Experimental Aspects of Light Stop Searches

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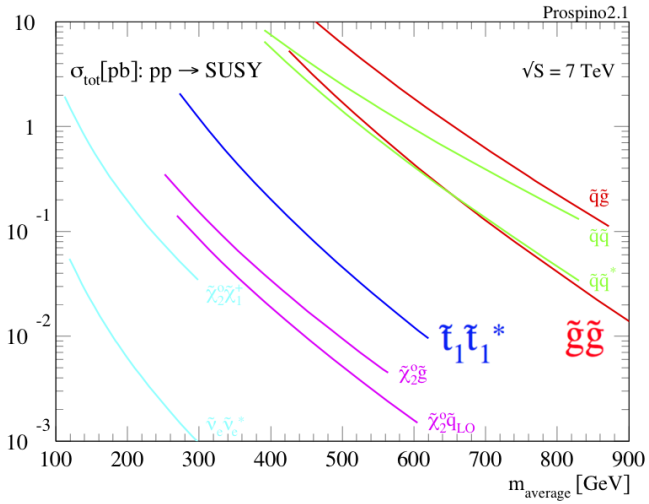
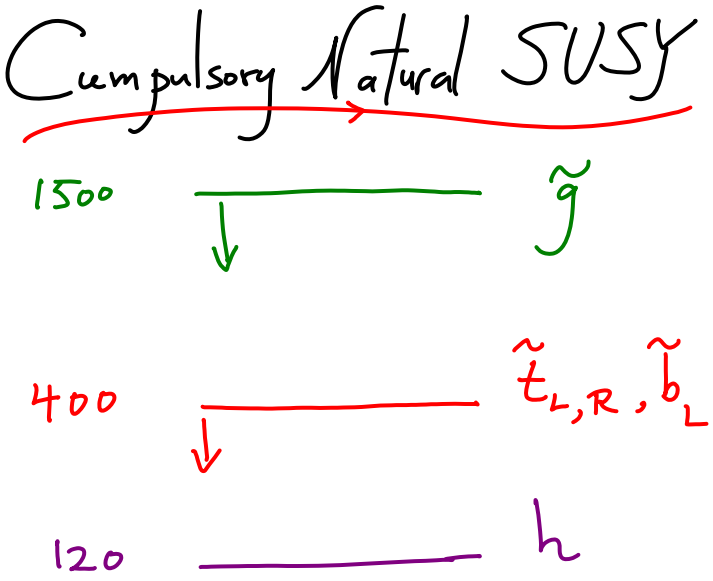
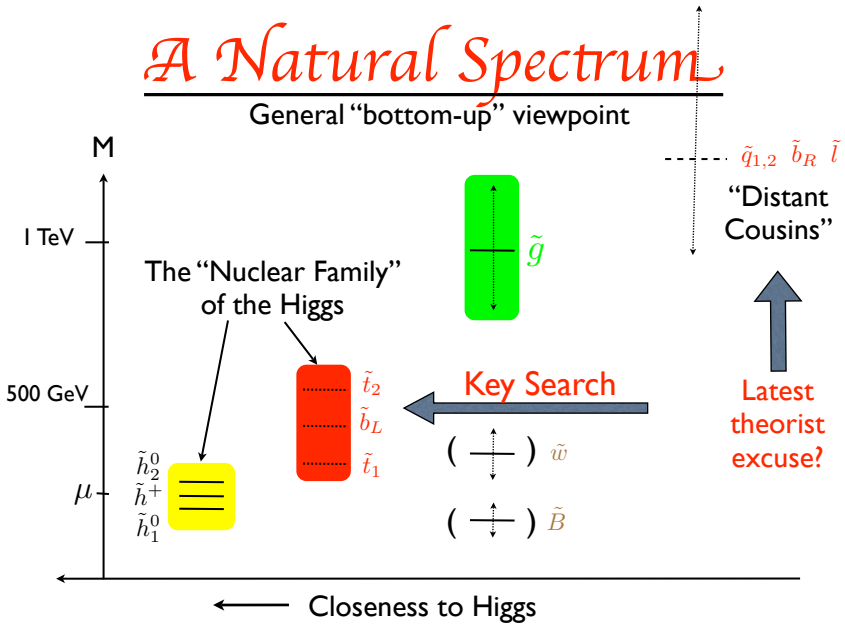
Introduction

- Sizeable mixing of gauge eigenstates to form mass eigenstates for the third generation squarks
- Lightest stop squark ($\tilde{t}_1$):
  - Can be relatively light (150-250 GeV)
  - Can be produced in pairs with high cross section at the LHC or appear in the gluino cascade decay
  - Produce b and t in its decay
  - Ligh stops favored in several models for SUSY to solve the hierarchy problem naturally



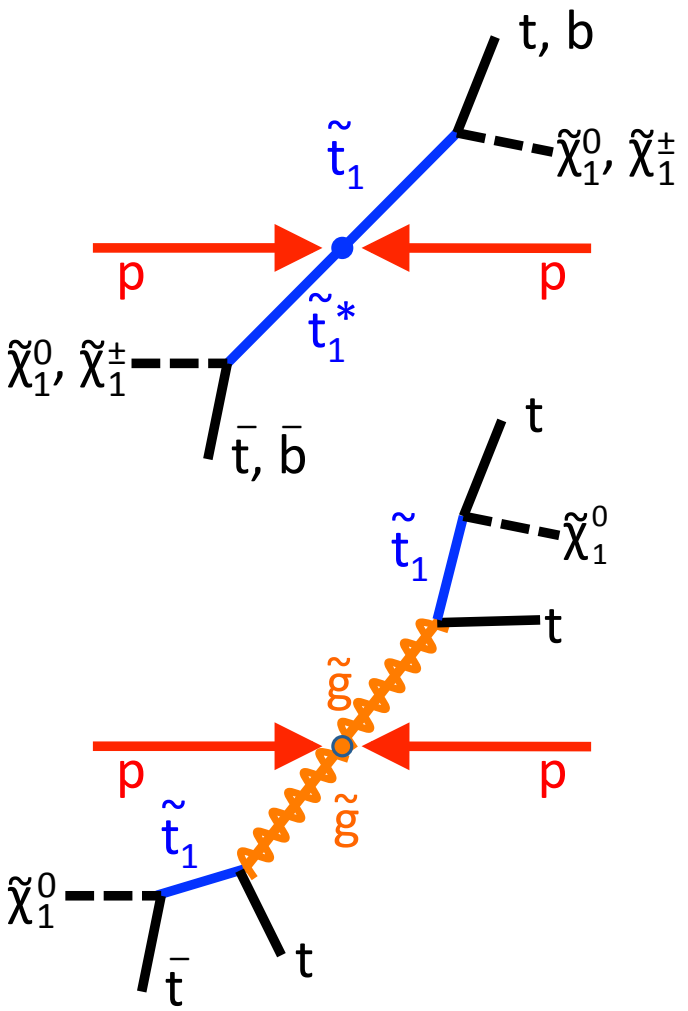


Nima Arkani-Hamed, Oct 31st, 2011



Lawrence Hall, Oct 21st, 2011

Signal Production and Decay



- Stop production :
  - Direct $\tilde{t}_1\tilde{t}_1^*$ production
  - Gluino-mediated with $\tilde{g} \to \tilde{t}_1 t$
- Tevatron searches based on direct stop production and $\tilde{t}_1 \to c\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\ell\tilde{\nu}$ decays
- Stop decays explored at LHC:
  - $\tilde{t}_1 \to t\tilde{\chi}_i^0$
  - $\tilde{t}_1 \to b\tilde{\chi}_j^\pm$
- Final state with 2-4 heavy quarks (b or t)
- Signature: b-jets, E_T^{miss}, light jets, leptons
- Possible analysis strategies:
  - **b-jets:** 1 lepton+b-jets, several b-jets
  - **Jets:** large jet multiplicities
  - **Leptons:** 2 opposite- or same-sign leptons, 3 leptons
- In $\tilde{t}_1\tilde{t}_1^*$ production, leptonic decays in both legs lead to opposite-sign dileptons

Outline

- General talks on searches for New Physics with heavy flavor by R. Cavanaugh and T. Golling on Wednesday
- Summary of recent results from gluino-mediated and direct stop searches
- Results from stop searches in ATLAS and CMS:
  - ATLAS search for **gluino mediated stop** with 1 lepton, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1}): arXiv:1203.6193, submitted to PRD
  - ATLAS search for **gluino mediated stop** with large jet multiplicities and $E_{\mathrm{T}}^{\mathrm{miss}}$ (4.7 fb^{-1}): ATLAS-CONF-2012-037
  - ATLAS search for **gluino mediated stop** with 2 same-sign leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1}): arXiv:1203.5763, submitted to PRL
  - CMS search for **gluino mediated stop** with 2 same-sign leptons, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ (4.7 fb^{-1}): CMS-PAS-SUS-11-020
  - ATLAS search for **direct stop** in GMSB models with 2 same-flavour opposite-sign leptons, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1}): arXiv:1204.6736 submitted to PLB
- Some of those analysis have signal regions and interpretations aiming at other models (MSUGRA, sbottom production, SO(10), etc.), but only stop interpretations will be discussed in this talk

Background Estimation Methods

- Typical background estimation methods used in stop analyses:
  - Top, W+jets:
    - Estimated with "transfer factors" using background-enhanced control regions:

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

    - Correlated systematics between numerator and denominator largely cancel
  - QCD and fake-lepton backgrounds:
    - Estimated from data
    - Pass-fail matrix method based on a looser lepton definition commonly used for fake-lepton estimations
  - Smaller irreducible backgrounds: diboson, associated $t\bar{t}$ production, etc.
    - Using Monte Carlo
  - Charge flip in same-sign dilepton analyses: $e_{hard}^{\mp} \rightarrow \gamma_{hard} e_{soft}^{\mp} \rightarrow e_{soft}^{\mp} e_{soft}^{\mp} e_{hard}^{\pm}$
    - Semi data-driven
- Uncertainties affecting the results:
  - Experimental uncertainties: jet energy scale calibration, b-tagging efficiency, etc.
  - Theoretical uncertainties: renormalization and factorization scales, PDF, etc.

ATLAS $1\ell + b$-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1})

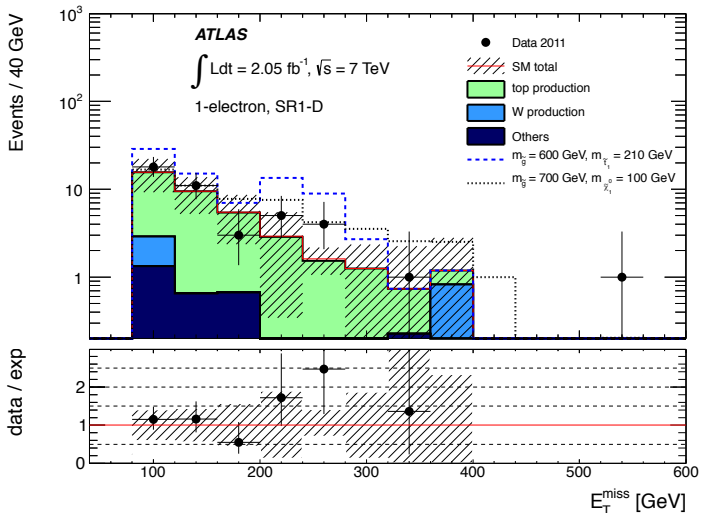
- Exploiting the presence of b-jets from the top decays and the leptons produced from the leptonic top decays
- Analysis selection:
  - Single lepton trigger $\rightarrow$ one lepton ($\ell \equiv e$ or μ) with $p_{\mathrm{T}}(e, \mu) > 25, 20$ GeV
  - Veto on additional leptons
  - At least four jets with $p_{\mathrm{T}}(\mathrm{jet}_1) > 60$ GeV and $p_{\mathrm{T}}(\mathrm{jet}_{2,3,4}) > 50$ GeV
  - One of the four leading jets must be b-tagged
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV
  - $m_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos(\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}}))} > 100$ GeV
- **Signal regions:**
  - **SR1-D**: $m_{\mathrm{eff}} = \sum_i p_{\mathrm{T}}^{\mathrm{jet},i} + \sum_j p_{\mathrm{T}}^{\ell,j} + E_{\mathrm{T}}^{\mathrm{miss}} > 700$ GeV
  - **SR1-E**: $m_{\mathrm{eff}} > 700$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
- Background estimation:
  - Non-QCD background:
    Semi data-driven estimation using transfer factors from control region
    ($40 < m_{\mathrm{T}} < 100$ GeV, $m_{\mathrm{eff}} > 500$ GeV)
  - QCD background:

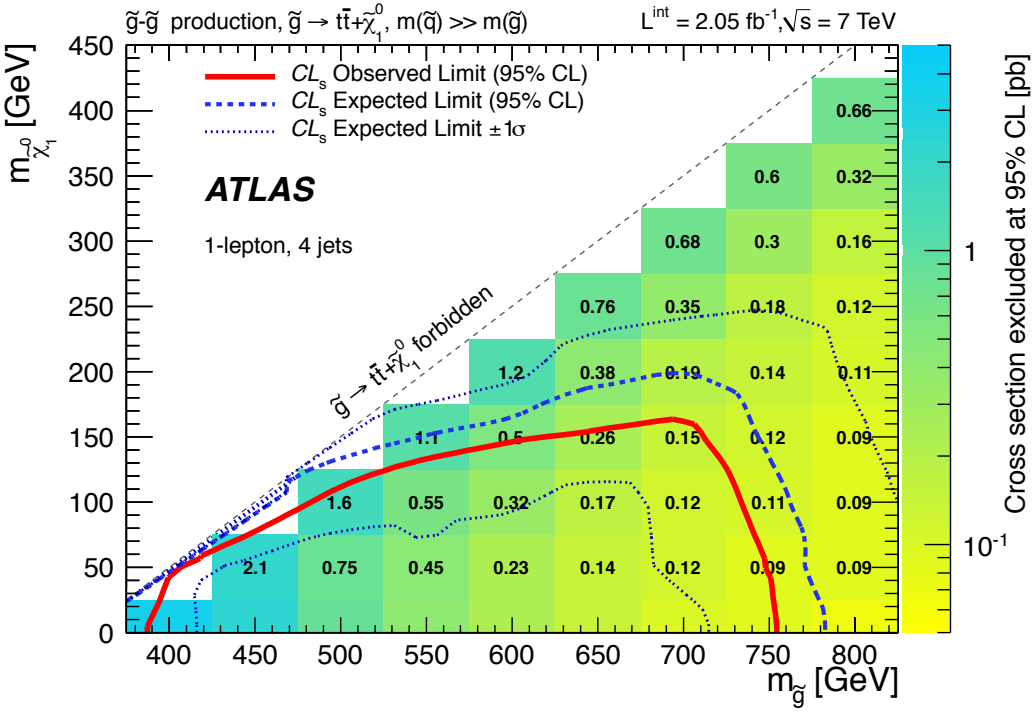
    Estimated from data using a pass-fail matrix method

ATLAS 1ℓ + b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1}): Results

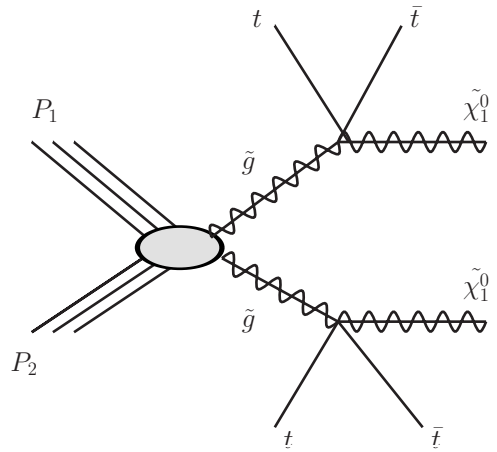
- No excess over the SM prediction observed:

Sig. Reg.	SM background	Data
SR1-D (e)	39 ± 12	43
SR1-D (μ)	38 ± 14	38
SR1-E (e)	8.1 ± 3.4	11
SR1-E (μ)	6.3 ± 4.2	6





- Interpretation in simplified models with $m_{\tilde{g}} < m_{\tilde{t}_1} \sim 1$ TeV and $\mathrm{BR}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0) = 1$



ATLAS Multijet Analysis (4.7 fb^{-1})

- Analysis requiring high $E_{\mathrm{T}}^{\mathrm{miss}}$, no isolated lepton, and $\geqslant 6$ to $\geqslant 9$ jets
- Multijet trigger (4 jets with $p_T > 45$ GeV or 5 jets with $p_T > 30$ GeV)
- 6 signal regions defined (8j55 and 9j55 sensitive to $\tilde{t}_1$ production):

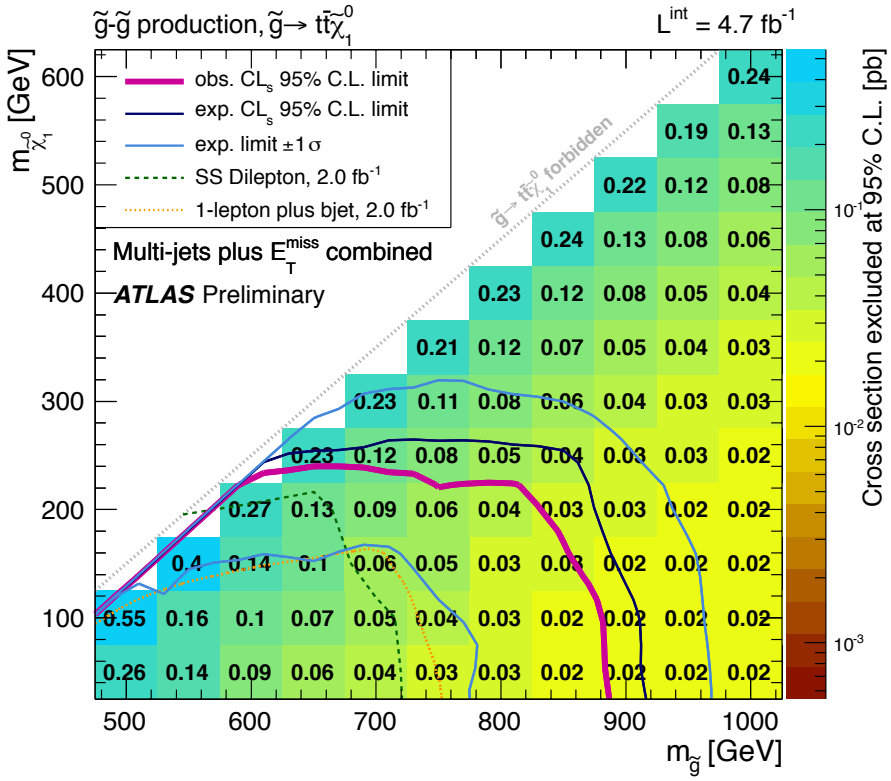
Signal region	**7j55**	**8j55**	**9j55**	**6j80**	**7j80**	**8j80**
Isolated leptons (e, μ)	=0					
Jet p_T	>55 GeV			>80 GeV		
Jet $\lvert\eta\rvert$	<2.8					
Number of jets	≥ 7	≥ 8	≥ 9	≥ 6	≥ 7	≥ 8
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T}$	>4 GeV$^{1/2}$					

- $E_{\mathrm{T}}^{\mathrm{miss}}$ cut as a function of $H_T = \sum_{jet} p_{\mathrm{T}}^{jet} \rightarrow$ Minimal cut on $E_{\mathrm{T}}^{\mathrm{miss}} > 84, 89$ GeV for 8j55, 9j55
- Background estimation:
  - "Multi-jet" backgrounds (QCD, fully hadronic $t\bar{t}$, W and Z decays):
    Estimated from data using control regions with lower $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T}$ and/or jet multiplicity
  - "Leptonic" backgrounds (non-fully-hadronic decays of $t\bar{t}$, W+jets and Z+jets):
    Estimated from control regions using transfer factors

ATLAS Multijet Analysis (4.7 fb^{-1}): Results

- No excess observed over the SM prediction:

Signal region	8j55	9j55
Multi-jets	10±3	1.2±0.4
$t\bar{t} \to q\ell, \ell\ell$	5.7±6.0	0.70±0.72
W + jets	0.81±0.72	0+0.13
Z + jets	0.05±0.19	0+0.12
Total Standard Model	**17±7**	**1.9±0.8**
Data	**22**	**3**



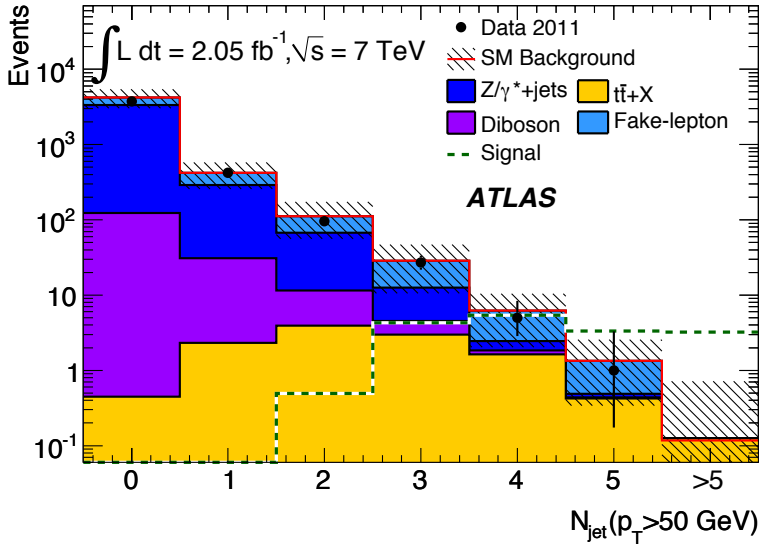
- Results interpreted in the same $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ model used for the 1 lepton+b-jet analysis

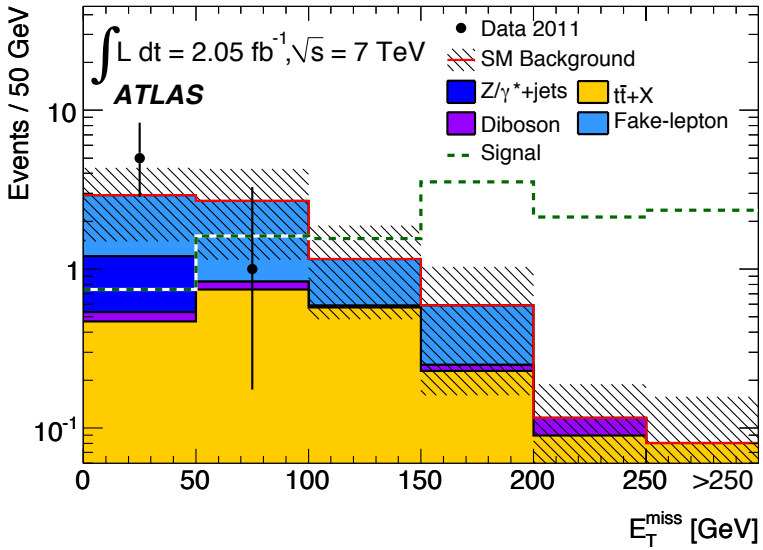
- Low sensitivity in the region close to the kinematic limit ($m_{\tilde{g}} \gtrsim 2m_t + m_{\tilde{\chi}_1^0}$) similarly to the 1 lepton+b-jets analysis
- Both analyses have strong requirements on m_{eff}, around 500-700 GeV → Reduced sensitivity for final states with small mass splitting between $\tilde{g}$ and its decays products

ATLAS 2ℓ SS + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1})

- Exploit same-sign (SS) dilepton signature with softer jet cuts
- Analysis selection:
  - Single lepton and dilepton triggers
  - At least two leptons (e or μ) with $p_{\mathrm{T}} > 20$ GeV
  - The leading lepton pair must be SS
  - At least four jets with $p_{\mathrm{T}} > 50$ GeV
- Signal region for stop search:
  - **SR2**: $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $m_{\mathrm{T}} > 100$ GeV
- SM background evaluation:
  - "Fake-lepton" background: Matrix method
  - Electron charge mis-ID: Semi data-driven
  - Diboson and associated $t\bar{t}$ production ($t\bar{t} + X$):

    Directly from MC

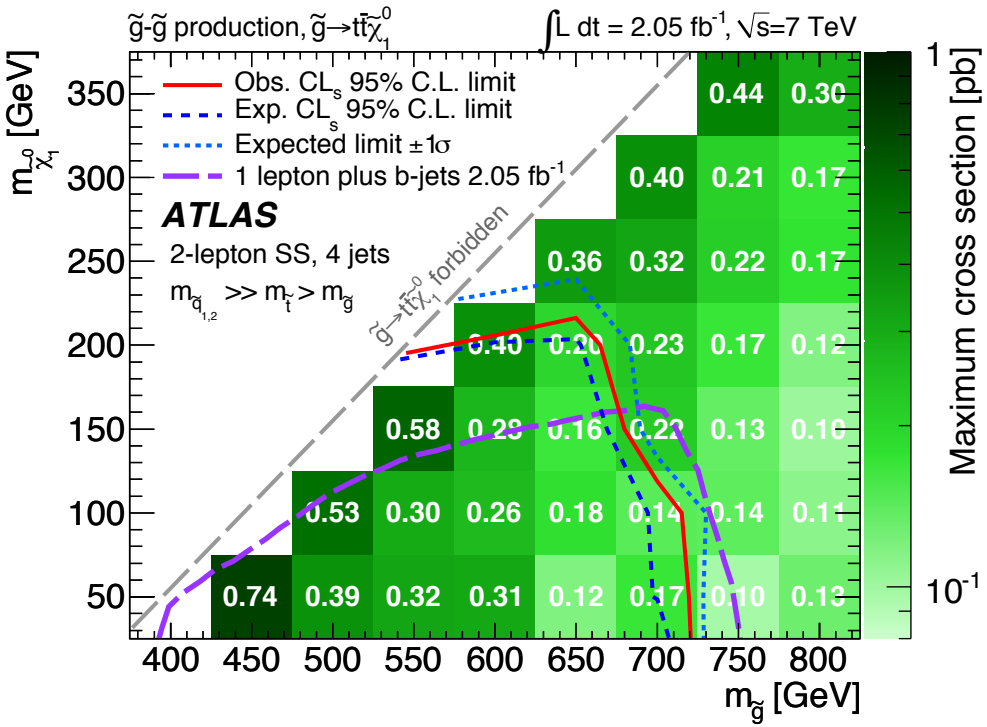




ATLAS 2ℓ SS + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1}): Results

- Very small background expectation
- No event observed in signal region:

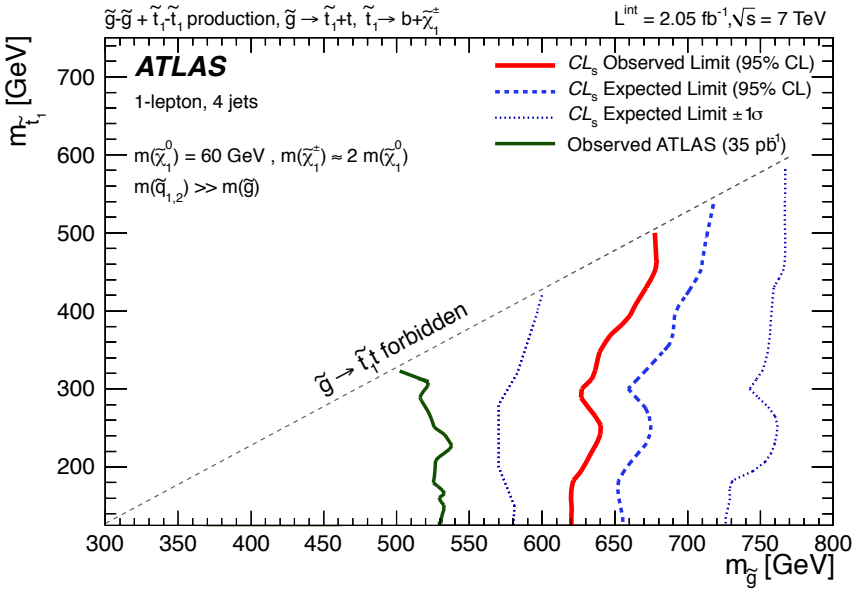
	SR2
$t\bar{t}$ +X	0.21 ± 0.16
Diboson	0.02 ± 0.01
Fake-lepton	< 0.17
Charge mis-ID	0.039 ± 0.007
Total SM	0.27 ± 0.24
Observed	0

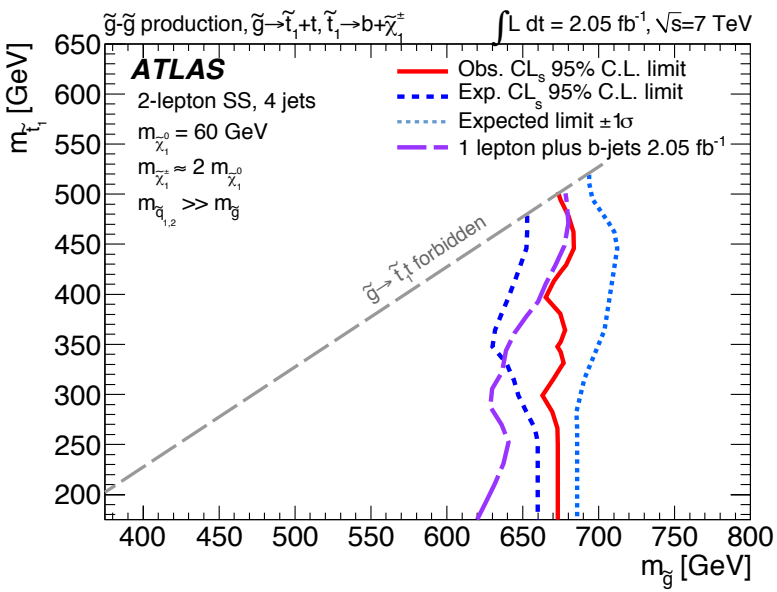


- Results interpreted in the $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ simplified model
- Comparison with 1 lepton+b-jets: 2 SS lepton slightly worse at high $m_{\tilde{g}}$ but better at high $m_{\tilde{\chi}_1^0}$ (softer cuts: 4 jets of 50 GeV and $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV)

Other Interpretations: $\tilde{g} \longrightarrow t\tilde{t}_1 \longrightarrow tb\tilde{\chi}_1^{\pm}$

- Results from the 1 lepton+b-jets and 2 SS lepton analysis also interpreted in other models
- MSSM scenario considering both $\tilde{g}\tilde{g}$ and $\tilde{t}_1\tilde{t}_1^*$ production
- Mass spectrum:
  - All quarks heavier than gluino except stop with $m_{\tilde{g}} > m_{\tilde{t}_1} + m_t$
  - $m_{\tilde{\chi}_1^{\pm}} \simeq 2m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^0} = 60$ GeV
- Decays: BR($\tilde{g} \longrightarrow \tilde{t}_1 t$) = 1, BR($\tilde{t}_1 \longrightarrow b\tilde{\chi}_1^{\pm}$) = 1 and BR($\tilde{\chi}_1^{\pm} \longrightarrow \tilde{\chi}_1^0 \ell^{\pm}\nu$)=11%

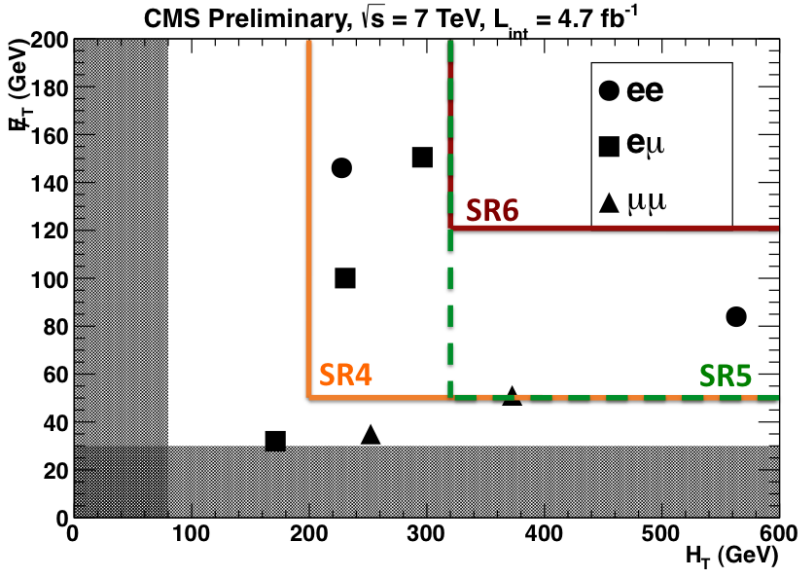




- Exclusion of stop masses of ∼450 GeV for gluino masses of ∼650 GeV

CMS 2ℓ SS + b-jets + E_T^{miss} (4.7 fb^{-1})

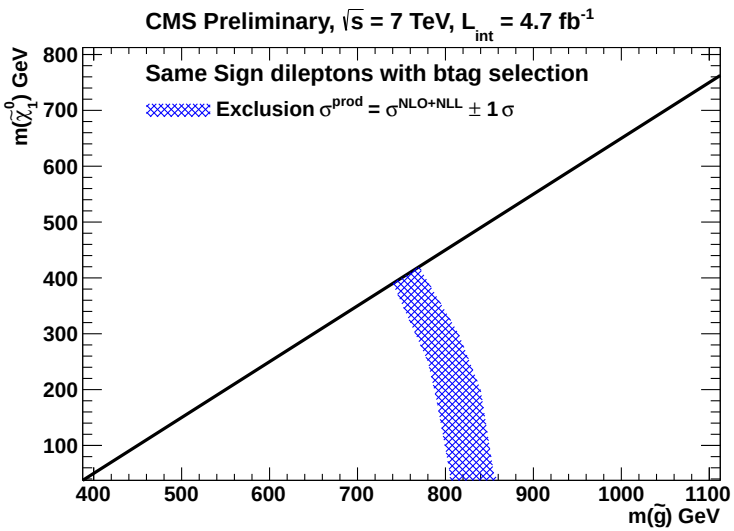
- Using the SS dilepton and b-jet signatures together
- Analysis selection:
  - Dilepton triggers
  - Two SS leptons (e or μ) with $p_T > 20$ GeV
  - Veto events with a third lepton if compatible with a Z boson
  - At least two b-jets with $p_T > 40$ GeV
- Signal regions built with E_T^{miss} and H_T cuts (SR4, SR5 and SR6 aiming at stop production)
- SM background evaluation:
  - "Fake-lepton" background: Control sample with loose leptons scaled with probability of passing tight selection
  - Charge flip: Semi data-driven
  - Rare SM processes producing SS leptons: Directly from MC

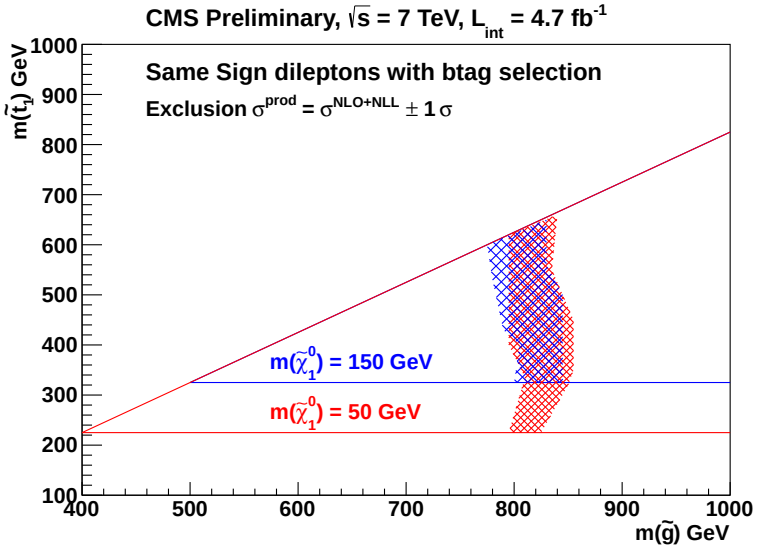


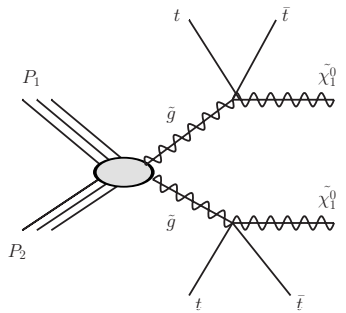
	SR4	SR5	SR6
No. of jets	≥ 2	≥ 2	≥ 2
No. of btags	≥ 2	≥ 2	≥ 2
$\not{E}_T$	≥ 50 GeV	≥ 50 GeV	≥ 120 GeV
H_T	≥ 200 GeV	≥ 320 GeV	≥ 320 GeV
q-flip BG	0.3 ± 0.1	0.12 ± 0.03	0.026 ± 0.009
Fake BG	1.5 ± 1.1	0.81 ± 0.78	0.15 ± 0.45
Rare SM BG	2.0 ± 1.0	1.04 ± 0.52	0.39 ± 0.20
Total BG	3.7 ± 1.5	2.0 ± 0.9	0.6 ± 0.5
Event yield	5	2	0

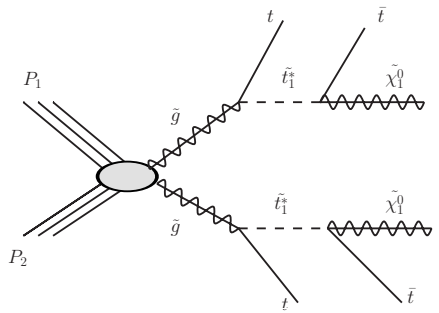
CMS 2ℓ SS + b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (4.7 fb^{-1}): Interpretation

- Results interpreted in two models:
  - Model A1: $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (off-shell stop), same as in ATLAS analysis
  - Model A2: $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow \tilde{t}_1 t \rightarrow t\bar{t}\tilde{\chi}_1^0$ (on-shell stop) with fixed $m_{\tilde{\chi}_1^0} = 50$, 150 GeV





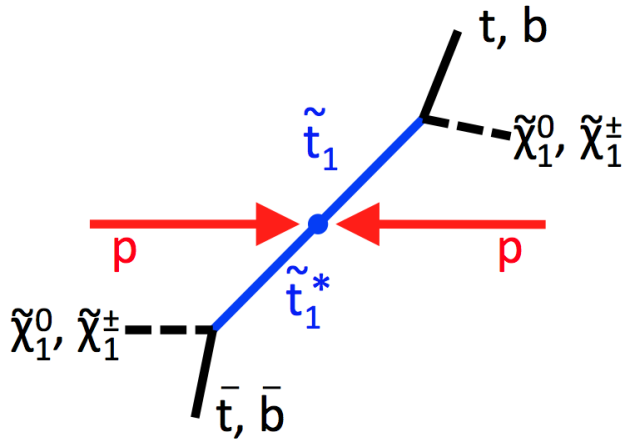




ATLAS GMSB 2ℓ SF-OS + b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1})

- Only LHC result about direct stop searches so far was obtained within the context of GMSB models with light higgsinos
- Model parameters: $m_{\tilde{q}_3} = m_{\tilde{u}_3} = -A_t/2; \quad \tan\beta = 10$
- Light higgsinos: $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^{\pm}$ almost degenerate in mass

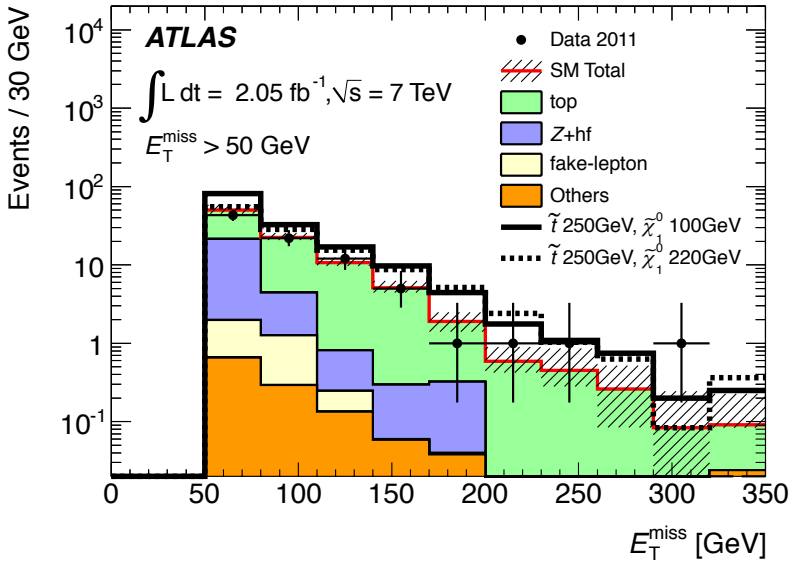
- Only $\tilde{t}_1\tilde{t}_1^*$ pair production considered
- Squark and gluino mass above 2 TeV
- Stops decays: $\tilde{t}_1 \to b\tilde{\chi}_1^+$ or $\tilde{t}_1 \to t\tilde{\chi}_{1(2)}^0$ (if kinematically allowed)
- Neutralino decays: BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=0.65-1 for $m_{\tilde{\chi}_1^0} = 100 - 350$ GeV

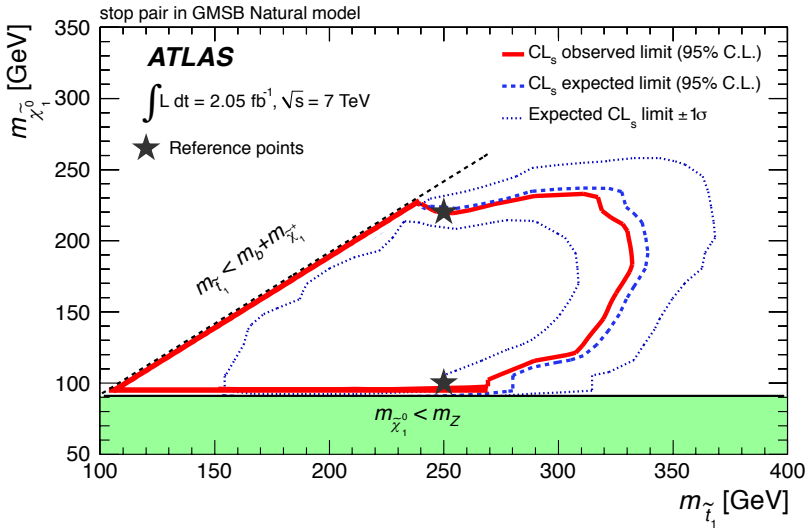


- Expected signal: two b-jets, decay products of Z (or h) and large $E_{\mathrm{T}}^{\mathrm{miss}}$ from the undetected gravitinos.
- Exploring signature with 2 same-flavor opposite-sign leptons, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$

ATLAS GMSB 2ℓ SF-OS + b-jets + $E_{\mathrm{T}}^{\mathrm{miss}}$ (2.05 fb^{-1})

- Analysis selection:
  - Single electron and muon+jet triggers
  - Two same-flavor opposite-sign leptons (e or μ) with $p_{\mathrm{T}} > 20$ GeV (leading lepton $p_{\mathrm{T}} > 25$ GeV if it is an electron)
  - Invariant mass: $86 < m_{\ell\ell} < 96$ GeV
  - At least two jets with $p_{\mathrm{T}}(\mathrm{jet}_{1,2}) > 60, 50$ GeV
  - At least one b-jet with $p_{\mathrm{T}} > 50$ GeV
- Signal regions: SR1 ($E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV) and SR2 ($E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV)
- SM background evaluation:
  - Top: with transfer factors from control region of inverted $m_{\ell\ell}$
  - Z+hf: from MC and validated in low-$E_{\mathrm{T}}^{\mathrm{miss}}$ control regions
  - Fake leptons (W+jets, multi-jet): Matrix method
  - Diboson, $t\bar{t} + X$: from MC





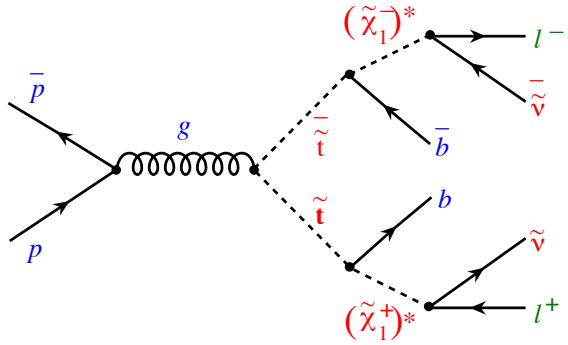
Summary

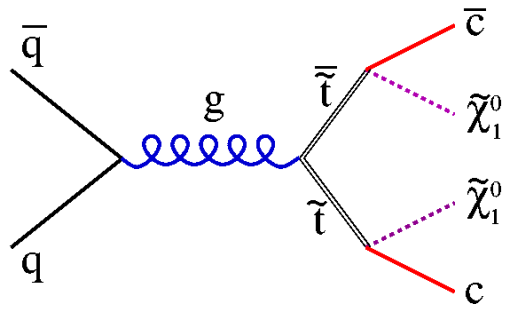
- Several searches for stop performed with 2.05-4.7 fb^{-1} of LHC data in ATLAS and CMS
- Exploring signatures with one or several b-jets, one or two leptons (same-sign or opposite-sign), jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
- No excess observed so far:
  - Model independent limits on $\sigma \times \epsilon \times A$
  - Interpretations within specific models ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$, $\tilde{g} \to \tilde{t}_1 t$ with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$) or GMSB scenarios
  - CMS limit in $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ model with 2-lep (SS) + b-jets: $\tilde{g}$ mass of 740 GeV ($m(\tilde{\chi}_1^0) < 380$ GeV) [CMS-PAS-SUS-11-020]
  - Summary of ATLAS limits:

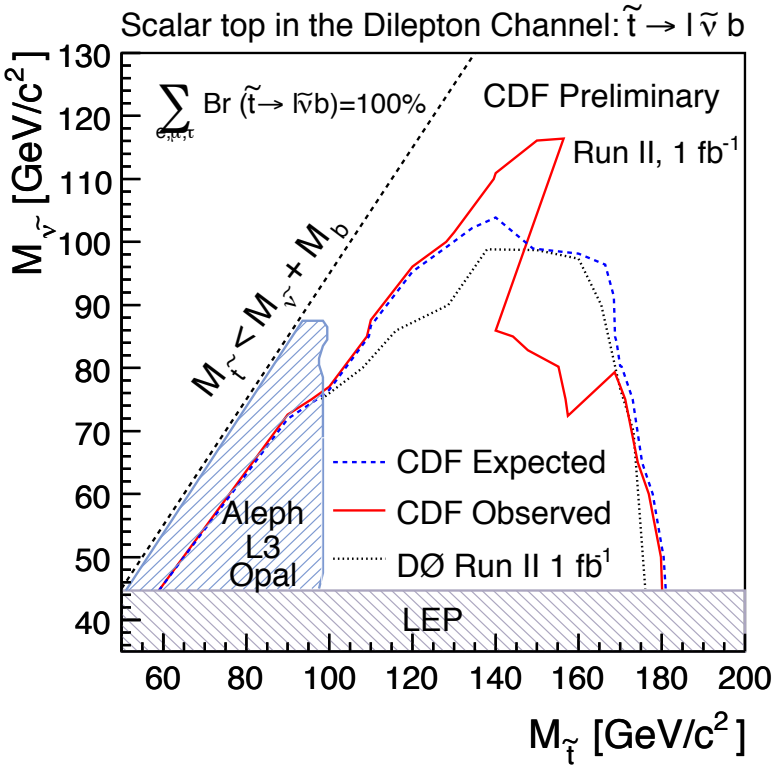
- Updates to full 2011 dataset and other analyses for direct stop production in preparation $\to$ Results about regions never probed before: **STAY TUNED!**

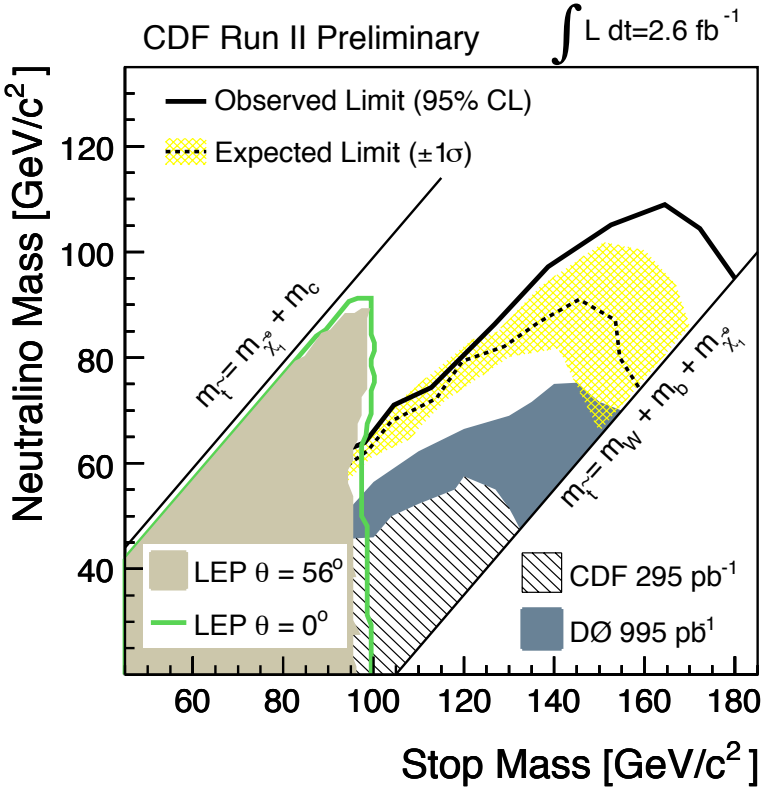
BACKUP

Pre-LHC Results on Stop Searches

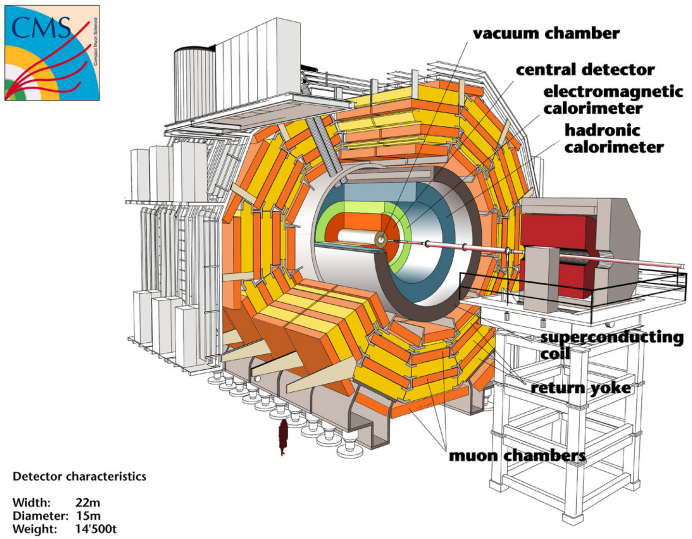


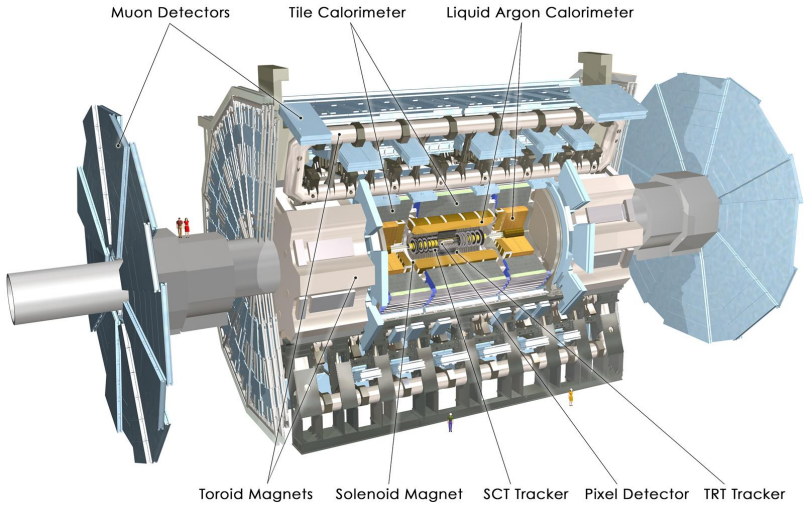


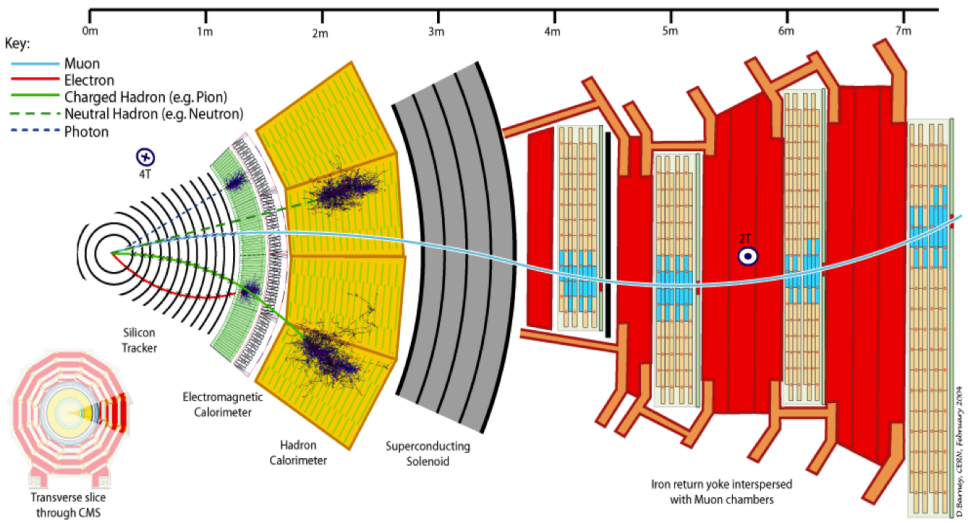


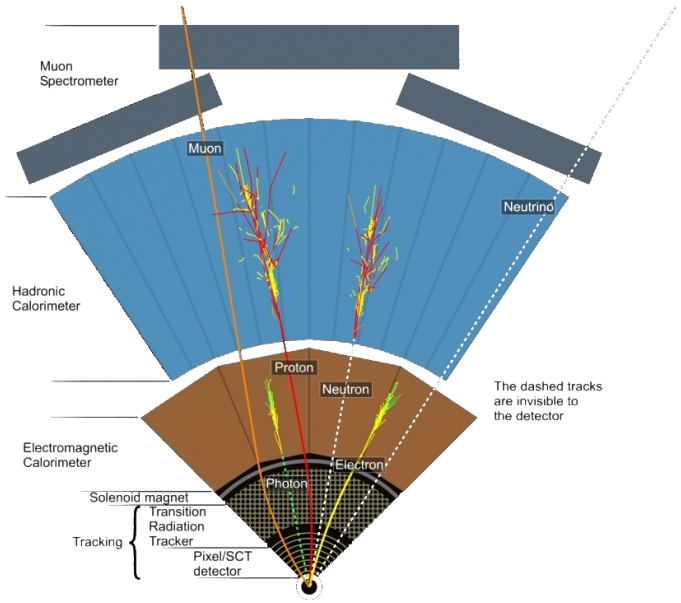


ATLAS and CMS Experiments









Data Taking in 2011