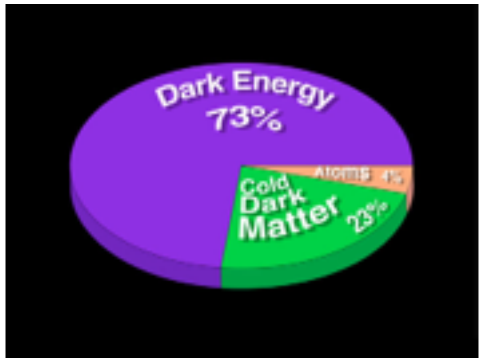
Status of Weak scale SUSY and interpretation of data

Michihisa Takeuchi (Kavli IPMU, Univ. of Tokyo)

at SUSY2017 (TIFR, Mumbai) on 13th Dec 2017

Two big problems in particle physics

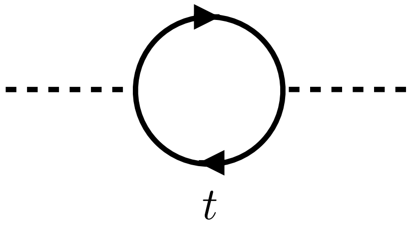
Existence of DM (serious problem)



Naturalness (Fine tuning in Higgs sector)

$$m_{h,\text{phys}}^2 = m_{h,\text{tree}}^2 + \delta m_h^2 \sim 125^2\text{GeV}^2 \sim 10^4\text{GeV}^2$$

$\delta m_h^2 \sim$

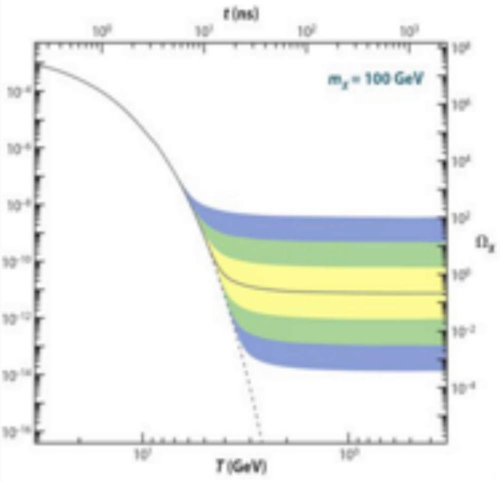


$$\sim -\frac{3}{4\pi} y_t^2 \Lambda_{\text{SM}}^2$$

$$\sim 10^{38}\text{GeV}^2 (\Lambda_{\text{SM}} = M_{\text{Planck}})$$

$$\sim 10^6\text{GeV}^2 (\Lambda_{\text{SM}} = 1\text{TeV})$$

Weak scale SUSY elegantly solve both problems



WIMP miracle

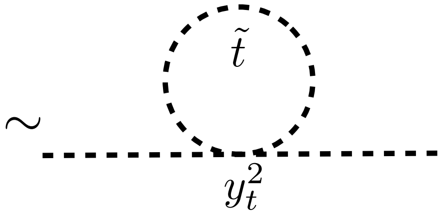
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{\alpha^2} \sim 10^9\text{GeV}^2$$

neutralino DM

perfect WIMP DM

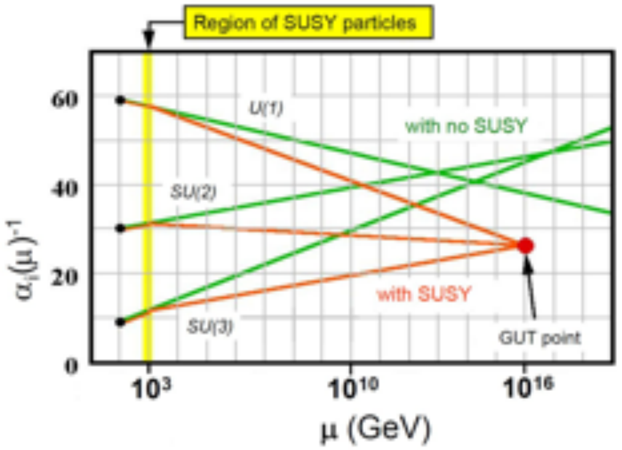
new partner particle, same coupling by symmetry

$\delta m_h^2 \sim$



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

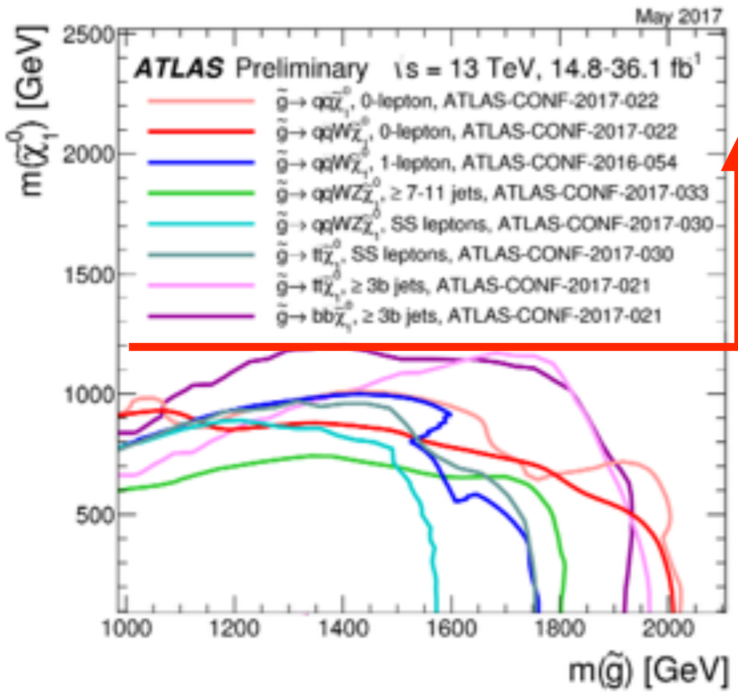
gauge coupling unification also suggests new states at TeV



SUSY search results at LHC 13TeV with ~ 36 fb-1

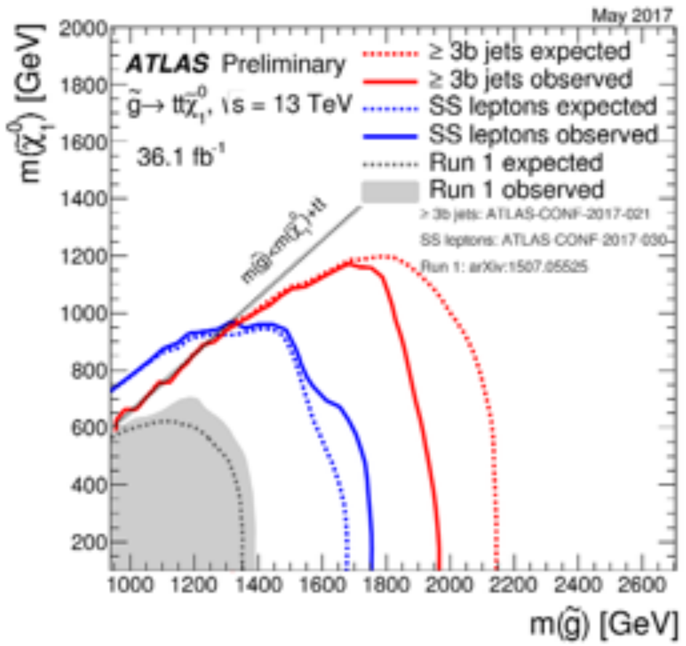
For massless LSP

~2 TeV gluino excluded

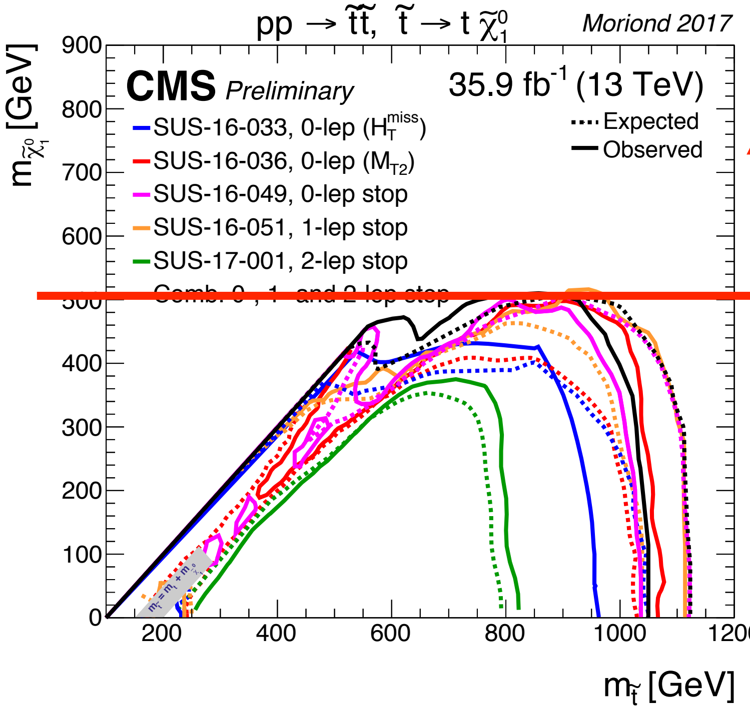


no constraint

LSP＞1.2TeV

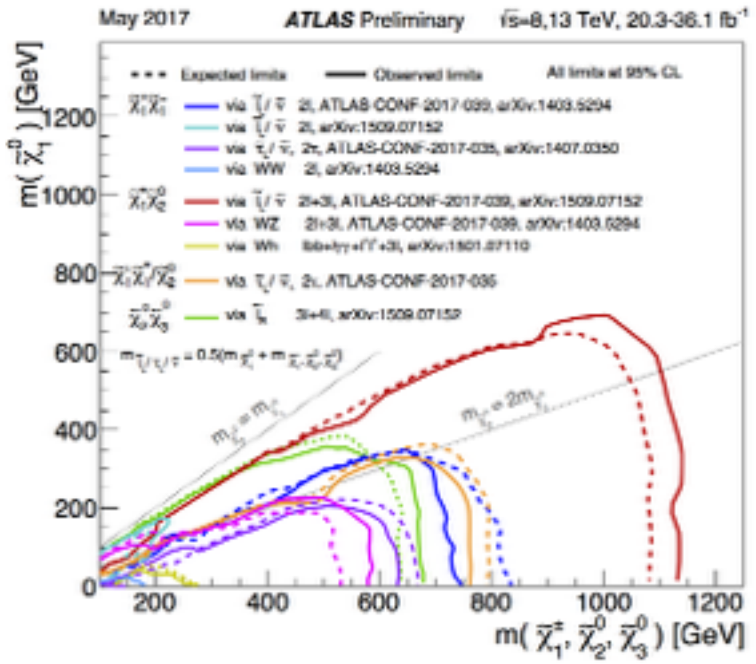


~1 TeV stop excluded



no constraint

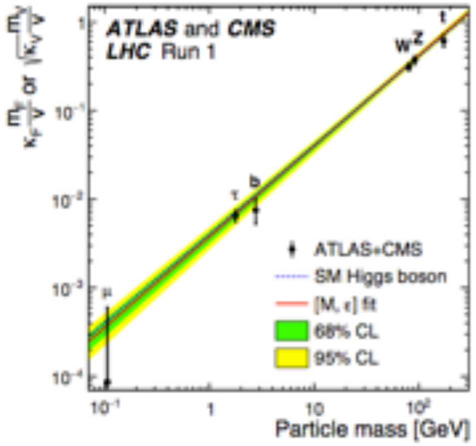
LSP>500GeV

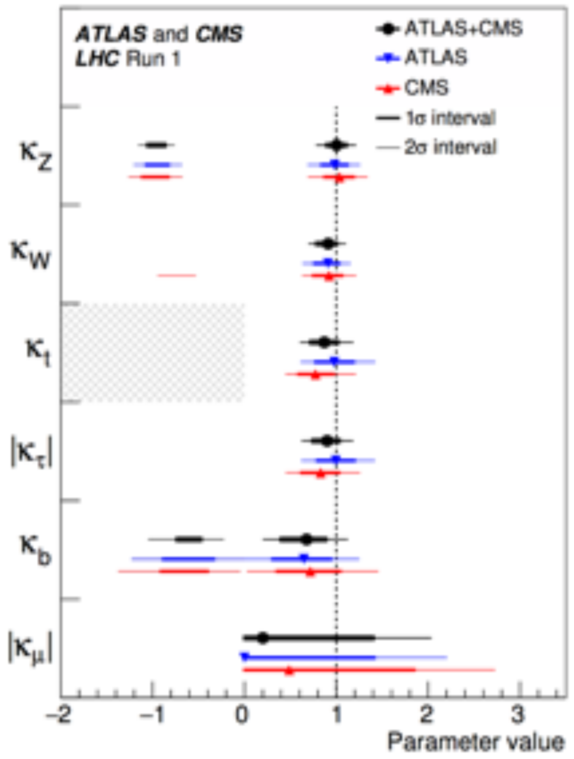


~600 GeV EWkino (W/Z) excluded
(highly depends on BR)

Note: For enough massive LSP no constraints

SM Higgs and no heavy higgses





Higgs couplings measured
consistent to SM Higgs in 10-20%

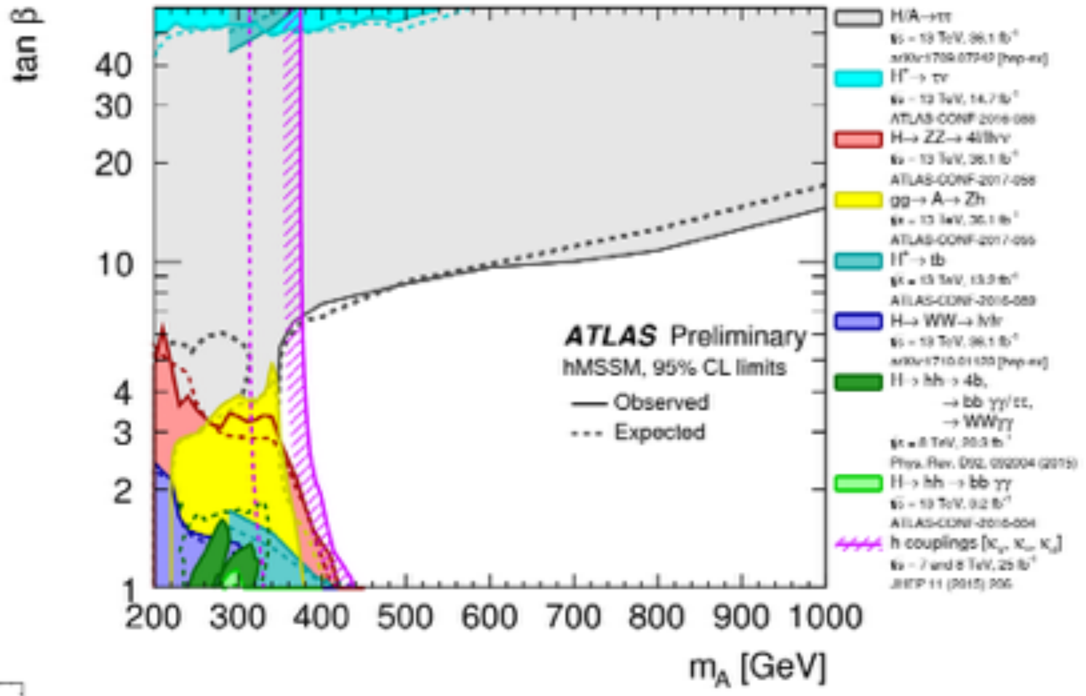
it is also the MSSM prediction in decoupling limit
also there are some 10-20% room for deviation

Heavy higgs searches

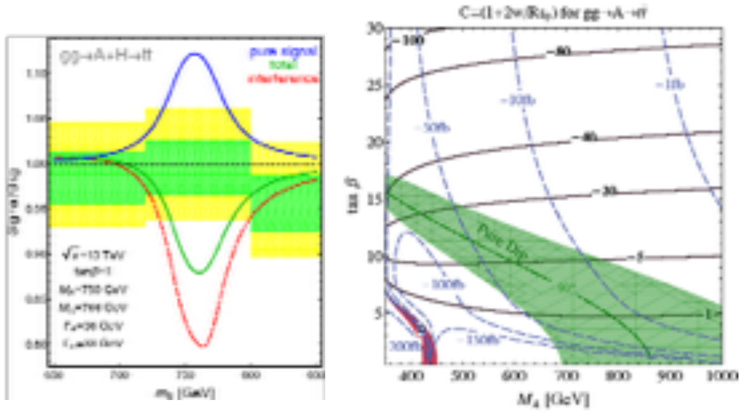
For large $\tan\beta$, $A \to \tau\tau$ dominates

Unlike a general 2HDM, MSSM Higgs sector
can be parameterized with $(m_A, \tan\beta)$

→ Light higgs coupling measurements already
constrain $m_A \gtrsim 400\text{GeV}$

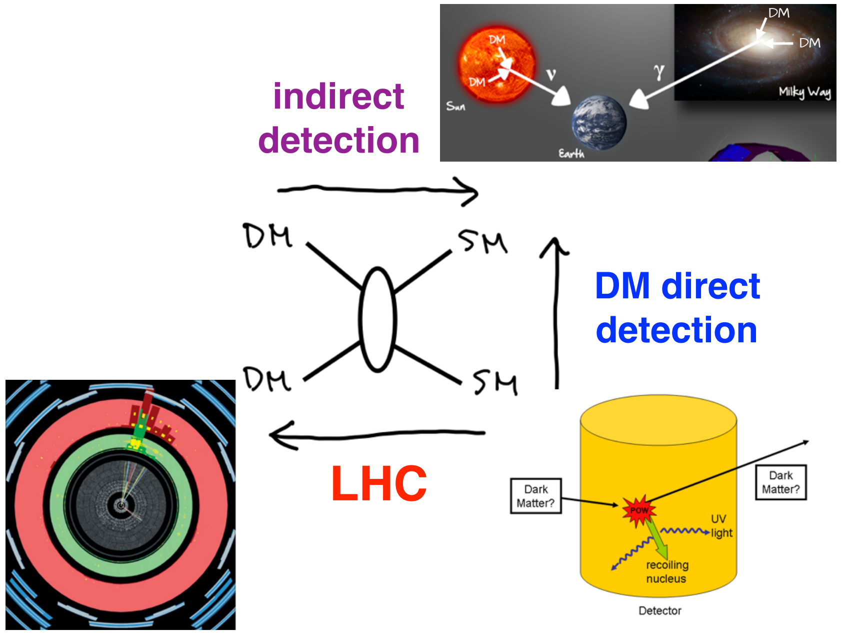


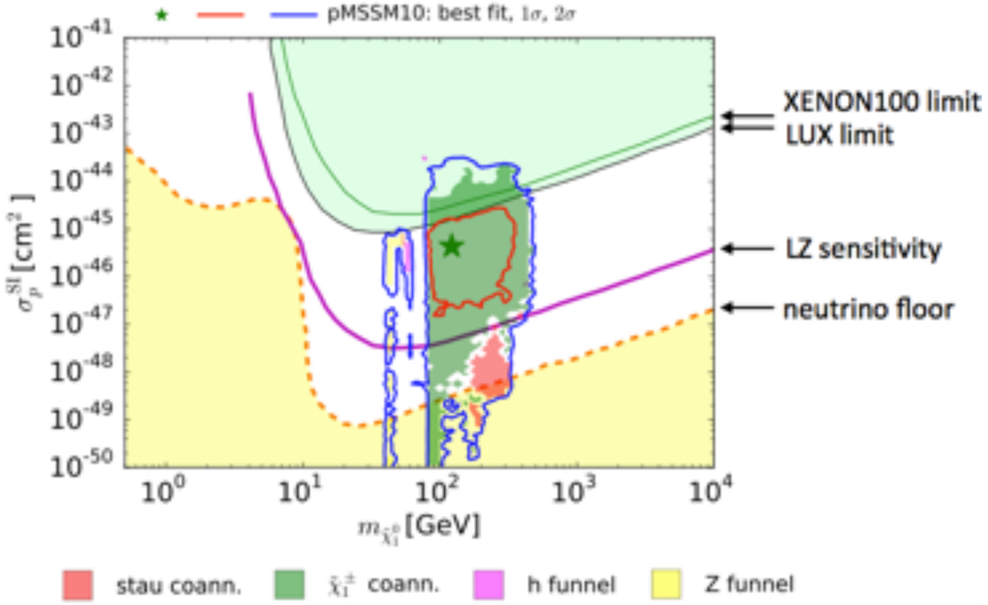
interesting interference effect
with tt continuum BG
→ Dip search

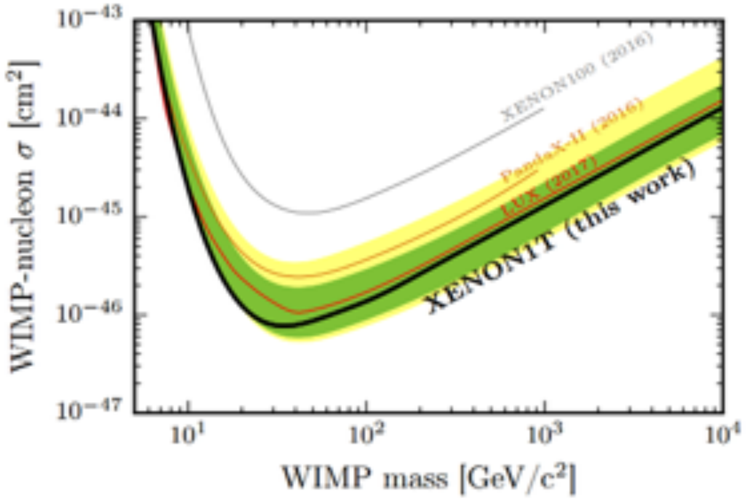


[S.Martin, PhysRevD.86 (2102)073016, Phys.Rev. D88 (2013)013004]
[S.Jung, J. Song, Y.-W. Yoon Phys.Rev. D92 (2015) no.5]
[A. Djouadi, J. Ellis, J. Quevillon JHEP 1607 (2016) 105]
[M. Carena, Z. Liu JHEP 1611 (2016) 159]

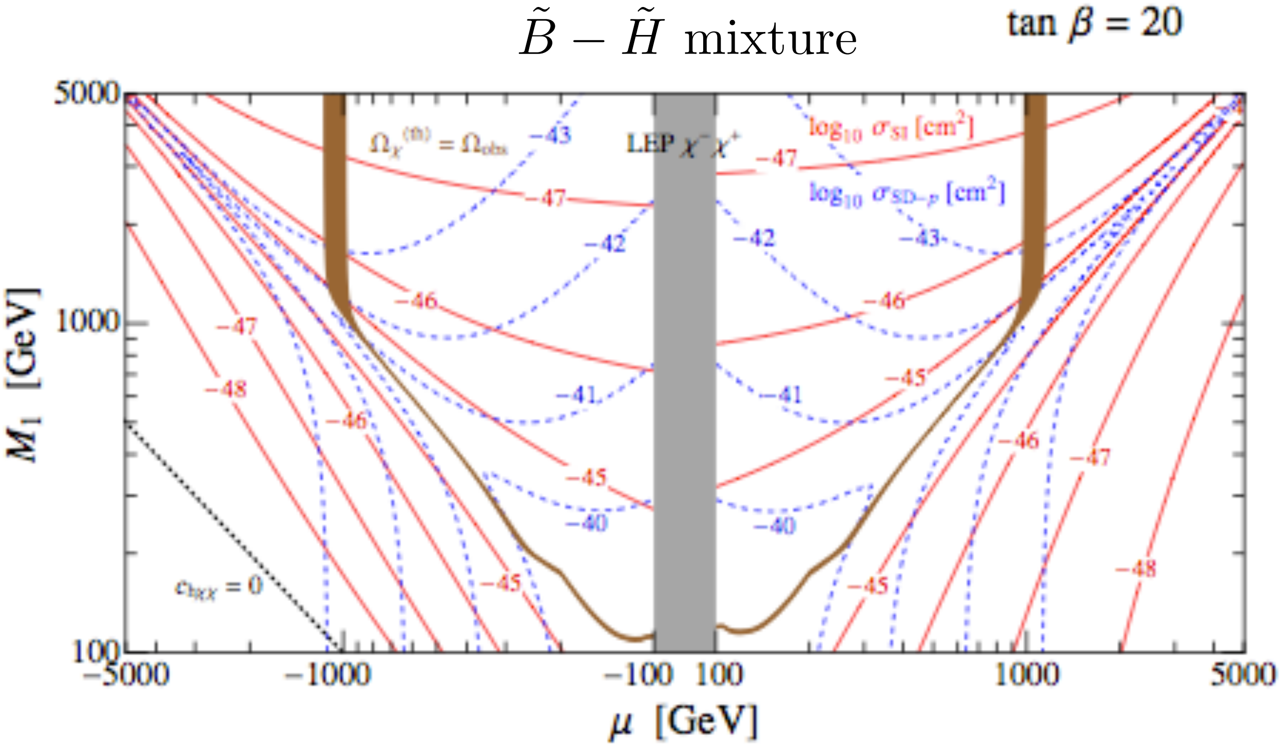
Null results from DM Direct Detection experiments







$$\sigma_{SI} < 10^{-45} \sim 10^{-46}\text{cm}^2$$



Typically, spin independent cross section in MSSM

$$10^{-44} \sim 10^{-47}\text{cm}^2$$

Not yet fully excluded but remaining regions are mainly pure states, blind spots, co-annihilation

No signature of SUSY anywhere yet

No evidence at LHC, Higgs measurement, Direct-Detection…

Is it meaning weak SUSY dead? Maybe not.

Where to hide?

just heavy, just above the current search reaches

compressed spectrum - compatible to co-annihilation
- consistent to null DM-DD result if DM is dominantly Bino

RPV, Stealth SUSY [J. Fan, M. Reece, J. Ruderman]

(g-2)μ : Hint for low scale new physics?

$$a_\mu(\mathrm{exp}) = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$

$$a_\mu(\mathrm{SM}) = \begin{cases} (11\,659\,182.8 \pm 4.9) \times 10^{-10} & \text{[K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, T. Teubner]} \\ (11\,659\,180.2 \pm 4.9) \times 10^{-10} & \text{[M. Davier, A. Hoecker, B. Malaescu, Z. Zhang]} \end{cases}$$

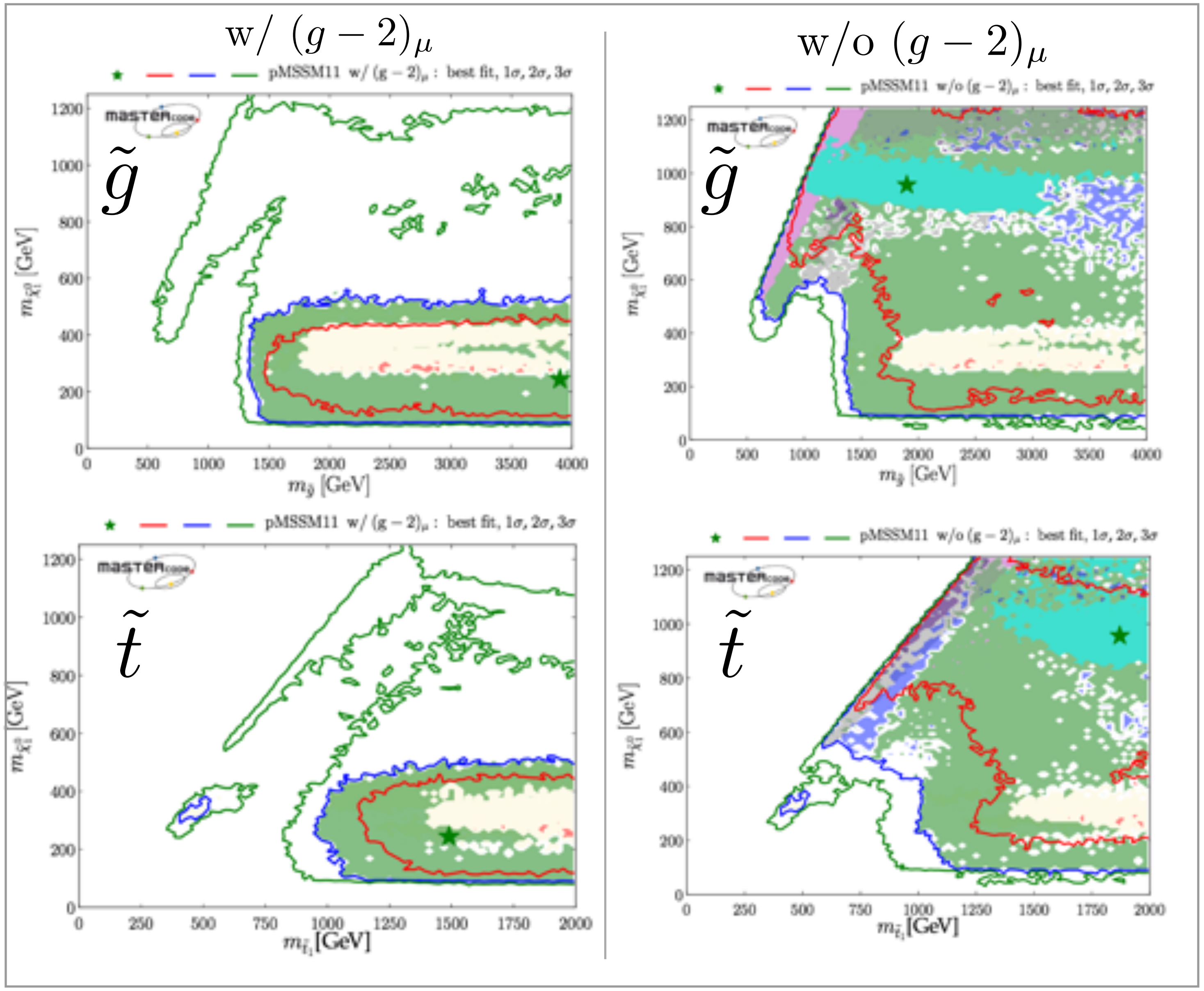
at least three of $\tilde{B}, \tilde{H}, \tilde{\mu}_L, \tilde{\mu}_R$ must be $\mathcal{O}(100\mathrm{GeV})$

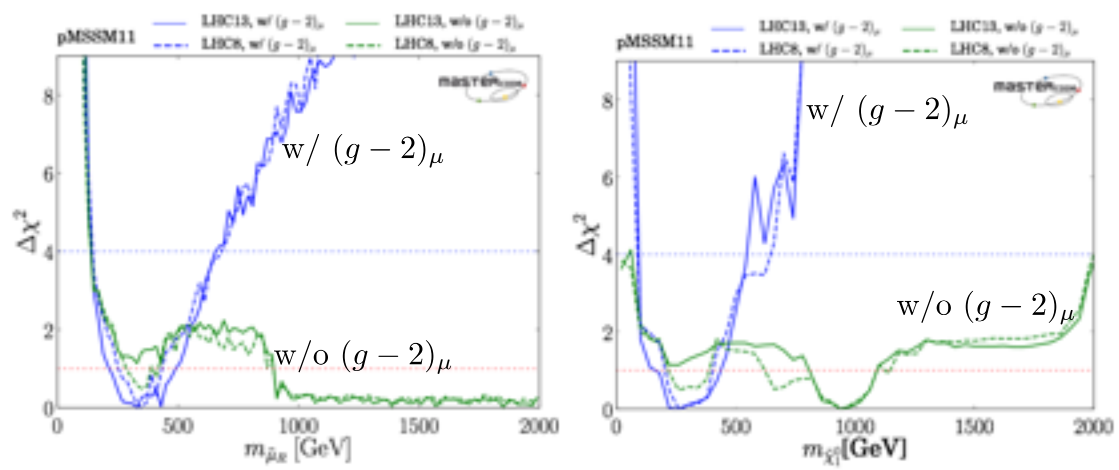
global fit with pMSSM11

Liklihood analysis of pMSSM11 [arXiv:1710.11091: E. Bagnaschi, et. al]

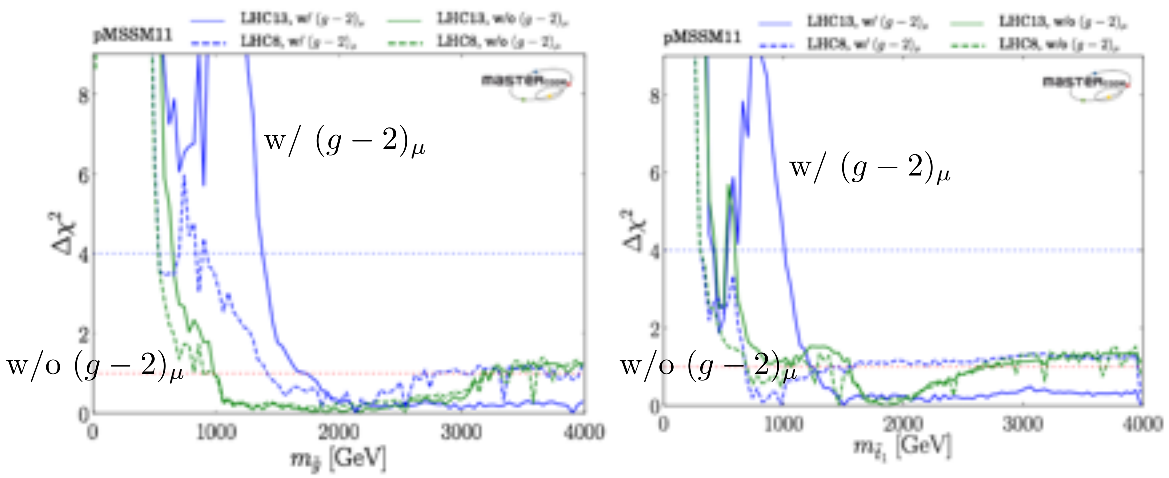
11 param. : $M_{1,2,3}, m_{\tilde{q}}, m_{\tilde{q}_3}, m_{\tilde{\ell}}, m_{\tilde{\ell}_3}, A, \mu, m_A, \tan\beta$

LHC, B-physics, Higgs, EWPO, DM, with/without $(g-2)_\mu$





with g-2 only light DM acceptable



interestingly, without $(g-2)_\mu$ prefer lighter mass spectrum (heavy DM and compressed)

DM co-annihilation processes important. heavy or compressed spectrum favored: Is it fine tuning?

Naturalness

$$-\mathcal{L}_{\rm SM} = -\mu^2 H^\dagger H$$

μ : only dimension full parameter ~ 100 GeV

d=2

$$+\mathcal{L}_{\rm kin} + g A_\mu \bar{f}\gamma^\mu f + y_{ij}\bar{f}_i H f_j + \lambda (H^\dagger H)^2$$

d=4

Naturalness

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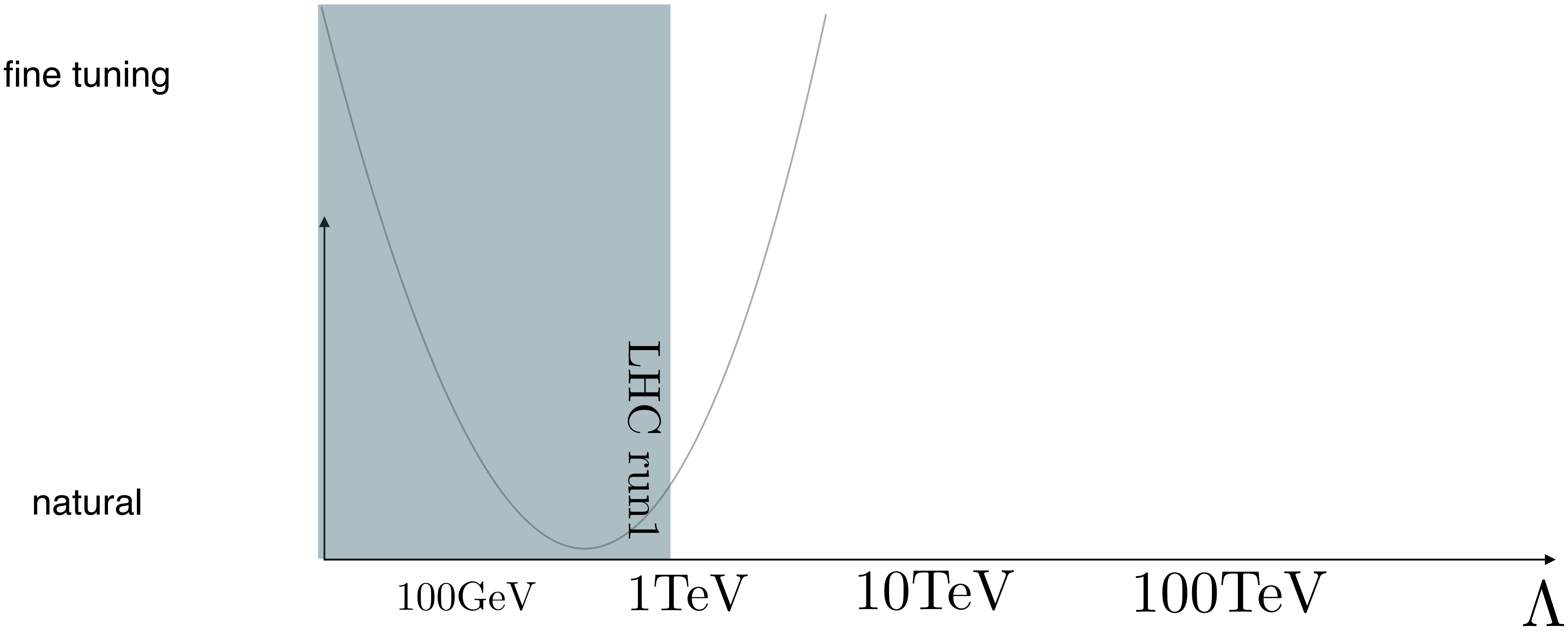

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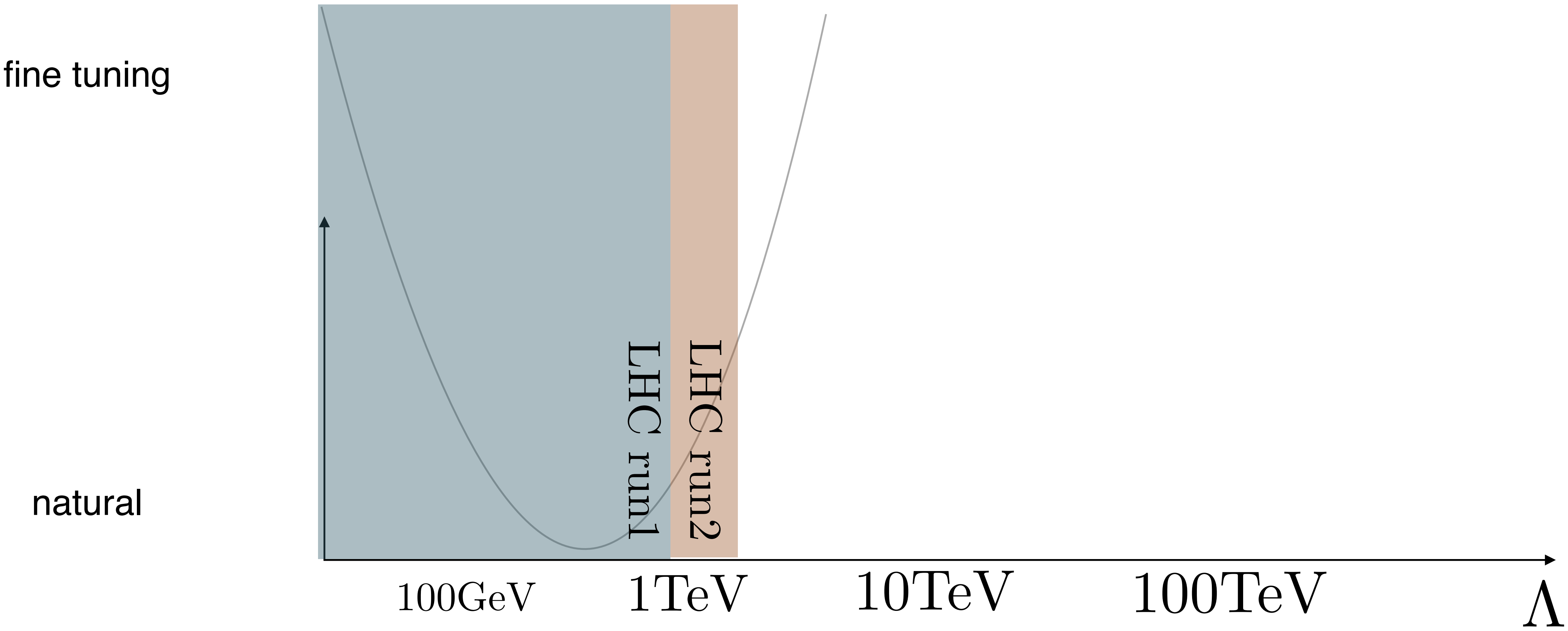

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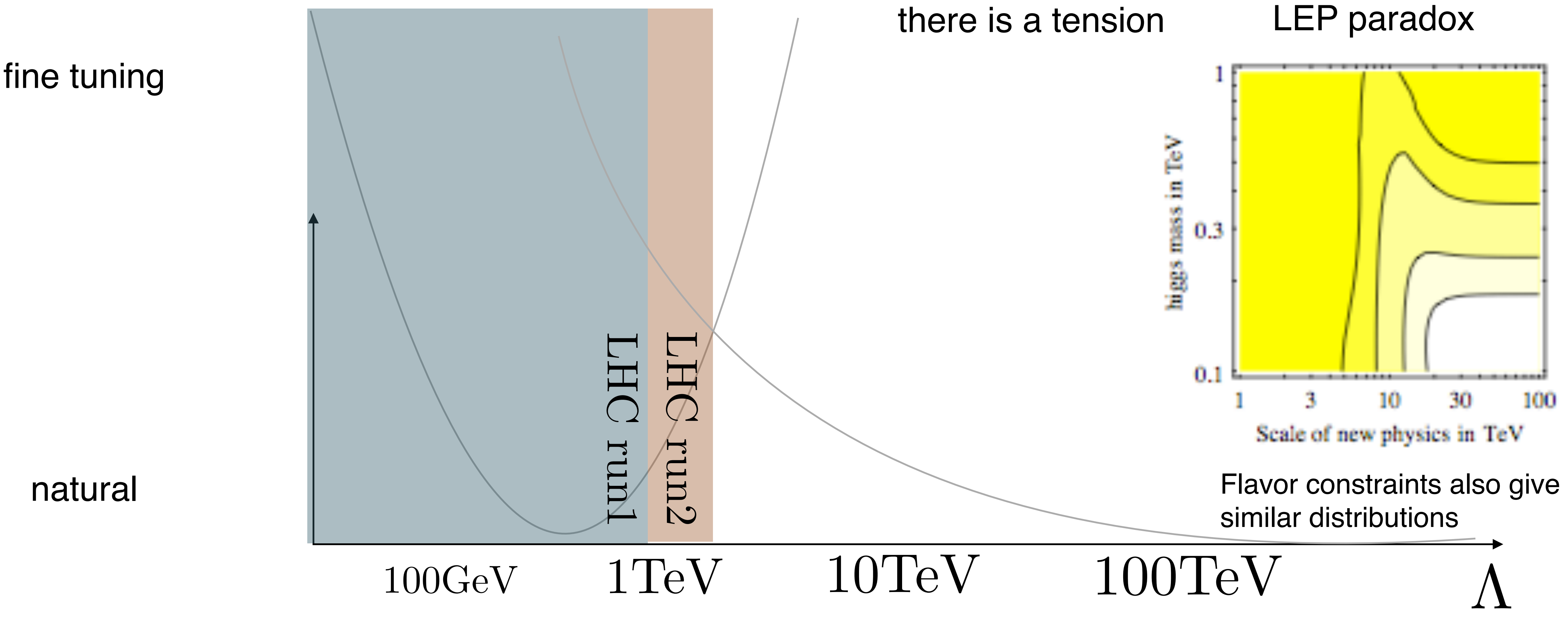
$$+\frac{b_{ij}}{\Lambda}(LH)(LH) + \frac{c_{ij}}{\Lambda}(\bar{f}_i\sigma_{\mu\nu}f_j)G^{\mu\nu} + \frac{c_{ijkl}}{\Lambda^2}(\bar{f}_i f_j)(\bar{f}_k f_l) \qquad \text{d>4}$$



there is a tension

Flavor constraints also give similar distributions

Naturalness

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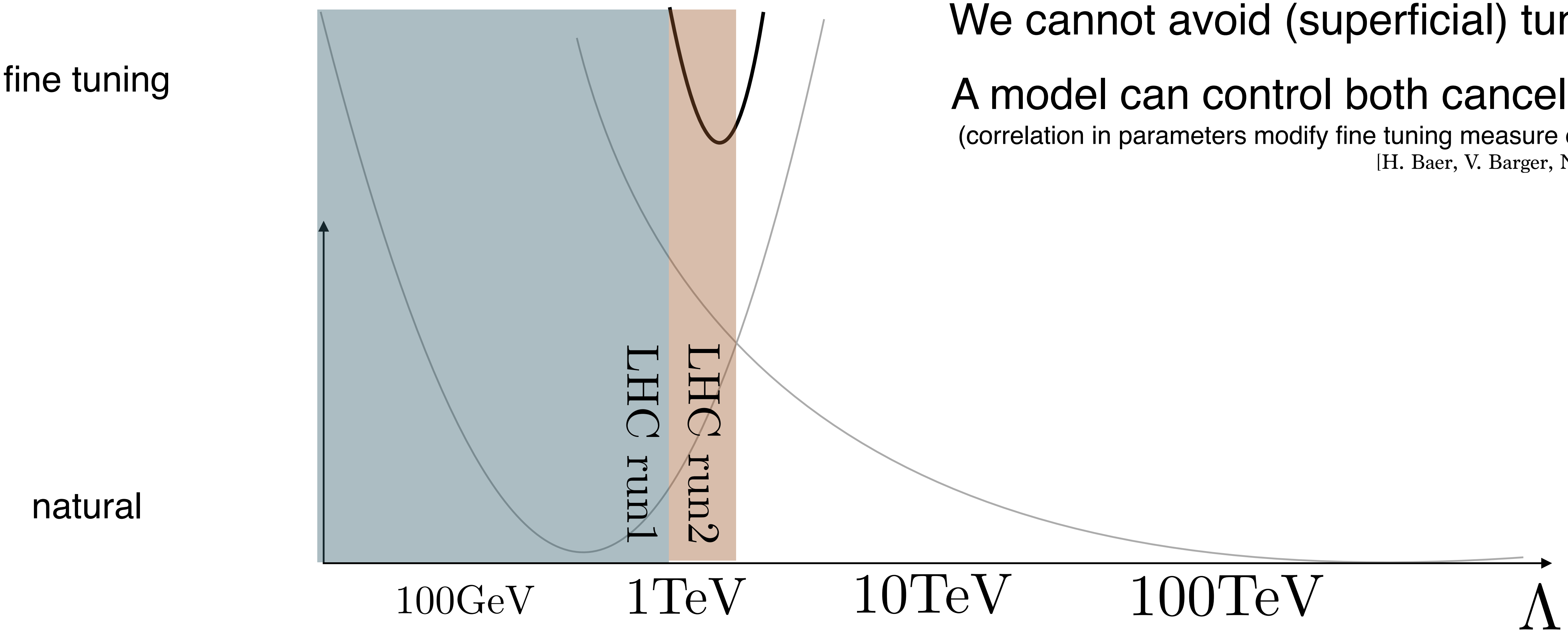

We cannot avoid (superficial) tuning!

A model can control both cancelations

(correlation in parameters modify fine tuning measure dep. on models)

[H. Baer, V. Barger, N. Nagata, M. Savoy]

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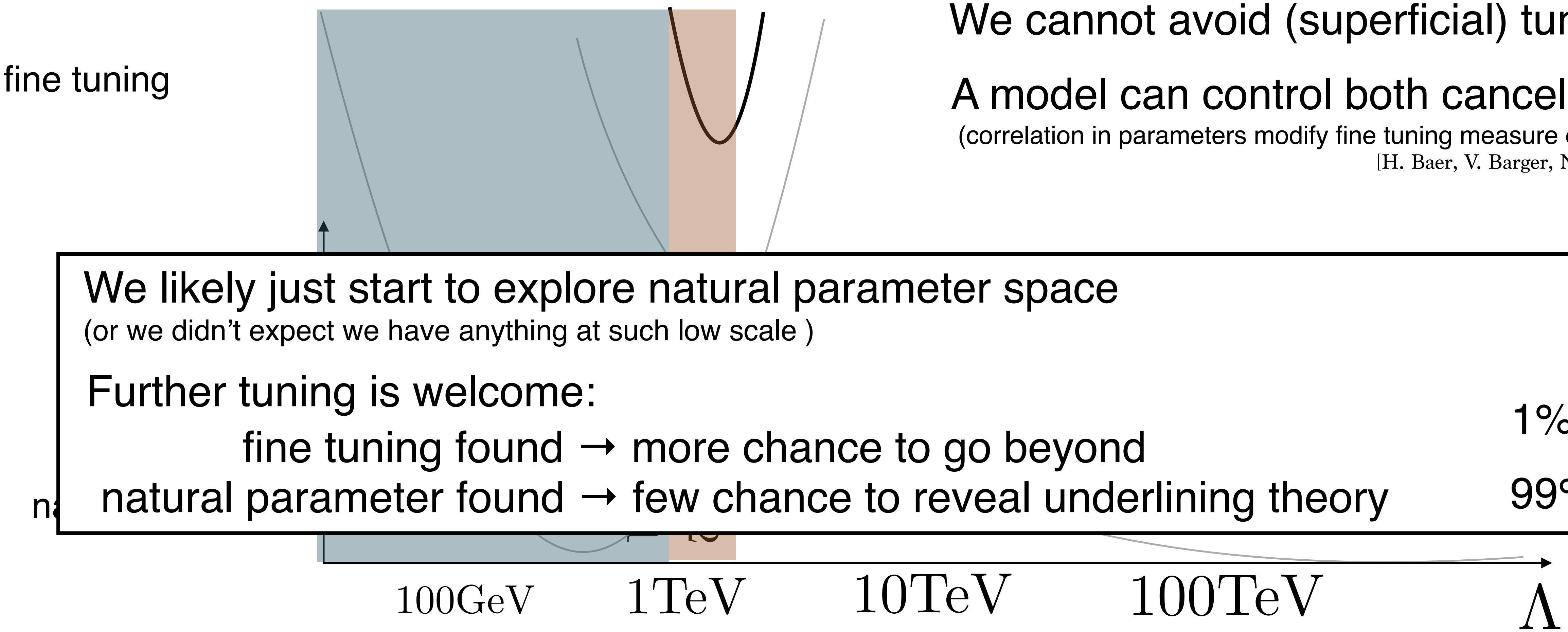

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We likely just start to explore natural parameter space

(or we didn't expect we have anything at such low scale)

Further tuning is welcome:

fine tuning found → more chance to go beyond

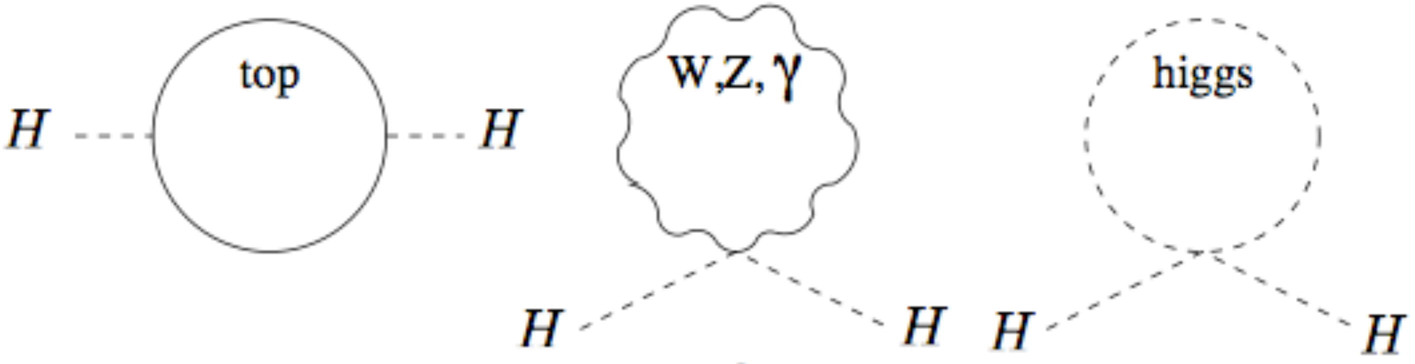
natural parameter found → few chance to reveal underlining theory

1%*99%

=

99%*1%

Naturalness



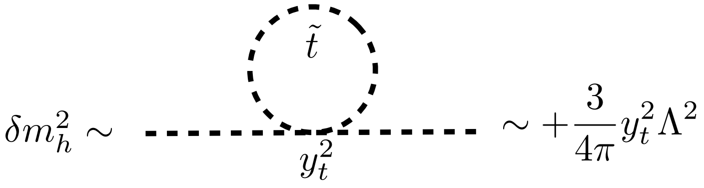
$$-\frac{3y_t^2}{8\pi^2}\Lambda^2 \qquad \frac{9g^2}{64\pi^2}\Lambda^2 \qquad \frac{3\lambda}{8\pi^2}\Lambda^2$$

~3.8% ~0.6% ~0.5%

What we expect next?

top contribution is the largest among radiative corrections in Higgs mass

→ light stop



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

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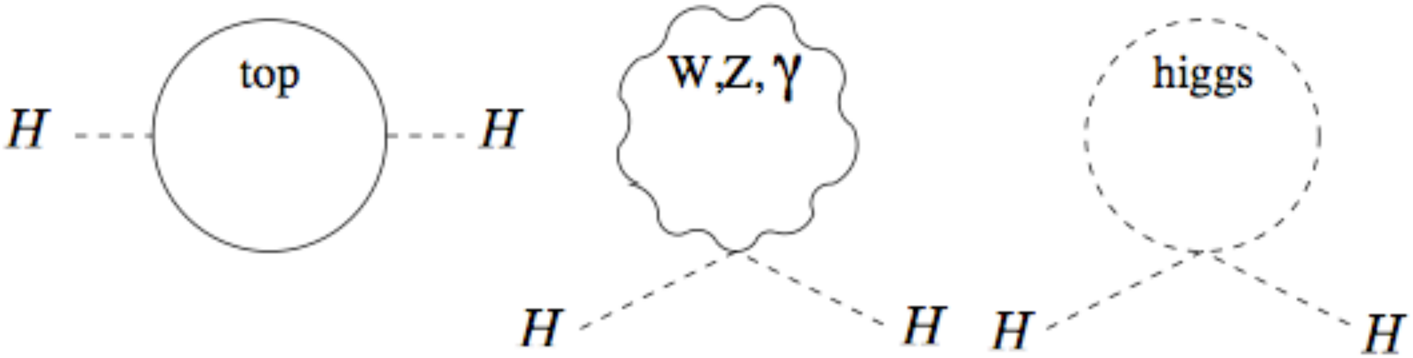

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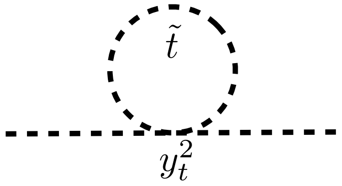
→ light stop $\delta m_h^2 \sim$  $\sim +\frac{3}{4\pi}y_t^2\Lambda^2$

problem is the observed Higgs mass

before higgs discovery, MSSM successfully predicts

$m_h \lesssim 130\text{GeV}$ unless stops are not too heavy

This is one of the collateral evidences of the SUSY

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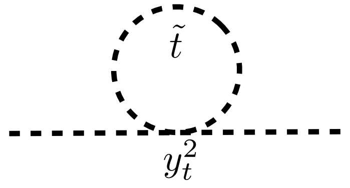

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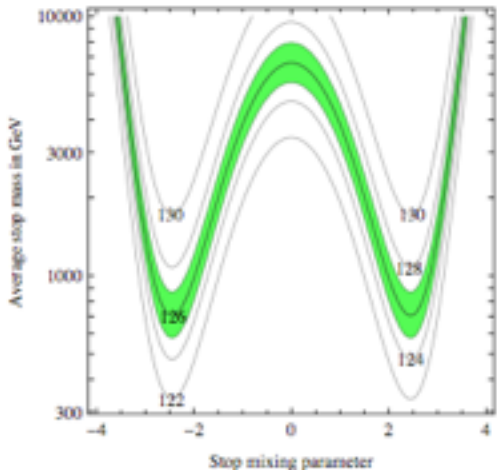
On the other hand, to obtain 125 GeV from the formula:

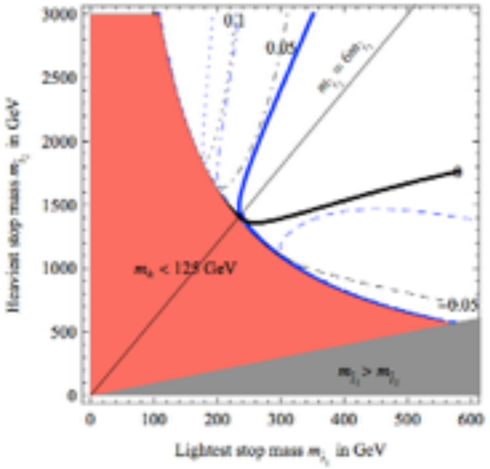
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} y_t^2 m_t^2 \sin^2\beta \left[\log\frac{m_S^2}{m_t^2} + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \dots$$

We need **heavy** or light but **highly mixed** stops

$5 \sim 10\ \mathrm{TeV}$ $\quad m_S$ as low as 600 GeV

m_{t_1} as low as 200 GeV





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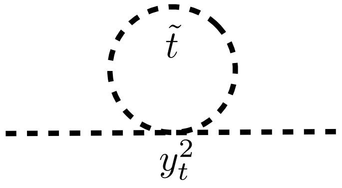

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We need **heavy** or light but **highly mixed** stops

$5 \sim 10$ TeV

m_S as low as 600 GeV

m_{t_1} as low as 200 GeV

Further, light stops require some tuning

to avoid S,T,U and Higgs couplings constraints

to reproduce higgs mass → stop blind spot

$$\mathcal{L}_{\text{eff}} = \left(y_t^2 - \frac{y_t^2 X_t^2}{m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2}\right) |H_u|^2 \left|\tilde{t}_l\right|^2. \quad X_t^* = \left(m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2\right)^{1/2}$$

[J. Fan, M. Reece, L-T Wang]

no one can guarantee next new physics looks no fine tuned

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Natural SUSY

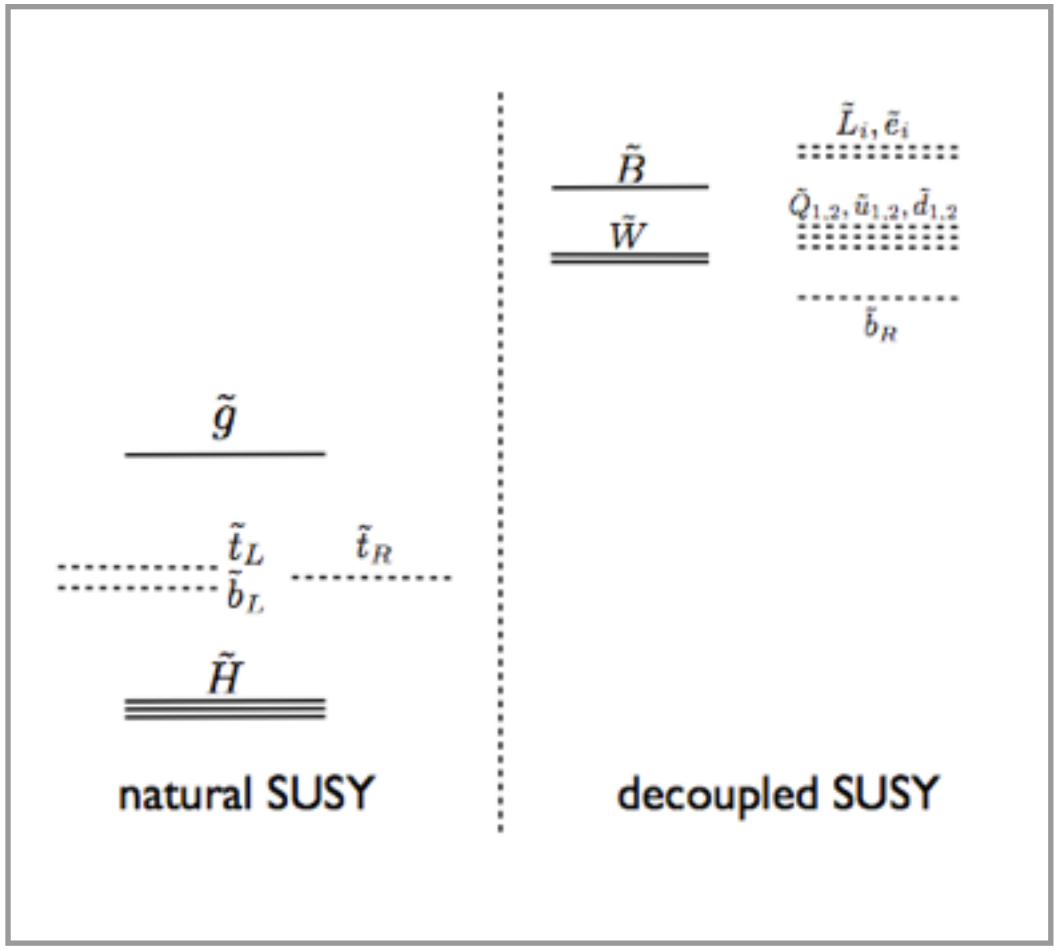
[M. Papucci, J. T. Ruderman, A. Weiler]

EWSB condition:

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

- Higgsinos: $\delta m_H^2 = \mu^2$
- Stops: $\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{\text{stop}}^2 \log\frac{\Lambda}{Q}$
- Gluinos: $\delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4}|M_3|^2\left(\log\frac{\Lambda}{Q}\right)^2$

2-loop eff.



Higgsino-LSP preferable

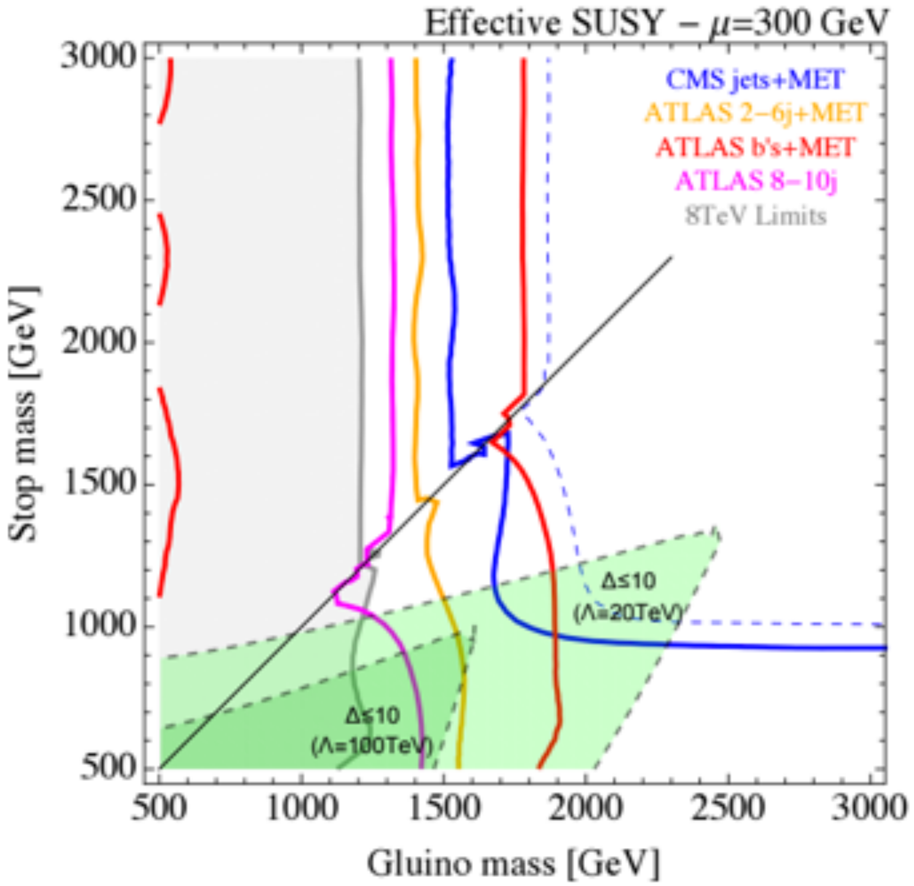
natural spectrum:	light higgsino	200-350 GeV
	light stop	500-700 GeV
	not too heavy gluino	900-1500 GeV

How natural? the current status of natural SUSY ?

[arXiv: 1610.08059, M. R. Buckley, D. Feld, S. Macaluso, A. Monteux, D. Shih]

Effective SUSY:

1st/2nd squarks decoupled



$$\Delta = \max_{M_i} \Delta_{M_i^2} \qquad \Delta_{M^2} = \frac{\partial \log m_h^2}{\partial \log M^2}$$

- Higgsinos: $\delta m_H^2 = \mu^2$
- Stops: $\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{\text{stop}}^2 \log \frac{\Lambda}{Q}$
- Gluinos: $\delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4} |M_3|^2 \left(\log \frac{\Lambda}{Q}\right)^2$

2-loop

important to take the mass correlation into account

heavy $\tilde{g}$ imply heavy $\tilde{t}$, vice versa

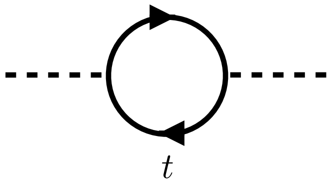
more natural neither $\tilde{g}$ nor $\tilde{t}$ observed than one observed

$$\Delta \leq 10 \text{ still ok}$$

Stop searches

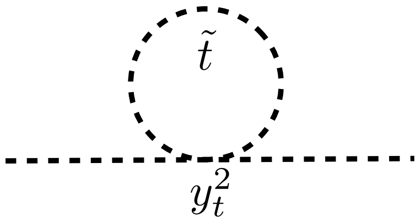
Solving hierarchy problem requires top partner: stop

$\delta m_h^2 \sim$



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

$\delta m_h^2 \sim$



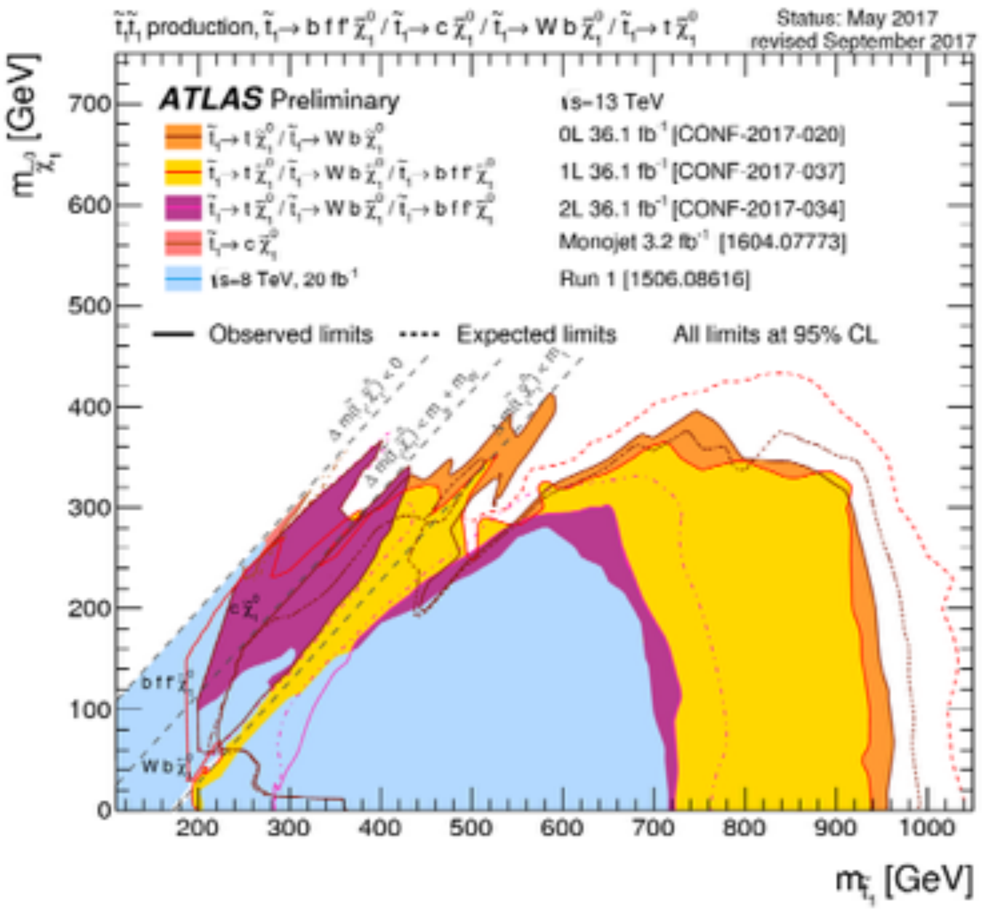
$\sim +\frac{3}{4\pi} y_t^2 \Lambda^2$

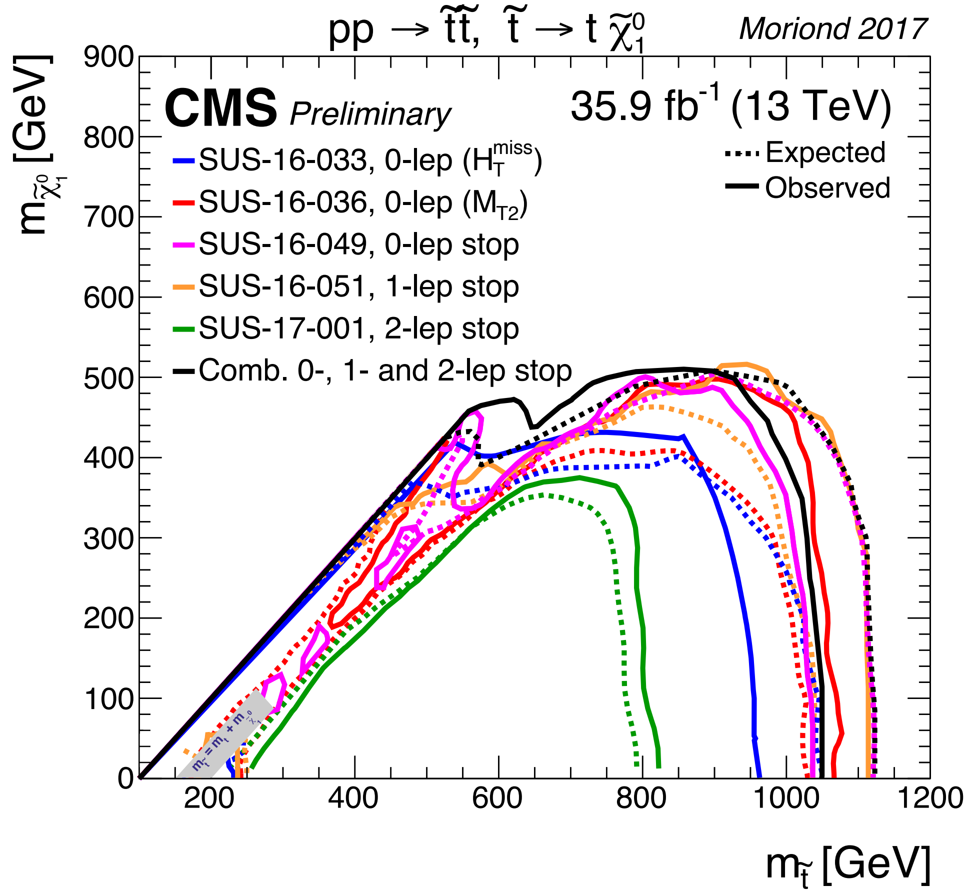
current status (Bino LSP: tt+missing)

up to ~1 TeV excluded ?

CMS-PAS-SUS-16-049

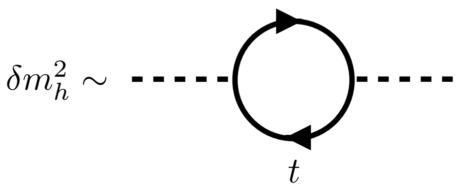
CMS-PAS-SUS-16-051





Stop searches

Solving hierarchy problem requires top partner: stop



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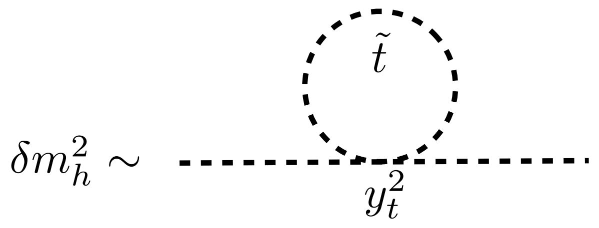

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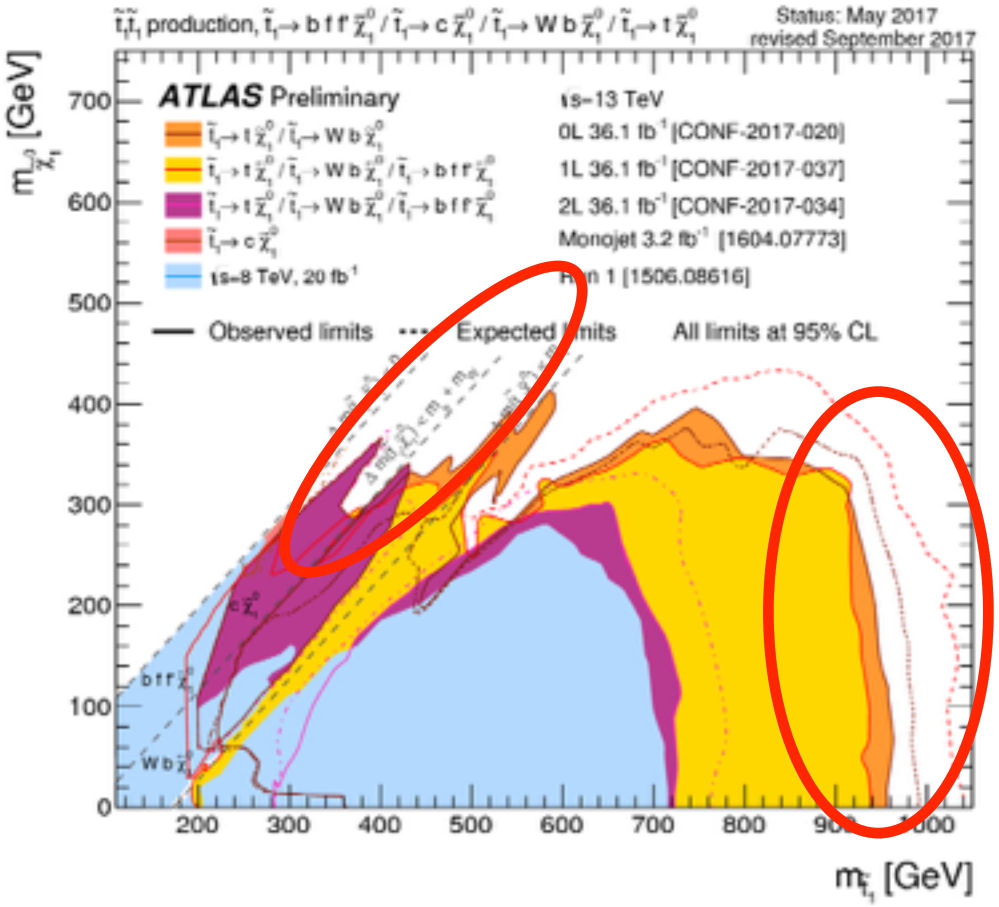
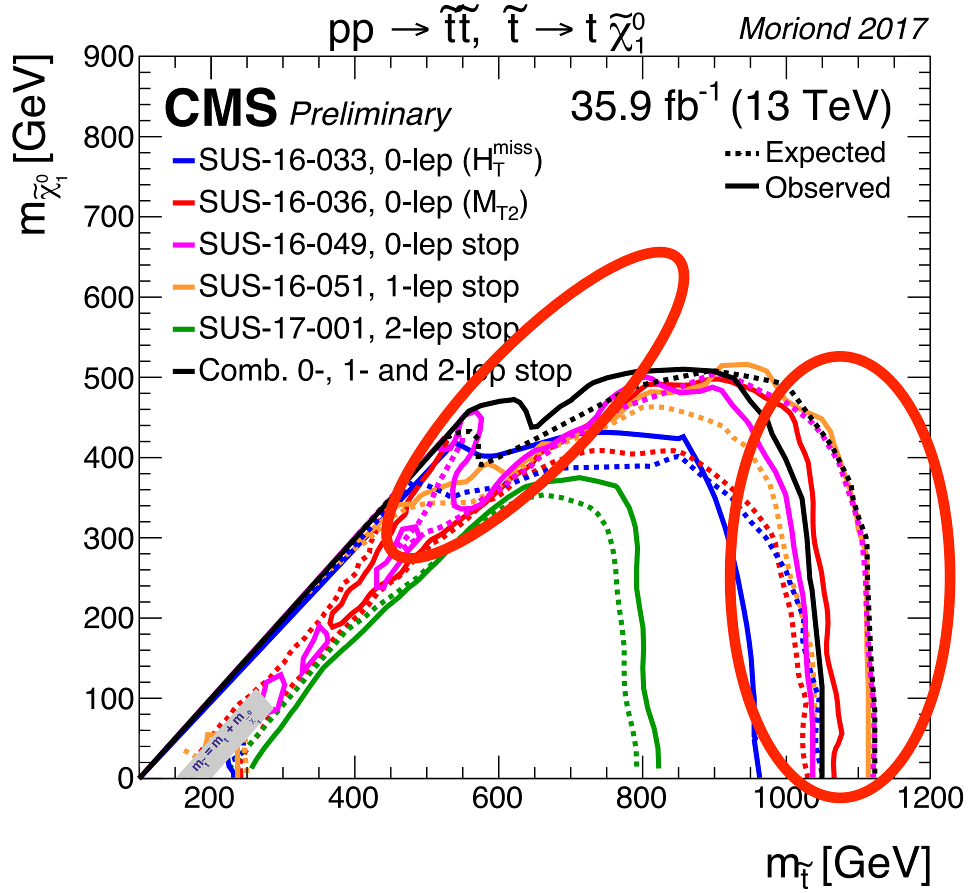




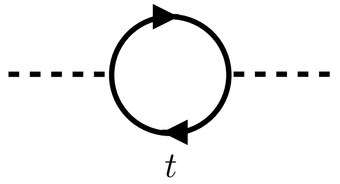
At the search frontier, additional care must be taken

very heavy region: boosted top reconstruction

compressed region: mono-jet, soft-leptons

Stop searches

Solving hierarchy problem requires top partner: stop



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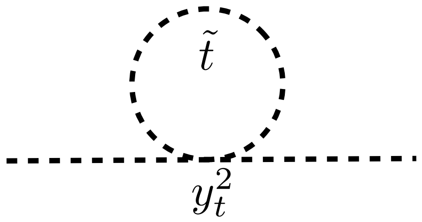

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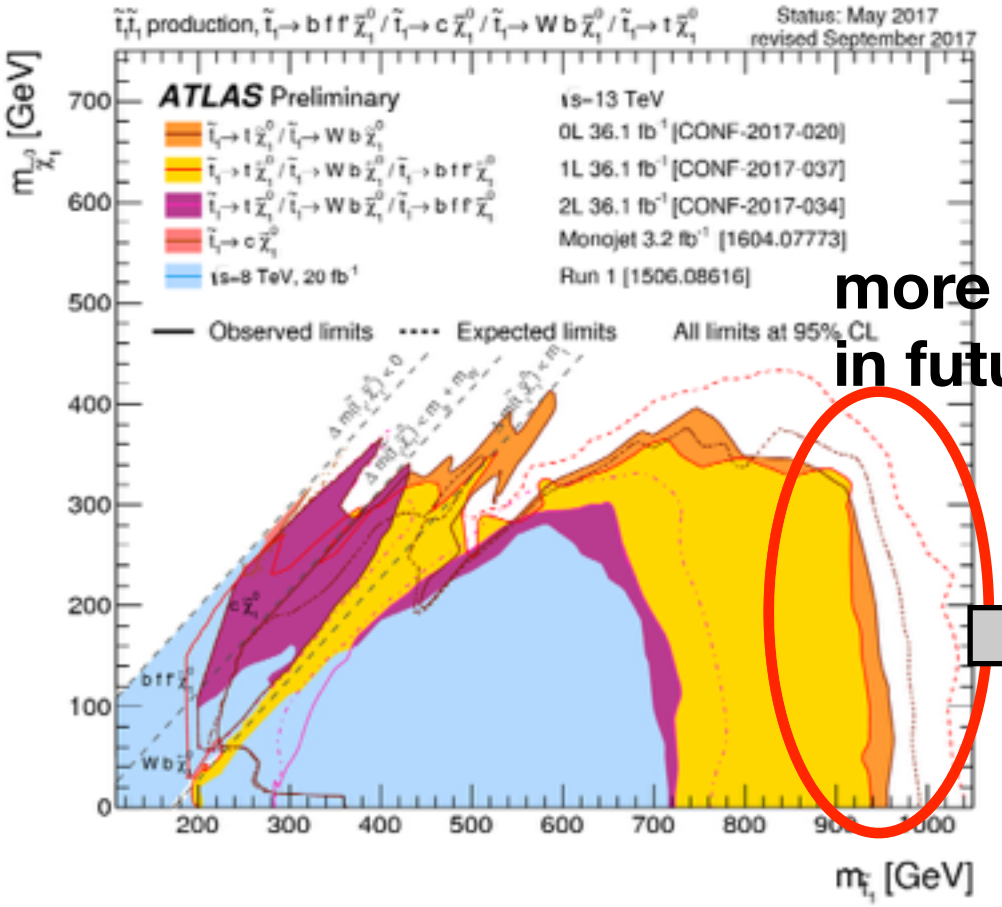
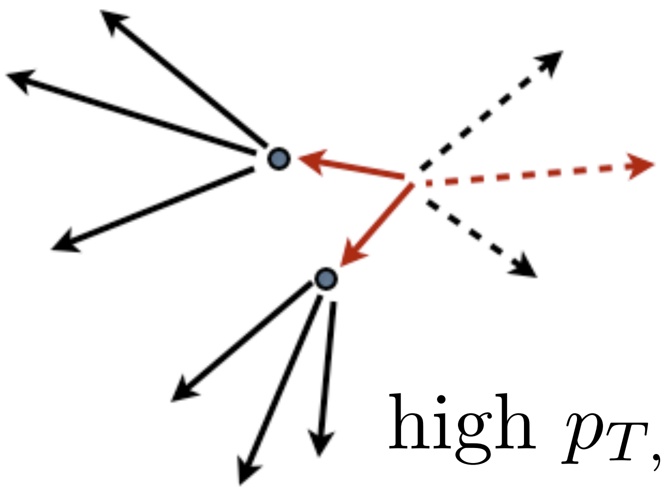
CMS-PAS-SUS-16-049
CMS-PAS-SUS-16-051



more boosted in future



high $p_{T,t}$ = high $\not{E}_T$

Boosted kinematic regime is most sensitive to New Physics

At the search frontier, additional care must be taken

very heavy region: boosted top reconstruction

compressed region: mono-jet, soft-leptons

What changes with a boost?

roughly speaking 1 TeV stop provide 500 GeV pT tops

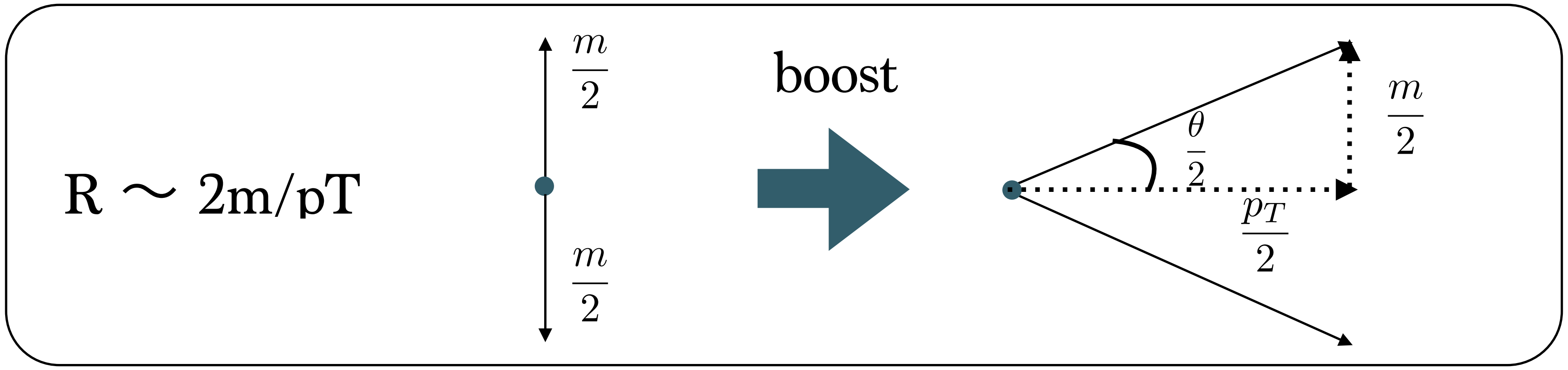
With a boost, jets from top decay start to be overlapping

At LHC

Cone size 0.4

→ pT > 2mW/0.4 ~ 400 GeV

pT > 2mt/0.4 ~ 900 GeV



R $\sim$ 2m/pT

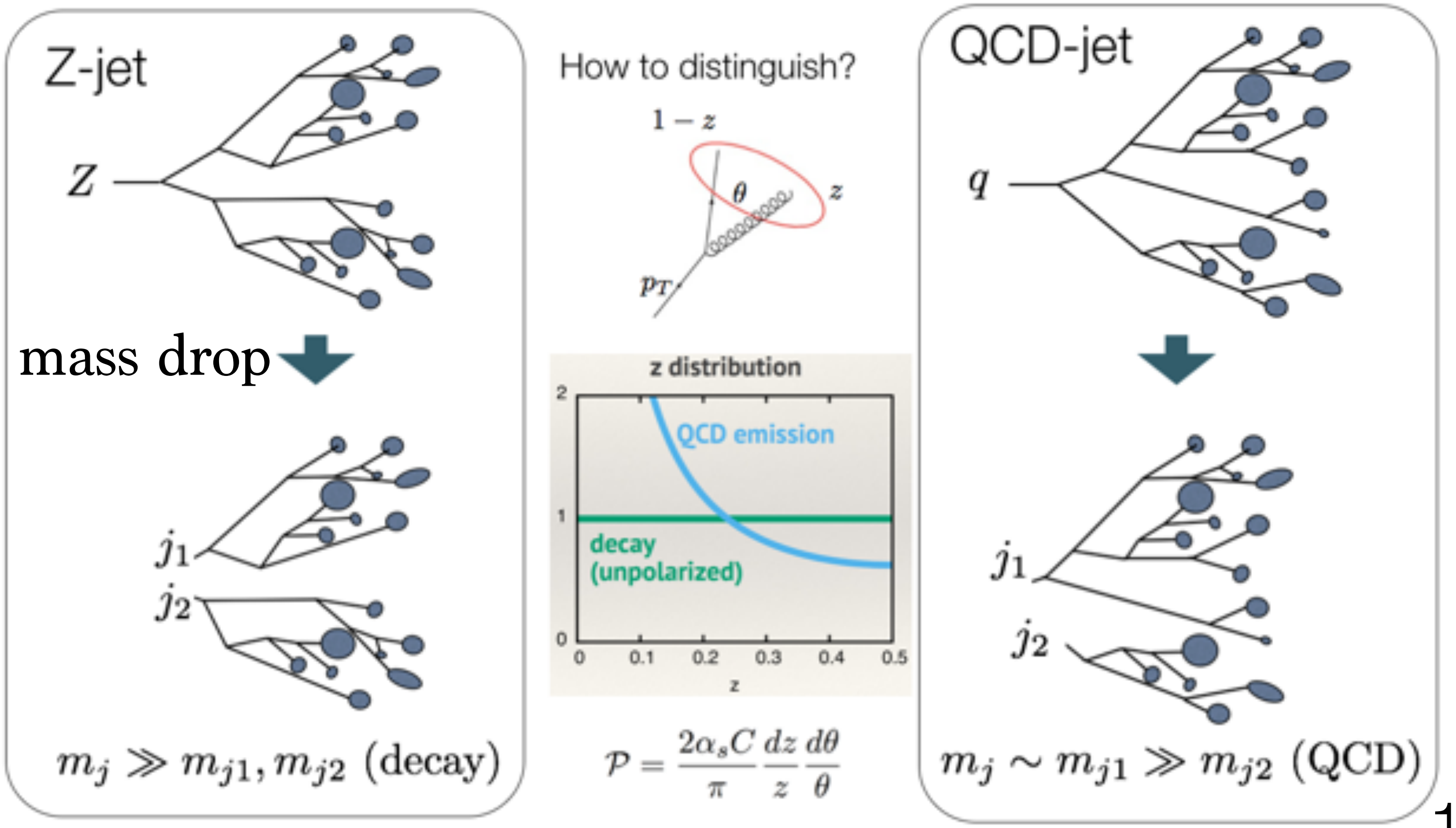
boost

more reasonable to consider fat-jet

and distinguish from QCD jets

using jet substructure

[J. M. Butterworth, A. R. Davison, M. Rubin, G. P. Salam]



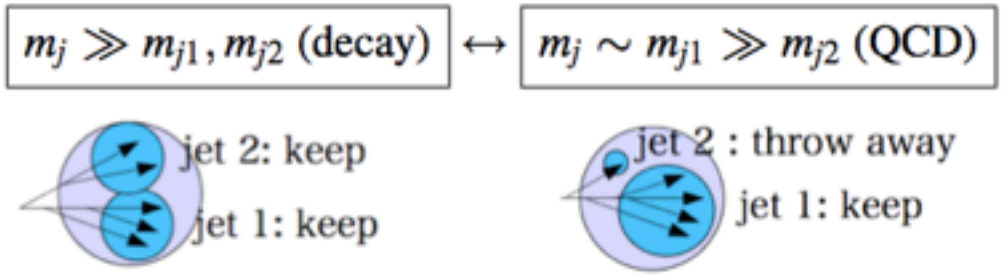
mass drop

HEPTopTagger Algorithm

JHEP 1010:078,2010. arXiv:1006.2833 [hep-ph]
[T. Plehn, M. Spannowsky, MT, D. Zerwas]

1. define fatjet C/A, R=1.5 to capture 200 GeV tops

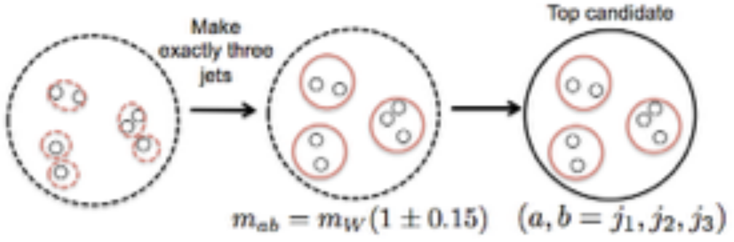
2. look for subjets by mass drop



3. select paring with filtered mass closest to top mass

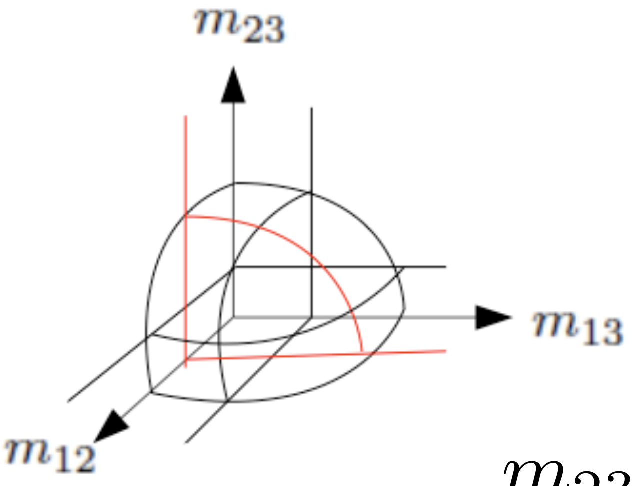
$$|m^{\text{filt}}_{jjj} - m_t| < 25 \text{ GeV}$$

4. mass ratio check (top kinematics consistency)

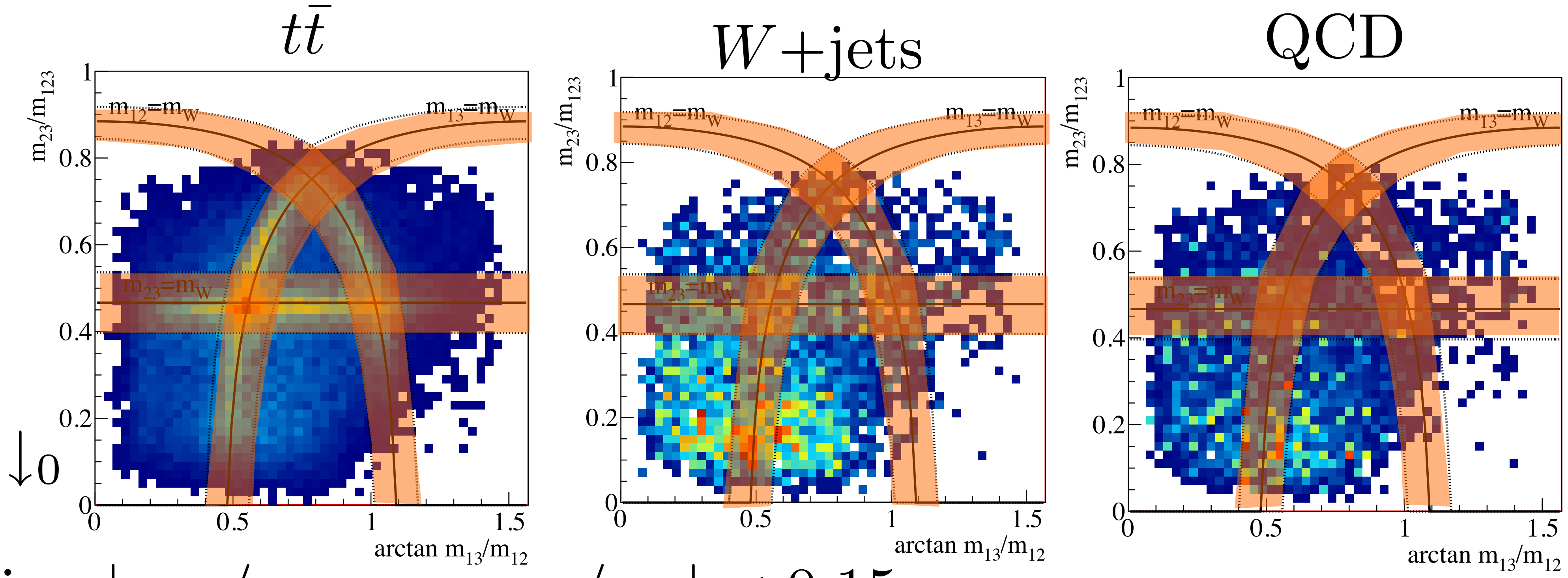


$$3 \text{ subjets: } p_1, p_2, p_3 \to m_{12}, m_{13}, m_{23}$$

$$m_t^2 \simeq m_{123}^2 \simeq m_{12}^2 + m_{13}^2 + m_{23}^2 \to \text{2D mass ratios}$$



$m_{23} \downarrow 0$

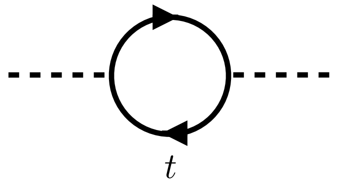


W mass condition $|m_{ij}/m_{123} - m_W/m_t| < 0.15$

Stop searches

Solving hierarchy problem requires top partner: stop

$\delta m_h^2 \sim$



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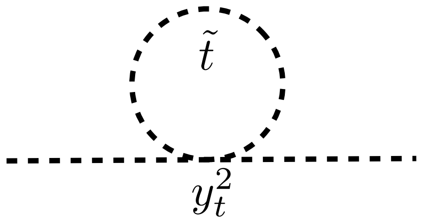

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current status (Bino LSP: tt+missing)

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CMS-PAS-SUS-16-049

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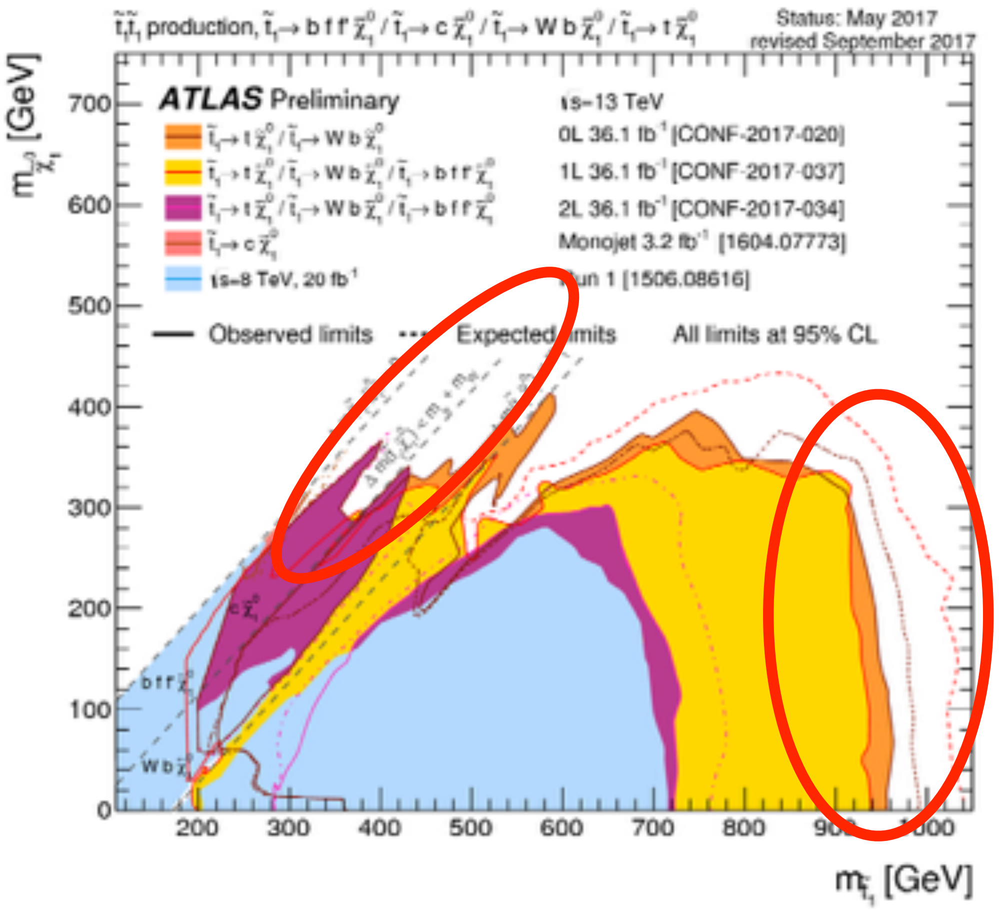
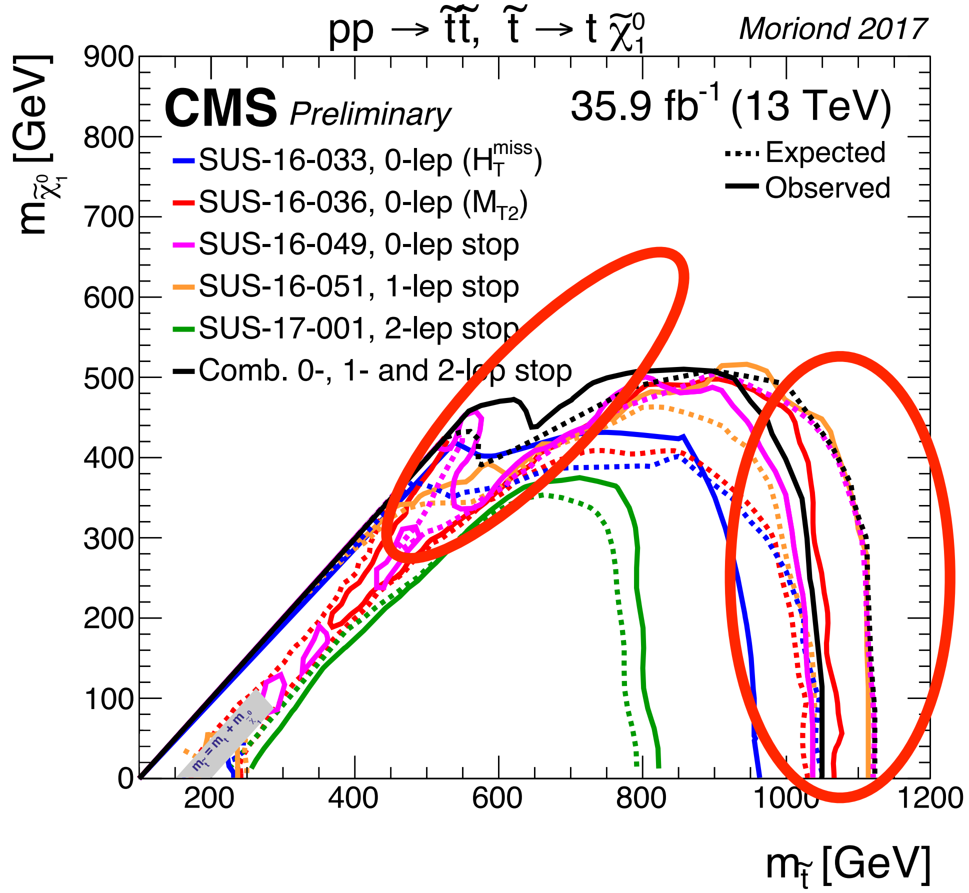




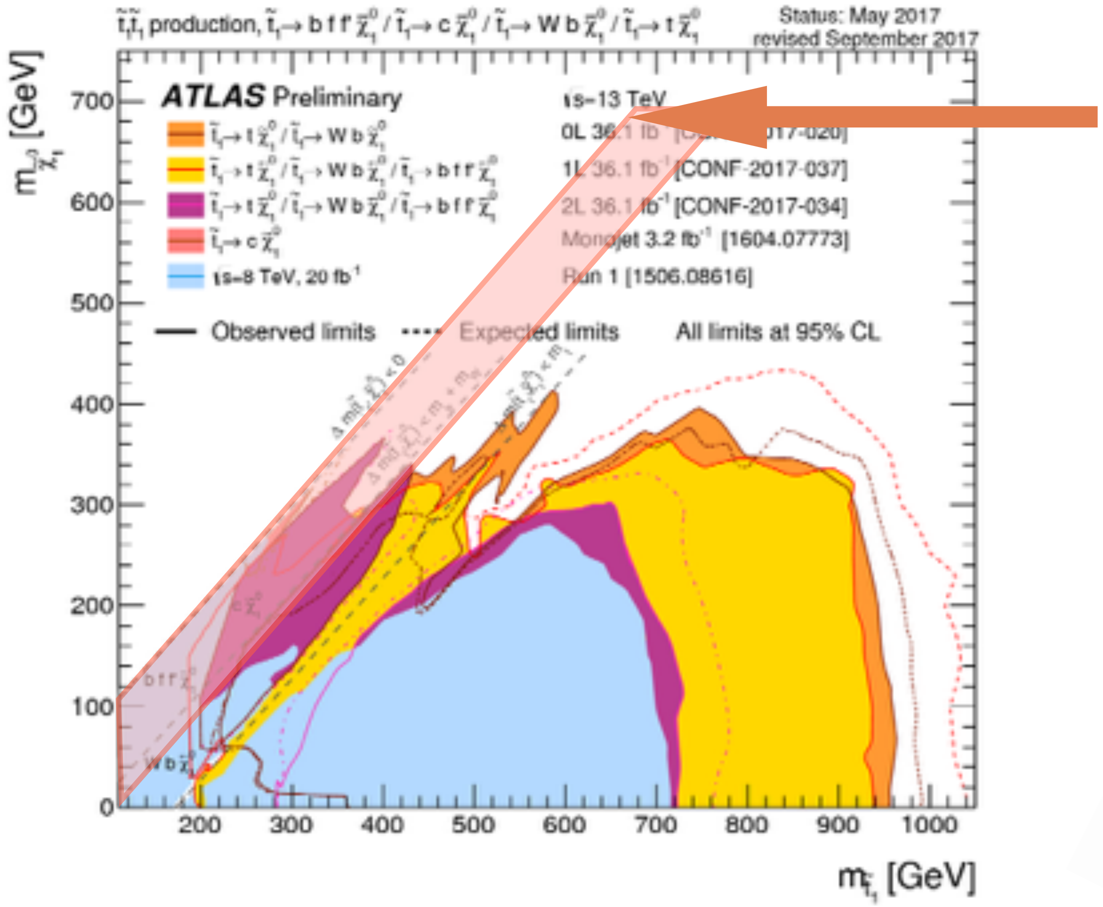
At the search frontier, additional care must be taken

very heavy region: boosted top reconstruction

compressed region: mono-jet, soft-leptons

Stop search (compressed region)

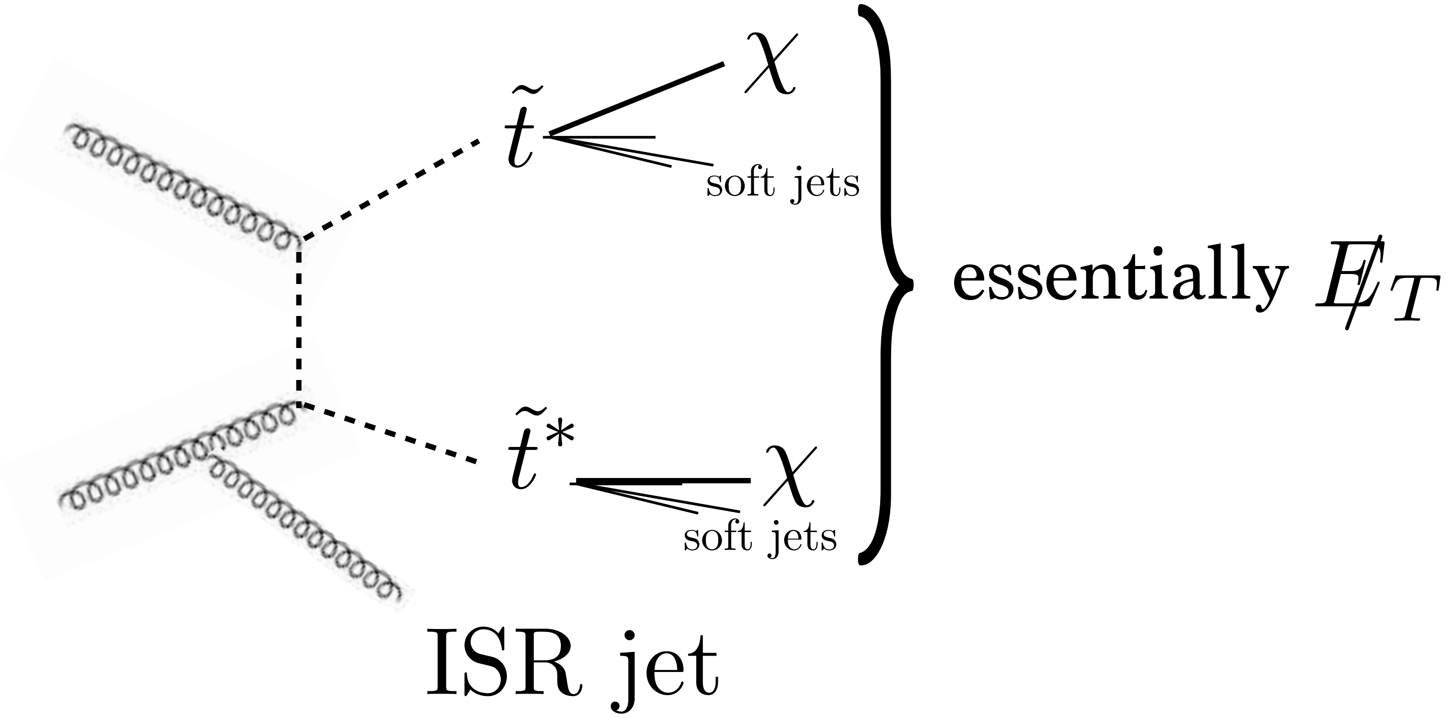
current status



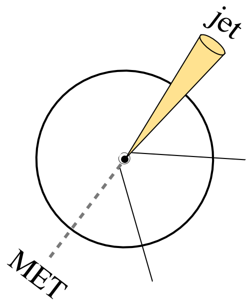
compressed mass spectrum

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

mono-jet search: sensitive to this region

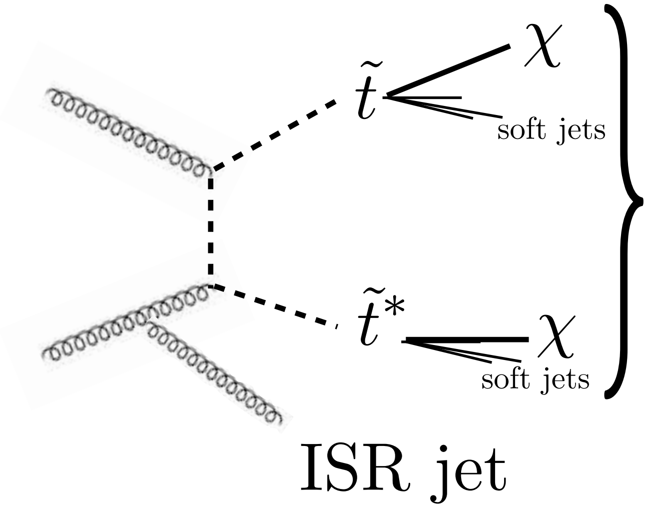


mono-jet search

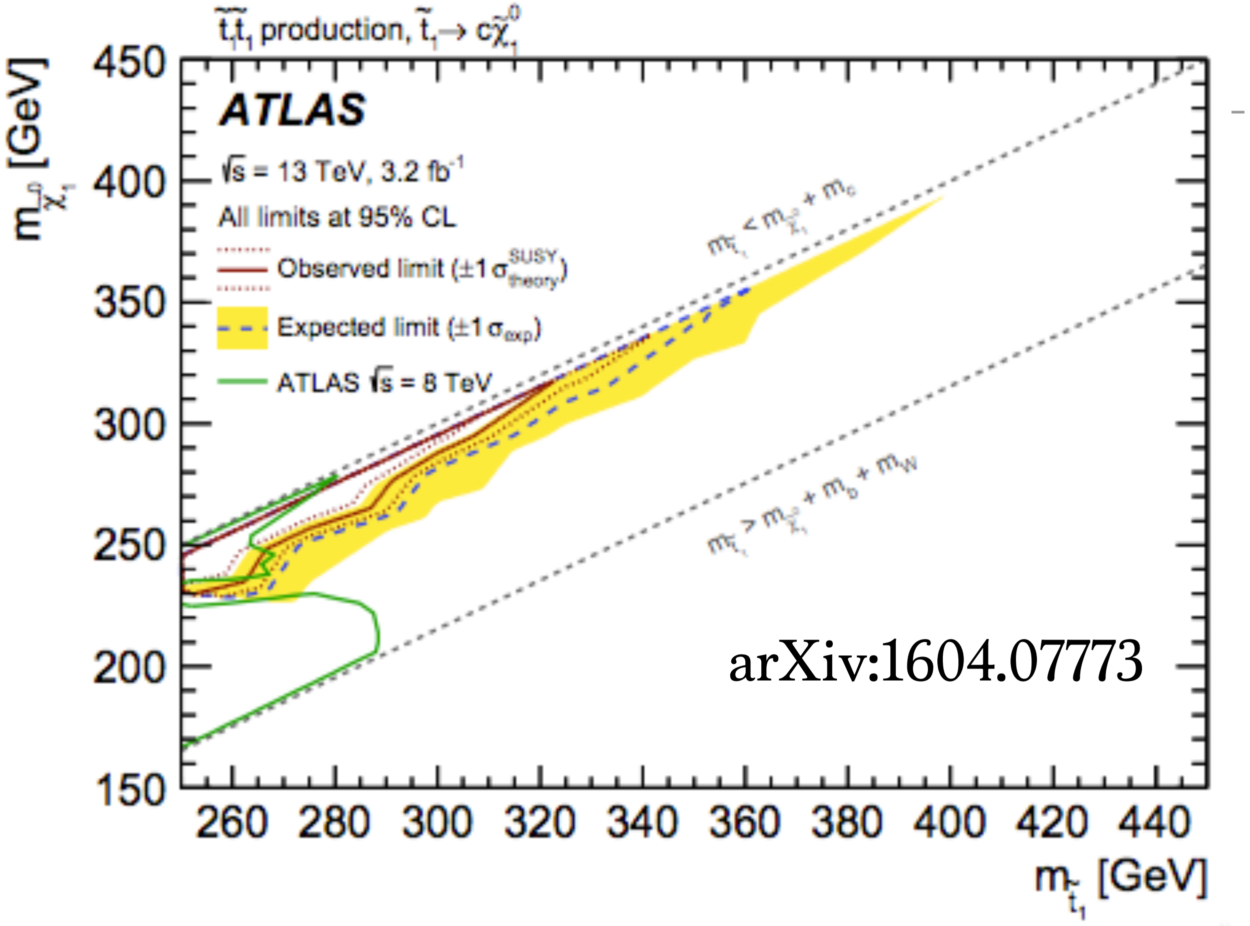


simple strategy

BG: Z+jets

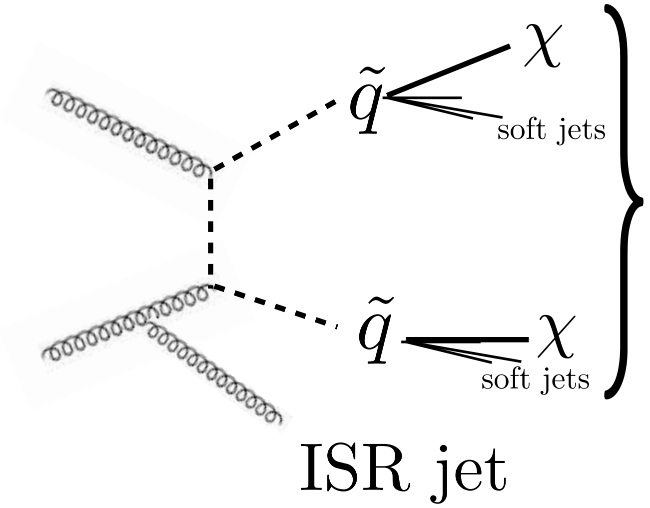


essentially $\not{E}_T$

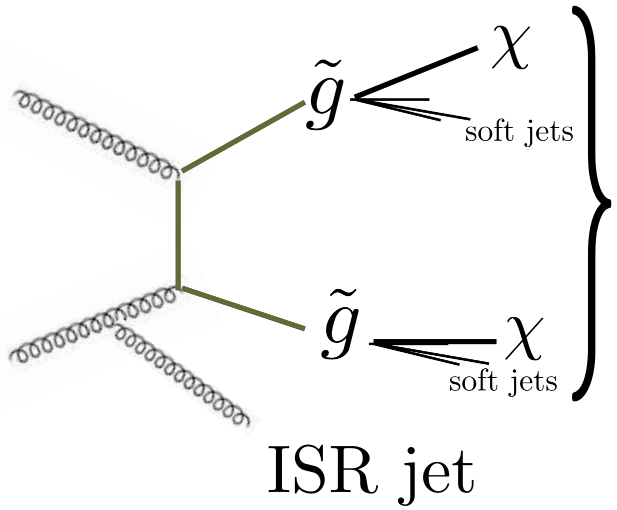


arXiv:1604.07773

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



essentially $\not{E}_T$

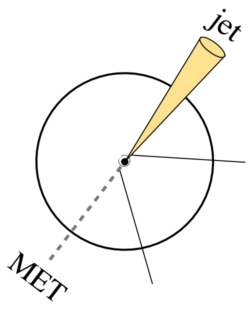


essentially $\not{E}_T$

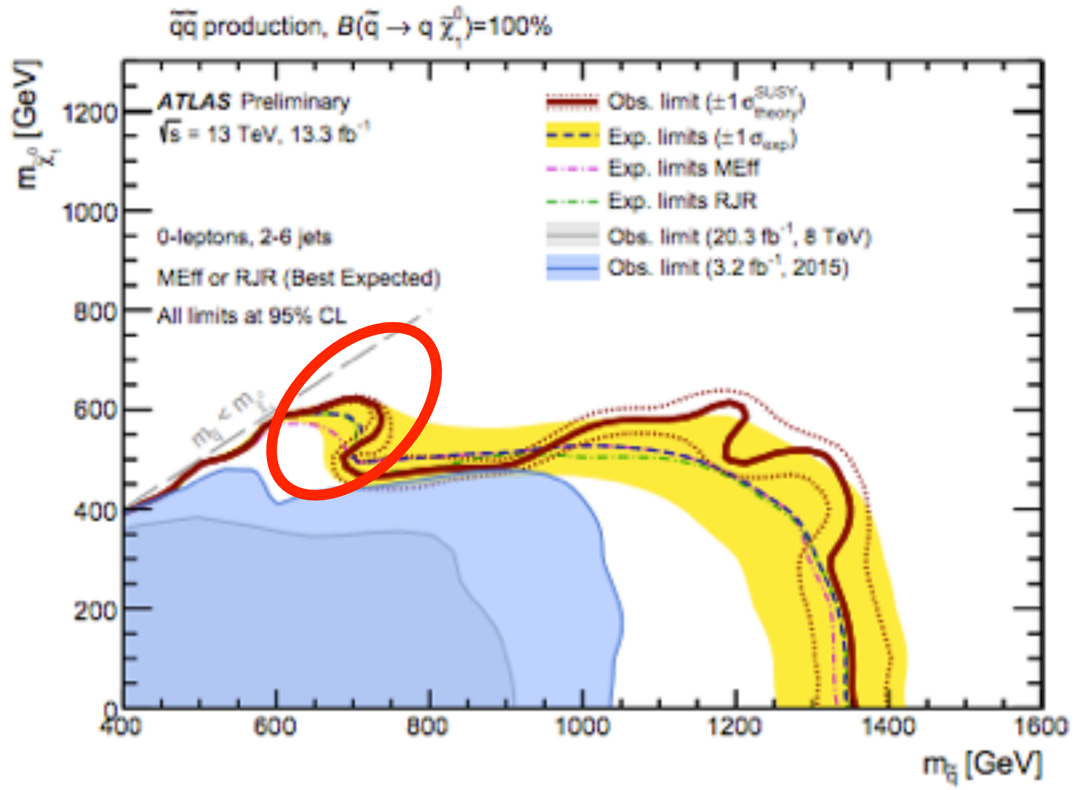
gluino, squark, other simplified model, for whatever sensitive

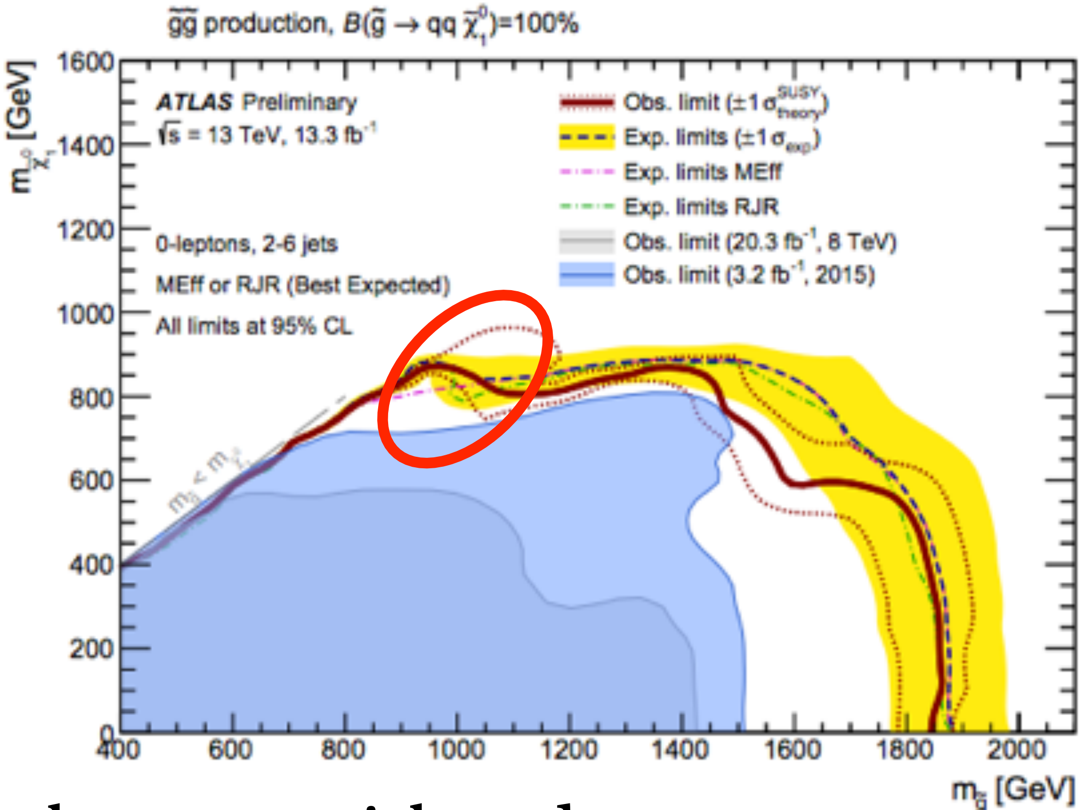
http://arxiv.org/pdf/1409.2893.pdf

mono-jet search



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





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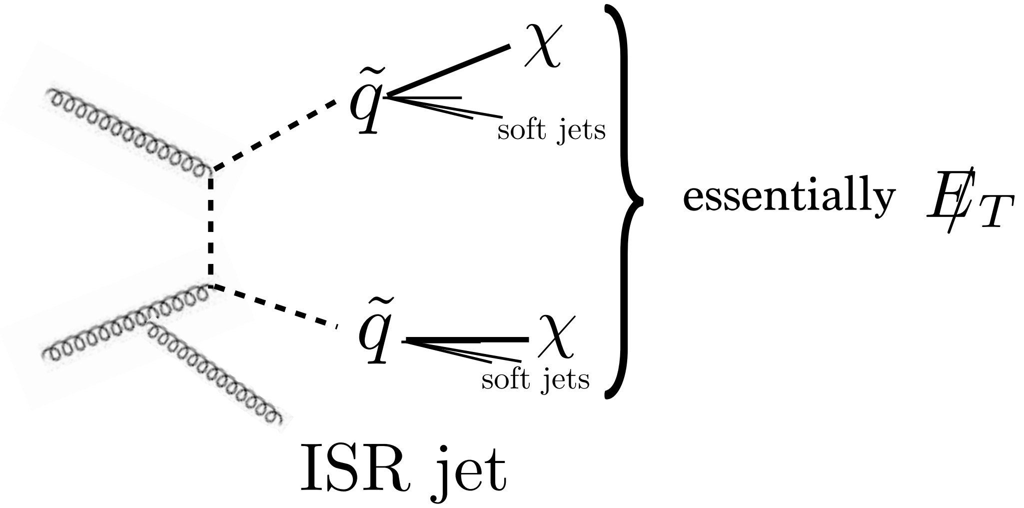
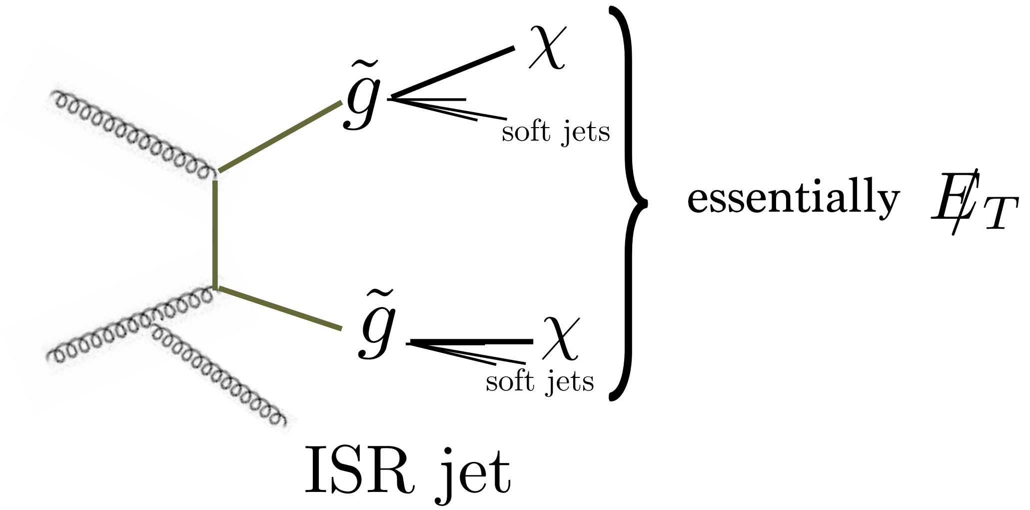




gluino, squark, other simplified model, for whatever sensitive

http://arxiv.org/pdf/1409.2893.pdf

mono-jet search

Advantage

whatever particles degenerate with DM can be probed

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

Disadvantage

whatever particles degenerate with DM can be probed

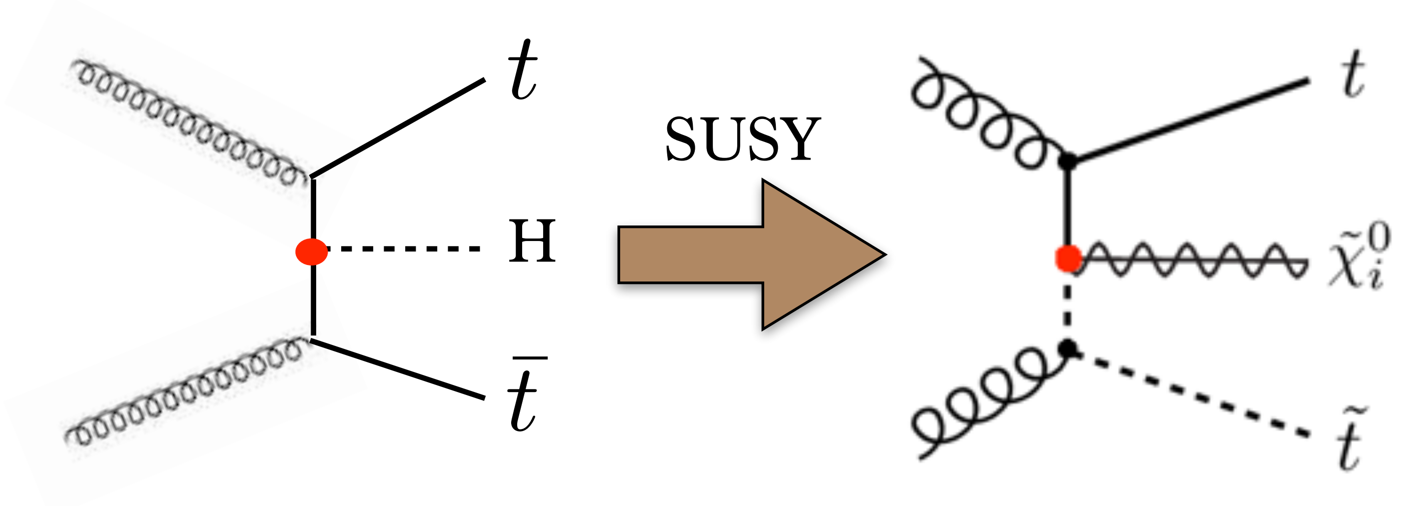
= we cannot distinguish among the particles assumption

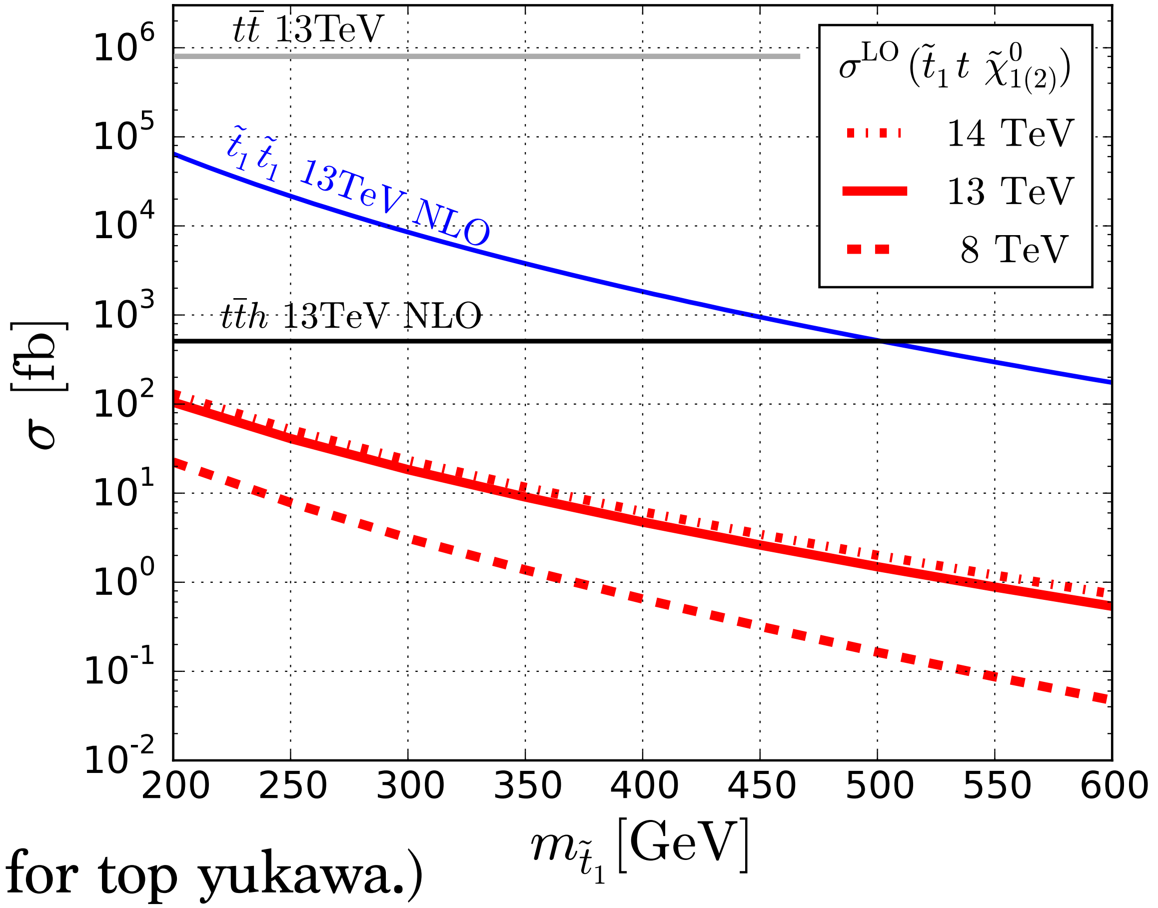
Once we see the signal, advantage turn out to become disadvantage
we propose an interesting process to solve this degeneracy

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

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

in Natural SUSY (light higgsino + stop)





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

$\sigma(\tilde{t}^* t \tilde{h})$ provide direct measurement of the coupling

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

$y_t T_R H_u Q_{3L}$ in super potential

$$\rightarrow y_t h \bar{t} t$$

$$\rightarrow y_t \tilde{t}_R \tilde{h}_u t_L, y_t t_R \tilde{h}_u \tilde{t}_L$$

Non trivial relation due to SUSY, this measurement could be the first confirmation of SUSY

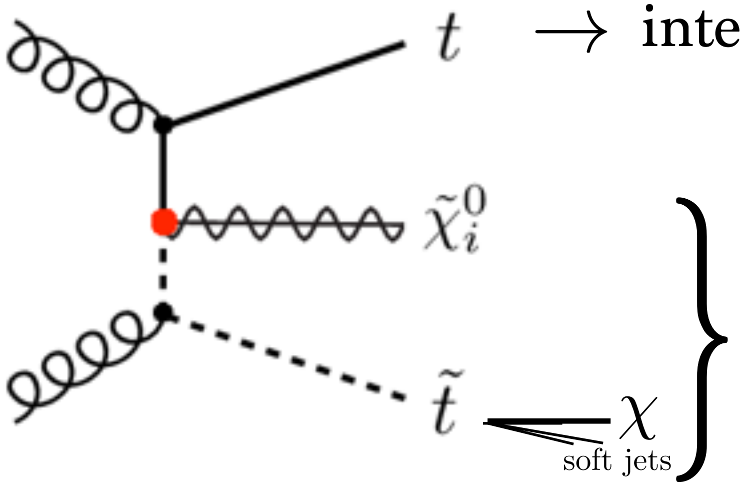
$\sigma(\tilde{t}^* \tilde{t})$ only probes gauge coupling (not necessarily from SUSY) just QCD gauge principle can explain

Mono-top in compressed stop

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

consider compressed case

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



→ interesting signature: mono-top

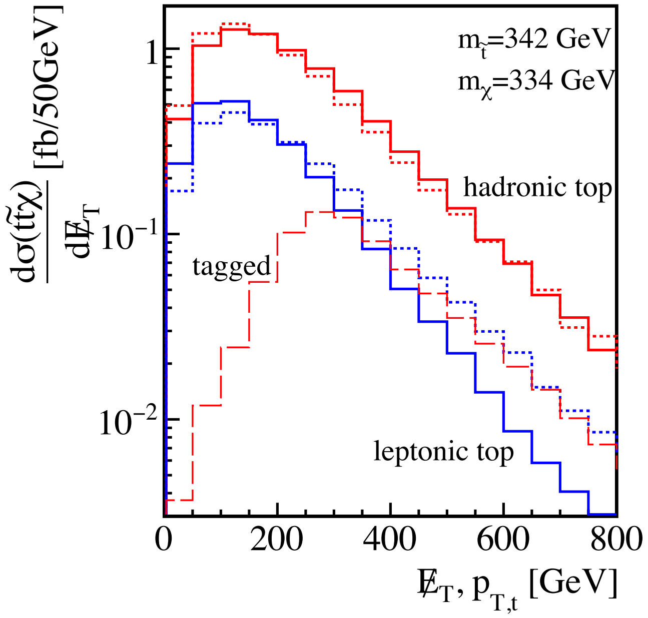
essentially $\slashed{E}_T$

often considered in top flavor violation models J. Andrea, B. Fuks, F. Maltoni

mono-top with no flavor violation, by kinematical suppression

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

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

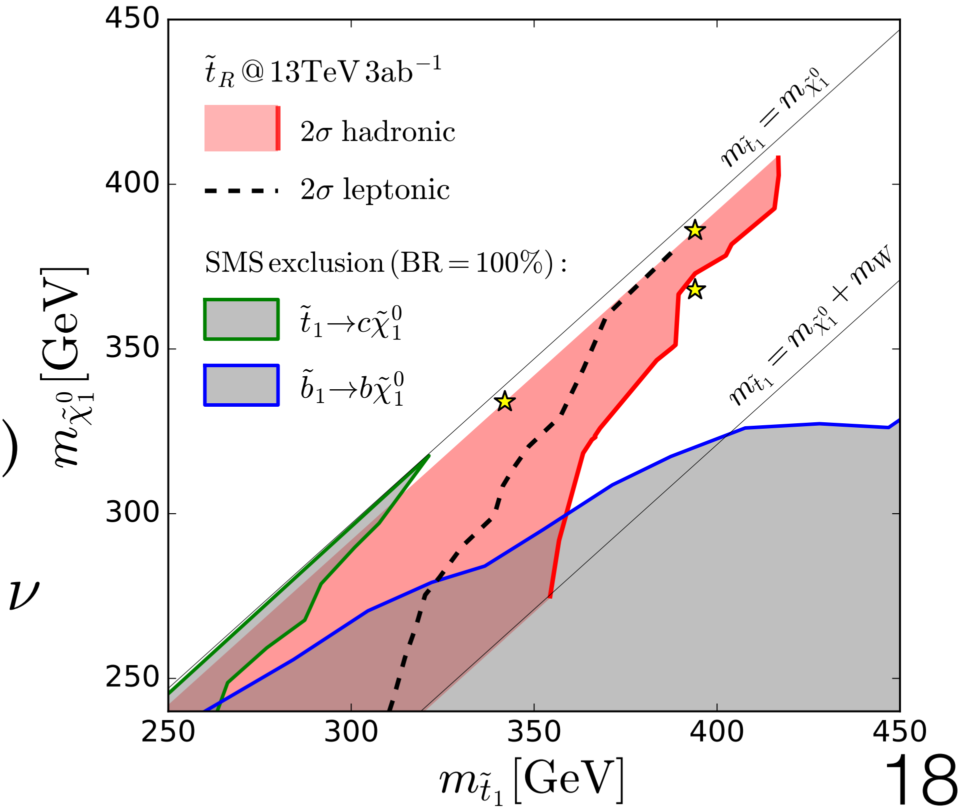


large $\slashed{E}_T$/boost needed

→ Top Tagging (HEPTopTagger)

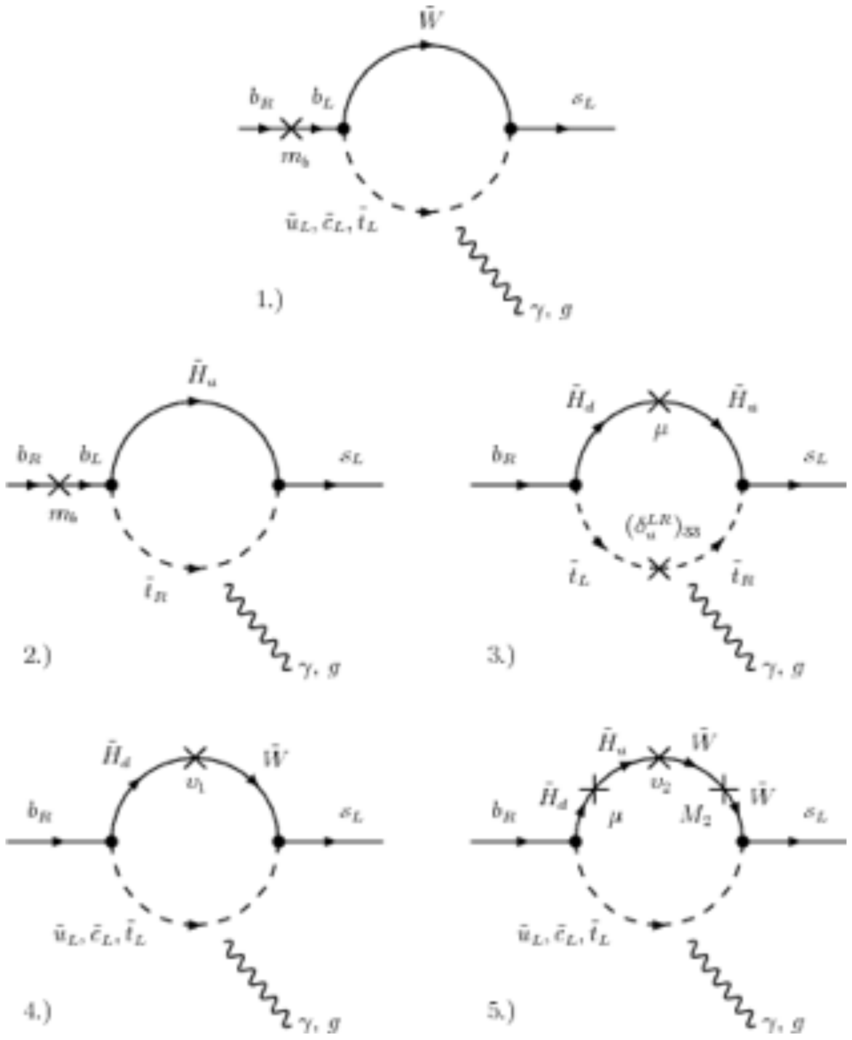
leptonic mode: $\slashed{E}_T$ partly cancel by ν

hadronic mode: $\slashed{E}_T$ fully usable

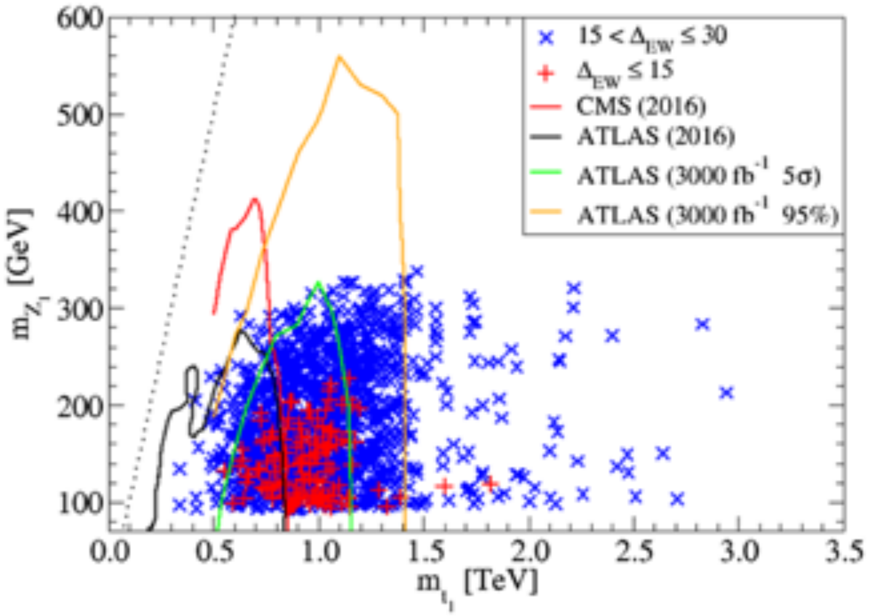


b →s γ

light stop, light higgsino naturally initiate $b \to s\gamma$

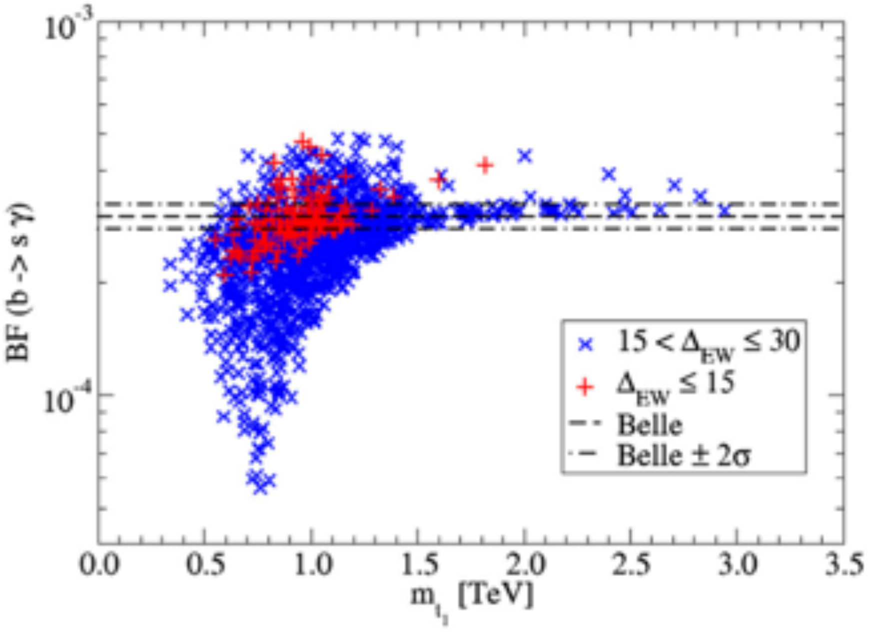


[H. Baer, V. Barger, N. Nagata, S. Michael, PRD 95, 055012 (2017)]



compressed spectrum require a tuning based on their measure

$$\Delta_{EW}$$



We should have observed some deviation $m_{\tilde{t}} < 500\mathrm{GeV}$ and if not tuned.

EWikino as thermal relic

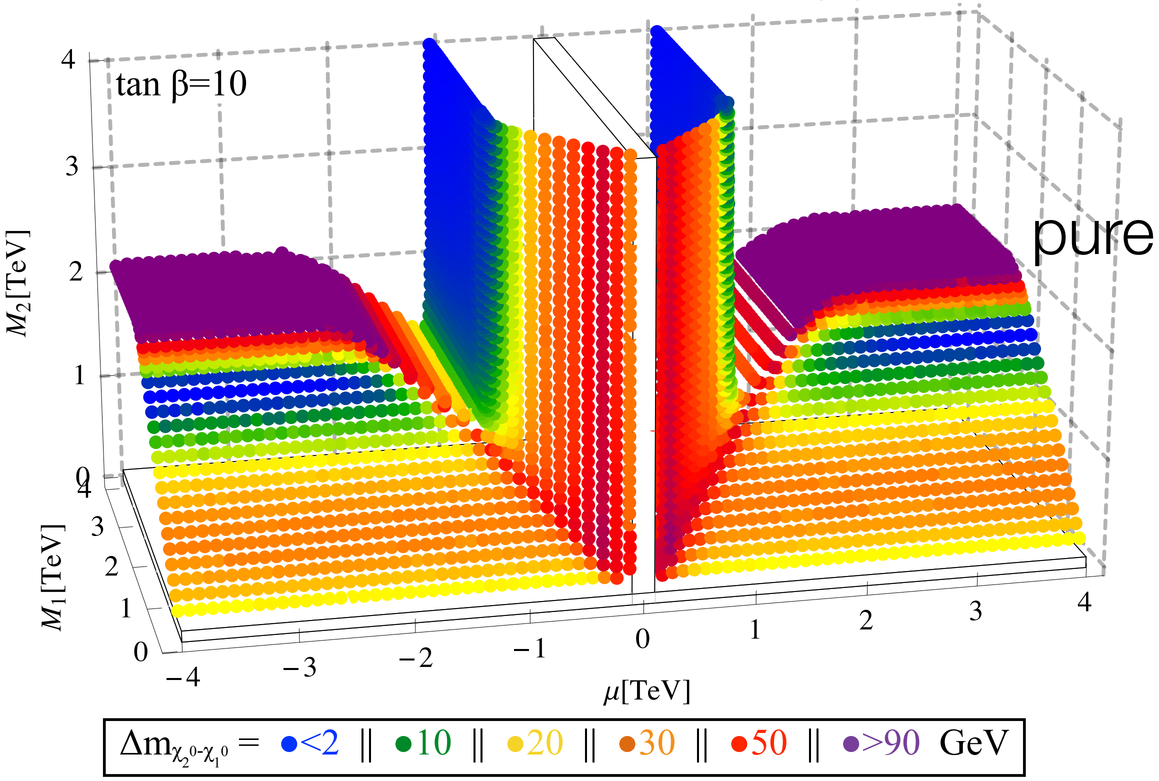
Size of acceptable fine tuning is subjective, 10TeV SUSY still successfully solve the gauge hierarchy problem of $\sim 10^{-30}$ tuning

An attractive point of SUSY is neutralino thermal relic DM, which can provide an upper bound.

pure Higgsino : 1.1TeV
pure Wino : 3 TeV with Sommerfeld Enhancement

cf) squark co-annihilation: 3 TeV
stop co-annihilation: 6 TeV
gluino co-annihilation: 8 TeV

if all particles decoupled other than $\tilde{B}, \tilde{W}, \tilde{H}$, we can parametrize model with (M_1, M_2, μ) and obtain "Relic neutralino surface" to satisfy $\Omega_\chi h^2 = 0.12$

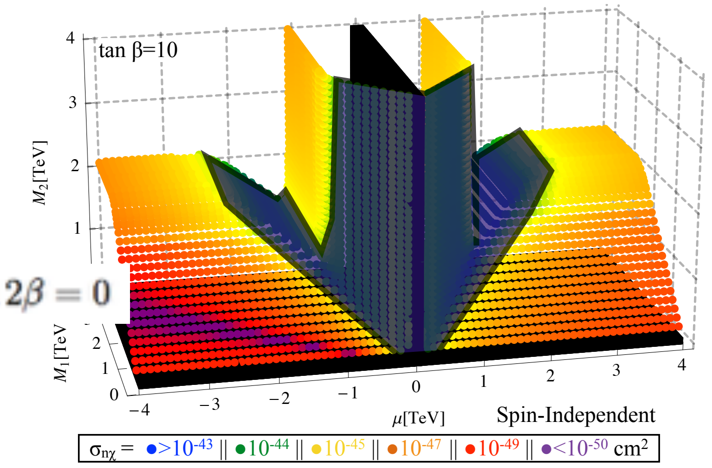


pure Higgsino DM

pure Wino DM

[J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, MT]

DMDD SI constraints



$m_{\chi_1} + \mu \sin 2\beta = 0$

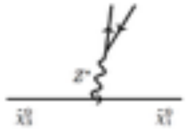
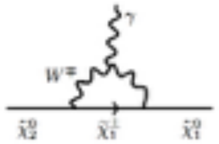
pure wino, higgsino, wino-bino mixture remain mass difference always small

$m_{\chi_2^0} - m_{\chi_1^0}, m_{\chi_1^\pm} - m_{\chi_1^0}$ $\Delta m \lesssim 30 \text{ GeV}$

EWkino search strategies at LHC

$\Delta m = m_{NLSP} - m_{LSP}$

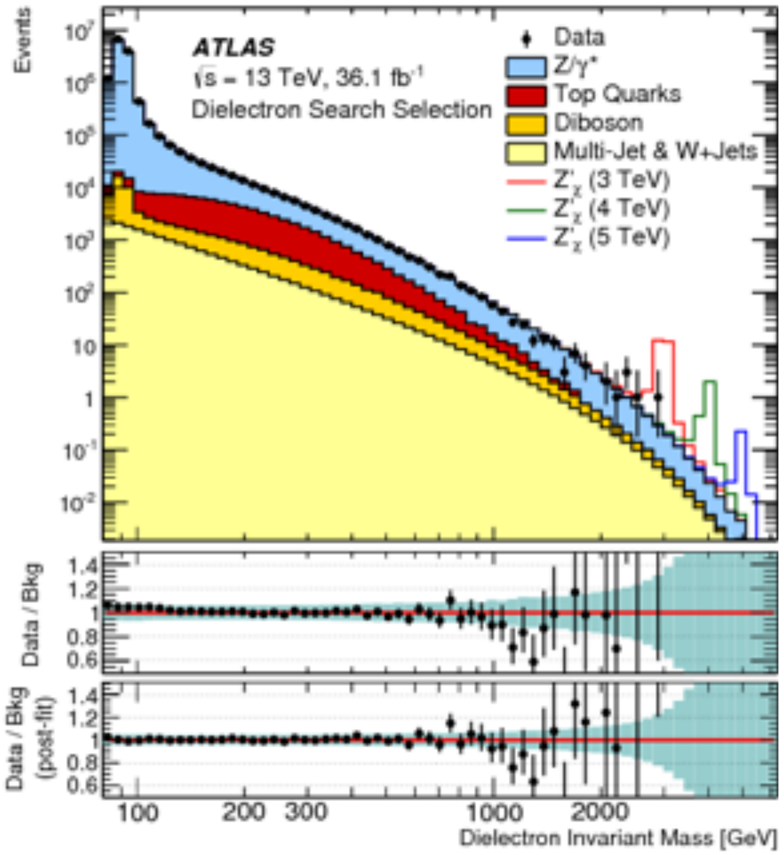
more compressed

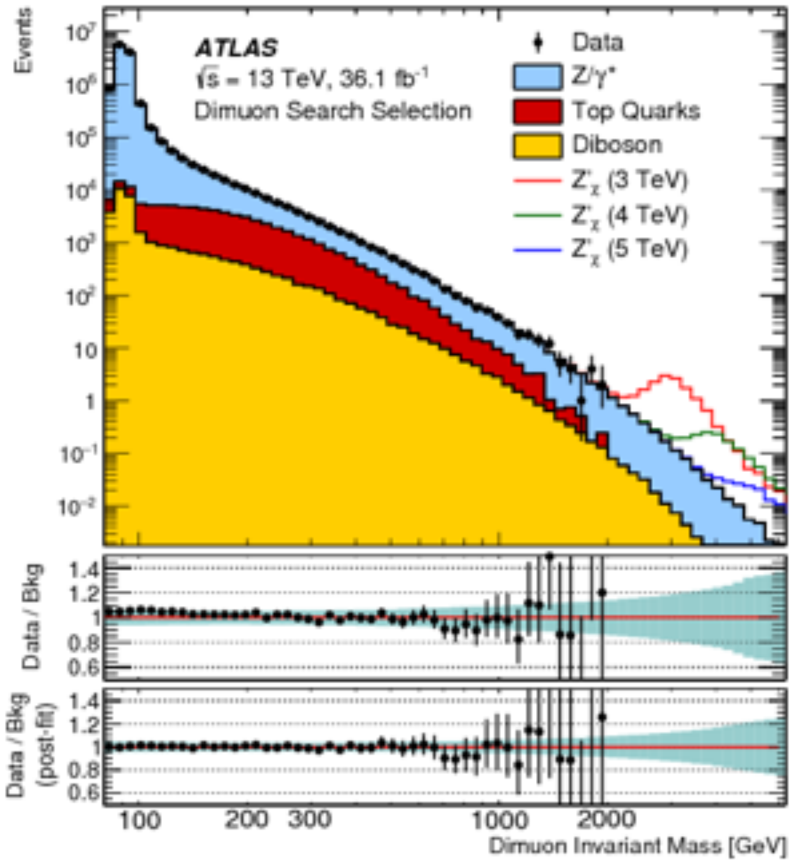
$\Delta m > m_Z, m_W$	$\not{E}_T + 3\ell$	$\chi_2^0 \to \chi_1^0 Z, \chi_1^\pm \to \chi_1^0 W^\pm$
$0.2\text{GeV} < \Delta m < m_W$	$j^{\text{ISR}} + \not{E}_T + 2^+\ell^{\text{soft}}$ For the same trigger ISR jet pT, BG is more boosted. $\not{E}_T + 2^+\ell^{\text{soft}} + \gamma$ $j^{\text{ISR}} + \not{E}_T + \ell^{\text{soft}} + \gamma$ $j^{\text{ISR}} + \not{E}_T$ (mono-jet)	$\chi_2^0 \to \chi_1^0 \ell^+\ell^-$ via Z^*  [Z. Han, G. Kribs, A. Martin, A. Menon] $\chi_2^0 \to \chi_1^0 \gamma$ (1-loop)  [J. Bramante, A. Delgado, F. Elahi, A. Martin, B. Ostdiek] [C. Han, L. Wu, J-M. Yang, M. Zhang, Y. Zhang] too soft decay products
$\Delta m < 0.2\text{GeV}$	Disappearing tracks $+j^{\text{ISR}} + \not{E}_T$	long-lived $\chi^\pm$

Main targets: 1.1TeV Higgsino, 3 TeV Wino, but even with 100TeV collider would be difficult would be covered Bino-Wino mixed case [J. Bramante, P. J. Fox, A. Martin, B. Ostdiek, T. Plehn, T. Schell, MT]

Tracker upgrade and aggressive analysis at HE-LHC might reach 1.1 TeV pure Higgsino by DT [H. Fukuda N. Nagata, H. Otono, S. Shirai, arXiv:1703.09675]

EWkino search via loop at HL-LHC



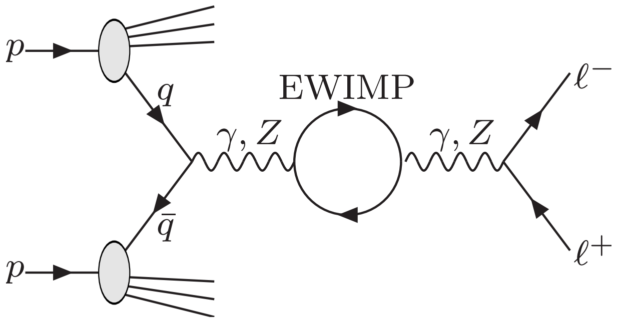


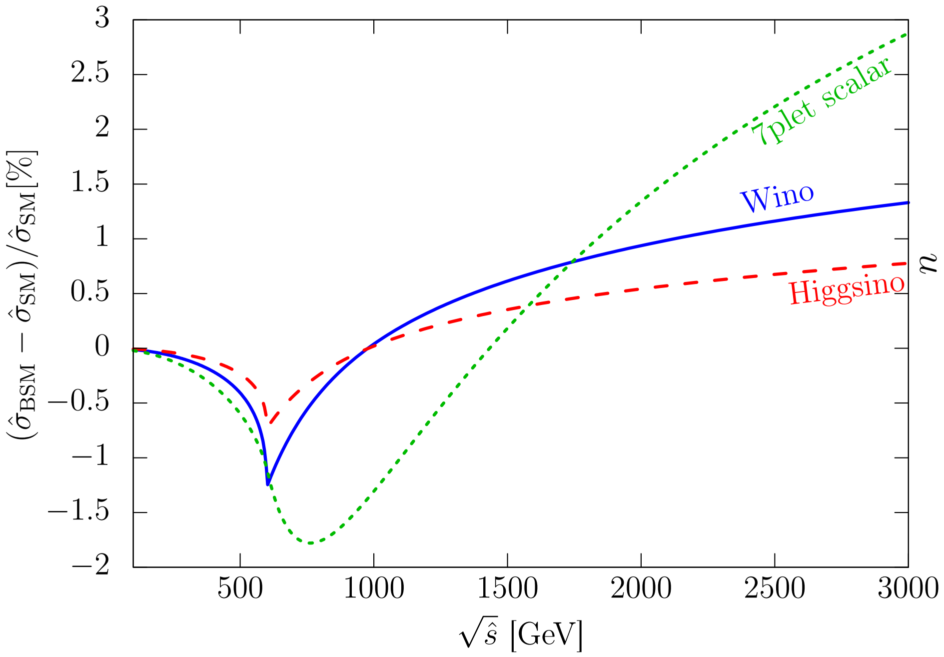
[S. Matsumoto, S. Shirai, MT, arXiv:1711.05449]

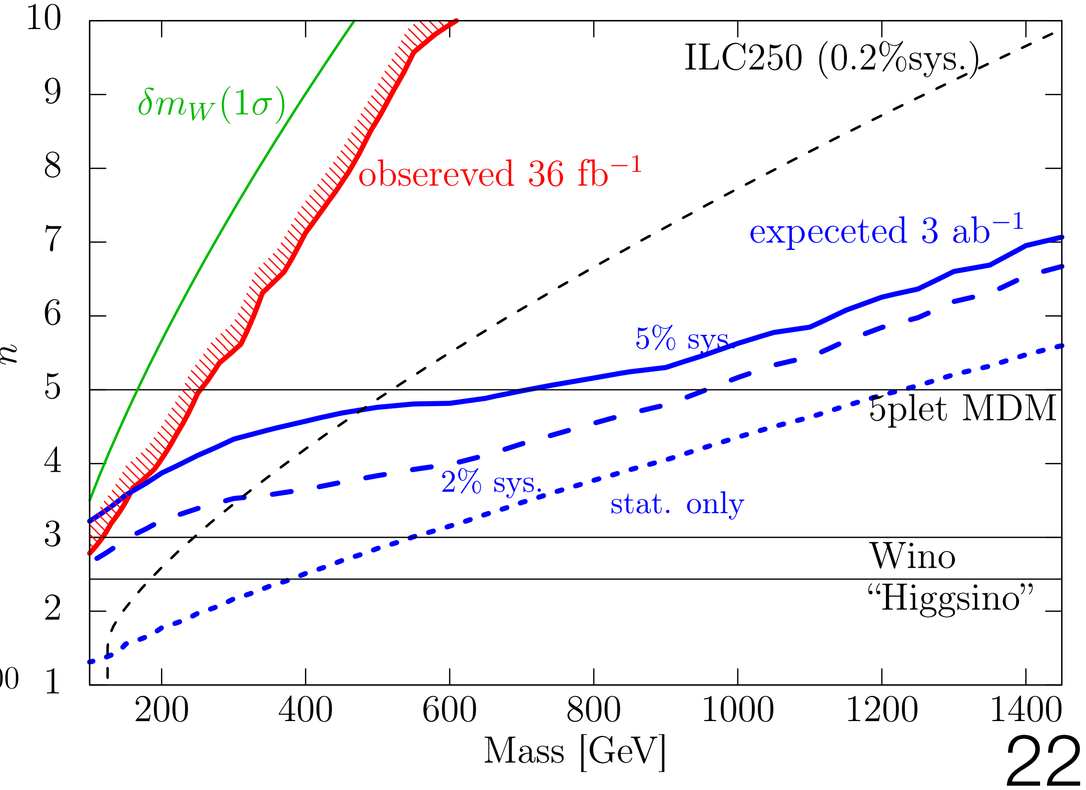
DY production of di-lepton distribution
very large statistics available

Due to signal-BG interference,
O(1%) dip-peak structure expected

At HL-LHC, it might be sensitive
to Higgsino for optimistic case







Summary

Naturalness: we probably just start to explore the natural parameter space finally
not surprising either we find/don't find SUSY soon
lots of opportunities at LHC

important targets :

scalar top → important to check the coupling relations
(SUSY relation from superpotential, $t\tilde{t}\tilde{\chi}$)

boosted technique

degenerate region → mono-jet, mono-top for additional information

b → s γ

EWkinos → being thermal relic set upper bound, require co-annihilation partners

degeneracy → soft-leptons, mono-jet, long-lived particles
(disappearing track, displaced vertex)

loop correction possibly detectable at HL-LHC

Anywhere SUSY below Planck scale better than no-SUSY, thermal relic set upper bound