Top and SUSY

a theoretical point of view

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top 2014

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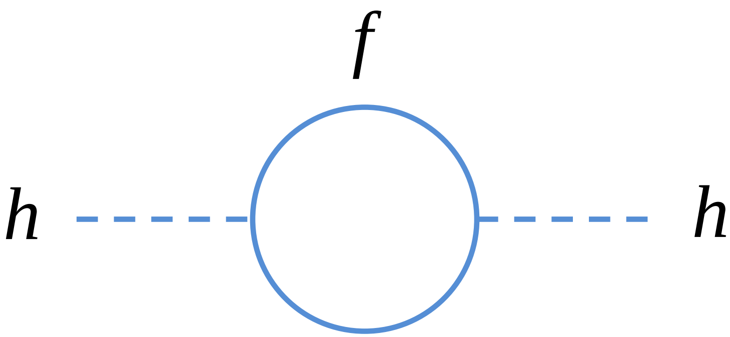
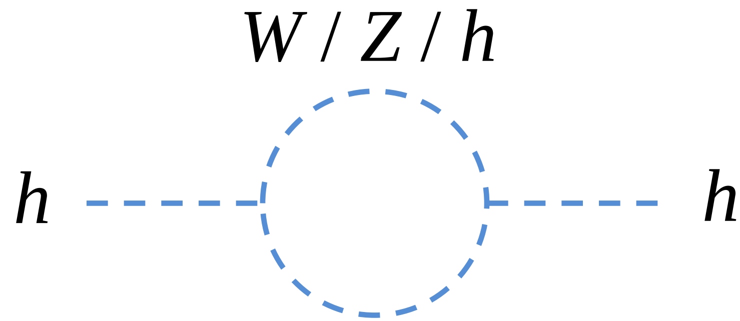
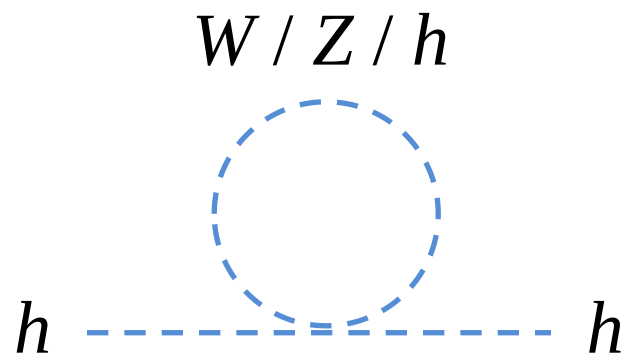
Outline

- top **motivates** SUSY at LHC energies
- Stops often lead to top in **SUSY signal**
- SM top production is dominant **background** to SUSY (but often quite manageable)
- Measurements of top **cross section** and **properties** are sensitive to light superpartners
- SM top production is a useful **calibration** sample for SUSY (and other scenarios)

Top motivates SUSY @ LHC



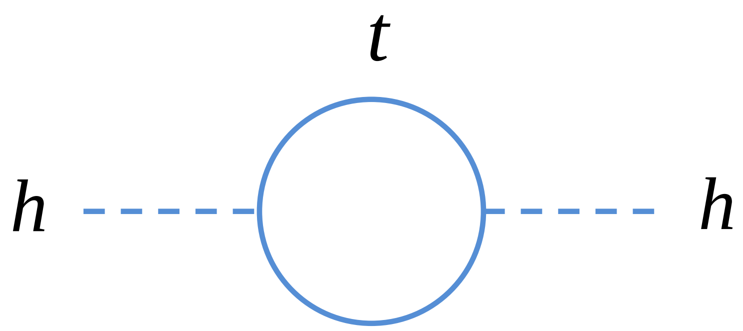




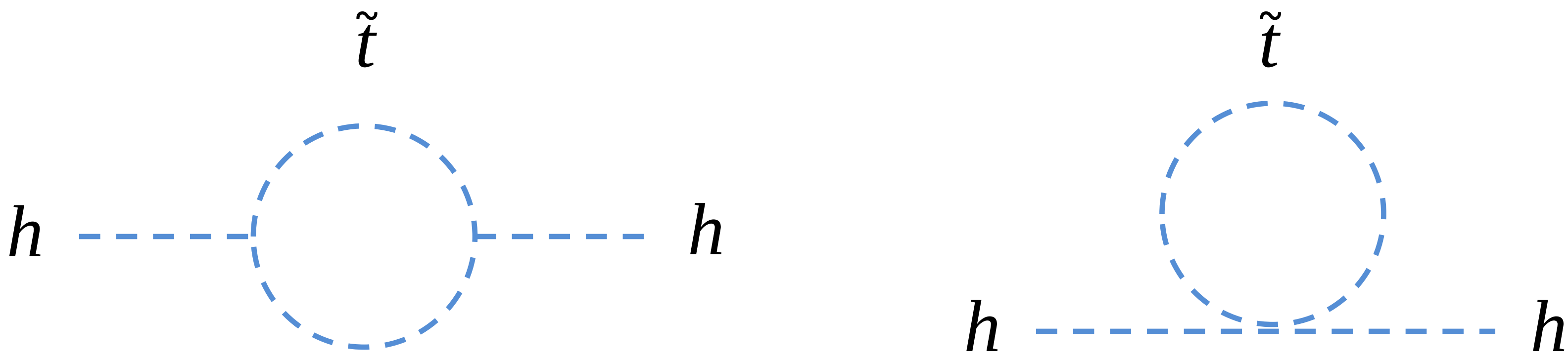
Largest contribution to Higgs mass divergence – from top

$$\Delta m_h^2 \sim -\frac{\alpha}{\pi}\left[\sum_f m_f^2 - \frac{3}{4}\left(m_W^2 + m_Z^2 + m_h^2\right)\right]\frac{\Lambda^2}{m_W^2}$$

Top motivates SUSY @ LHC

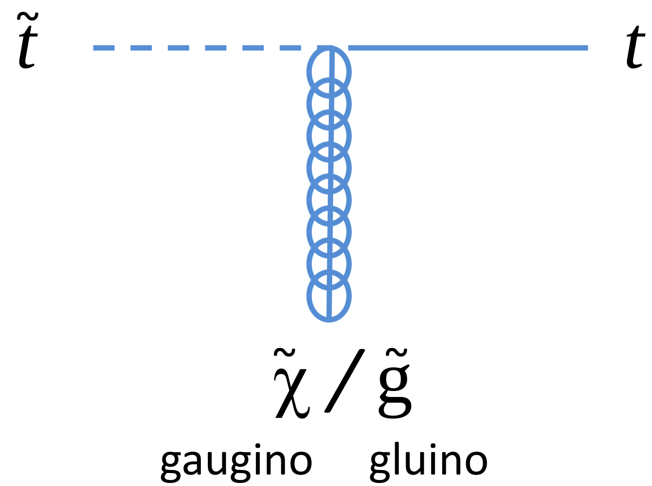


Stops cancel top divergences



SUSY gives tops in return

SUSY counterpart
of gauge interaction



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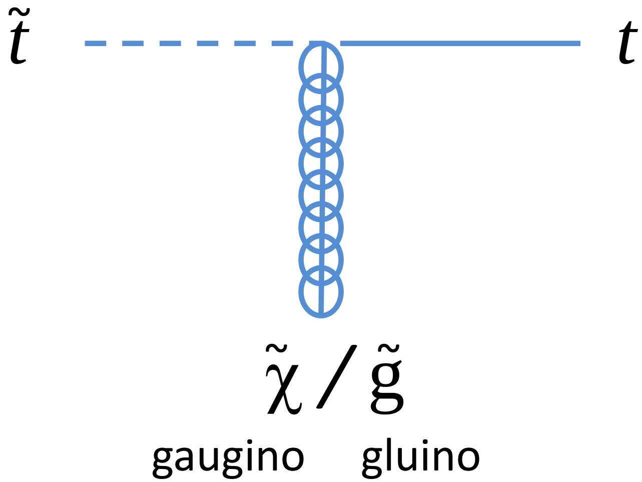

Example with stop pair production

$$pp \to \tilde{t}\tilde{t}^* \,, \quad \tilde{t} \to t\tilde{\chi}^0 \,, \quad \tilde{\chi}^0 \text{ stable}$$

overall: $pp \to t\bar{t} + \text{invisible}$

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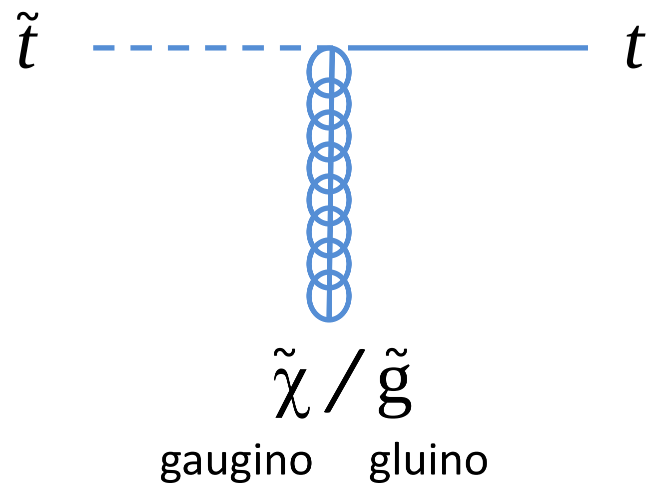

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$$pp \to \tilde{g}\tilde{g} \,, \quad \tilde{g} \to \tilde{t}\,\bar{t} \,, \quad \tilde{t} \to jj \text{ via RPV}$$

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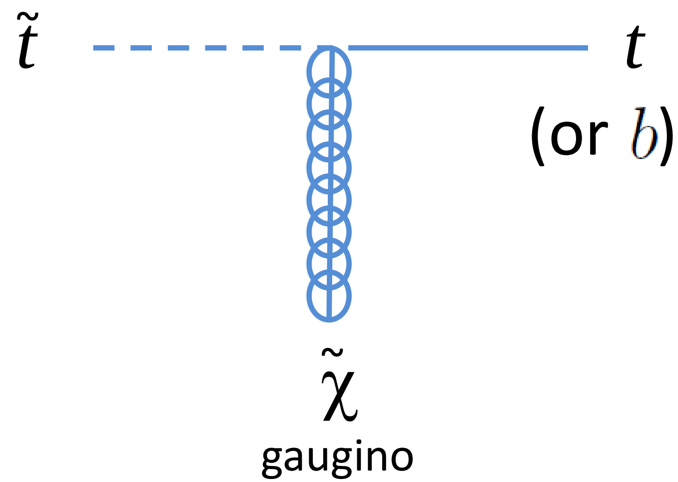

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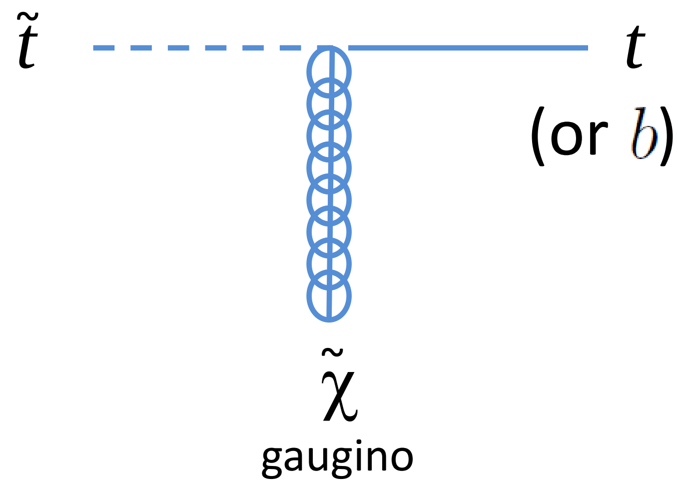

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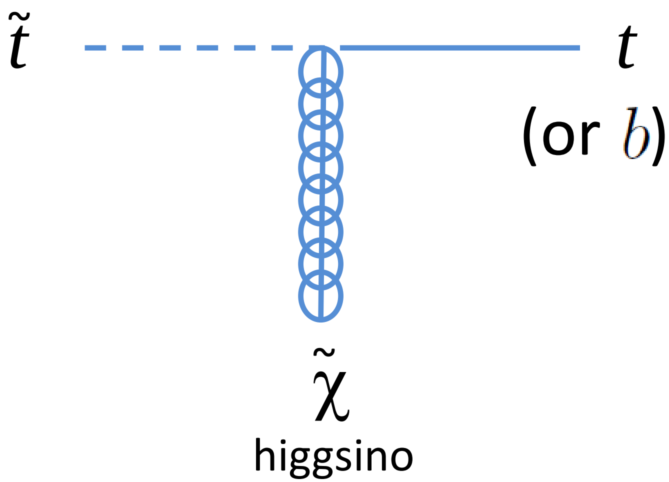
Different $t\bar{t}$ channels
are affected differently!

SUSY gives tops in return

SUSY counterpart of Higgs interaction



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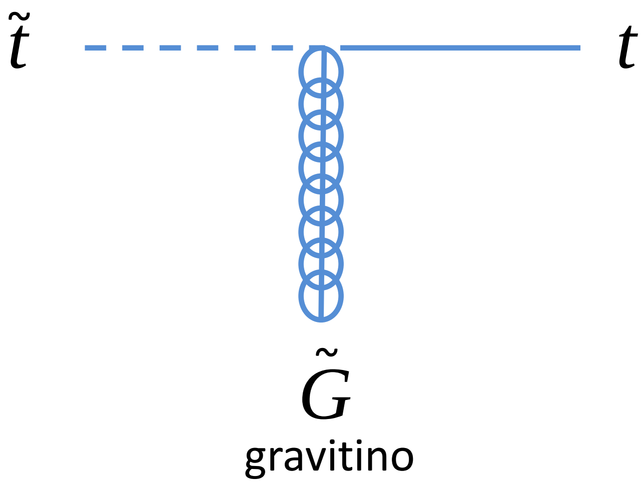

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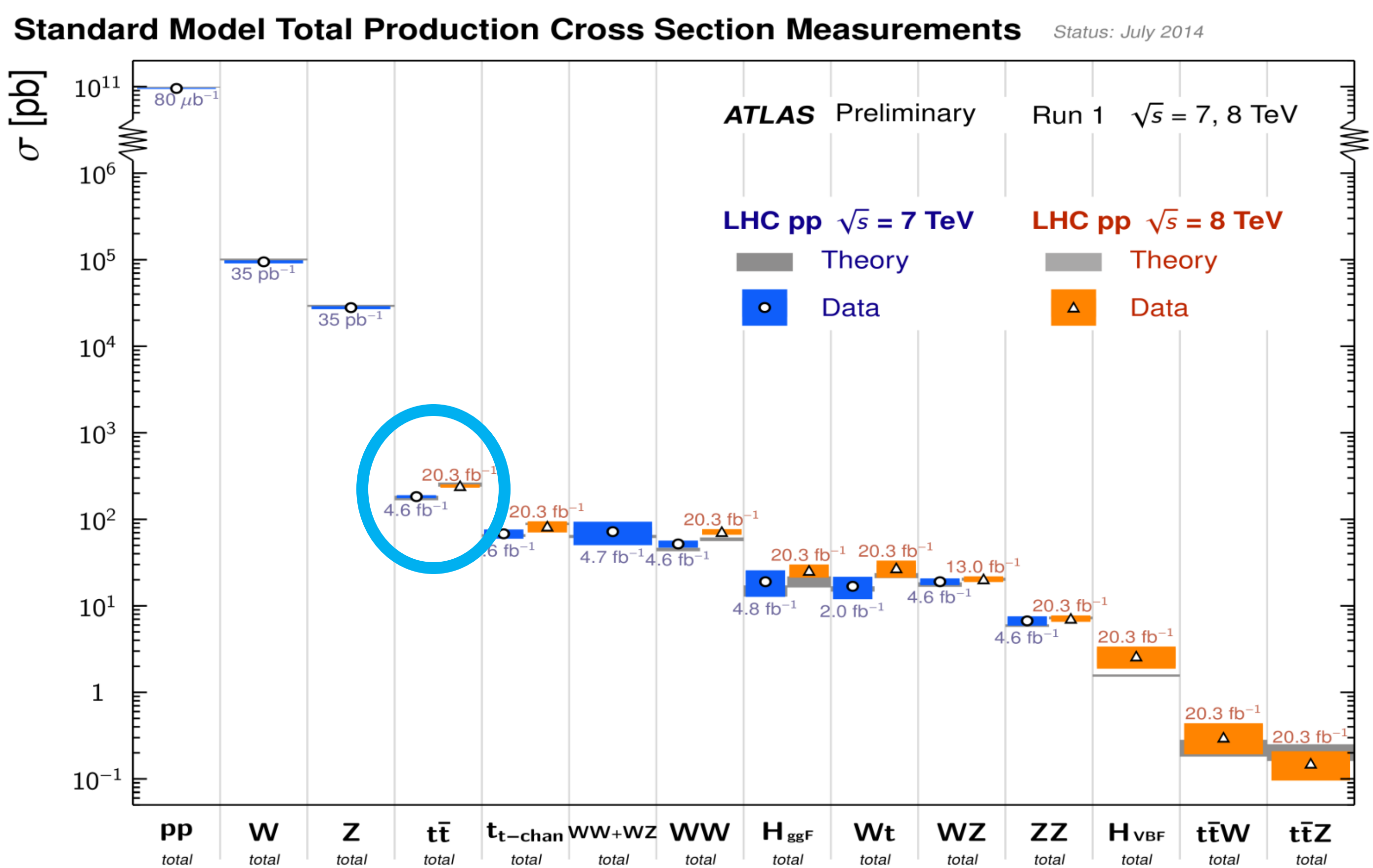

Top background dominates in many SUSY searches due to

- **High multiplicity** (colored pair-production, then cascade)
- ***b* jets** (due to stops, sbottoms, higgsinos, RPV)

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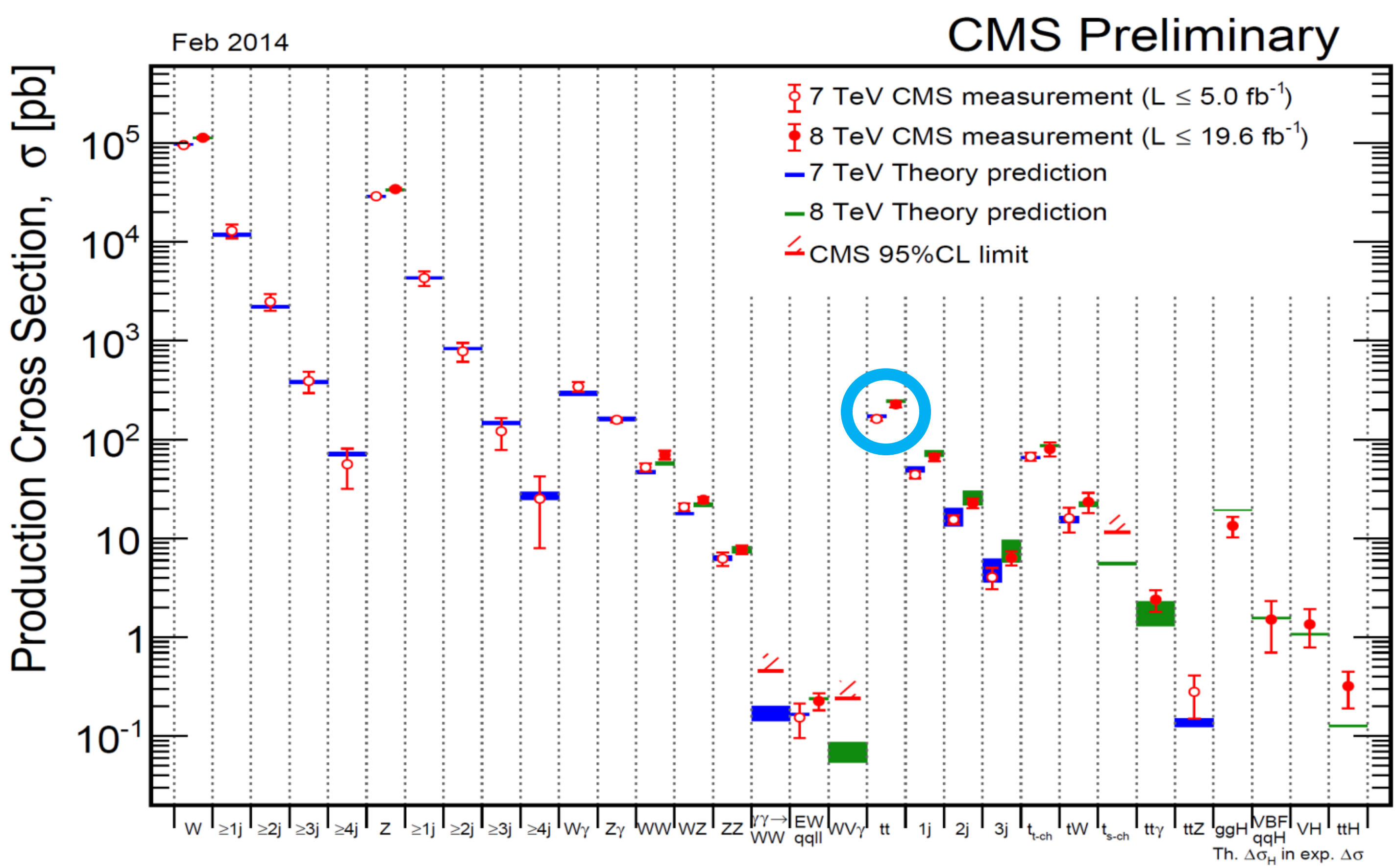

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Gluino / 1st-generation squarks are constrained even when

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In particular, generic searches for **many (7-10) jets + low MET** are sensitive very generally almost up to the kinematic limit.

ATLAS: JHEP 1310 (2013) 130
CMS: JHEP 1406 (2014) 055

Asano, Rolbiecki, Sakurai, JHEP 1301 (2013) 128
Evans, YK, Shih, Strassler, JHEP 1407 (2014) 101
*Assuming a naturally light LSP (< 400 GeV)

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Scenarios where only lower cross section particles (e.g., stops) are accessible might still be hiding in the top sample.

Light stops with top-like final states

Example: decay to massless gravitino (gauge mediation)

$pp \to \tilde{t}\,\tilde{t}^*\,, \quad \tilde{t} \to W^+ b\,\tilde{G}\,, \quad \tilde{G}$ stable

YK and Shih
JHEP 08 (2011) 049

overall: $pp \;\to\; W^+ b\, W^- \bar{b} + \text{invisible}$

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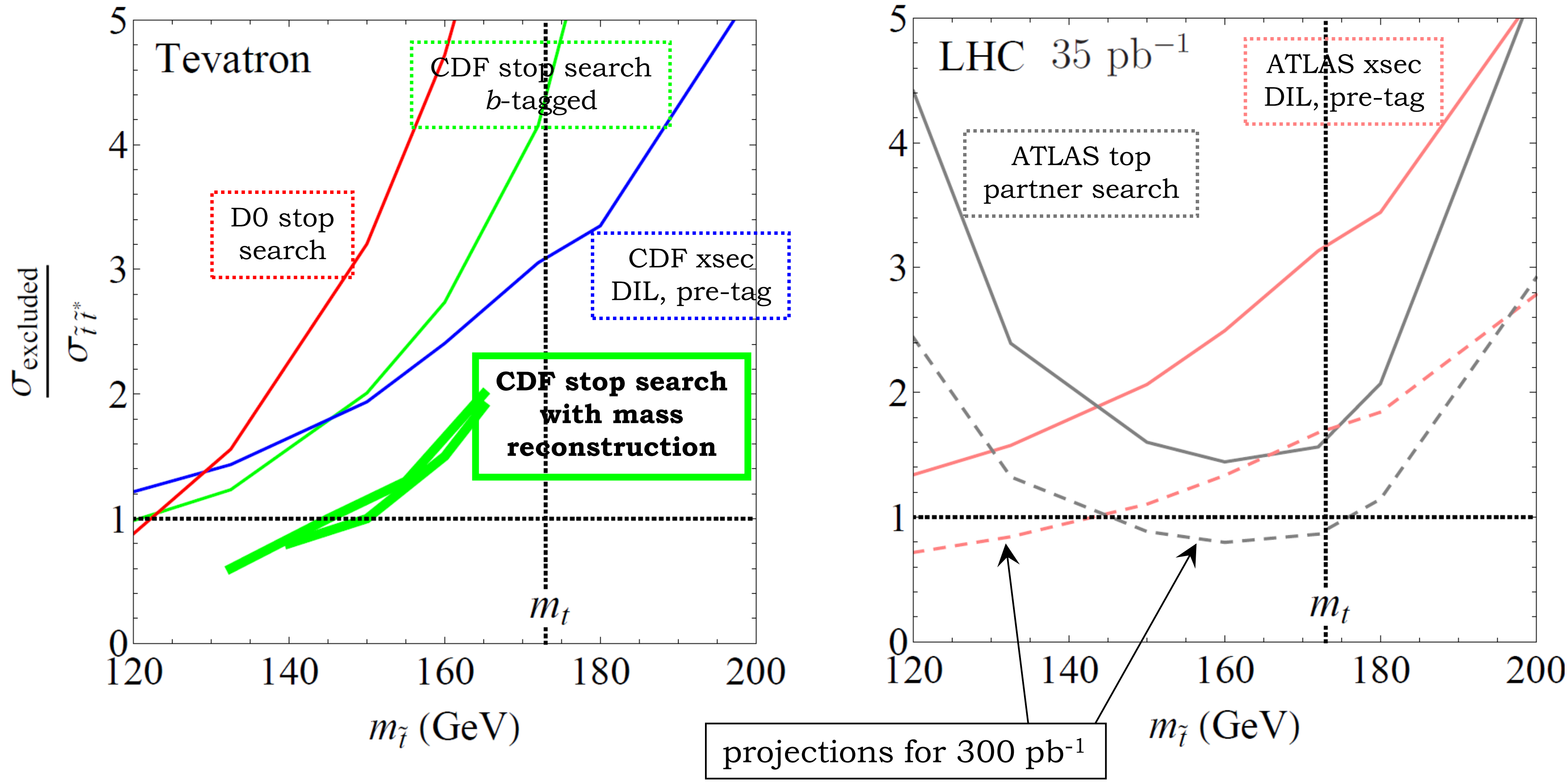
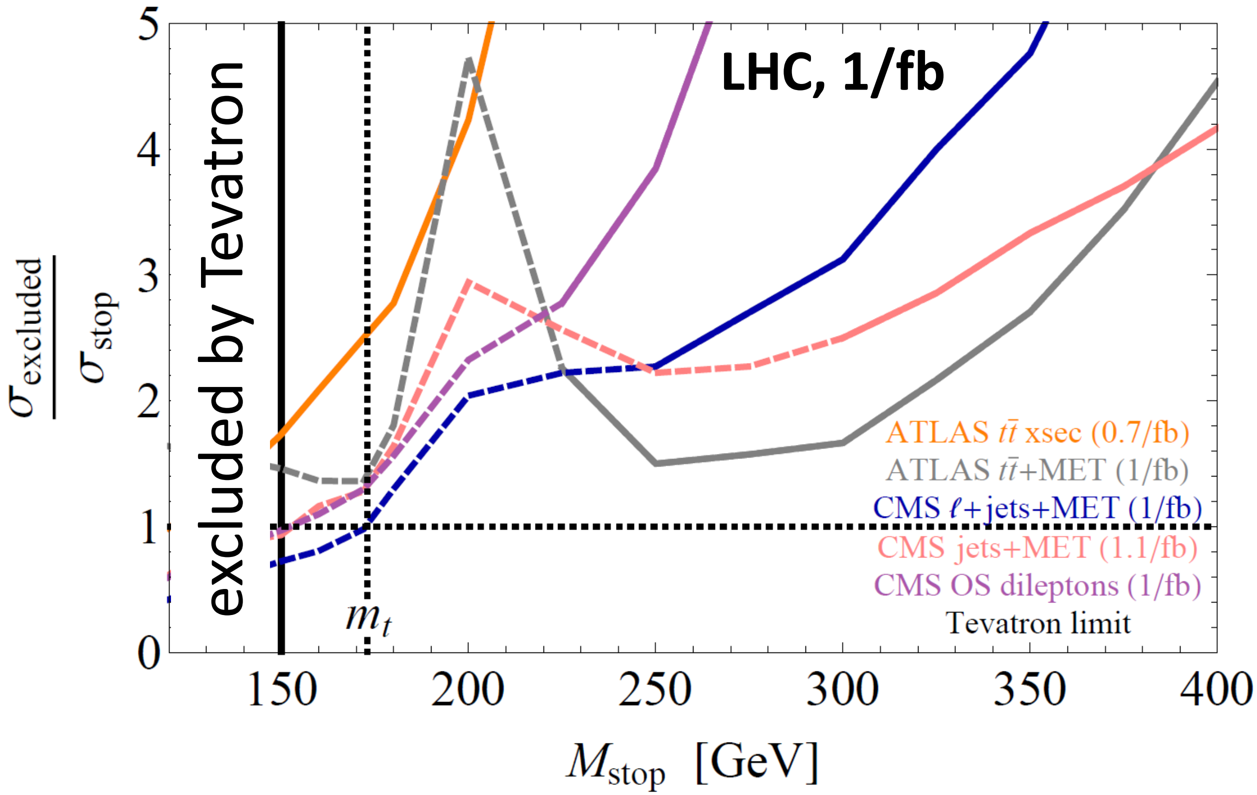


Light stops with top-like final states

Later updated with new searches (and more data)



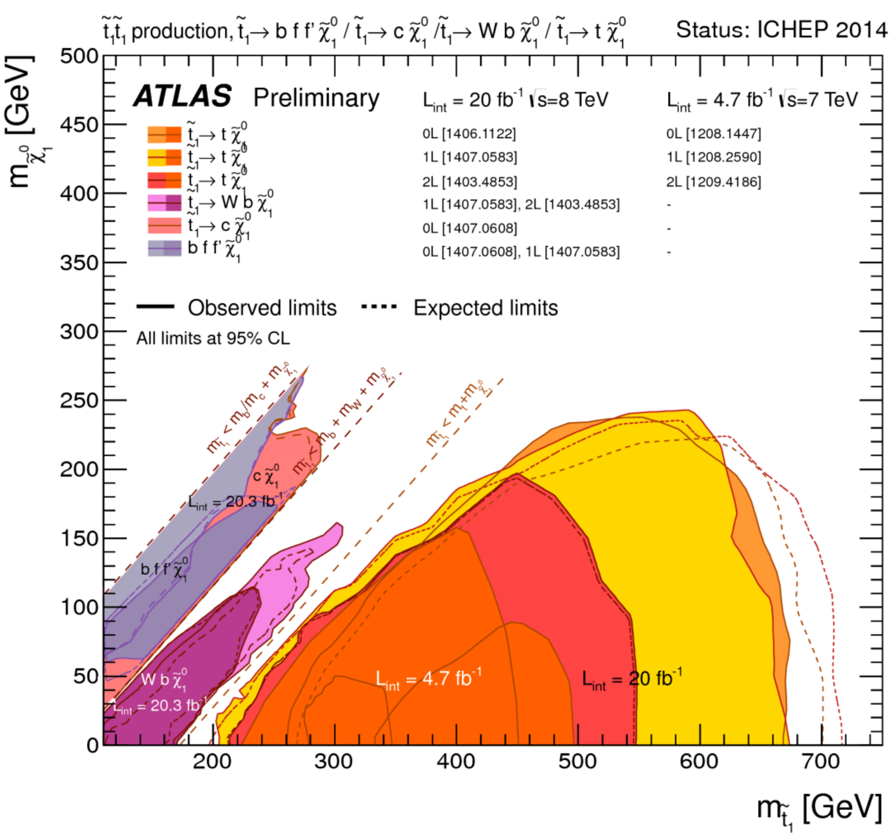
YK, Meade, Reece, Shih
JHEP 1202 (2012) 115

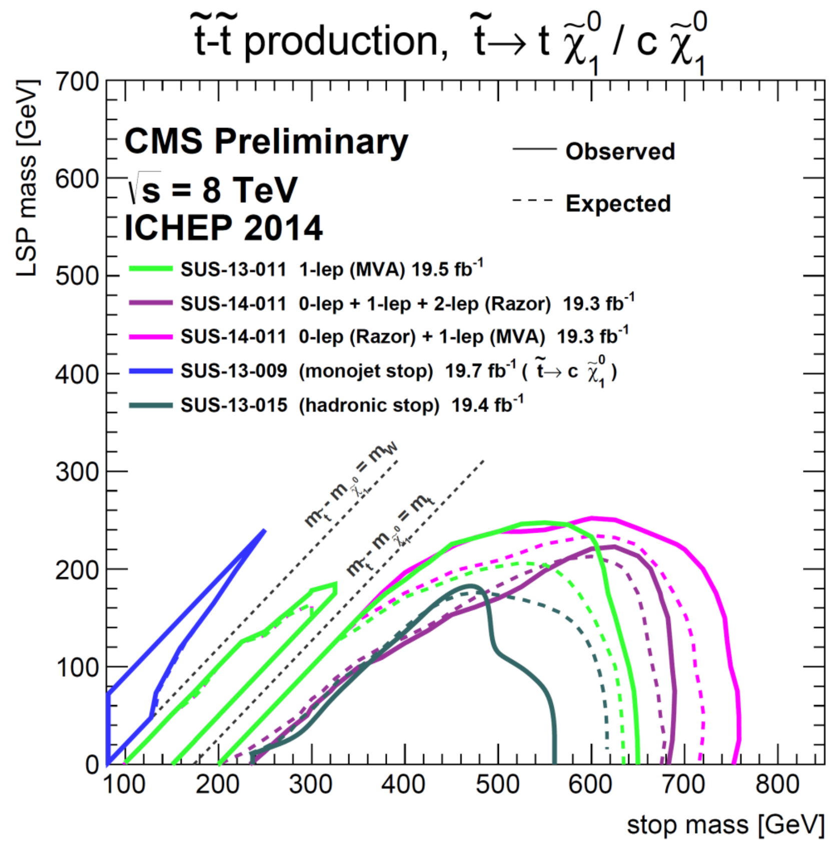
dashed parts of curves:
eff(jet, MET cuts) < 1%

- Generic SUSY searches are formally sensitive at low masses, but cannot be interpreted reliably due to low efficiencies.
- Limits from $t\bar{t}$ cross section are weaker, but robust.

Light stops with top-like final states

Eventually a very comprehensive set of dedicated stop searches were developed by ATLAS and CMS. More details in Till Eifert's talk.





But low-MET corners, where the signature is very $t\bar{t}$-like remained unconstrained.

Light stops with top-like final states

Most recent updates

Using NNLO + NNLL theory cross section

Czakon, Fiedler, Mitov, PRL 110, 252004 (2013)

and CMS dilepton channel (2.3/fb at 7 TeV)

CMS Collaboration, JHEP 1211, 067 (2012)

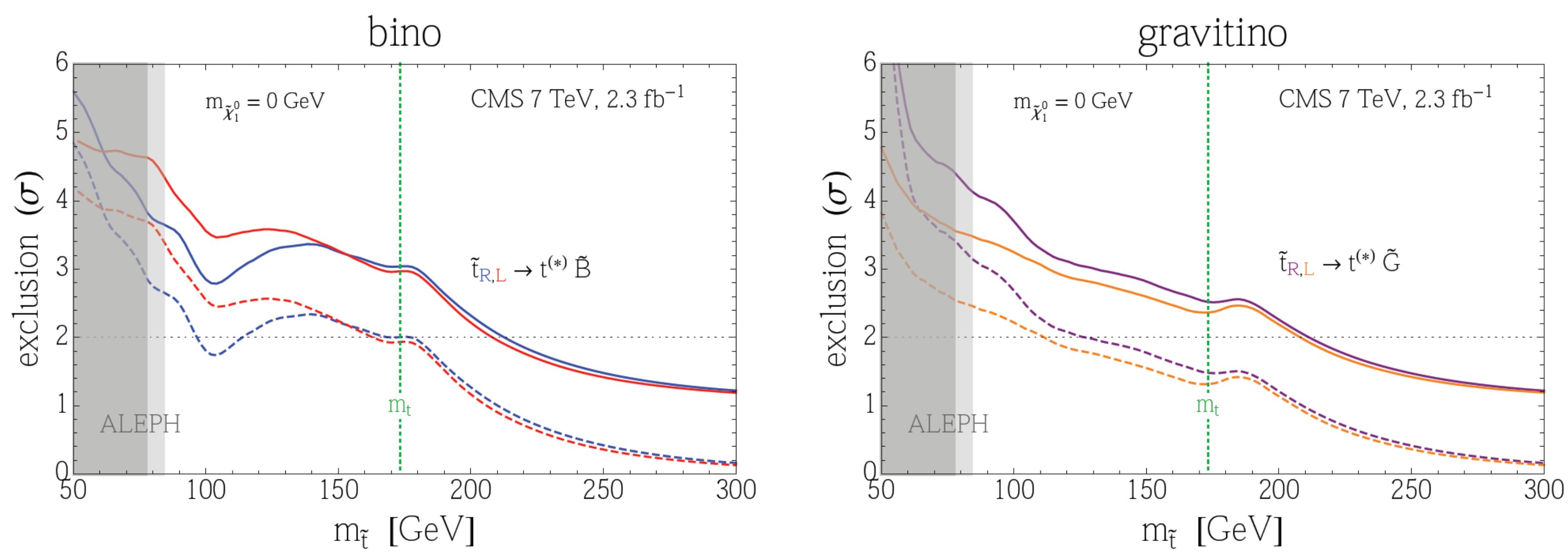


FIG. 2: Exclusion limits for stop decaying into a massless LSP, for bino (left) and gravitino (right). Left and right stop polarization are shown with (red, blue) and (orange, purple) lines respectively. Solid lines correspond to the observed limits while dashed lines correspond to the expected limits. LEP exclusions from ALEPH [63] are shown as shaded gray (the case for minimal and maximal stop coupling to the Z boson are shown).

Czakon, Mitov, Papucci, Ruderman, Weiler, arXiv:1407.1043

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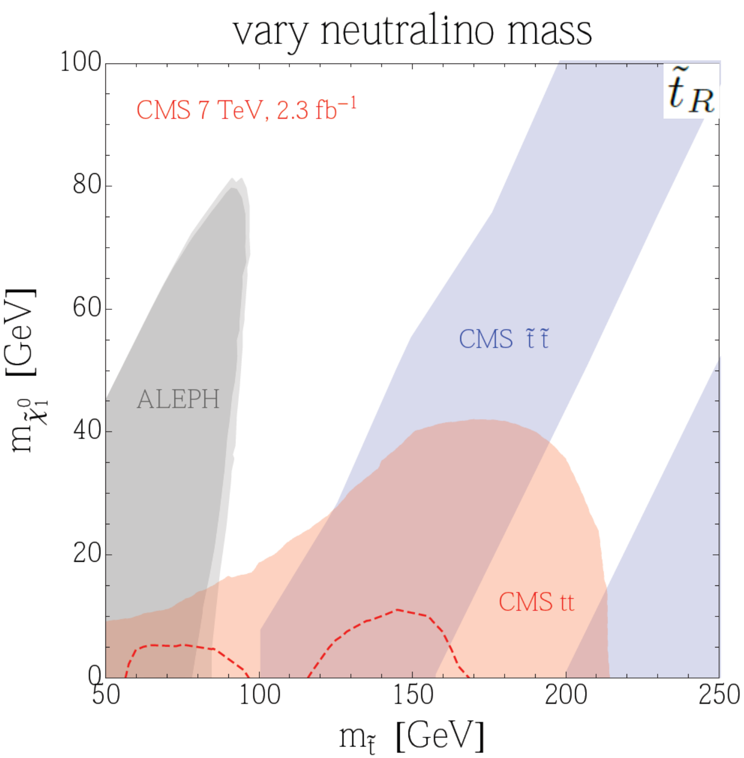

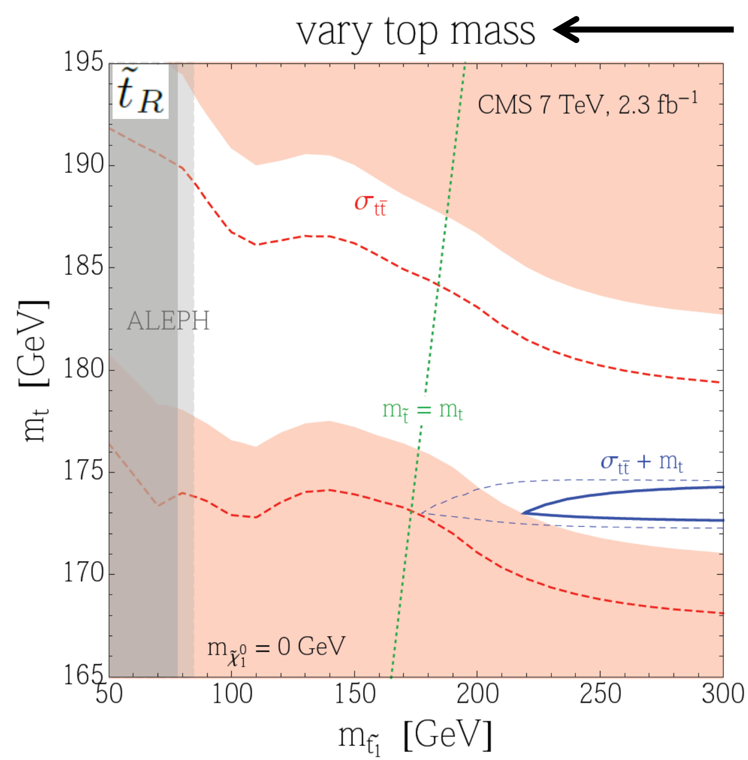

In case top mass measurement is affected by stop contamination…

Czakon, Mitov, Papucci, Ruderman, Weiler, arXiv:1407.1043

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Czakon, Fiedler, Mitov, PRL 110, 252004 (2013)

and ATLAS dilepton channel (4.6/fb at 7 TeV + 20/fb at 8 TeV)

ATLAS Collaboration, arXiv:1406.5375

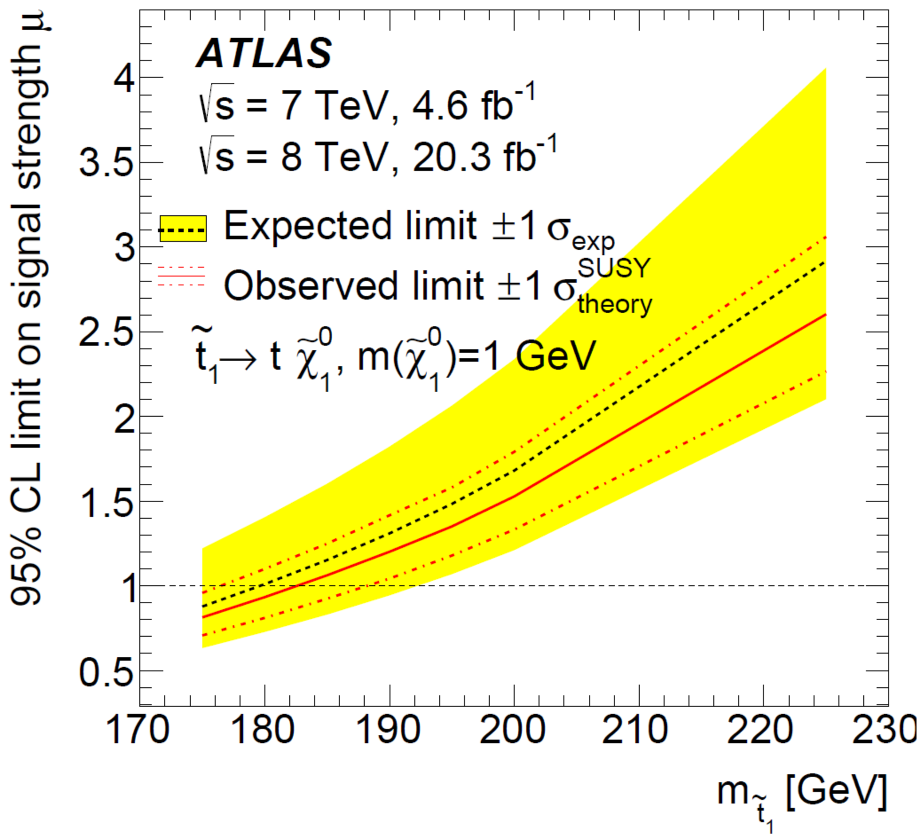

Fig. 9. Expected and observed limits at 95 % CL on the signal strength μ as a function of $m_{\tilde{t}_1}$, for pair produced top squarks $\tilde{t}_1$ decaying with 100 % branching ratio via $\tilde{t}_1 \to t\tilde{\chi}_1^0$ to predominantly right-handed top quarks, assuming $m_{\tilde{\chi}_1^0} = 1\,\mathrm{GeV}$. The black dotted line shows the expected limit with $\pm 1\sigma$ contours, taking into account all uncertainties except the theoretical cross-section uncertainties on the signal. The red solid line shows the observed limit, with dotted lines indicating the changes as the nominal signal cross-section is scaled up and down by its theoretical uncertainty.

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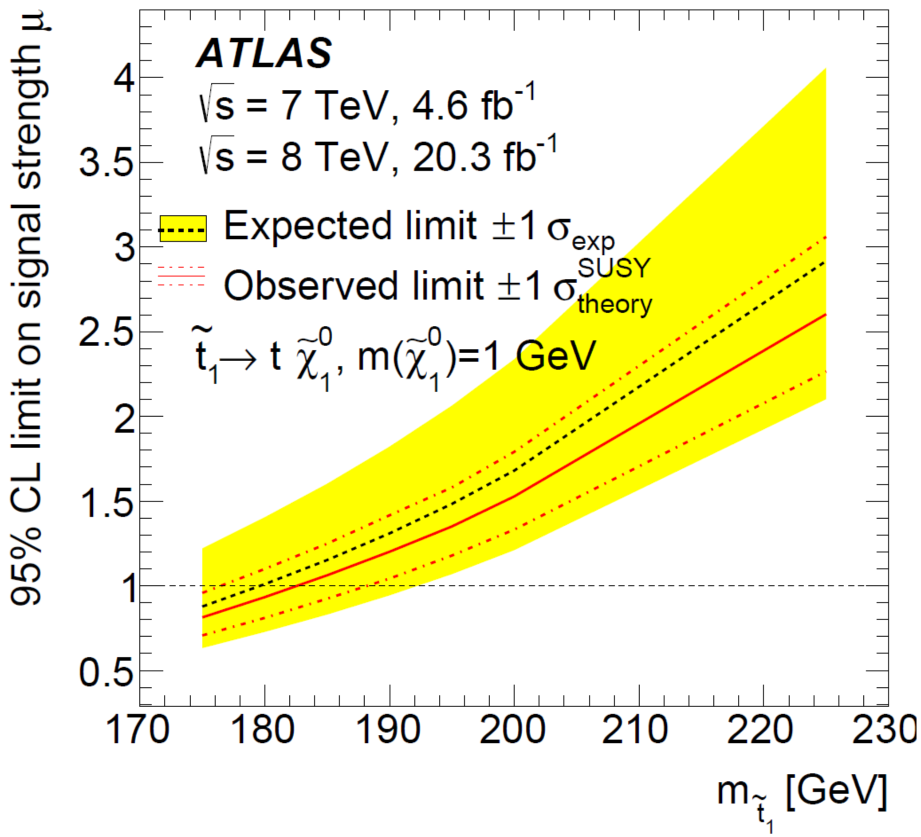

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ATLAS Collaboration, arXiv:1406.5375

Limits improve further by 30-40% by using top-antitop spin correlation

ATLAS-CONF-2014-056

To be presented in Till Eifert's talk

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A different example

multi-body decay with

RPV coupling LQD321

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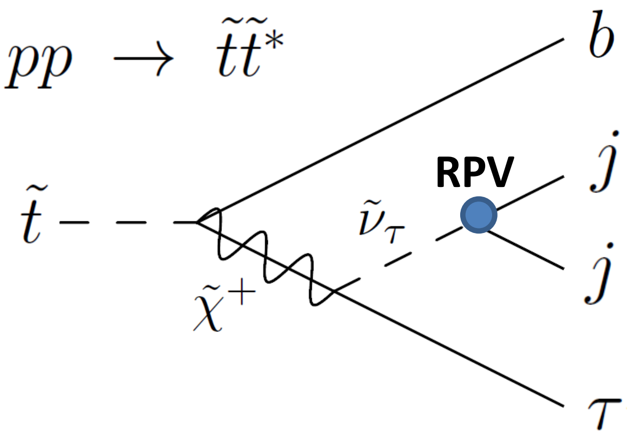

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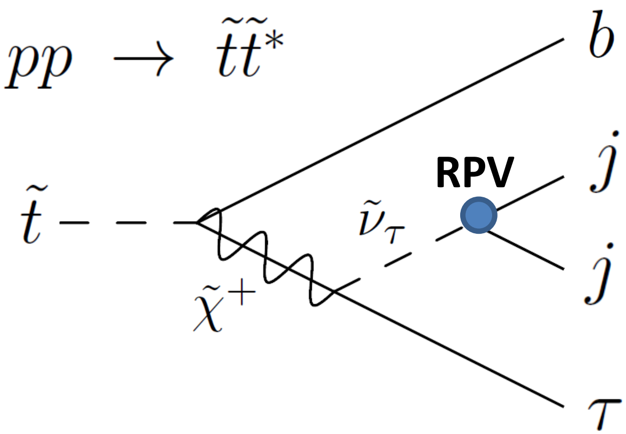
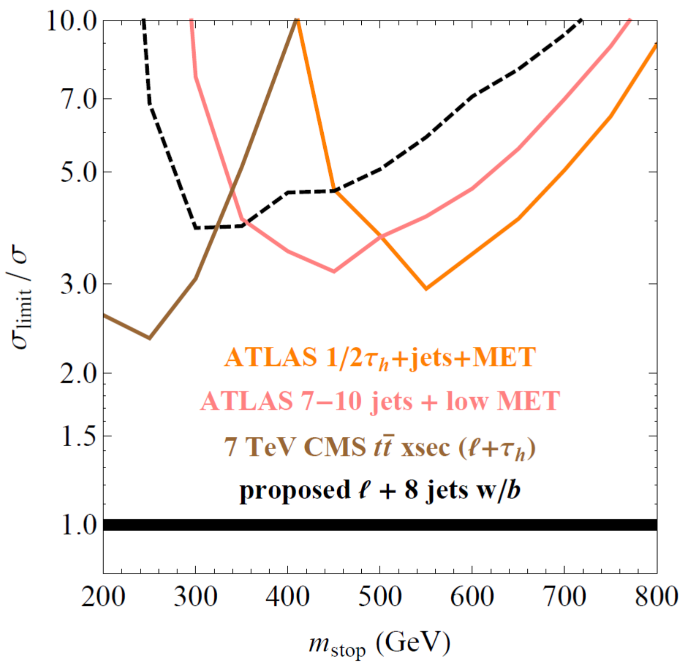


Evans and YK, arXiv:1311.0890



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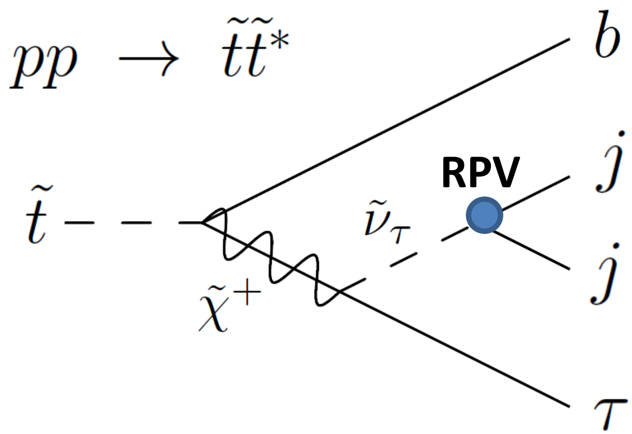

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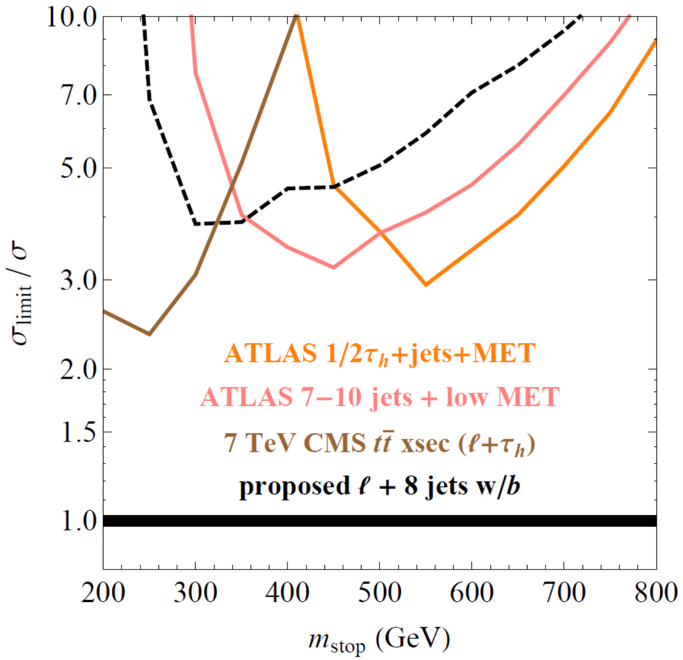

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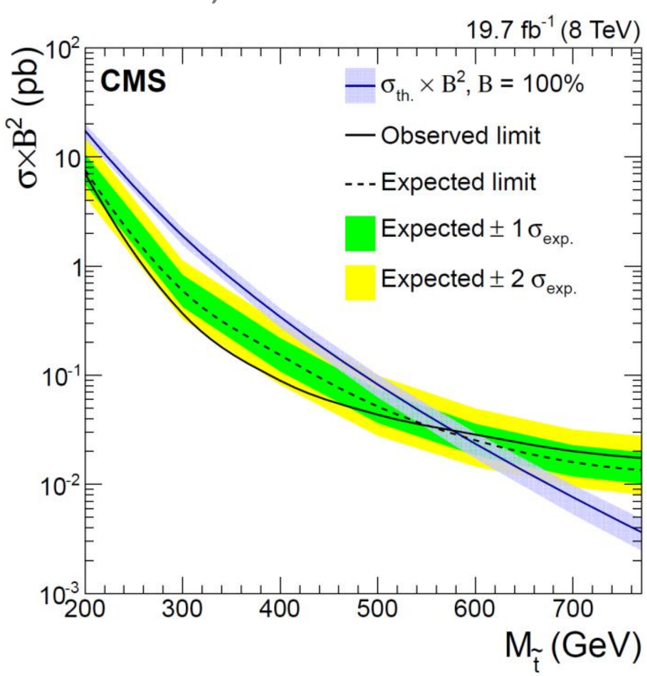
CMS, arXiv:1408.0806



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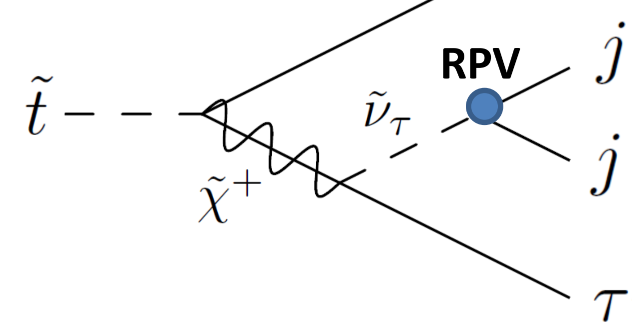

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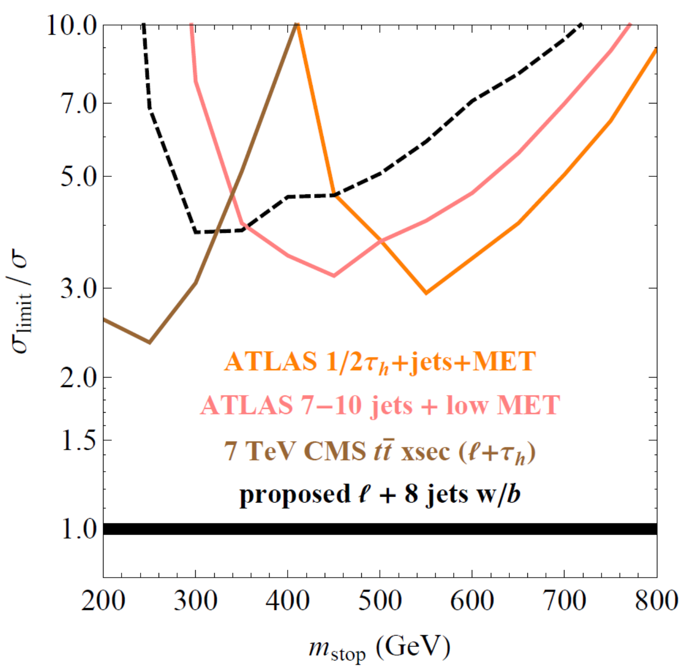
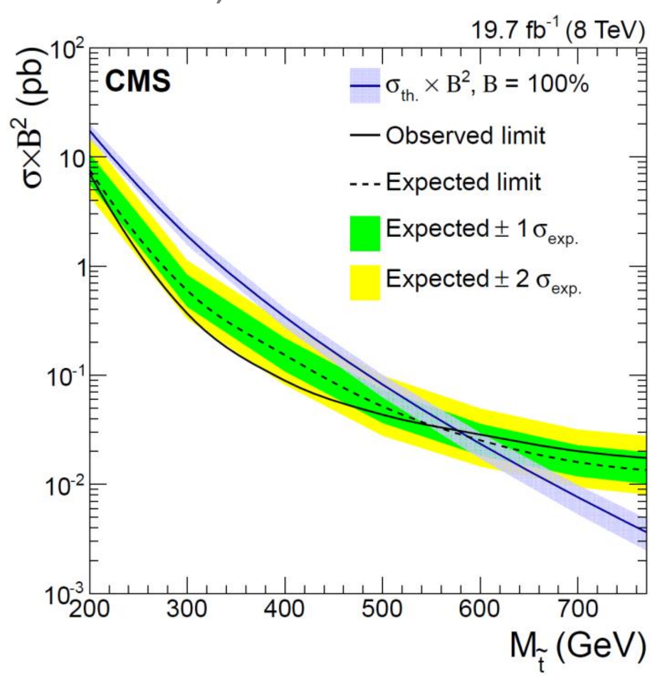
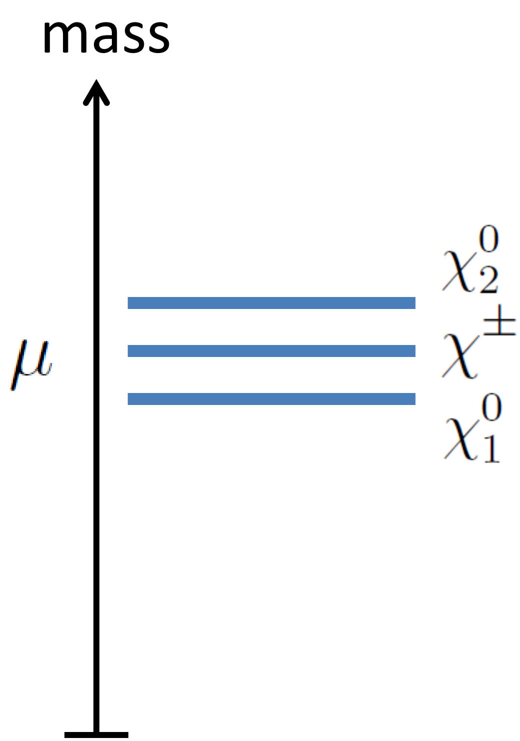


CMS, arXiv:1408.0806



It's becoming increasingly difficult to find examples with stops…

Light higgsinos with top-like final states



- Model-independent EW production

$$pp \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \,,\ \tilde{\chi}_{1,2}^0 \tilde{\chi}_1^\pm \,,\ \tilde{\chi}_1^+ \tilde{\chi}_1^-$$

Cross section roughly 1/40 of stops

- EW naturalness strongly suggests

$$\mu \lesssim 200 \text{ GeV}$$

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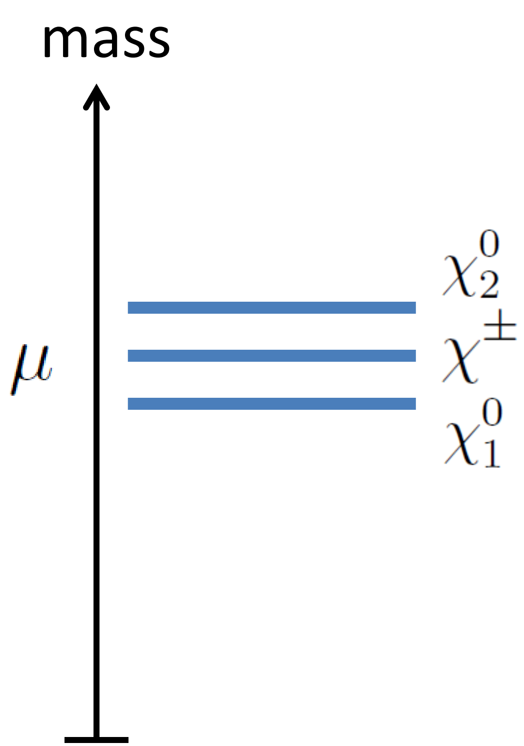

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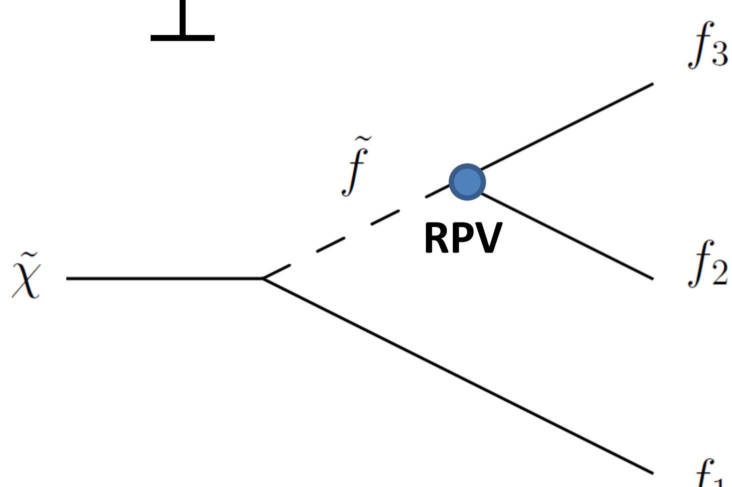
- RPV decays provide a great source for interesting benchmark models to search for!

- Two options for intermediate decays

$\chi^\pm \;\to\; \chi_1^0 + \mathrm{soft}$	$\chi_1^0 \;\to\; f_1\, f_2\, f_3$
$\chi_2^0 \;\to\; \chi_1^0 + \mathrm{soft}$	$\chi_2^0 \;\to\; f_1\, f_2\, f_3$
$\chi_1^0 \;\to\; f_1\, f_2\, f_3$	$\chi^\pm \;\to\; f_1'\, f_2'\, f_3'$



Light higgsinos with top-like final states

Many final states enter the $t\bar{t}$ sample (examples in the table).

Clearly not excluded by their low cross sections (relative to $t\bar{t}$ uncertainty), but maybe by their distinct **properties**?

- Jet multiplicity
- b-jet multipicity
- Excess in just one of the channels
- Same sign tops/τ's (due to $\tilde{\chi}^0$)
- Variety of kinematic variables

$$pp \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \,,\; \tilde{\chi}_{1,2}^0 \tilde{\chi}_1^{\pm} \,,\; \tilde{\chi}_1^+ \tilde{\chi}_1^-$$

RPV coupling		mediator $\tilde{f}$	$\tilde{\chi}^0 \to$	$\tilde{\chi}^+ \to$
UDD	312	$\tilde{t}_R$	tqq	bqq
	213	$\tilde{b}_R$	bqq	tqq
	323	$\tilde{t}_R$	tbq	bbq
LQD	323	$(\tilde{\nu},\, \tilde{\ell})_L$	τbq	τbq
		$\tilde{b}_R$	$\tau bq,\, \nu bq$	$\tau tq,\, \nu tq$
	232	$(\tilde{t},\, \tilde{b})_L$	$\mu tq,\, \nu bq$	$\mu bq,\, \nu tq$
	233	$(\tilde{t},\, \tilde{b})_L$	$\mu tb,\, \nu bb$	$\mu bb,\, \nu tb$
	332	$(\tilde{\nu},\, \tilde{\ell})_L$	τtq	τbq
	333	$(\tilde{\nu},\, \tilde{\ell})_L$	τtb	τbb

Evans and YK (in progress)

Nice benchmark models for interpreting top measurements as new physics searches.

Tops as calibration for SUSY
(and other kinds of new physics)

- *b* tagging
- Boosted techniques
  - Boosted tops from new heavy particles
  - Boosted BSM particles (e.g., stops) from new heavy particles
- Measurement of b-quark polarization (**NEW!**)

  (e.g., to distinguish between $\tilde{b}_L \to b\,\tilde{\chi}^0$ and $\tilde{b}_R \to b\,\tilde{\chi}^0$)

  Top is a great source of polarized b-quarks for calibration.

  (Similarly for c-quark polarization.)

Measurement of *b*-quark polarization

- Despite hadronization, bottom **baryons** partly retain polarization.

  Falk and Peskin, PRD 49, 3320 (1994)

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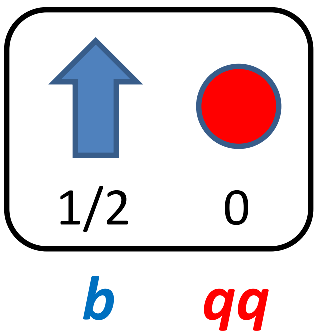

Λ_b

b spin **preserved** during lifetime

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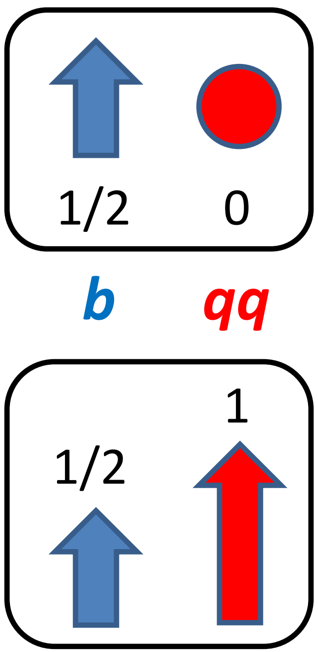

Λ_b

b spin **preserved** during lifetime

Σ_b

Σ_b^*

b spin **oscillates** during lifetime

Λ_b sample contaminated by $\Sigma_b^{(*)} \to \Lambda_b \pi$

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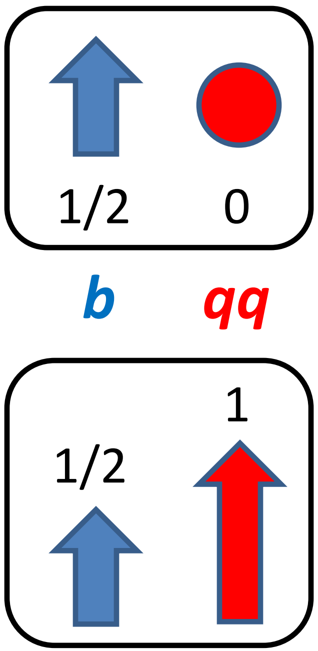

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Σ_b

Σ_b^*

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Fragmentation fraction into baryons ≈ 10%

(Mesons don't contribute because the lightest are scalars)

Measurement of *b*-quark polarization

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  Falk and Peskin, PRD 49, 3320 (1994)

- Size of the effect depends on unknown hadronization parameters.

  Need to **calibrate** the measurement on a **SM sample**.

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  ALEPH: PLB 365, 437 (1996) OPAL: PLB 444, 539 (1998) DELPHI: PLB 474, 205 (2000)

- At the **LHC,** $Z \to b\bar{b}$ has large QCD background.

  Top provides a clean sample of polarized b's: $pp \to t\bar{t}\,,\ t \to Wb$

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- Pick up semileptonic Λ_b decays using "soft muon b-tagging".

  Reconstruct them to determine the polarization.

  In lepton + jets channel of $t\bar{t}$, 3σ significance seems possible even

  with 8 TeV data. Galanti, Giammanco, Grossman, YK, Stamou, Zupan (in progress)

Measurement of *c*-quark polarization

- Despite hadronization, charm **baryons** partly retain polarization.

  Falk and Peskin, PRD 49, 3320 (1994)

- Size of the effect depends on unknown hadronization parameters.

  Need to **calibrate** the measurement on a **SM sample**.

- Probably best to use $\Lambda_c^+ \to pK^-\pi^+$

- **Top provides a clean sample** of polarized c's for calibration:

$$pp \to t\bar{t}\,,\ t \to W^+ b\,,\ W^+ \to c\,\bar{q}$$

Summary

- top **motivates** SUSY at LHC energies
- Stops often lead to top in **SUSY signal**
- SM top production is dominant **background** to SUSY (but often quite manageable)
- Measurements of top **cross section** and **properties** are sensitive to light superpartners
- SM top production is a useful **calibration** sample for SUSY (and other scenarios)