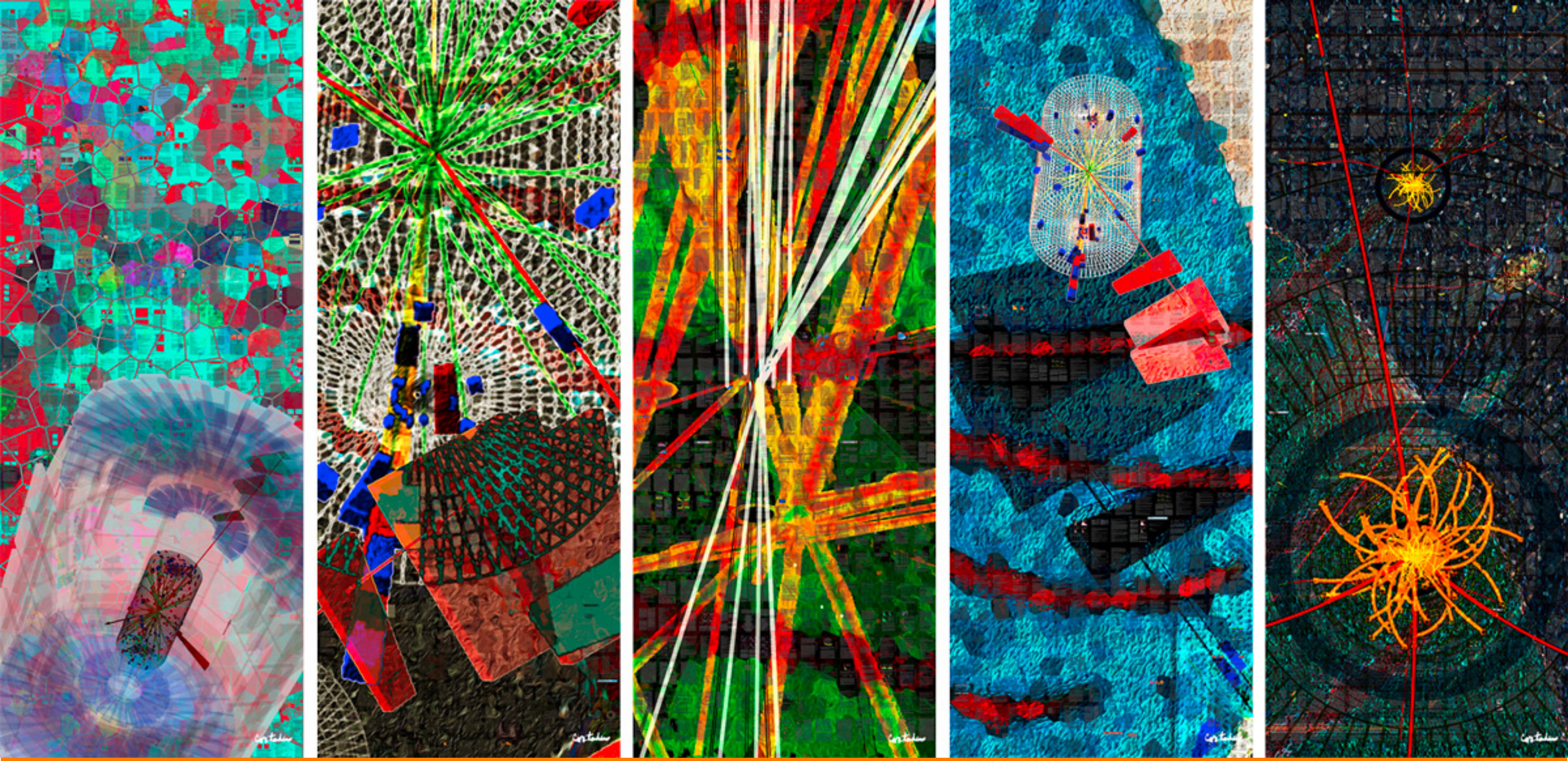


Searches for Top Squark Pairs at the LHC

Verena I. Martinez Outschoorn

University of Illinois Urbana-Champaign

U. of Chicago HEP Seminar, November 10th, 2014

Art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz)

Outline

Why search for top squarks (stops) ?

Top squark production and decay

Inclusive search in 1ℓ + jets mode in CMS

Limitations

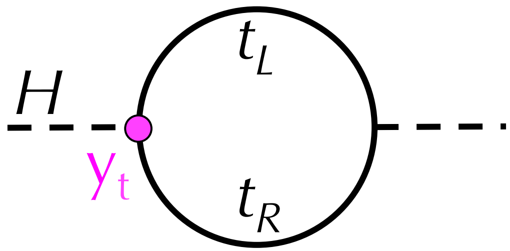
Prospects and conclusions

SUSY

Hierarchy Problem & Naturalness

$$\Delta m_H^2 \sim |y_t|^2 \left[-\Lambda_{UV}^2 + \frac{3}{2} m_t^2 \log\left(\frac{\Lambda_{UV}^2}{m_t^2} \right) \right]$$

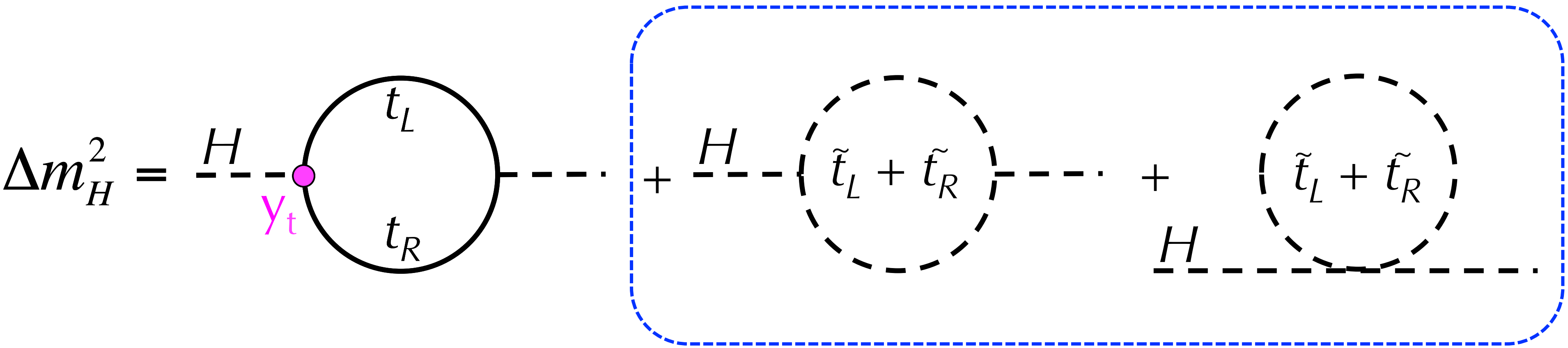
$\Delta m_H^2 =$



Enormous radiative corrections to m_{higgs} in SM: $\Delta m^2 \sim \Lambda^2_{UV}$

Hierarchy Problem & Naturalness

$$\Delta m_H^2 \sim |y_t|^2\left[-\Lambda_{UV}^2 + \frac{3}{2}m_t^2\log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right)\right] + \Lambda_{UV}^2 - \frac{3}{2}m_{\tilde{t}}^2\log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}\right) + \ldots\Big]$$



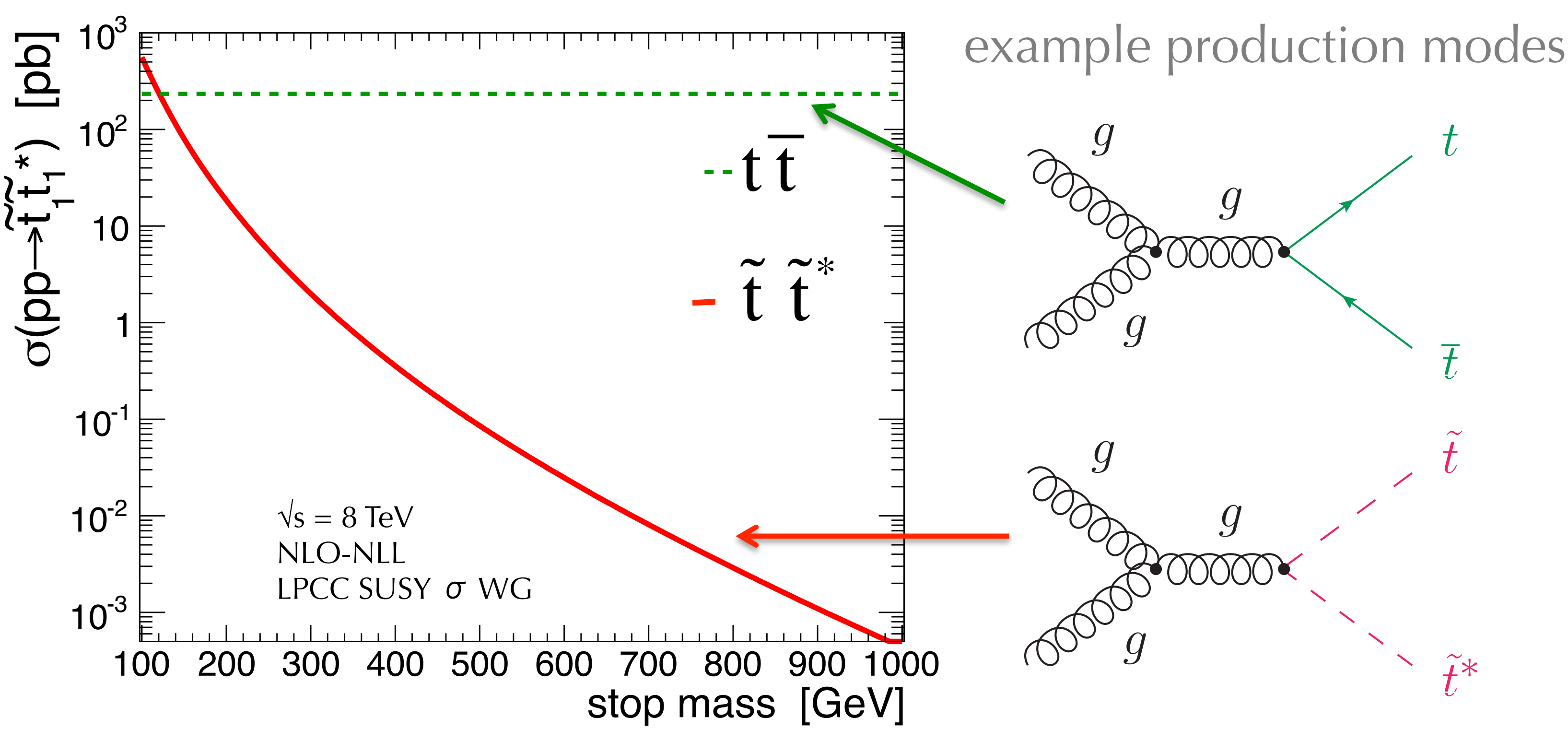
Enormous radiative corrections to m_{higgs} in SM: $\Delta m^2 \sim \Lambda^2_{UV}$

Top squarks cancel the Λ^2_{UV} term, remainder depends on difference between m_t^2 and m^2_{stop}

Light stops needed for "natural" (not fine-tuned) solution to the hierarchy problem

Stop Production & Decay

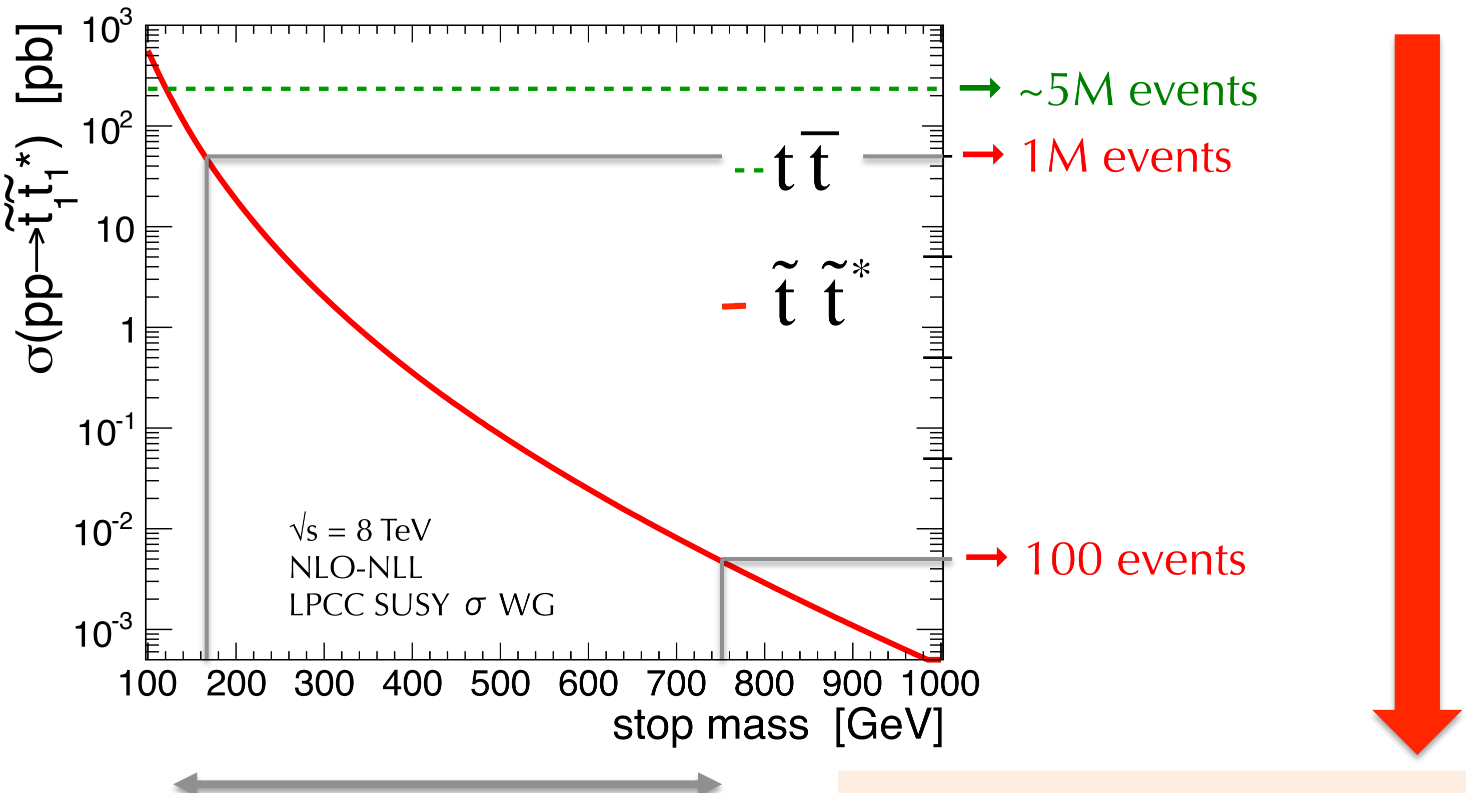
Top Squark Production at the LHC



Top Squark Production at the LHC

$N = \sigma \cdot \mathcal{L}$

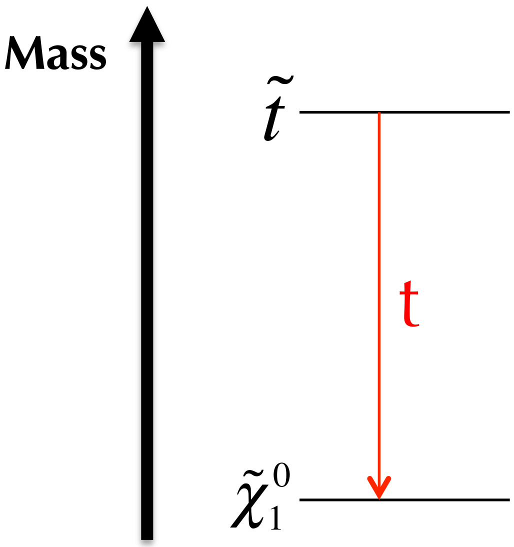
Events in 2012

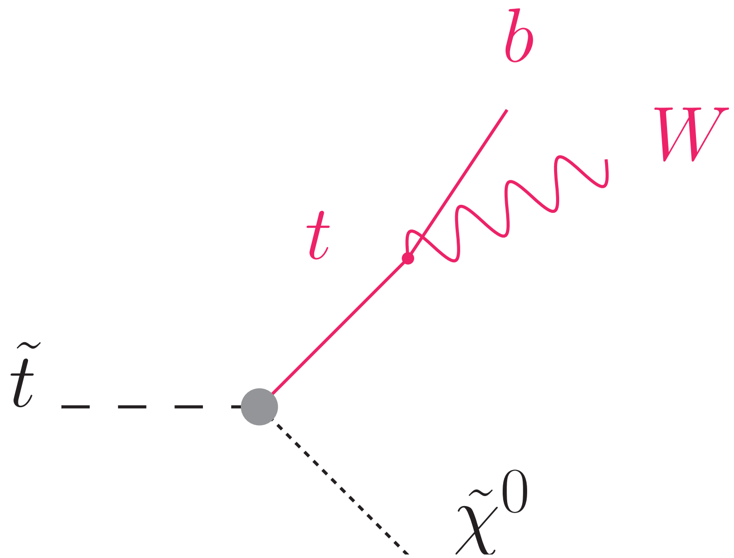


Sensitive up to m_{stop} ~ 700 GeV

SM tt is ~10-10000 more likely to be produced in LHC collisions

Top Squark Decays

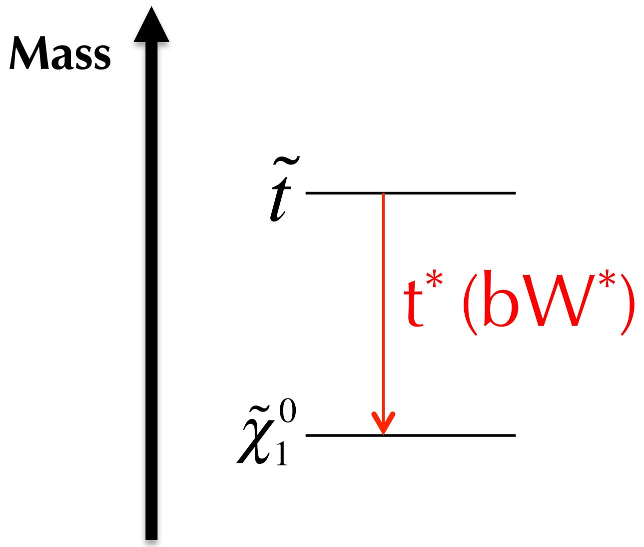


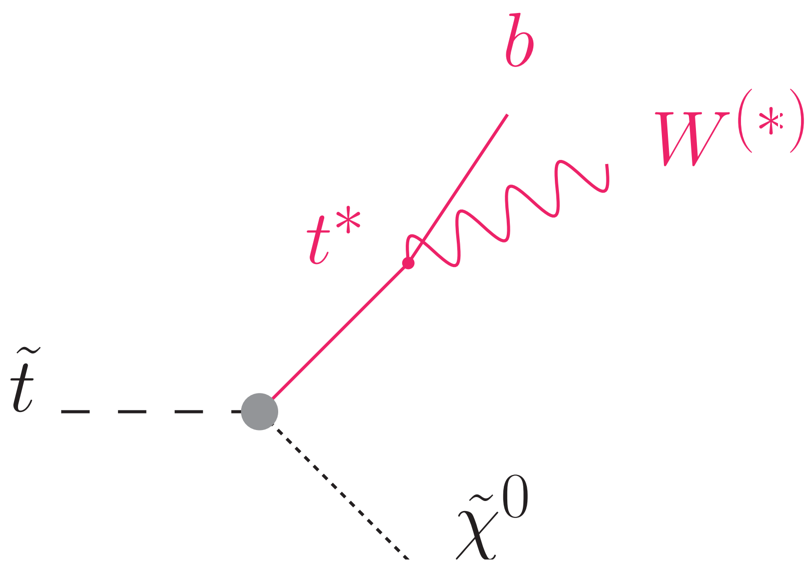


Δm > m$_{top}$ on-shell top

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

Top Squark Decays

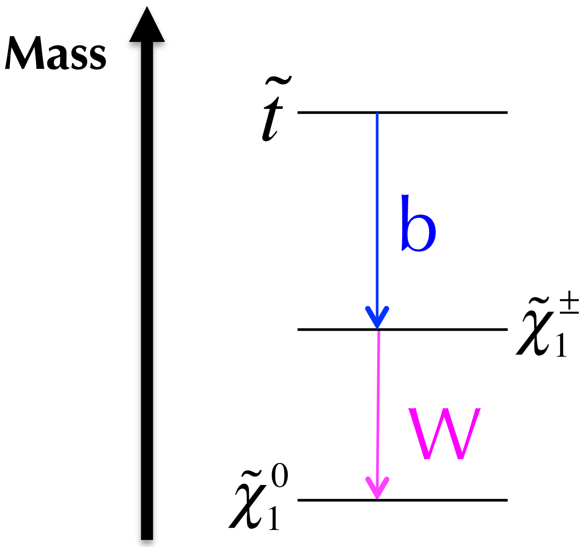


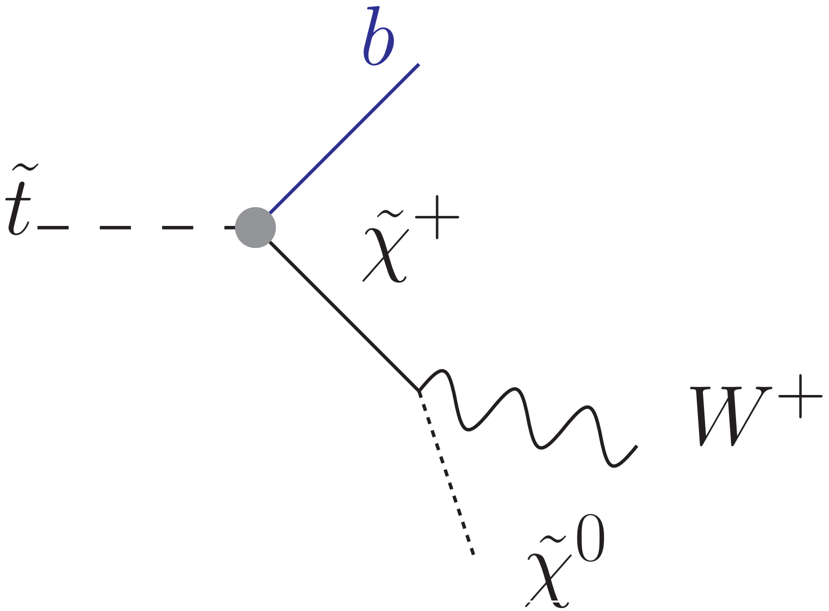


Δm < m_{top} off-shell top
Δm < m_W off-shell W

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

Alternative Top Squark Decays





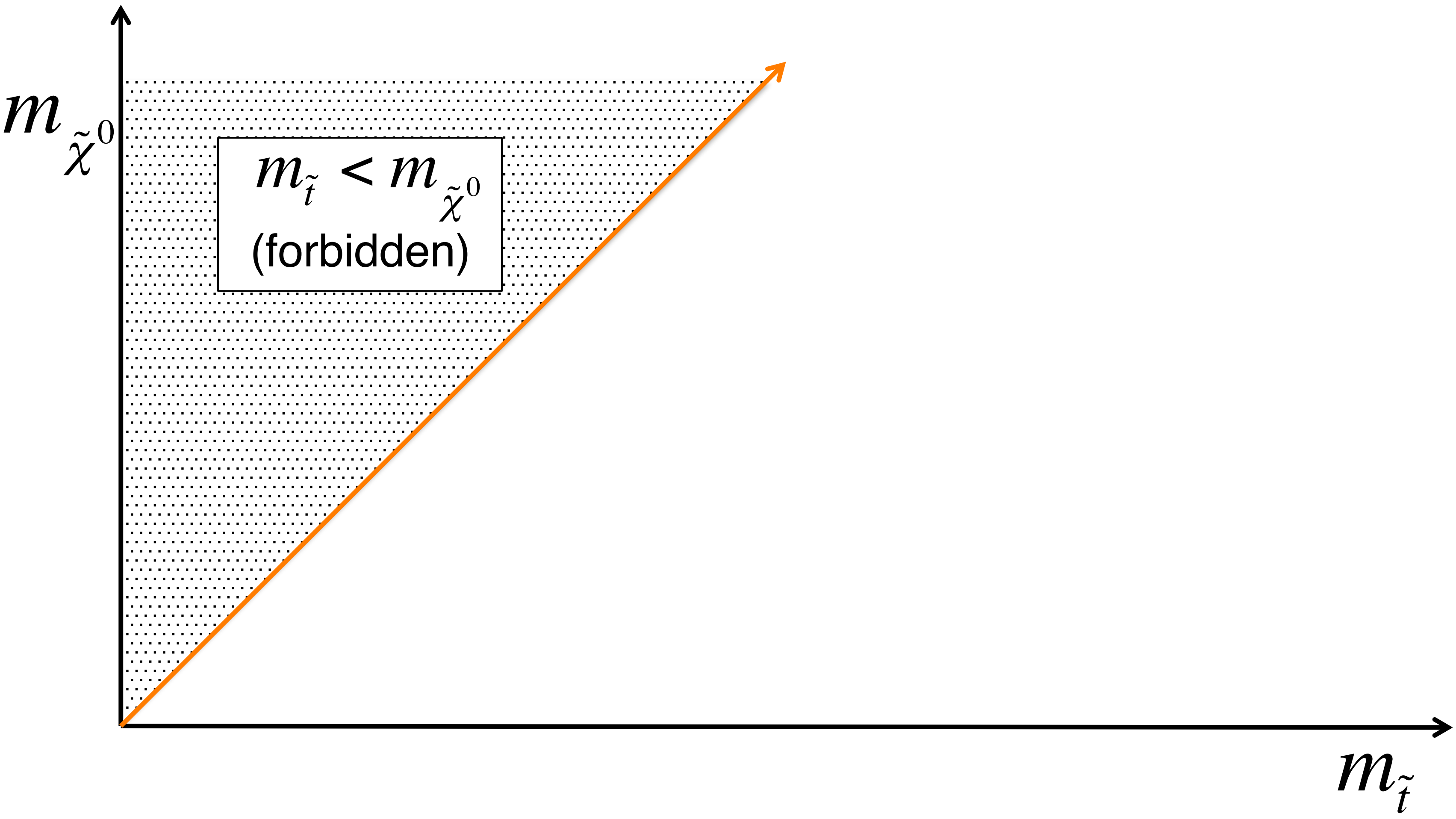
$$\tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0$$

Same objects in the final state as

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

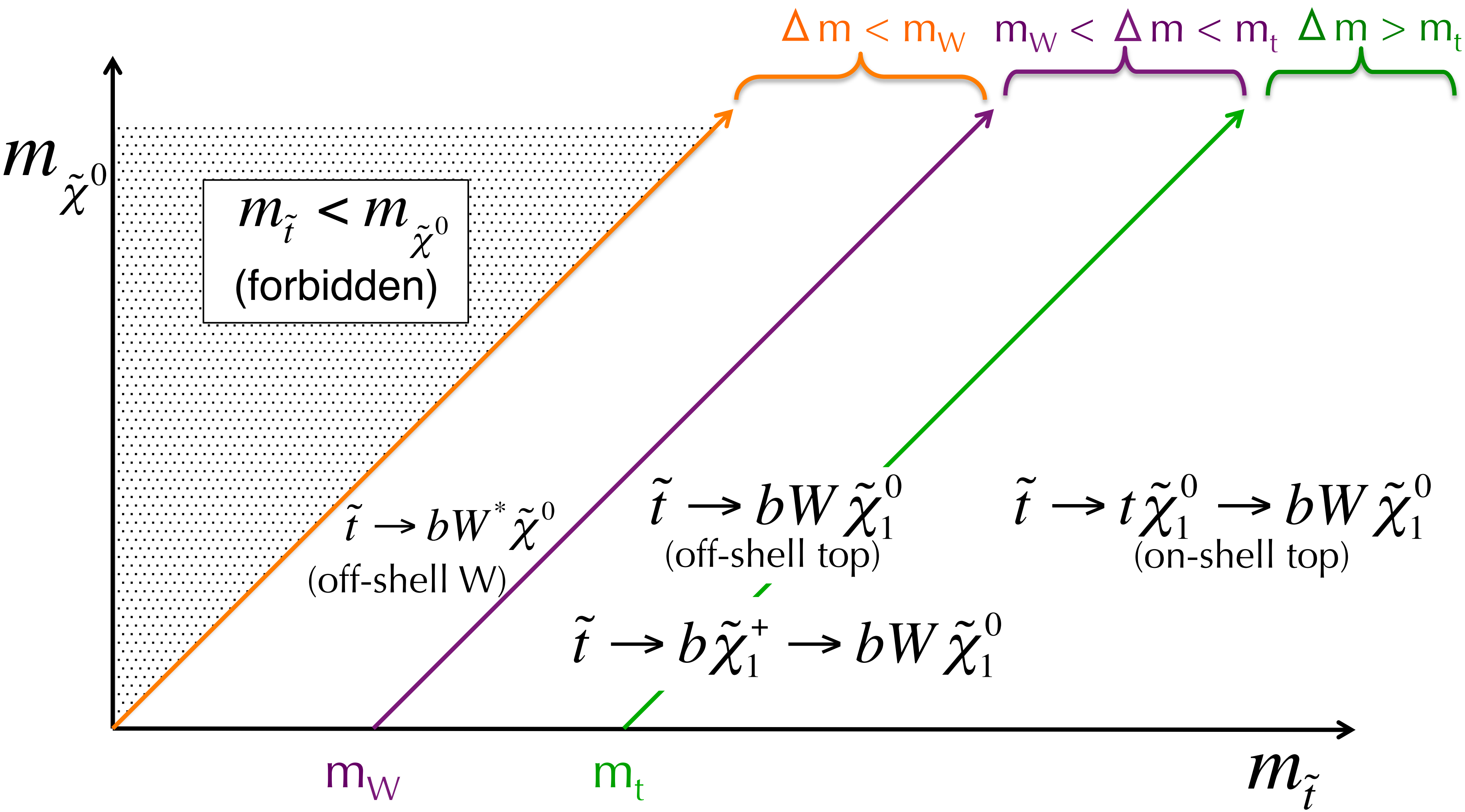
Top Squark Decays

$$\Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0}$$

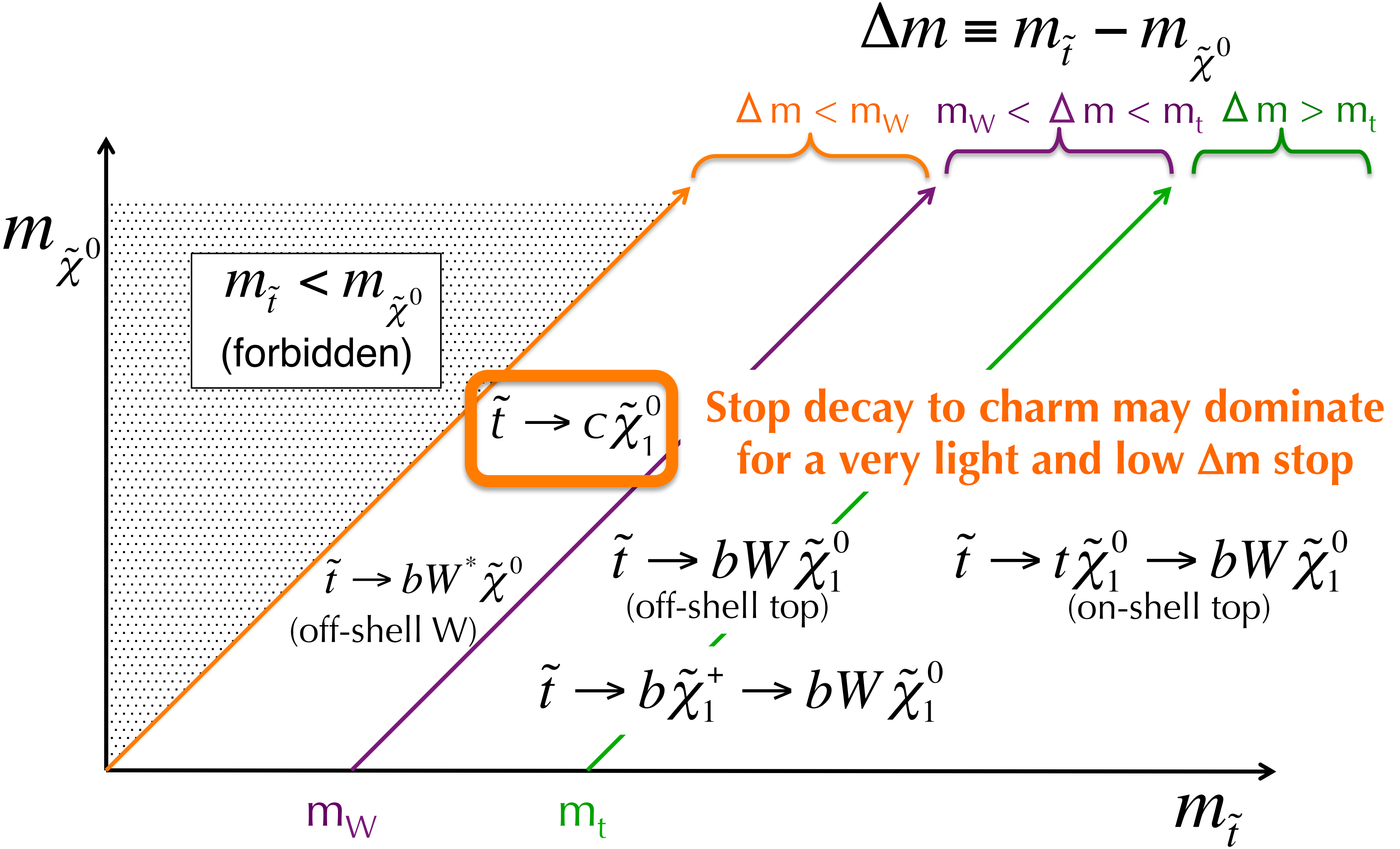


Top Squark Decays

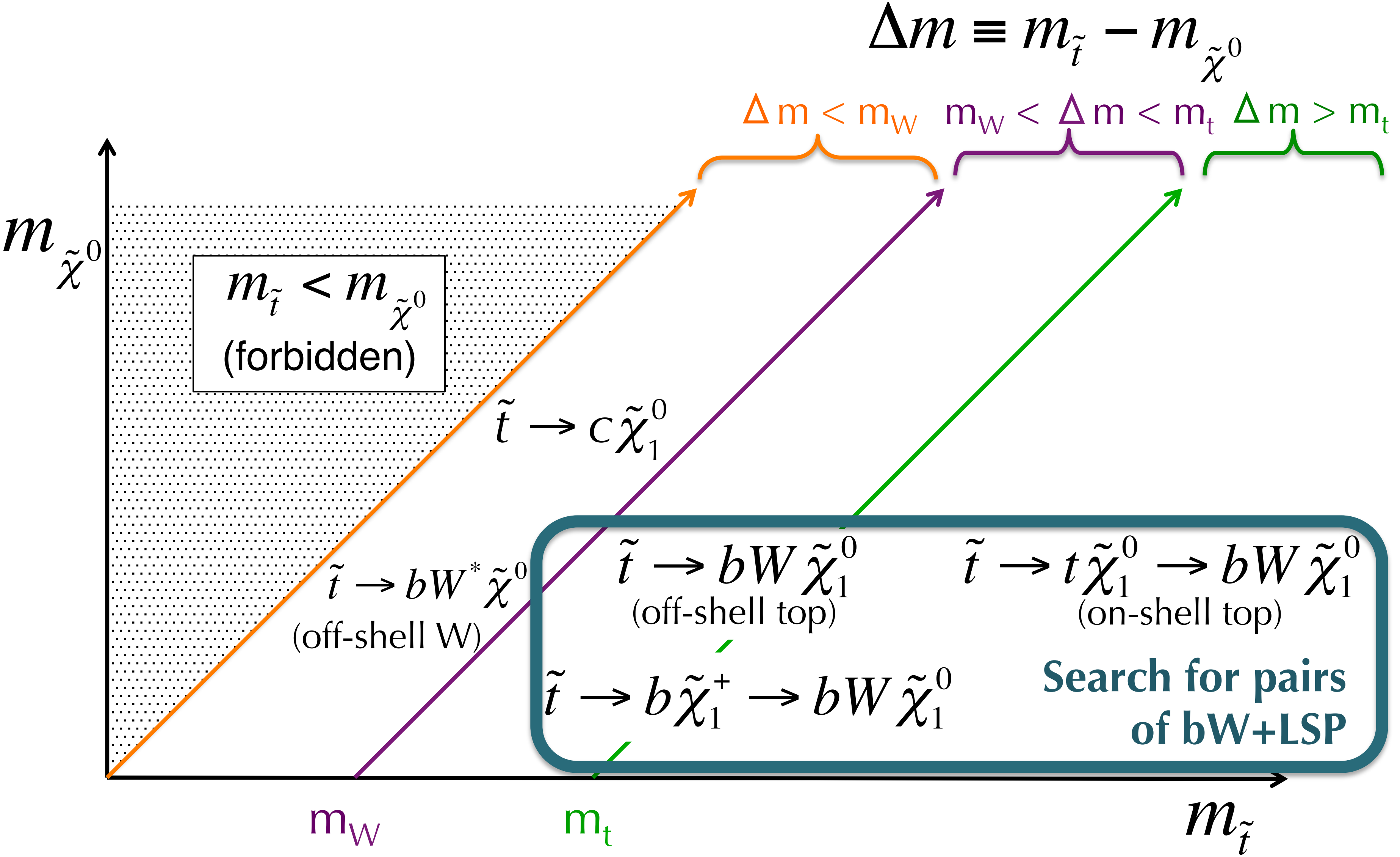
$$\Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0}$$



Top Squark Decays



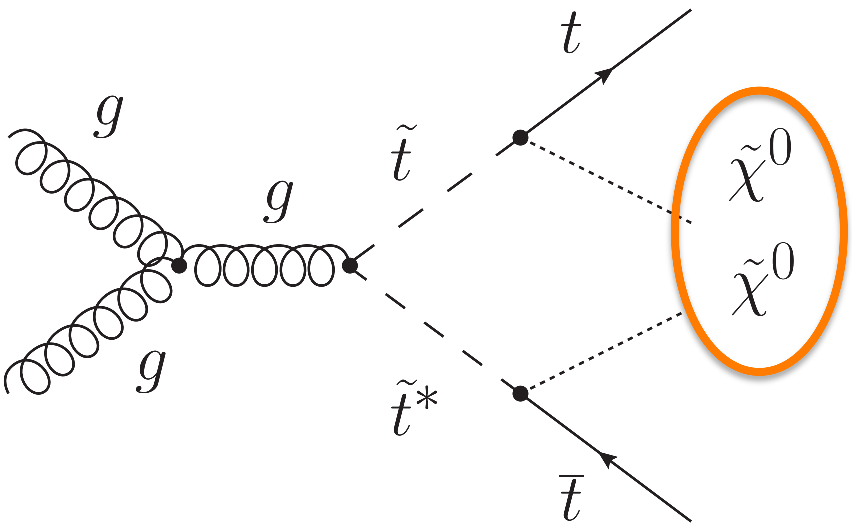
Top Squark Decays



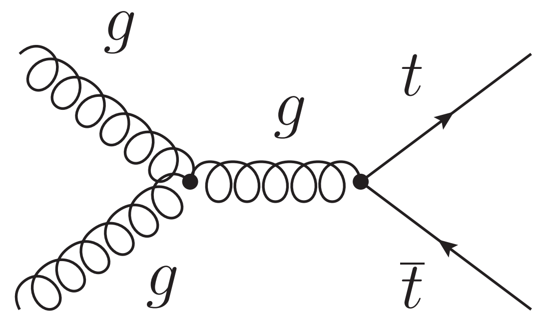
Search in 1ℓ + jets mode in CMS

Top Squark Search

stop signal

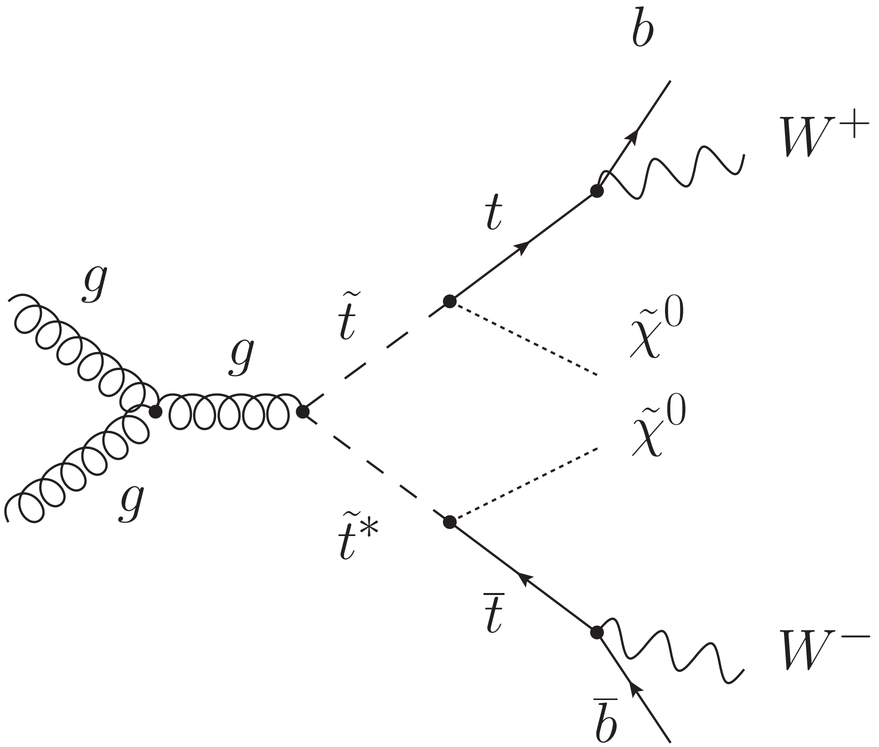


top background

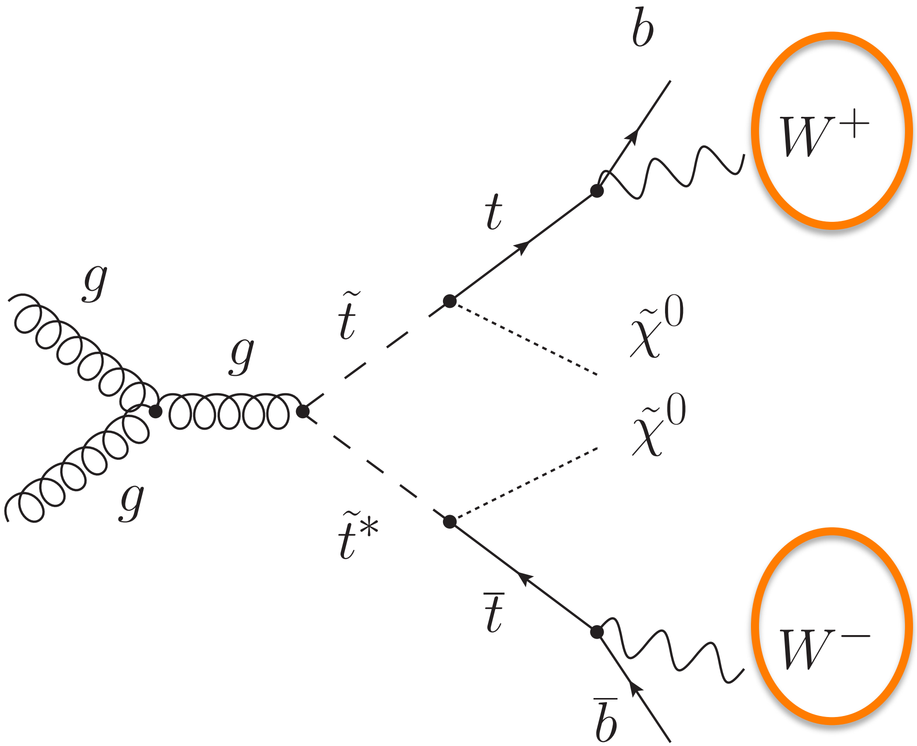


Signal is tt with extra missing energy

Top Squark Signature

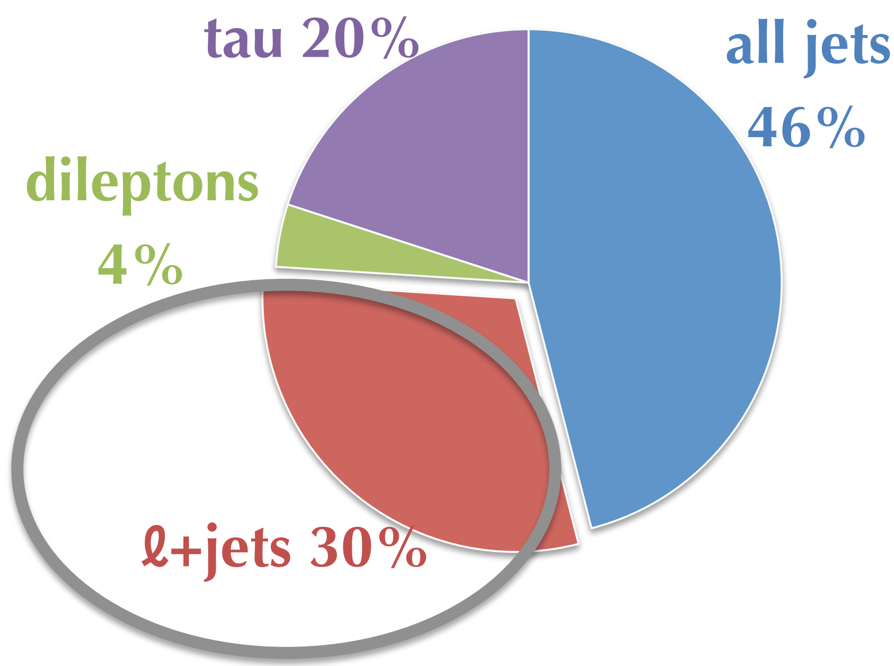


Top Squark Signature



Signature depends on W decay modes

lepton ℓ = e or μ



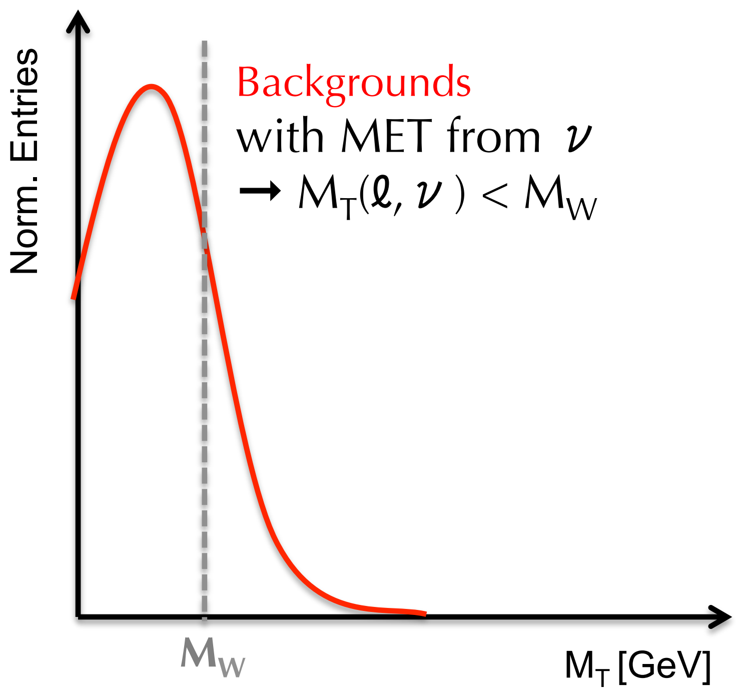
Eur. Phys. J. C 73 (2013) 2677 hep-ex/1308.1586

Kinematics: Transverse Mass

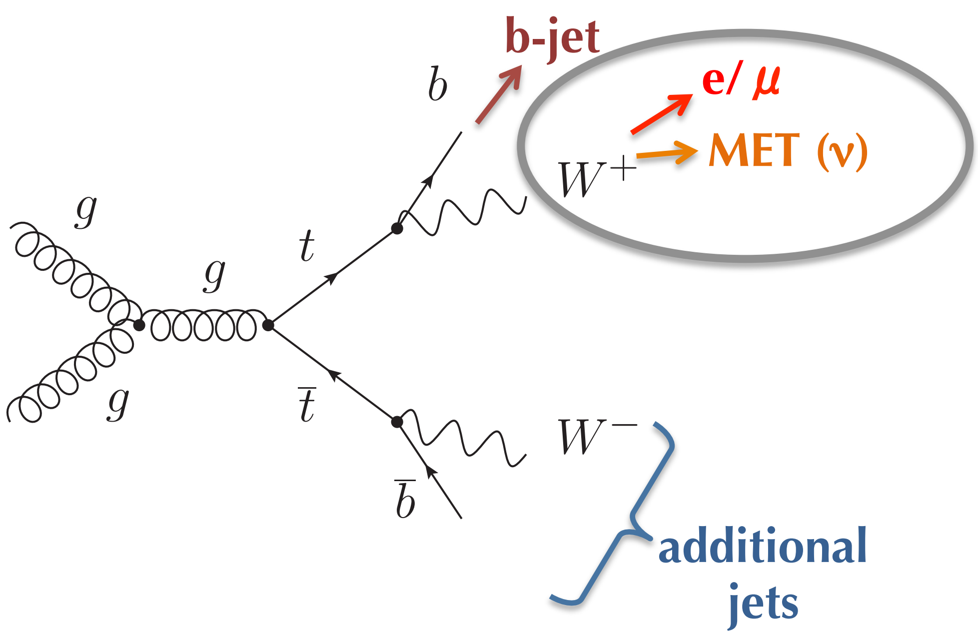
$$M_T^W(\ell,\nu)^2 = (E_T(\ell) + E_T(\nu))^2 - (\vec{p_T}(\ell) + \vec{p_T}(\nu))^2$$

$$\rightarrow 2E_T(\ell)E_T(\nu)(1 - \cos(\Delta\phi))$$

MET



top background



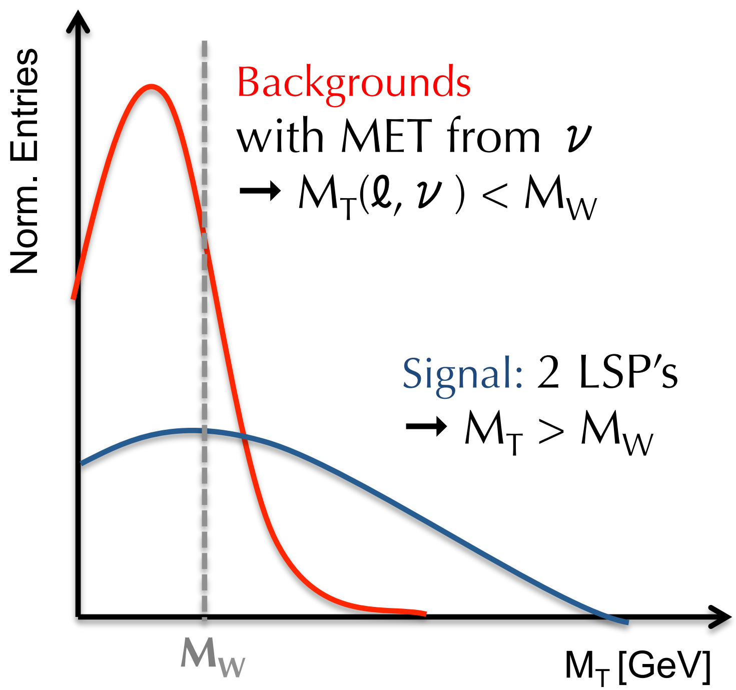
Also other backgrounds: W+jets, single top, rare processes (e.g. ttZ)

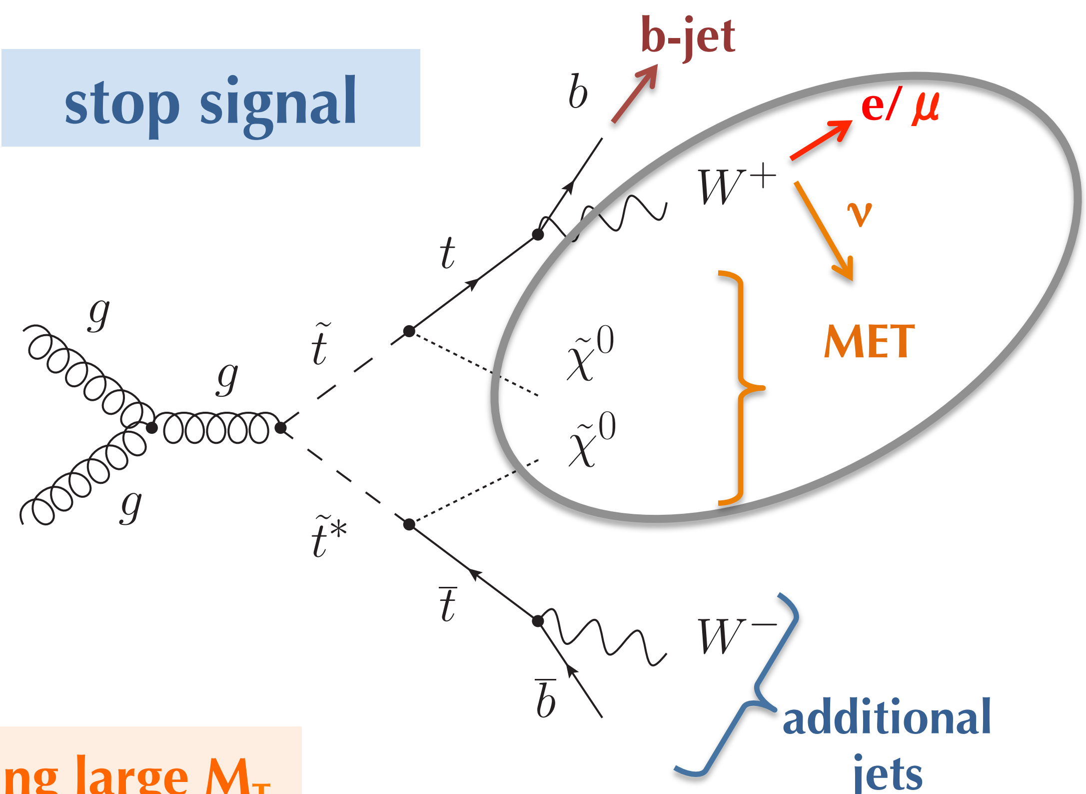
Kinematics: Transverse Mass

$$M_T^W(\ell,\nu)^2 = (E_T(\ell)+E_T(\nu))^2 - (\vec{p_T}(\ell)+\vec{p_T}(\nu))^2$$

$$\rightarrow 2E_T(\ell)E_T(\nu)(1-\cos(\Delta\phi))$$

MET

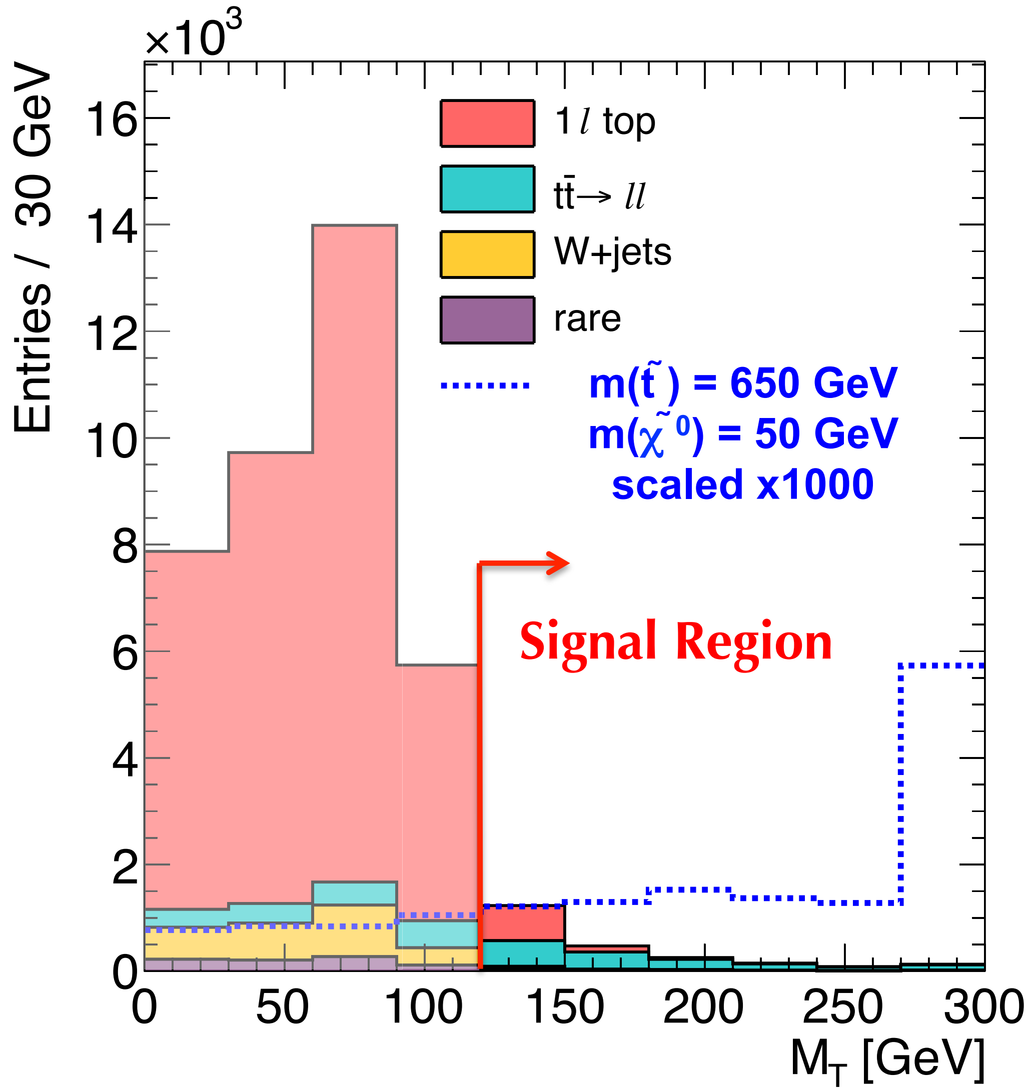




Suppress backgrounds by requiring large M_T

The Transverse Mass

Predictions from Monte Carlo simulation

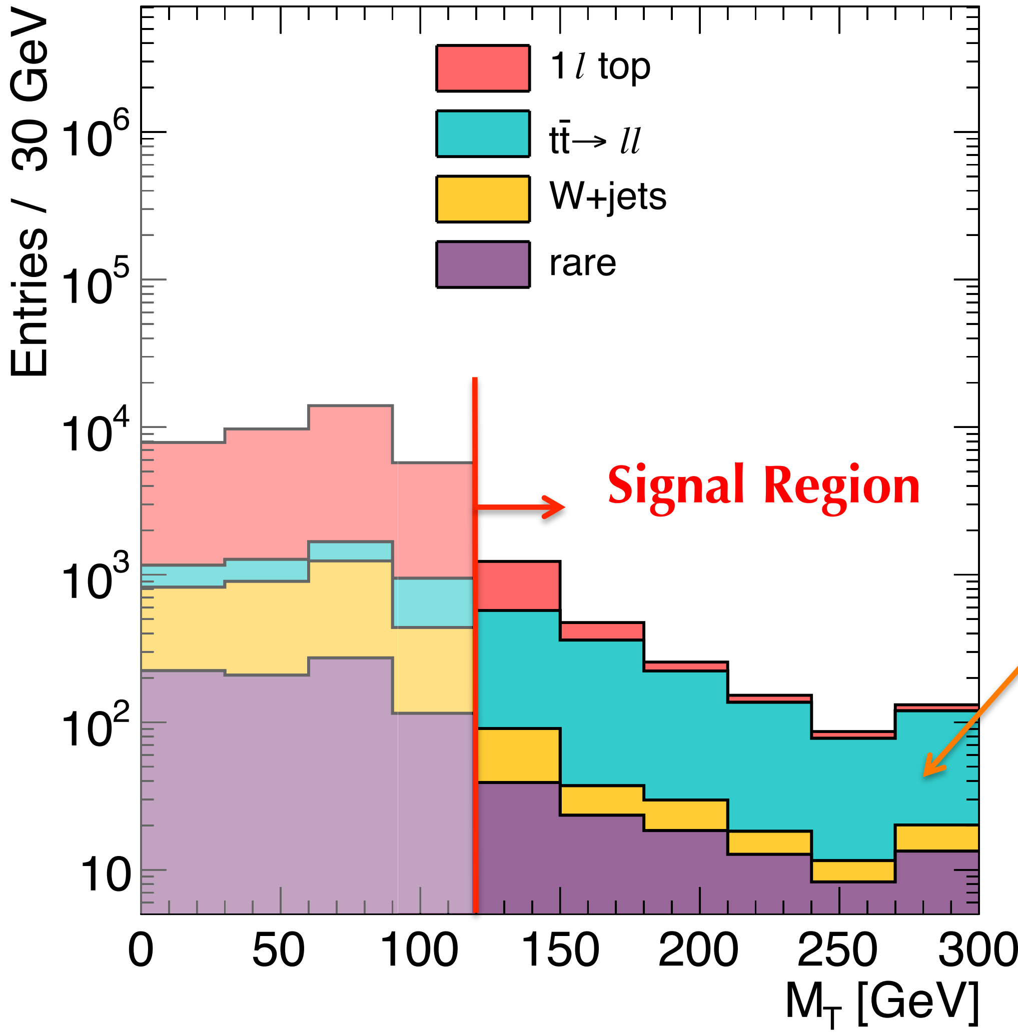


1ℓ + jets signature

Search for an excess of events at large M_T

The SM at High Transverse Mass

Predictions from Monte Carlo simulation



1ℓ + jets signature

tt→ ℓℓ dominant
~60 %

Aggressive 2nd lepton veto does not completely solve problem!

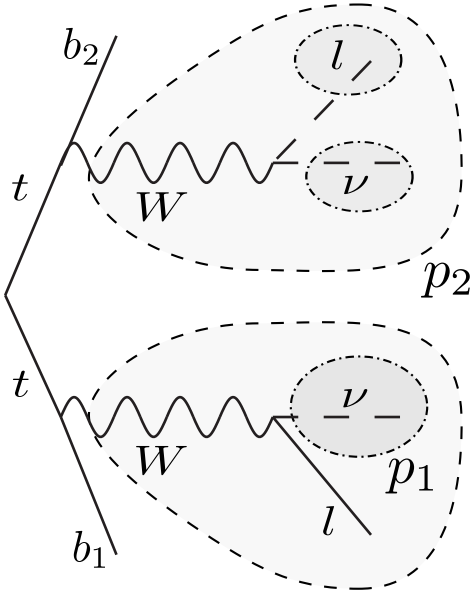
Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

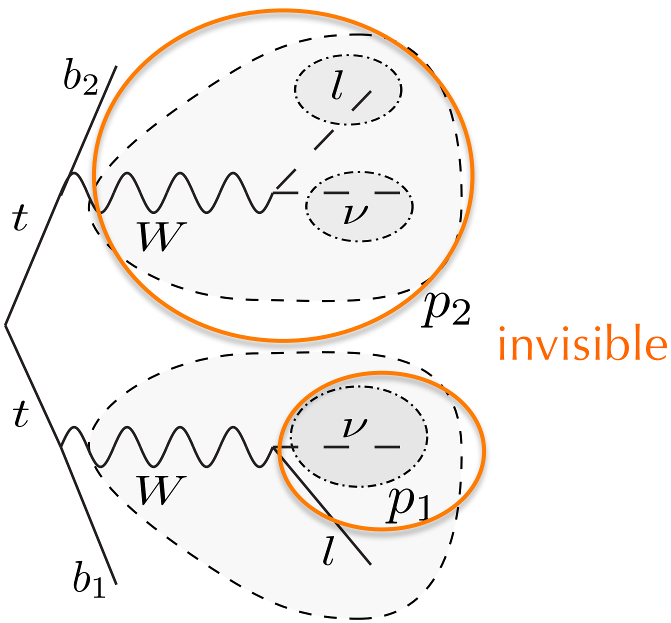
Top background



Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

Top background



$M_{T2}{}^W$ is minimum mother particle mass consistent with kinematic constraints

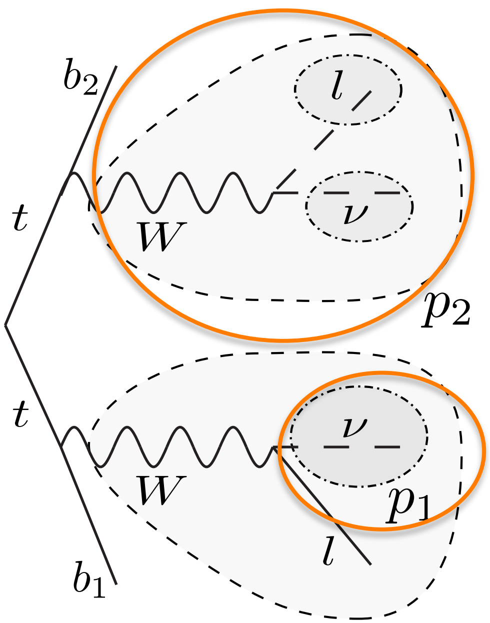
$$M_{T2}^W = \min\left\{ m_y \text{ consistent with: } \left[\begin{array}{c} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\text{miss}},\ p_1^2 = 0,\ (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array} \right] \right\}$$

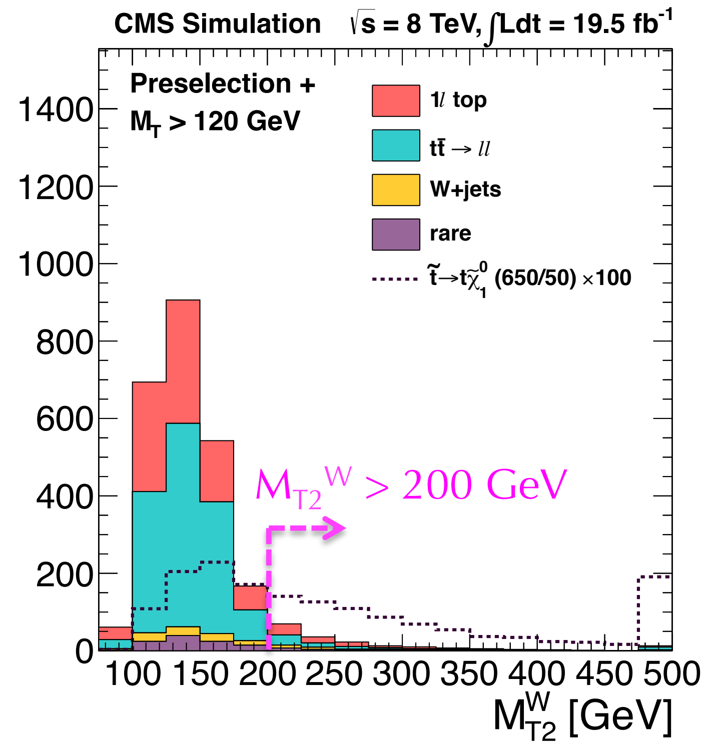
Gallichio et al. hep-ph/1203.4813

Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

Top background





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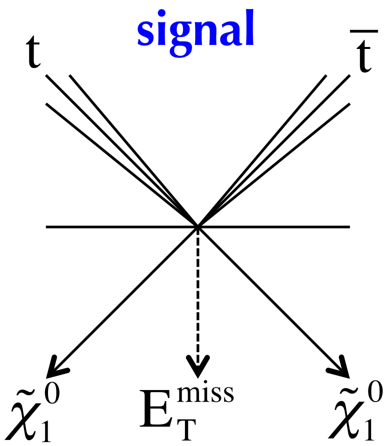
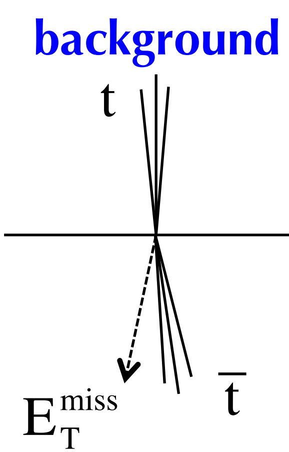
Gallichio et al. hep-ph/1203.4813

Kinematic Variables

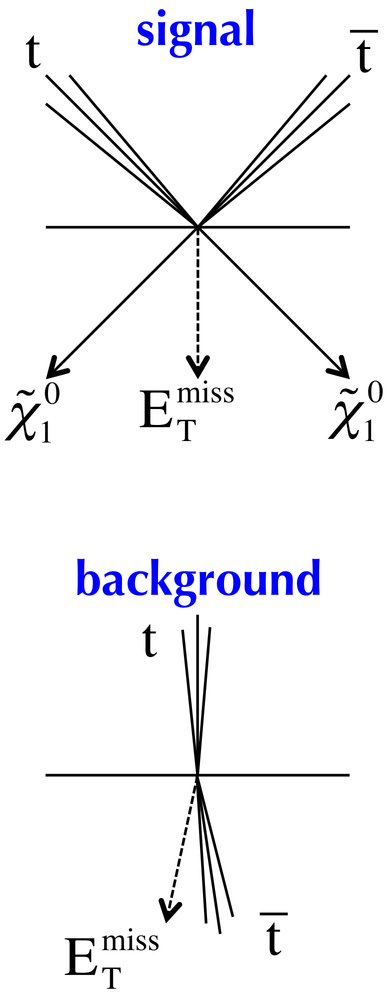
Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

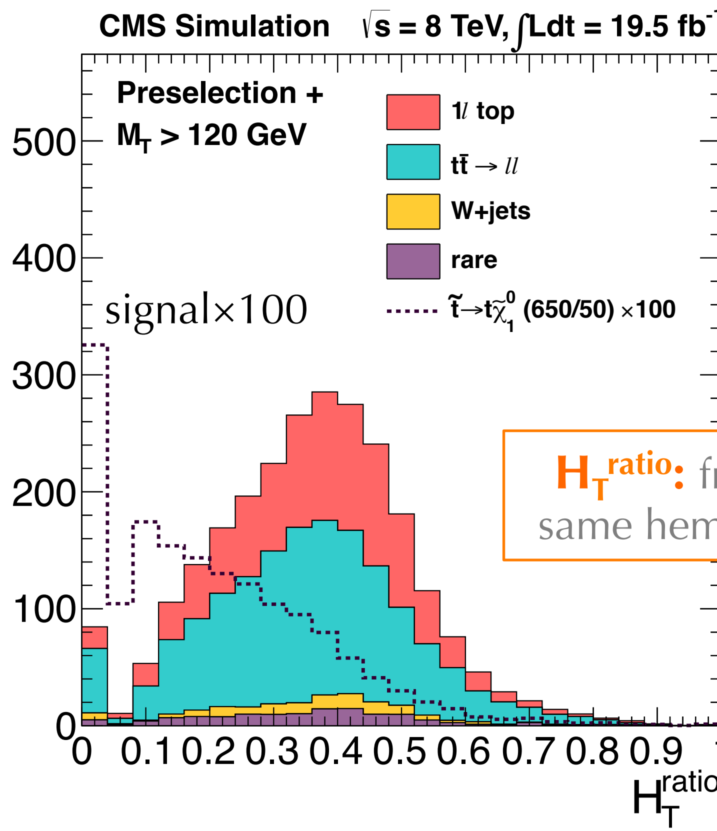




Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

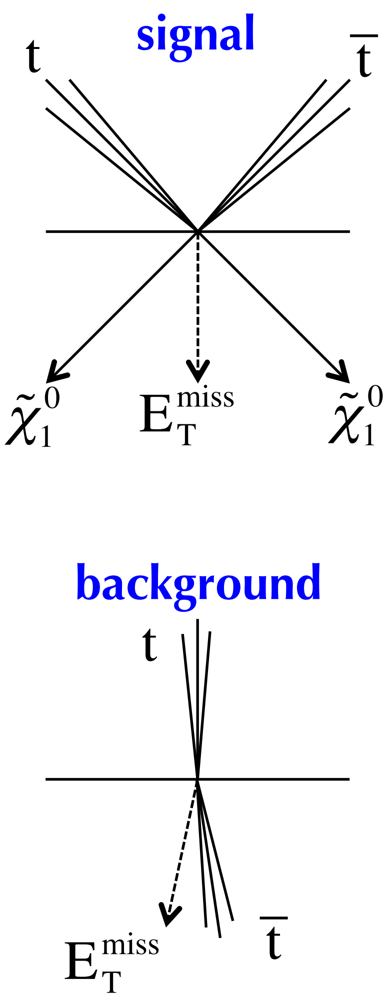


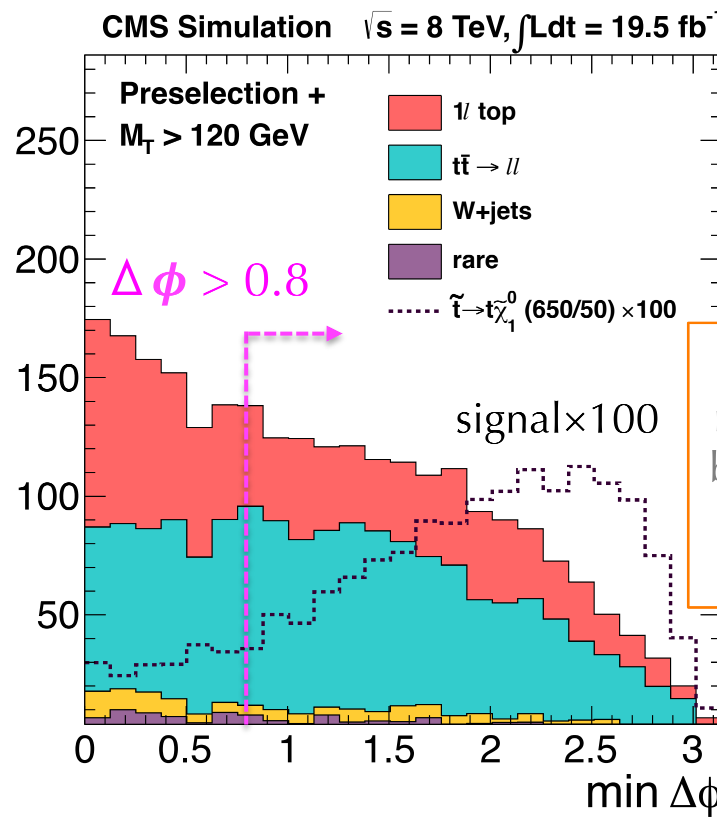


H_T^{ratio}: fraction of H_T in same hemisphere as E_T^{miss}

Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt



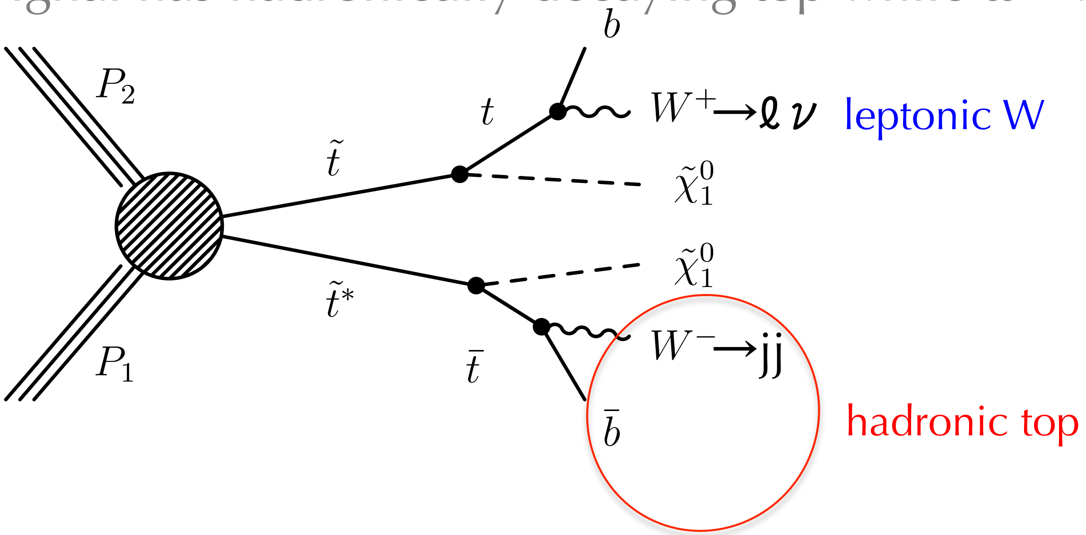


min $\Delta\phi$: minimum $\Delta\phi$ between either of 2 leading jets and E_T^{miss}

Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

Signal has hadronically decaying top while tt→ℓ+ℓ- does not

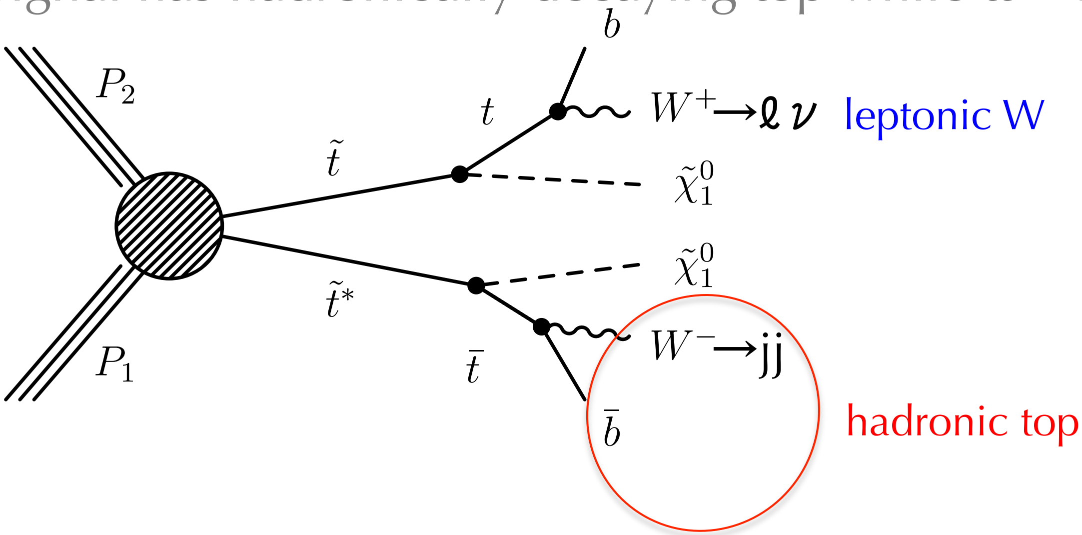


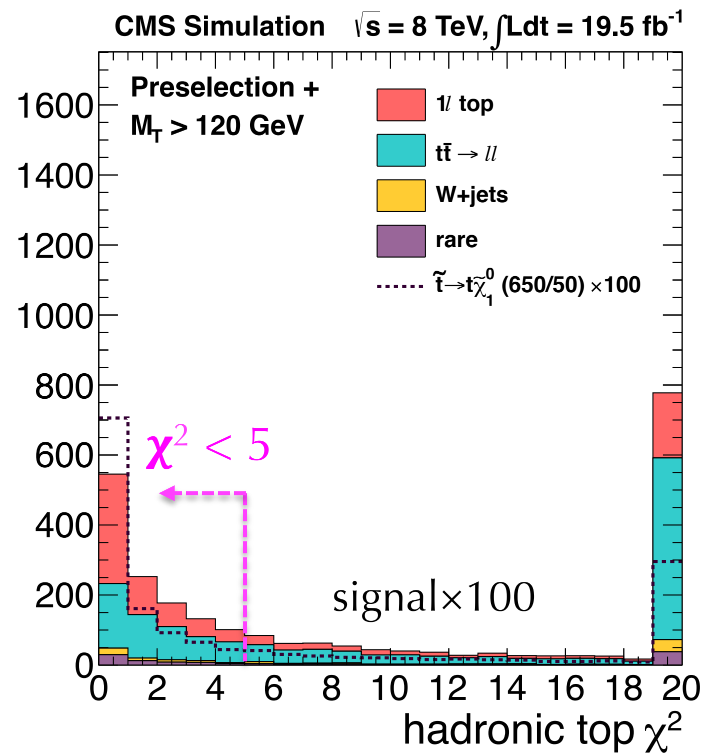
Construct 3-jet hadronic top χ^2 hypothesis

Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

Signal has hadronically decaying top while tt→ℓ⁺ℓ⁻ does not

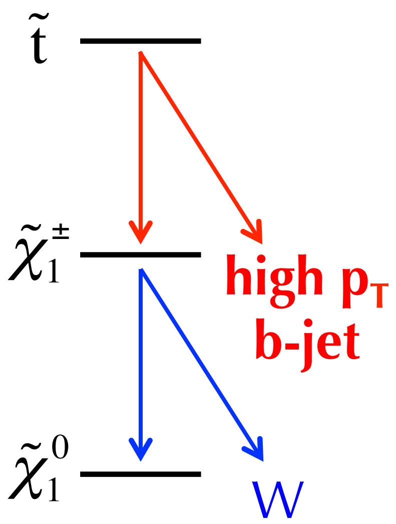


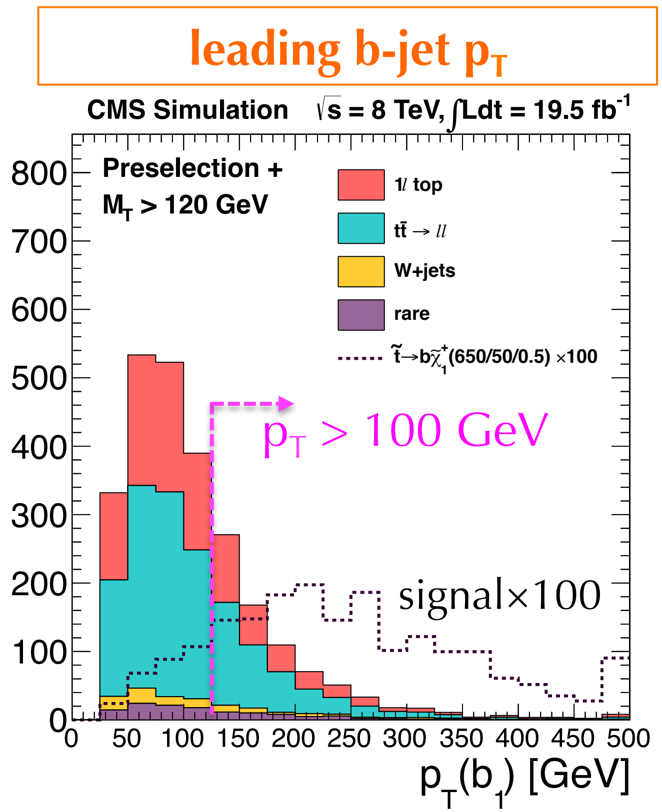


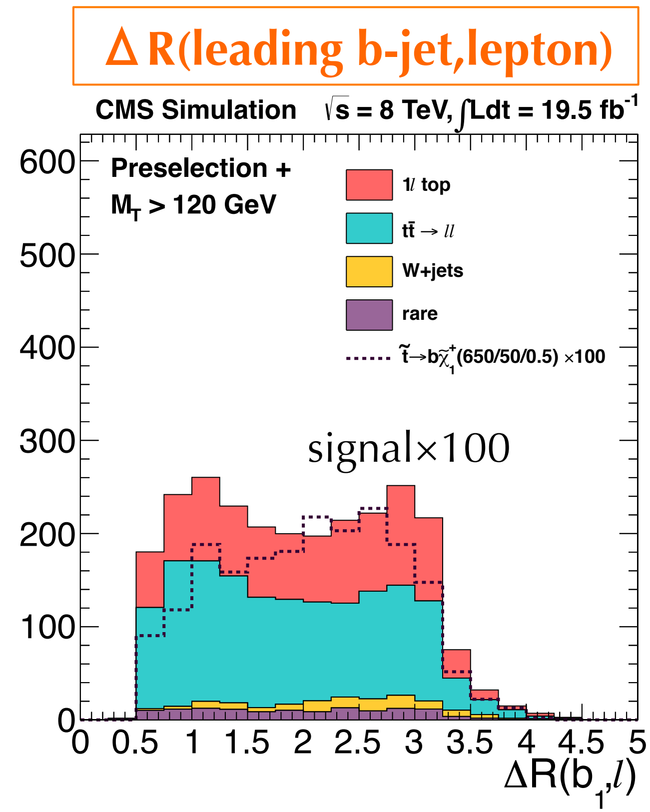
Construct 3-jet hadronic top χ^2 hypothesis

Kinematic Variables

Use kinematical information in addition to E_T^{miss} and M_T to reduce tt

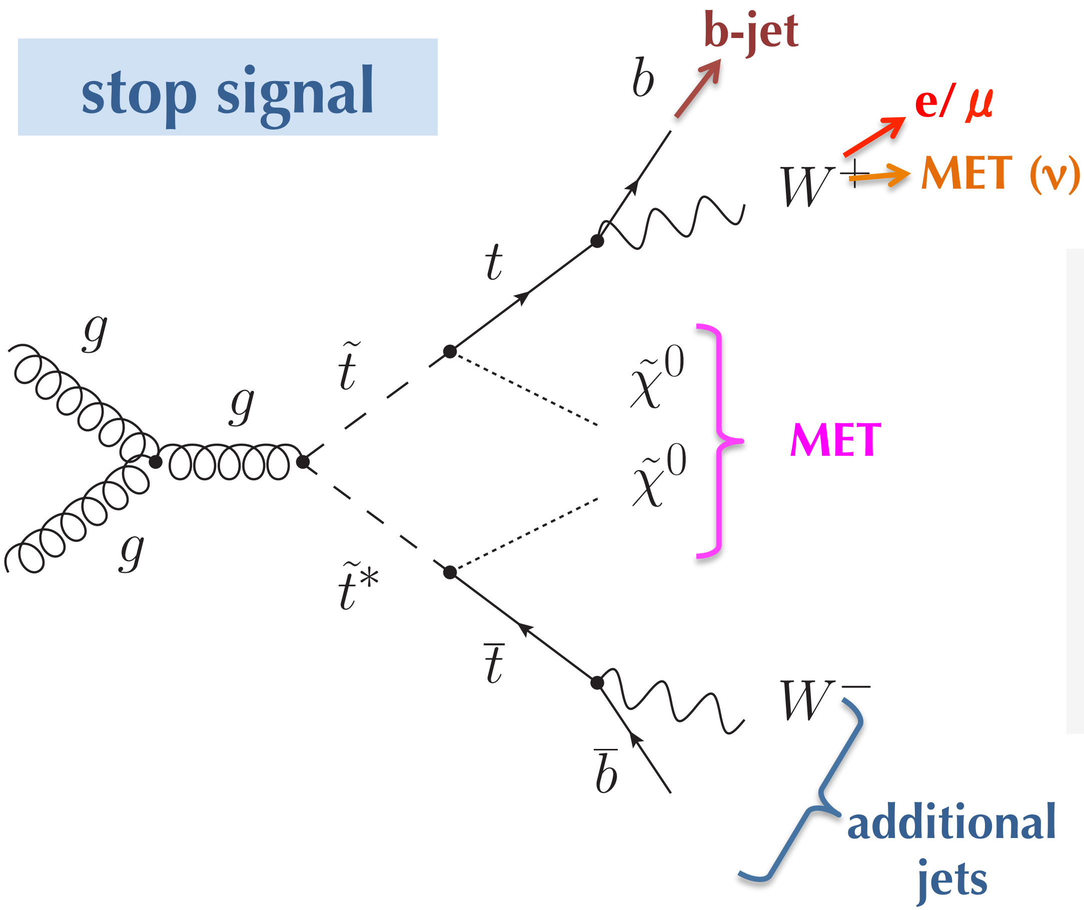






1ℓ Top Squark Selection

stop signal

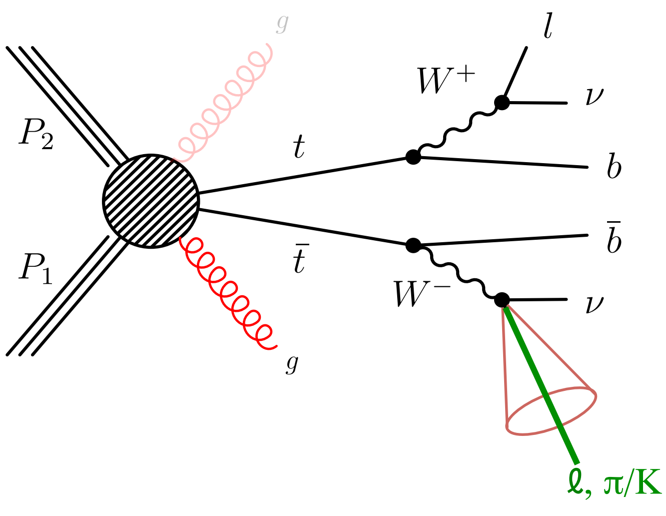


1ℓ signature:

- 1 e/ μ $p_T > 30$ GeV
- 2nd lepton veto
- ≥4 jets $p_T > 30$ GeV
- ≥1 b-jet
- $E_T^{miss} > 100$ GeV

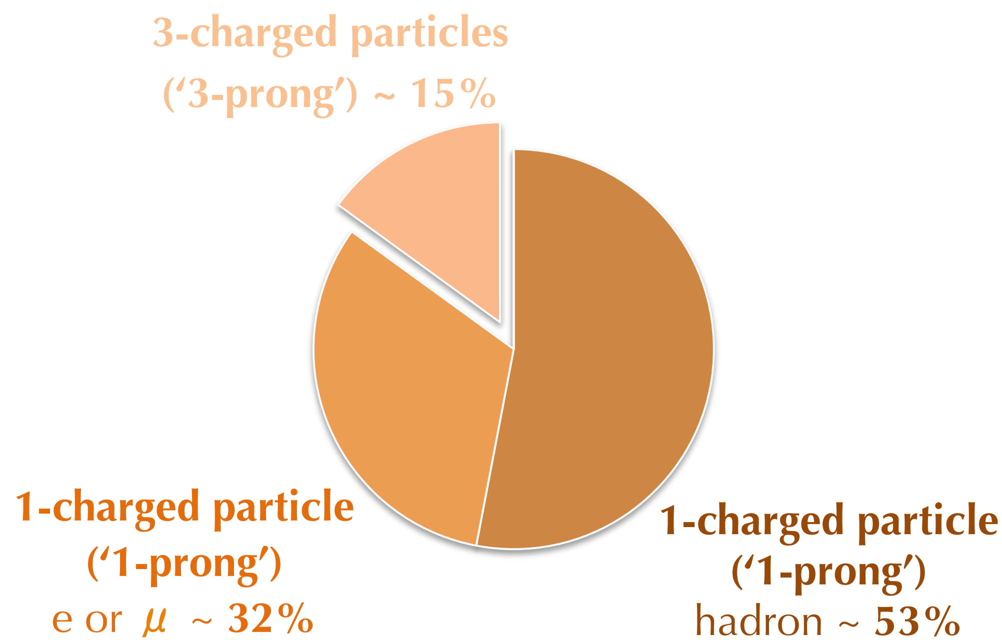
Second Lepton Rejection

Veto on events with an isolated track



Isolated track catches leptons or hadrons from τ -decay

Main tau branching fractions

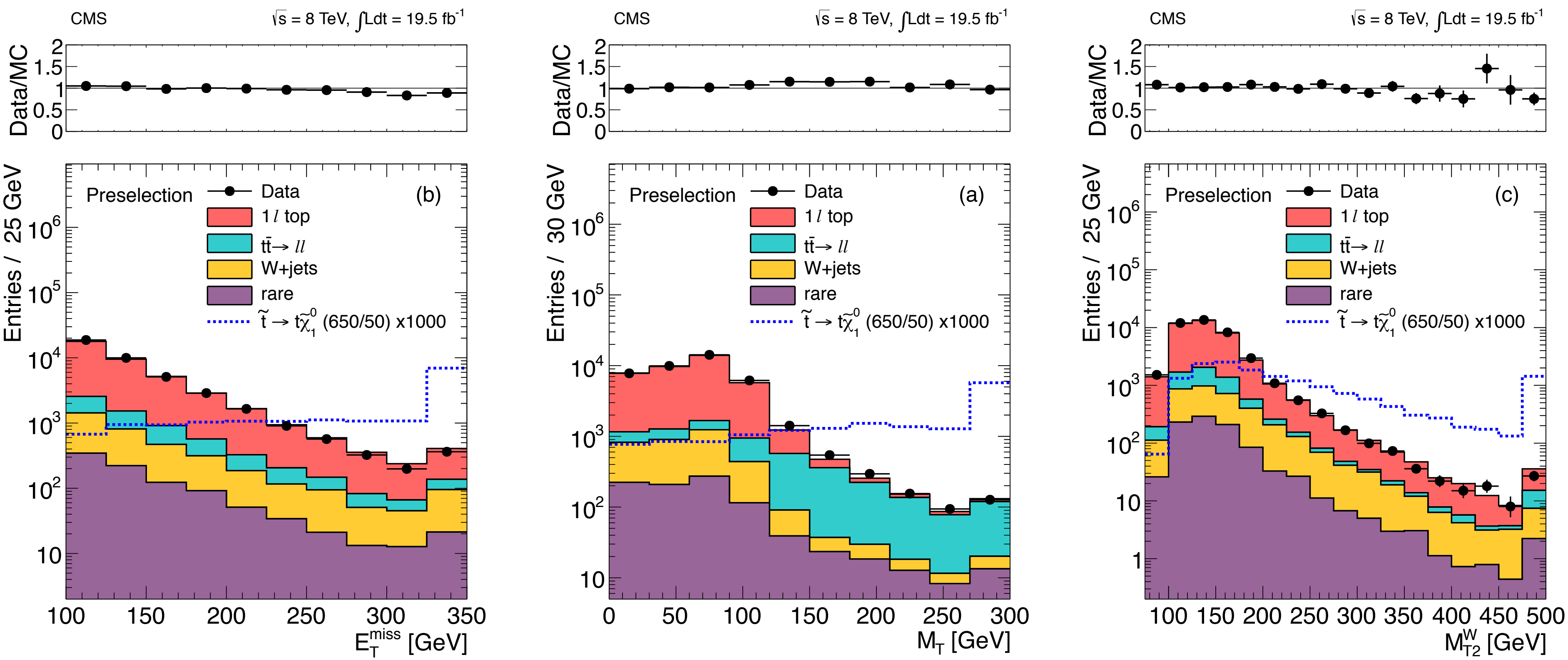


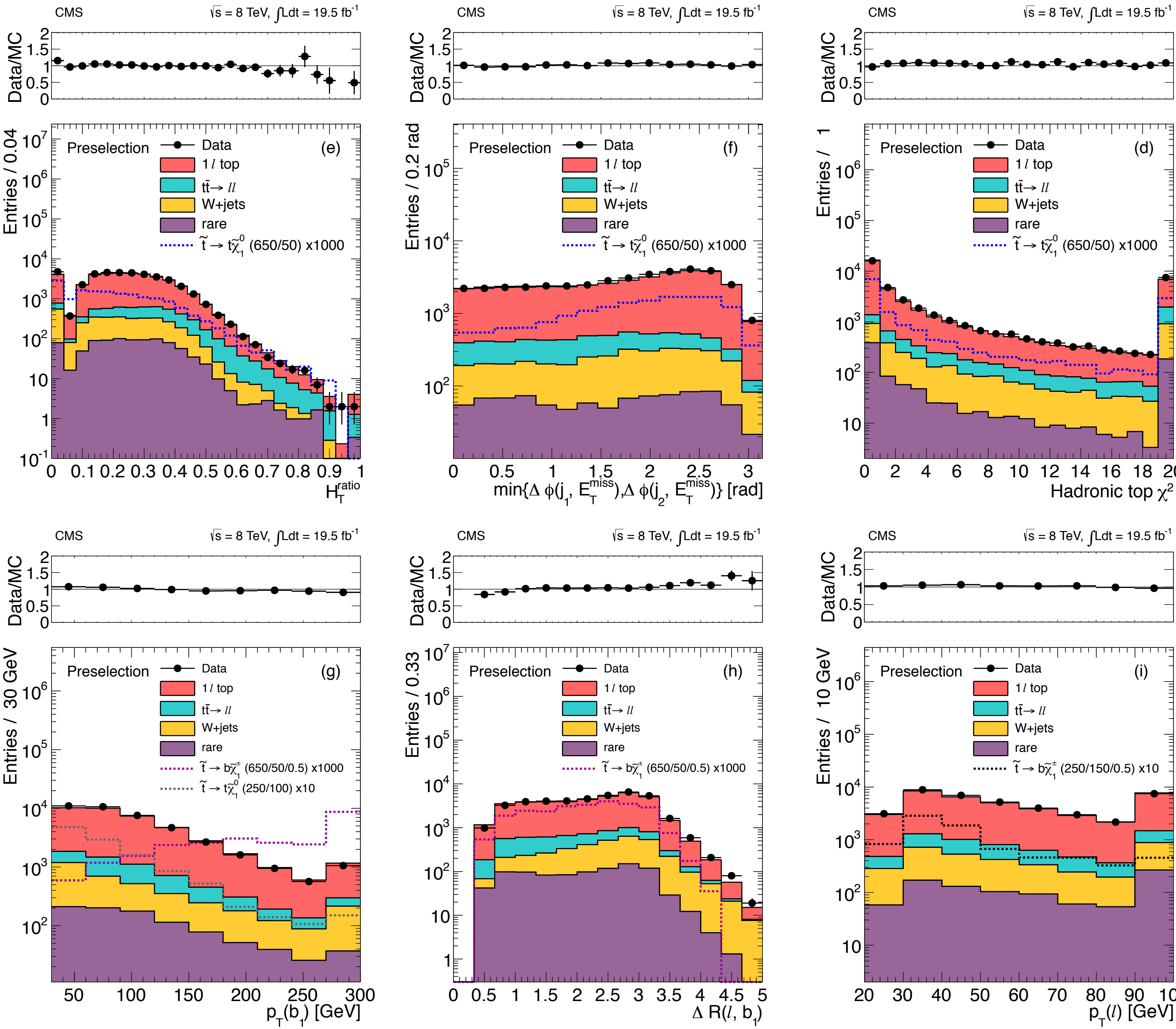
p_T > 10 GeV
If e or μ p_T> 5 GeV and loosen isolation

Veto hadronic τ candidates with p_T> 20 GeV
Catches multiprong decays

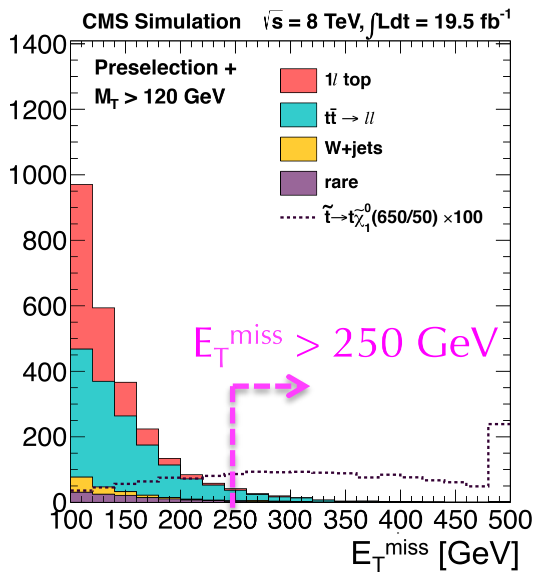
Kinematical Quantities

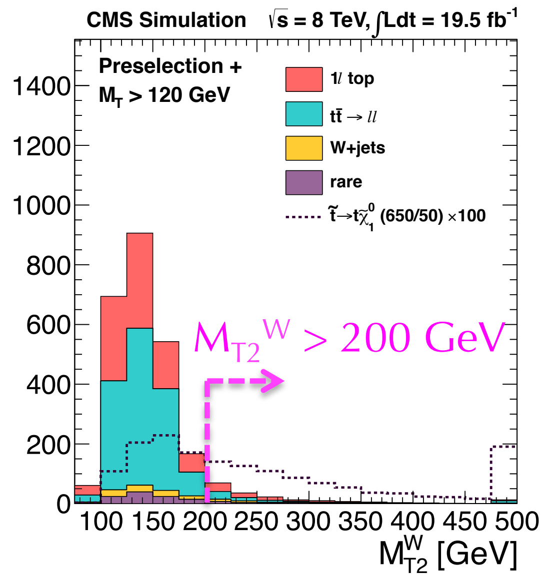
At preselection

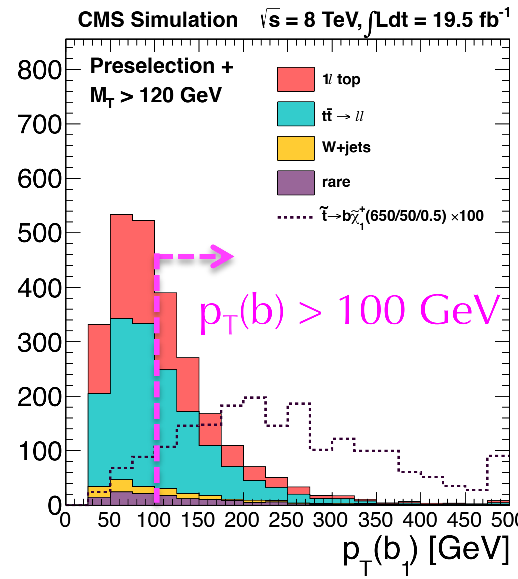


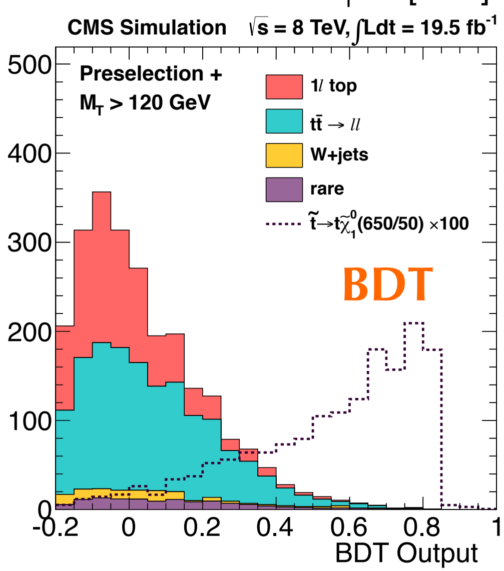

CMS
√s = 8 TeV, ∫Ldt = 19.5 fb-1
Data/MC
Entries / 0.04
Preselection
(e)
Data
1 l top
tt̄→ ll
W+jets
rare
t̃ → tχ̃10 (650/50) x1000
H_T^ratio
Entries / 0.2 rad
(f)
min{Δ φ(j1, E_T^miss),Δ φ(j2, E_T^miss)} [rad]
Entries / 1
(d)
Hadronic top χ2
Entries / 30 GeV
(g)
t̃ → bχ̃1± (650/50/0.5) x1000
t̃ → tχ̃10 (250/100) x10
pT(b1) [GeV]
Entries / 0.33
(h)
Δ R(l, b1)
Entries / 10 GeV
(i)
t̃ → bχ̃1± (250/150/0.5) x10
pT(l) [GeV]

Signal Selection









Main analysis combines several variables in BDTs

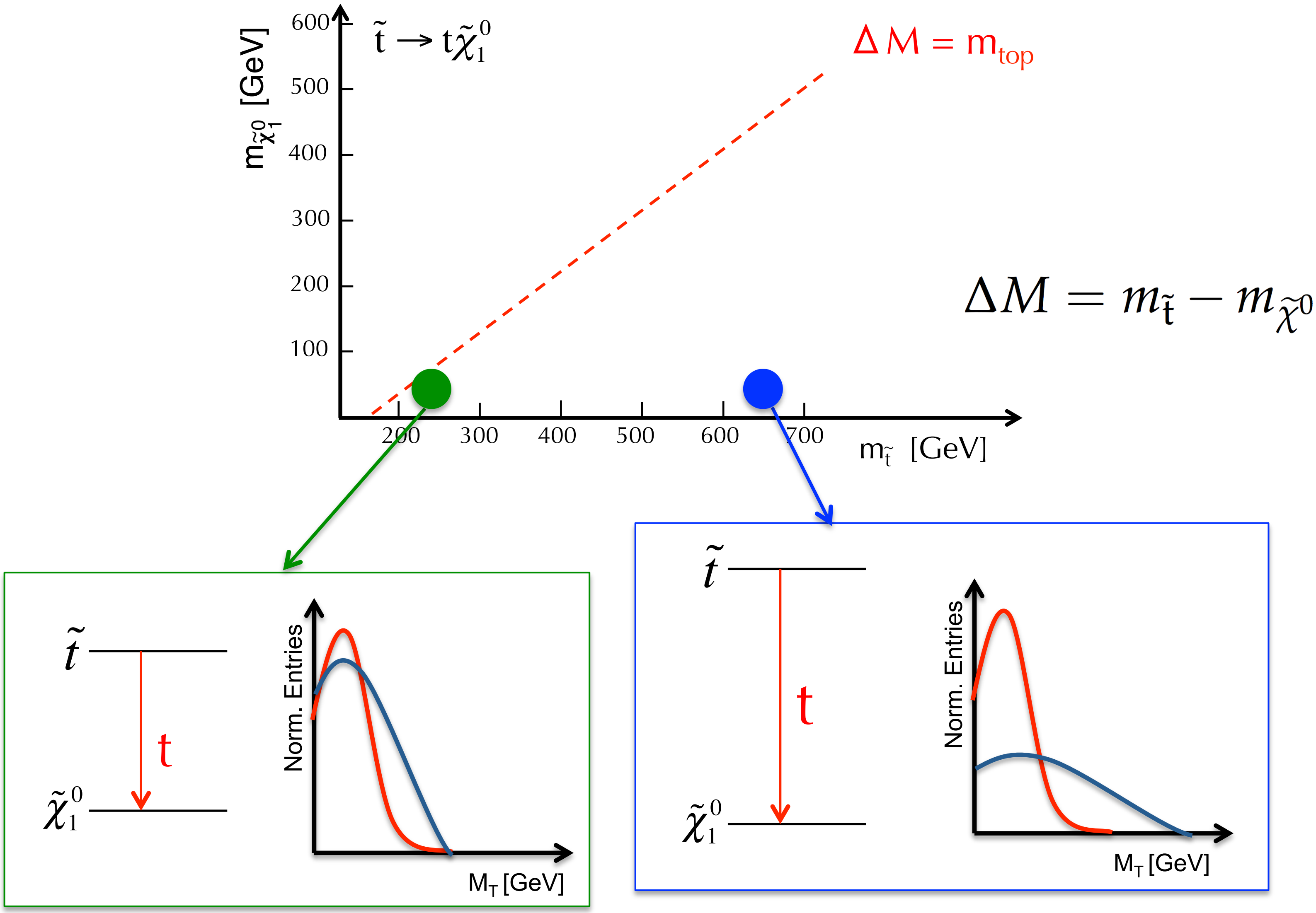
➞ signal regions defined by cuts on BDT output

Cross checked with cut-based analysis

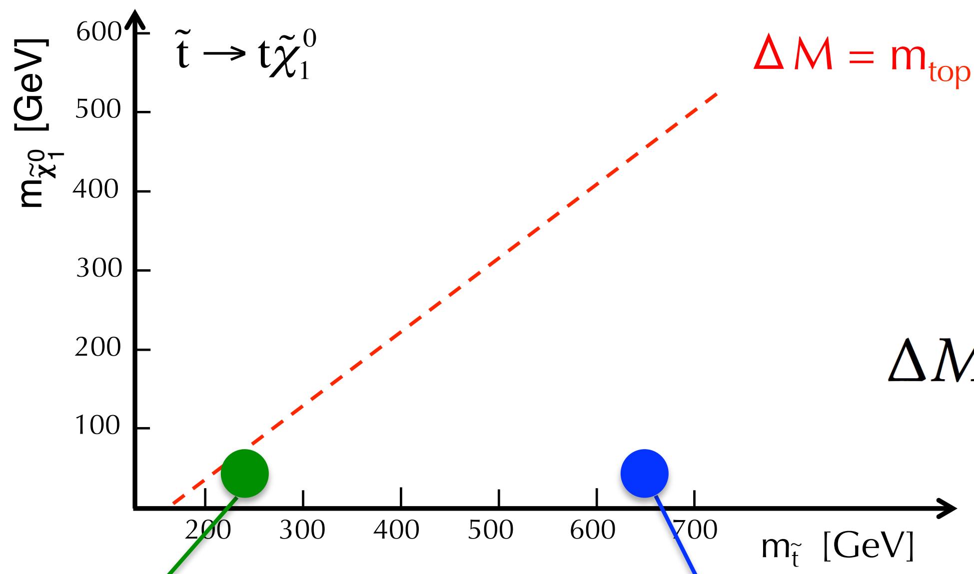
➞ less sensitivity to model details

Do both in parallel ➞ 18 BDT and 16 cut-based signal regions!

Signal Region Selection

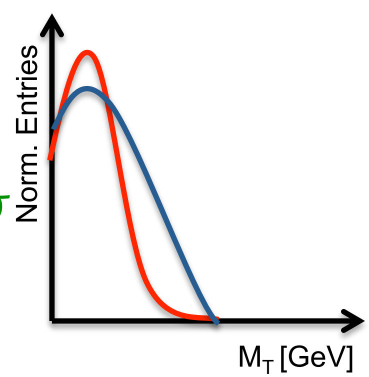


Signal Region Selection

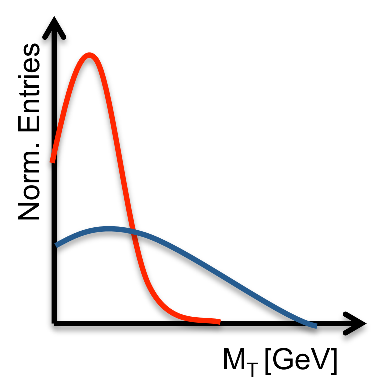


$$\Delta M = m_{\tilde{t}} - m_{\tilde{\chi}^0}$$

Looser selections
→ more signal due to larger σ but larger backgrounds

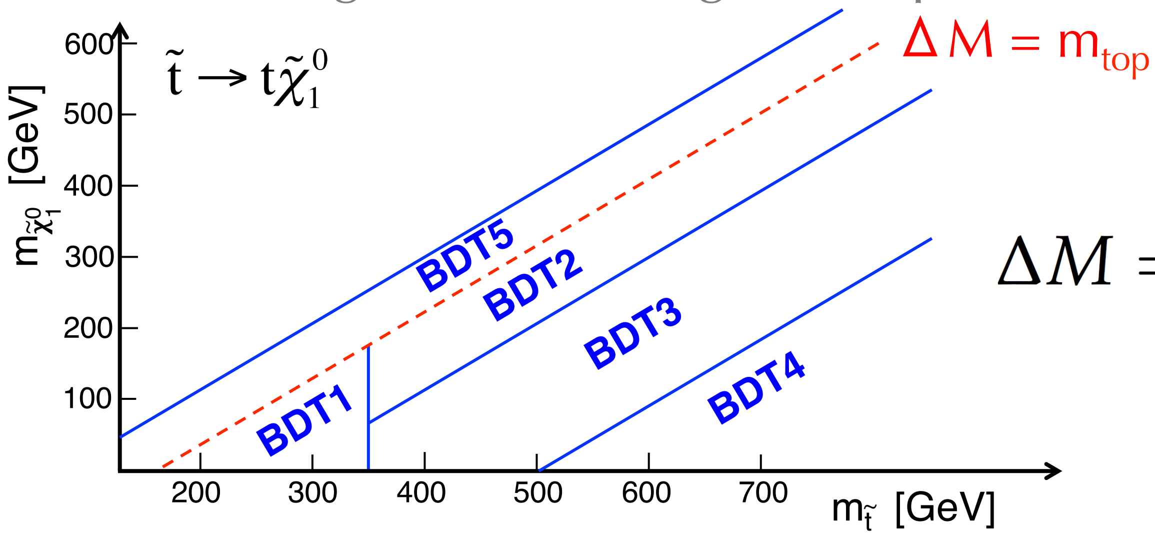


Tighter selections
→ smaller backgrounds but less signal due to lower σ



$t\tilde{\chi}^0$ Mode

Train 5 BDTs to target different regions of parameter space



$$\Delta M = m_{\tilde{t}} - m_{\tilde{\chi}^0}$$

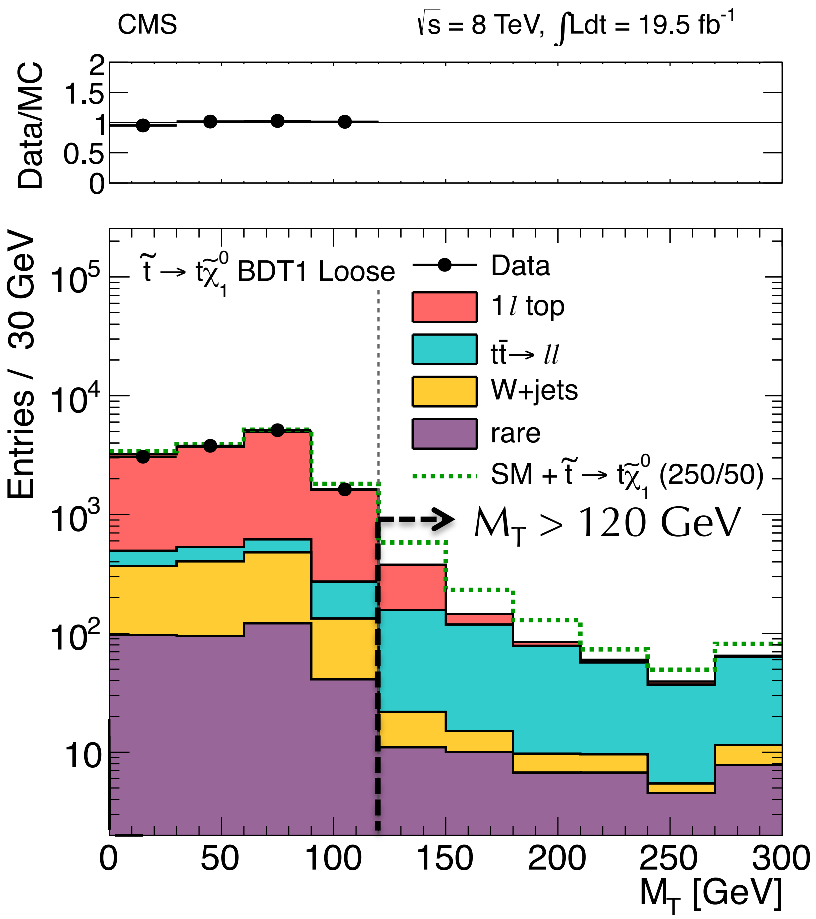
	small m_{stop}		small ΔM ⟷		large ΔM	off-shell top
Sample	**BDT1 Loose**	**BDT1 Tight**	**BDT2**	**BDT3**	**BDT4**	**BDT5**

More BDTs to target $b\chi^{\pm}$ mode

Background Estimation

Backgrounds from Monte Carlo ➞ Calibrate/correct with "control regions"

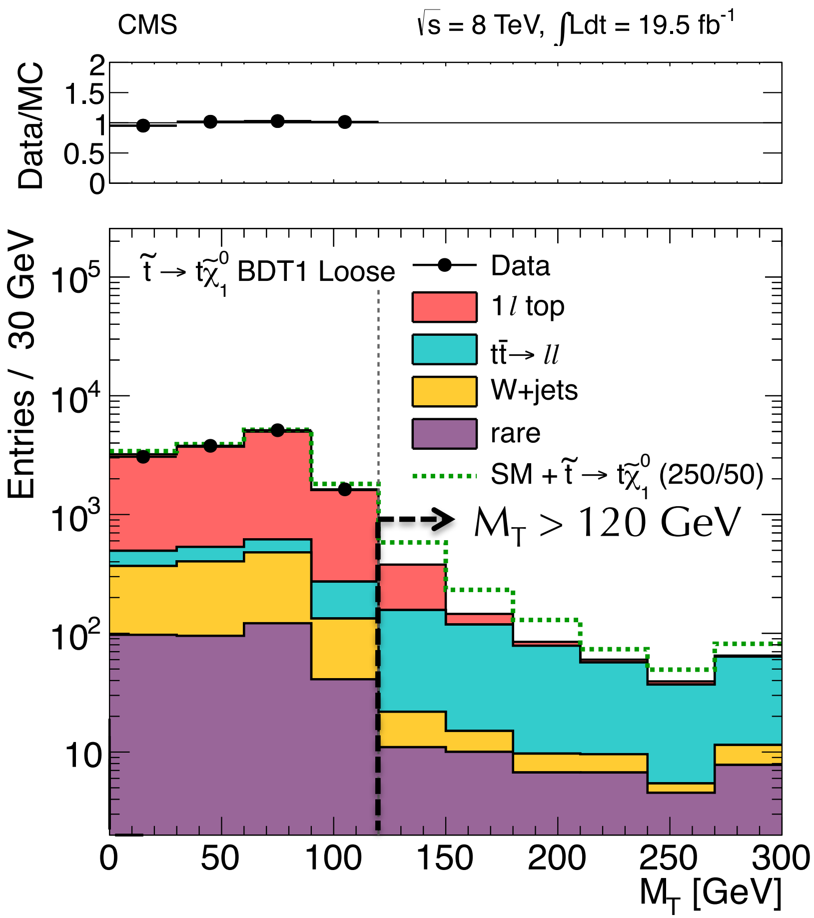
Signal sample



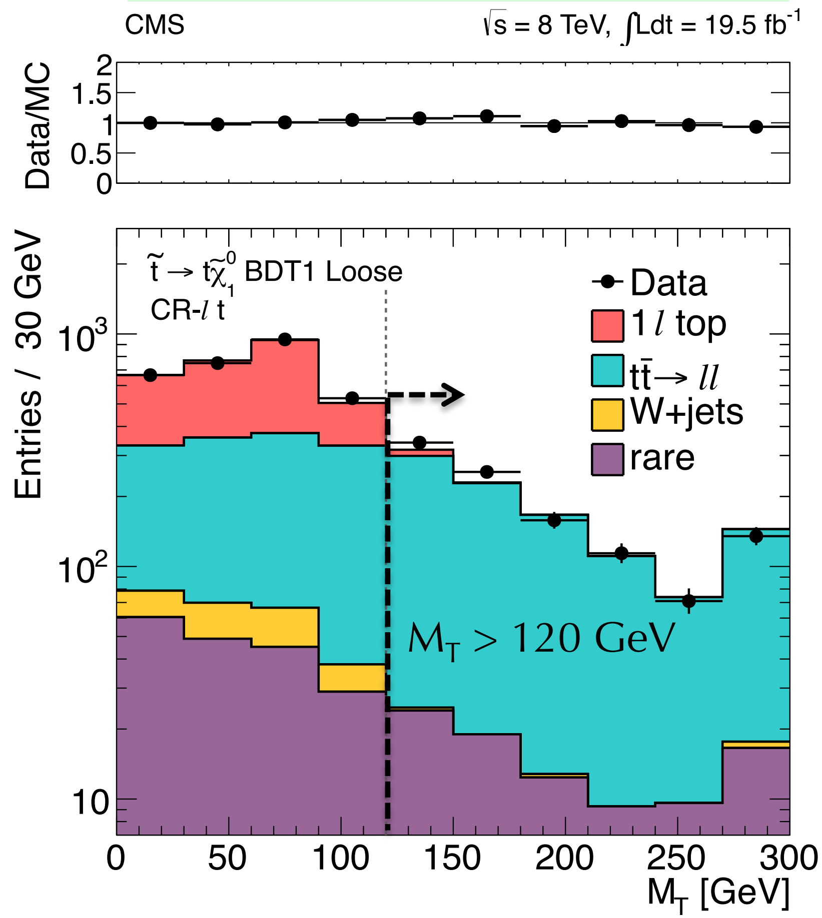
Background Estimation

Backgrounds from Monte Carlo ➞ Calibrate/correct with "control regions"

Signal sample



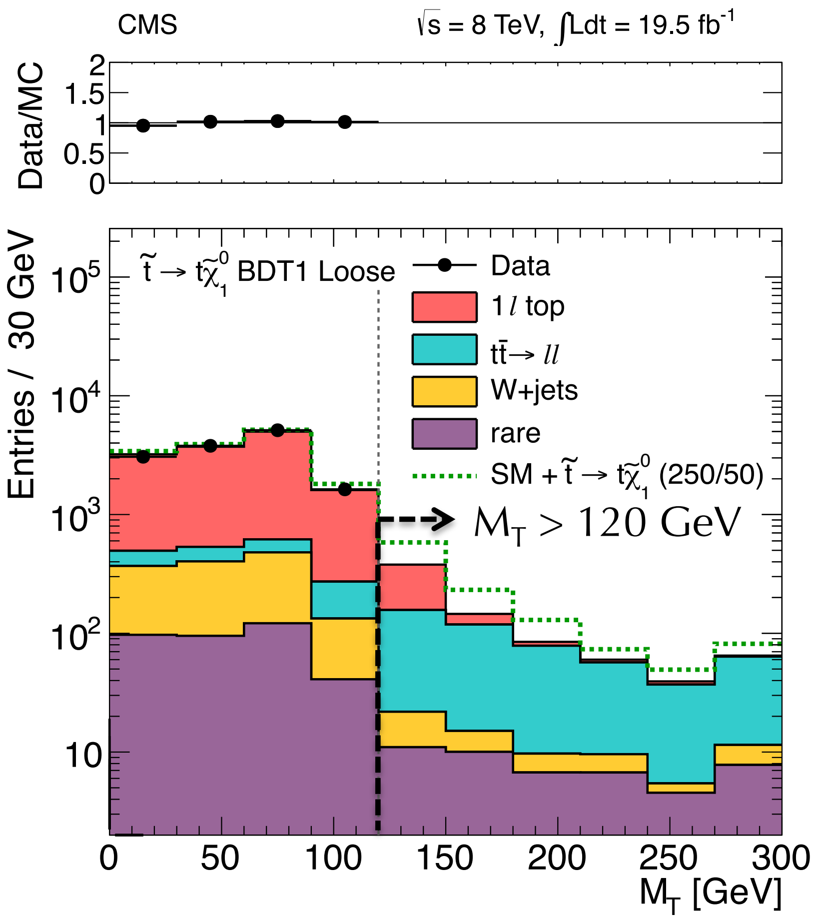
tt→ℓ+ℓ- sample: Invert 2nd lepton veto



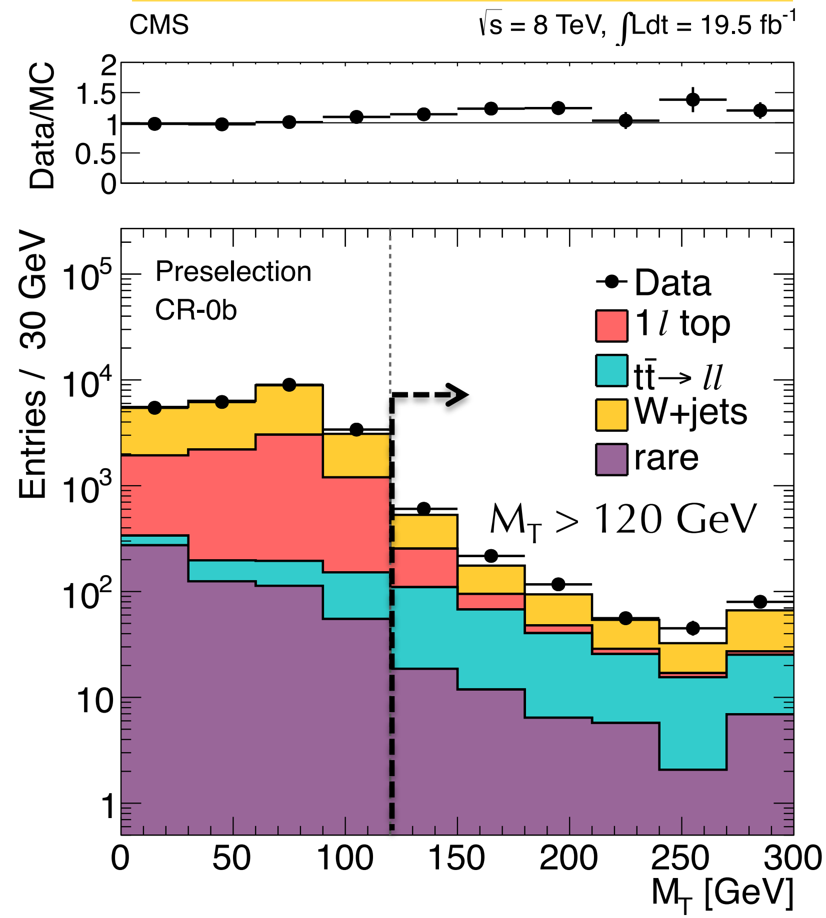
Background Estimation

Backgrounds from Monte Carlo ➞ Calibrate/correct with “control regions”

Signal sample



W+Jets sample: Invert b-tagging



Background Estimation

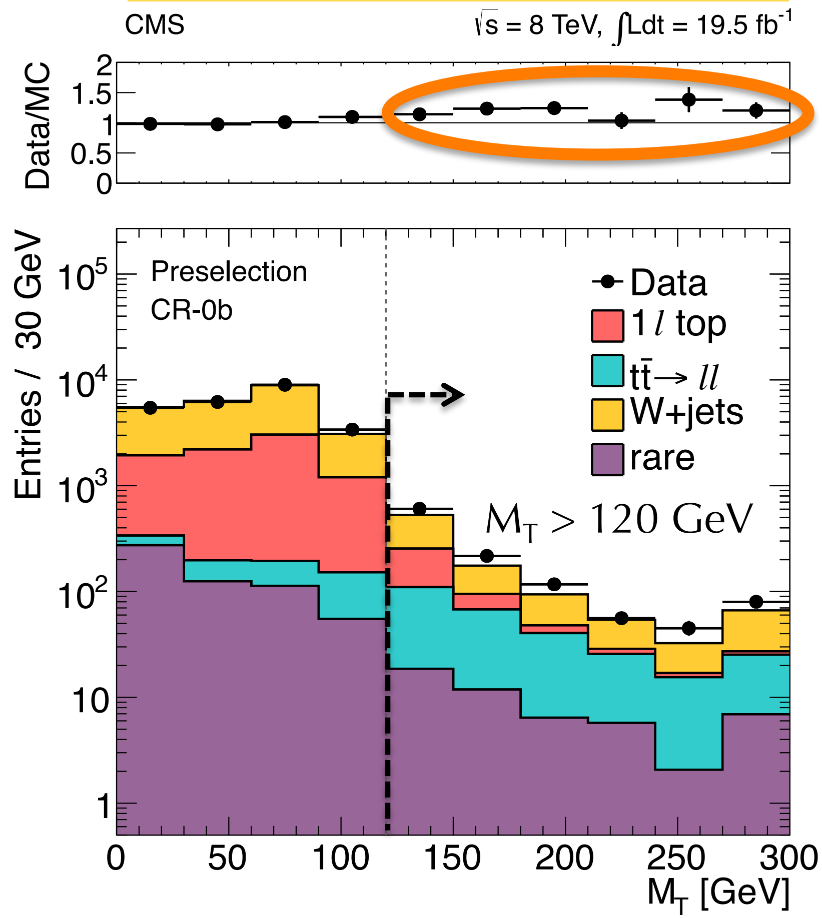
Backgrounds from Monte Carlo ➞ Calibrate/correct with “control regions”

W+Jets sample:
Invert b-tagging

Issue with E_T^{miss} resolution affecting M_T

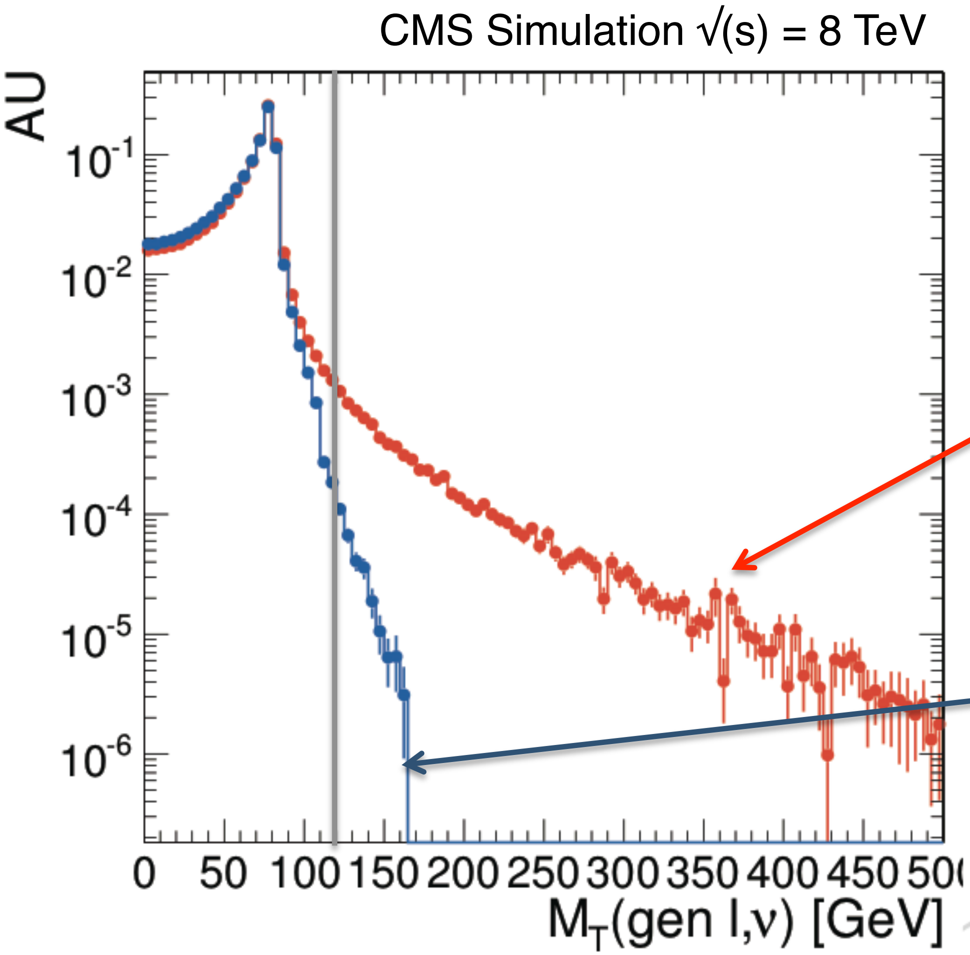
➞ measured in W+jets, corrected via scale factor 1.2±0.3

➞ transfer to tt➞ℓ+jets not straightforward



Single Lepton Backgrounds

Two contributions to high M_T tail



W+jets: dominated by off-shell W production $M_T(\ell, \nu) > m_W$

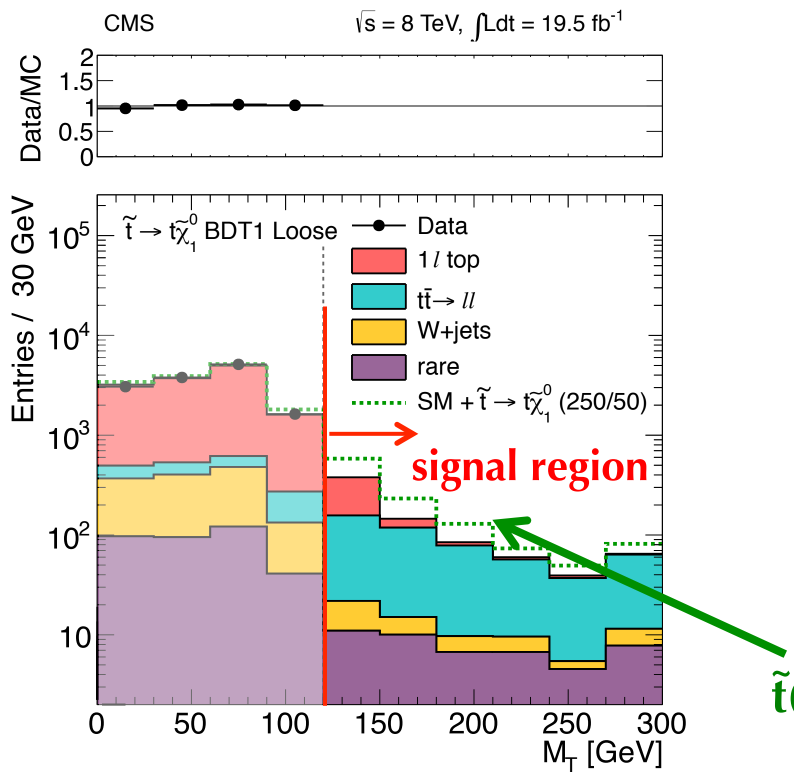
$$W \rightarrow l\nu$$

1ℓ top: M_T is bounded $M_T(\ell, \nu) < m_{top} - m_b$ → detector resolution effects dominate

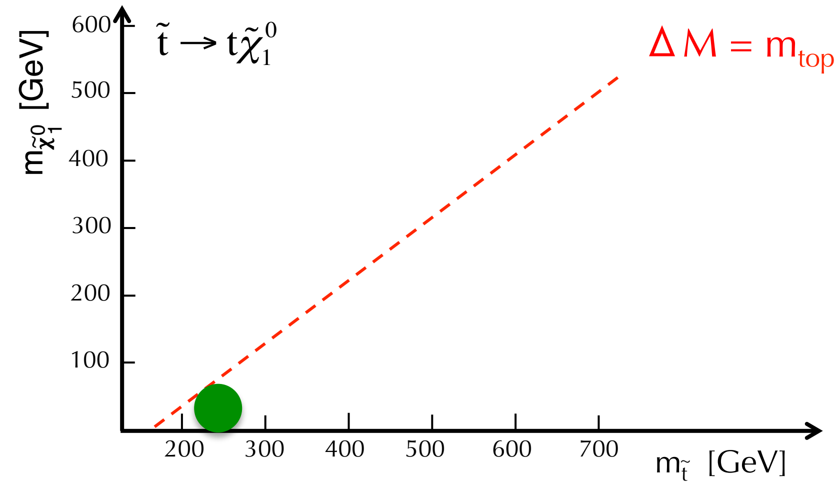
$$t \rightarrow Wb \rightarrow l\nu b$$

1ℓ top ~ 25% & W+jets ~ 5% of total background

Signal and Background Expectations



Looser signal regions target low m_{stop} and low Δm

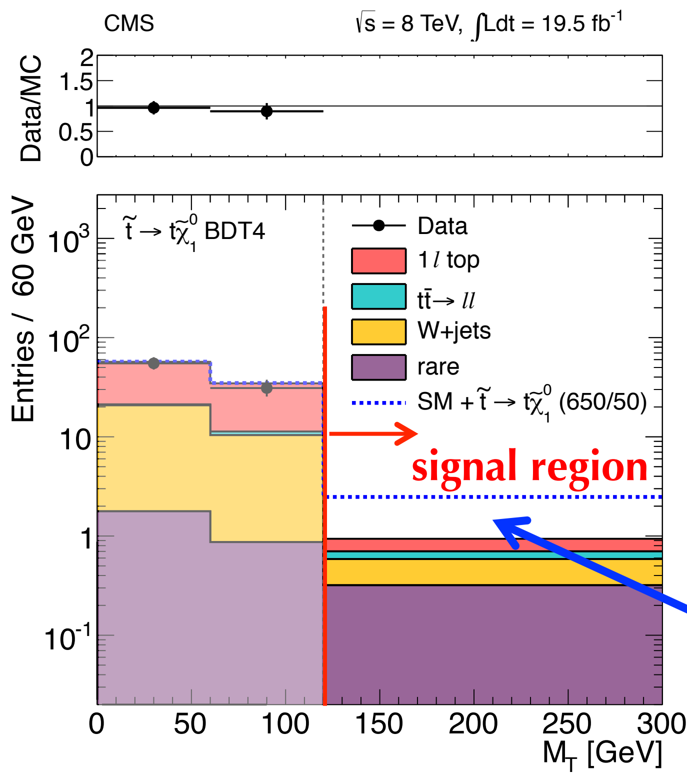


$\tilde{t}(250) \to t\tilde{\chi}^0(50)$

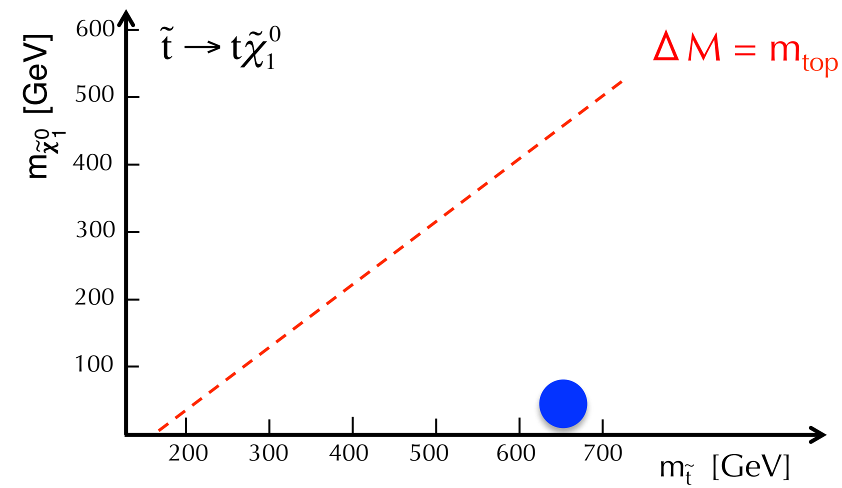
Total Background	763 ± 102
Signal (250/50)	285 ± 8.5

Limited by systematic uncertainty (13%)
largest contribution from
estimate of 1-lepton background

Signal and Background Expectations



Tighter signal regions target high m_{stop} and large Δm

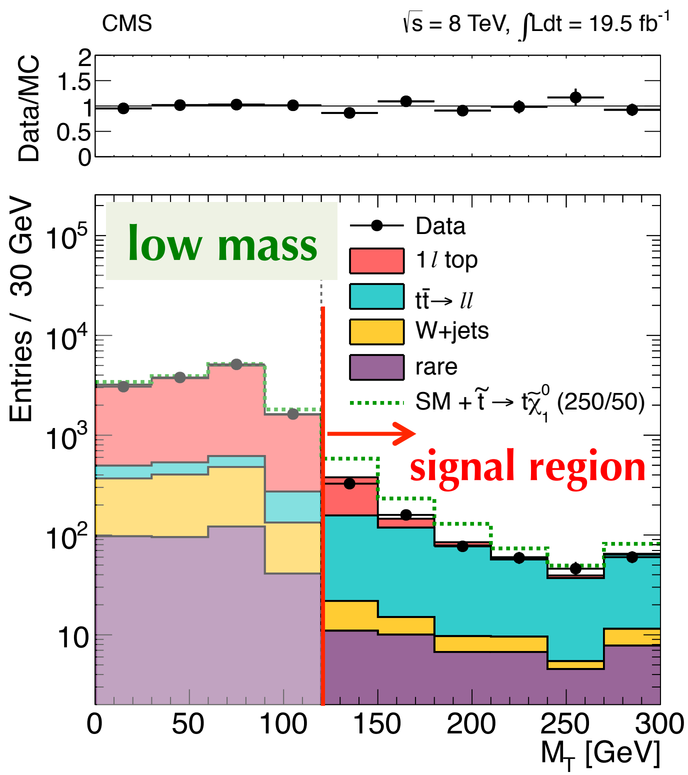


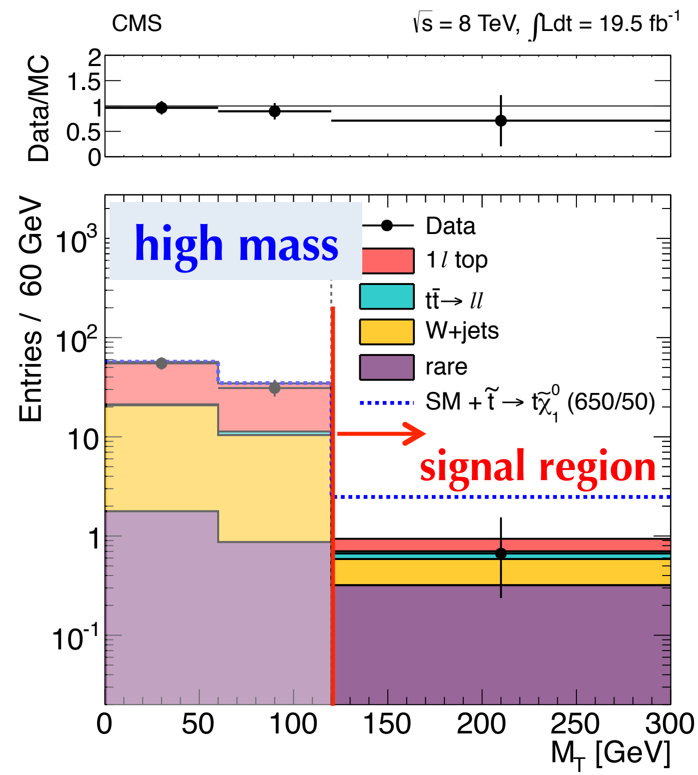
$\tilde{t}(650) \to t\tilde{\chi}^0(50)$

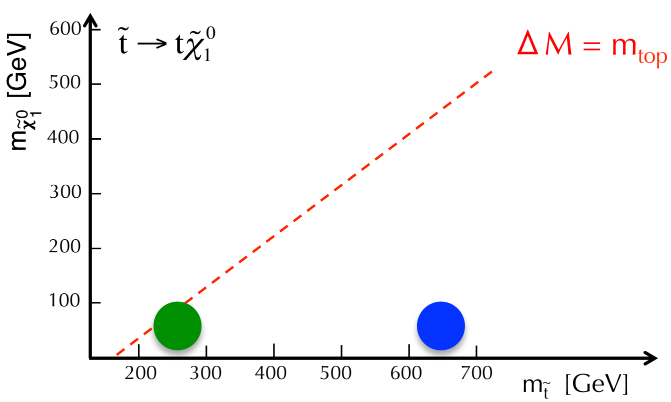
Total Background	2.9 ± 1.1
Signal (650/50)	4.3 ± 0.1

Limited by statistics

The Results





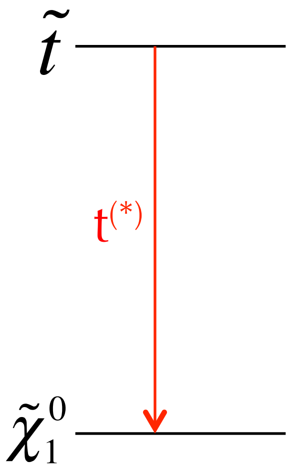


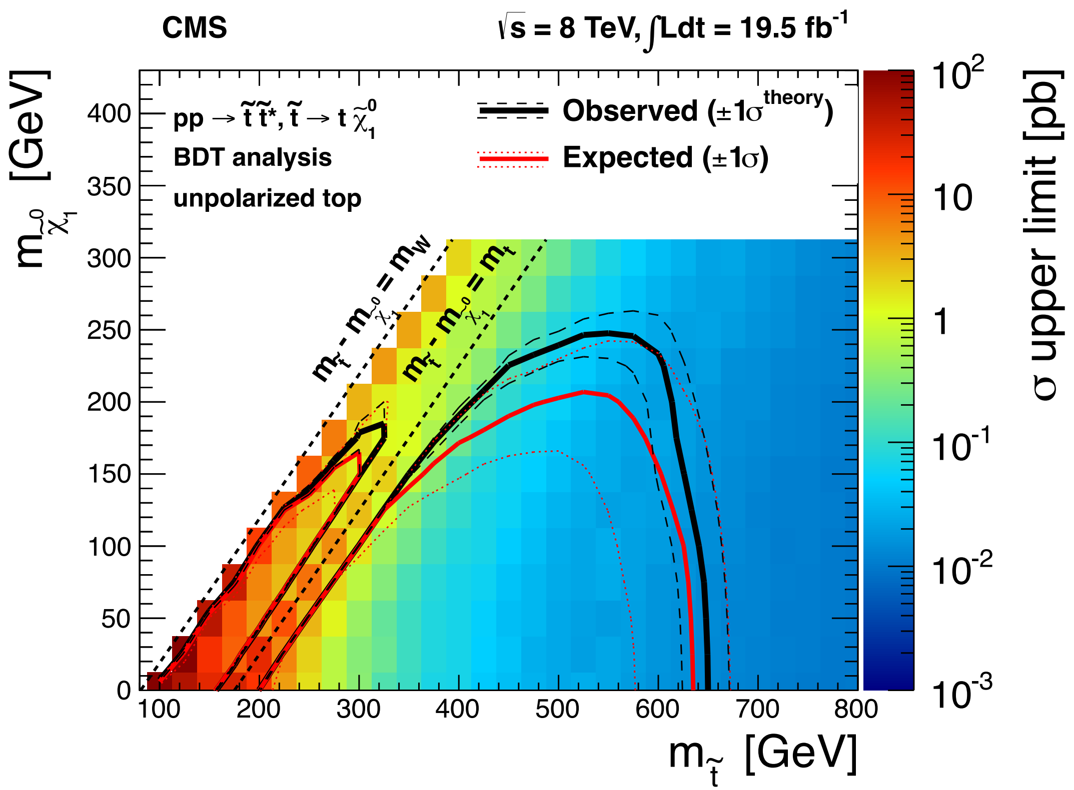
	low mass	high mass
Data	**728**	**2**
Total Background	**763 ± 102**	**2.9 ± 1.1**
Signal	**285 ± 8.5 (250/50)**	**4.3 ± 0.1 (650/50)**

4 other signal regions in backup

What does this search tell us?

Set limits using results from the signal region with the best expected sensitivity



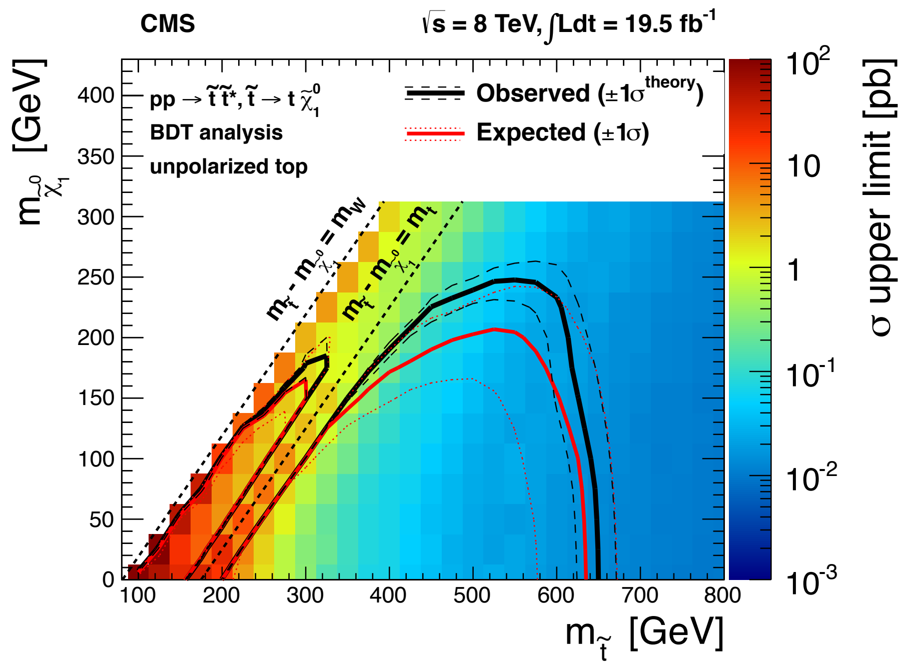


Results probe $m(\tilde{t}) \lesssim 650$ GeV for $m(\tilde{\chi}^0) \lesssim 225$ GeV

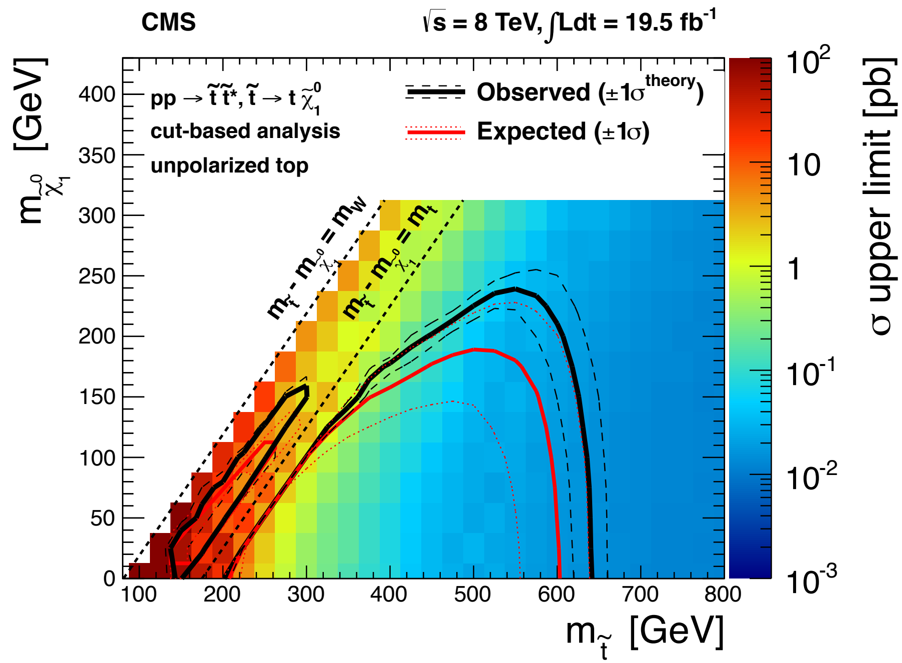
Sensitive to the $\Delta M < m_{top}$ and $m_{stop} < m_{top}$ regions

Multivariate vs. Cut Based

Multivariate

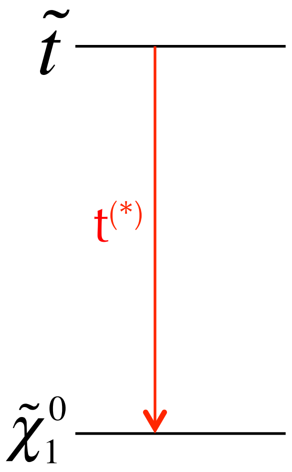


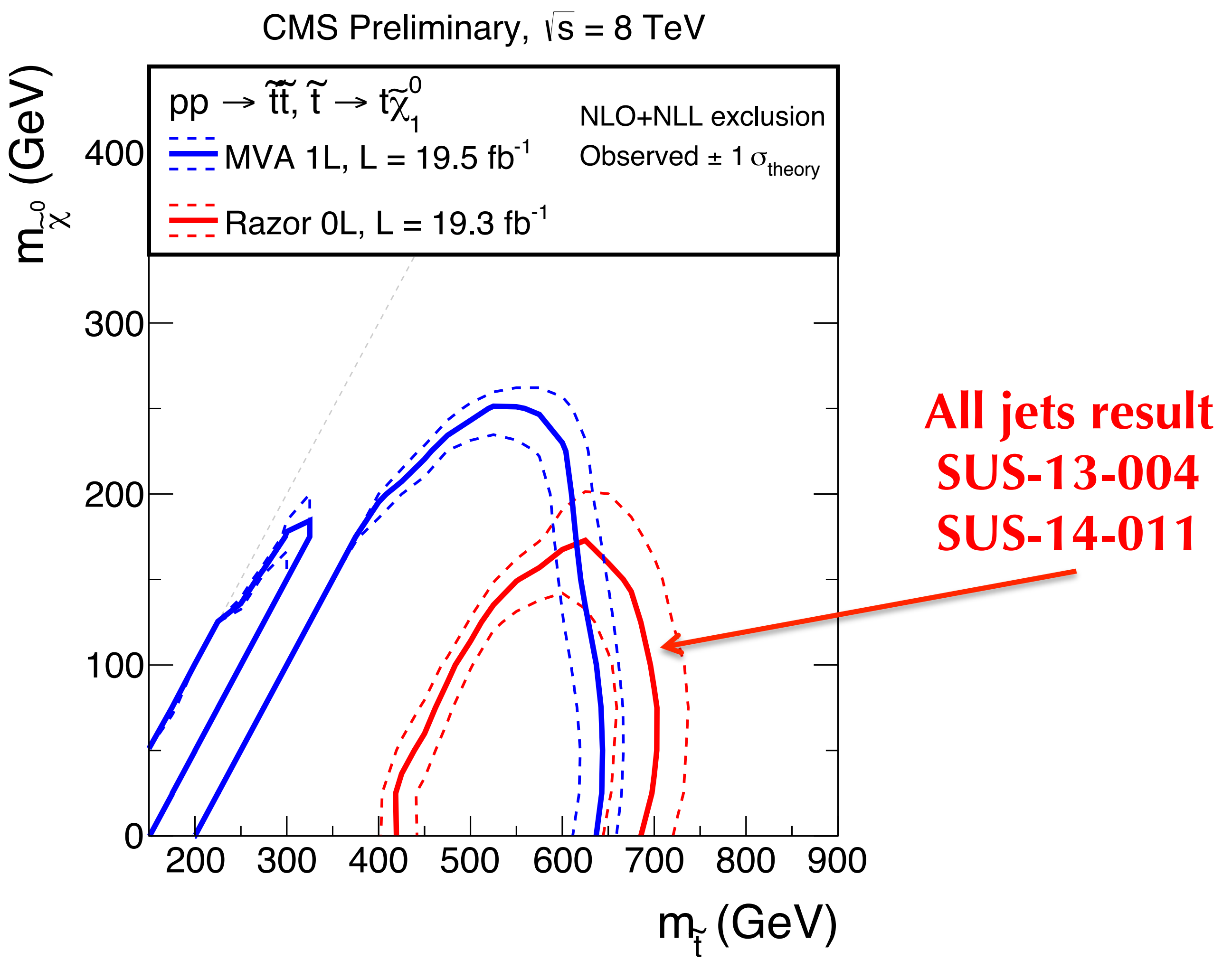
Cut-based



Limits from cut-based analysis a little worse

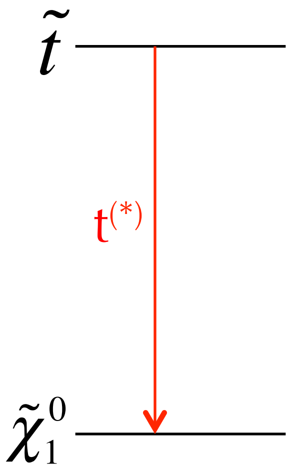
1ℓ + 0ℓ Comparison of Stop Results

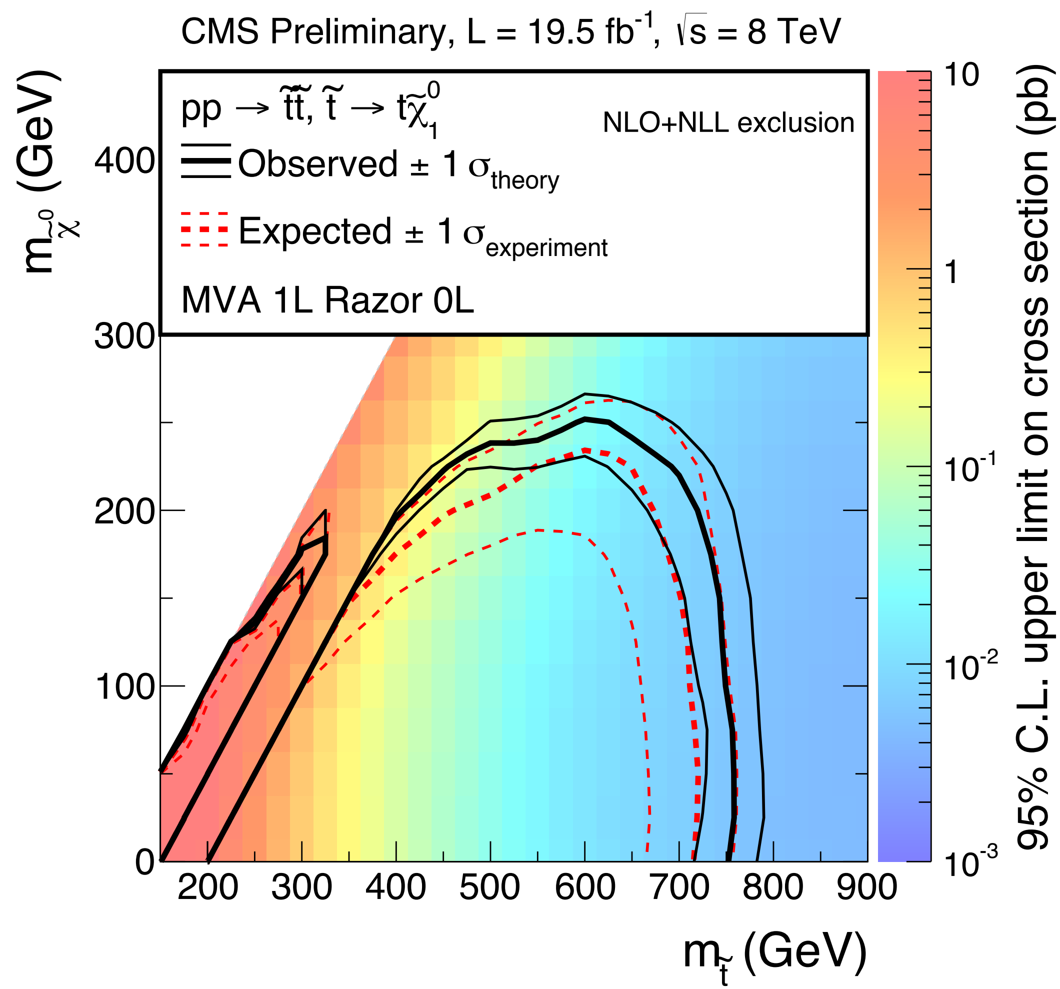




All jets search extends sensitivity to higher top squark mass

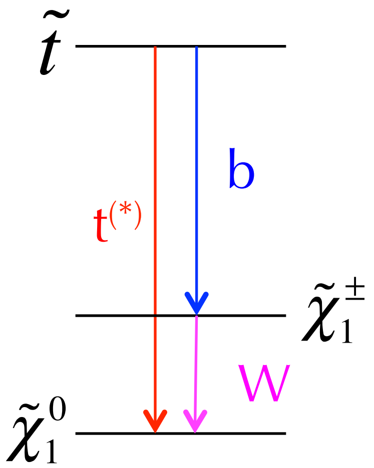
1ℓ + 0ℓ Combination of Stop Results

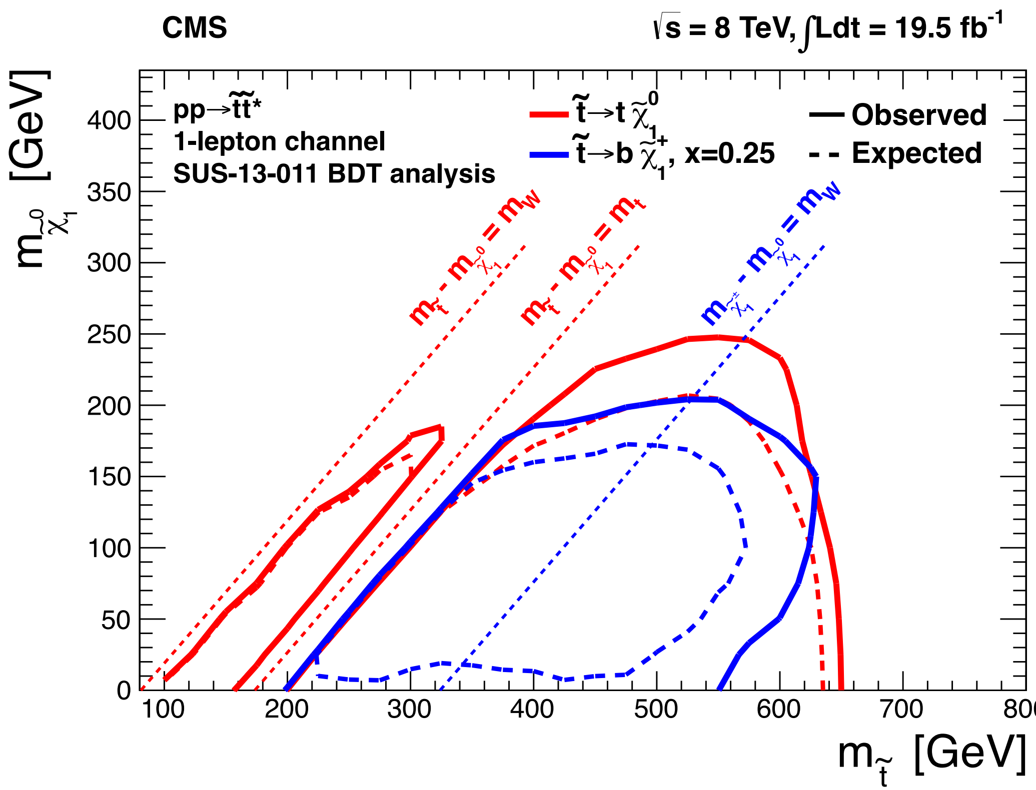




Results sensitive to top squarks to m_{stop} ~ 750 GeV

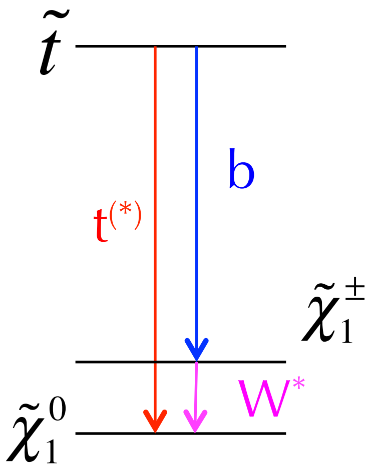
1ℓ Decay Mode Comparison

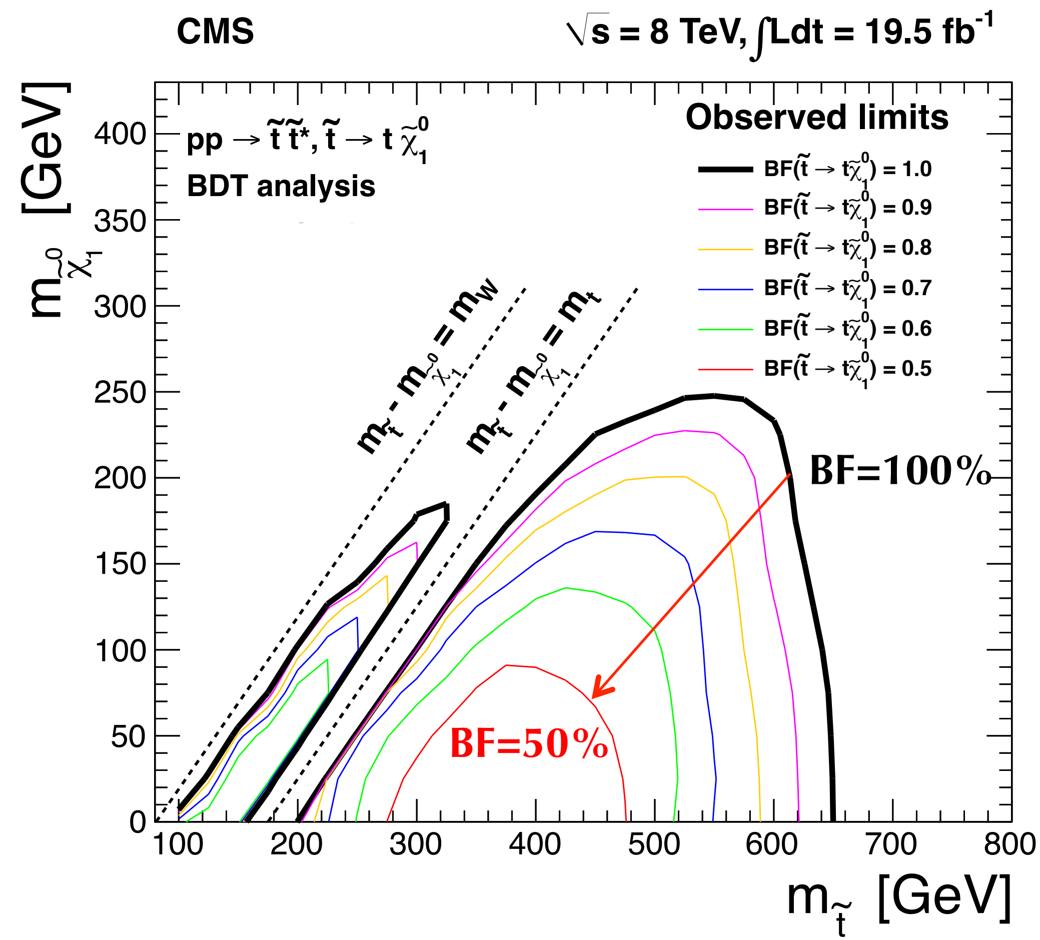




Results probe m_{stop} ~100 – 650 GeV

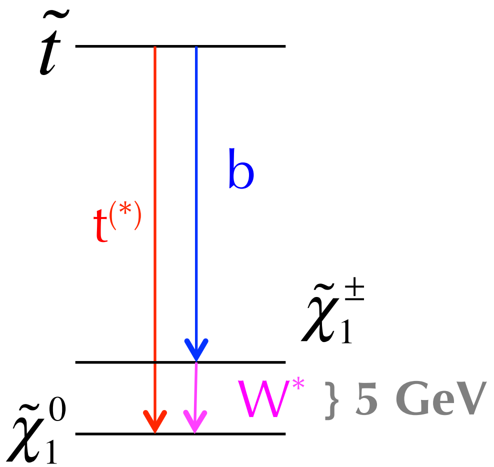
1ℓ Interpretation: Branching Fraction



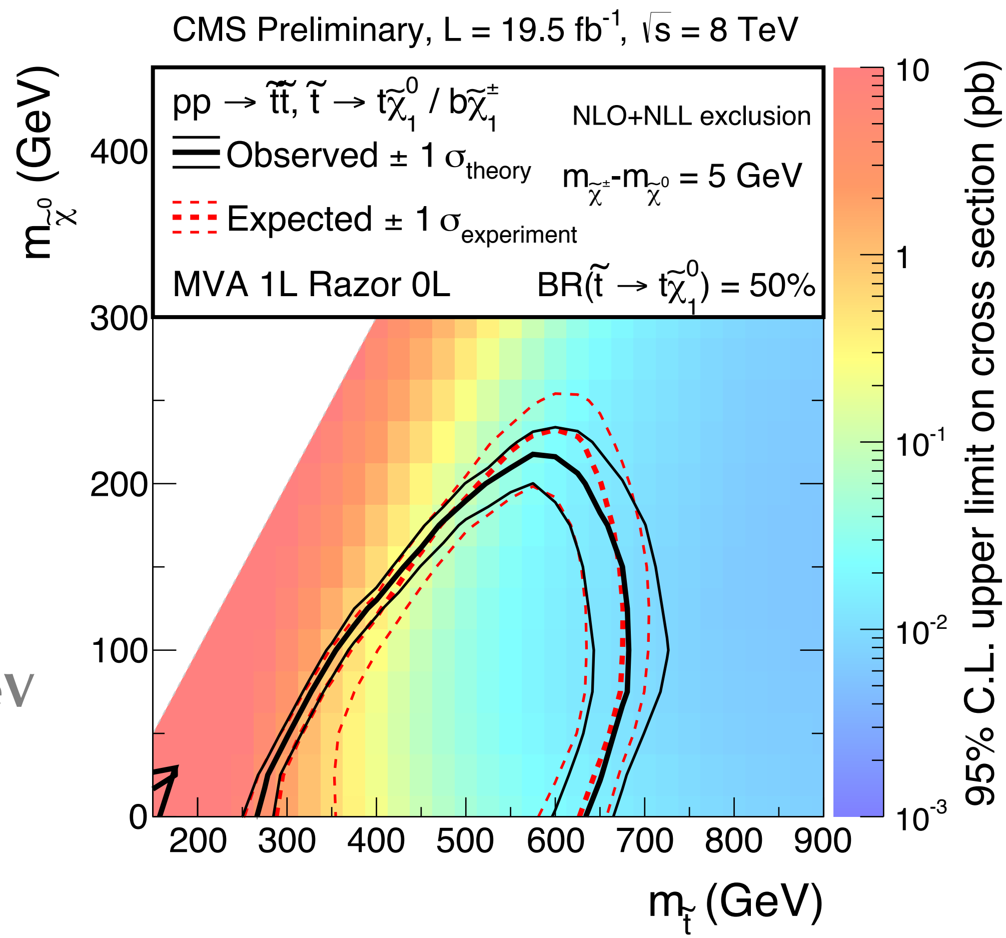


For m($\tilde{\chi}^\pm$) ~ m($\tilde{\chi}^0$), strong dependence on BF(stop → t + $\tilde{\chi}^0$)

1ℓ + 0ℓ Combination: Branching Fraction

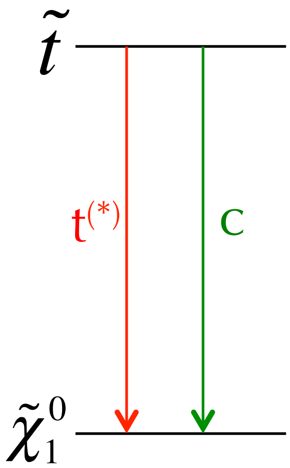


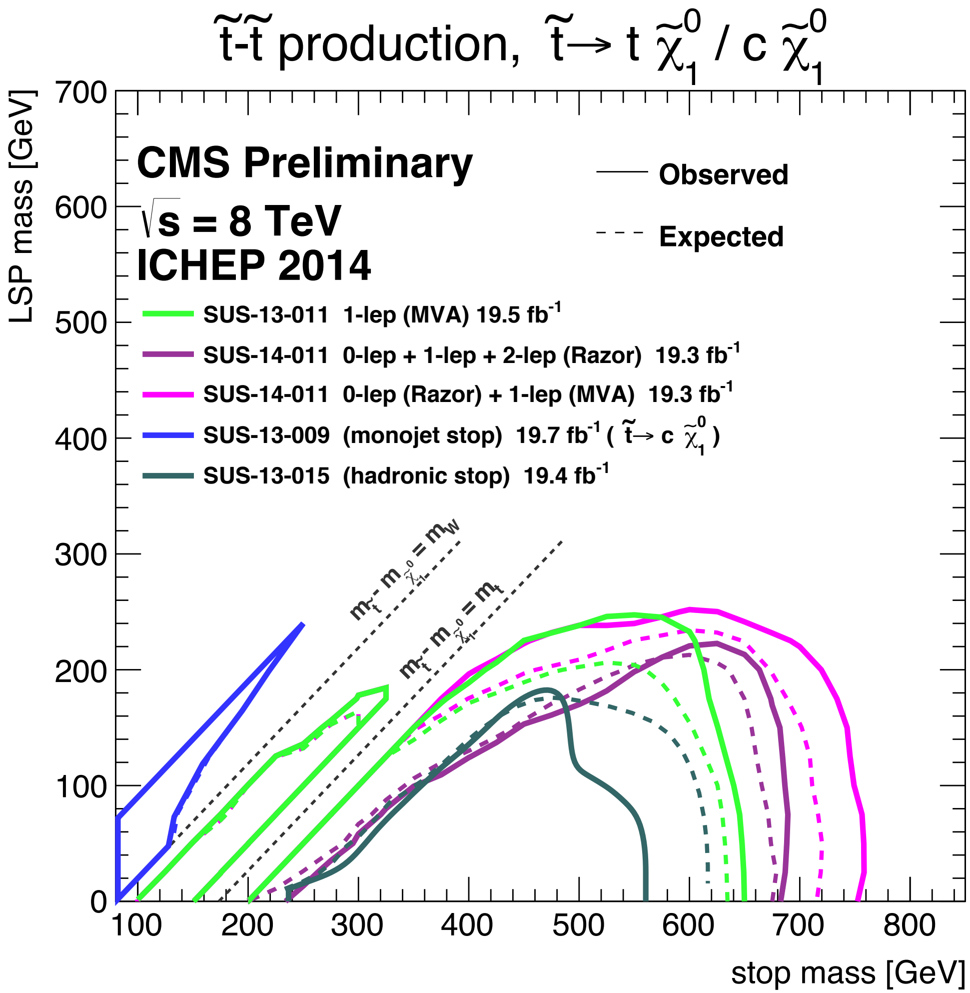
BF=50%



Combination with low jet multiplicity fully hadronic search is sensitive to a wider range of possible branching fractions

Summary of Stop Mass Limits





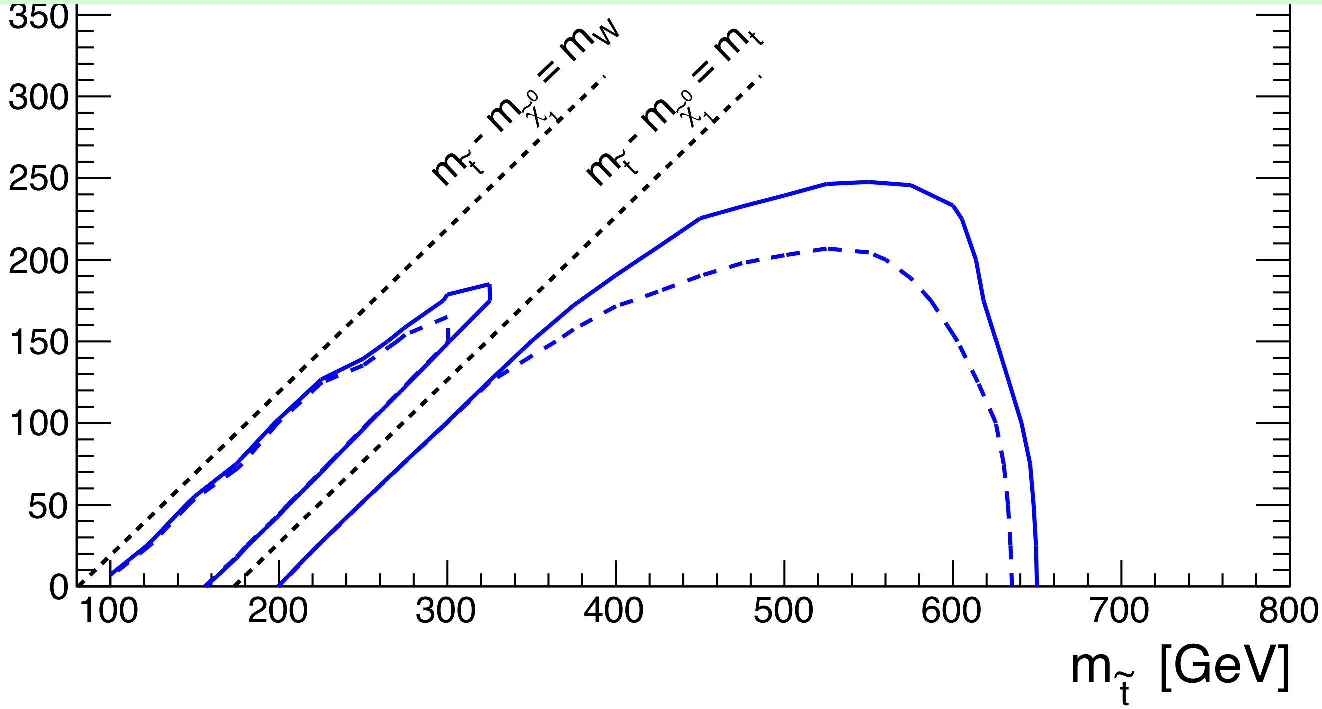
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Similar results from ATLAS

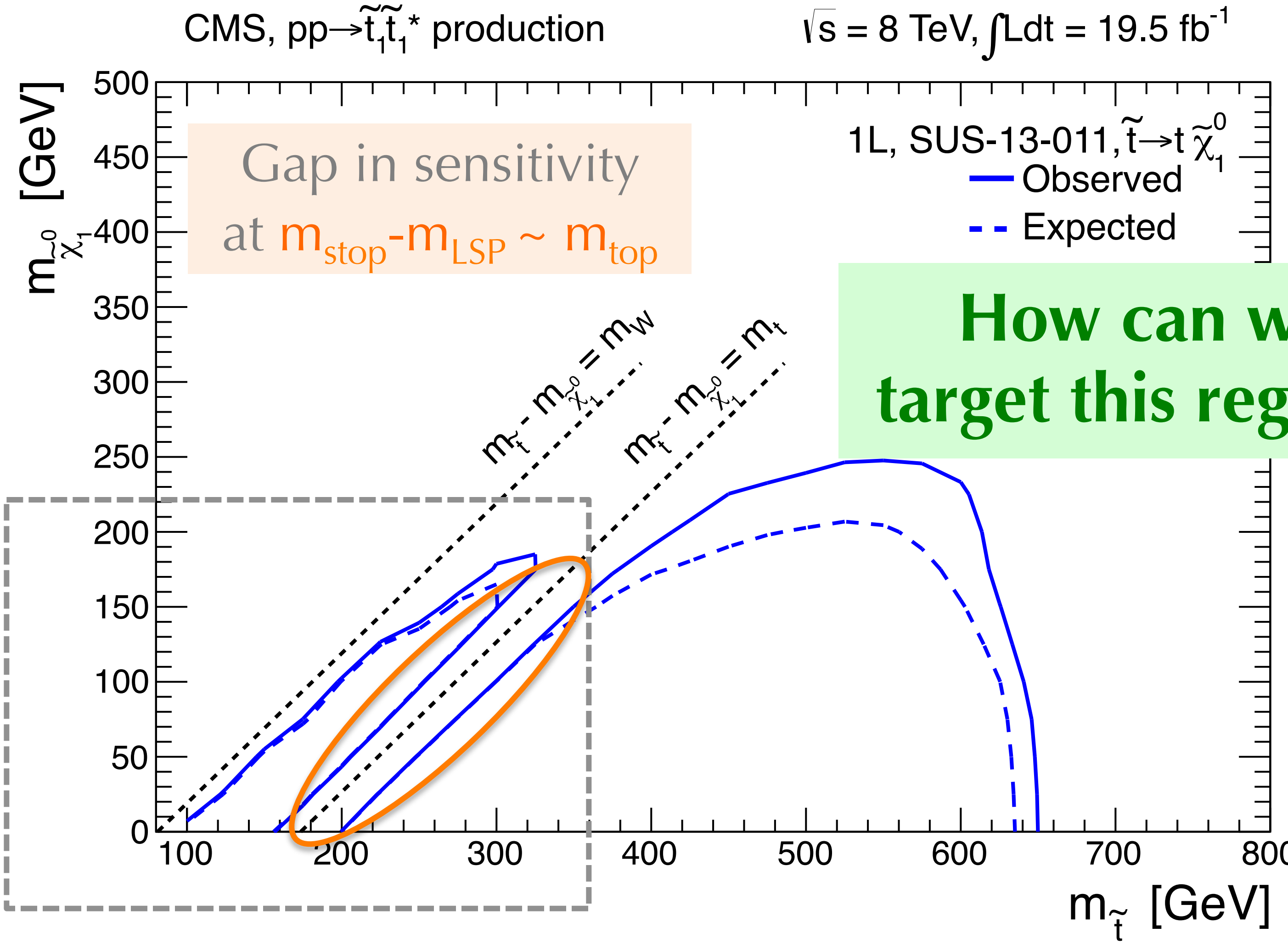
Limitations

The Gaps

Results probe m_{stop} ~100 – 650 GeV
BUT $m_{stop} \lesssim 650$ GeV is not conclusively ruled out because of gaps!



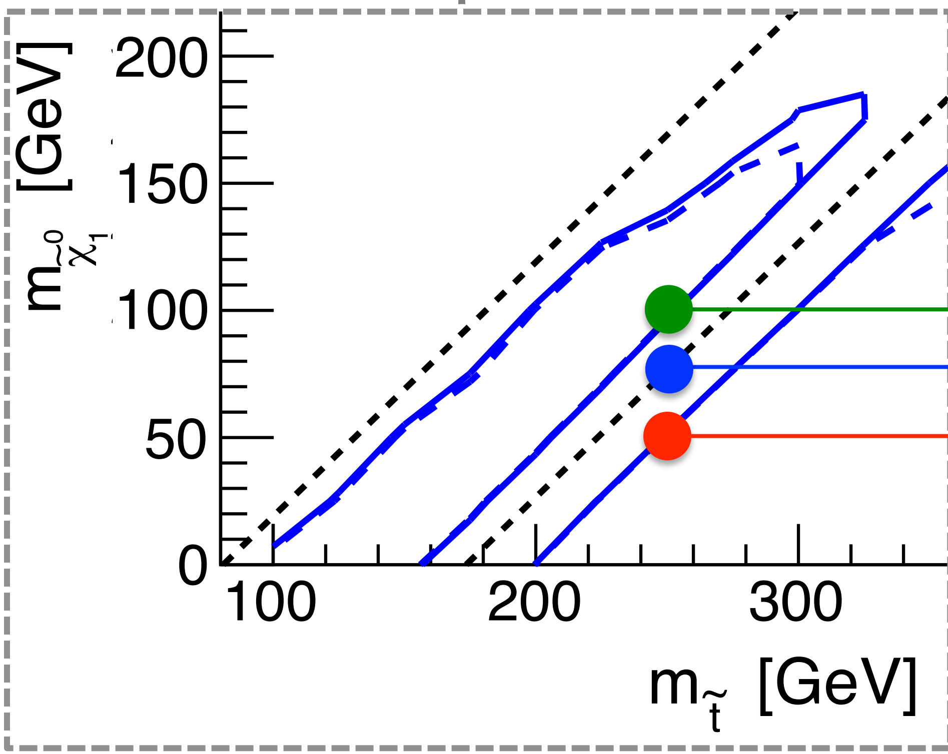
The Gap around m_{top}



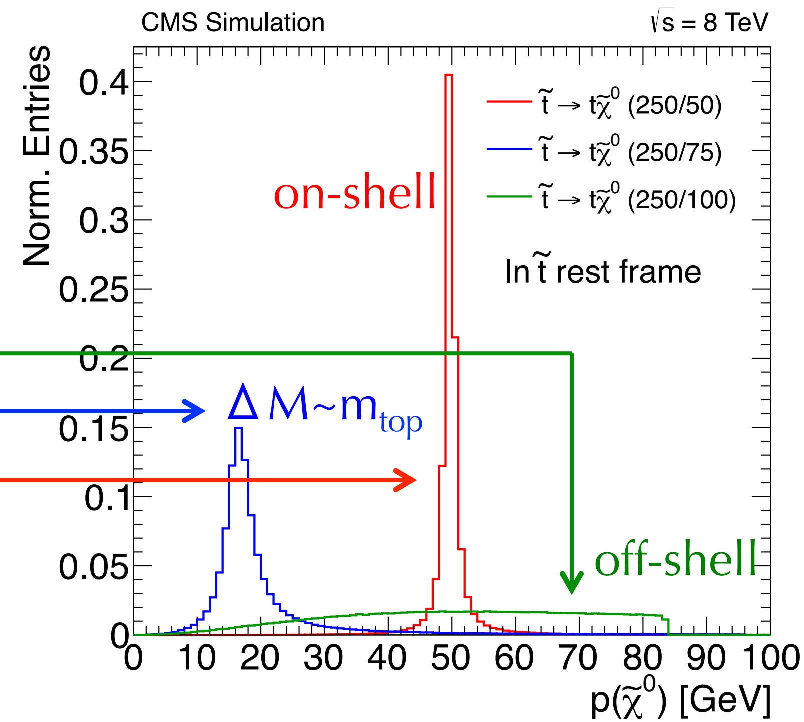
How can we target this region?

Kinematics around m_{top}

Inset from exclusion plot

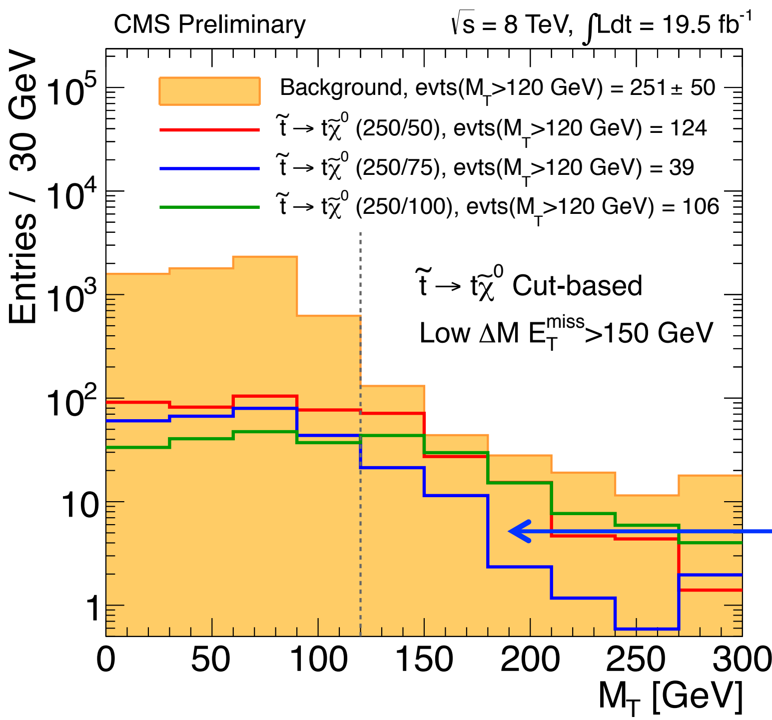


$\tilde{\chi}^0$ momentum in stop rest frame

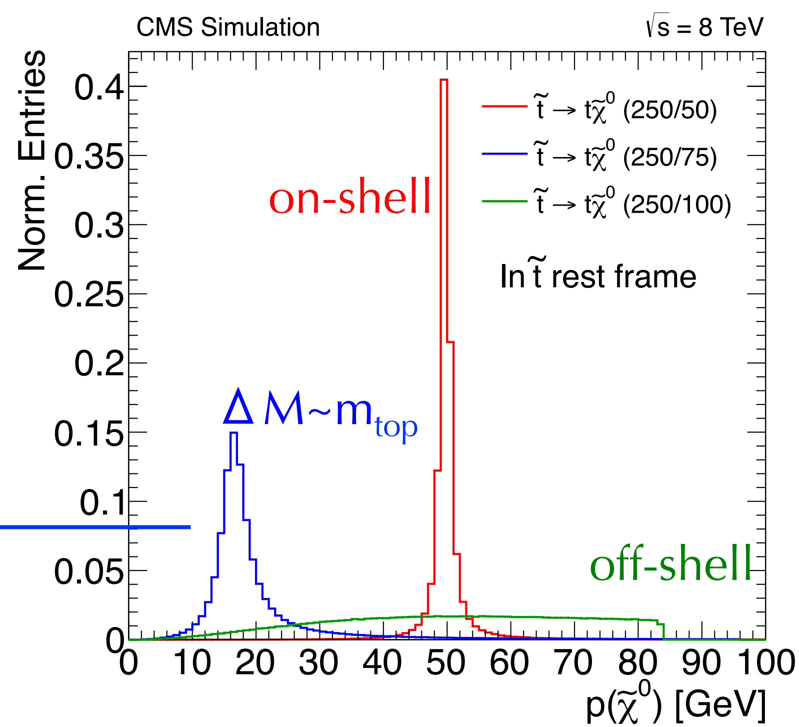


$\Delta M \sim m_{top}$ → low momentum LSP

Sensitivity around m_{top}



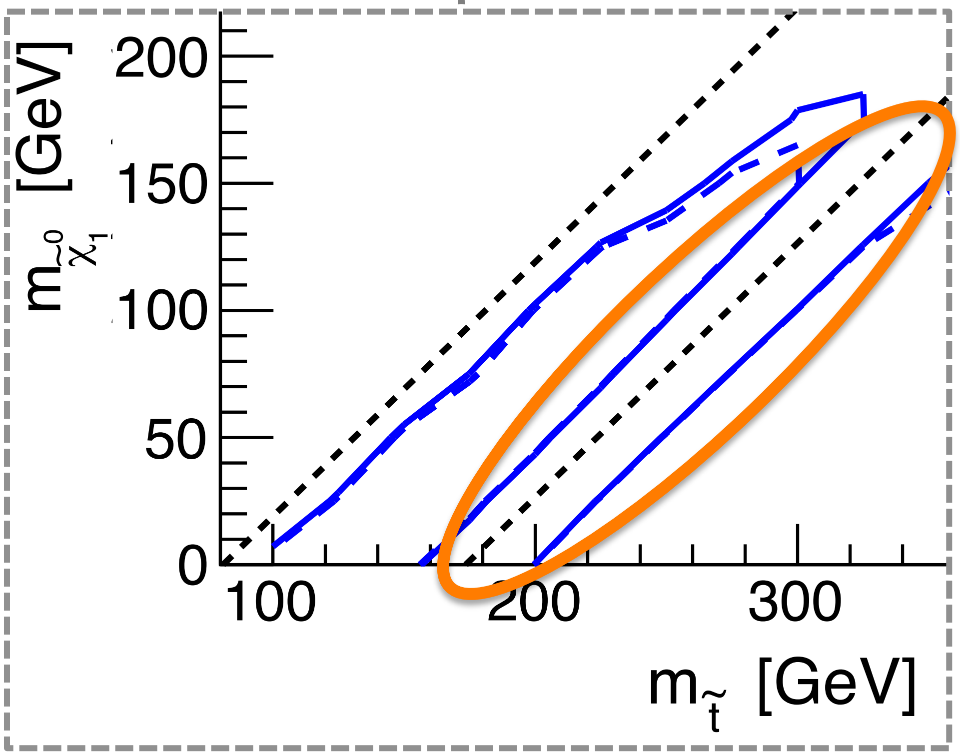
$\tilde{\chi}^0$ momentum in stop rest frame



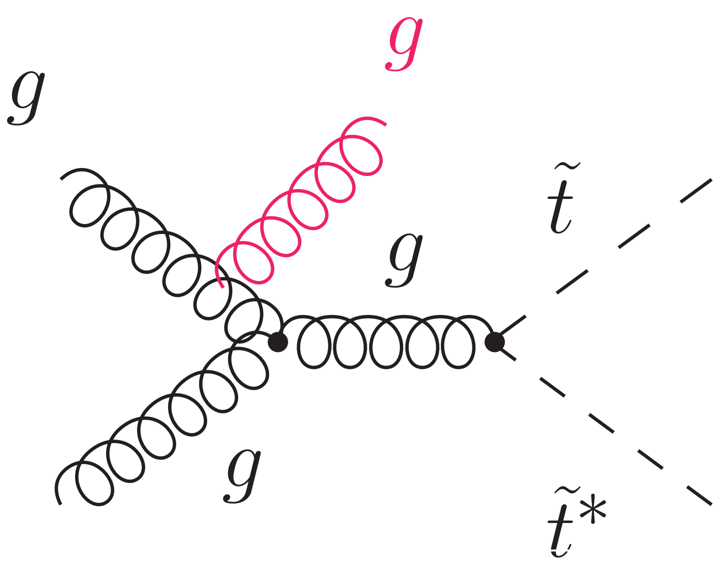
low momentum LSP
→ low MET
→ low M_T acceptance

Recoiling Signals

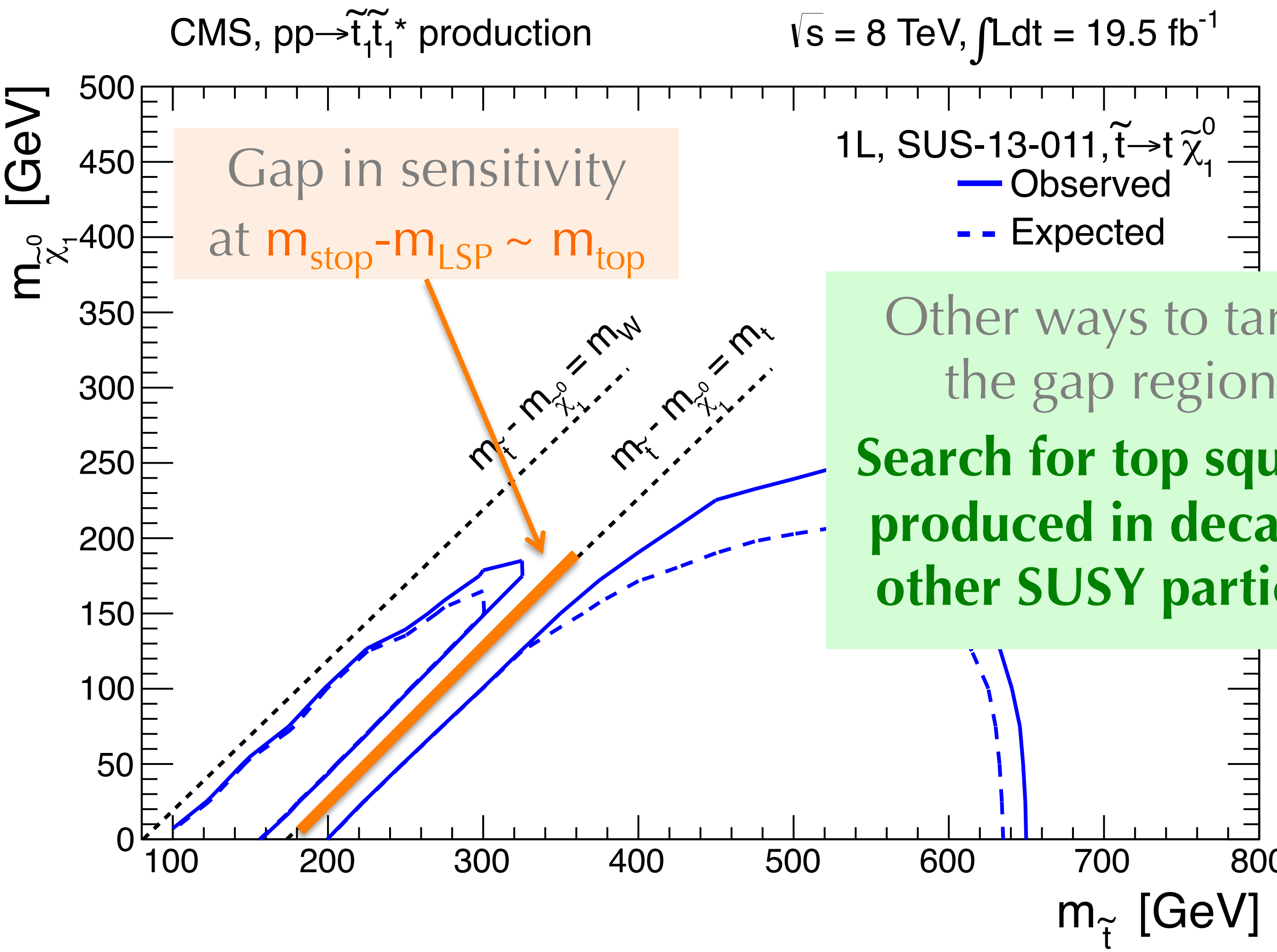
Inset from exclusion plot



Design event selection for stops recoiling against ISR jets
→ increase LSP momentum
→ gain sensitivity



Revisiting the Gap around m_{top}

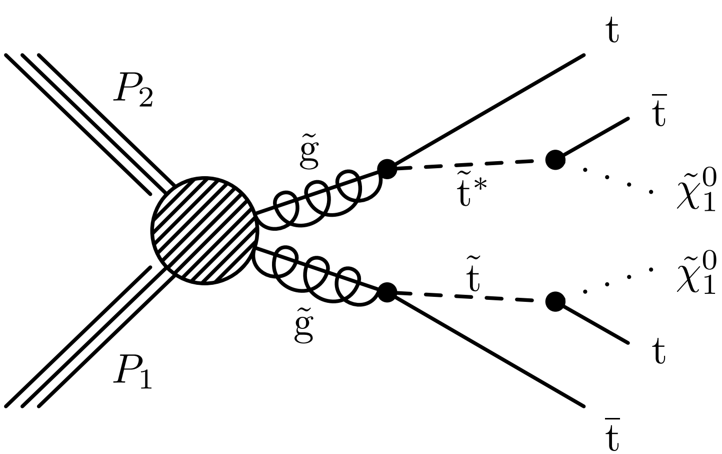


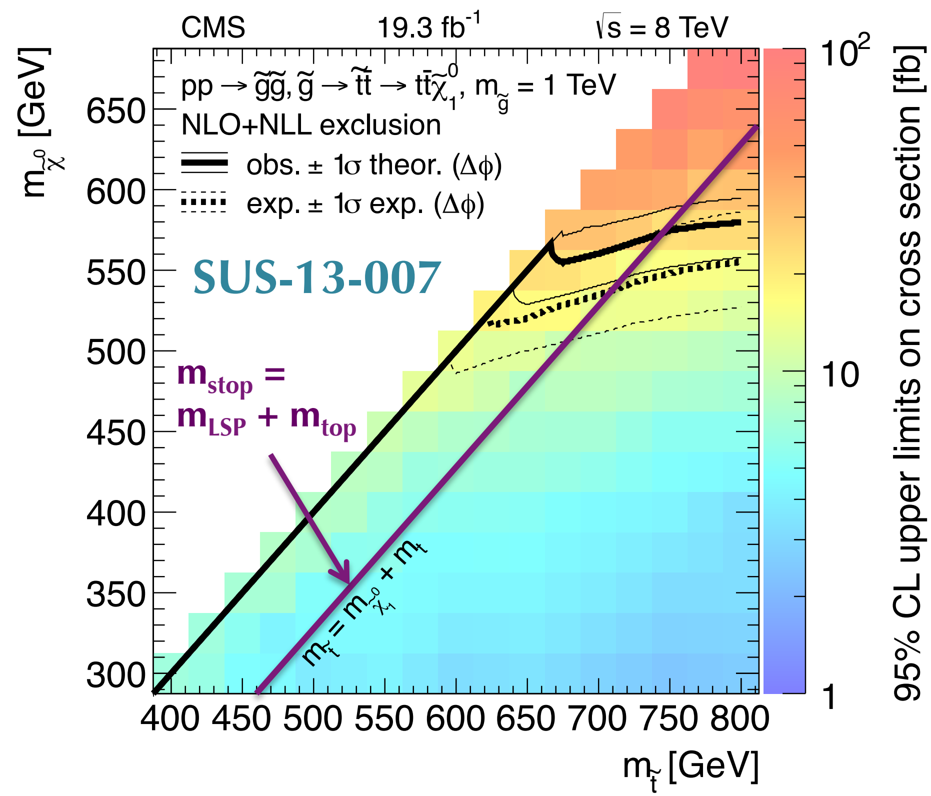
Other ways to target the gap region:

Search for top squarks produced in decay of other SUSY particles

Stop in Gluino Cascade Decays

If the lightest stop is hiding in the top,
could see it in the decay of the gluino

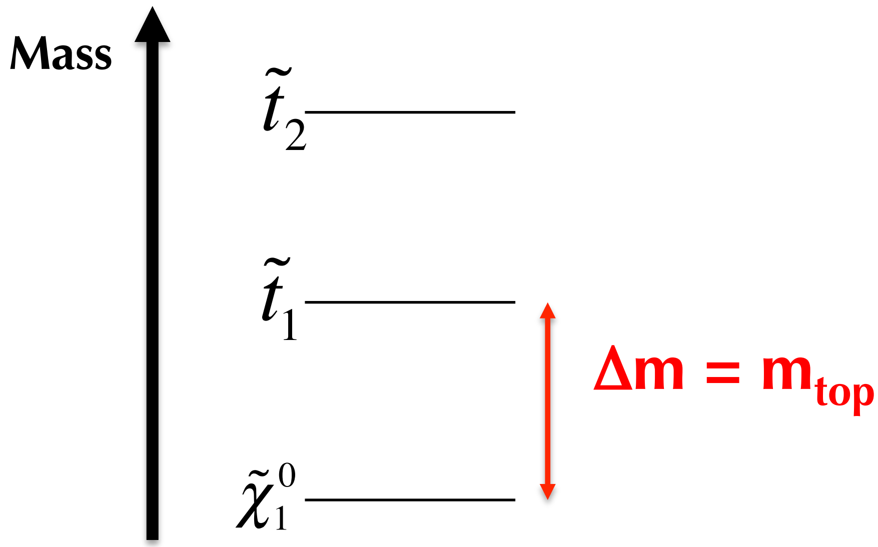


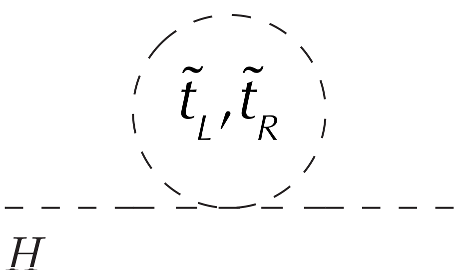


Hole closed for 100% BF if m_{gluino} below ~1.3 TeV

Stop$_1$ in Stop$_2$ Cascade Decays

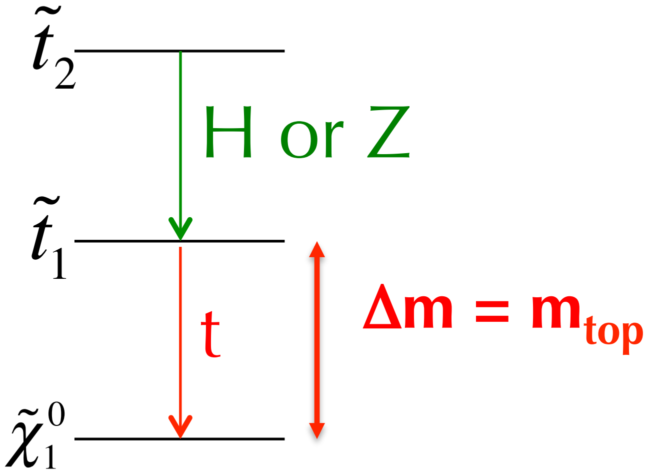
If the lightest stop is hiding in the top,
could see it in the decay of a heavier stop



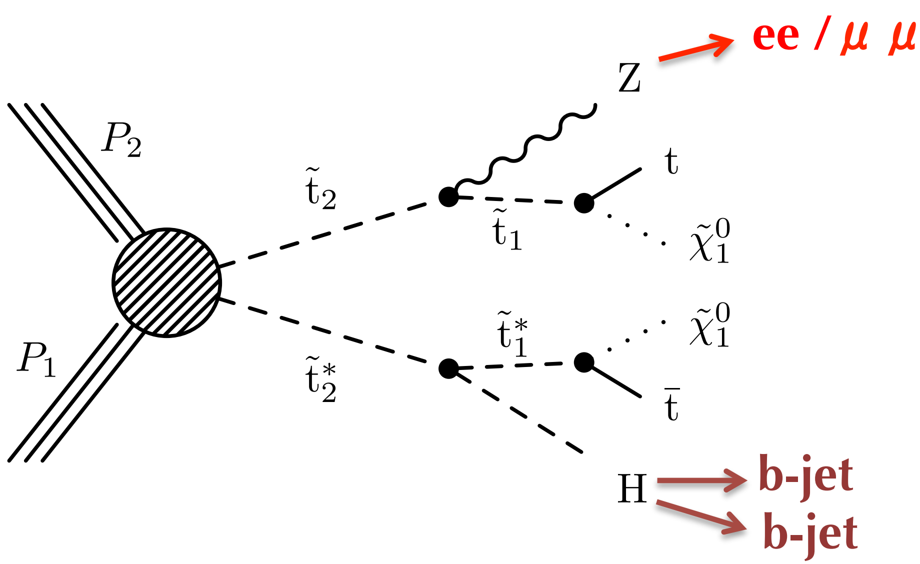


$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_t & \sin\theta_t \\ -\sin\theta_t & \cos\theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$Stop_2$ Signature



Signature tt
with Higgs or Z bosons

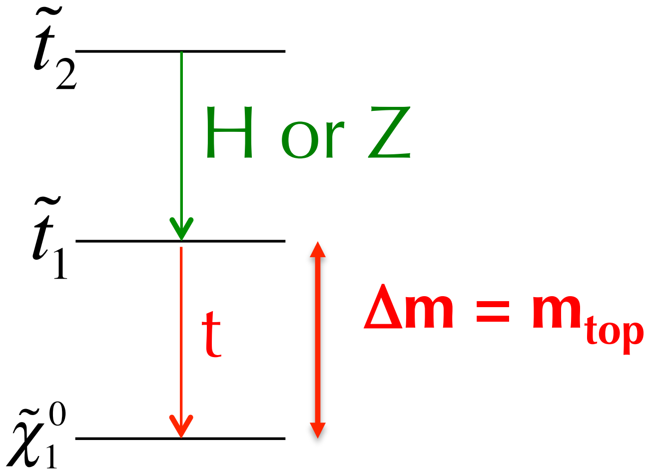


Z signature
→ additional leptons

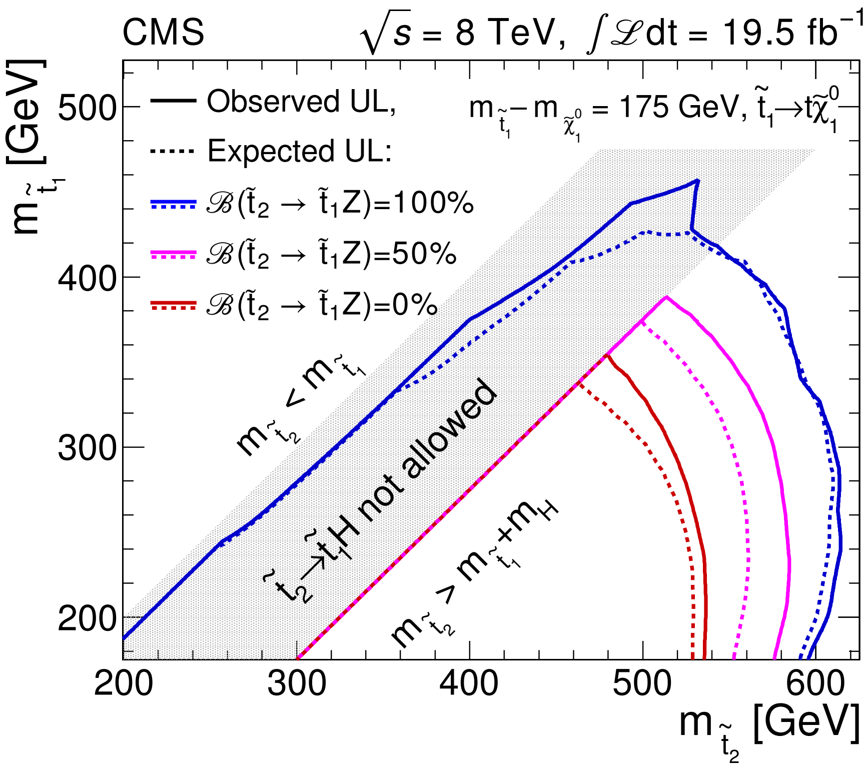
H signature
→ additional b-jets

Interpretation

Set limits combining results from searches with multiple b-jets and multiple leptons



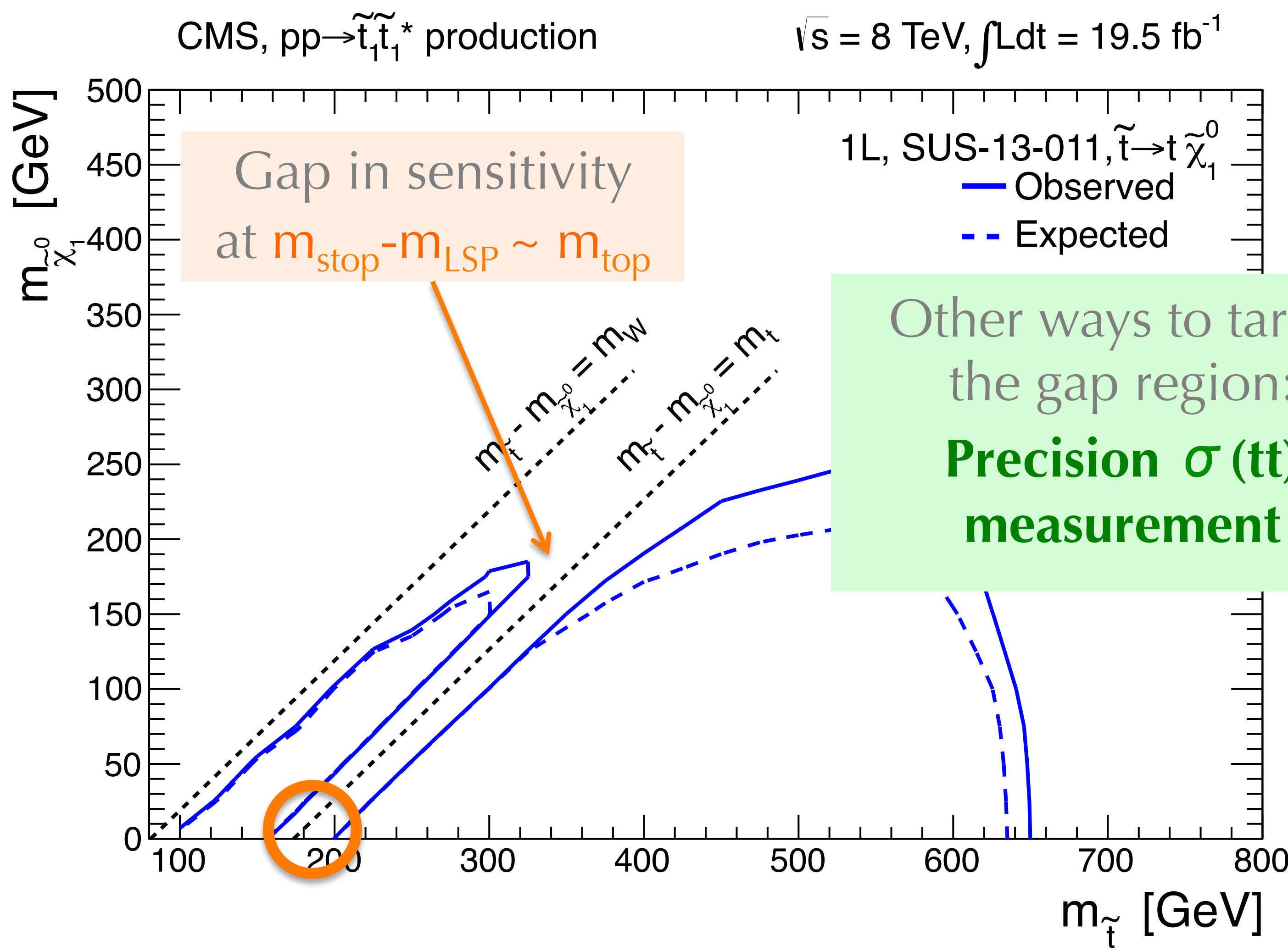
Consider all possible branching fractions to H or Z



PLB 736 (2014) 371
hep-ex/1405.3886

Hole closed for m_{stop2} below ~ 550-600 GeV

Revisiting the Gap around m_{top}

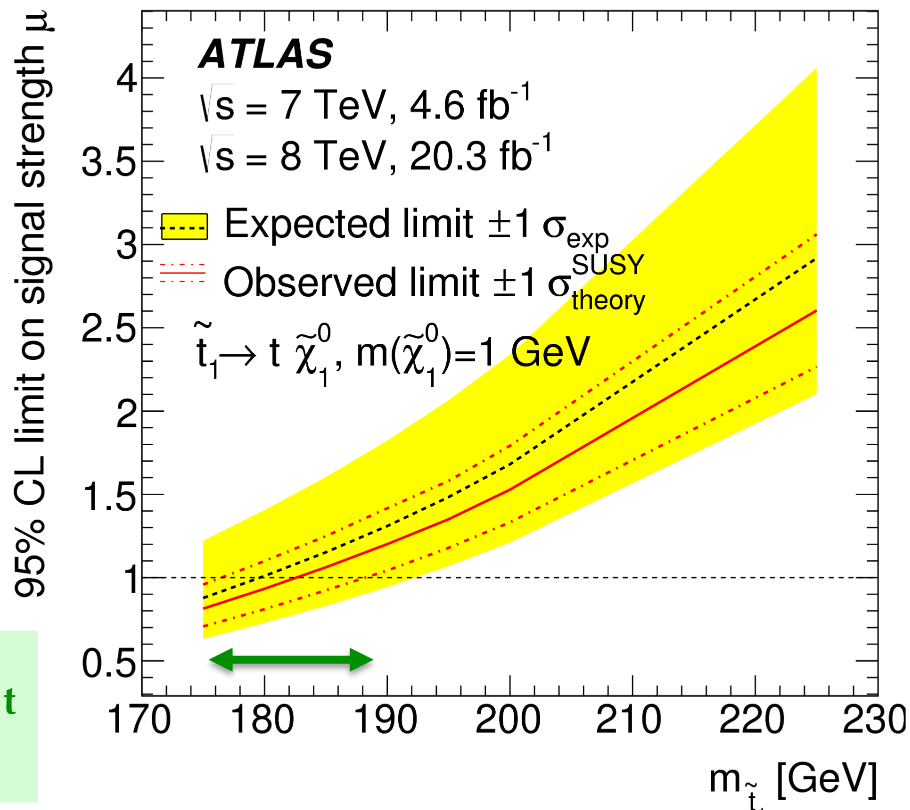


Stops hiding in the Top

Consider the impact of a light stop on the measured tt cross section

Stop would increase observed σ (tt)~15%
Experiment $\Delta\sigma$ ~ 4%
NNLO theory $\Delta\sigma$ ~ 6%

$\sqrt{s}$ [TeV]	7	8
Experiment σ (tt) [pb]	182.9 ± 7.1	242.4 ± 10.3
Theory σ (tt) [pb]	$177.3^{+11.5}_{-12.0}$	$252.9^{+15.3}_{-16.3}$

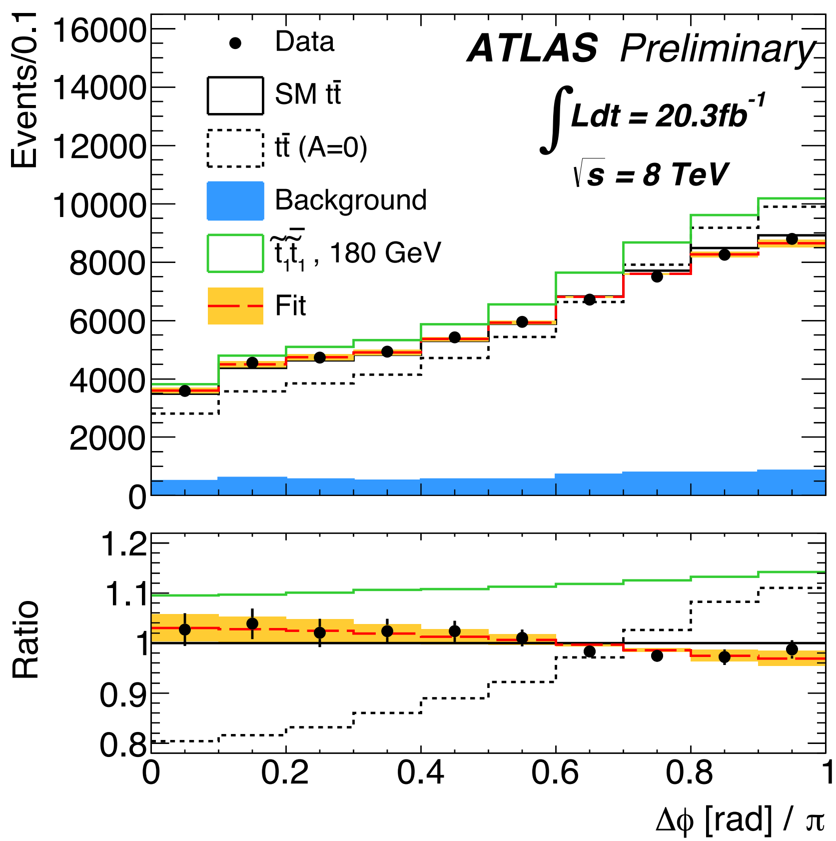


hep-ex/1406.5375
Submitted to EPJC

Constrain m_{stop} ~ m_t for 100% BR $t\chi^0$

Stops hiding in the Top

$\Delta\phi(l_1,l_2)$ in $tt \rightarrow \ell^+\ell^-$ affected by presence of stops (spin 0)

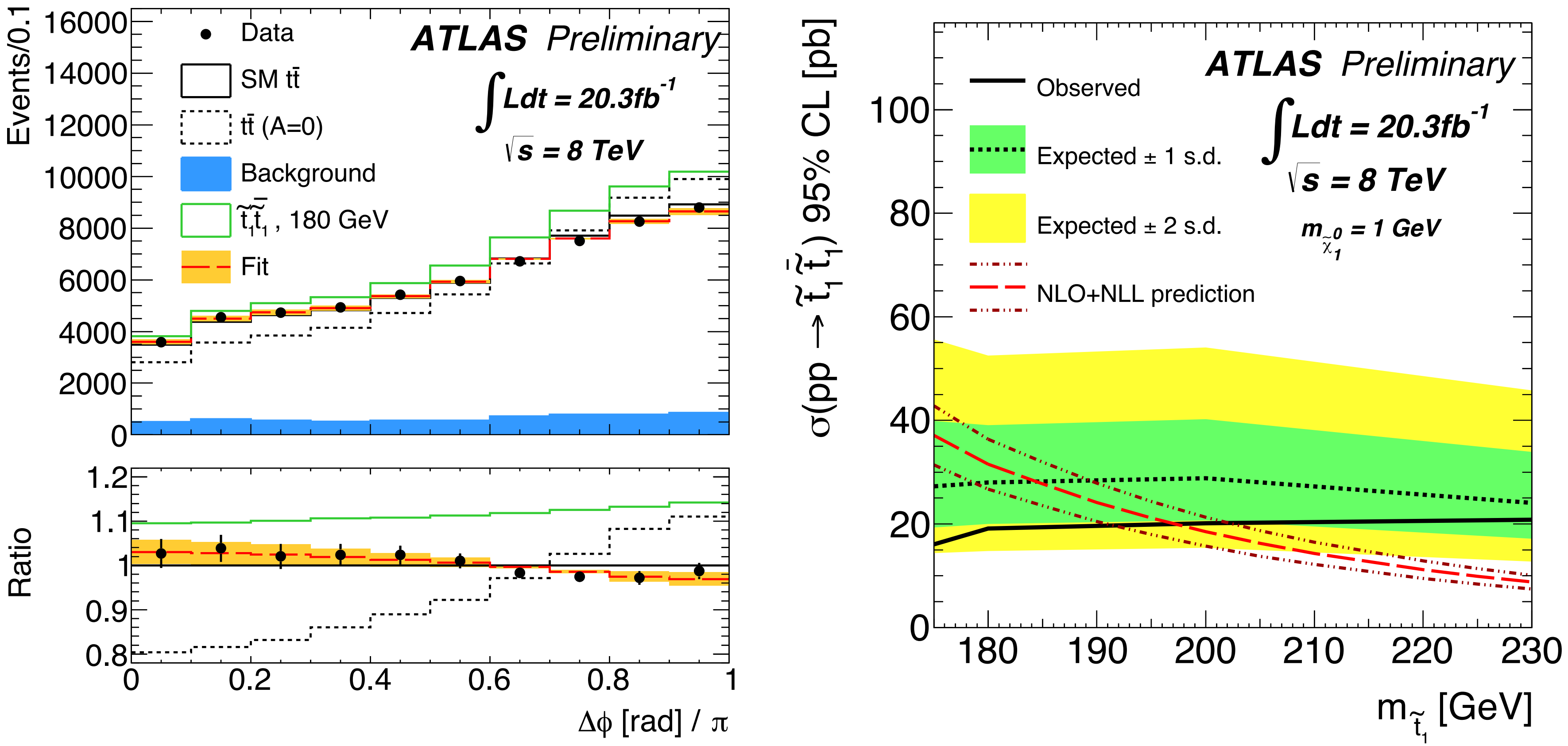


ATLAS-CONF-2014-056

Stops hiding in the Top

$\Delta\phi(l_1,l_2)$ in $tt \rightarrow \ell^+\ell^-$ affected by presence of stops (spin 0)

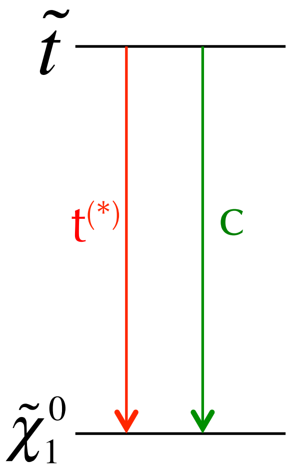
Measurement can be used to constrain stops with $m_{stop} \sim m_t$

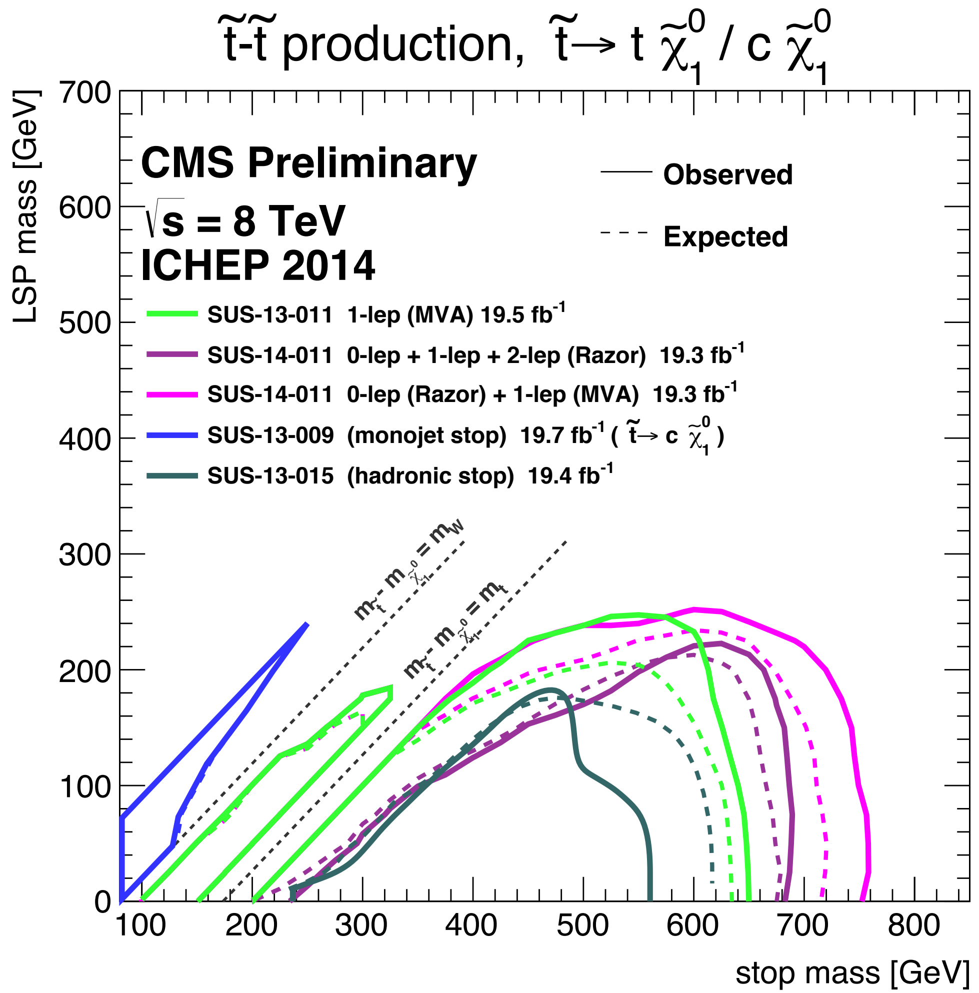


ATLAS-CONF-2014-056

Prospects & Conclusions

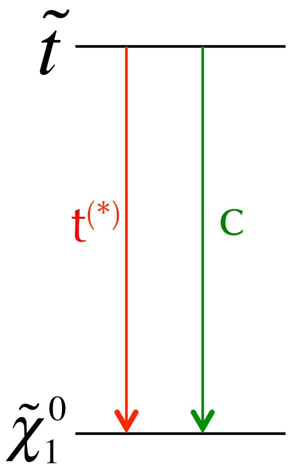
Summary of Run1 Stop Mass Limits

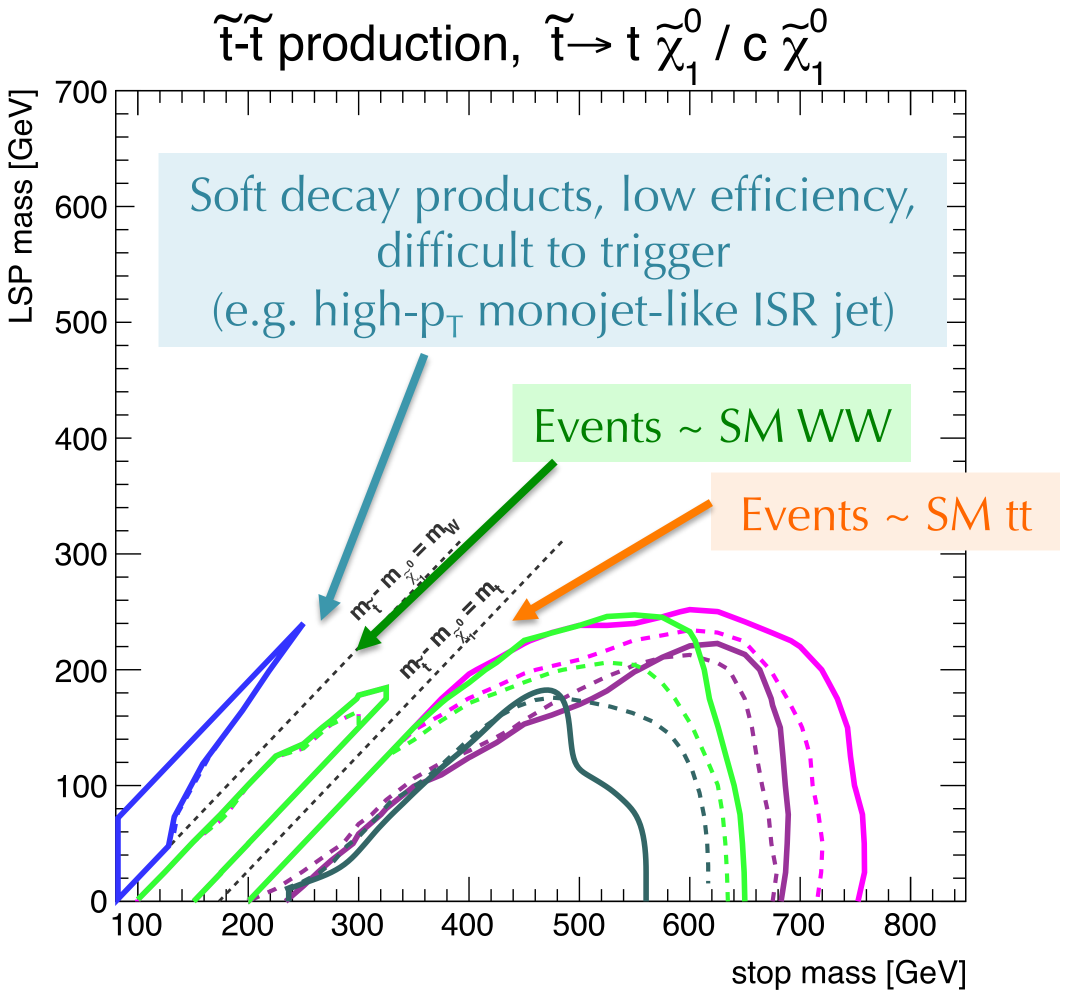




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

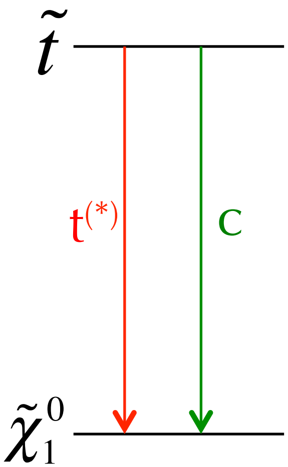
Summary of Run1 Stop Mass Limits

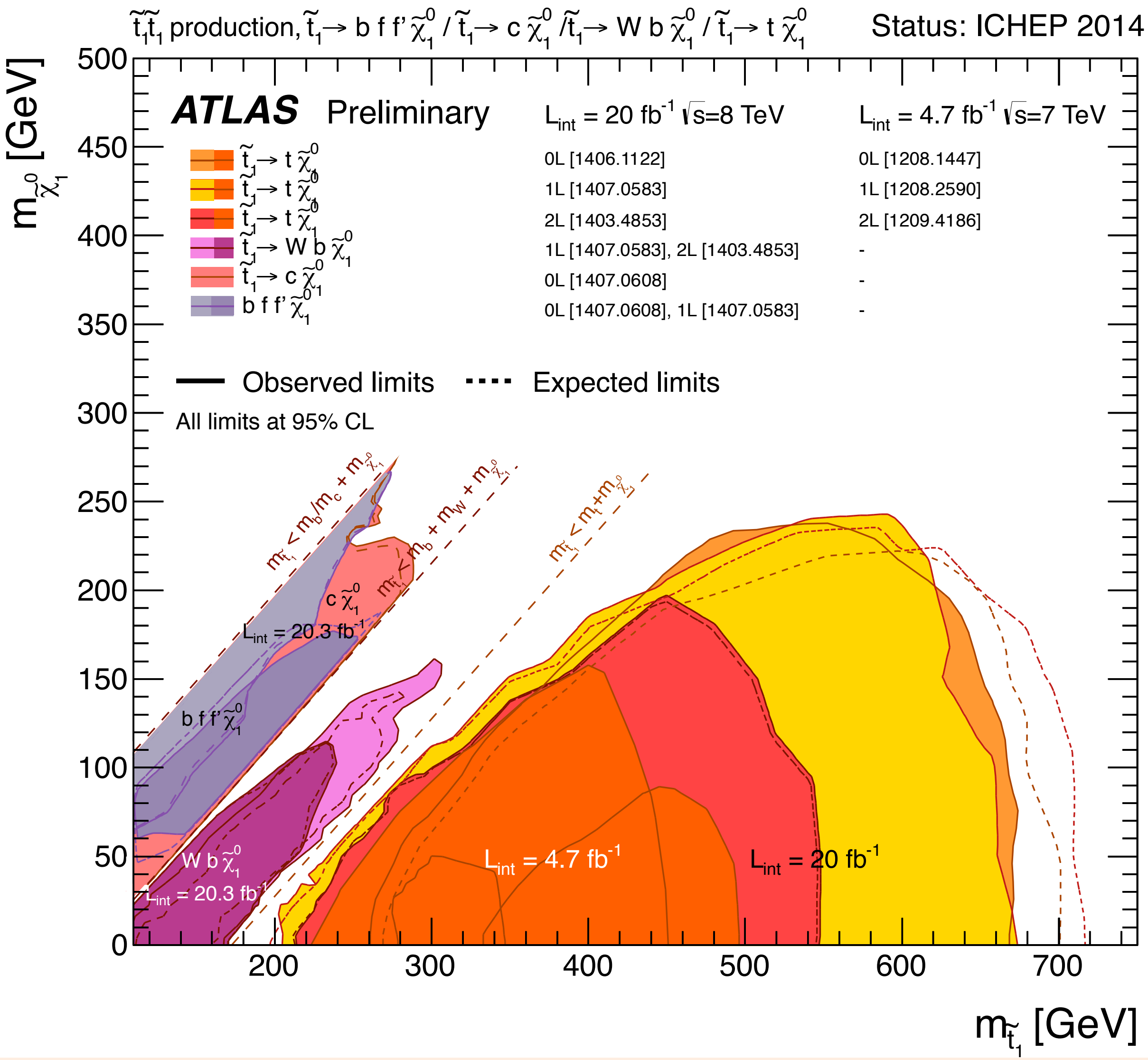




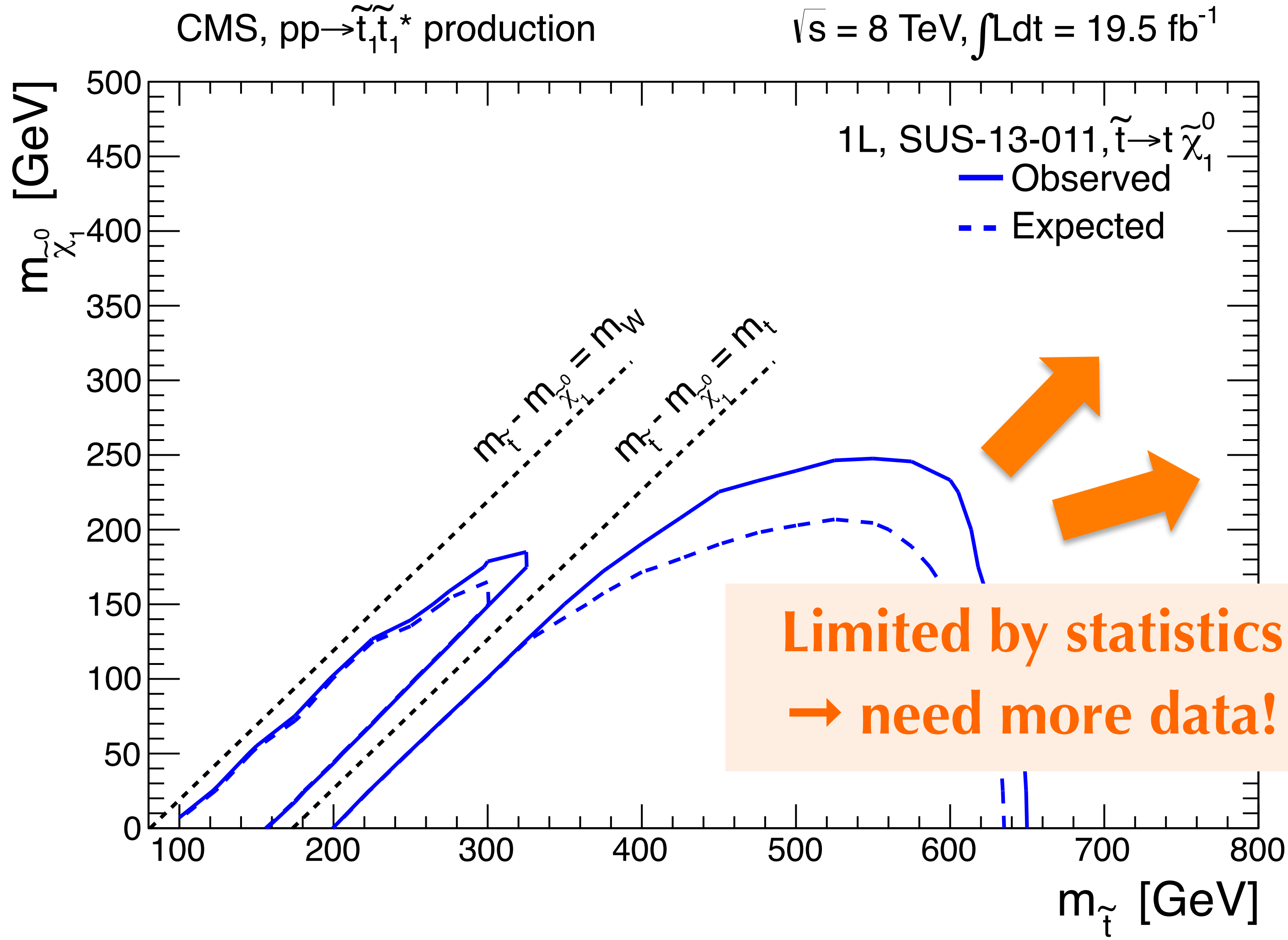
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Summary of ATLAS Results





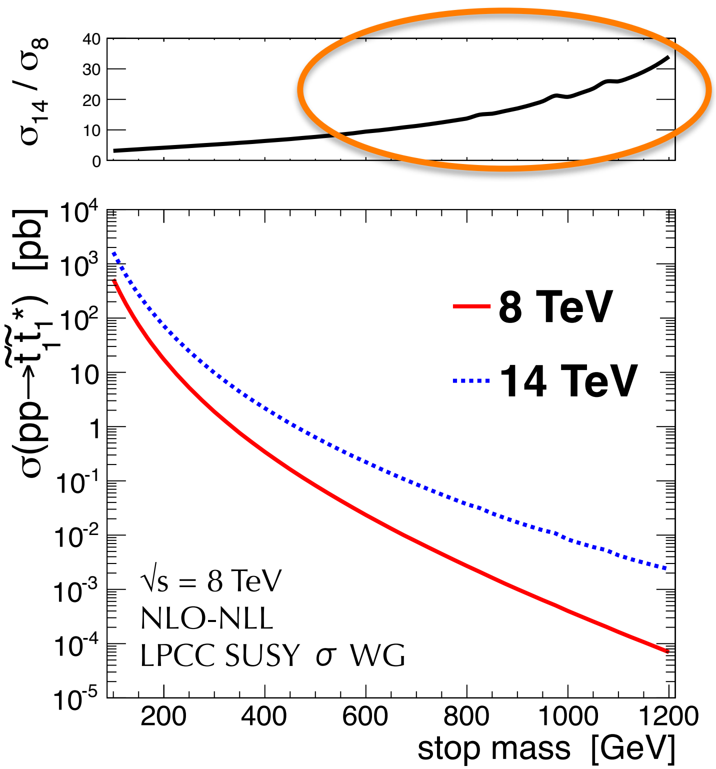
Extending to Higher Masses

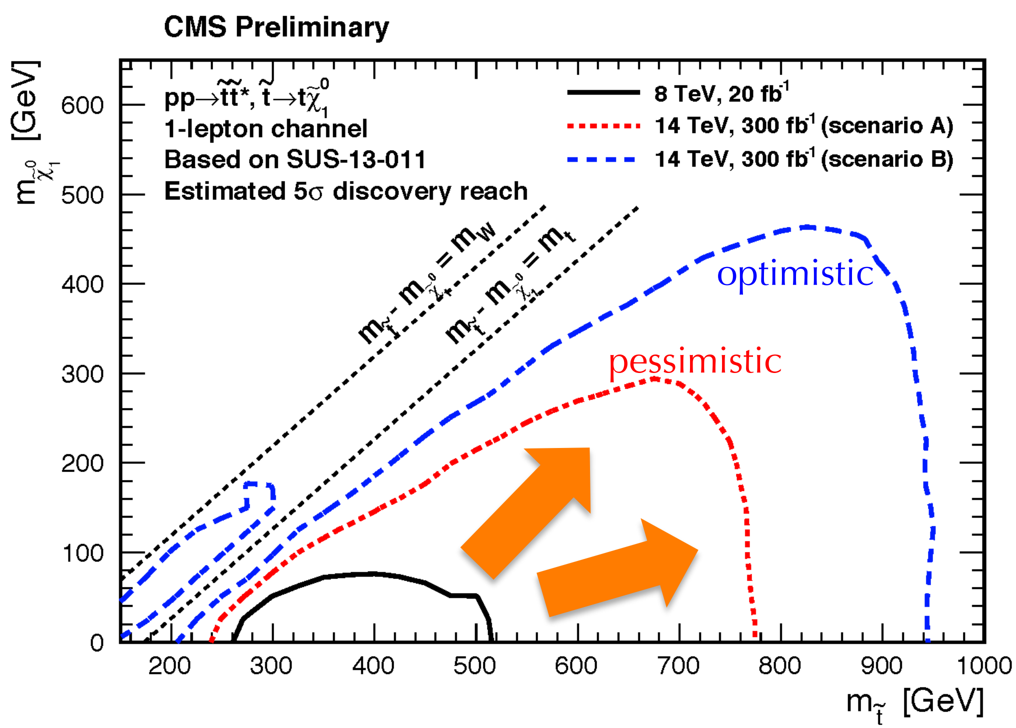


Limited by statistics
→ need more data!

Top Squarks at LHC Run 2

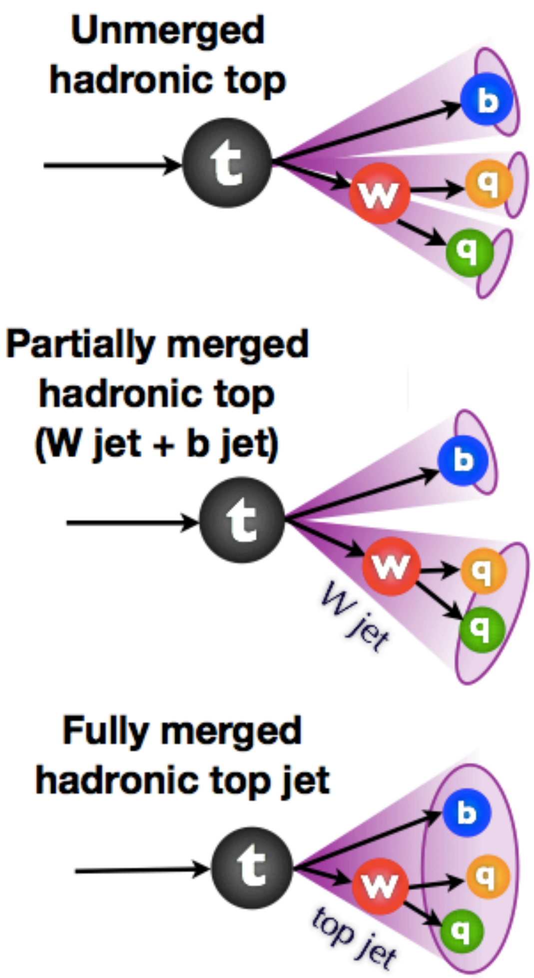
LHC Run2 (~2015-2021) expect ~300 fb^{-1} of data at $\sqrt{s}$ = 13-14 TeV

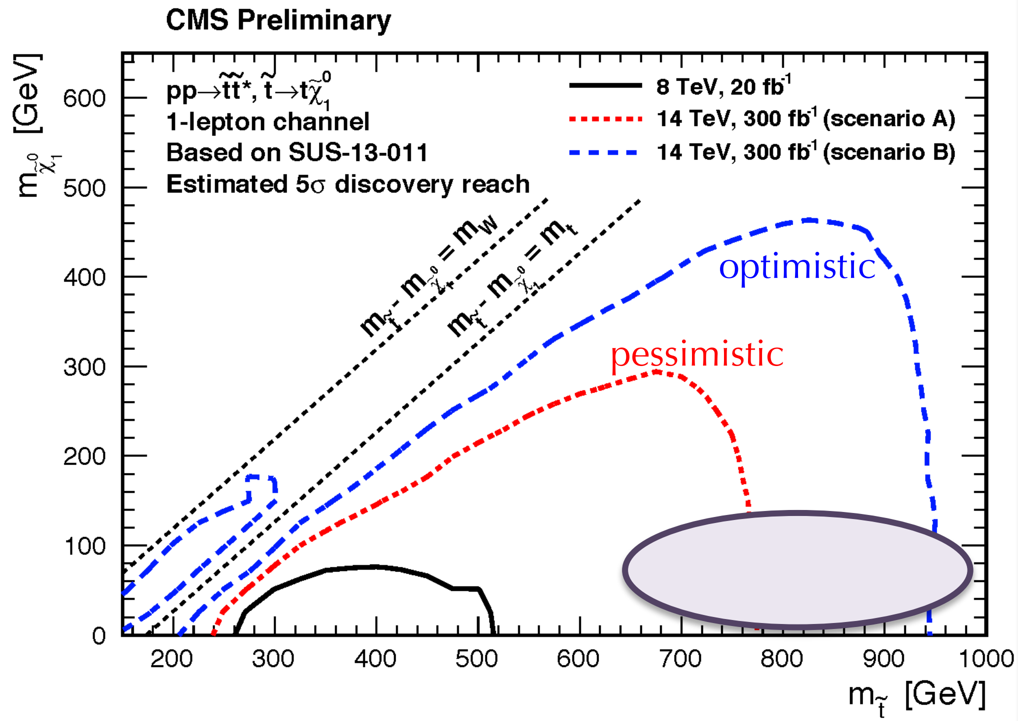




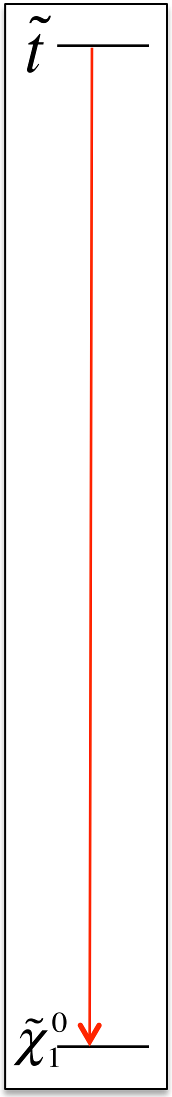
Expect *discovery* reach up to m_{stop}~750-950 GeV

Analysis Updates



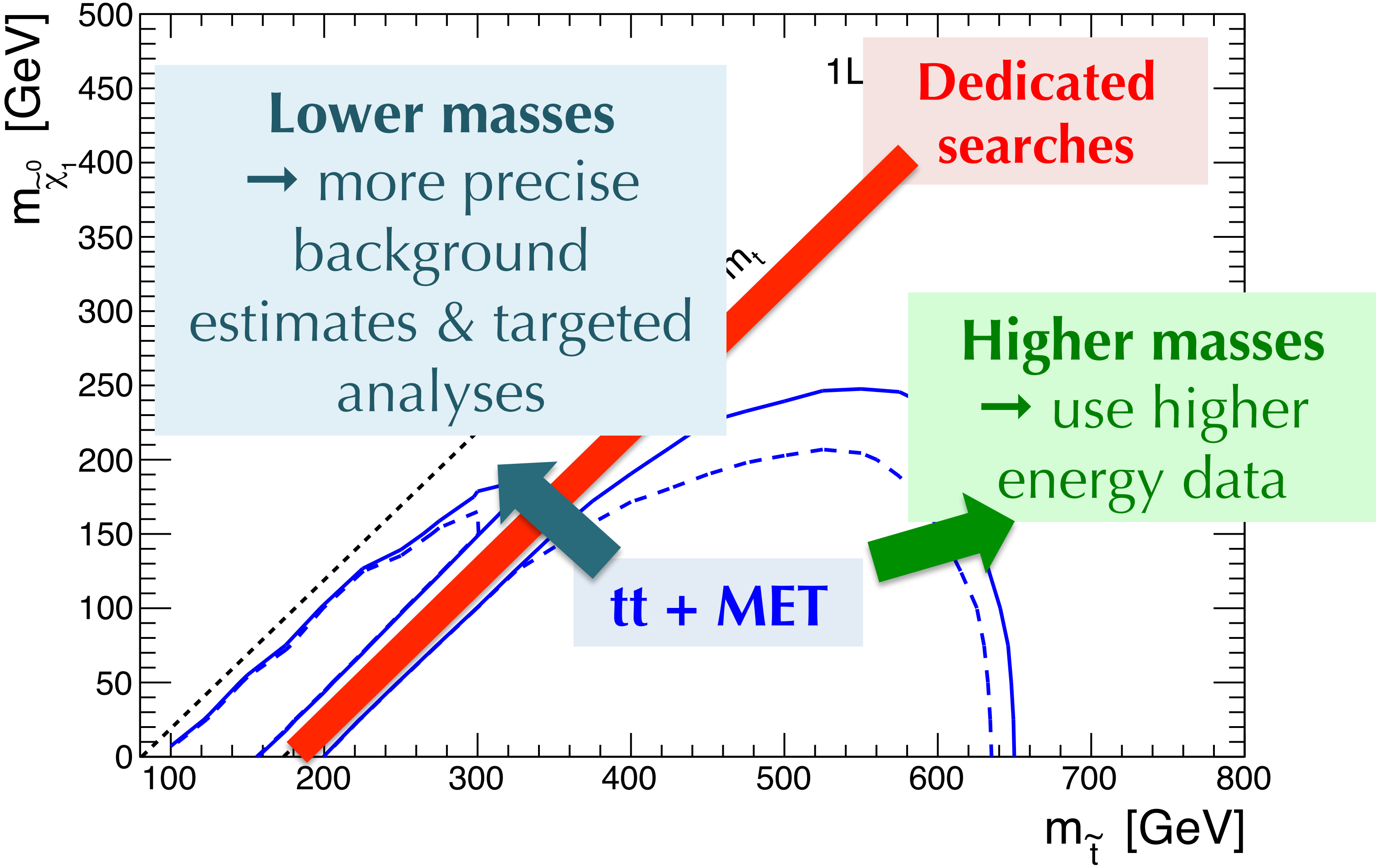


Revisit analysis for large m_{stop}
→ boosted decay products



Summary of Searches and Outlook

In the next years can cover a lot of the gaps!



Conclusion

Light stops are a powerful signature of new physics to search for at the LHC

Searches for stops at the LHC are the first to explore significant regions of interesting parameter space
No signs of stops, but understanding of SM backgrounds is the key to any future discovery

There are loopholes, even for light stops, some are currently being addressed
→ need to cover the gaps in sensitivity

The next years are going to be crucial to discover light stops or to set severe constraints on Natural SUSY
→ the higher energy data will extend the sensitivity to close to 1 TeV

Thank you

Art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz)