

Beyond the SM

(SUSY and non-SUSY)

新学術領域
先端加速器LHCが切り拓くテラスケールの素粒子物理学
—真空と時空への新たな挑戦—
研究会

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名古屋大学 2013年5月23-25日

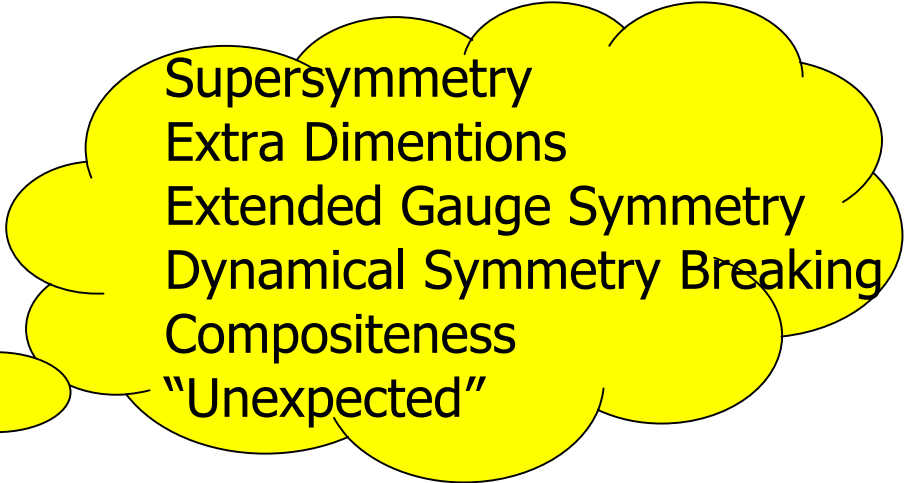
BSM探索@LHC Why?

2012年7月: ヒッグス粒子発見

これで標準モデルで予言されたすべての粒子が実験的に検証された!

次なる大発見? 新現象@TeVスケール

- 階層問題
- 大統一
- 3世代?
- ニュートリノの質量
- ダークマター/ダークエネルギー?
- $m_h=125\text{GeV}$, $g-2$, $B_s \rightarrow \mu\mu$.

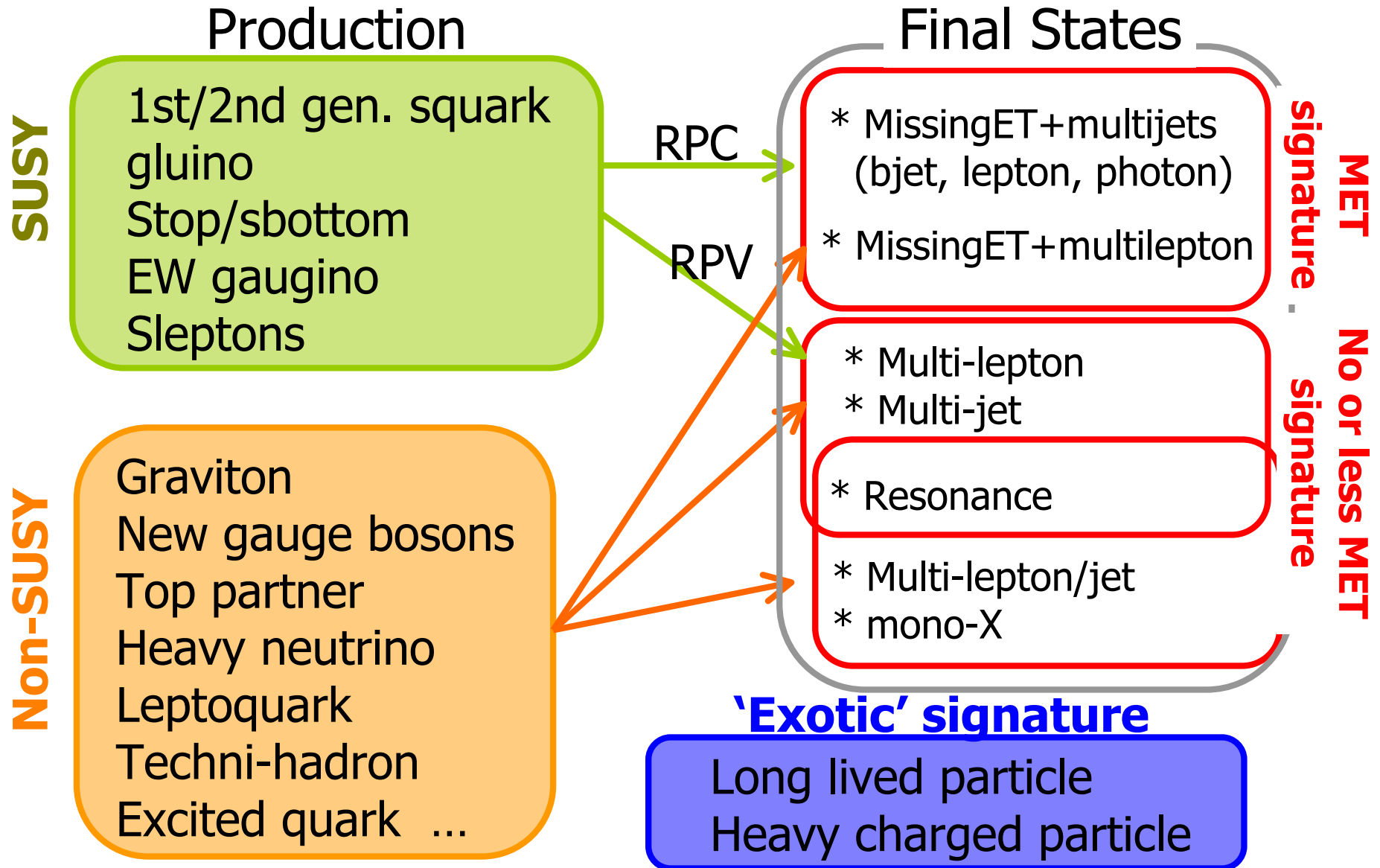


Supersymmetry
Extra Dimensions
Extended Gauge Symmetry
Dynamical Symmetry Breaking
Compositeness
"Unexpected"

BSMデータ解析 still on-going...

夏の国際会議(SUSY13)までにはほぼ全部の解析が終わる予定。

BSM探索@LHC



トークの流れ

1, SUSY探索

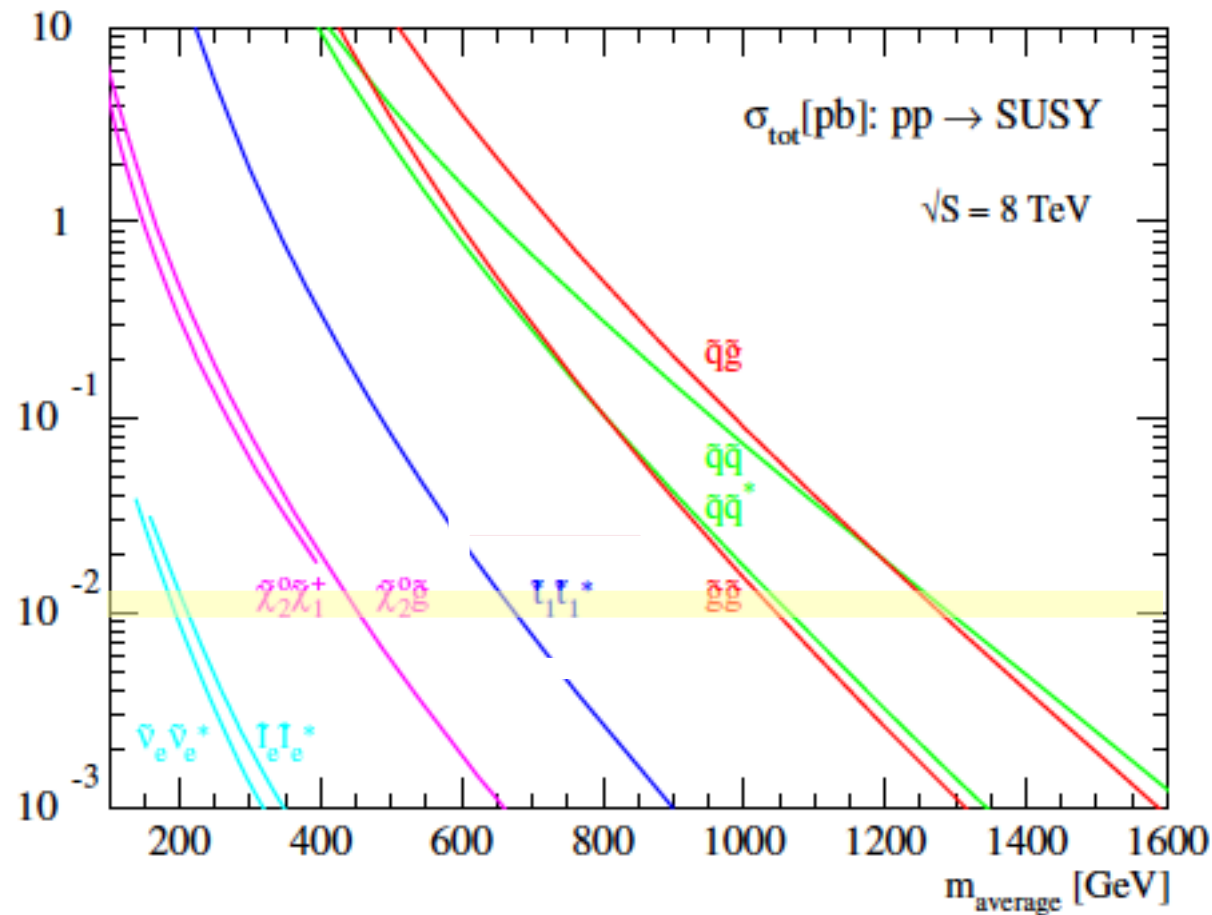
2, non-SUSY(aka Exotic)探索

3, まとめ

SUSY探索

SUSY@LHC8

2012年: Luminosity $\sim 20 \text{ fb}^{-1}$ @8TeV

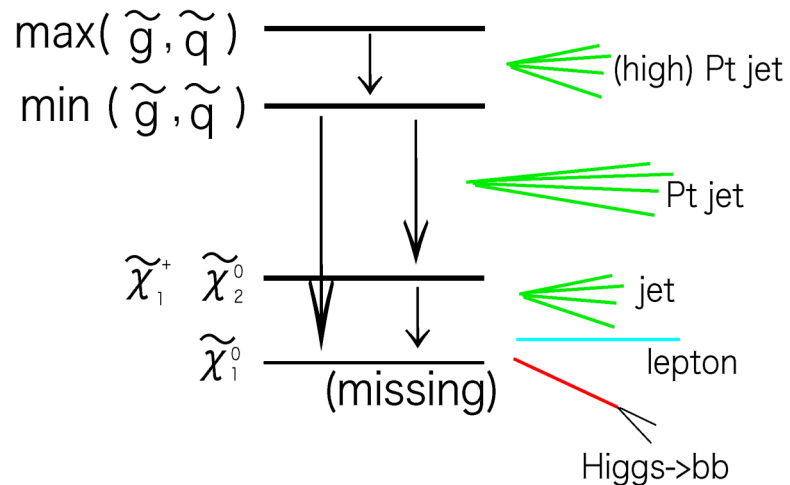


Mass scale
for cross-section=10fb

$\tilde{g}\tilde{g}$	1TeV
$\tilde{t}_1\tilde{t}_1$	700GeV
$\tilde{\chi}_2^0\tilde{\chi}_1^0$	400GeV

SUSY探索@ATLAS/CMS

BSM signature



R-parity conserving (RPC) SUSY探索では横方向運動量損失(mET)が鍵。

スクォーク・グルイーノ生成

MET + jets + (leptons, b-jets, γ s)

スレプトン/EWゲージーノ生成

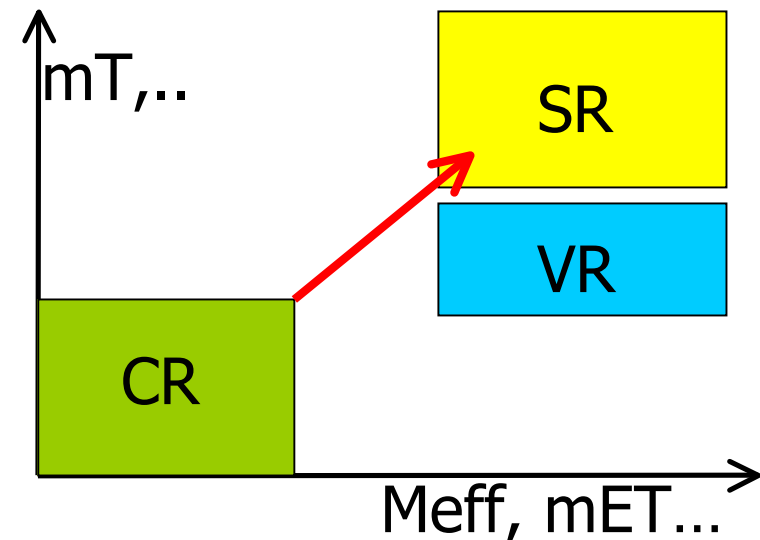
MET + 2-3 leptons (+jet veto)

一般的な背景事象推定方法

$$N(SR, data) = N(CR, data) \times \frac{N(SR, MC)}{N(CR, MC)}$$

“Transfer factor” (MC依存)

通常1つ以上のコントロール領域で
同時フィットしてデータに規格化する

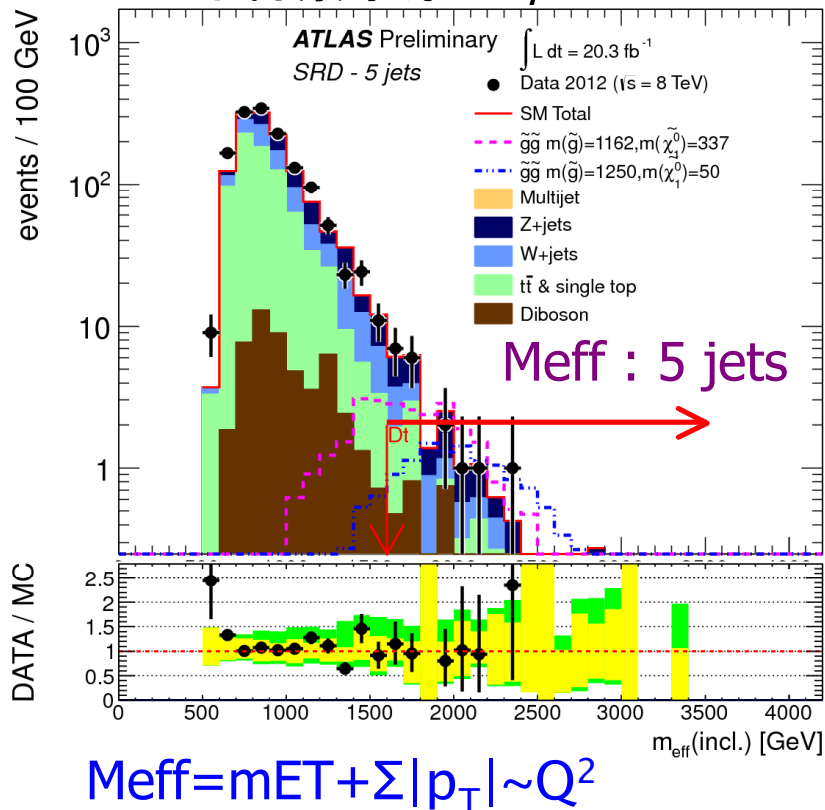


Inclusive (All hadronic)

軽いgluino/1st/2nd squark -> promising discovery channel!

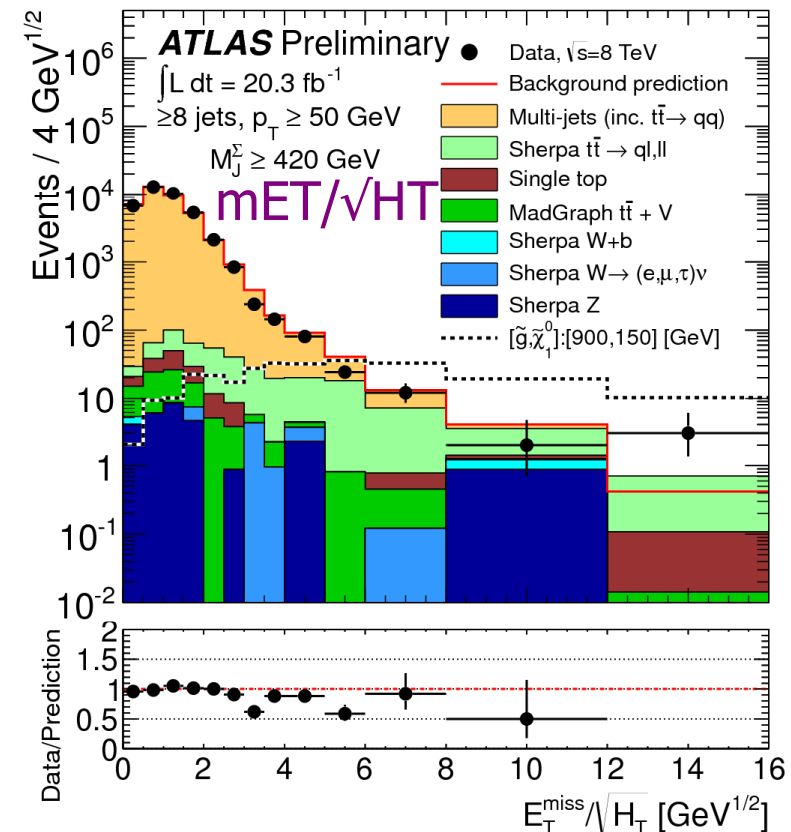
mET+2-6 jets

Discriminant: mET, Meff
主な背景事象: W/Z and tt

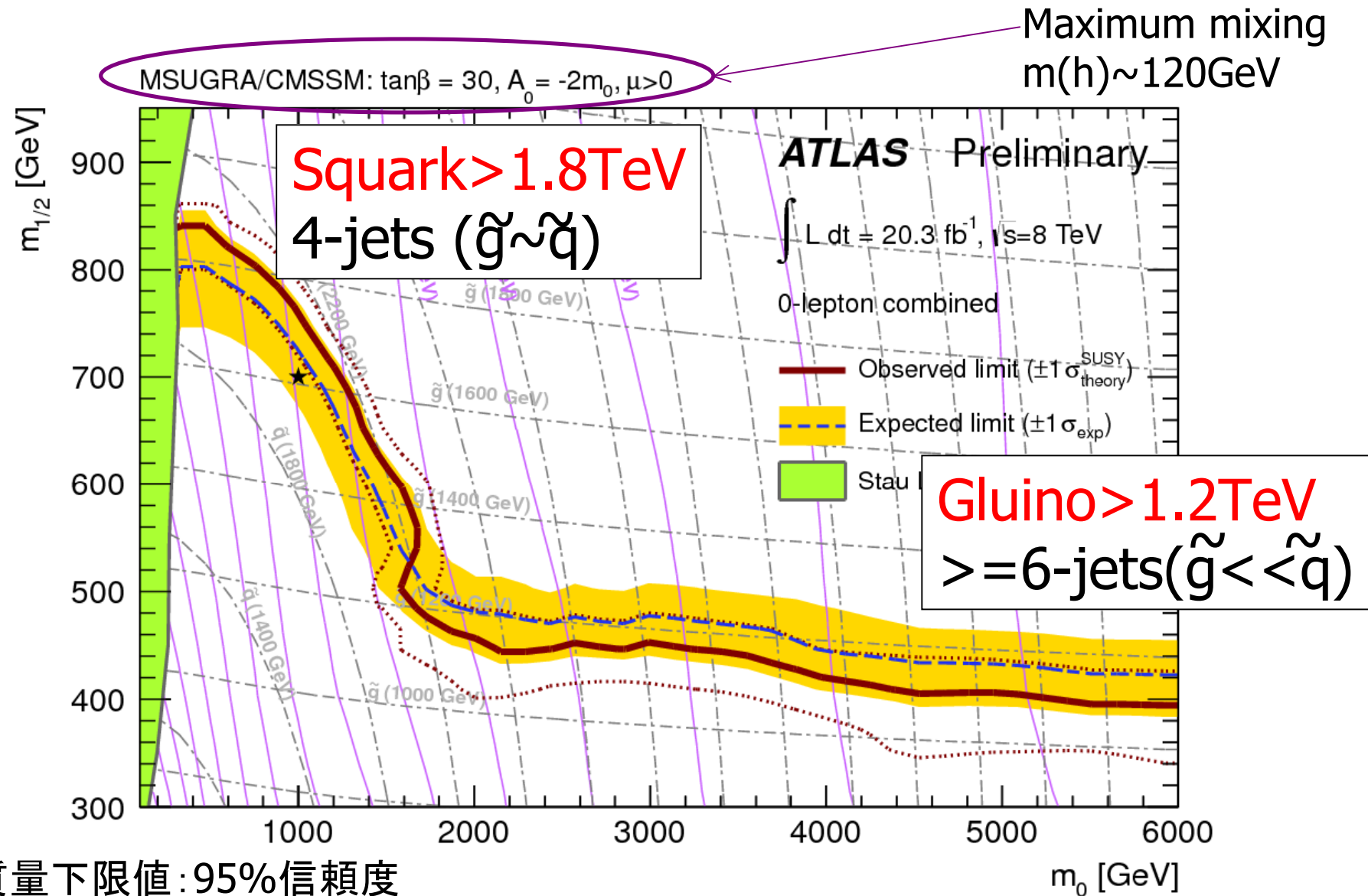


7-10 jets

Discriminant: nJet, mET/ $\sqrt{H_T}$
主な背景事象: tt, QCD



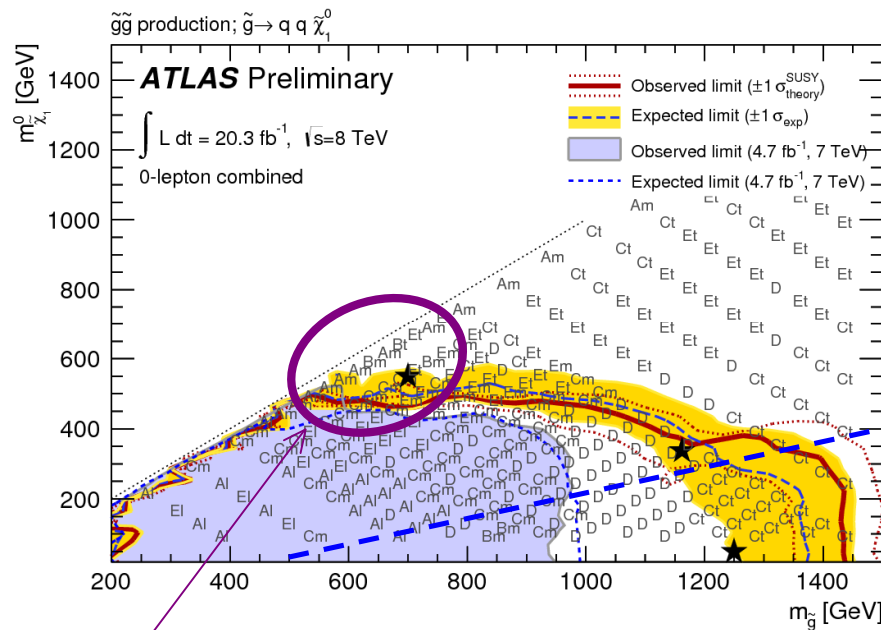
Inclusive (All hadronic)



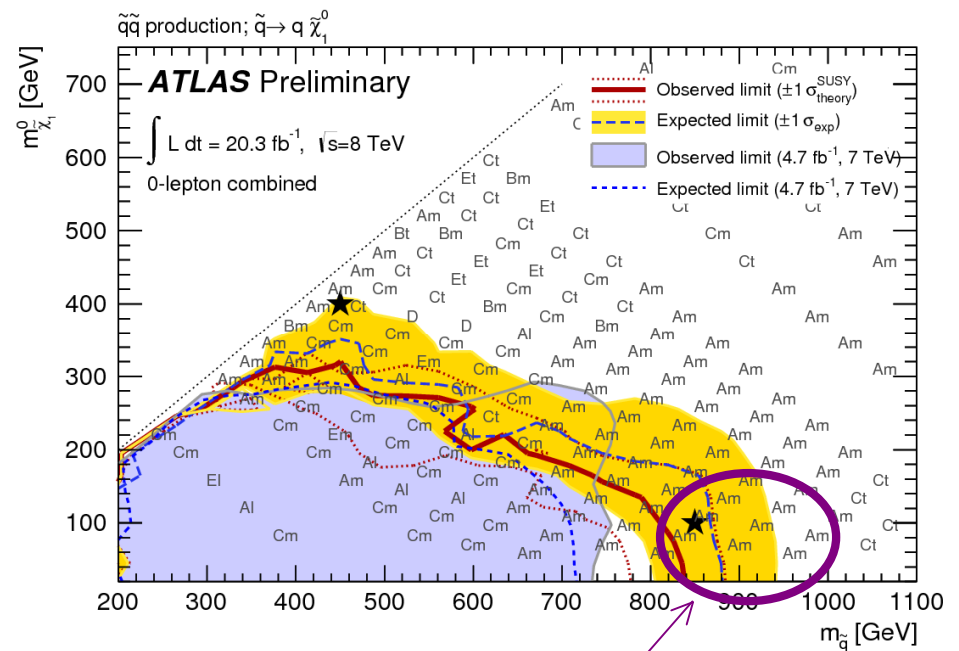
Inclusive (All hadronic)

モデル依存度(低)、ほぼ質量できる

質量縮退度 : $C = m_{\text{LSP}}/m_{\text{gluino}} < 15\text{--}20\%$ (mSugra-like)



ISR+jet type 解析 (topology/exclusive解析で多少改良)



ジェットマルチプリシティが低い
(sub-leading jet pTを上げるべき)

Gluino decaying stop

$$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$$

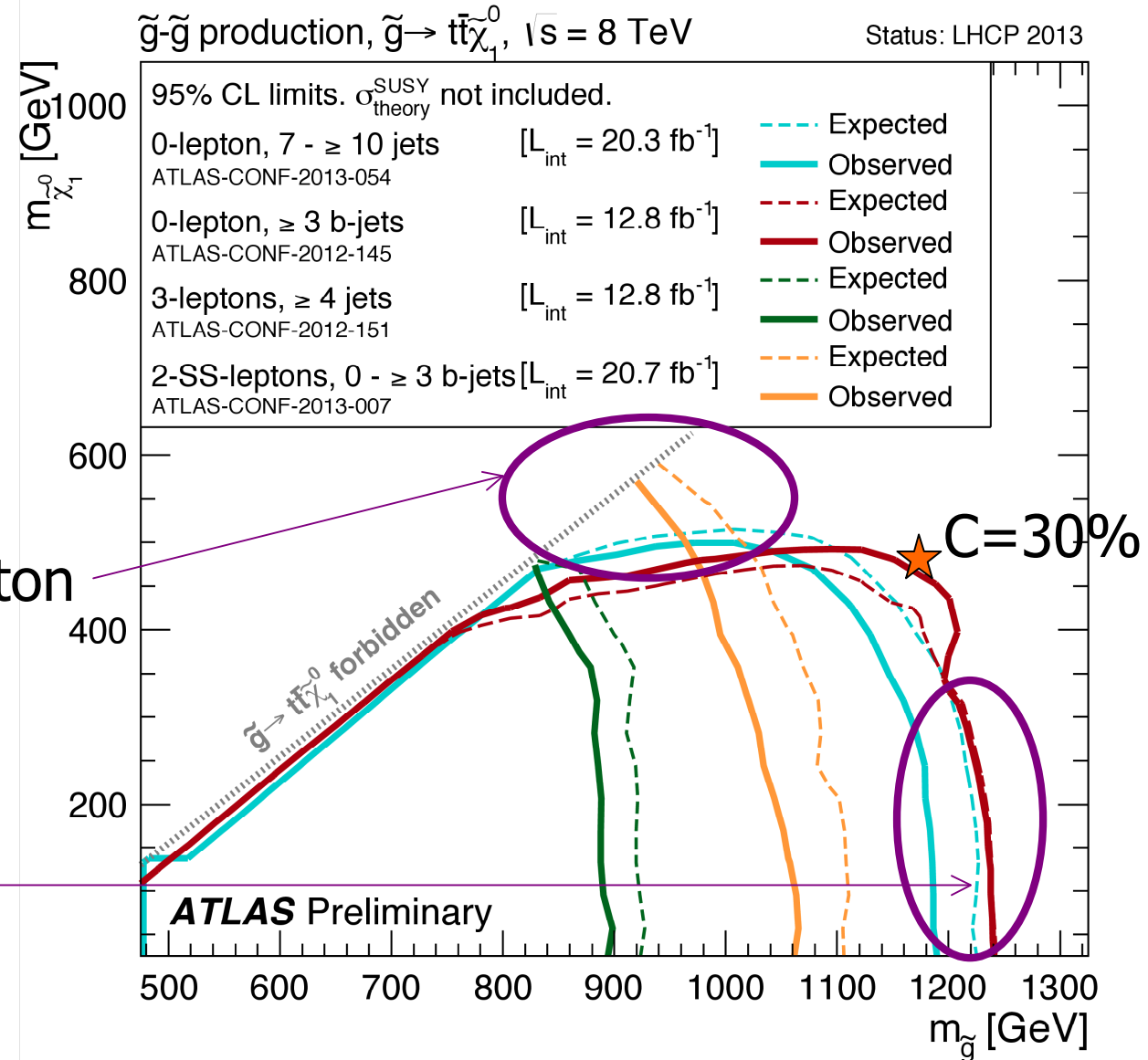
- high multiplicity
- 4b jet

ほぼバックグラウンド
フリー

- Same-sign di-lepton
- Multijet 解析

- 3b analysis

~200GeVくらい
のびるはず

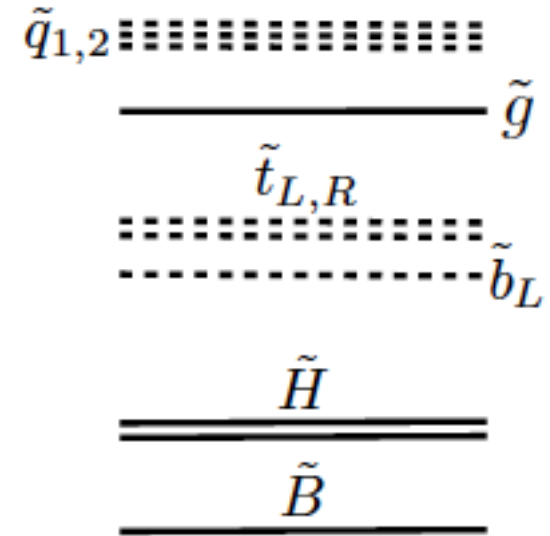
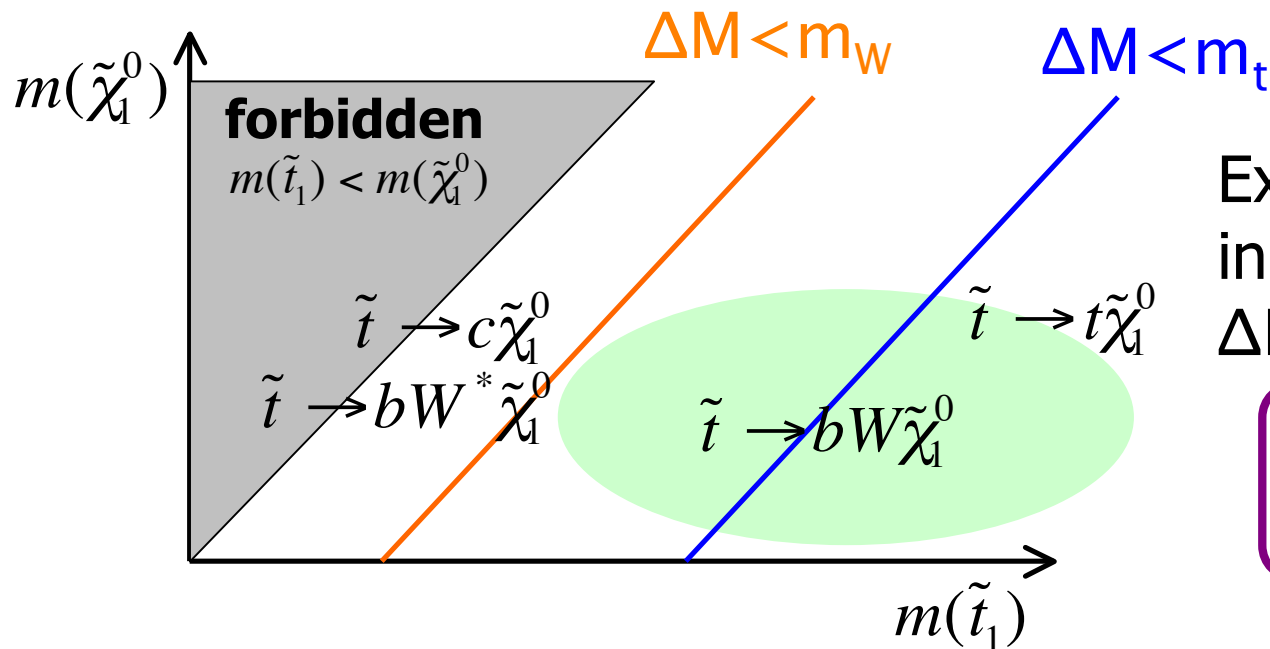


Stop/sbottom search

Naturalness vs $m_h=126\text{GeV}$

$$m(\tilde{t}) < (500 - 600)\text{GeV} \sqrt{\Delta/10}$$

LHC8でのreach -> close to 700GeV
Very Interesting regime!



Extensive study done in ATLAS to cover large ΔM region in

$$\begin{aligned} \tilde{t} &\rightarrow \tilde{\chi}_1^0 \\ \tilde{t} &\rightarrow \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \end{aligned}$$

Stop search (All hadronic, ttbar)

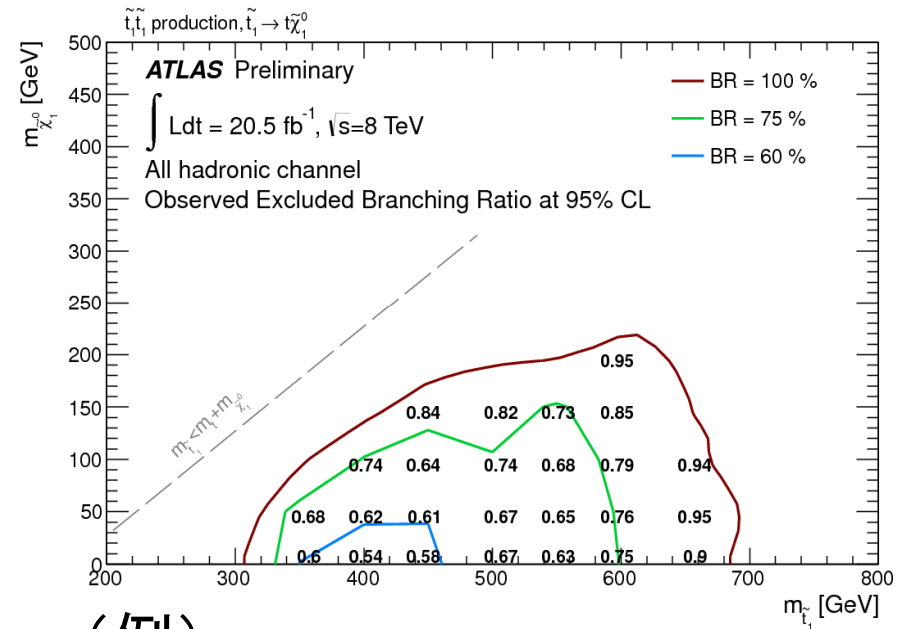
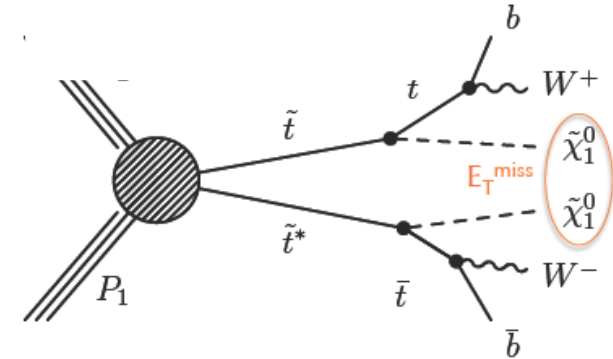
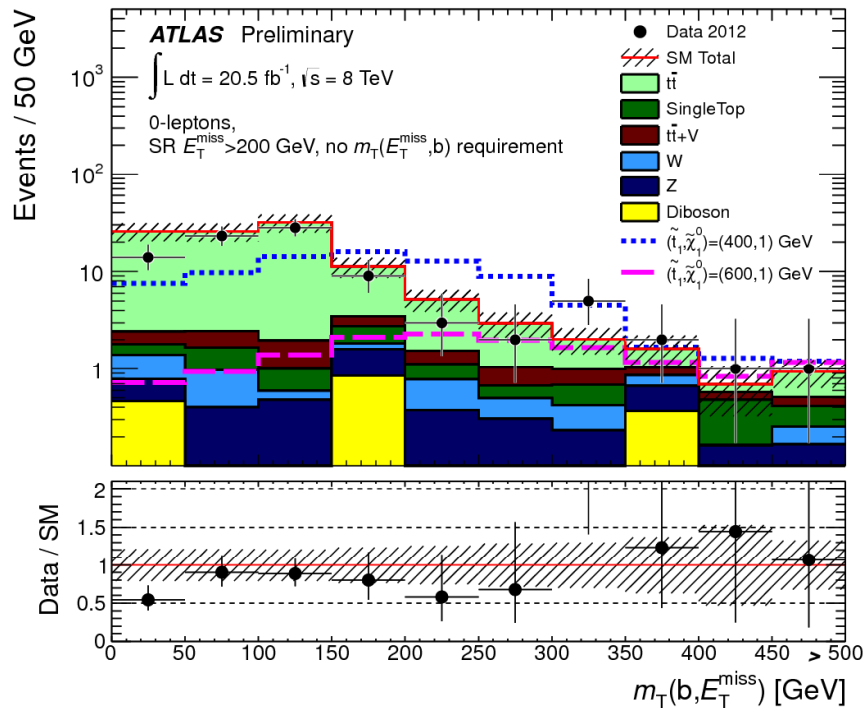
Target: Heavy stop: $\tilde{t} \rightarrow t\tilde{\chi}_1^0$

事象選択:

6 jets (2 bjets)

$M_{jjj}=80-270\text{GeV}$, $m_T(b, m_{ET}) > 175\text{GeV}$

$m_{ET} > 200-350\text{GeV}$



(例)
 $\tilde{t}_R \rightarrow \tilde{H}$

tb 50%
 tt, bb 25%

Stop/sbottom search (2-bjet)

Sbottom could be light enough:

$$\tilde{b} \rightarrow b\tilde{\chi}_1^0$$

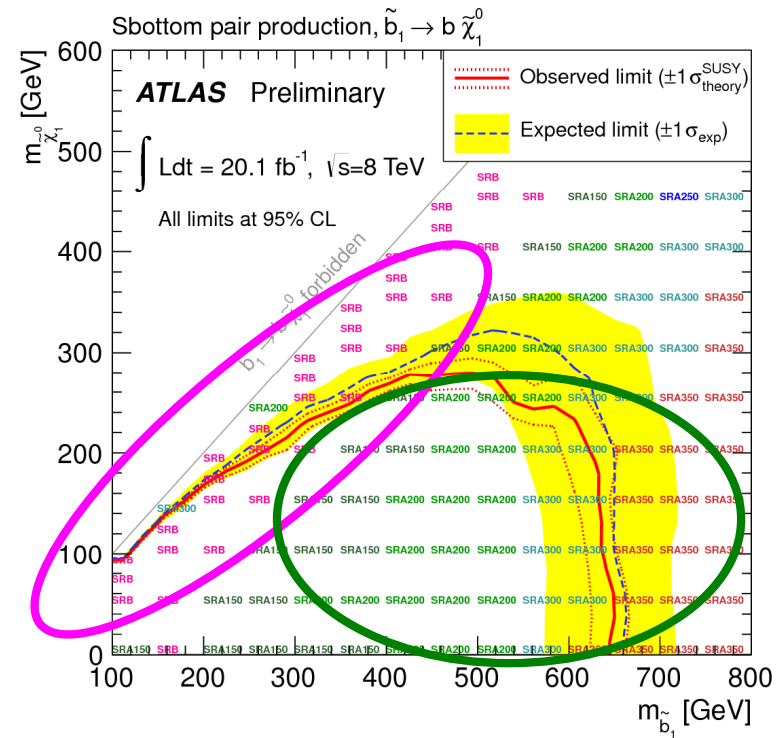
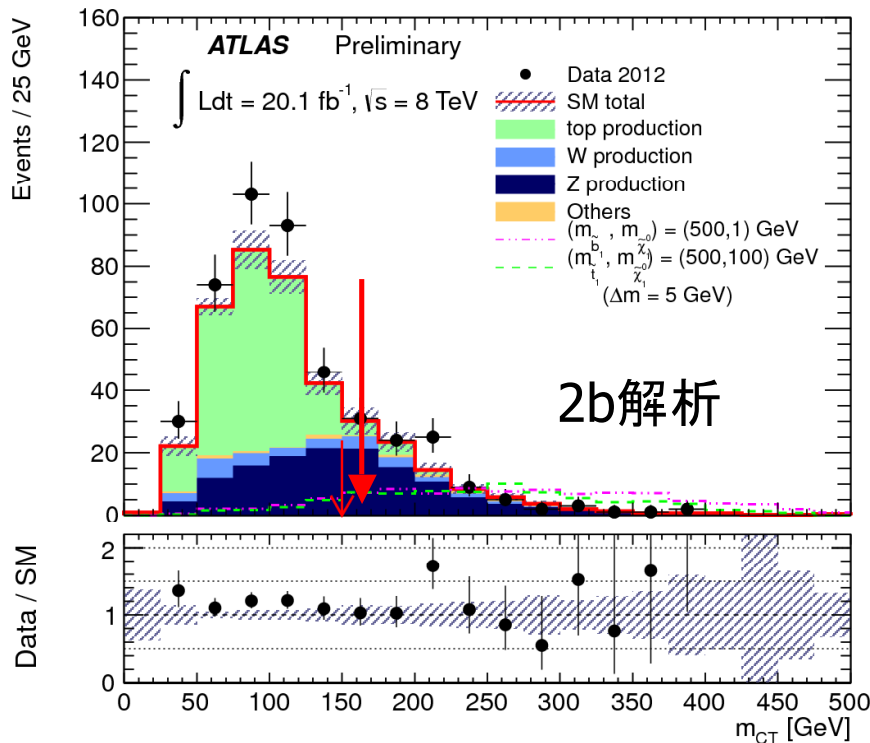
Sensitive to stop with Higgsino-like LSP: $\tilde{t} \rightarrow bW^{(*)}\tilde{\chi}_1^0$

1. 2b解析

$$m_{CT}^{\max} = \frac{m^2(\tilde{b}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{b})} \sim 135 \text{ GeV}$$

2. ISR+b解析

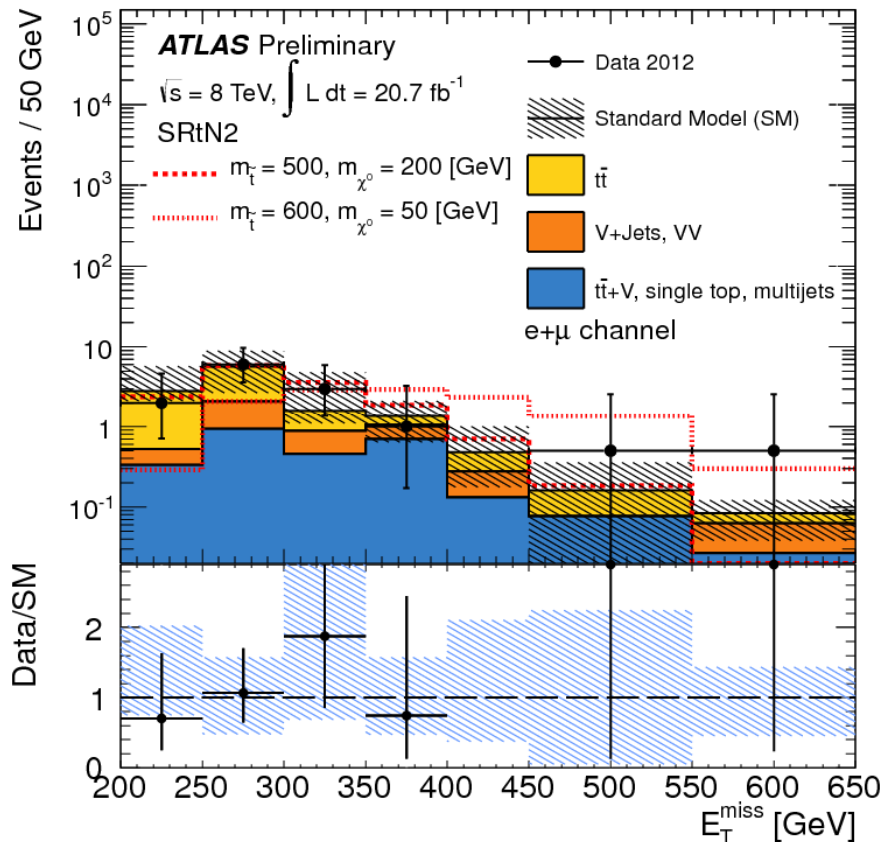
ISR jet + 2 b-jets, $m_{ET} > 250 \text{ GeV}$



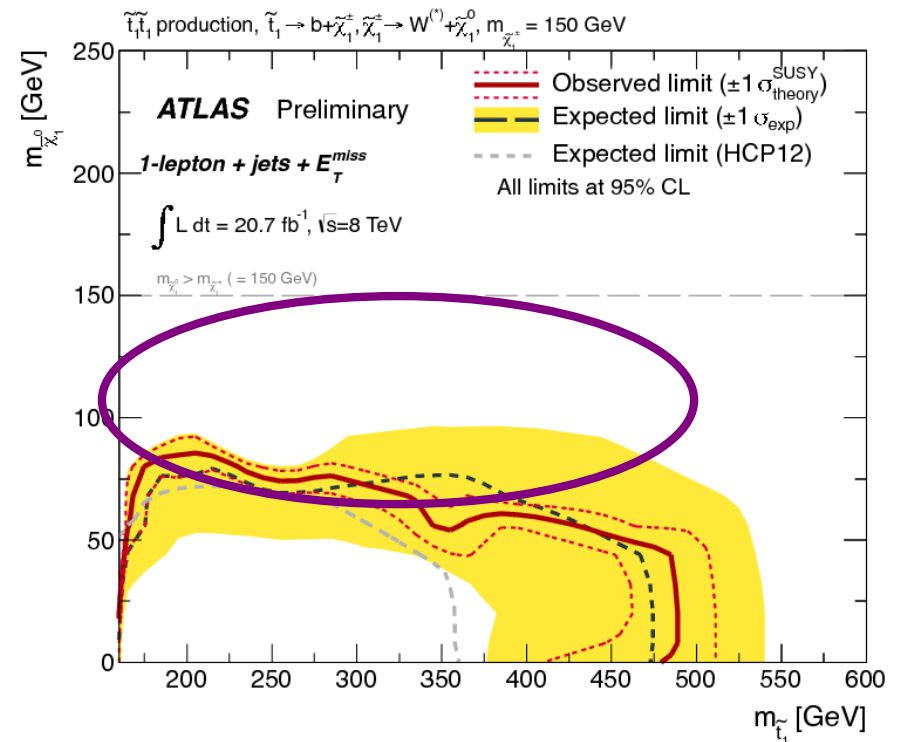
Stop search (1lepton)

Cover parameter space with $\Delta M > m_W$ $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ / $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$

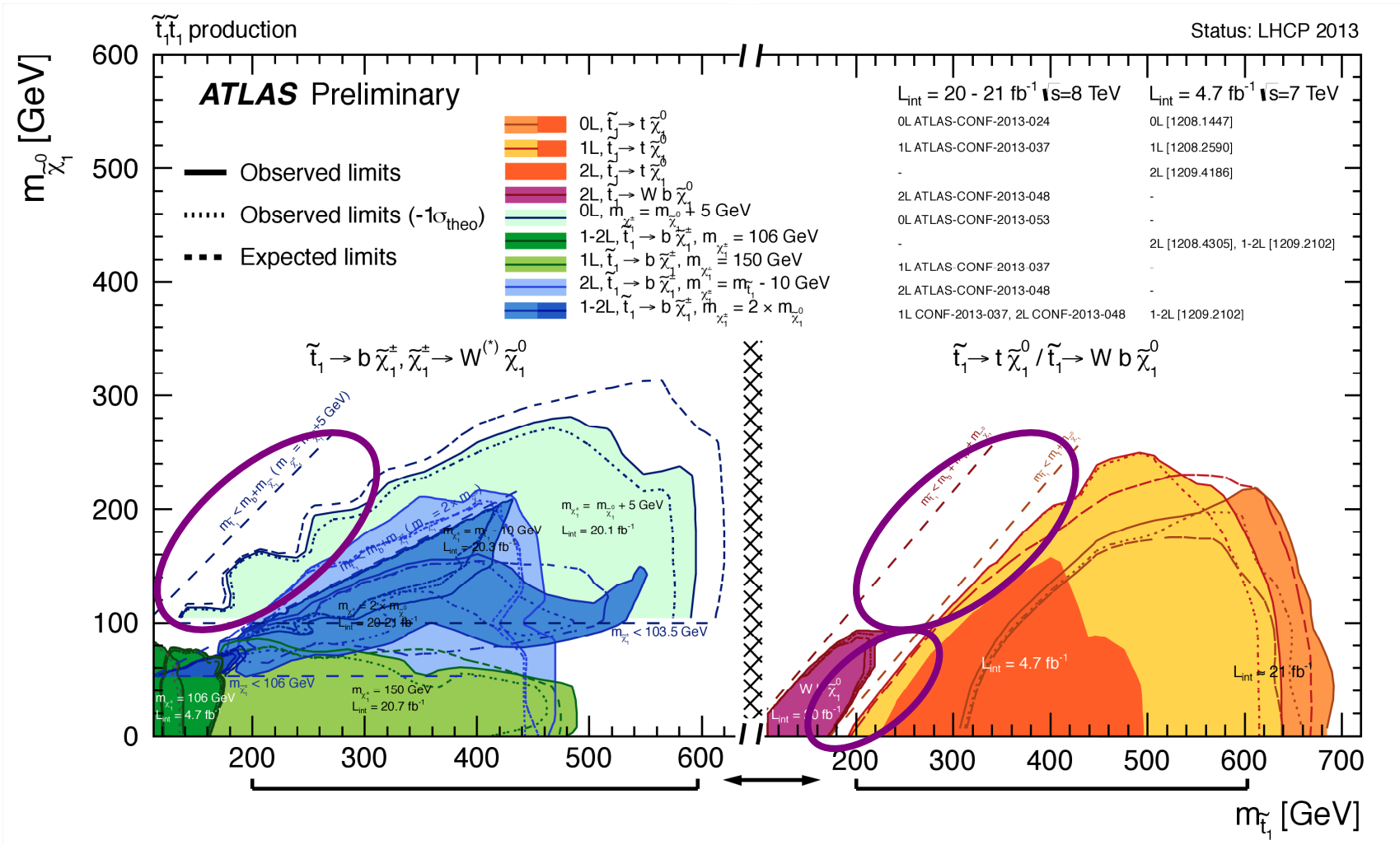
- 4jets (bjet=1 or 2)
- $m_{ET} > 150$ -275 GeV
- $m_T > 120$ -200 GeV



Could be covered by 0-lepton and soft-lepton ($W^* \rightarrow l\nu$)



Summary of stop search

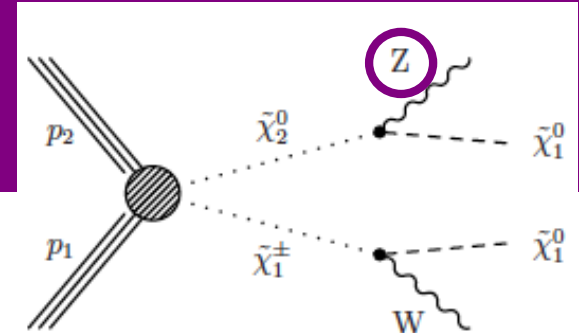


Note: Assume 100% BR and symmetric decay tree.

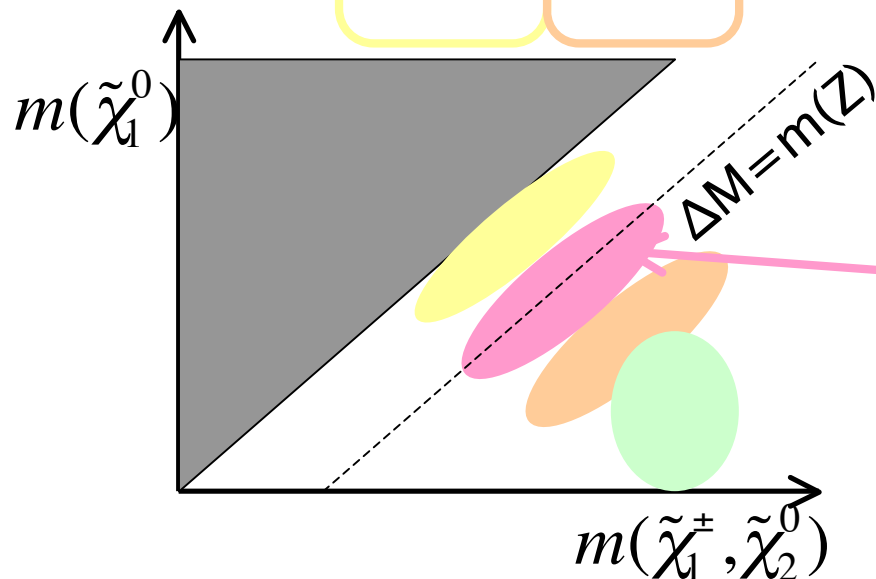
Direct EW gaugino search

Getting interesting!

- スクォーク・グルイーノが重すぎる場合
- 軽いEW gaugino as expected (naturalness, Darkmatter)



Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
m_{SFOS} [GeV]	<60	60–81.2	<81.2 or >101.2	81.2–101.2	81.2–101.2	81.2–101.2
$E_{\text{T}}^{\text{miss}}$ [GeV]	>50	>75	>75	75–120	75–120	>120
m_{T} [GeV]	–	–	>110	<110	>110	>110
$p_{\text{T}} 3^{\text{rd}} \ell$ [GeV]	>10	>10	>30	>10	>10	>10



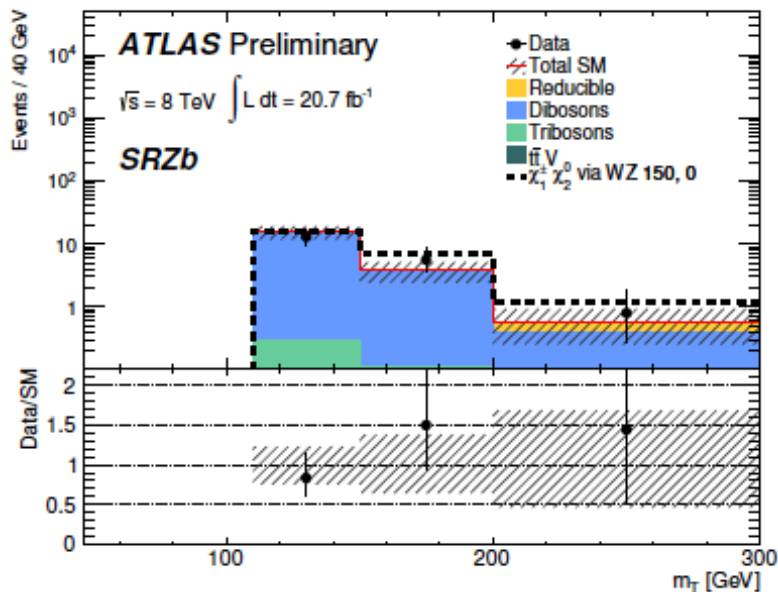
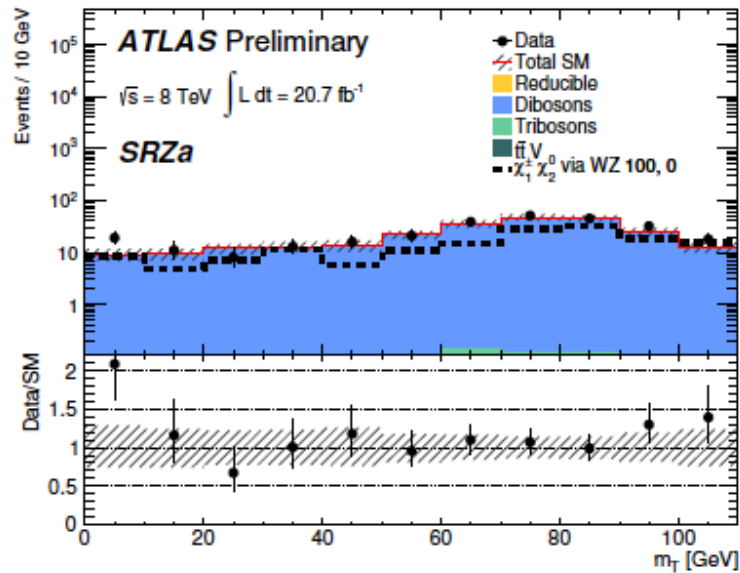
WZ-like

WZバックグラウンドからの
分離はとても難しい

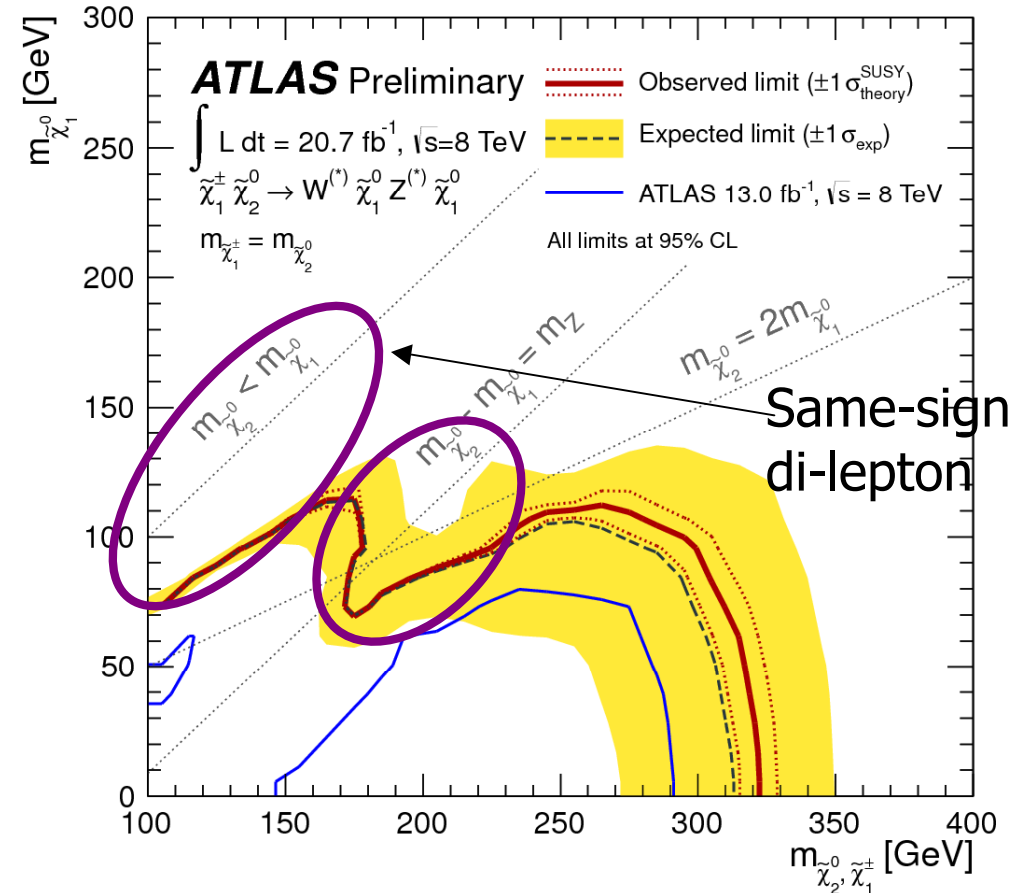
$$\sigma(\text{WZ}) \sim 20 \text{ pb}$$

$$\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) \sim 0.5 \text{ pb (200 GeV)}$$

Direct EW gaugino search

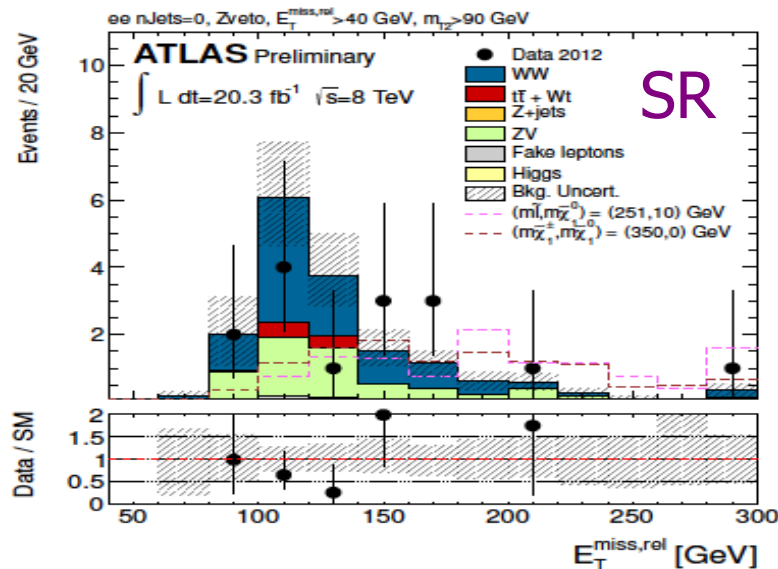
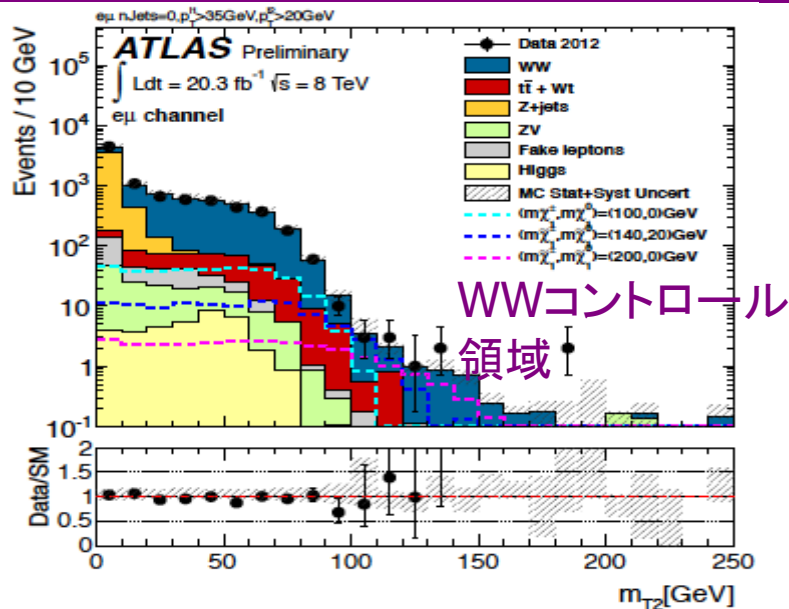


主な系統誤差: diboson 断面積
 13-24% (WZ like)



$\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$ の解析は進行中

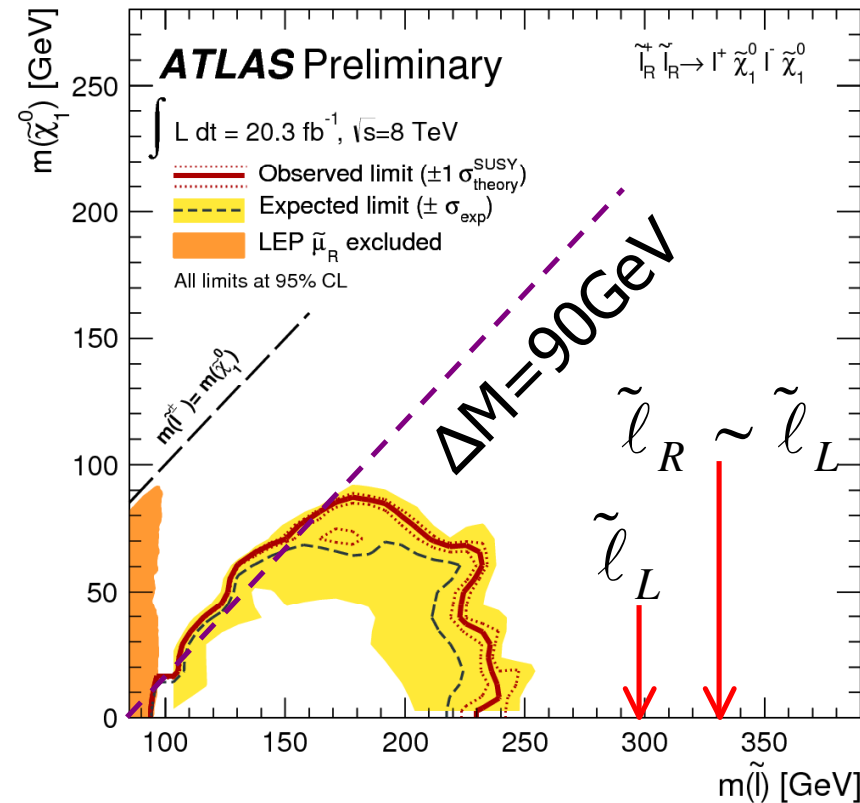
Direct slepton search



m_{T2} (分布の端が質量差に相当)

$$m_{T2} = \min_{q_T} \left[\max \left(m_T(p_T^{\ell 1}, q_T), m_T(p_T^{\ell 2}, p_T^{\text{miss}} - q_T) \right) \right]$$

質量が大きい場合に有効 ($m_{T2} > 90, 110 \text{ GeV}$)



スタウは厳しい... (トリガー) → 14 TeV に

Non-SUSY探索

ここでは以下の新粒子探索(終状態)の最新結果を紹介します。

- (1) Graviton/New gauge bosons (resonance)
- (2) Vector-like quark/Heavy boson (top/same-sign lepton)
- (3) Dark Matter (mono-jet)

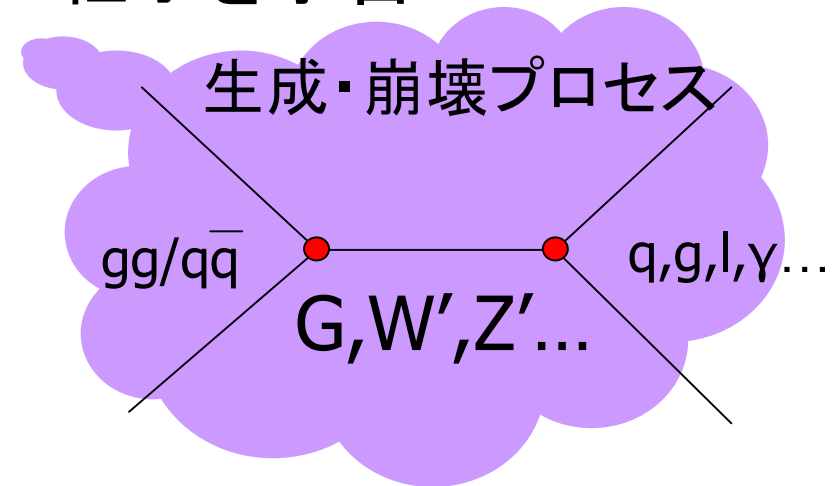
Resonance探索

多くのBSMモデル→新しい重たい粒子を预言

- New W/Z bosons (spin=1)
- Graviton (spin=2)

...

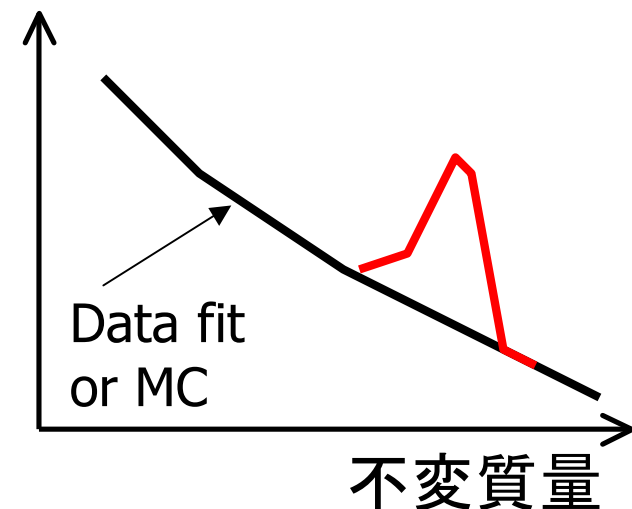
TeV scaleでs-channel分布に
何か新しい構造がみえる？



シンプルな解析(質量ピーク!)

High p_T オブジェクトの同定とキャリブレーション
が重要。

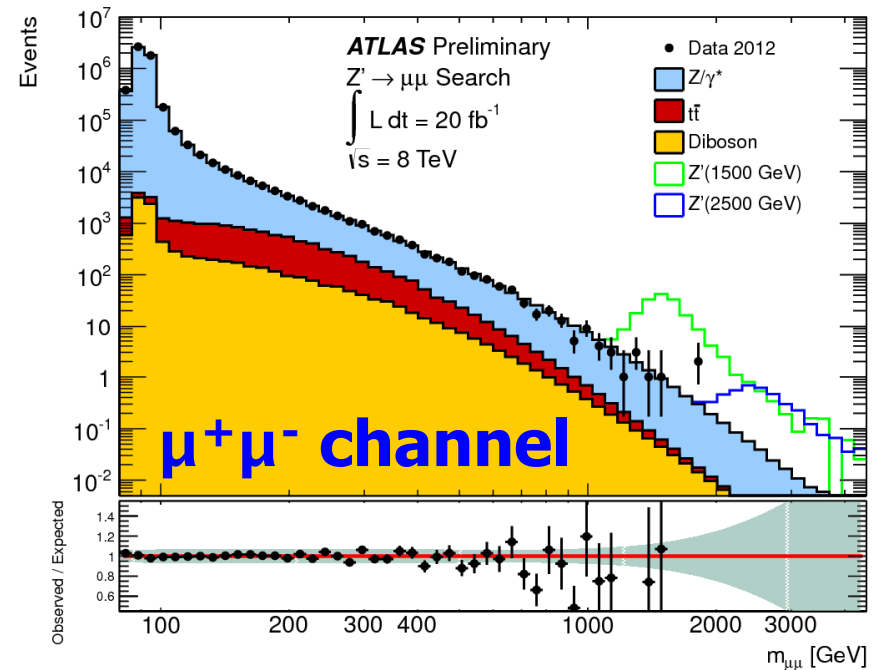
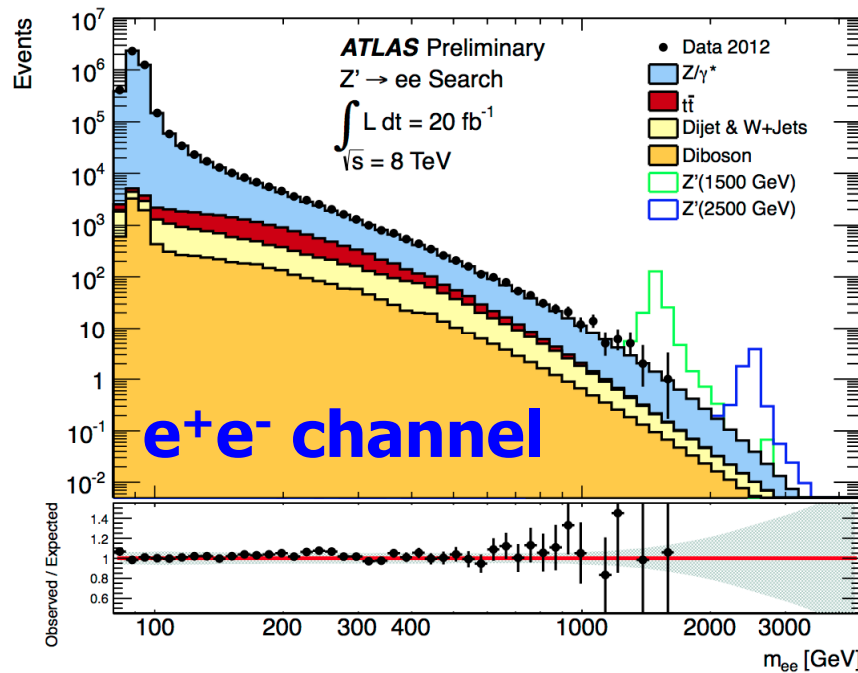
分解能	$\sigma(p_T)/p_T$
Jet	5%
Electron	1%
muon	10%



Graviton/ Z' (di-lepton)

事象選択

- single lepton trigger
- Two isolated opposite sign/same flavor leptons
- $p_T > \{40, 30\} \text{ GeV} (\text{electron}), > 25 \text{ GeV} (\text{muon})$



Main background

Drell-Yan($qq \rightarrow Z/\gamma^* \rightarrow ll$)

Generator: Powheg+Pythia8

Cross-section: NNLO+NLO EW correction

質量下限値

Poor p_T resolution for μ @high PT

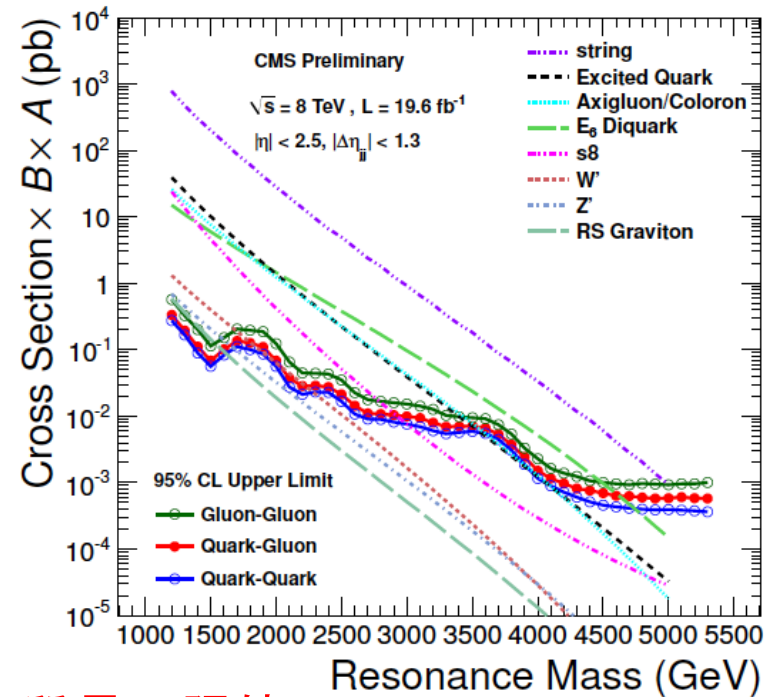
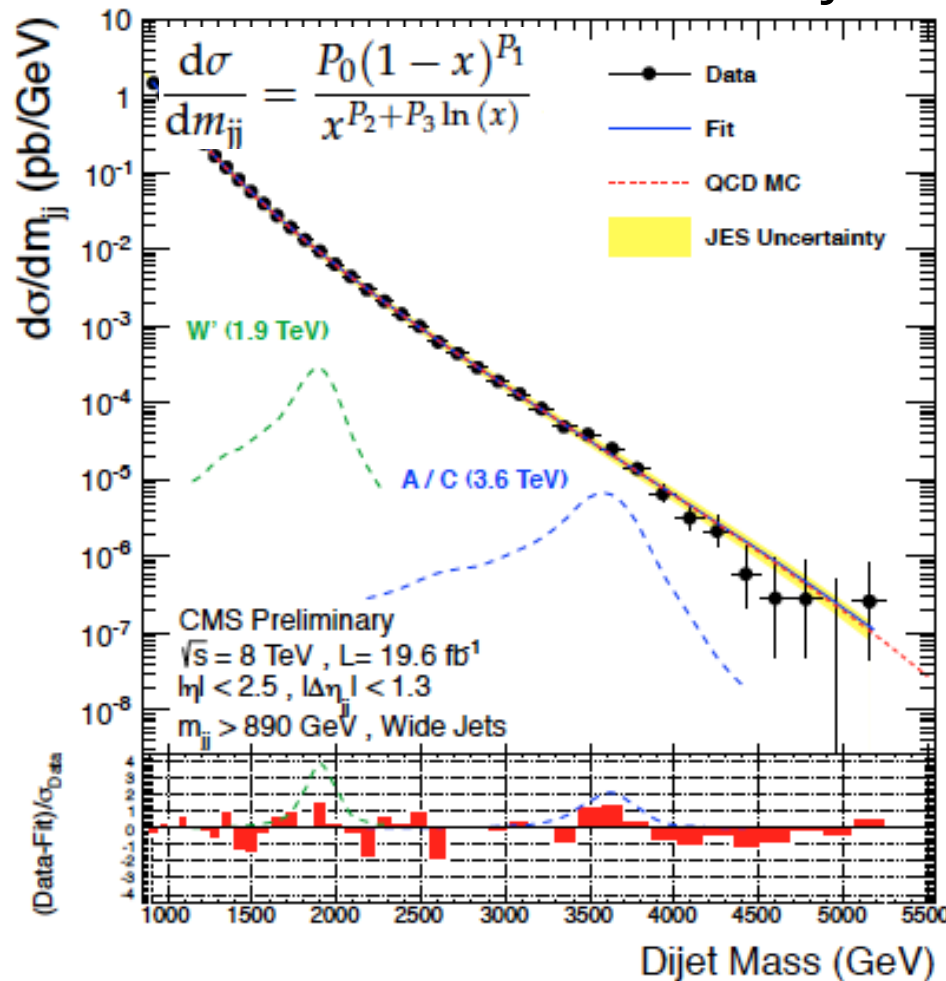
Z' : $> 2.86 \text{ TeV}$

RS-graviton: $> 2.47 \text{ TeV}$

Graviton/Z' (di-jet)

事象選択

- HT/Mjj trigger (HT>650GeV && mjj>750GeV)
- All jets : $|\eta| < 2.5$, $p_T > 30\text{GeV}$
- Two 'wide-jets' : ($R_{\text{wide}} = 1.1$), $\Delta\eta_{jj} < 1.3$, $m_{jj} > 890\text{GeV}$



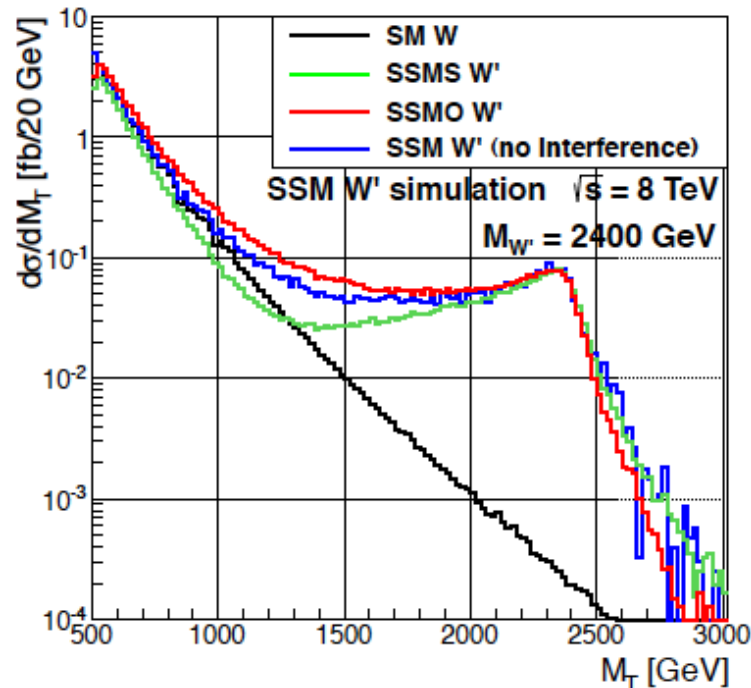
質量下限値

Exited quark : $> 3.50\text{ TeV}$
RS Graviton : $> 1.58\text{ TeV}$

W' (ln)

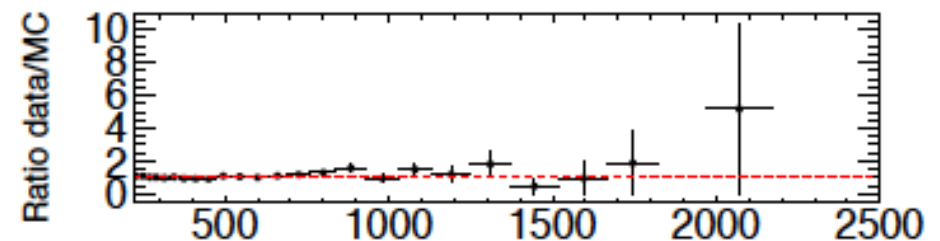
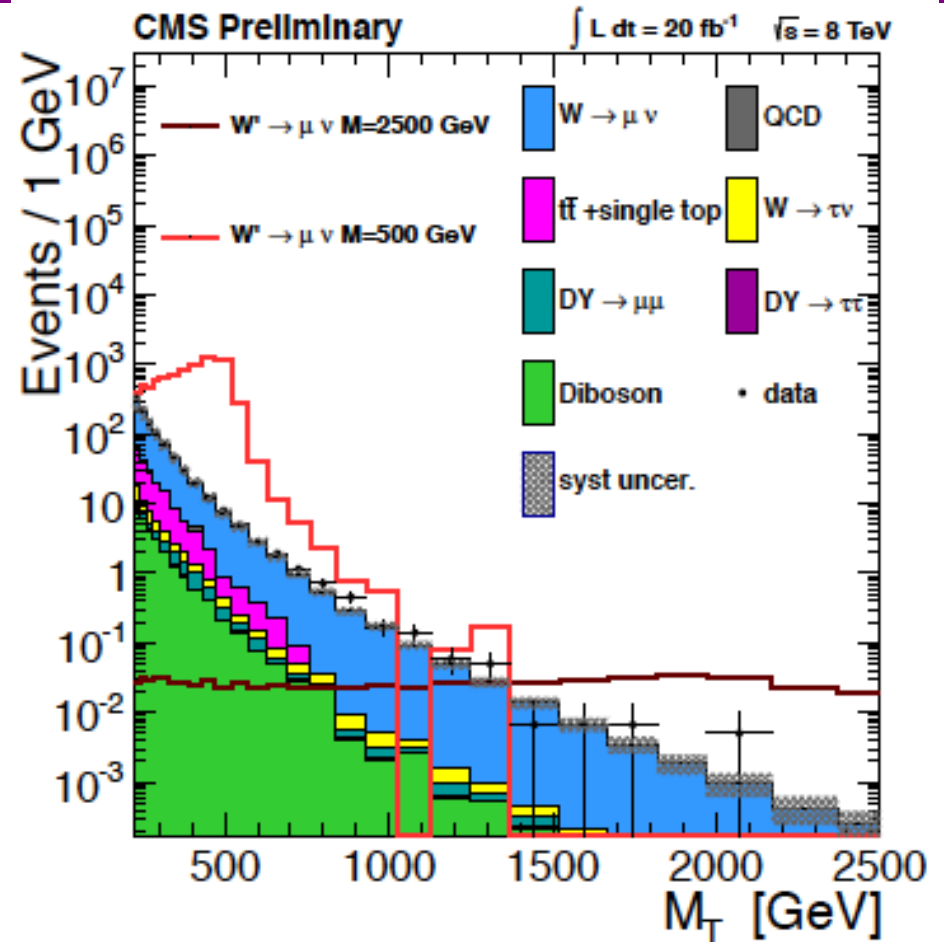
Single lepton trigger

PT > 100 GeV(e), >45GeV(mu)



Binned likelihood : $m_T > 250 \text{ GeV}$

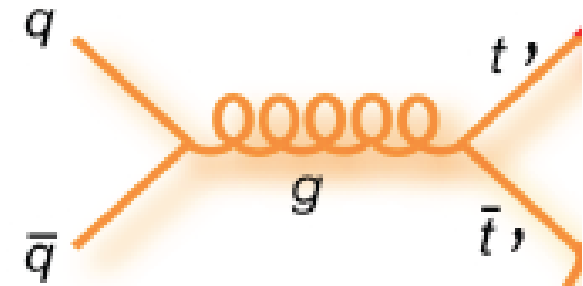
SSM W' 質量下限値
 R-handed: 3.35 TeV
 L-handed : 3.60 - 3.10 TeV



Vector-like quark/Heavy boson

Vector-like quark

- Solve the hierarchy problem w/o SUSY
 - Not excluded by 126GeV higgs discovery
- Little Higgs model, Extra-dimensions..

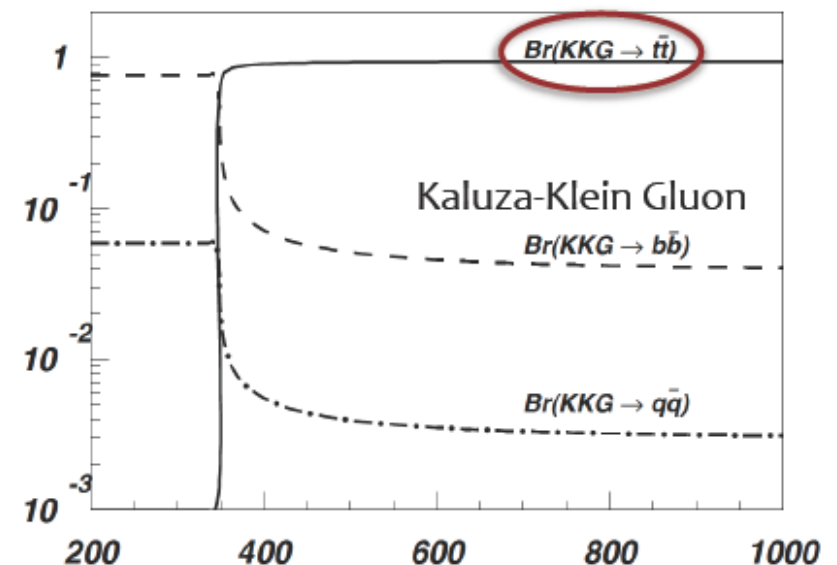


$T_{+2/3} : W^+b, Ht, Zt$
 $T_{+5/3} : W^+t$
 $B_{-1/3} : W^-t, Hb, Zb$
 $B_{-4/3} : W^-b$

Heavy boson (ttbar resonance)

Heavy boson may couple to ll/jj
very weakly...

トップ対を含む終状態にて探索
(same sign leptonsも感度有)



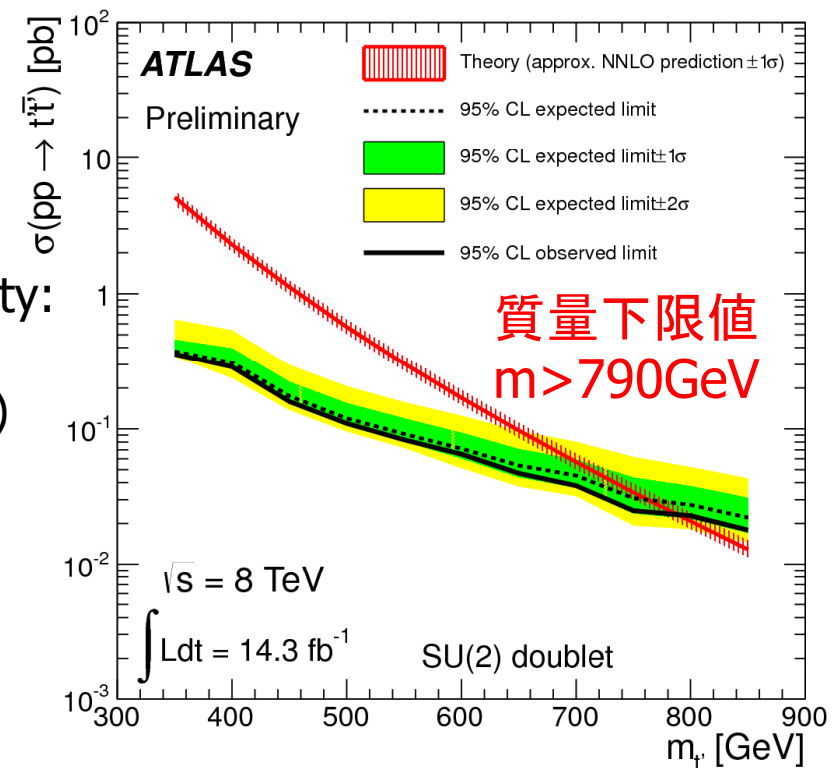
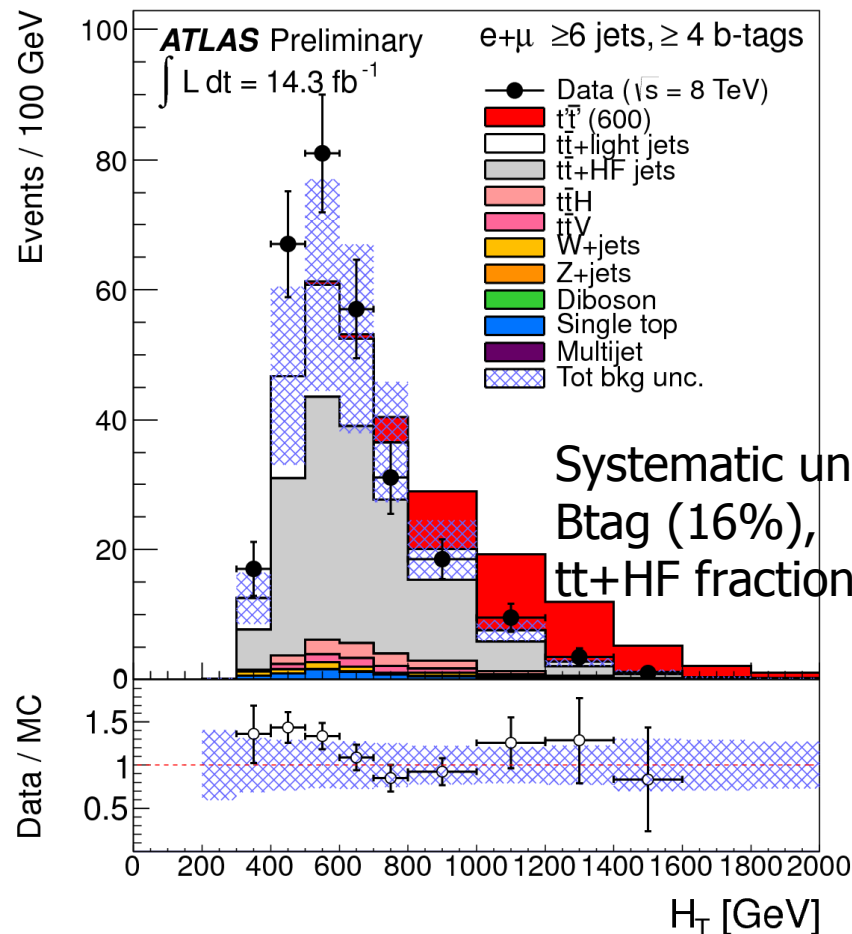
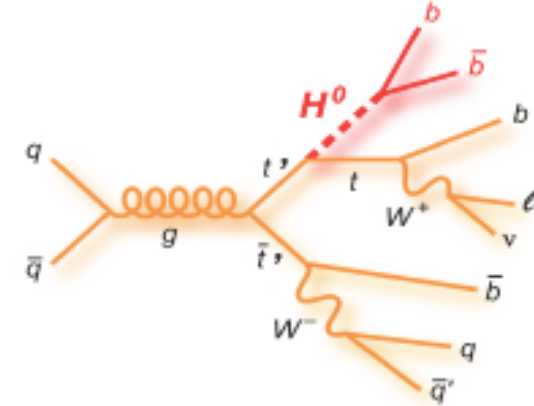
$t't' \rightarrow Ht + X$ (l+jet+MissingET)

14.3 fb⁻¹

6jets + ≥ 4 b-jets + lepton (from W)

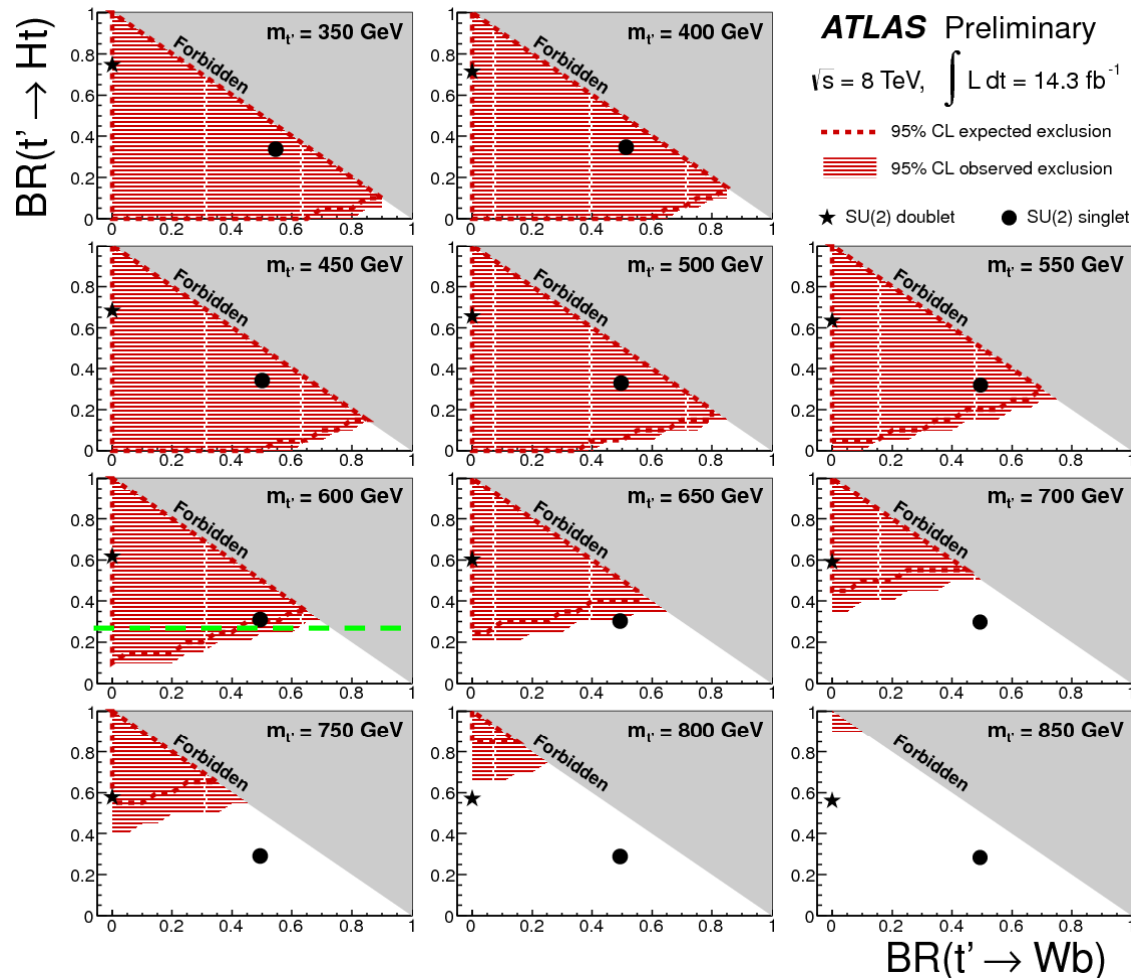
Main background: $t\bar{t}$ +heavy flavor(Alpgen)

Assume SM Higgs with $m=125\text{GeV}$



$t't' \rightarrow Ht + X$ (l+jet+MissingET)

	≥ 6 jets, 2 b -tags	≥ 6 jets, 3 b -tags	≥ 6 jets, 4 b -tags
Prediction	11860 ± 260	2990 ± 210	270 ± 60
Data	11885	2922	318



Consider signal contaminations from the other decay

★ Doublet
● Singlet

t' mass limit

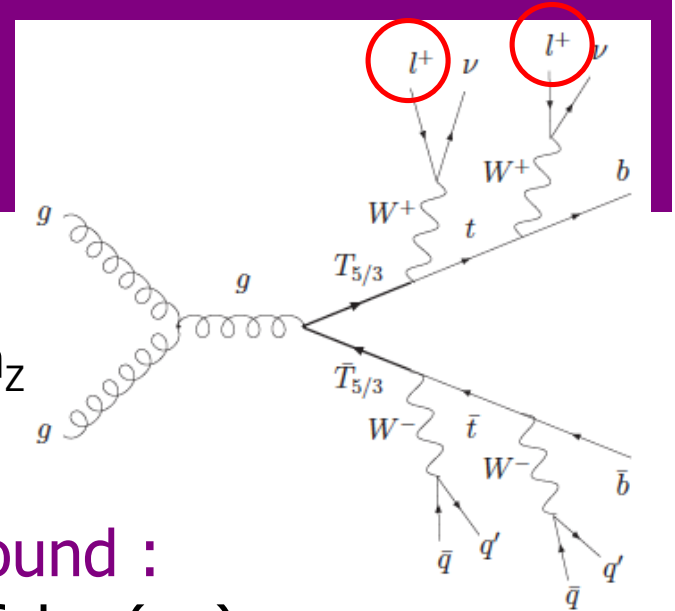
SU(2) doublet
 $m > 790 \text{ GeV}$

SU(2) singlet
 $m > 640 \text{ GeV}$

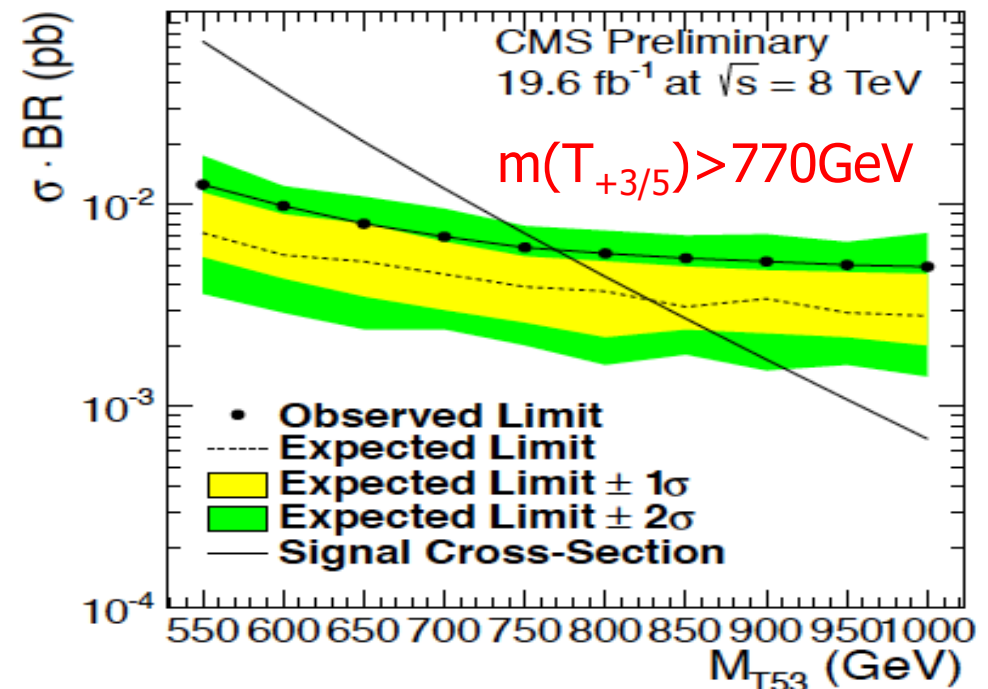
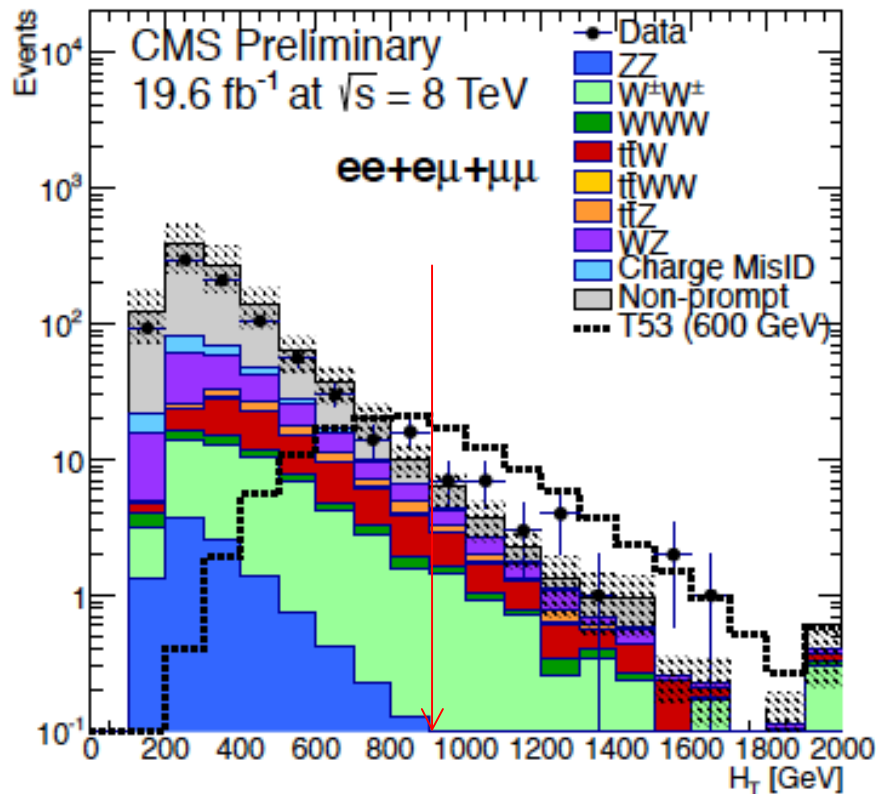
$T_{+5/3}$ (in SS di-lepton)

Event selection:

- Same-sign dilepton : $m_{ll} > 20 \text{ GeV}$, $m(ee) \neq m_Z$
- top-tagger: top-jet, W-jet, multi-jets
- $HT > 900 \text{ GeV}$

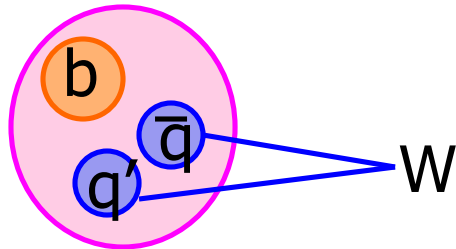


SM background :
 $t\bar{t}V, W^+W^+, \text{fake}(ee)$



tt resonance (semi-leptonic)

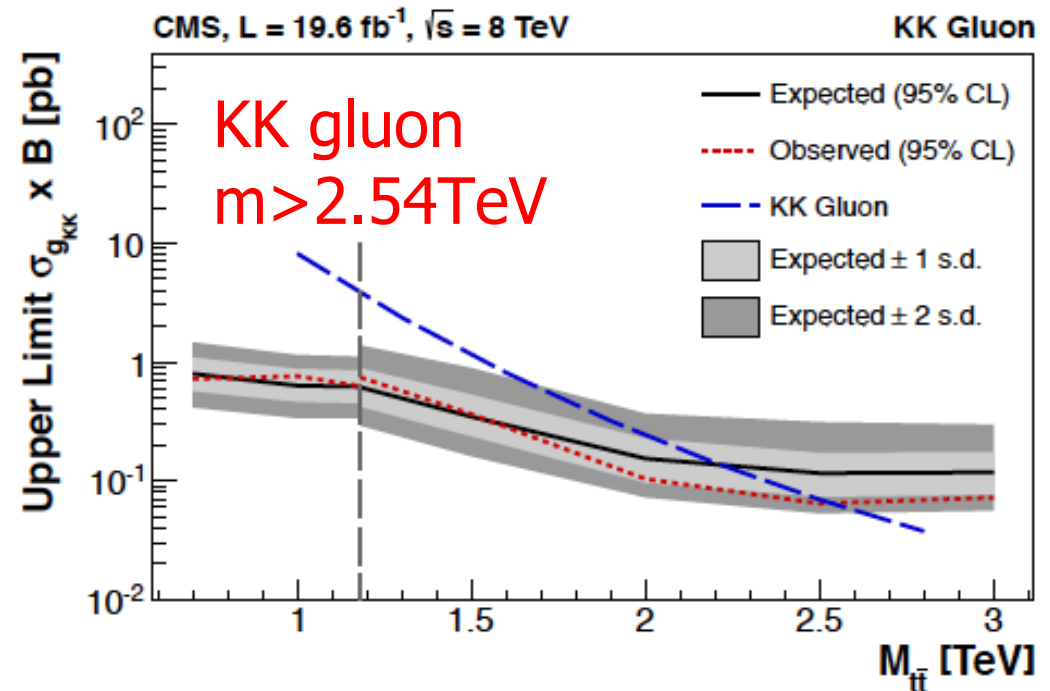
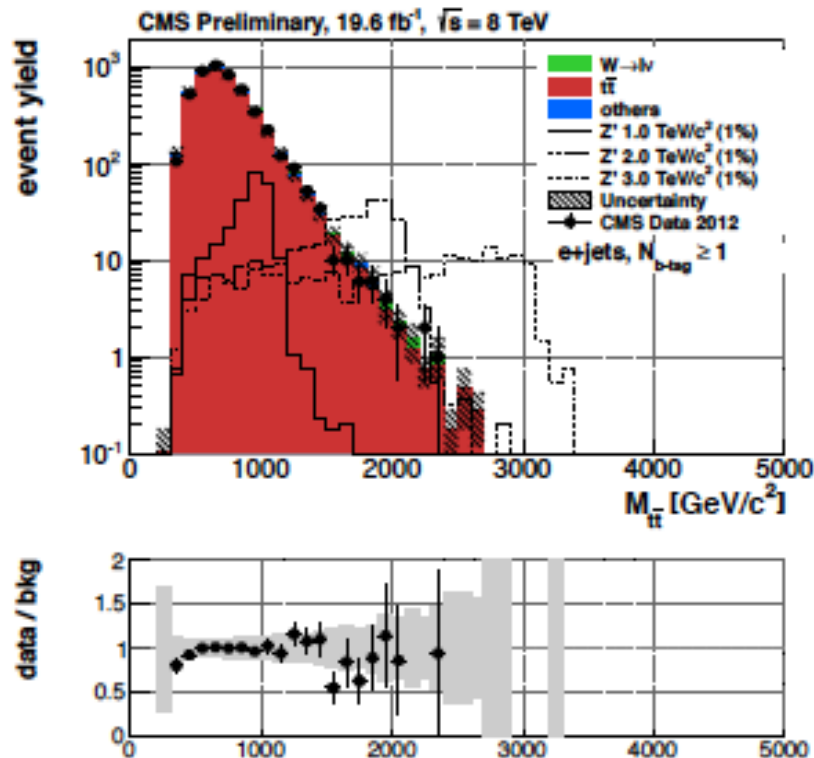
- Threshold analysis (0.3-1TeV)
- Boosted top analysis (>1TeV)



4jets + isolated lepton
2jets + lepton

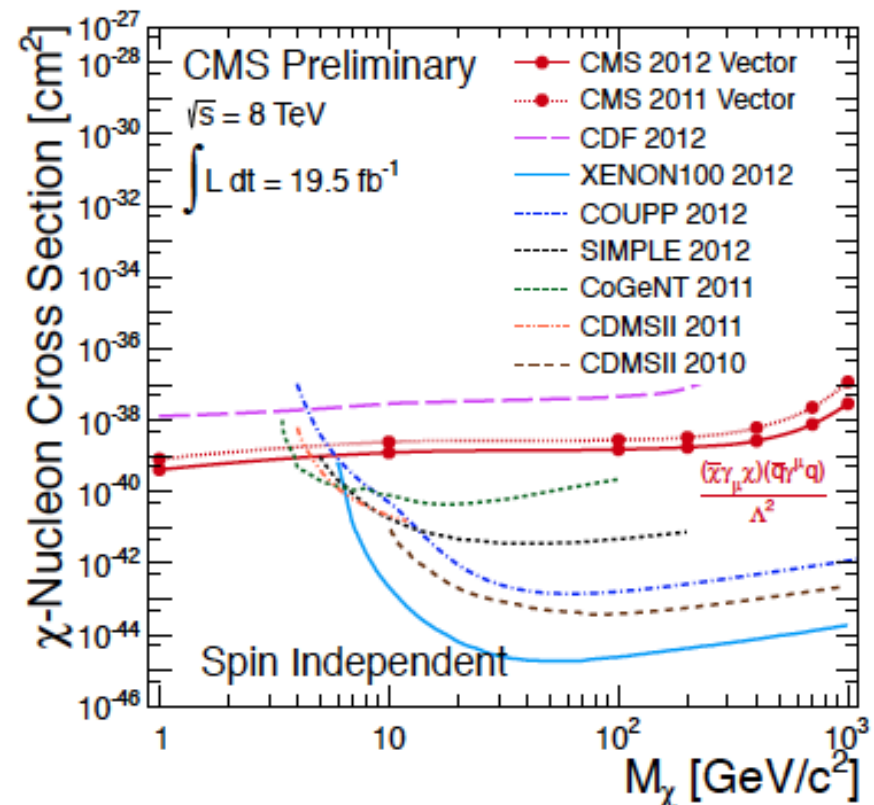
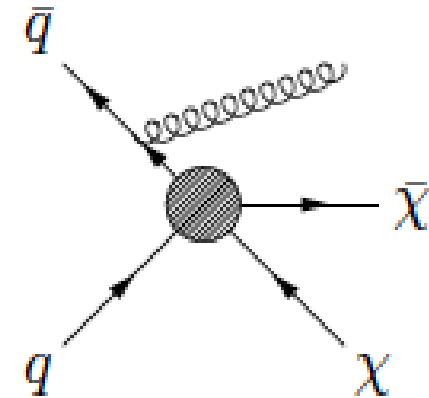
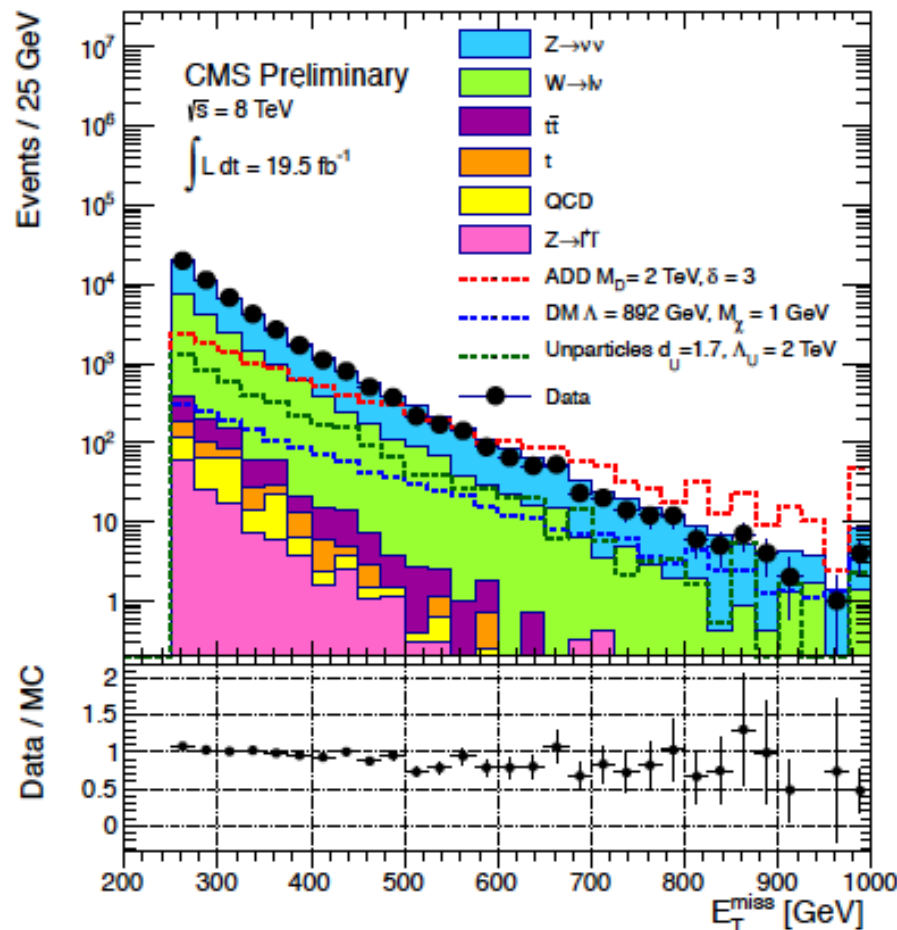
tt reconstruction

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W} \right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h - W}}{\sigma_{t_h - W}} \right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}} \right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{\text{diff } p_T}} \right]^2$$



Dark matter search in mono-jet

- MET/MET+JET trigger
- 1st jet > 110 GeV, met > {250-550} GeV
- 3rd jet veto ($p_T > 30 \text{ GeV}, |\eta| < 4.5$)



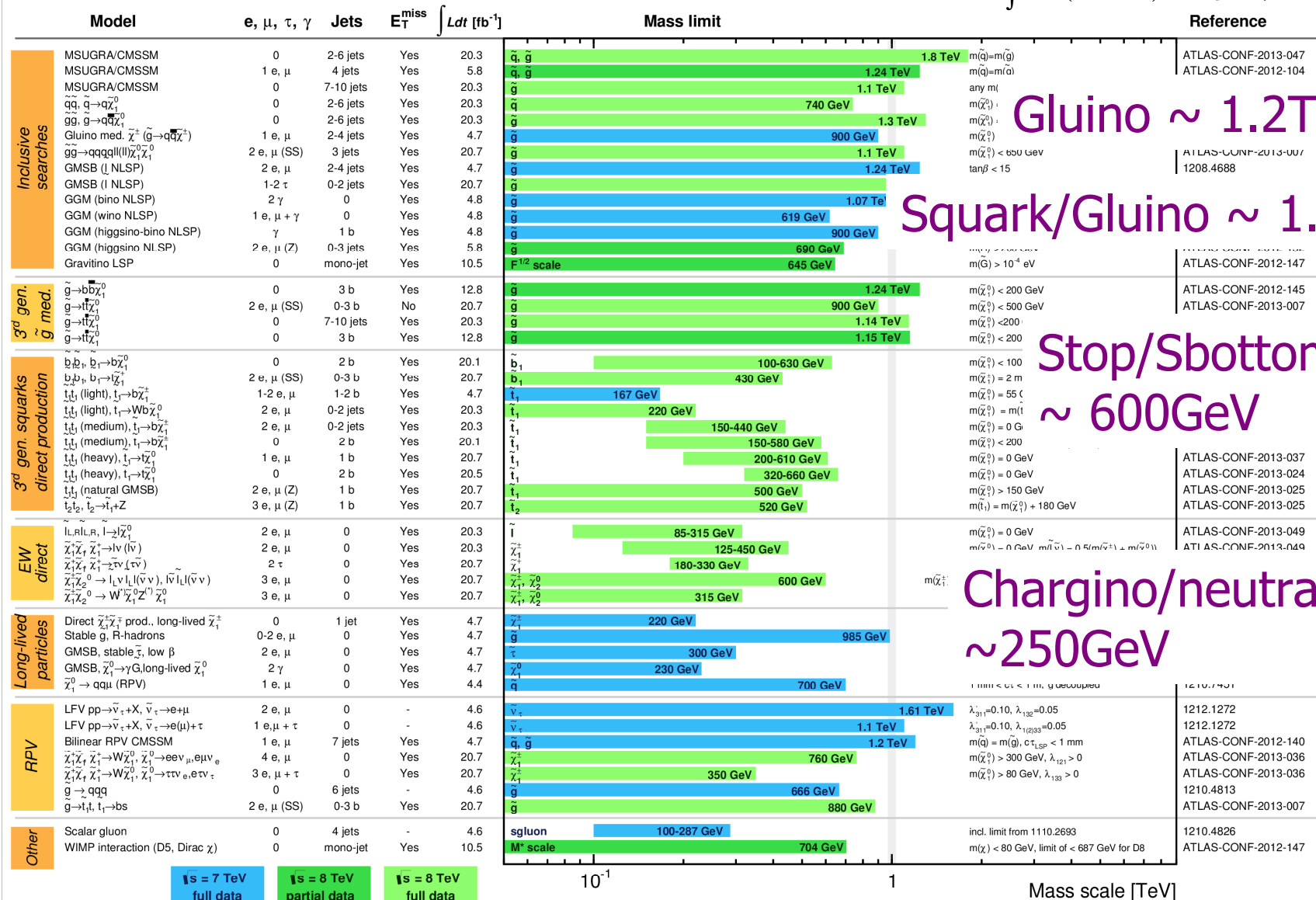
現在(LHCP13)までのATLAS実験による制限(SUSY)

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LHCP 2013

ATLAS Preliminary

$$\int Ldt = (4.4 - 20.7) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$



Gluino $\sim 1.2\text{TeV}$

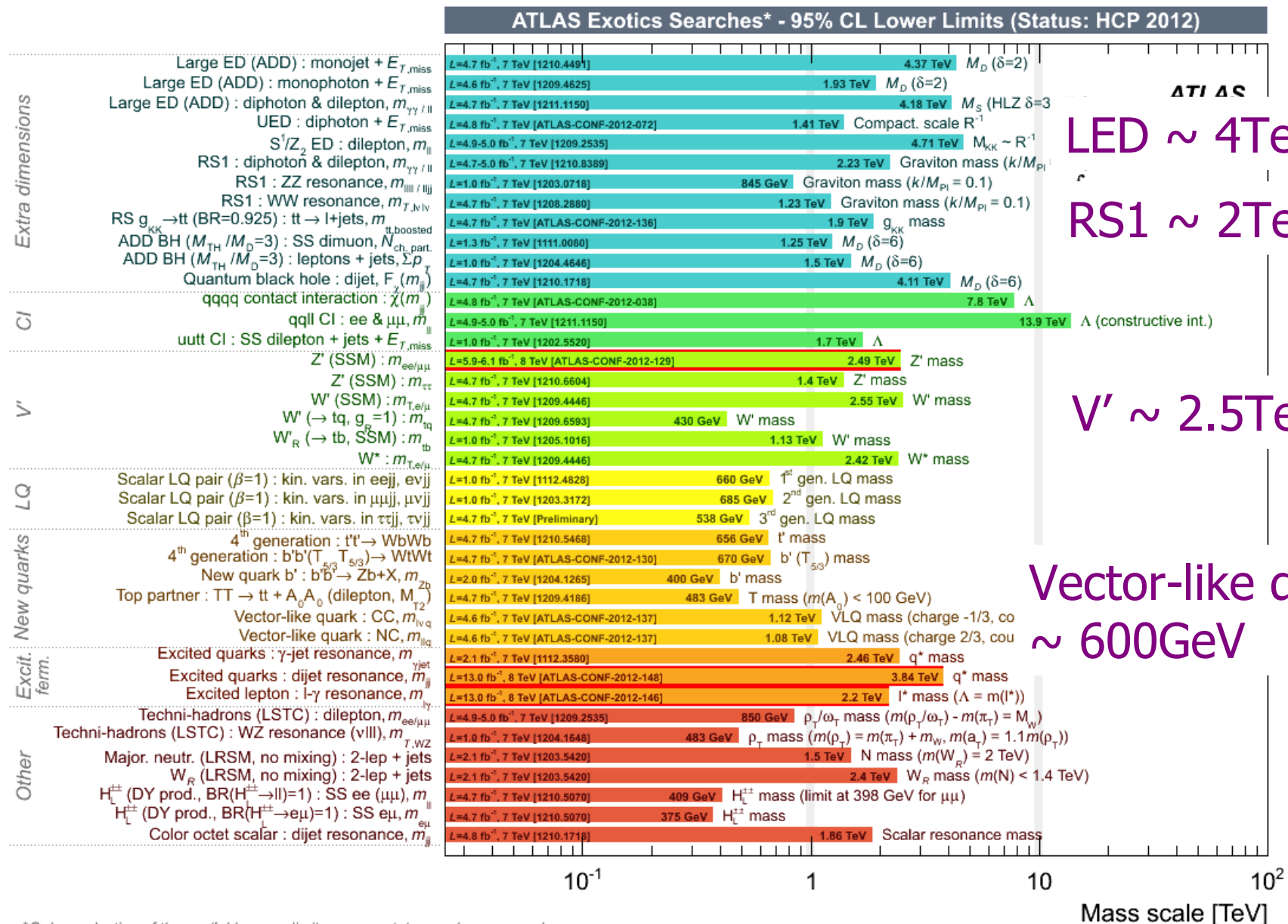
Squark/Gluino $\sim 1.8\text{TeV}$

Stop/Sbottom $\sim 600\text{GeV}$

Chargino/neutralino $\sim 250\text{GeV}$

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

現在(LHCP13)までのATLAS実験による制限(Exotic)



Summary

2012年、ATLAS/CMS各々で約 20fb^{-1} のデータをレコード

CONFeRence notes using full dataset:

ATLAS SUSY	13 (submitted)	~20 more (expected)
ATLAS Exotic	1 (submitted)	~30 more (expected)

今のところ、残念ながらBSM-likeな徴候はみえていない。。。

ATLAS: 解析進行中。夏の国際会議までにはほぼ全解析結果が出そう予定。2013年末までにpublication。

LHC8 解析。まだやり残しがあるか??

まだカバーしきれていないphase space (compressed, RPV, Exotic signature).
今のapproach or interpretationで問題ないか(simplified model)、
バックグラウンド推定方法 for discovery...

LHC13/14 →明日の山中さん(SUSY)、寺師さん(non-SUSY)