SUSY Searches at the LHC

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Göttingen, 29. Februar 2012

HELMHOLTZ ASSOCIATION

DESY

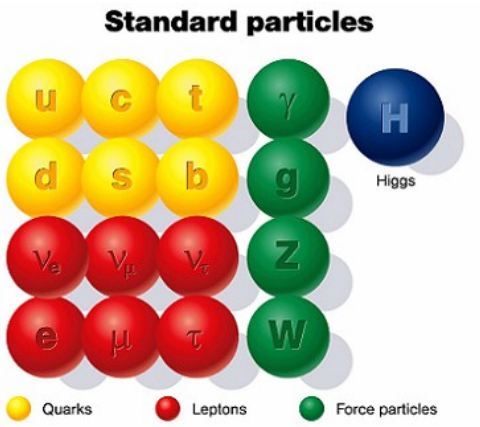
Outline

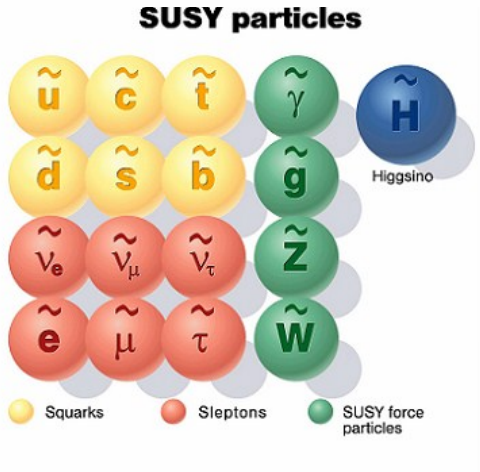
- Introduction
- LHC and ATLAS/CMS
- Final states
  - Jets and missing E_T
  - Third generation
  - Multi-leptons
  - Photons
- Summary

Supersymmetry (SUSY)

One of the most popular extensions of the SM

- SUSY postulates “superpartners” to each SM particles (same quantum numbers, but spin differs by ½)
- SUSY must be broken
- R-parity: $R = (-1)^{3(B-L)+2s}$
  If R-parity is conserved, SUSY particles are pair produced and the lightest one (LSP) is stable
- Why is SUSY popular? It answers many open questions at once:
  - Allows unification of gauge couplings
  - Provides a solution to the hierarchy problem: the fermion/boson contribution to the Higgs mass exactly cancel
  - If R-parity is conserved the LSP is stable and is a dark matter candidate

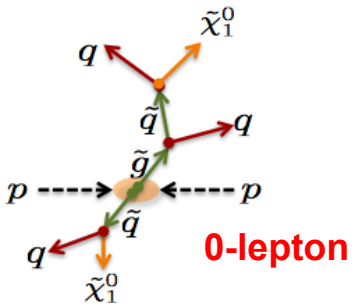


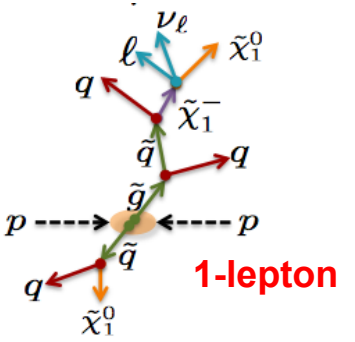


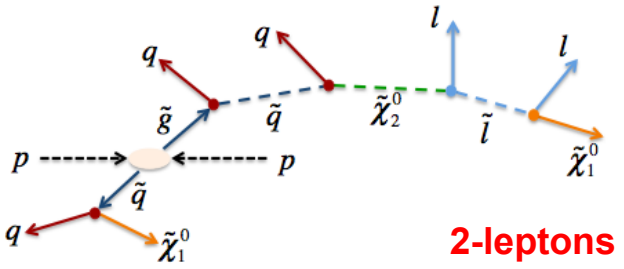
Search Strategies for SUSY

- Assume R-parity conservation for the moment
- At the LHC sparticles are pair produced
  - dominantly squarks and gluinos via the strong interaction
  - they decay via cascades into the stable LSP (neutralino or gravitino)
- common signature:
  - multiple, high energetic jets and transverse missing momentum
  - distinguish final states by additional particles

    zero, one, two, .. leptons (e, μ), two photons, …
    b-jets if 3rd generation squarks are lighter than other generation squarks
- incomplete event reconstruction due to LSP
  - no mass peak
    → SUSY is in the tails of the distributions
  - SM backgrounds (top, W/Z+jets, QCD) are taken from/verified in control regions







SUSY Analysis in Detail

1. Event selection cuts and definition of signal region:
   - Cut on a set of variables that can discriminate between signal and background jets, missing E_T, leptons, b-jets, …
   - Coherent with the choice of trigger to ensure high trigger efficiency
2. Background determination:
   - QCD and fake backgrounds: estimate from data
   - top, W/Z + jets: estimate from data when possible or with transfer factors using background-enhanced control regions:

$$N_{SR}^{est,Bkg} = \frac{N_{SR}^{MC}}{N_{CR}^{MC}}(N_{CR}^{data} - N_{CR}^{MC,others})$$

   - Smaller irreducible backgrounds: using Monte Carlo simulation
3. Estimate all uncertainties:
   - Experimental uncertainties: jet energy scale calibration, b-tagging efficiency, …
   - Theoretical uncertainties: renormalisation and factorisation scales, PDF, …
4. Look into the signal region: Any excess in data? If not, derive exclusion limits
5. Interpretation

A Word on Models

- Model independent interpretation:
  The main experimental result is the limit on the number of signal events in the signal region and the limit on the visible cross section
- Model specific interpretation:

mSUGRA/CMSSM:

- **m_0:** common scalar mass
- **$m_{1/2}$:** common gaugino mass
- **A_0:** common trilinear coupling
- **tan β:** ratio of Higgs vacuum expectation values
- **sign(μ):** sign of SUSY Higgs potential parameter

GMSB:

- **Λ:** SUSY breaking scale
- **M_{mess}:** messenger mass scale
- **N_5:** number of messenger fields
- **tan β:** ratio of Higgs vacuum expectation values
- **sign(μ):** sign of SUSY Higgs potential parameter
- **C_{grav}:** ratio of the gravitino mass to its value at the breaking scale Λ

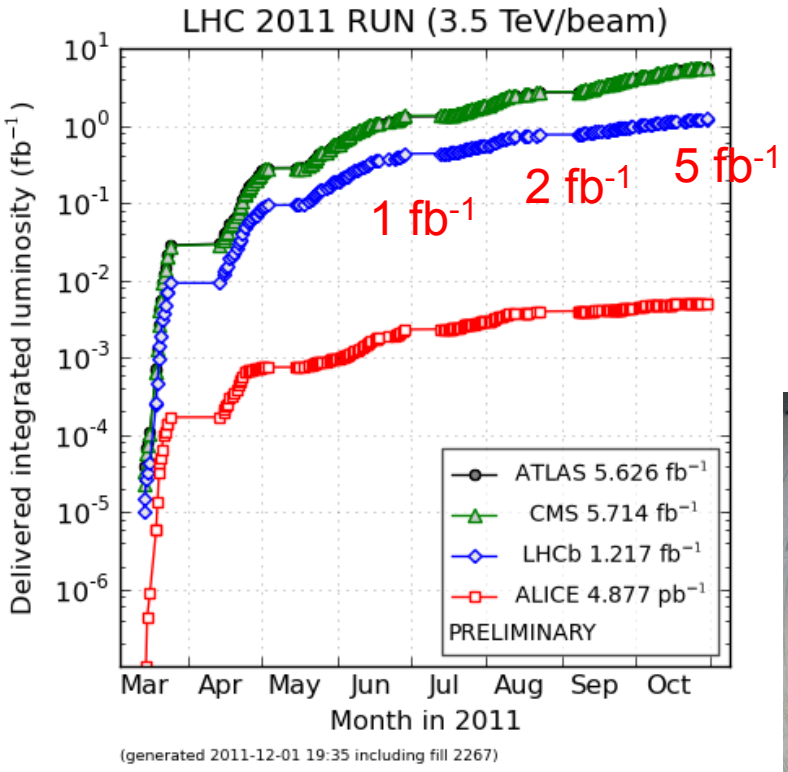
Reduce number of free parameters and predict mass spectrum

Simplified models

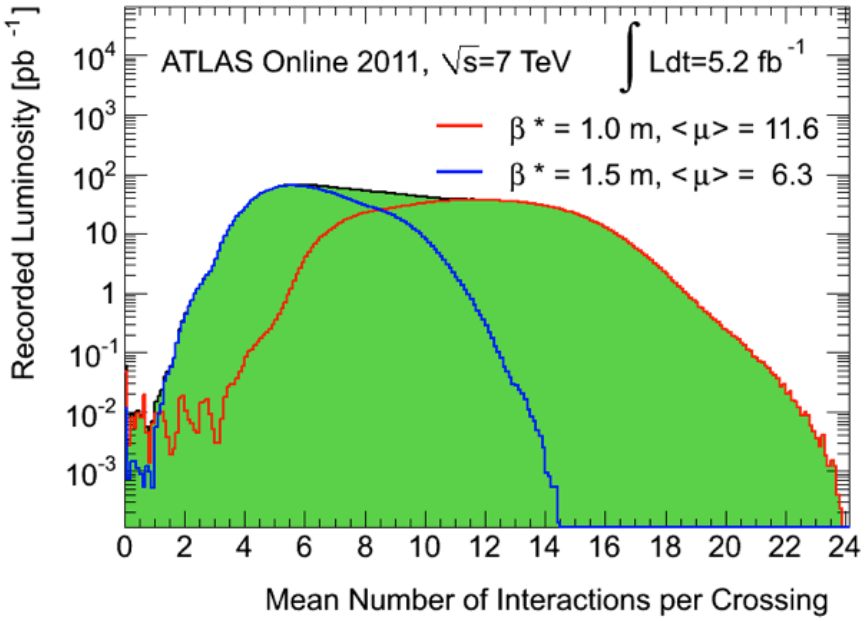
- **reduced particle spectrum:** test different mass combinations

Large Hadron Collider (LHC)

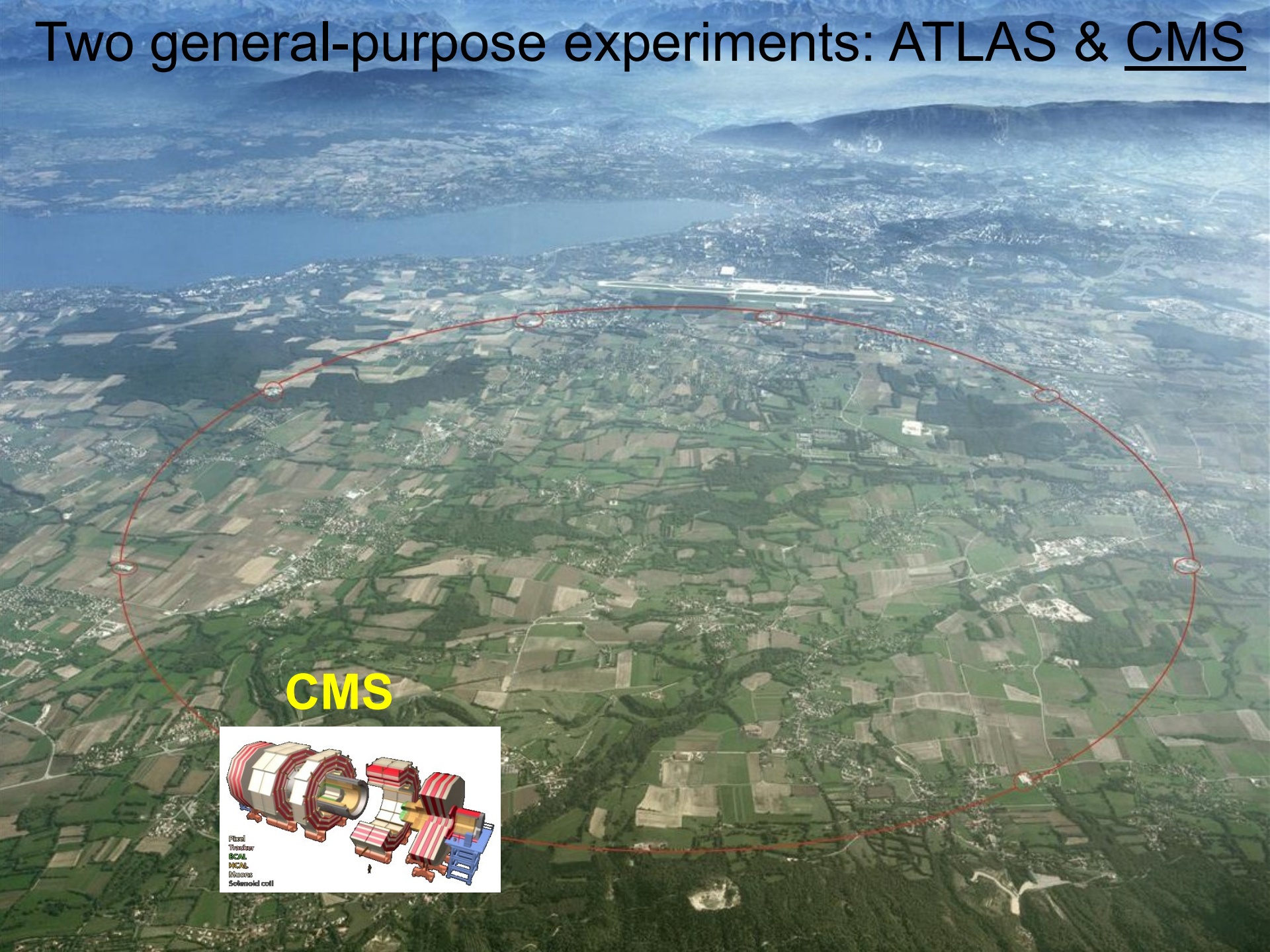
- √s = 7 TeV pp
- Outstanding 2011 Performance
  - ~ 3.5 × 10^{33} $cm^{-2}s^{-1}$ peak lumi
  - ~ 5.6 fb^{-1} delivered



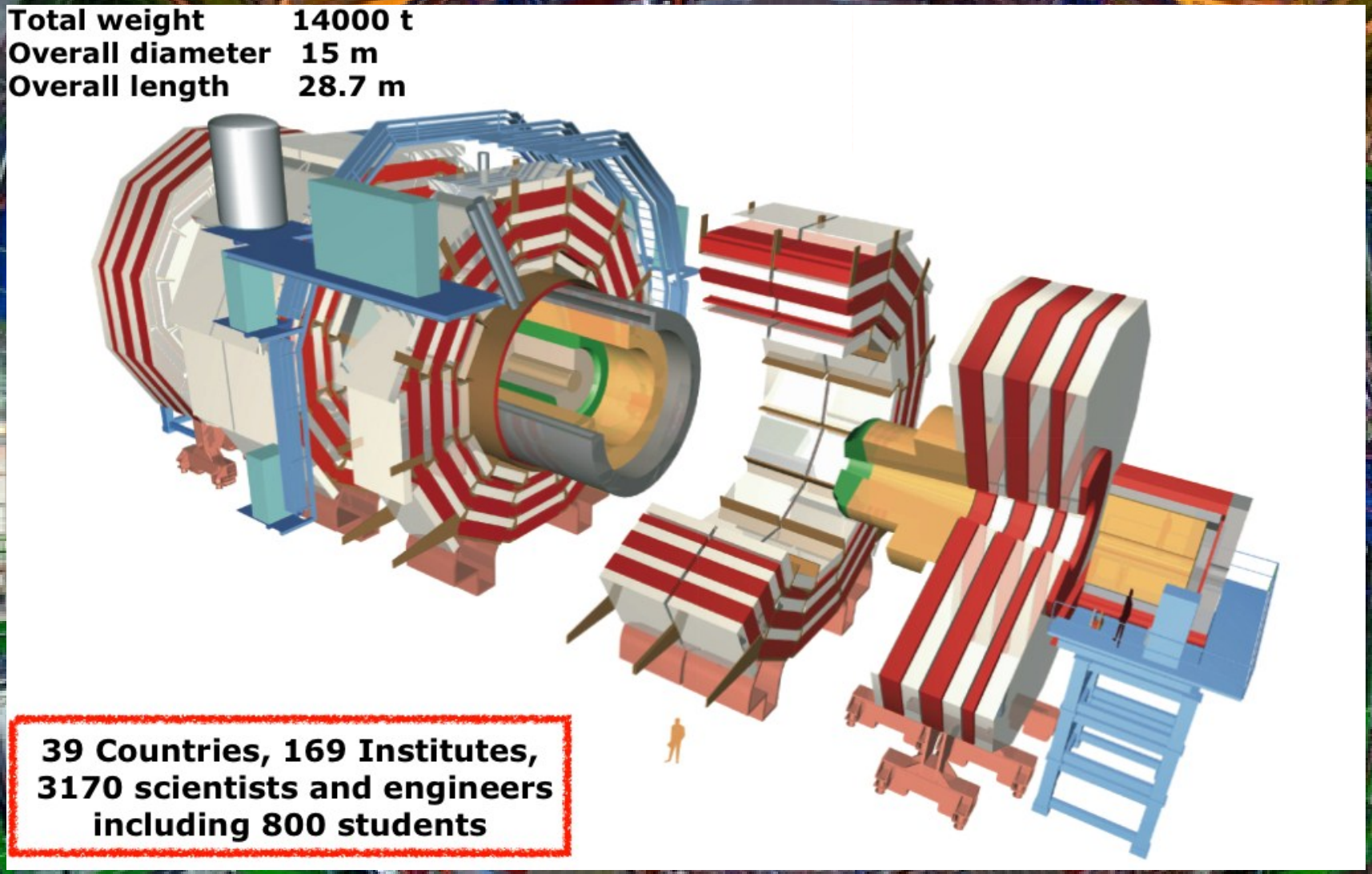
- Bunch spacing 50 ns
- ~ 12 pp collisions / crossing (avg.)



Two general-purpose experiments: ATLAS & CMS

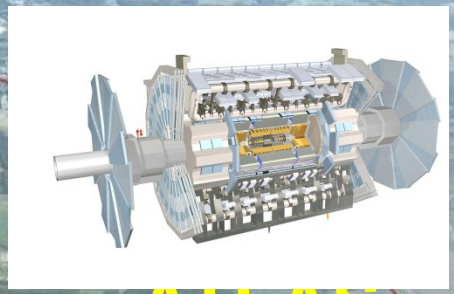


Two general-purpose experiments: ATLAS & CMS



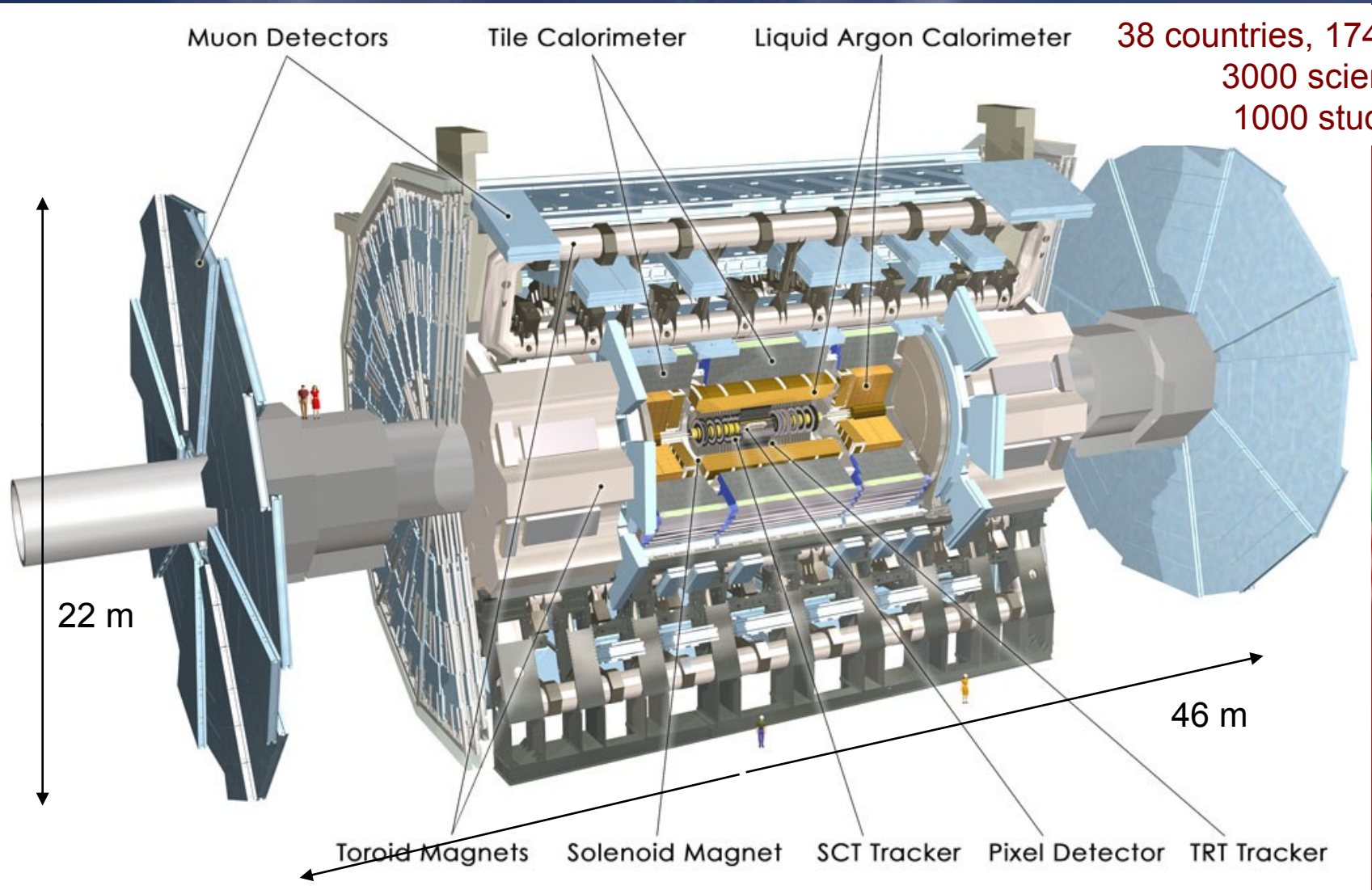
Emphasis on excellent resolution (energy, momentum, mass) of electrons, photons, muons

Two general-purpose experiments: ATLAS & CMS

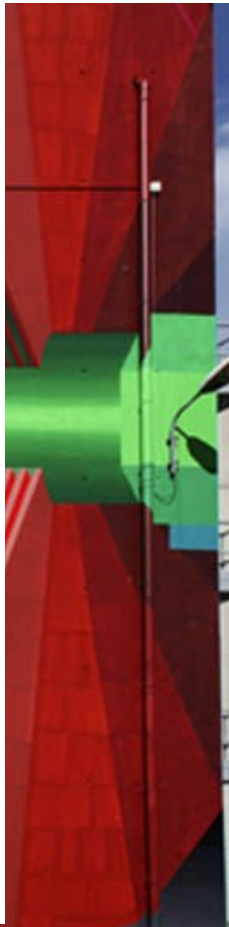


ATLAS

Two general-purpose experiments: ATLAS & CMS

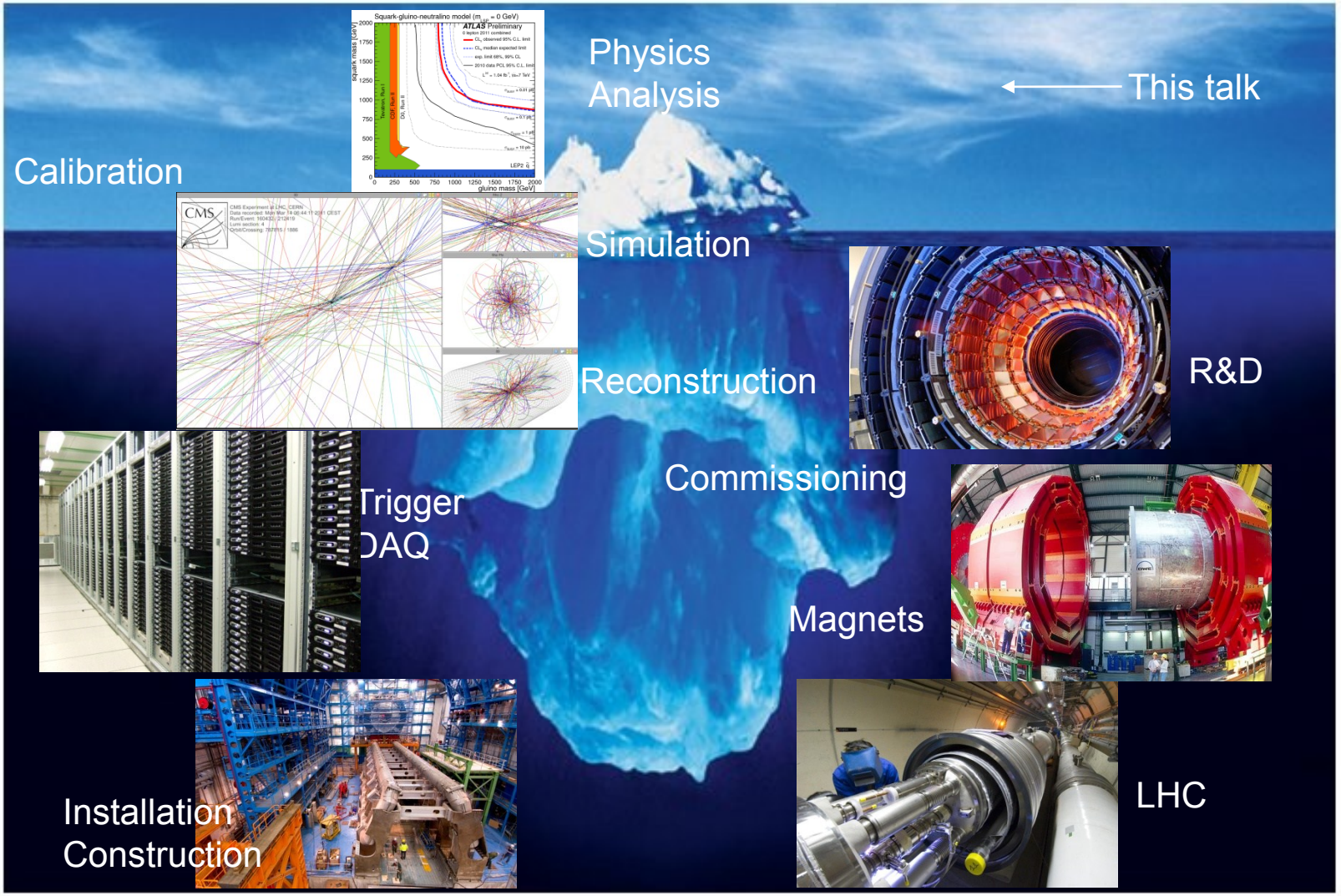


38 countries, 174 institutions
3000 scientists,
1000 students



Emphasis on excellent jet and missing-E_T (MET) resolution, particle identification, and standalone muon reconstruction

Acknowledgements



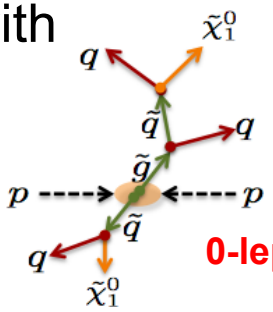
Courtesy of Henri Bachacou

Jets and Missing E_T

Jets + Missing E_T

CMS PAS-SUS-11-004

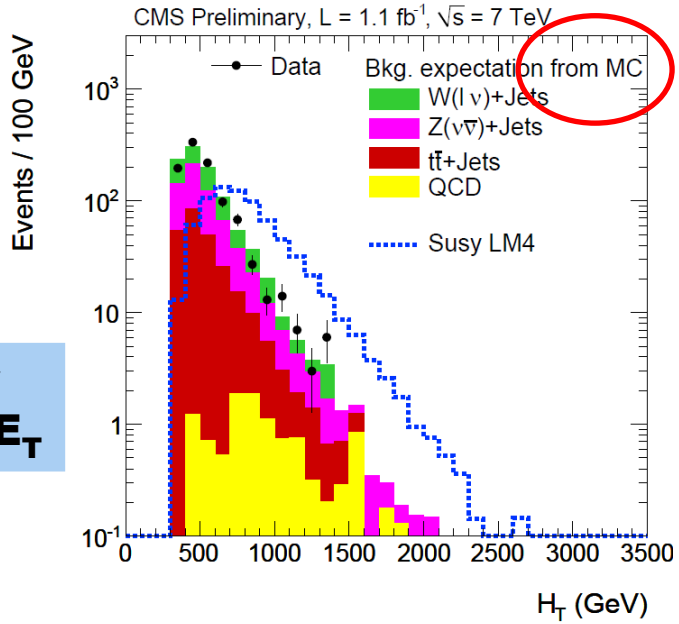
- Probe strong production of SUSY particles
- Select events with
  - many jets
  - missing E_T

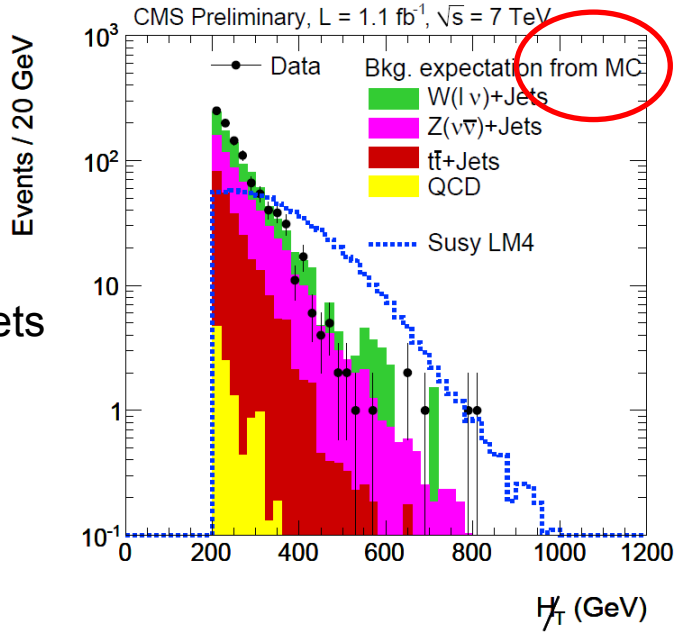


0-lepton

H_T = scalar sum of jet E_T

- Selection:
  - H_T and missing H_T trigger
    → H_T > 350 GeV, missing H_T > 200 GeV
  - ≥ 3 jets with p_T > 50 GeV
  - $|\Delta\phi(\text{jet}_{1,2}, H_T^{\text{miss}})|$ > 0.5 and $|\Delta\phi(\text{jet}_3, H_T^{\text{miss}})|$ > 0.3
  - Veto on isolated electrons and muons
  - Define signal regions based on H_T and missing H_T
- Background estimated from data
  - Model W→ τν and W → e/μν background using μ + jets
  - Z → νν using γ + jets by removing γ
  - Model multi-jet background from multi-jet events using the rescale and smear method





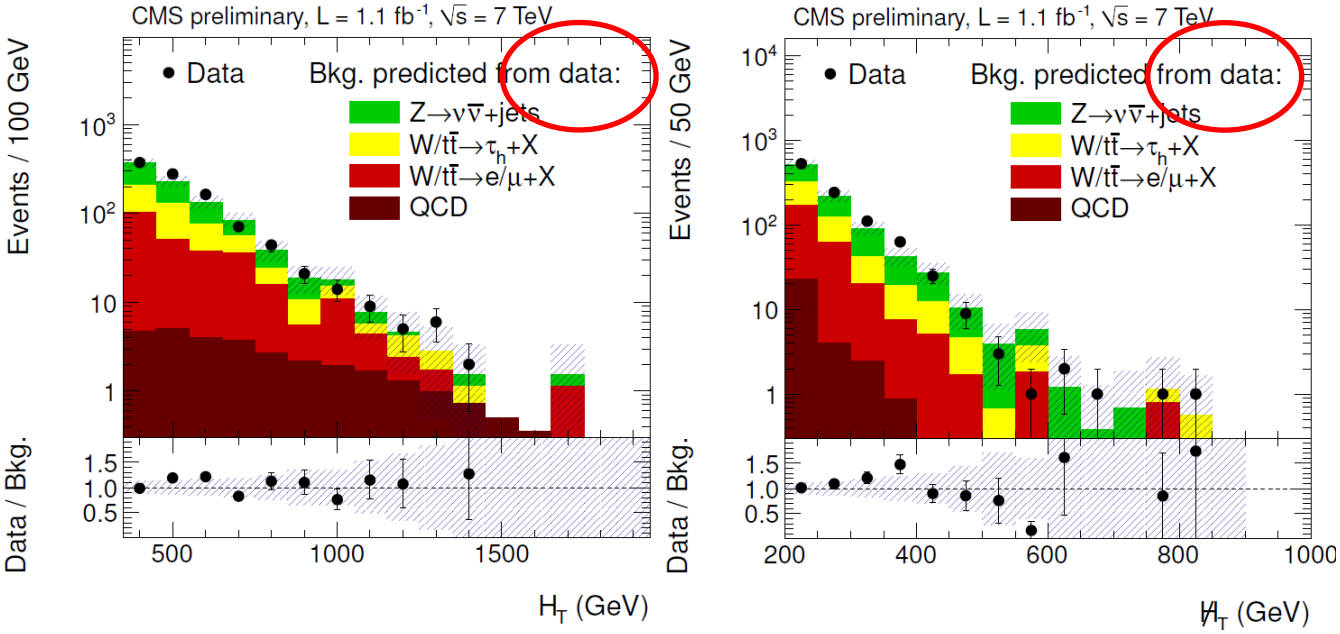
Jets + Missing E_T: Results

CMS PAS-SUS-11-004

- Four signal regions:

Method	Baseline H_T > 350 GeV and H_T^{miss} > 200 GeV	Medium H_T > 500 GeV and H_T^{miss} > 350 GeV	High H_T H_T > 800 GeV and H_T^{miss} > 200 GeV	High H_T^{miss} H_T > 800 GeV and H_T^{miss} > 500 GeV
$Z \to \nu\nu$ from γ+jets	376.3 ± 12.3 ± 79.2	42.6 ± 4.4 ± 8.9	24.9 ± 3.5 ± 5.2	2.4±1.1 ± 0.5
$t\bar{t}$/W → e,μ+X	243.5 ± 19.8$^{+30.0}_{-30.9}$	12.7 ± 3.3 ± 1.5	22.5 ± 6.7$^{+3.0}_{-3.1}$	0.8±0.8 ± 0.1
$t\bar{t}$/W → τ_{hadr}+X	263 ±8 ± 7.4	17 ± 2 ± 0.7	18 ± 2 ± 0.5	0.73 ± 0.73 ± 0.04
QCD	30.9 ±35.2$^{+16.6}$	1.3 ±1.3$^{+0.6}$	13.5 ±4.1$^{+7.3}$	0.09 ±0.31$^{+0.05}$
Total background	927.5 ±103.1	73.9 ±11.9	79.4 ±12.2	4.6 ±1.5
Observed in data	986	78	70	3

- Data well described by background estimate from data

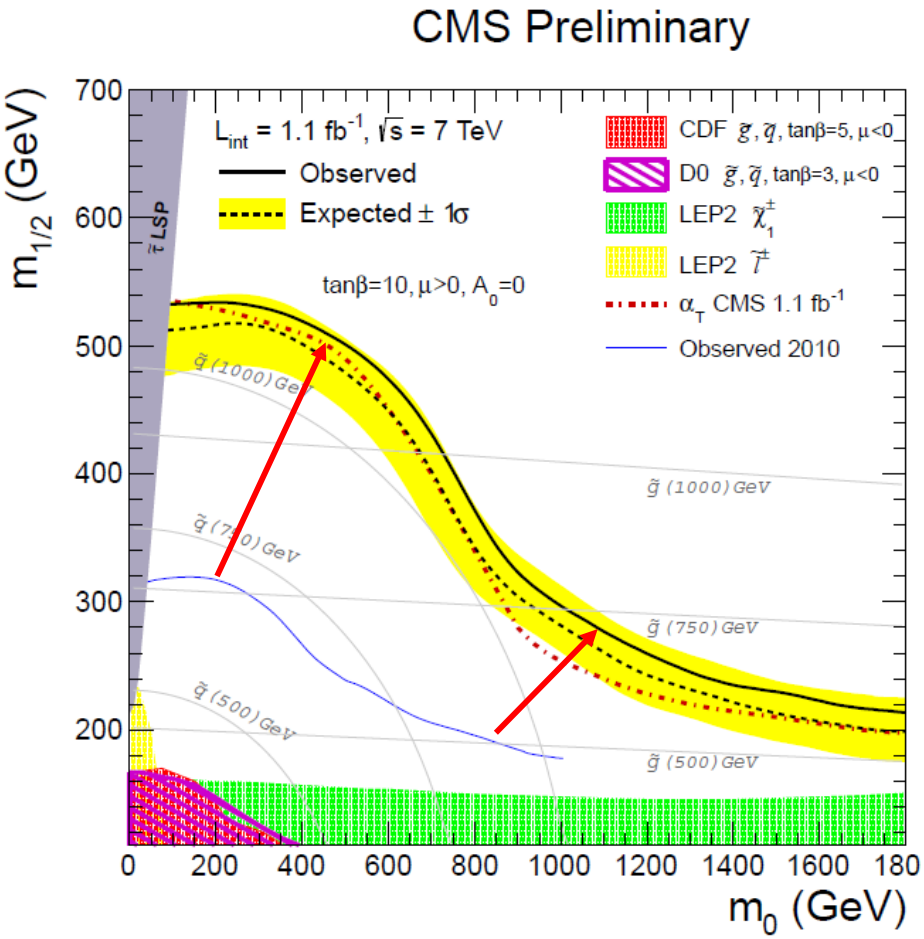


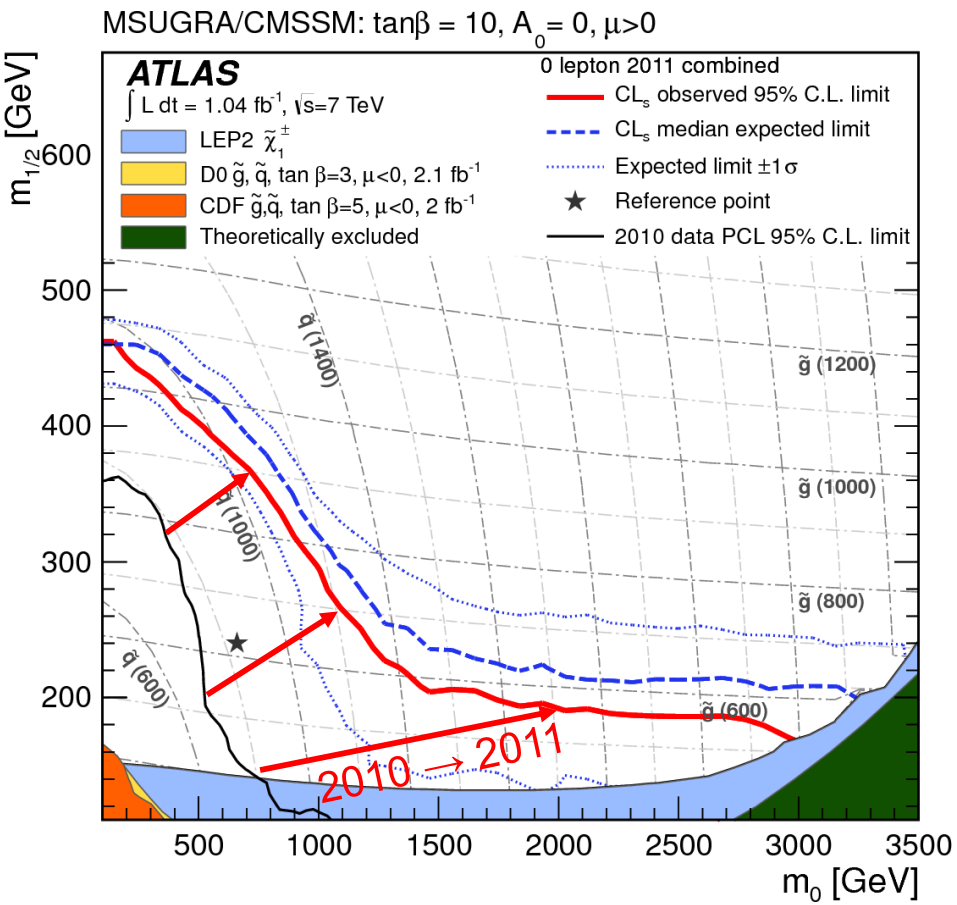
Interpretation in mSUGRA/CMSSM

CMS PAS-SUS-11-004

ATLAS arXiv:1109.6572

- Excluding $m_0 < 600$ GeV for $m_{1/2} < 500$ GeV
- Excluding squark masses < ~1 TeV and gluino masses < ~600 GeV





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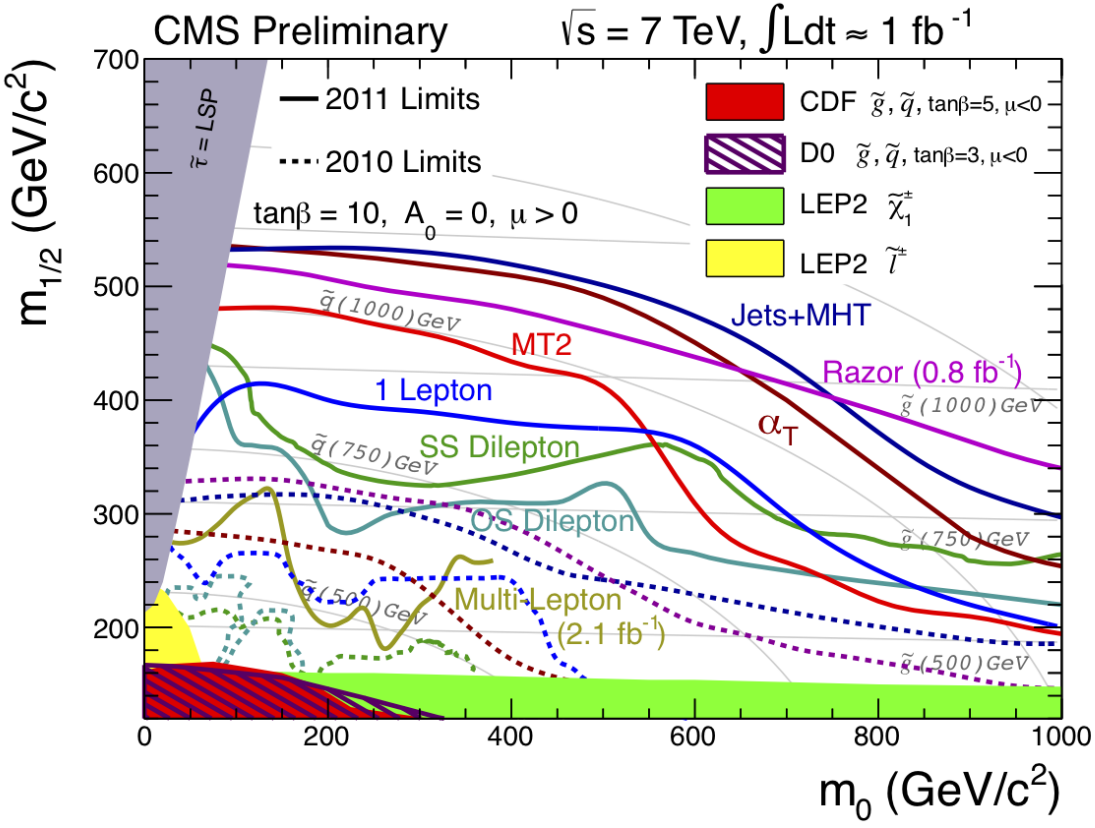
Interpretation in mSUGRA/CMSSM

- CMS

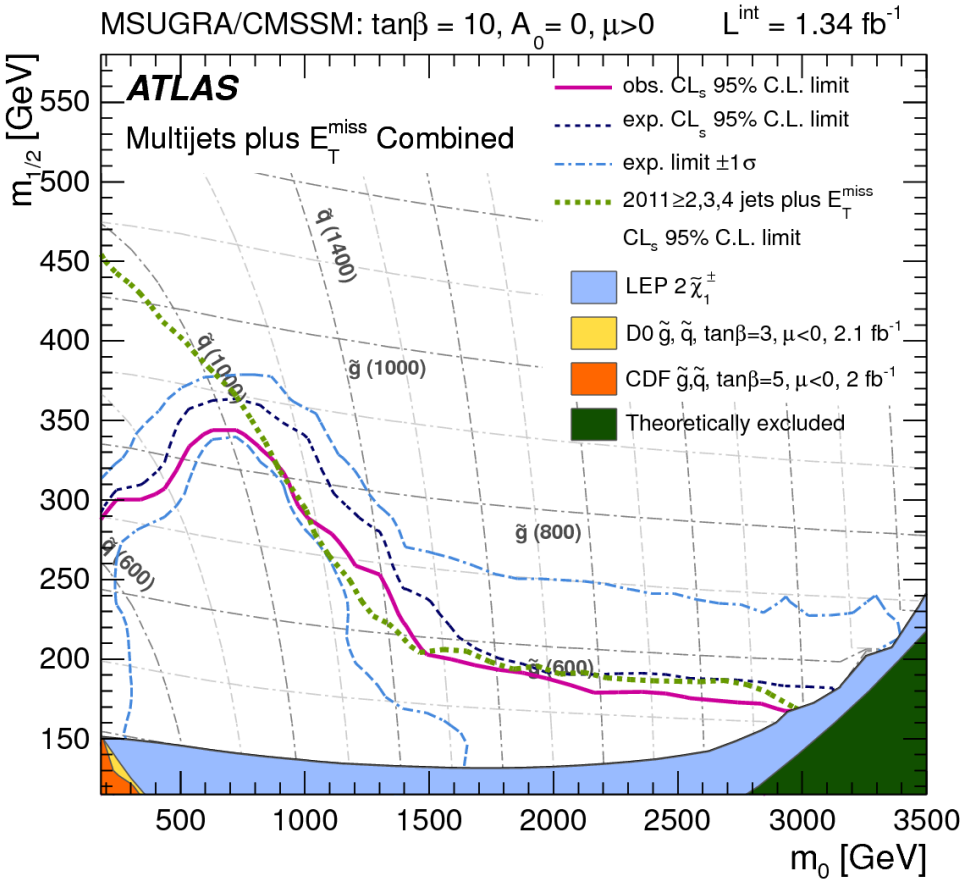


- Other methods:
  - α_T [PRL 107, 221804 (2011)]
  - m_{T2} [CMS PAS-SUS-11-005]
  - Razor [CMS PAS-SUS-11-008]

Interpretation in mSUGRA/CMSSM

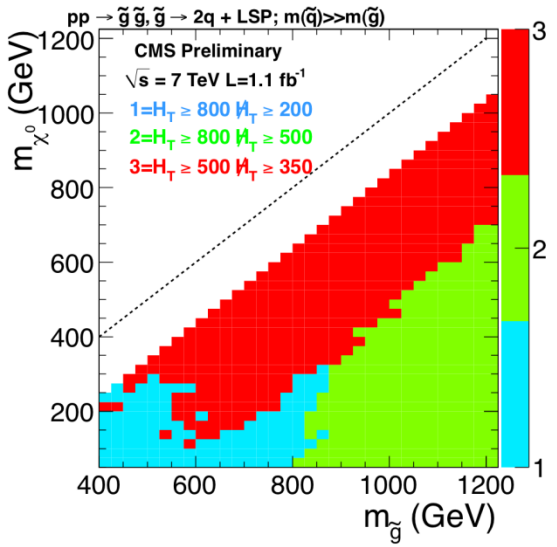
- ATLAS

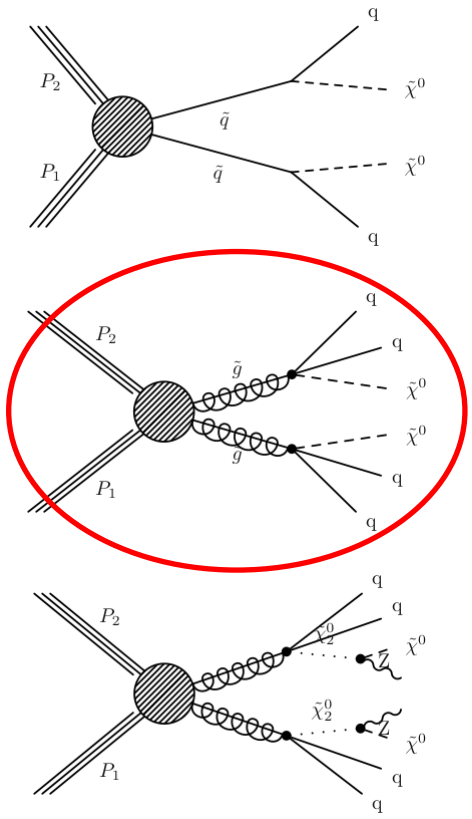
- Multi-jet plus missing E_T [JHEP 11 (2011) 99]
- Select events with ≥ 6 jets

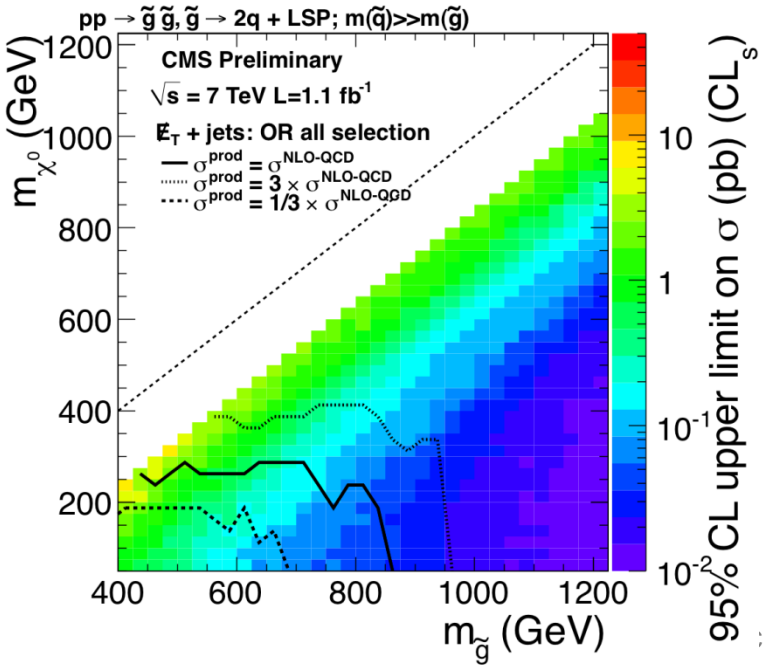


Interpretation using Simplified Models

- Reduce the particle content and couplings to produce a given topological signature
- Give limit on production cross section
- For each signal point, the signal region with the best expected sensitivity is used



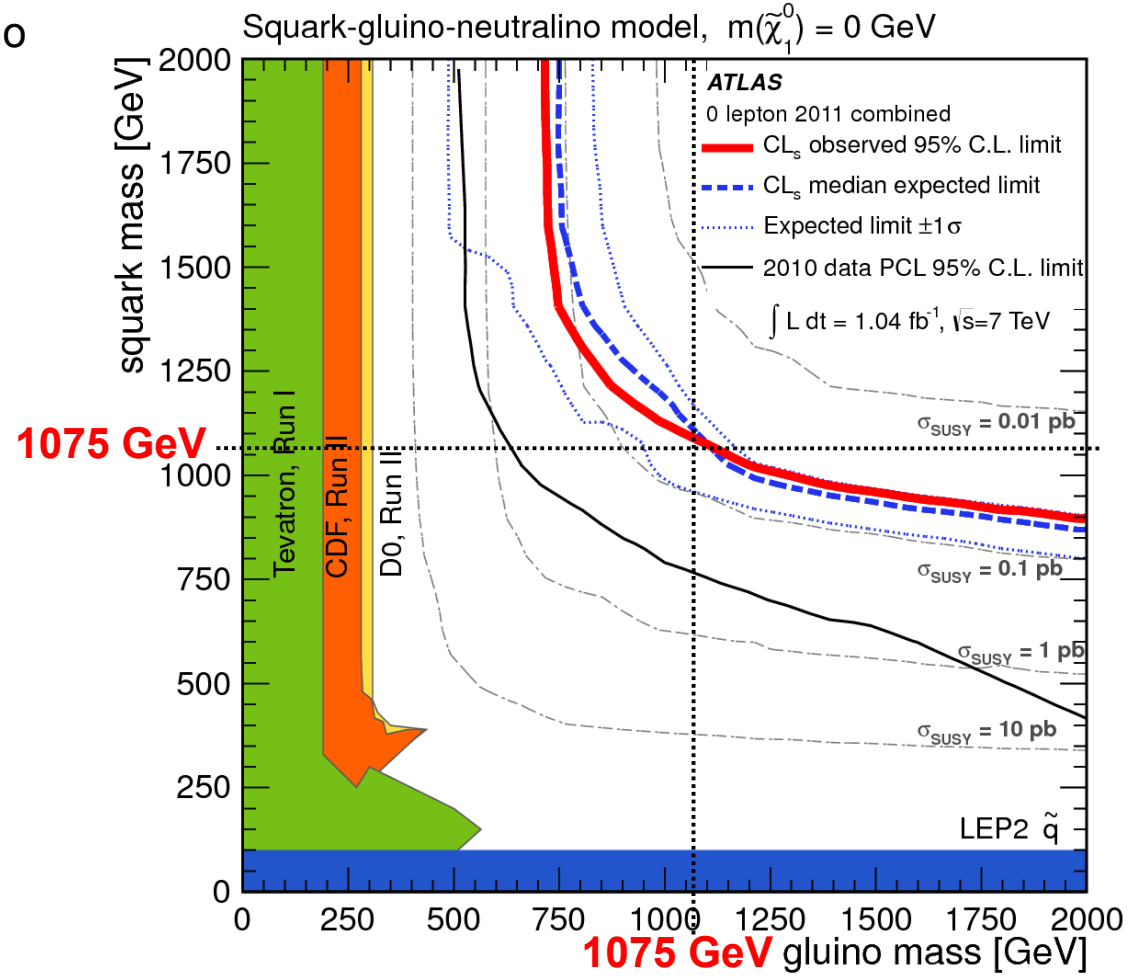




Interpretation using Simplified Models

ATLAS-CONF-2011-155

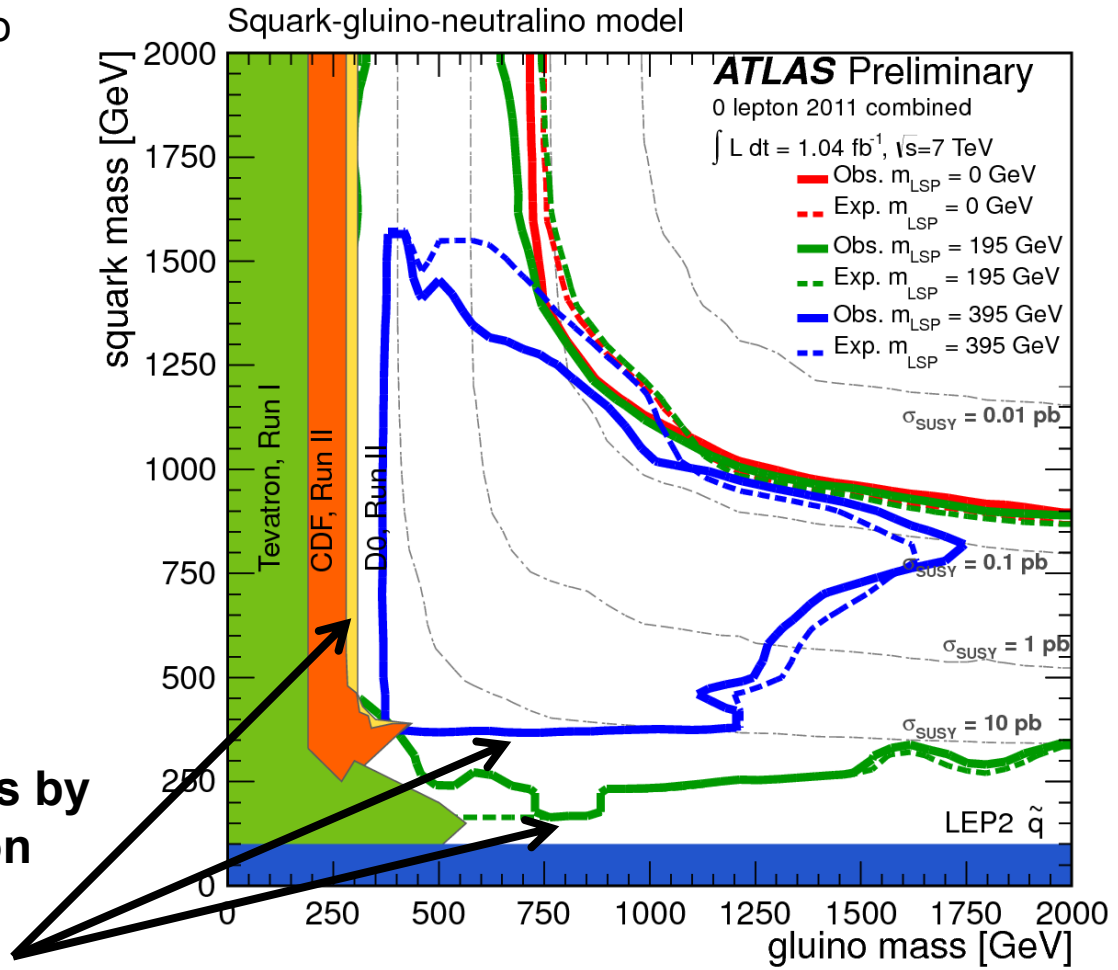
- Simplified model:
  - gluino, light squarks, neutralino
- Exclude up to ~ 1 TeV for m(squark) = m(gluino) for massless neutralino



Interpretation using Simplified Models

ATLAS-CONF-2011-155

- Simplified model:
  - gluino, light squarks, neutralino
- Exclude up to ~ 1 TeV for m(squark) = m(gluino) for massless neutralino
- Test different neutralino masses
  - 195 GeV
  - 395 GeV

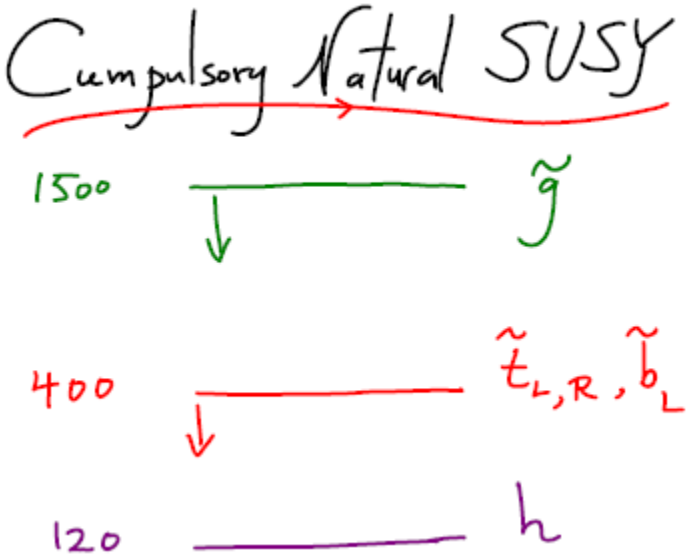


Lower limits by construction

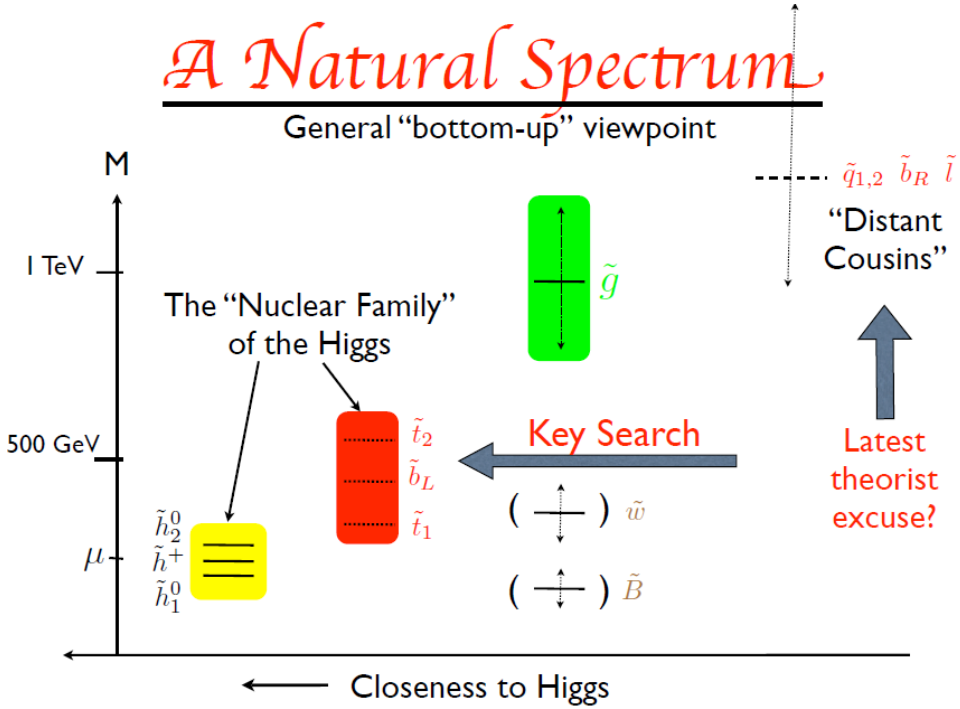
Third Generation

Third Generation

- Can the third generation of SUSY particles be light if the first two are heavy?



Nima Arkani-Hamed, 31. October 2011

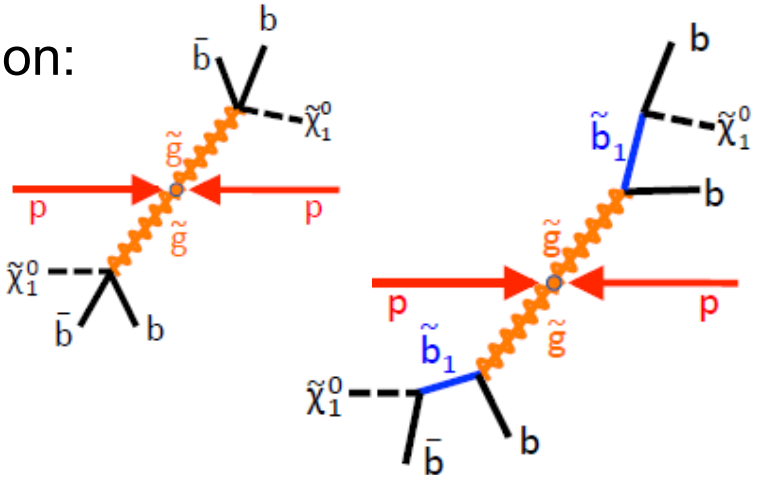


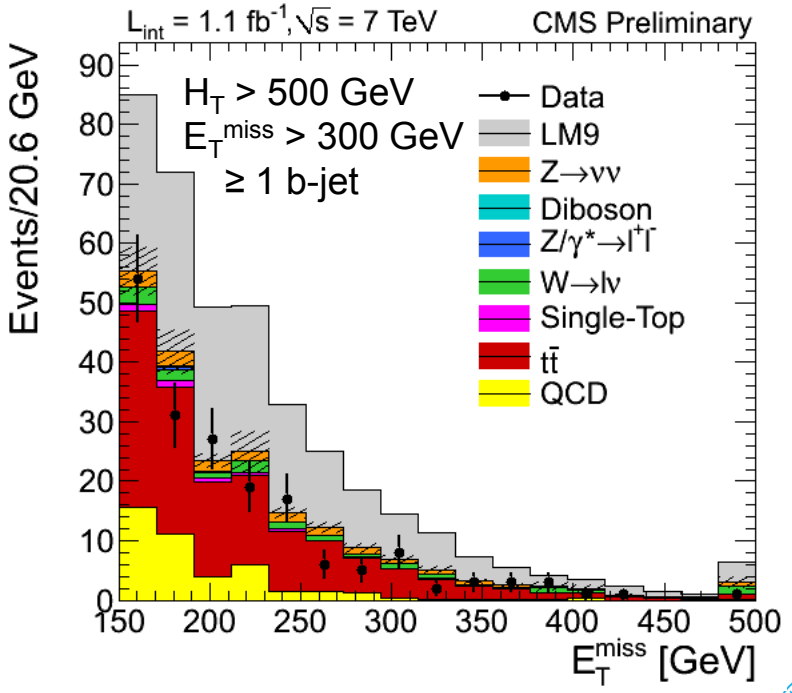
Lawrence Hall, 21. October 2011

Gluino Mediated Sbottom Production

CMS PAS-SUS-11-006

- Probe gluino mediated sbottom production:
  - $\tilde{g} \to b\tilde{b} \to bb\tilde{\chi}^0$ or $\tilde{g} \to bb\tilde{\chi}^0$
- Select several b-jets and missing E_T
  - H_T and missing H_T trigger
    → H_T > 350 GeV, missing E_T > 150 GeV
  - ≥ 3 jets with p_T > 50 GeV
  - ≥ 1 jets must be b-tagged
  - Veto on isolated electrons and muons
  - $\Delta\phi_N^{min}$ > 4.0
  - Define signal regions based on H_T and missing E_T





Four signal regions:

- H_T > 350 GeV, missing E_T > 200 GeV
- H_T > 500 GeV, missing E_T > 300 GeV

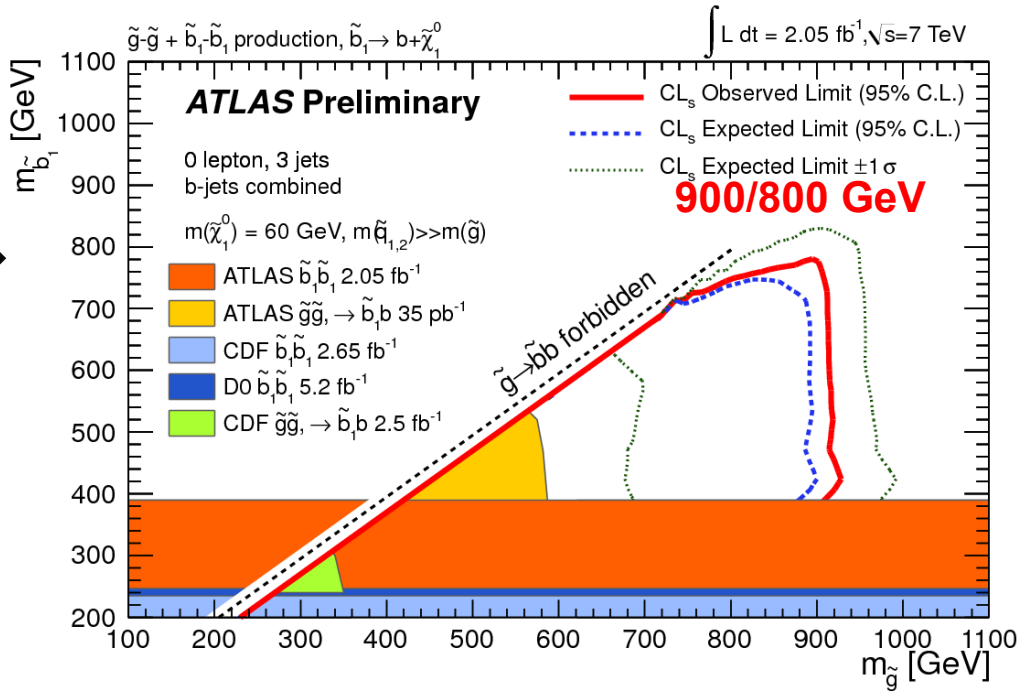
for one and two b-tags

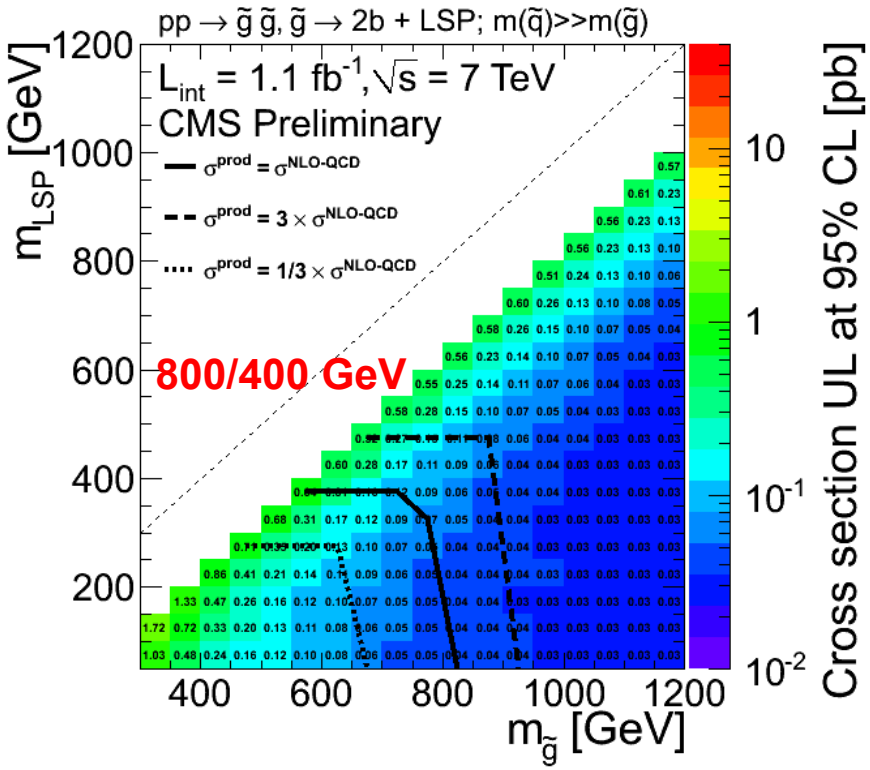
Interpretation

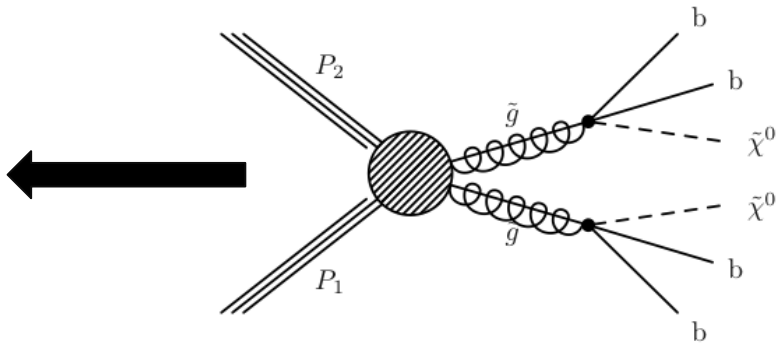
ATLAS-CONF-2012-003

CMS PAS-SUS-11-006

- Simplified model:
  - gluino, sbottom,neutralino
  - $\tilde{g}\tilde{g}$ or $\tilde{b}\tilde{b}$ production
  - m_{χ^0} = 60 GeV
  - BR($\tilde{g} \rightarrow \tilde{b}b$) = 1
  - BR($\tilde{b} \rightarrow b\tilde{\chi}^0$) = 1







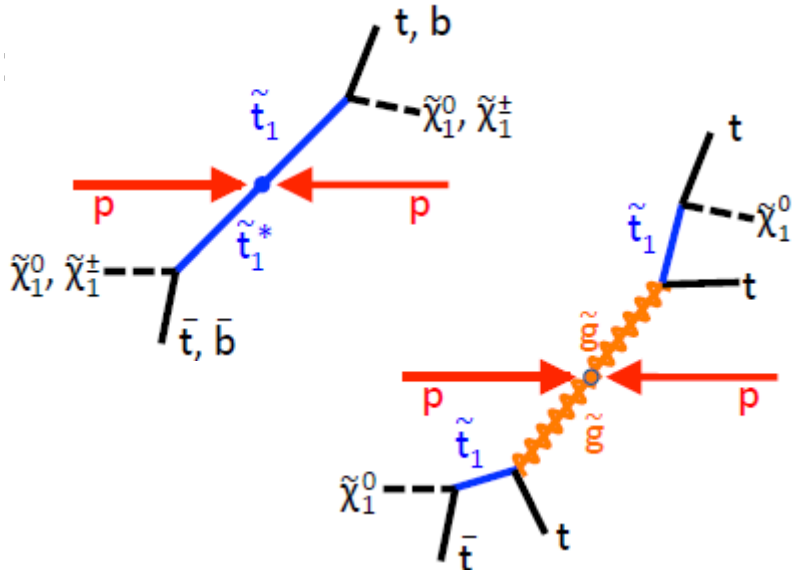
Stop Production

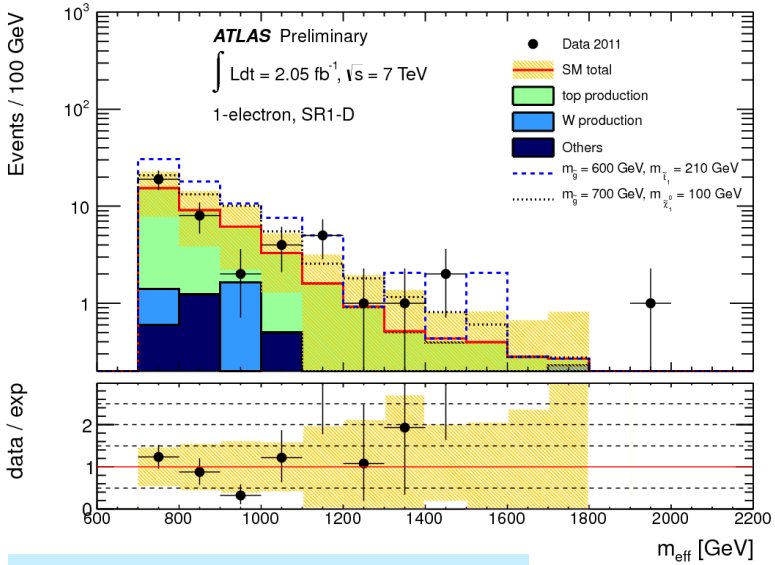
ATLAS-CONF-2012-003

- Probe gluino mediated stop production
  - $\tilde{g} \rightarrow \tilde{t}t \rightarrow tt\tilde{\chi}^0$ or $\tilde{t} \rightarrow t\tilde{\chi}^0/b\tilde{\chi}^{\pm}$
  - Events with several top/bottom quarks and neutralinos
- Select one lepton, several b-jets and missing E_T
  - Single lepton trigger
    -> e/μ with p_T(e,μ) > 25,20 GeV
  - Veto on additional leptons (e/μ)
  - At least four jets with $p_T(jet_1)$ > 60 GeV and $p_T(jet_{2,3,4})$ > 50 GeV
  - One of the jets must be b-tagged
  - Missing E_T > 80 GeV
  - m_T > 100 GeV

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

- Two signal regions:
  - m_{eff} > 700
  - m_{eff} > 700, missing E_T > 200 GeV



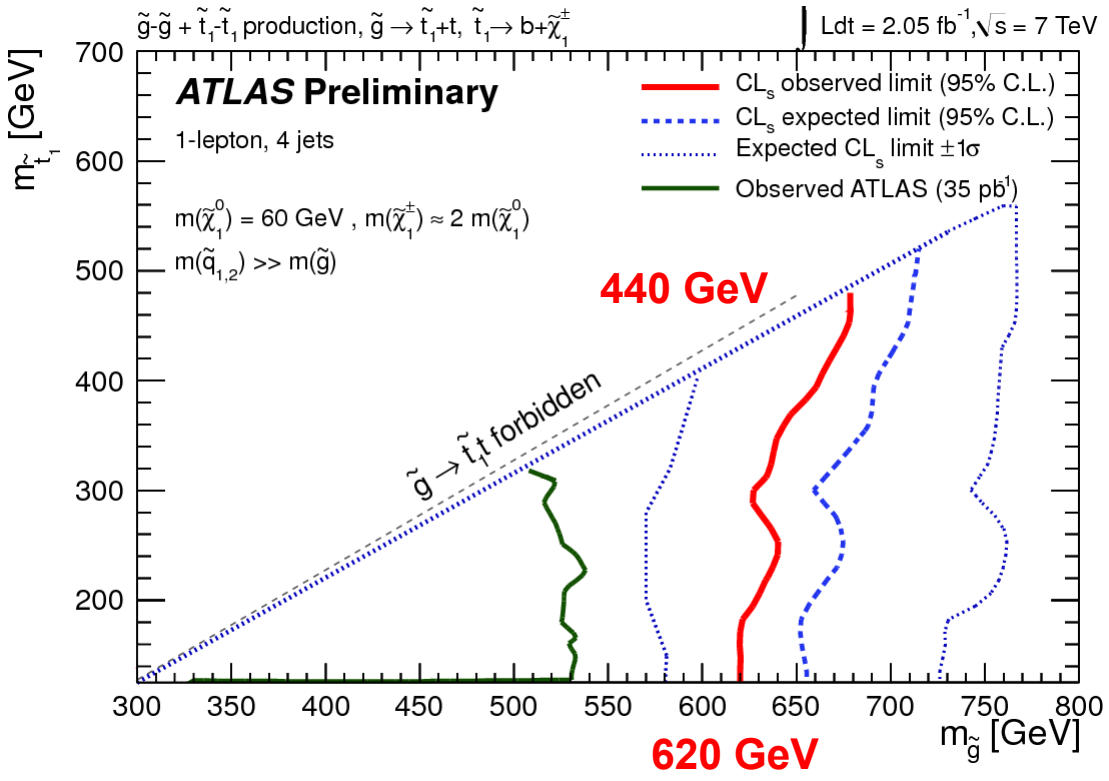


m_{eff} = H_T + missing E_T

Interpretation

ATLAS-CONF-2012-003

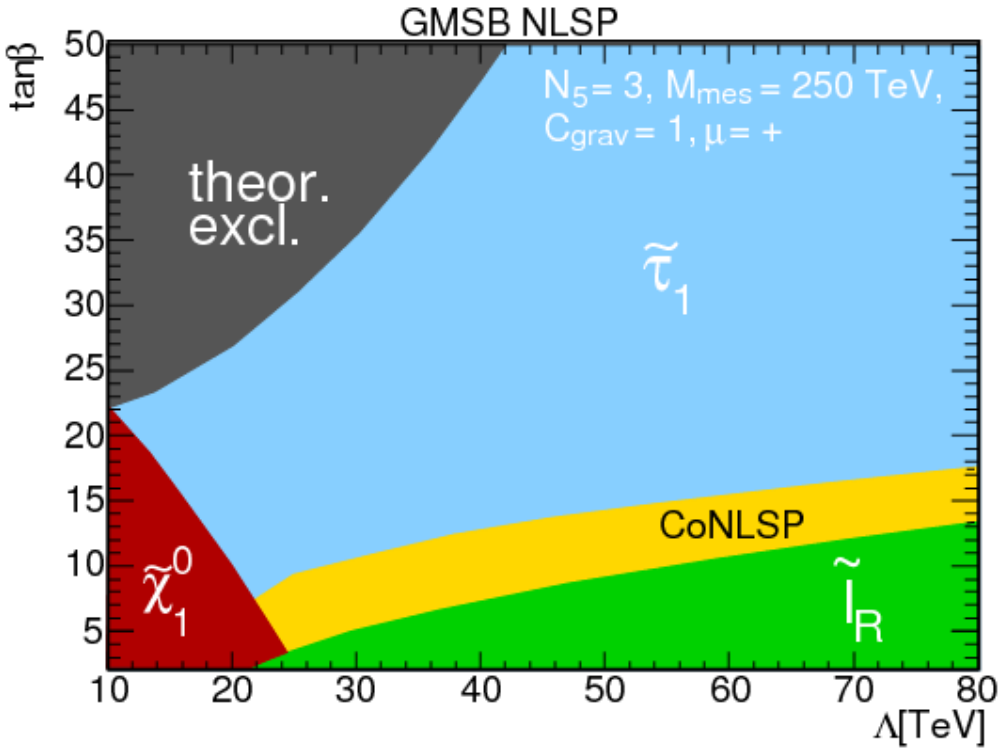
- Simplified model:
  - gluino, stop,neutralino
  - $\tilde{g}\tilde{g}$ or $\tilde{t}\tilde{t}$ production
  - $m_{\tilde{g}} > m_{\tilde{t}} + m_t$
  - $m_{\chi^\pm} \sim 2\, m_{\chi^0}$
  - m_{χ^0} = 60 GeV
  - BR($\tilde{g} \to \tilde{t}t$) = 1
  - BR($\tilde{t} \to b\tilde{\chi}^\pm$) = 1
  - BR($\tilde{\chi}^\pm \to \tilde{\chi}^0 lv$) = 0.11



- Gluino masses of 620 GeV excluded for stop masses up to ~440 GeV

Third Generation: Tau Leptons

- Gauge Mediated SUSY Breaking (GMSB)
  - the very light gravitino is the LSP
  - event topology defined by next to lightest sparticle (NLSP)
  - For N_5 = 3 stau and slepton NLSP enriched
  - $\tilde{\tau} \rightarrow \tau\tilde{G}, \tilde{\chi}^0 \rightarrow \tau\tilde{\tau}$

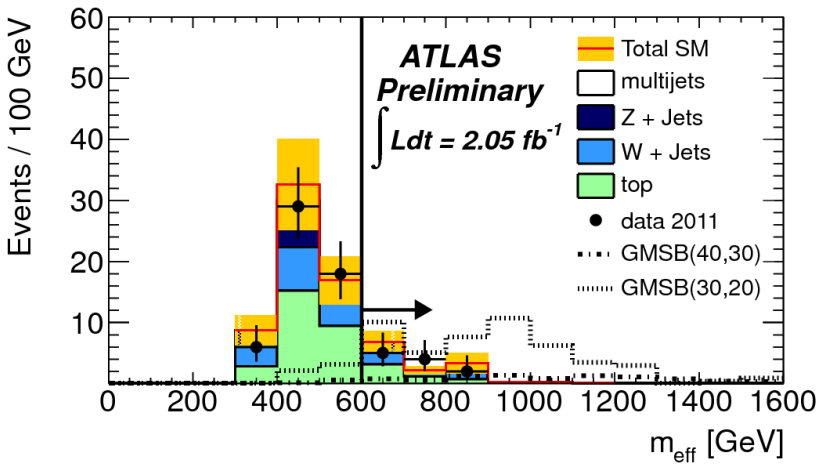


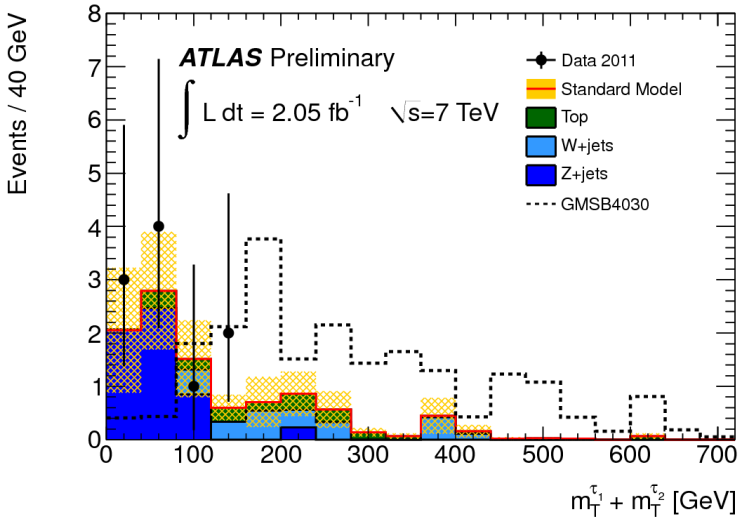
Third Generation: Tau Leptons

ATLAS-CONF-2012-002

ATLAS-CONF-2012-005

- Squark/gluino mediated stau production in GMSB
- Common selection:
  - Jet + missing E_T trigger → $p_T(jet_1)$ > 130 GeV, missing E_T > 130 GeV
  - Veto on electrons and muons
  - At least two jets with $p_T(jet_2)$ > 30 GeV





- Analysis with at least one tau:
  - ≥ 1 tight tau lepton with p_T > 20 GeV
  - Missing E_T/m_{eff} > 0.25
  - m_{eff} > 600 GeV
  - $m_T(\tau)$ > 110 GeV

- Analysis with at least two tau:
  - ≥ 2 loose tau leptons with p_T > 20 GeV
  - m_{eff} > 700 GeV
  - $m_T(\tau_1) + m_T(\tau_2)$ > 80 GeV

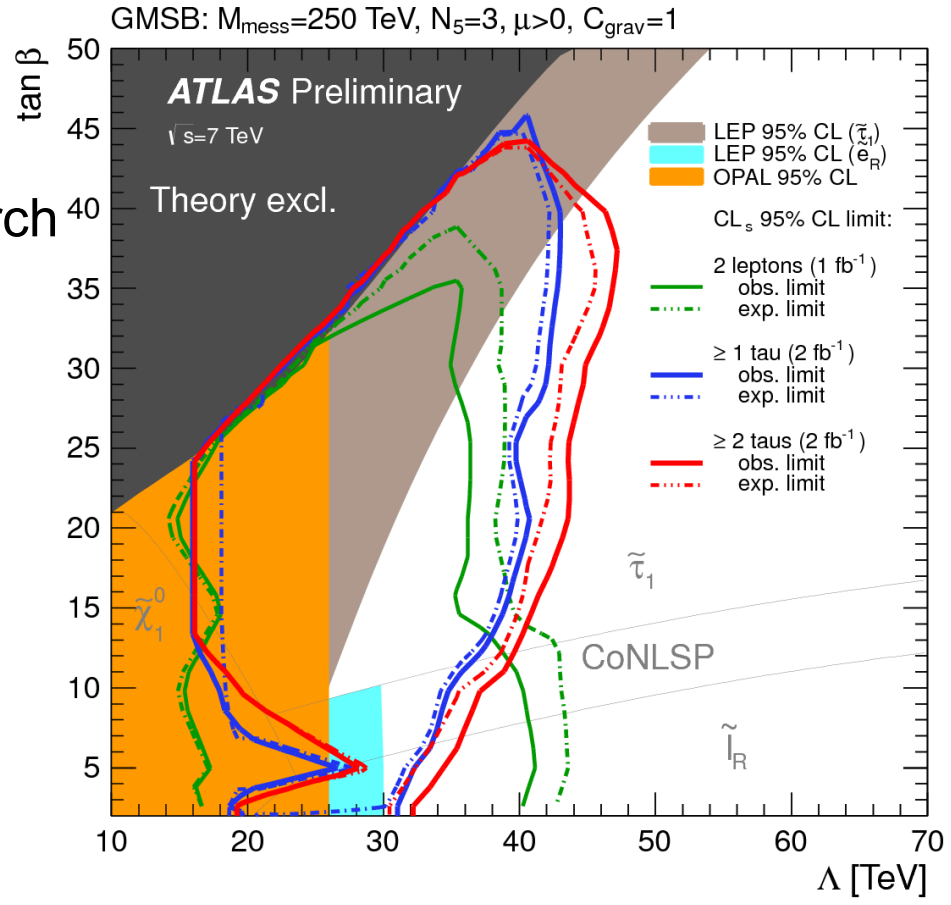
Search for Tau Leptons - Interpretation

ATLAS-CONF-2012-002

ATLAS-CONF-2012-005

- Good agreement between data and MC
- Results interpreted in a minimal GMSB model with:
  M_{mess} = 250 TeV, N_5 = 3, $\mu > 0$, C_{grav} = 1
- ATLAS dilepton opposite-sign search
  - ATLAS-CONF-2011-156 (1 fb^{-1})
- 2 τ analysis:
  - Best exclusion set for Λ = 47 TeV and tan β = 37
  - Independent of tan β, Λ < 32 TeV is excluded
- 1 τ analysis:
  - Best exclusion set for Λ = 40 TeV and tan β = 44
  - Independent of tan β, Λ < 31 TeV is excluded

	SM background	Observed	σ_{vis} [fb]
1τ analysis	13.2 ± 4.2	11	< 4.0
2τ analysis	5.3 ± 2.6	3	< 2.7



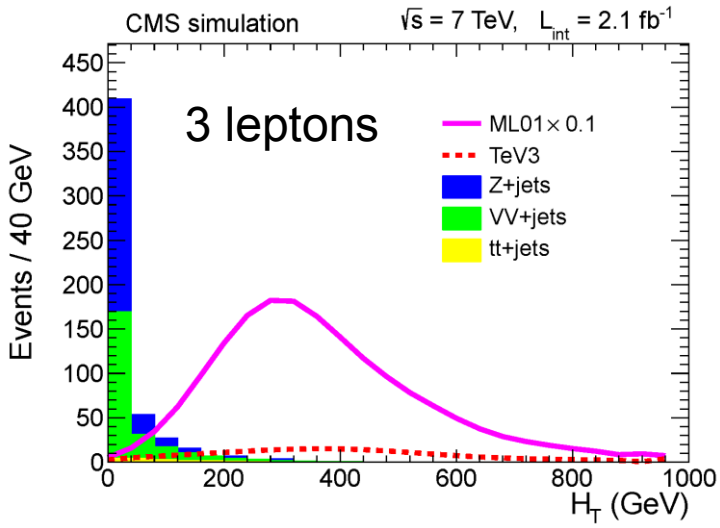
DESY

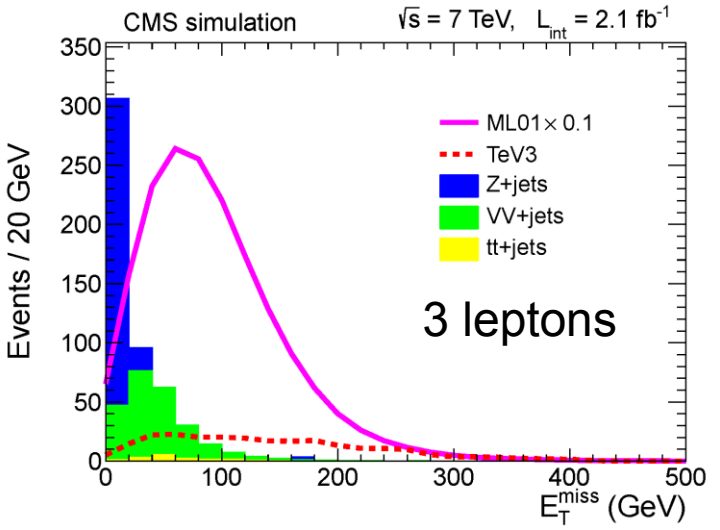
Multi-Leptons

Multi-Leptons

CMS PAS-SUS-11-013

- Probe final states with multiple leptons from $\tilde{\chi}^0, \tilde{\chi}^{\pm}$ and $\tilde{l}$.
- Consider three and four lepton final states
  - Electrons
  - Muons
  - Hadronically decaying tau leptons
- Background suppression by requiring
  - H_T > 200 GeV
  - Missing E_T > 50
- 52 channels in total
- Background estimate:
  - From MC, checked in control regions
  - Misidentified leptons
  - Irreducible background from WZ/ZZ production
  - Internal photon conversion: Z→llγ with γ→ee/μμ





Multi-Leptons

CMS PAS-SUS-11-013

CMS: 2 fb^{-1} – missing E_T > 50 GeV

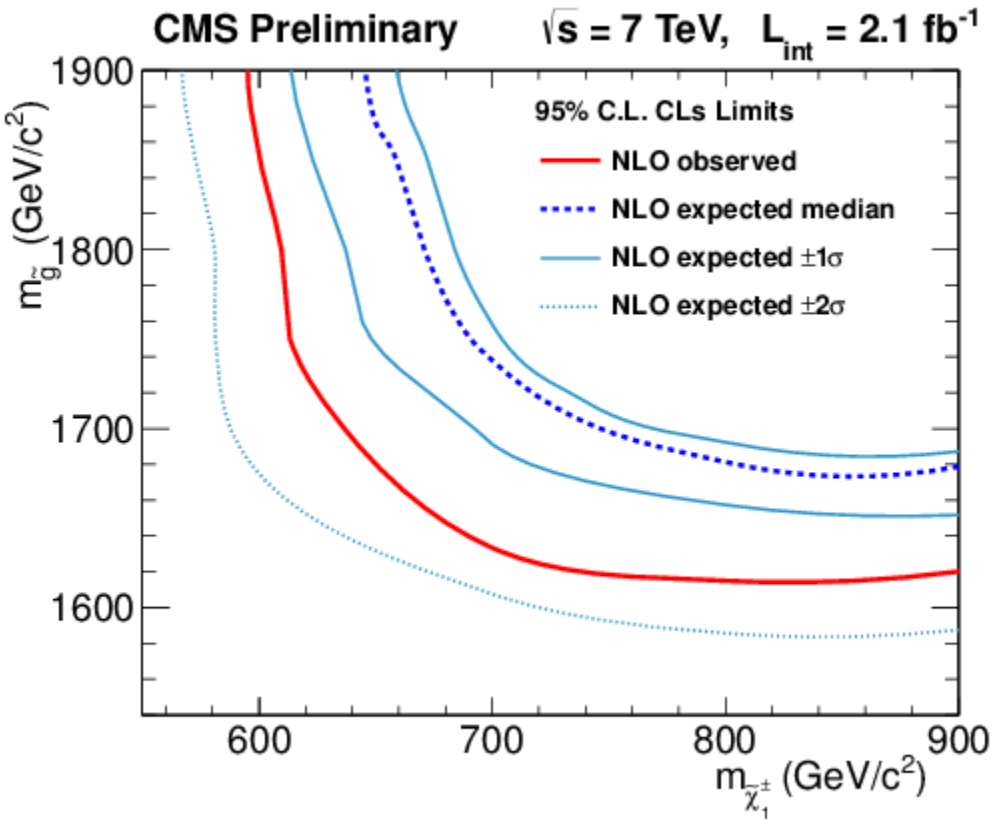
Channel	$\ell\ell + Jet$	$\ell\ell + \gamma$	$t\bar{t}$	VV	Total SM	Data	Signal
$OS(\ell\ell)e$	0.33±0.08	0.42±0.42	1.5±0.8	3.3±1.3	6.0±1.7	10	76±19
$OS(\ell\ell)\mu$	0.42±0.10	0.17±0.17	2.2±1.1	4.3±1.7	7.5±2.1	14	106±21
$OS(\ell\ell)\tau$	28.4±4.4	0.35±0.35	29±15	4.5±1.7	63±16	71	202±30
$\ell\ell'\tau$	24.6±6.0	1.7±1.7	38±19	7.5±2.9	73±20	88	29±10
$SS(\ell\ell)\ell'$	0.45±0.08	0.35±0.35	2.3±1.1	0.49±0.18	4.3±1.3	6	9.1±5.4
$SS(\ell\ell)\tau$	3.9±1.5	0.48±0.48	1.7±0.9	3.4±1.3	9.9±2.3	21	4.0±4.0
$\ell\tau\tau$	96±18	NA	12.3±6.2	1.7±0.6	110±19	88	24.0±9.1
$\sum \ell(\ell/\tau)(\ell/\tau)$	154±28	3.1±3.1	87±44	25.3±9.7	273±53	298	450±49
$\ell\ell\ell\ell$	0.0000±0.0006	<0.0002	<0.006	0.016±0.005	0.016±0.006	1	14.6±7.4
$\ell\ell\ell\tau$	0.00±0.07	<0.007	<0.07	0.14±0.04	0.23±0.11	0	14.8±7.7
$\ell\ell\tau\tau$	0.34±0.33	<0.005	0.27±0.13	0.14±0.04	0.89±0.40	0	7.8±5.6
$\sum \ell\ell(\ell/\tau)(\ell/\tau)$	0.34±0.34	0.00±0.00	0.27±0.13	0.29±0.08	1.14±0.42	1	37±12

- Some channels show excess in data

Multi-Leptons: Interpretation

CMS PAS-SUS-11-013

- Gauge-mediated theory with split messengers (GMSM)
  - Gravitino LSP
  - $\tilde{g}/\ \tilde{q}$ decay down to $\tilde{\chi}^0$
  - $\tilde{\chi}^0 \rightarrow\ \tilde{l}^{\pm}l^{\mp}$ and $\tilde{l}^{\pm} \rightarrow\ \tilde{G}l^{\pm}$
- Excess in data can be clearly seen in observed limit

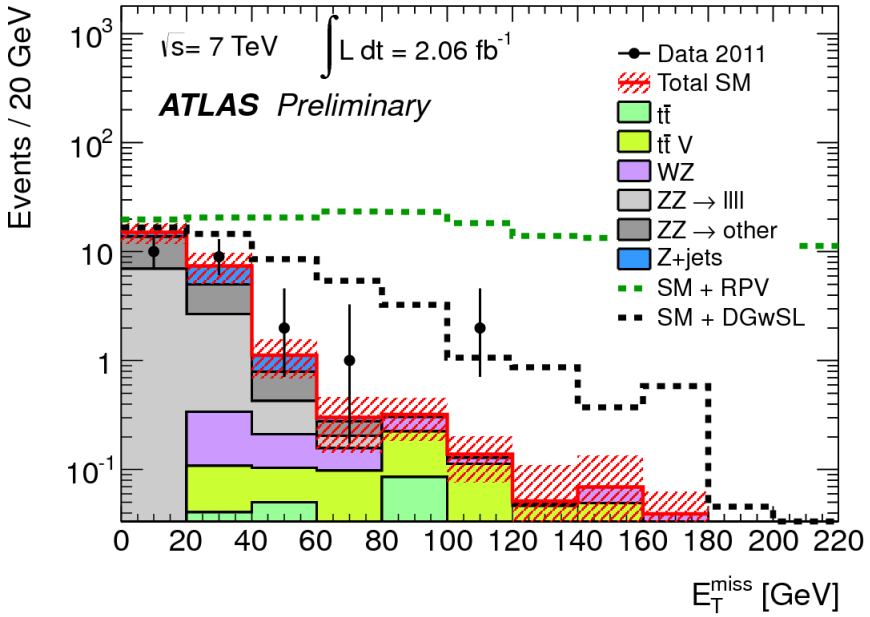


4 Leptons

ATLAS-CONF-2012-001

Selection

- Four leptons (e,μ)
- Veto on low mass Drell-Yan pairs (m_{ll} < 20 GeV)
- Missing E_T > 50 GeV
- Two signal regions based on Z-boson veto ($|m_{ll} - m_Z|$ < 10 GeV)



SR1	All	*eeee*	*eeeμ*	*eeμμ*	*eμμμ*	*μμμμ*
Σ SM	1.7±0.9	0.6±0.8	0.24±0.57	0.5±0.6	0.32±0.55	0.08±0.57
Data	4	0	1	2	0	1

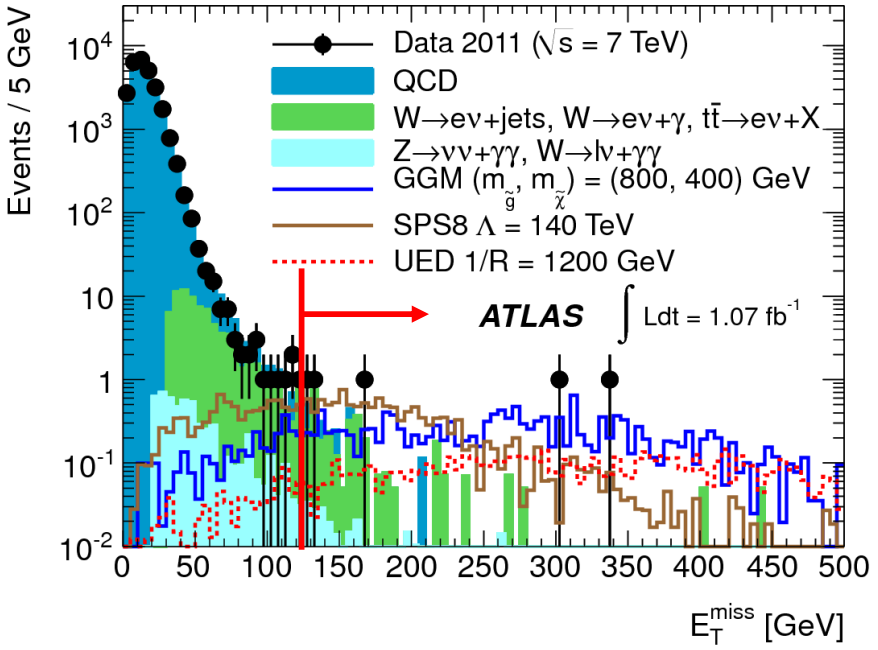
Z-boson veto:

Σ SM	0.7±0.8	0.35±0.83	0.05±0.57	0.13±0.57	0.12±0.55	0.005±0.567
Data	0	0	0	0	0	0

Photons

Final States with Photons and Missing E_T

- Gauge Mediated SUSY Breaking (GMSB)
  - The very light gravitino is the LSP
  - Event topology defined by next to lightest sparticle (NLSP)
  - Large parameter space has neutralino NLSP:
    - If bino like → decay into photon and gravitino
    - If zino like → decay into Z and gravitino
    - If wino like → chargino is the NLSP, but mass degenerated with neutralino
- Final states with one/two photons
- ATLAS: [arXiv:1111.4116]
  - Diphoton + missing E_T
- CMS: [PAS SUS-11-009]
  - Diphoton + jet + missing E_T
  - Photon + 3 jets + missing E_T
- Background estimated from data:
  - Fakes from jets
  - Fakes from electrons



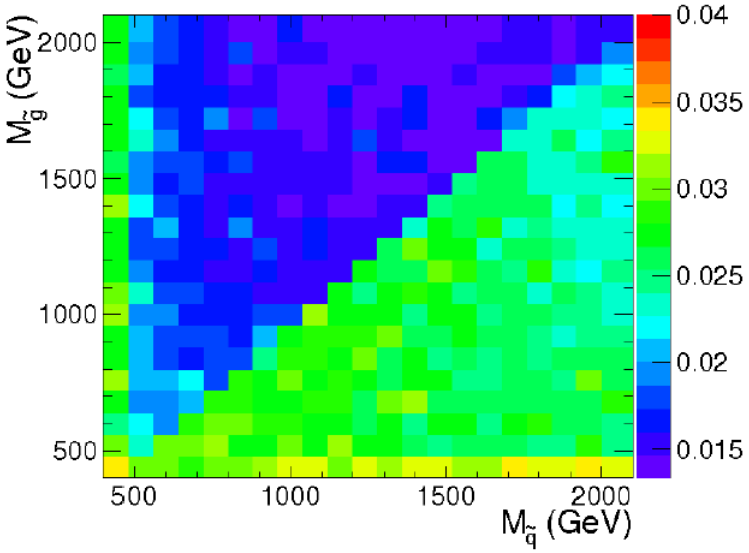
2 Photons + Missing E_T: Interpretation

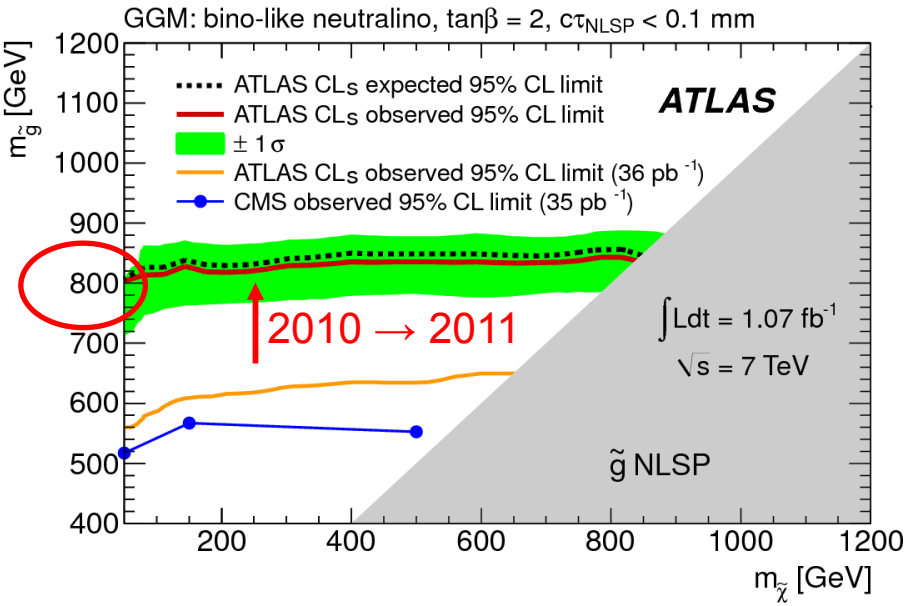
- General Gauge Mediation (GGM)
  - simplified model with three/four sparticles:

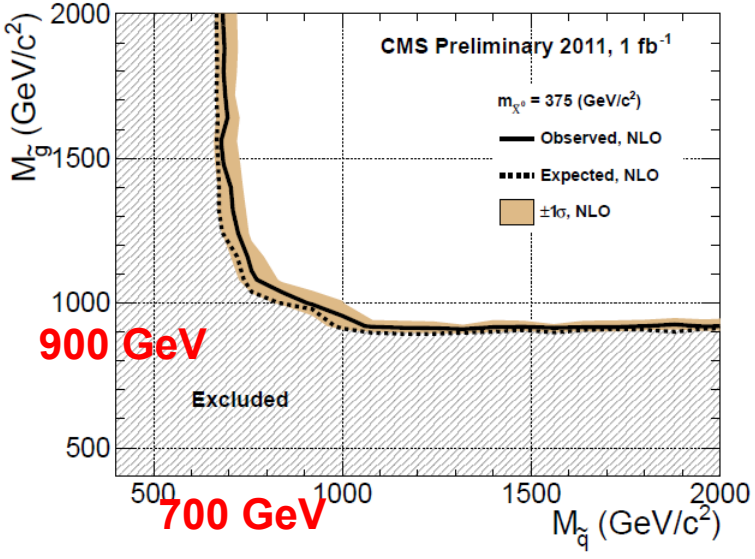
    Gluino/squarks for production
    Bino-like neutralino as NLSP
    Gravitino

  - Exclusion limits on m(gluino) ~ 800-900 GeV

CMS: Cross section limit [pb]



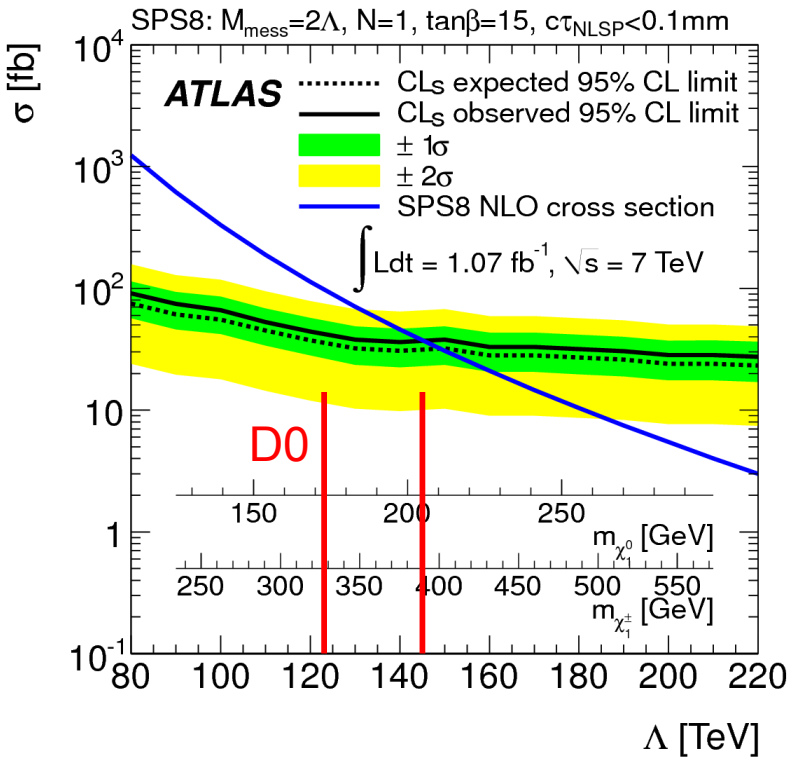




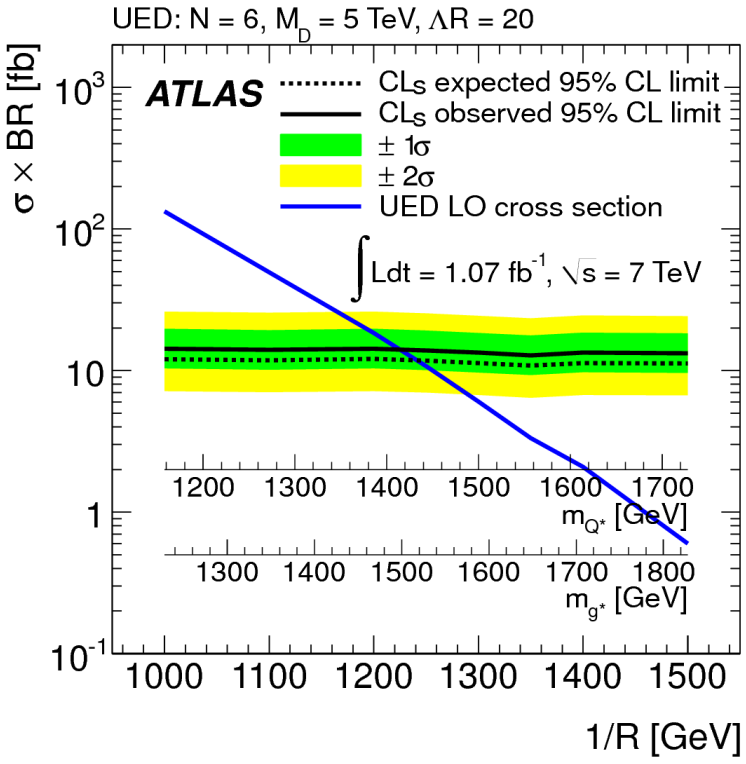
Diphoton + Missing E_T: Interpretation

arXiv:1111.4116

- minimal GMSB / SPS8 slope
  - full mass spectrum
  - Λ < 145 TeV excluded



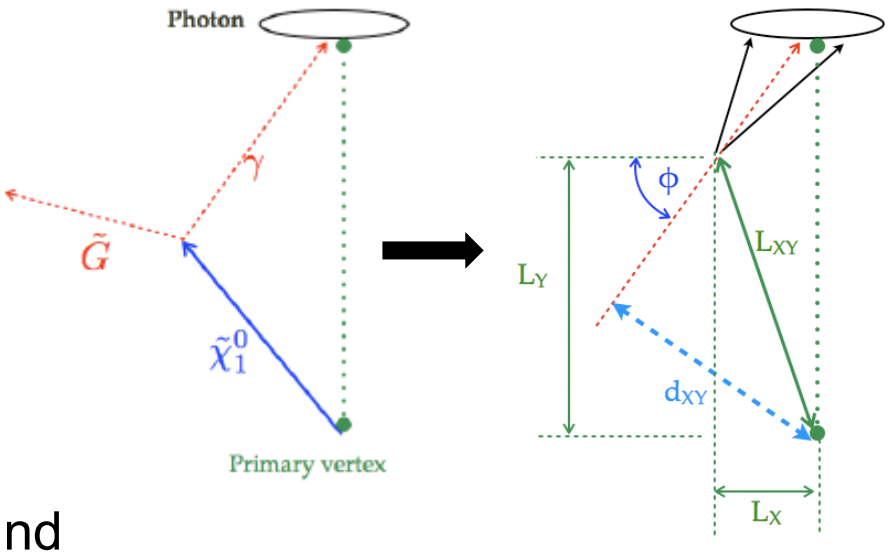
- Universal Extra Dimension (UED)
  - mass spectrum similar to SUSY
  - 1/R < 1224 GeV excluded

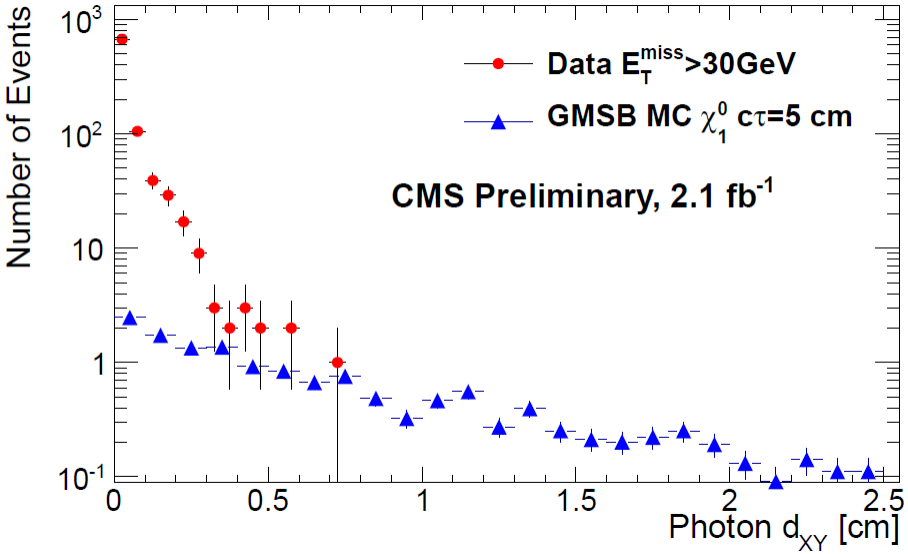


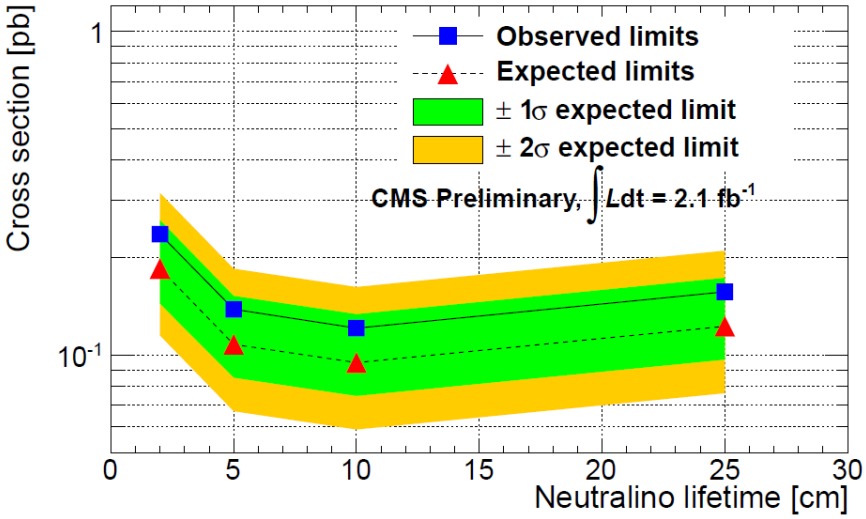
Long-Lived Neutralinos → Non-Pointing Photons

CMS PAS-EXO-11-067

- The neutralino can decay late
- Selection:
  - ≥ 2 isolated photons with E_T > 45/30 GeV
  - ≥ 2 jets with p_T > 80/40 GeV
  - Require converted photons to reconstruct (displaced) vertex
  - Missing E_T > 30 GeV
  - d_{xy} > 6 mm
- Use sidebands to estimate background

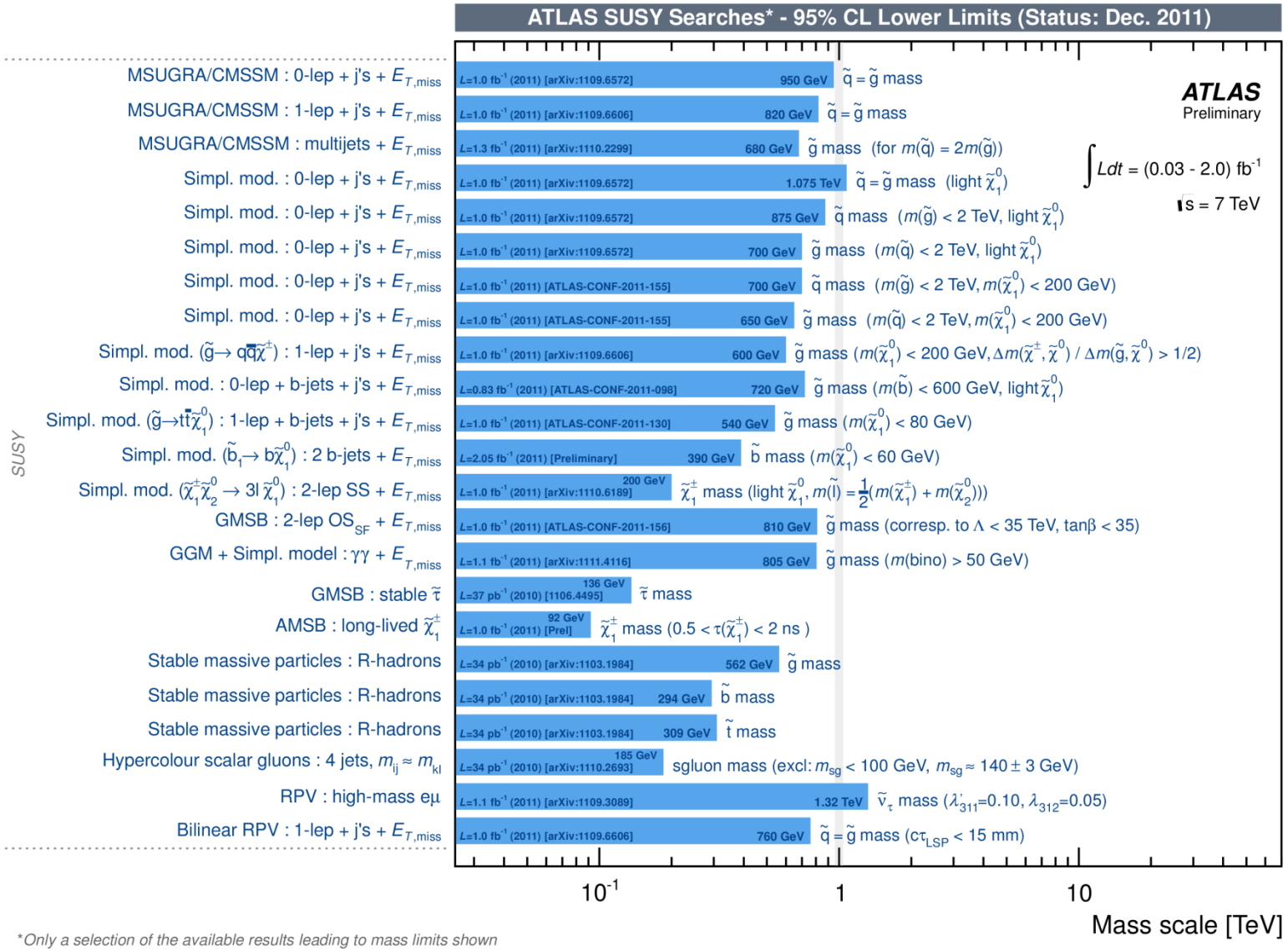






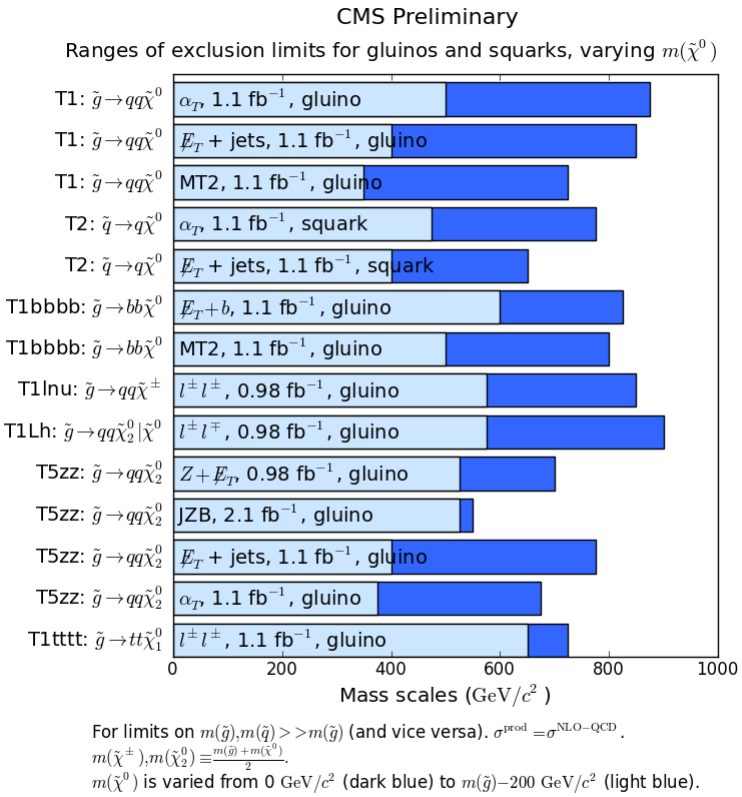
Summary

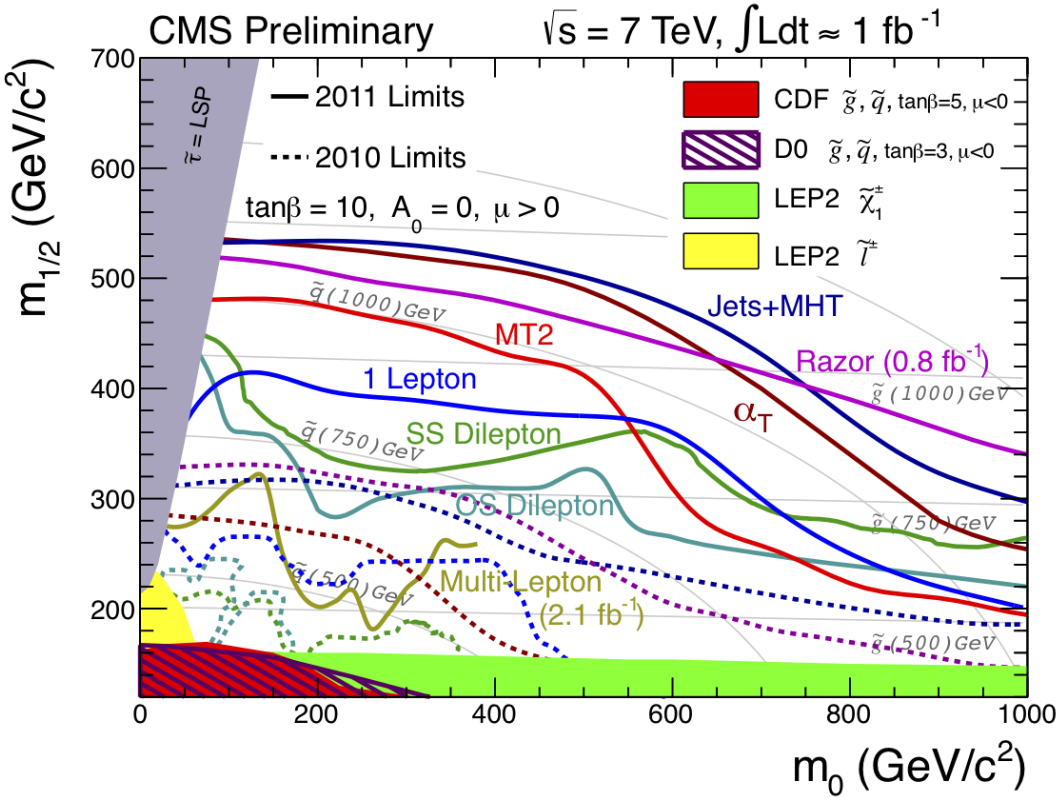
Summary of ATLAS SUSY Searches



*Only a selection of the available results leading to mass limits shown

Summary of CMS SUSY Searches





Conclusion and Outlook

- ATLAS and CMS have produced an impressive number of papers/conference notes using the 2011 data
- In the channels searched so far, no significant excess above the Standard Model was found
- SUSY was not “just around the corner”
- Limits have surpassed those from Tevatron/LEP
- Besides MSUGRA/CMSSM also gauge mediated and simplified models considered
- Many updates and new analysis with the full 2011 data expected in the next weeks/months
- Both experiments will search for SUSY in 8 TeV collisions (15 fb^{-1})