Supersymmetry: Present and Future

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Recent Issues in Nuclear and Particle Physics
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Department of Physics,
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Outline

- Supersymmetry and Phenomenology
- LHC Results
- Future prospects
- Summary

The Standard Model:

The SM based on Gauge theory: SU(2) X U(1)

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \bar{\psi}_i\gamma_\mu D_\mu\psi_i$$

Gauge Symmetry works fine

$$+\psi_i y_{ij}\psi_j\phi - V(\phi)$$

Spectrum of Particles?
Symmetry is broken

Brout, Englert, Higgs,'64, Weinberg, Salam, '67

$$\mathrm{V}(\phi) = -\mu^2\phi + \lambda\phi^4(\mu^2, \lambda > 0)$$

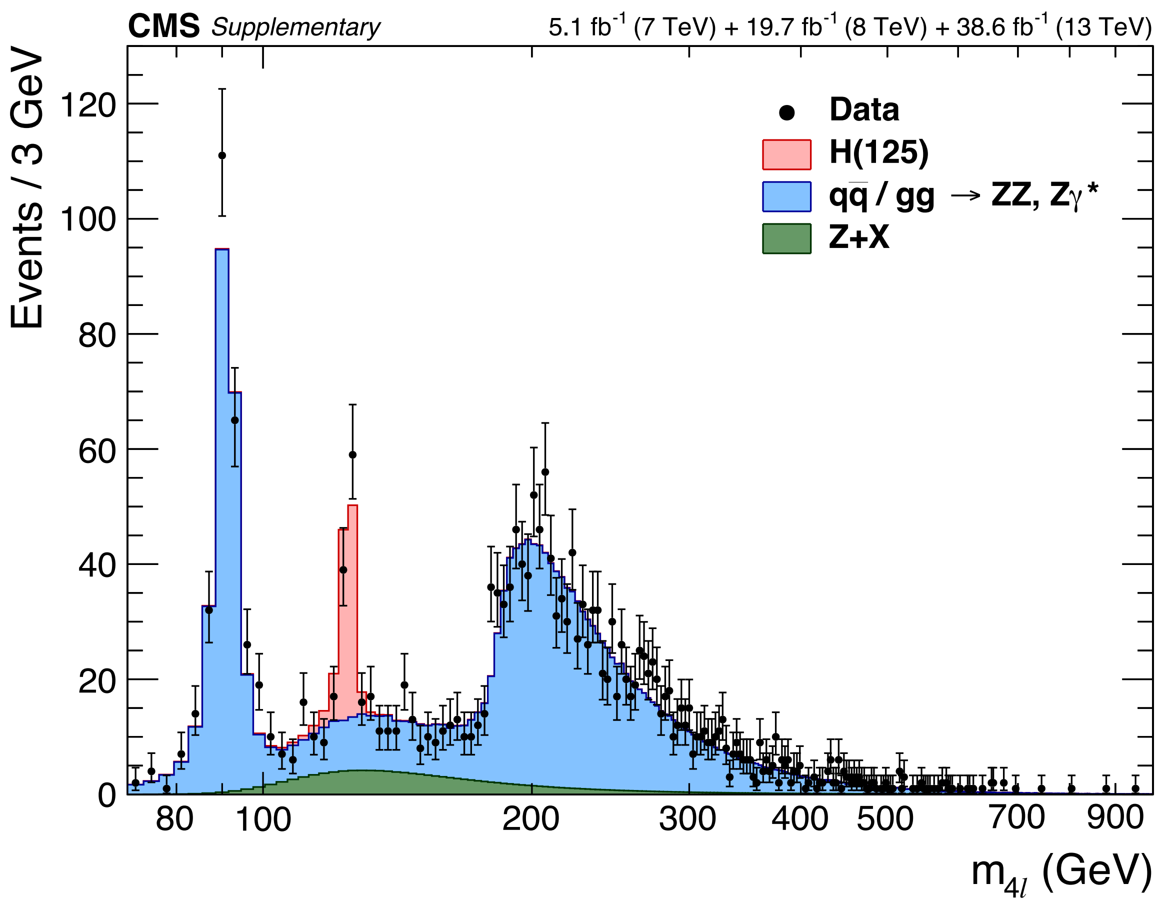
Higgs Mechanism

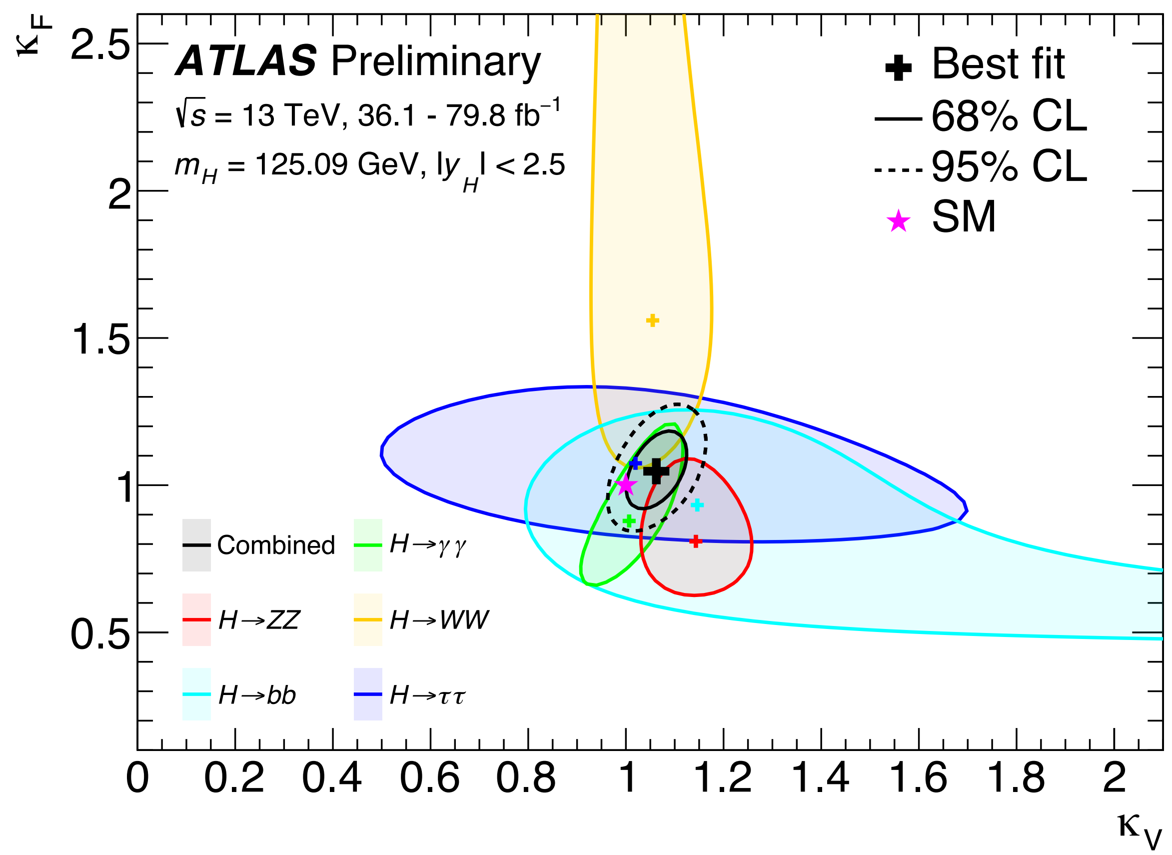
↓

Higgs Scalar

1967-2012: SM passed all tests

Higgs Discovery



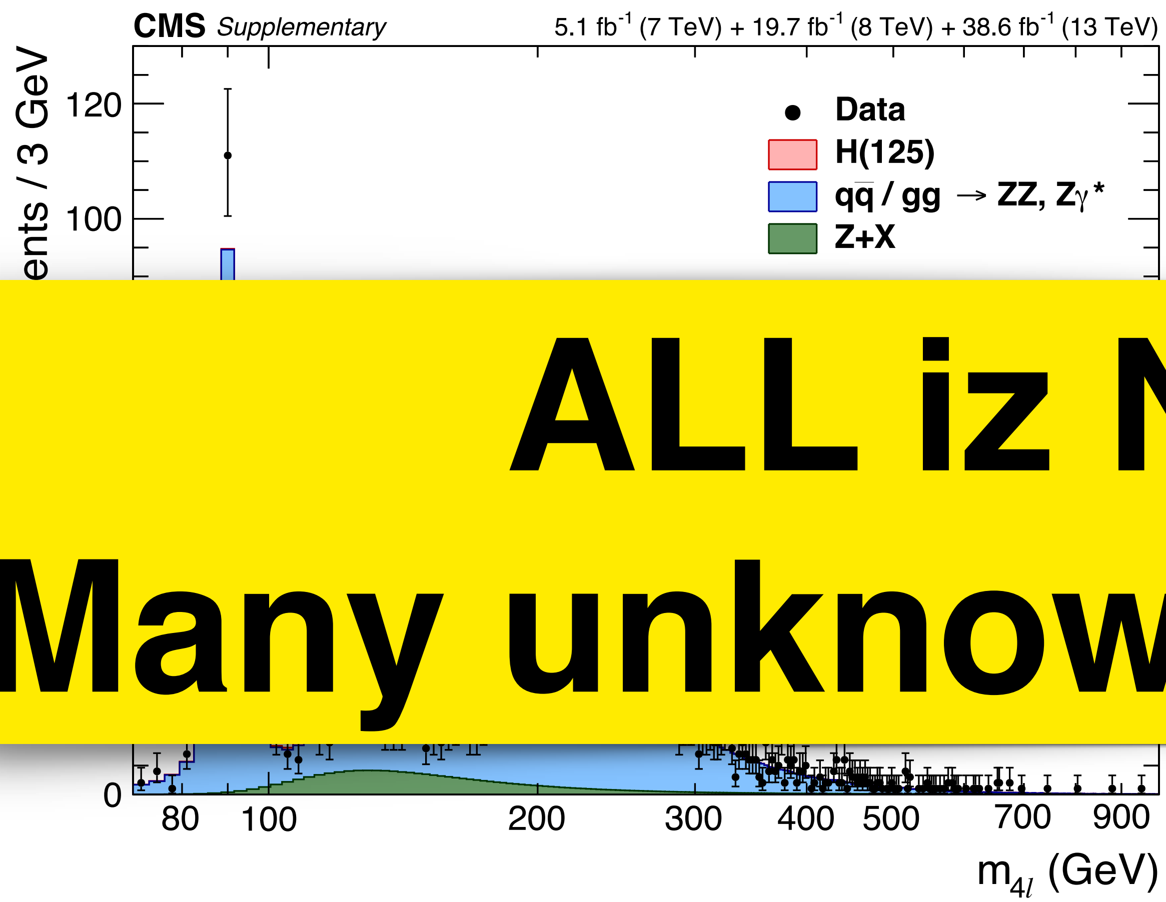


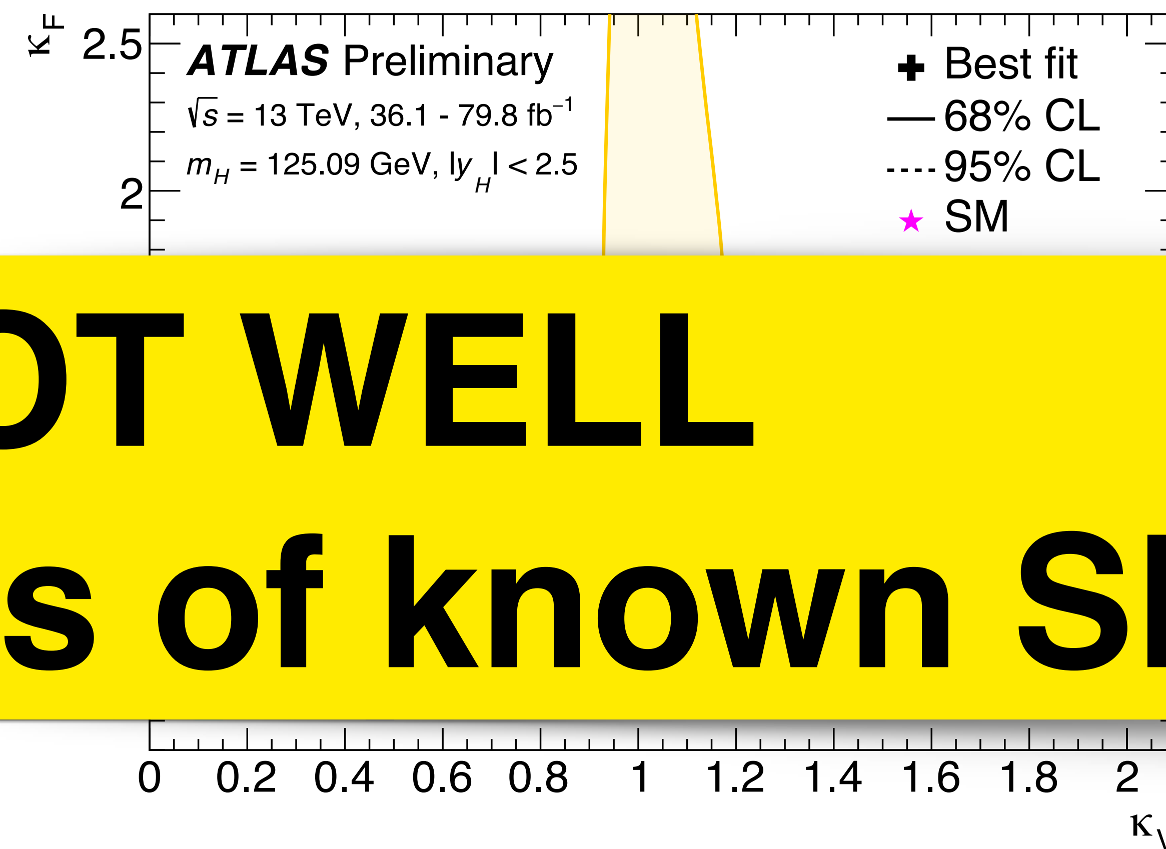
$$m_H = 125.26 \pm 0.21\ GeV \quad \Gamma_H < 1.10\ \text{GeV} \quad @ \quad 95\% \quad C.L$$

$$\mu = 1.17 \pm 0.10$$

H(125) is very likely SM Higgs boson

Higgs Discovery





ALL iz NOT WELL

Many unknowns of known SM

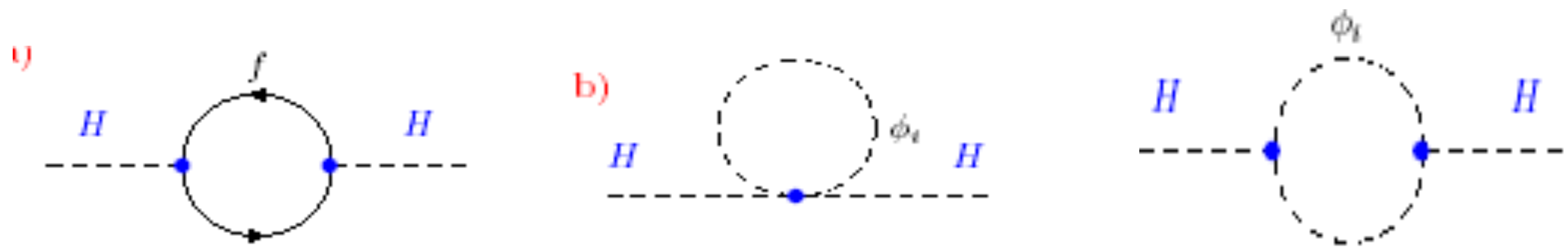
$$m_H = 125.26 \pm 0.21\ GeV \quad \Gamma_H < 1.10\ \mathrm{GeV} \quad @ \quad 95\% \quad C.L$$

$$\mu = 1.17 \pm 0.10$$

H(125) is very likely SM Higgs boson

Higgs Mass: Theoretical Issue

In SM, masses of fermions and gauge bosons are protected by chiral and Gauge Symmetry



$$m_H^2 = m_{0H}^2 + \delta m_H^2$$

$$\delta m_H^2 \sim \frac{3G_F}{\sqrt{2}\pi^2}\Lambda^2 \qquad \Lambda \rightarrow M_{pl}(10^{19})\ \text{GeV}$$

$$m_H^2 = m_{0H}^2 + \delta m_H^2$$

$$\sim 10^2 \qquad \sim 10^{38}$$

$$W^+W^- \rightarrow W^+W^-$$

$$m_H = 125\ GeV$$

Fine Tuning

$$1 \quad part \quad in \quad 10^{36}$$

Each order in perturbation theory

Gauge Hierarchy problem

Higgs Mass: Stabilisation

Introduce a symmetry to control the radiative corrections

OR

Lower the cut-off of the effective theory containing elementary scalar(extra Dimension, compositeness model)

Supersymmetry: the most elegant solution

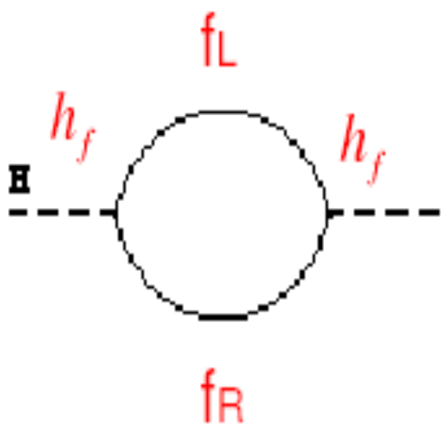
Virtual fermions and virtual bosons contribute with opposite sign and would cancel each other, if for every fermions there is a boson of same mass and charge : divergence would cancel without any FT and in all order of perturbation theory.

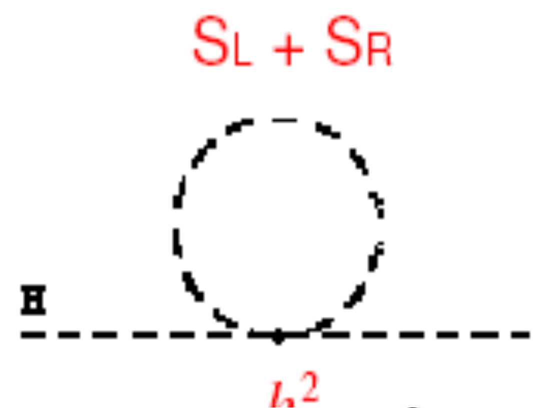
Q|fermion>=|boson>

Q|boson>=|fermion>

Stabilising Higgs mass

“Gauge Hierarchy problem”





$$\delta m_H^2 \sim -\frac{\lambda_f}{16\pi^2}\Lambda^2 \qquad \delta m_H^2 \sim +\frac{\lambda_{\tilde{f}}}{16\pi^2}\Lambda^2$$

$$\delta m_H^2 \sim \frac{\lambda_f}{8\pi^2}(m_f^2 - m_{\tilde{f}}^2) ln(\frac{\Lambda^2}{m_f^2})$$

$$\Rightarrow \lambda_f = \lambda_{\tilde{f}}, \quad m_f = m_{\tilde{f}}$$

Higgs mass is stable

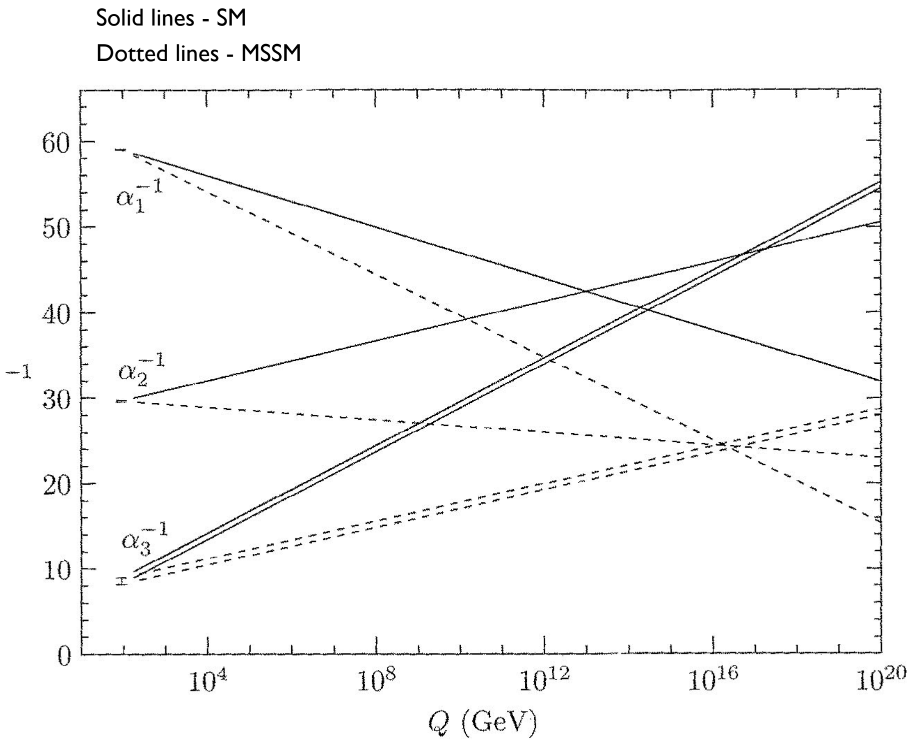
Naturalness

Motivation: Supersymmetry

Gauge Hierarchy problem

$$m_{EW} \sim M_W, M_Z$$
$$m_{pl} \sim 10^{19} GeV$$

Unification



Dark matter candidate : Neutralino, Gravitino..

Supsersymmetry: Particle Spectrum

Q|fermion, bosons>=|bosons, fermions>

Minimal Supersymmetric Standard Model(MSSM)

SM + $\widetilde{\text{SM}}$ + 2 Higgs Doublet

Quarks,Leptons ⟷ Squarks, sleptons

Gluons, W, Z, photons ⟷ Gluinos, Charginos, Neutralinos

$$H_1, H_2$$

$$h, H, A, H^+, H^-$$

5 Higgsses

Next to MSSM

$$H_1, H_2, S \qquad H_1, H_2, H_3, A_1, A_2, H^+, H^-$$

Supersymmetry: Model

100+ free parameters

No prediction of super particle masses, Higgs mass calculable

$m_f \neq m_{\tilde{f}}$ → SUSY is not exact symmetry

Soft breaking → SUGRA, AMSB, GMSB…

Stabilisation of Higgs mass → Mass range of sparticles

Naturalness

Constrained by Flavour Physics experiments

Talk by A. Kundu.

Naturalness

SUSY at the EW scale is motivated by solving gauge hierarchy problem

Natural electroweak symmetry breaking is the leading motivation

$$-\frac{M_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

Contribution to the right must be tuned against each other

to achieve electroweak symmetry breaking at the observed scale.

μ Should not be very high ~ Higgsino like scenario.

Stop and gluino masses should not be very heavy

Supeersymmetry: Naturalness(2)

Measure of Naturalness

Barbieri, Giudice, 1988

$$\Delta|a| = \frac{\delta log\ M_Z^2}{\delta log\ a^2}$$

$$\boxed{-\frac{M_Z^2}{2} = |\mu|^2 + m_{H_u}^2}$$

$$\Lambda = 10\ TeV$$

Tata et .al 1710.09103

$$\Delta_{EW} = \frac{max|each\ term|}{M_Z^2/2}$$

$$\begin{aligned} \delta m_{H_u}^2(\tilde{t}) &= -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log(\Lambda/m_{\tilde{t}}) \\ \delta m_{H_u}^2(\widetilde{W}) &= -\frac{3g^2}{8\pi^2}(m_{\widetilde{W}}^2 + m_{\tilde{h}}^2)\log(\Lambda/m_{\widetilde{W}}) \\ \delta m_{\tilde{t}}^2 &= \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \log(\Lambda/m_{\tilde{g}})\ , \end{aligned}$$

FT=10%

$$\mu \lesssim 200\ \text{GeV}\ ,\ m_{\tilde{t}} \lesssim 400\ \text{GeV}\ ,\ m_{\widetilde{W}} \lesssim 1\ \text{TeV}\ ,\ m_{\tilde{g}} \lesssim 800\ \text{GeV}\ , m_{\tilde{q}} < 4 - 10\ TeV$$

FT=100%

$m_{\tilde{t},\tilde{g}}$ **~ few TeV** **Beyond the reach of current LHC**

Dark matter: Sparticle masses

Supersymmetry provides an excellent WIMP candidate for DM, when lightest Neutralino is the DM candidate.

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \propto \tilde{m}^2$$

→ Upper bound on Masses

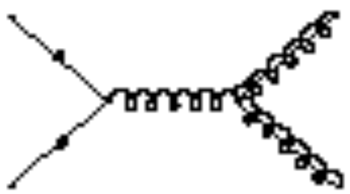
For mixed Bino-Higgsino LSP $m_{\tilde{W}-\tilde{H}} < 1.0 TeV$

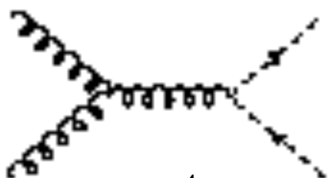
For mixed Wino like LSP $m_{\tilde{W}} < 2.7 - 3.0 TeV$

Beyond the sensitivity of current LHC.

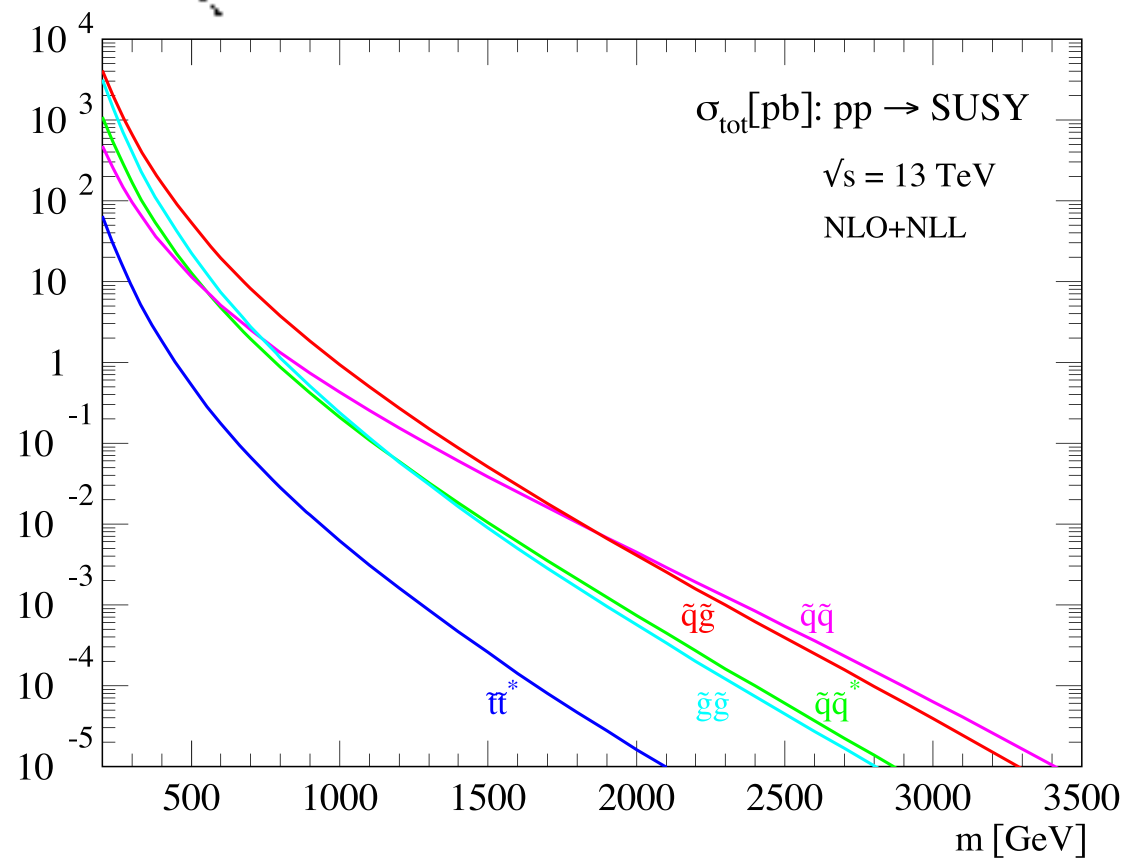
Supersymmetry @ LHC

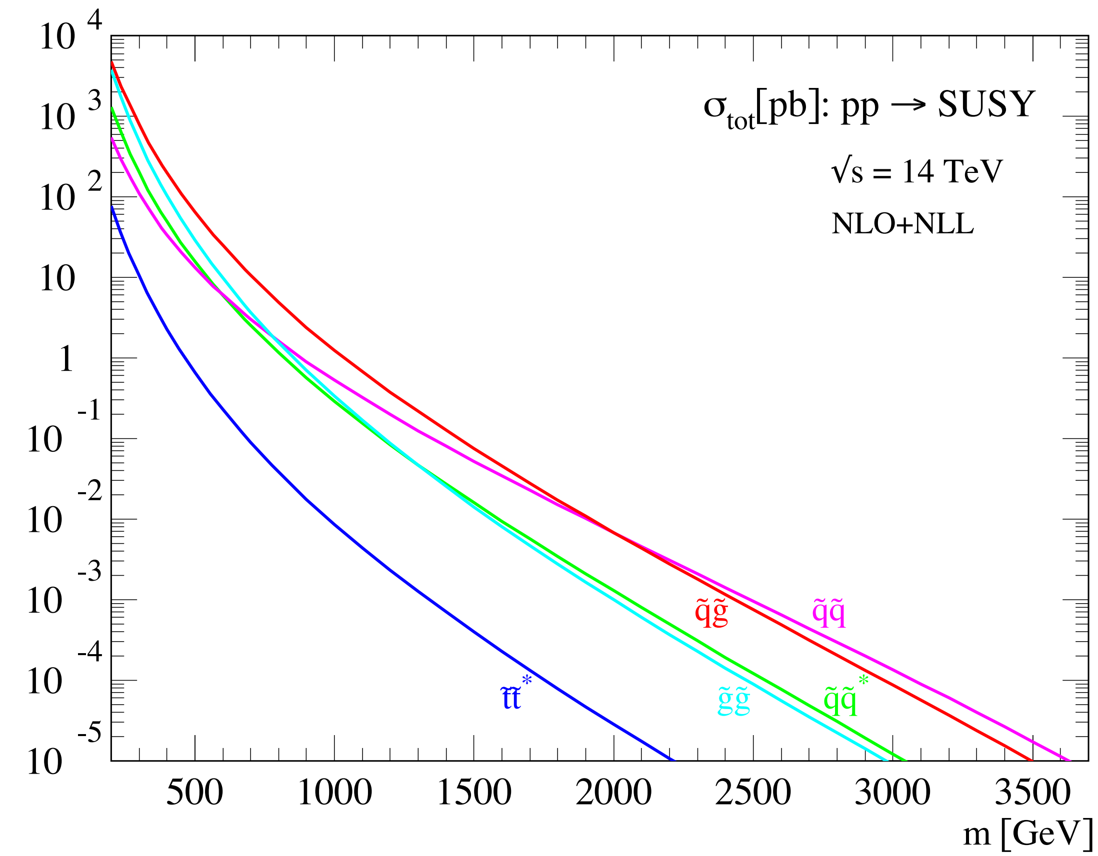
Sparticle production @ LHC





$$pp \to gg, qq \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}, \tilde{t}_1\tilde{t}_1, \tilde{\chi}\tilde{\chi}$$





m ~ 2 TeV

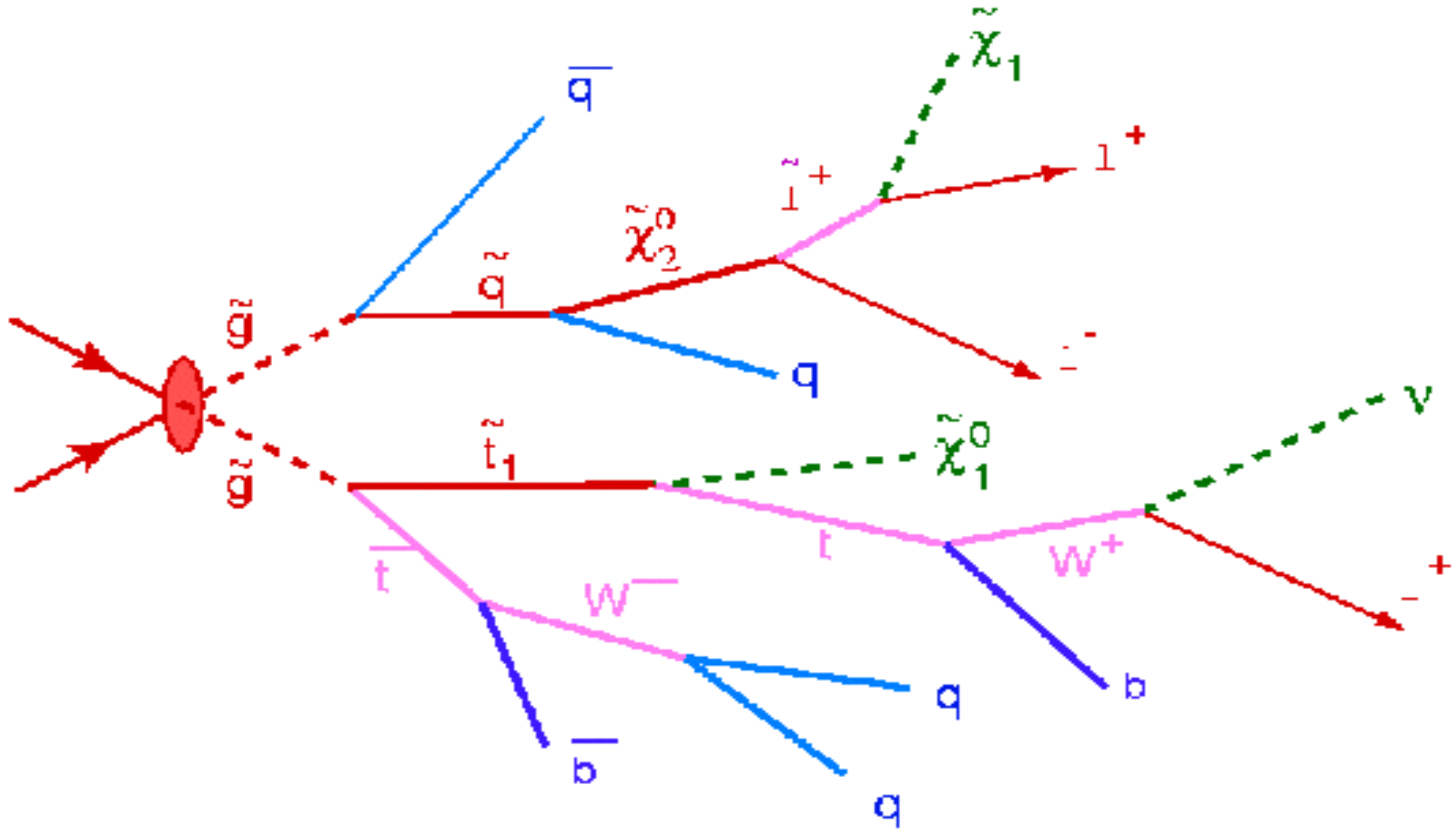
$$\sigma(\tilde{t}\tilde{t}) \sim 0.003 \ fb$$

$$\sigma(\tilde{g}\tilde{g}) \sim 1 \ fb$$

$$\sigma(\tilde{g}\tilde{q}, \tilde{q}\tilde{q}) \sim 10 \ fb$$

1407.5066

Sparticle Production and Decay

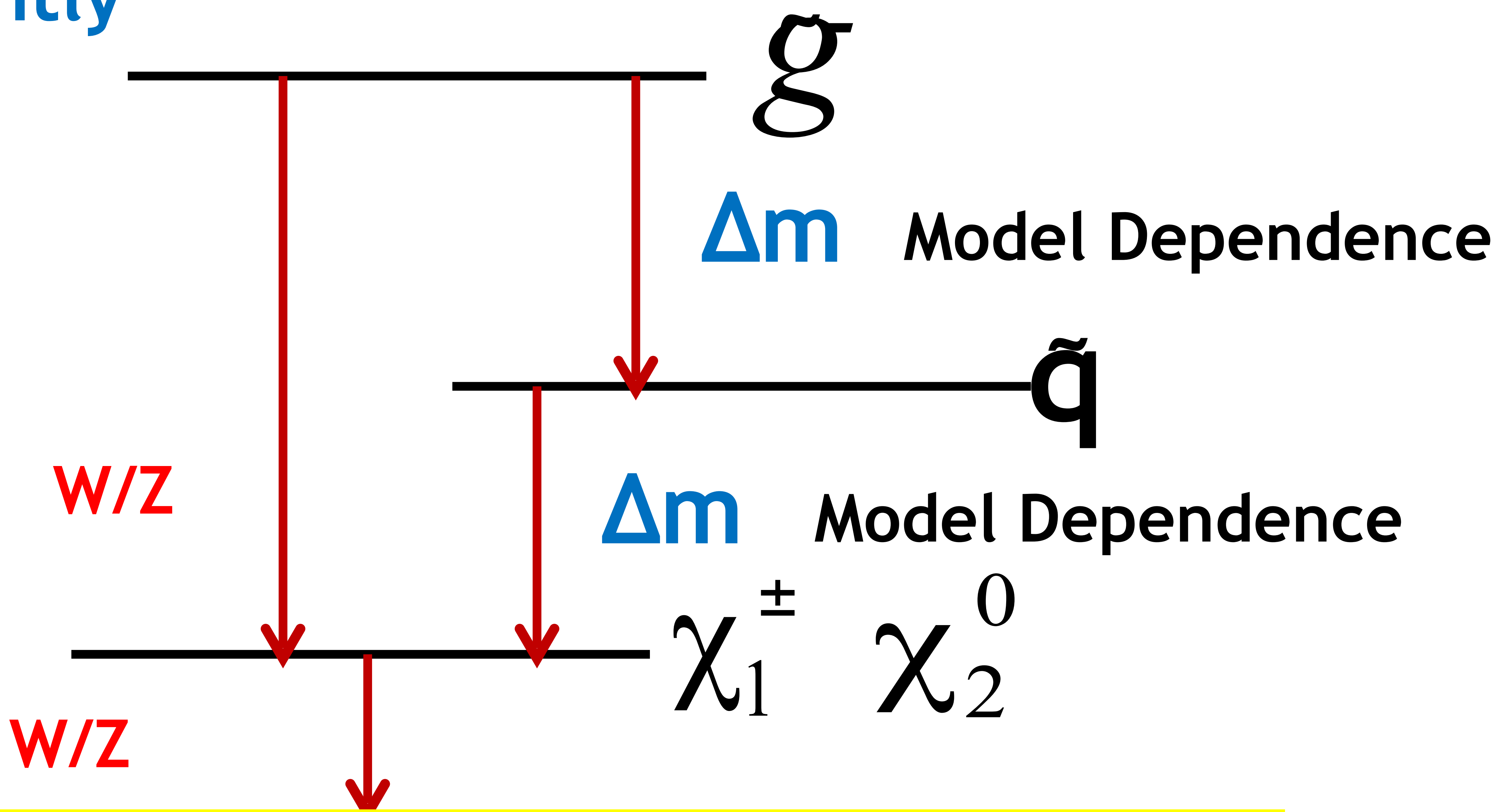


3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

Leptons+jets+b jets + tau jets+photon+MET
Tracks, Displaced vertex etc..

SUSY signals in Colliders

At the LHC, gluinos and squarks are produced dominantly



Leptons+photons+jets+Missing energy.

SUSY signal

Signal sensitivity depends

- Production cross sections
- Branching Ratio, couplings
- Mass difference between daughter and parent

Experimental conditions

- Energy, Luminosity
- Triggering events
- Detector acceptance, Resolution etc.
- Understanding Backgrounds, very important
  cross sections 10^3 to 10^6 pb

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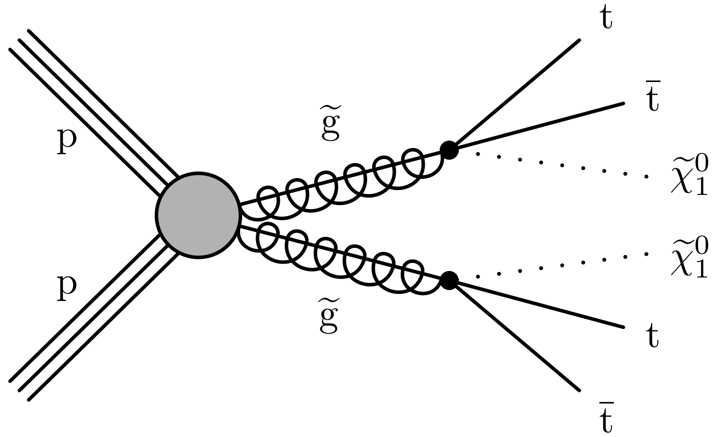
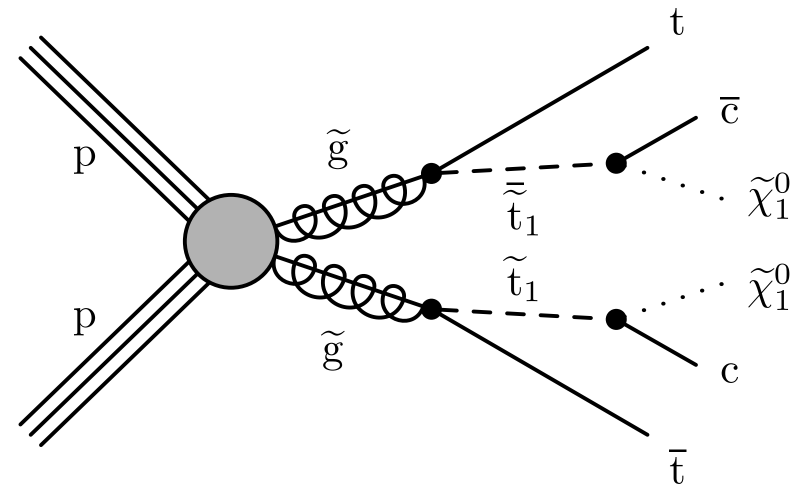
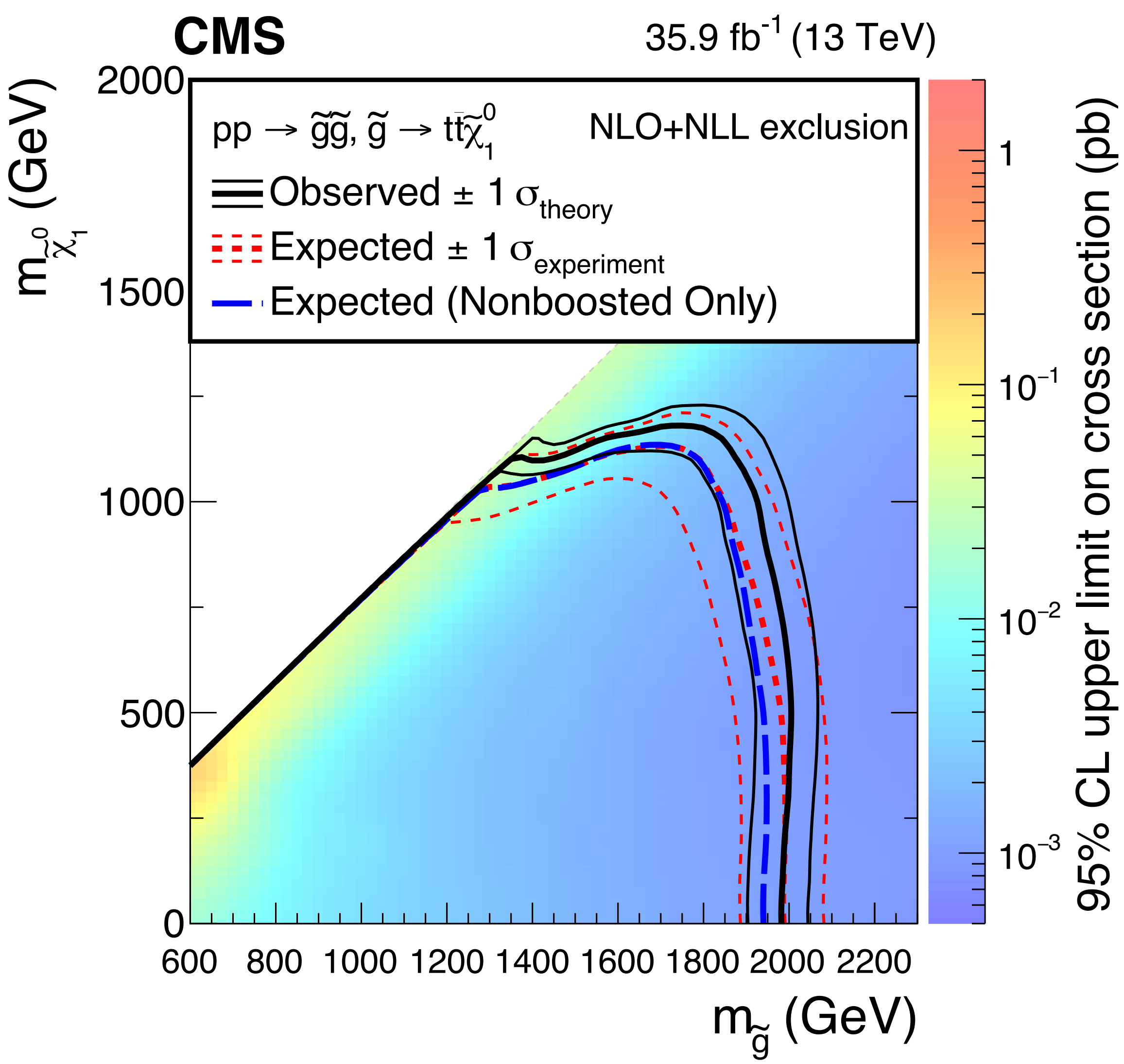
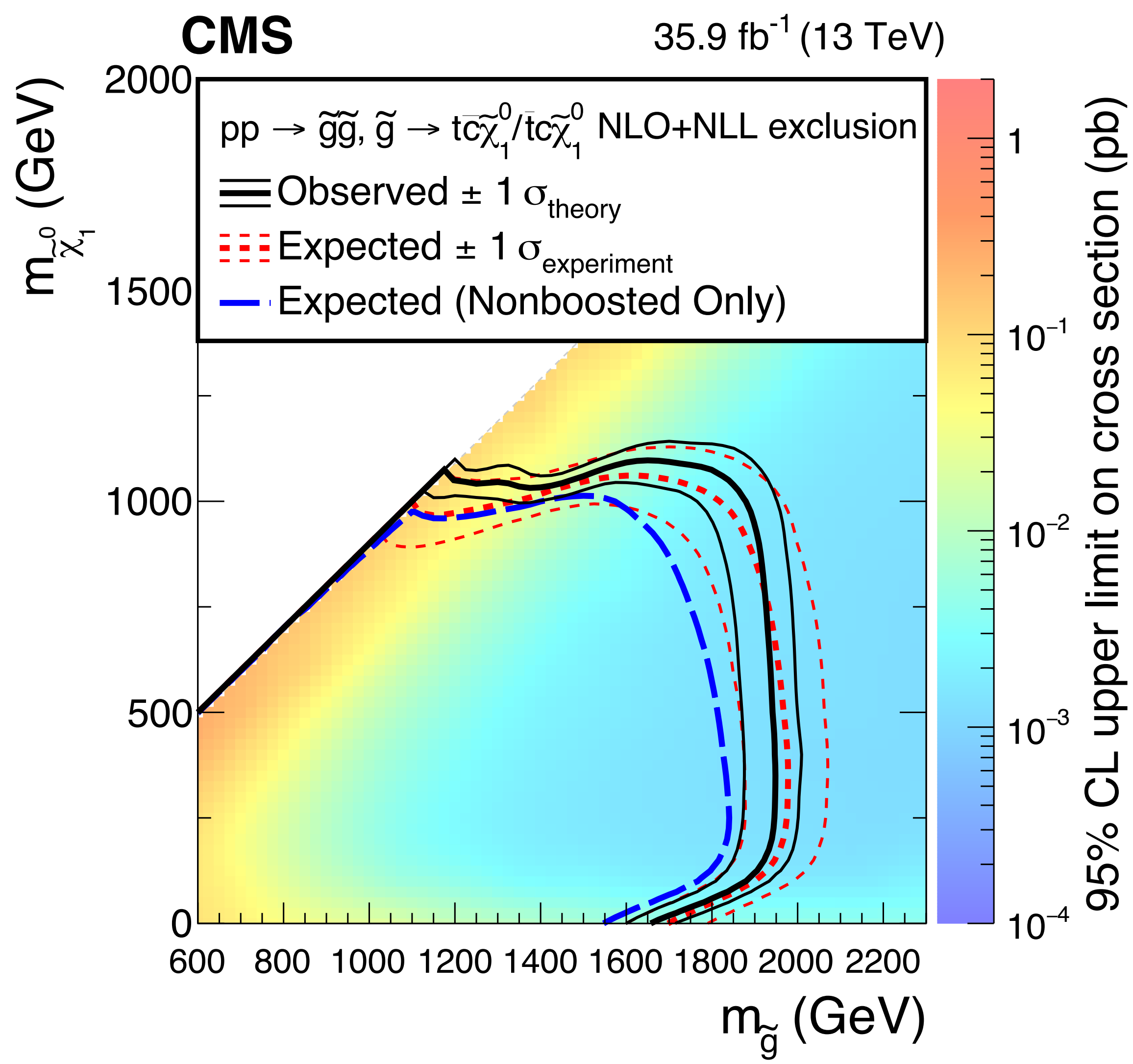
No EXCESS found.
Masses are excluded in SMS model.

Gluino@ 13 TeV LHC



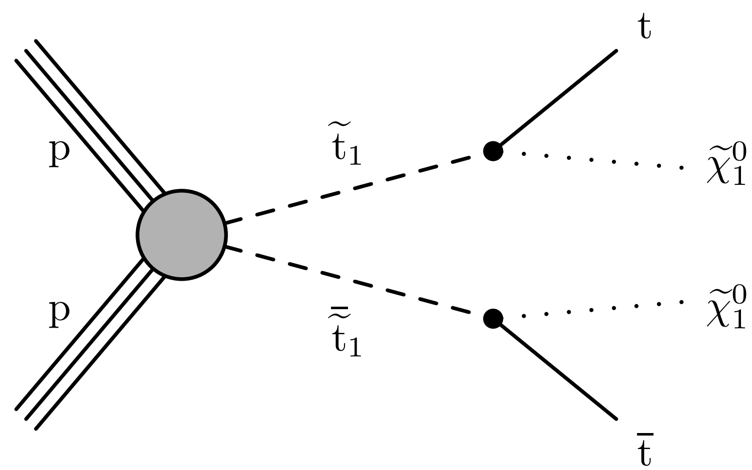


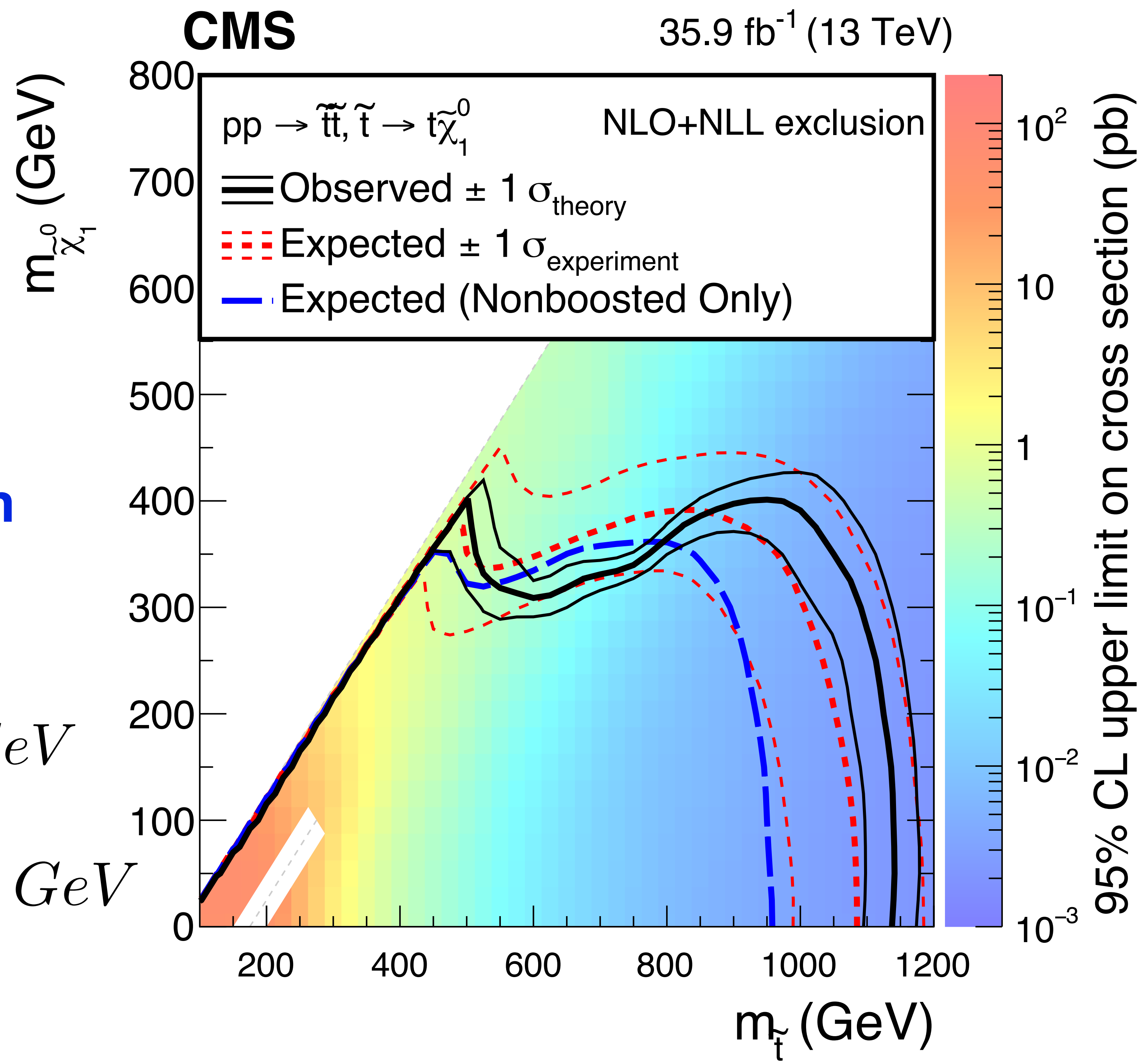




$$m_{\tilde{g}} > 2\ TeV \quad @ \quad m_{\tilde{\chi}_1^0} = 1\ GeV$$

Stop@13 TeV





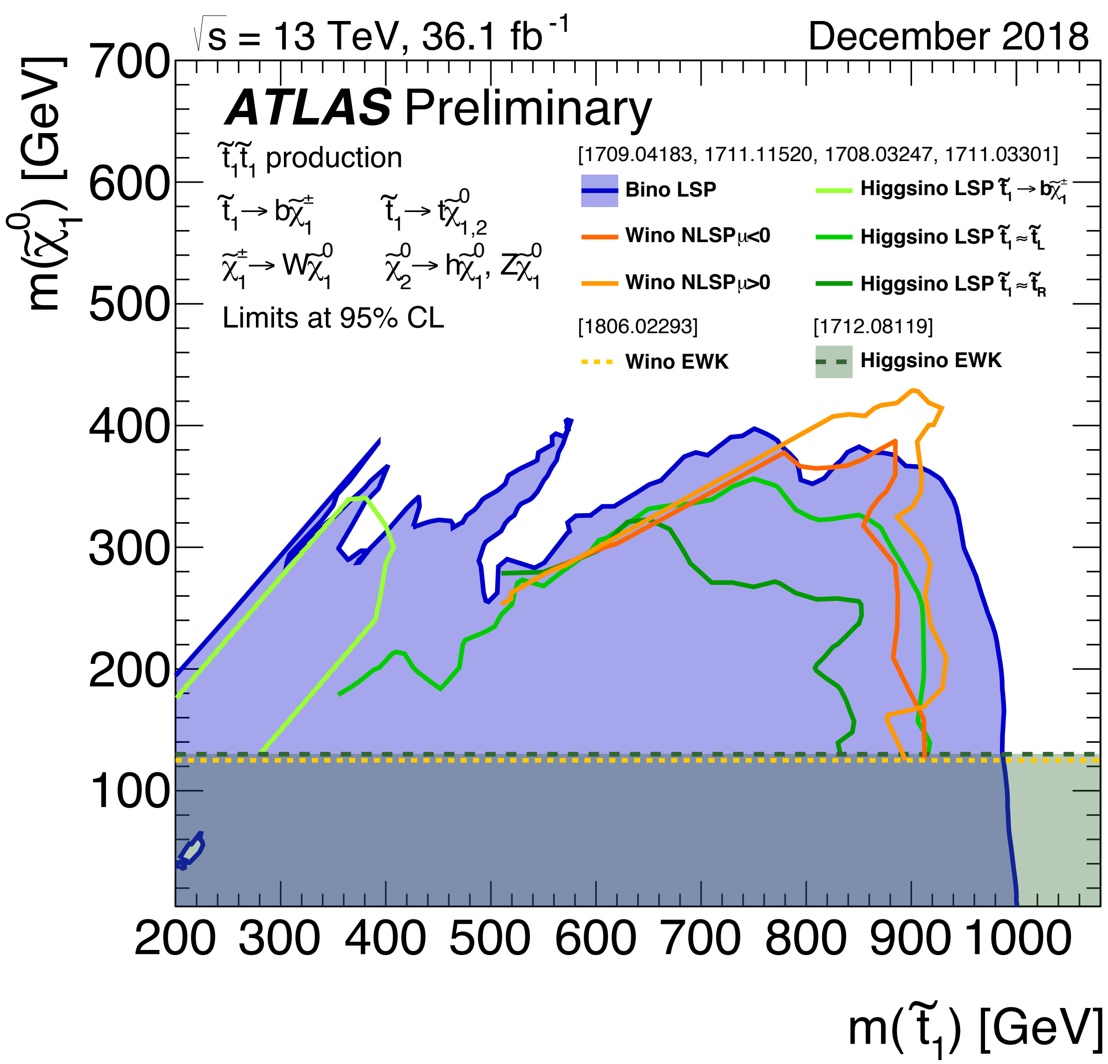
Hadronic event or one lepton
Boosted and no Boosted

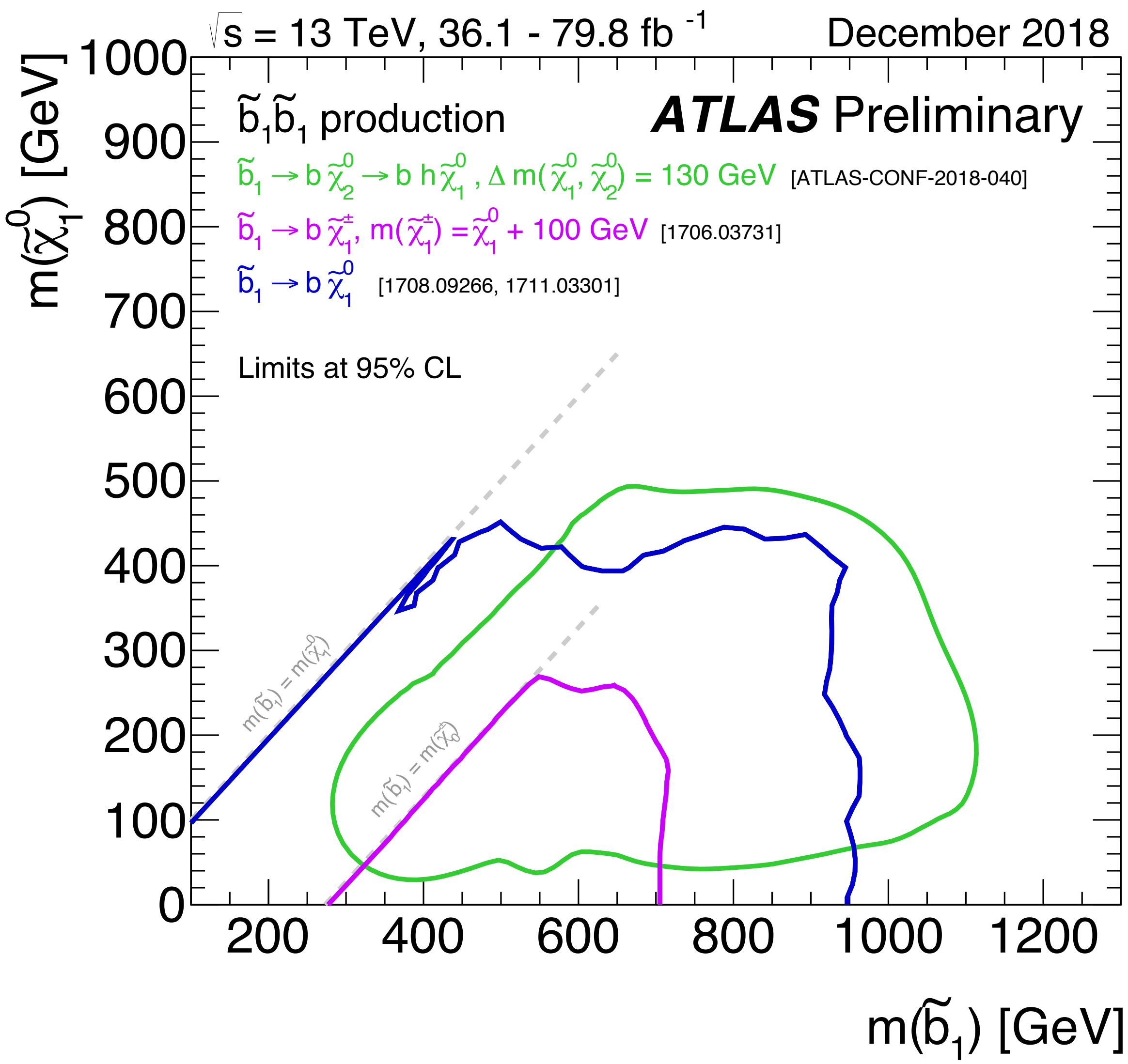
$$m_{\tilde{t}} > 1.14\ TeV \quad @ \quad m_{\tilde{\chi}_1^0} = 1\ GeV$$

$$m_{\tilde{\chi}_1^0} > 200\ GeV \ @ \ m_{\tilde{\chi}_1^0} \sim 100\ GeV$$

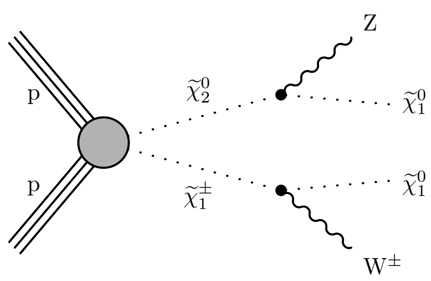
Limits are not absolute, very sensitive to LSP mass,
In particular in compressed scenario.

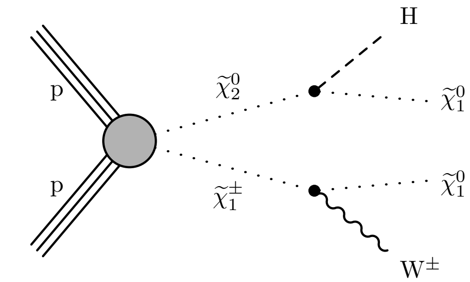
3rd Generation

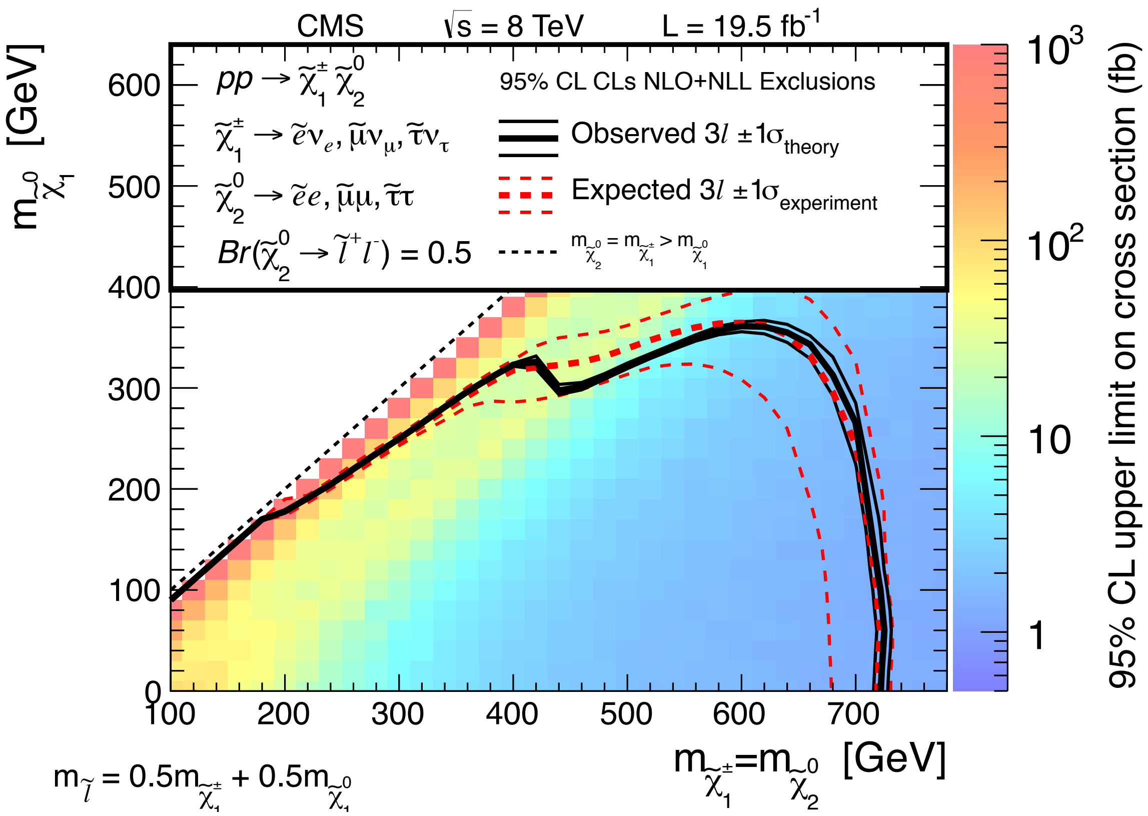


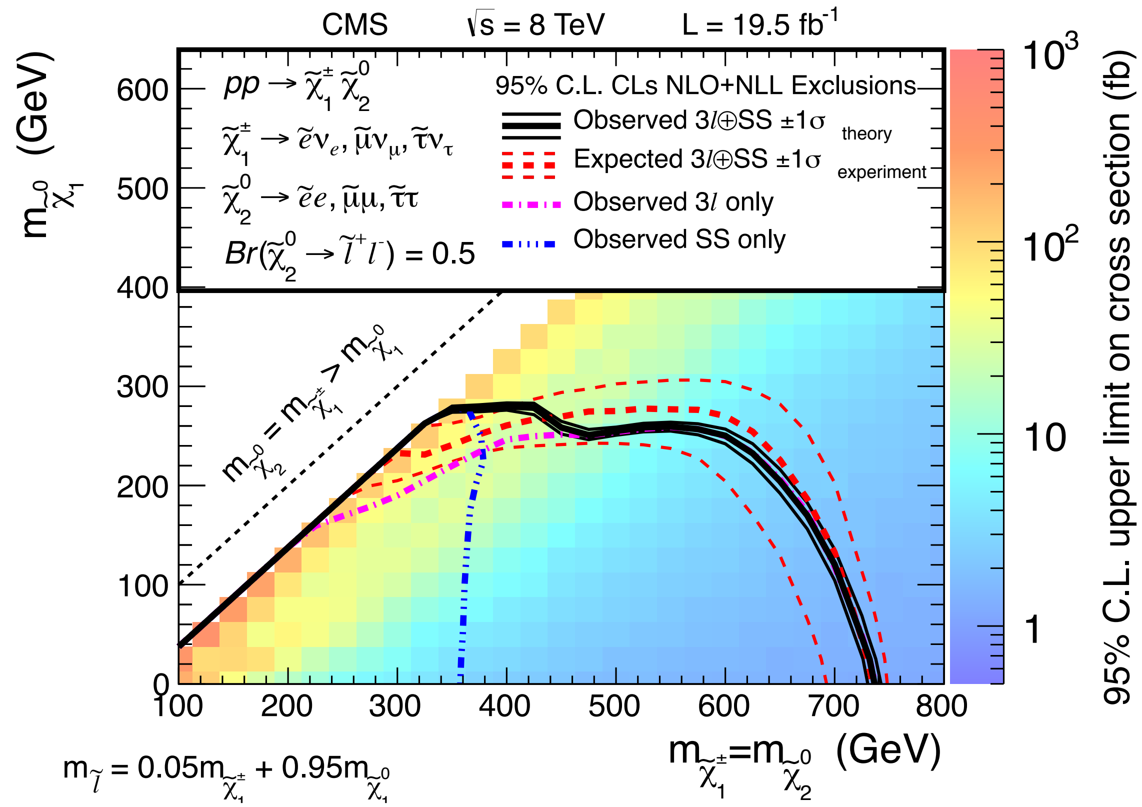


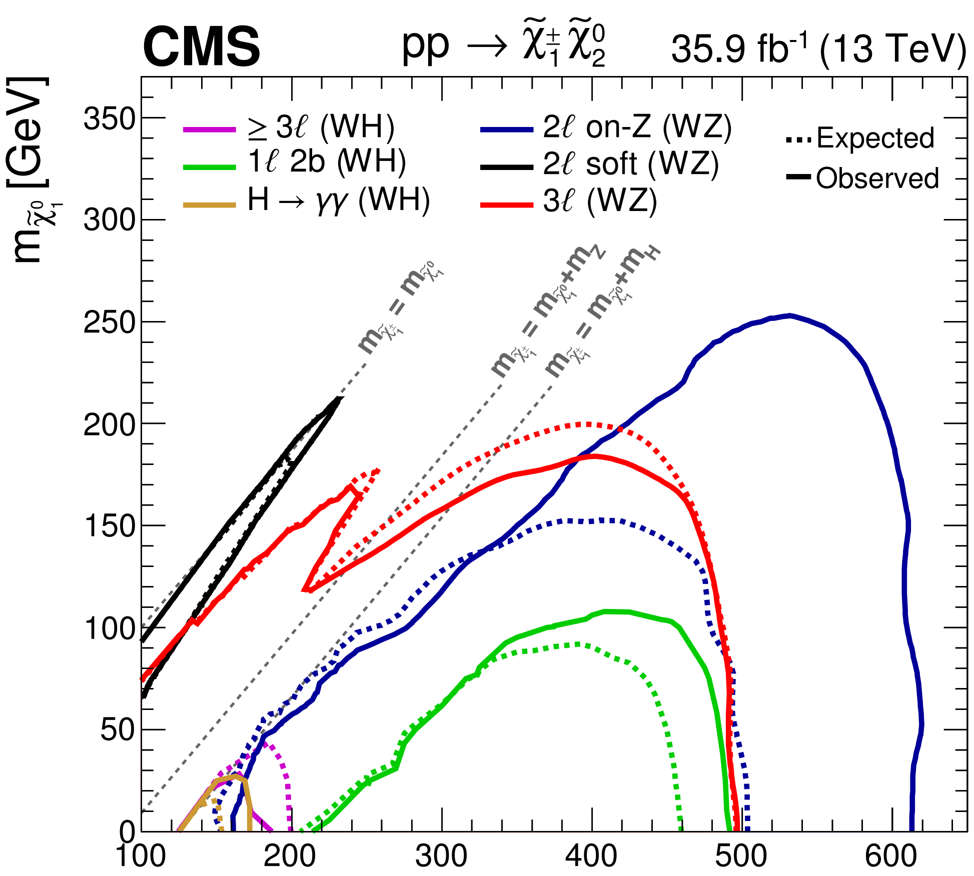
Chargino-Neutralino

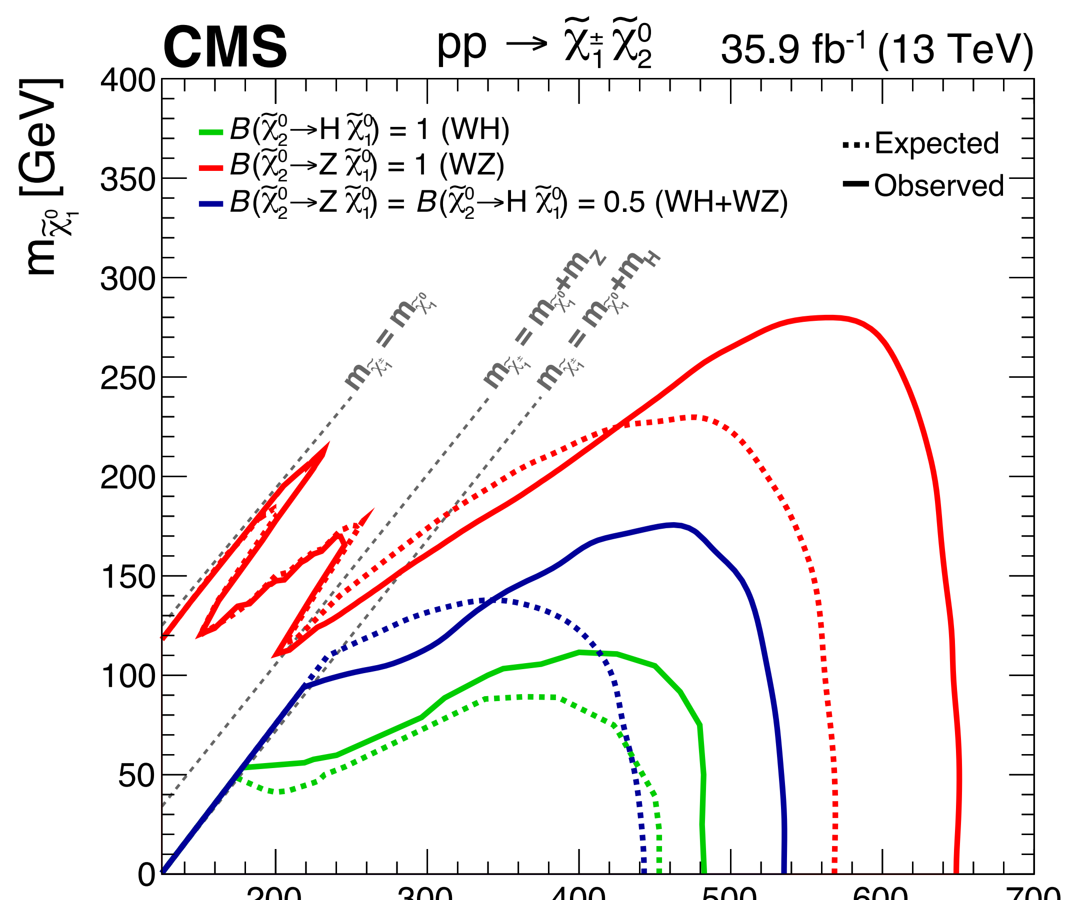




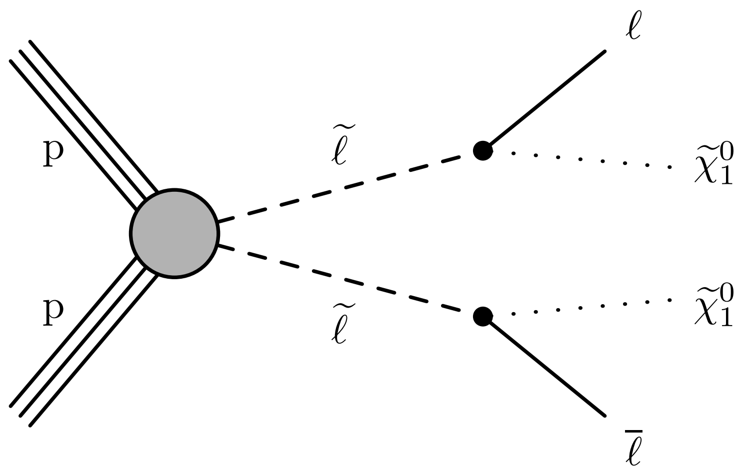






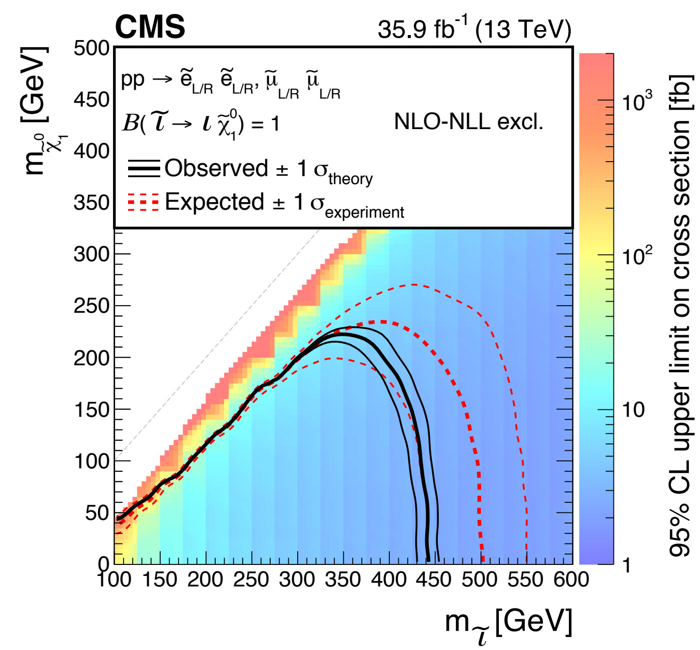


Slepton



$$\tilde{e}_{L,R}, \tilde{\mu}_{L,R}$$

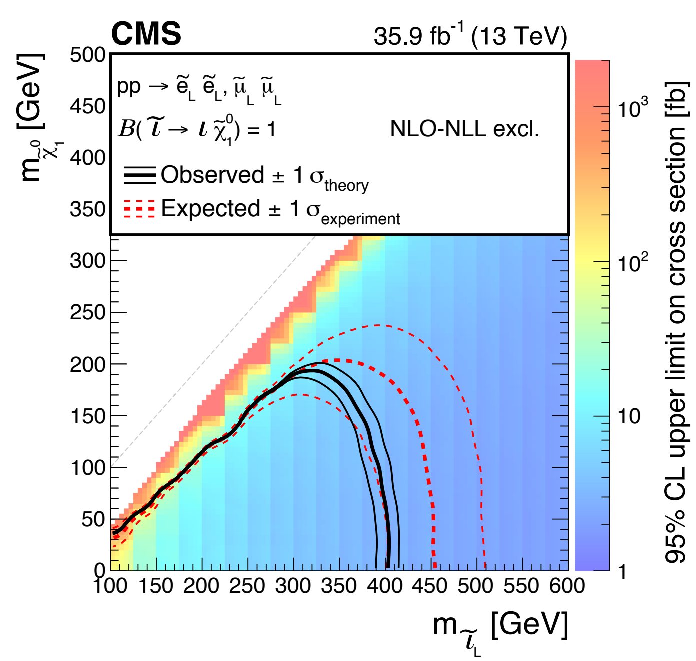
2 lepton + Missing energy + No jets

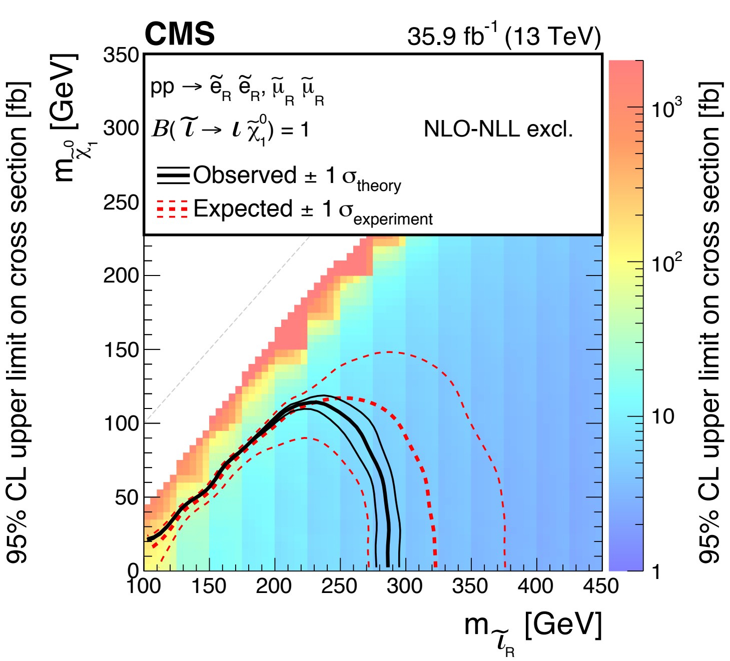


L+R $m_{L,R} > 450\ GeV$

L $m_L > 400\ GeV$

R $m_R > 290\ GeV$





Summary of Exclusion

Exclusion Limits @ $m_{\tilde{\chi}_1^0}$ **=1 GeV**

$$m_{\tilde{g}} > 2 - 2.2\ TeV \ \Rightarrow m_{\tilde{g}} > 800\ GeV \quad for \quad m_{\tilde{\chi}_1^0} = 500\ GeV$$

$$m_{\tilde{t}} > 1.1\ TeV \qquad \Rightarrow m_{\tilde{t}_1} > 200\ GeV \quad for \quad m_{\tilde{\chi}_1^0} = 200\ GeV$$

$$m_{\tilde{\chi}_1^\pm} m_{\tilde{\chi}_2^0} > 600 - 700\ GeV$$

$$m_{\tilde{\ell}} > 400 - 300\ GeV$$

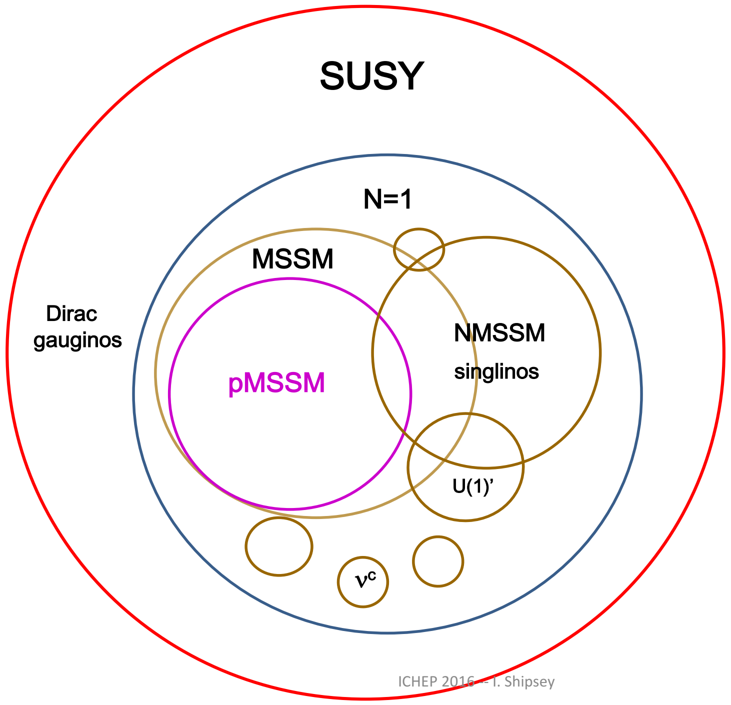
Limits are sensitive to decay channel, and mass difference

SMS Model

Simplified Mass Spectra(SMS). is not a model,

Assumptions on,

- **Masses**
- **Branching ratios(100%)**
- **R-parity conserving model(LSP is stable)**
- **NO specific model inputs.**
- **Limits may be valid for a very particular context.**



R-parity violating SUSY model, LSP decays, MET soften, Loss of sensitivity

Ian Shipsey, ICHEP 2016 Talk

Warning:

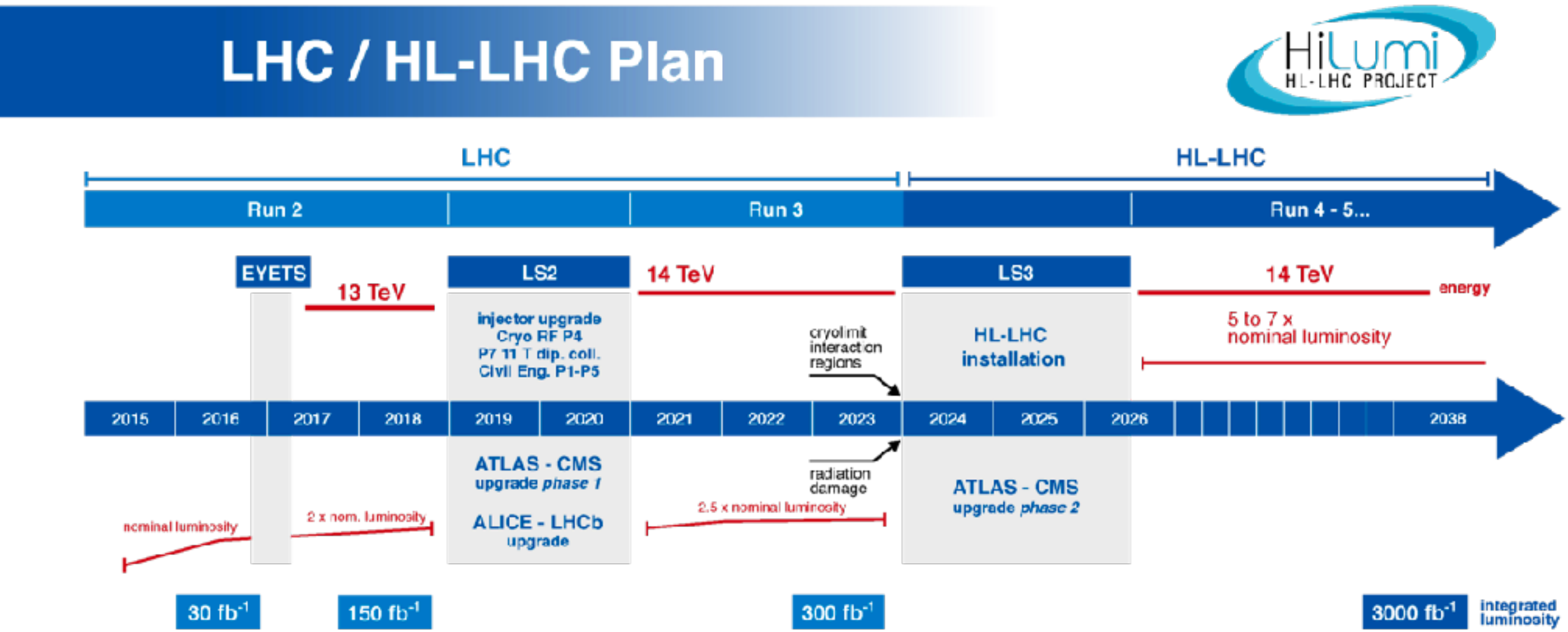
Exclusions are not absolute, need to reinterpret using specific model before drawing any conclusion.

Bounds on Ewinos reduced, once model specifications are used

A.Datta et al., N Ganguly, S. Poddar, '15,'16

Supersymmetry: Future

High Luminosity: LHC



No Physics before May 2021(LHCC)

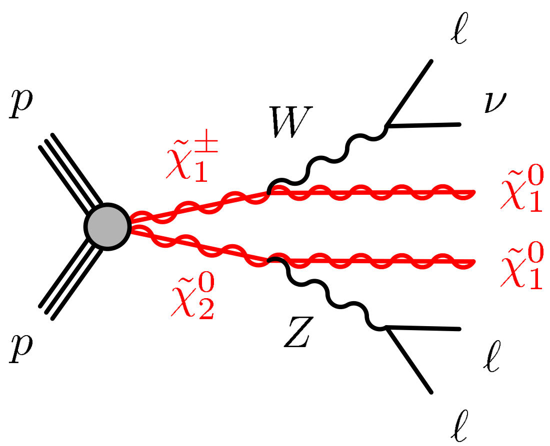
Challenges of HL-HE LHC

Detector elements and electronics are already exposed to high radiation dose. Need upgrades

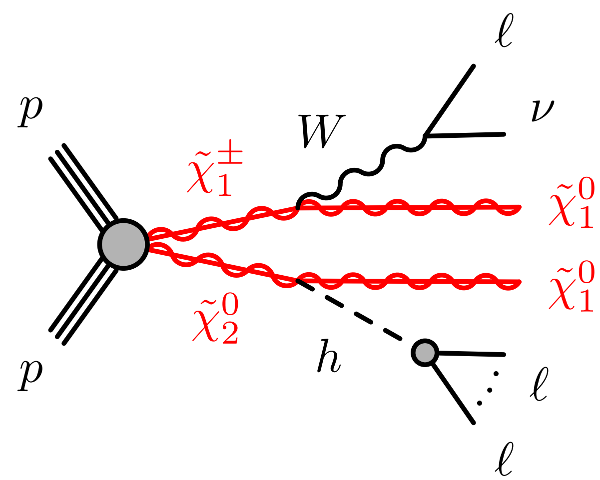
High Pile UP:

Increased rate of fake tracks,
Spurious energy deposition of energy in calorimeters,
Affect object reconstruction
Trigger rates.
Storing events etc…

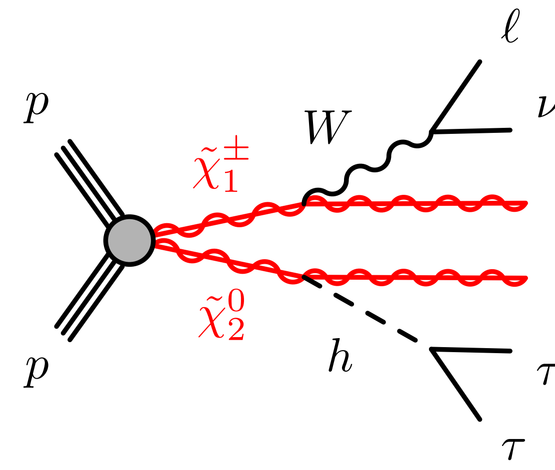
Chargino and Neutralino(1)



(a) WZ-mediated



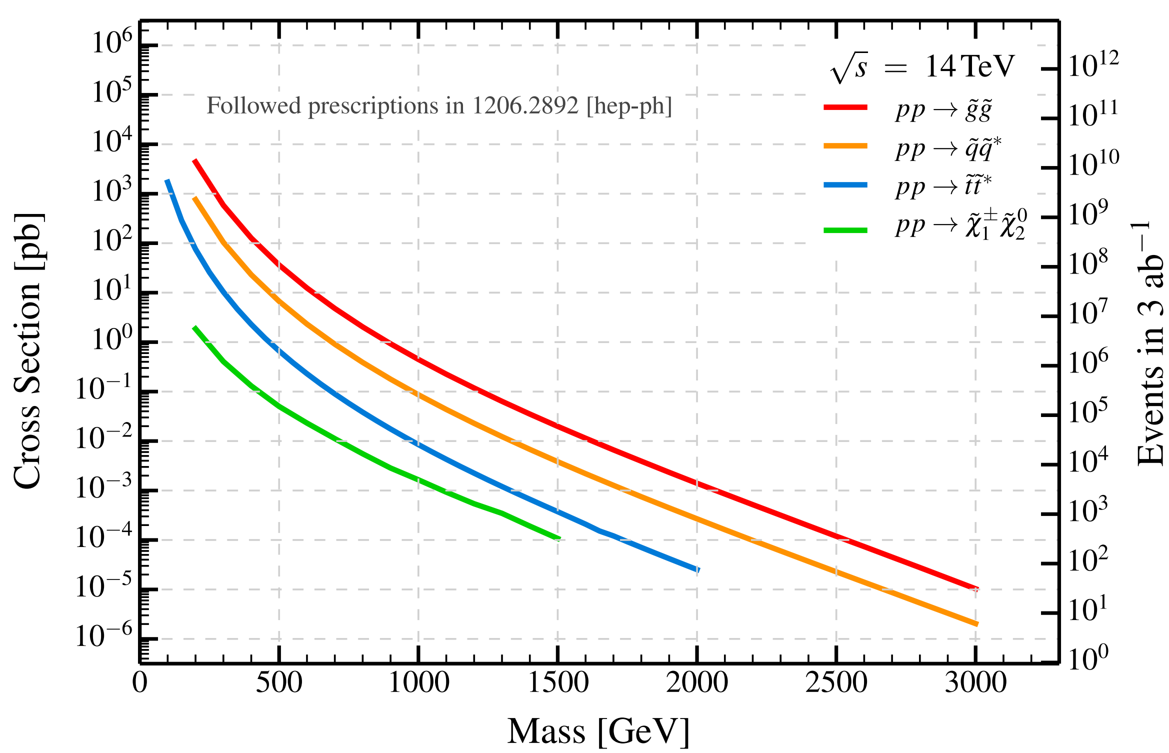
(b) Wh-mediated ($h \to \ell\ell$)



(c) Wh-mediated ($h \to \tau\tau$)

3ℓ

$1\ell 2\tau$

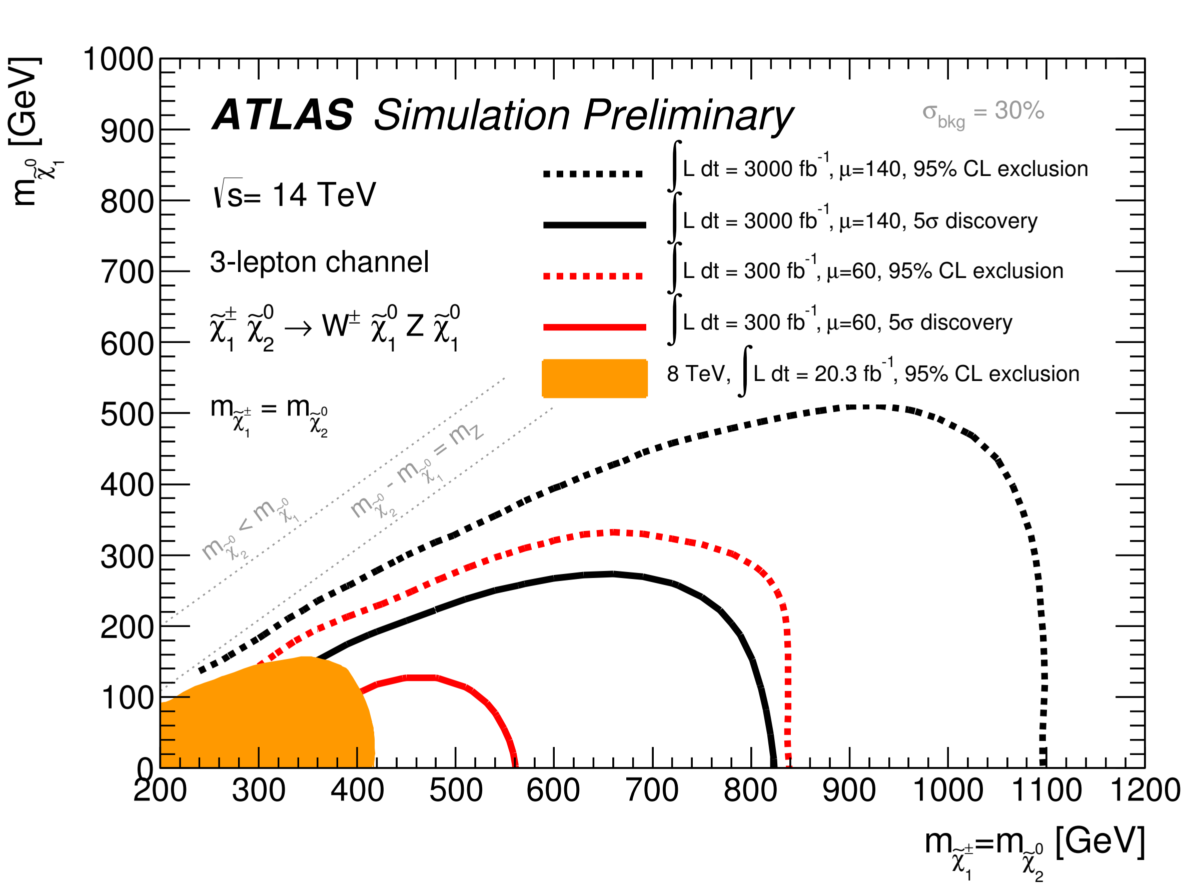


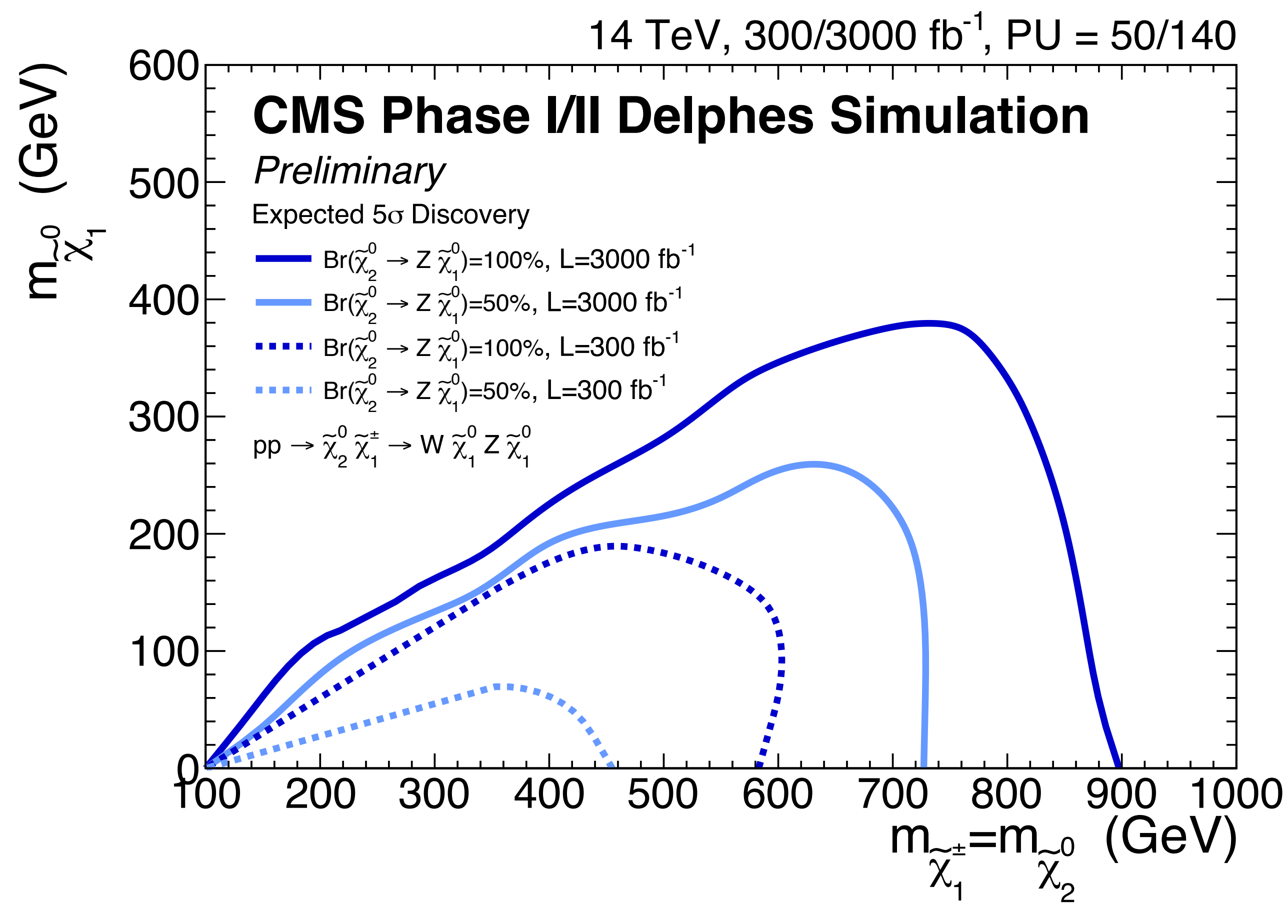
Selection	SRA	SRB	SRC	SRD
m_{SFOS}[GeV]	81.2-101.2			
# b-tagged jets	0			
lepton p_T (1,2,3)[GeV]	> 50			
E_T^{miss}[GeV]	> 250	> 300	> 400	> 500
m_T [GeV]	> 150	> 200	> 200	> 200
$\langle\mu\rangle$ = 60, 300 fb^{-1} scenario	yes	yes	yes	–
$\langle\mu\rangle$ = 140, 3000 fb^{-1} scenario	yes	yes	yes	yes

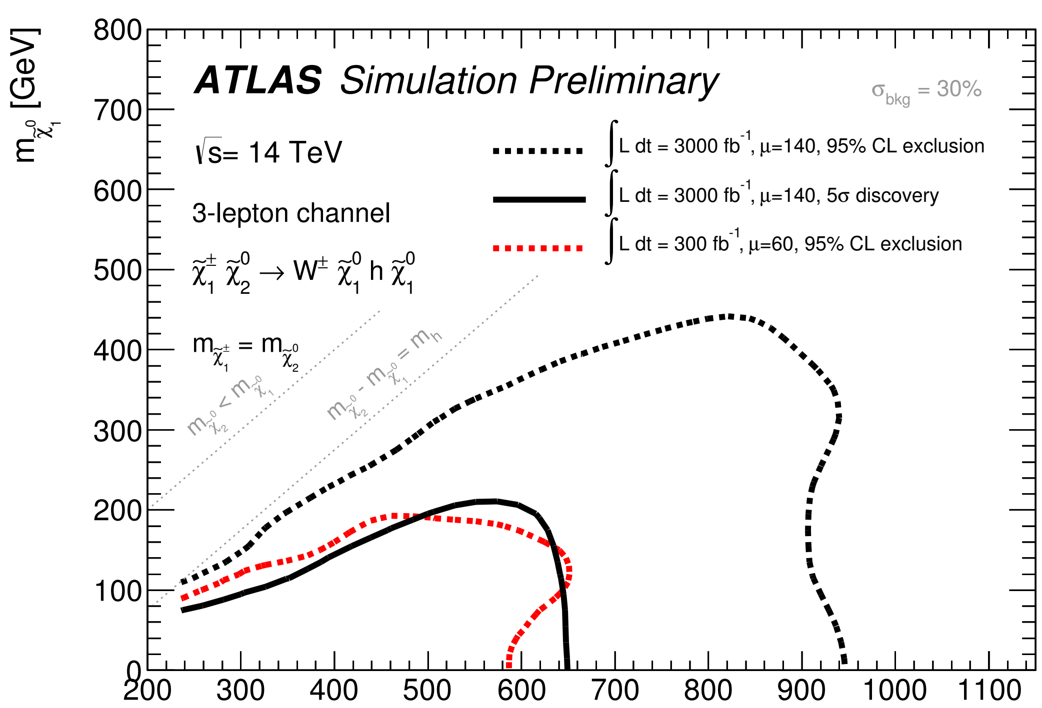
ATLAS

Chargino and Neutralino(2)

SMS Model



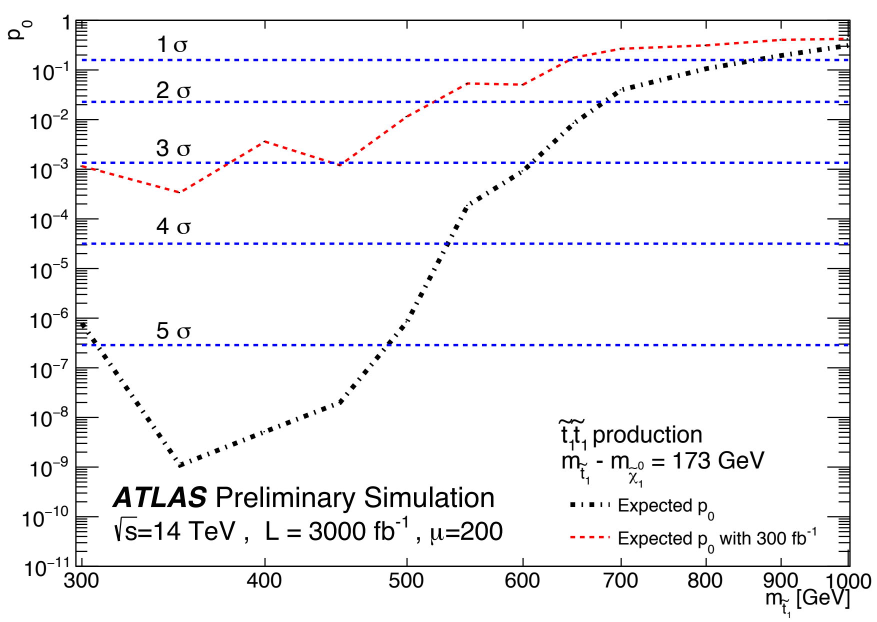


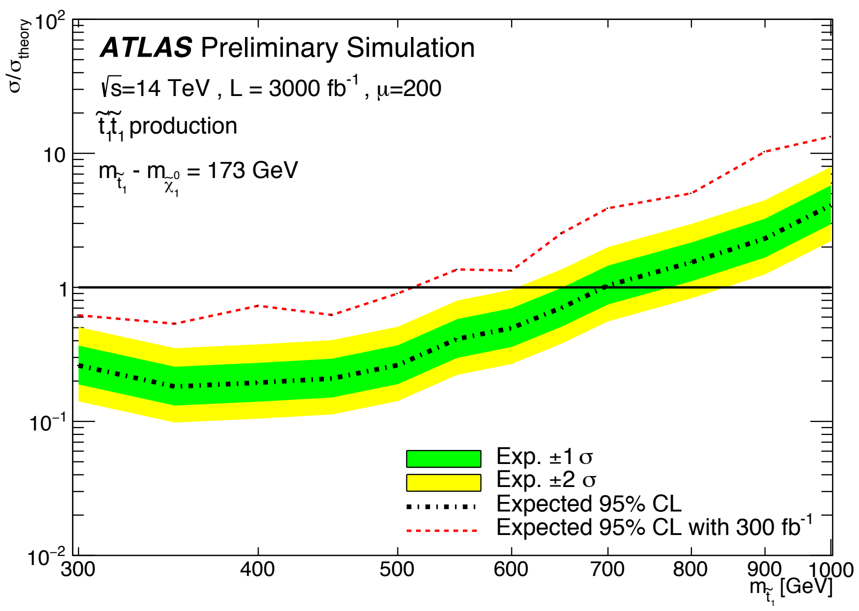


Stop@HL-LHC

	SR
Expected Standard Model	13.8 ± 6.5
$t\bar{t}$	11.4 ± 5.1
$t\bar{t} + Z$	2.4 ± 1.5
Others	$0.0^{+1.8}_{-0.0}$
$\tilde{t}_1\,\tilde{t}_1\; m(\tilde{t}_1, \tilde{\chi}^0_1) = (350, 177)$ GeV	62.7 ± 7.5
$\tilde{t}_1\,\tilde{t}_1\; m(\tilde{t}_1, \tilde{\chi}^0_1) = (700, 527)$ GeV	11.0 ± 2.0

$$\Delta m \sim m_t$$



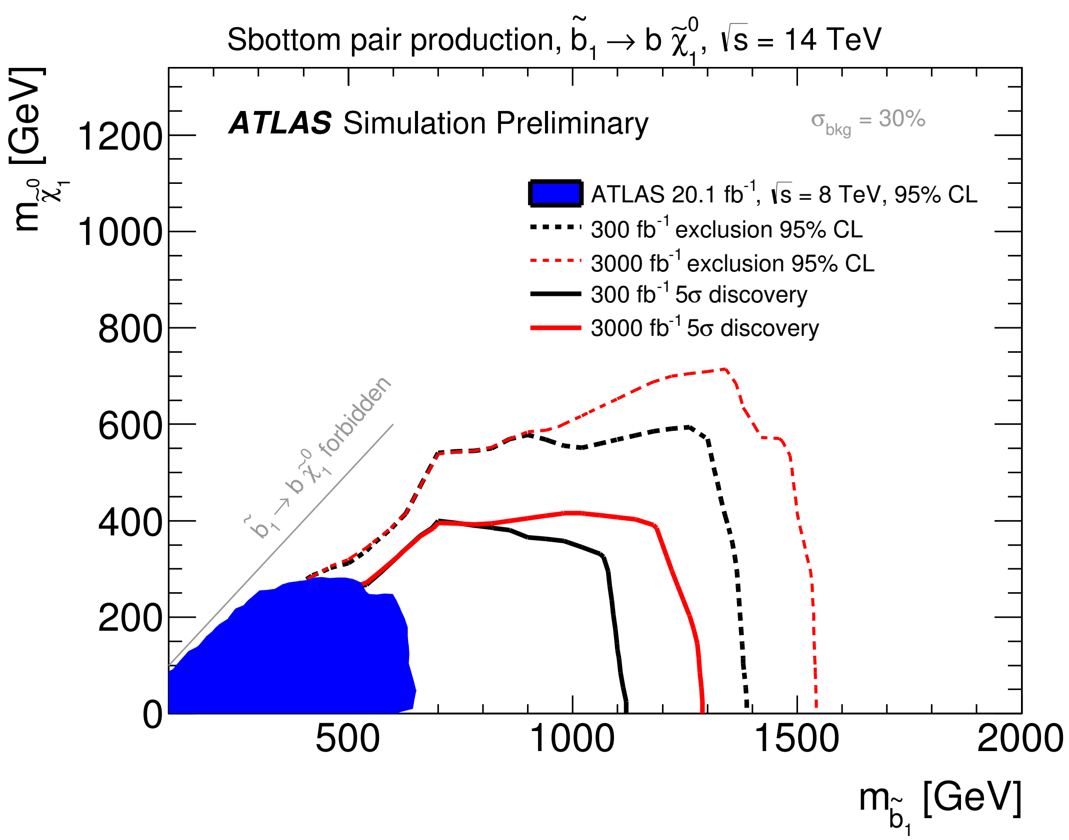


Mass discoverable upto 480 GeV

Exclusion ~ 700 GeV

ATL-PUB-PHYS-2016-22

Sbottom search



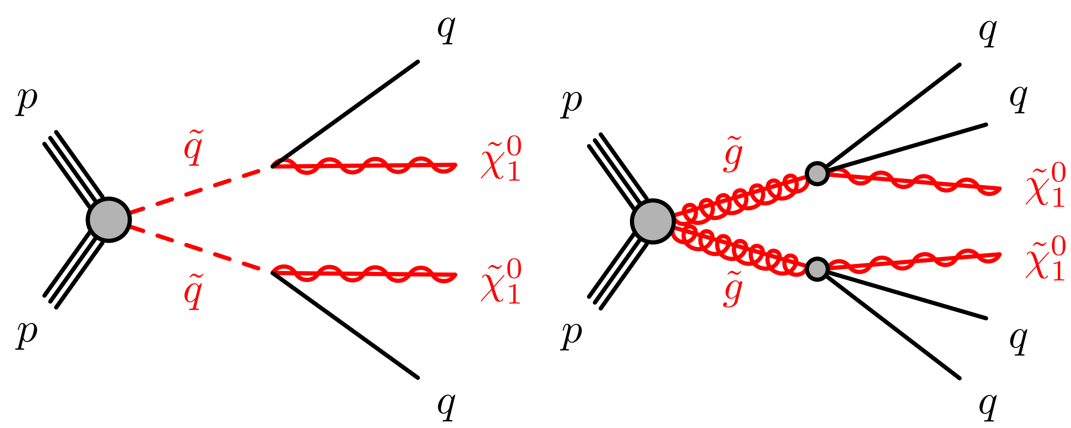
Exclusion

$$m_{\tilde{b}_1} > 1.4(1.55)\ TeV, L = 300(3000) fb^{-1}$$

Discovery

$$m_{\tilde{b}_1} > 1.1(1.3)\ TeV, L = 300(3000) fb^{-1}$$

Gluino and Squark



Jets + Missing energy

Event Selection:

$$p_T^{j_1} > 160 \text{ GeV}, N_j : 2-6, E_T^{miss} > 160 \text{ GeV}$$

$$\Delta\phi(jet, E_T^{miss})_{min} > 0.4(j_1, j_2, j_3), 0.2(\text{all jets } p_T > 40\ GeV)$$

Signal Region:

$$m_{eff} + \sum p_T^j, E_T^{\text{miss}}/m_{eff}, E_T^{miss}/\sqrt{H_T}$$

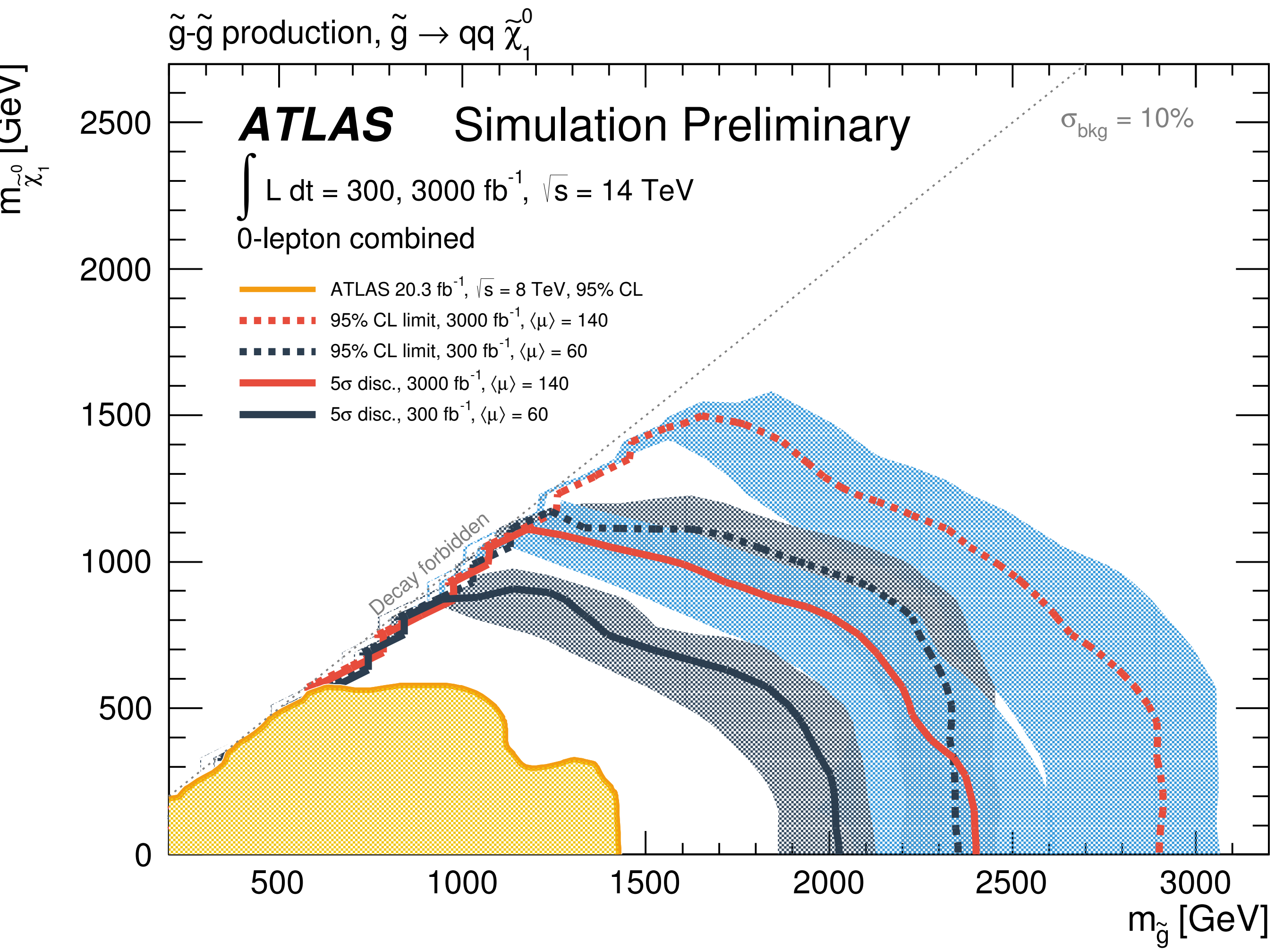
Cuts are optimised for :

$$< \mu >= 60, 300 fb^{-1}$$

$$< \mu >= 140, 3000 fb^{-1}$$

ATL-PHY-PUB-2014-10

Gluino: Sensitivity



(a) $\tilde{g}\tilde{g}$

Discovery

$$m_{\tilde{g}} = 2(2.35)\ \text{TeV}, L = 300(3000) fb^{-1}$$

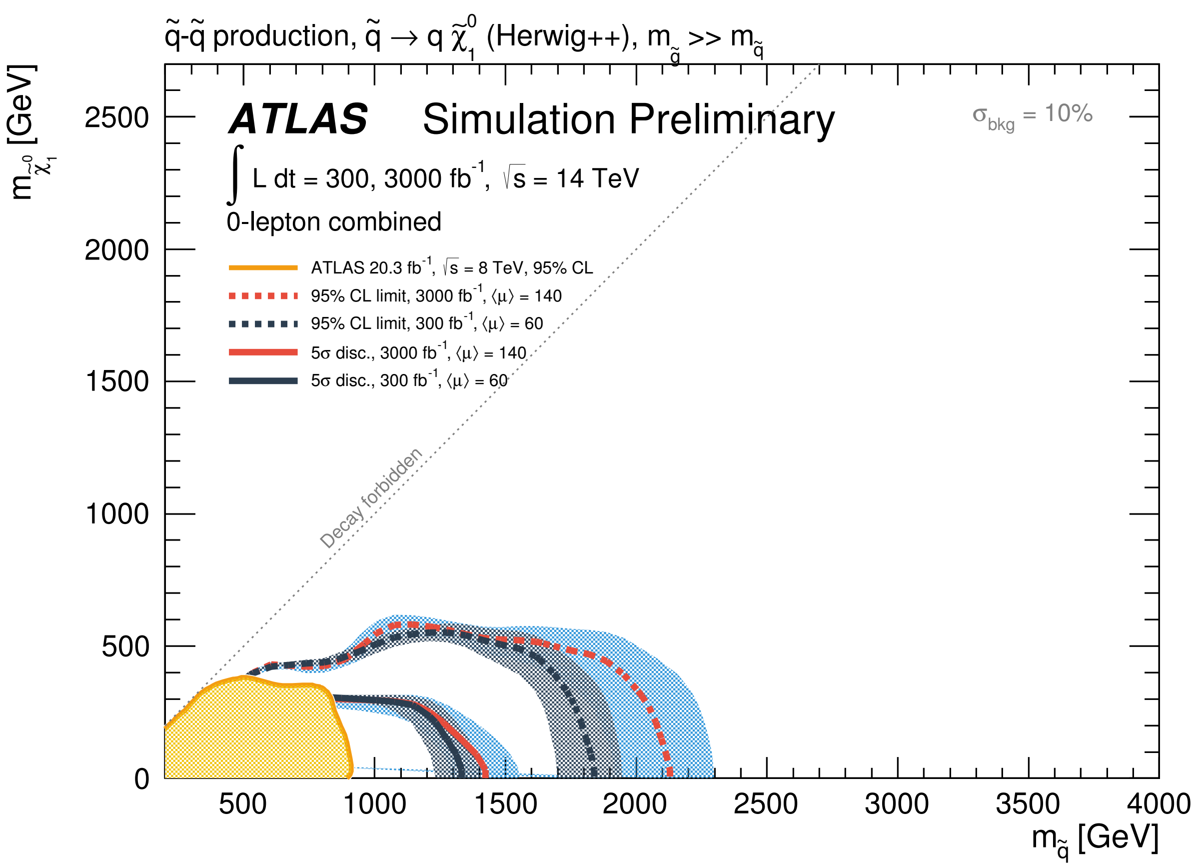
$$m_{\tilde{\chi}_1^0} = 0.9(1.1)\ \text{TeV}, L = 300(3000) fb^{-1}$$

Exclusion

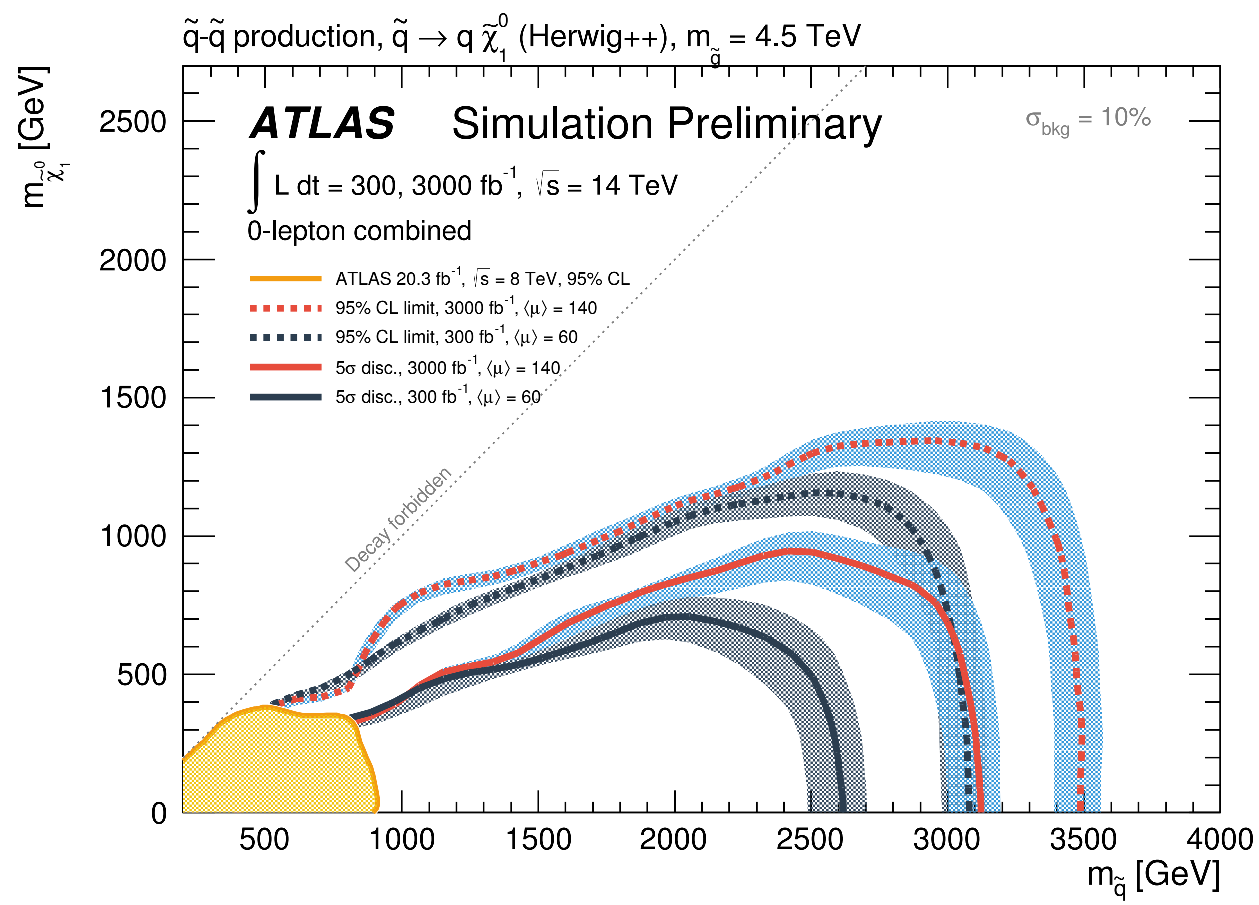
$$m_{\tilde{g}} = 2.35(2.95)\ \text{TeV}, L = 300(3000) fb^{-1}$$

$$m_{\tilde{\chi}_1^0} = 1.1(1.5)\ \text{TeV}, L = 300(3000) fb^{-1}$$

Squark: Sensitivity



(b) $\tilde{q}\tilde{q}$, decoupled $\tilde{g}$



(c) $\tilde{q}\tilde{q}$, $m_{\tilde{g}} = 4.5$ TeV

Discovery

$$m_{\tilde{q}} = 1.4\ TeV, L = 3000 fb^{-1}$$

Exclusion

$$m_{\tilde{q}} > 1.85(2.0)\ TeV, L = (300)3000 fb^{-1}$$

Discovery

$$m_{\tilde{q}} = 2.4(3.1)\ TeV, L = (300)3000 fb^{-1}$$

Exclusion

$$m_{\tilde{q}} > 3.1(3.5.0)\ TeV, L = (300)3000 fb^{-1}$$

Physics 100 TeV

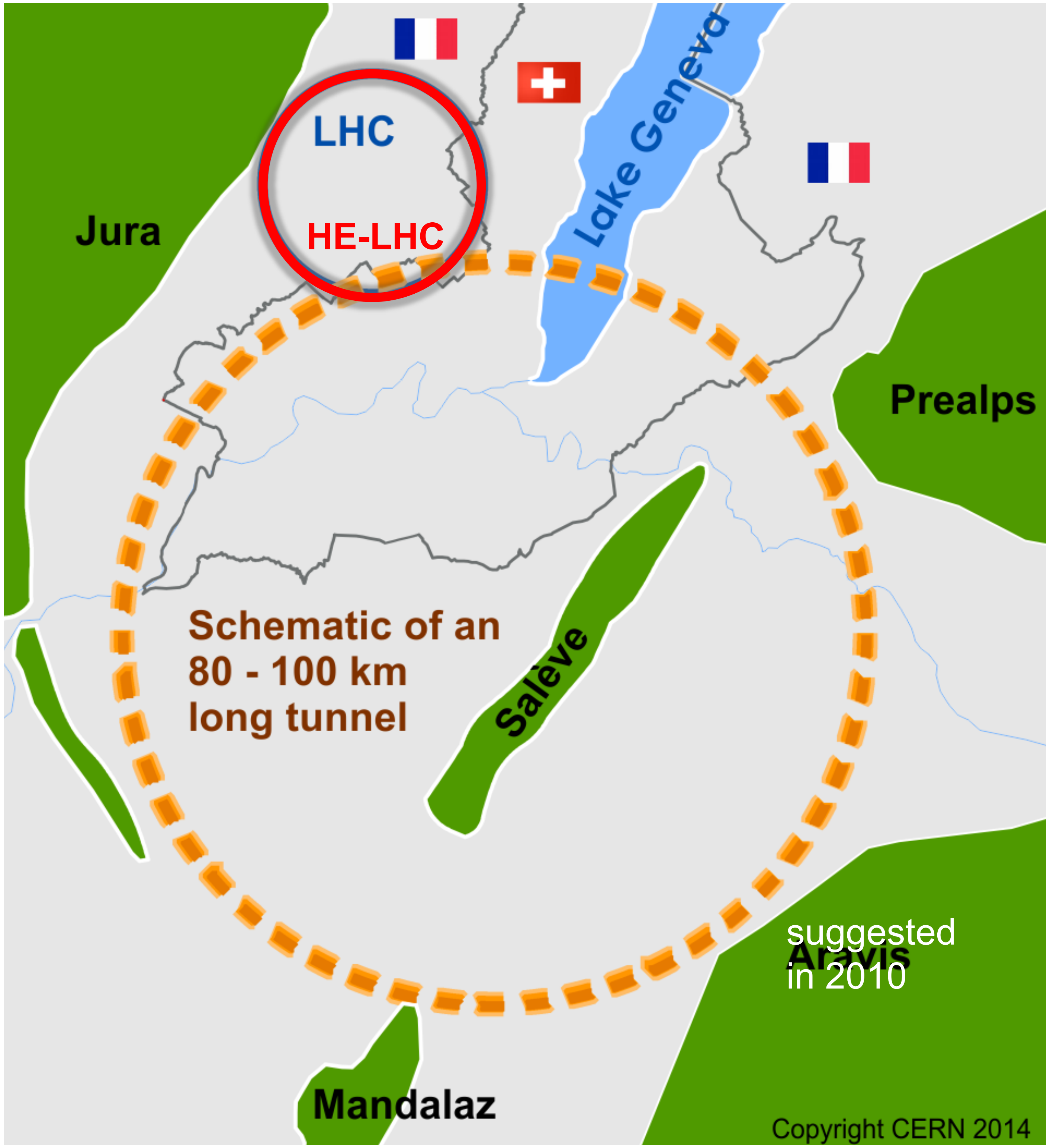
Future Circular Collider Study

international FCC collaboration (CERN as host lab) to design:

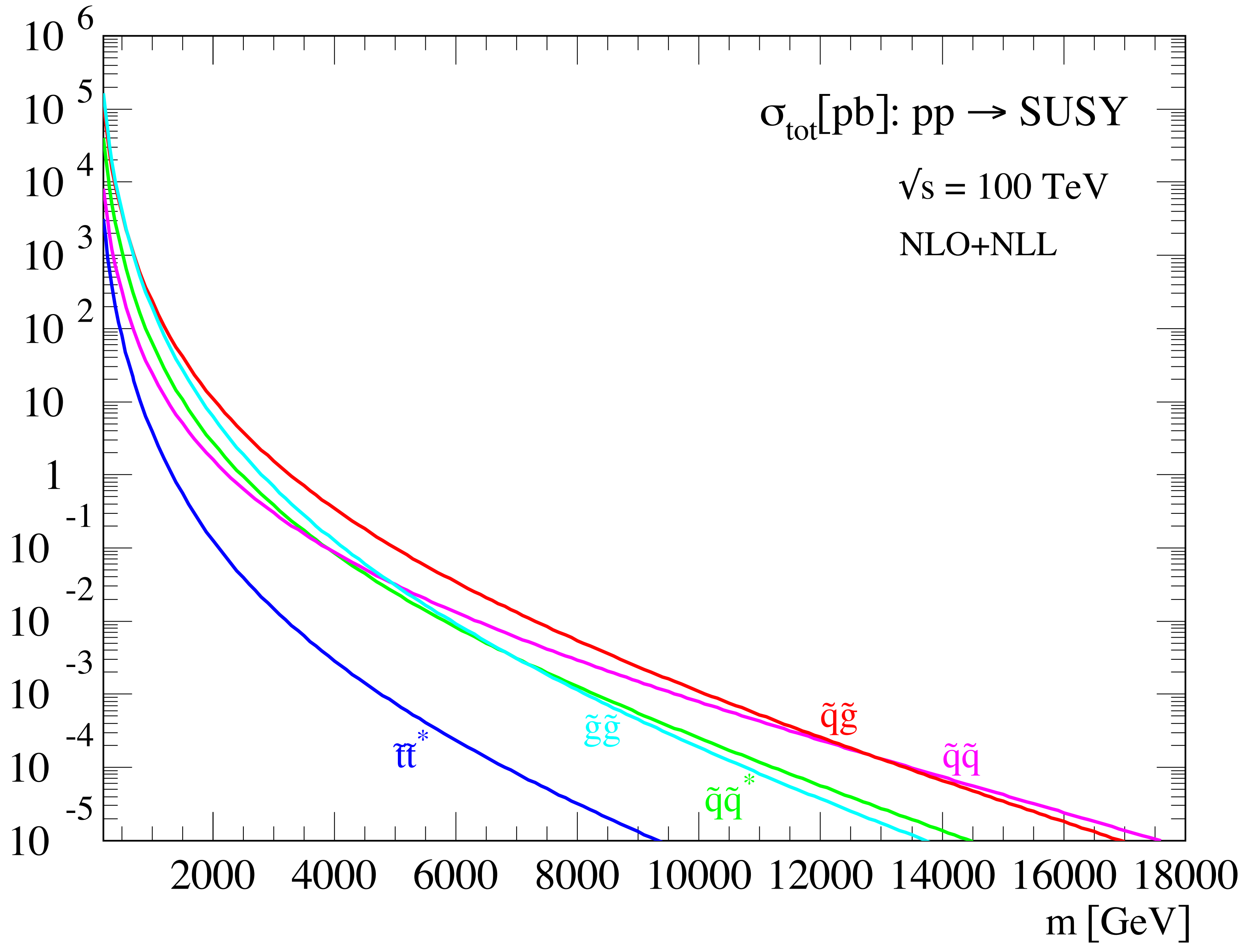
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology

Talk by,
M. Benedikt, F. Zimmermann
for the FCC collaboration



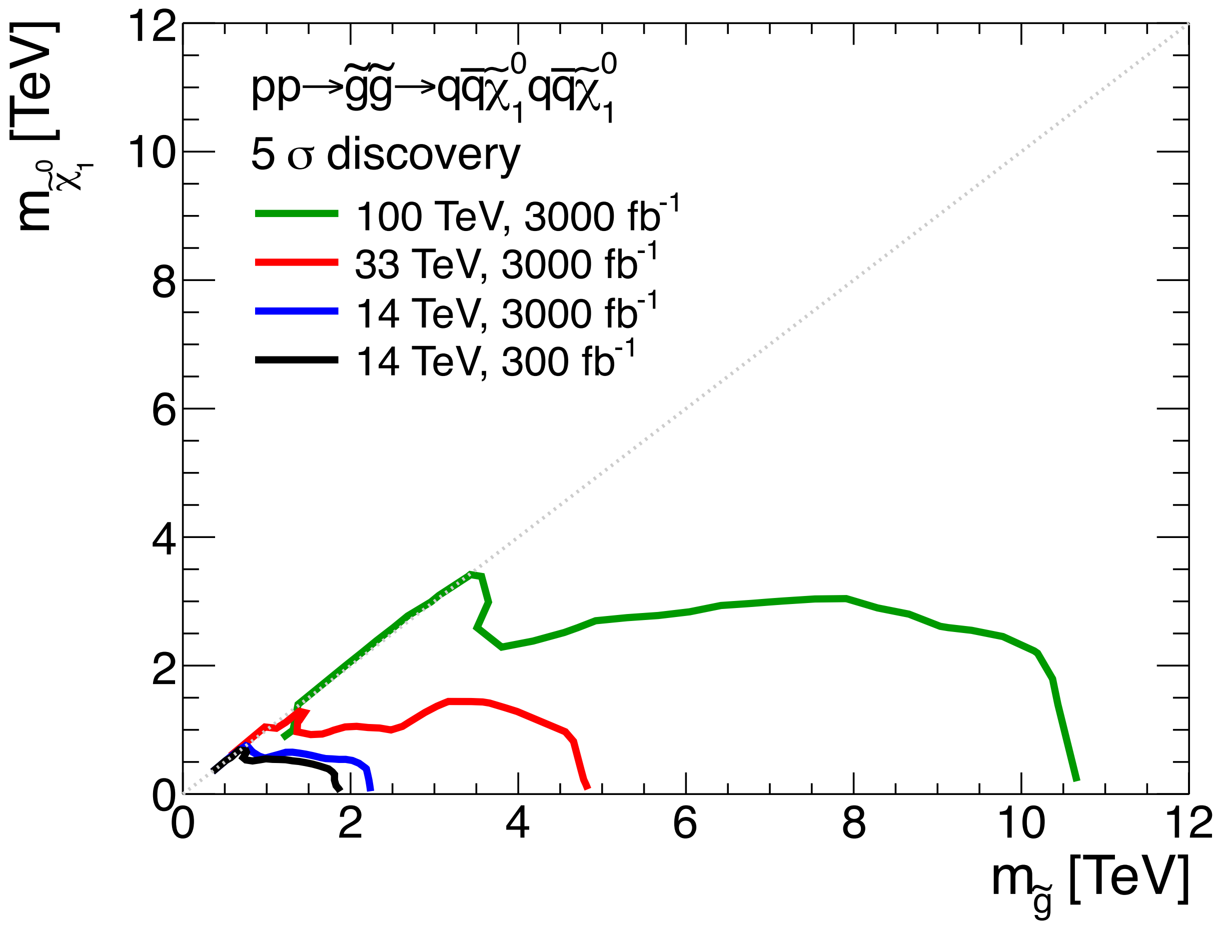
Sparticle Production

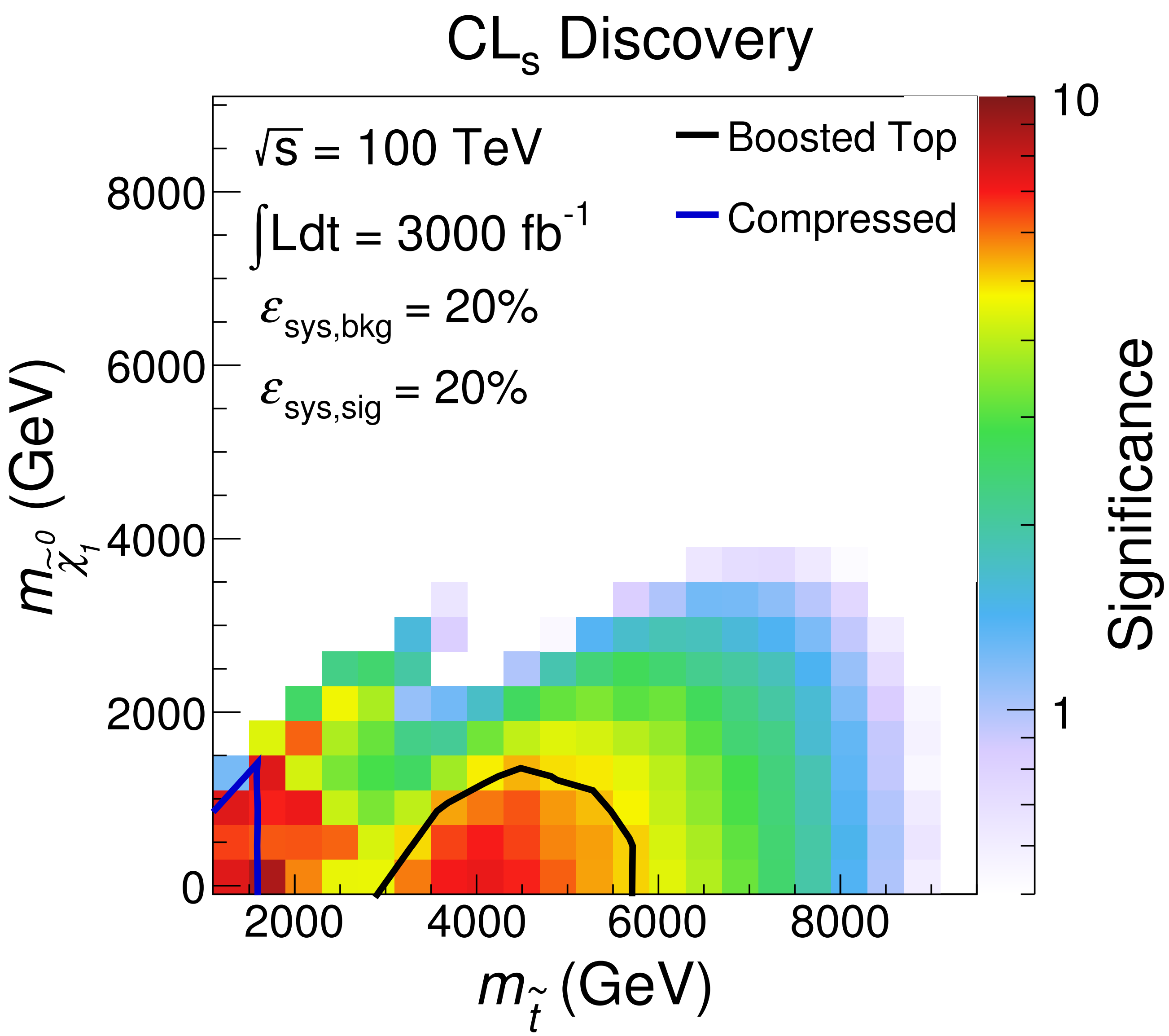


$$\sigma \sim 4 \times \sigma(14TeV)$$

1407.5066

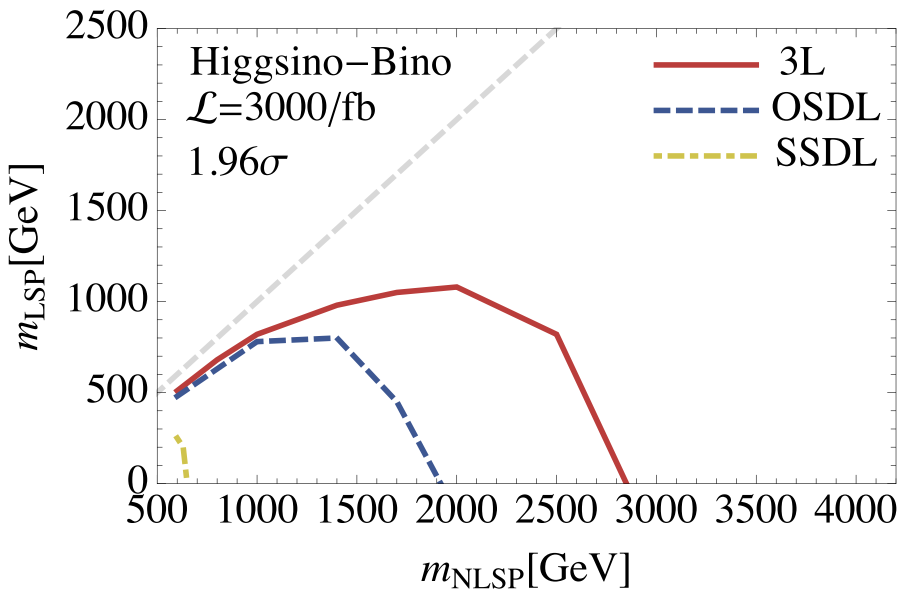
Gluino and Stop@100 TeV

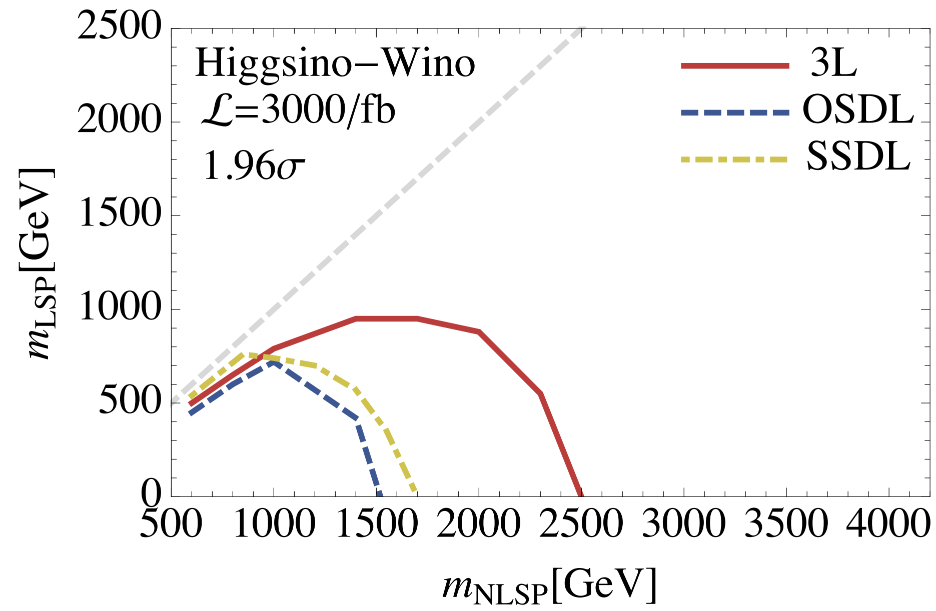


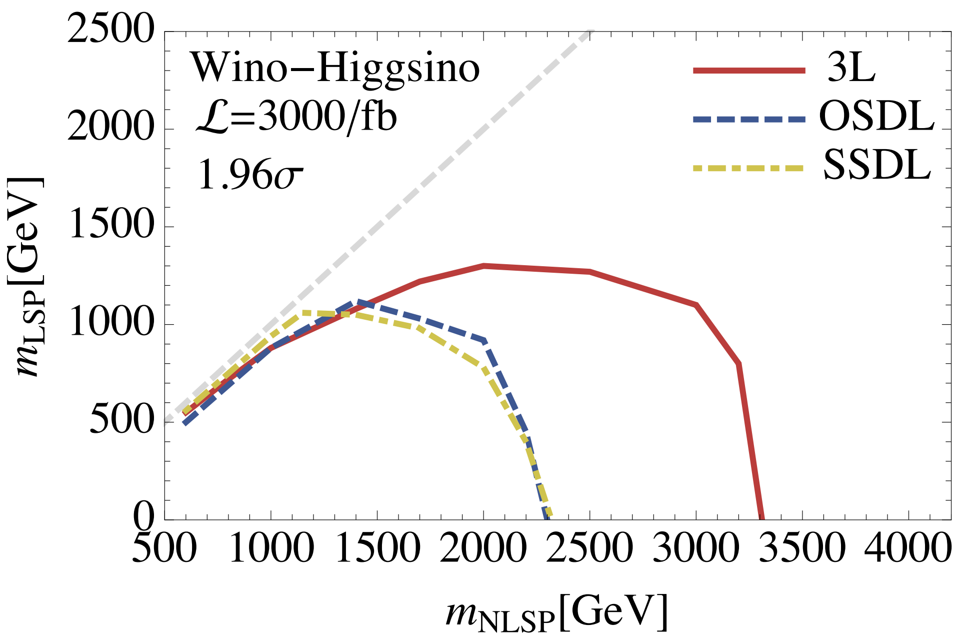


1606.00947

EWinos@100 TeV





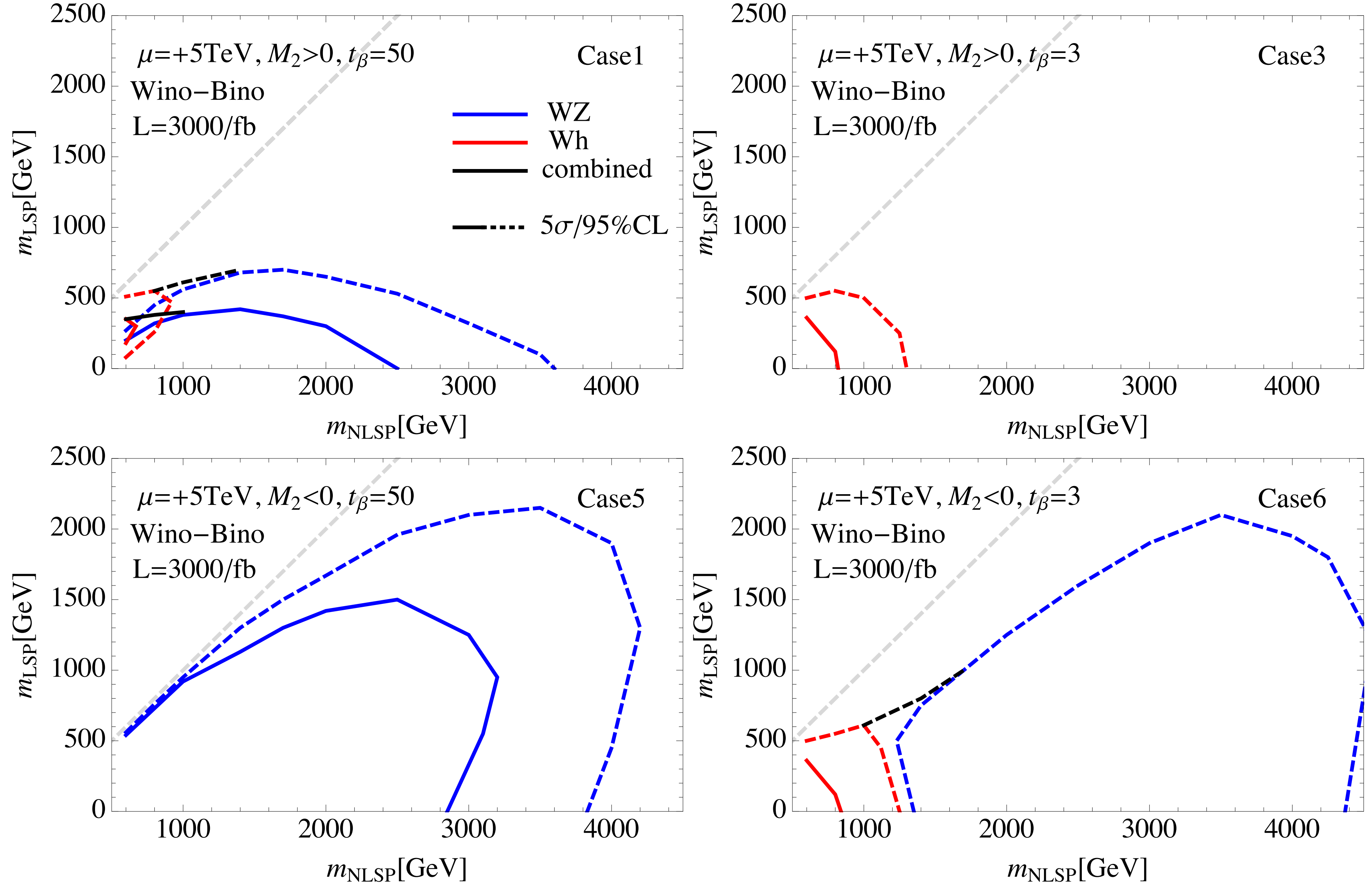


Not so sensitive to tan beta and relative sign

Reach ~1.5 - 2.3 TeV

EWinos@100 TeV

Wino-Bino Scenario



Outlook

Gluinos/squarks/EWinos are constrained in SMS,
More data are waiting to be analysed.

Model specific interpretation are needed, to draw conclusion.
More work needed.

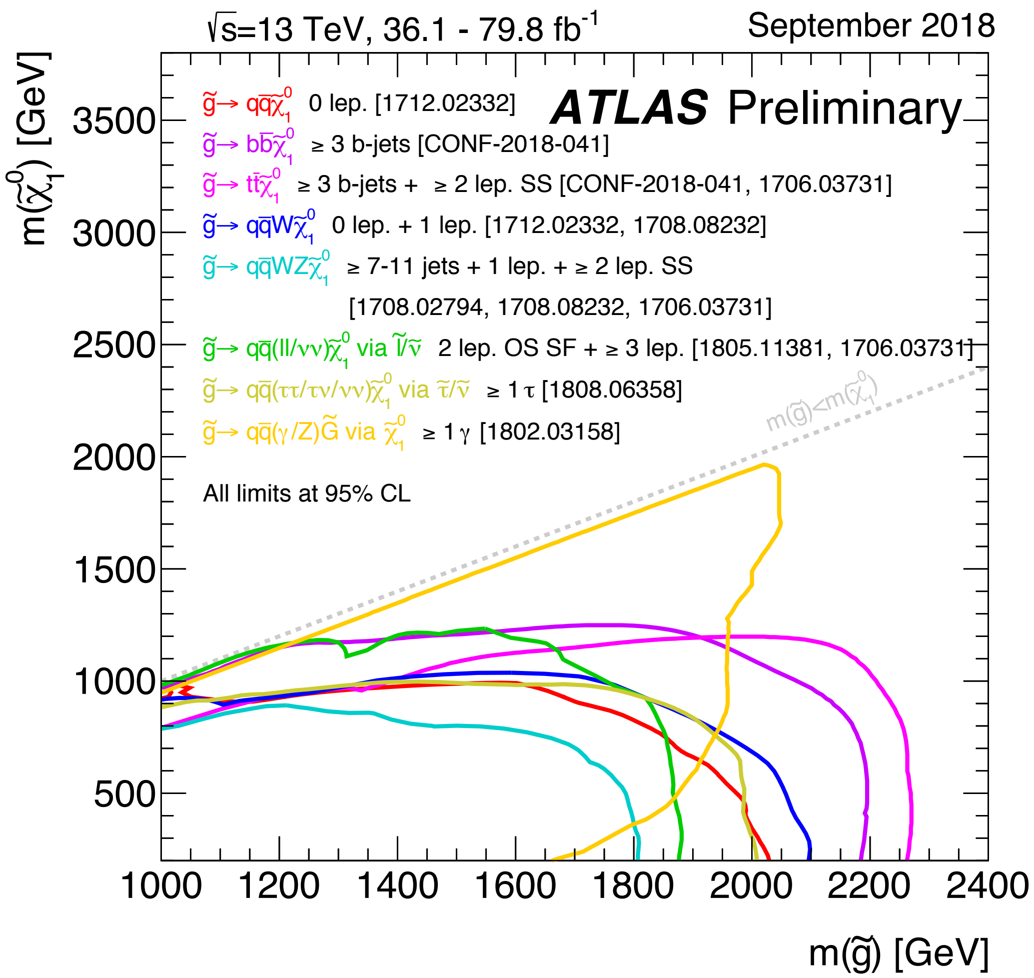
HE/HL data will exclude more mass range, may be ‘
More useful, if we see some signal before it starts

100 TeV collider can probe SUSY upto 10 TeV

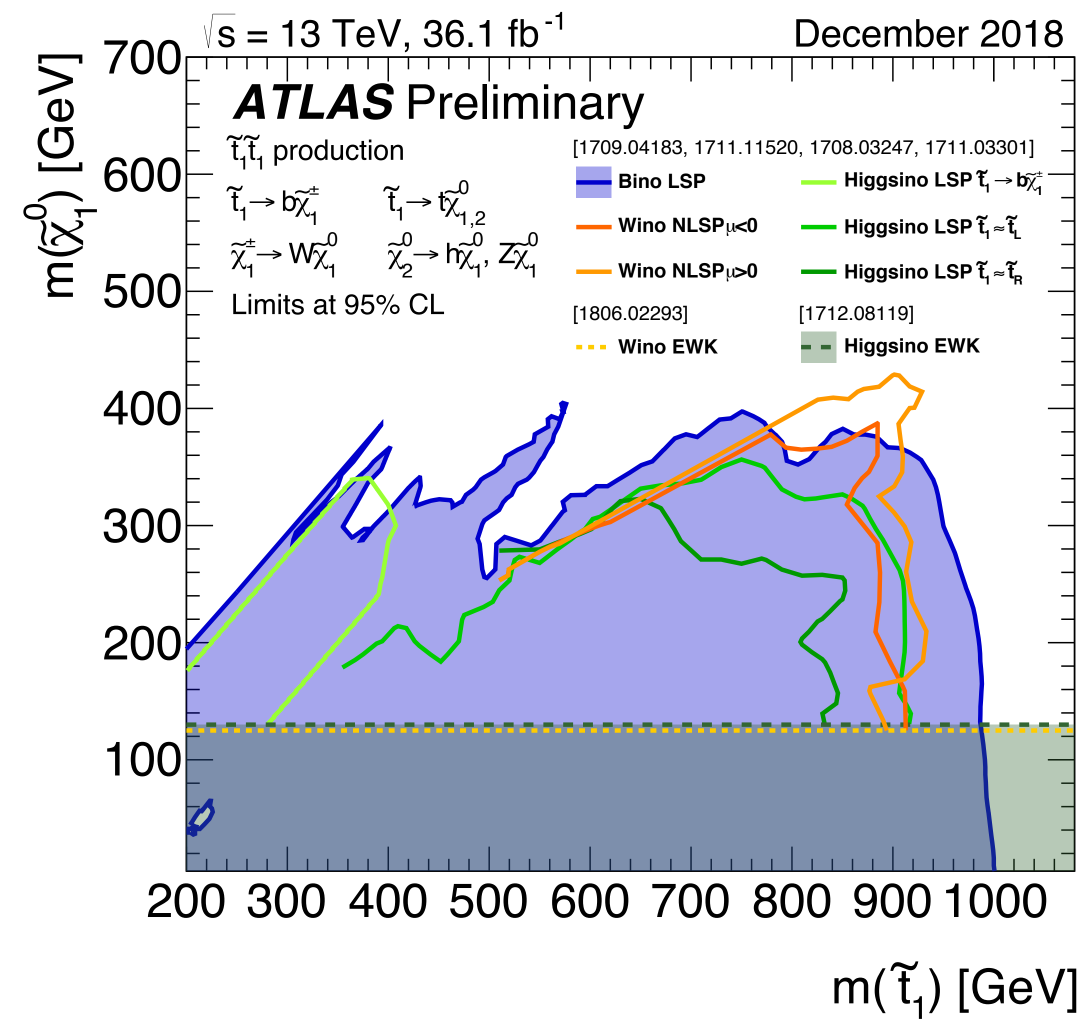
Remarks

Finally, SUSY is dead or alive, depends on perception.

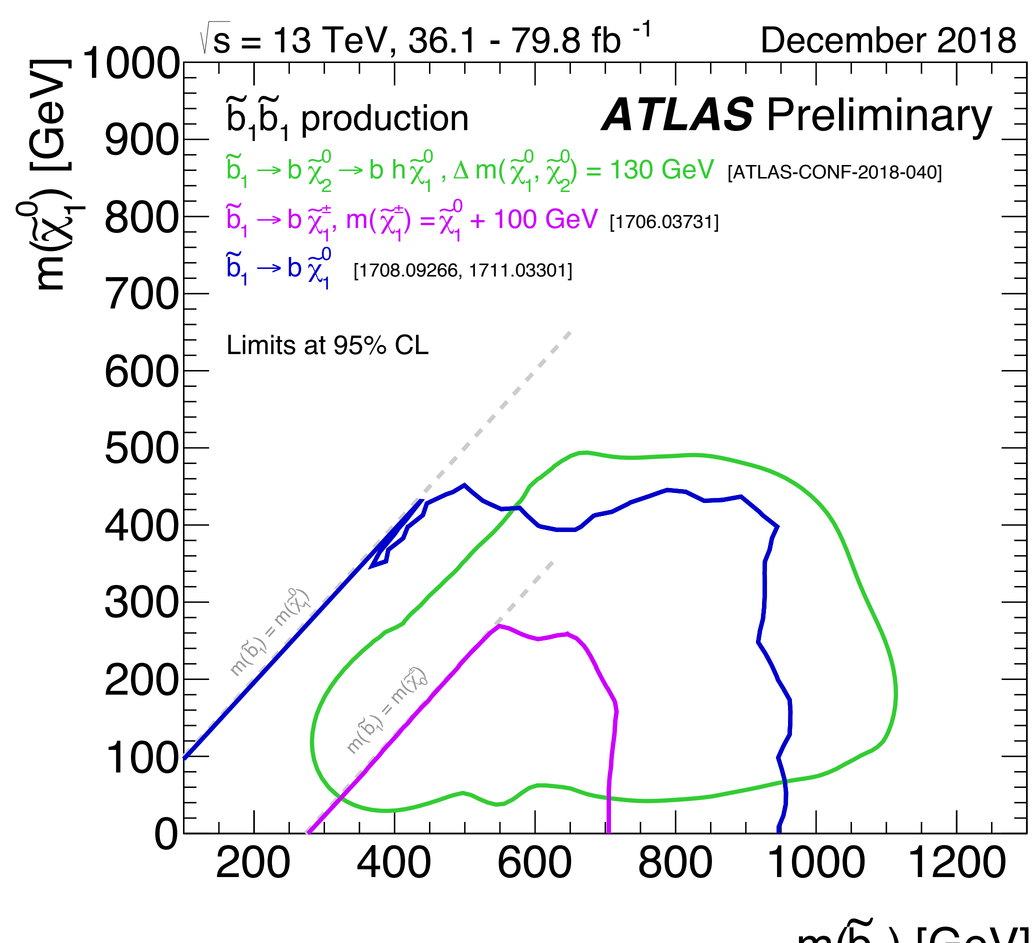
May be SUSY exists, but in different avatar. Fresh idea…



√s=13 TeV, 36.1 - 79.8 fb⁻¹
September 2018
ATLAS Preliminary
g̃→ qq̄χ̃⁰₁ 0 lep. [1712.02332]
g̃→ bb̄χ̃⁰₁ ≥ 3 b-jets [CONF-2018-041]
g̃→ tt̄χ̃⁰₁ ≥ 3 b-jets + ≥ 2 lep. SS [CONF-2018-041, 1706.03731]
g̃→ qq̄Wχ̃⁰₁ 0 lep. + 1 lep. [1712.02332, 1708.08232]
g̃→ qq̄WZχ̃⁰₁ ≥ 7-11 jets + 1 lep. + ≥ 2 lep. SS
[1708.02794, 1708.08232, 1706.03731]
g̃→ qq̄(ll/νν)χ̃⁰₁ via l̃/ν̃ 2 lep. OS SF + ≥ 3 lep. [1805.11381, 1706.03731]
g̃→ qq̄(ττ/τν/νν)χ̃⁰₁ via τ̃/ν̃ ≥ 1 τ [1808.06358]
g̃→ qq̄(γ/Z)G̃ via χ̃⁰₁ ≥ 1 γ [1802.03158]
All limits at 95% CL
m(g̃)<m(χ̃⁰₁)
m(χ̃⁰₁) [GeV]
m(g̃) [GeV]



√s = 13 TeV, 36.1 fb⁻¹
December 2018
ATLAS Preliminary
t̃₁t̃₁ production
t̃₁→ bχ̃±₁
t̃₁→ tχ̃⁰₁,₂
χ̃±₁→ Wχ̃⁰₁
χ̃⁰₂→ hχ̃⁰₁, Zχ̃⁰₁
Limits at 95% CL
[1709.04183, 1711.11520, 1708.03247, 1711.03301]
Bino LSP
Wino NLSP μ<0
Wino NLSP μ>0
Higgsino LSP t̃₁→bχ̃±₁
Higgsino LSP t̃₁≈t̃L
Higgsino LSP t̃₁≈t̃R
[1806.02293]
Wino EWK
[1712.08119]
Higgsino EWK
m(χ̃⁰₁) [GeV]
m(t̃₁) [GeV]



√s = 13 TeV, 36.1 - 79.8 fb⁻¹
December 2018
b̃₁b̃₁ production
ATLAS Preliminary
b̃₁ → b χ̃⁰₂ → b h χ̃⁰₁ , Δ m(χ̃⁰₁, χ̃⁰₂) = 130 GeV [ATLAS-CONF-2018-040]
b̃₁ → b χ̃±₁, m(χ̃±₁) = χ̃⁰₁ + 100 GeV [1706.03731]
b̃₁ → b χ̃⁰₁ [1708.09266, 1711.03301]
Limits at 95% CL
m(b̃₁) = m(χ̃⁰₁)
m(b̃₁) = m(χ̃⁰₂)
m(χ̃⁰₁) [GeV]
m(b̃₁) [GeV]