# Tagging a mono-top signature in natural supersymmetry

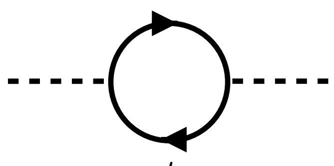
in collaboration with Kazuki Sakurai (Warsaw) and Dorival Goncalves (Pittsburgh)

at Planck 2017 on 24th May 2017

THE UNIVERSITY OF TOKYO
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
wpi World Premier International Research Center Initiative

# Stop search

## Solving hierarchy problem requires top partner: stop

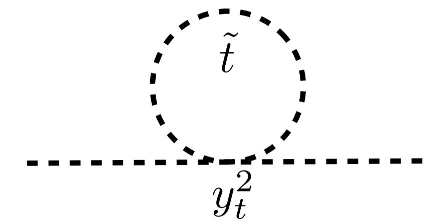
$\delta m_h^2 \sim$  $\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\rm SM}^2 \quad \sim 10^{38}\,{\rm GeV}^2 (\Lambda_{\rm SM} = m_{\rm Pl})$



Higgs mass receives quantum corrections of the order of highest mass scale

⇒ New physics should appear around TeV scale to avoid fine tuning

SUSY: popular candidate

$\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

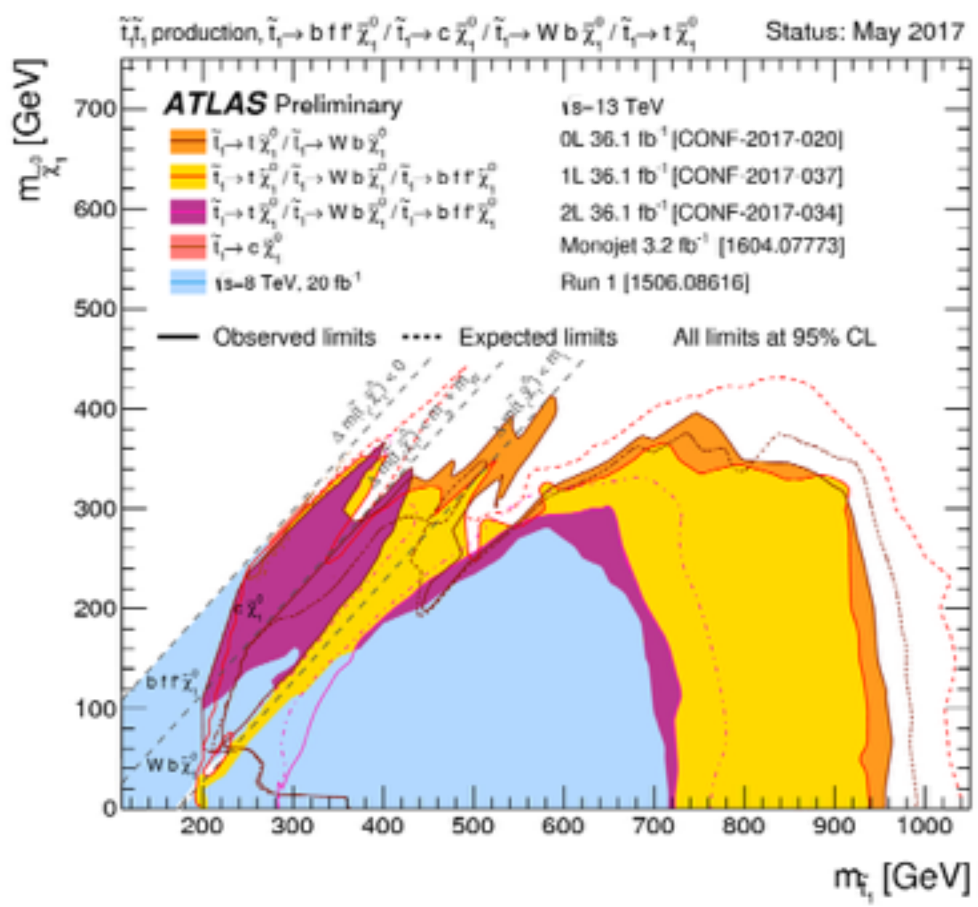


new particle, same coupling by symmetry

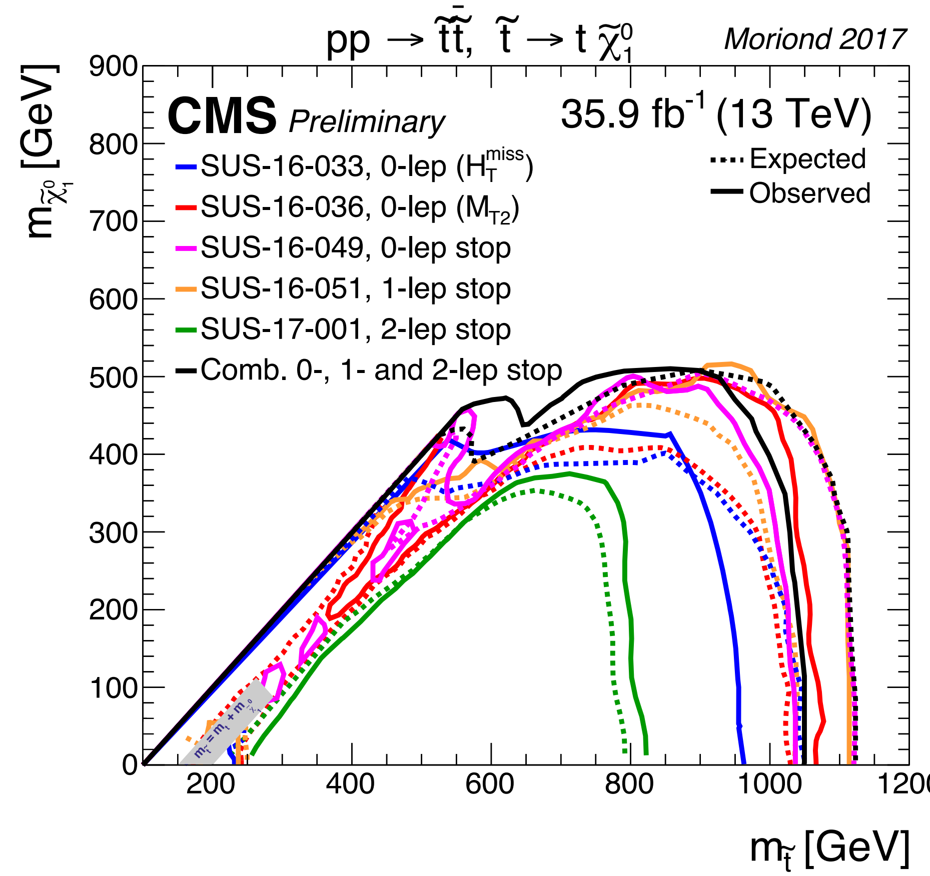
## current status (Bino LSP: tt+missing)

CMS-PAS-SUS-16-028

CMS-PAS-SUS-16-029









up to ~1TeV excluded ?

some excess ?

# Natural SUSY

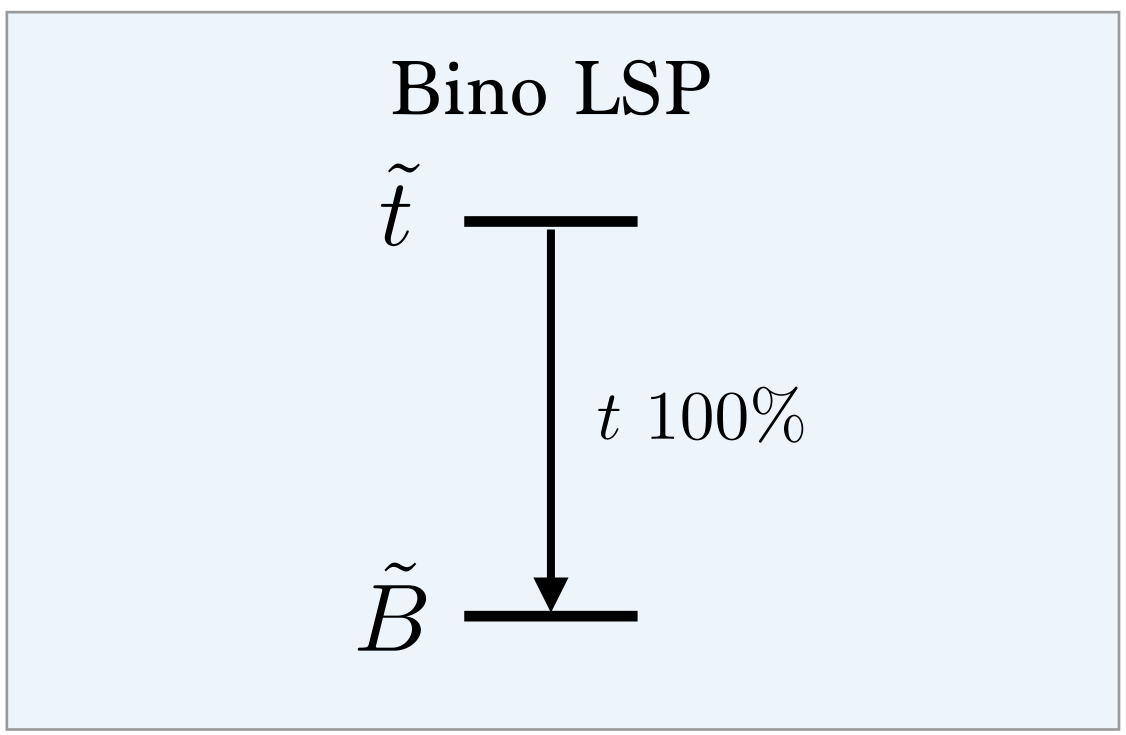
natural spectrum: light higgsino and light stop

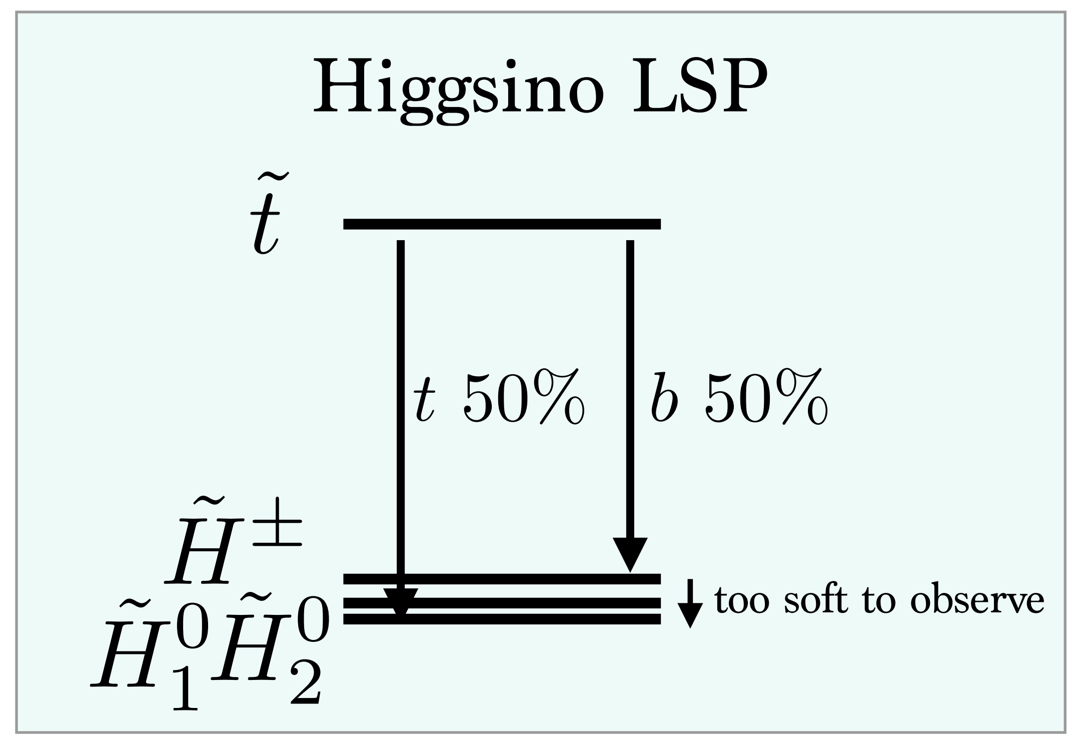
EWSB condition:

$$-\frac{m_Z^2}{2} \simeq \underbrace{|\mu|^2}_{\text{higgsinos}} + m_{H_u}^2 - \frac{3y_t^2}{8\pi^2} \underbrace{m_{\tilde{t}}^2}_{\text{stop}} \log\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)$$

Higgsino-LSP preferable

$\chi_1^0, \chi_2^0, \chi_1^{\pm}$ degenerate




depending on decay mode, search strategy differs
BR has information on stop/neutralino sector (important to test this scenario)

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higgsinos　　stop

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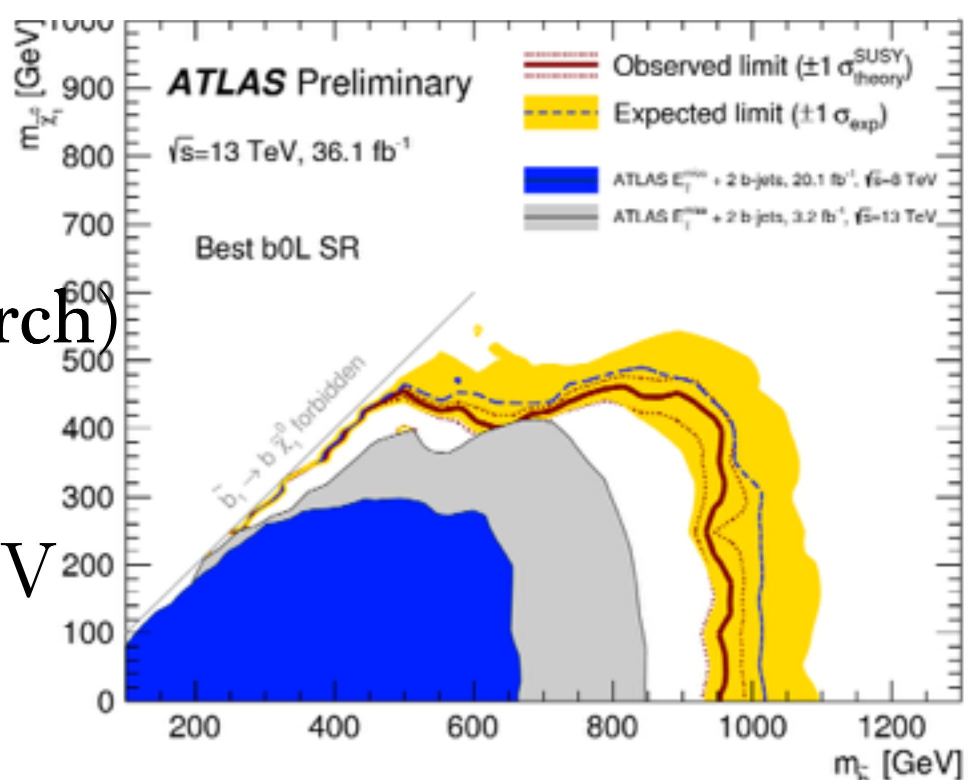
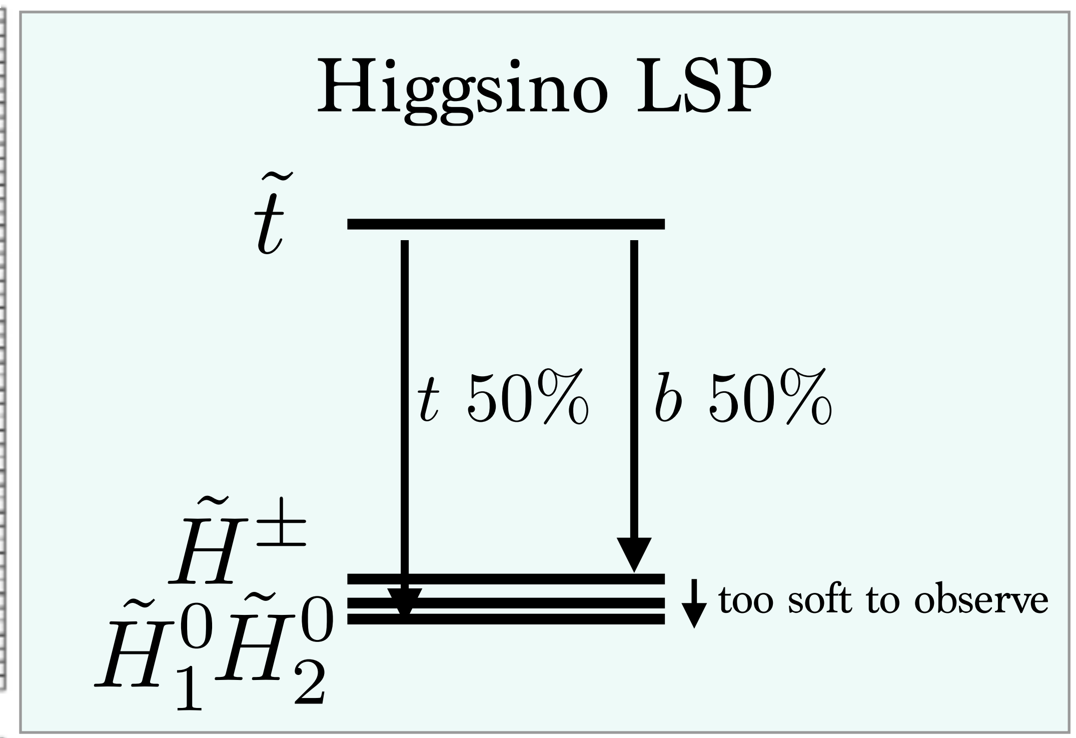
bb + missing
(sbottom search)

estimate
$m_{\tilde{t}} \gtrsim 950\text{GeV}$

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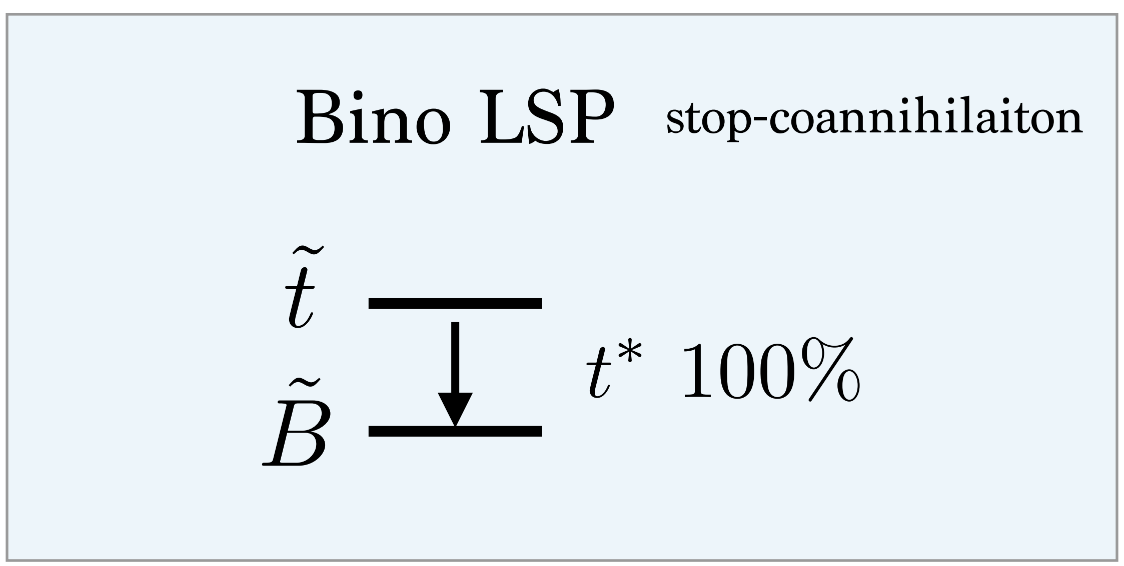
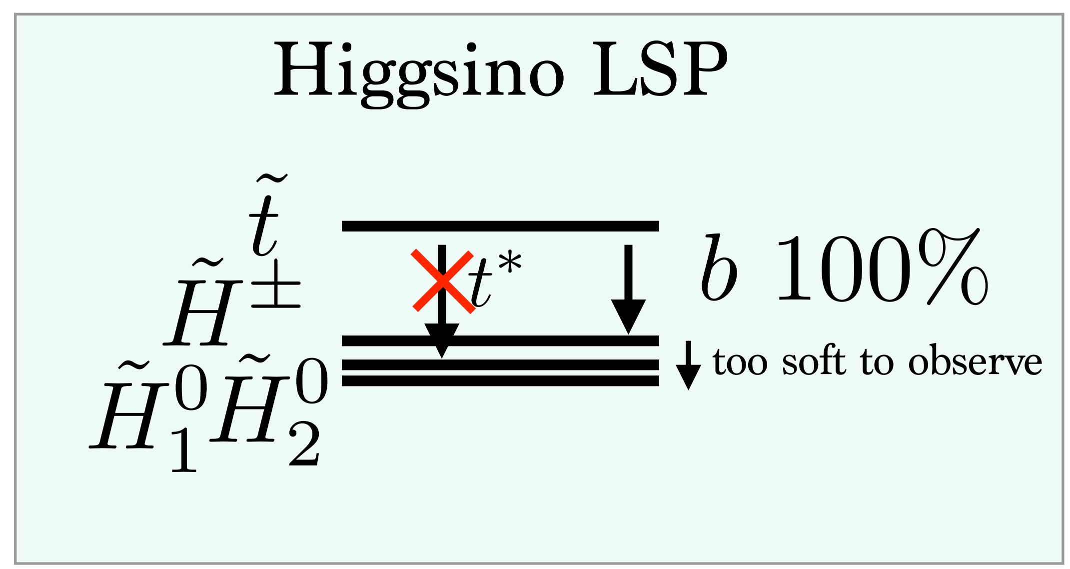
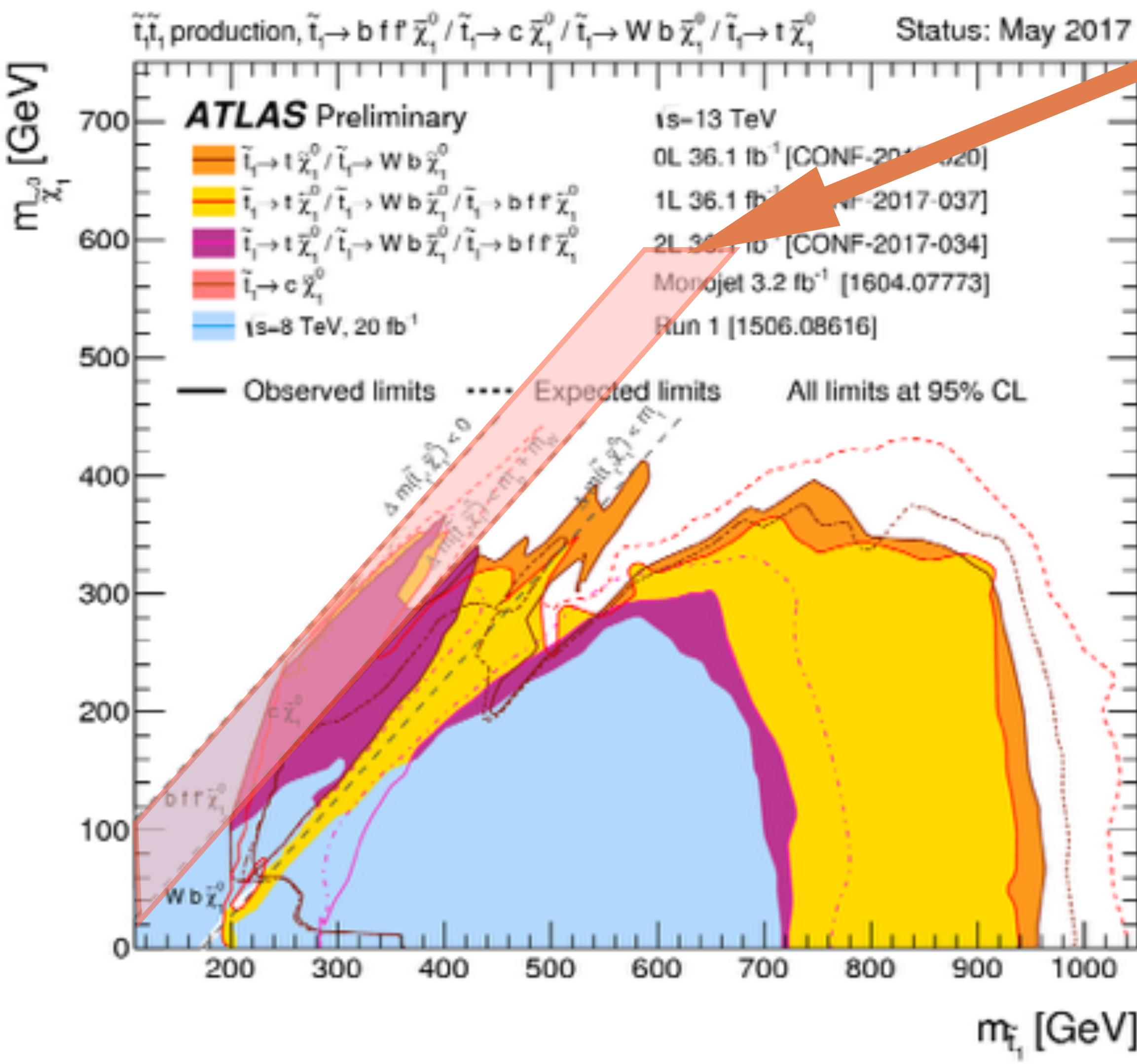



essentially we cannot observe any stop decay products

# Stop search (degenerate)

current status

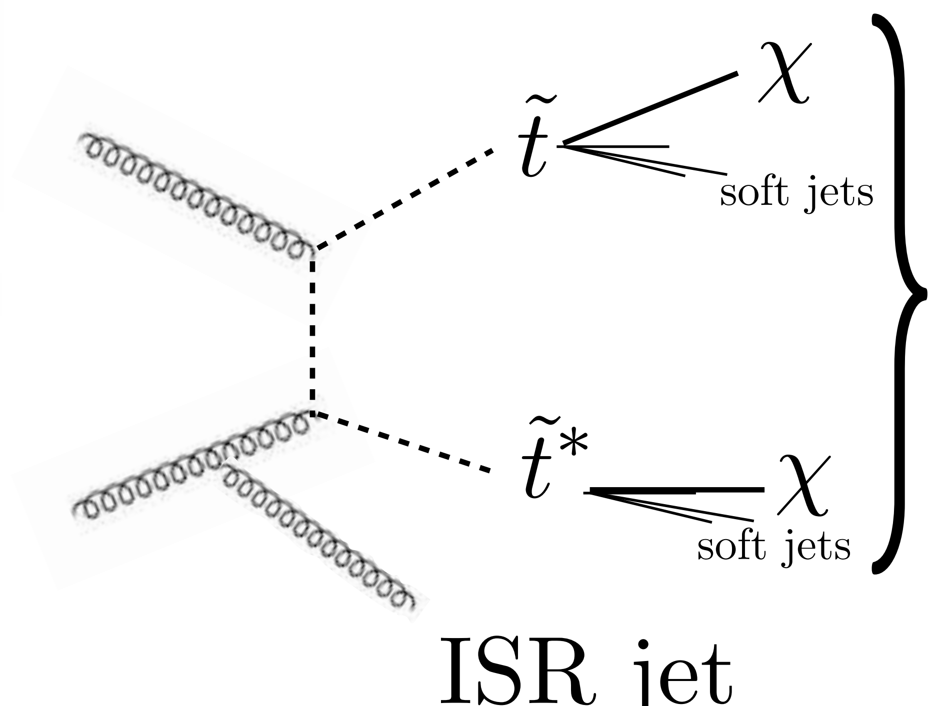



today's focus: degenerate mass spectrum

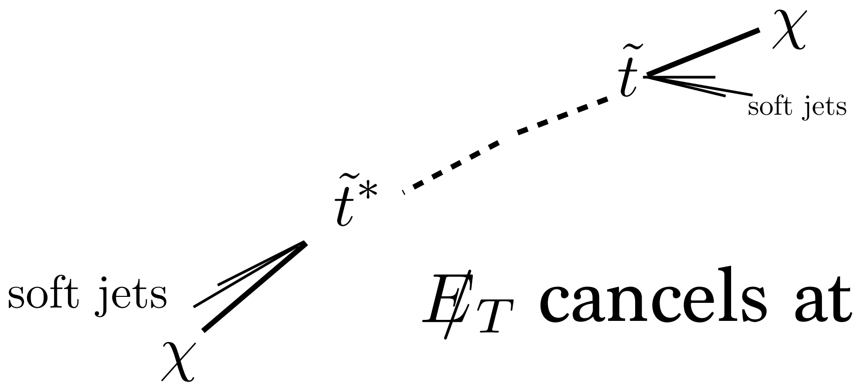
$$m_{\tilde{t}} \sim m_{\chi}$$

1. tt+missing sensitivity lost
2. accessibility on BR info lost

mono-jet search: sensitive to this region




essentially $\not{E}_T$

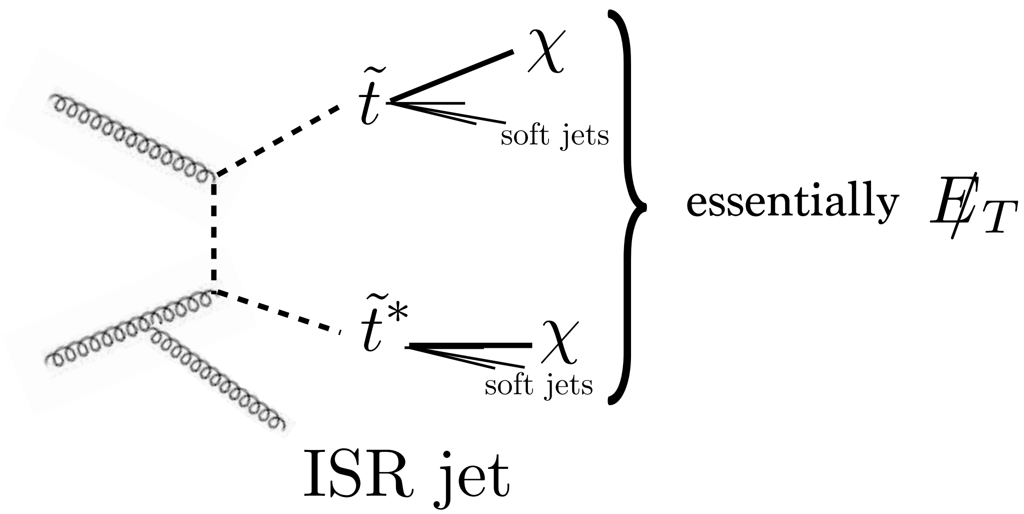


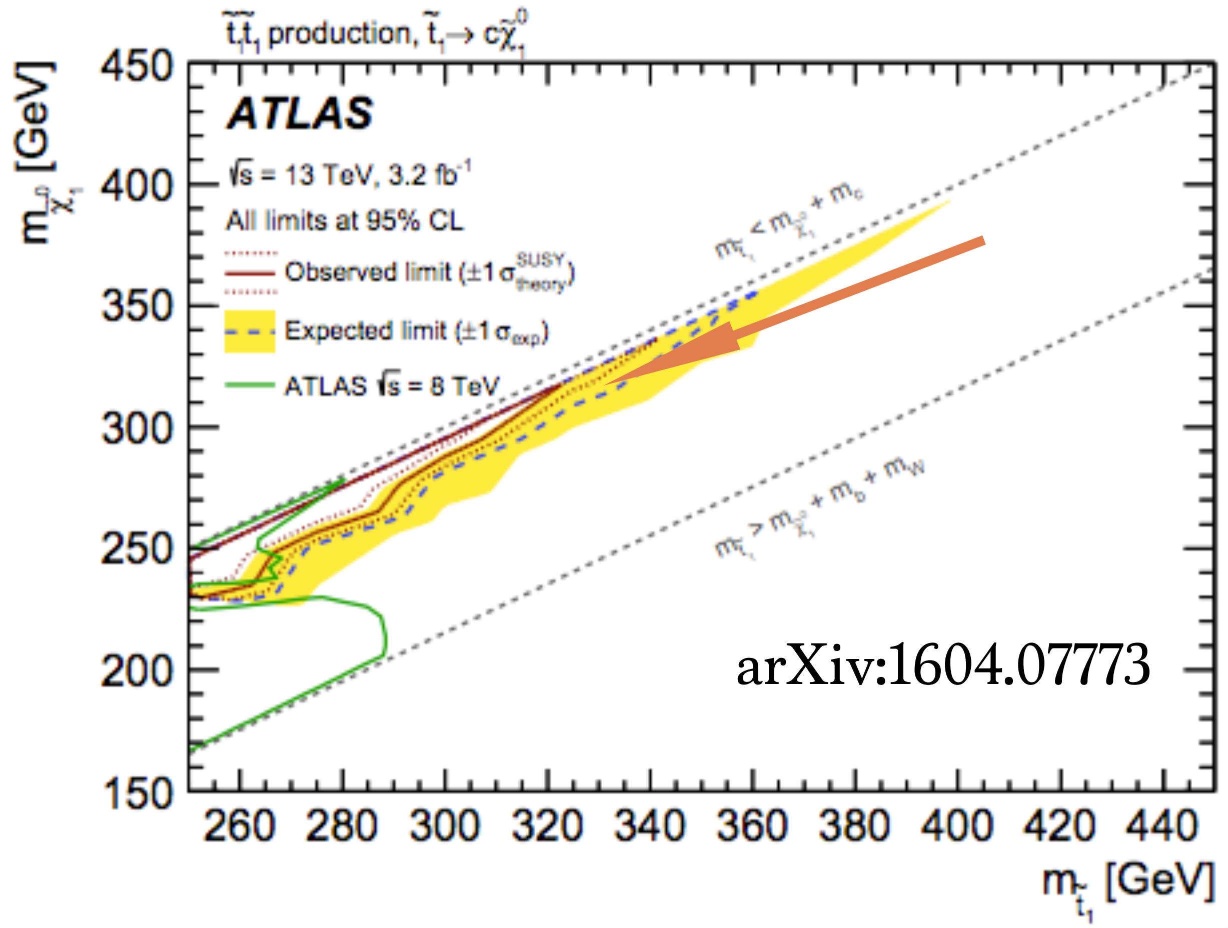

$\not{E}_T$ cancels at LO

# mono-jet search

simple strategy

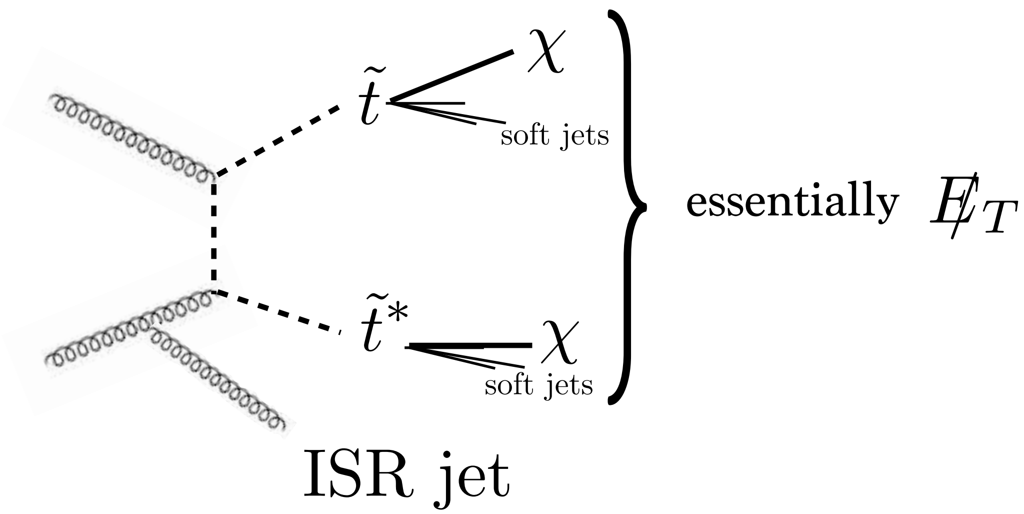
BG: Z+jets

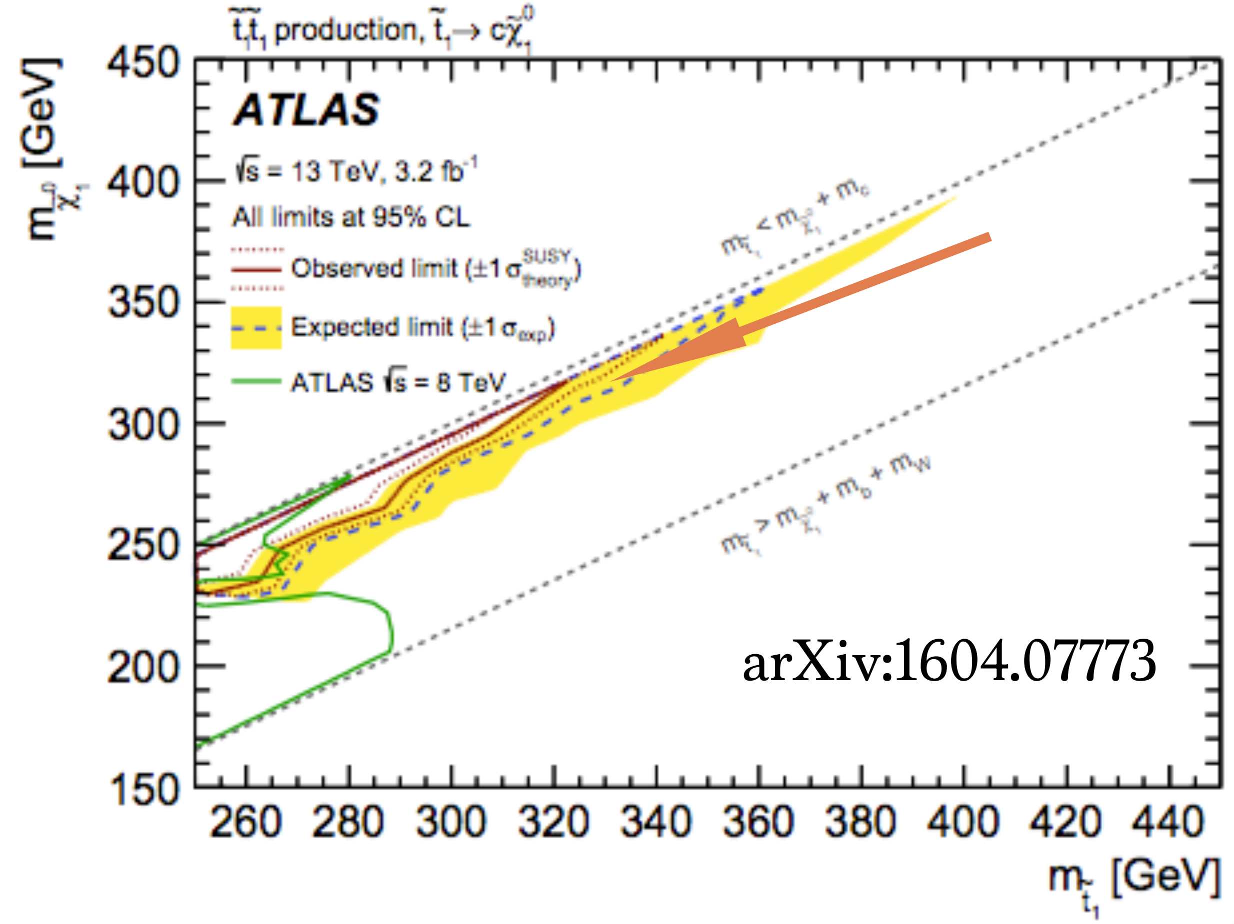


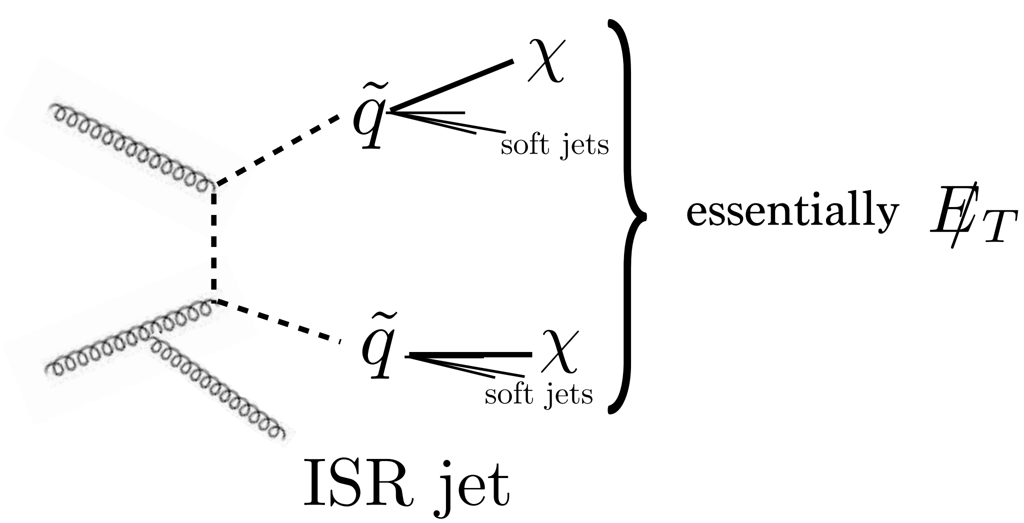
# mono-jet search

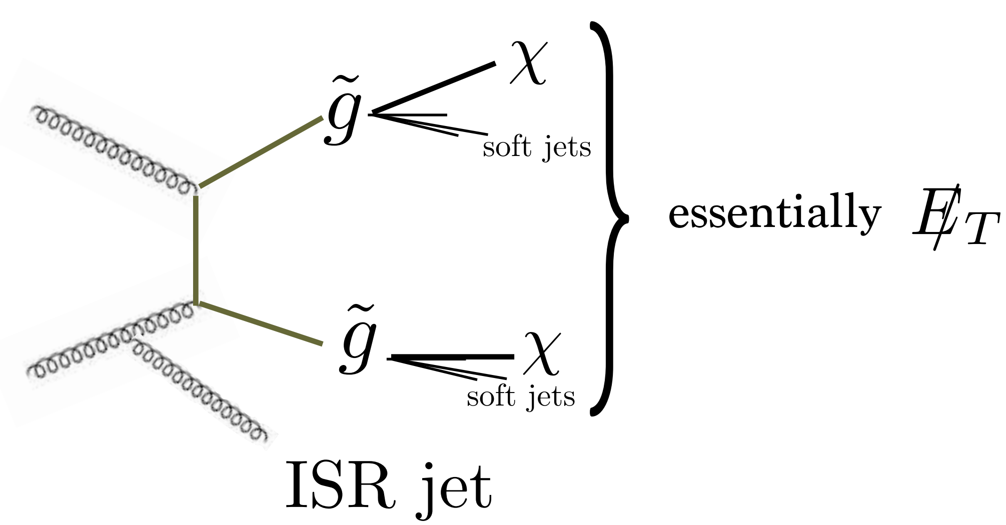
simple strategy BG: Z+jets




however, the same signal expected for whatever with a degenerate spectrum

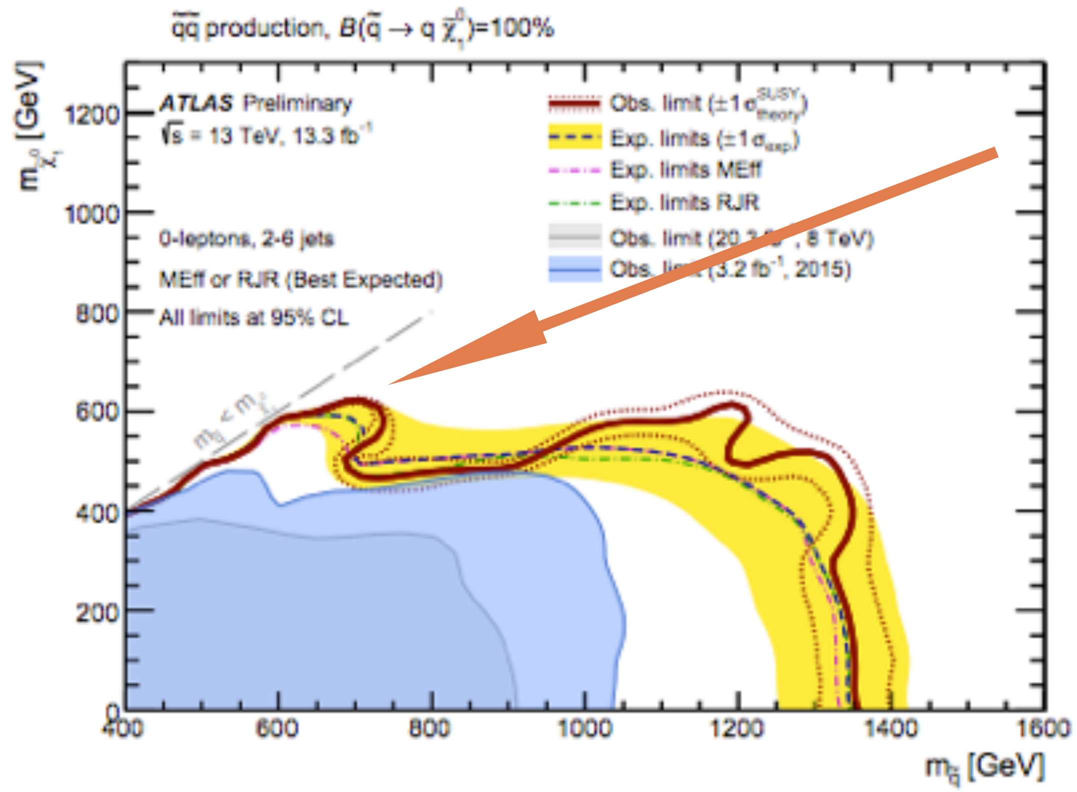


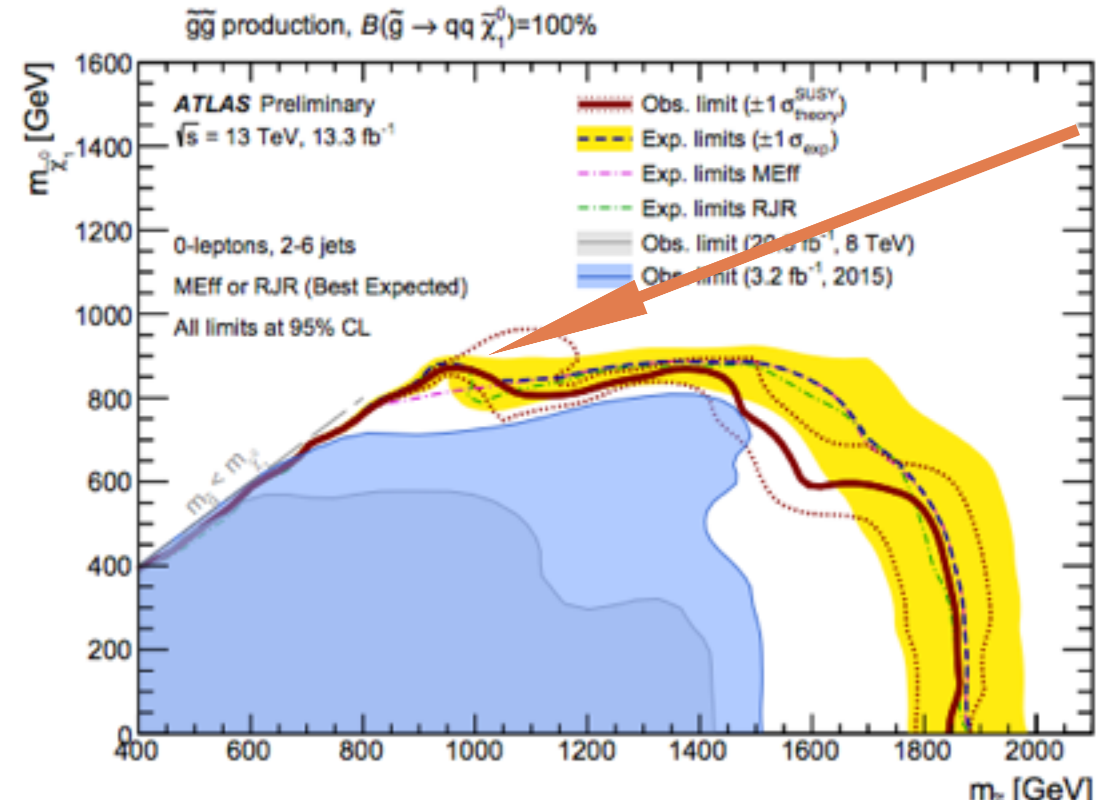




gluino, squark, other simplified model, for whatever sensitive http://arxiv.org/pdf/1409.2893.pdf

(ATLAS-CONF-2015-062)
(1605.03814)
ATLAS-CONF-2016-078

# mono-jet search

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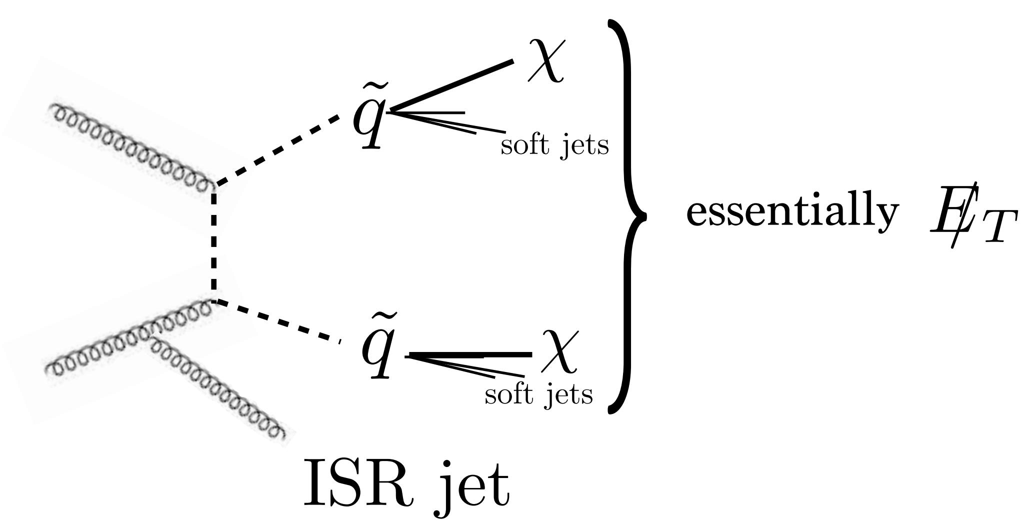


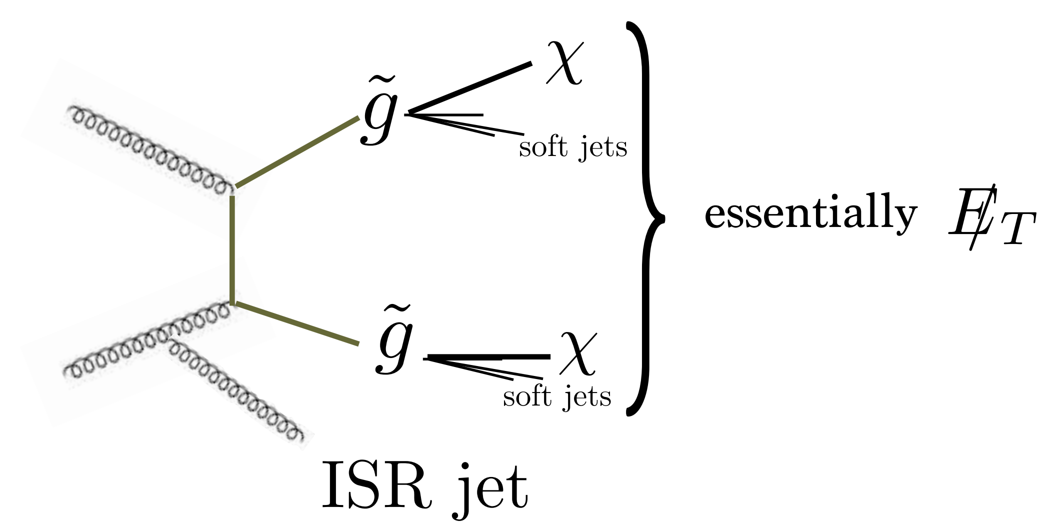


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# mono-jet search

also sensitive for degenerate stop

## Good

whatever particles degenerate with DM can be probed

robust prediction based on QCD (only depends on mass, color, spin)

## Bad

whatever particles degenerate with DM can be probed

= we cannot distinguish among the particles assumption

cross section $\alpha_S$ suppressed

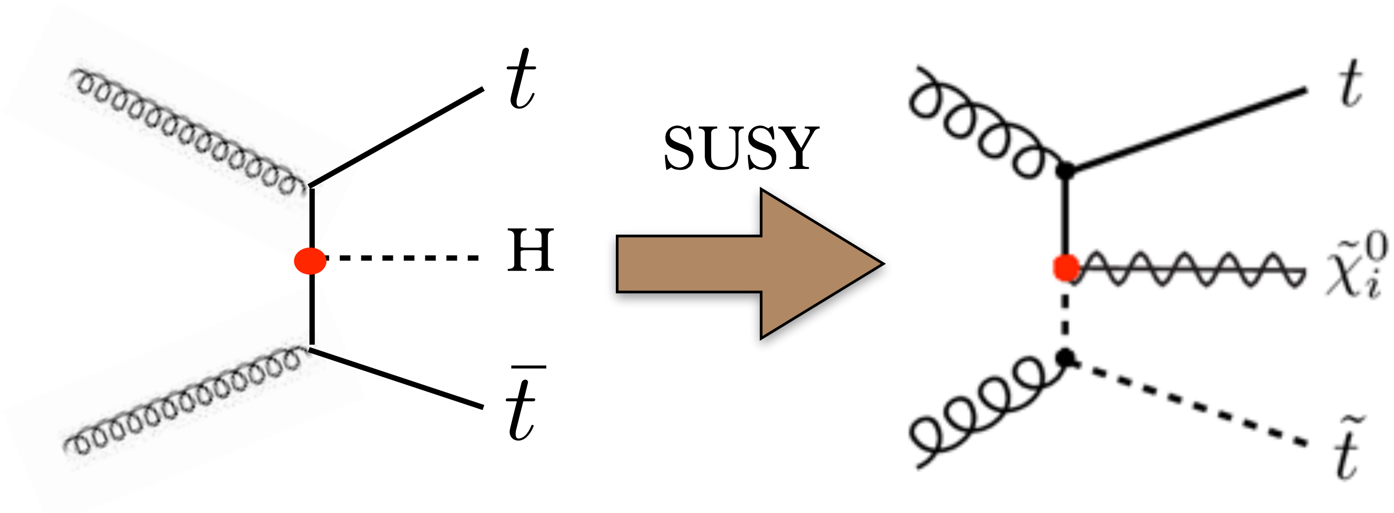
large QCD BG (Z + jets)

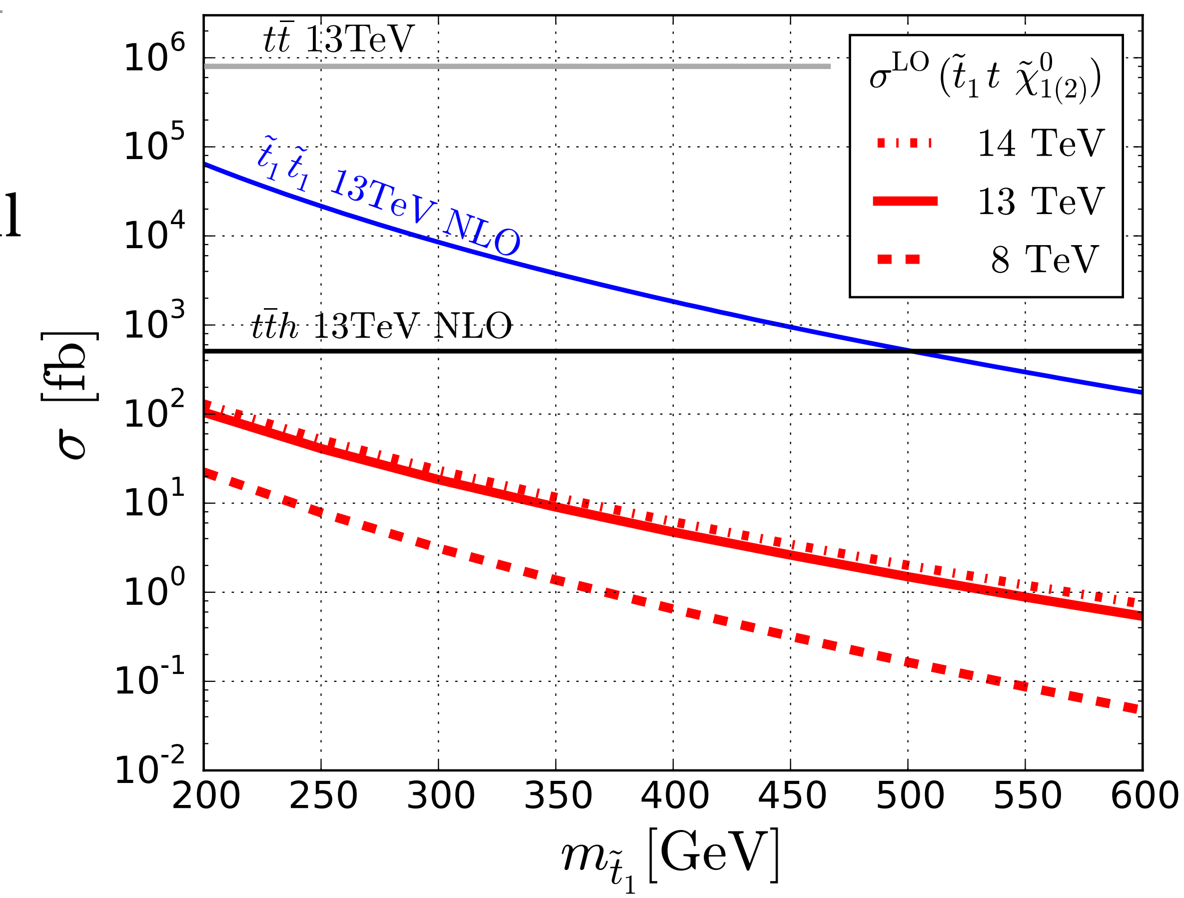
# SUSY ttH process $\tilde{t}^* t \tilde{h}_u^0$

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]

motivation: Natural susy (light higgsino + stop)

top yukawa is large, 3body production is not so small




direct measurement of the coupling

same relation between tt and ttH (tt for top mass, ttH for top yukawa.)

can access to stop/neutralino mixing information

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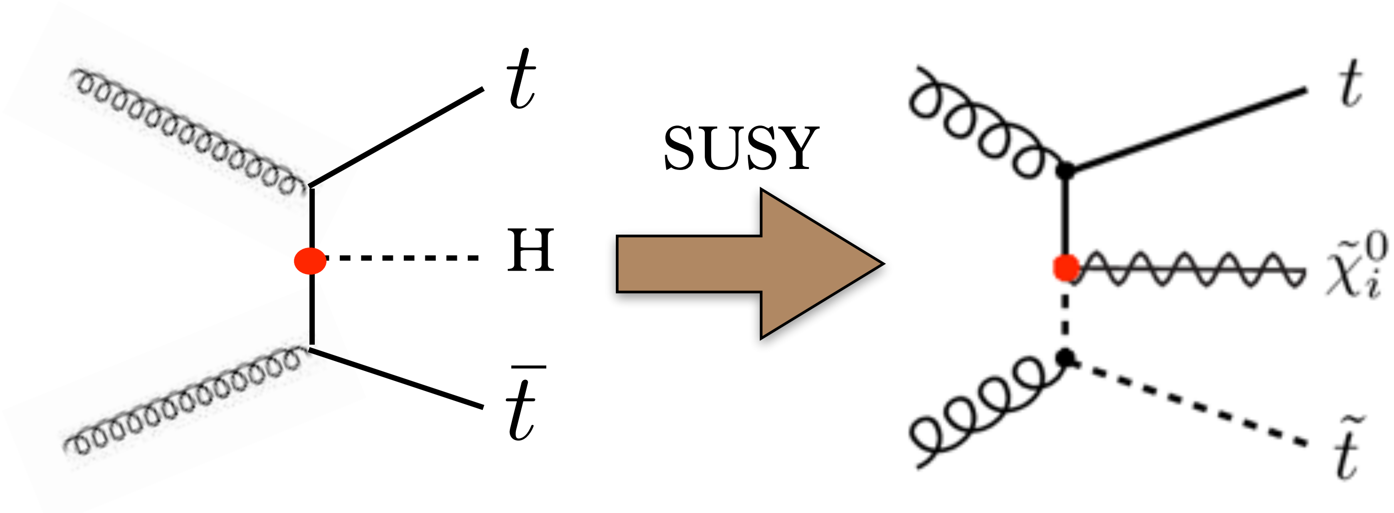


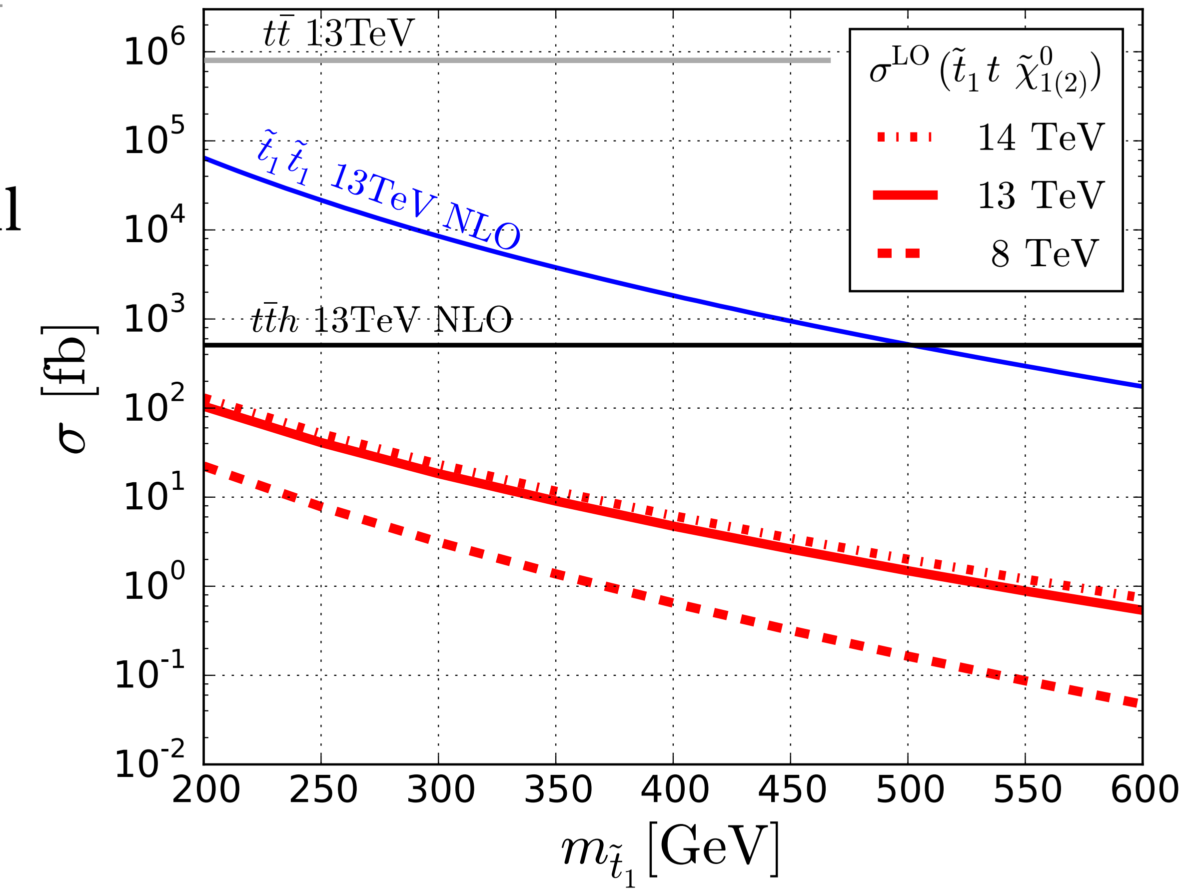


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$y_t T_R H_u Q_{3L}$ in super potential $\rightarrow \tilde{t}_R \tilde{h}_u t_L, t_R \tilde{h}_u \tilde{t}_L$ $\quad (\sin^2\theta_{\tilde{t}} + \cos^2\theta_{\tilde{t}} = 1)$

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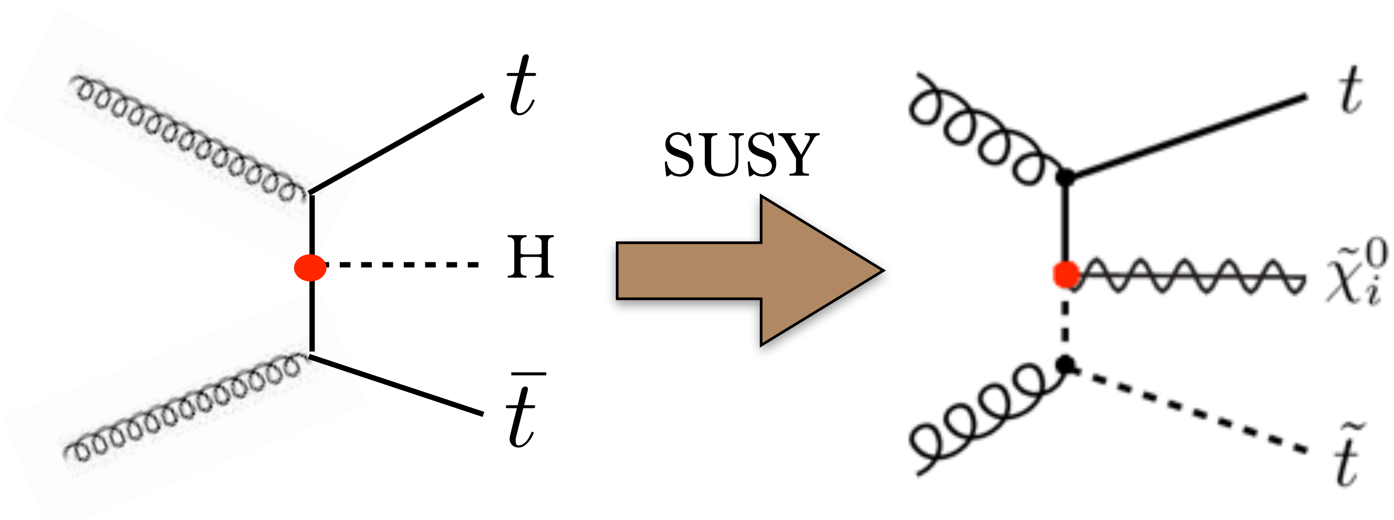


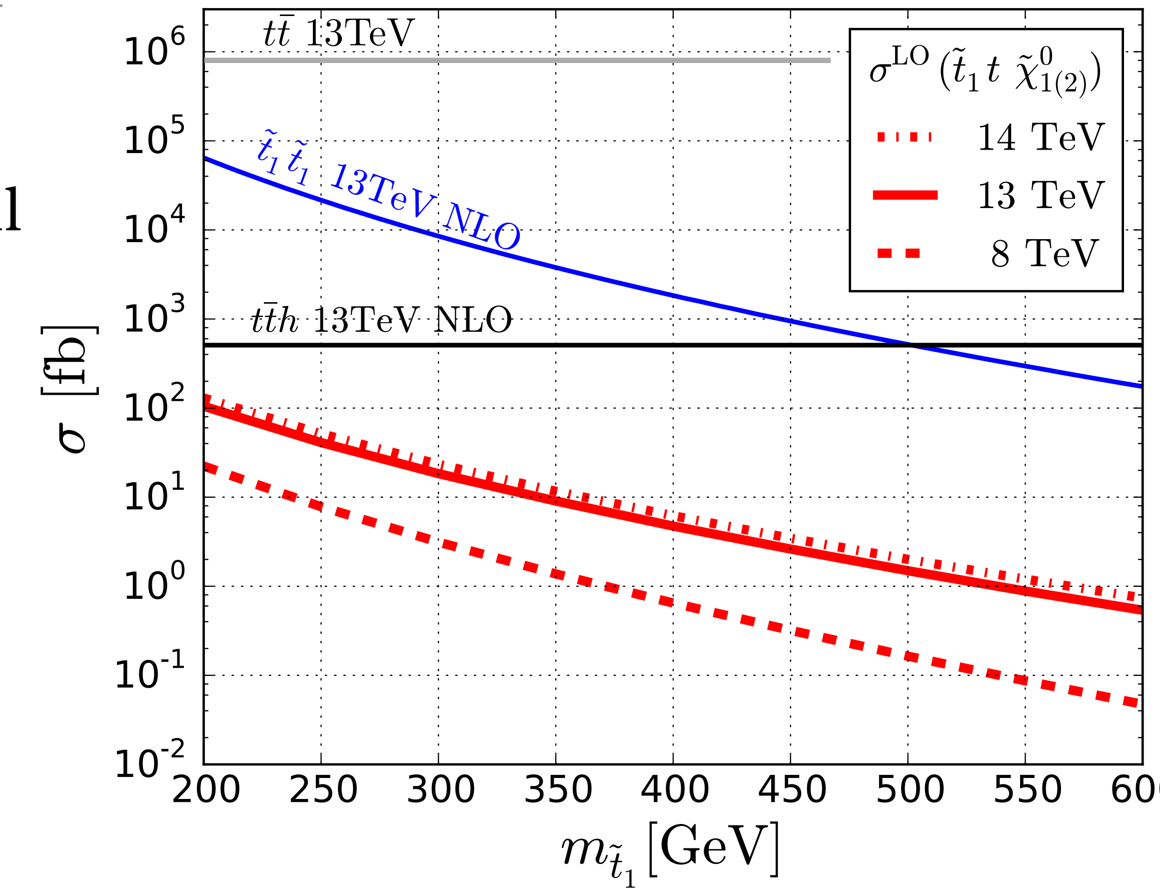


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but depend on neutralino mixing matrix: $N_{14}, N_{24}$ $(\tilde{h}_u$ in $\chi^0_1, \chi^0_2)$

measuring $\sigma(\tilde{t}_1 t \chi^0_{1(2)}) = \mathcal{R}\sigma_{\tilde{h}}$ to access LSP nature

$(\sigma_{\tilde{h}}$: pure higgsino limit$)$

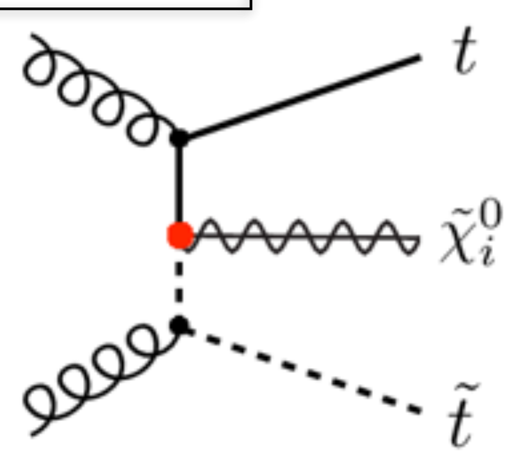
*higgsino measure:* $\mathcal{R} \simeq \dfrac{|N_{14}|^2 + |N_{24}|^2}{\sin^2\beta}$

# New signature: mono-top

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]

consider degenerate case

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



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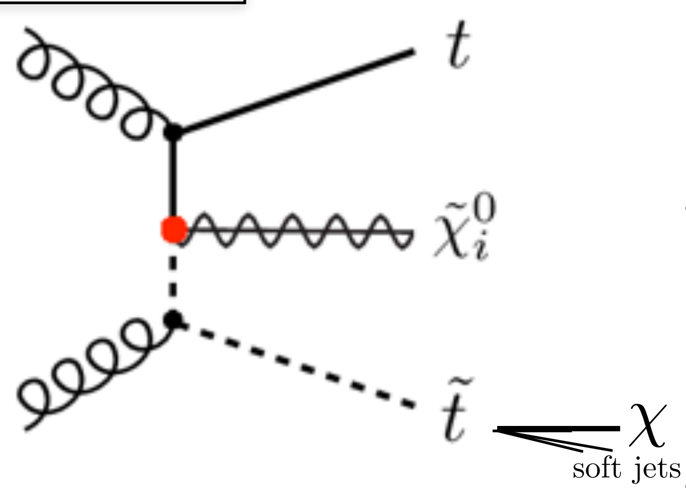


essentially $\not{E}_T$

$\longrightarrow$ interesting signature: mono-top

often considered in top flavor violation

J. Andrea, B. Fuks, F. Maltoni

mono-top with no flavor violation,
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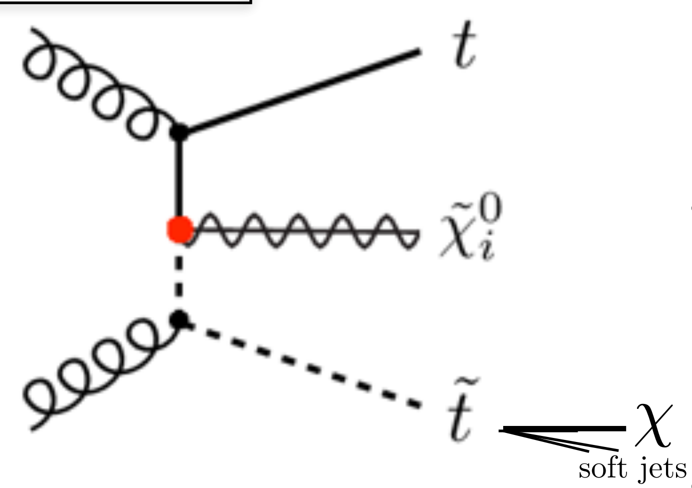


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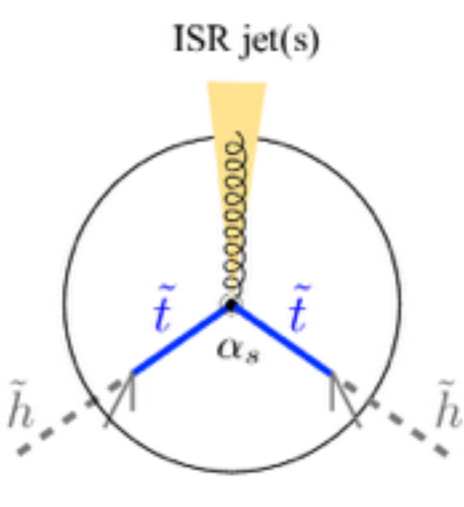
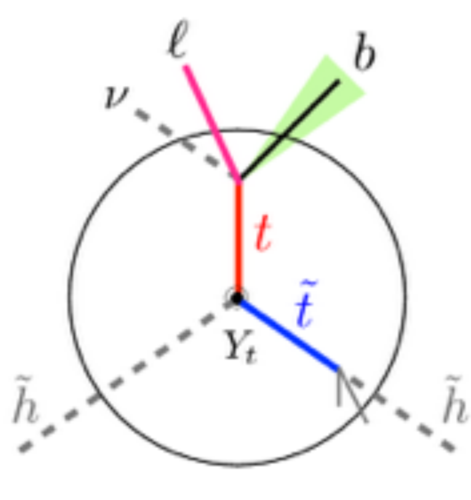



mono jet + $E_T^{\rm miss}$ + soft

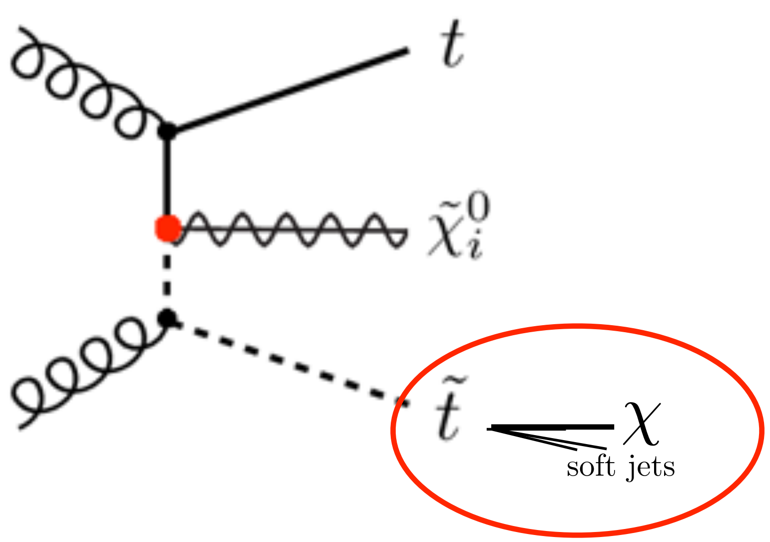



mono top + $E_T^{\rm miss}$ + soft

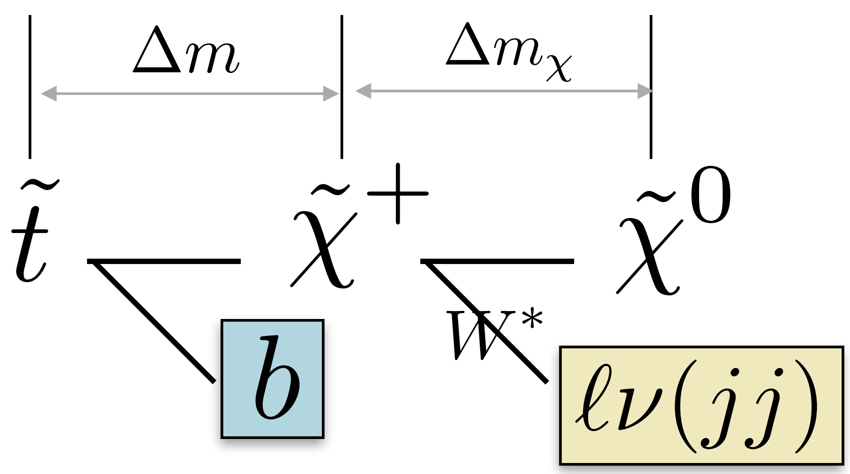
combine mono-jet and mono-top allow to access both *stop mass* $m_{\tilde{t}}$ and *higgsino measure* $\mathcal{R}$

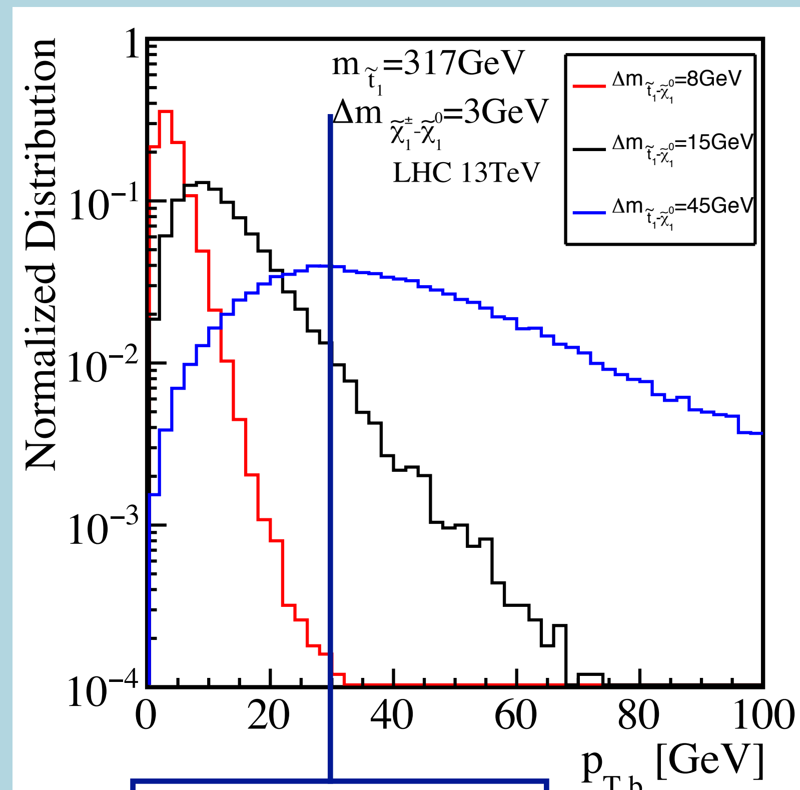
# invisible stop decay

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]



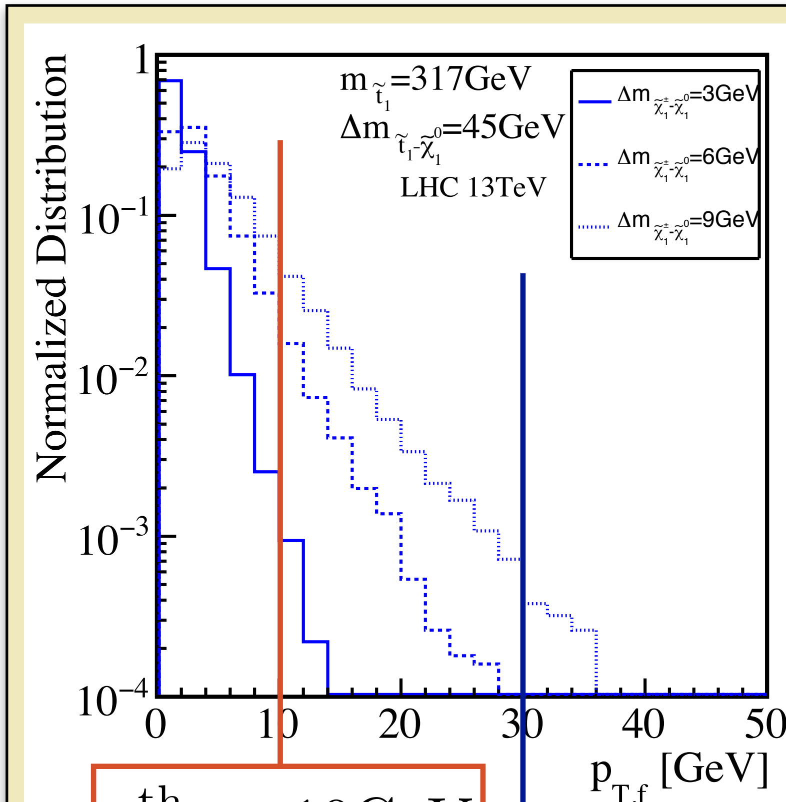

when stop invisible?




$p_{T,j}^{\text{th}} = 30\text{GeV}$

$\Delta m \lesssim 15\text{GeV}$




$p_{T,\ell}^{\text{th}} = 10\text{GeV}$

$p_{T,j}^{\text{th}} = 30\text{GeV}$

$\Delta m_\chi \lesssim 6\text{GeV}$

true for higgsino

* soft-activity might be able to use [A. Chakraborty, S. Chakraborty, T. S. Roy 1606.07826]

# Search strategy

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]

focus on easiest channel ( $t_\ell + \not{E}_T$ ) Baseline: $n_\ell = 1 \quad n_b = 1 \quad n_j \leq 3$

$(p_{T,j} > 30\text{GeV})$

| Process | $\sigma$ | Baseline |
|---|---|---|
| $t\bar{t}$ | 831 pb | $206 \cdot 10^6$ |
| $tW$ | 71 pb | $26.2 \cdot 10^6$ |
| $tZ$ | 0.88 pb | $22.8 \cdot 10^3$ |
| $W + b\bar{b}$ | 7.65 pb | $1.82 \cdot 10^6$ |
| BG total | 903 pb | $226 \cdot 10^6$ |
| BP(317, 309) | 23.7 fb | 5883 |
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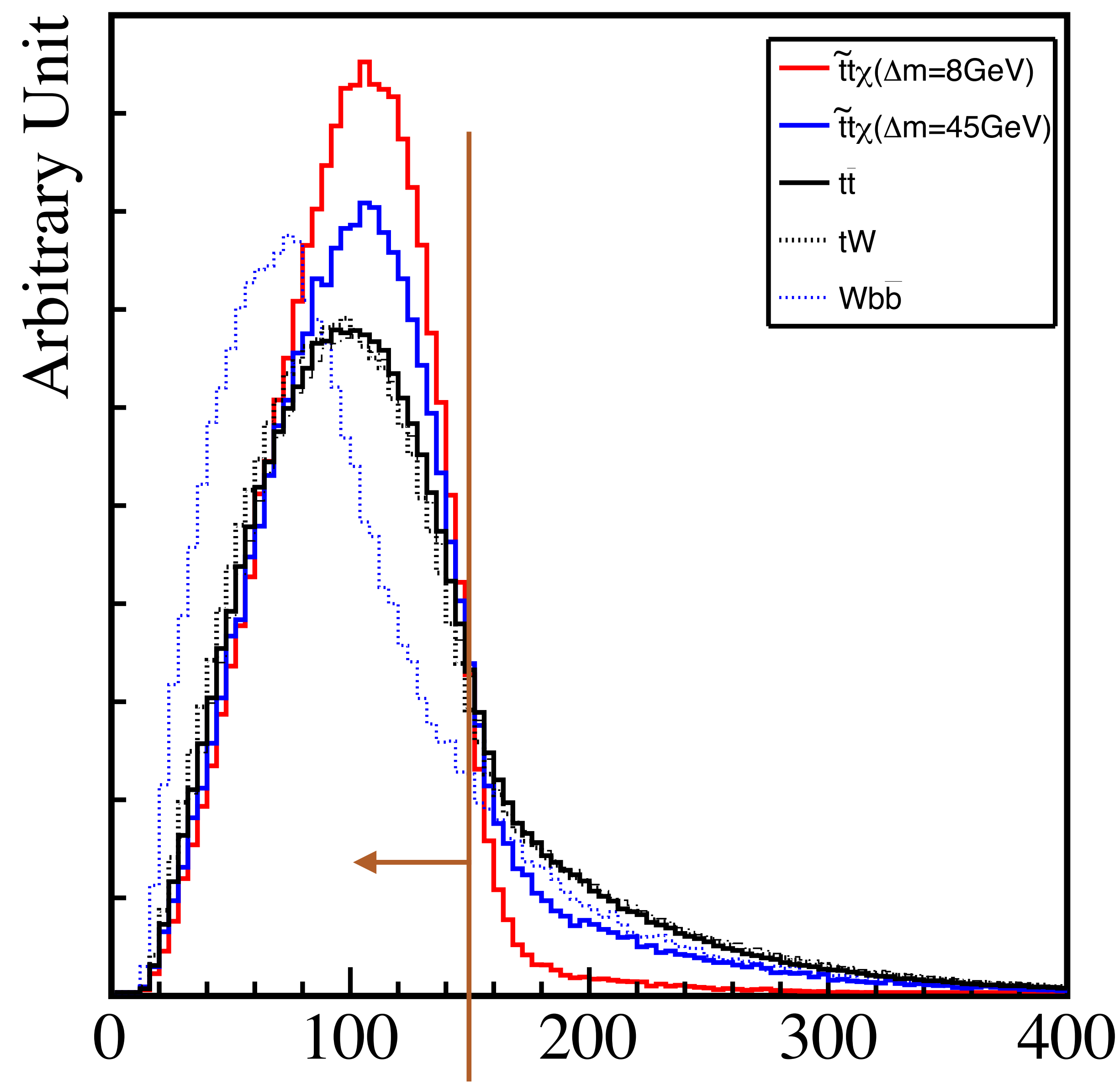


consistency check with top kinematics

to reduce non top BG (Wbb)
combinatorial BG

$m_{b\ell} < 150\text{GeV}$

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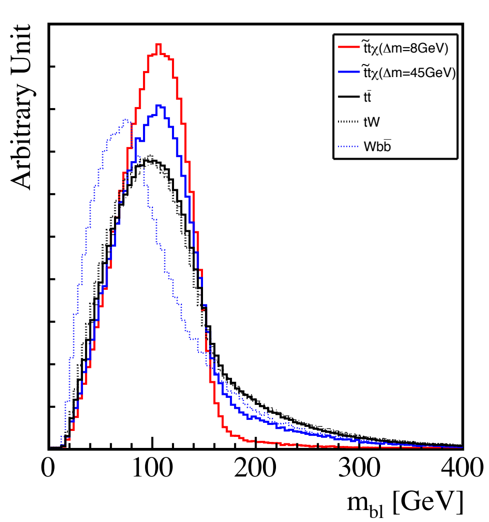
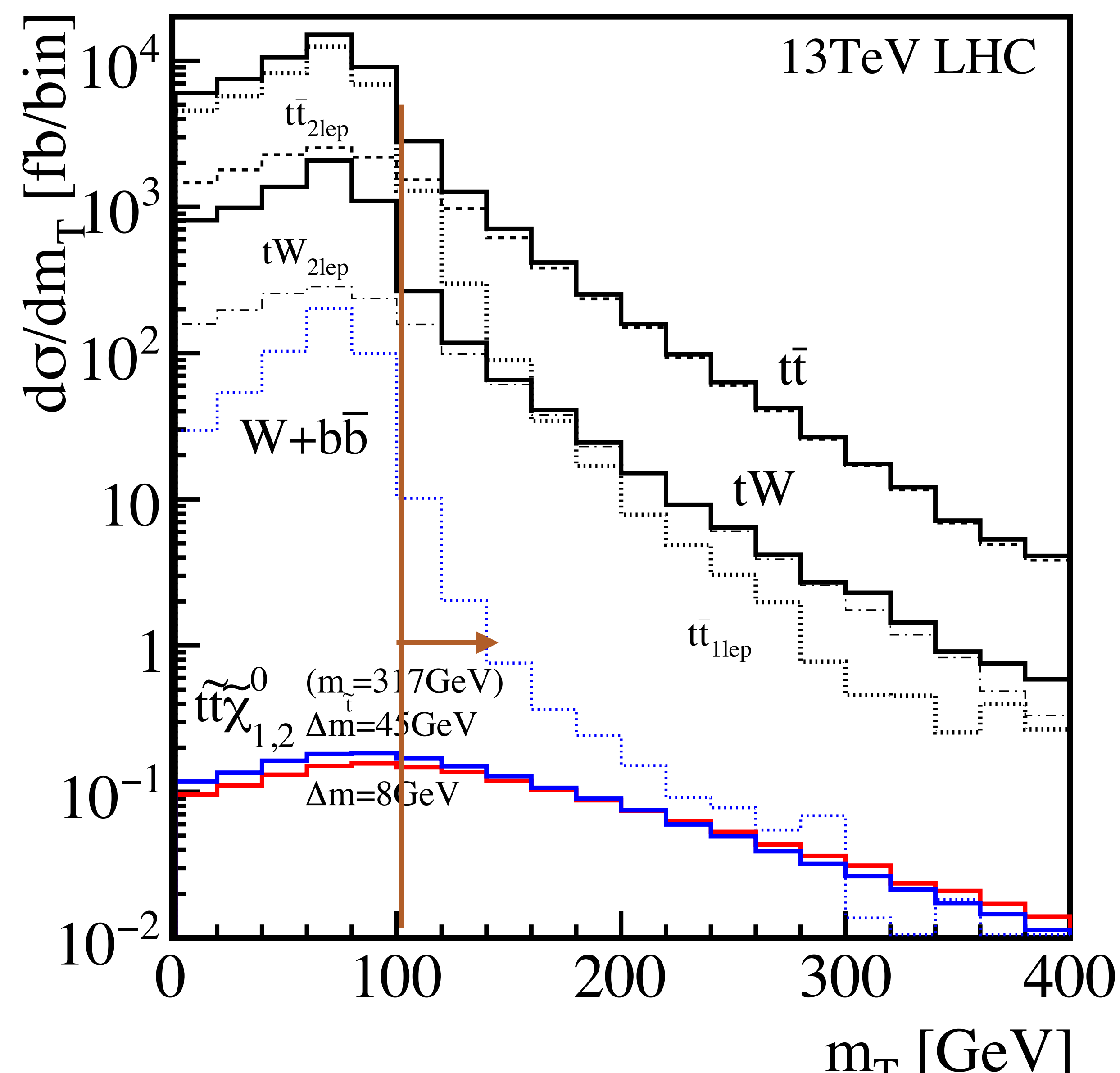
| Process | $\sigma$ | Baseline | $m_{b\ell} < 150$ |
|---|---|---|---|
| $t\bar{t}$ | 831 pb | $206 \cdot 10^6$ | $165. \cdot 10^6$ |
| $tW$ | 71 pb | $26.2 \cdot 10^6$ | $20.7 \cdot 10^6$ |
| $tZ$ | 0.88 pb | $22.8 \cdot 10^3$ | $21.6 \cdot 10^3$ |
| $W + b\bar{b}$ | 7.65 pb | $1.82 \cdot 10^6$ | $1.51 \cdot 10^6$ |
| BG total | 903 pb | $226 \cdot 10^6$ | $41.1 \cdot 10^6$ |
| BP(317, 309) | 23.7 fb | 5883 | 5491 |
| BP(317, 272) | 30.8 fb | 6522 | 5491 |




$m_{b\ell} < 150\text{GeV}$




$m_T > 100\text{GeV}$

reject events only $\not{E}_T$ from $W$: $2\ell(t\bar{t}, tW)$ left

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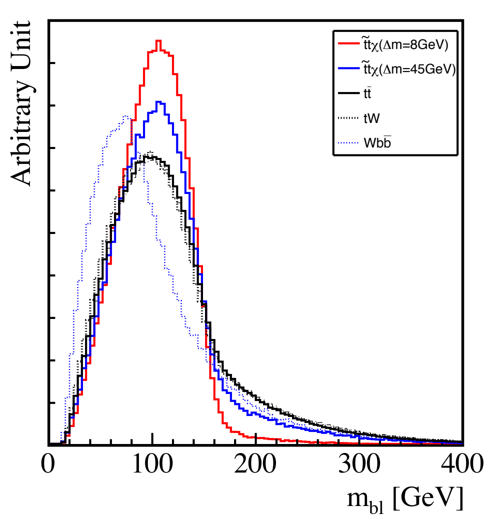
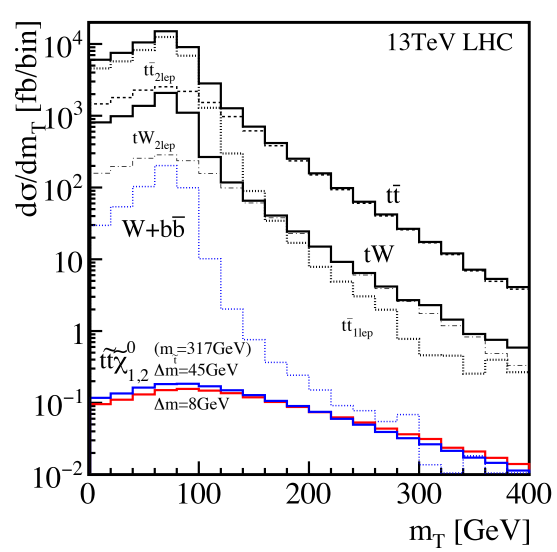
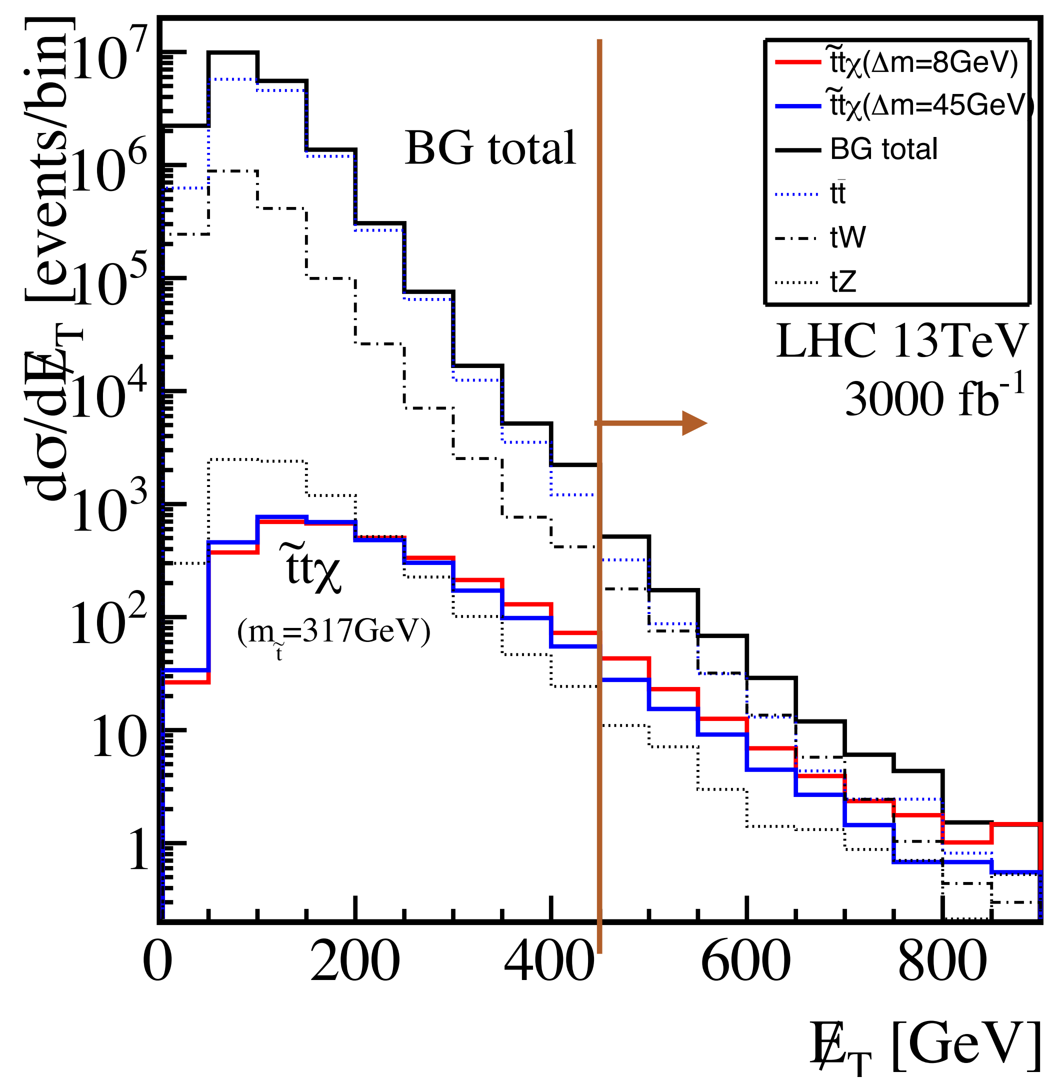
| Process | $\sigma$ | Baseline | $m_{b\ell} < 150$ | $m_T > 100$ |
|---|---|---|---|---|
| $t\bar{t}$ | 831 pb | $206 \cdot 10^6$ | $165. \cdot 10^6$ | $17.7 \cdot 10^6$ |
| $tW$ | 71 pb | $26.2 \cdot 10^6$ | $20.7 \cdot 10^6$ | $1.68 \cdot 10^6$ |
| $tZ$ | 0.88 pb | $22.8 \cdot 10^3$ | $21.6 \cdot 10^3$ | $7.3 \cdot 10^3$ |
| $W + b\bar{b}$ | 7.65 pb | $1.82 \cdot 10^6$ | $1.51 \cdot 10^6$ | $42.3 \cdot 10^3$ |
| BG total | 903 pb | $226 \cdot 10^6$ | $41.1 \cdot 10^6$ | $19.4 \cdot 10^6$ |
| BP(317, 309) | 23.7 fb | 5883 | 5491 | 3387 |
| BP(317, 272) | 30.8 fb | 6522 | 5491 | 3123 |




$m_{b\ell} < 150\text{GeV}$




$m_T > 100\text{GeV}$




require high $\not{E}_T > 450\text{GeV}$

BG from back to back $(2\ell)$

$p_{T,\nu}$ partly cancel

# Search strategy

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]

focus on easiest channel ( $t_\ell + \not{E}_T$ ) Baseline: $n_\ell = 1 \quad n_b = 1 \quad n_j \leq 3$

| Process | $\sigma$ | Baseline | $m_{b\ell} < 150$ | $m_T > 100$ | SR1 |
|---|---|---|---|---|---|
| $t\bar{t}$ | 831 pb | $206 \cdot 10^6$ | $165. \cdot 10^6$ | $17.7 \cdot 10^6$ | 463.3 |
| $tW$ | 71 pb | $26.2 \cdot 10^6$ | $20.7 \cdot 10^6$ | $1.68 \cdot 10^6$ | 308.5 |
| $tZ$ | 0.88 pb | $22.8 \cdot 10^3$ | $21.6 \cdot 10^3$ | $7.3 \cdot 10^3$ | 26.1 |
| $W + b\bar{b}$ | 7.65 pb | $1.82 \cdot 10^6$ | $1.51 \cdot 10^6$ | $42.3 \cdot 10^3$ | 5.9 |
| BG total | 903 pb | $226 \cdot 10^6$ | $41.1 \cdot 10^6$ | $19.4 \cdot 10^6$ | 803.8 |
| BP(317, 309) | 23.7 fb | 5883 | 5491 | 3387 | 109 (3.8, 0.13) |
| BP(317, 272) | 30.8 fb | 6522 | 5491 | 3123 | 60.2 (2.1, 0.07) |

for $3000\text{fb}^{-1}$

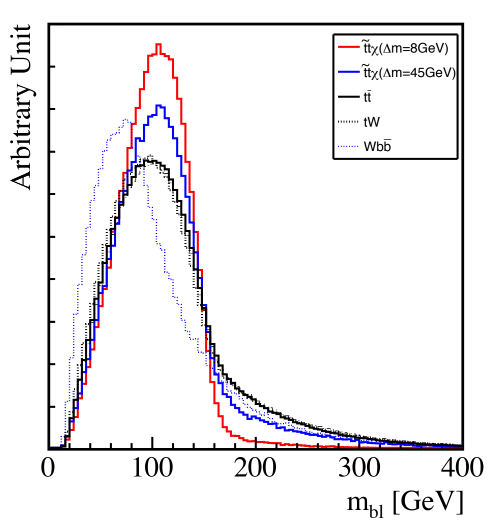
$(S/\sqrt{B}, S/B)$

compressed case

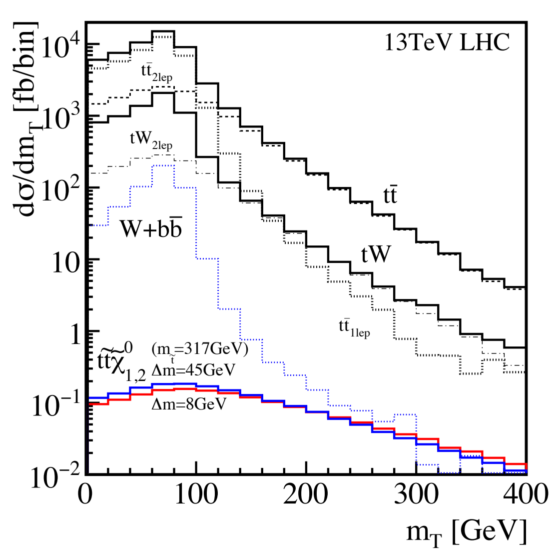
smaller cross section

better significance

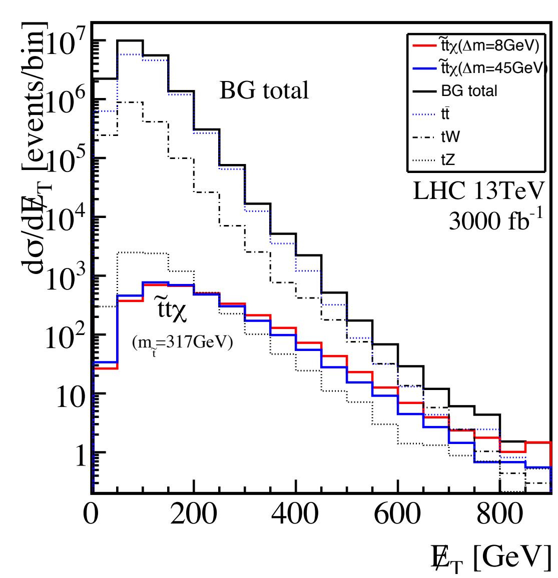
(better efficiency)




$m_{b\ell} < 150\text{GeV}$



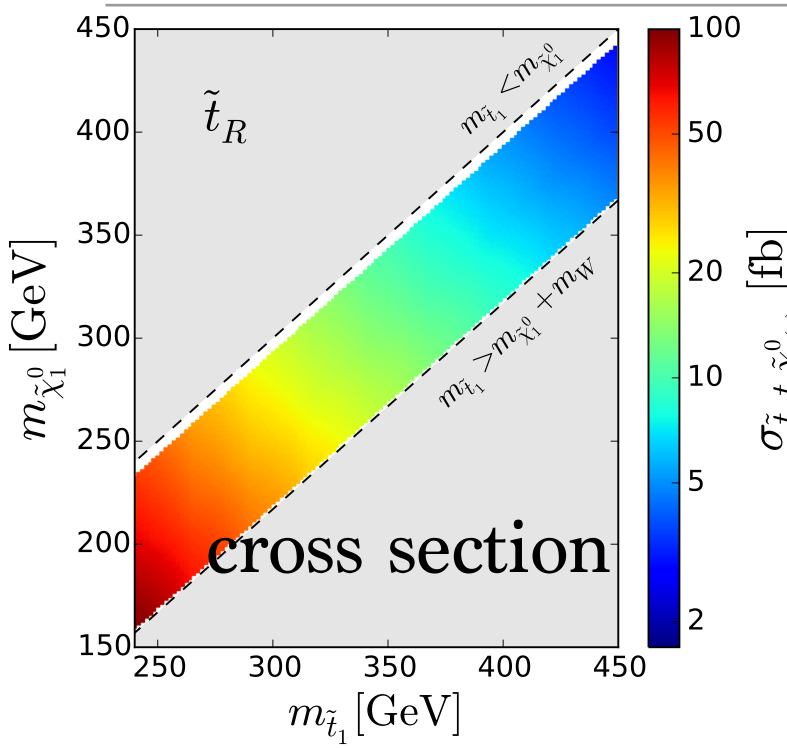

$m_T > 100\text{GeV}$

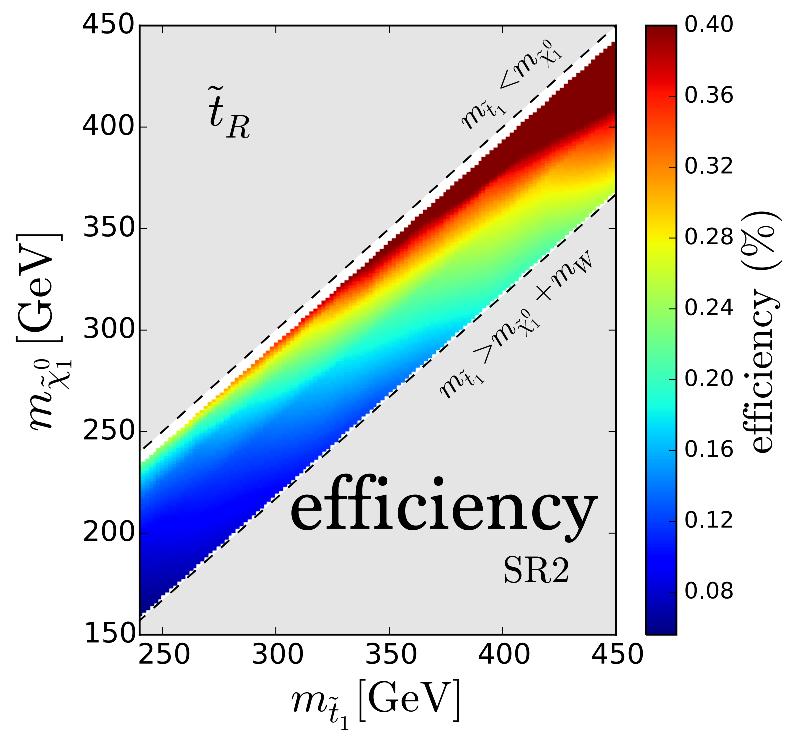



$\not{E}_T > 450\text{GeV}$

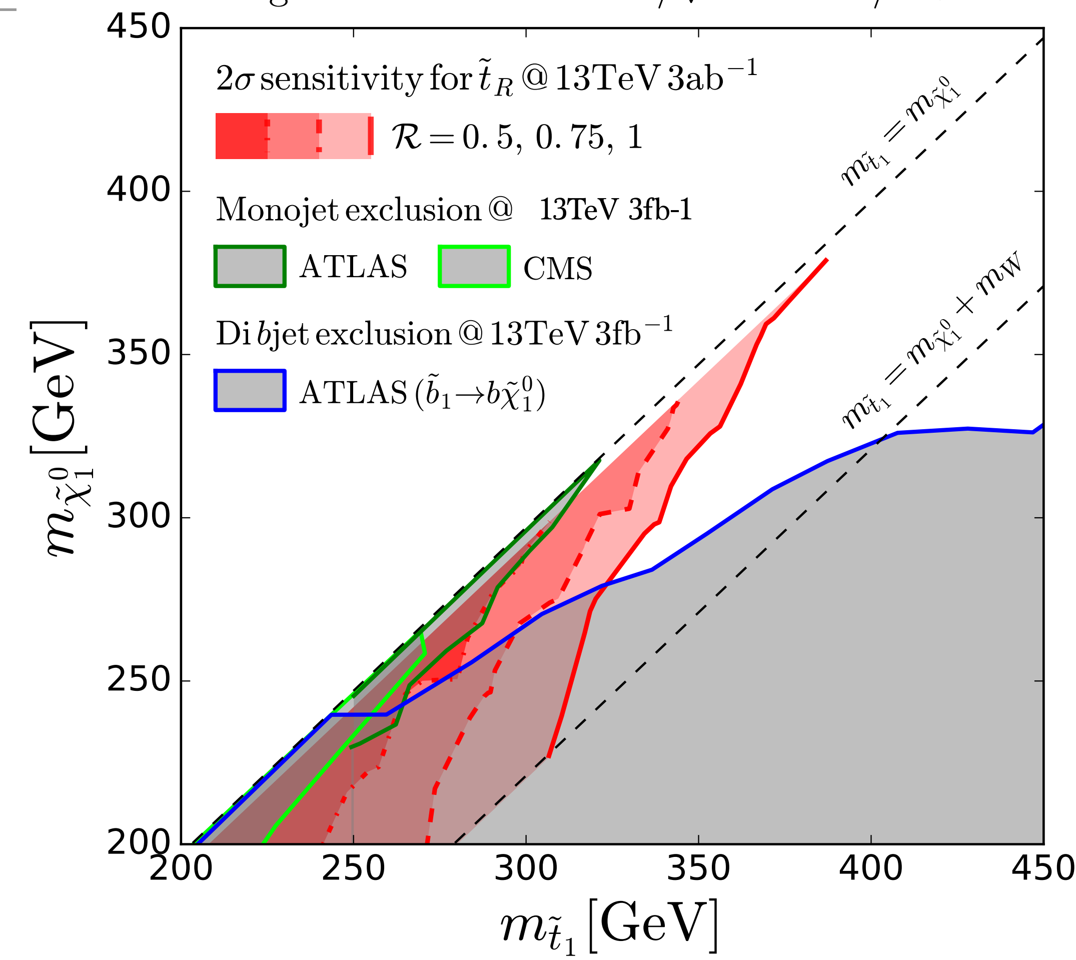
# sensitivity

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]




using best SR with best $S/\sqrt{B}$ with $S/B > 0.1$



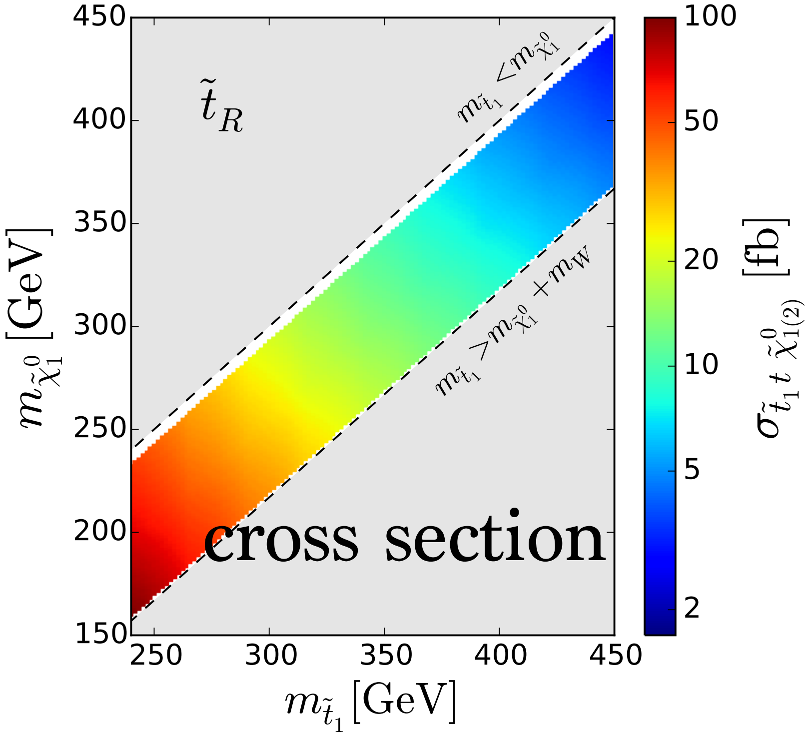

up to 380 GeV sensitive

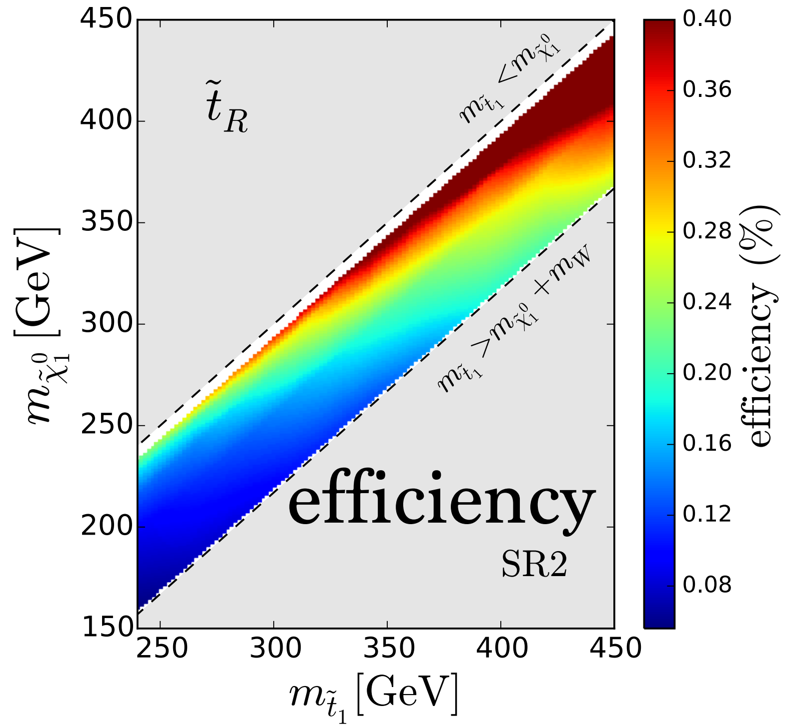
mono-jet: finally up to 500 GeV at 3ab-1
(conservative)

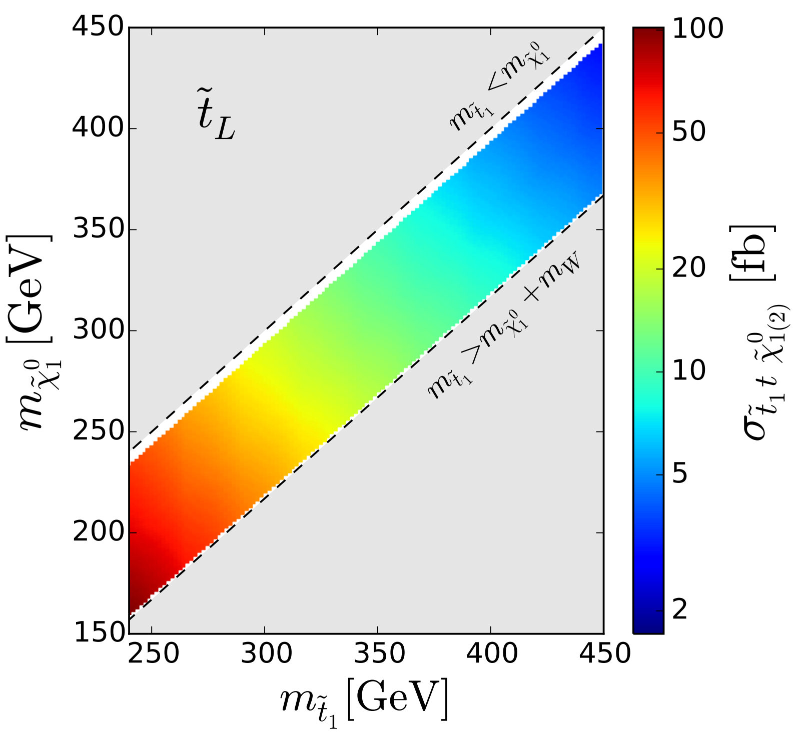
[M.Low, L.T.Wang JHEP08(2014)161]

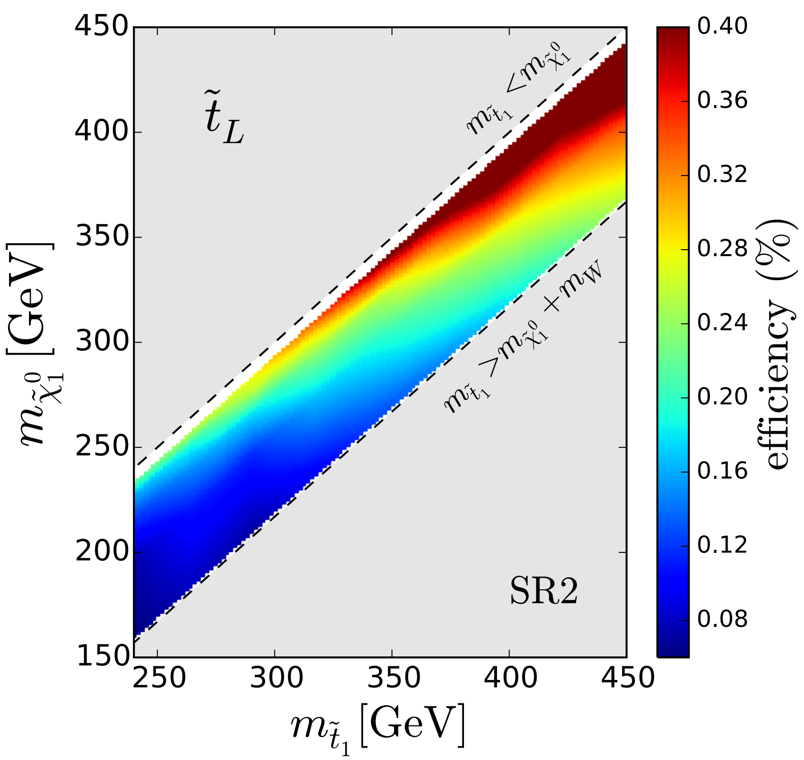
# sensitivity

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]

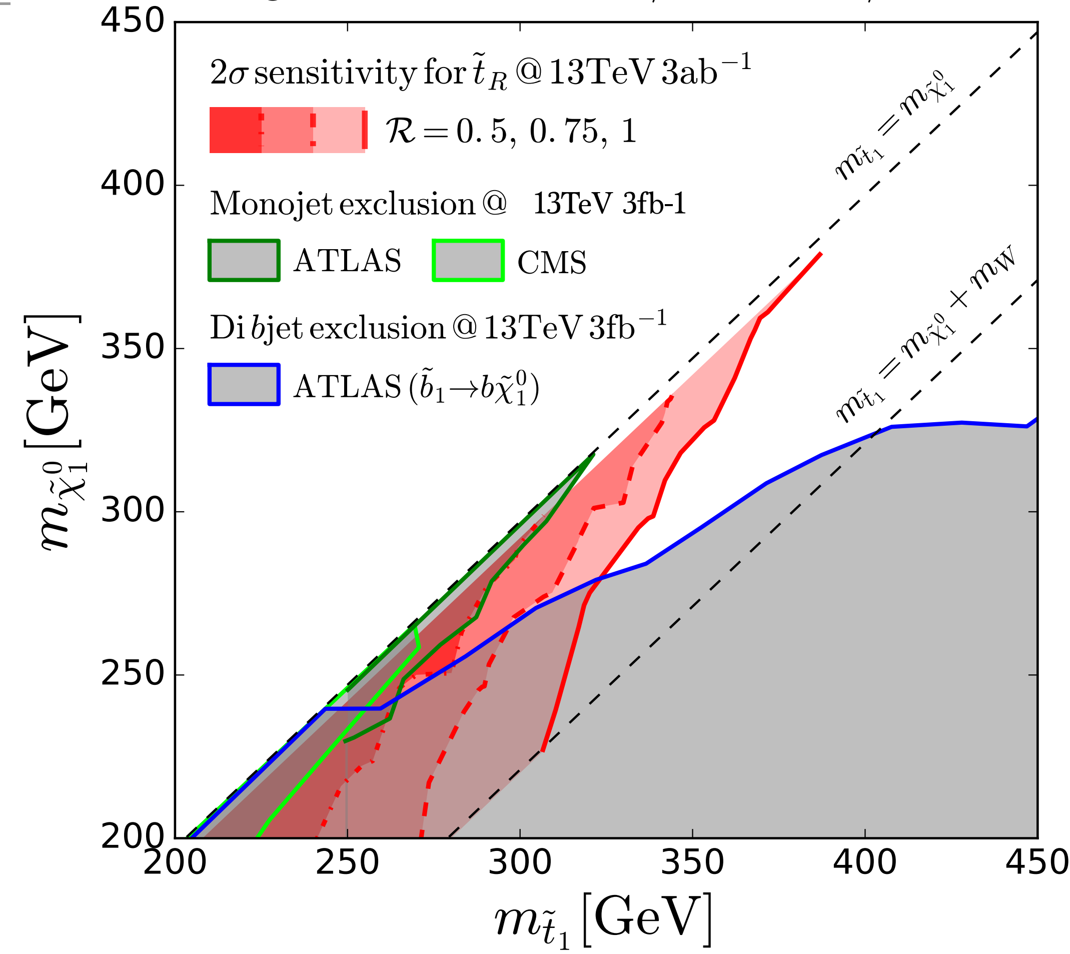



using best SR with best $S/\sqrt{B}$ with $S/B > 0.1$




up to 380 GeV sensitive

mono-jet: finally up to 500 GeV at 3ab-1 (conservative)

[M.Low, L.T.Wang JHEP08(2014)161]

L-handed stop case almost the same

[D. Goncalves, K. Sakurai, MT arXiv:1604.03938]

# helicity structure in stop sector

$\sigma(\tilde{t}_1 t \chi^0_{1(2)})$ : no dependence on stop mixing: $\theta_{\tilde{t}}$ efficiency also not much sensitive

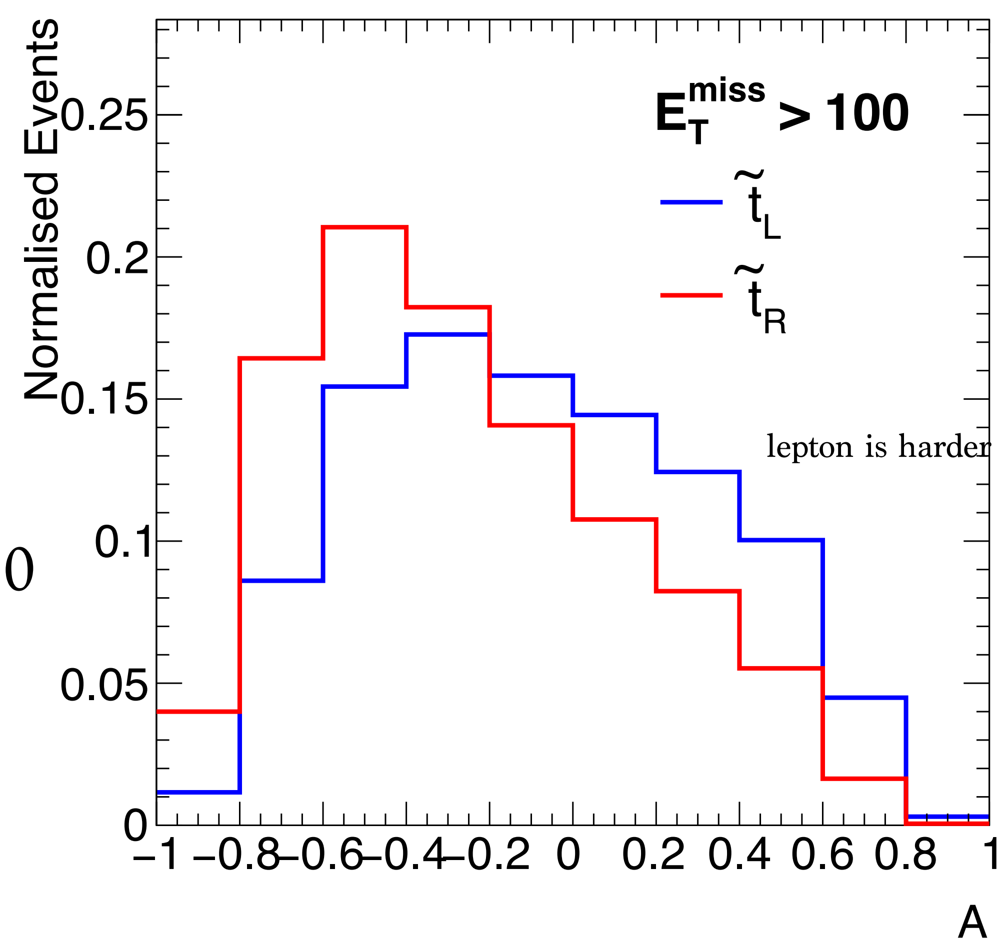
L-handed stop -> R-handed top produced

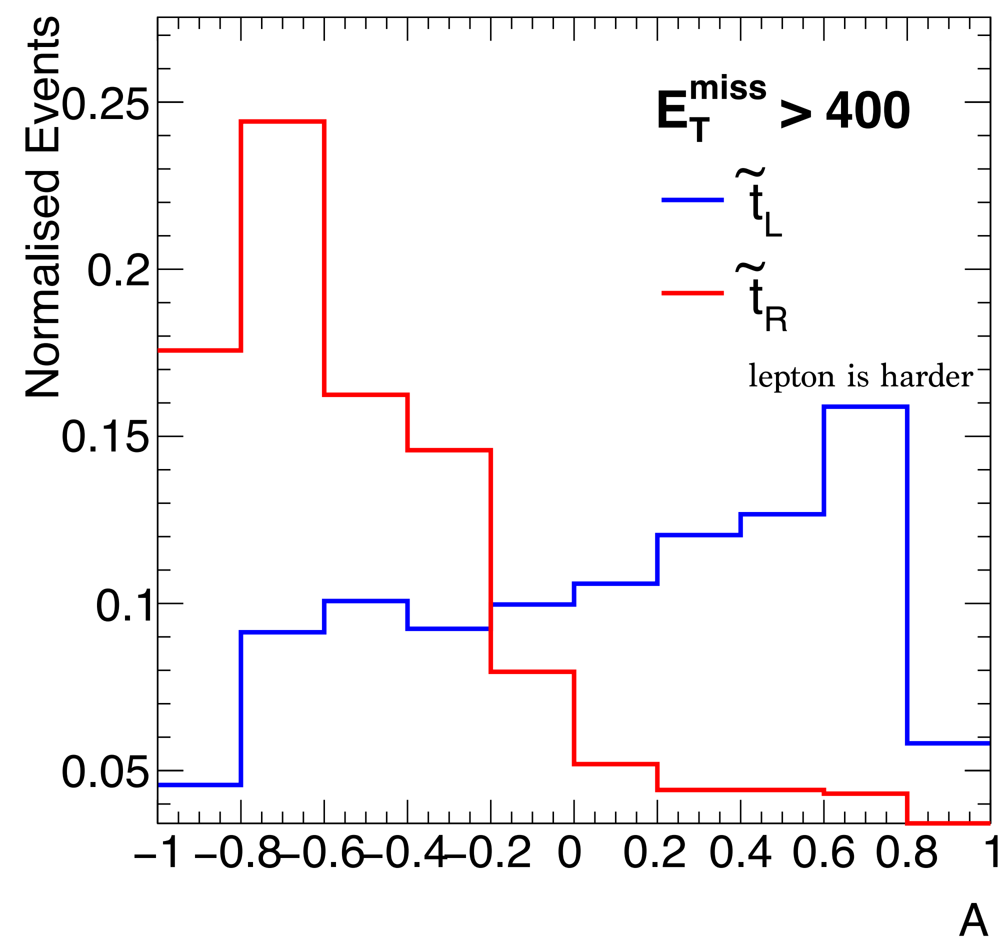
$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1+\omega_f P_t \cos\theta_f) \quad \omega_b = -0.41, \omega_\ell = 1$$

bottom: backward, lepton: forward

$$\mathcal{A} \equiv \frac{p_T(\ell) - p_T(b)}{p_T(\ell) + p_T(b)} > 0$$

lepton is harder



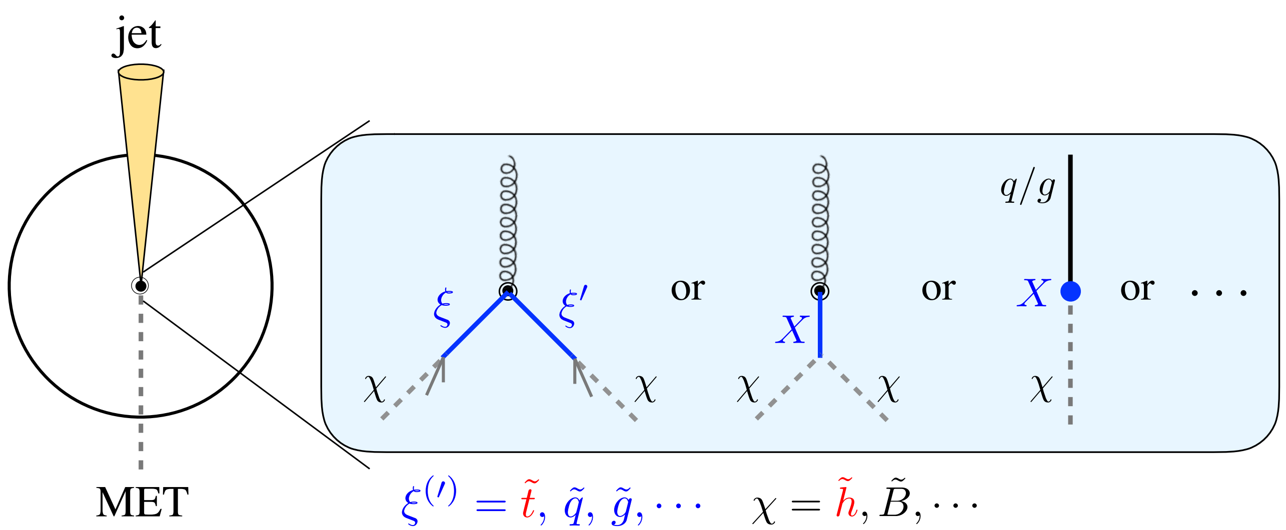

sensitive for L-R, or $\theta_{\tilde{t}}$

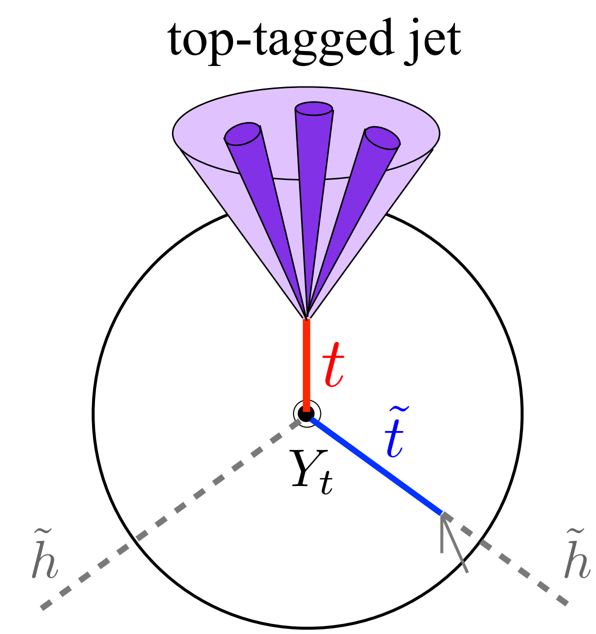
more prominent in boosted regime

# Hadronic channel

[D. Goncalves, K. Sakurai, MT arXiv:1610.06179]

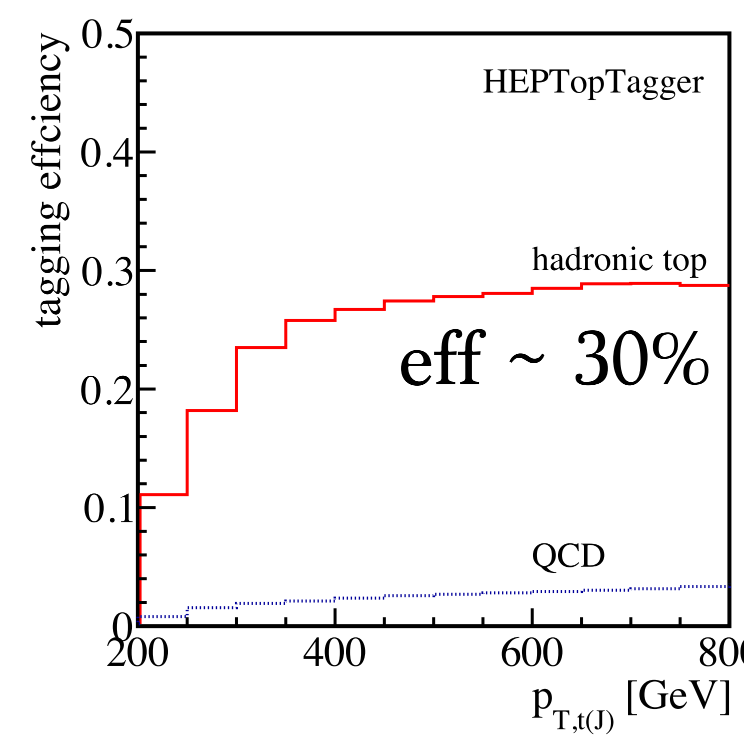
large Emiss, large boost needed -> Top Tagging (HEPTopTagger)




obvious advantage of hadronic mode

larger branching ratio ~ 67%



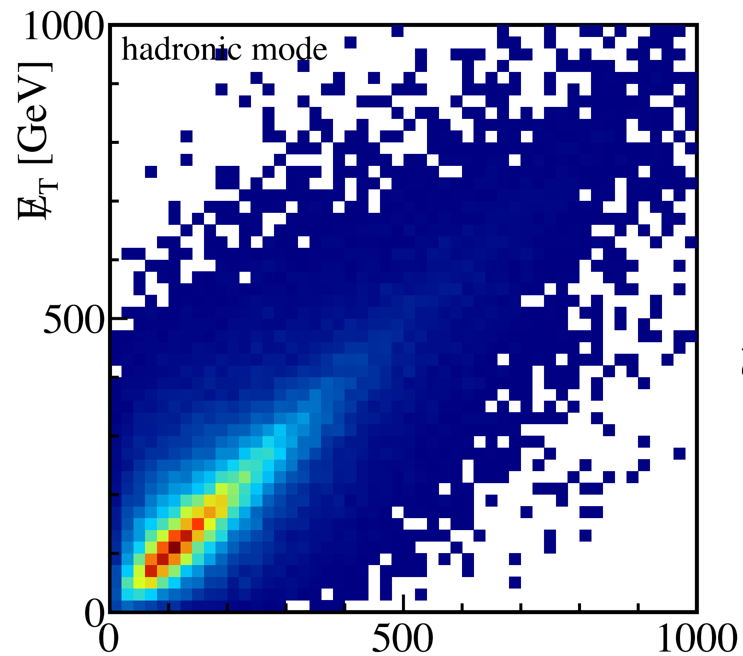
# Hadronic channel

[D. Goncalves, K. Sakurai, MT arXiv:1610.06179]

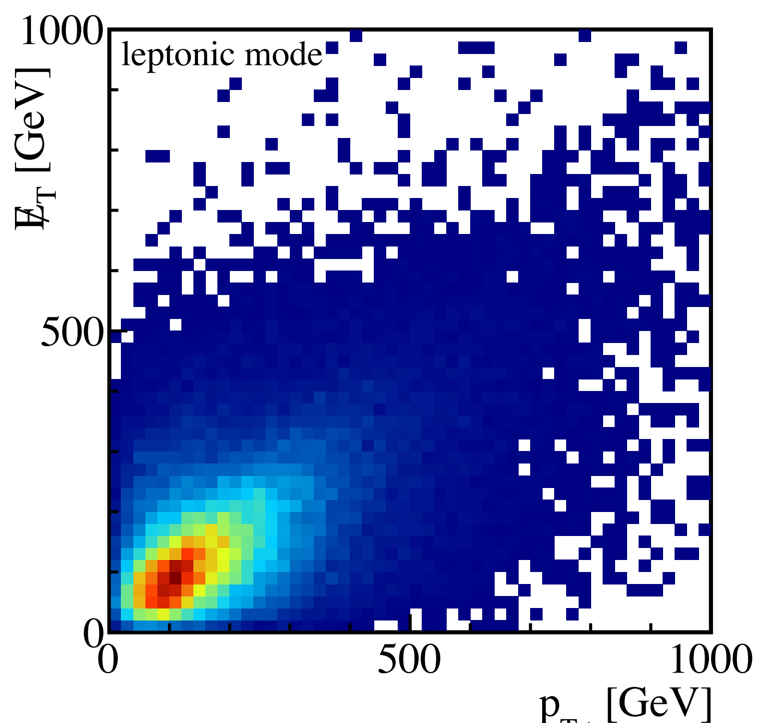
large Emiss, large boost needed -> Top Tagging (HEPTopTagger)

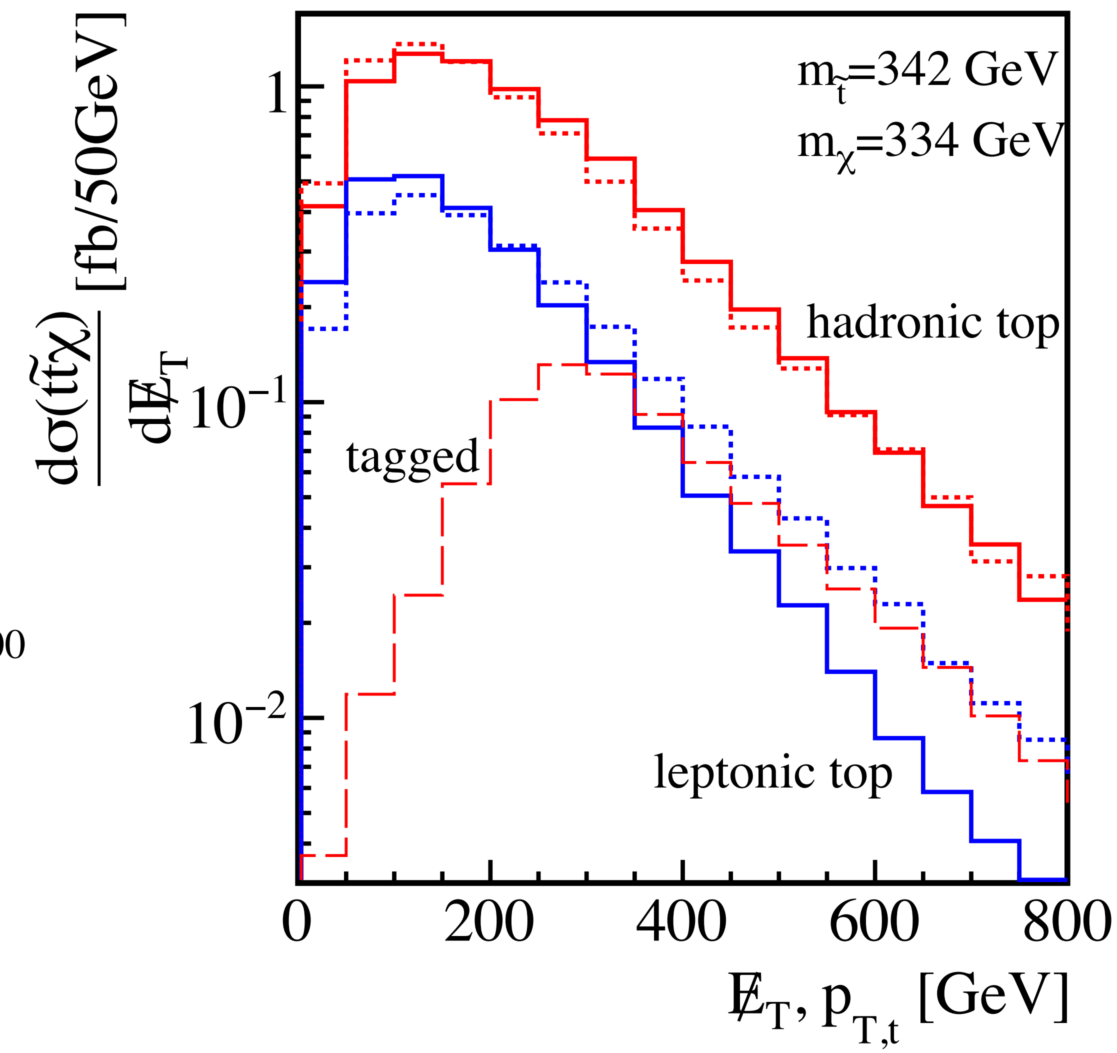
another (and essential) advantage of hadronic mode

hadronic mode:
$\not{E}_T$ fully usable




leptonic mode:
$\not{E}_T$ partly cancel by $\nu$




leptonic $\not{E}_T$ rapidly drops
(solid blue line)

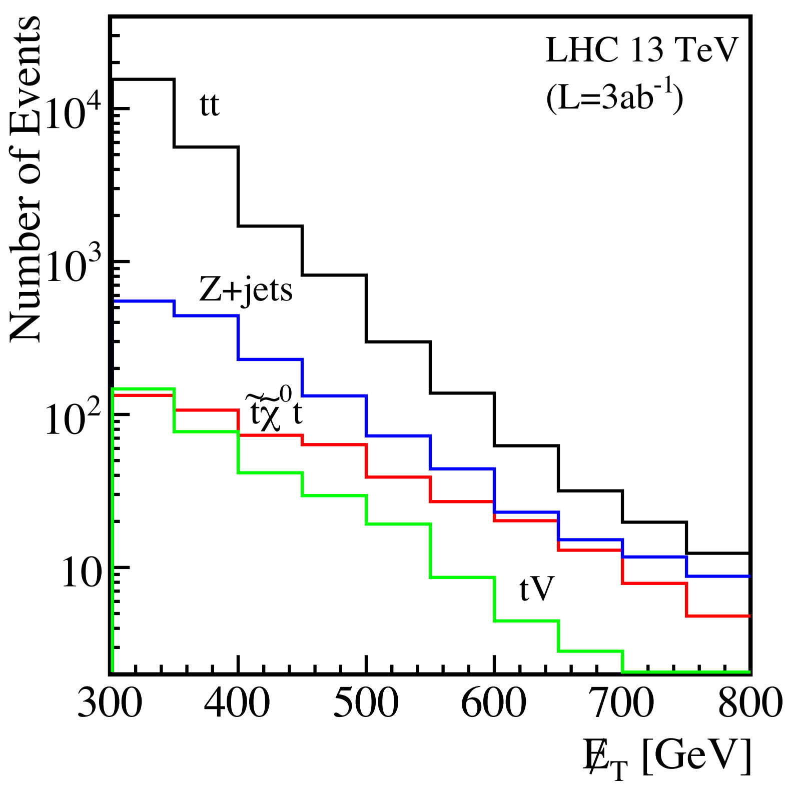
Even after top-tag, hadronic wins

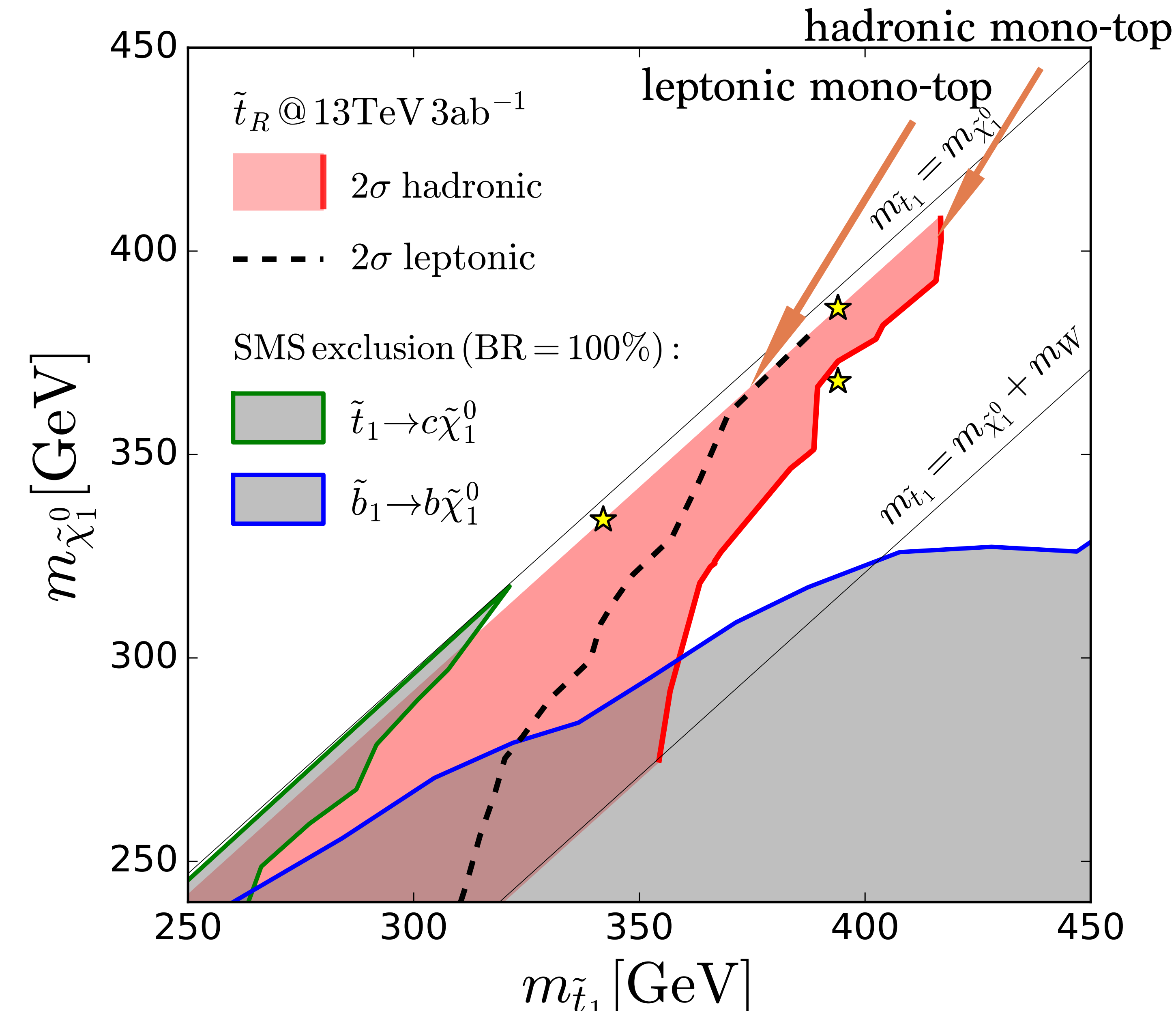
# Hadronic channel

[D. Goncalves, K. Sakurai, MT arXiv:1610.06179]

large Emiss, large boost needed -> Top Tagging (HEPTopTagger)

$n_\ell = 0$, top-tag, $p_{TJ} > 200$ GeV, $\not{E}_T > 300$ GeV
$b$-tag in $t_{\rm tag}$ (70%, 1%×3 combinatorial)
$n_j = 0$ ($p_{Tj} > 30$ GeV, $|\eta_j| < 2.5$)




hadronic mode sensitivity higher than leptonic mode
very generic statement — the reason why fully hadronic mode set strongest limits
it would be more true at 100 TeV collider

# Summary

Natural SUSY: light stop, light higgsino → degenerate: mono-jet signature

mono-jet signature only cannot distinguish the produced particles

We propose mono-top signature via $t\tilde{t}\tilde{\chi}$ for additional information.

LSP nature (higgsino component) through σ, stop mixing through $\frac{p_{T,\ell}}{p_{T,b}}$

hadronic mode sensitivity higher than leptonic mode
very generic statement — the reason why fully hadronic mode set strongest limits
it would be more true at 100 TeV collider, boosted objects help a lot !

boost helps to solve combinatorics, restrict kinematics

Boosted objects ubiquitous at LHC and more at 100 TeV