Supersymmetric particle searches at the Large Hadron Collider

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CHIPP

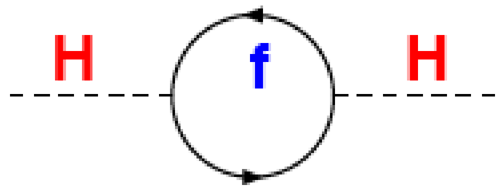
Engelberg, 22-27 January 2012

index

- Introduction
- SUSY particle production
- SUSY searches in the jets + E_T^{miss} channel
- SUSY seraches in the lepton+jets+E_t^{miss} and dilepton channels
- Sbottom ans stop searches

The Hierarchy problem - 1

- **The question: why the weak force is ~ 10^{32} times stronger than the gravitational force?**
  - **$F \sim 1/[M^2_{Pl} \bullet r^2]$; $M_{Pl} = 1.22\times10^{19}$ GeV ⇔ $M_H \sim 10^2$ GeV**
- Both forces involve constants of nature:
  - The Fermi's constant
  - The Newton's constant
- In the Standard Model the quantum corrections to the Fermi constant appear unnaturally large, unless a delicate cancellation between the bare value of this constant and its quantum corrections take place (**fine tuning**)

$\Delta M^2_H \equiv$ 

$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$

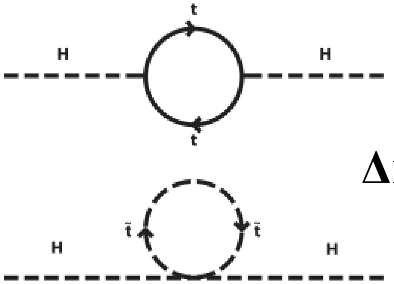
  - More technically the question is why the Higgs boson mass is so much lighter than the Planck mass (or the Grand Unification energy)

The Hierarchy problem - 2

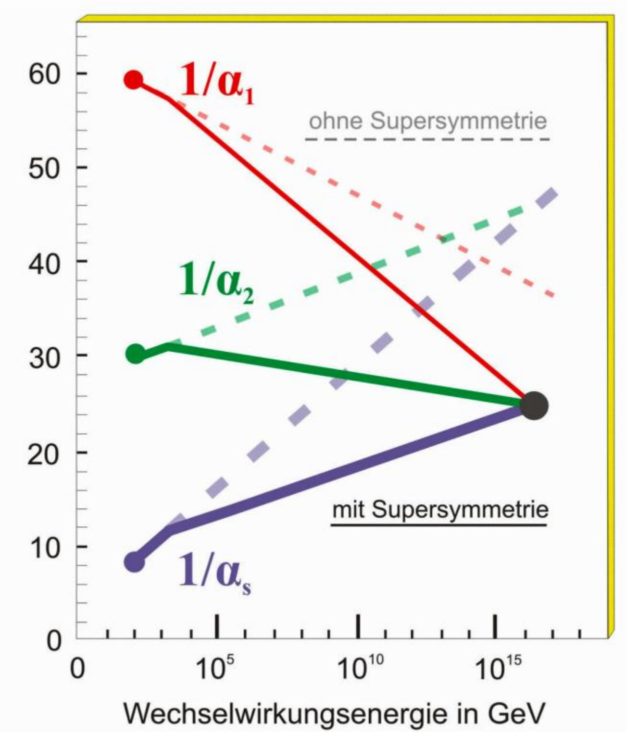
- **Three main avenues** for solving the hierarchy problem:
- ***Supersimmetry***
  - *A set of new (light) SUSY particles cancel the divergence*
- ***Extra dimensions***
  - *There is a cut-off at the ~TeV scale where gravity sets in; in other words the "actual" gravity constant is larger then the one observed (or the Planck mass is much smaller)*
- ***Strong interactions/compositness***
  - *The Higgs is not an elementary scalar particle*
  - *The Higgs emerges as a Nambu-Goldostone boson of a strongly interacting sector*

Supersymmetry

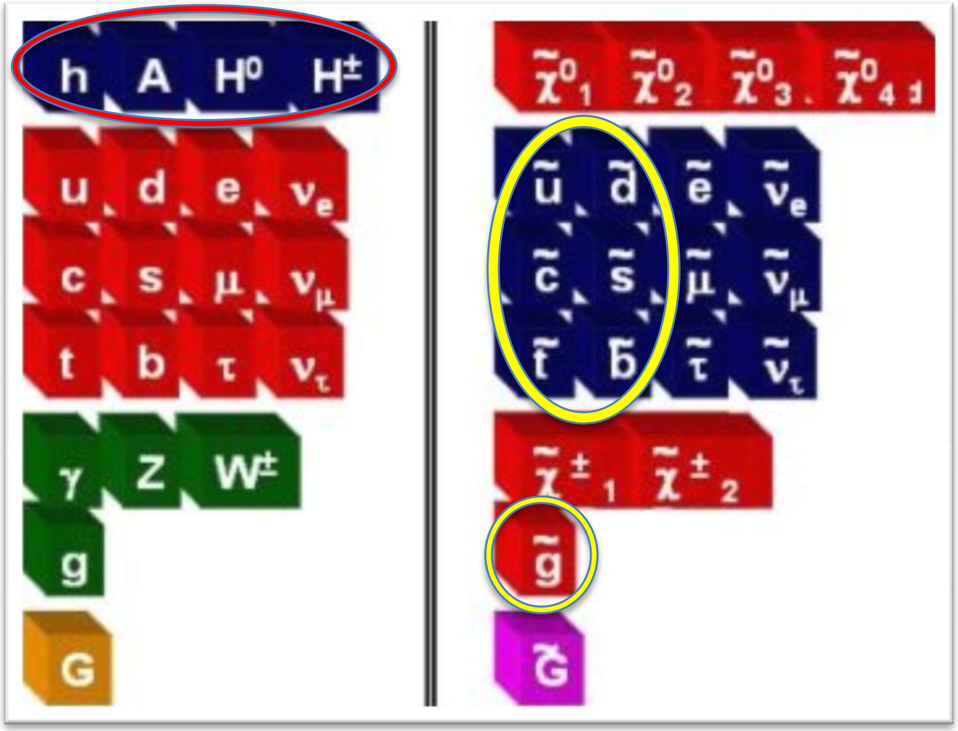
- Supersymmetry provides a natural mechanism to keep small quantum corrections to the Higgs boson mass
- Supersymmetry provides a natural candidate for dark matter (the lightest supersymmetric particle)
- Supersymmetry facilitates the grand-unification of the em, weak and strong couplings
- Supersymmetry is an “extension” of the SM, it is consistent with the observed data



$\Delta m = f(m^2_B - m^2_F)$



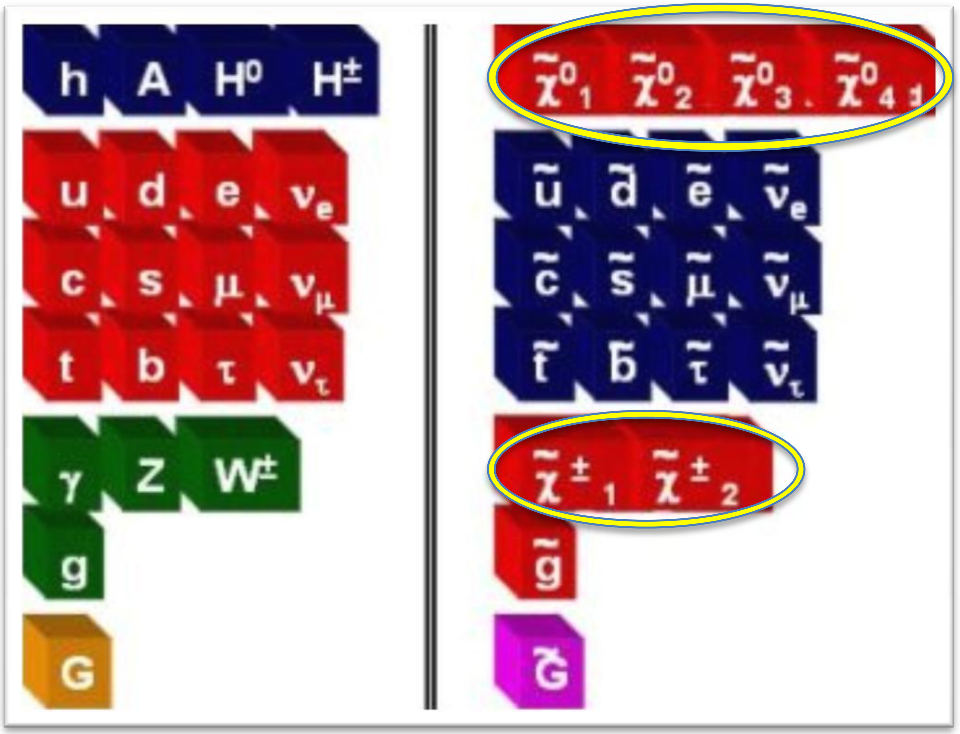
The Minimal SuperSymmetric Model (MSSM)



- More than 100 parameters to define the MSSM
- Enlarged Higgs sector: in the MSSM model there are two Higgs doublets, with five physical mass states:
  - h^0, H^0, neutral CP even;
  - A, neutral, CP odd
  - H^+, H^- charged;

The new colored particles are produced with a high rate by the strong force

The Minimal SuperSymmetric Model (MSSM)



$P_R = (-1)^{2s+3B+L}$, where:
S is the spin
B is the baryon number
L is the lepton number

All Standard Model particles have R-parity of 1 while supersymmetric particles have R-parity -1.

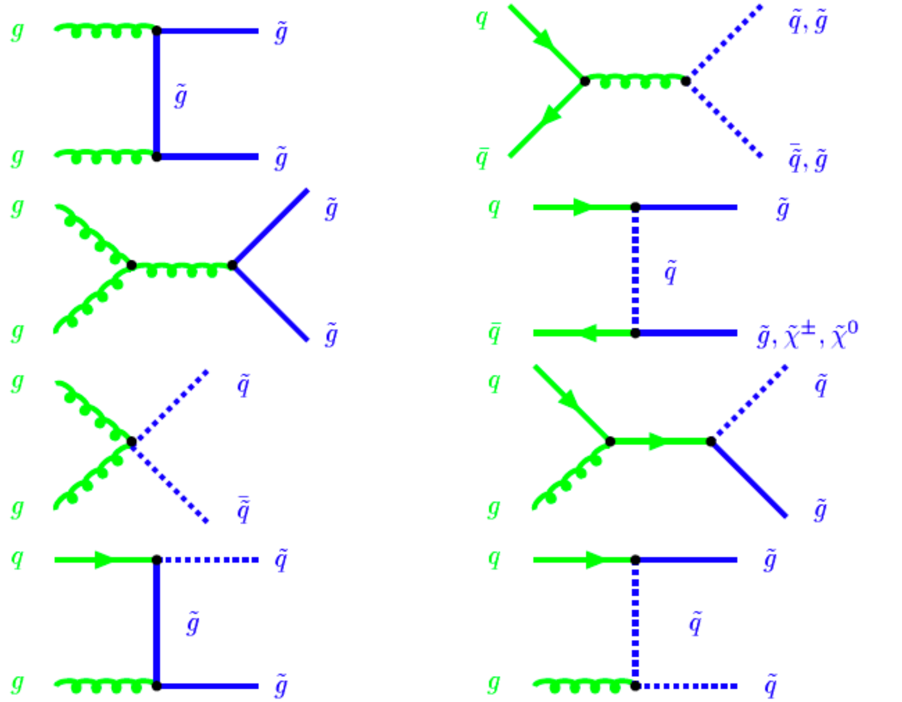
- There are also Neutralinos and Charginos:
  - the neutral Wino and Bino, and the neutral Higgsinos mix to the 4 neutralinos $\tilde{\chi}^0_{1,2,3,4}$
  - the charged Wino fields and the charged Higgsino fields mix to the 4 charginos $\tilde{\chi}^\pm_{1,2}$
- If R-parity is conserved the lightest neutralino is stable, weakly interacting and massive ➔ ideal Dark Matter candidate

mSUGRA/cMSSM

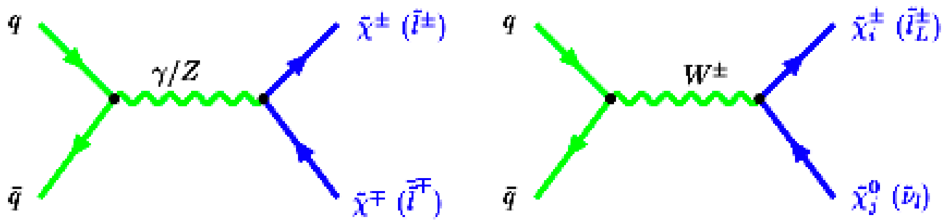
- Specific models with less parameters:
  - mSUGRA/cMSSM
  - GMSB
  - AMSB
  - …
- Most studied scenario is the 5 parameter mSUGRA model
  - $\mathbf{m_0}$: common boson mass at GUT scale;
  - $\mathbf{m_{1/2}}$ common fermion mass at GUT scale
  - **tanβ**: ratio of higgs vacuum expectation values
  - $\mathbf{A_0}$: common GUT trilinear coupling
  - **μ**: sign of Higgs potential

SUSY particle production at the LHC

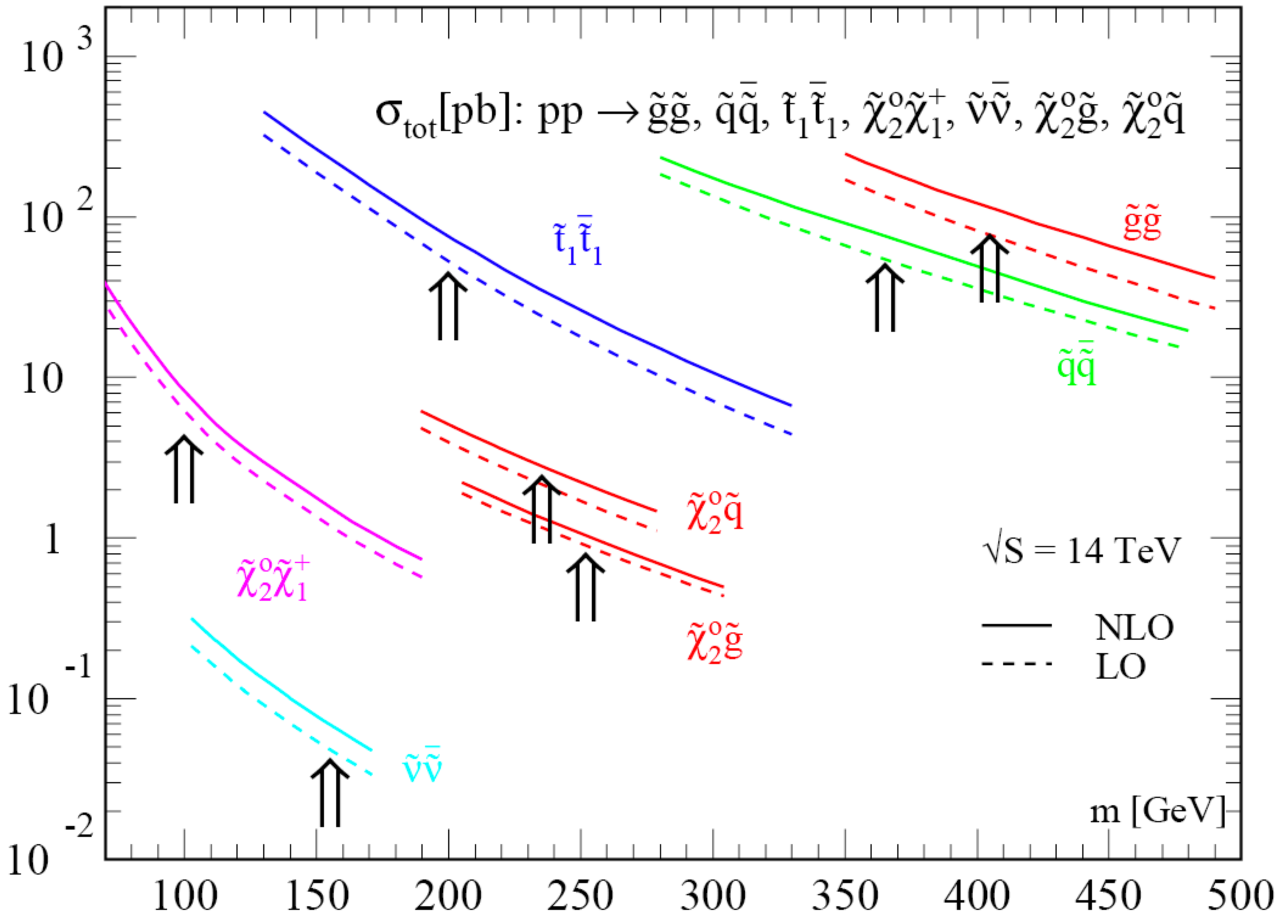
Initial state: gg, qq, qg
Final state: squarks and gluinos via strong interaction (α_s); this is the dominant SUSY particle production



Drell-Yan production of sleptons, charginos and neutralinos (lower cross sections)

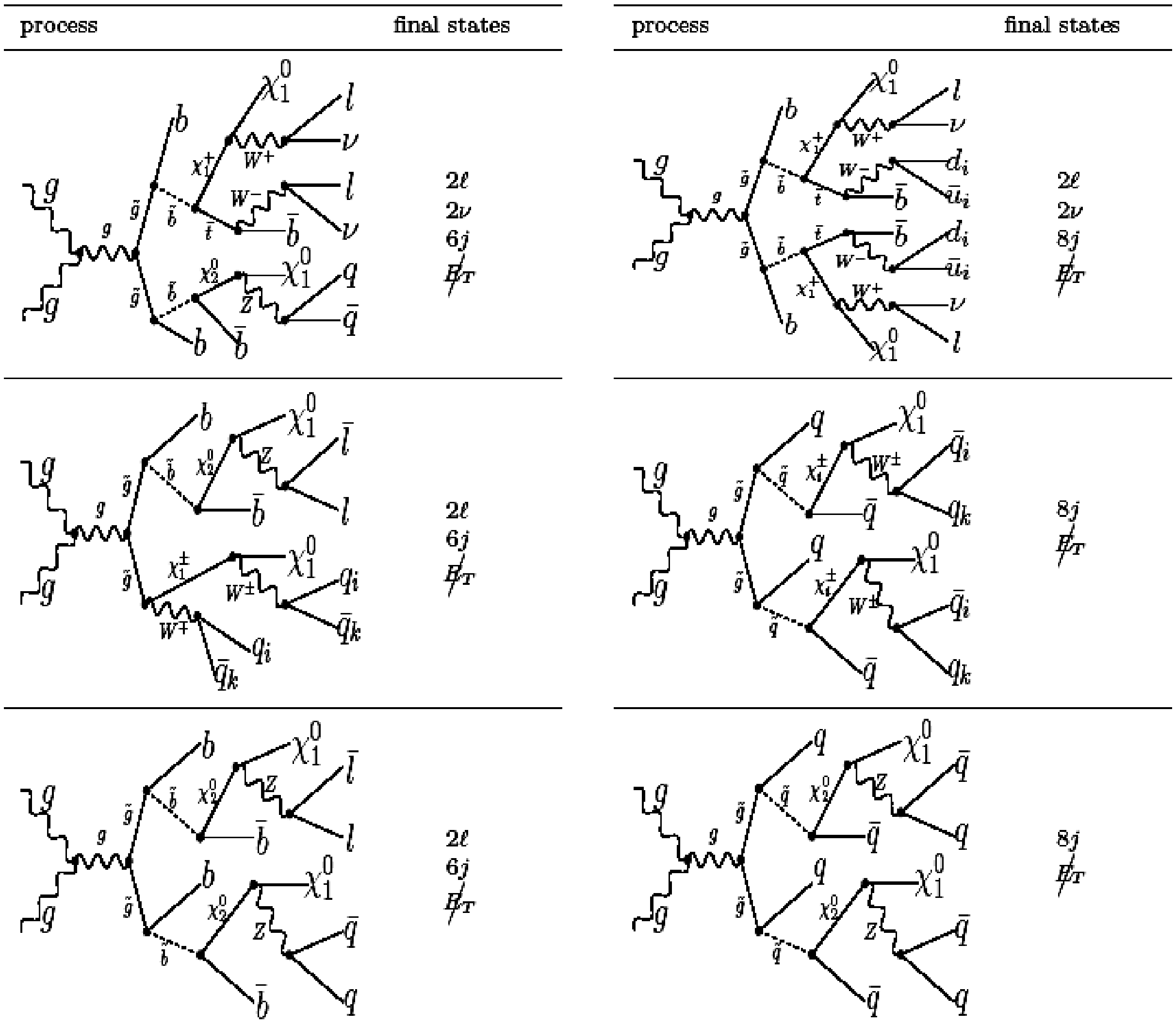


SUSY particle production at the LHC



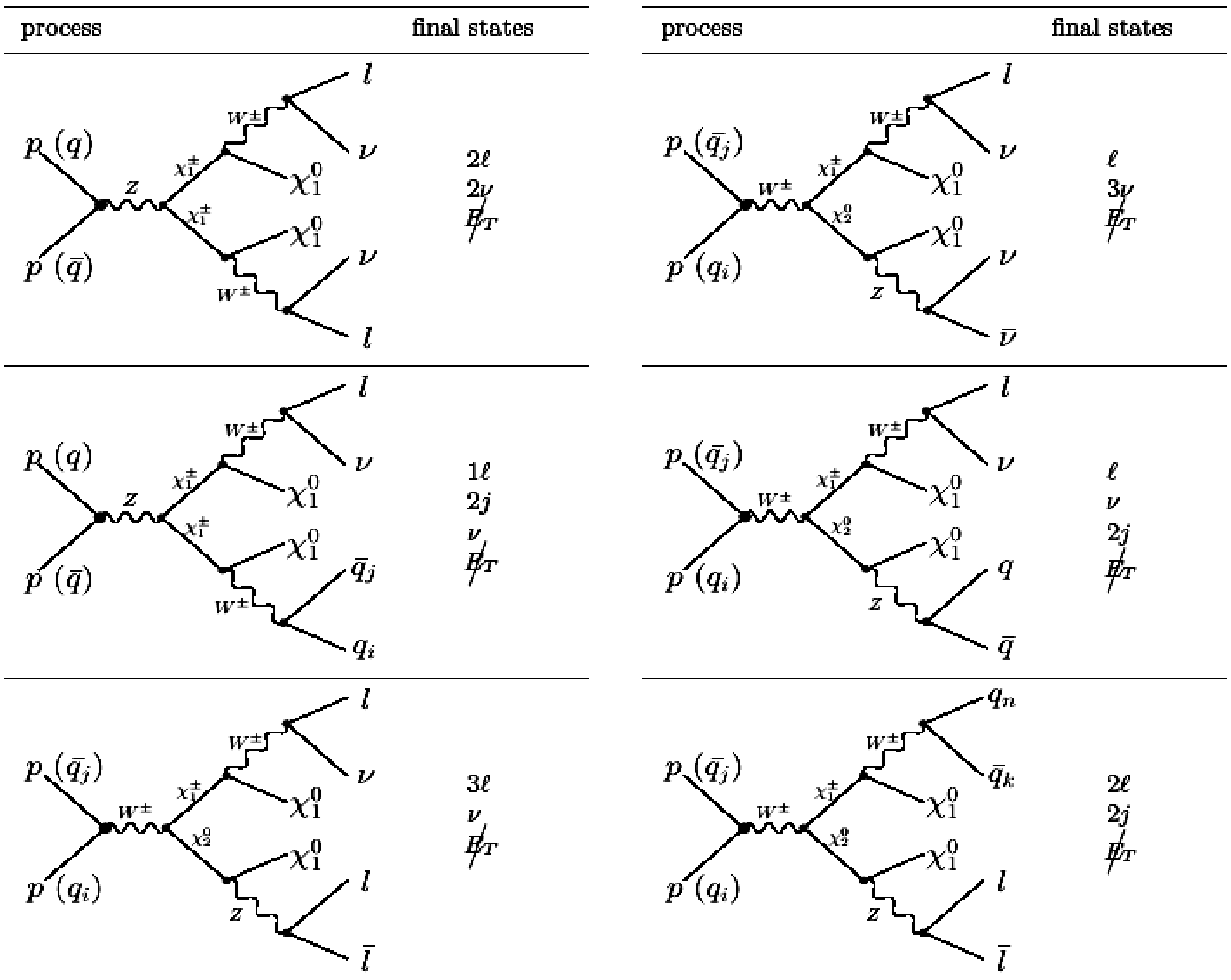
- Production cross section of SUSY particles
  - NLO corrections in pQCD are known

SUSY particle production at the LHC



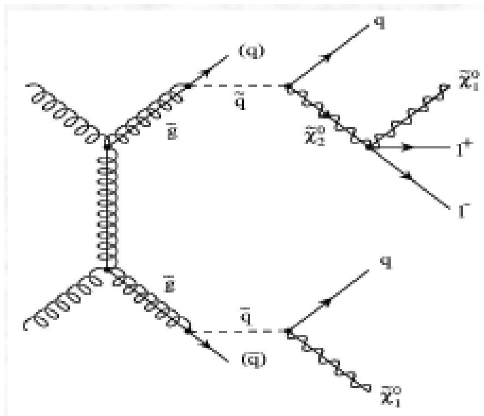
- Decays of heavy SUSY particles → long and complex decay chains
- Invariants in R-parity conserving SUSY: jets, (large) E_T^{miss} (2 LSPs)

SUSY particle production at the LHC



- Shorter decay chains for chargino/neutrali no direct production

Baseline SUSY searches at the LHC



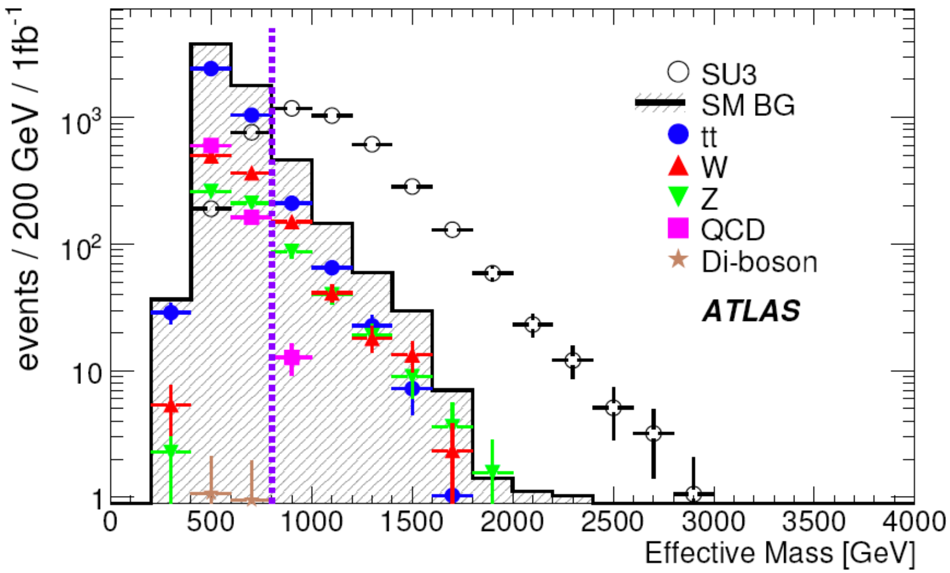
- Squarks and gluinos are strongly produced
- They decay through a particle cascade that includes high p_T jets and high p_T LSPs, (i.e. large E_t^{miss})

- Strategy for searching for SUSY particles at the LHC:
  - Select events with final state produced by SUSY cascades. Example: Multijet + large E_t^{miss} signature
  - Define inclusive variable(s) sensitive to SUSY at different mass scales, e.g. effective mass M_{eff};
  - Study the distribution of this(these) variable(s) in the Standard Model and look for deviations from the predictions of this theory.

A typical search for squarks and gluinos

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and large E_t^{miss}
- Typical selection:
  - At least 4 high p_T jets, satisfying the thresholds 100, 50, 50, 50 GeV;
  - no lepton with $p_T > 20$ GeV
  - $E_T^{miss} > 100$ GeV;
  - $M_{eff} = \Sigma$ pT(jets) + E_T^{miss}

simulation



- Example: example: mSUGRA, point SU3 (bulk region)
  - $m_0 = 100$ GeV,
  - $m_{1/2} = 300$ GeV,
  - $\tan\beta = 6$,
  - $A_0 = -300$ GeV,
  - $\mu > 0$

Strategy for SUSY searches at the LHC

- Search for excesses in multijet + no-lepton + missing transverse energy events
- Search for excesses in single lepton, opposite sign dilepton, same sign dilepton, taus, in association with jets and missing transverse energy
- Look for special features (γ's, long lived sleptons)
- End-point analyses, global fit → SUSY model parameters

If we found an excess, is it SUSY?

A very long list of models x signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

A complex 2D problem

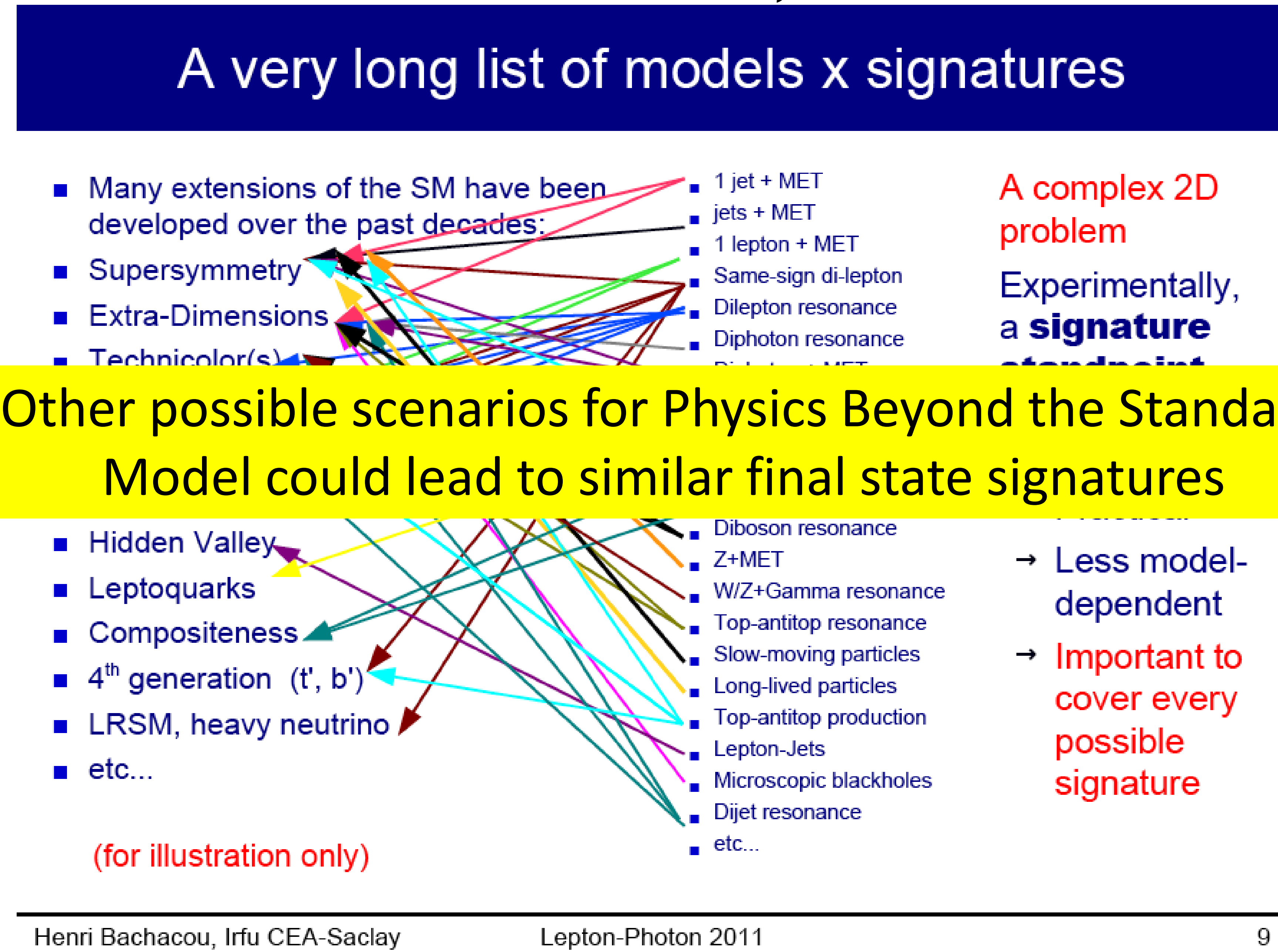
Experimentally, a **signature standpoint** makes a lot of sense:

→ Practical

→ Less model-dependent

→ Important to cover every possible signature

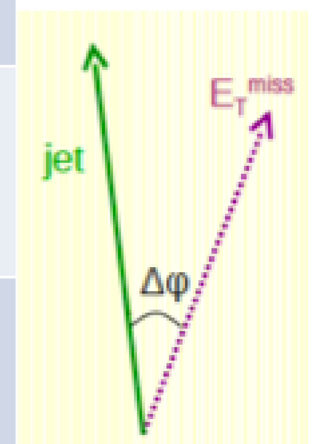
If we found an excess, is it SUSY?



Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures

Some useful quantities used in SUSY analyses

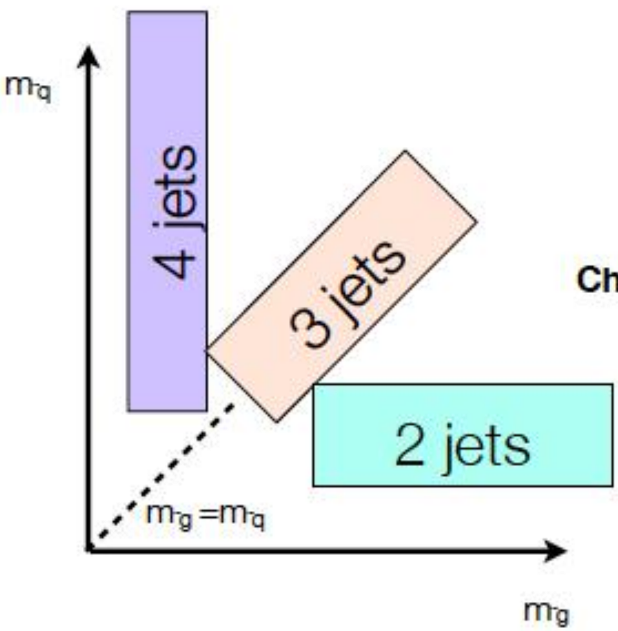
Quantity	Definition
m_T	transverse mass (in general: m_T lepton, p_T^{miss}))
E_T^{miss}	missing transverse energy, (measured from the energy depositions in the calorimeters and from muons)
M_{eff}	effective mass, scalar sum of transverse energies of selected high p_T objects, and E_t^{miss} (including leptons if selected in the analysis)
H_T	scalar sum of total transverse energy in selected jets (hadronic activity)
H_T^{miss}	Magnitude of vector sum of selected jet
α_T	In two-jet events, $\alpha T = E_T^{j2}/M_T$, where E_T^{j2} is the transverse energy of the less energetic jet, and M_T is the transverse mass of the dijet system
$\Delta\varphi$(jet; p_T^{miss})	angle between the missing transverse energy vector and a jet in the transverse plane important to reject “fake” background from QCD jet production



Search in the jets + E_T^{miss} channel

- Based on L=1.04 fb^{-1} of data
- Selection of events with high-p_T jets and large E_T^{miss}
- Split the analysis according to jet multiplicities:
  - ≥2, ≥3, and ≥4 jets
- ➔ this optimize sensitivity to squark/gluino mass combination, i.e. to different regions of the SUSY phase space

Five signal regions



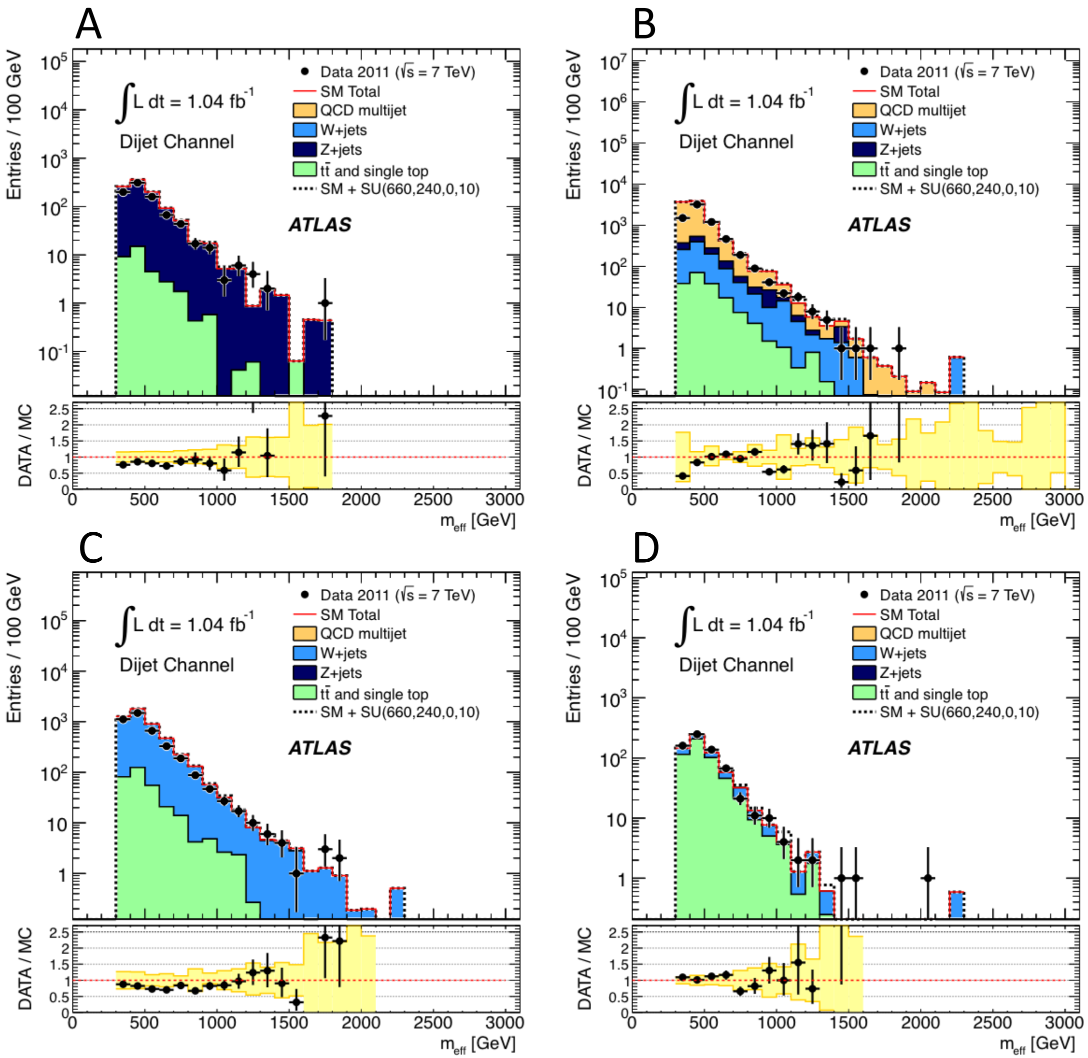
	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

Search in the jets + E_T^{miss} channel

- Three different type of analysed are performed, depending on the squark gluino mass:
  - Dijet analysis $\tilde{q}\,\bar{\tilde{q}} \rightarrow q\,\tilde{\chi}_1^0\,\bar{q}\,\tilde{\chi}_1^0$
  - Trijet analysis $\tilde{q}\,\tilde{g} \rightarrow q\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$
  - Four jet (gluino) analysis $\tilde{g}\,\tilde{g} \rightarrow q\,\bar{q}\,\tilde{\chi}_1^0\,q\,\bar{q}\,\tilde{\chi}_1^0$

0-jet + E_t^{miss}: control of backgrounds



- 5 "control regions" per each of the 5 signal regions
- Extrapolate the observations from the control regions to the signal regions with "transfer factors"
  - obtained with a combination of data and MC inputs.

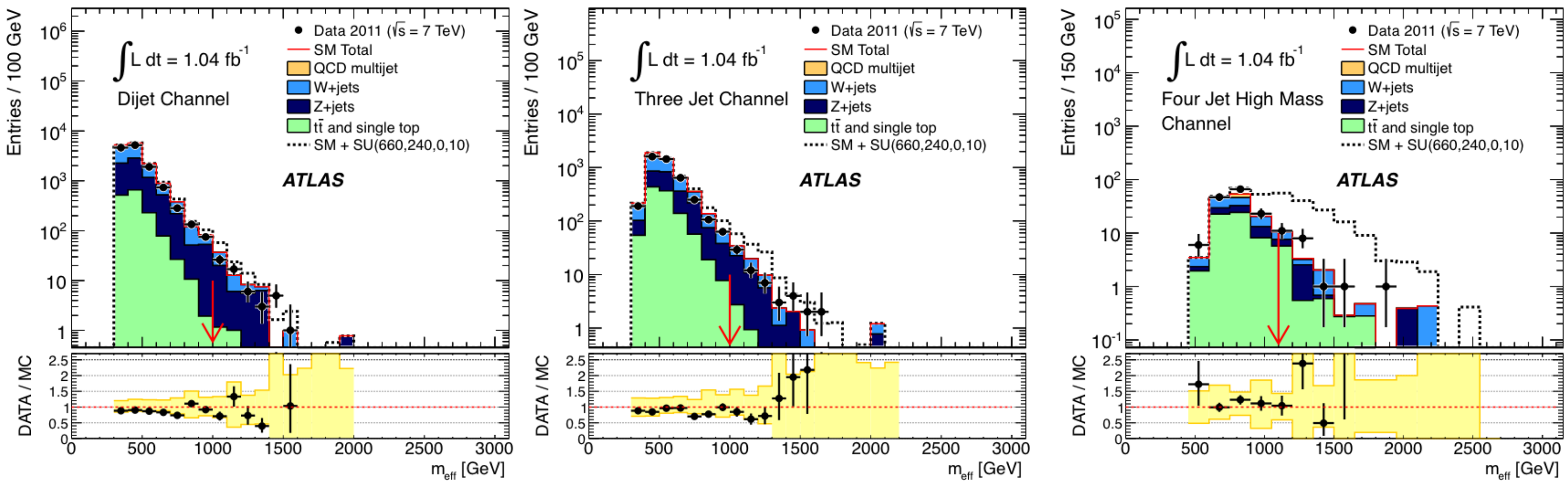
A **estimate Z→νν+jets:** use Z→ll+jets events (transfer the lepton pair momentum to E_t^{miss}); plot: no E_T^{miss} and m_{eff} cuts are applied

B **estimate multi-jet:** revert $\Delta\phi(\text{jet}; E_t^{miss})_{min}<0.2$

C **estimate W→lν+jets:** select events with one lepton+E_t^{miss} with 30<m_T<100 GeV, and b-jet veto; threat the lepton as a jet;

D **estimate top quark back.:** as for W→lν+jets, but require at least one b-tagged jet

0-jet + E_T^{miss}: Results



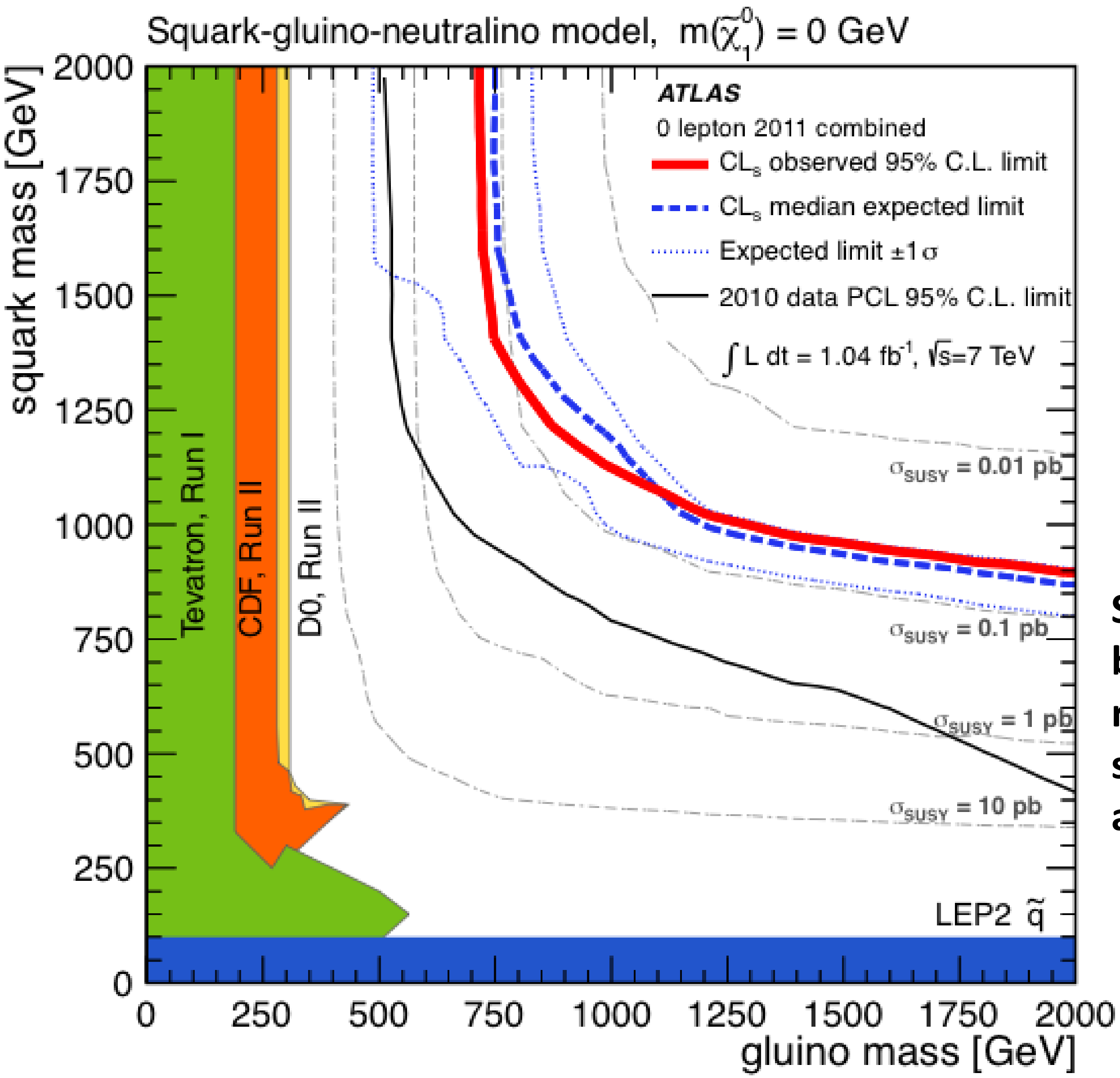
The observed m_{eff} distribution in the various signal regions considered in the analysis

Fitted background in each SR, compared with the number of the observed events in data. Systematic uncertainties are taken into account

Process	Signal Region				
	≥ 2-jet	≥ 3-jet	≥ 4-jet, $m_{\text{eff}} > 500$ GeV	≥ 4-jet, $m_{\text{eff}} > 1000$ GeV	High mass
Z/γ+jets	32.3 ± 2.6 ± 6.9	25.5 ± 2.6 ± 4.9	209 ± 9 ± 38	16.2 ± 2.2 ± 3.7	3.3 ± 1.0 ± 1.3
W+jets	26.4 ± 4.0 ± 6.7	22.6 ± 3.5 ± 5.6	349 ± 30 ± 122	13.0 ± 2.2 ± 4.7	2.1 ± 0.8 ± 1.1
$t\bar{t}$+ single top	3.4 ± 1.6 ± 1.6	5.9 ± 2.0 ± 2.2	425 ± 39 ± 84	4.0 ± 1.3 ± 2.0	5.7 ± 1.8 ± 1.9
QCD multi-jet	0.22 ± 0.06 ± 0.24	0.92 ± 0.12 ± 0.46	34 ± 2 ± 29	0.73 ± 0.14 ± 0.50	2.10 ± 0.37 ± 0.82
Total	62.4 ± 4.4 ± 9.3	54.9 ± 3.9 ± 7.1	1015 ± 41 ± 144	33.9 ± 2.9 ± 6.2	13.1 ± 1.9 ± 2.5
Data	58	59	1118	40	18

εσA limit (fb): 22 25 429 27 17

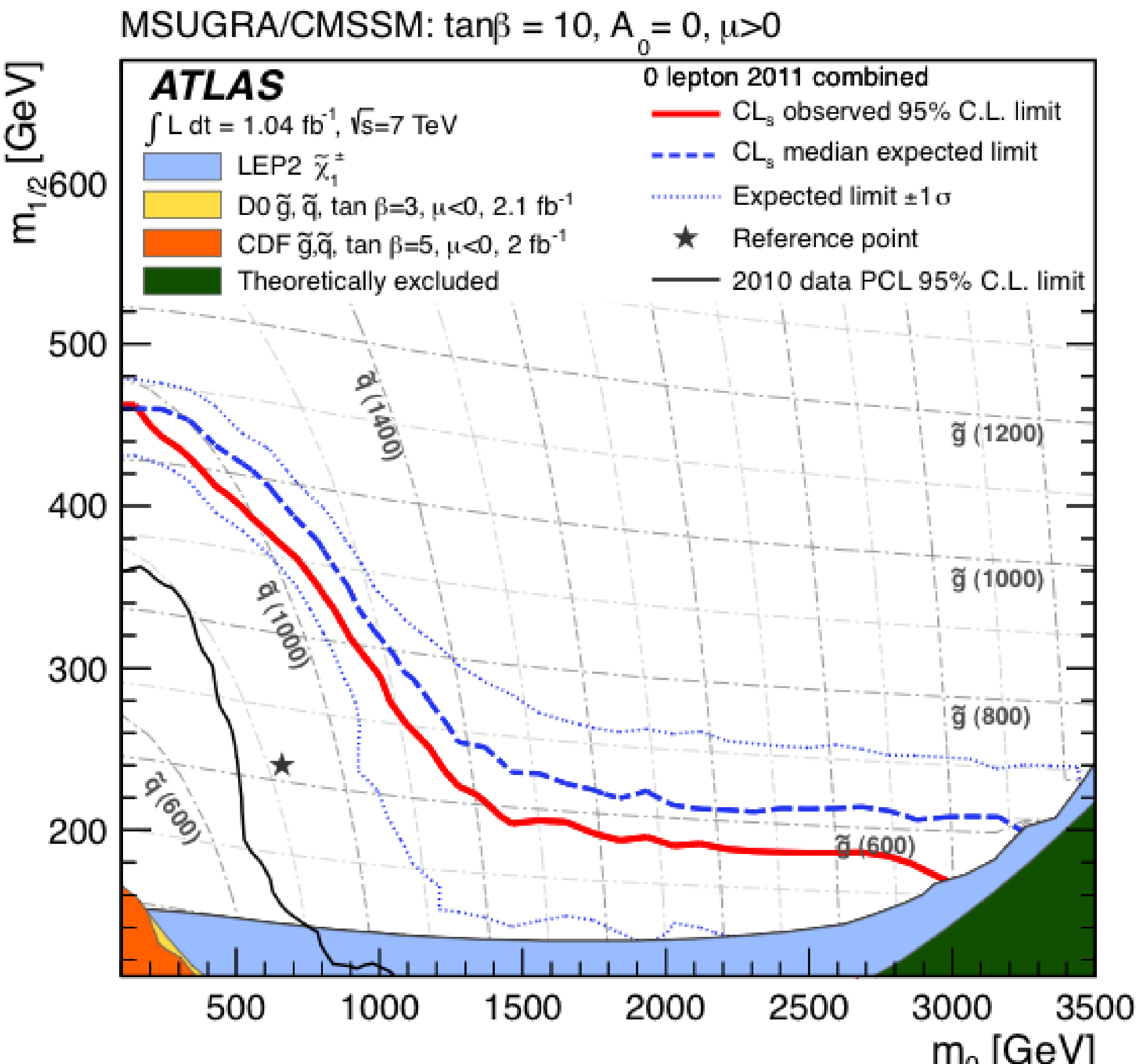
Interpretation: simplified SUSY Model



- $m_X = 0$
- Masses of gluinos and squarks of 1st and 2nd generation as given on plot
- All other SUSY masses are decoupled, by being given masses of 5 TeV

Squark and gluino with mass below 0.875 TeV and 0.700 TeV respectively for gluino and squark with mass below 2 TeV, are excluded at 95% C.L.

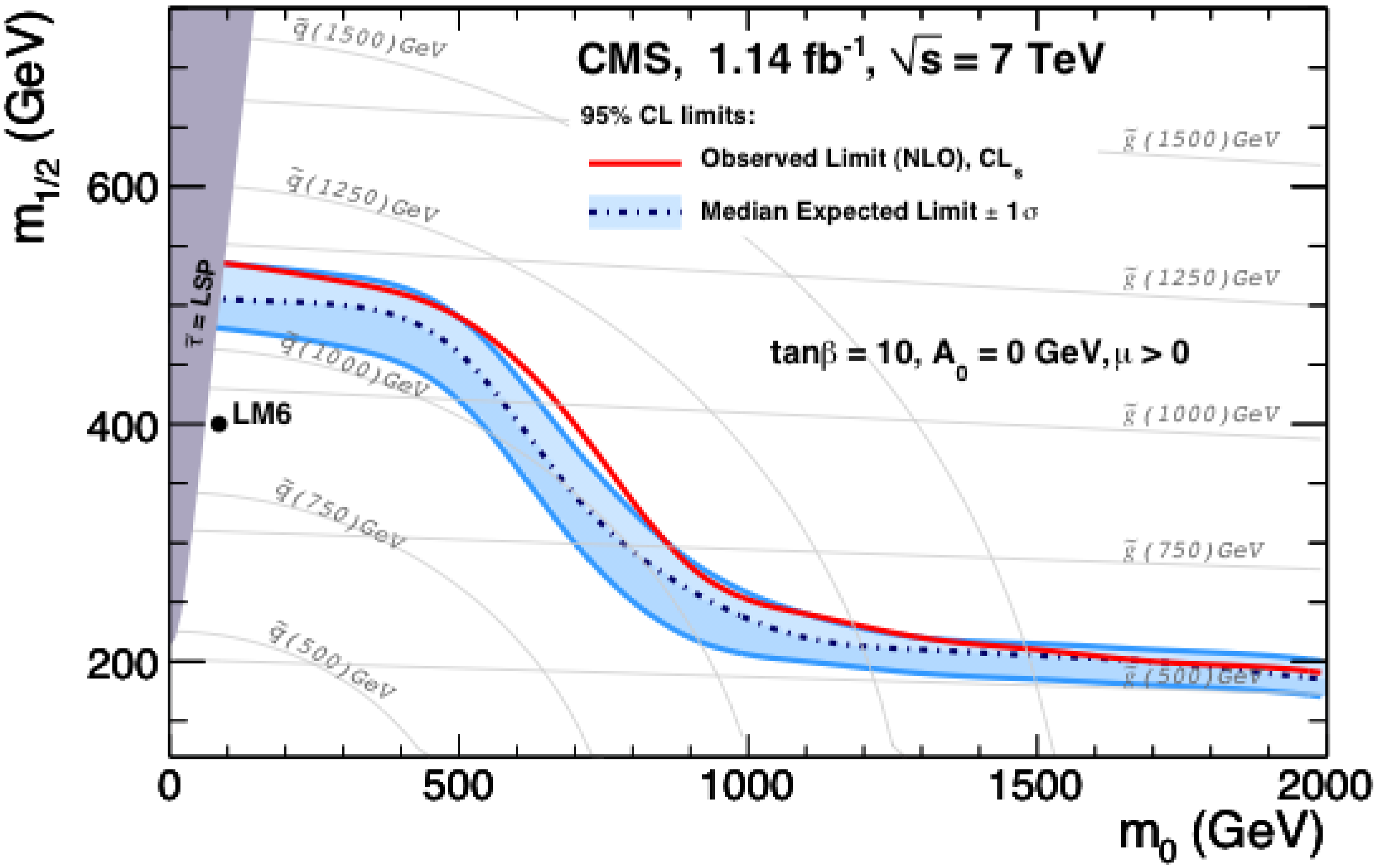
Interpretation: simplified SUSY Model



- $\tan\beta = 0$
- $A_0=0$
- $\mu>0$

Squark and gluino with mass below ~ 1 TeV are excluded at 95% C.L.

SUSY with Jets and E_T^{miss}: CMS



CMS exclusion limits in the cMSSM model

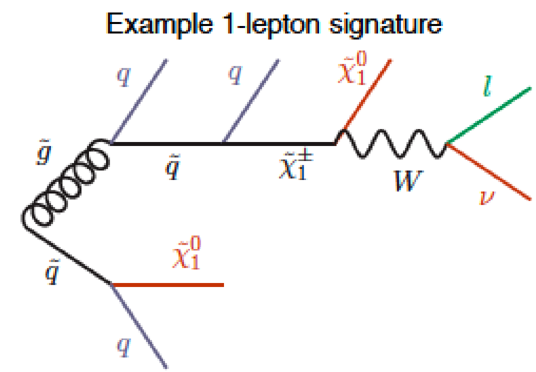
Similar exclusion as from the ATLAS experiment

Squark and gluinos with mass can be excluded at 95% CL for m_0<500 GeV

SUSY: searches in lepton+jets+E_T^{miss}

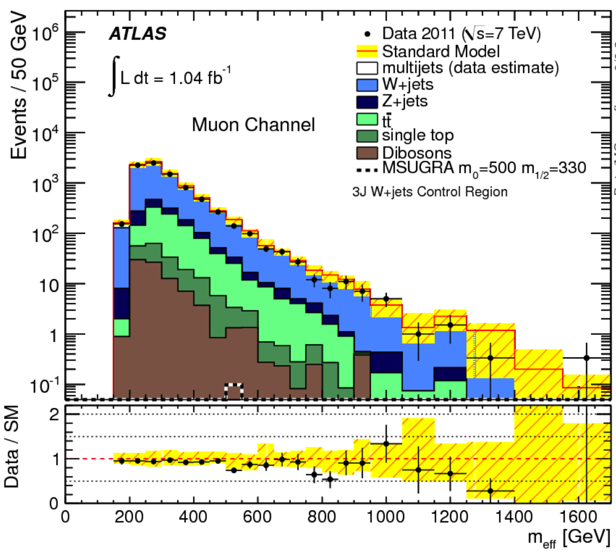
1 isolated lepton + jets + E_T^{miss}

Selection	Signal Regions 3JL	3JT	4JL	4JT	Control Regions 3J	4J
Number of Leptons	= 1					
Lepton p_T (GeV)	> 25(20) for electrons (muons)					
Veto lepton p_T (GeV)	> 20(10) for electrons (muons)					
Number of jets	≥ 3		≥ 4		≥ 3	≥ 4
Leading jet p_T (GeV)	60	80	60	60	60	60
Subsequent jets p_T (GeV)	25	25	25	40	25	25
$\Delta\phi(\vec{\text{jet}}_i, \vec{E}_T^{miss})$	[> 0.2 (mod.π)] for all 3 (4) jets					
m_T (GeV)	> 100				$40 < m_T < 80$	
E_T^{miss} (GeV)	> 125	> 240	> 140	> 200	$30 < E_T^{miss} < 80$	
E_T^{miss}/m_{eff}	> 0.25	> 0.15	> 0.30	> 0.15	–	–
m_{eff} (GeV)	> 500	> 600	> 300	> 500	> 500	> 300

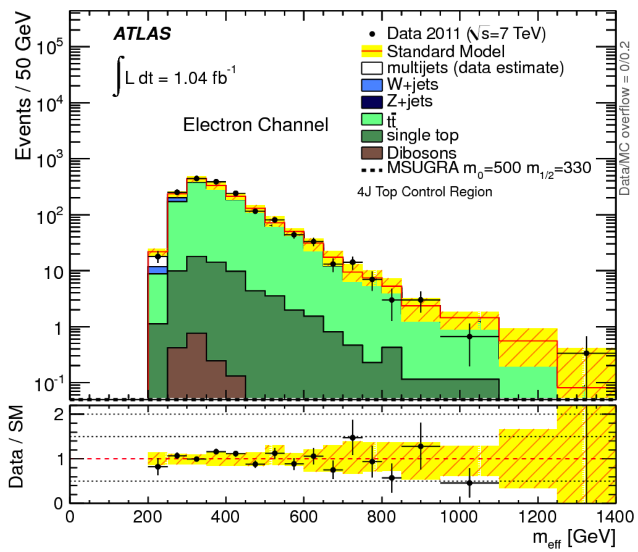


- Dominant background:
  - W(Z)+jets
  - Ttbar
  - Multijet contamination is negligible

3J W+jets CR

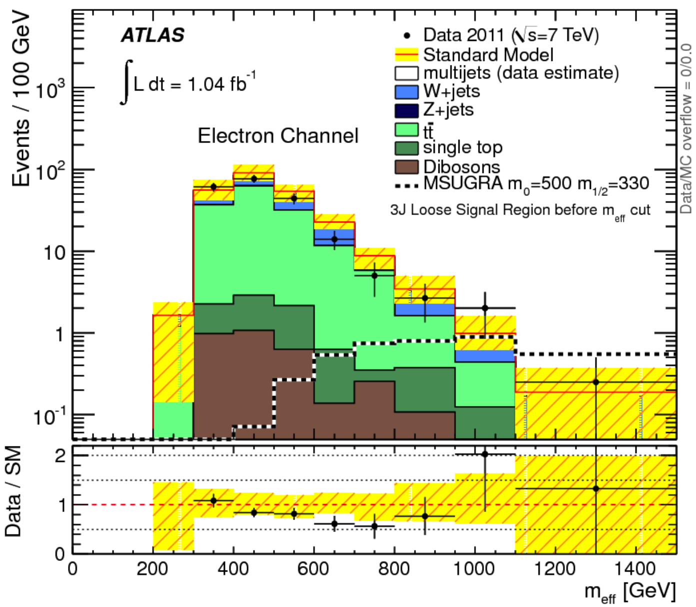


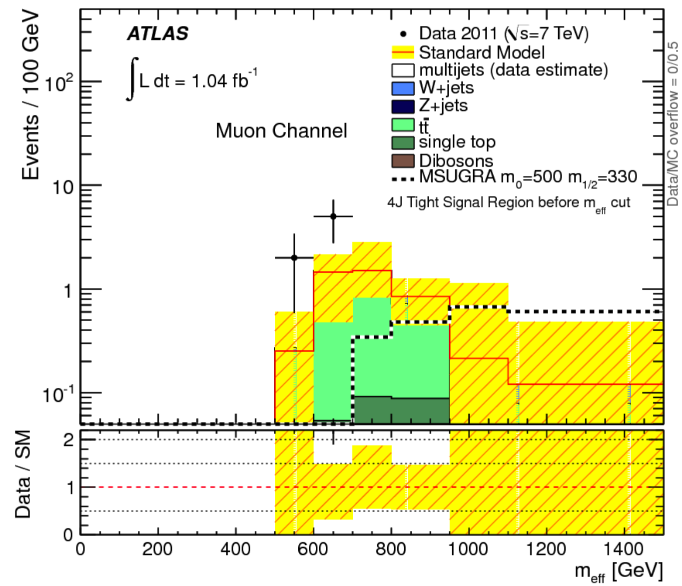
4J top CR



Background is evaluated using data in control regions

SUSY: searches in lepton+jets+E_T^{miss}



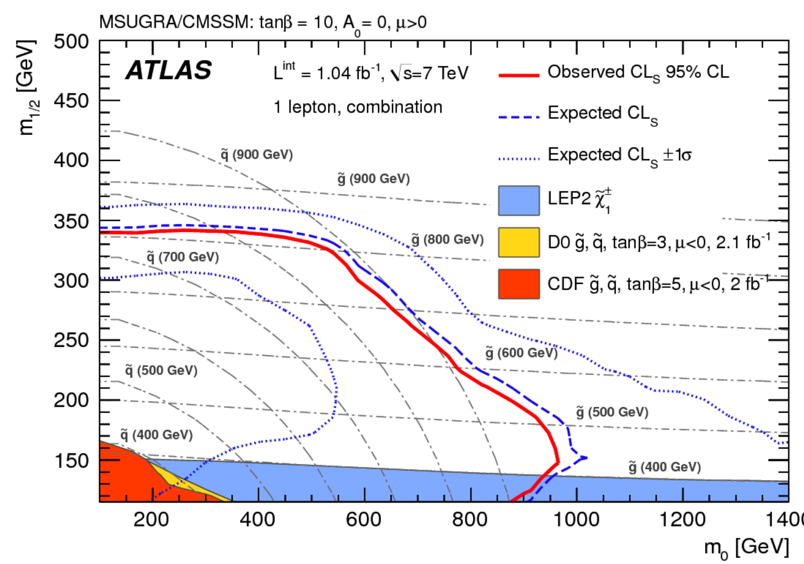


Electron channel	3JL SR	3JT SR	4JL SR	4JT SR
Observed events	71	14	41	9
Fitted background events	98 ± 28	18.5 ± 7.4	48 ± 18	8.0 ± 3.7

Muon channel	3JL SR	3JT SR	4JL SR	4JT SR
Observed events	58	11	50	7
Fitted background events	64 ± 19	13.9 ± 4.3	53 ± 16	6.0 ± 2.7

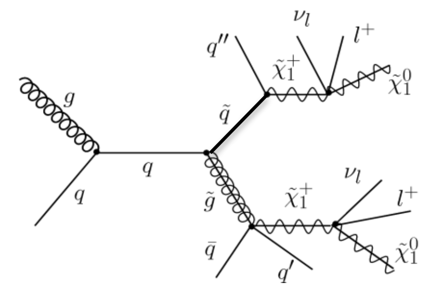
εσA limits (fb) e: 50 14 33 10

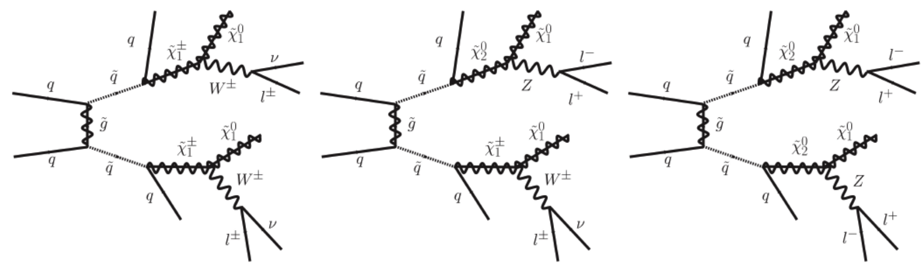
μ: 36 10 31 9



SUSY: E_T^{miss} + 2 leptons

- dilepton final states can be produced by cascade decays yielding flavour correlated lepton pairs
- Like-sign dilepton production appears in many models of Physics Beyond the Standard Model, including SUSY
- Backgrounds from Standard Model are in general small. Main contributions from:
  - Diboson (WZ)
  - ttbar production (where one lepton comes from the semileptonic b-decay)
  - Fake leptons
- Lepton pt values in SUSY cascade might be low, depending on the mass difference of the SUSY particles involved → search for low pt lepton as possible



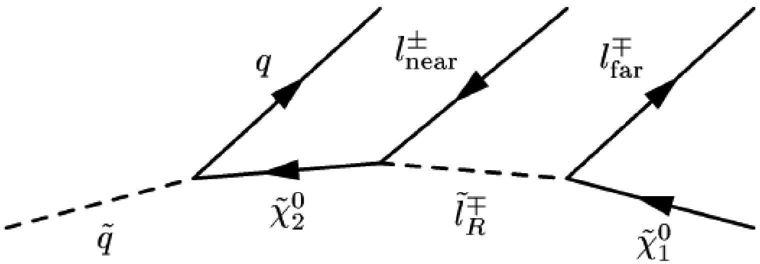


- Taus (3rd generation) may play an important role, stau could the lightest slepton

SUSY: E_T^{miss} + 2 leptons

$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$$

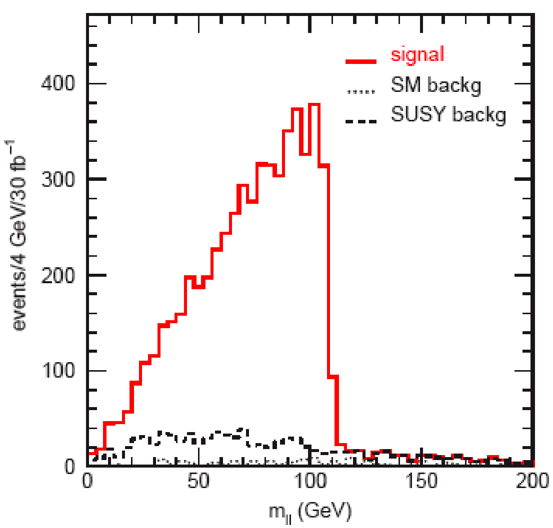
$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)}}{m_{\tilde{\ell}}}$$

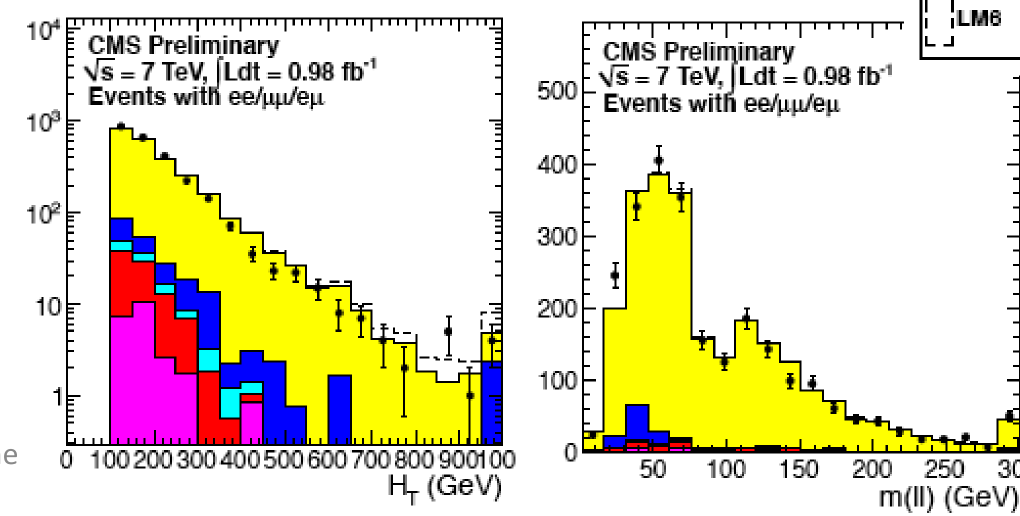


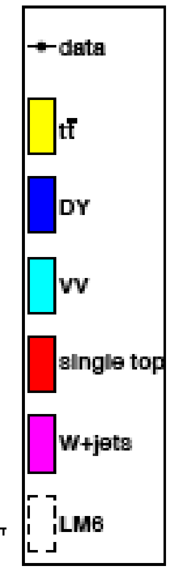
CMS: event preselection: similar to the one of made for ttbar cross section measurement in the dilepton channel:

- Two opposite-sign isolated high-pT leptons
- At least two high-pT jets
- Large E_t^{miss}

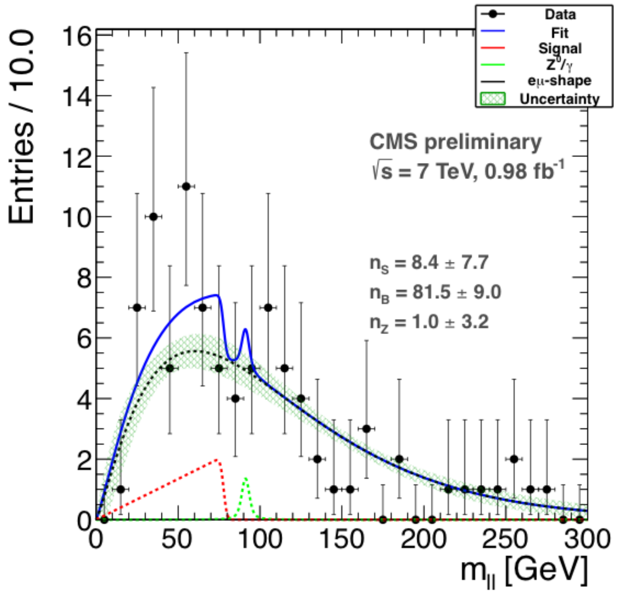
- An example: search for a characteristic edge in the opposite-sign dilepton mass spectra

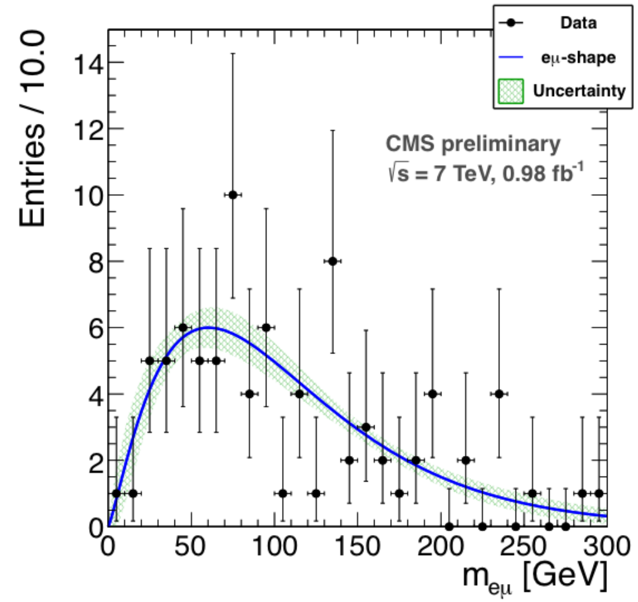






SUSY: E_T^{miss} + 2 leptons



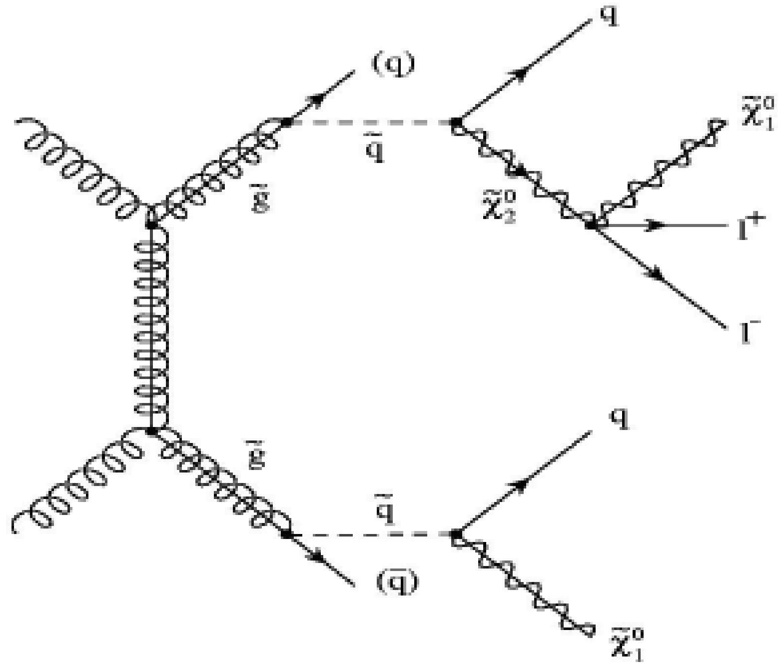


- Signal region: select events with H_T>300 GeV, Etmiss > 100 GeV
  - ee,μμ events (left) and eμ events (right)

- No evidence for a characteristic di-lepton edge in the data

SUSY: sbottom and stop searches

- In the MSSM the scalar partners of right-handed and left-handed quarks, sq_R and sq_L, can mix to form two mass eigenstates
- The mixing is proportional to the mass of the corresponding SM fermions, and therefore it becomes important for the 3^{rd} generation
- Large mixing can yeld sbottom and stop with mass eigenstates which are signficantly lighter than other squarks
- → stop and sbottom could be produced with large cross sections at the LHC

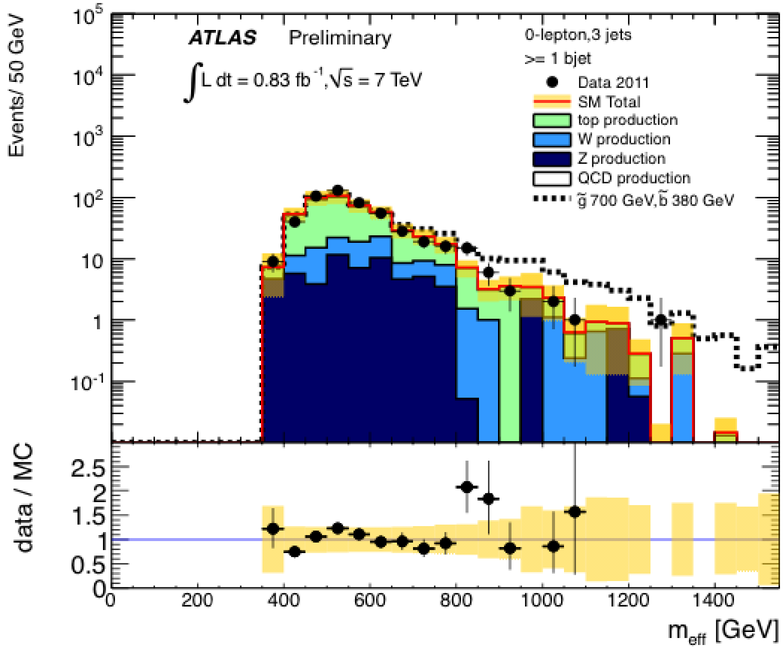


$$\tilde{g} \to \tilde{b}_1 b \text{ or } \tilde{g} \to \tilde{t}_1 t$$

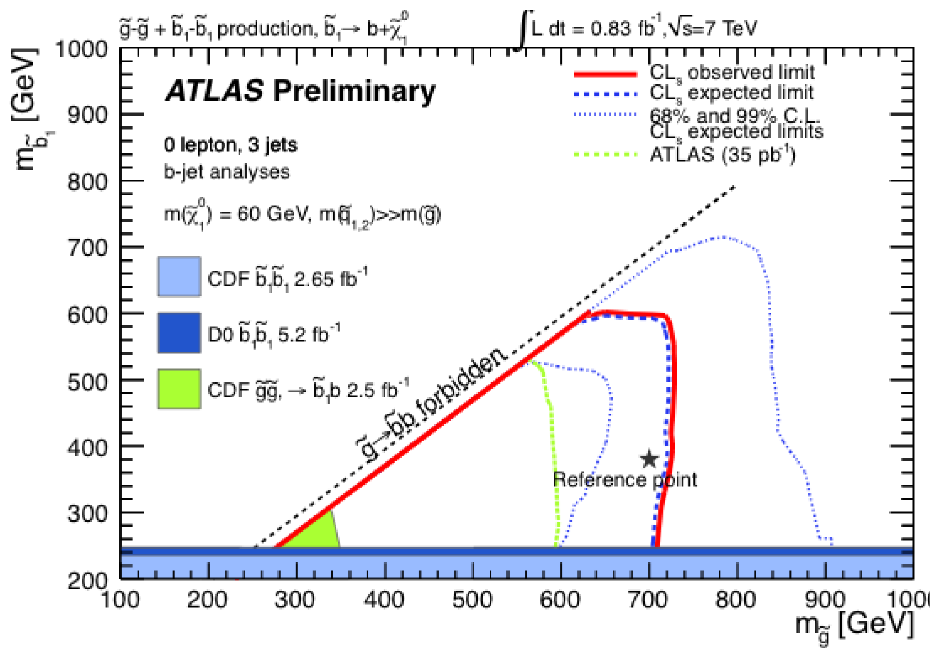
- → b-quarks appear in their decays

SUSY: sbottom searches

Exclusion limits in the ($m_{sbottom}$-m_{gluino}) plane, that the lightest squark (sbottom1) is produced via gluino gluino mediated production, or direct pair production, assuming 100% BR sb1→bX_1^0



Events with 1 b-tagged jet

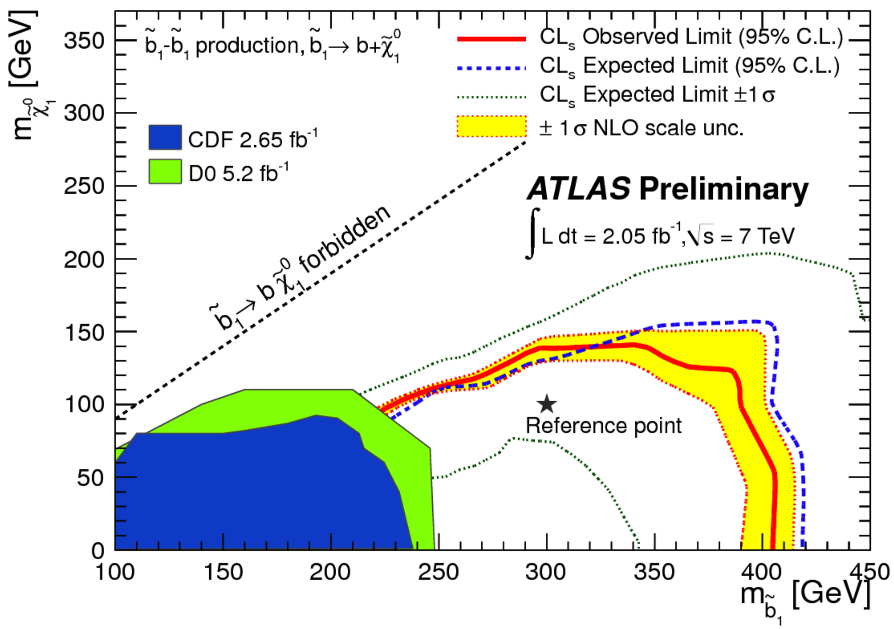


- Gluino masses below 0.72 TeV for sbottom masses of below ~ 0.6 TeV are excluded

SUSY: sbottom searches

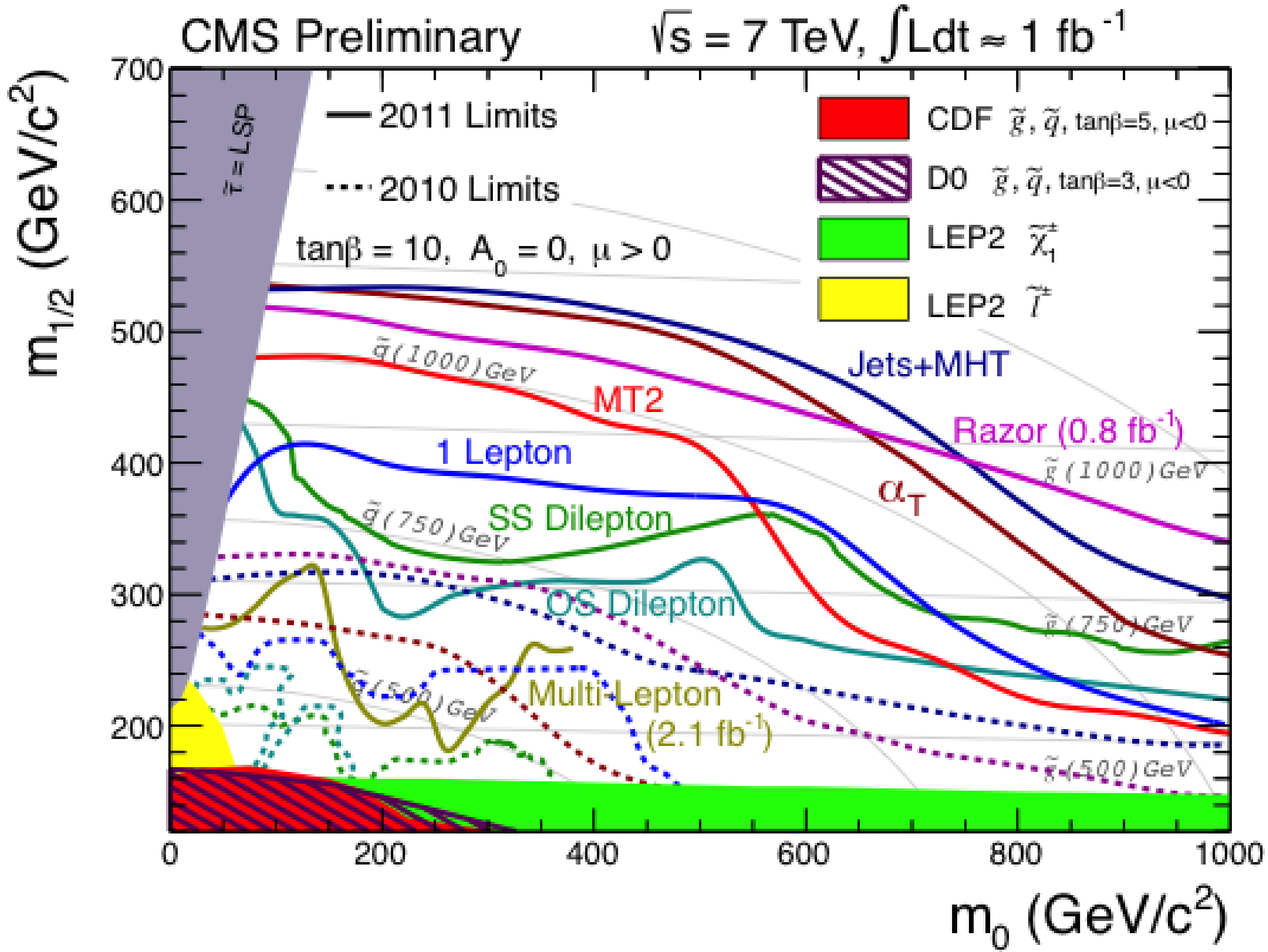
$\tilde{b}_1$-$\tilde{b}_1$ production, $\tilde{b}_1 \rightarrow b+\tilde{\chi}_1^0$

Selection: 2 b-jets, p_T > 130,50 GeV
E_T^{miss} > 130 GeV, E_T^{miss}/m_{eff} > 0.25
$\Delta\Phi(\text{jet},E_T^{miss})$>0.4
Veto leptons and 3rd jet > 50 GeV

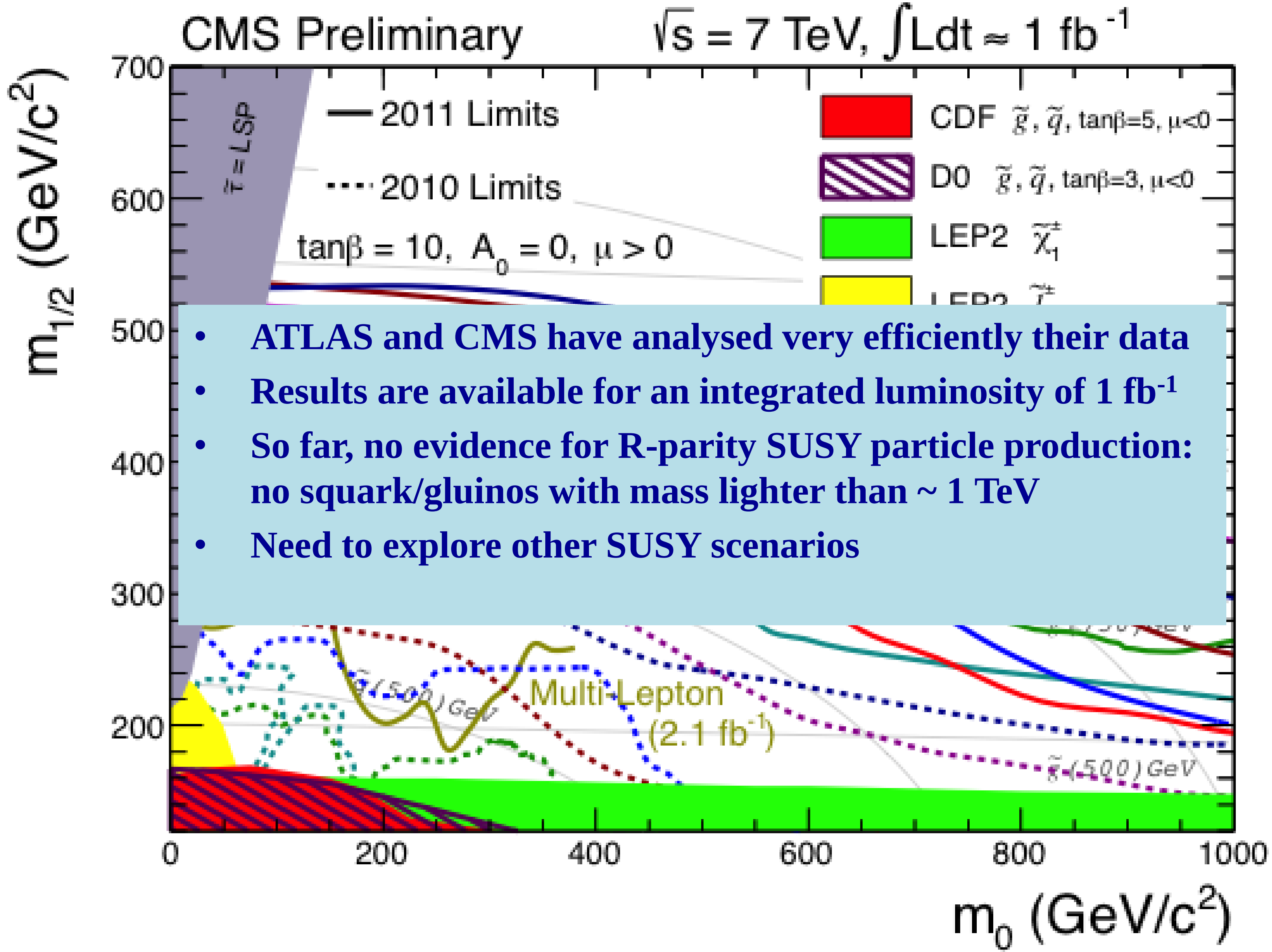


Assuming 100% BR, sbottoms are excluded up to 385 GeV (for LSP < 60 GeV)

Summary of R-parity conserving SUSY searches in CMS



Summary of R-parity conserving SUSY searches in CMS



- **ATLAS and CMS have analysed very efficiently their data**
- **Results are available for an integrated luminosity of 1 fb^{-1}**
- **So far, no evidence for R-parity SUSY particle production: no squark/gluinos with mass lighter than ~ 1 TeV**
- **Need to explore other SUSY scenarios**

Search for Gauge Mediated SUSY breaking scenarios (GMSB)

- In Gauge mediated SUSY breaking models (GMSB), SUSY breaking occurs at energy scales much smaller than the Planck scale, breaking linked to gauge interactions
- The gravitino is the LSP, escaped detection → E_T^{miss} signature
- Phenomenology is determined by the NLSP (next-to-lightest SUSY particle).

In many scenarios the NLSP are the super-partners of the SU(2) gauge fields

- Decay scenarios

  $\tilde{W} \rightarrow \gamma \tilde{G}$ $\quad$ $\tilde{W}^{+} \rightarrow W^{+} \tilde{G}$

- Also $X^0{}_1$ can be the NSLP with decay $\chi_1^0 \rightarrow \gamma \tilde{G}$
- → expect/search for events with photons, leptons, Etmiss
- In GMSB models, sleptons squarks, gluinos might have long lifetime

… and much more!

- Many other scenarios have been investigated
- Not presented in these lectures
- Final states with photons and Etmiss
- Long liftime new particles
- Heavily ionizing particles
- R-parity violating models
- Disappearing tracks
- …..

perspectives

√s=14 TeV

Analyse other SUSY Scenario
Example: "compressed SUSY"

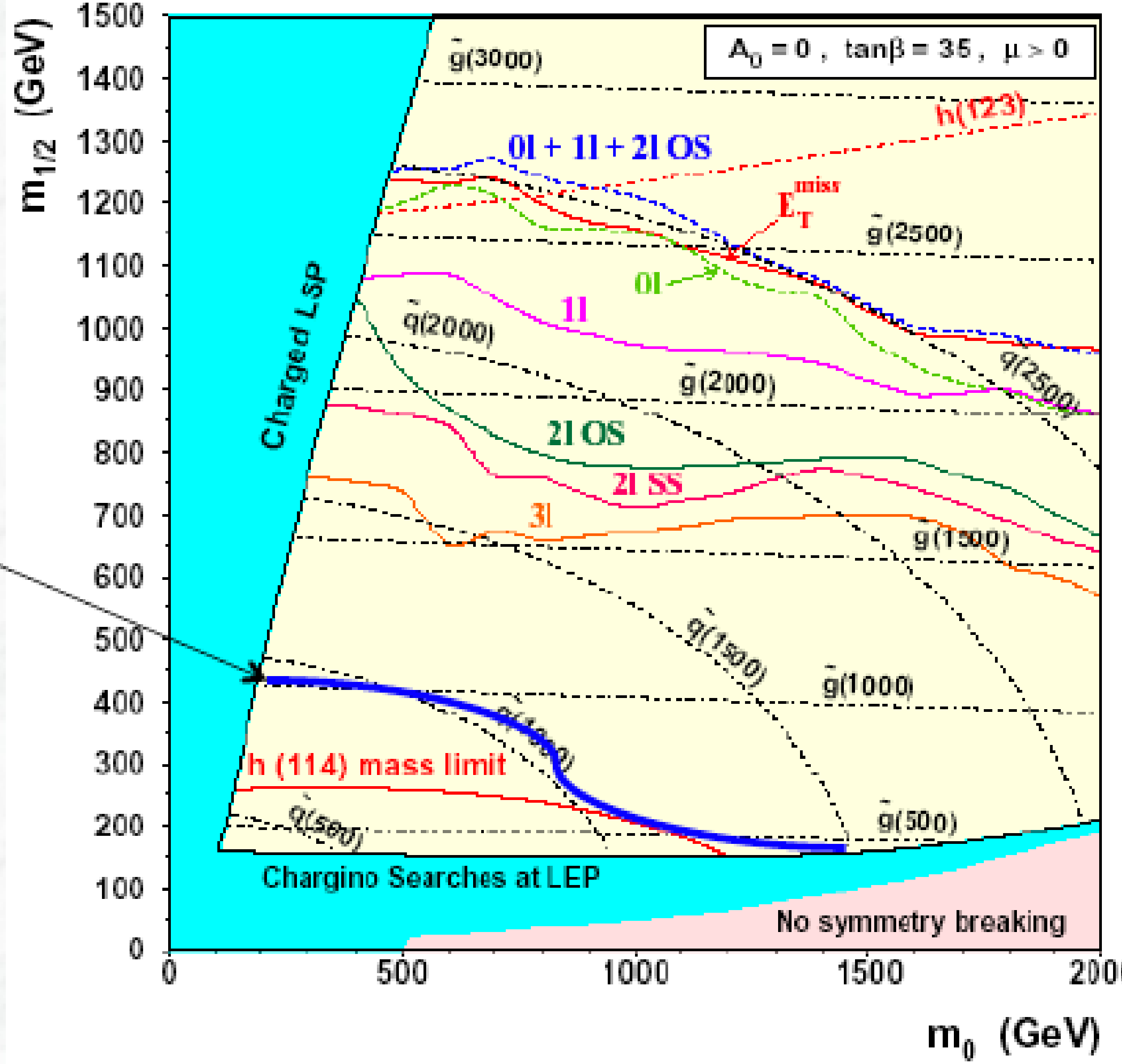
Serach for EWK production of gauginos

Search for direct sbottom and stop production

present ATLAS and CMS limits

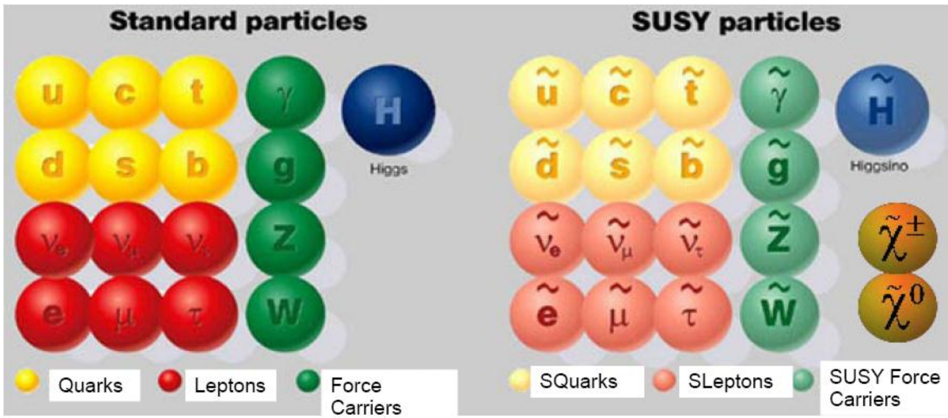
Go to higher pp collision energies

mSUGRA reach in various final states for 100 fb^{-1}



Backup

The Minimal SuperSymmetric Model (MSSM)



- More than 100 parameters to define the MSSM
- In the MSSM model there are five Higgs bosons:
  - h^0, H^0, neutral CP even;
  - A, neutral, CP odd
  - H^{+}, H^{-} charged;
- Specific models with less parameters:
  - mSUGRA/cMSSM
  - GMSB
  - AMSB
  - …

The new colored particles are produced with a high rate by the strong force