Searching for stops at compressed regions

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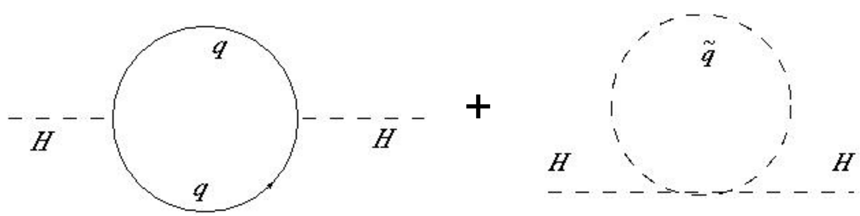
Caltech

HA, L.-T. Wang 1506.00653, PRL 2015
HA, J. Gu, L.-T. Wang 1611.09868
HA, Zhen Liu, A. Ridgeway 16XX.XXXXX

Motivations

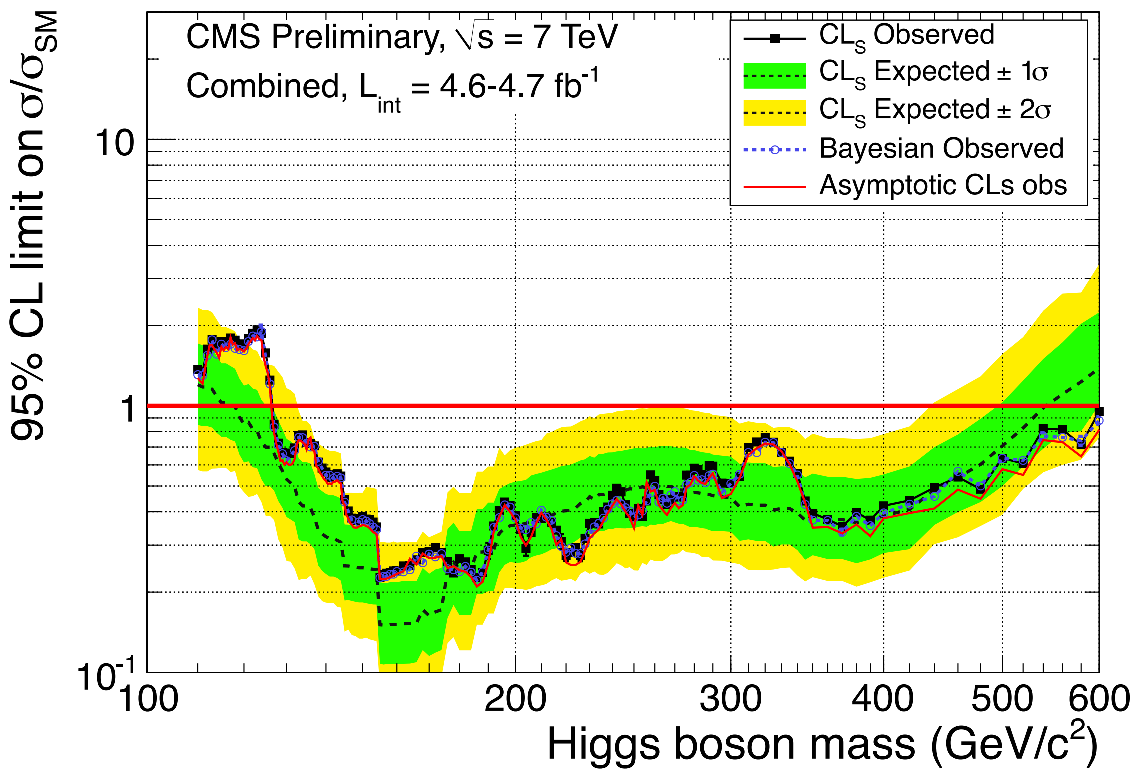
- A mechanism to stabilize the electroweak scale is still highly desired.
- Supersymmetry is still the leading candidate.
- In the SM, top quark yields the most contribution to the hierarchy problem. Therefore, if SUSY is the solution, we must see light stops.



$$\approx \frac{3y_t^2}{8\pi} m_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\rm EW}}\right)$$

The need to cover "last corners"

One year before the discovery of the Higgs:



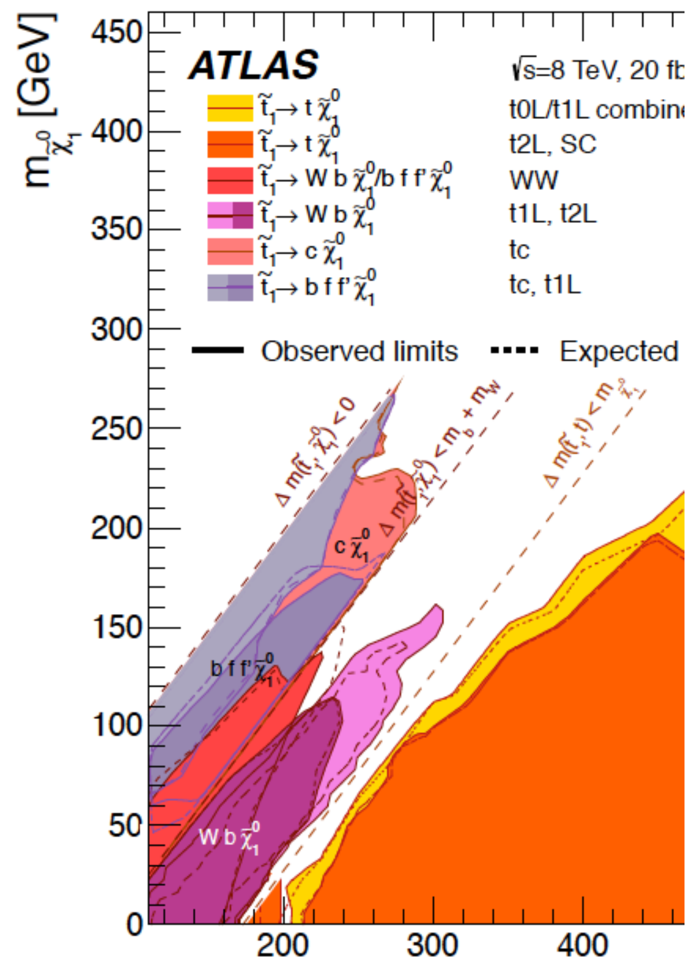
Only 3% of parameter space was left, without a discovery. Should we say that the SM Higgs had almost been excluded? No!

Outline:

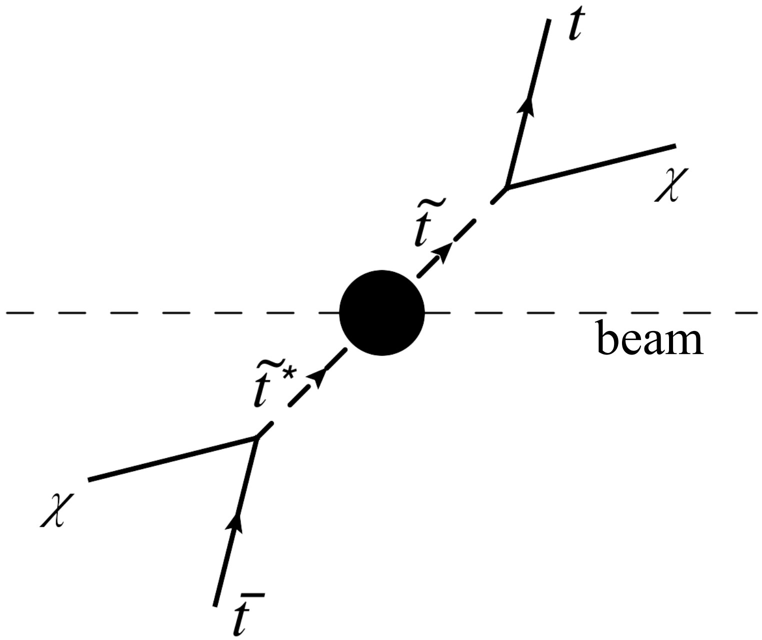
- 1. $m_{\tilde{t}} \approx m_t + m_\chi$

- 2. $m_{\tilde{t}} \approx m_W + m_b + m_\chi$

- 3. $m_{\tilde{t}} \gtrsim m_\chi$



Why the compressed region is difficult to search?



$$m_{\tilde{t}} \approx m_t + m_\chi$$

$$\vec{p}_T(\tilde{t}) + \vec{p}_T(\tilde{t}^*) = 0$$

$$\Downarrow$$

$$\gamma(\tilde{t})\vec{v}_T(\tilde{t}) + \gamma(\tilde{t}^*)\vec{v}_T(\tilde{t}^*) = 0$$

In the compressed region:

$$\vec{v}(\chi) \approx \vec{v}(\tilde{t})$$

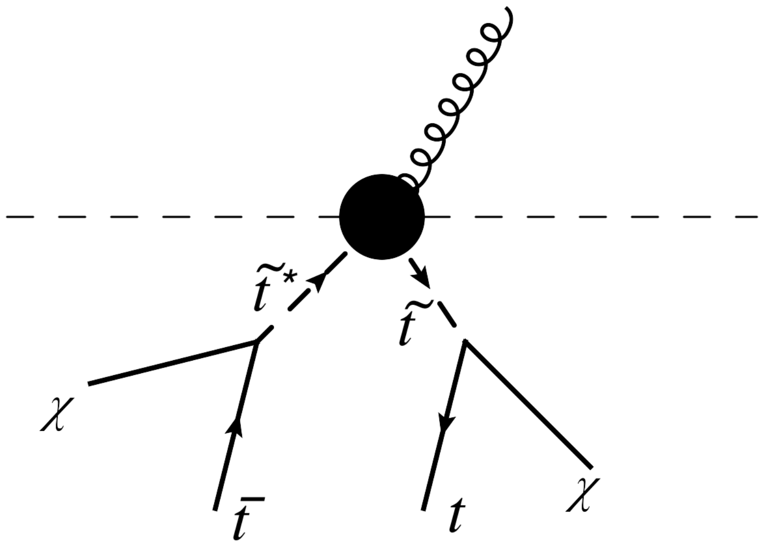
$$\Downarrow$$

$$\vec{p}_T(\chi_1) + \vec{p}_T(\chi_2) = 0$$

MET from the neutralinos gets canceled and the kinematics of the signal is the same as the ttbar background!

Trigger a hard jet?

$$m_{\tilde{t}} \gtrsim m_t + m_\chi$$



$$\vec{p}_T(\tilde{t}) + \vec{p}_T(\tilde{t}^*) = -\vec{p}_T(j_{\rm ISR})$$

$$\parallel$$

$$m_{\tilde{t}}(\gamma(\tilde{t})\vec{v}_T(\tilde{t}) + \gamma(\tilde{t}^*)\vec{v}_T(\tilde{t}^*))$$

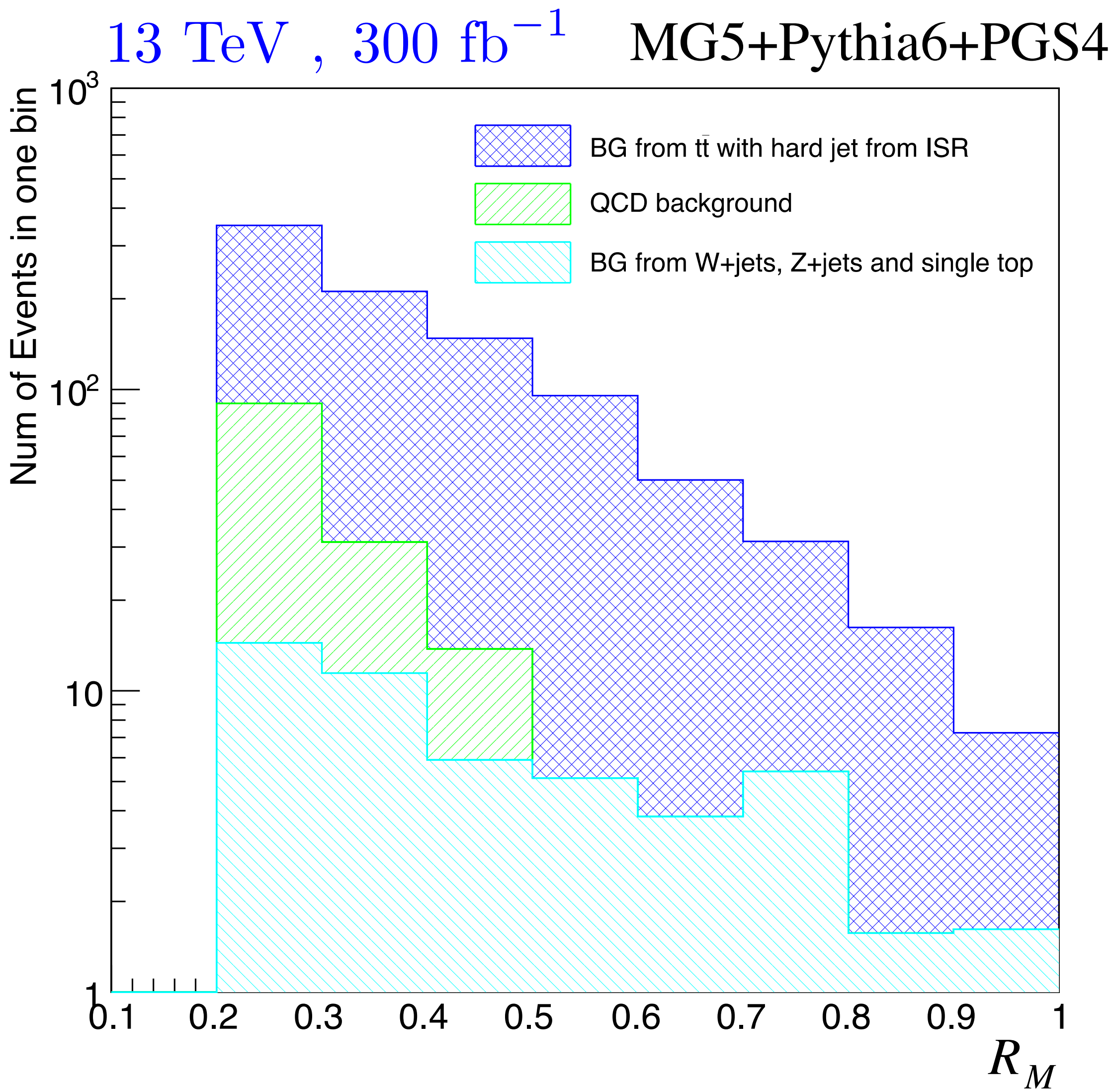
With the compressed condition:

$$\vec{v}(\chi) \approx \vec{v}(\tilde{t})$$

$$\vec{p}_T(\chi_1) + \vec{p}_T(\chi_2) = -\frac{m_\chi}{m_{\tilde{t}}} \times \vec{p}_T(j_{\rm ISR})$$

If both the tops decay hadronically, $R_M \equiv \dfrac{\not{p}_T}{p_T(j_{\rm ISR})} \approx \dfrac{m_\chi}{m_{\tilde{t}}} \approx 1 - \dfrac{m_t}{m_{\tilde{t}}}$.

Background

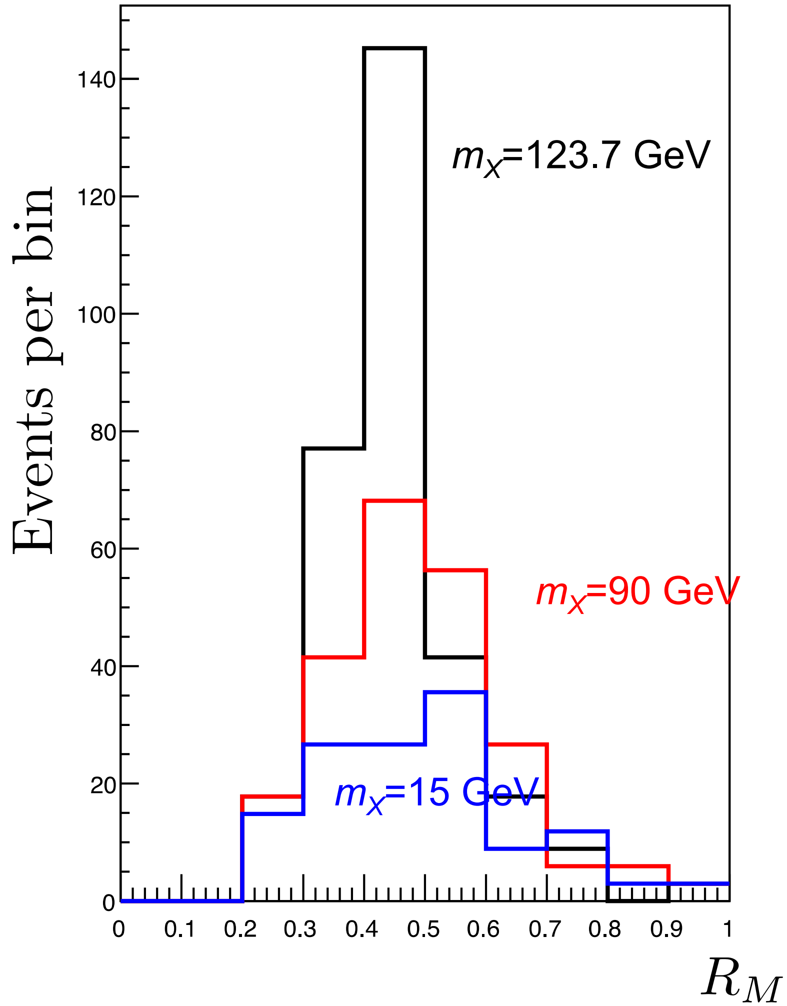


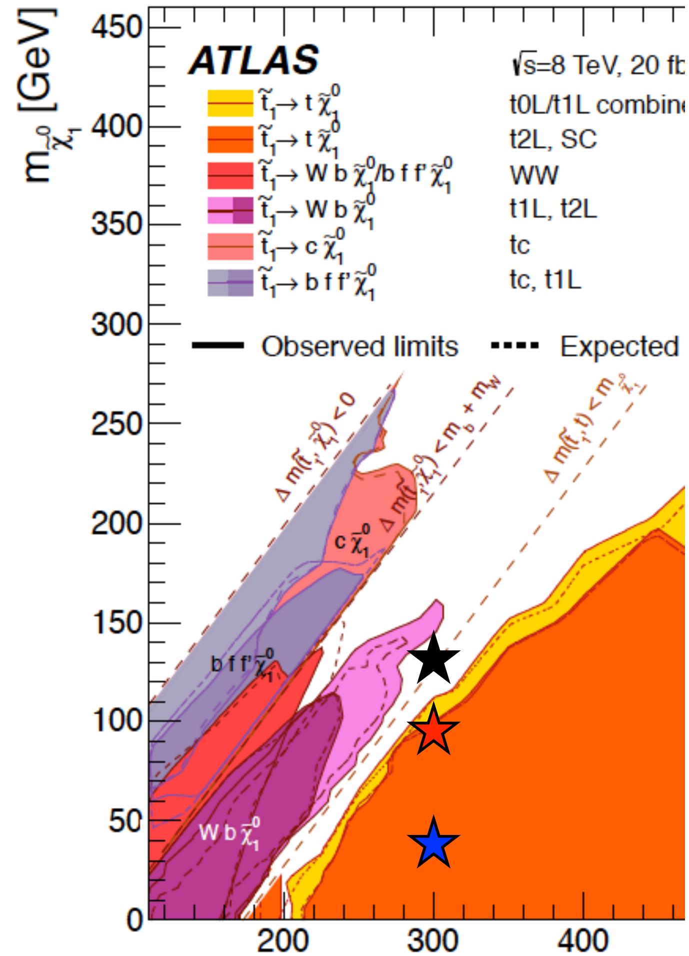
$$\frac{d\sigma}{dR_M} = A\exp(-BR_M)$$

$$A = 47\ \text{fb}\ , \quad B = 5.6$$

Signal

$$13\ \text{TeV},\ 300\ \text{fb}^{-1}, m_{\tilde{t}} = 300\ \text{GeV}$$





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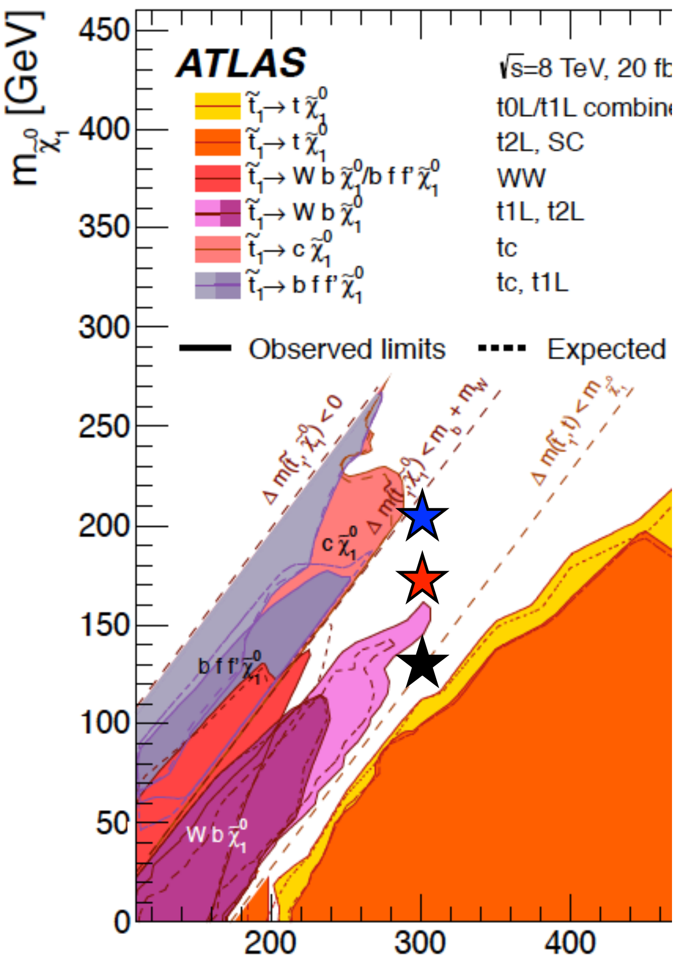
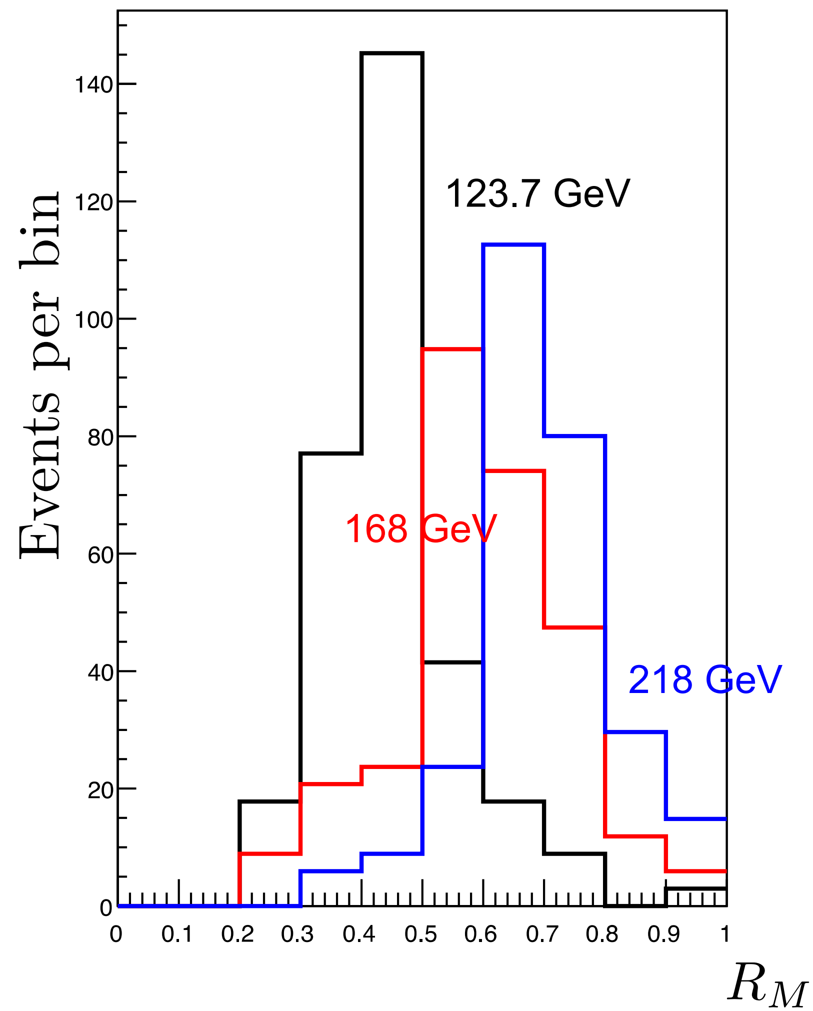
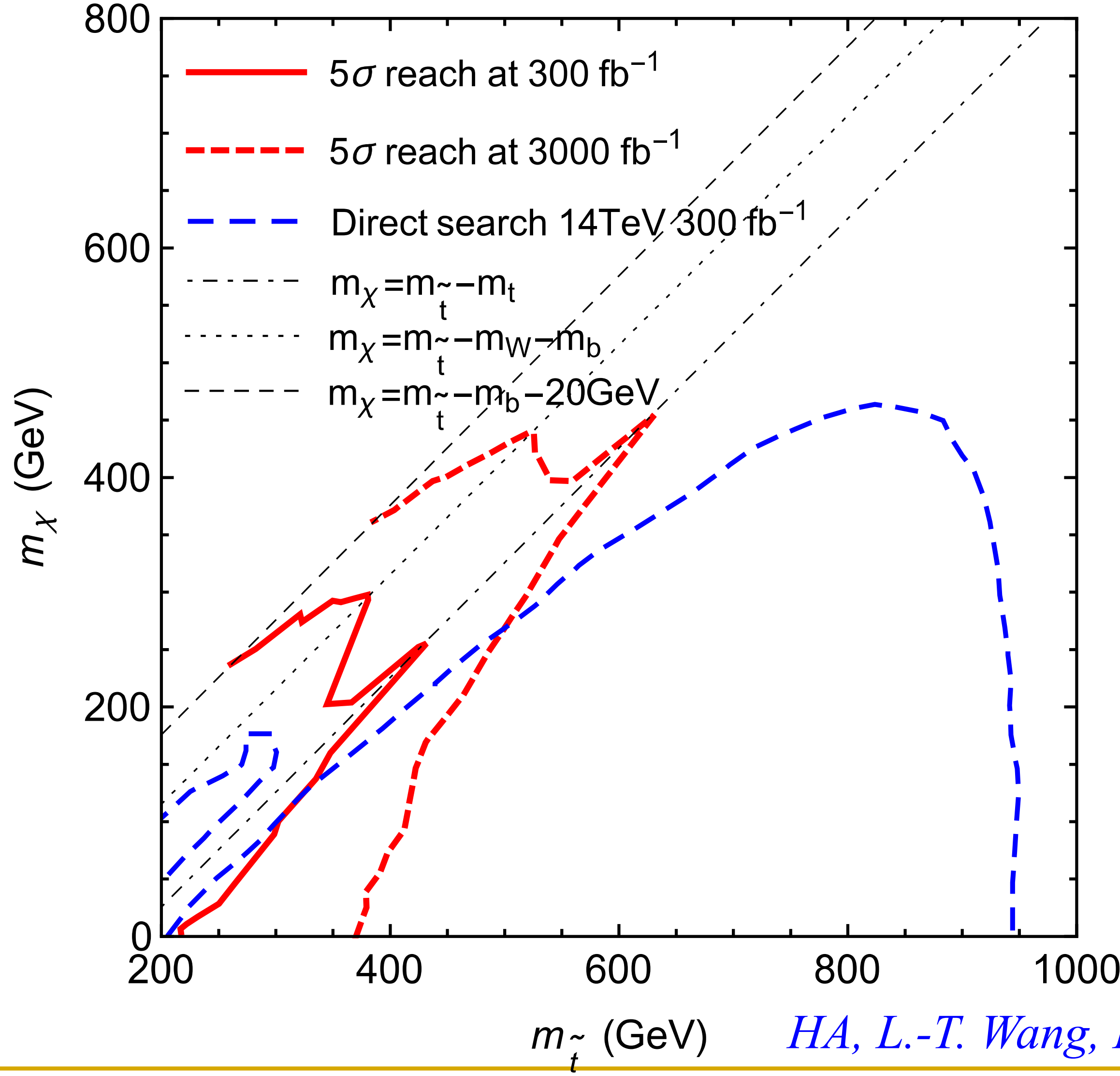




Results



5 sigma reach defined as

$$S/\sqrt{B} = 5$$

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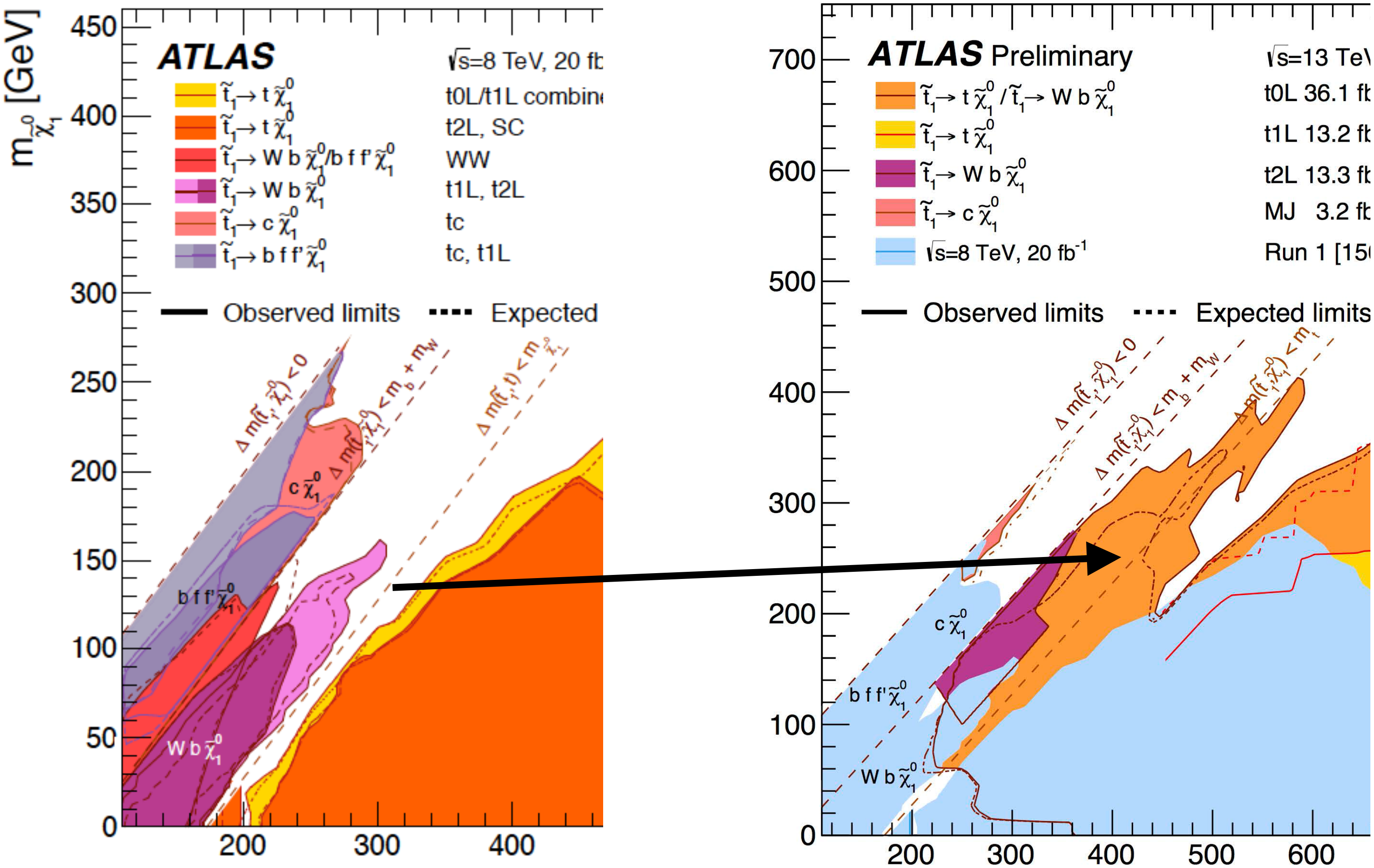
ATLAS result

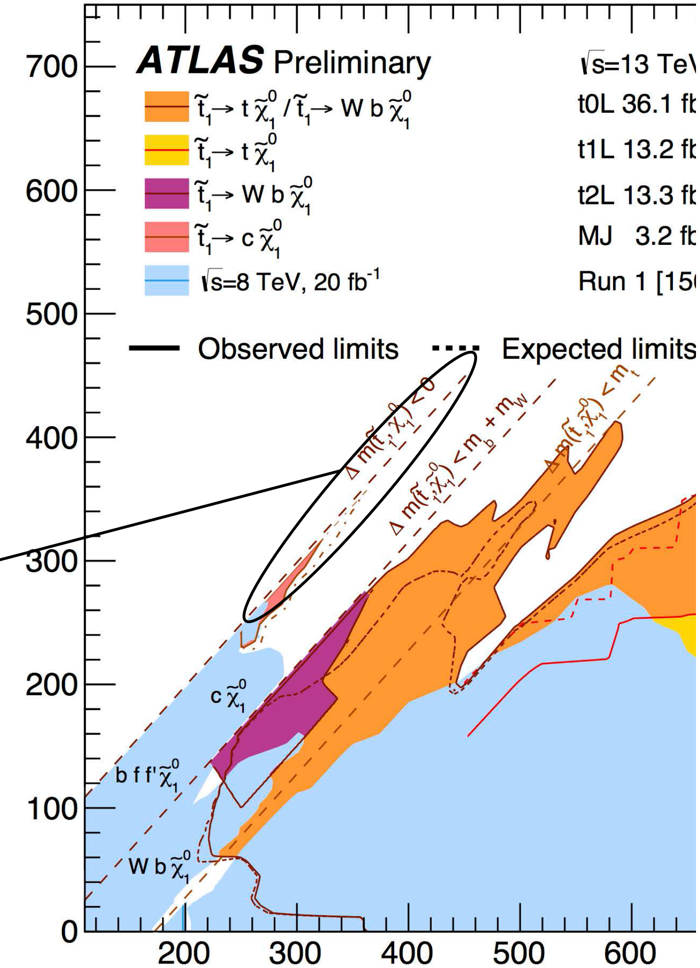


Ideas of searching for stop at compressed regions

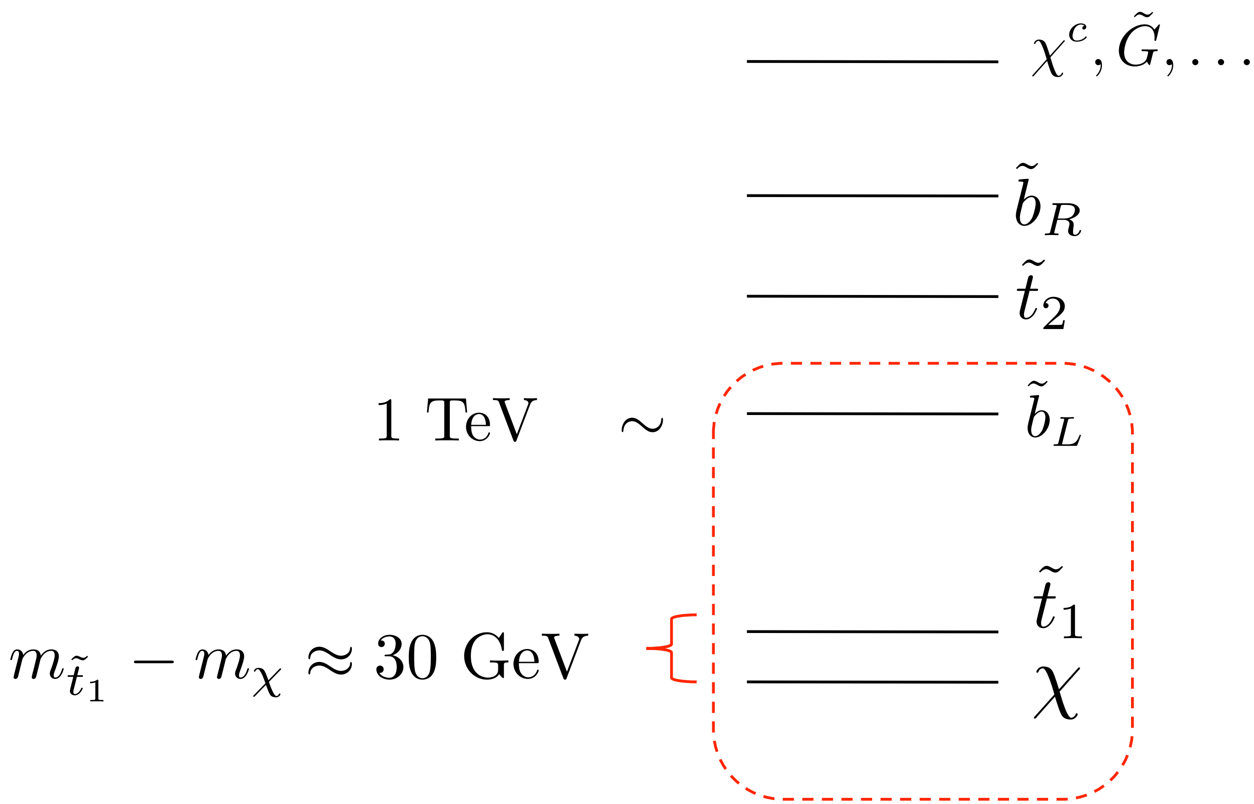
- 1. Using the sbottom
- 2. Monojet + displaced vertices

$$m_{\tilde{t}} \gtrsim m_{\chi}$$

Bino-stop co-annihilation



Use the sbottom



Use the sbottom

- Decay channels (1) $\tilde{b} \to b + \chi^0$ (2) $\tilde{b} \to \tilde{t} + W$

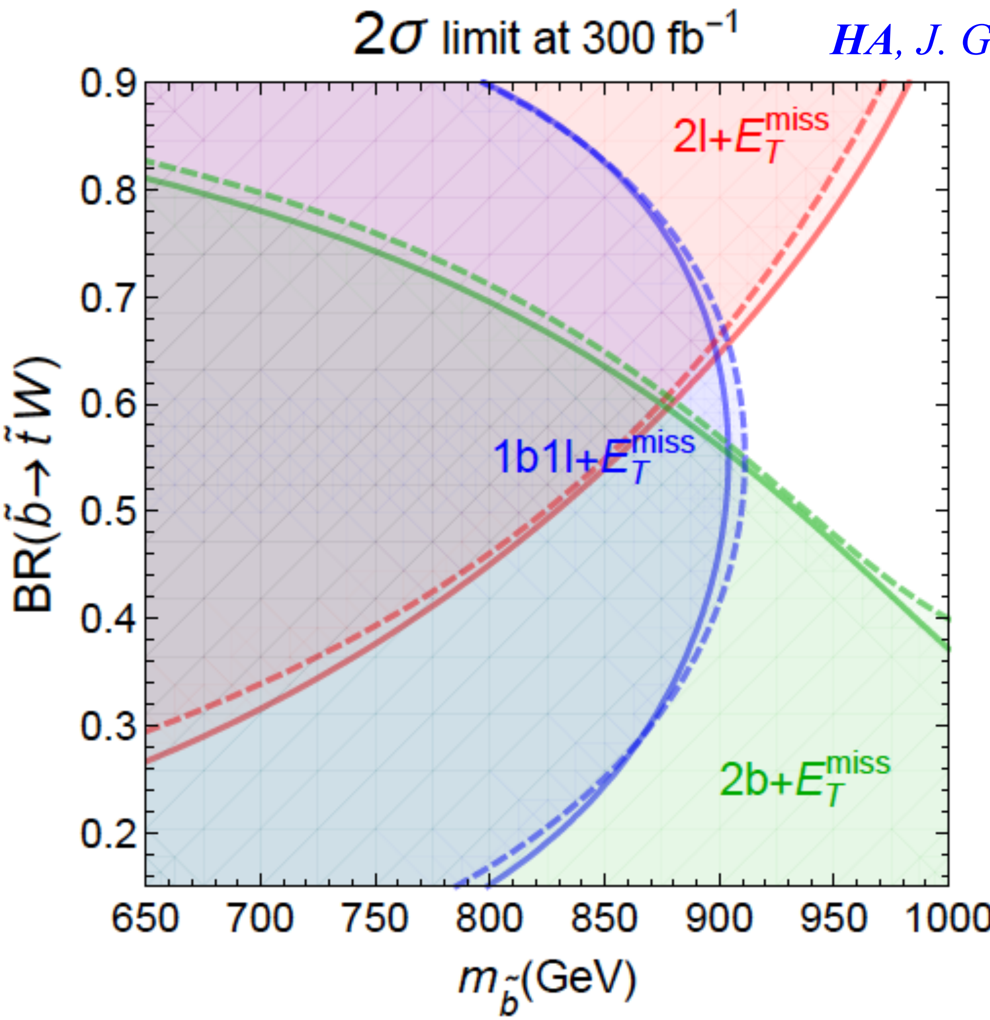
$\tilde{t}$ → Missing; W → $\ell + \nu$

- Signals

Br_1^2	$b\bar{b} + \mathrm{MET}$
$2\mathrm{Br}_1\mathrm{Br}_2$	$b + \ell + \mathrm{MET}$
Br_2^2	$\ell^+\ell^- + \mathrm{MET}$

- The branching ratios depend on the mixing angles and can be anything.

Use the sbottom



HA, J. Gu, L.-T. Wang 1611.09868

$$m_{\tilde{b}} - m_{\tilde{t}} = 400\ \text{GeV}$$

$$m_{\tilde{t}} - m_{\chi} = 30\ \text{GeV}$$

Monojet + displaced vertices

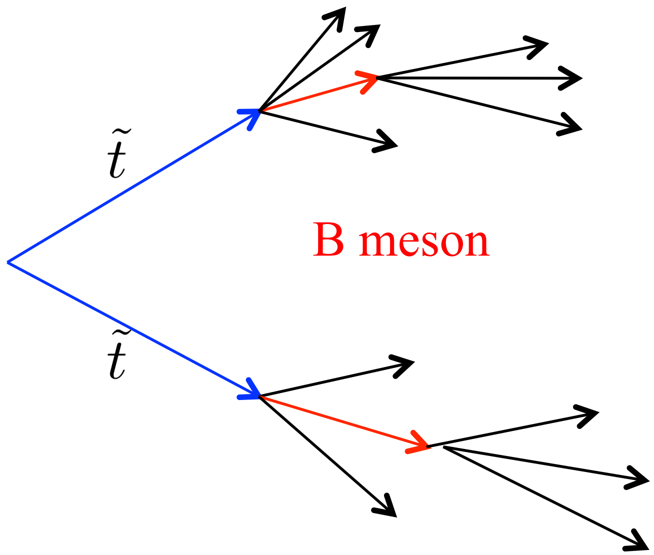
- Monojet search suffers from the irreducible Z + jets background.
- Lifetime is long (Bino LSP case)

$$\Gamma_{\tilde{t}} \approx \frac{2\alpha_{\rm em} G_F^2 (\Delta m)^8}{315\pi^4 \cos^2\theta_W m_t^2 m_{\tilde{t}}} = (1.64\ \text{mm})^{-1} \left(\frac{\Delta m}{20\ \text{GeV}}\right)^8 \left(\frac{600\ \text{GeV}}{m_{\tilde{t}}}\right)$$

- Both ATLAS and CMS can distinguish tracks with IP > 0.5 mm with PT > 0.5 GeV. They just need a trigger.
- We can use monojet to trigger the events and then use displaced tracks to get rid of the Z+jets background.

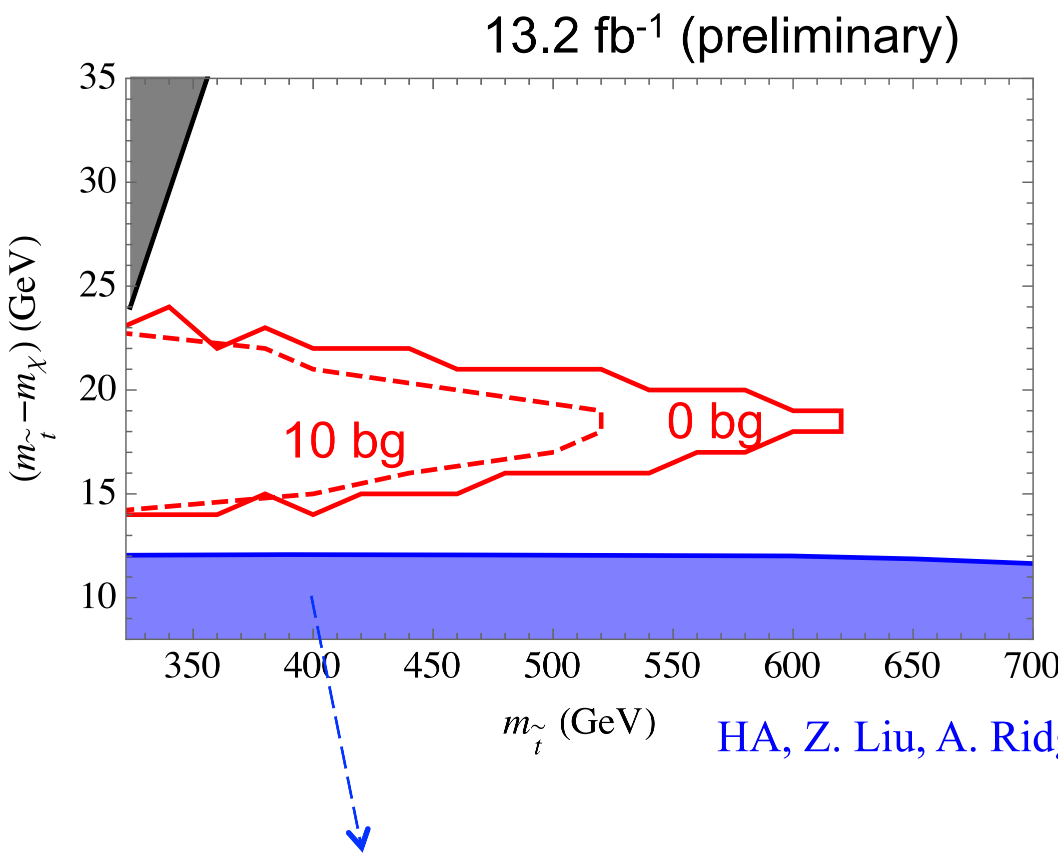
Monojet + displaced vertices

- Signal



Four displaced vertices

Monojet + displaced vertices



HA, Z. Liu, A. Ridgeway to be appeared

1. Requiring 2 displaced vertices
2. Each contains at least 4 tracks with PT > 1 GeV and transverse IP > 0.5 mm.
3. The distance between the 2 vertices larger than 5 mm
4. Exclude the region within 1 mm surround the beam pipe.
5. MET > 200 GeV

Constraint from searching for stable charged particle (Liu and Tweedie 1503.05923)

Summary

- 1. $m_{\tilde{t}} \approx m_t + m_\chi$
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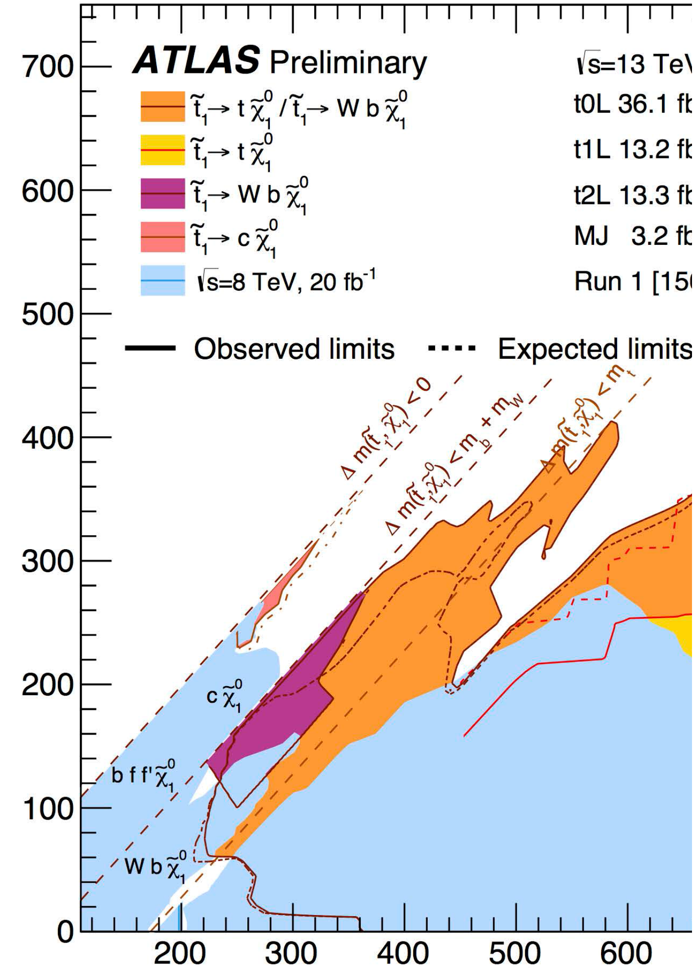
- 3. $m_{\tilde{t}} \gtrsim m_\chi$

Using the sbottom
Monojet + Displaced vertices



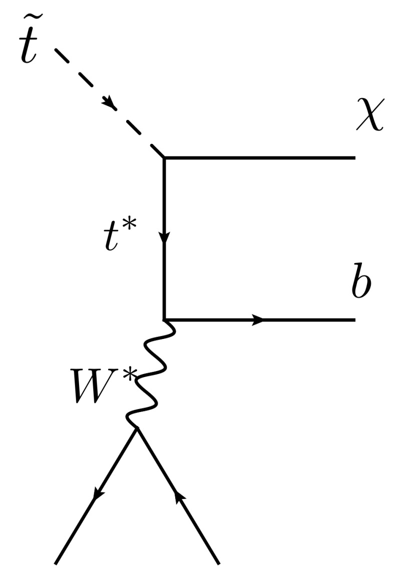
Backups

Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- Two main decay channels:

$$\tilde{t} \to b + \chi + W^*(\text{off shell } W)$$

$$\tilde{t} \to \chi + c$$ (Depends on the flavor structure of the squark sector)

- 

$$\Gamma \sim \frac{g_{\text{eff}}^2 g_2^4 (m_{\tilde{t}} - m_\chi - m_b)^7}{2048\pi^5 m_t^2 m_W^4}$$

$\tilde{t}_R,\ \tilde{B}$ case :

$$\Gamma \approx 1.4 \times 10^{-13}\ \text{GeV} \times \left(\frac{\Delta m}{20\text{GeV}}\right)^7$$

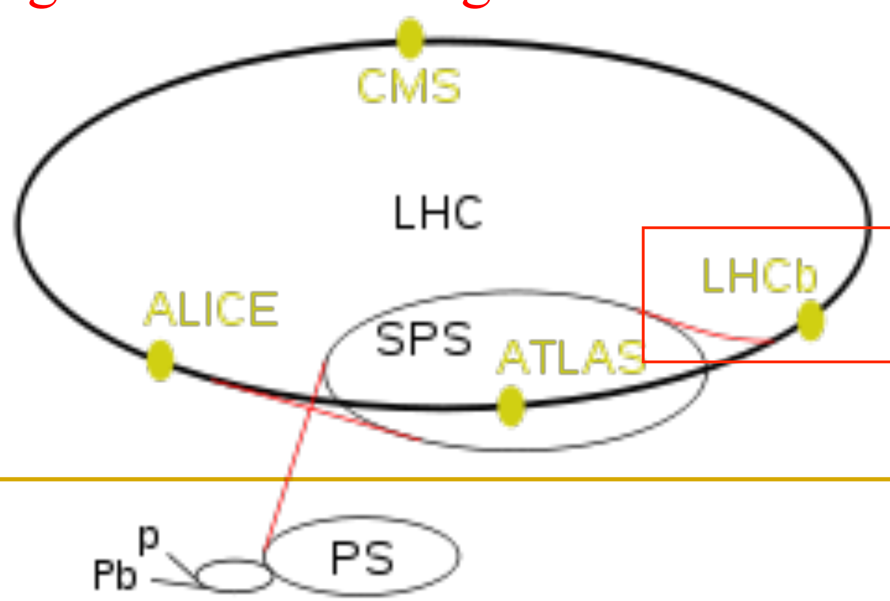
1 mm displaced vertex!

Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- 1 mm might be too short for ATLAS and CMS.
- 20 GeV kinetic energy is also too soft.
- Must we trigger something else?

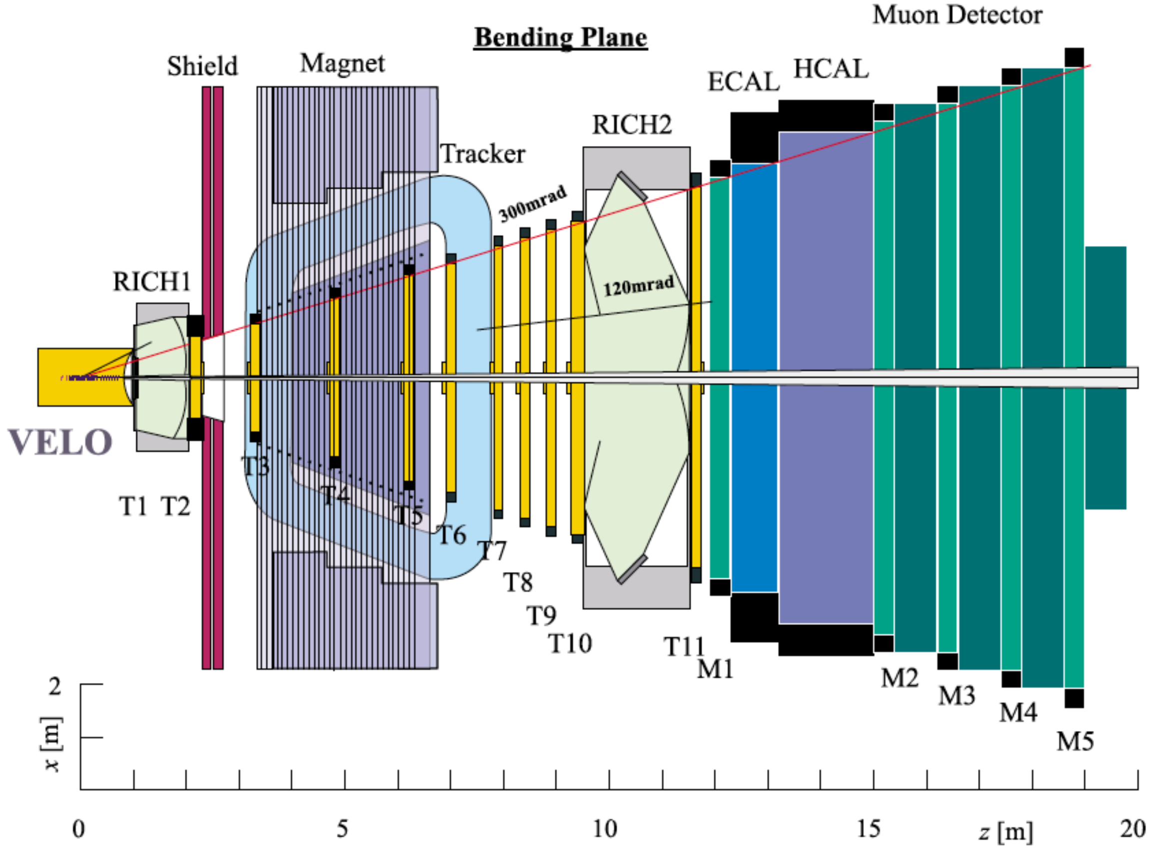
Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- 1 mm might be too short for ATLAS and CMS.
- 20 GeV kinetic energy is also too soft.
- Must we trigger something else?
- LHCb is just designed for such a signal



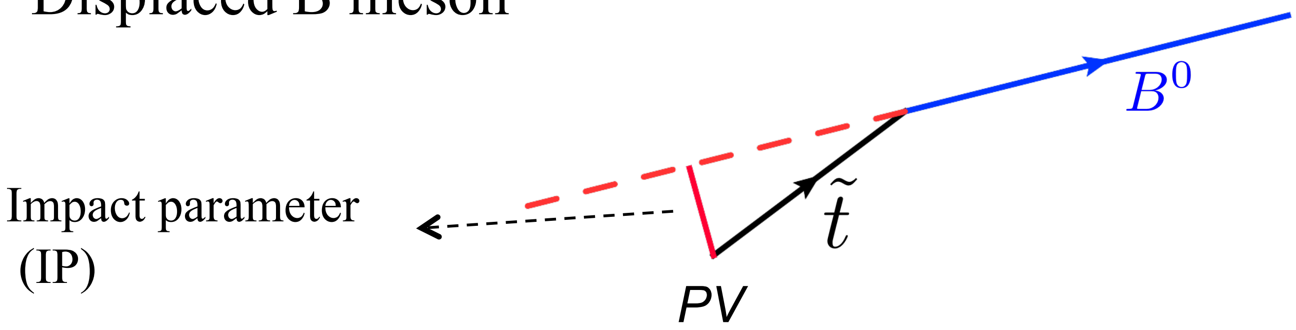
Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- Covers the forward region $2 < \eta < 5$



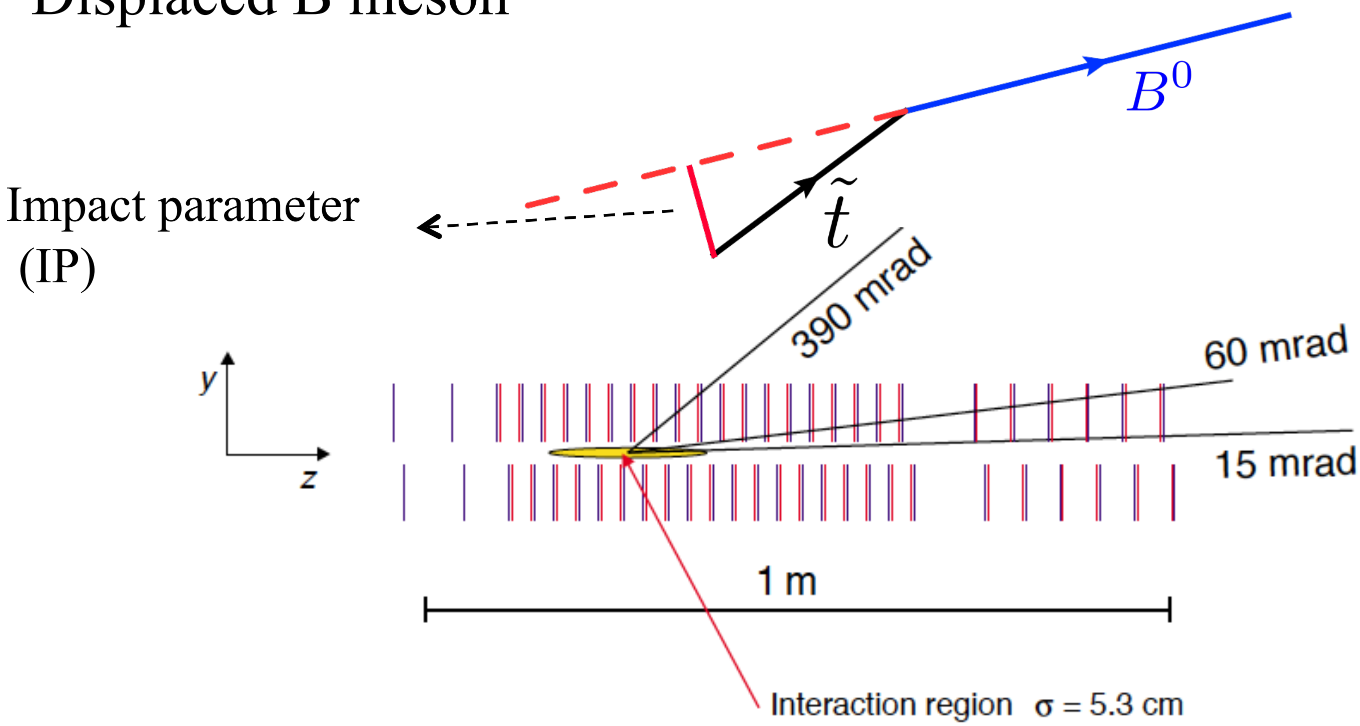
Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- Displaced B meson



Ideas of searching for stop at compressed regions $m_{\chi} \approx m_{\tilde{t}}$

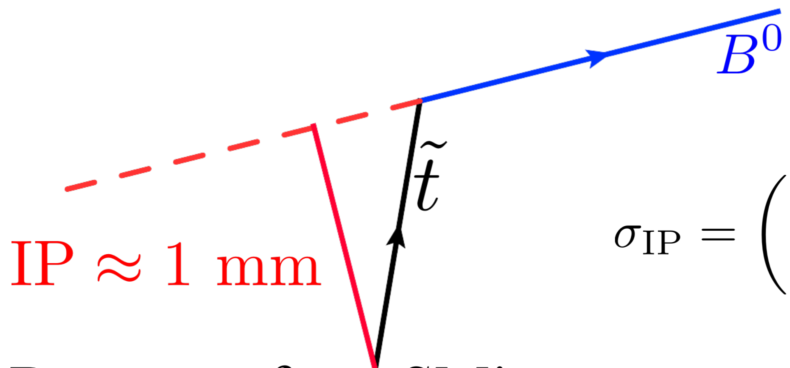
- Displaced B meson



$$\sigma_{\mathrm{IP}} = \left(11.0 + \frac{13.1\ \mathrm{GeV}}{p_T}\right)\ \mu\mathrm{m}$$

Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- The boost of the stops are small.
- The decay products of the stops are isotropically distributed.

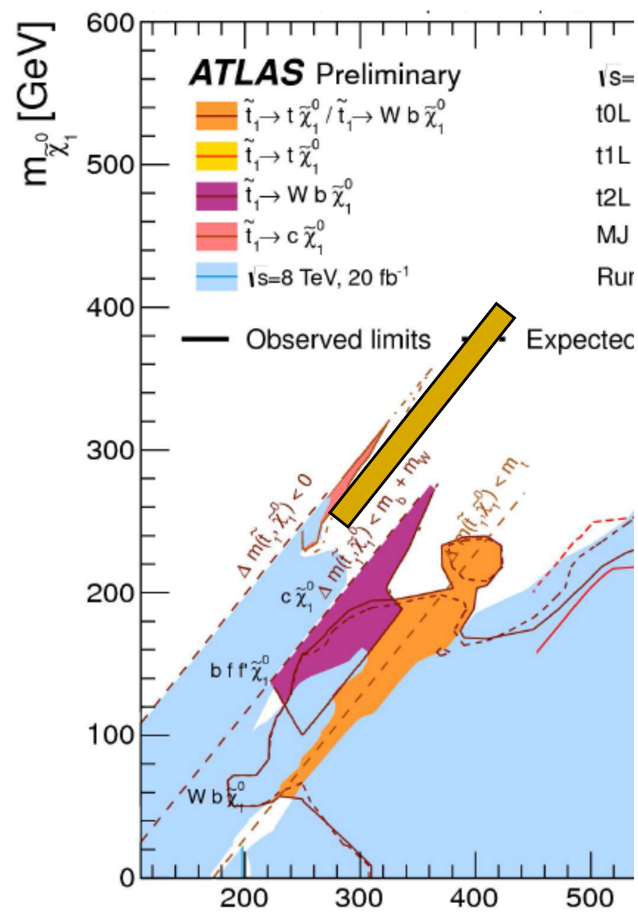


$$\sigma_{\rm IP} = \left(11.0 + \frac{13.1\ \text{GeV}}{p_T}\right)\ \mu\text{m}$$

- No displaced B mesons from SM!
- c tau of B meson is about 0.5 mm.
- The uncertainty can be as small as about 0.03 mm. There are about 10^{12} B mesons produced at 1 fb^{-1}. Naively we expect no SM events with IP larger than 1 mm. (Detailed simulation is needed to confirm it.)

Ideas of searching for stop at compressed regions $m_\chi \approx m_{\tilde{t}}$

- 2000 stops can be produced for 400 GeV stops in 1 fb^{-1}.
- The trigger efficiency can be around 20%.
- Geometric acceptance is about 2~3%.
- About 10 events per fb^{-1} left with zero background.
- In progress with Liu Zhen and Alexander Ridgeway.



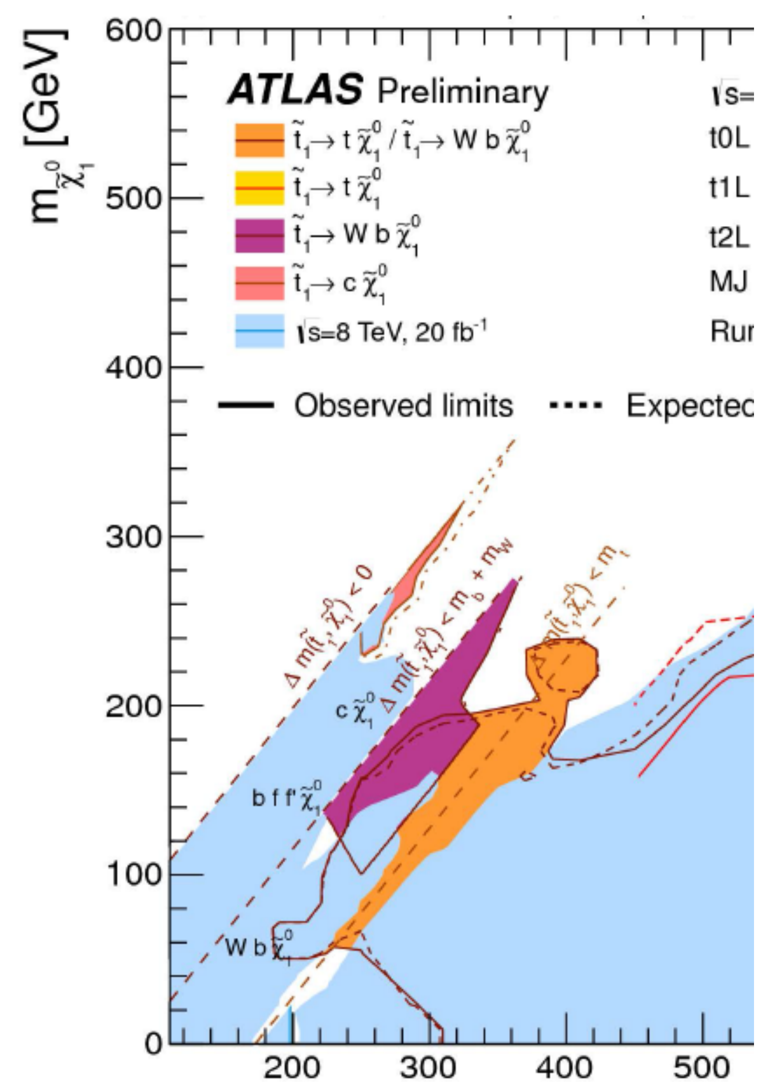
Summary

- 1. $m_{\tilde{t}} \approx m_t + m_\chi$
- 2. $m_{\tilde{t}} \approx m_W + m_b + m_\chi$

$$R_M \equiv \frac{\not{p}_T}{p_T(j_{\rm ISR})} \approx \frac{m_\chi}{m_{\tilde{t}}} \approx 1 - \frac{m_t}{m_{\tilde{t}}}$$

- 3. $m_{\tilde{t}} \gtrsim m_\chi$

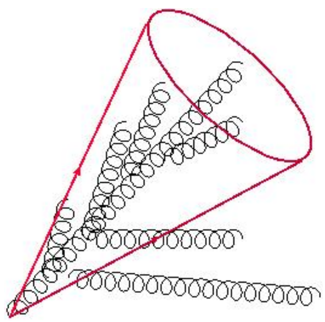
We hope LHCb will give us better sensitivity!



The width of the R_M peak

- The stop search in the compressed region now becomes a search for the R_M peak. The width of the peak is determined by
  - The phase space of the stop decay $\Delta R_{\text{parton}} \approx \Delta p_\chi / p_T(j_{\text{ISR}})$
  - QCD shower effect
  - Detector effect

$$\frac{\delta E_J}{E_J} = \frac{a}{\sqrt{E_J/\text{GeV}}} \oplus b$$



- A large $p_T(j_{\text{ISR}})$ can suppress the effect of all these smearing effects.

Identify the ISR jet

- The stop is usually heavy, so the boosts of the tops are small in the compressed region. Therefore, the p_T of the jets from the top quark decay should be smaller than m_t.

- Therefore, if we select a leading jet with $p_T > m_t$, it is very probable to be the jet we want.

Cuts

- Veto events with electrons and muons
  - No MET from neutrinos

- $p_T(j_{\mathrm{ISR}} = j_{\mathrm{leading}}) > 700$ GeV
  - to suppress the smearing of the peak
  - to identify the jet not from the top decay

Cuts

- At least three sub-leading jets with $p_T > 60$ GeV, at least one of them is b-tagged.
- $|\phi(j_0) - \phi_{MET} - \pi| < 0.15$.
  - $p_T(j_0)$ and MET is anti-aligned in the compressed region.
- $|\phi_{MET} - \phi_j| > 0.2$ for the sub-leading jets with $p_T > 60$ GeV.
  - To kill the background from the mis-measurement of jet energy.

Final cut based on the R_M peak

$$m_{\tilde{t}} > m_t + m_\chi$$

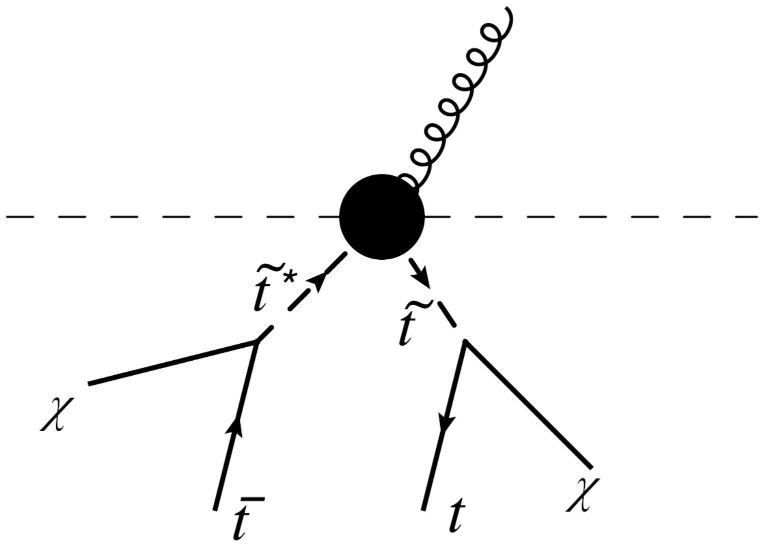
$$\left(\frac{m_{\tilde{t}} - m_t}{m_{\tilde{t}}}\right) - 0.05 < \frac{\not{p}_T}{p_T(j_0)} < \left(\frac{m_{\tilde{t}} - m_t}{m_{\tilde{t}}}\right) + 0.15 \ ,$$

and for $m_{\tilde{t}} < m_t + m_\chi$

$$\left(\frac{m_\chi}{m_{\tilde{t}}}\right) - 0.05 < \frac{\not{p}_T}{p_T(j_0)} < \left(\frac{m_\chi}{m_{\tilde{t}}}\right) + 0.15 \ .$$

Trigger a hard jet?

$$m_{\tilde{t}} \gtrsim m_t + m_\chi$$

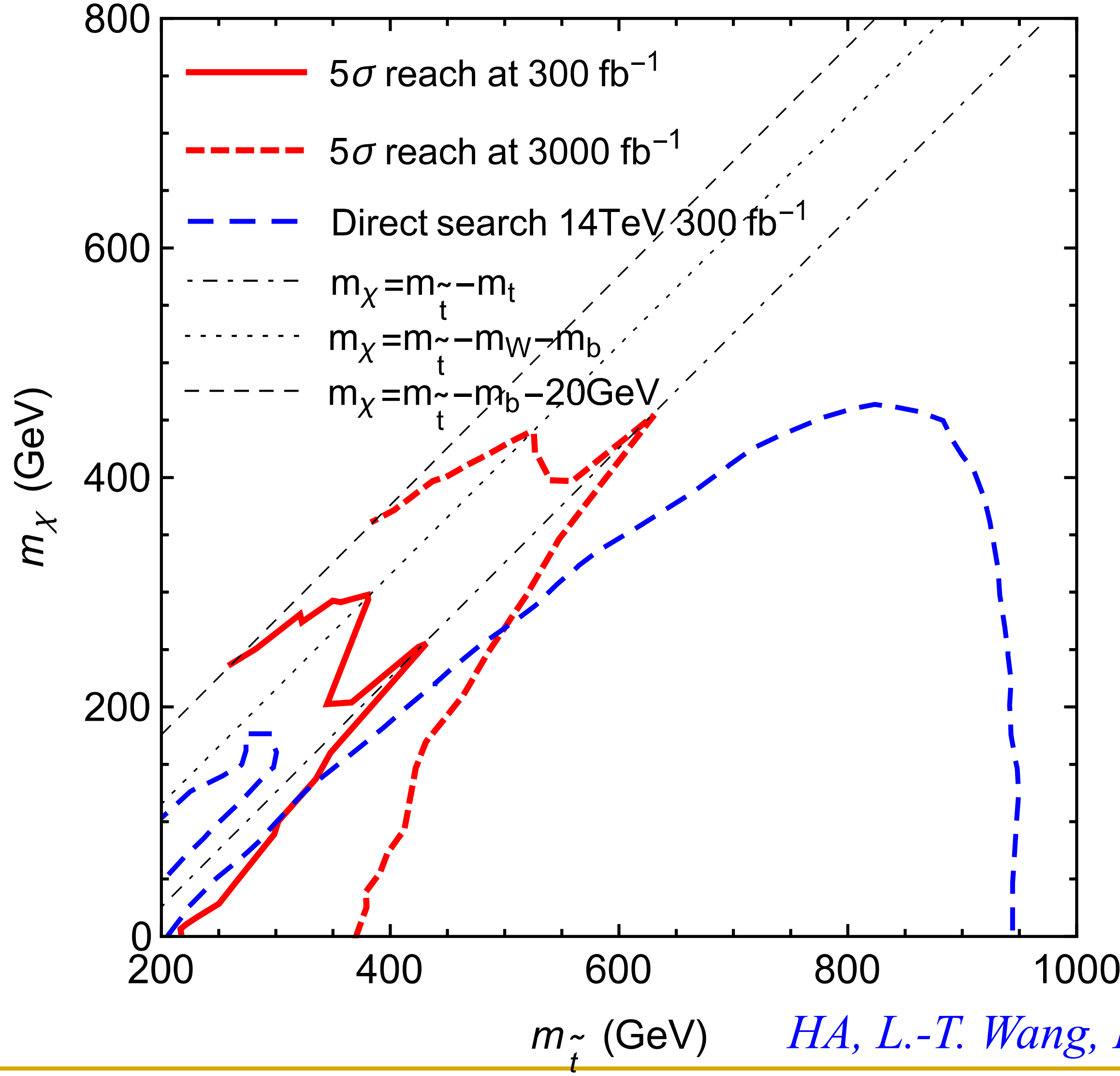


$$\vec{p}_T(\chi_1) + \vec{p}_T(\chi_2) \neq 0!$$

Hagiwara and Yamada, 1307.1553
HA and Wang, 1506.00653
Macaluso, Park, Shih, Tweedie 1506.07885

In the compressed region, considering signal with a hard jet will convert the stop search into a bump search.

Results



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Generalization of R_M variable

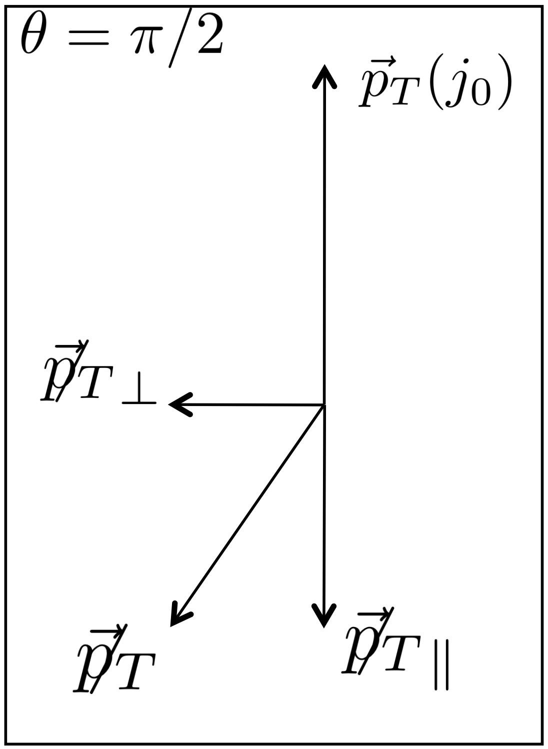
- Can we use the semi-leptonic channel?
  - Pro: It is cleaner than the hadronic channel.
  - Con: The neutrino in this channel generates additional missing energy which may ruin the relation between MET and the leading jet PT.

- A method to separate the neutrino contribution from MET is in need.

Semileptonic channel

Hsin-Chia Cheng et al 1604.00007

$$\vec{p}_T(\chi_1) + \vec{p}_T(\chi_2) \text{ in parallel with } \vec{p}_T(j_0)$$



$$\not{p}_{T\perp} = p_T(\nu)_\perp$$

Semileptonic channel

Hsin-Chia Cheng et al 1604.00007

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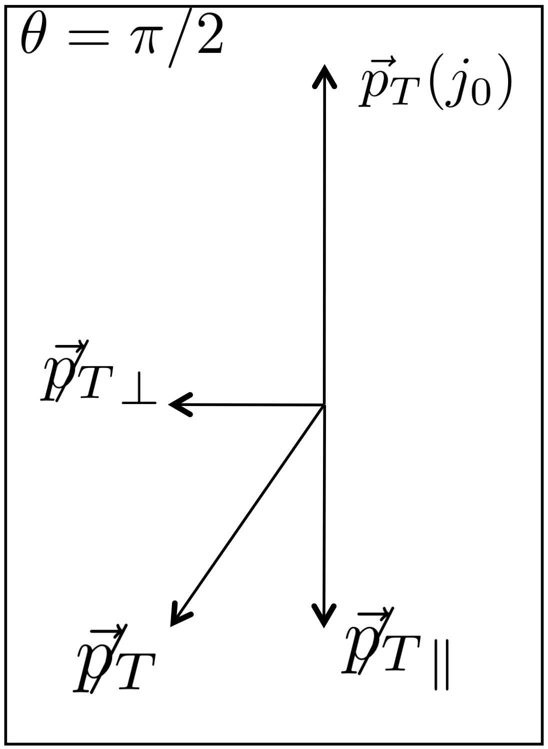


$$\left.\begin{aligned} \not{p}_{T\perp} &= p_T(\nu)_\perp \\ p_\nu^2 &= 0 \\ (p_l + p_\nu)^2 &= m_W^2 \\ (p_l + p_\nu + p_b)^2 &= m_t^2 \end{aligned}\right\} \; p_T(\nu)_\parallel$$

$$\bar{R}_M \equiv \frac{\not{p}_T(\chi)}{p_T(j_0)} \approx \frac{\not{p}_{T\parallel} - p_T(\nu)_\parallel}{p_T(j_0)} \approx \frac{m_\chi}{m_{\tilde{t}}}$$

Generalization of R_M variable

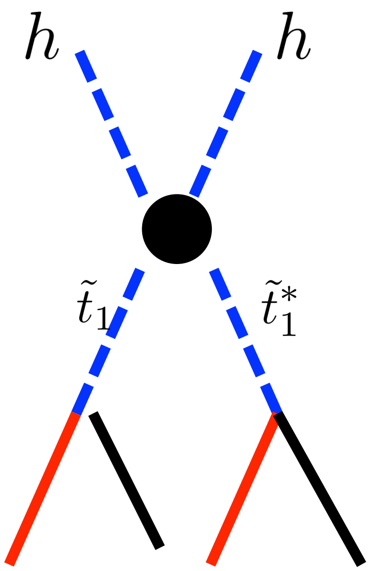
- Search for the gluino at the compressed region. (Delgado, Martin and Raj 1605.06479)

- Make use of the second stop (the first stop at the compressed region)

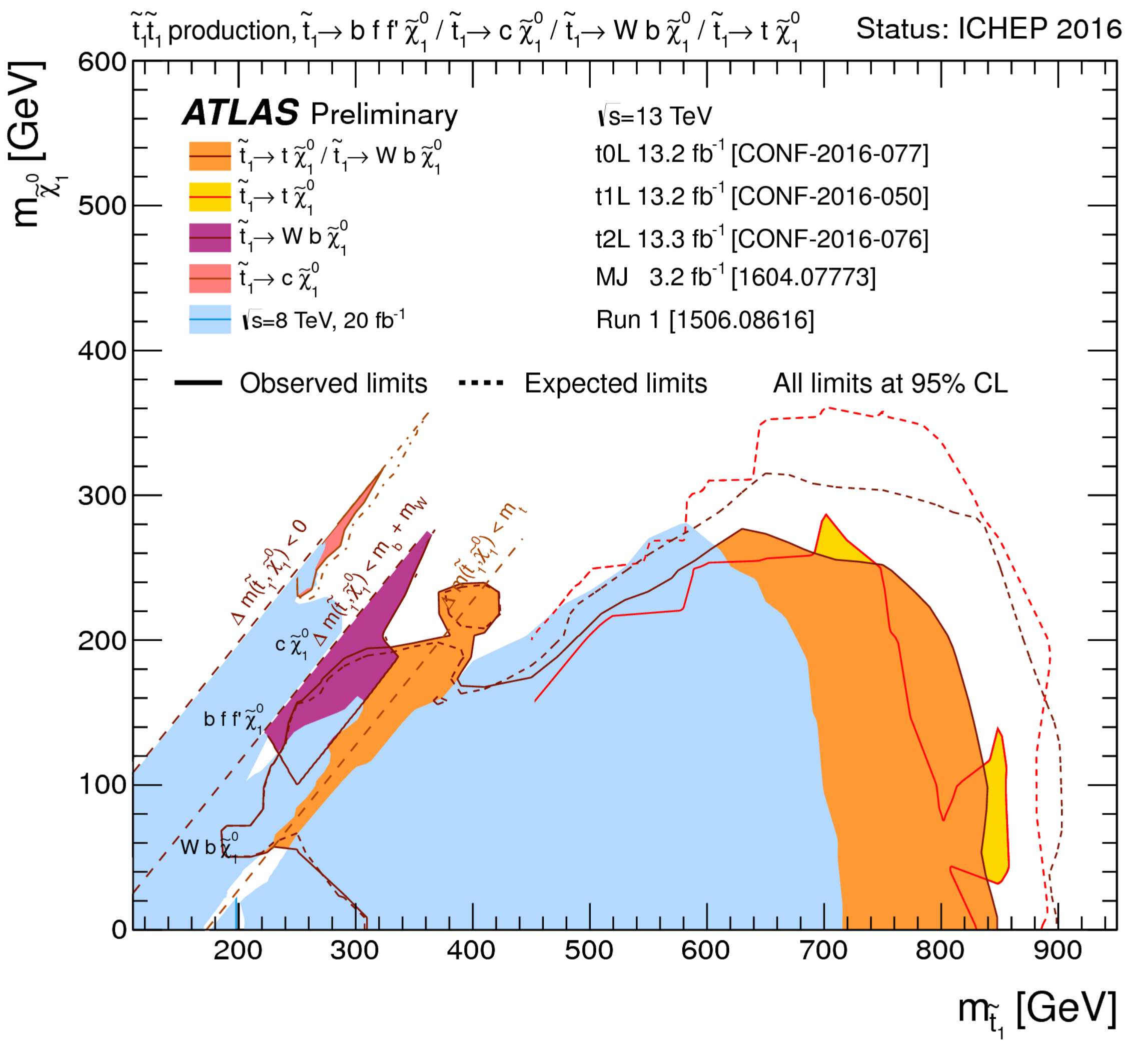
$$pp \to \tilde{t}_2 \tilde{t}_2^* \qquad \tilde{t}_2 \to \tilde{t}_1 h(Z)$$

$$\tilde{t}_2^* \to \tilde{t}_1^* h(Z)$$

h and Z play the roll of the hard jet



New results from ATLAS



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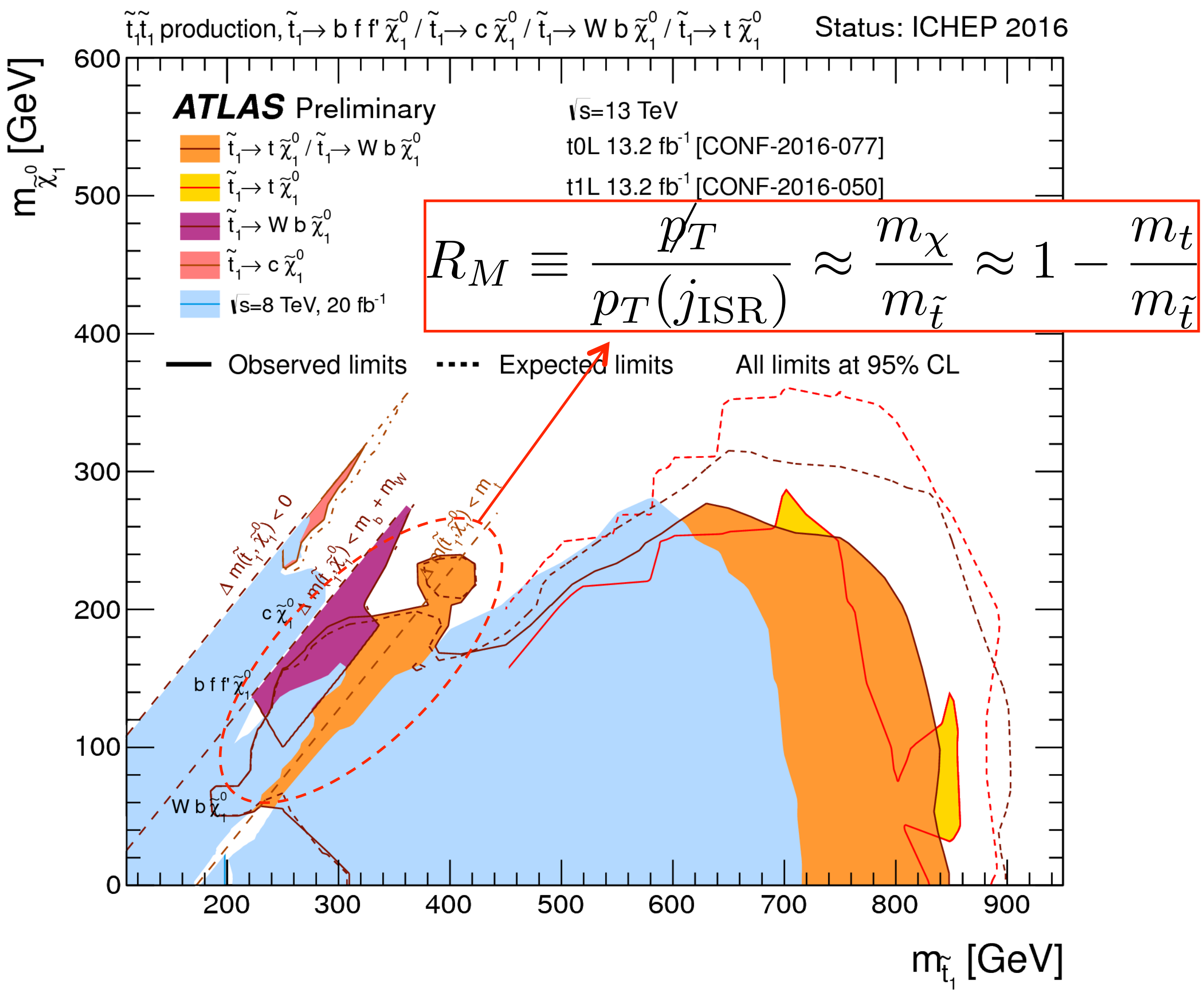

$$R_M \equiv \frac{\not{p}_T}{p_T(j_{\mathrm{ISR}})} \approx \frac{m_\chi}{m_{\tilde{t}}} \approx 1 - \frac{m_t}{m_{\tilde{t}}}$$

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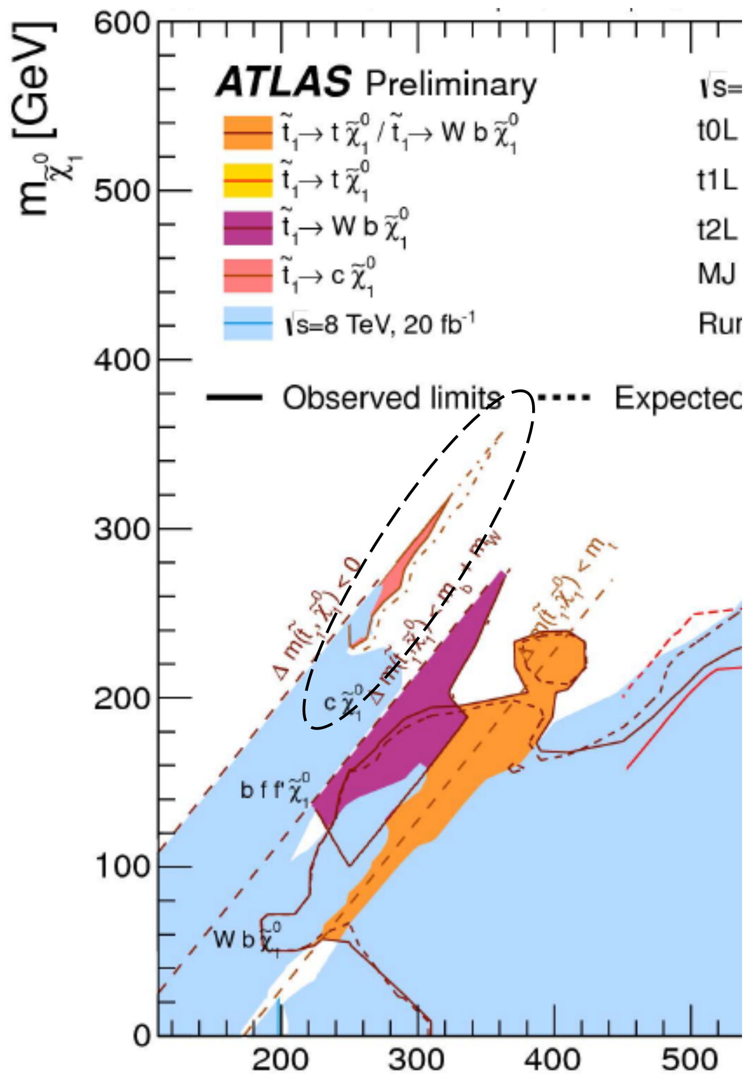
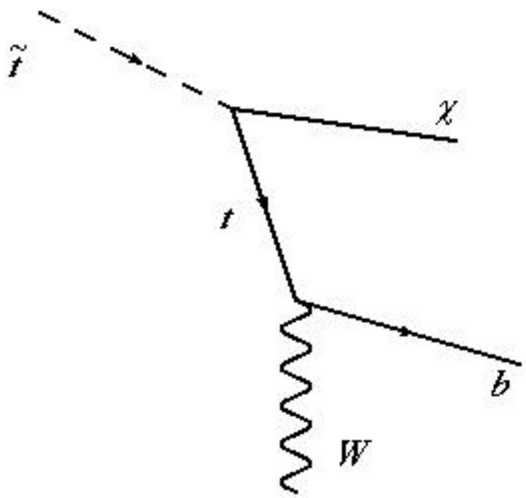


Trigger a hard ISR jet?

$$m_{\tilde{t}} \lesssim m_t + m_\chi \qquad \frac{d\Gamma_{\tilde{t}}}{dq_t} \propto \frac{1}{(q_t^2 - m_t^2)^2}$$

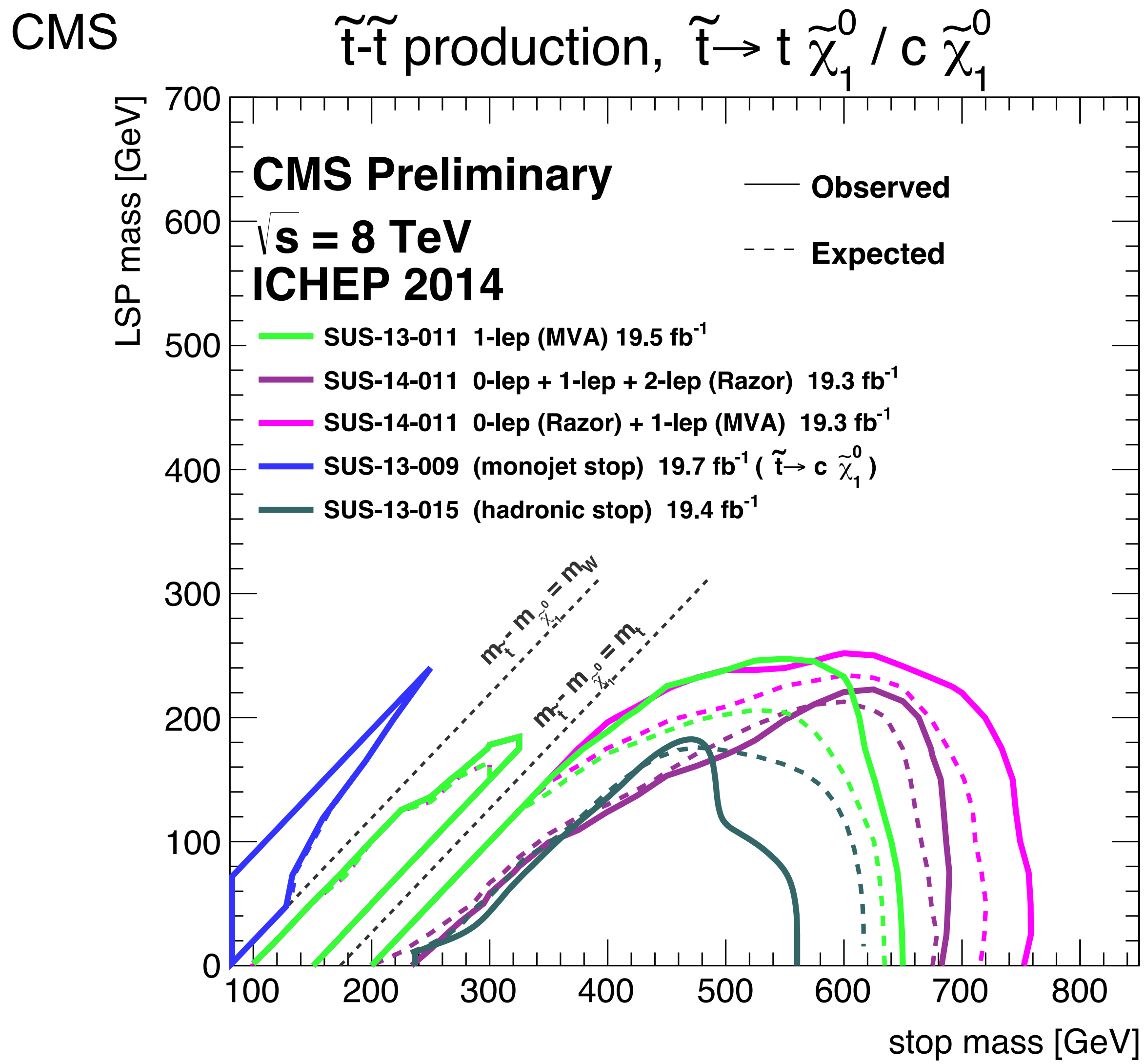


The virtual top prefers to be as less virtual as possible. Therefore, χ prefers to be stationary in the rest frame of its mother stop.

As a result, we still expect the relation

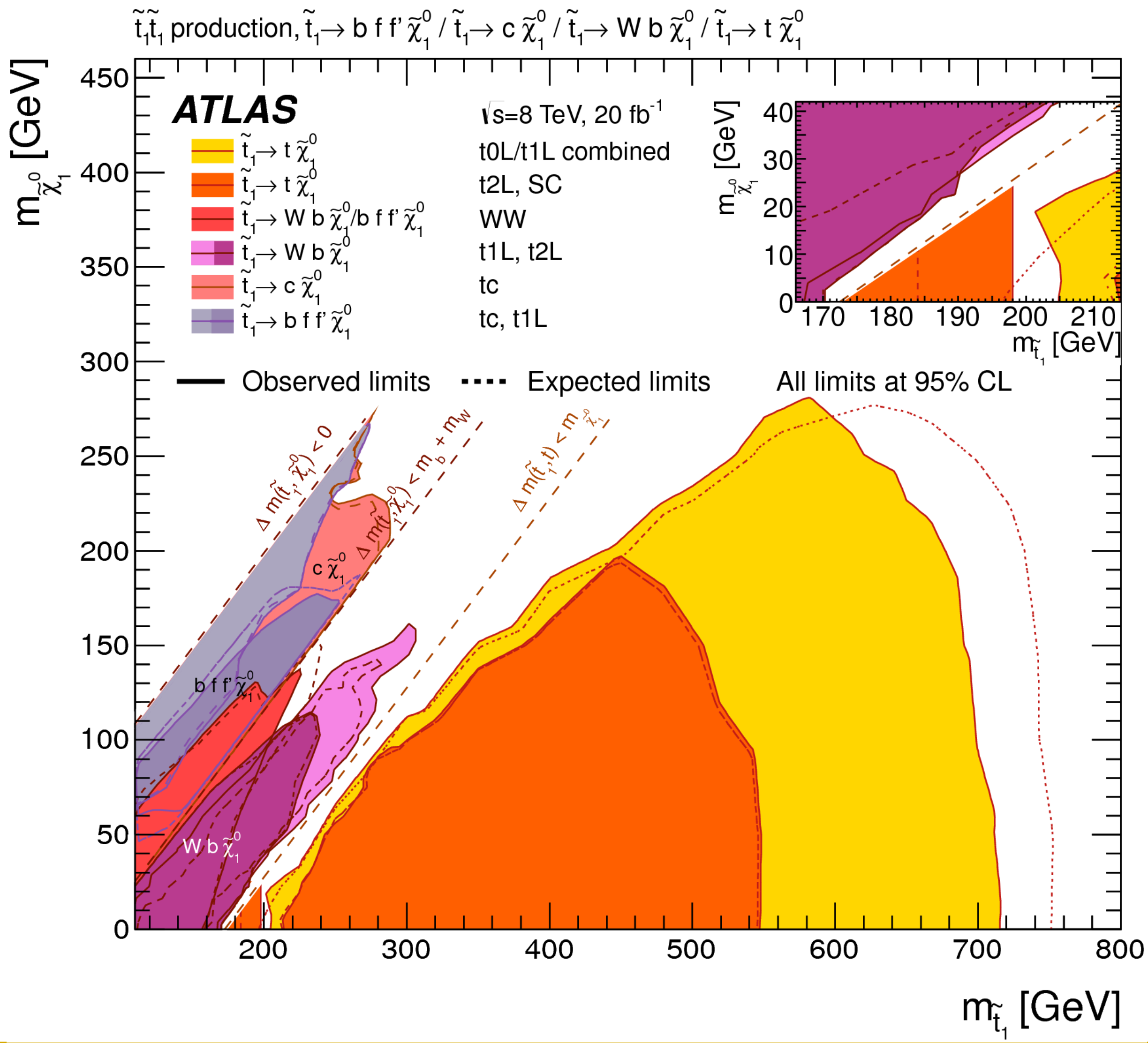
$$R_M \equiv \frac{\not{p}_T}{p_T(j_{\rm ISR})} \approx \frac{m_\chi}{m_{\tilde{t}}} \approx 1 - \frac{m_t}{m_{\tilde{t}}}$$

Current status of stop search



Current status of stop search

ATLAS



Compressed region of the stop search