LHC実験における8TeVでのSUSY探索および14TeVへの展望

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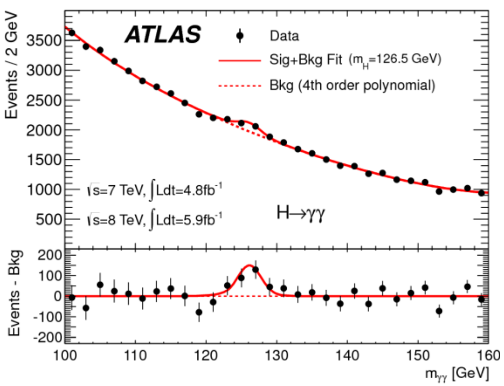
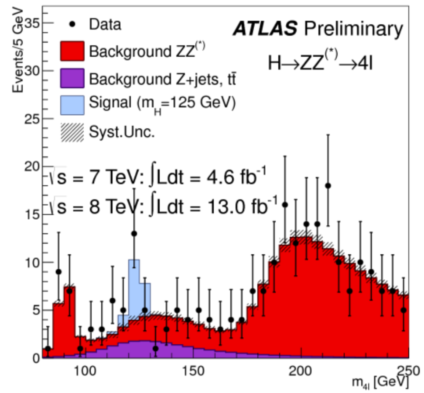
Discovery of a Higgs Boson

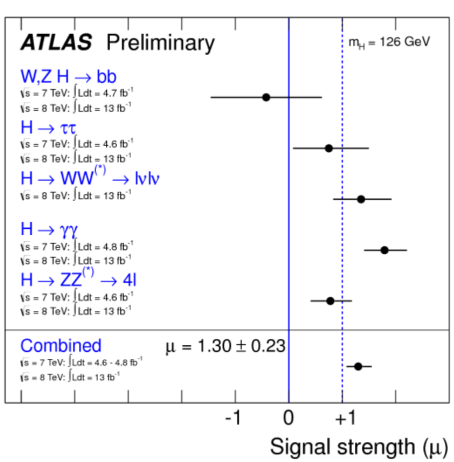
- LHC Run1のハイライト

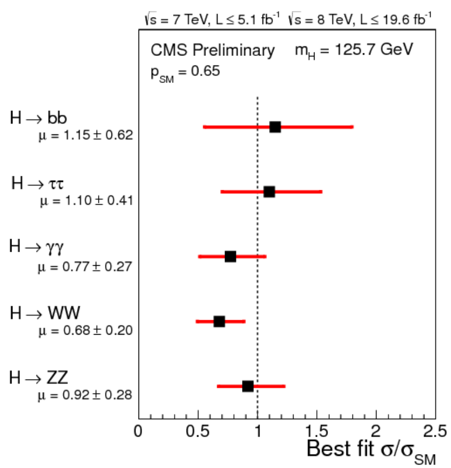


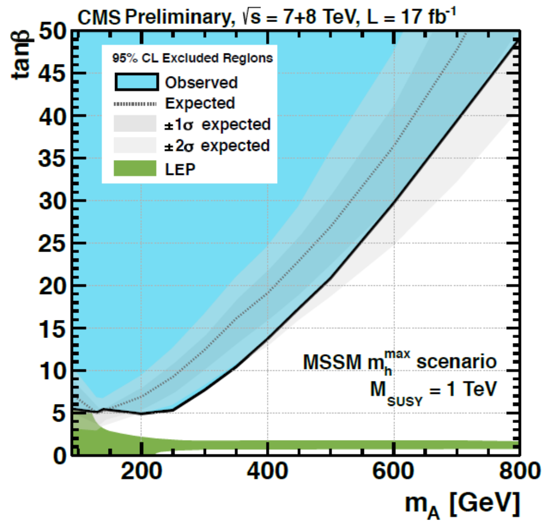


ヒッグス粒子（らしきもの）をm=126 GeVに発見！

見えている粒子はSM Higgsにほぼconsistent



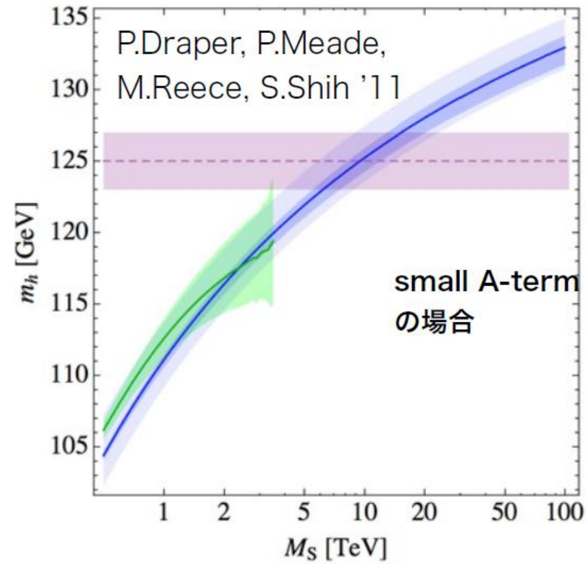




しかし、その他のHiggs particleに関する示唆は今のところ無い
← MSSM Higgs exclusion limit

126 GeV Higgs for SUSY

- ヒッグス粒子126 GeVをnaïveに考えると、SUSYのmass scaleは~10 TeV
  - → LHC √s=14 TeVでは不可能（m~g, m~q < 2.5 TeV）
  - → HE LHC (√s=~33 TeV)
  - でも不可能 ~ 6 TeV
  - → VHE LHC (√s=100 TeV)なら可能か?



その場合、14TeV LHCでの探索は可能か？

Naturalness?

Yes → stop search (stop mass < 1 TeV)

No → squark mass ~10 TeV?

gluino mass < 2.5 TeV

Yes → gluino search

No → EW gaugino mass < 1 TeV

Yes → EW gaugino search

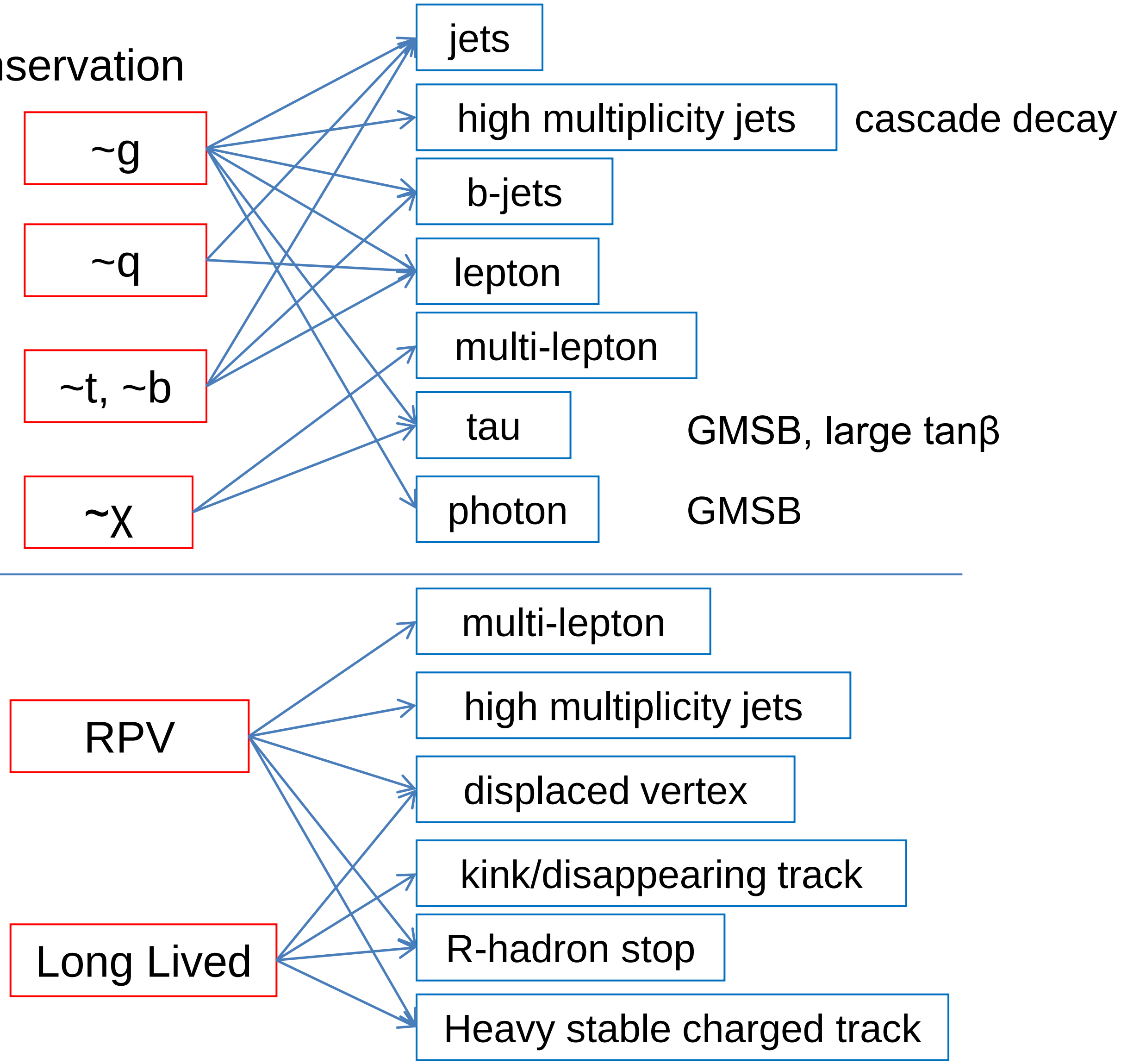
No → その他

Strategy for SUSY Search

RP Conservation

topologyごとに分けて解析→
model independentに広く
cover

MET



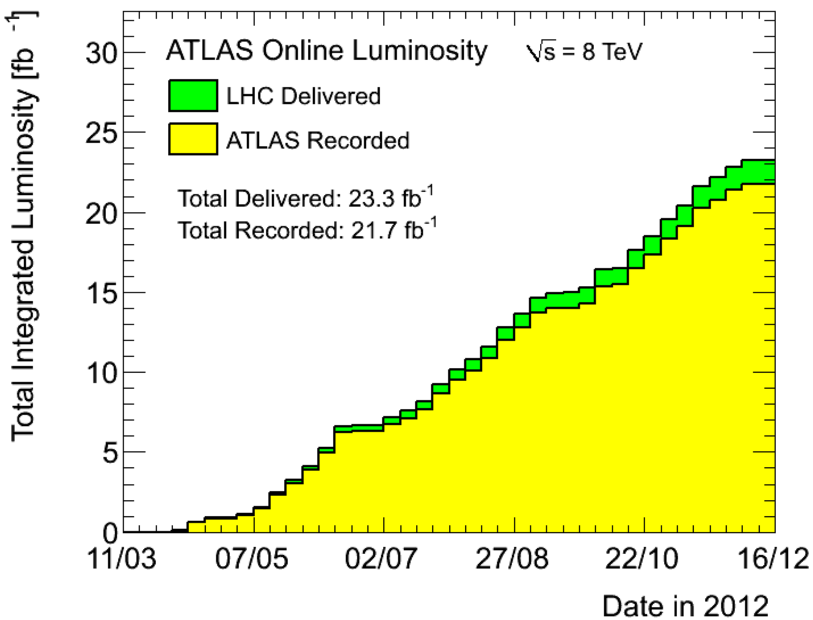
without MET

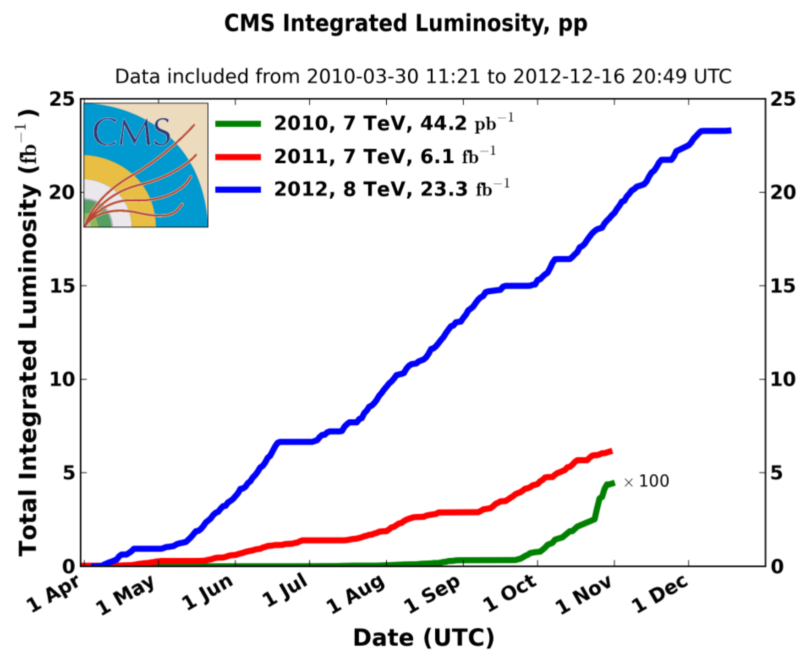
Contents

- 2012年のLHC運転状況
- √s=8 TeVでのSUSY探索
  - MET-based Analysis
    - gluino (squark) search
    - stop search
      - Gluino mediated stop
    - EW gaugino search
  - Without MET Analysis
    - Long lived particle
    - Exotic signature
- √s=14 TeVでのSUSY探索
- まとめ

LHC 2012

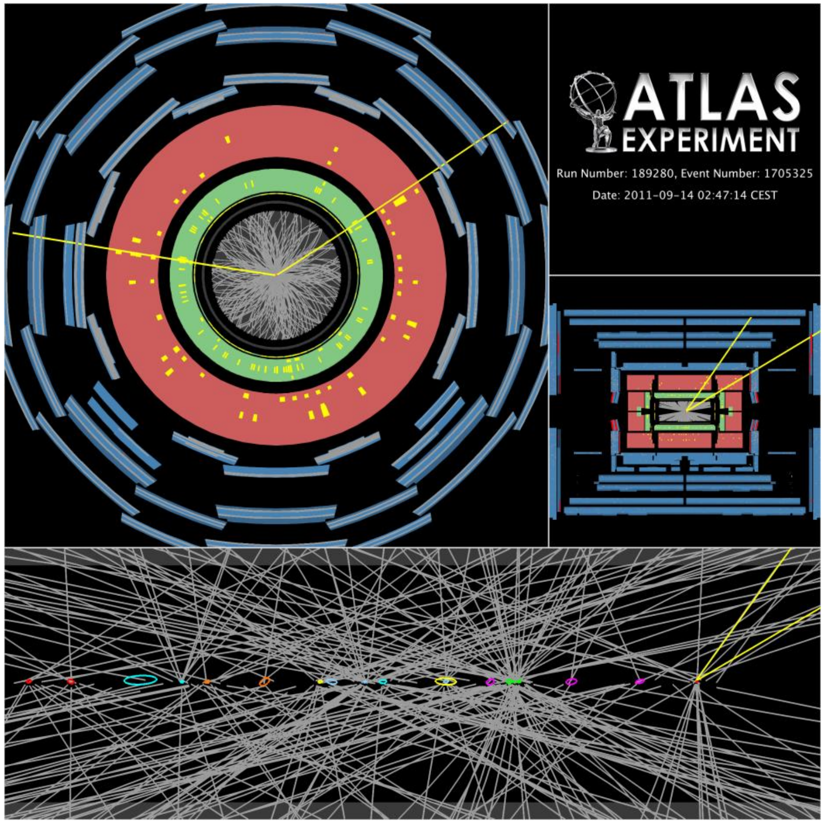
- 2012年には√s=8 TeVで、約20/fbのデータを取得
  - 高い効率で取得　(Recorded/Delivered=93% at ATLAS)
  - また、高い効率で検出器がGood condition (Good/Recorded>96% at ATLAS)



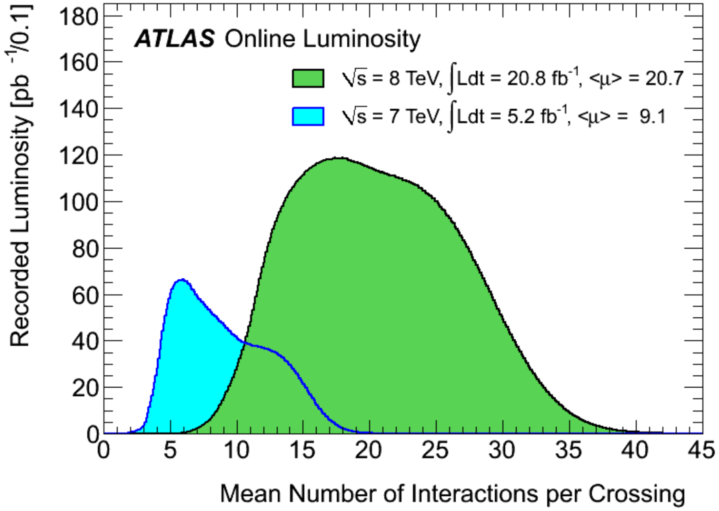


Pileup

- Pileupへの対処が重要



Z→μμ with 20 pileup event (p_T>0.4 GeV tracks are shown, yellow lines show muons from Z)



1衝突あたりのPileup数の分布

Pileupへの対処

online trigger

- electron: calorimeter isolation, hadronic leackage

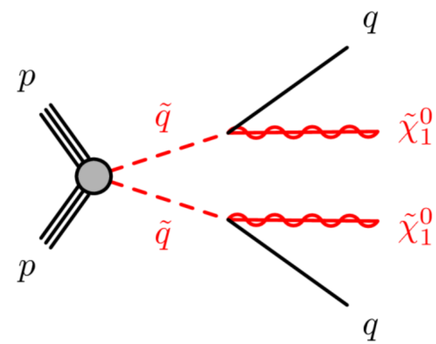
offline analysis

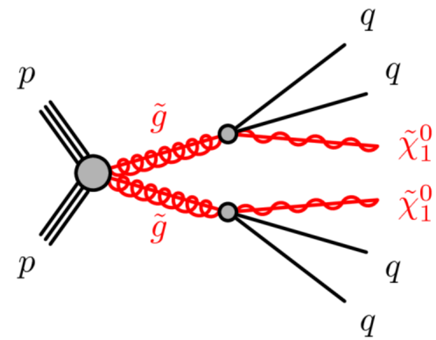
- jet, MET: pileup subtraction, vertex association
- Monte Carlo**:** pileup reweighting

MET-based Analysis

Gluino/Squark Search

- ~q~qから~g~gまで広くtopologyをcoverするために、jet数ごとにsignal regionを設定（2-6 jets)
- 更にm_{eff} (=MET+jet pt sum)のselectionを各jet数ごとに数個に分けることにより、広いkinematics regionをcover





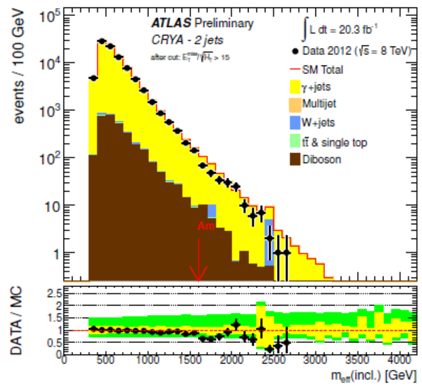
Requirement	Channel									
	A (2-jets)		B (3-jets)		C (4-jets)		D (5-jets)	E (6-jets)		
	L	M	M	T	M	T	–	L	M	T
E_T^{miss}[GeV] >	160									
$p_T(j_1)$ [GeV] >	130									
$p_T(j_2)$ [GeV] >	60									
$p_T(j_3)$ [GeV] >	–		60		60		60	60		
$p_T(j_4)$ [GeV] >	–		–		60		60	60		
$p_T(j_5)$ [GeV] >	–		–		–		60	60		
$p_T(j_6)$ [GeV] >	–		–		–		–	60		
$\Delta\phi(\text{jet}_i, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, (3 \text{ if } p_T(j_3) > 40 \text{ GeV})\}$)				0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_T > 40$ GeV jets)					
$E_T^{miss}/m_{eff}(Nj)$ >	0.2	–[a]	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
m_{eff}(incl.) [GeV] >	1000	1600	1800	2200	1200	2200	1600	1000	1200	1500

(a) For SR A-medium the cut on $E_T^{miss}/m_{eff}(Nj)$ is replaced by a requirement $E_T^{miss}/\sqrt{H_T} > 15$ GeV$^{1/2}$.

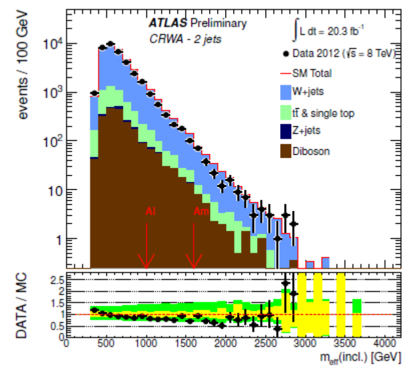
Gluino/Squark Search at ATLAS

- Background estimation
  - 各backgroundをenhanceするように取られたcontrol regionからsignal regionへのtransfer factorをMC sampleでestimate
  - control regionでMCをdataにfitし、transfer factorを使い、signal regionでのbackgroundをestimate

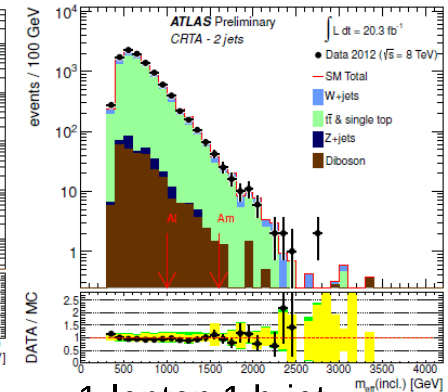
2jets CRの場合



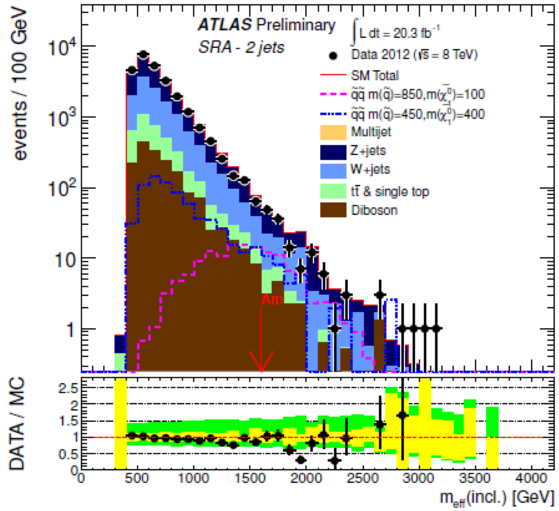
1-photon (Z→νν+jets のestimation)



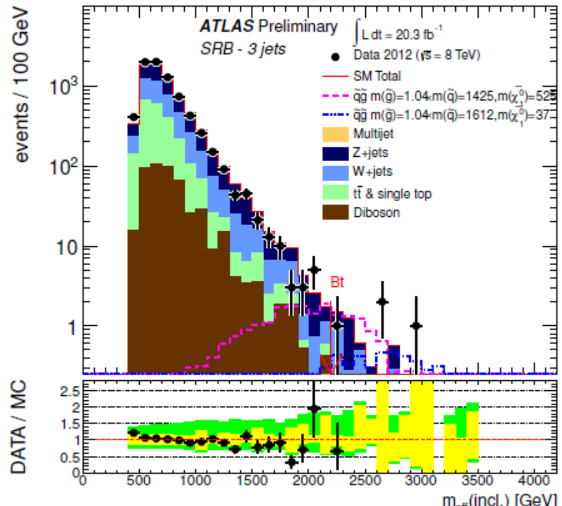
1-lepton b-jet veto (W→lν+jets CR)



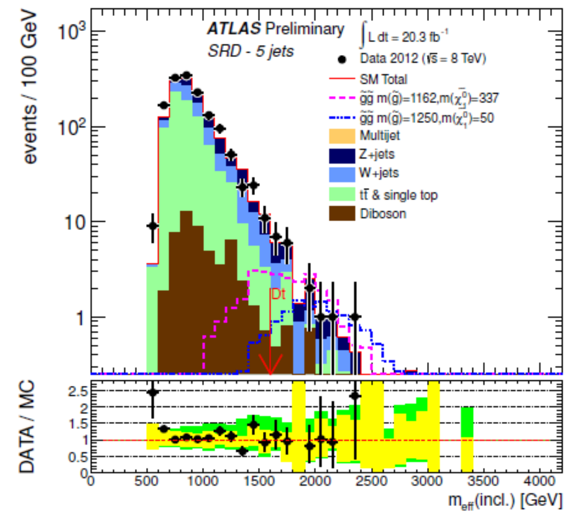
1-lepton 1 b-jet (ttbar CR)



2jets



3jets

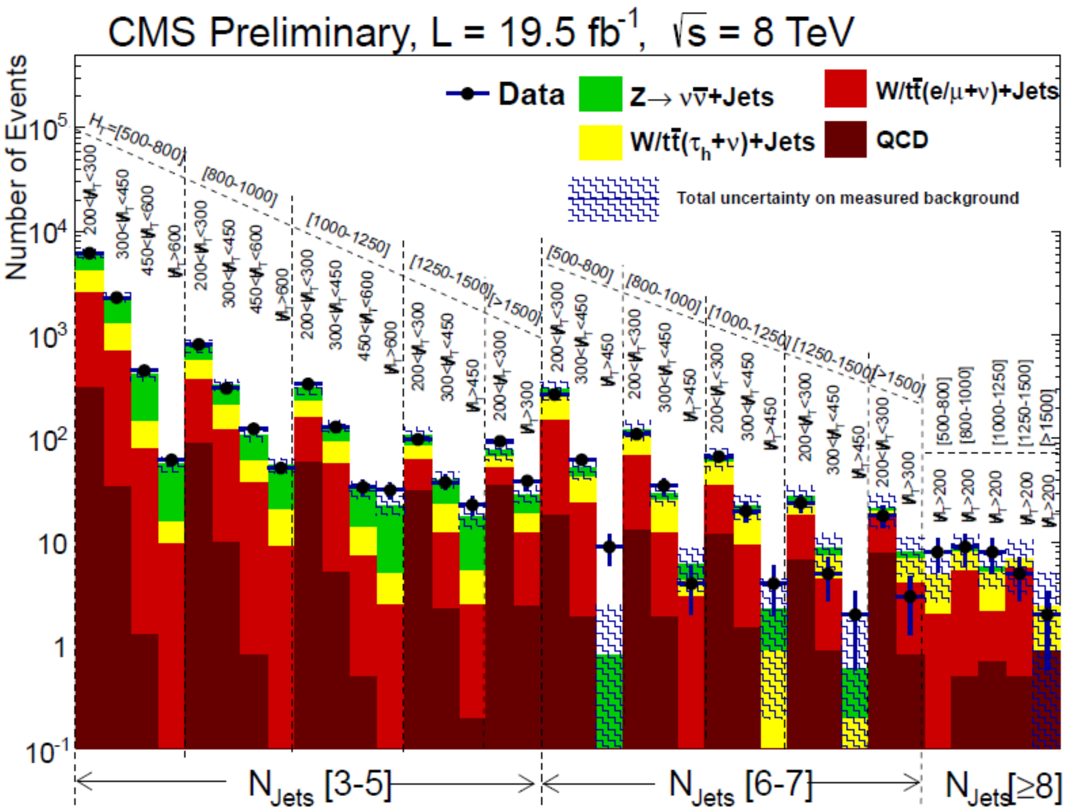


5jets

各signal regionでのm_{eff}分布

Gluino/Squark Search at CMS

- CMSも基本的な解析方針は同じ



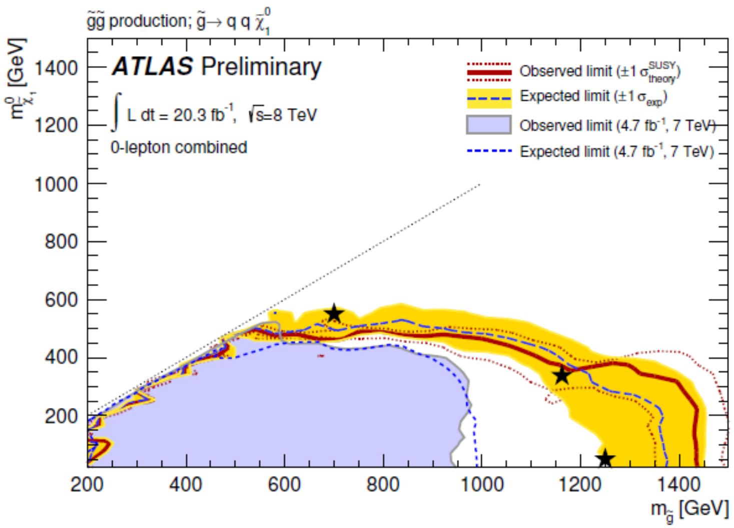
- Number of jetsごとにsignal regionを分ける
- 各Njet regionをさらにHT (=jet pt sum)とMETの2次元で分けることにより、広いkinematics regionをcover

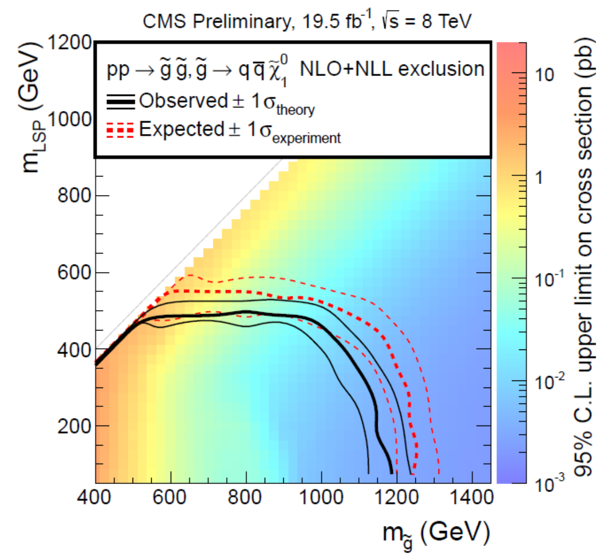
Background estimationはほぼdata-driven

- QCD: jet resolution smearing
- W→τν (hadronic)+jets: μ+jets replacement
- W→e/μν+jets: lepton ID inversion
- Z→νν+jets: γ+jets replacemnt

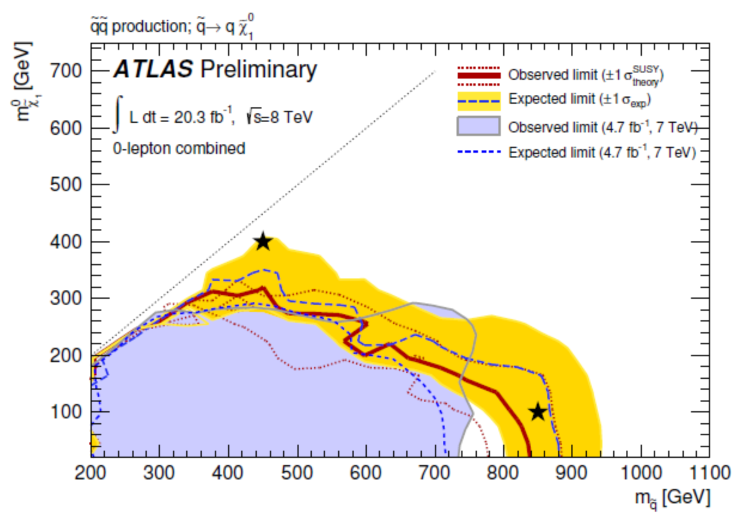
Results

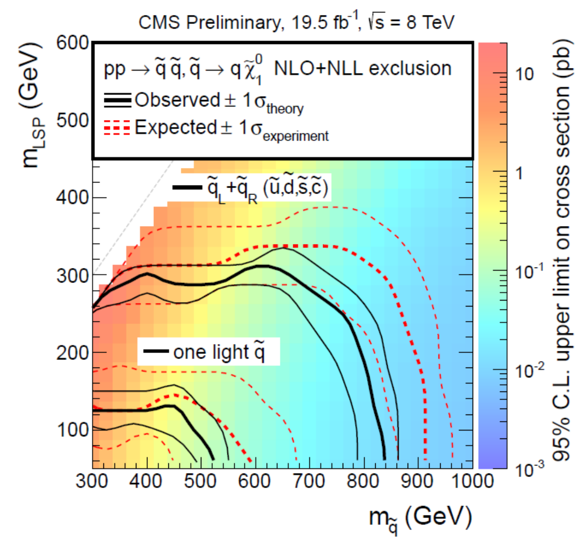
~g~g production





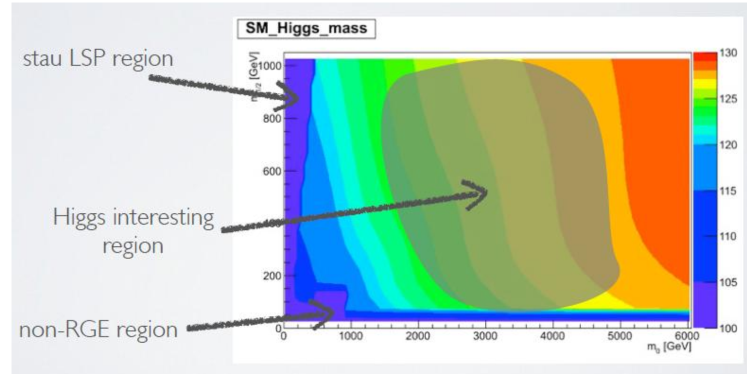
~q~q production

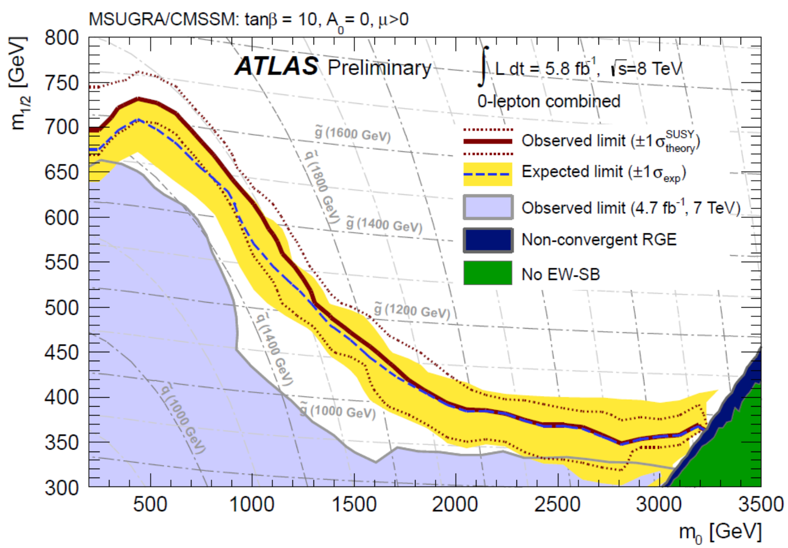




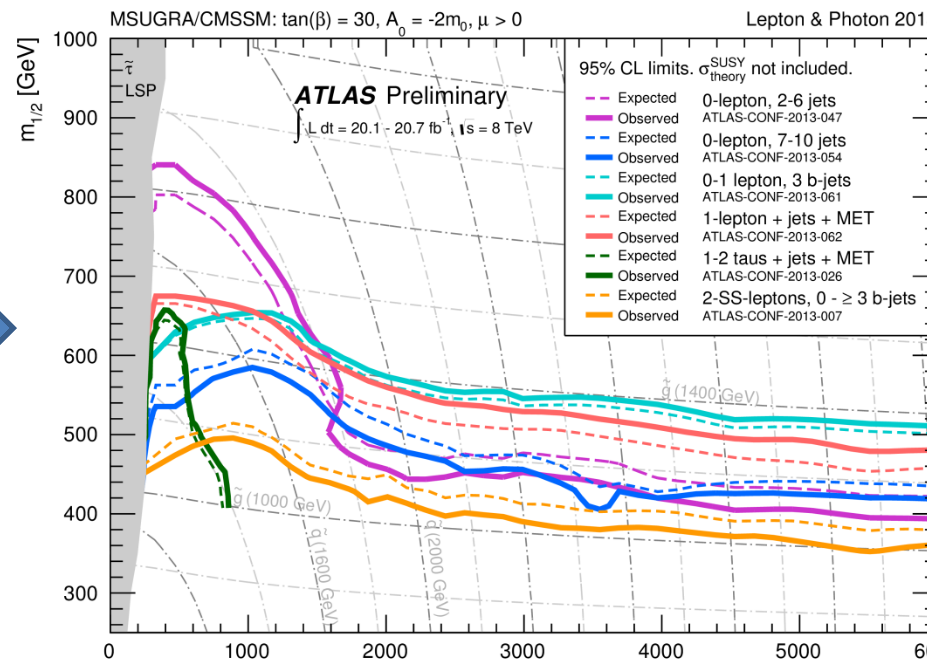
Gluino/Squark (Higgs Aware CMSSM)

- もはやHiggs 126 GeVを説明しないmodelはnon-sense
- $|A_0|$をほぼstopのmaximal mixingを満たすよう取り、Higgs massにconsistentに調整したmodelでのinterpretation.



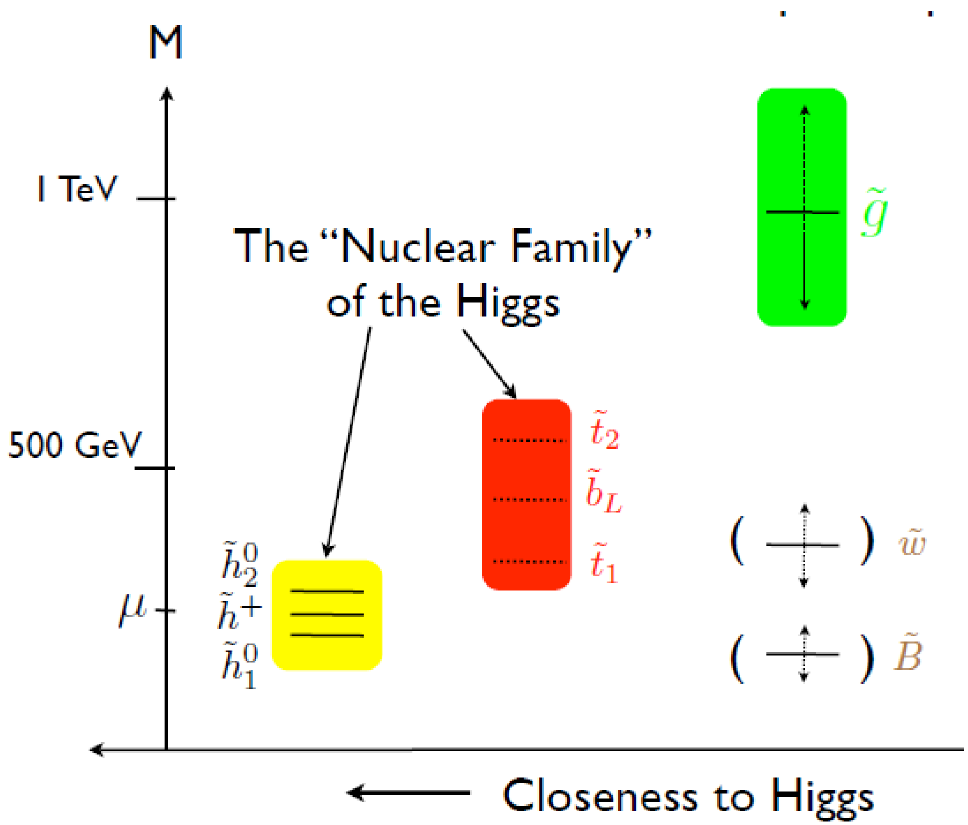


A_0=0, tanβ=10



A_0=-2m_0, tanβ=30

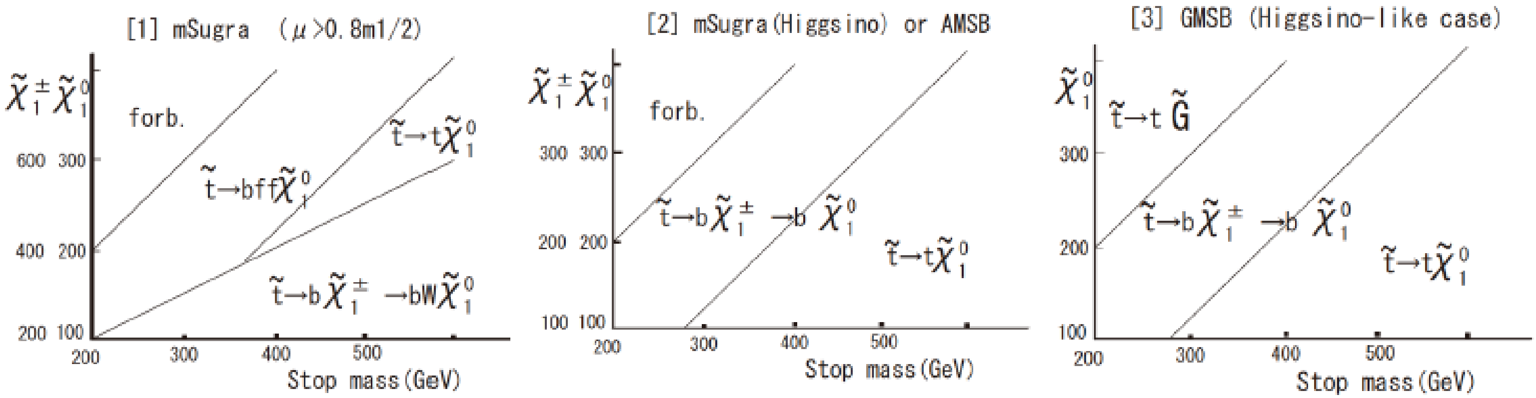
Naturalness



- 比較的stop (and sbottom)が軽いのでdirect productionが可能
- gluinoも比較的軽いことが期待され、そのdecay modeではstop (top)へが優勢になる
- Higgsinoも同様に軽いことが期待される

Stop Signature

- Stop pair productionからの崩壊過程でもmodel (parameter)によってkinematicsが大きく異なる。



主にchargino/neutralinoのmass relationおよびwino/bino/higgsino compositionにより崩壊過程が変わる。
→ Topology baseで解析することによりmodel independentにcover

	0-lep 6-jets	1-lep 4-jets	2-lep 2-jets	0-lep 2-jets	2/3-lep (Z) 3-jets
t+N1	○	○	△		
b+C1	△	○	○	○	
b+W+N1	△	○	○		
c+N1				○ (c-tag)	
b+f+f'+N1	△	○(？)		○(？)	
b+C1/t+N1 (GMSB)	△				○

△：可能なfinal stateだがsensitivityは低い
（？）：まだBackground study中

1-lepton Analysis

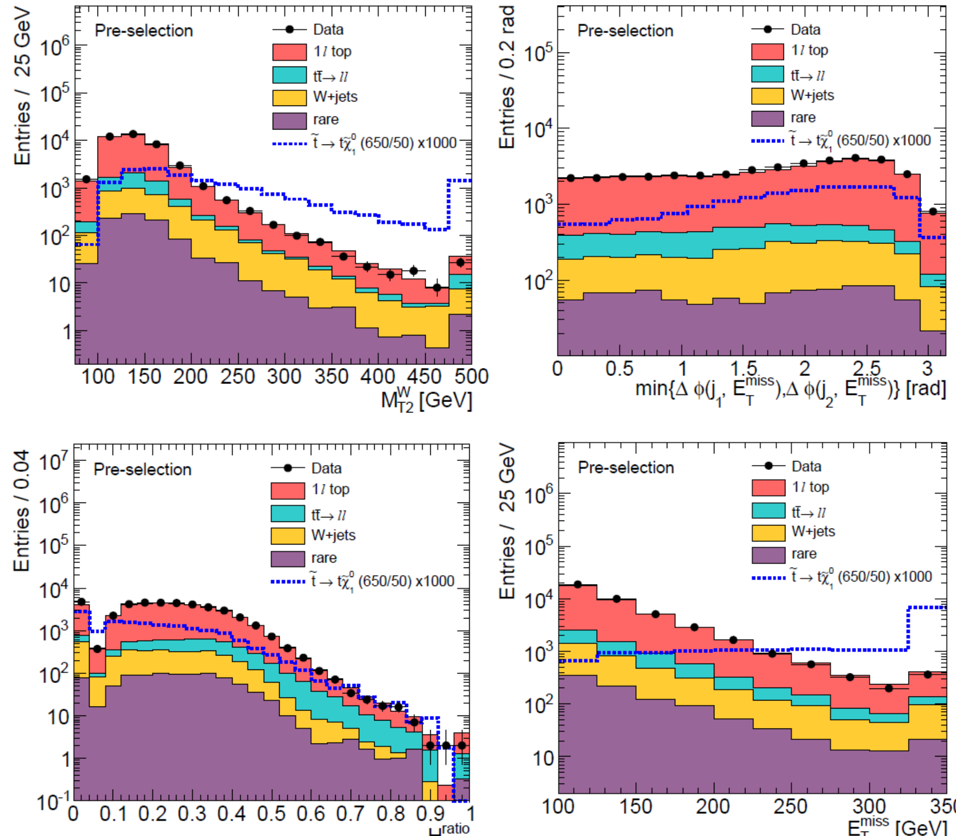
- 1-lepton channel: W, WからのBRが比較的大きく、triggerによるlossも少ない → 縮退したmodelからhigh METのtailまで広くcoverできる

Pre-selection
- 1-electron (pT>30GeV) or 1-muon (pT>25 GeV)
- At least 4-jets pT>30 GeV
- At least 1 b-tagged jet
- MET>100 GeV
- MT>120 GeV

BDT (multivariate discriminant)を用いてsignalをenhanceする。
使用する変数
- MET
- HTratio
- M_T^{2W}
- Hadronic top χ^2 or leading b-jet pT
- minΔφ(MET vs. 2 leading jets)

$$\chi^2 = \frac{(M_{j_1j_2j_3} - M_{\rm top})^2}{\sigma^2_{j_1j_2j_3}} + \frac{(M_{j_1j_2} - M_{\rm W})^2}{\sigma^2_{j_1j_2}}$$

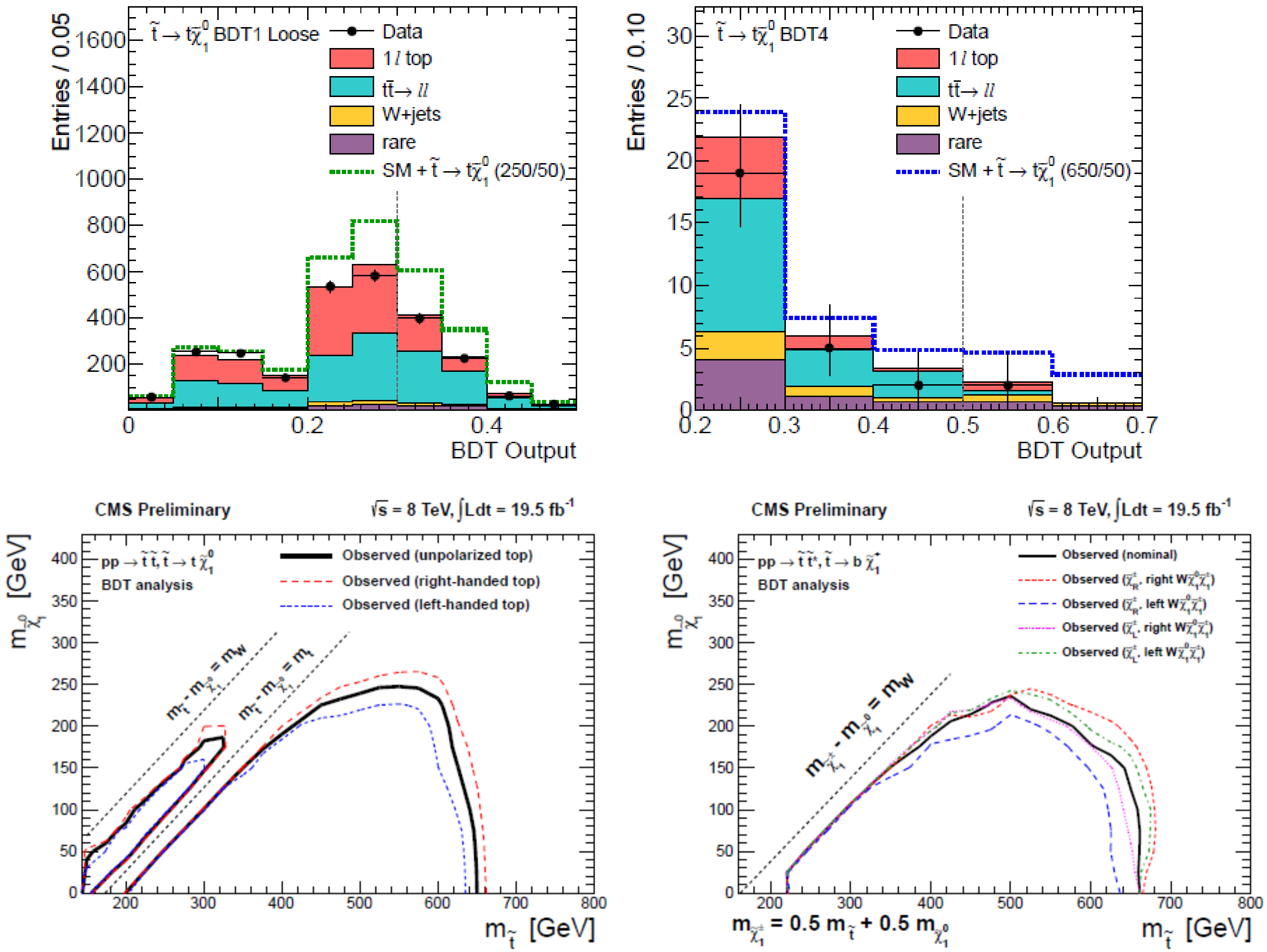
$$M_{T2}^{W} = \text{minimum}\left\{ m_y \text{ consistent with: } \left[\begin{array}{c} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{miss}, p_1^2 = 0, (p_1 + p_l)^2 = p_2^2 = M_W^2, \\ (p_1 + p_l + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$



BDTに使用した変数の分布

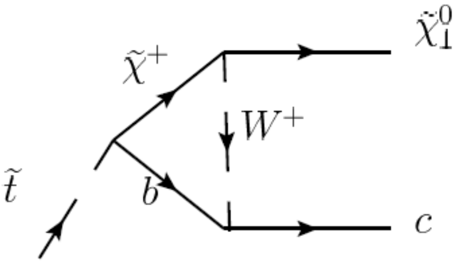
Stop 1-lepton Analysis

- BDT results



Stop→Charm+LSP

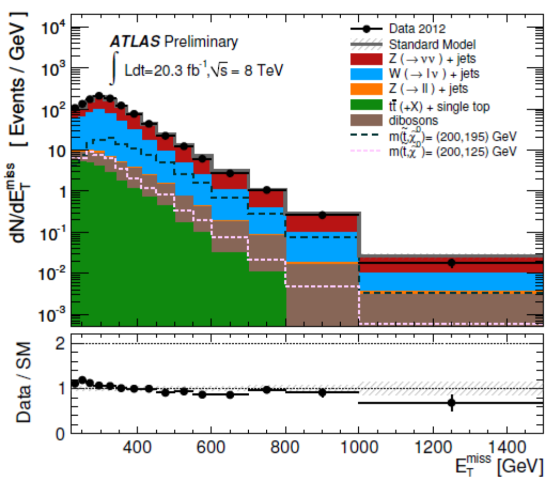
- もしm(~t)-m(~chi10) < m(W)+m(b)なら、stop→c+~chi10が主なdecay processになりえる。→stop pair productionからのc+LSPへのdecayを探索

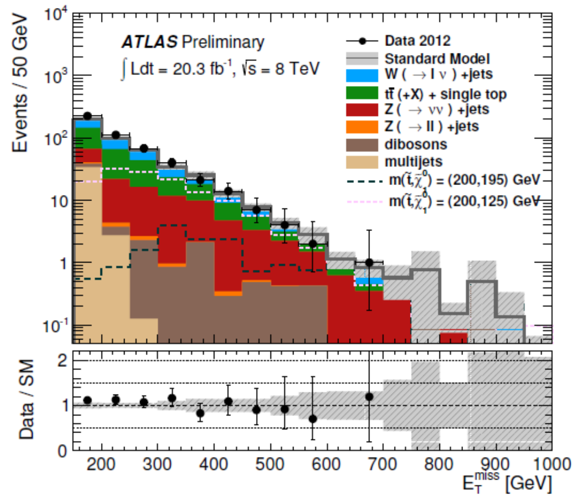


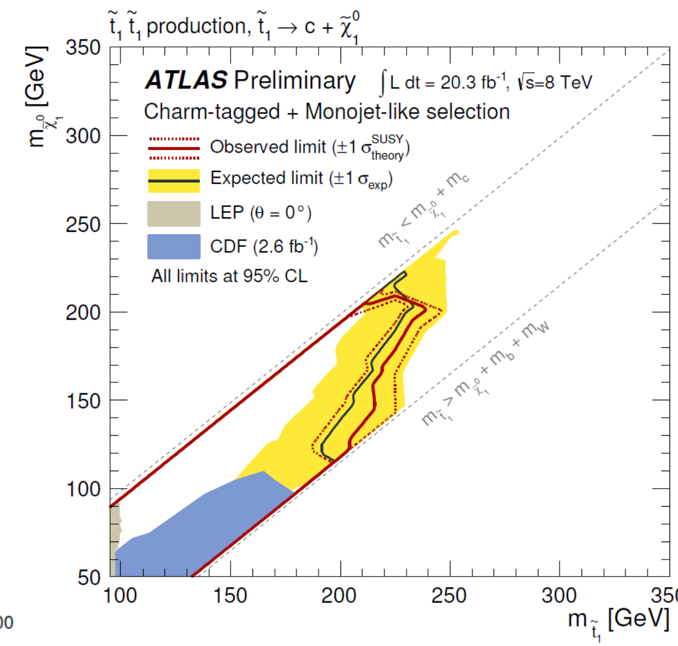
Charm tagging
- ~20% efficiency to c-jets
- ~5 rejection to b-jets and ~140 rejection to light jets.

Monojet-like selection
- At most 3 jets pT>30 GeV
- Δφ(jet,MET) > 0.4
- leading jet pT >280 GeV
- MET > 220 GeV

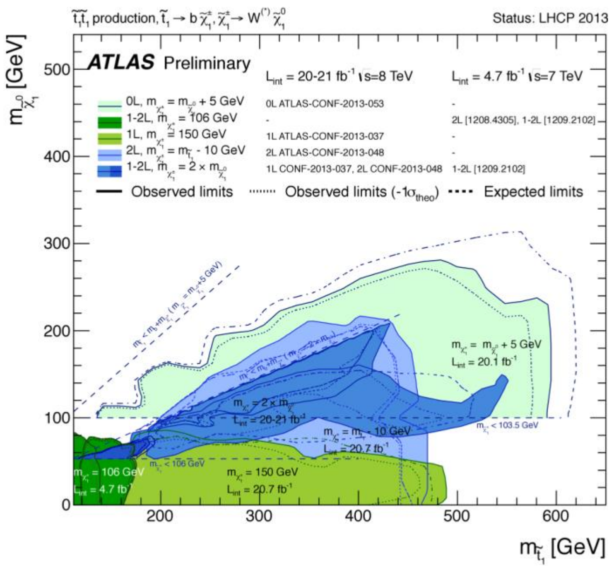
Charm-tagged selection
- At least 4 jets pT>30 GeV
- b-veto to 2nd, 3rd jets
- c-tag to 4th jet
- Δφ(jet,MET)>0.4
- leading jet pT >270 GeV
- MET > 410 GeV



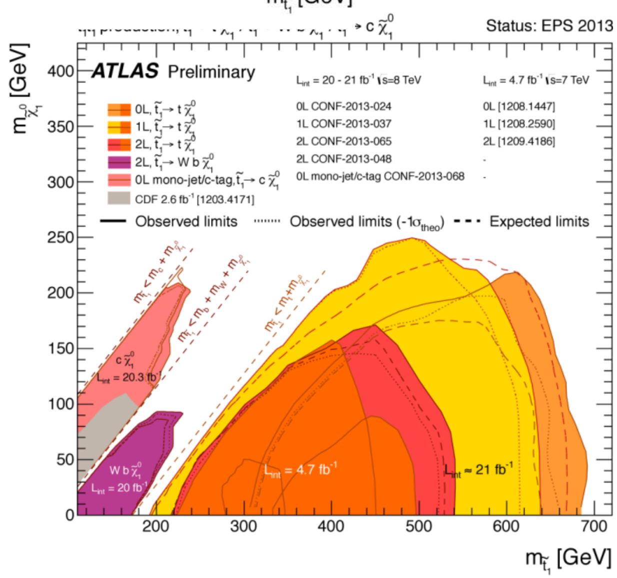


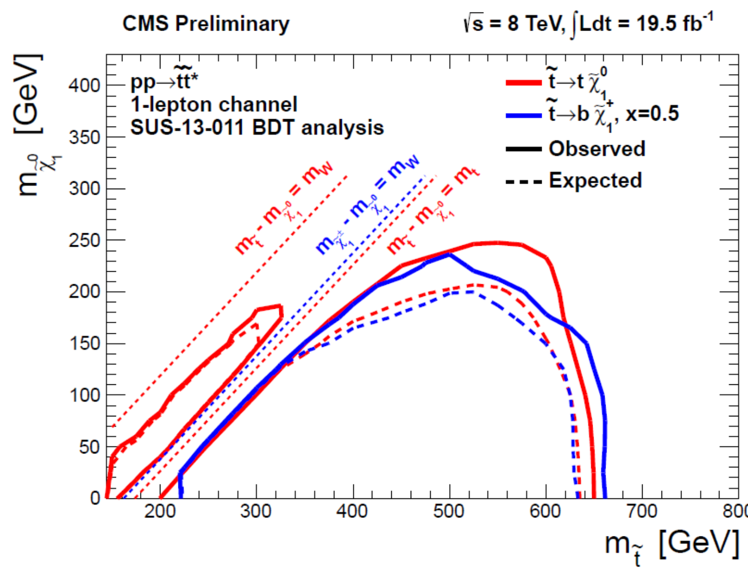


Summary of Stop Search



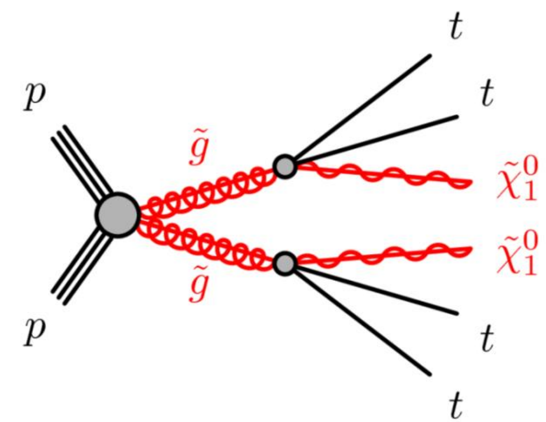
- stop mass ~ 650 GeV, neutralino mass ~ 200 GeV　までの領域をほぼexclude
- Stop mass~neutralino massの領域ではS/Nが悪く、まだ強いlimitが付いていない





Gluino→t+t+LSP

- Glunoも軽ければ、gluino productionがdominant
- Stopが軽いため、stopへのdecayが優勢になる



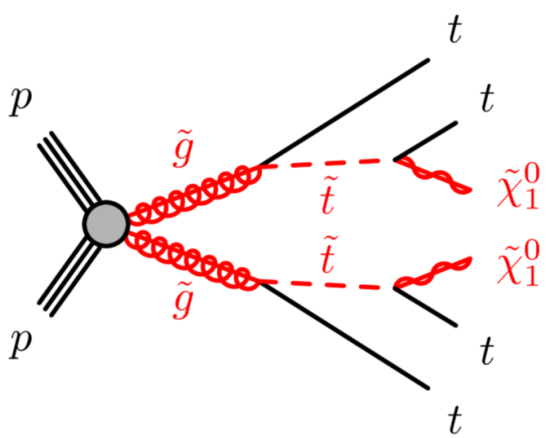
2種類のmodelを探索

- stop mass>>gluino massとして

gluino→t+tbar+LSPの3体崩壊

- gluino mass > stop mass > neutralino

massとして、gluinoからの1-step decay



終状態の多様さからさまざまなsignatureでの解析が可能

- 0-lepton, multi-jets (>6)
- 0/1-lepton, 3b-jets
- 2-lepton same sign, b-jets
- 3-lepton, b-jets

3b-jets 解析

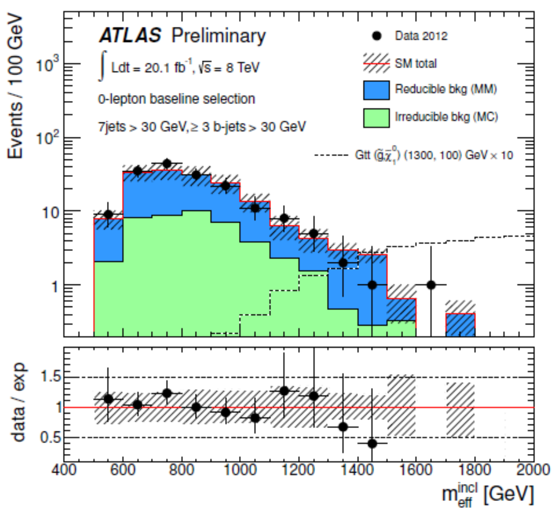
- 3 b-jetsを要求することでttbar backgroundを抑制

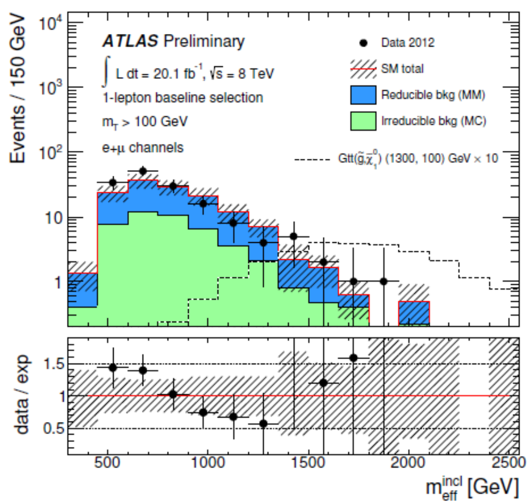
0-lepton
- At least 7 jets p_T>30 GeV
- MET>{200,350,250} GeV
- m_{eff} > {1000,1000,1500} GeV

1-lepton
- At least 6 jets p_T>30 GeV
- MET>{175,225,275} GeV
- mT > {140,140,160} GeV
- m_{eff} > {700,800,900} GeV

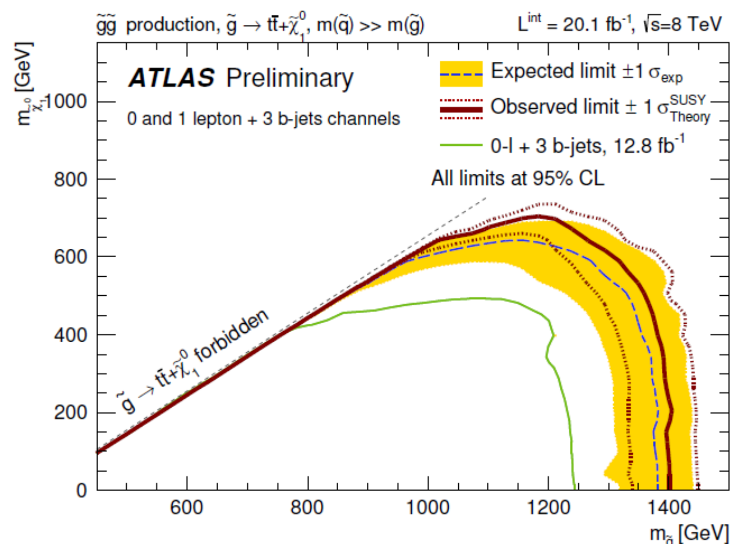
m_{eff}: pT sum of jets (and lepton pT)

$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos\Delta\phi(\ell, E_T^{miss}))}$$





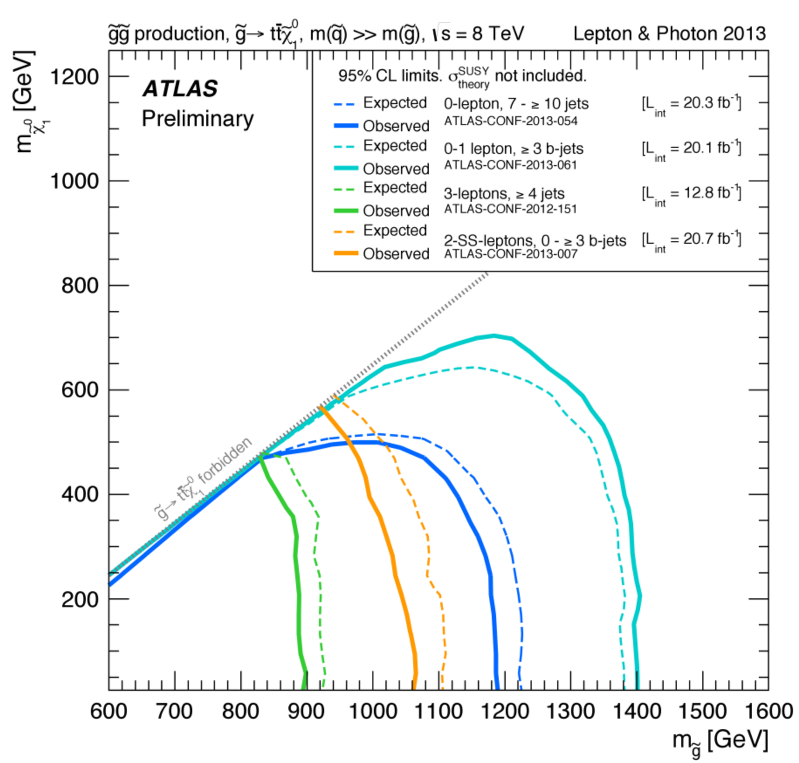
0, 1-lepton channelのm_{eff}分布.
- Reducible background (fake b-jet events)はdata-drivenに推定



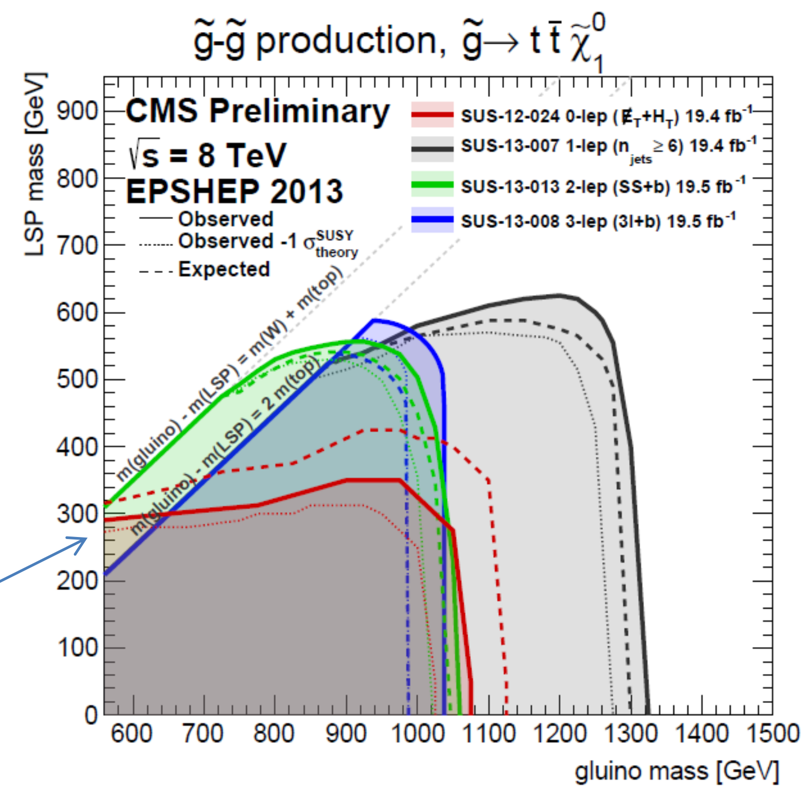
gluino, neutralino mass上でのexclusion limit
- gluino production cross-sectionでlimitされる領域までほぼexclude

Gluino→t+t+LSP まとめ

- gluino mass ~ 1400 GeV, neutralino mass = 600 GeVまでをexclude.
  - on-shell topを仮定すればsoftなkinematicsはあまりない。
  - CMSはoff-shell top decayまでextend



topのoff-shell decayまで拡張

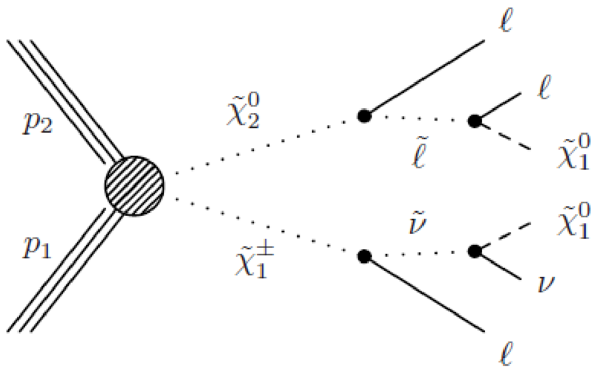


EW Production

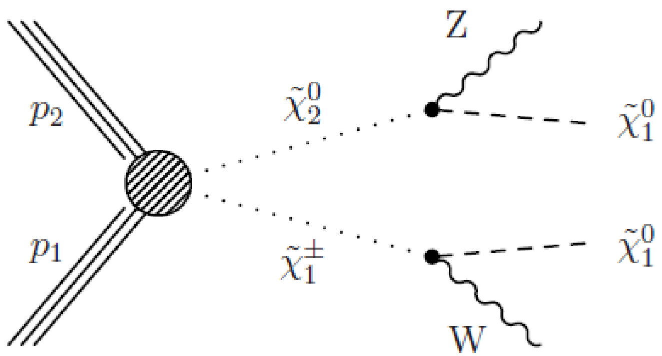
- Direct productionのcross sectionが小さいため、leptonを用いたcleanな環境で解析がmain
- Topology-baseで、
  - 2-lepton+MET (opposite sign/same sign)
  - 2-lepton+2-jets + MET
    - 2jets from W or Z hadronic decay
  - 3-lepton+MET, with or w/o Z mass veto
  - 4-lepton+MET

3-lepton Analysis

- Main backgroundがWZで、比較的cleanなchannel.
- Event selection
  - leading lepton (e,mu,hadronic tau) pT>20 GeV
  - other two lepton pT>10 GeV
  - Include opposite sign same flavor lepton pair
  - MET>50 GeV
- Events are “binned” in
  - Mll [0, 75, 105, ∞] GeV
  - MET [50,100,150,200,∞] GeV
  - MT [0, 120, 160, 160] GeV



sleptonを介してのdecay



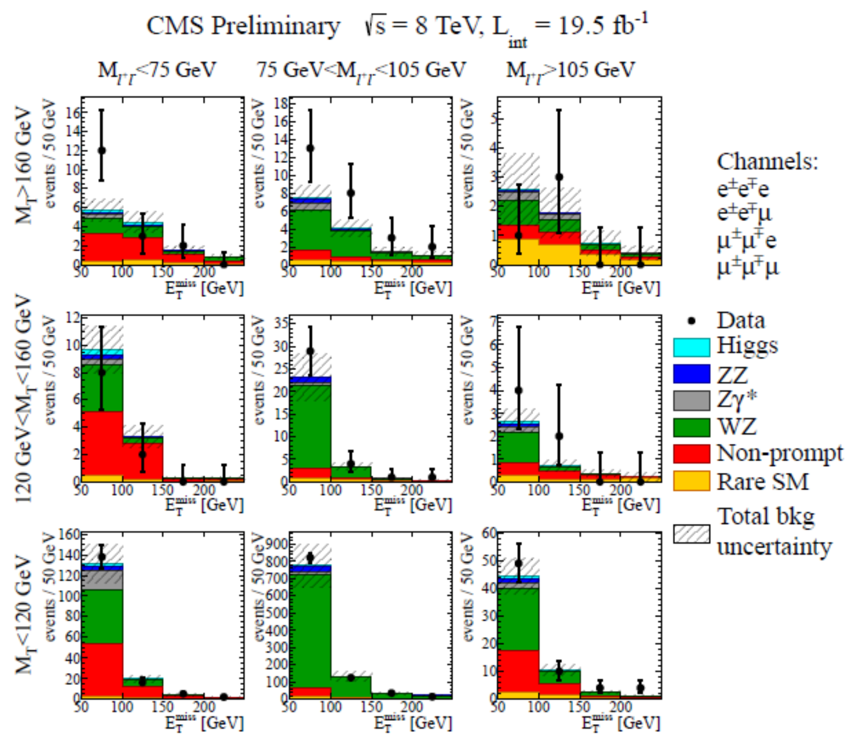
3-lepton Analysis

- Background estimation
  - WZ
    - MET resolutionがvertex数とHT (jet pt sum)で表されるとしてdataに一致するparameterを決定
    - MC sampleにMET resolutionのdegradationをかけて推定

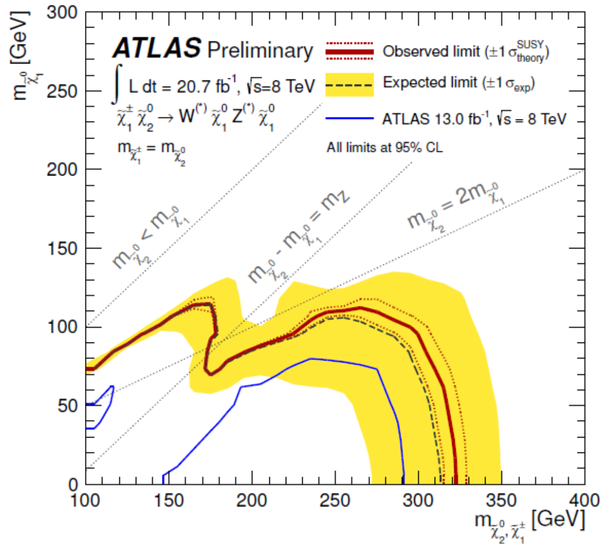
$$p(E_{\mathrm{T}}^{\mathrm{miss}}) = \sum_{ij} W_{ij} \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{\sigma_{ij}^2} e^{-E_{\mathrm{T}}^{\mathrm{miss}2}/2\sigma_{ij}^2}$$

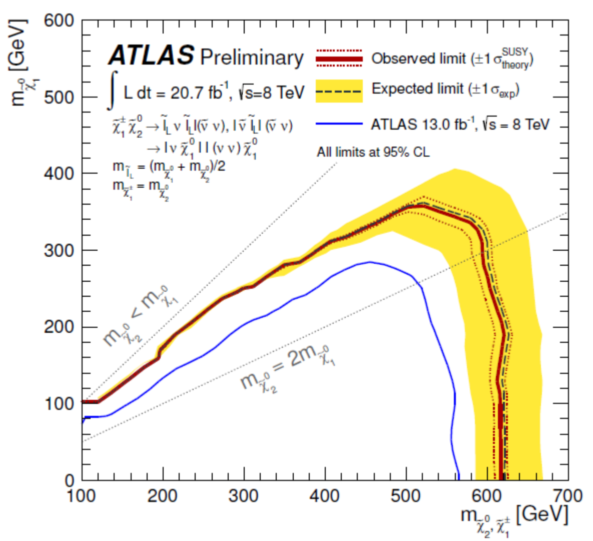
  - Fake lepton
    - Fake-leptonがIsolationのselectionを通る確率をQCD dijet eventsで測定（その他Z+jets, ttbar eventsも使用）
    - 3-leptonの内1-leptonのisolation requirementを逆にしたeventsからsignal regionに残るeventsにfake rateをかけて推定

各MET, Mll, MTのbinでのDataとestimationの比較

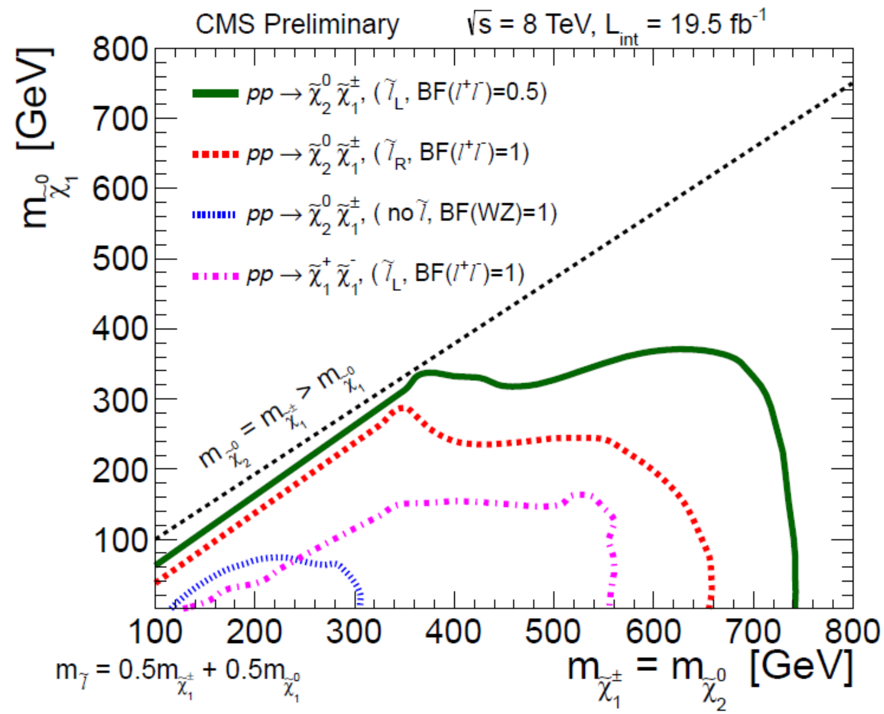


EW Productionまとめ





- 仮定するlepton BRによって、sensitivityが大きく変化
  - 最もoptimisticな場合では~chi1+, ~chi20 mass 740 GeVまでをexclude
  - 逆に最もpessimistic (Wのleptonic decay)の場合には300 GeV程度のexclude



without MET Analysis

Long Lived Particle Search

Motivation

- AMSB Wino LSP
- GMSB stau NLSP
- GMSB neutralino NLSP (→γ+~G)
- Split SUSY gluino→R-hadron
- R-parity violation (RPV)

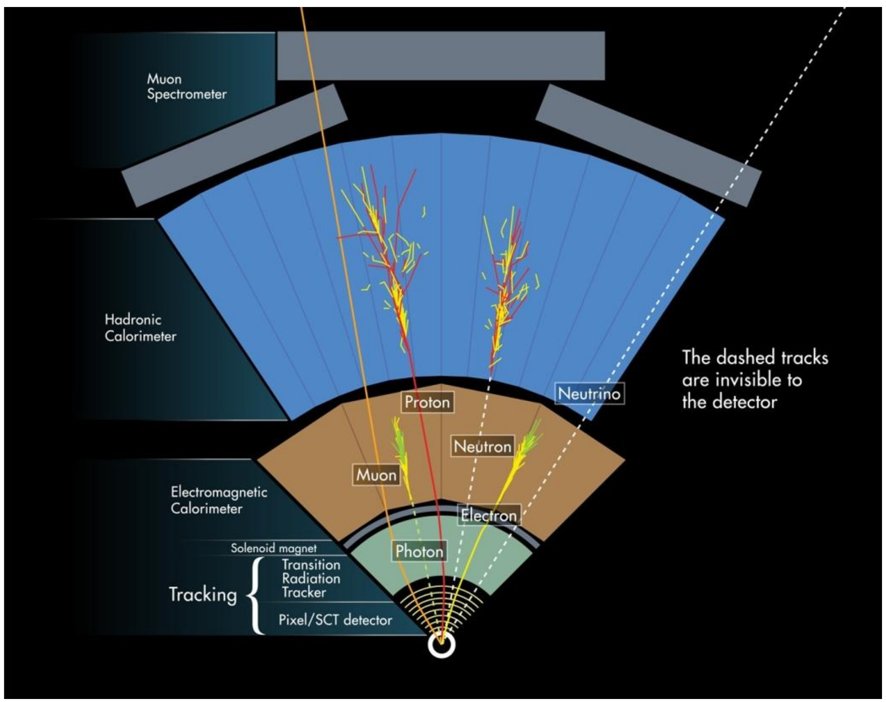
探索方法

- Heavy stable charged particle (stau, R-hadron)
- Decay in flight (AMSB wino, RPV)
  - Kink/disappearing track
  - Displaced vertex
  - Non-pointing photon
- Stopped particle

Detector Layout

$c\tau$ 0.1mm 1 cm 10 cm 1 m

	Displaced vertex	dE/dx in Pixel	Kink/disappearing track	Time of flight in Calorimeter	Time of flight in Muon Spectrometer	Stopped in detector
RPV	○		○(?)			
AMSB		○(?)	○			
Stau		○	○	○	○	
R-hadron		○		○	△	○



	ATLAS	CMS
Vertex	0.1 mm	0.1 mm
Pixel (dE/dx)	5-10 cm	5-100 cm
TRT	50-100 cm	No
HCal	2-4 m	1.5-2.5 m
Muon	5-10 m	4-6 m

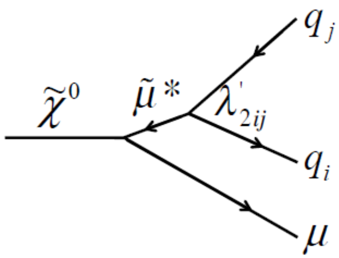
TRT: Transition Radiation Tracker

Heavy Stable Particle

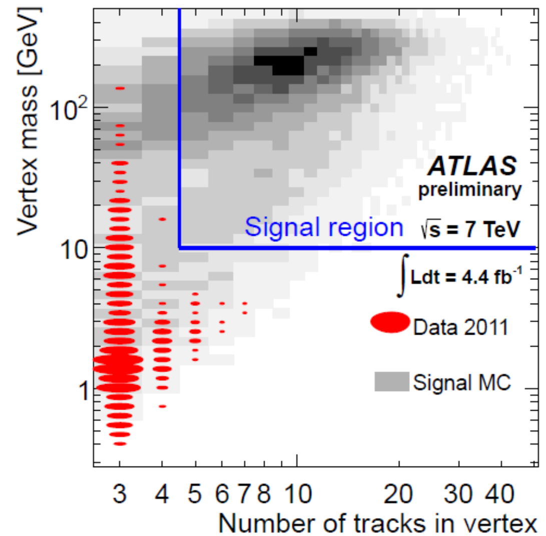
- β、βγ、momentumを使い、$m=p/\beta\gamma$から質量を求める
- 2種類の解析方法
  - Inner Detector - Calorimeter
    - Calorimeter cell timeからβを、Inner detectorでのenergy lossからβγ、Inner detectorでmomentumを測定
    - R-hadronの場合、detectorと相互作用してchargeが変わる可能性があるため、Muon spectrometerを必要としないこの方法が取られる
  - Inner Detector - Muon Spectrometer
    - Muon spectrometer hitsとcalorimeter cell timeからβを、Inner detectorでのenergy lossからβγを、Inner detectorとMuon spectrometerをcombineしてmomentumを測定
    - sleptonの場合にこの方法が可能

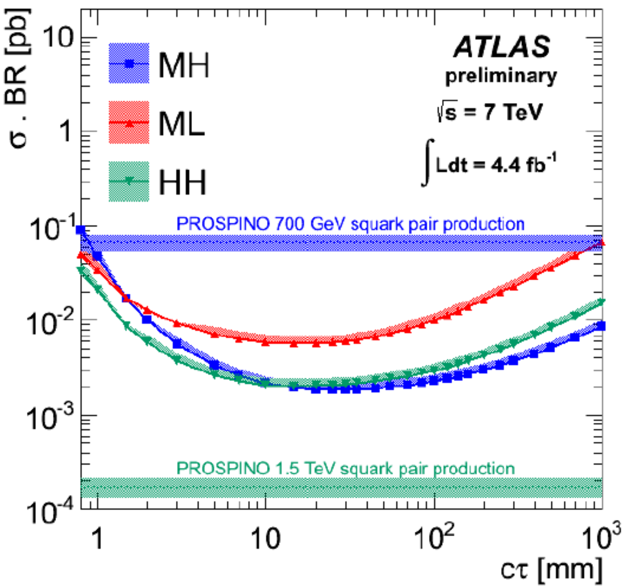
Displaced Vertex

- Primary vertexから数mm～数10cm離れたvertexを探索
- Pileupと区別するため、muonがあるvertexについてのみ探索を行っている
  - 主なbackgroundはmis-reconstruction、残留ガスとのhadronic interaction.



残留ガスからのbackgroundの場合、vertex massが小さく出るため、signalと分離可能





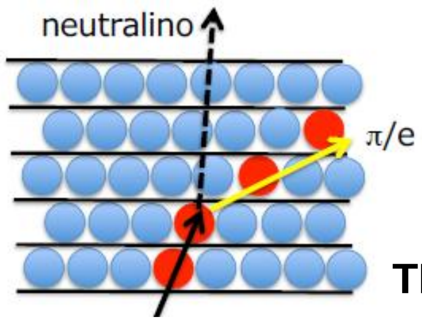
RPV modelでのexclusion limit

Sample	$m_{\tilde{q}}$ [GeV]	σ [fb]	$m_{\tilde{\chi}_1^0}$ [GeV]	$\langle\gamma\beta\rangle_{\tilde{\chi}_1^0}$	$c\tau_{MC}$ [mm]	λ'_{211}
MH	700	66.4	494	1.0	78	3.0×10^{-6}
ML	700	66.4	108	3.1	101	1.5×10^{-5}
HH	1500	0.2	494	1.9	82	1.5×10^{-5}

RPV bench mark modelのparameter

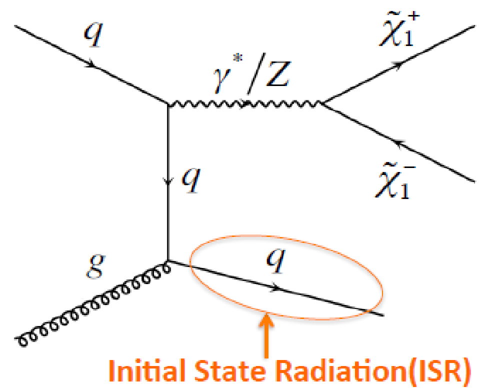
Disappearing Track

- Anomaly Mediated SUSY Braking (AMSB) model
  - Mass of Bino:Wino:Gluino～3:1:8
  - NLSP,LSP→wino-like, Δm(~chi1+ -~chi10)~150 MeV ➔ charginoの寿命は~0.1-1 ns → O(1-10) cm

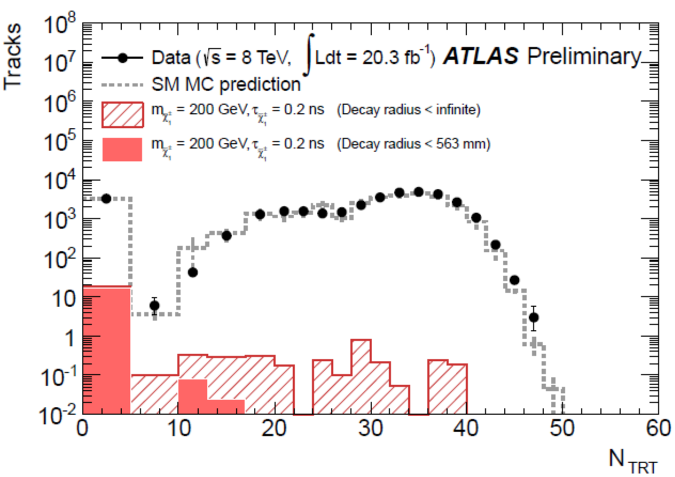


連続飛跡検出器であるTRTを使うことでDisappearing trackとして観測される

TRTでの模式図



EventをtriggerするためISR-jetを利用

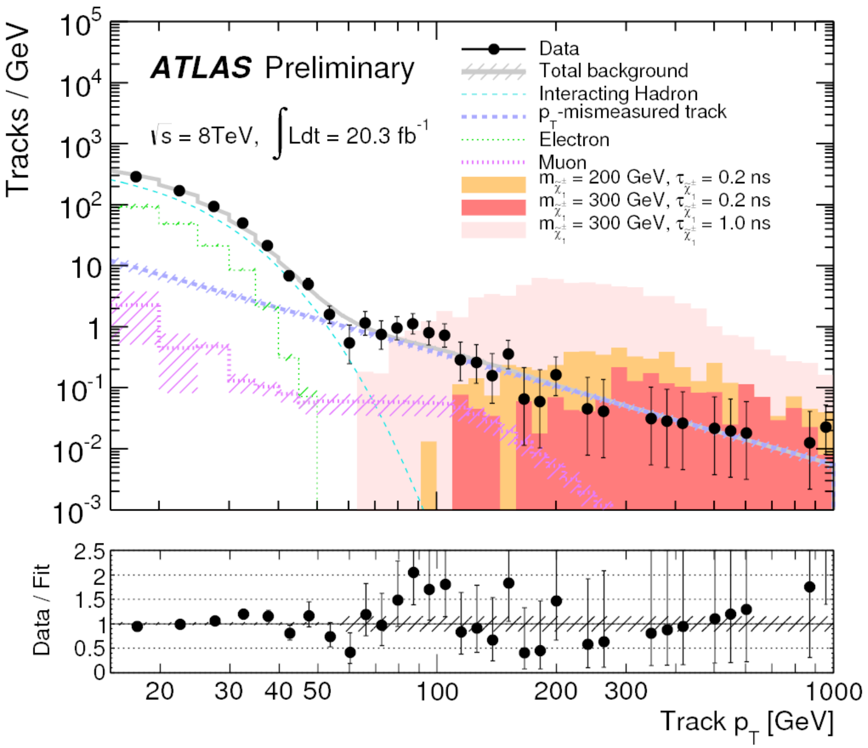


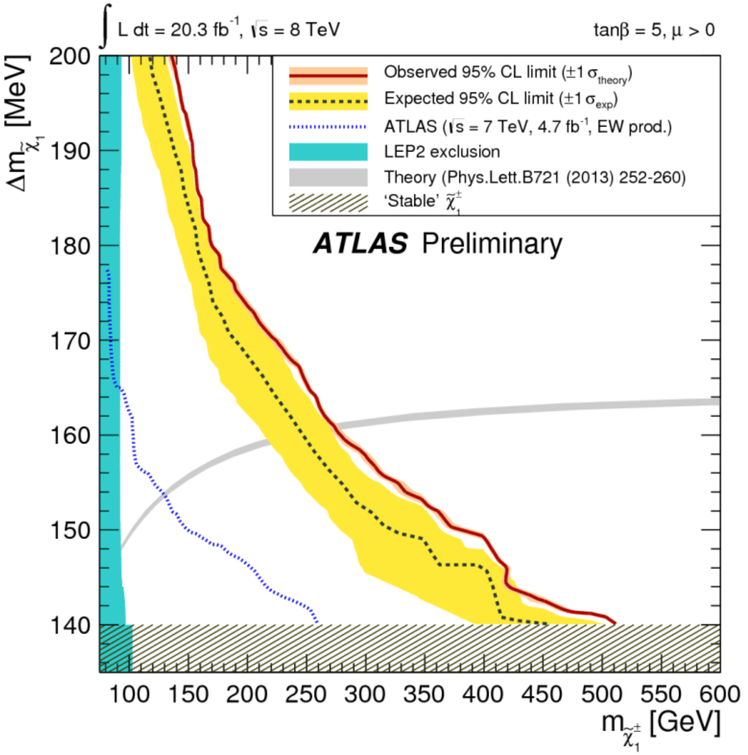
←TRT hit数の分布
N_{TRT}<5を要求することでsignalをenhance

- Lepton veto
- Leading jet pT>90 GeV
- MET>90 GeV
- minΔφ(jet,MET) > 1.5
- High pt track
- Disappearing track

Results

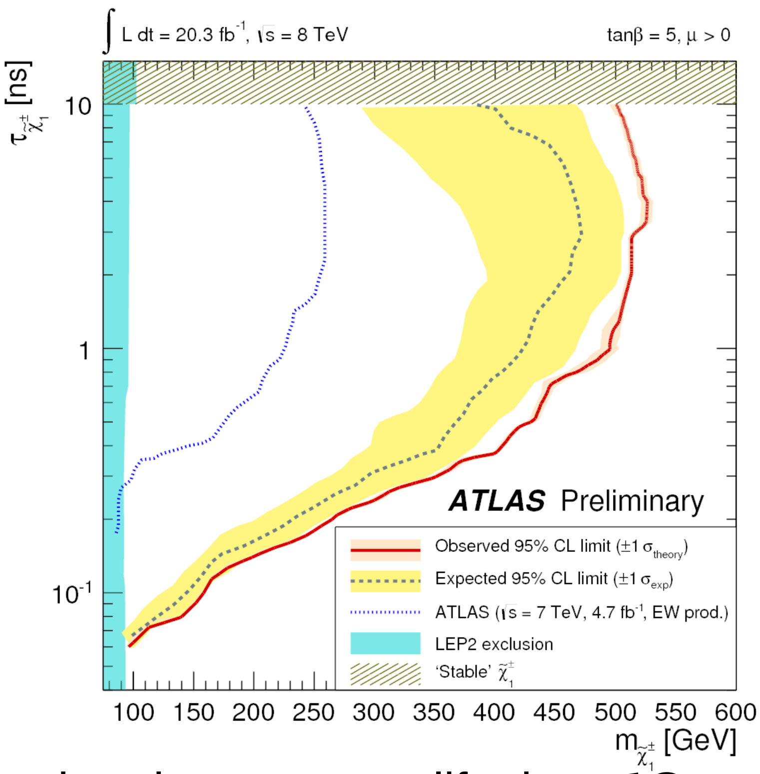
- 8 TeVでの解析結果
  - Track pt spectrumをbackgroundとsignalのshapeを使ってfit
    - 主なbackgroundはfaketrackとhadron track
  - AMSBから予測される高いtrack pt regionには有意はexcessはなし
    - pure AMSBを考えた場合、m(chargino)<270 GeVをexclude



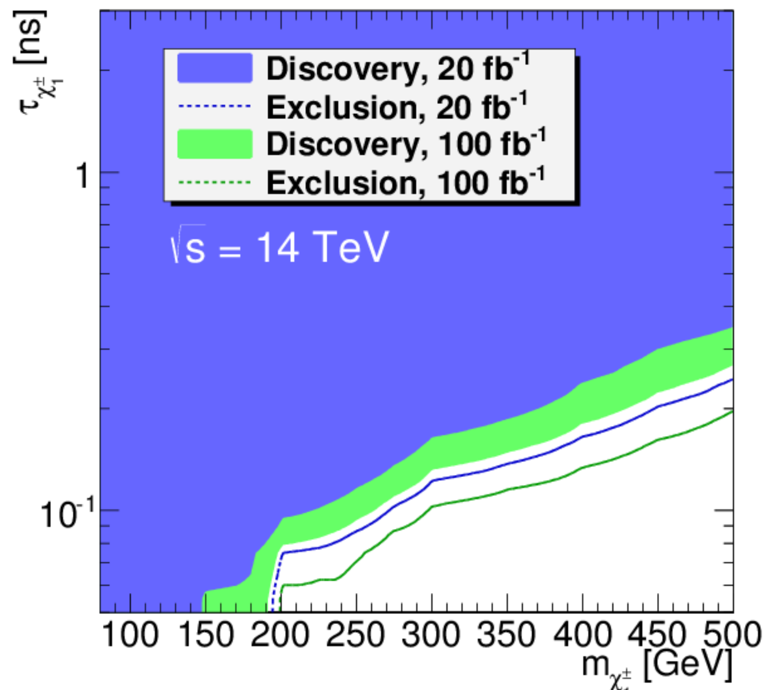


Expectation for 14 TeV

- Δm=160 MeVはlife time~0.2 nsに相当
- 14 TeVではchargino mass 500 GeV程度までdiscovery/exclusion potentialがあると推定



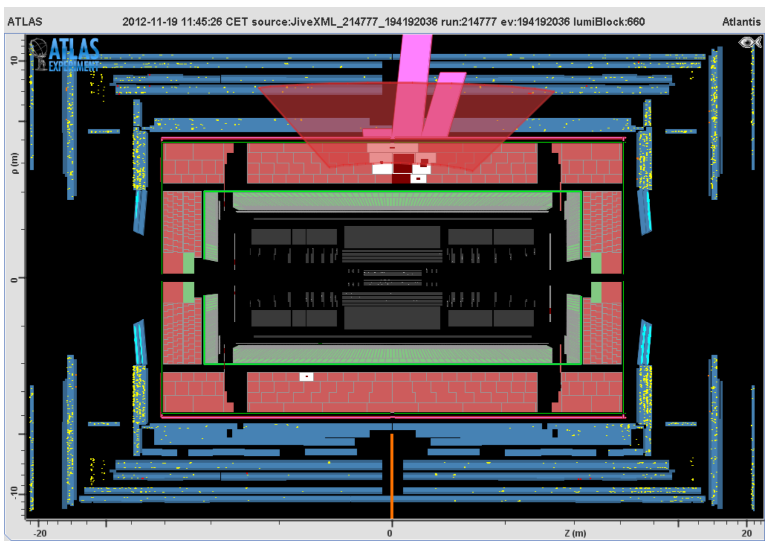
chargino mass vs. life timeでのexclusion limit at 8 TeV



chargino mass vs. life timeでのdiscovery (5σ) reachとexclusion limitのexpecation at 14 TeV

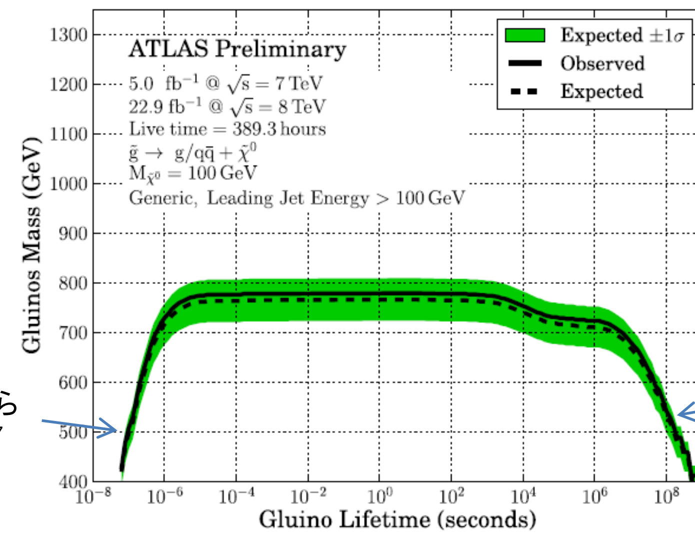
Stopped Particle

- β<<1のR-hadronがenergyを失って、検出器内で止まり、しばらくしてからdecayする信号を探索
- Collision backgroundを減らすためempty bunchでtrigger
  - empty bunchを使うことで、proton/bunch < 10^8 (filled bunchでは10^{11})
- 主なbackgroundは宇宙線とBeam halo



2012年にATLASで検出されたsignal candidate event

短寿命側はbunch間隔から決まり、~10^{-7} secから。

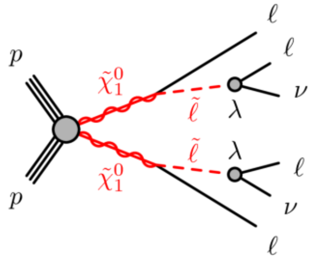


長寿命側はdata taking preriodから決まり、~年

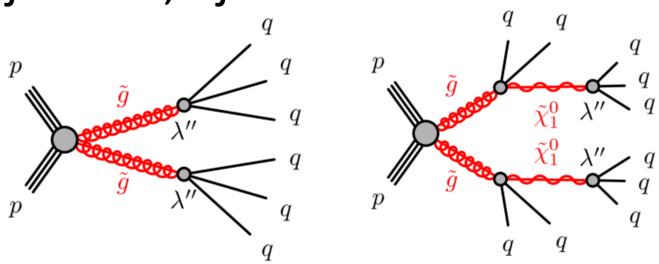
Gluino massとlifetimeに対するexclusion limit

Other Exotic Signature

- RPVの場合、LSPによる消失エネルギーがないため、代わりに特殊な終状態を利用して探索
  - multi-leptons
    - neutralinoのdecayからの4-lepton+MET（この場合METあり）



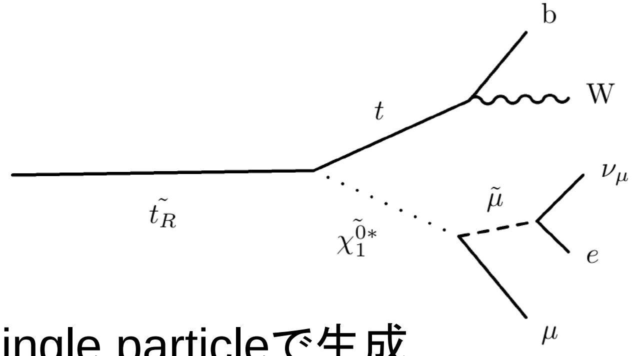
  - multi-jets
    - ~g pair productionからのdecay → 3jets×2, 5jets×2



  - resonance
    - RPVならsingle particle productionが可能になるため、終状態の粒子でmassを組むことで元のSUSY粒子のmassを再構成可能

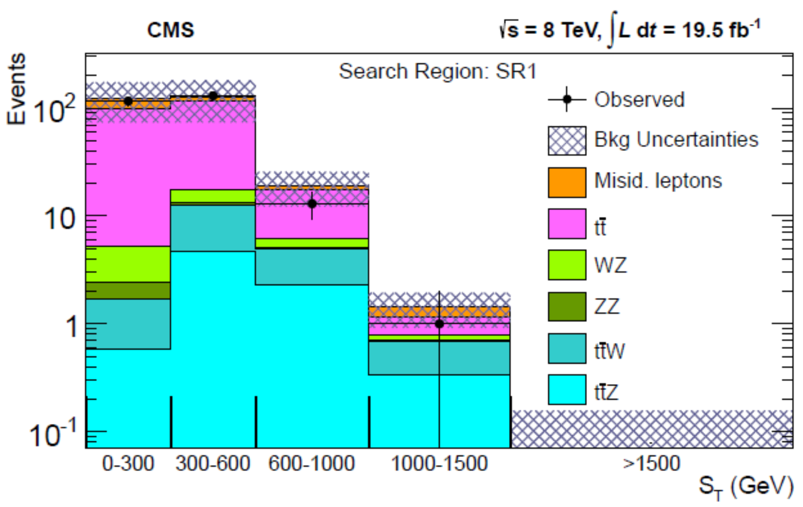
RPV Stop

- RPVであることにより、naturalnessの条件が緩くなる
- またMET based searchでstopが発見出来ていなかった可能性を考慮

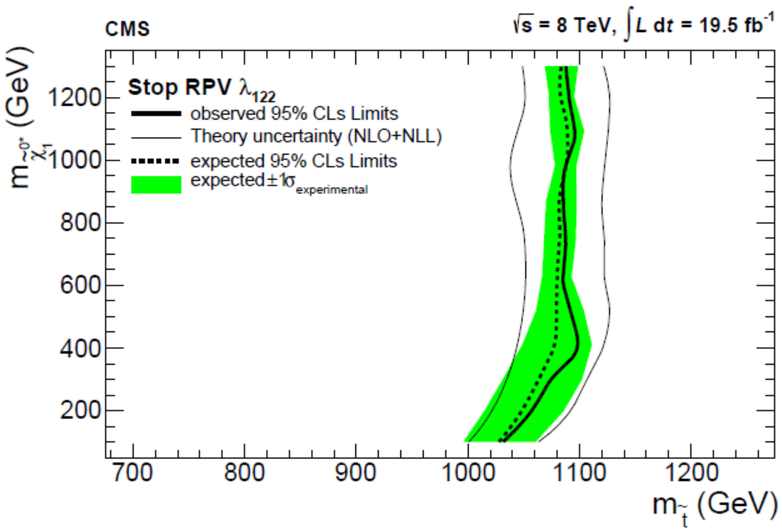


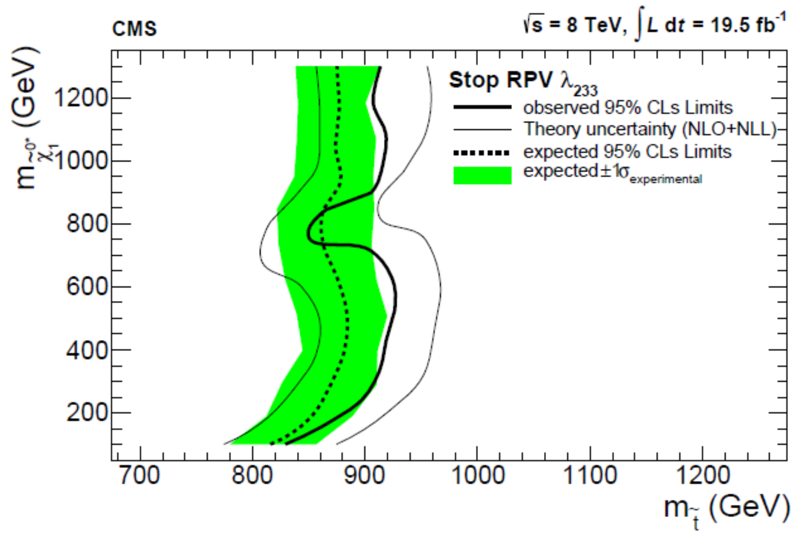
- single particleで生成
- LSPがunstableでSM particlesに崩壊

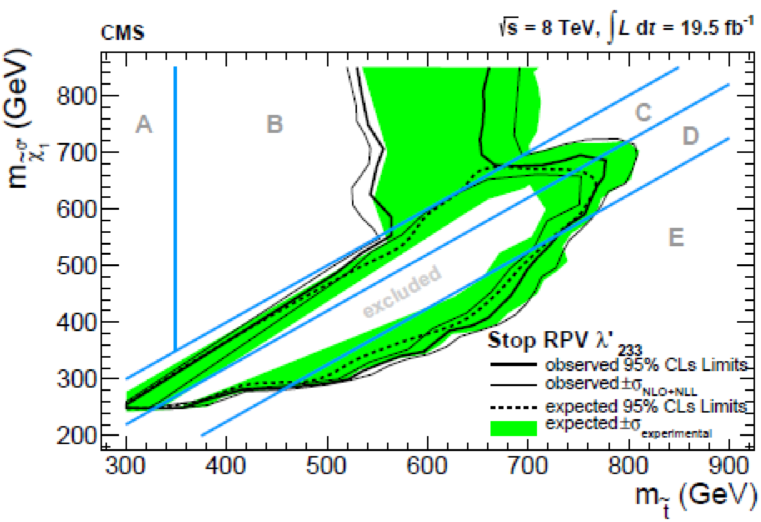
Event selection
- 3-lepton以上(tauを含む)
- S_T (MET, jet pT, lepton pTのscalar sum)を用いてsignalをenhance



RPV Stop Result



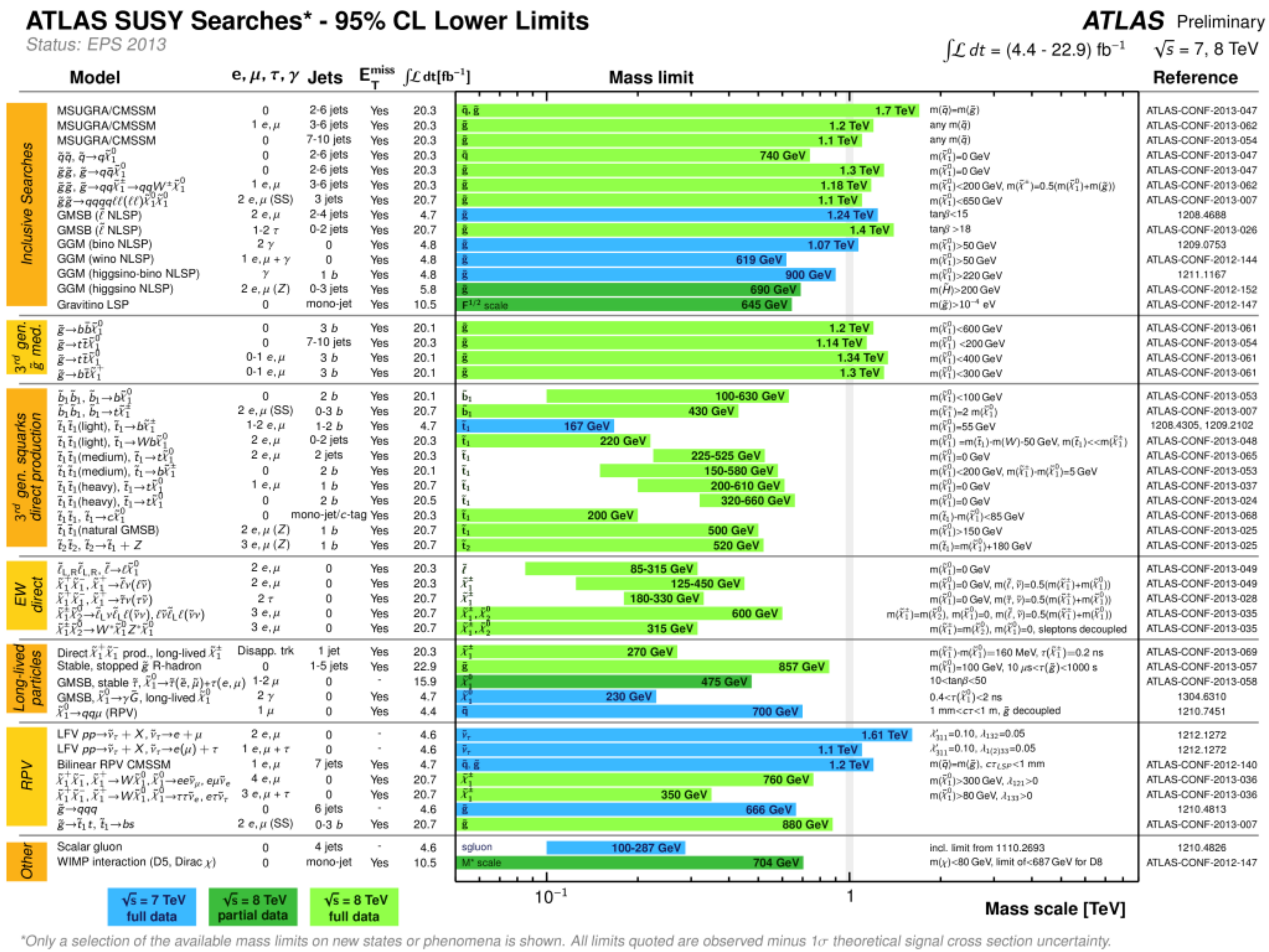




stop mass vs. neutralino massでのexclusion limit

$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk}L_iL_j\overline{E}_k + \lambda'_{ijk}L_iQ_j\overline{D}_k + \frac{1}{2}\lambda''_{ijk}\overline{U}_i\overline{D}_j\overline{D}_k$$

Summary of 8 TeV Analysis



√s=14 TeVでの展望

Plan for 14 TeV LHC

- 13-14 TeVでのLHC運転
  - bunch spacing 50 ns →25 ns
  - peak luminosity 2-3×10^{34} $cm^{-2}s^{-1}$ 、1回のビーム衝突時の平均反応回数μ～69
- 2020年までに300 fb^{-1} (Phase-I)
- High Luminosity LHCで3000 fb^{-1} (Phase-II)
  - L=5×10^{34} $cm^{-2}s^{-1}$, μ～140
- PDFによるhigh mass particleのcross sectionの増加
- 一方でpileupによるresolutionの悪化など

Trigger@14 TeV

- High massのSUSY探索では√s=14 TeVでのtrigger thresholdの上昇による影響はほとんどない
- ただし、縮退したmodelやMETなしの解析では無視できない影響
  - 現在、調査中

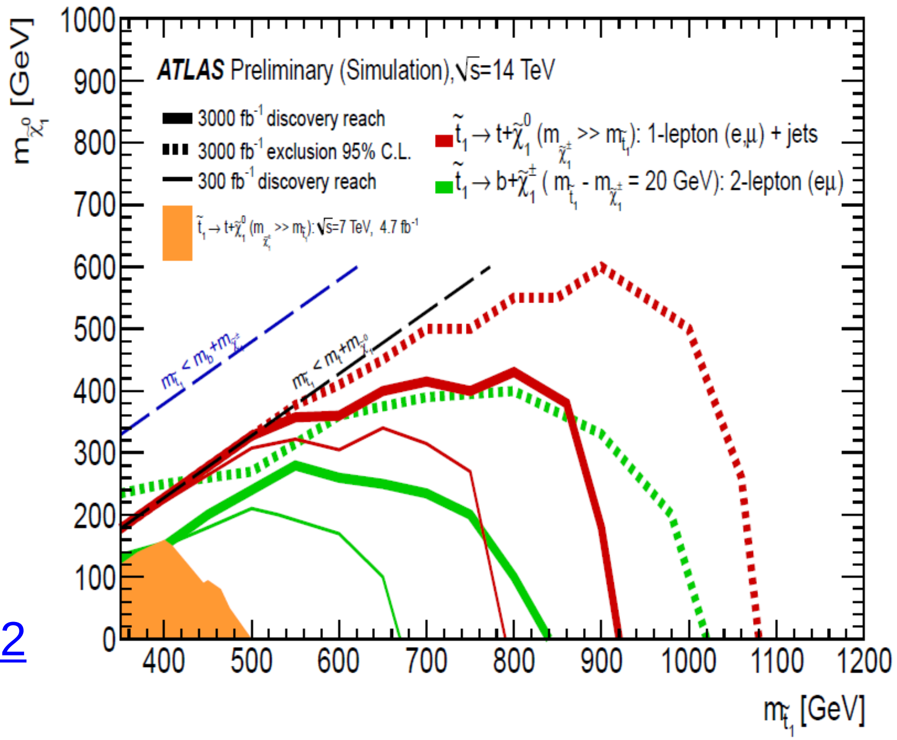
L=2×10^{34} $cm^{-2}s^{-1}$でのtrigger thresholdの予測値

	L1 threshold	Offline threshold
single electron (pT)	28 GeV	33 GeV
single muon (pT)	20 GeV	25 GeV
single jet (pT)	100 GeV	250 GeV
pure ETmiss	60 GeV	190 GeV

Stop Search@14 TeV

- Event selection (for t+LSP)
  - 1-lepton (electron or muon) p_T>25 GeV
  - 4 jets p_T>120,100,50,50 GeV
  - At least one b-tagged jet p_T>40 GeV
  - E_T^{miss}>225 GeV
  - m_T(lepton, E_T^{miss})>140 GeV
  - Optimum 1st, 2nd jet p_T, E_T^{miss}, $E_T^{miss}/\sqrt{H_T}$, m_T cuts for each signal point

300 fb^{-1}ではstop→t+LSPの場合、stop mass 800 GeV (LSP mass ~0 GeVのとき) まで発見の可能性あり



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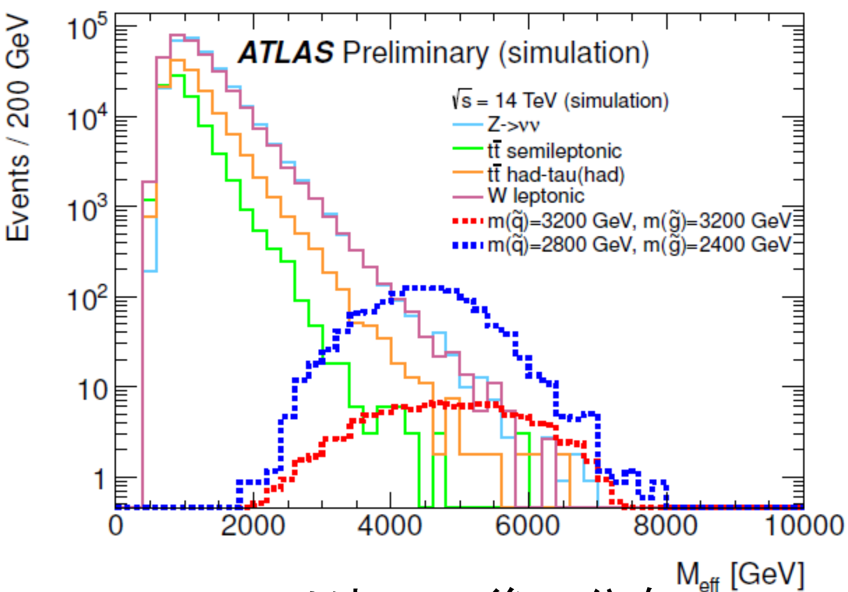
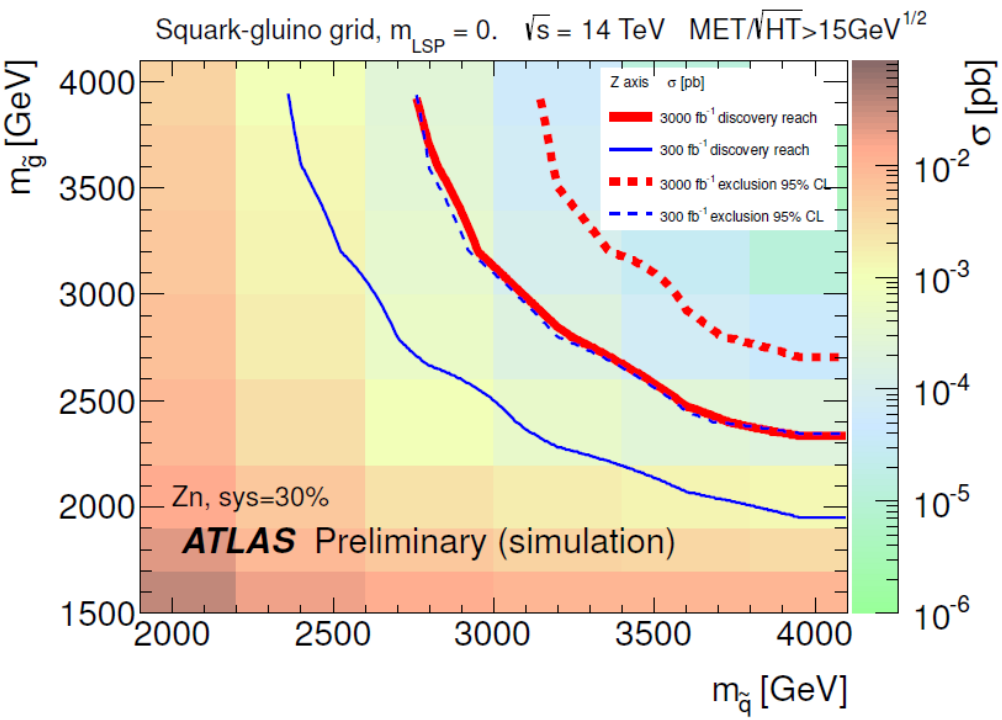
Squark, Gluino Search@14 TeV

- √s=14 TeVでの発見感度の予測
- Event selection
  - No electron or muon (p_T>20 GeV)
  - At least 4 jets p_T>60 GeV
  - $E_T^{miss}/\sqrt{H_T}$>15 $GeV^{1/2}$
  - Optimum M_{eff} ($E_T^{miss}+H_T$) cut for

300 fb^{-1}ではsquark mass 2.4 TeV, gluino mass 2 TeV程度まで発見の可能性あり



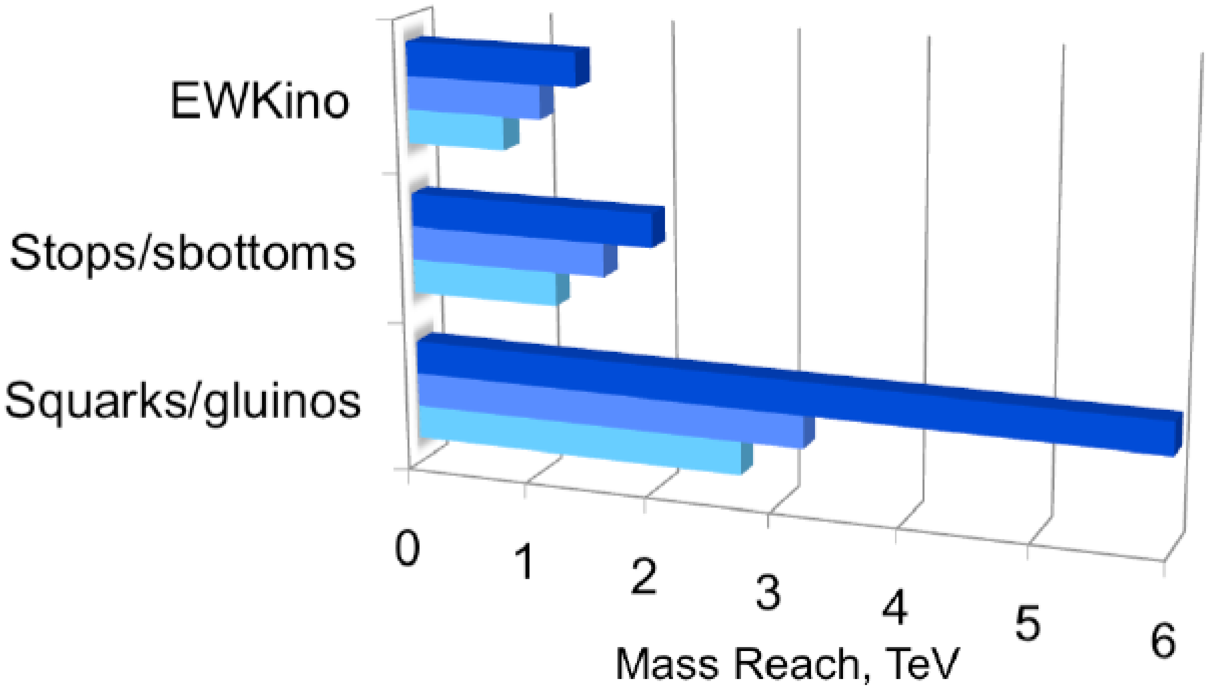
M_{eff}以外のcut後の分布



Simplified modelでの予測感度

CMS 14 TeV Expectation

- 現在の探索結果から外挿した予測値
  - おおよそATLASと同程度の感度



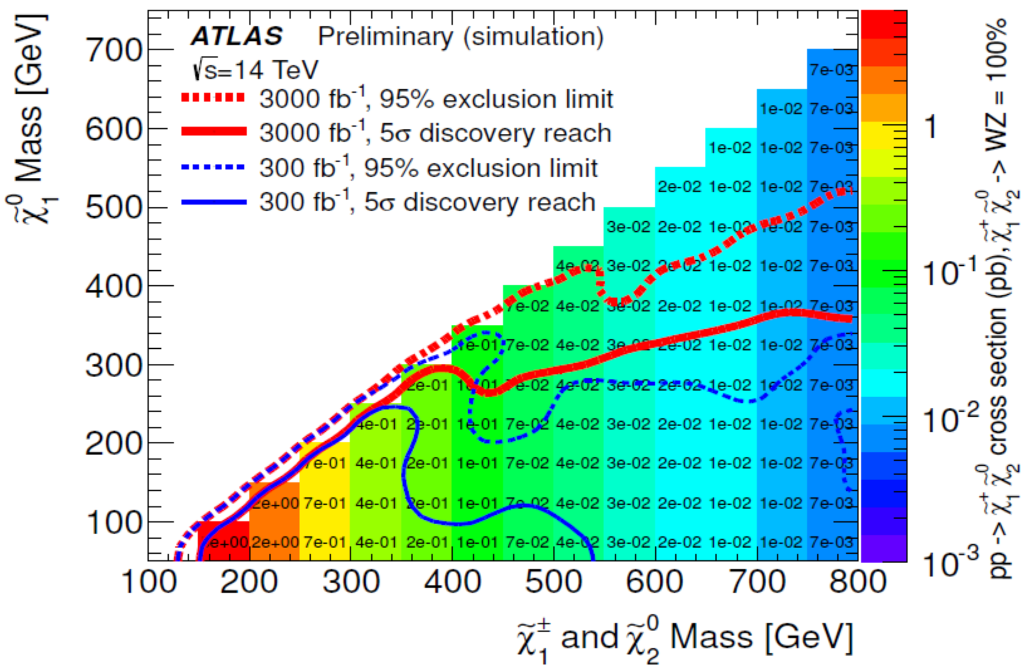
300 fb^{-1}
3000 fb^{-1}
300 fb^{-1}

[CMS Submission to the European Strategy Preparatory Group]

EW Gaugino Search@14 TeV

- √s=14 TeVでのEW gauginoの発見感度
- Event selection
  - 3 lepton pT>10 GeV, at least one lepton pT> GeV
  - no b-jet
  - same flavor, opposite sign lepton pair mass > 20 GeV
  - E_T^{miss} >150 GeV
  - Multivariate of E_T^{miss}, mT, lepton pT, mll, pT(ll), ΣpT(jet)

300 fb^{-1}ではneutralino2, chargino mass 540 GeV (LSP mass ~50 GeV のとき) まで発見の可能性あり



Summary

- LHC √s=8 TeVでのSUSY探索においてその兆候はなし
- Higgs 126 GeVを考えると軽いSUSYは難しそう
  - 何かおまけが必要
    - Naturalness (large |A| term): light stop
    - Gaugino sector
- いずれにせよ、LHC √s=14 TeVでもこれまでの解析を踏まえてtopology baseに探索