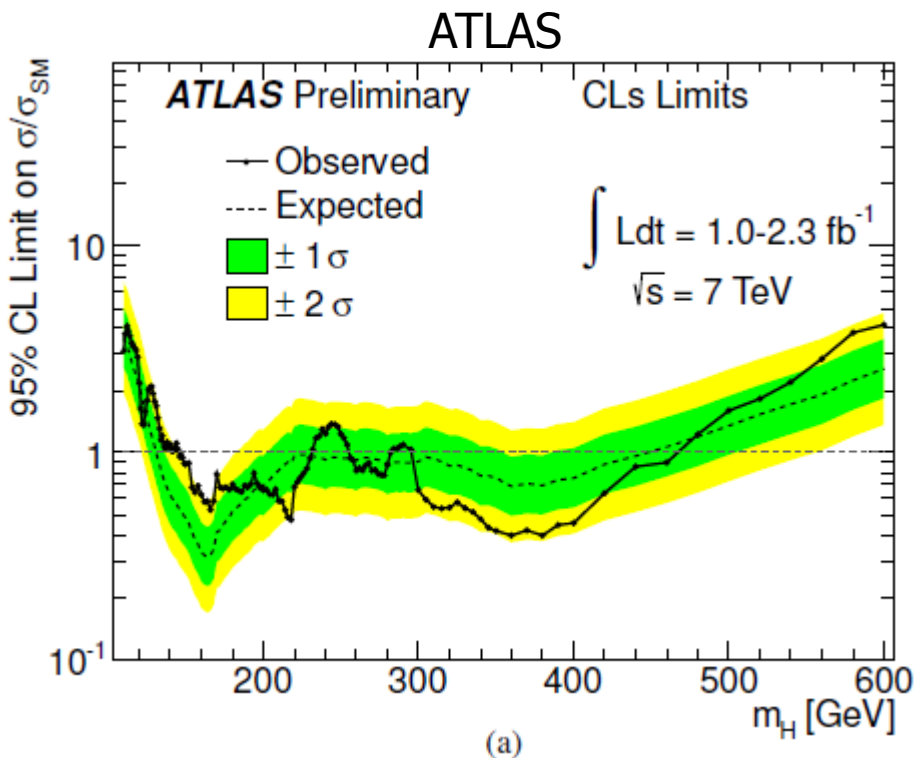
$H \rightarrow ZZ \rightarrow ll \nu\nu$

$H \rightarrow ZZ \rightarrow ll ll$





# Combination Limit

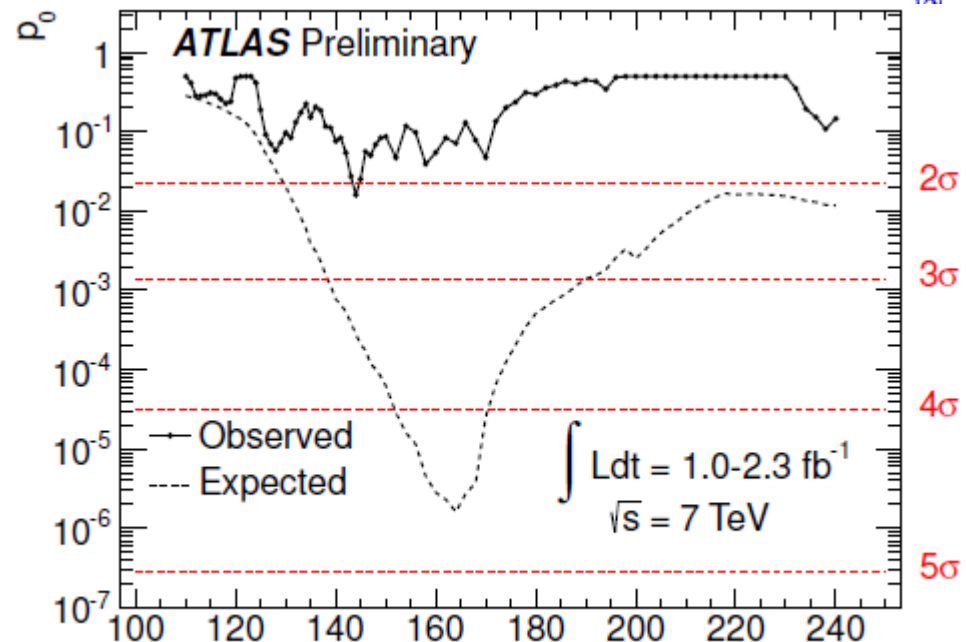
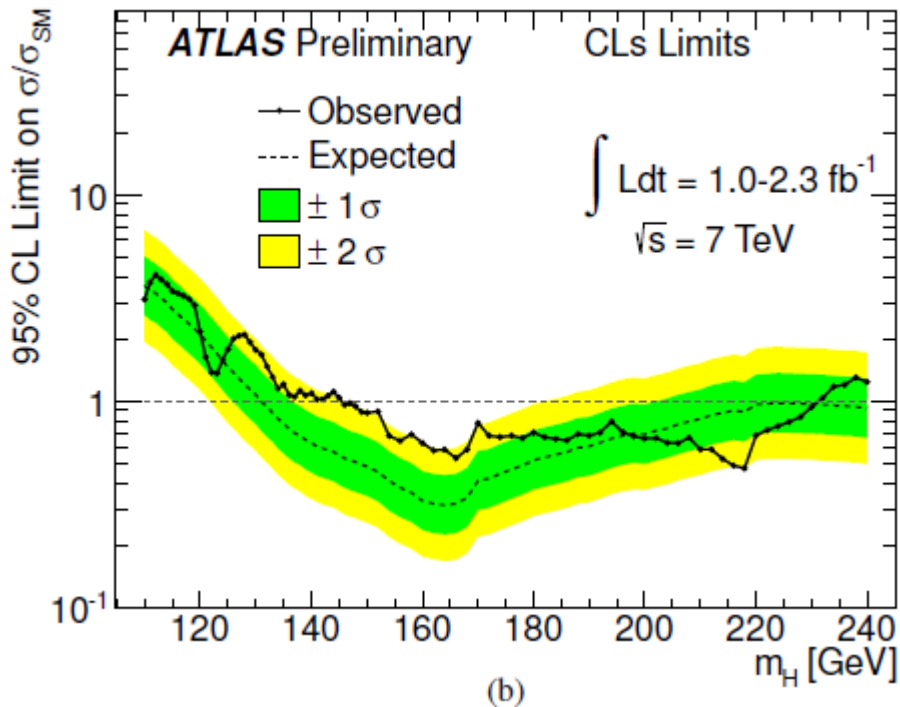


	ATLAS	CMS
Expected	131-447	130-440
Observed	146-232, 256-282, 296-446	145-216, 226-288, 310-400

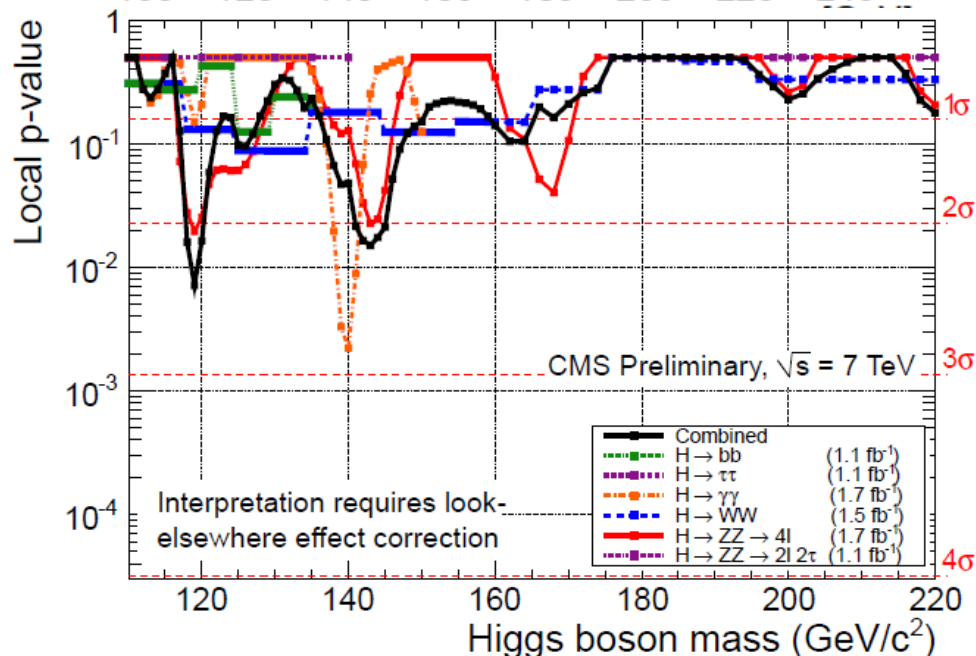
**残された領域 :  $<145\text{GeV}, 288-296\text{GeV}, >446\text{GeV}$**



# Combination Limit



- 140GeV付近のExcessはマイルドになった。
- 軽いヒッグスは<145GeVに絞られた。

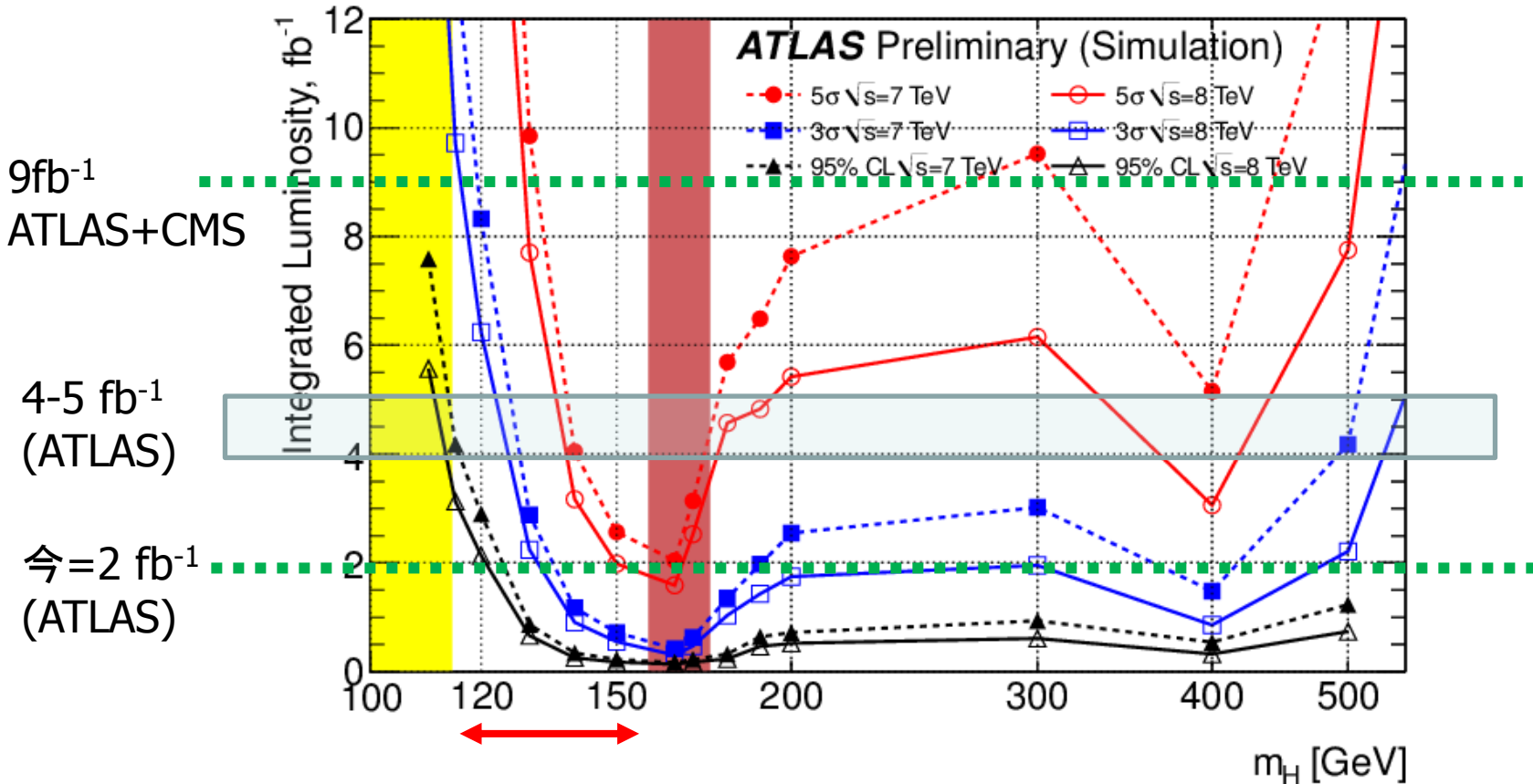




# Prospects in 2011

SM Higgs

→ 次のMoriondで期待される結果



If SM Higgs does not exist, ATLAS+CMS will exclude all the mass region in this year. But we hope that we'll get an indication of Higgs existence in this year.

→ 3 $\sigma$  for m<sub>H</sub> > 130GeV with ATLAS and 120GeV with ATLAS+CMS combination





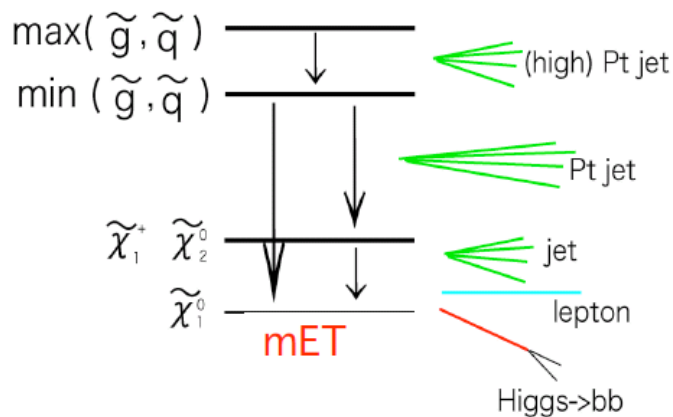
# SUSY





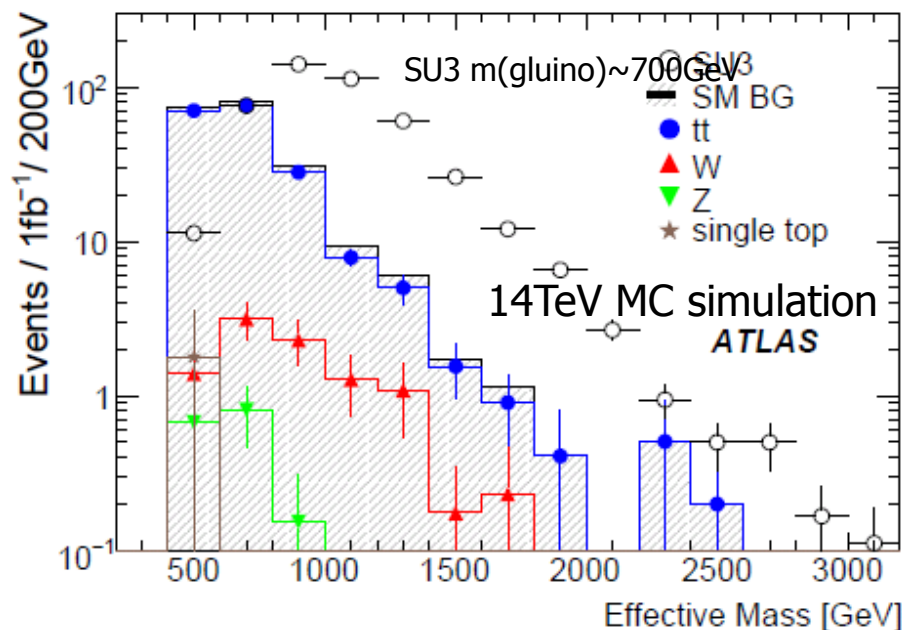
# SUSY at LHC

- エネルギーが十分高ければ、LHCではColored sparticles productionが主。
  - A few cascade decay
  - Large Missing ET(MET) due to  $\chi^0_1$



- Search for “Large Missing ET + jets + X”
  - 0 lepton + jets + MET
  - 1 lepton + jets + MET
  - 2 lepton(OS/SS) + jets + MET
 etc

### Effective mass $\Sigma pT + MET$



1lep  $pT > 20 GeV$   
 1jet  $pT > 100 GeV + 3jets pT > 50 GeV$   
 MET  $> \max(100 GeV, 0.2 Meff)$   
 Transverse Mass  $> 100 GeV$   
 Sphericity  $> 0.2$



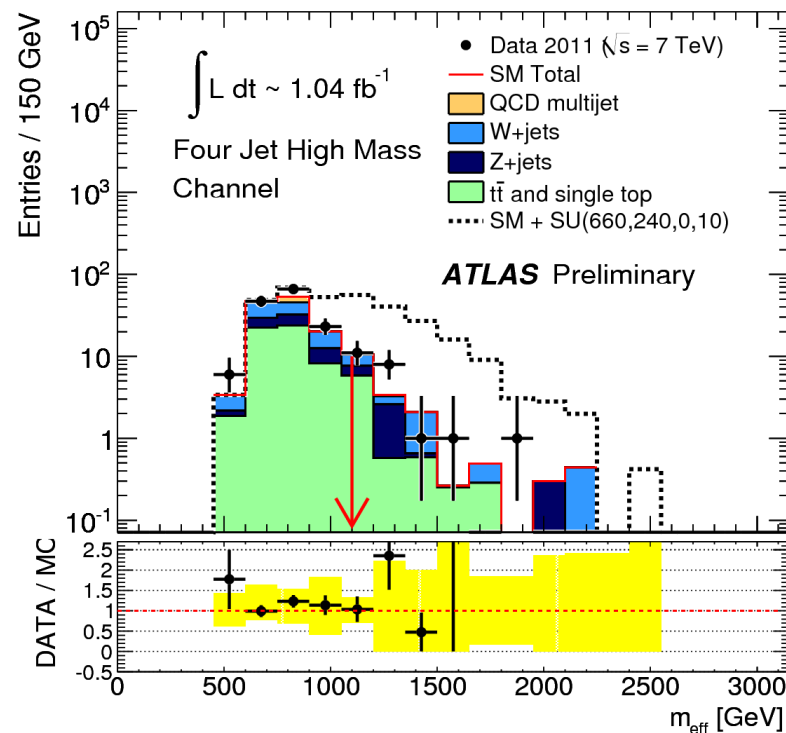
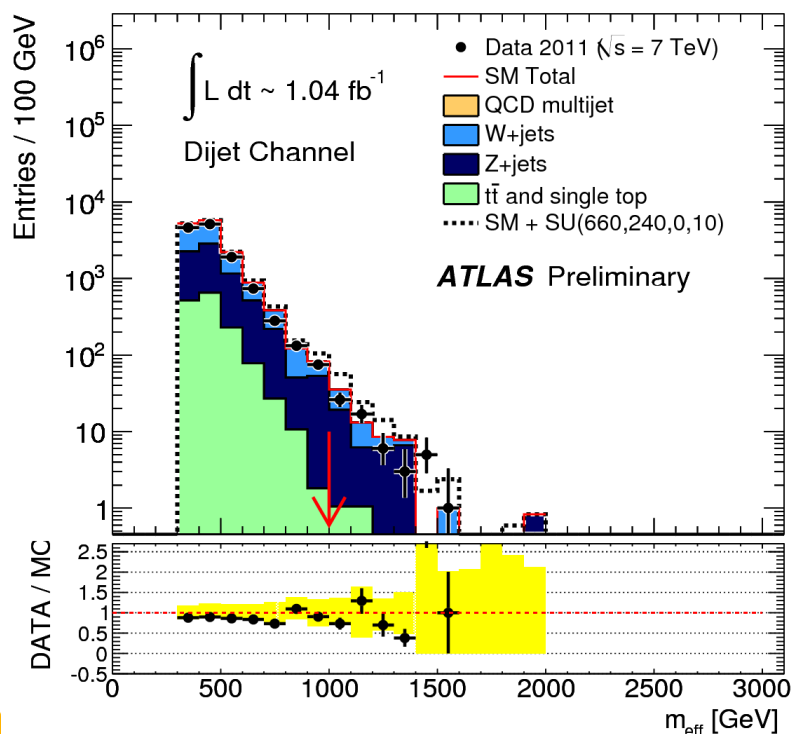


# Jets+MET

発見するならこれ!

[One of selections] (ATLAS)

- (1)  $\geq 2/3/4$  jets,  $p_T > 130, 40$  or  $80$  GeV
- (2)  $MET > 130$  GeV
- (3)  $MET > (0.2, 0.25$  or  $0.3)m_{\text{eff}}$
- (4)  $\Delta\phi_{\text{min}}(\text{jet}, MET) > 0.4$
- (5)  $m_{\text{eff}} > 500$  GeV,  $1$  TeV or  $1.1$  TeV







# Jets+MET(続き)

ATLAS

Process	Signal Region				
	$\geq 2\text{-jet}$	$\geq 3\text{-jet}$	$\geq 4\text{-jet},$ $m_{\text{eff}} > 500 \text{ GeV}$	$\geq 4\text{-jet},$ $m_{\text{eff}} > 1000 \text{ GeV}$	High mass
$Z/\gamma\text{+jets}$	$32.5 \pm 2.6 \pm 6.8$	$25.8 \pm 2.6 \pm 4.9$	$208 \pm 9 \pm 37$	$16.2 \pm 2.1 \pm 3.6$	$3.3 \pm 1.0 \pm 1.3$
$W\text{+jets}$	$26.2 \pm 3.9 \pm 6.7$	$22.7 \pm 3.5 \pm 5.8$	$367 \pm 30 \pm 126$	$12.7 \pm 2.1 \pm 4.7$	$2.2 \pm 0.9 \pm 1.2$
$t\bar{t}\text{+ Single Top}$	$3.4 \pm 1.5 \pm 1.6$	$5.6 \pm 2.0 \pm 2.2$	$375 \pm 37 \pm 74$	$3.7 \pm 1.2 \pm 2.0$	$5.6 \pm 1.7 \pm 2.1$
QCD jets	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.74 \pm 0.14 \pm 0.51$	$2.10 \pm 0.37 \pm 0.83$
Total	$62.3 \pm 4.3 \pm 9.2$	$55 \pm 3.8 \pm 7.3$	$984 \pm 39 \pm 145$	$33.4 \pm 2.9 \pm 6.3$	$13.2 \pm 1.9 \pm 2.6$
Data	58	59	1118	40	18

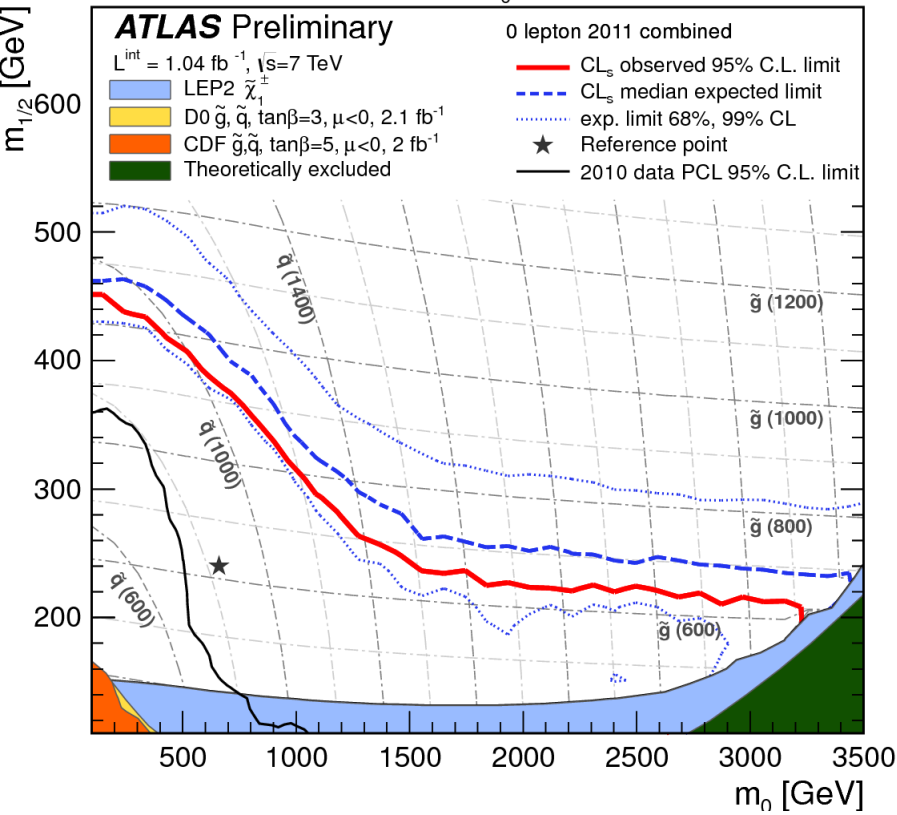
誤差の範囲でSM predictionとconsistent



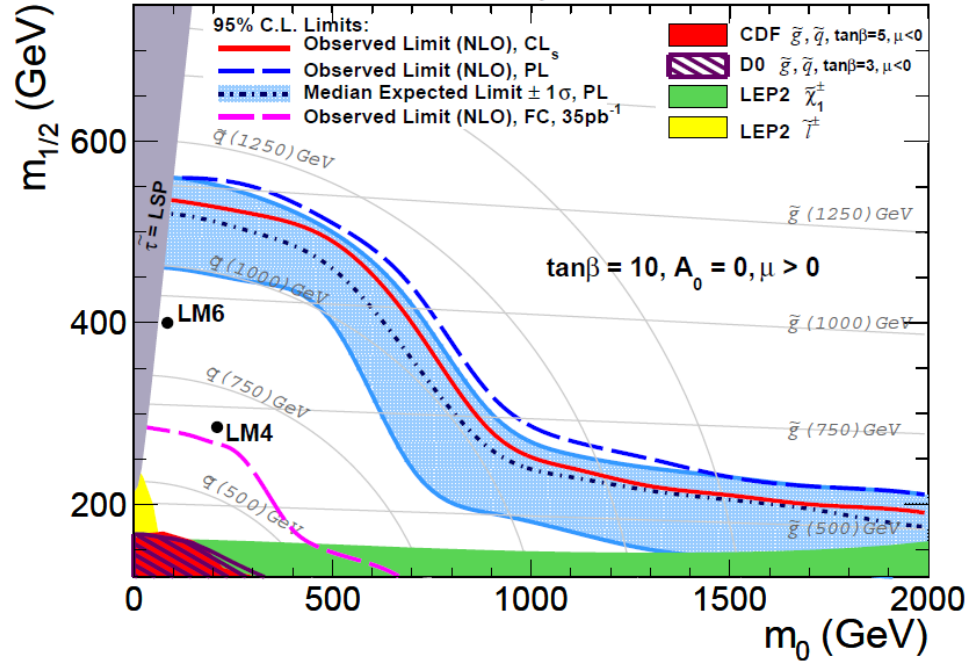
# Jets+MET(続き)



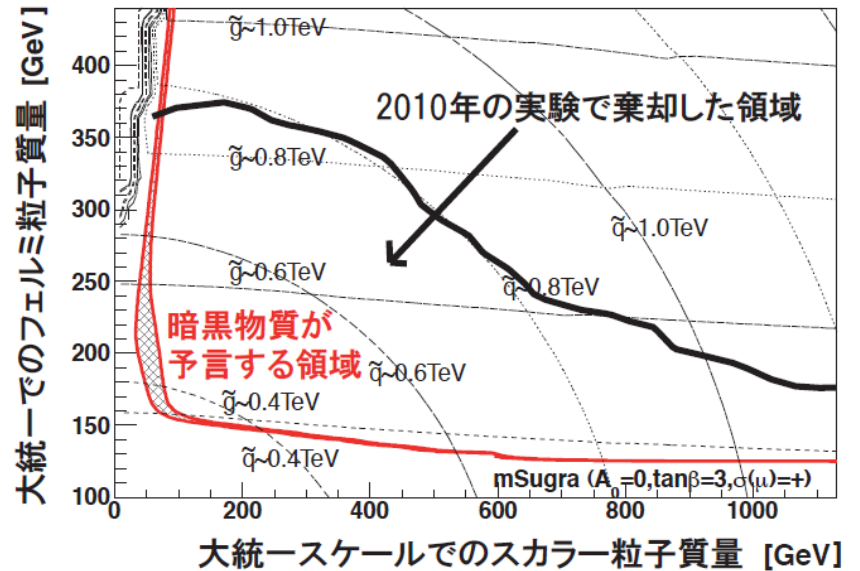
MSUGRA/CMSSM:  $\tan\beta = 10, A_0 = 0, \mu > 0$



CMS preliminary  $\alpha_T \int L dt = 1.1 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV}$



昨年から分かっていたことですが、  
WMAPを信じるならmSUGRAはほぼダメ



2011年9月10日

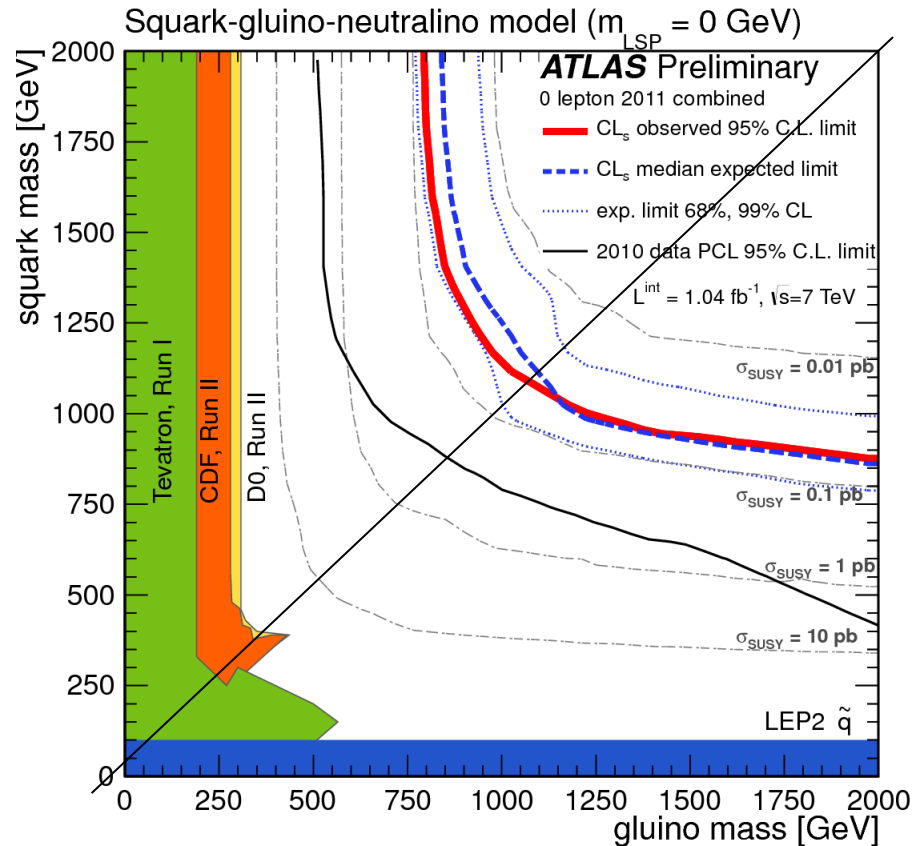
コライダー加速器による高エネルギー

大統一スケールでのスカラー粒子質量 [GeV]



# Jets+MET(続き)

“Simplified” modelで解釈した場合(主要なDecayだけ残して単純化)



Glucionとsquarkが同じ質量なら、~1TeVまで棄却

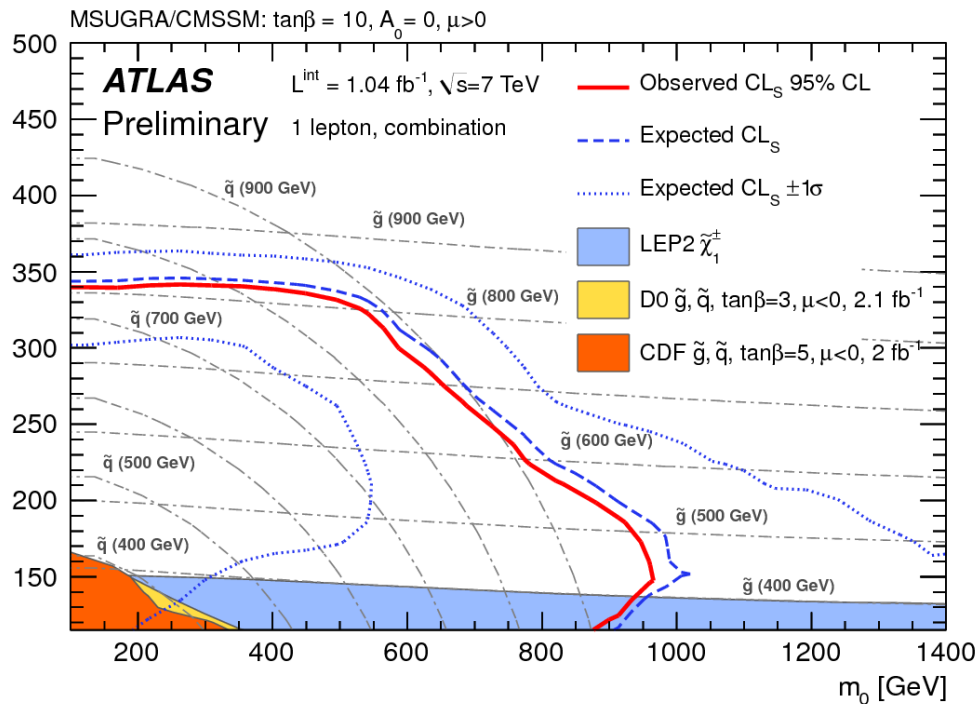
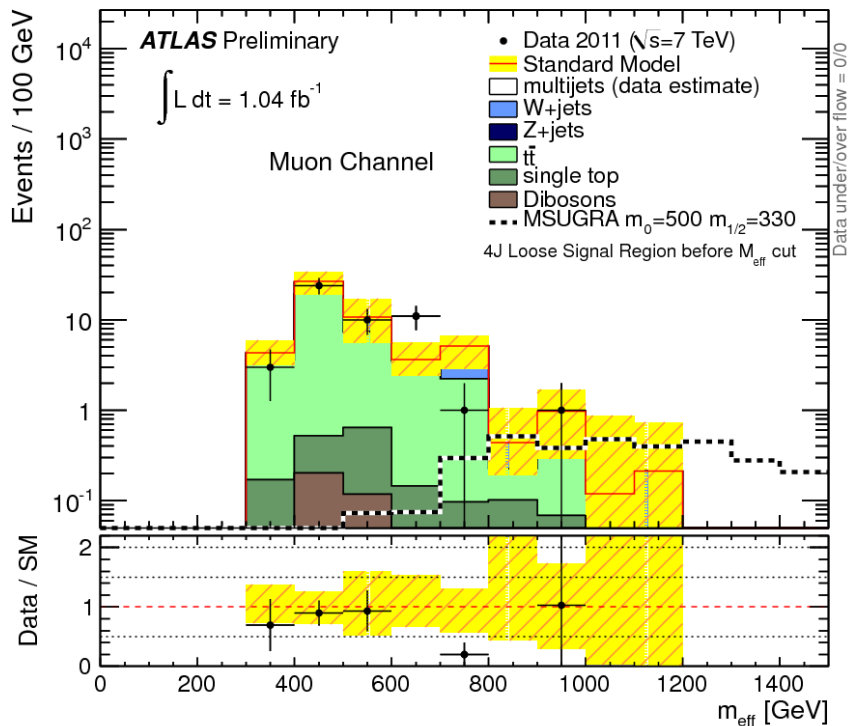




# 1-lepton+Jets+MET

[Selection] (4 jet loose=4JL at ATLAS)

- (1) One lepton (elec/muon)  $p_T > 25/20 \text{ GeV}$
- (2)  $\geq 4$  jets  $p_T > 60, 25, 25, 25 \text{ GeV}$
- (3)  $\text{MET} > 140 \text{ GeV}$
- (4)  $\text{MET} > 0.30 m_{\text{eff}}$
- (5)  $m_T > 100 \text{ GeV}$ , then  $m_{\text{eff}} > 300 \text{ GeV}$

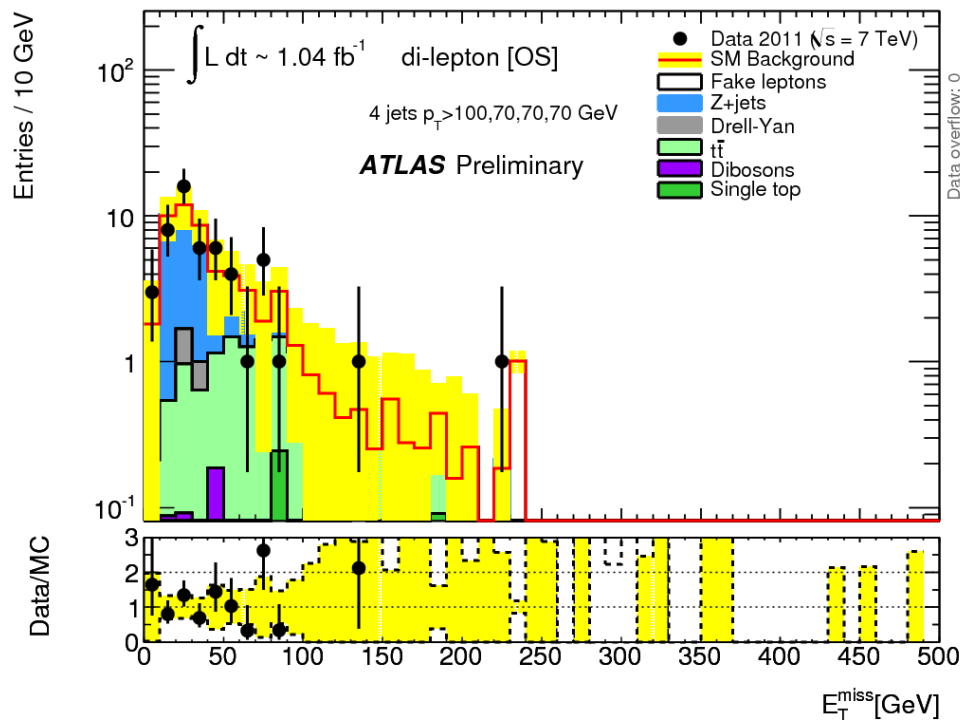


Exclude up to  $m(q,g) \sim 800 \text{ GeV}$  in mSugra





# 2-leptons+Jets+MET

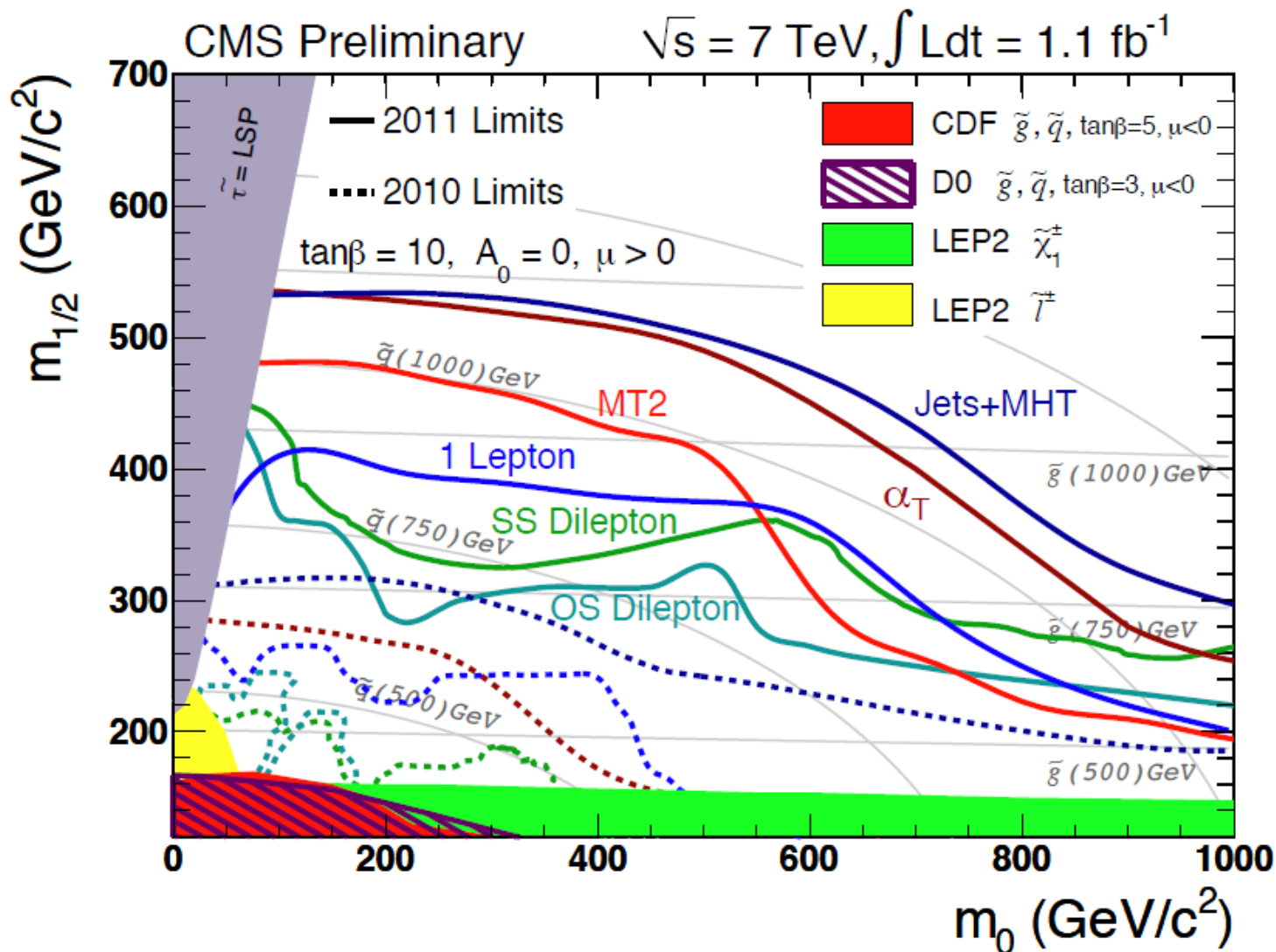


	Background	Obs.	95% C.L.
OS-SR1	$15.5 \pm 1.2 \pm 4.4$	13	9.5 fb
OS-SR2	$13.0 \pm 1.8 \pm 4.1$	17	15.2 fb
OS-SR3	$5.7 \pm 1.1 \pm 3.5$	2	5.0 fb
SS-SR1	$32.6 \pm 4.4 \pm 4.4$	25	10.2 fb
SS-SR2	$24.9 \pm 4.1 \pm 6.6$	28	20.3 fb





# Limit by CMS (0/1/2 lep)





# New Heavy Particles



2011年9月10日

コライダー加速器による高エネルギー物理学の将来展望

39



# Extra Heavy W-like Particle

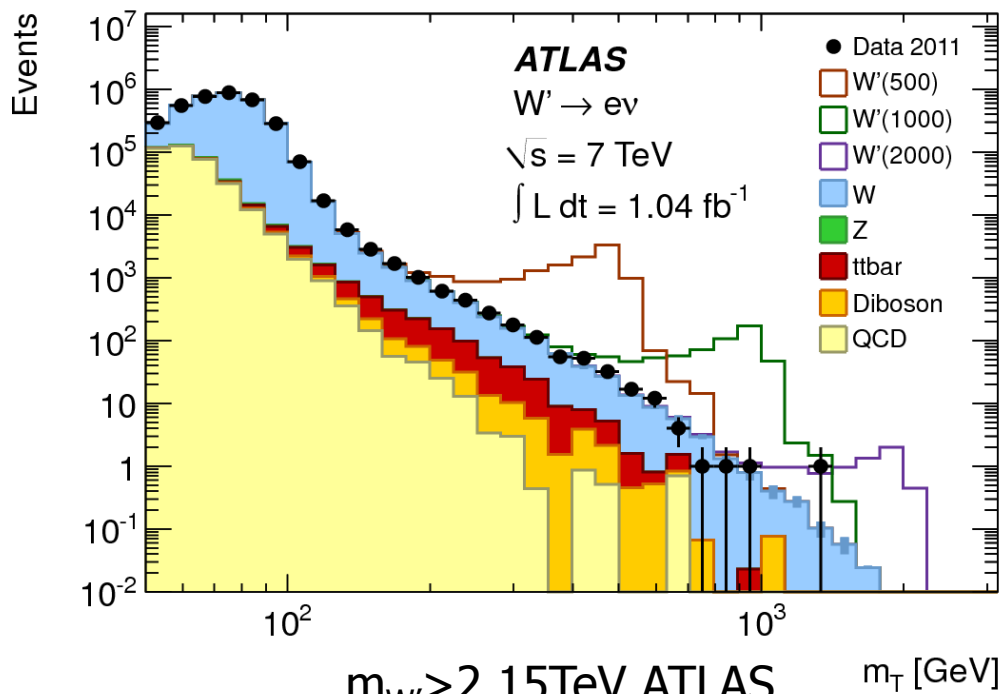
Extend W search, that is, search for excess in  $m_T$  distribution

[Selection] (ATLAS)

(1) One isolated electron or muon;  $p_T > 25 \text{ GeV}$

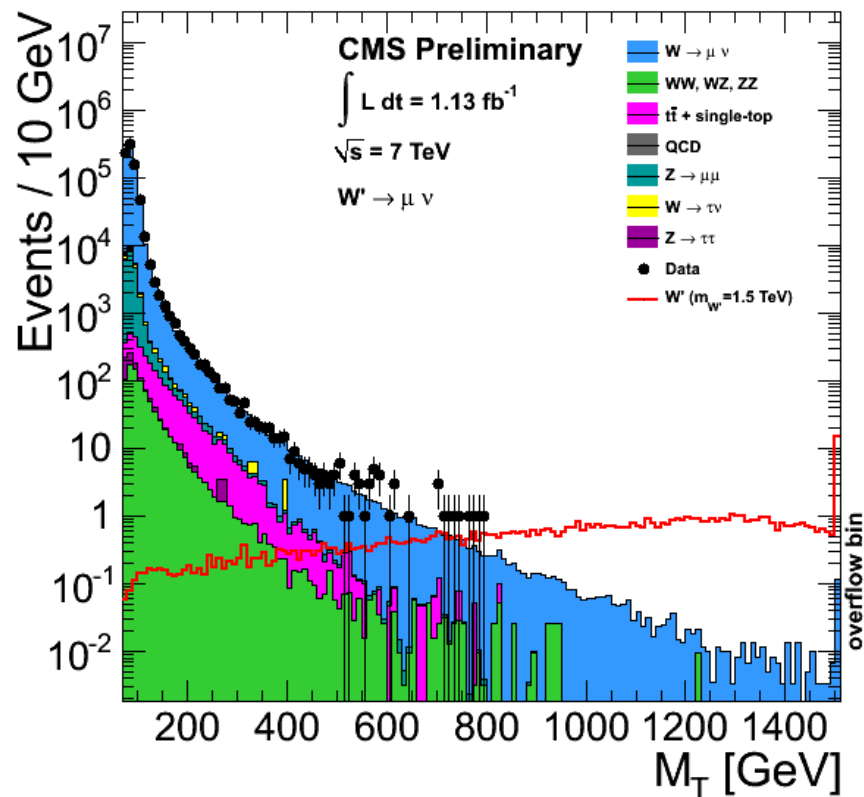
(2) Large MET;  $\text{MET} > 25 \text{ GeV}$

-> Reconstruct  $M_T$   $M_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi)}$



$m_{W'} > 2.15 \text{ TeV}$  ATLAS

$m_{W'} > 2.27 \text{ TeV}$  CMS







# Extra Heavy Z-like Particle

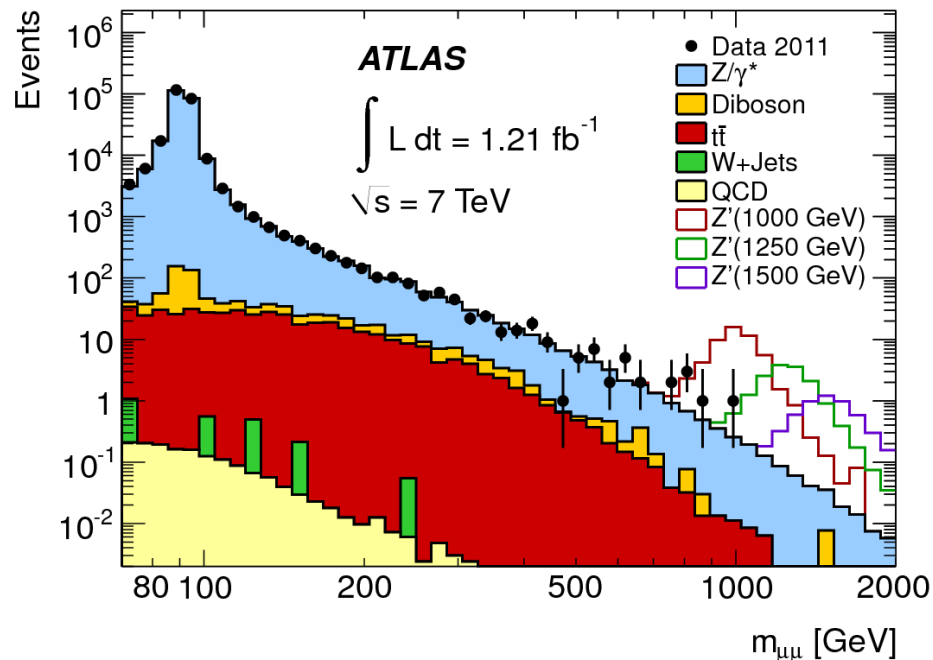
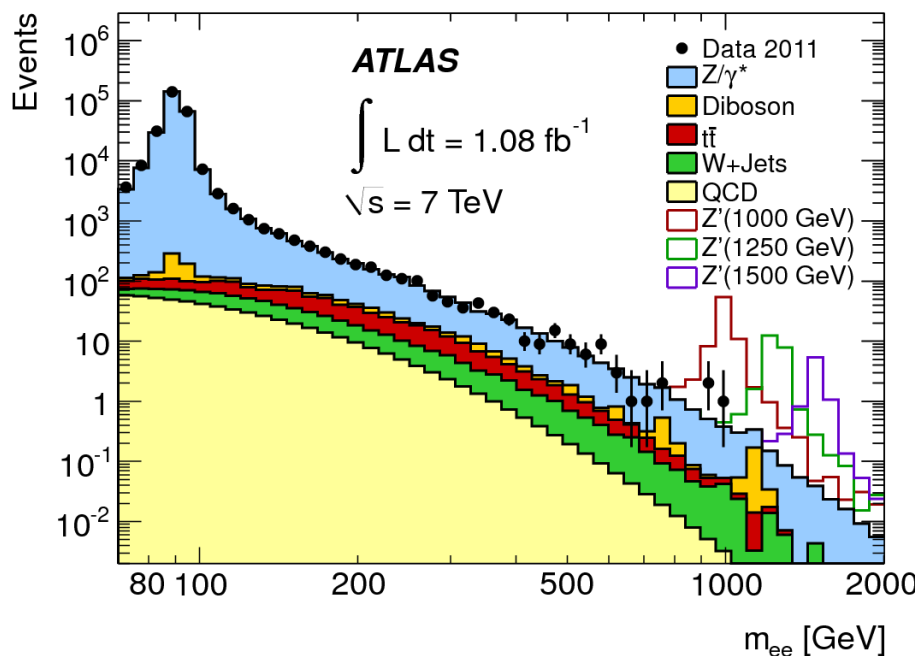
Extend Z search, that is, search for excess in  $m_{ll}$  distribution

[Selection] (ATLAS)

Two isolated electrons or muons;  $p_T > 25 \text{ GeV}$

-> require opposite-sign, the same flavor

-> Reconstruct  $M_{ll}$



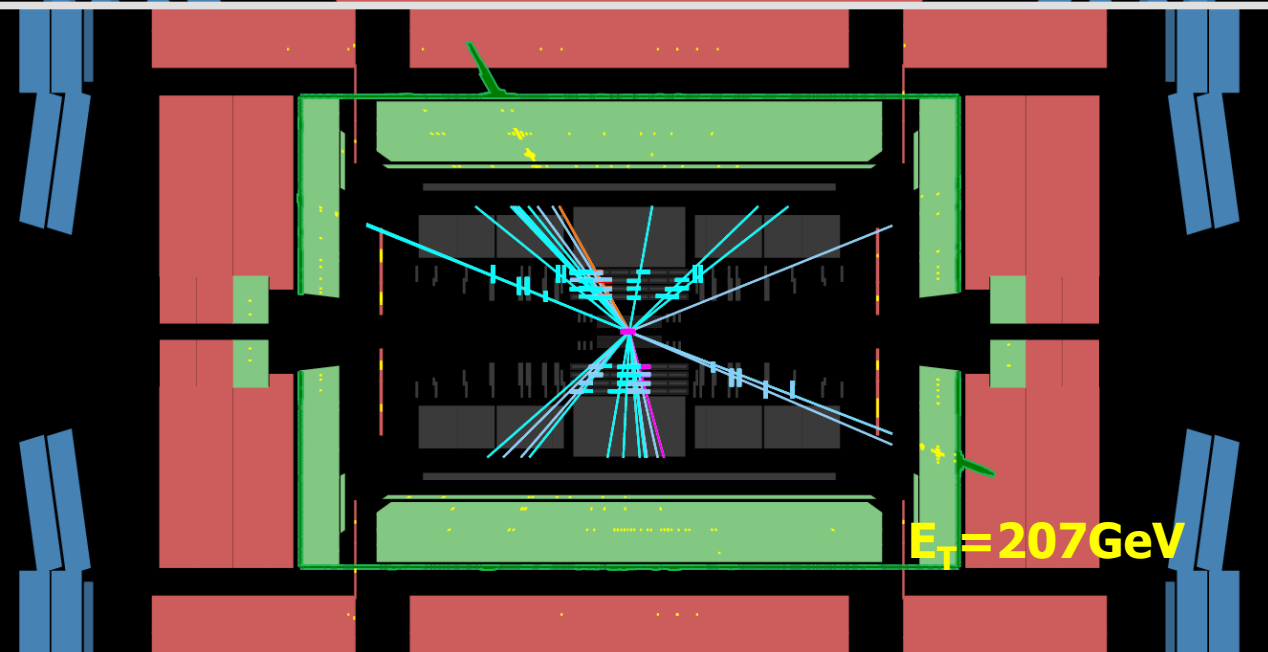
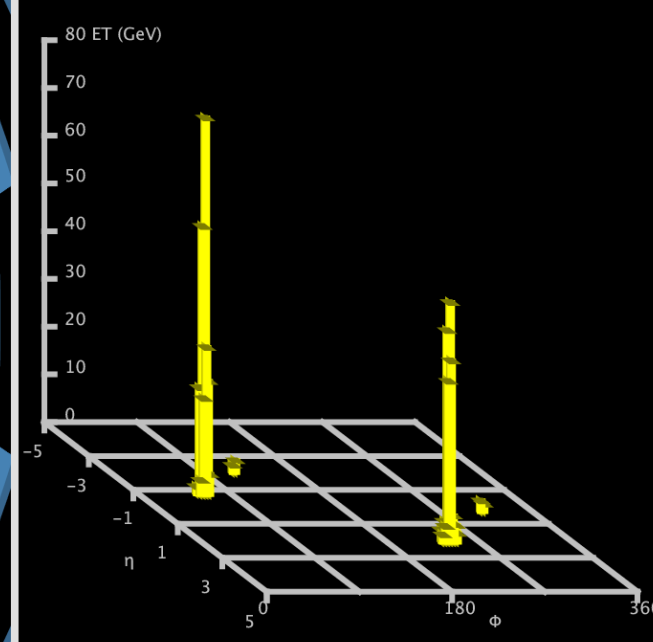
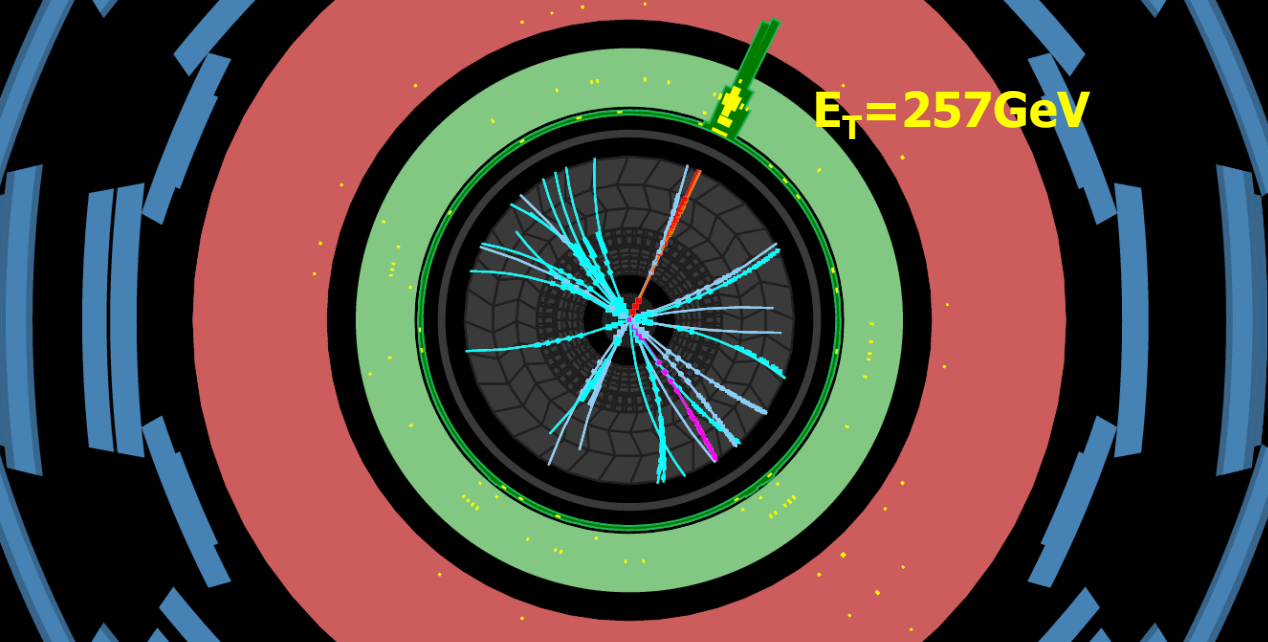
$Z'$  mass  $> 1.83 \text{ TeV}$  ATLAS

$Z'$  mass  $> 1.94 \text{ TeV}$  CMS

$G^*(k/M_{pl}=0.1)$  mass  $> 1.63 \text{ TeV}$  ATLAS

$G^*(k/M_{pl}=0.1)$  mass  $> 1.78 \text{ TeV}$  CMS





# ATLAS EXPERIMENT

Run Number: 183462, Event Number: 48979599

Date: 2011-06-14 02:48:15 PDT

**$m_{ee} = 993 \text{ GeV}$**





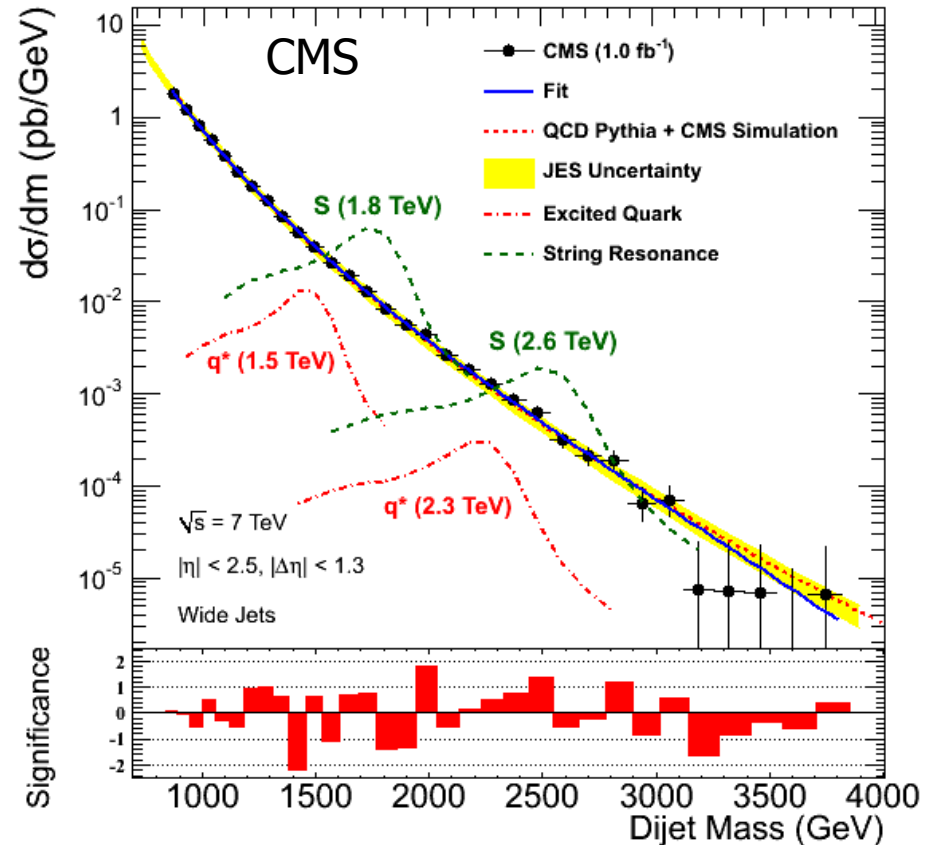
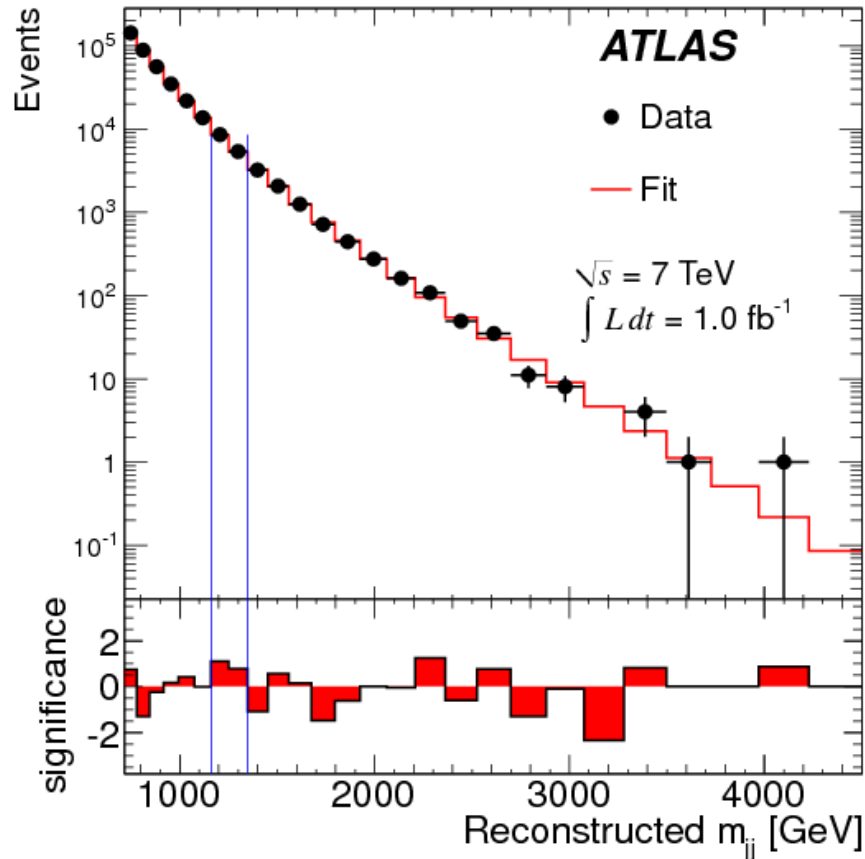
# Dijet Resonance

Excited quark  $q^*$ , Randall-Sundrum gravitons etc  $\rightarrow$  decay into two-jets  
 $qg \rightarrow q^* \rightarrow qg$

[Selection] (ATLAS)

Two leading jets (with 180GeV single jet trigger)

$\rightarrow$  Reconstruct  $M_{jj}$  ( $>717\text{GeV}$  for trigger)

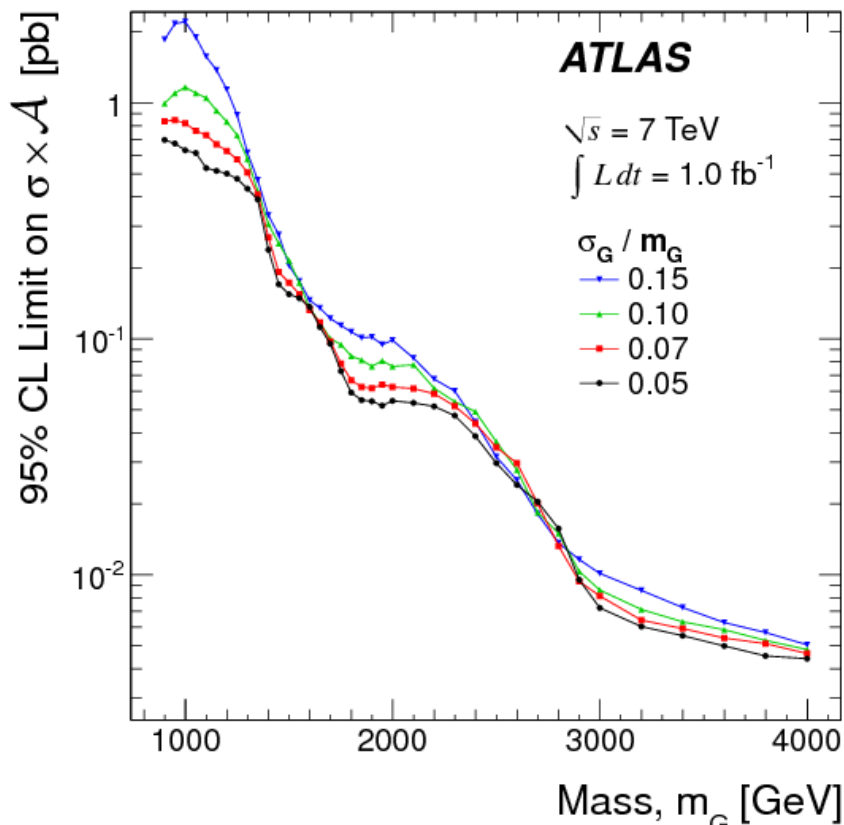


Model	95% CL Limits (TeV)	
	Expected	Observed
Excited Quark $q^*$	2.81	2.99
Axigluon	3.07	3.32
Colour Octet Scalar	1.77	1.92

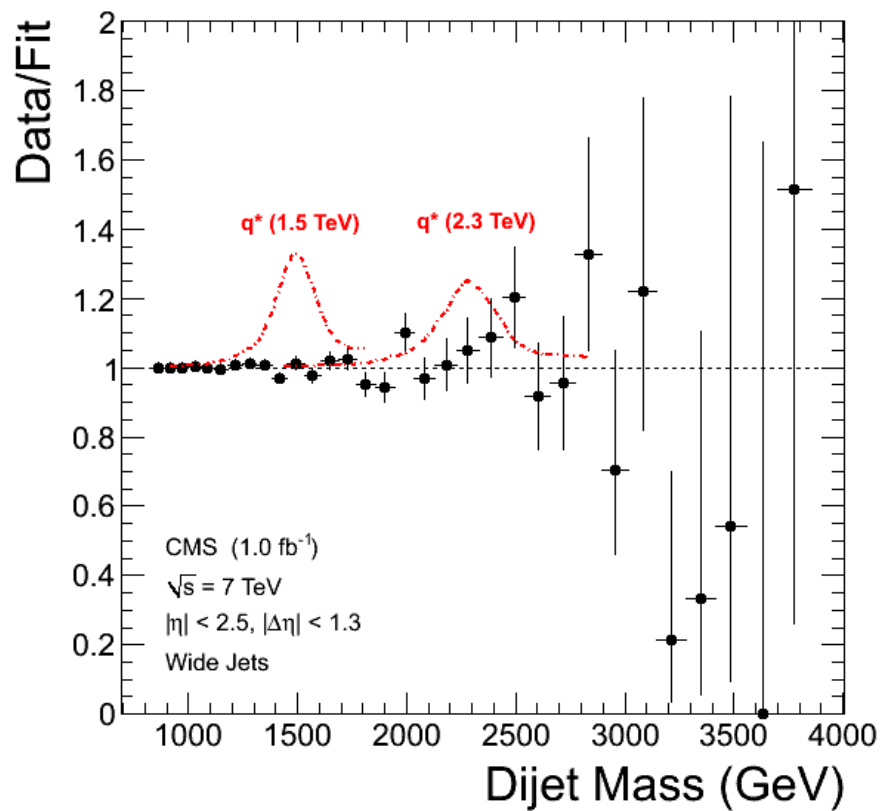


Model	Excluded Mass (TeV)	
	Observed	Expected
String Resonances	4.00	3.90
$E_6$ Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
$W'$ Bosons	1.51	1.40

Model independent x-sec



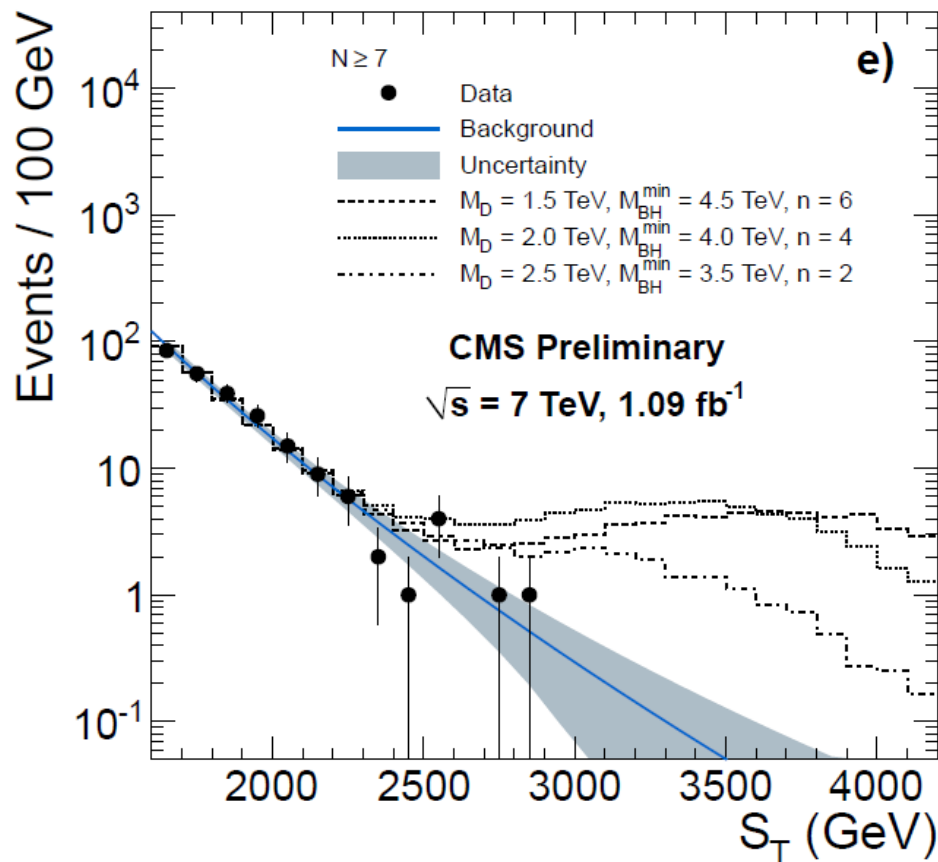
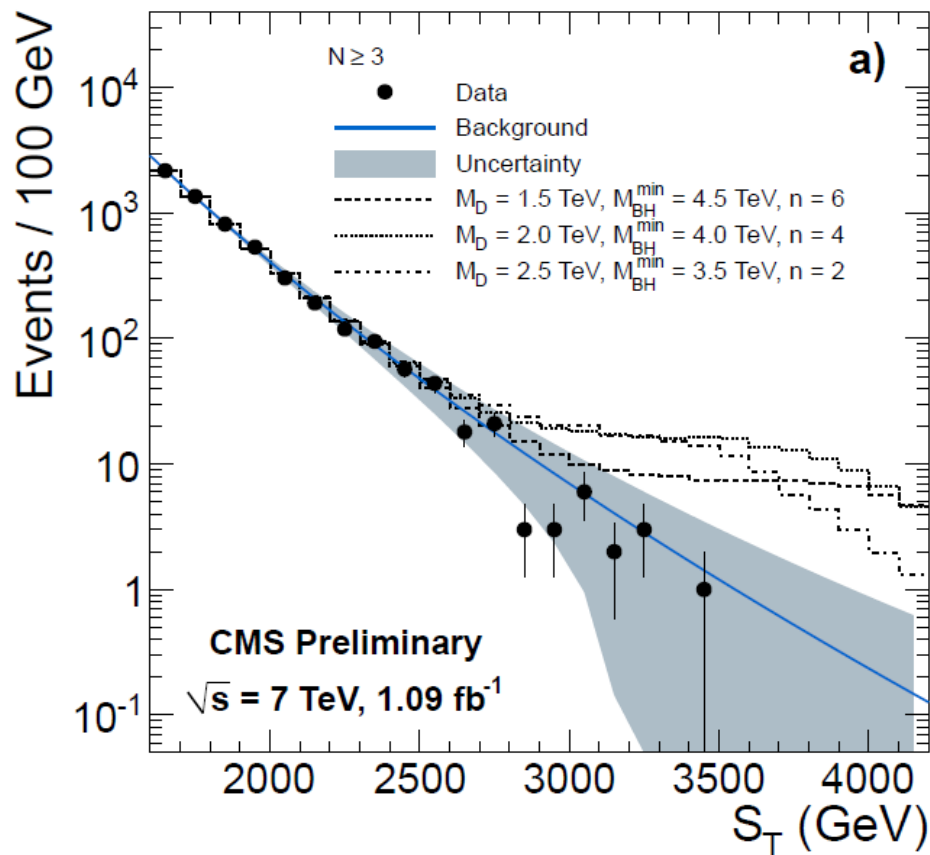
差分





# Multi-objects (BH) search

Mini black holes at LHC in some models,  
ADD etc -> TeV planck scale => 複数のオブジェクトを伴うイベント

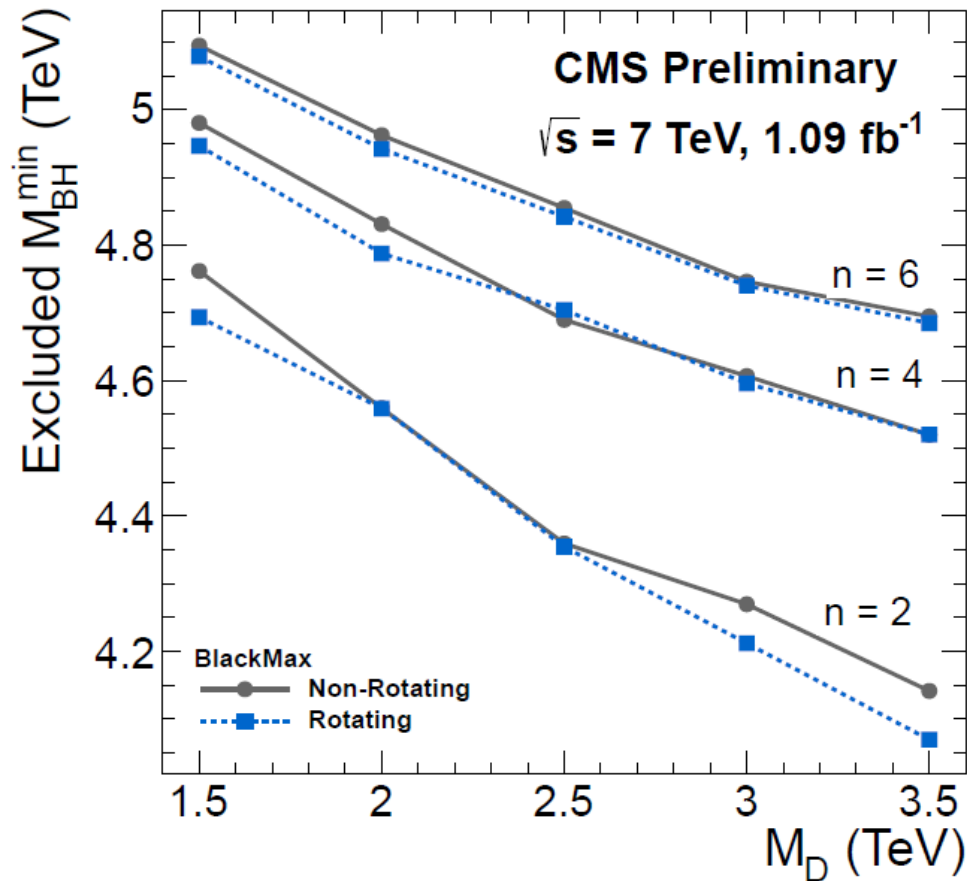


$S_T$  = total transverse energy (jets, electrons, photons, muons, MET if their  $E_T > 50 \text{ GeV}$ )





# Multi-objects (BH) search



$M_D$ (プランクスケール),  $n$ (余剰次元)に依存するが $M_{\text{BH}} \sim 4\text{-}5\text{ TeV}$ は棄却  
(派手なイベントが特別多くはない。。。)





No surprise in a TeV energy region at the moment...





# Summary

**ATLAS/CMS detectors work very well.  
LHC performance is also fine.  $L \sim 2.8 \text{ fb}^{-1}$**

## **No surprise in a TeV region (so far)**

**→ MSUGRA is almost excluded**

**→ No heavy resonance**

**SUSY: 探索するトポロジーの変更が必要(戦略変更)**

**- 期待していたほどHigh pT jetsがたくさんでないのか？**

**→ “Degenerated”なケース**

**- Colored sparticleは重いのか？**

**→ Naïve GUTは期待しないで、軽いGaugino**

## **A hint for a low mass Higgs**

**存在しなければ今年ほぼexcludeできます  
そうならないはずです!**







# バックアップ





# $B_s \rightarrow \mu\mu$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$

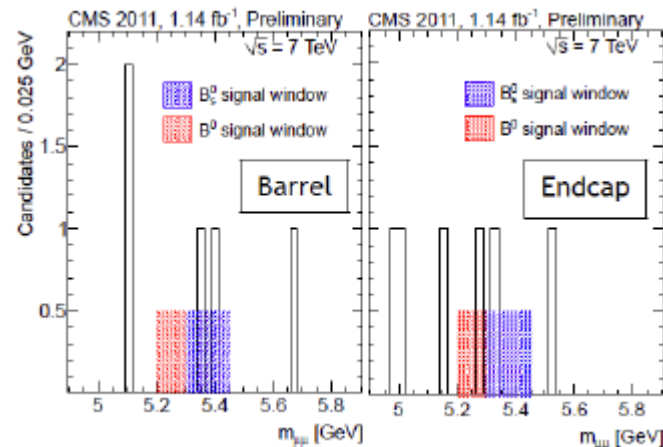
CDF (7fb<sup>-1</sup>)

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (1.8_{-0.9}^{+1.1}) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 4.0 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

Combined result

- LHCb : 0.34 fb<sup>-1</sup>
- CMS : 1.14 fb<sup>-1</sup>

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 1.08 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

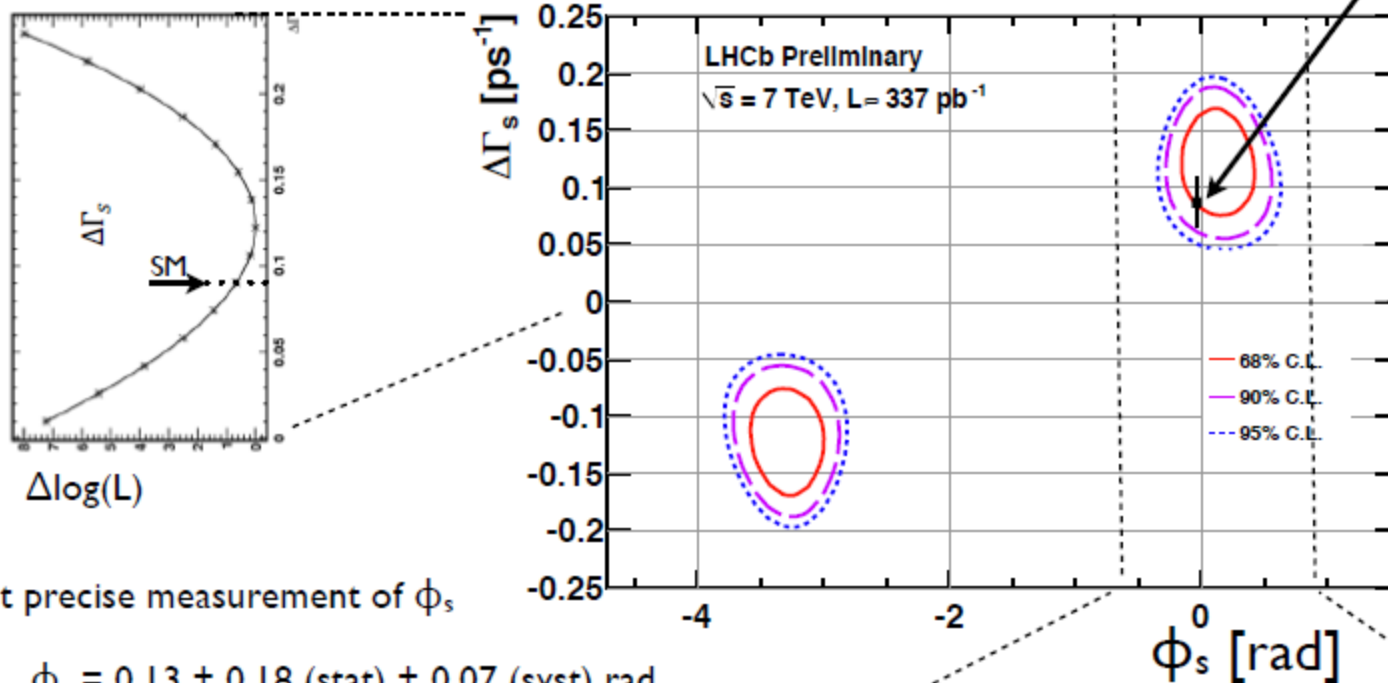




# $B_s \rightarrow J/\psi\phi$ : $\Delta\Gamma_s$ vs. $\phi_s$

Standard Model  
(Lenz, Nierste: arXiv:1102.4274)

LHCb-CONF-2011-49

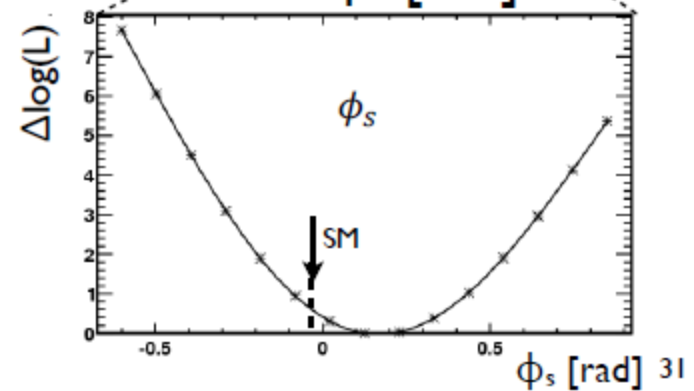


Most precise measurement of  $\phi_s$

- $\phi_s = 0.13 \pm 0.18$  (stat)  $\pm 0.07$  (syst) rad
- Consistent with SM

4  $\sigma$  Evidence for  $\Delta\Gamma_s \neq 0$ :

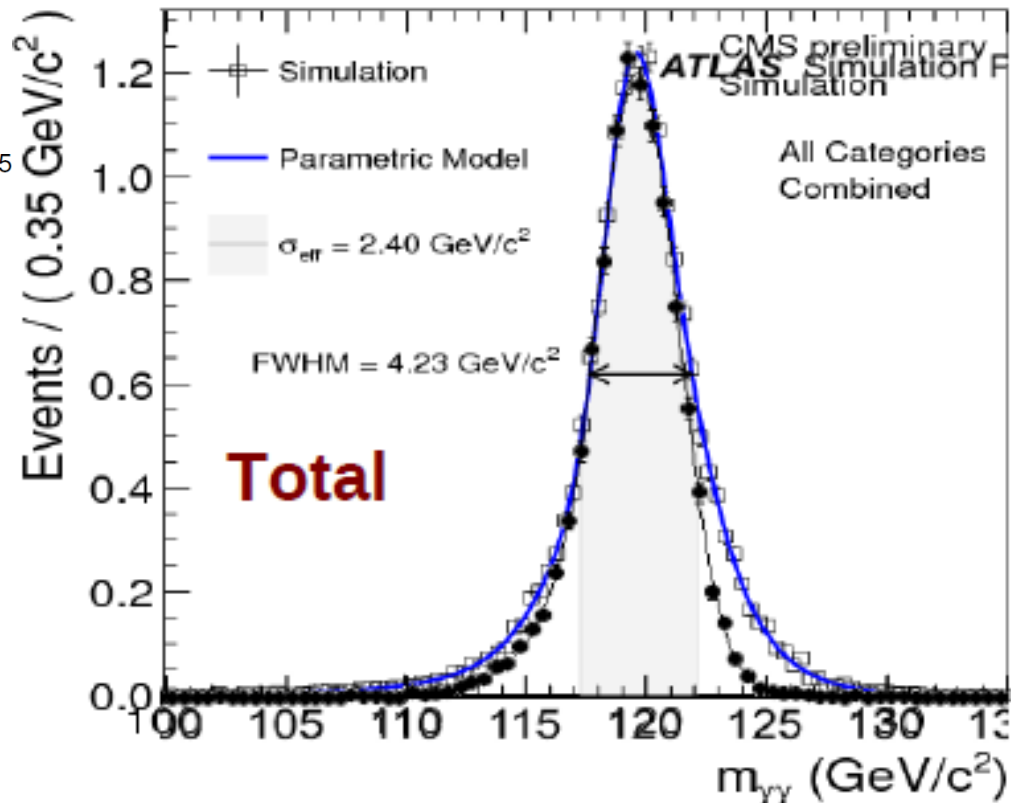
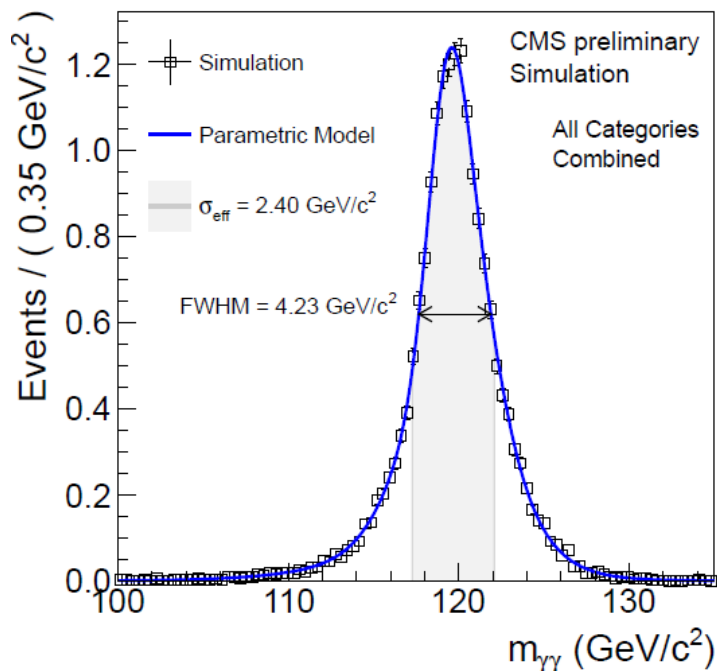
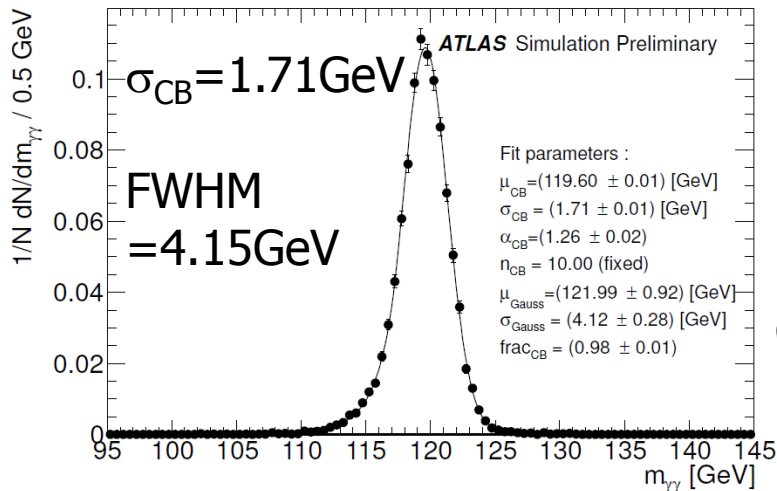
- $\Delta\Gamma_s = 0.123 \pm 0.029$  (stat)  $\pm 0.008$  (syst)  $\text{ps}^{-1}$
- $\Gamma_s = 0.656 \pm 0.009$  (stat)  $\pm 0.008$  (syst)  $\text{ps}^{-1}$





# Resolution

重なると、ATLAS健闘！ (~1.5GeV@CSC note)



CMSのクリスタルはCalibrationが大変。

resolution observed in the data. It is expected that the calibration and energy resolution will improve as the techniques for using measurements from the laser and LED system to correct changes in transparency are developed, and increasingly precise intercalibration is deployed.

