Searching for Bino-Stop coannihilaton in CMS Open Data

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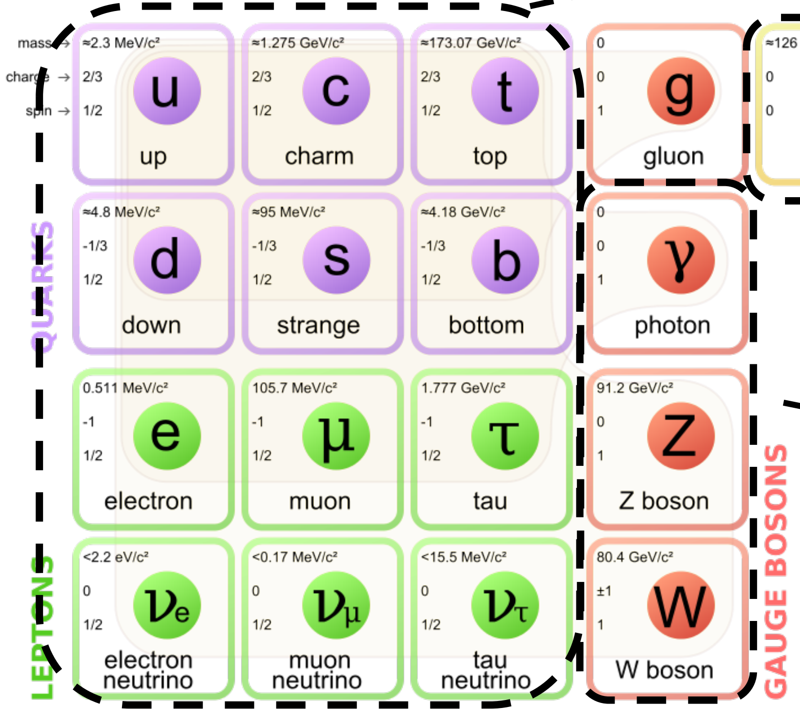
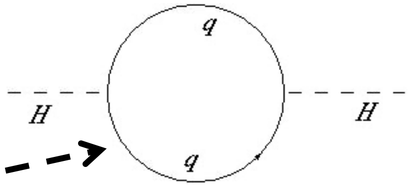
Snowmass 2021, EF10 DM@Colliders, topical meeting on LOIs on WIMPs and other models

Oct. 21, 2020

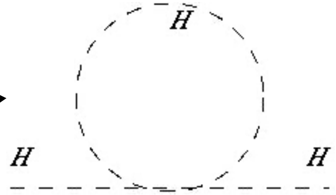
In collaboration with Zhen Hu, Zhen Liu, Daneng Yang

Why we are still interested in SUSY?

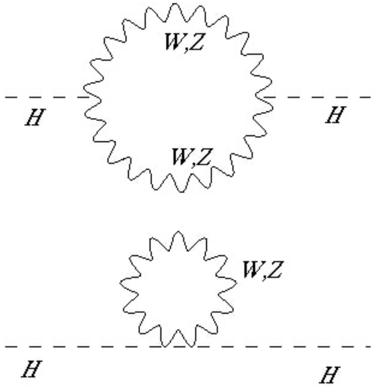




$$\approx -\frac{y_q^2}{8\pi}\Lambda_{\mathrm{UV}}^2$$



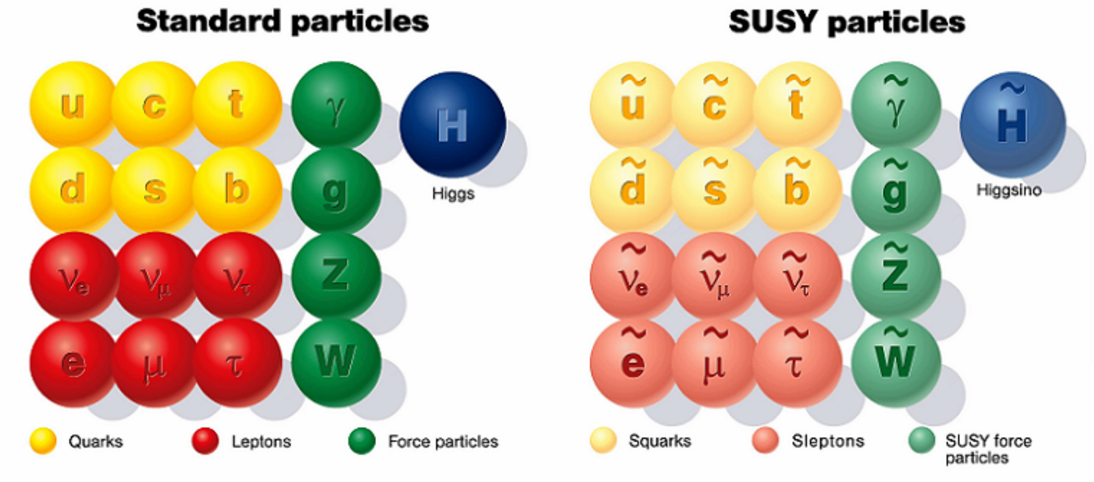
$$\approx \frac{\lambda}{8\pi}\Lambda_{\mathrm{UV}}^2$$



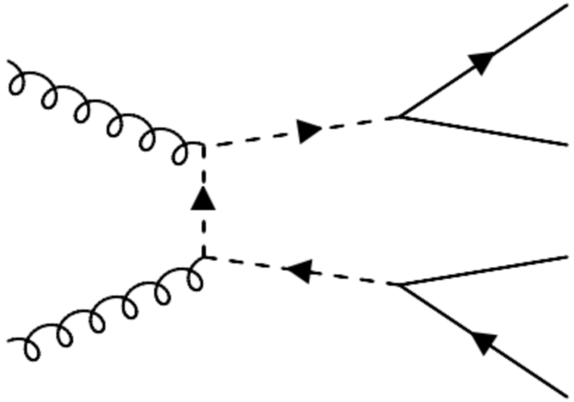
$$\approx -\frac{g^2}{8\pi}\Lambda_{\mathrm{UV}}^2$$

The importance of top quark superpartner

- Quadratic divergences canceled completely.
- Supersymmetry must be broken!
- Top SUSY partner must be light.



Status of stop search

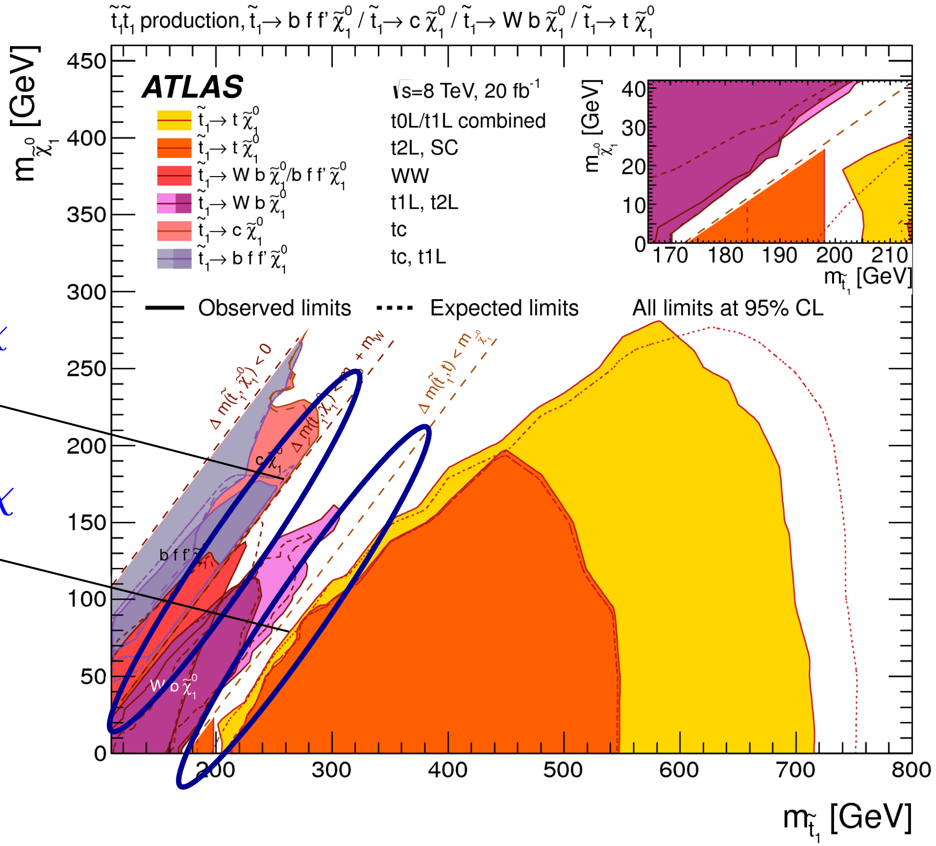


Tradtional search:
top pair + MET

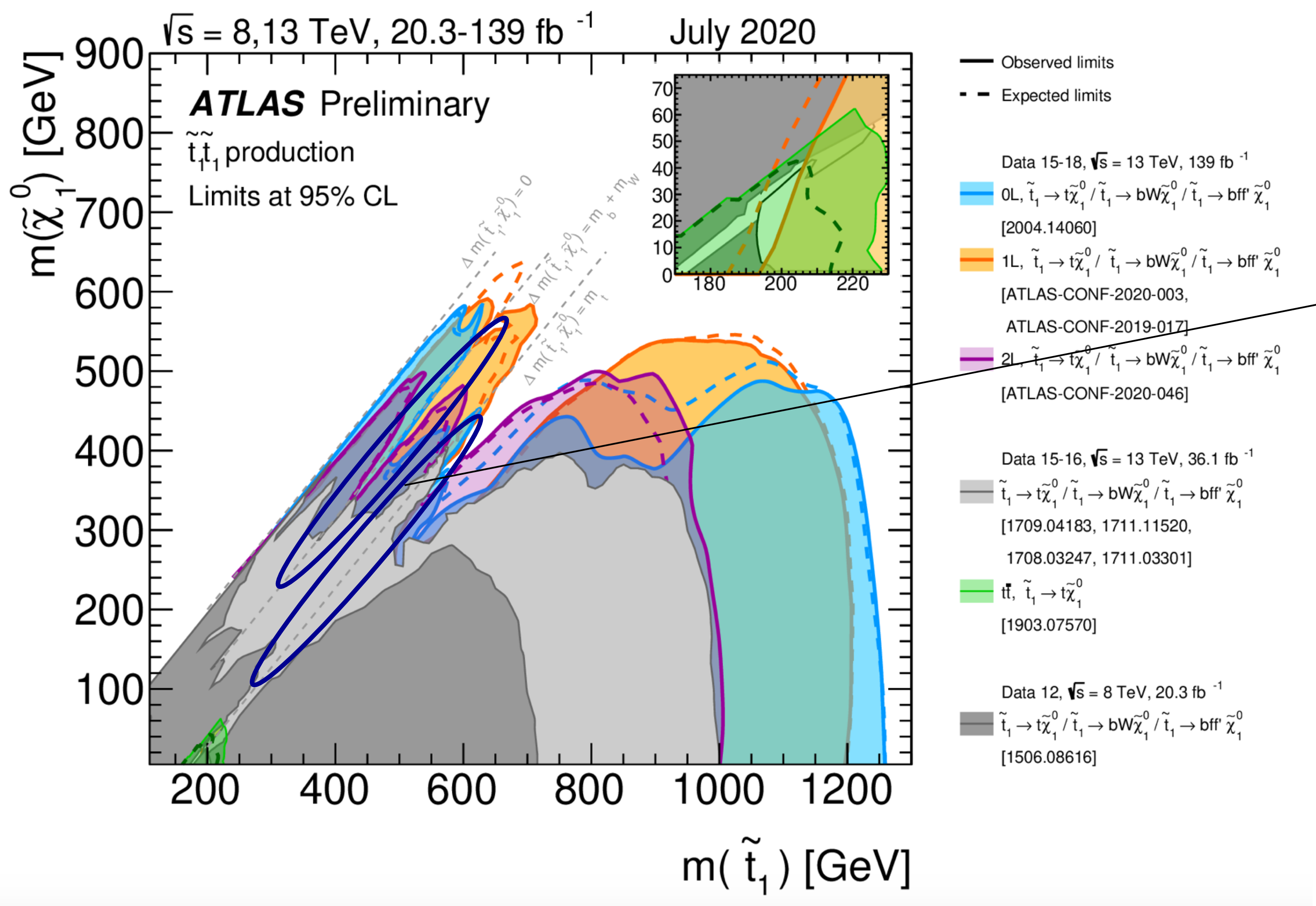
$$m_{\tilde{t}} \approx m_W + m_b + m_\chi$$

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

ATLAS results before 2015

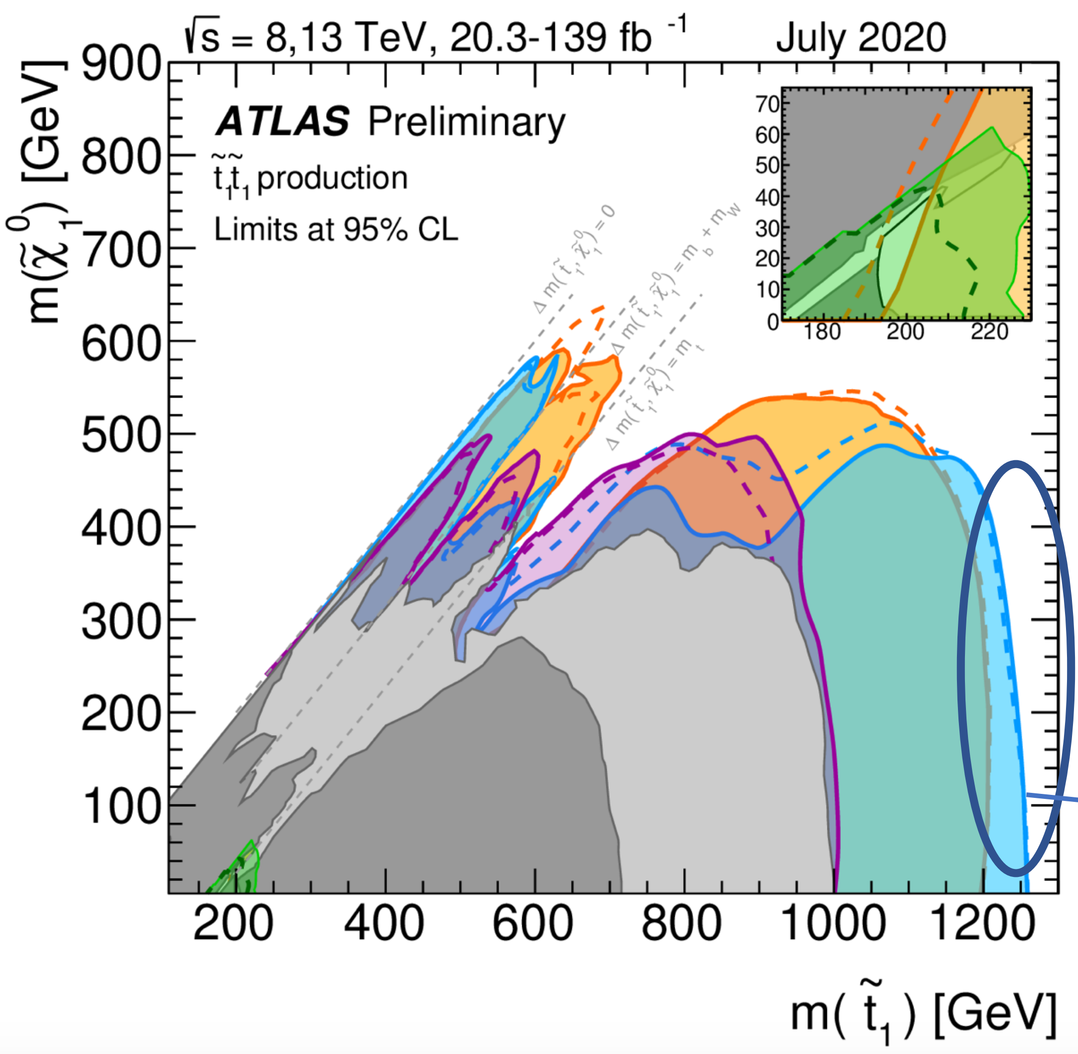


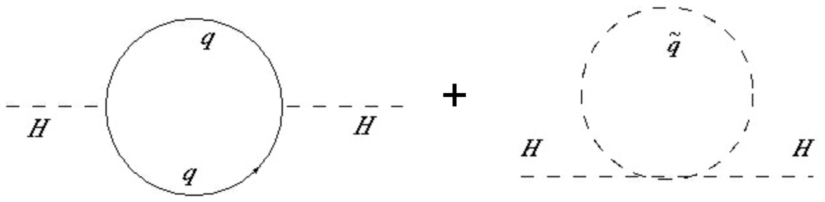
The compressed regions



Partially filled with new searches

The compressed regions

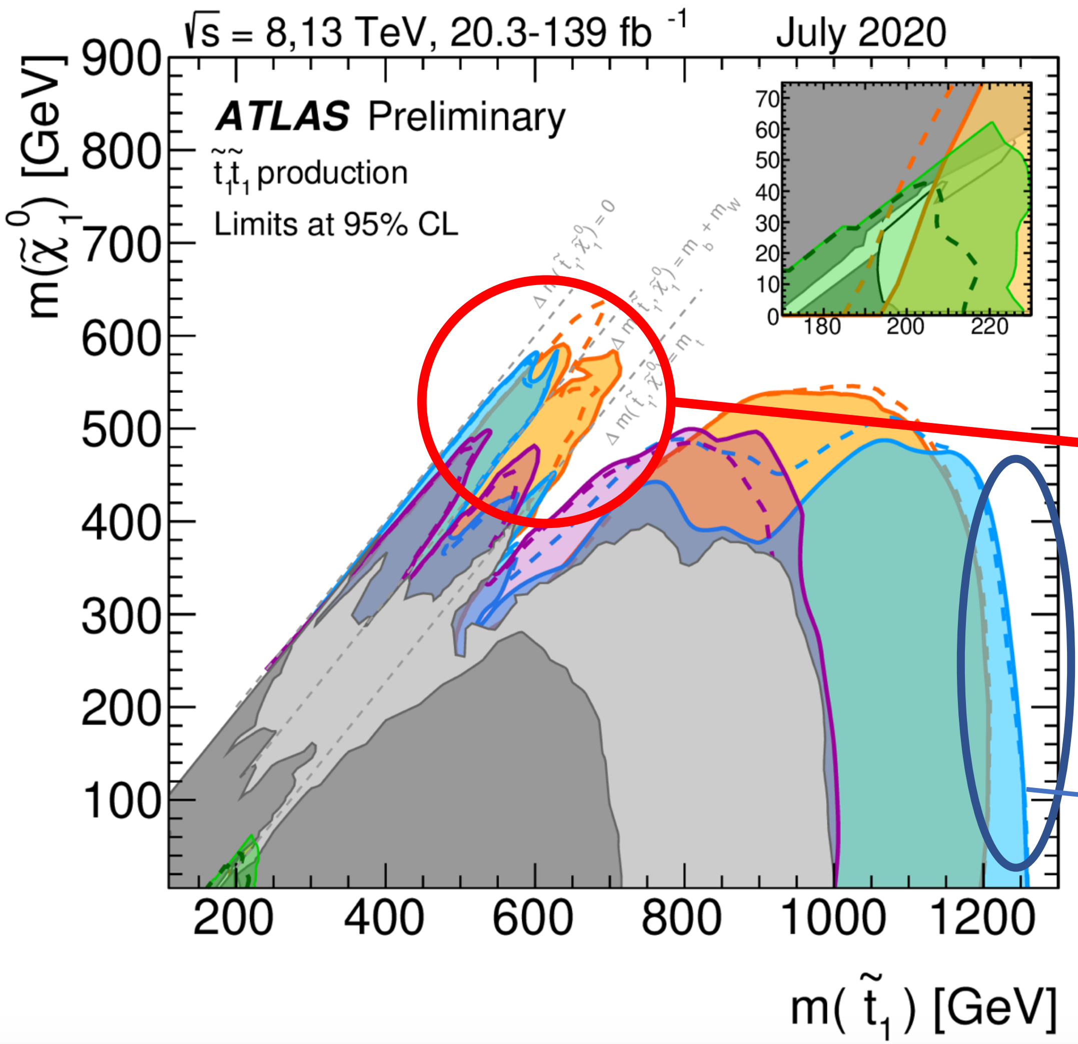


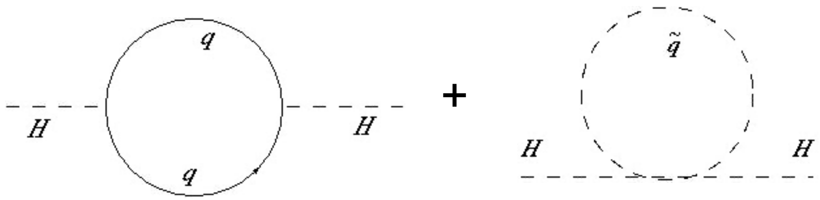


$$\approx \frac{3y_t^2}{8\pi} m_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\rm EW}}\right)$$

$$\frac{m_H^2}{\frac{3y_t^2}{8\pi} m_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\rm EW}}\right)} \sim (10^{-3})$$

The compressed regions



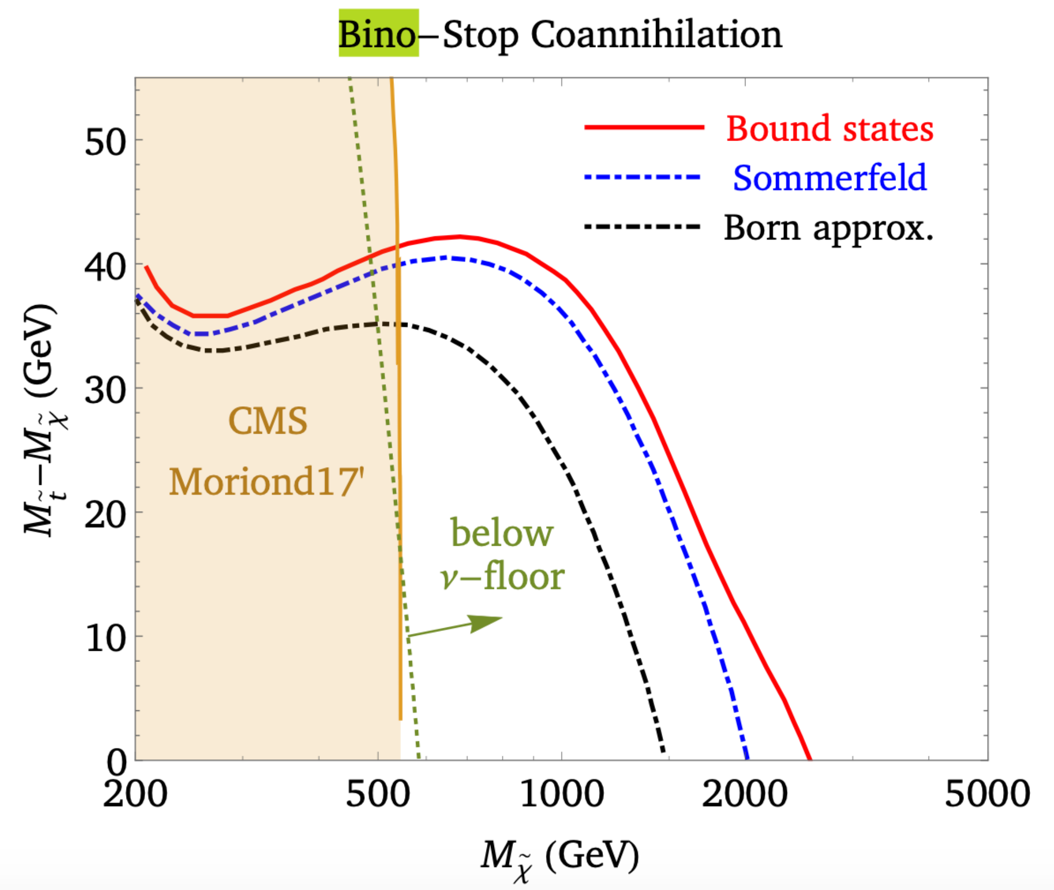


$$\approx \frac{3y_t^2}{8\pi} m_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\rm EW}}\right)$$

More interesting in the sake of EW hierarchy problem!

$$\frac{m_H^2}{\frac{3y_t^2}{8\pi} m_{\tilde{t}}^2 \log\left(\frac{\Lambda}{m_{\rm EW}}\right)} \sim (10^{-3})$$

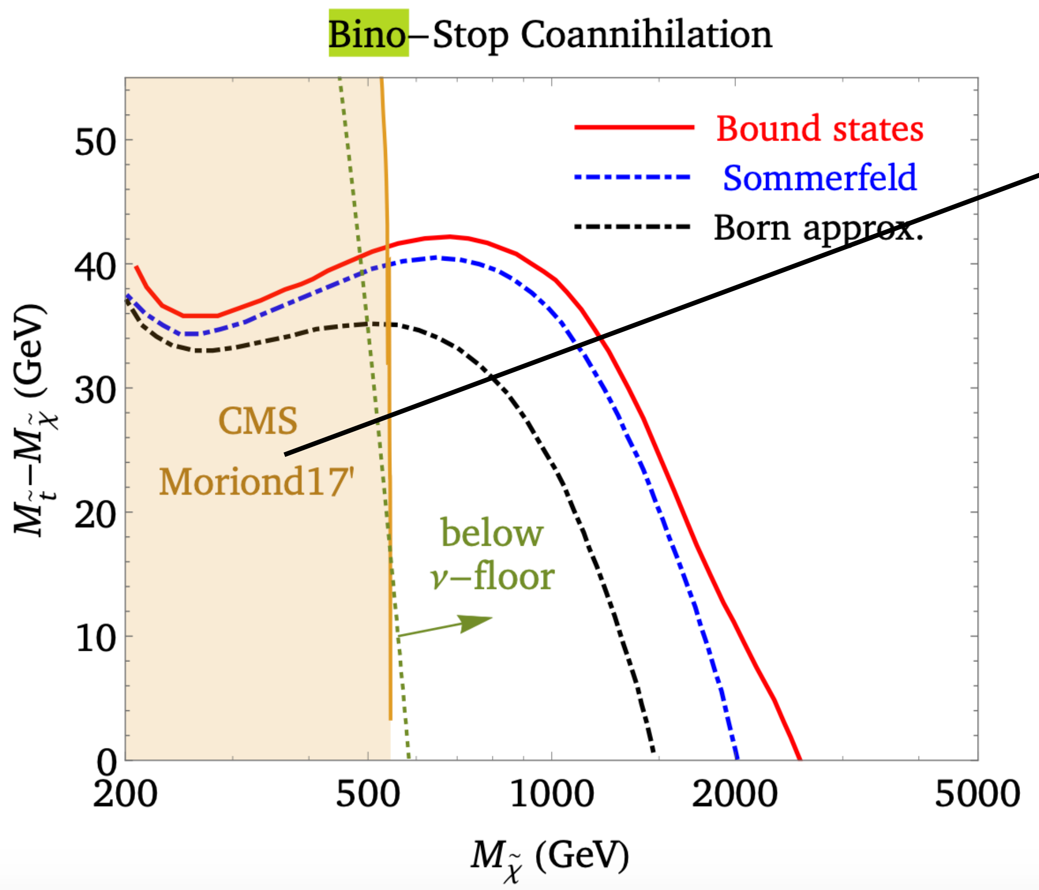
Bino LSP + stop NLSP

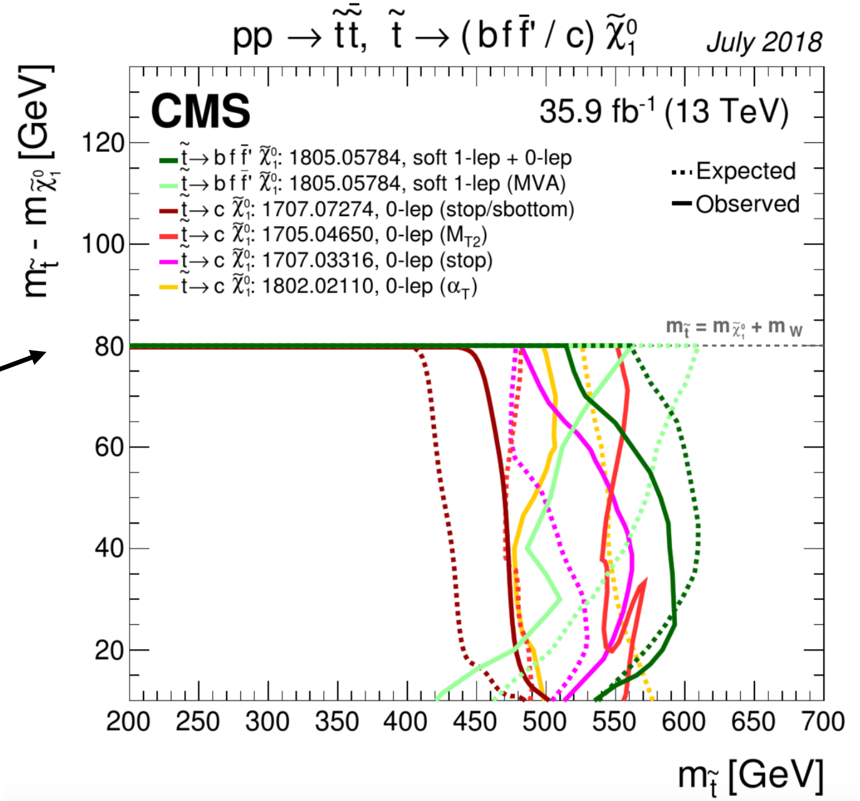


W.-Y. Keung, I. Low, Y. Zhang, 1703.02977

- In the bino-stop model, the mass gap between bino and stop must be smaller than 30-40 GeV or the bino will overclose the universe.
- We don't need to assume bino is the dark matter candidate.

Bino LSP + stop NLSP





- **Prompt** decay of stop is assumed.
- Does **NOT** apply to the stop-bino case.
- There is still a gap that cannot be covered by existing searches.

Stop decay channels

- Two channels
  - Flavor changing

$$\tilde{t} \to \chi + c$$

Model dependennt.

  - Flavor conserving

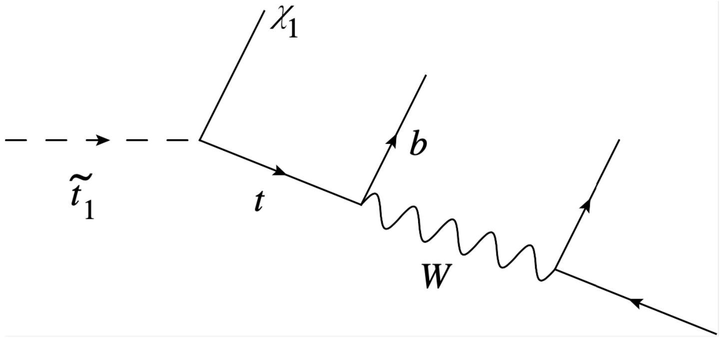
$$\tilde{t} \to \chi + t^*(\to b + W^*(\to f\bar{f}'))$$

Inreducible

- We assume flavor conserving processes dominate.

Stop life time in the compressed region

- Tree level analysis



$$\tilde{t}_1 \equiv \cos\theta_{\tilde{t}}\tilde{t}_L + \sin\theta_{\tilde{t}}\tilde{t}_R$$

$$\chi_1^0 \equiv N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_u + N_{14}\tilde{H}_d$$

$$\mathcal{L}^{\rm tr} = C_R^{(\ell)}\mathcal{O}_R^{(\ell)} + C_R^{(h)}\mathcal{O}_R^{(h)} + C_L^{(\ell)}\mathcal{O}_L^{(\ell)} + C_L^{(h)}\mathcal{O}_L^{(h)}$$

$$\left.\begin{aligned} \mathcal{O}_R^{(h)} &= (\bar{U}_i\gamma_\mu\mathbb{P}_L D_j)V_{ij}(\bar{b}\gamma^\mu\mathbb{P}_L\chi\tilde{t}_1), \\ \mathcal{O}_R^{(\ell)} &= (\bar{\nu}_i\gamma_\mu\mathbb{P}_L l_j)(\bar{b}\gamma^\mu\mathbb{P}_L\chi\tilde{t}_1) \end{aligned}\right\} \quad \tilde{t}_1 = \tilde{t}_R$$

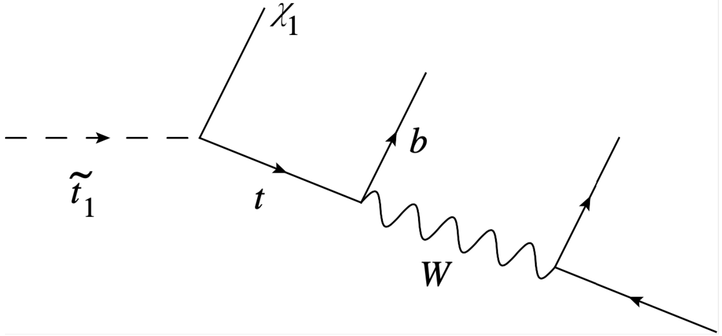
Dimension-7

$$\left.\begin{aligned} \mathcal{O}_L^{(h)} &= (\bar{U}_i\gamma_\mu\mathbb{P}_L D_j)V_{ij}(\bar{b}\gamma^\mu\mathbb{P}_L i\not{D}(\chi\tilde{t}_1)) \\ \mathcal{O}_L^{(\ell)} &= (\bar{\nu}_i\gamma_\mu\mathbb{P}_L l_j)(\bar{b}\gamma^\mu\mathbb{P}_L i\not{D}(\chi\tilde{t}_1))\ , \end{aligned}\right\} \quad \tilde{t}_1 = \tilde{t}_L$$

Dimension-8

Stop life time in the compressed region

- Tree level analysis



For pure right handed stop and pure bino, neglecting m_b.

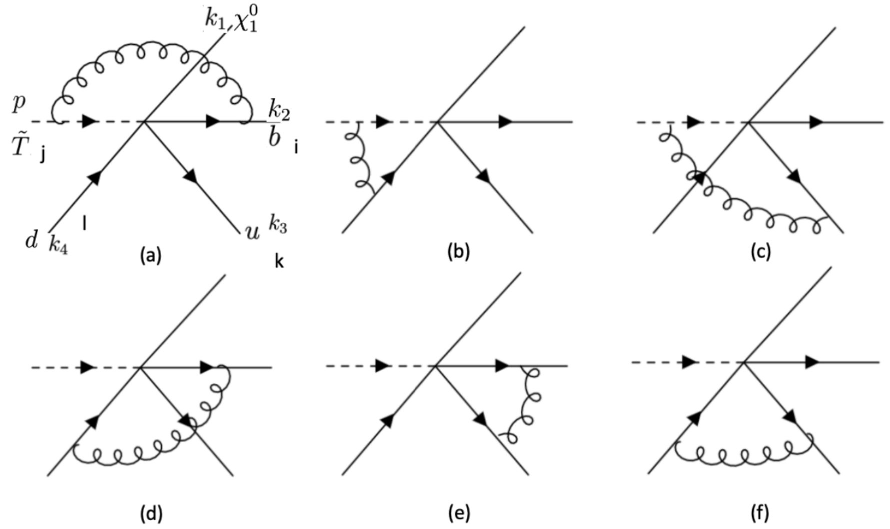
$$\Gamma = \frac{g_2^4 g_1^2 \Delta m^8}{20160\pi^5 m_W^4 m_t^2 m_{\tilde{t}}}.$$

$$c\tau \approx 1.4 \text{ mm} \times \left(\frac{20 \text{ GeV}}{\Delta m}\right)^8$$

Larger $c\tau$ if $\tilde{t}_1$ contains $\tilde{t}_L$ component.

NRQCD corrections

- A mass hierarchy appears in the process $m_{\tilde{t}_1} \gg \Delta m$
- Large logrithmic factors may appear $\frac{\alpha_S}{\pi} \log\left(\frac{m_{\tilde{t}_1}^2}{\Delta m^2}\right)$
- NRQCD techniques are employed to resum.
- Operator mixing



$$\mathcal{O}_R^{\prime(h)} = (\bar{b}\gamma_\mu \mathbb{P}_L D_j) V_{ij} (\bar{U}_i \gamma^\mu \mathbb{P}_L \chi \tilde{t}_1)$$

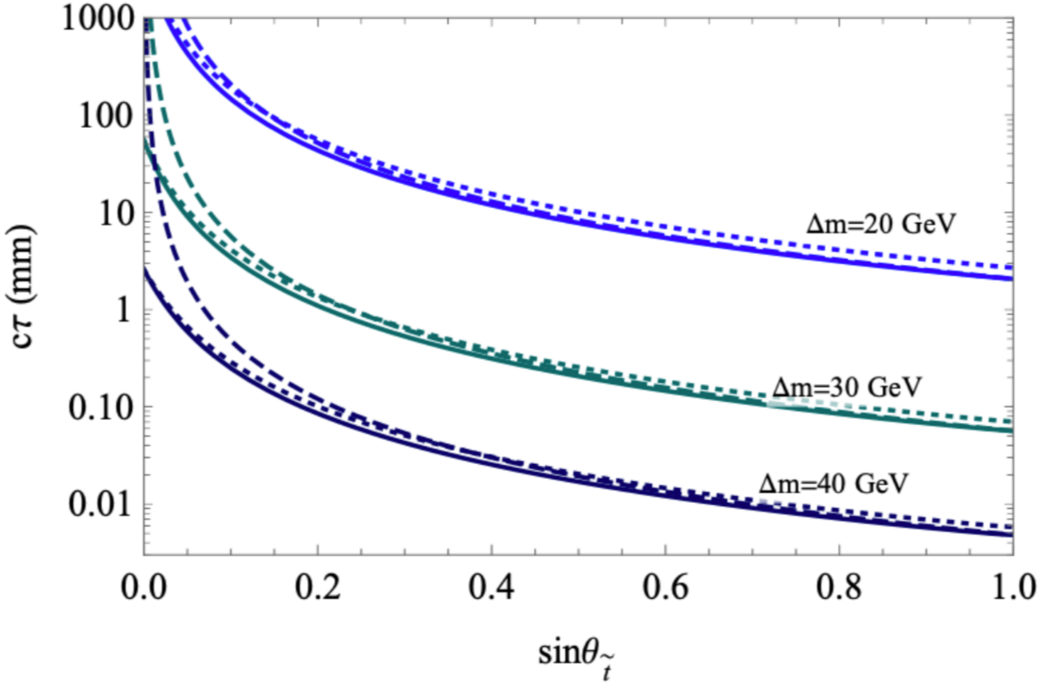
$$\frac{d}{d\log\mu}\begin{pmatrix} C_R^{(h)} \\ C_R^{\prime(h)} \end{pmatrix} = \frac{\alpha_S}{4\pi}\begin{pmatrix} -5 & 3 \\ 3 & -5 \end{pmatrix}\begin{pmatrix} C_R^{(h)} \\ C_R^{\prime(h)} \end{pmatrix}$$

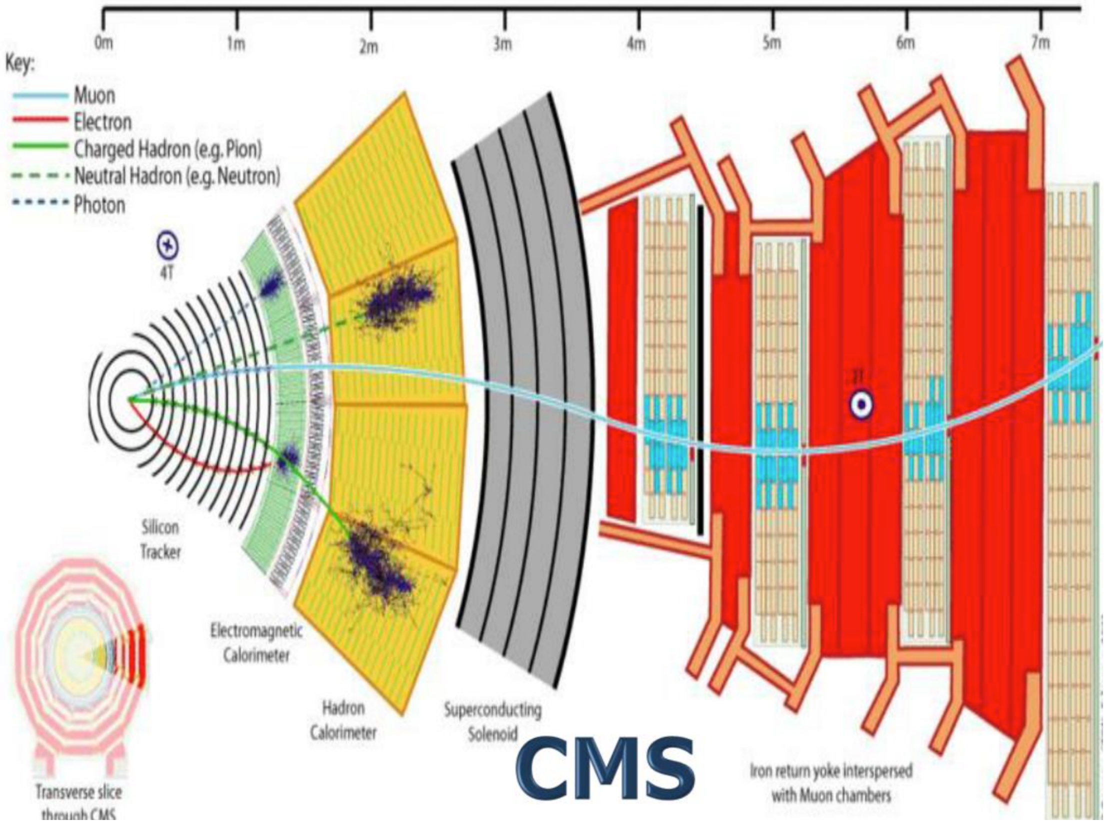
$$\frac{d}{d\log\mu} C_R^{(\ell)} = -\frac{\alpha_S}{\pi} C_R^{(\ell)}$$

Lifetime of stop

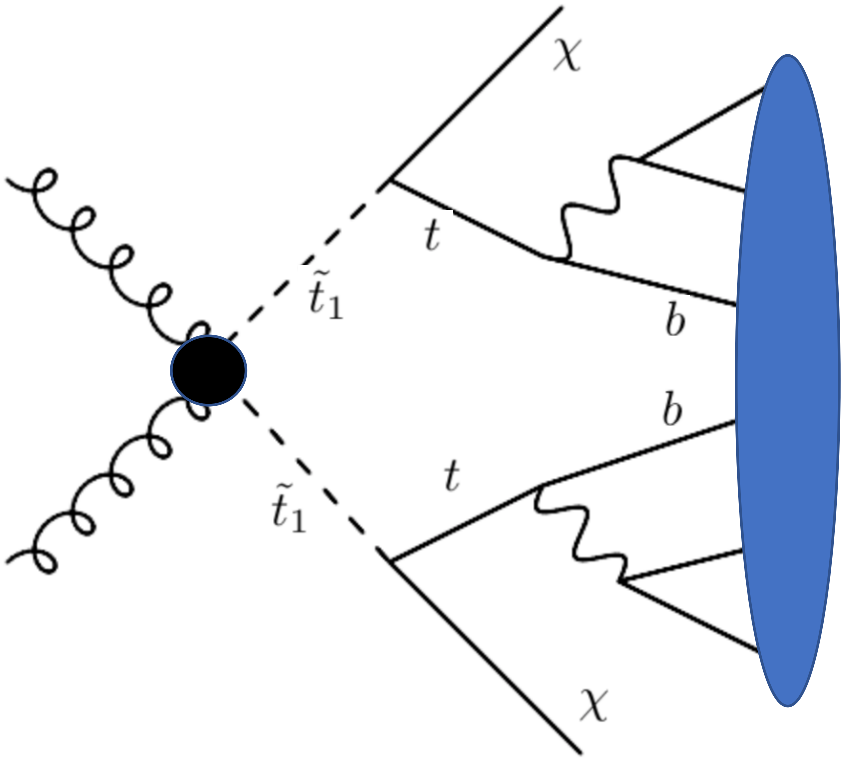
$\tilde{t}_1 = \tilde{t}_L$

$\tilde{t}_1 = \tilde{t}_R$





Our strategy



Displaced
soft tracks

Ideally,

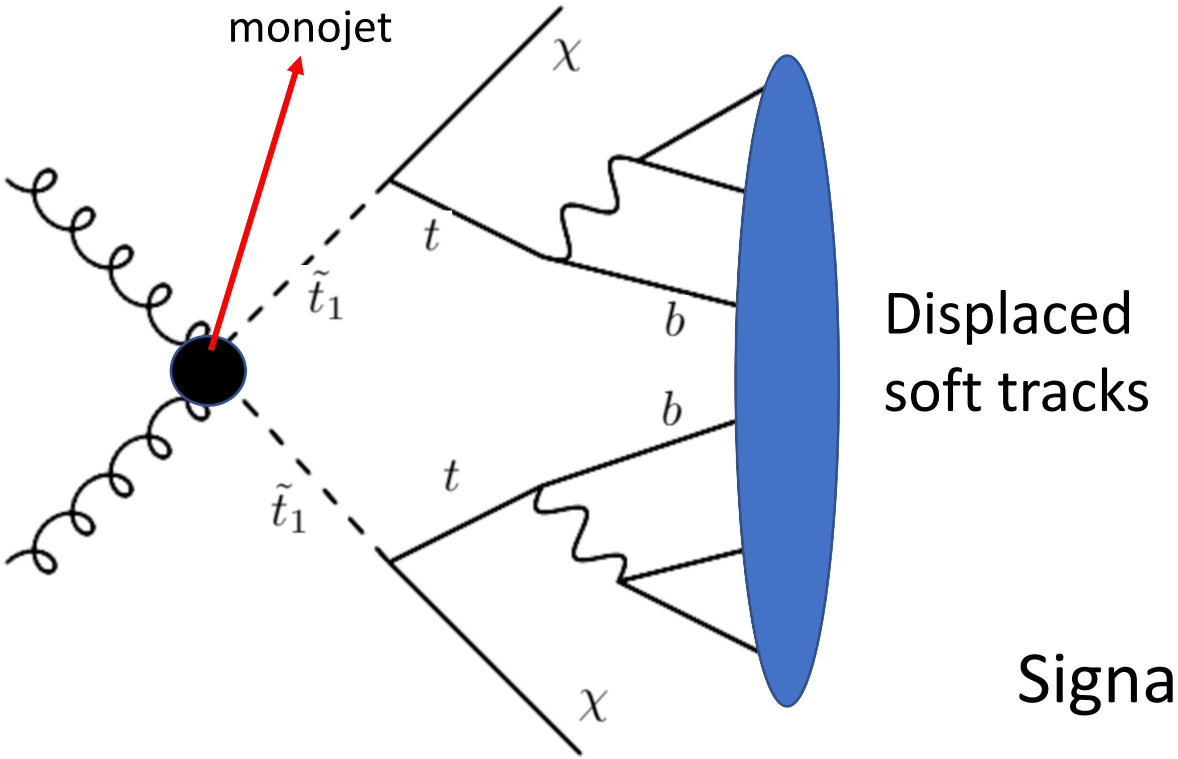
Four displaced vertices:

Two from stops

Two from B mesons

We still need a trigger

Our strategy



Four displaced vertices:

Two from stops

Two from B mesons

We still need a trigger

Signal: Monojet + displaced vertices

Detailed simulations

- MadGraph:
  - Generate parton level events
  - Calcualte the jet + stop pair cross section
- Pythia:
  - Parton shower
  - Hadronization (generate tracks)
- We find the tracks from the stop and B meson vertices, and displace them randomly with our own code based on lifetime.
- We simulate the background.
- We apply the cuts and compare the signal with the background to get the sensitivity.

Bingo!

Detailed simulations

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Without the knowledge of detailed information of the detectors it is very difficult for us to simulate the background!

Bingo!

CMS Open Data

- Dataset: HLT_PFMET150 (MET > 150) includes Run B, Run C data with total luminosity of 11.6 fb^{-1}.
- Analyzing with CMSSW 5.3.32
- Trigger and basic cuts: MET > 150 GeV, PT(j1) > 150 GeV

- Study the properties of the displaced soft tracks in the dataset.
  - Reconstruct displaced vertices
  - Compute various efficiencies

CMS Open Data

- Identify the primary vertex (associated with the leading jet)
- We consider high purity tracks

  - PT > 1 GeV   - $|\eta|$<2.4
- For displacement, we require $|d_{xy}/\sigma_{\mathrm{d}xy}| > 4$ for each track.

Transverse impact parameter

resolution

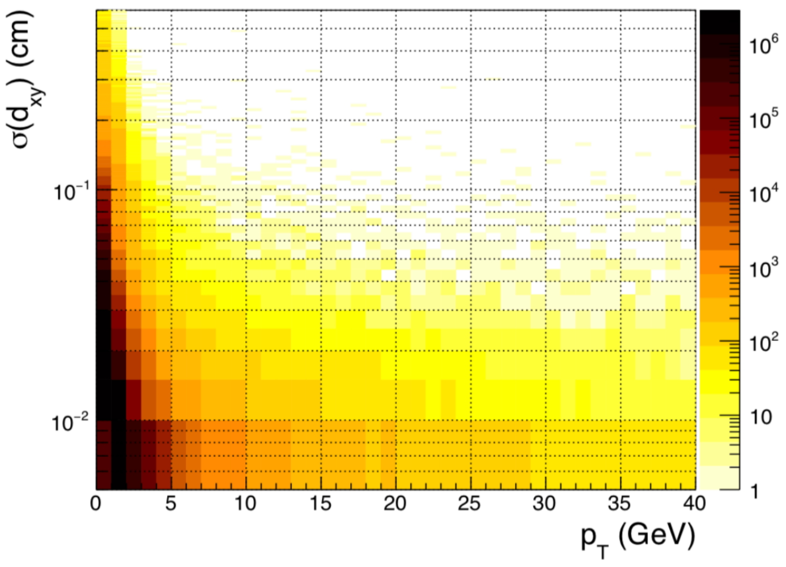
- Vertices are reconstructed with the Trimmed Kalman Vertex Finder.

Displaced track efficiency in the simulation

- For real data we require $|d_{xy}/\sigma_{\mathrm{d}xy}| > 4.$
- For simulated data, we define the efficiency

$$N(\sigma_{d_{xy}} < |d^0_{xy}|/4 \mid p^0_{\mathrm{T}})/N(\sigma_{d_{xy}} > 0 \mid p^0_{\mathrm{T}})$$

Then generate the random number based on this efficiency to determine if the track can survive or not.



Vertex reconstruction efficiencies

- We use the ttbar sample in the open data to calculate the vertex reconstruction efficiency.

Catalog	$N_{gen,tk}=2$	$N_{gen,tk}=3$	$N_{gen,tk}=4$	$N_{gen,tk}=5$	$N_{gen,tk}\geq 6$
Efficiency from TF (%)	23.8 ± 0.4	36.6 ± 1.0	46.1 ± 2.9	45.3 ± 6.2	32.4 ± 10.8
Efficiency from VD (%)	17.5 ± 0.3	25.7 ± 1.0	32.6 ± 2.4	32.6 ± 5.0	40.5 ± 12.4
Overlapping fraction (%)	59.7	62.0	64.3	70.5	83.3
Vertex error (μm)	173	170	164	175	155
Vertex error RMS (μm)	110	110	103	119	94.5
Probability of passing $N_{vtx,tk}\geq2$	1.0	1.0	1.0	1.0	1.0
Probability of passing $N_{vtx,tk}\geq3$	0.61	0.78	0.83	0.82	0.83
Probability of passing $N_{vtx,tk}\geq4$	0.23	0.39	0.54	0.64	0.58

We require at least four tracks from each displaced vertex.

HT of soft tracks from displaced vertices

- Since the tracks from stop decay are soft, we require

$$H_T \equiv \sum_i |p_T^{(i)}| < 40 \text{ GeV}$$

Set limit

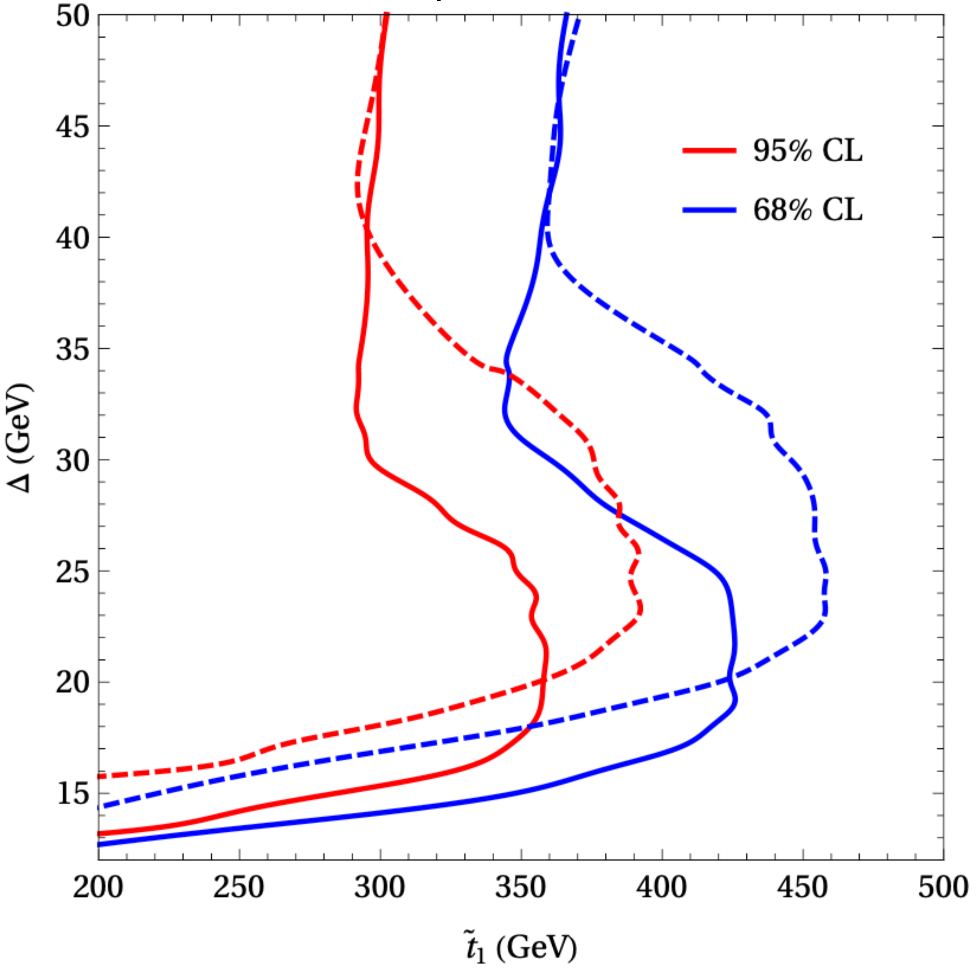
- Currently, we don't have the ability to do simulation, we have to assume that all the events after cuts are signal to have a conservative bound.

Selection	Data	Signal BM
MET primary	$4.3{\times}10^7$	-
$p_T^{j1} > 150$ GeV, $E_T^{\mathrm{miss}} > 150$ GeV	$1.4{\times}10^6$	830
One displaced vertex ($N_{vtx,tk} \geq 2$)	$3.7{\times}10^5$	310
One displaced vertex ($N_{vtx,tk} \geq 3$)	$4.7{\times}10^4$	240
One displaced vertex ($N_{vtx,tk} \geq 4$, default)	$5.5{\times}10^3$	140
Two displaced vertices	76	9.8
$p_T^{j1} > 300$ GeV, $E_T^{\mathrm{miss}} > 300$ GeV	1	3.0
Two displaced vertices with vertex $H_T < 40$	0	3.0

$$m_{\tilde{t}_1} = 360\ \mathrm{GeV},\ \Delta m = 20\ \mathrm{GeV}$$

Preliminary result

8 TeV, 11.6 fb^{-1}



$\tilde{t}_1 = \tilde{t}_R$

$\tilde{t}_1 = 0.3\tilde{t}_R + 0.95\tilde{t}_L$

Preliminary result

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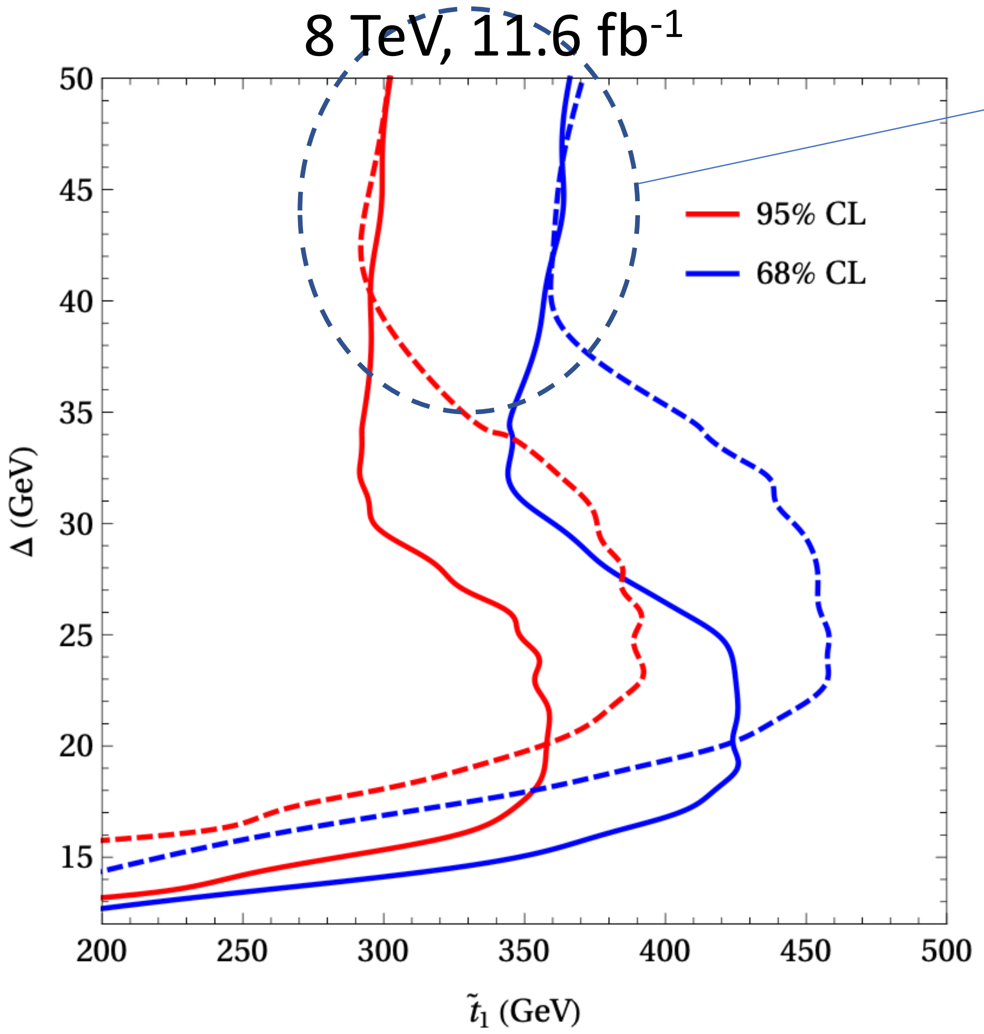

Stop displacement is negligible, displacement purely from B meson.

$$\tilde{t}_1 = \tilde{t}_R$$

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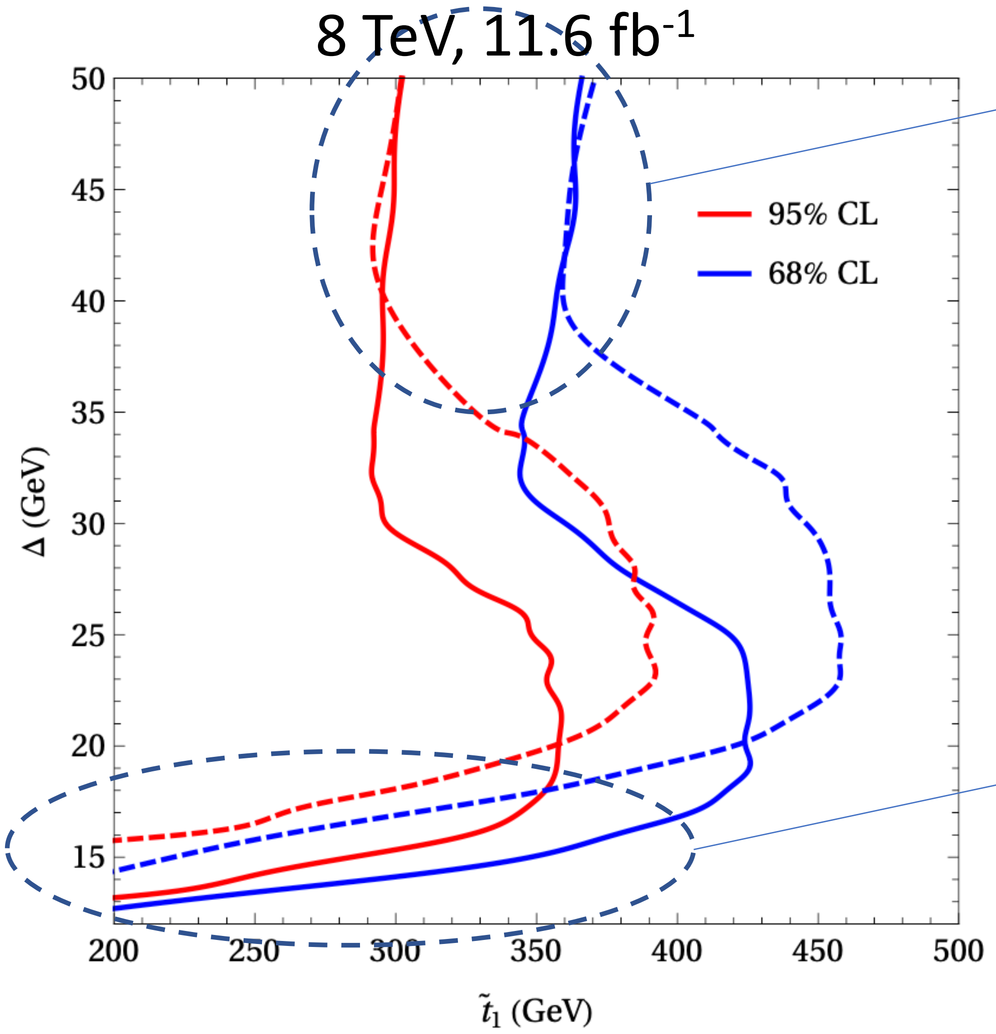

Stop displacement is negligible, displacement purely from B meson.

$$\tilde{t}_1 = \tilde{t}_R$$

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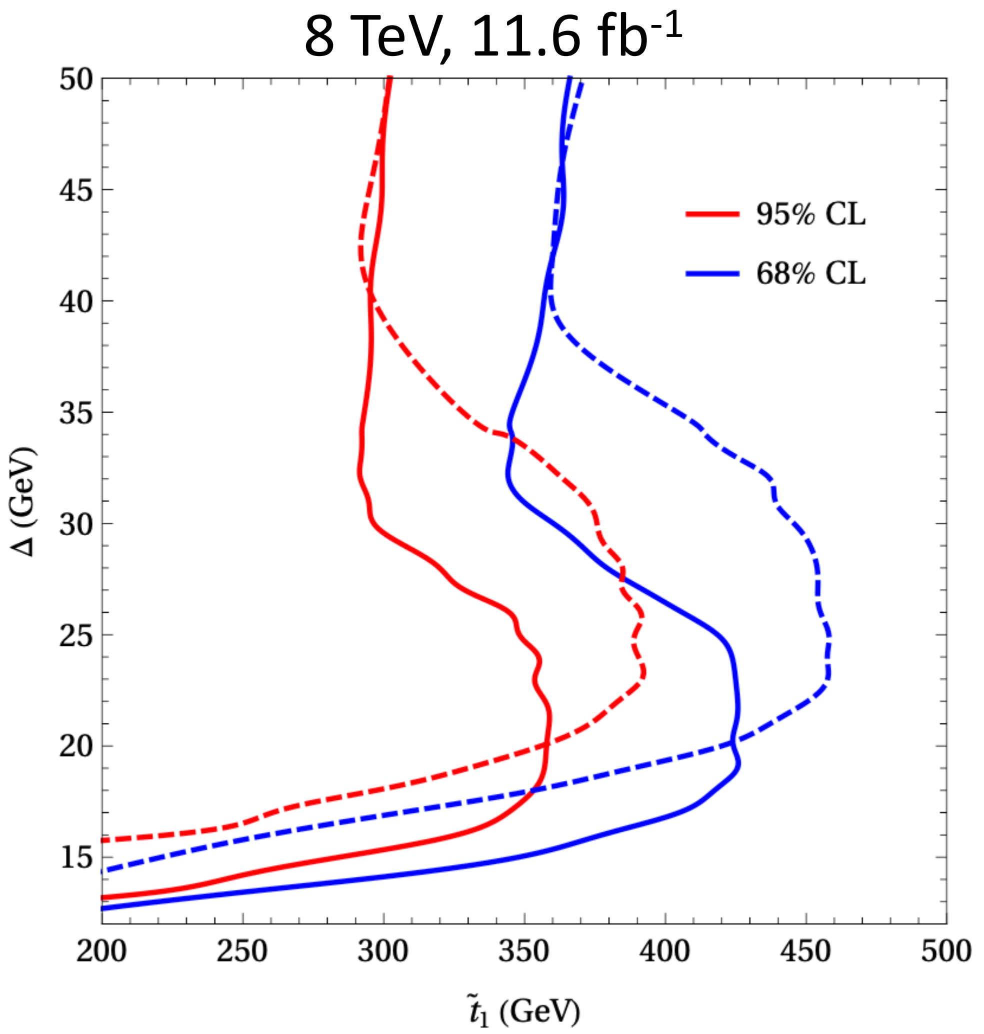
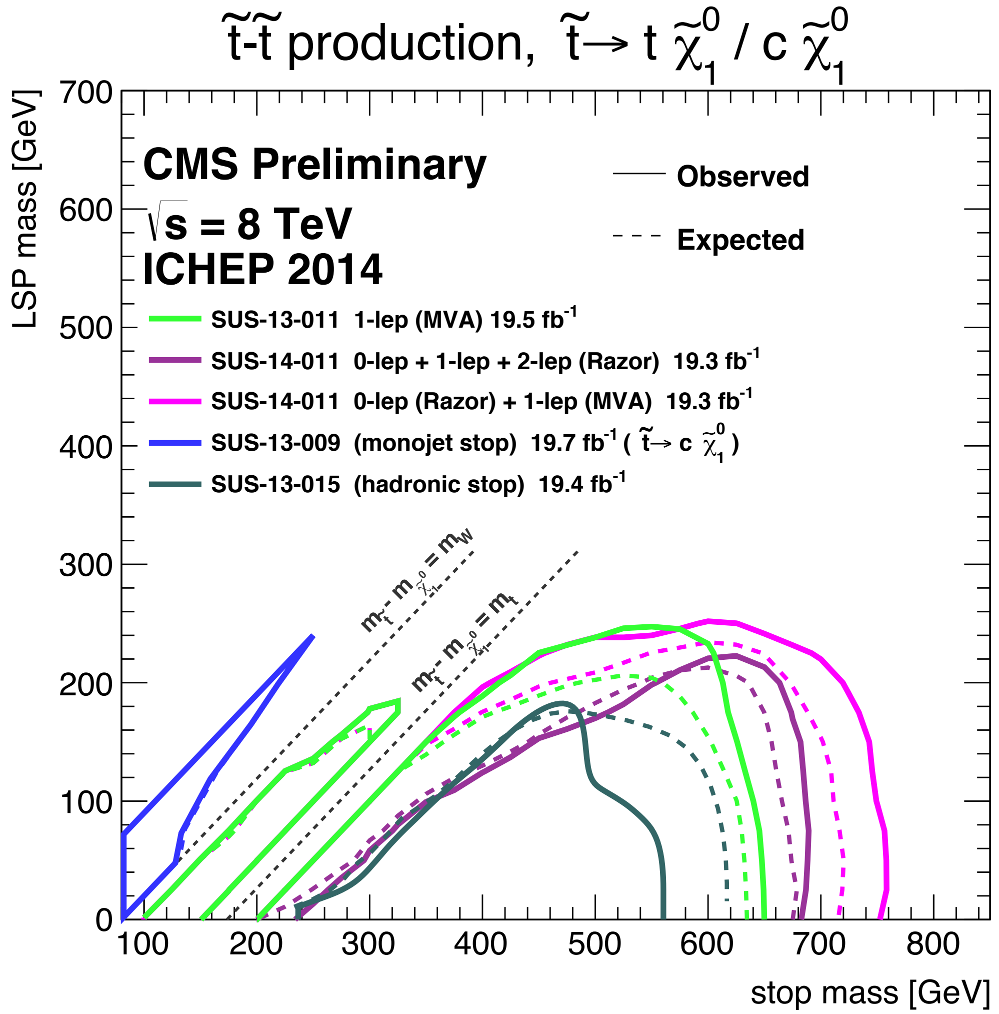
Tracks are too soft.

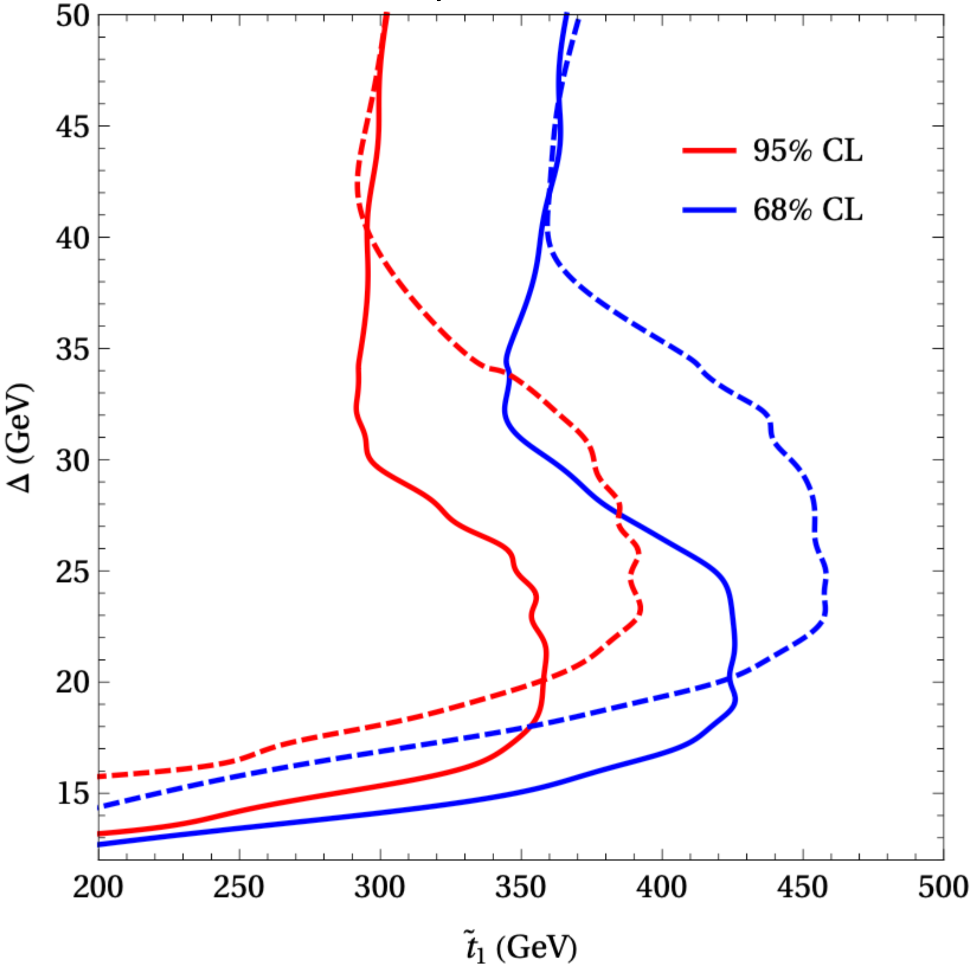
Compare with CMS 8 TeV, 20 fb^{-1}

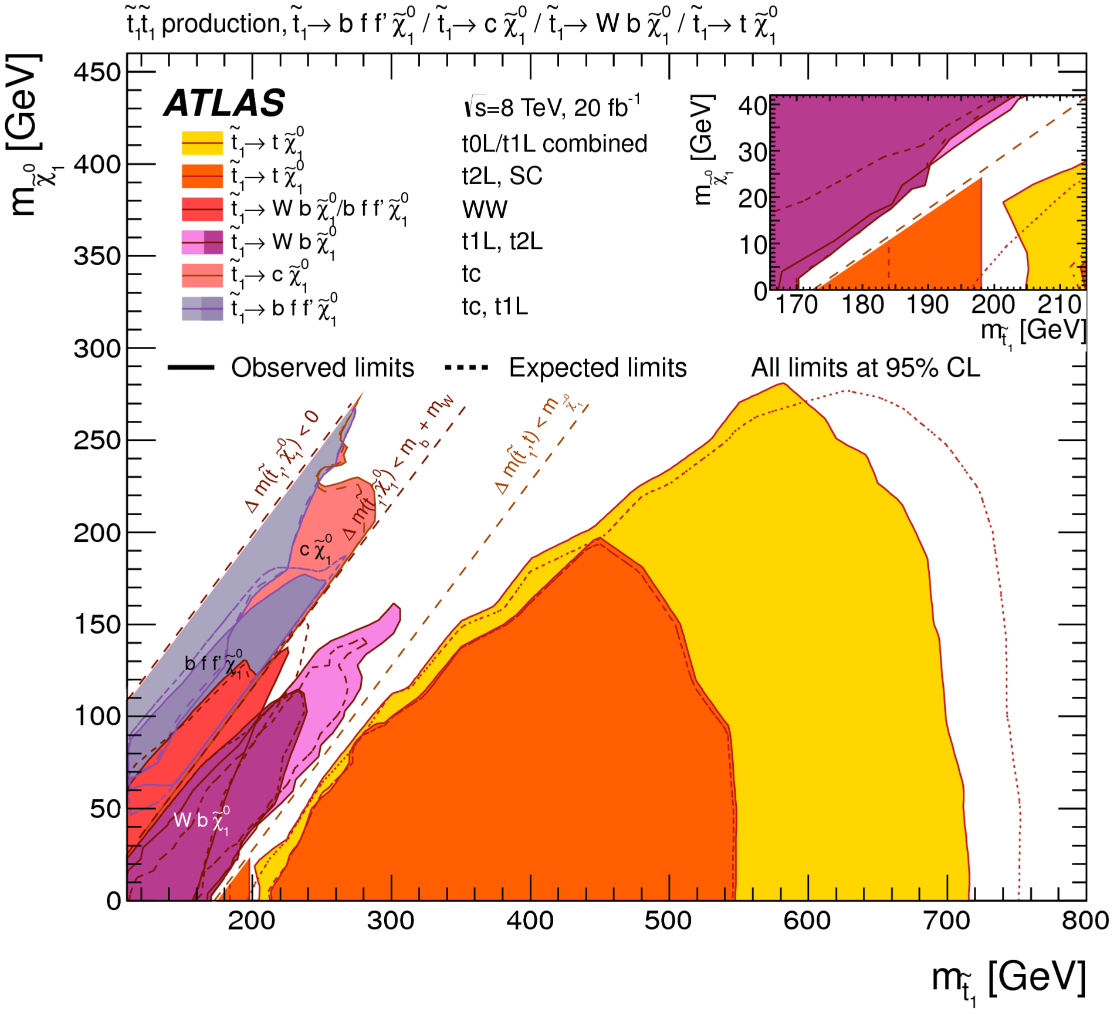




Compare with ATLAS 8 TeV, 20 fb^{-1}

8 TeV, 11.6 fb^{-1}





Summary

- We propose to search for the bino-stop coannihilation region with monojet + displaced tracks observable.
- With the CMS open data, we show that without simulating the background, the sensitivity is better than traditional monojet results.