Search for supersymmetry in the single-lepton final state with the CMS detector

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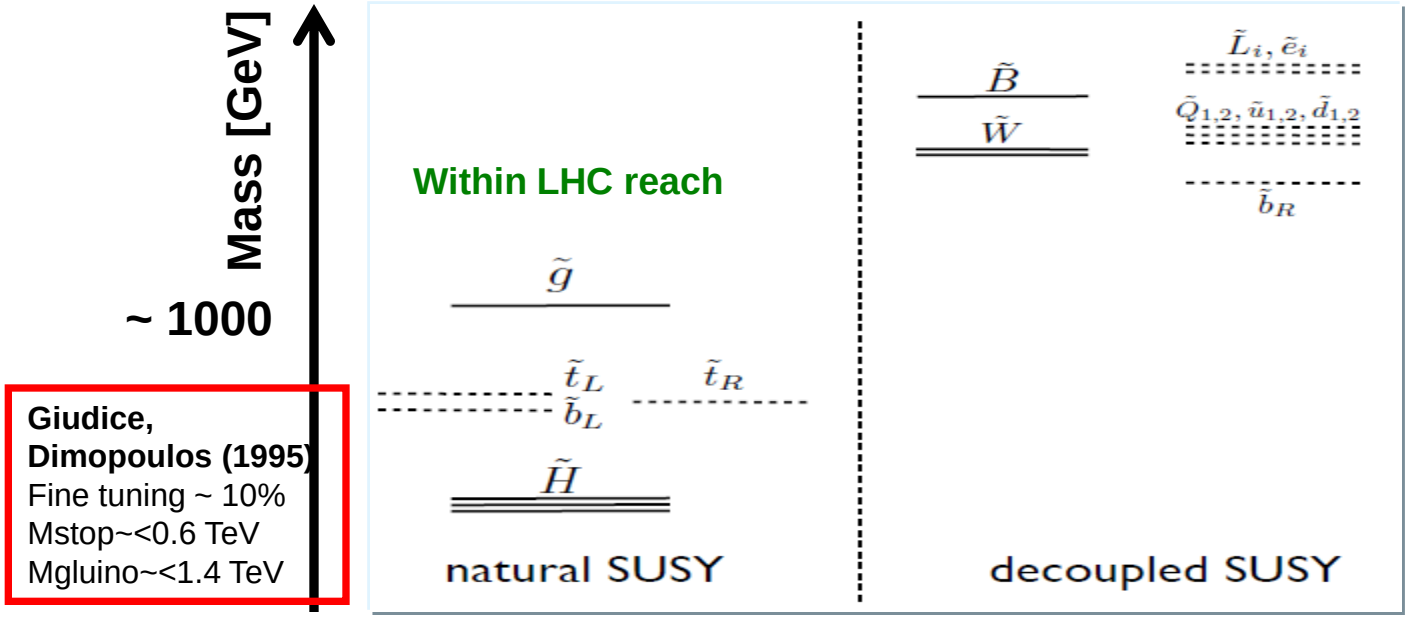
Outline:

- **Physics motivation**
- **Single-lepton searches for:**
  - **Stop production through gluino decays**
  - **Direct stop production**
  - **Associated stop – Higgs production**
- **Summary and conclusions**

Physics motivation

Physics motivation

- **Experimental results @7 TeV show no evidence of SUSY**
  - **Constrained SUSY models cornered – though not excluded yet**
- **Motivation for SUSY at the EWK scale: naturalness**
  - **Top/ bottom squarks [3G] and gluino masses at ~TeV scale**



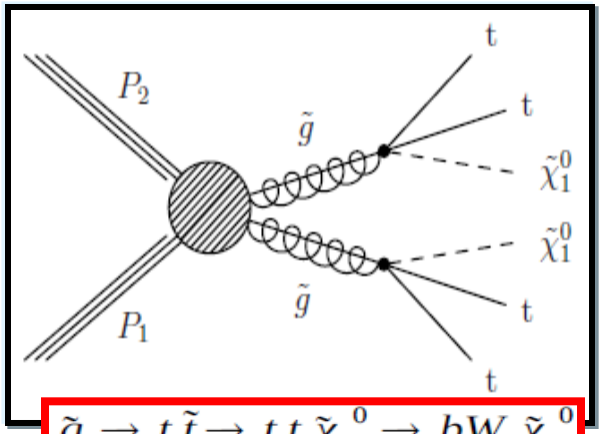
Papucci, Ruderman, Weiler hep-ph 1110.6926

Barbieri et al. hep-ph 9512388

Physics motivation (2)

- **stop production mechanisms:**

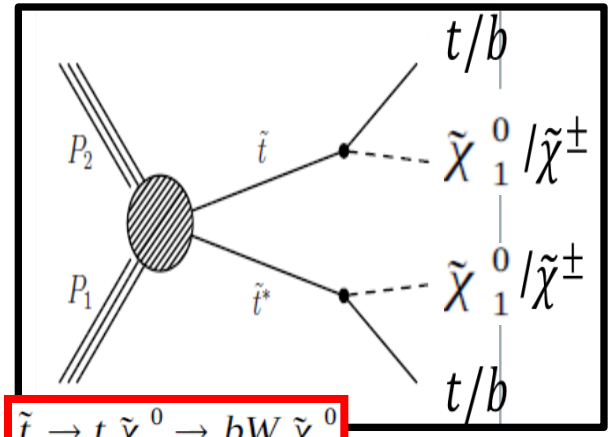
Gluino induced



$\tilde{g} \to t\,\tilde{t} \to t\,t\,\tilde{\chi}^0_1 \to bW\,\tilde{\chi}^0_1$

If M_g within LHC reach

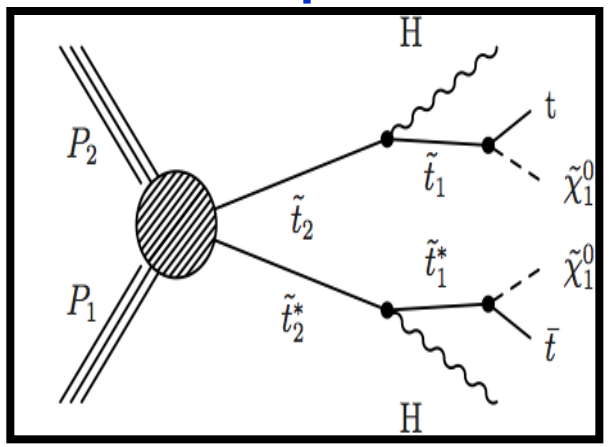
Direct production



$\tilde{t} \to t\,\tilde{\chi}^0_1 \to bW\,\tilde{\chi}^0_1$

$\tilde{t} \to b\,\chi^\pm \to bW^\pm\,\tilde{\chi}^0_1$

Associated prod. with H



$\tilde{t}_2 \to \tilde{t}_1 H \to Ht\,\tilde{\chi}^0_1$

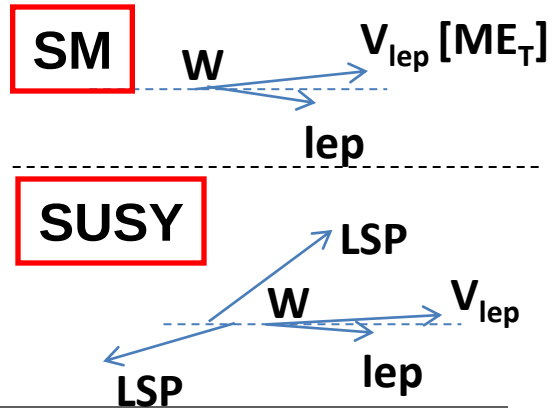
If M_g **not** in LHC reach

- **Multiple tops in final state: large BR to leptonic channels**
  - **1lep: ~40% for indirect production [~30% 0-lep]**
- **Speak about 1-lep searches: dedicated for stops**

Gluino-induced stop search

Gluino-induced stop search

- **1lep: Largest BR; sensitivity competitive to all hadronic**
- **Event selection:**
  - **1 isolated lepton [e/ μ]** → **Dominant bkg: ttbar + jets**
  - **$N_j \geq 6$, $N_b \geq 2$**
- **Handles that characterize the event "energy" scale**
  - **Hadronic sector: $H_T = \Sigma p_T$[jets]**
    - **In SUSY events generally harder jets compared to SM**
  - **Leptonic sector: $S_T^{lep} = p_T$[lep] + ME_T**
    - **In SUSY larger values of ME_T : pT[l] and MET less correlated**
- **Additional kinematic variable:**
  - **MET and charged lepton less aligned in SUSY events [3 sources of ME_T]**
    - **Angle between W and charged lepton [Δφ(W,l)] quite powerful**



Δφ: Strategy & EWK bkg estimation

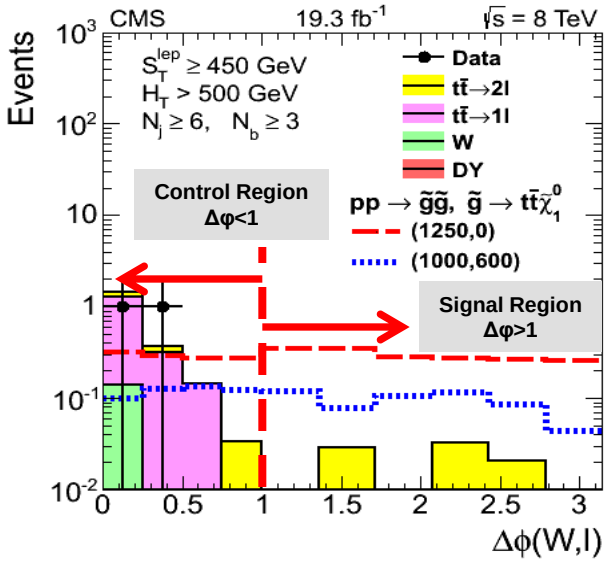
- **Require Δφ>1 [Δφ<1 control region]**
- **Define transfer factor R_{CS}:**

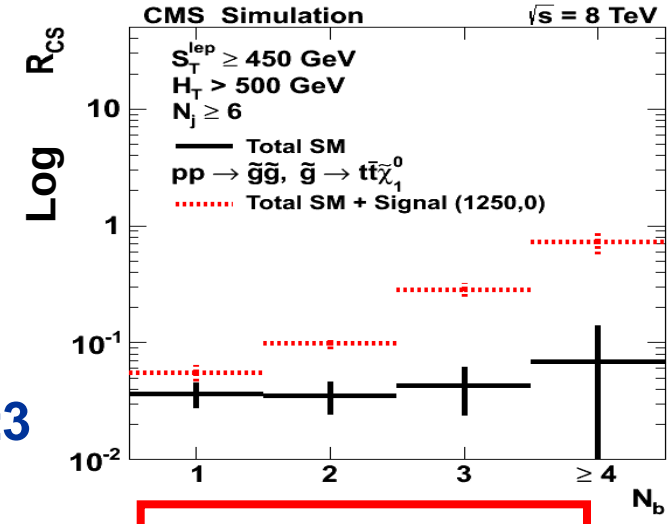
$$R_{CS} = \frac{N_{signal}}{N_{control}} = \frac{\text{Number of events with } \Delta\phi(W,l) > 1)}{\text{Number of events with } \Delta\phi(W,l) < 1)}$$

- **Prediction:**

$$N_{SM}^{pred}(\Delta\varphi > 1) = R_{CS} \cdot N_{data}(\Delta\varphi < 1)$$

- **Two possibilities to extract R_{CS}:**
  - **Use MC; assign large systematic unc.**
  - **Use a data-driven approach**
- **R_{CS} dependence on N_b very weak**
  - **measure in data in N_b=1, use in N_b=2,≥3**
  - **k_{CS} [MC] for residual differences**



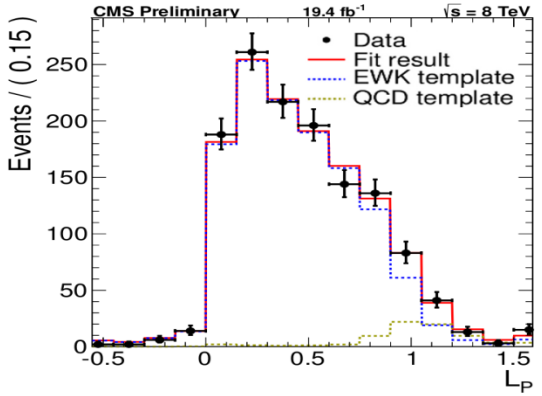


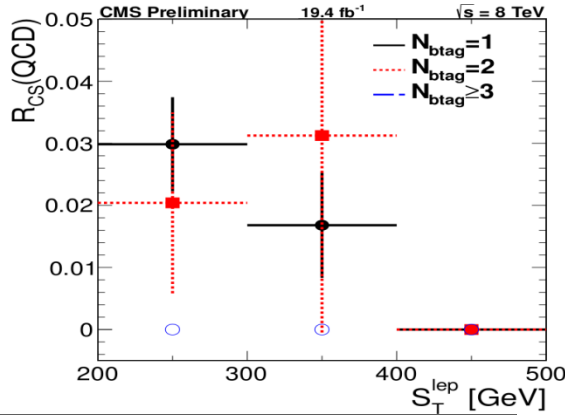
SUSY drastic effect on N[Δφ>1]

Δφ: QCD Bkg estimation

- **QCD background small compared to other bkgs**
  - negligible in the muon channel
- **Estimate QCD contribution using well tested method**
  [PRL (2011) 107:02180, CMS-SUS-11-015, CMS-SUS-12-010]
  - Invert electron id variables and estimate QCD shape from anti-selected data sample
  - Binned likelihood fit in Lp to estimate total QCD
    - EWK template from MC
  - Calculate R_{CS}[QCD] from anti-selected data
- **N_{QCD}<5% of total data, negl. for Δφ>1**
  - subtract contribution in control region
- **Prediction in electron channel:**

$$L_P = \frac{\vec{P}_T(l)\cdot\vec{P}_T(W)}{|\vec{P}_T(W)|^2}$$





$$N_{SMest.}(\Delta\phi(W,l)>1) = R_{CS}^{EWK}\cdot\left(N_{data}(\Delta\phi(W,l)<1) - N_{QCD}(\Delta\phi(W,l)<1)\right)$$

Δφ: Method validation and results

- **All ingredients of the analysis tested in bkg dominated sample [3≤N_j≤5] in data**

L=19.4 fb^{-1}

Control sample [3<=N_j<=5]

Results @ 19.4 fb^{-1}

			$3 \leq N_j \leq 5$			$N_j \geq 6$		
		S_T^{lep} [GeV]	Control	Pred.	Obs.	Control	Pred.	Obs.
$N_b = 2$	e	[250, 350]	548	34.2±5.4	30	112	3.8±1.8±0.6	9
		[350, 450]	174	5.1±1.9	8	28	2.7±1.9±0.8	2
		>450	61	5.6±2.1	1	9	0.0±0.4±0.2	0
	μ	[250, 350]	632	41.9±5.6	59	141	6.0±2.2±0.9	9
		[350, 450]	188	8.5±2.4	11	24	1.4±1.1±0.4	2
		>450	71	2.5±1.3	1	9	0.0±0.7±0.2	0
$N_b \geq 3$	e	[250, 350]	70	3.9±0.9	2	45	1.9±0.9±0.4	4
		[350, 450]	12	0.3±0.2	2	7	0.9±0.7±0.4	0
		>450	4	0.3±0.2	0	0	0.0±0.1±0.03	0
	μ	[250, 350]	59	3.9±0.8	5	28	1.9±0.8±0.4	0
		[350, 450]	25	1.1±0.4	0	13	0.6±0.5±0.3	0
		>450	7	0.3±0.2	0	2	0.0±0.2± 0.1	0

Stat. uncertainties only

total uncertainty (stat +/- sys)

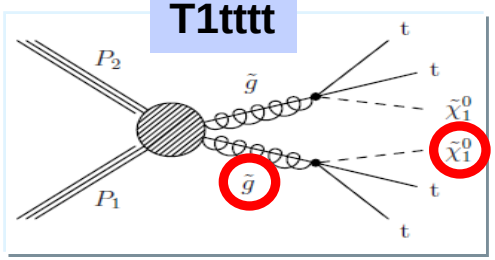
Good agreement between prediction and observed data [☺]

Observed data agree with SM expectations [☹]

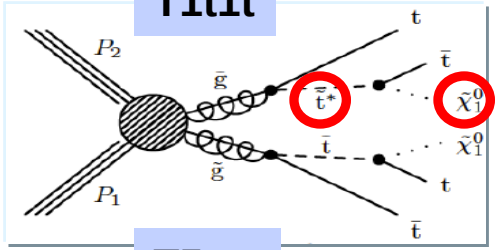
Interpretation in $\tilde{g} \rightarrow tt \rightarrow tt\tilde{\chi}^1_0$

- **Limits set for gluino-induced stop production using SMS models:**
  - **T1tttt [stop off-shell]**
    - Free parameters: M(gluino) and M(lsp)
    - top squark M(stop) >> M(gluino)
  - **T1t1t [stop on-shell]**
    - Free parameters: M(stop) and M(lsp)
    - M(gluino) = 1 TeV [fixed]
  - **T5tttt [stop on-shell]**
    - Free parameters: M(stop) and M(gluino)
    - M(lsp) = 50 GeV [fixed]

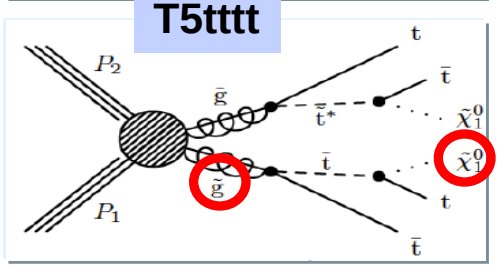
T1tttt



T1t1t



T5tttt



- **Results:**
  - **Simultaneous fit over all search regions**

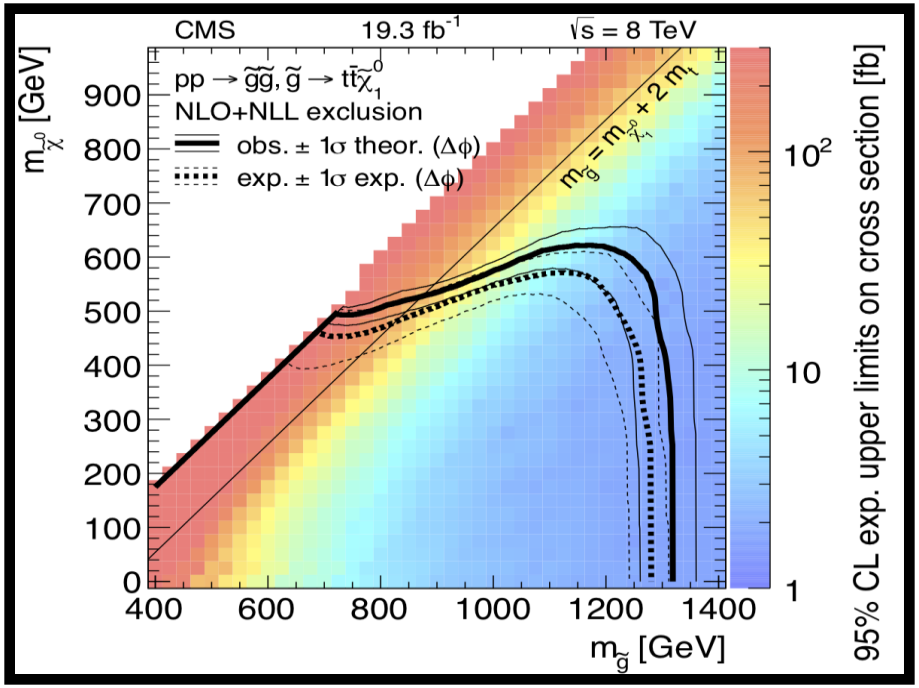
CMS-PAS-SUS-13-007 [acc. PLB]

Interpretation in $\tilde{g} \rightarrow tt \rightarrow tt\tilde{\chi}^1_0$

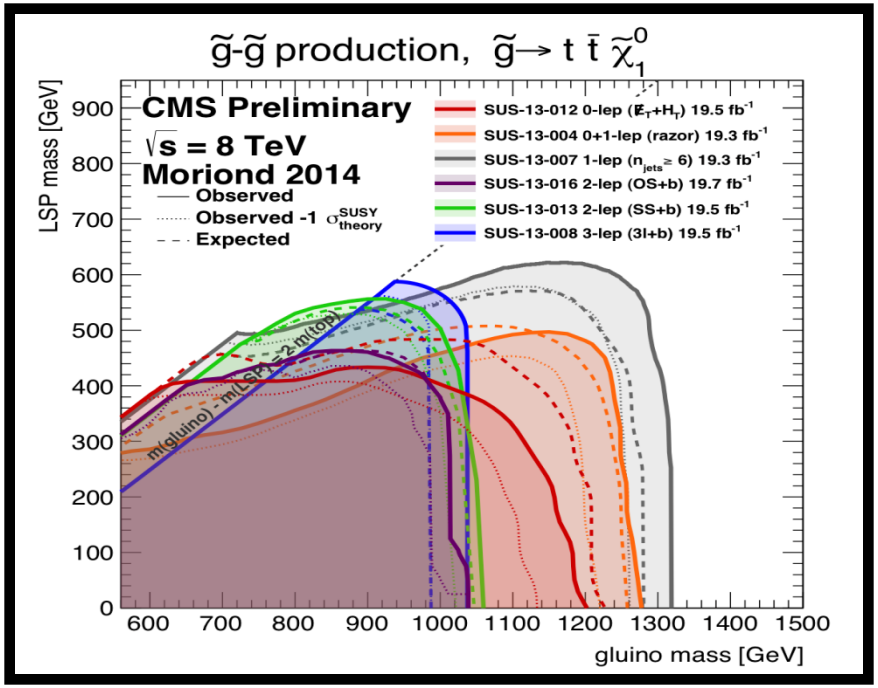
T1tttt

[BR 100%]

1-lep searches



Add 0-lep, ≥2-lep



Probes M_g~1280 GeV and M_{lsp} ~ 570 GeV

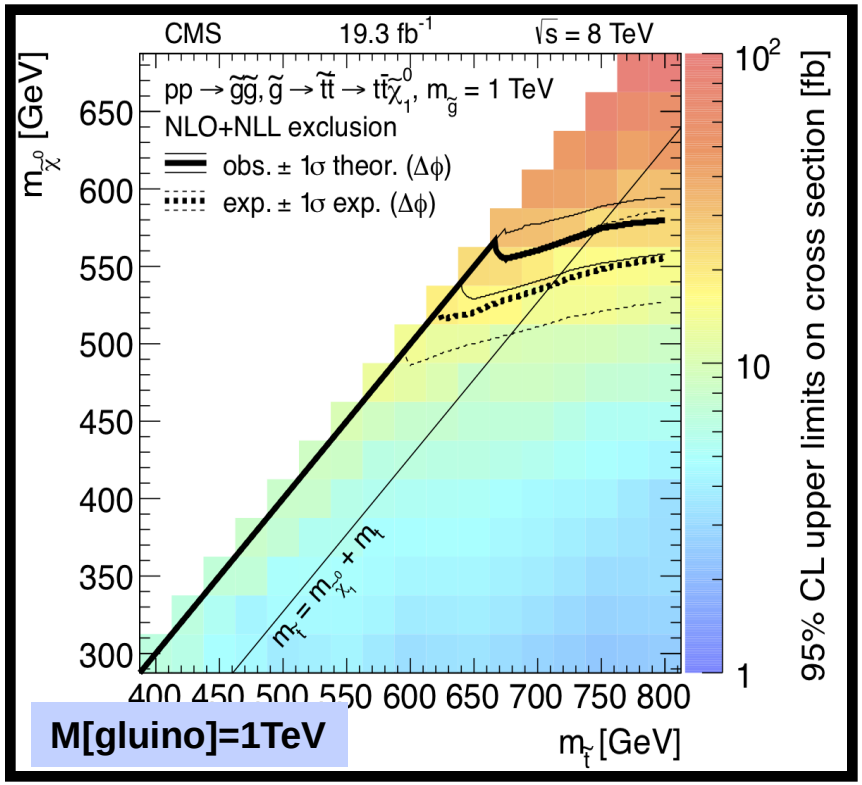
- **1lep: most competitive results**
- **≥ 2lep: quite sensitive in compressed spectra due to low ME_T requirement**

CMS-PAS-SUS-13-007 [acc. PLB]

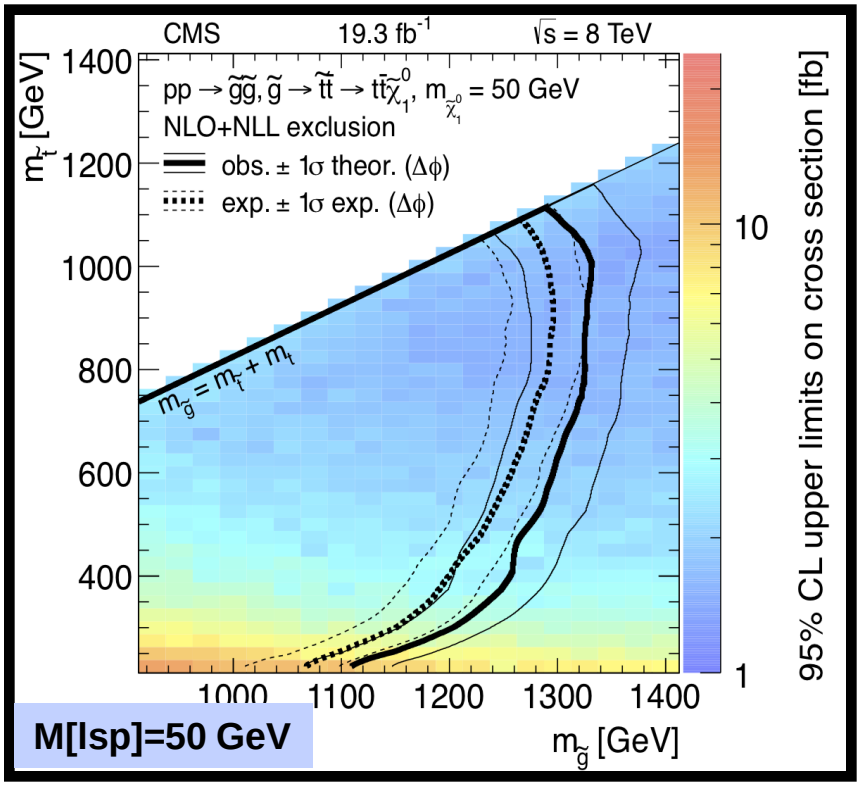
Interpretation in $\tilde{g} \rightarrow tt \rightarrow tt\tilde{\chi}^1_0$

[BR 100%]

T1t1t



T5tttt



Probes light stops

Direct stop search

EPJ C (2013) 73:2677

Direct stop search: selection

- **Event selection:**
  - 1 isolated lepton [e/μ], $N_j \geq 4$, $N_b \geq 1$ → **Dominant bkg: ttbar (2lep)**
  - ME_T>100 GeV [suppress QCD]
  - $M_T(l,ME_T)$>120 GeV [suppress tt(1l) & W+jets]
  - Veto events with additional isolated track [suppress tt(2l)]
- **Additional kinematic variables:**
  - M_{T2}^W: generalization of M_{T2} [event with 2 undetected particles]

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

    - suppress tt(2l) when 2nd lep lost; BKG: low M_{T2}^W ; SUSY high
  - Hadronic top $\chi^2 = \frac{(M_{j_1 j_2 j_3} - M_{\text{top}})^2}{\sigma^2_{j_1 j_2 j_3}} + \frac{(M_{j_1 j_2} - M_W)^2}{\sigma^2_{j_1 j_2}}$

    only used in: $\tilde{t} \to t \tilde{\chi}_1^0 \to bW \tilde{\chi}_1^0$
    - suppress tt(2lep) by identifying the hadronic top decay
- **Additional topological variables:**
  - $\min\Delta\varphi[j_{1,2}, ME_T]$ and H_T^{ratio} [fraction of H_T in ME_T-hemisphere]

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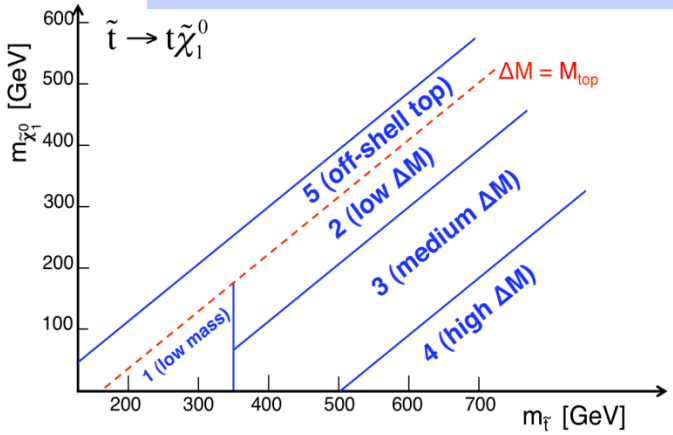
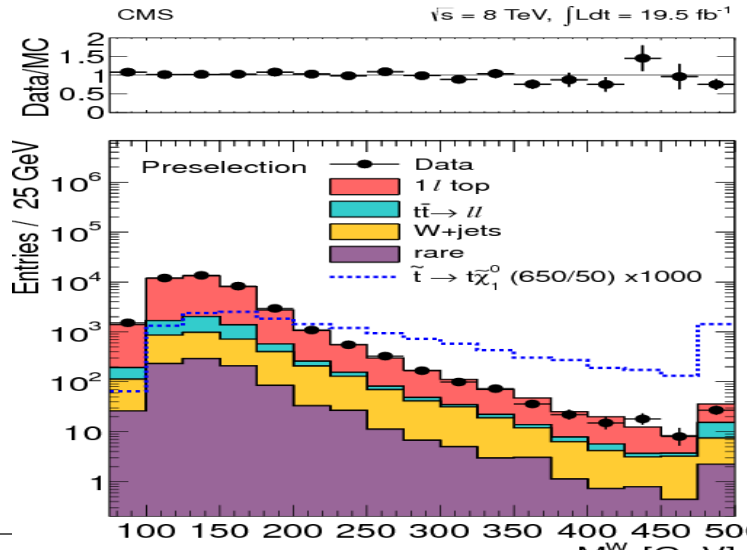
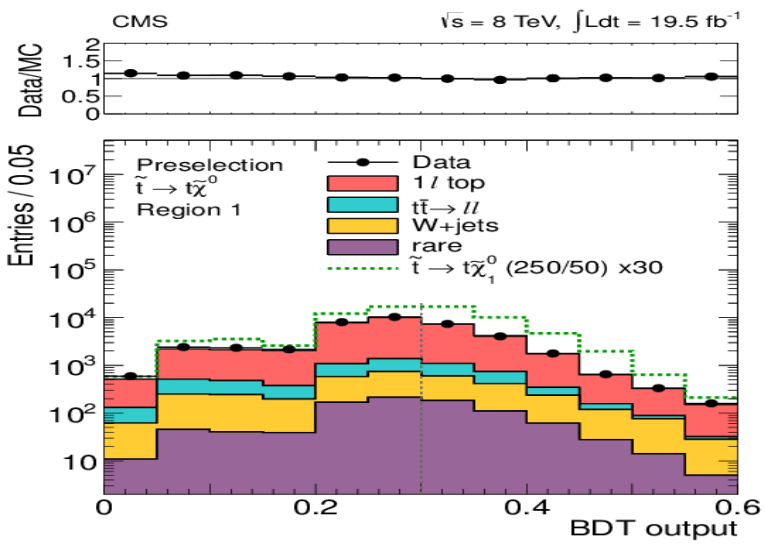
Direct stop search: strategy

(*) Boosted Decision Tree type of multivariate technique

- Two search approaches:
- BDT (*) [primary approach]
  - BDT inputs [in addition to slide 14]:
    - pT [lead b], ΔR(l,lead b], pT[lep]
  - Separate BDTs based on Δm
- Cut-based [x-check]
  - Search in different MET regions; selection for low & high Δm







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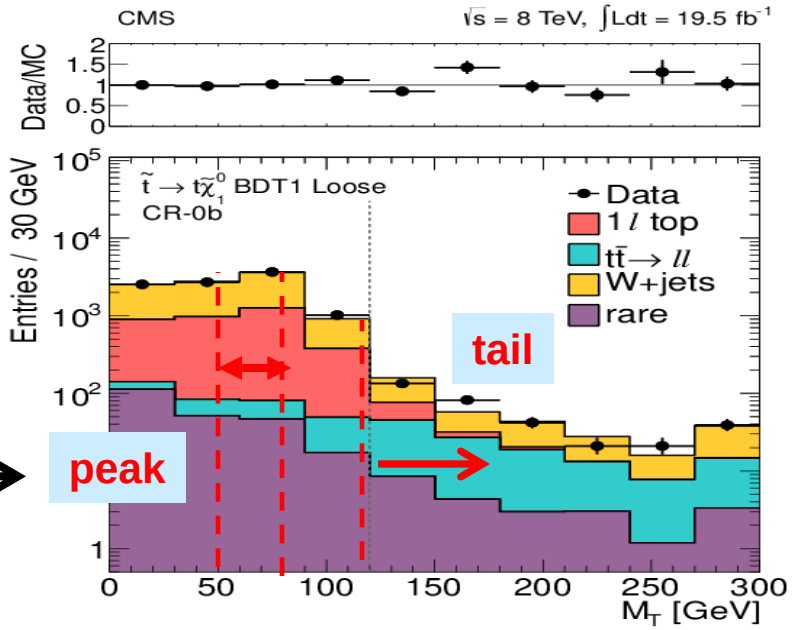
Direct stop search: BKG estimation

- **BKG shapes from simulation**
- **Estimate scale factors from a signal depleted-region using the "peak-to-tail" method:**
  - **Normalize MC to data in M_T-peak region [50-80 GeV]**
  - **Extrapolate results in M_T-tail region [> 120 GeV]**
- **Partial or full cancelation of uncertainties associated to:**
  - **Luminosity, process x-section**
  - **Lepton efficiency**
  - **JES, etc..**

W+jets validation
N_l=1, N_b=0



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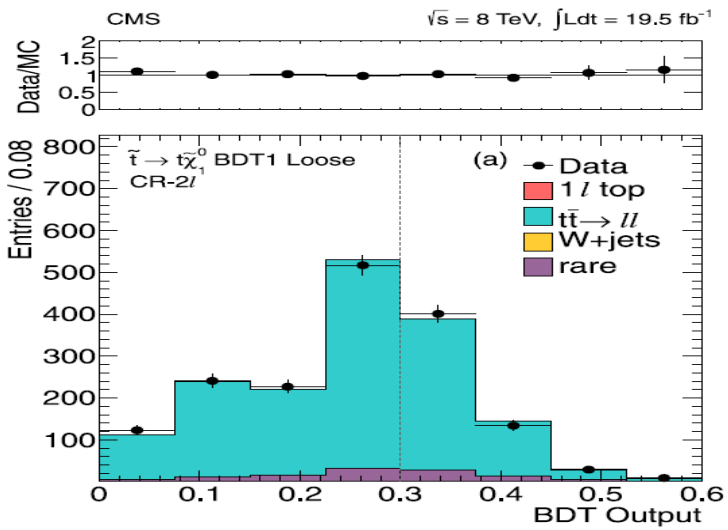
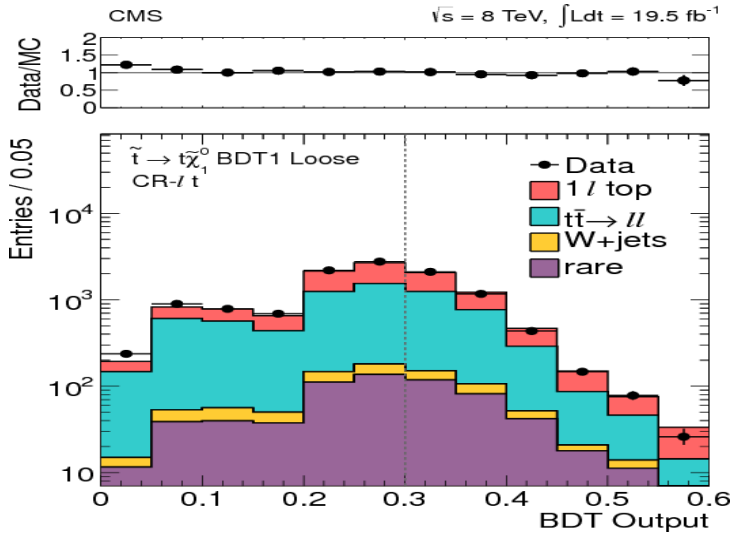
Direct stop search: BKG estimation

- **Background estimation methods validated in control regions in data:**
  - **3 CRs: tt(2lep), tt(1lep) + tt(2lep), W+jets**
  - **"rare" bkgs [i.e. multi-V, tV, ..] from MC with large uncertainties**

tt(2l) validation, N_{lep}=2



tt(2l), tt(lτ) validation, 1 iso track



- **Systematic uncertainties / process derived from these control regions**

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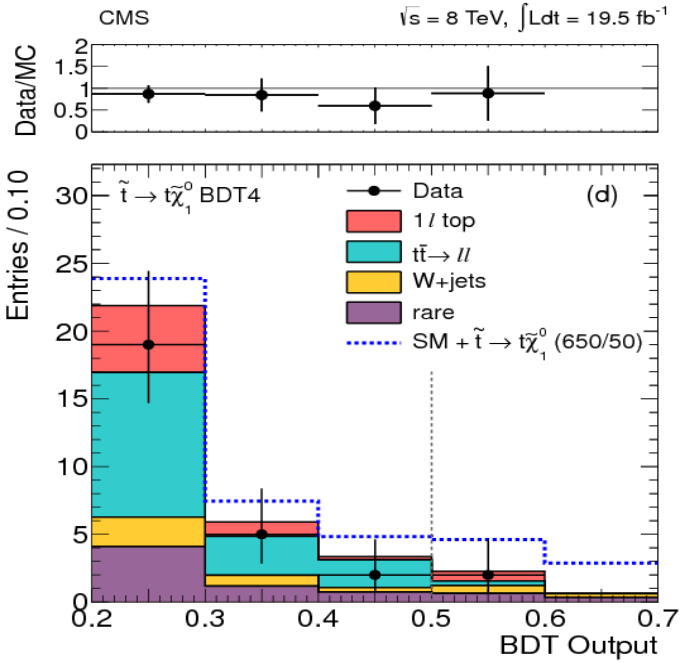
Direct stop search: results

- **Search performed in 18 SR [BDT] ; 16 SR [cut-based]**
- **No statistically significant excess observed**

Results @ 19.5 fb^{-1} [BDT]

$\tilde{t} \to t\tilde{\chi}_1^0$

Sample	BDT1–Loose	BDT1–Tight	BDT2	BDT3	BDT4	BDT5
$t\bar{t} \to \ell\ell$	438 ± 37	68 ± 11	46 ± 10	5 ± 2	0.3 ± 0.3	48 ± 13
1ℓ top	251 ± 93	37 ± 17	22 ± 12	4 ± 3	0.8 ± 0.9	30 ± 12
W + jets	27 ± 7	7 ± 2	6 ± 2	2 ± 1	0.8 ± 0.3	5 ± 2
Rare	47 ± 23	11 ± 6	10 ± 5	3 ± 1	1.0 ± 0.5	4 ± 2
Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76
$\tilde{t} \to t\tilde{\chi}_1^0$ (250/50)	285 ± 8.5	50 ± 3.5	28 ± 2.6	4.4 ± 1.0	0.3 ± 0.3	34 ± 2.9
$\tilde{t} \to t\tilde{\chi}_1^0$ (650/50)	12 ± 0.2	7.2 ± 0.2	9.8 ± 0.2	6.5 ± 0.2	4.3 ± 0.1	2.9 ± 0.1



- **Results for $\tilde{t} \to b\tilde{\chi}^+$ in back-ups**

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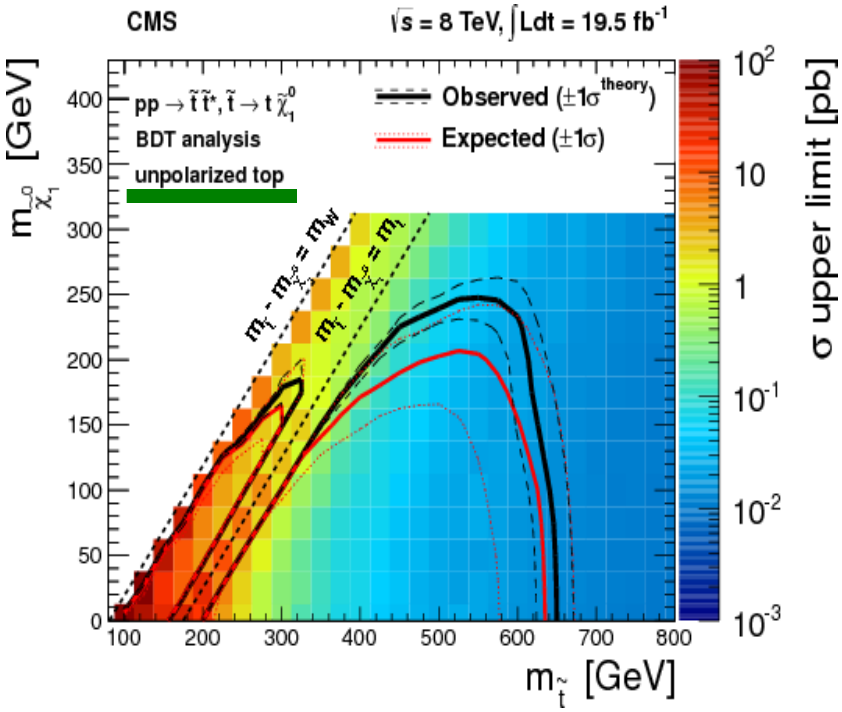
Direct stop search: interpretation

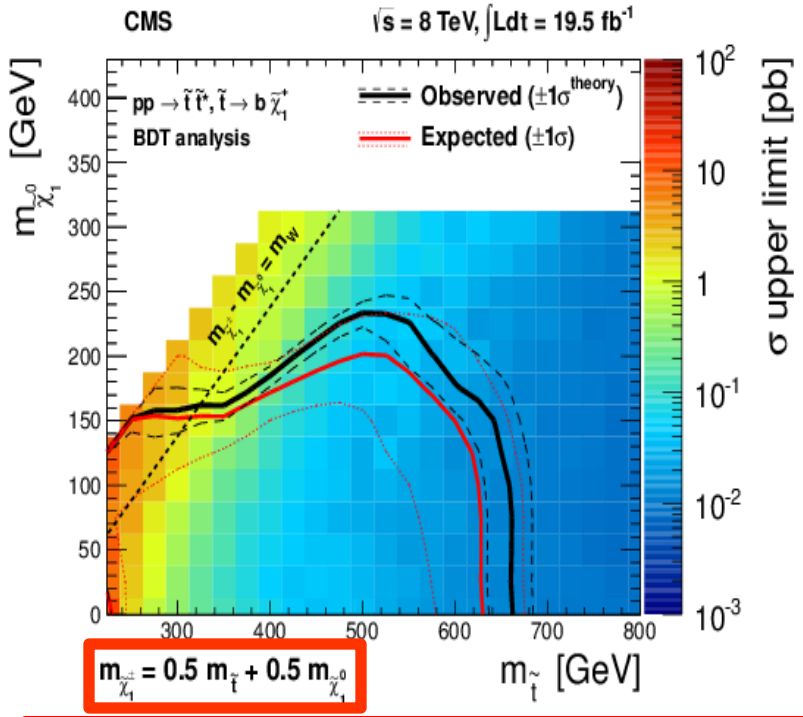
- **Direct stop production → 2 decay modes**
- **Use signal region with best expected limit**

$\tilde{t} \rightarrow t \tilde{\chi}^0_1 \rightarrow bW \tilde{\chi}^0_1$



Probes M_{stop} up to ~620 GeV

$\tilde{t} \rightarrow b \chi^{\pm} \rightarrow bW^{\pm} \tilde{\chi}^0_1$



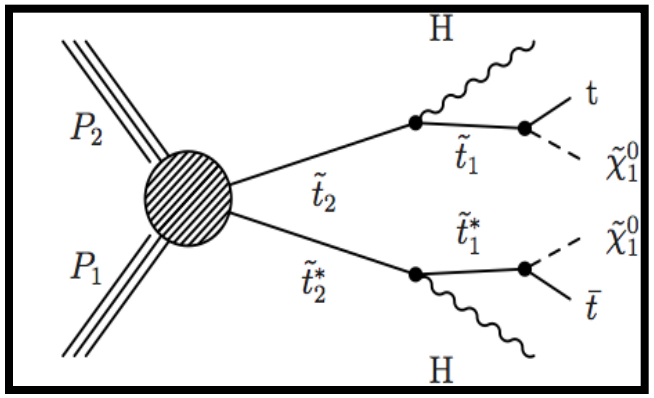
Probes M_{stop} up to ~650 GeV

Associated stop – Higgs production

Direct stop search with H: strategy

- **Search for direct stop production in association with H**
  - Leptonic final state
  - H→bb [large BR]
  - Focus on scenarios where:

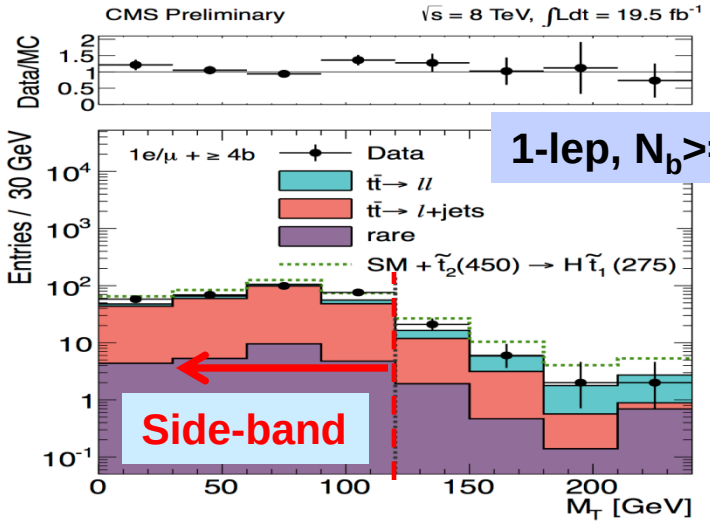
$$M(\tilde{t}_1)\text{-}M(\tilde{\chi}_1^0)\sim M(t)$$



    - Challenging kinematic region [low ME_T]
- **Event selection:**
  - 1 isolated lepton [e/μ], $N_j \geq 4$ (5), $N_b \geq 4$ (3)
  - $M_T(l,ME_T)>120$ (150) GeV [suppress tt(1l) & W+jets]
  - $ME_T>50$ GeV [W+jets]
  - Veto events with additional isolated track [suppress tt(2l)]
- **In addition to 1-lep, a 2-lep search is carried out**
  - details not discussed here

Direct stop search & H: BKG estim.

- **Main BKGs [i.e tt(1lep) & tt(2lep)] from side-bands in data and transfer factors from simulation**
  - **Inversion of M_T cut**
- **Advantage:**
  partial or full cancelation of uncertainties associated to:
  - **Luminosity, process x-section**
  - **Lepton efficiency**
  - **JES, etc..**



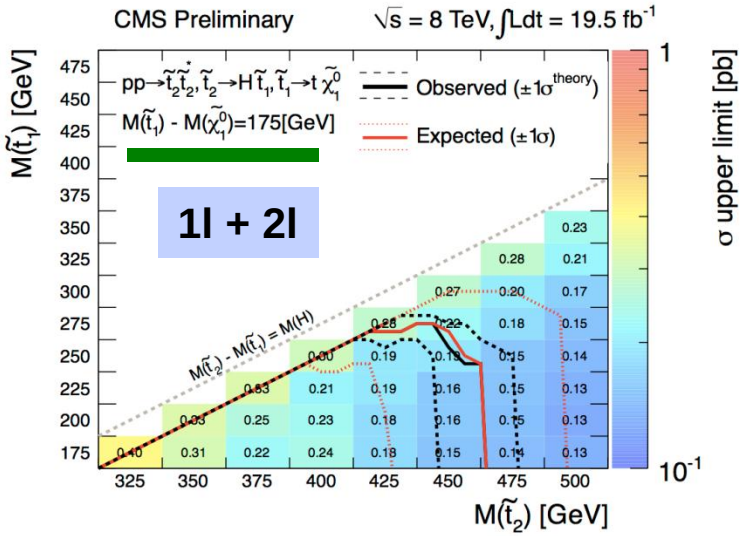
- **"Rare" BKGs [i.e ttV, 2-V, 3-V, V+jets] from simulation with large uncertainties**
- **Control regions in data used to derive scale factors**

Direct stop search & H: results

- **Results for both 1-lep & 2-lep channels**
  - **No statistically significant excess**

Results @ 19.5 fb^{-1}

Sample	1l + 3b	1l + ≥4b	2l + 3b	2l + ≥4b
$t\bar{t} \rightarrow \ell$ + jets	6.1 ± 1.1	13.2 ± 3.2	0.0 ± 0.1	0.1 ± 0.1
$t\bar{t} \rightarrow \ell\ell$ + jets	3.2 ± 0.9	10.4 ± 4.3	7.2 ± 2.1	8.8 ± 3.8
Rare	0.8 ± 0.1	3.2 ± 0.8	1.2 ± 0.2	1.7 ± 0.6
Total background prediction	10.0 ± 1.8	26.8 ± 5.6	8.4 ± 2.7	10.6 ± 5.1
Total relative uncertainty [%]	17.5	20.9	31.7	48.2
Data	14	31	15	3



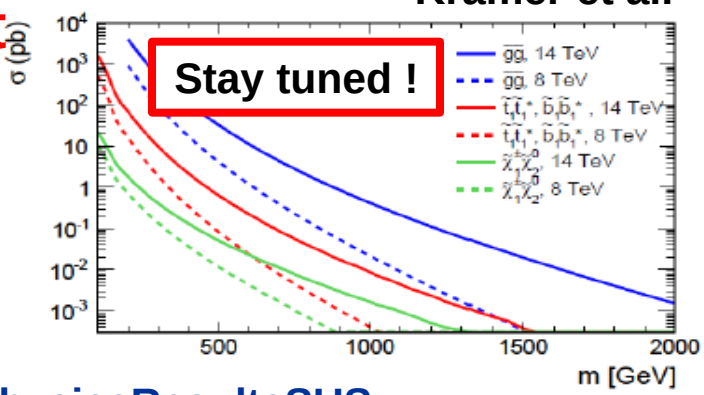
Probes M_{stop2} ~450 GeV for M_{stop1} ~250 GeV

Summary

Summary

- **Naturalness requires light gluinos, stops and sbottoms**
  - **[probably] within LHC reach**
- **Several searches [based on lepton multiplicity] for direct & indirect stop/sbottom production in CMS**
  - **Single-lepton searches provide very competitive results!**
- **No excess found: limits in m_{gluino}, m_{lsp}, m_{stop} tightened**
  - **M_{gluino} ~<1280 GeV, M_{stop}~< 650 GeV [~10% fine tuning]**
- **Natural SUSY constrained; still large open param.space**
- **Upcoming 13 TeV run significant impact on SUSY prod. x-section**
  - **Largest impact on gluino prod.**

Kramer et al.



CMS SUSY results:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Additional material

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Direct stop search: results

$\tilde{t} \to b\chi^{\pm} \to bW^{\pm}\tilde{\chi}^{0}_{1}$

$\tilde{t} \to b\tilde{\chi}^{+}$ $x = 0.25$			
Sample	BDT1	BDT2	BDT3
$t\bar{t} \to \ell\ell$	18 ± 4	2.2 ± 1.3	1.2 ± 1.0
1ℓ top	10 ± 5	4.0 ± 1.8	1.5 ± 0.8
W + jets	3 ± 1	2.0 ± 0.7	0.7 ± 0.3
Rare	4 ± 2	1.6 ± 0.8	1.0 ± 0.5
Total	35 ± 6	9.8 ± 2.4	4.4 ± 1.4
Data	29	7	2
$\tilde{t} \to b\tilde{\chi}^{+}$ (450/50/0.25)	19 ± 2.9	11 ± 2.2	5.2 ± 1.5
$\tilde{t} \to b\tilde{\chi}^{+}$ (600/100/0.25)	8.8 ± 0.8	7.5 ± 0.8	5.6 ± 0.7

$\tilde{t} \to b\tilde{\chi}^{+}$ $x = 0.5$					
Sample	BDT1	BDT2–Loose	BDT2–Tight	BDT3	BDT4
$t\bar{t} \to \ell\ell$	40 ± 5	21 ± 4	4 ± 2	6 ± 2	100 ± 16
1ℓ top	24 ± 10	15 ± 7	4 ± 3	4 ± 2	33 ± 12
W + jets	5 ± 1	5 ± 1	2 ± 1	3 ± 1	5 ± 1
Rare	8 ± 4	8 ± 4	3 ± 1	4 ± 2	8 ± 4
Total	77 ± 12	50 ± 9	13 ± 4	17 ± 4	146 ± 21
Data	67	35	12	13	143
$\tilde{t} \to b\tilde{\chi}^{+}$ (250/50/0.5)	45 ± 7.6	24 ± 5.2	5.7 ± 2.4	5.2 ± 2.6	55 ± 8.1
$\tilde{t} \to b\tilde{\chi}^{+}$ (650/50/0.5)	3.5 ± 0.4	9.5 ± 0.7	5.6 ± 0.5	8.3 ± 0.6	3.2 ± 0.4

$\tilde{t} \to b\tilde{\chi}^{+}$ $x = 0.75$				
Sample	BDT1	BDT2	BDT3	BDT4
$t\bar{t} \to \ell\ell$	37 ± 5	9 ± 2	3.1 ± 1.3	248 ± 22
1ℓ top	17 ± 9	6 ± 5	1.6 ± 1.6	188 ± 70
W + jets	4 ± 1	4 ± 1	1.6 ± 0.6	22 ± 6
Rare	4 ± 2	4 ± 2	1.8 ± 0.9	20 ± 10
Total	61 ± 10	22 ± 6	8.1 ± 2.3	478 ± 74
Data	50	13	5	440
$\tilde{t} \to b\tilde{\chi}^{+}$ (250/50/0.75)	115 ± 13	21 ± 5.6	8.0 ± 3.7	518 ± 28
$\tilde{t} \to b\tilde{\chi}^{+}$ (650/50/0.75)	3.9 ± 0.4	8.4 ± 0.6	6.8 ± 0.6	5.5 ± 0.5

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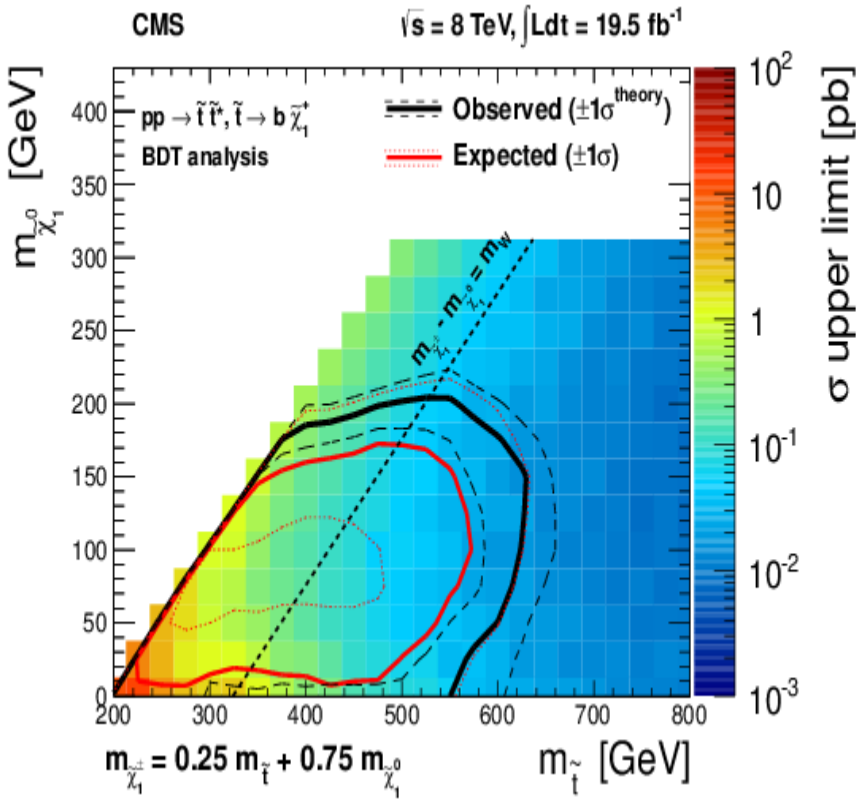
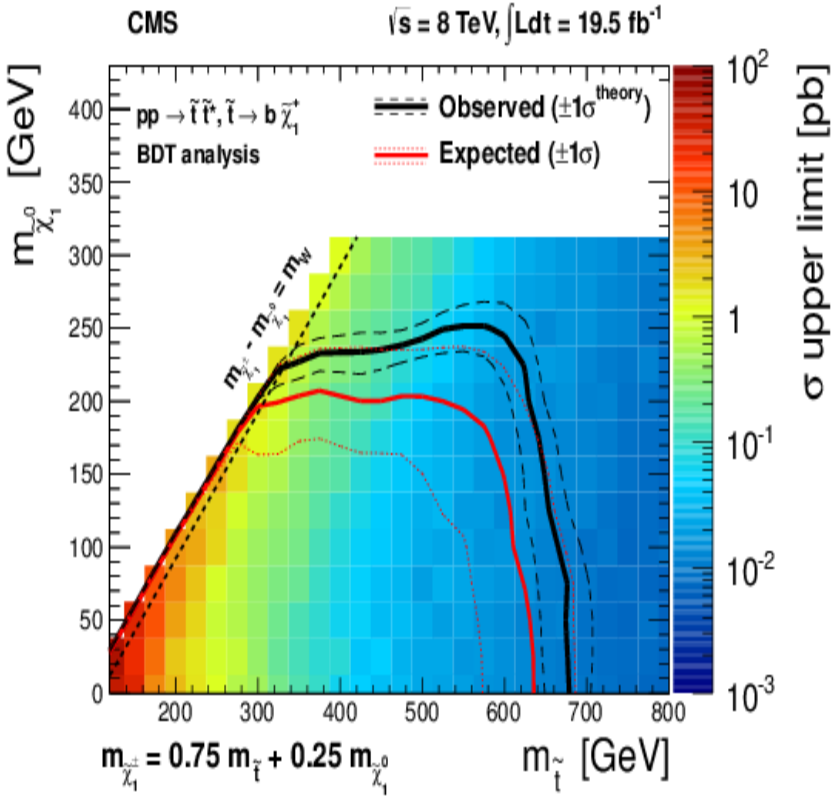
Direct stop search: interpretation

$$\tilde{t} \rightarrow b\chi^{\pm} \rightarrow bW^{\pm}\tilde{\chi}_1^0$$





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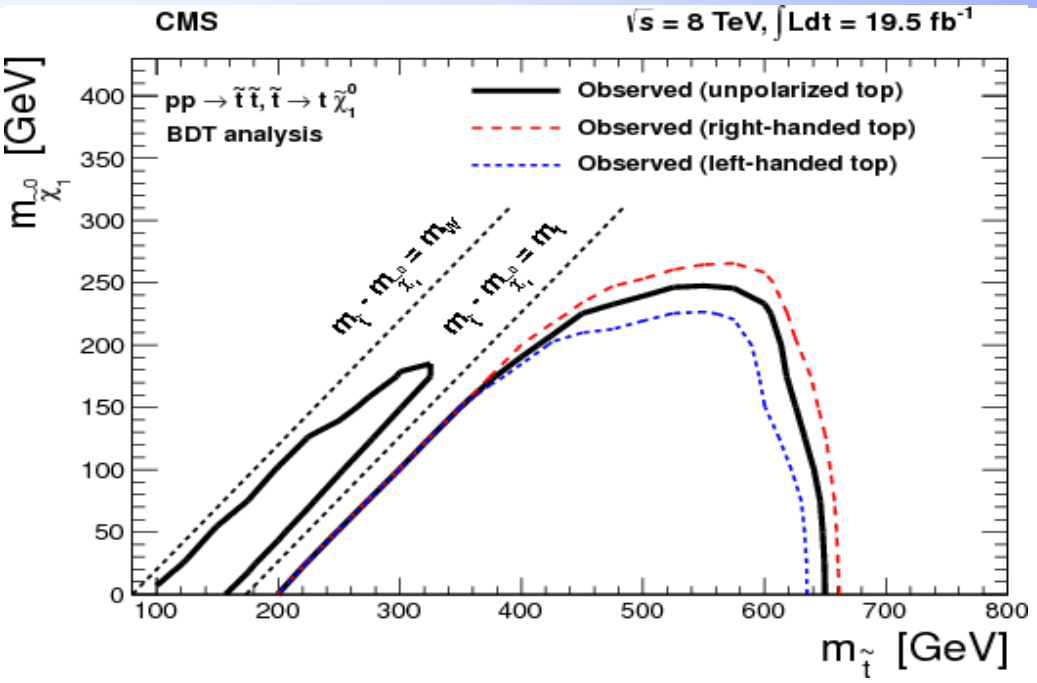
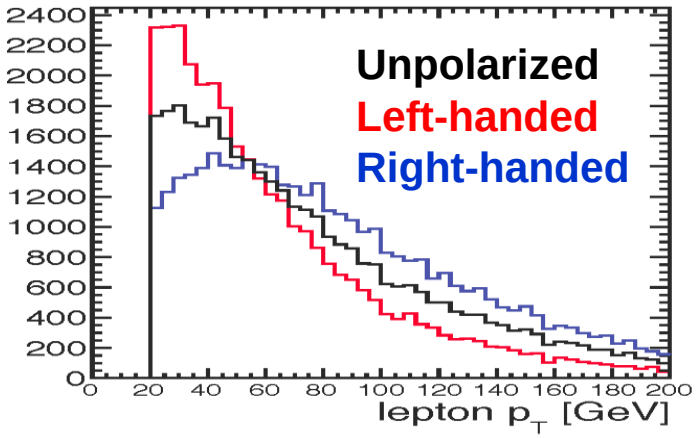
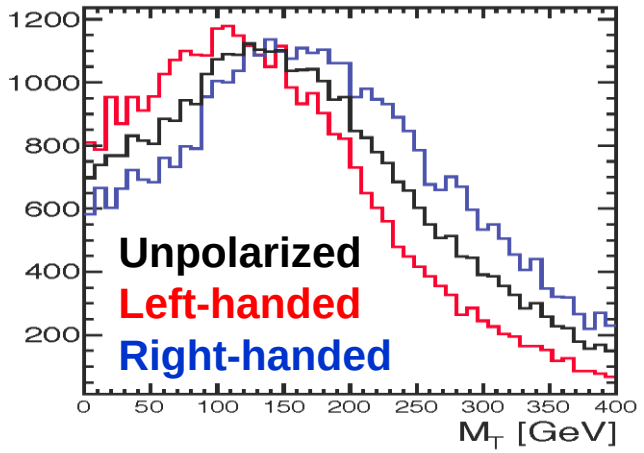
Direct stop search: interpretation

T2tt



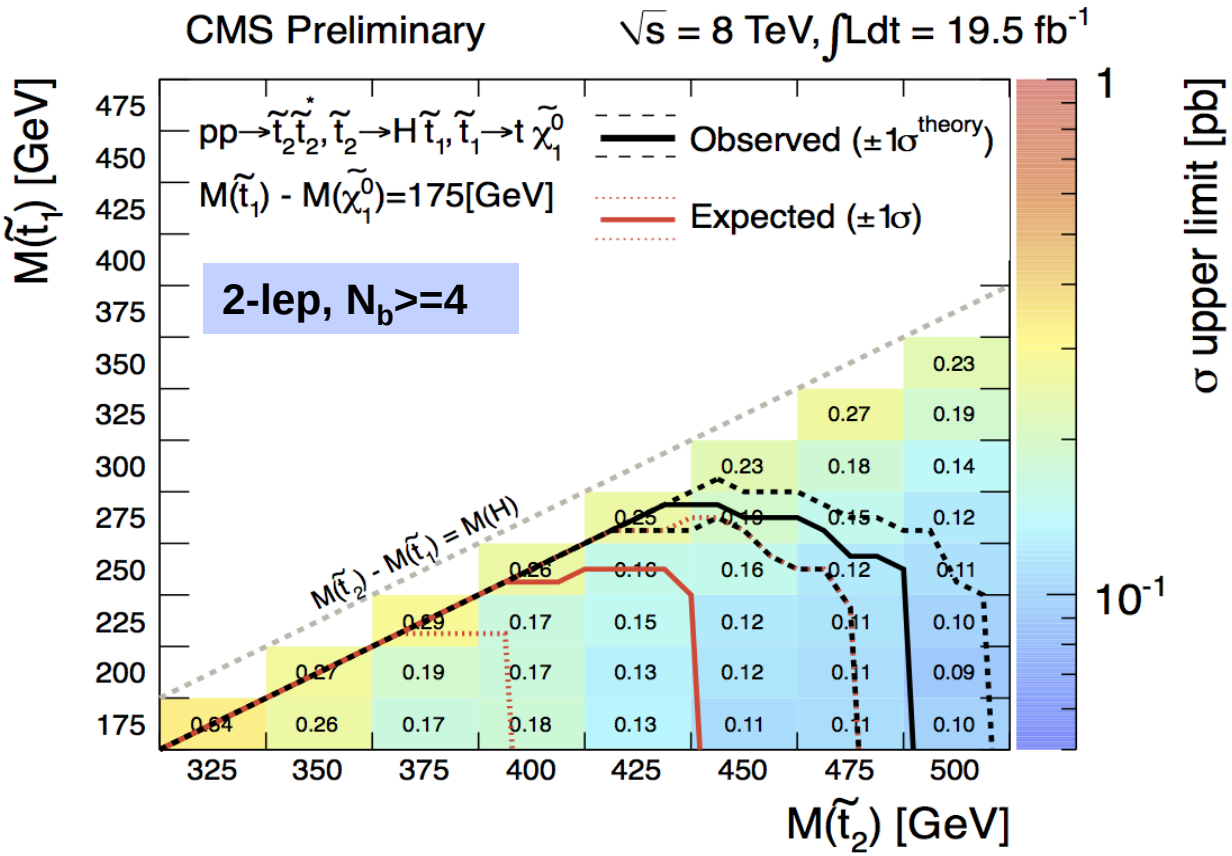
Charged lepton emitted mostly parallel to top boost





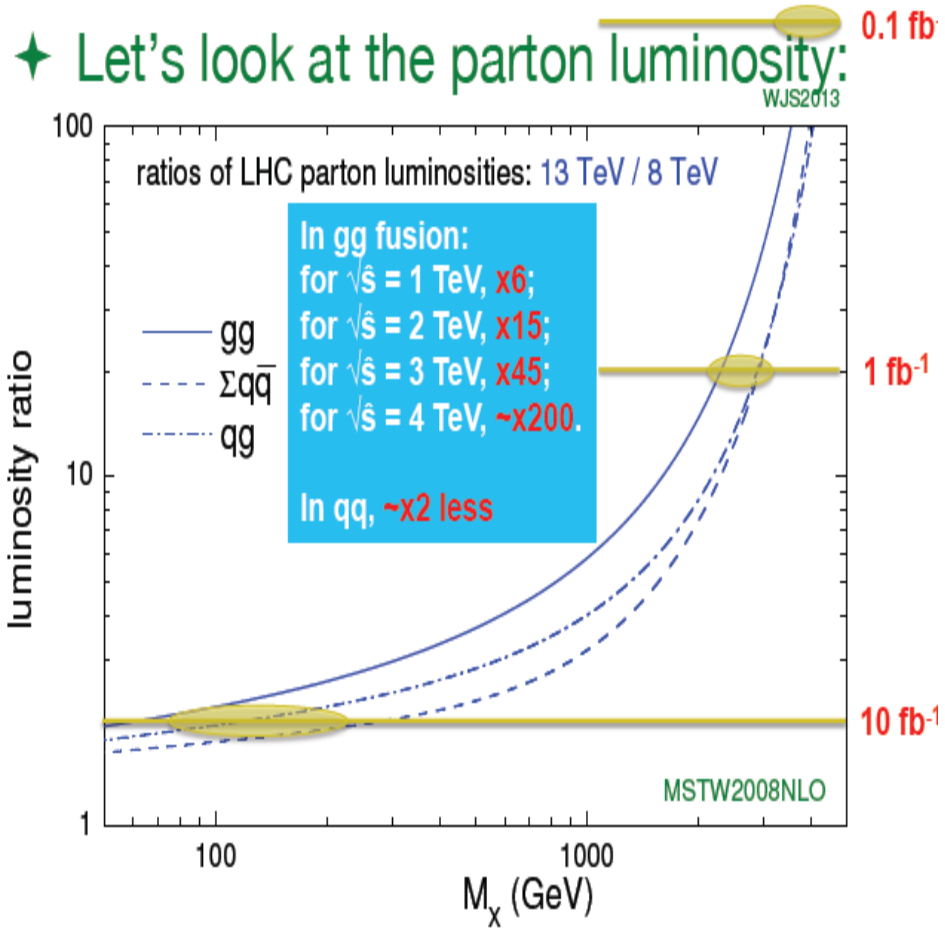
Direct stop search & H: results

- **Sensitivity driven by 2-lep search**



Direct stop search: interpretation

From Greg Landsberg's talk



- **RunI: M_g > 1.4 TeV @ 95% CL**
- **Probe M_g = 1.5 TeV**
  - **Corresponds to sqrt(s) = 3 TeV**
    - **Produced via g-g**
    - **boost in x-section @ 14 TeV ~ factor of 45**
  - **Exclusion sensitivity of M_g~1.5 TeV with ~0.5 fb^{-1}**