Stefano Zambito, Harvard - O.b.o ATLAS and CMS

A Dive Into Searches Involving Top Quarks

3rd Generation SUSY

Rare Production & Decays

Dark Matter

Top Quark(s)

Vector-like Quarks

Heavy Resonances

Public Results, SUSY: ATLAS, CMS - EXOTICA: ATLAS, CMS - B2G: CMS - TOP: ATLAS, CMS

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A Dive Into Searches Involving Top Quarks

3rd Generation SUSY & Rare Top Decays

La Thuile, Mar 2nd '18 - In this talk:

- Why *t* so important in BSM searches?
- Prototype of *stop* search: 1L ATLAS
- Prototype of *stop* search: 0L CMS
- *Sbottom* searches, in a nutshell
- *FCNC* in *t* production/decays

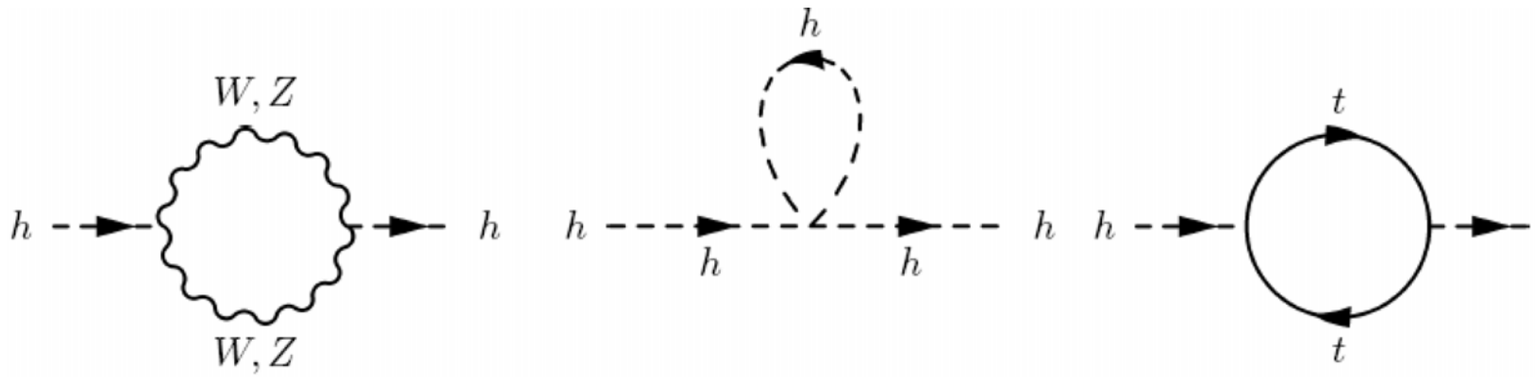
Introduction

Why the *top quark* is *so* interesting - and all the searches involving it?

"Massive" and *"point-like"* at the same time - key source of fundamental information

Heaviest elementary particle discovered so far: mass close to that of gold nucleus!
It decays much faster than timescale for formation of strong bound states

Large Yukawa coupling (close to unity) - main contribution to virtual m_H corrections:
Close connection to *hierarchy problem* (and its *natural* solution?)

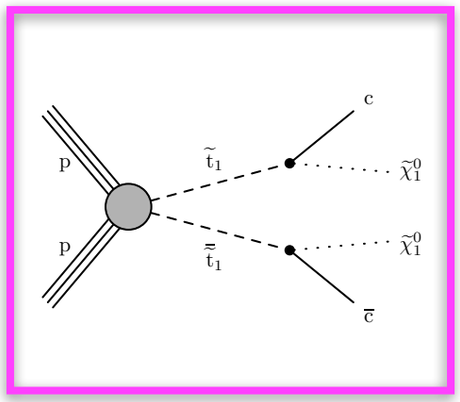


$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 \approx -(0.2\ \Lambda)^2$$

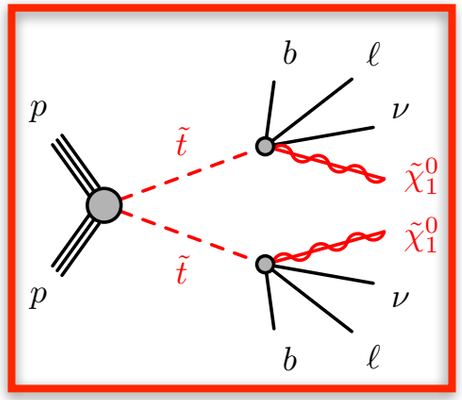
e.g. SUSY's solution: (natural) cancellations given by the top's superpartner, *stop*

Stop: Decays

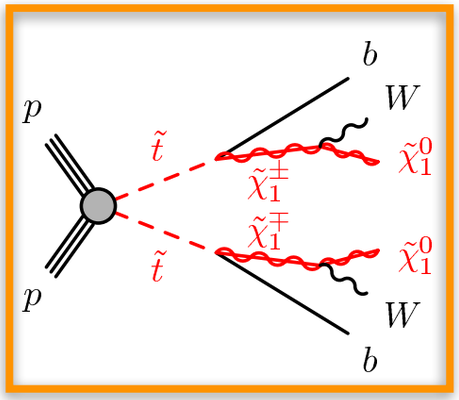
stop-to-charm



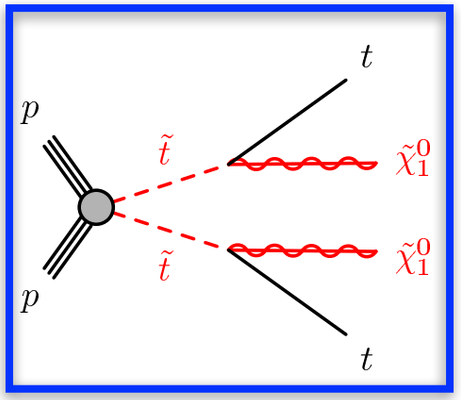
4-body



3-body



2-body decays



$\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$

mono-jet

$m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0}$

$\Delta m > 0$

$\Delta m > m_W + m_b$

$\Delta m > m_t$

$\tilde{t}_1 \to c\tilde{\chi}_1^0$

$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$

$\tilde{t}_1 \to bW\tilde{\chi}_1^0$

$\tilde{t}_1 \to t\tilde{\chi}_1^0$

$m_{\tilde{\chi}_1^0}$ [GeV]

0 100

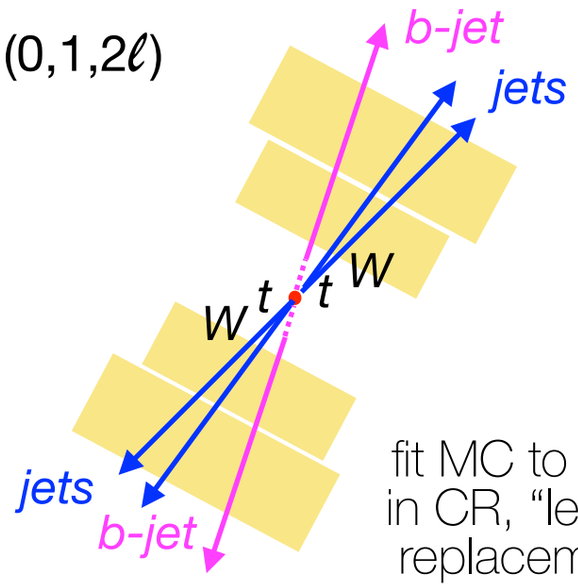
0 100 200 300 $m_{\tilde{t}_1}$ [GeV]

Main Backgrounds

Typical signature involves large $\not{E}_T$, b-jets and 0, 1 or 2 leptons

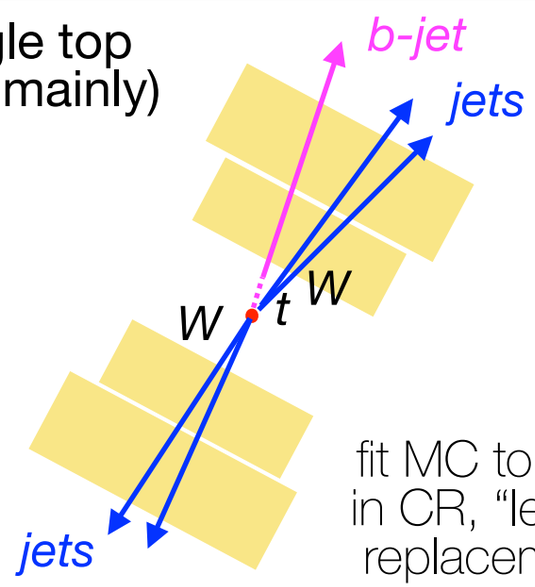
Control (CR) and validation (VR) regions used to extract / x-check background predictions

tt (0,1,2ℓ)



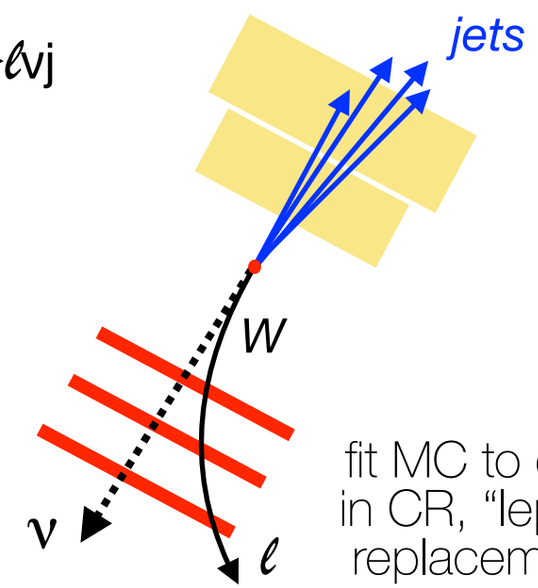
fit MC to data in CR, "lepton replacement"

single top (*Wt* mainly)



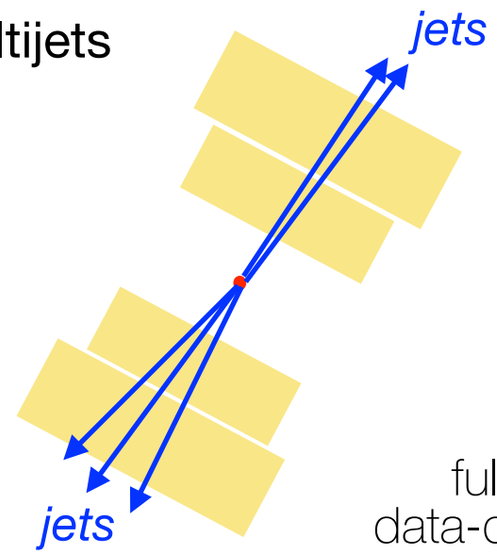
fit MC to data in CR, "lepton replacement"

*W*j→$\ell\nu$j



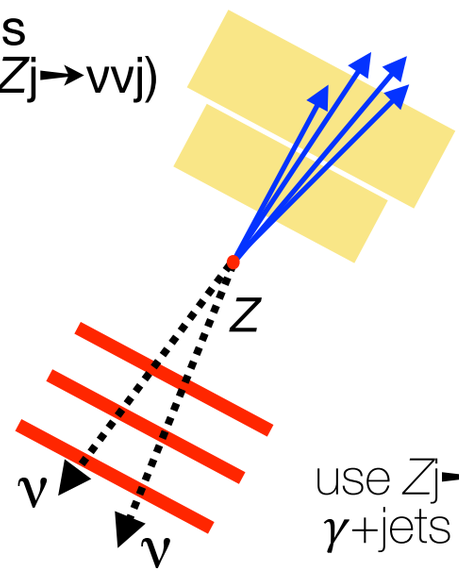
fit MC to data in CR, "lepton replacement"

multijets



fully data-driven

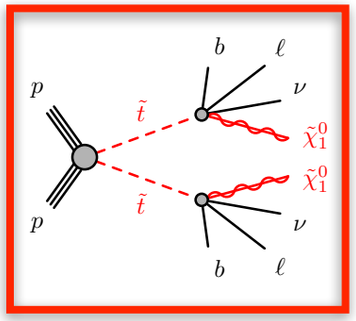
Z+jets (e.g. *Z*j→$\nu\nu$j)



use *Z*j→μμj or γ+jets events

arXiv:1711.11520

Stop 1L, ATLAS: Strategy (I)



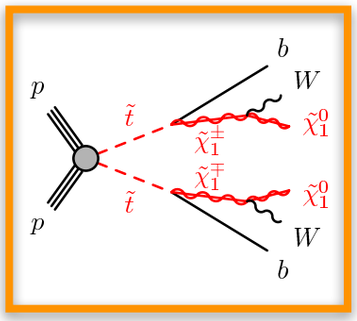
4-body decays

$\not{E}_T$>300 GeV, at least one b-tagged jet

one *soft* lepton

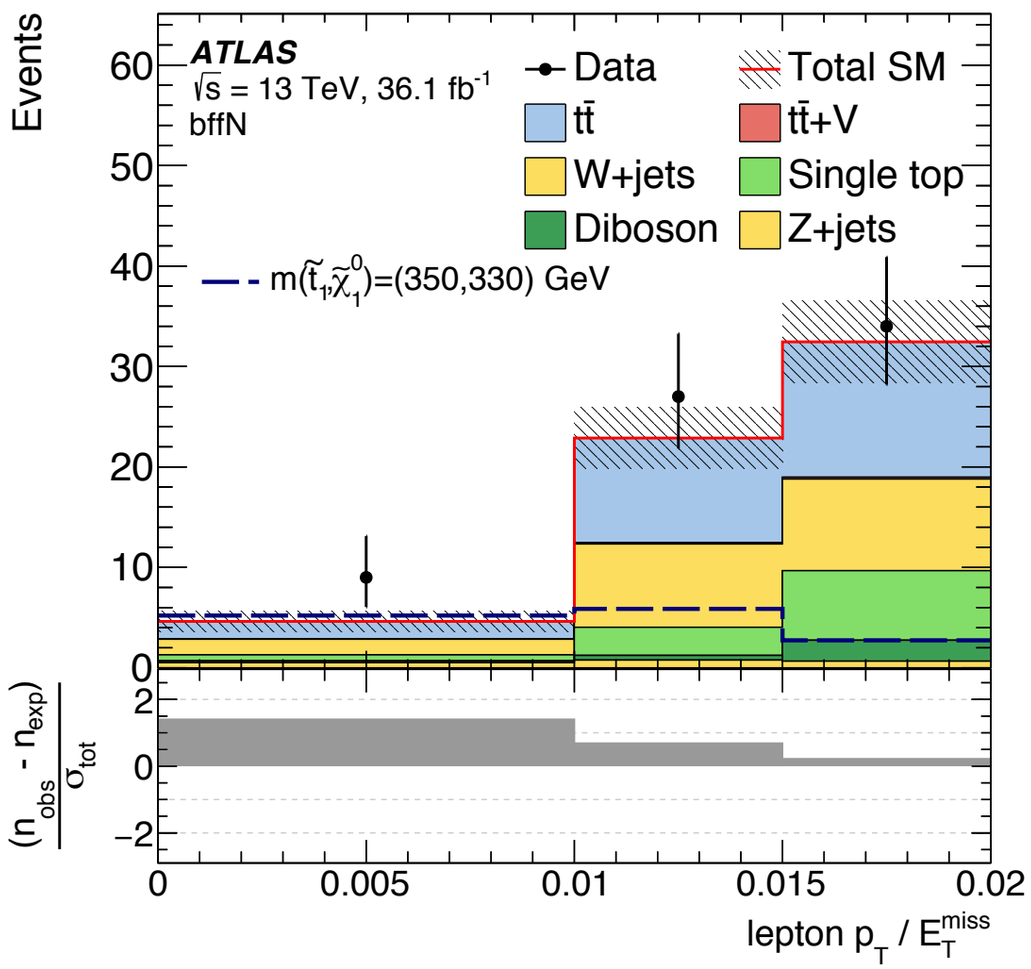
Cut & count selection,
shape fit to $p_{T,lep}/\not{E}_T$

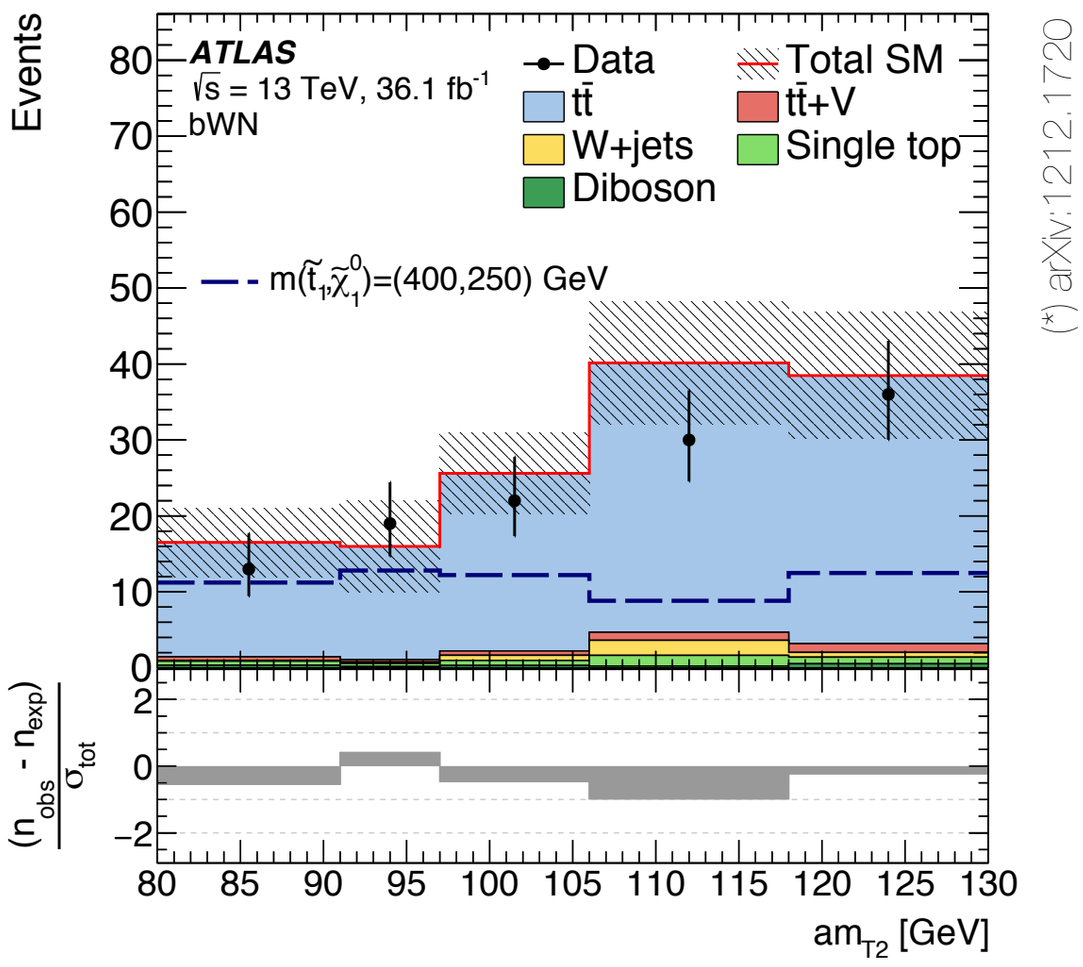
3-body decays



one *hard* lepton

Cut & count selection,
shape fit to *asymmetric-*m_{T2} (*)





(*) arXiv:1212.1720

arXiv:1711.11520

Stop 1L, ATLAS: Strategy (II)

Compressed, "diagonal" region

$m_{\tilde{t}} - m_{\tilde{\chi}} \approx m_t$: signal kinematics very close to SM $t\bar{t}$

Need ISR activity to "misalign" $\chi\chi$ and get contribution to $\not{E}_T$

arXiv:1711.11520

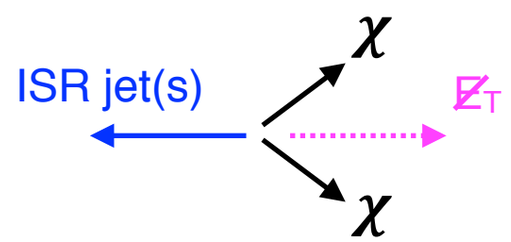
Stop 1L, ATLAS: Strategy (II)

Compressed, "diagonal" region

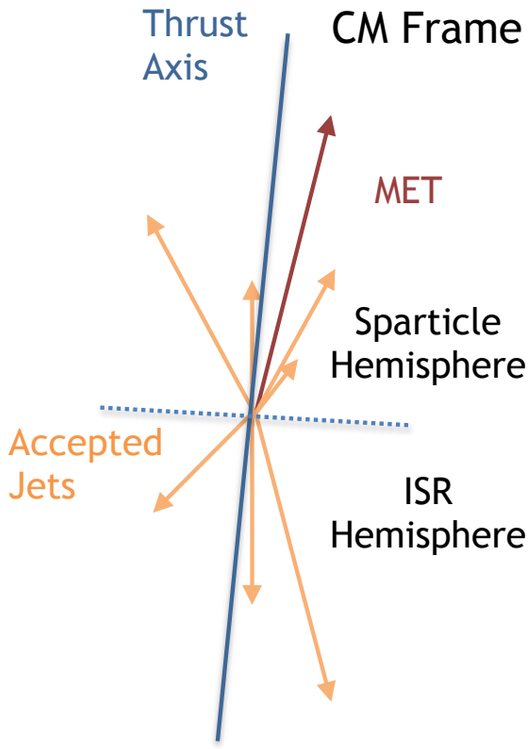
$m_{\tilde{t}} - m_{\tilde{\chi}} \approx m_t$: signal kinematics very close to SM $t\bar{t}$

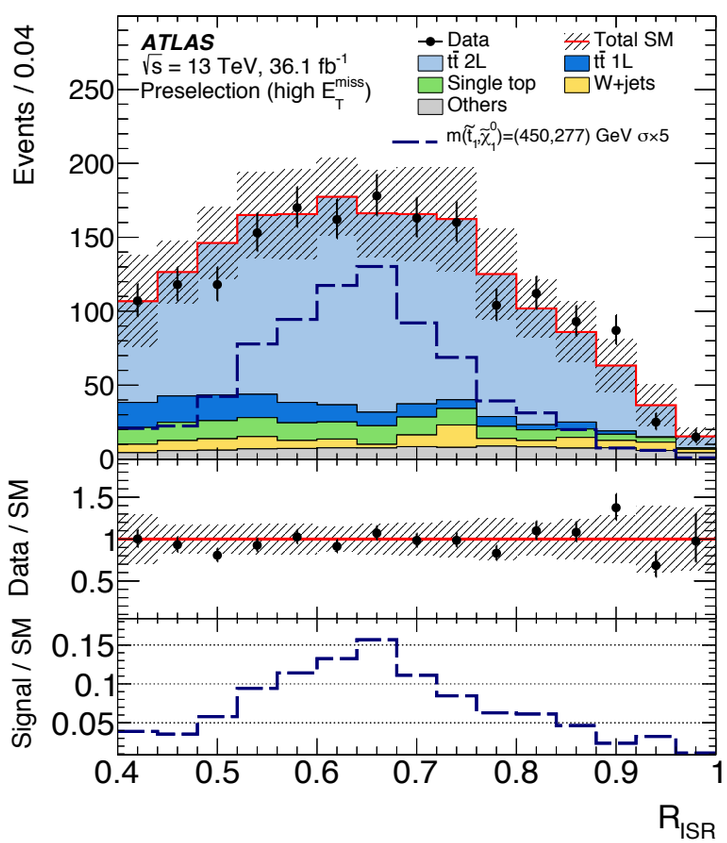
3 BDTs targeting different m_{stop},
exploiting correlation between ISR and $\not{E}_T$:
BDT_low, BDT_med, BDT_high

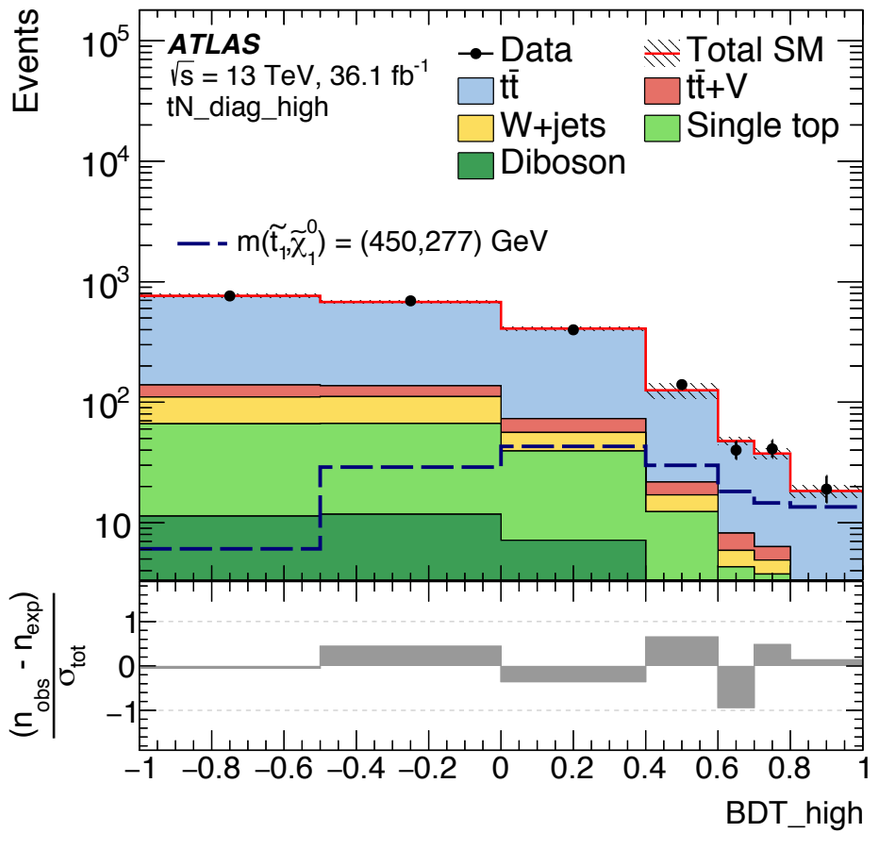
Need ISR activity to "misalign" $\chi\chi$
and get contribution to $\not{E}_T$



$R_{ISR} = \not{E}_T/p_{T,ISR}$ (in CM)

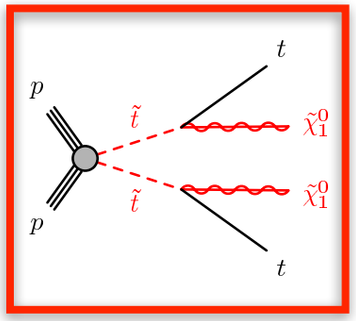






arXiv:1711.11520

Stop 1L, ATLAS: Strategy (III)

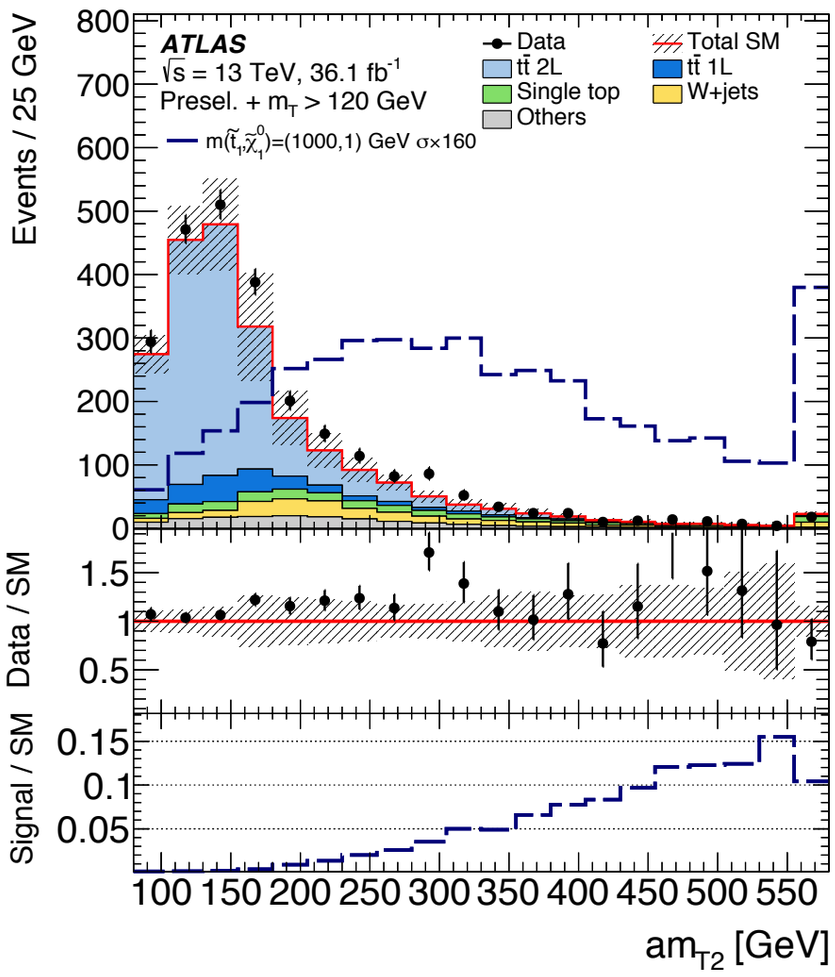


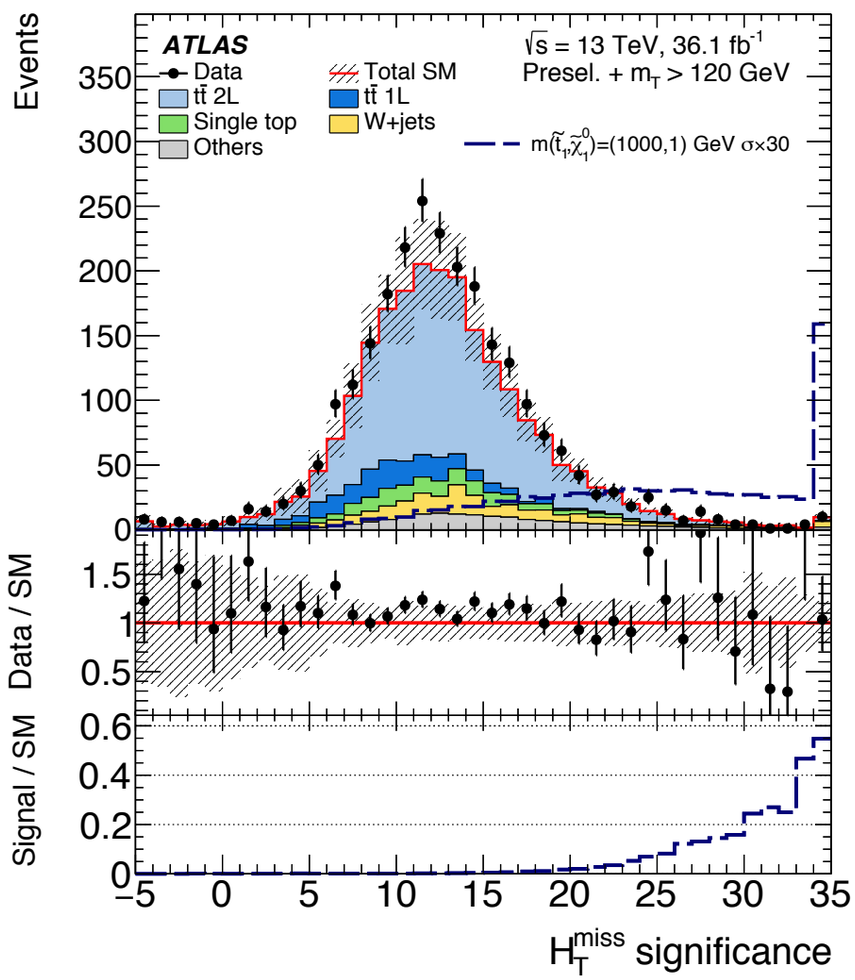
2-body decays

Two signal regions, simple requirements on powerful variables

Targeting, respectively, *intermediate* and *high* stop masses

↳ shape fit in $\not{E}_T$: 5 bins above 250 GeV





Negative vector sum of all jets momenta

Offset (100 GeV)

$$H_{\mathrm{T,sig}}^{\mathrm{miss}} = \frac{|\vec{H}_{\mathrm{T}}^{\mathrm{miss}}| - M}{\sigma_{|\vec{H}_{\mathrm{T}}^{\mathrm{miss}}|}}$$

Obtained from per-event jet energy uncertainties

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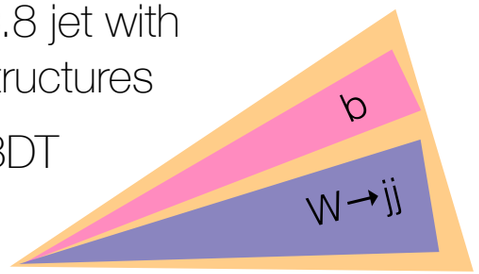
Stop 0L, CMS: Strategy (I)

Reconstructing kinematics of stop decay products key to reject backgrounds

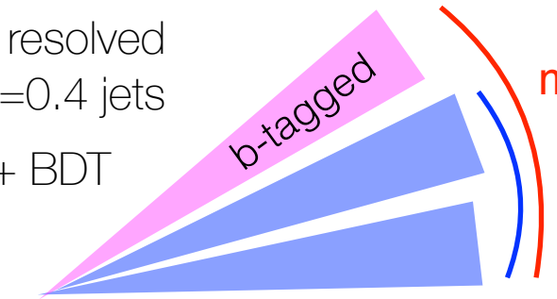
Low Δm (<m_W): reconstruct ISR from large-R jets; soft b-tagging via N_{SV} (secondary vertices)

High Δm: reconstruct *hadronic t* and *W* candidates (from stop decays)

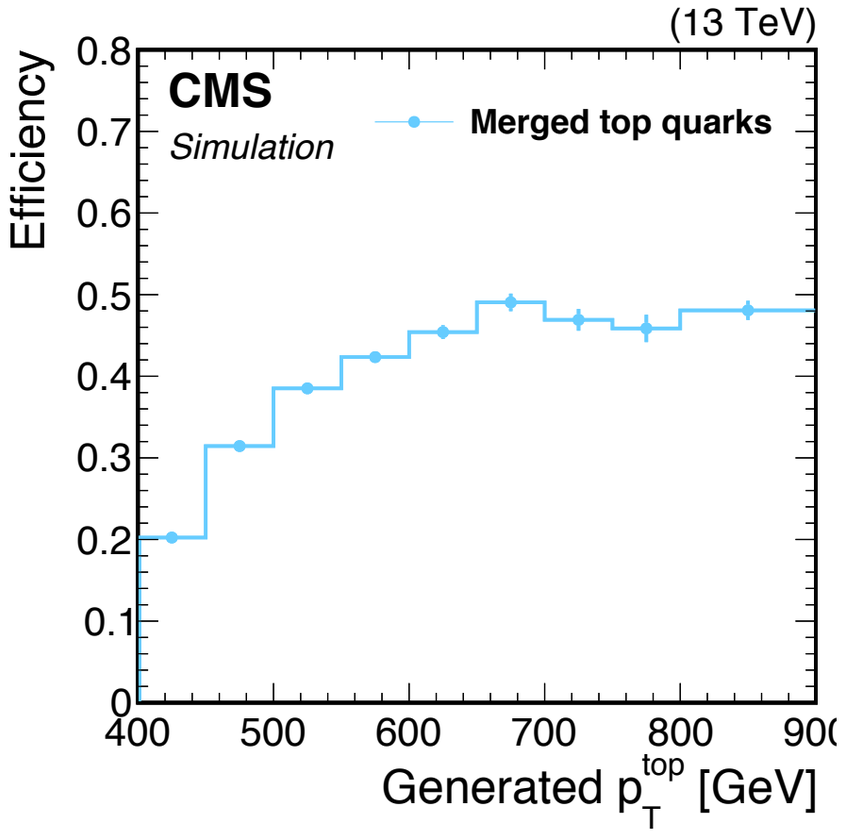
one R=0.8 jet with
2 substructures
+ BDT

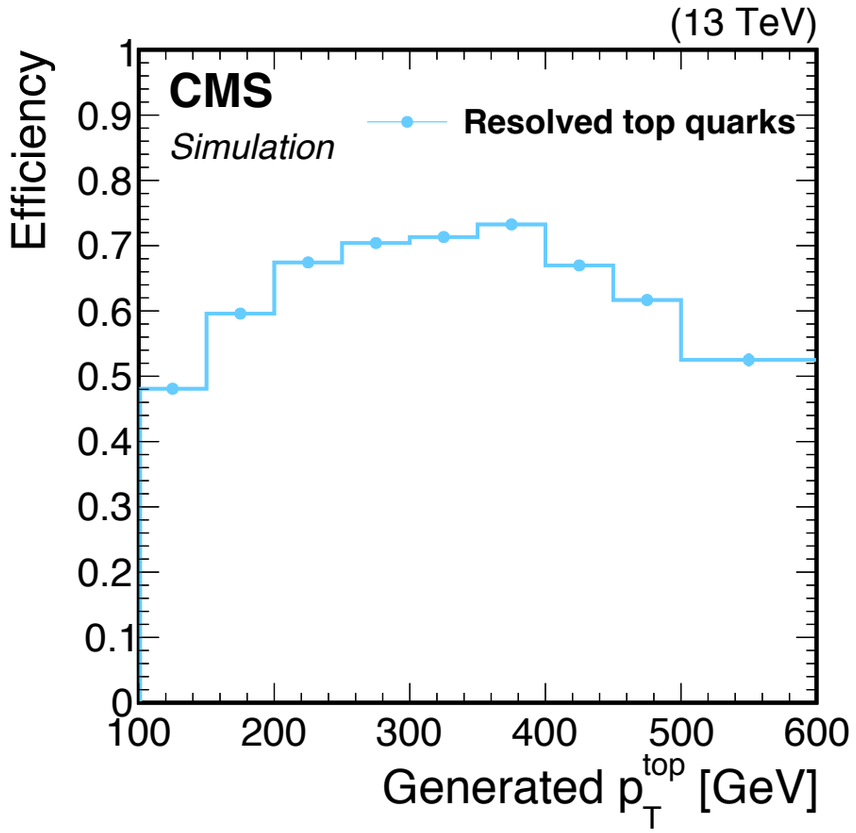


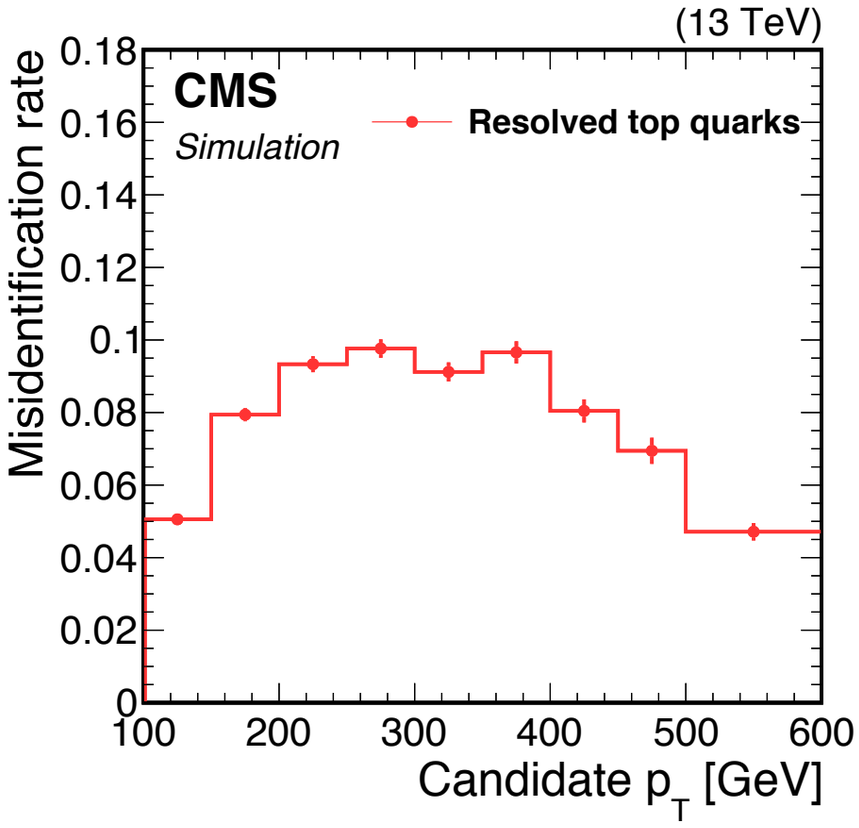
3 resolved
R=0.4 jets
+ BDT



Simulation corrected to match *t* and *W* tagging eff. measured in data







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Stop 0L, CMS: Strategy (II)

Trigger on $\not{E}_T$ (offline: >250 GeV), veto events with isolated leptons

Low Δm

$N_{jets} \geq 2$, $N_t = N_W = 0$, $m_T(\not{E}_T, \text{b-jet}) < 175$ GeV

one ISR jet, $p_{T,ISR} > 300$ GeV, $\Delta\phi(\not{E}_T, \text{ISR}) > 2$, …

53 search regions slicing:

N_{jets}, $N_{b\text{-tag}}$, N_{SV}, $p_{T,ISR}$, $p_{T,b}$, $\not{E}_T$

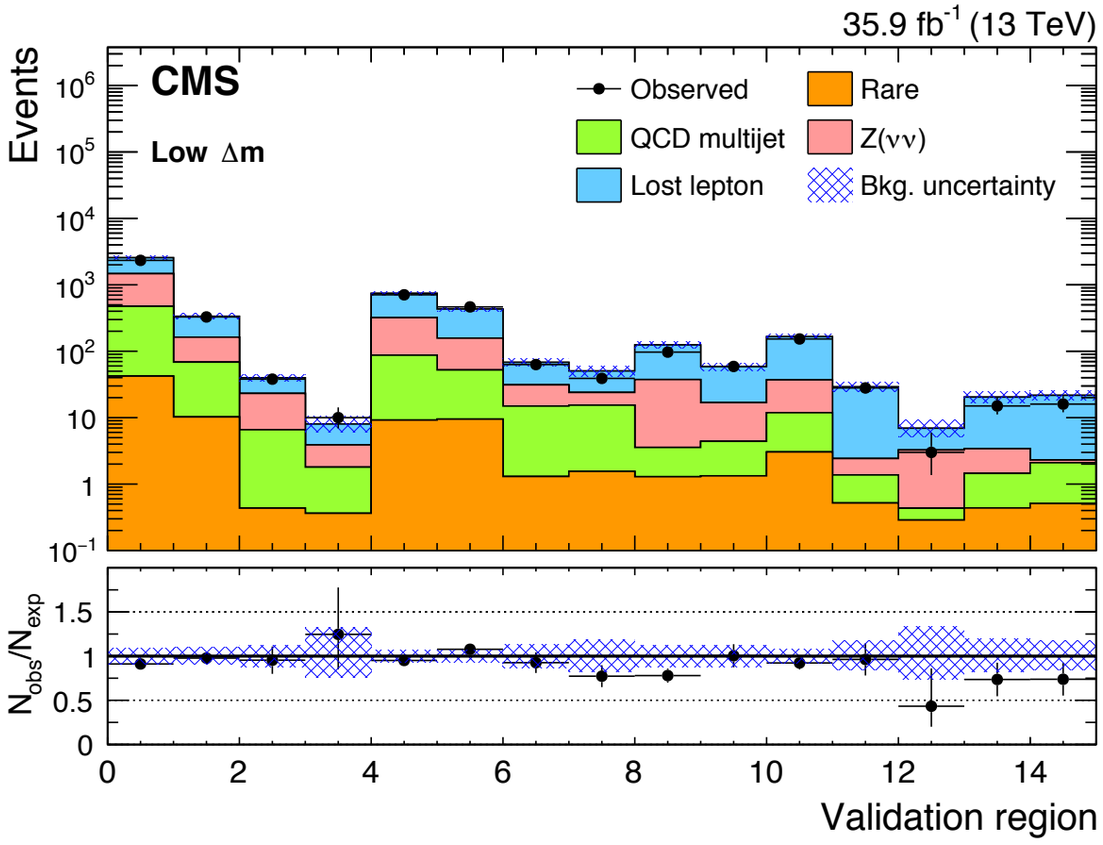
High Δm

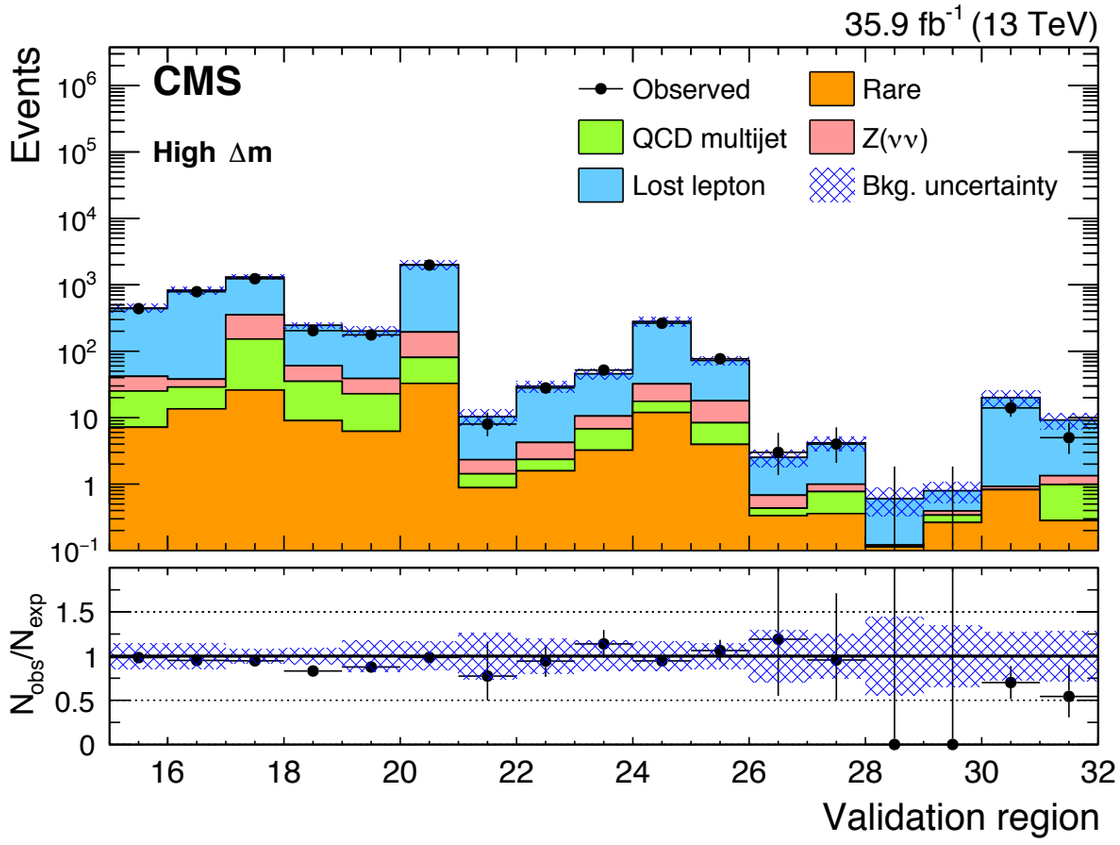
$N_{jets} \geq 5$, $N_{b\text{-tag}} \geq 1$, $\Delta\phi(\not{E}_T, j_{1..4}) \geq 0.5$

51 search regions slicing:

N_t, N_W, N_{res}, N_{jets}, $N_{b\text{-tag}}$,

$m_T(\not{E}_T, \text{b-jet})$, $\not{E}_T$

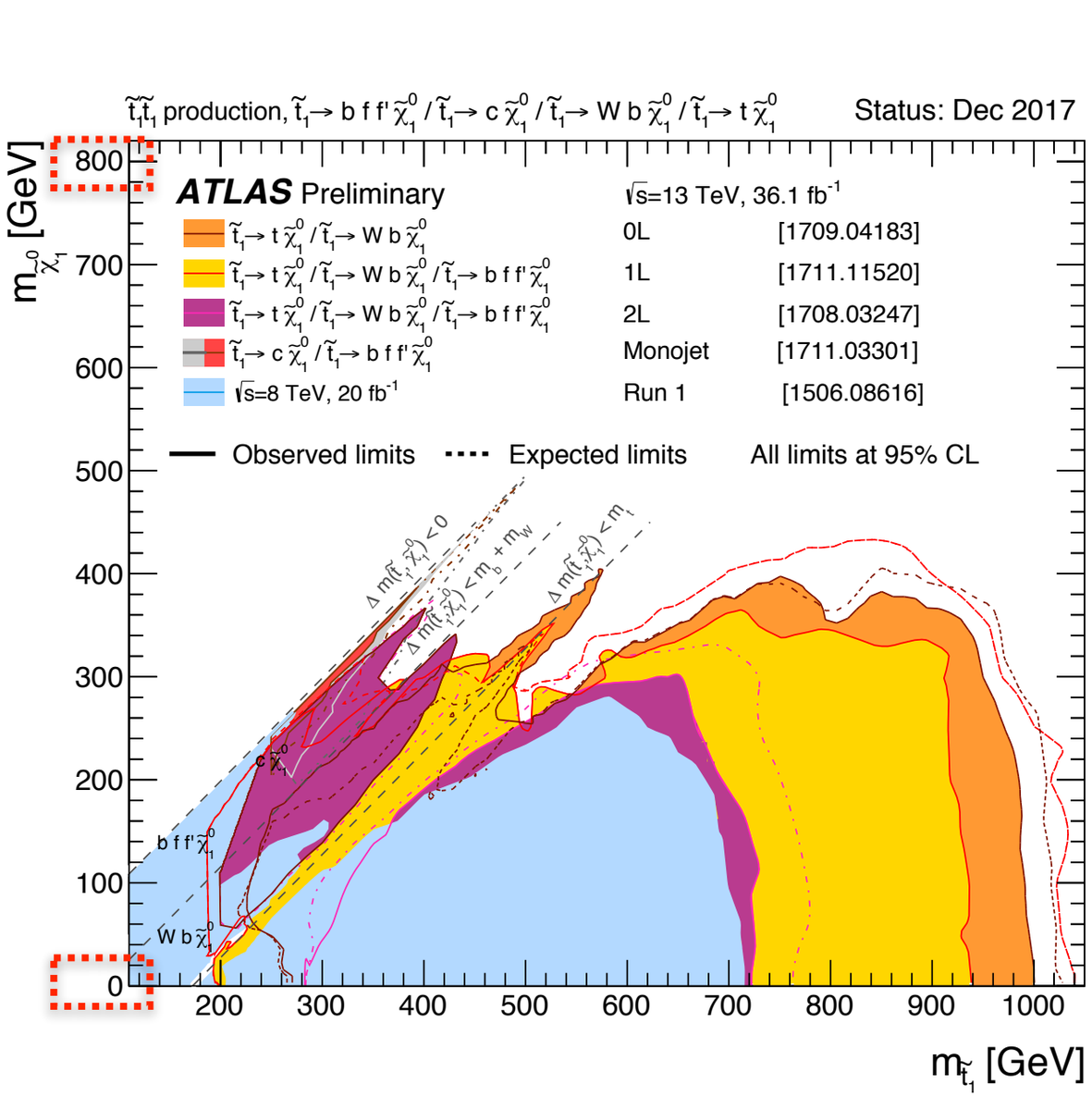




Stop: Exclusion Limits

Simplified models: excluded up to $m_{\tilde{t}}$ ~1.1 TeV (and up to $m_{\tilde{\chi}^0}$ ~500 GeV)

However, interesting holes at light stop mass: very challenging region!



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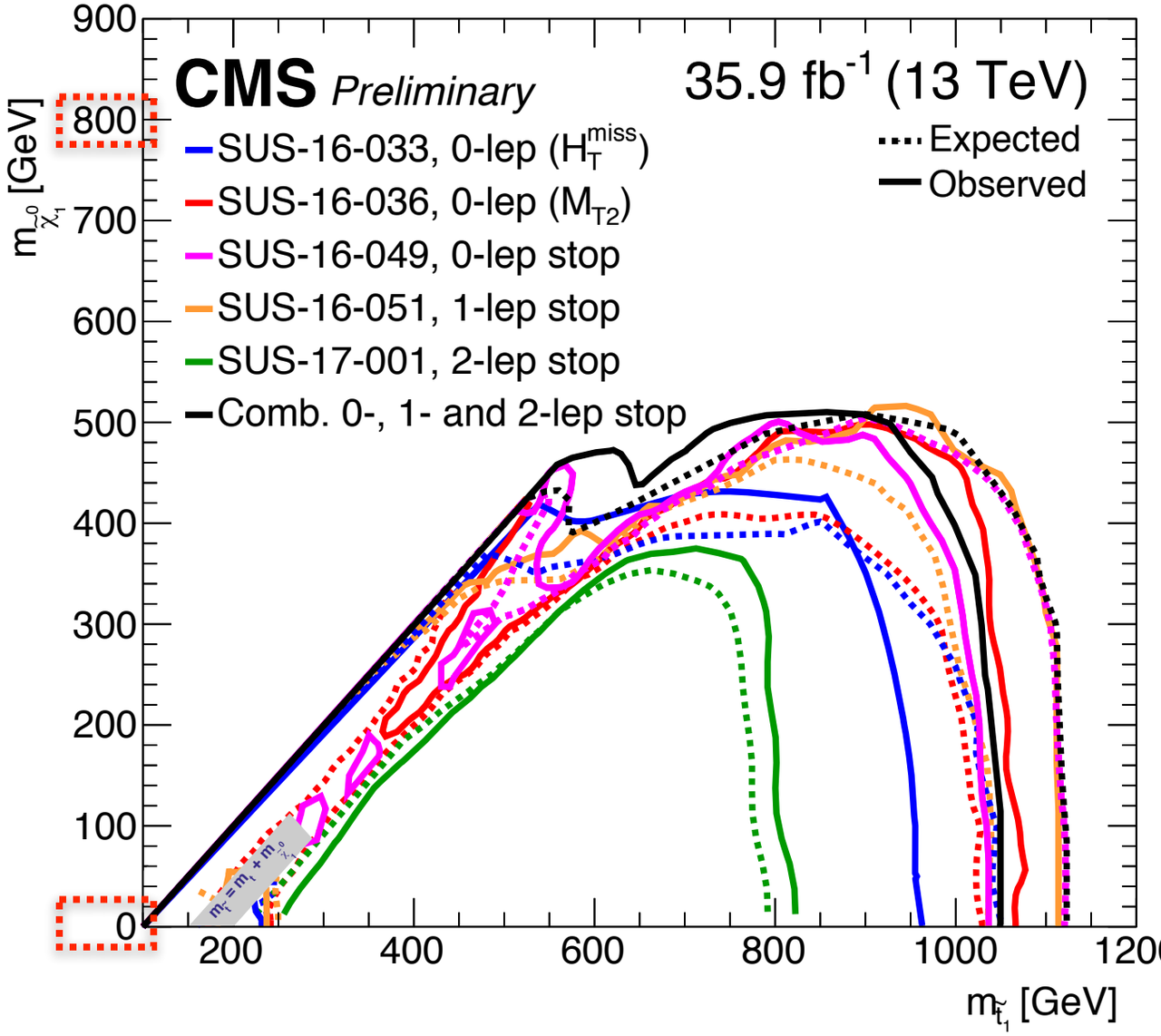

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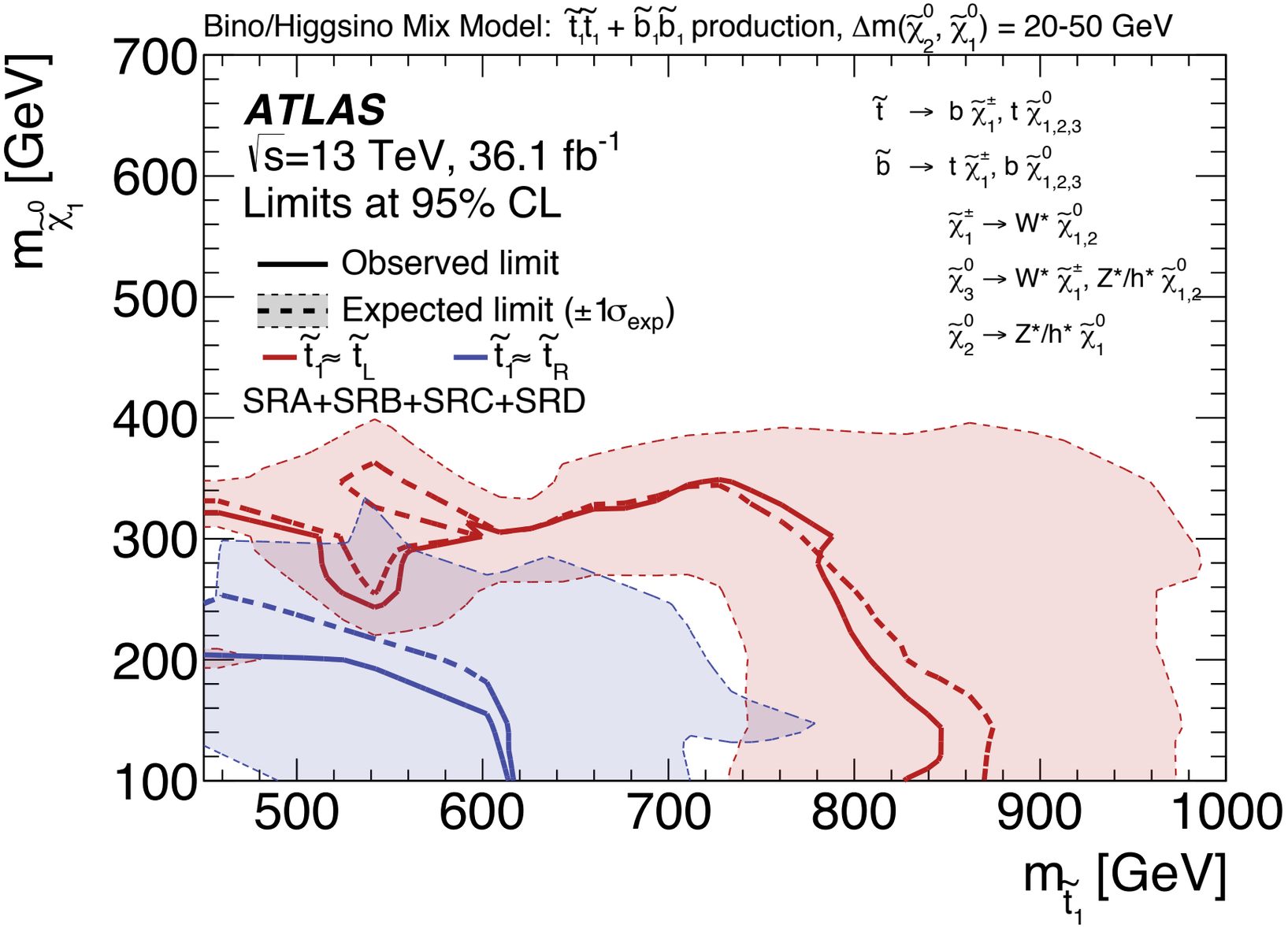
However, interesting holes at light stop mass: very challenging region!

pMSSM-inspired models show weaker limits: $m_{\tilde{t}}$ ~600 GeV + light LSP allowed



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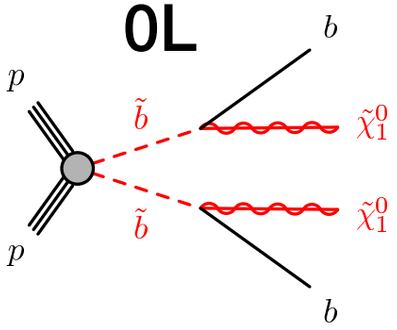
(*) for compressed signal mass spectra

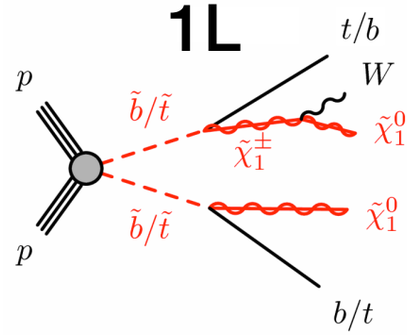
Sbottom: Strategy



$\tilde{t}_L$ and $\tilde{b}_L$ in same weak isospin multiplet

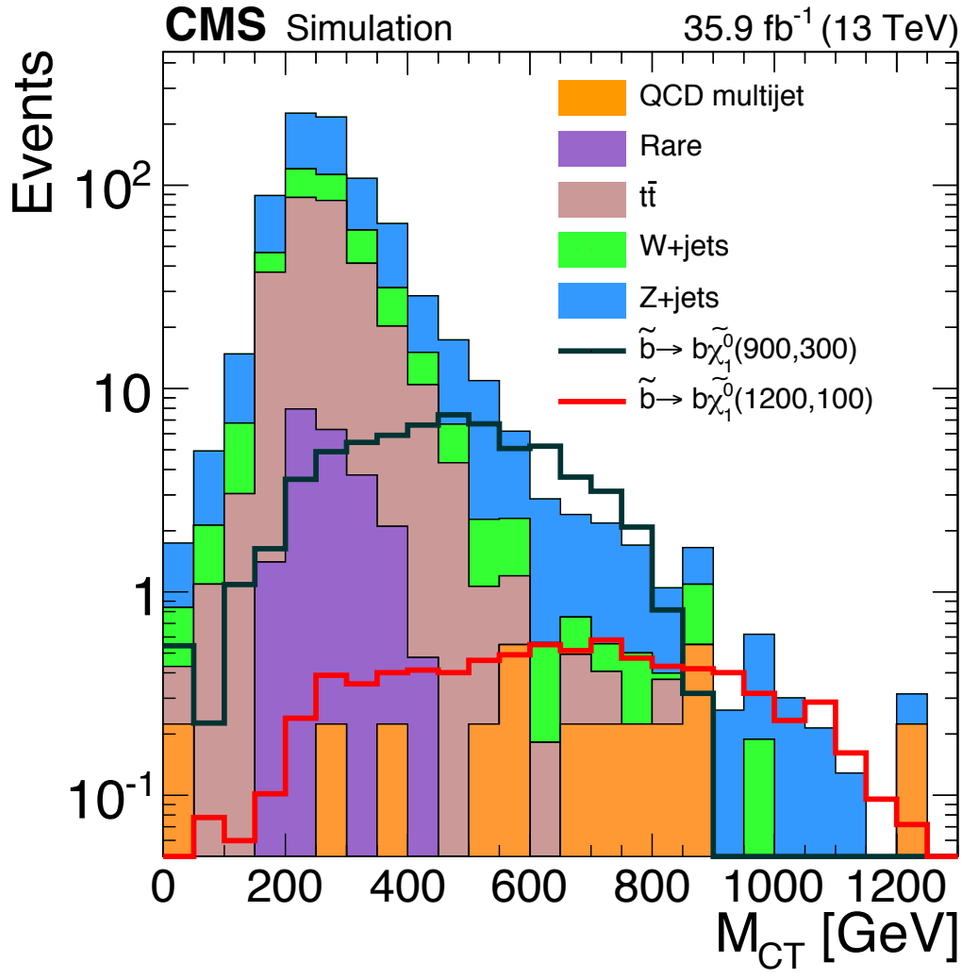
$\tilde{b}\tilde{b}$ less "jetty" than $\tilde{t}\tilde{t}$ events; harder b-jets

select events with 2 energetic b-jets and large $\not{E}_T$



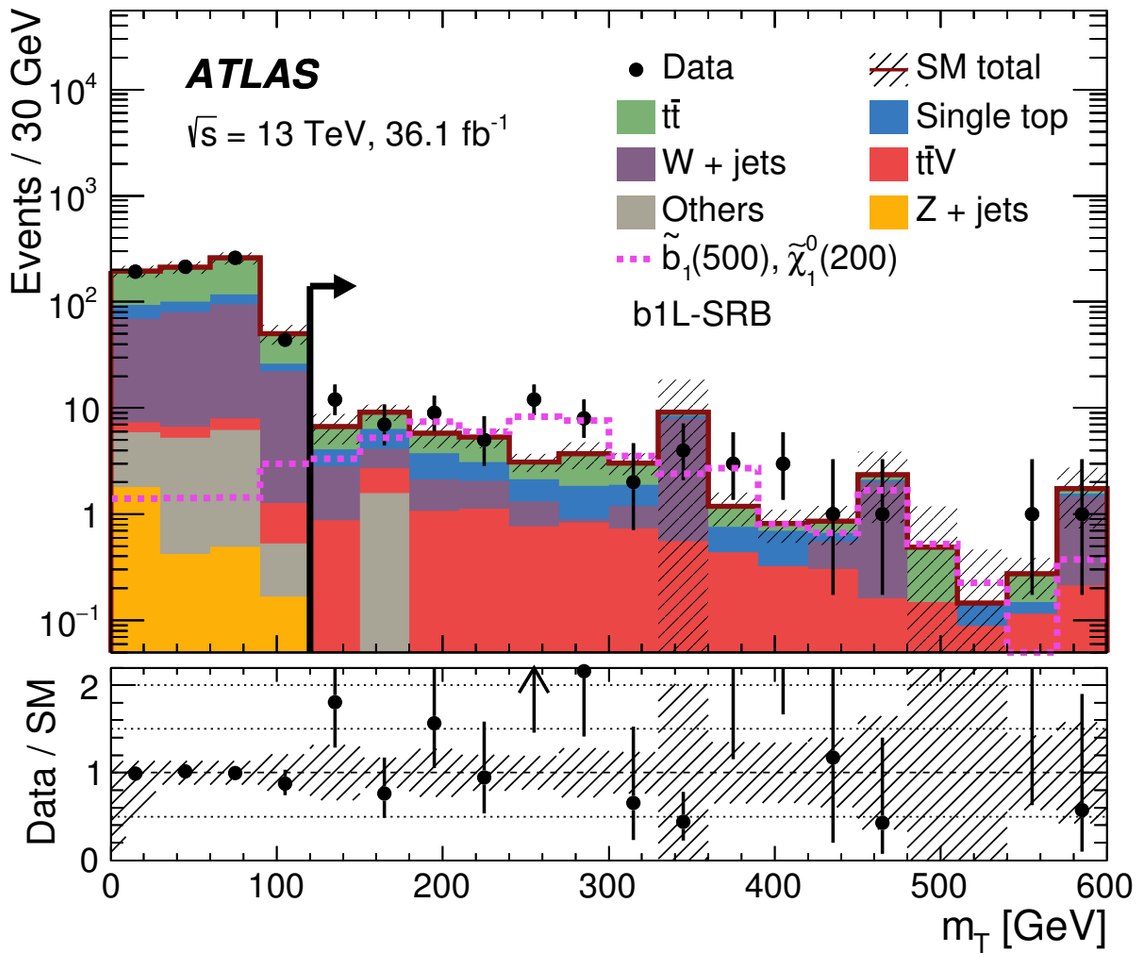
CMS: (soft(*)) c-/b-tagging

M_{CT}: endpoint at $(m_{\tilde{b}}^2 - m_{\tilde{\chi}}^2)/m_{\tilde{b}}$



ATLAS: tailored kinematic variables

$m_T(\ell, E_T)$: endpoint at m_W for $t\bar{t}$ and W+jets



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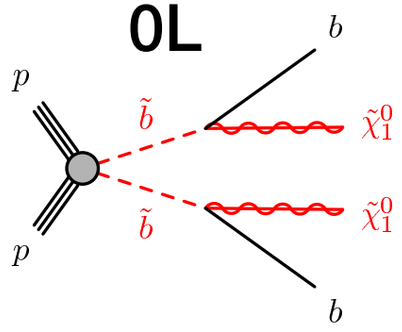
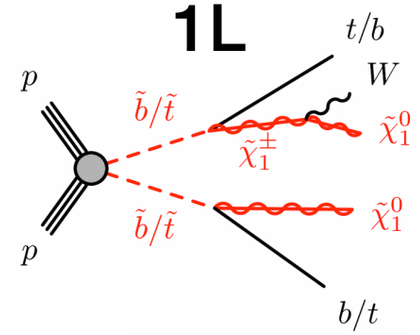
Sbottom: Exclusion Limits

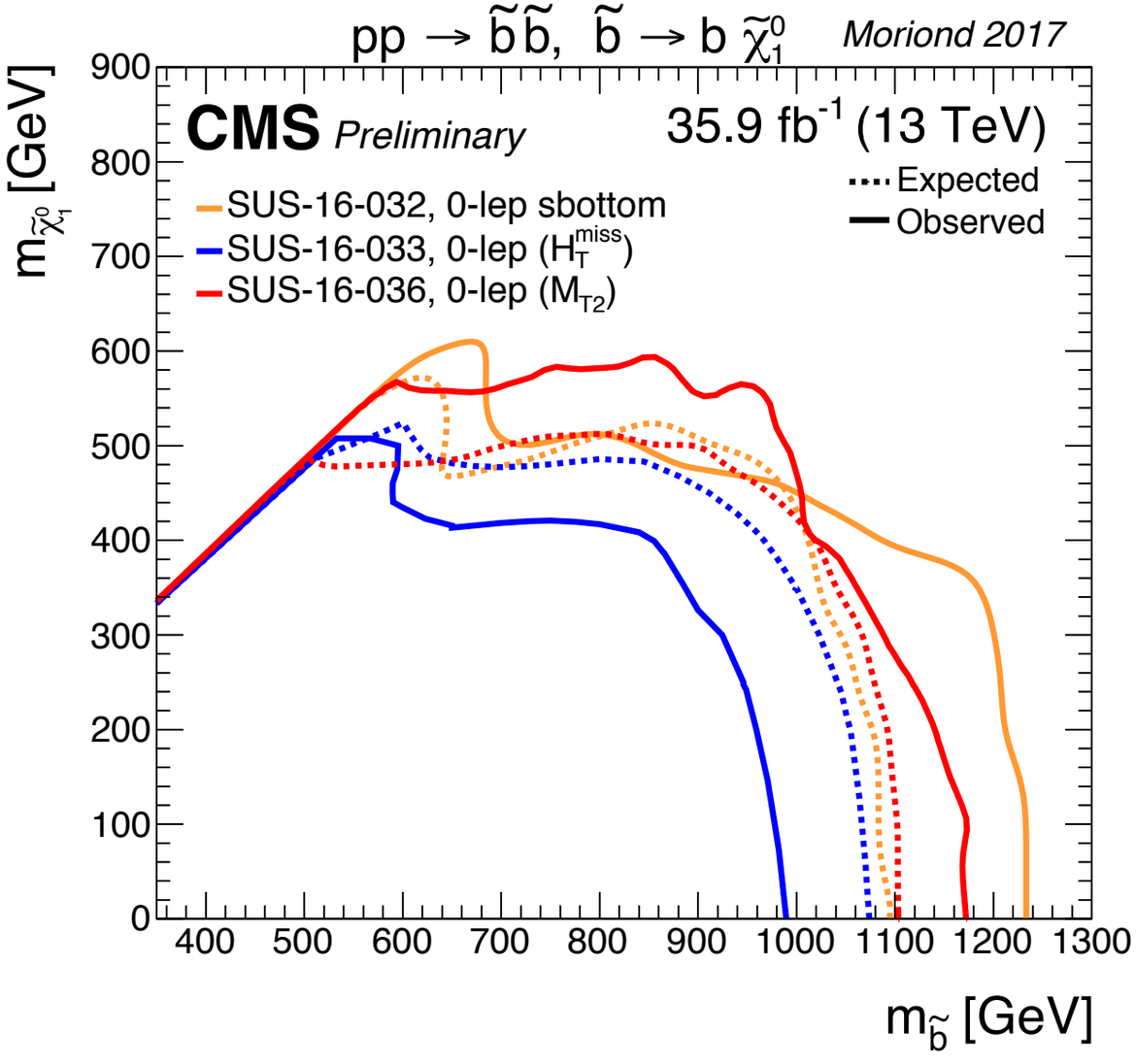


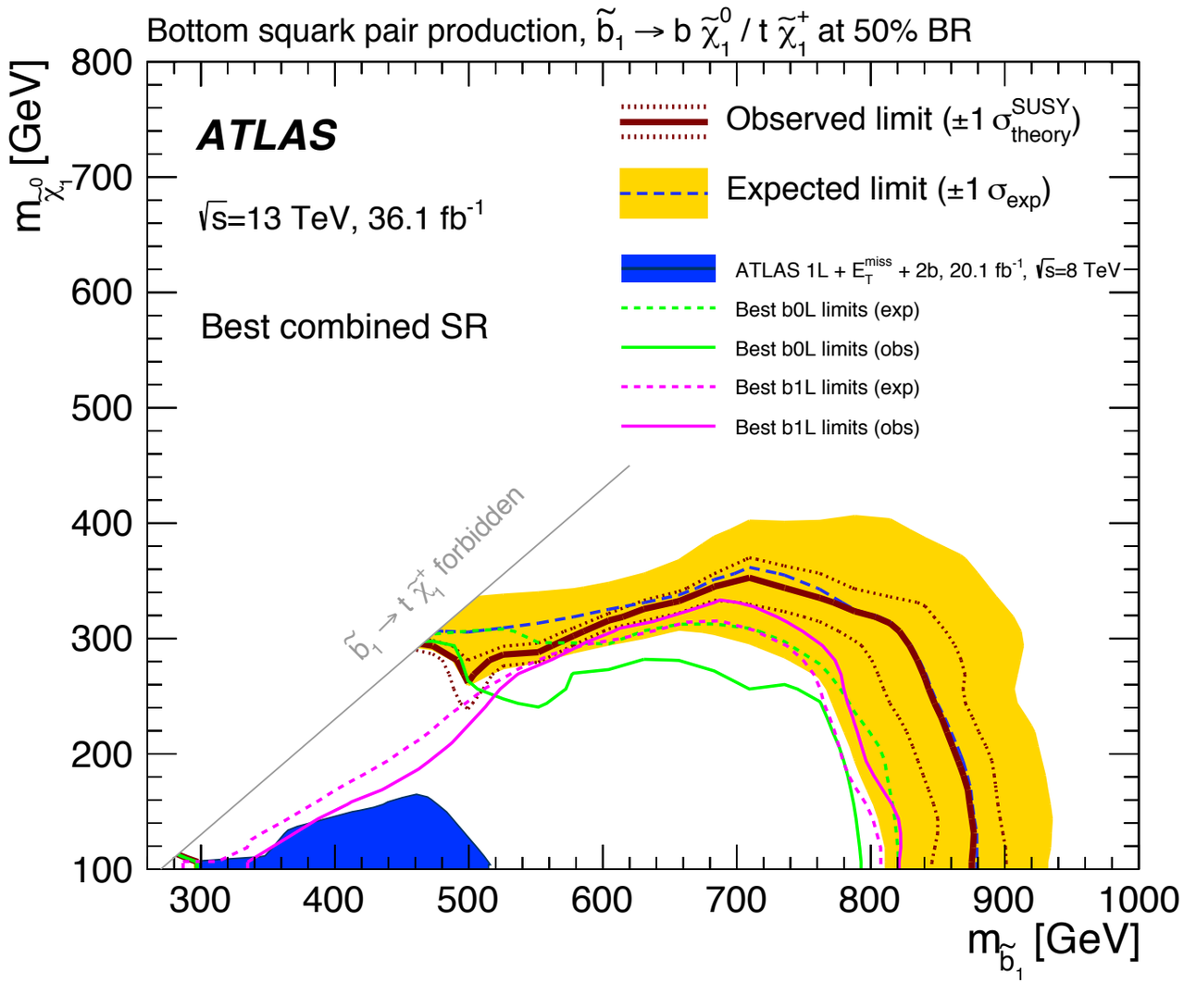
Exclusions reaching $m_{\tilde{b}}$ ~1.25 TeV, and:

~600 GeV in neutralino mass for direct decays

~350 GeV for decays with intermediate chargino







ATLAS-CONF-2017-070
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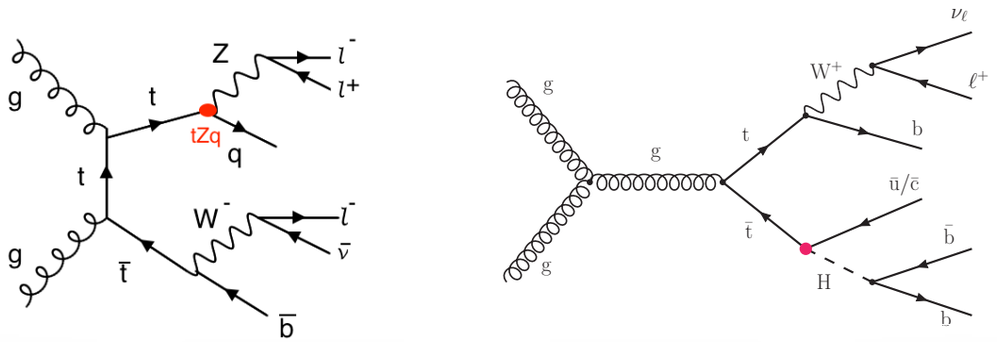
CMS-PAS-TOP-17-017
arXiv:1712.02399

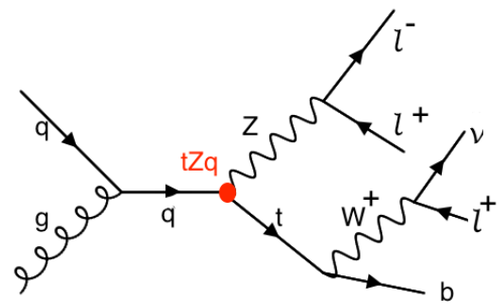
Rare Top Processes/Decays

FCNC highly suppressed in SM → enhanced rates signal of new physics

$t\bar{t}$ with FCNC decays (ATLAS+CMS)



FCNC single-top production (CMS)



SM: $\mathcal{B}(t \to qH) \sim 10^{-14}$; $\mathcal{B}(t \to qZ) \sim 3\times10^{-15}$; can go up to $\sim 10^{-3}$ in some BSM scenarios:
non-minimal *H* sector, SUSY, warped extra dimensions, composite *H* models, etc…

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Rare Top Processes/Decays

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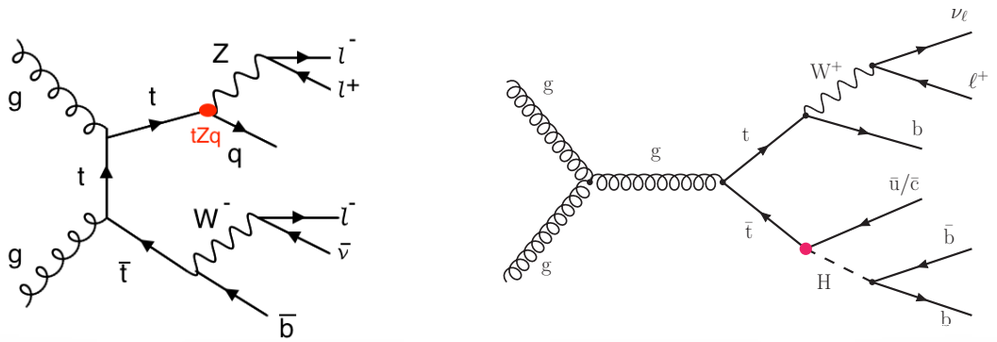

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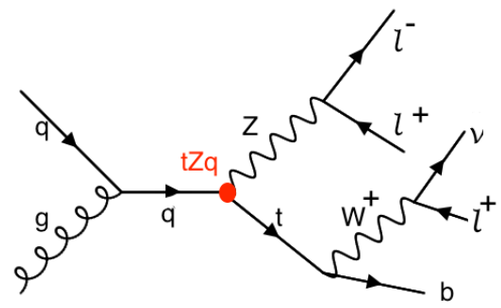

SM: $\mathcal{B}(t \to qH) \sim 10^{-14}$; $\mathcal{B}(t \to qZ) \sim 3\times10^{-15}$; can go up to $\sim 10^{-3}$ in some BSM scenarios:
non-minimal *H* sector, SUSY, warped extra dimensions, composite *H* models, etc…

FCNC tqH vertices (ATLAS: H→γγ, CMS: H→bb)

- Main backgrounds: $\gamma\gamma$+*jets*, $t\bar{t}\gamma$ and $V\gamma$ (ATLAS); $t\bar{t}$, single-top (CMS)
- Largest uncertainties: $t\bar{t}$ hard-process generation (ATLAS) and b-tagging (CMS)

FCNC tqZ vertices (3L final state, ATLAS+CMS)

- Main backgrounds: diboson, $t\bar{t}Z$, tZ, $t\bar{t}H$
- Largest uncertainties: background modeling

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FCNC: t→qH, H→$\gamma\gamma$

Hadronic $t\bar{t}$ selection

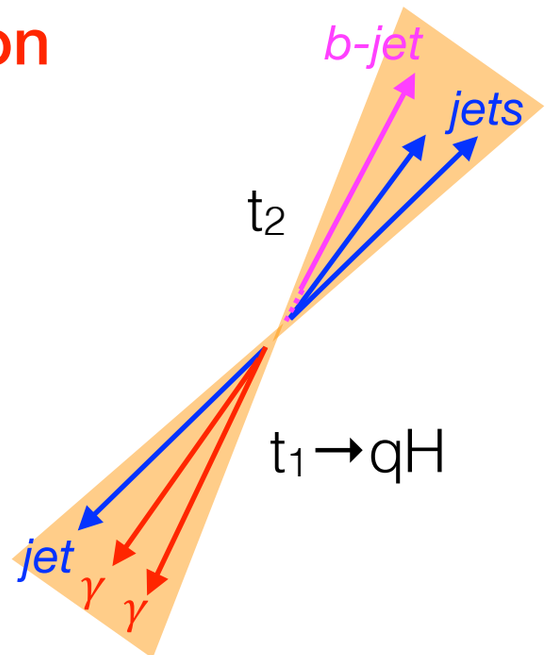
$N_{jets}\geq 4$, $N_{b\text{-}tag}\geq 1$

$152<m(t_1)<190$ GeV

$120<m(t_2)<220$ GeV

Signal from fit to m($\gamma\gamma$)

Bkg. from sidebands



Semileptonic $t\bar{t}$ selection

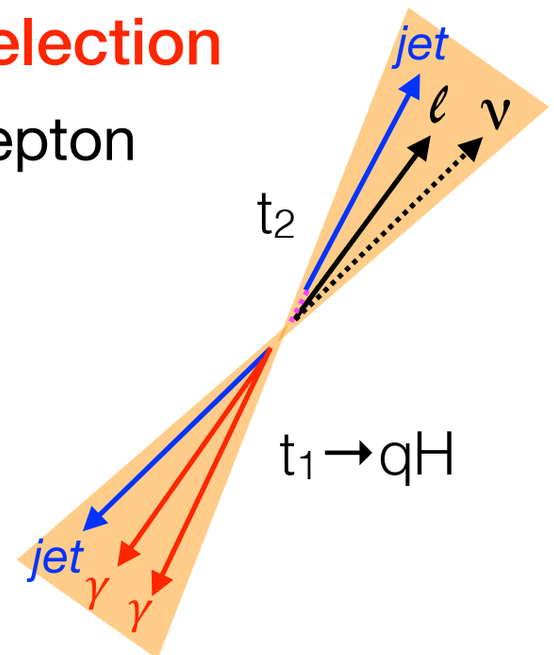
$N_{jets}\geq 1$, 1 isolated lepton

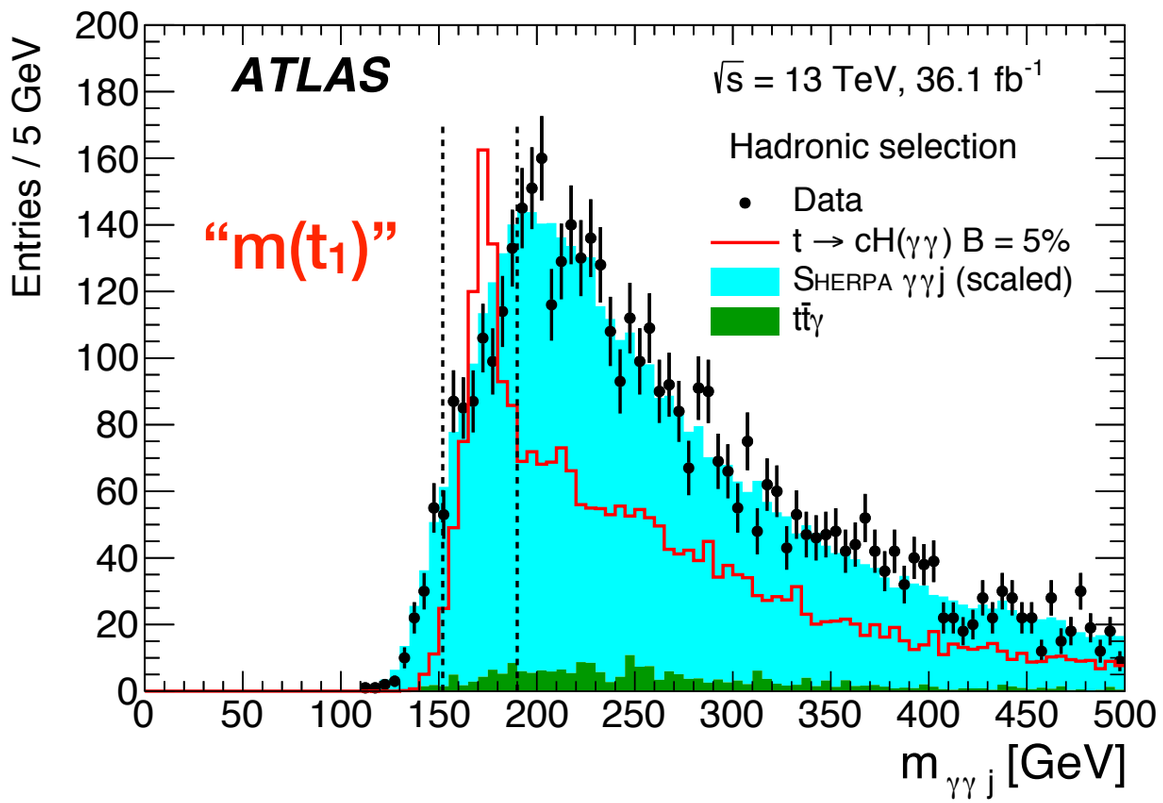
$152<m(t_1)<190$ GeV

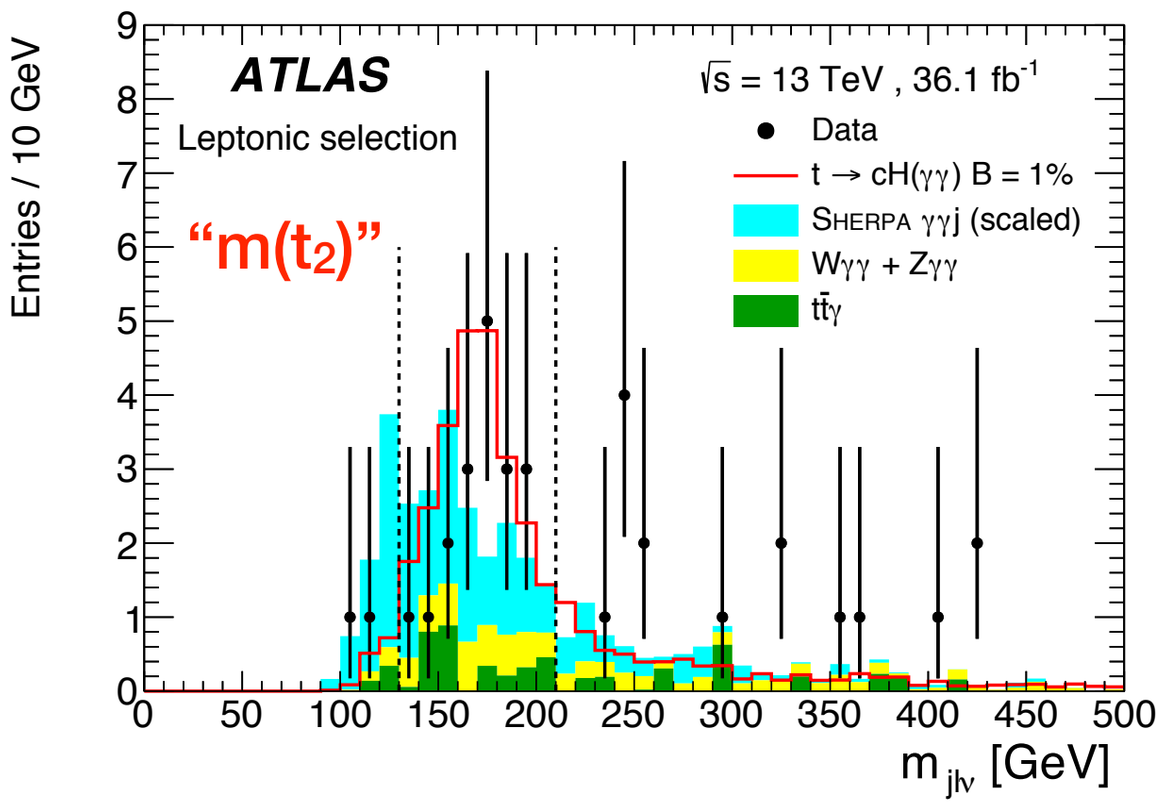
$130<m(t_2)<210$ GeV

Signal form fit to m($\gamma\gamma$)

Bkg. from sidebands







arXiv:1712.02399

FCNC: t→qH, H→bb

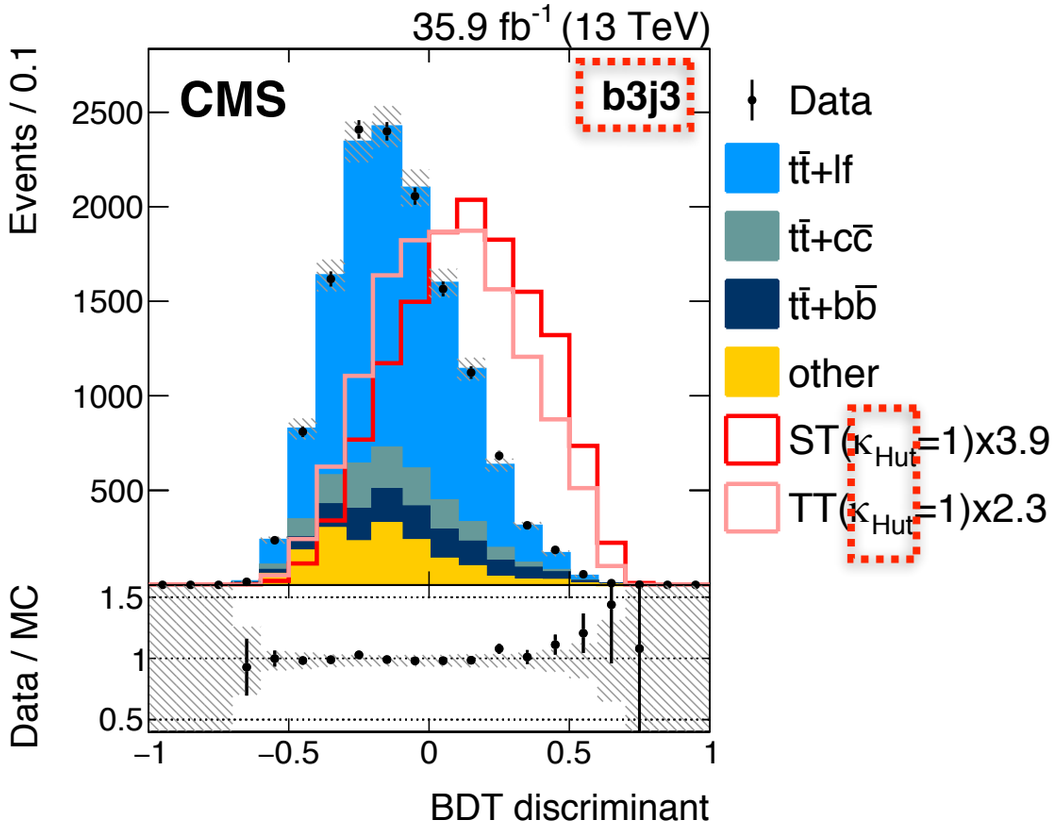
Events with 1L, $N_{jets}\geq3$ and $N_{b\text{-}tag}\geq2$ are split into 5 N_{jets}+$N_{b\text{-}tag}$ categories

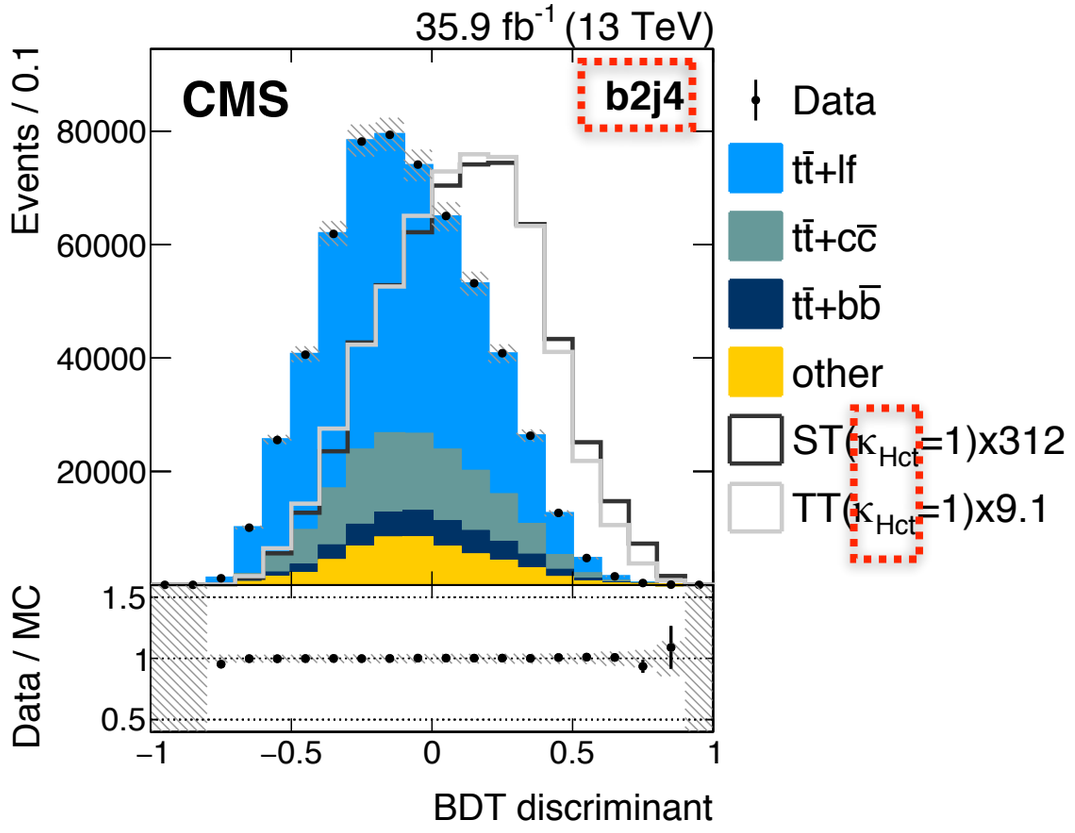
Full event kinematics reconstruction: all possible lepton, ν and (b-)jets combinations

BDT_{RECO} trained on simulation to select the correct b-jet assignment: 75% success rate

1 BDT per N_{jets}+$N_{b\text{-}tag}$ category, maximizing S/B separately for $t\to uH$ and $t\to cH$

Main variables in training are BDT_{RECO}, lepton charge, b-tagging discriminant score, m_{bb}





FCNC: t→qZ (3L Final State)

Simultaneous fit to 5 regions

Constrain bkg., isolate signal

Mainly defined by N_{jets}, $N_{b\text{-}tag}$ requirements

WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)

↓ ↓

BDT to improve S/B

χ^2-based $t\bar{t}$ reconstruction

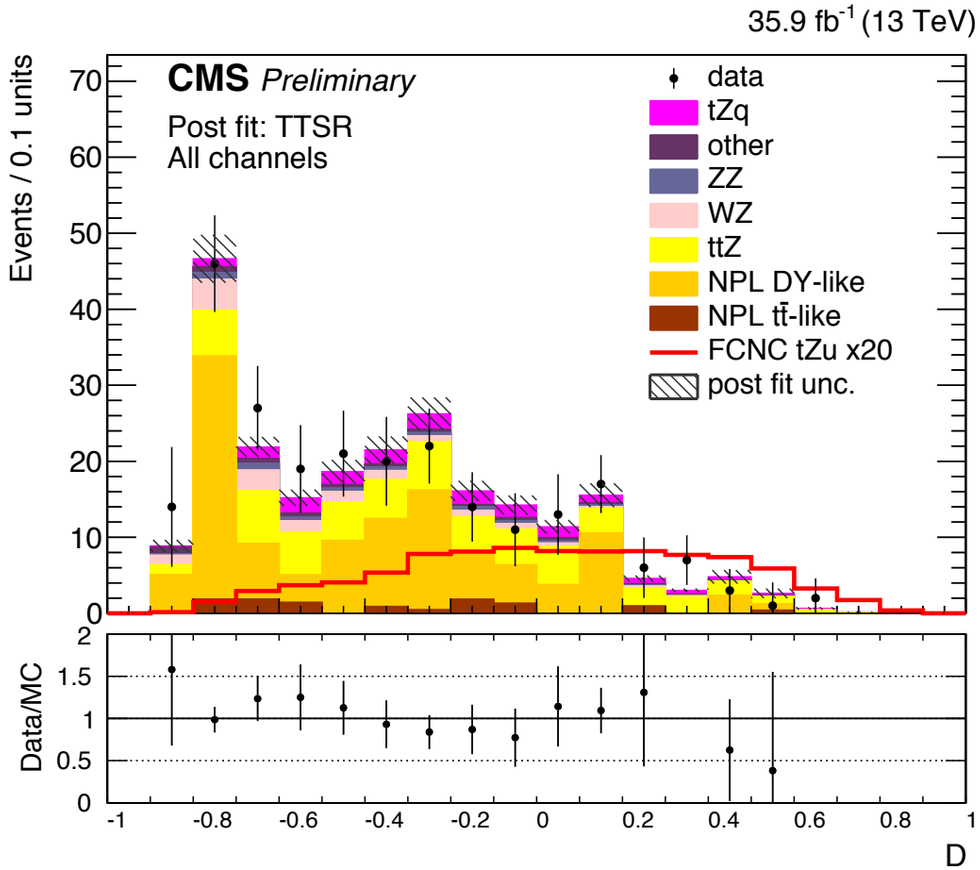
$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W},$$

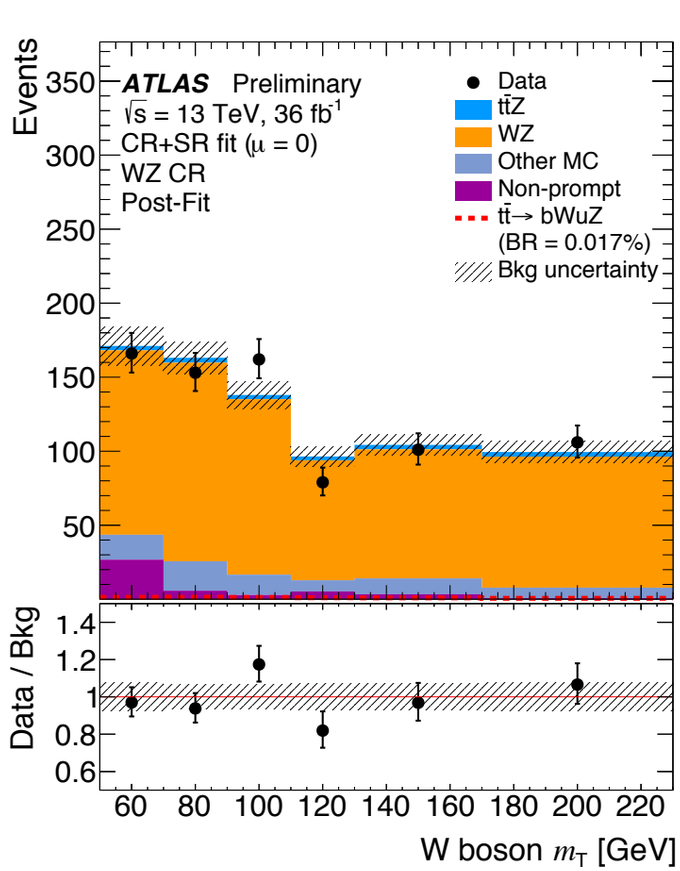
(qZ) (bW) (ℓν)

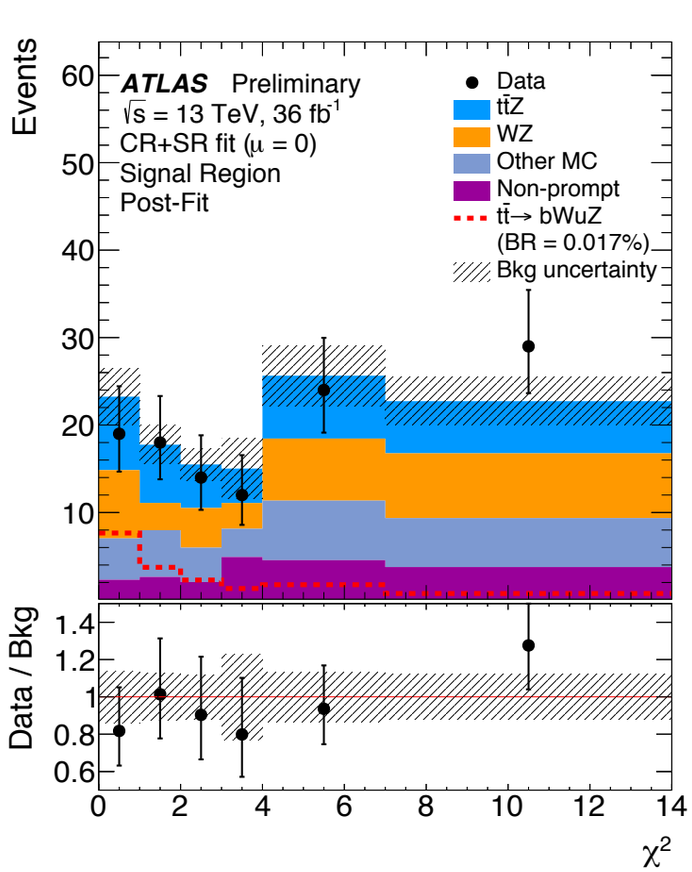
□ → from reconstructed simulation

Signal region defined by:

$$|m^{\text{reco}}_{j_a\ell_a\ell_b} - 172.5\ \text{GeV}| < 40\ \text{GeV}$$
$$|m^{\text{reco}}_{\ell_c\nu} - 80.4\ \text{GeV}| < 30\ \text{GeV}$$
$$|m^{\text{reco}}_{j_b\ell_c\nu} - 172.5\ \text{GeV}| < 40\ \text{GeV}$$







95% CL Limits

ATLAS EXPERIMENT

$\mathcal{B}(t\to uZ) < 0.017\ (0.024)\ \%$
$\mathcal{B}(t\to cZ) < 0.023\ (0.032)\ \%$

$\mathcal{B}(t\to uH) < 0.22\ (0.16)\ \%$
$\mathcal{B}(t\to cH) < 0.24\ (0.17)\ \%$ $(H\to\gamma\gamma)$

CMS

$\mathcal{B}(t\to uZ) < 0.024\ (0.015)\ \%$
$\mathcal{B}(t\to cZ) < 0.045\ (0.037)\ \%$

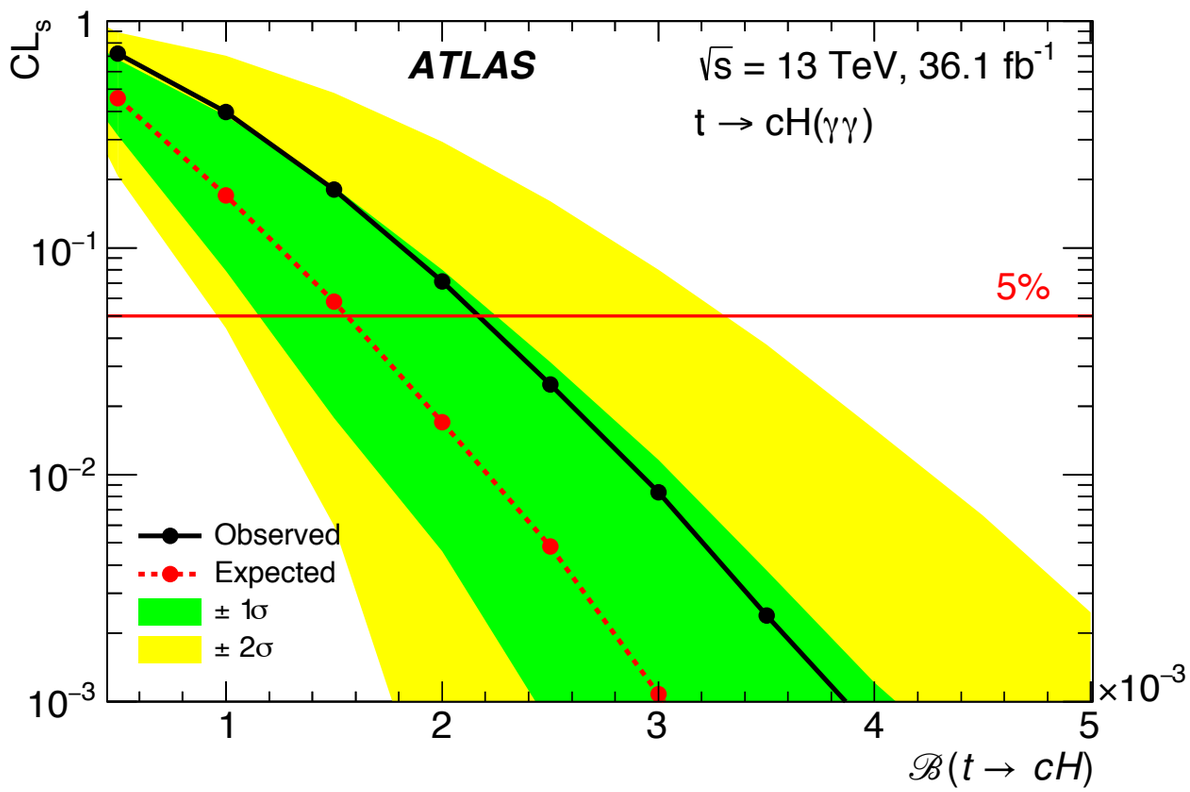
$\mathcal{B}(t\to uH) < 0.47\ (0.34)\ \%$
$\mathcal{B}(t\to cH) < 0.47\ (0.44)\ \%$ $(H\to bb)$

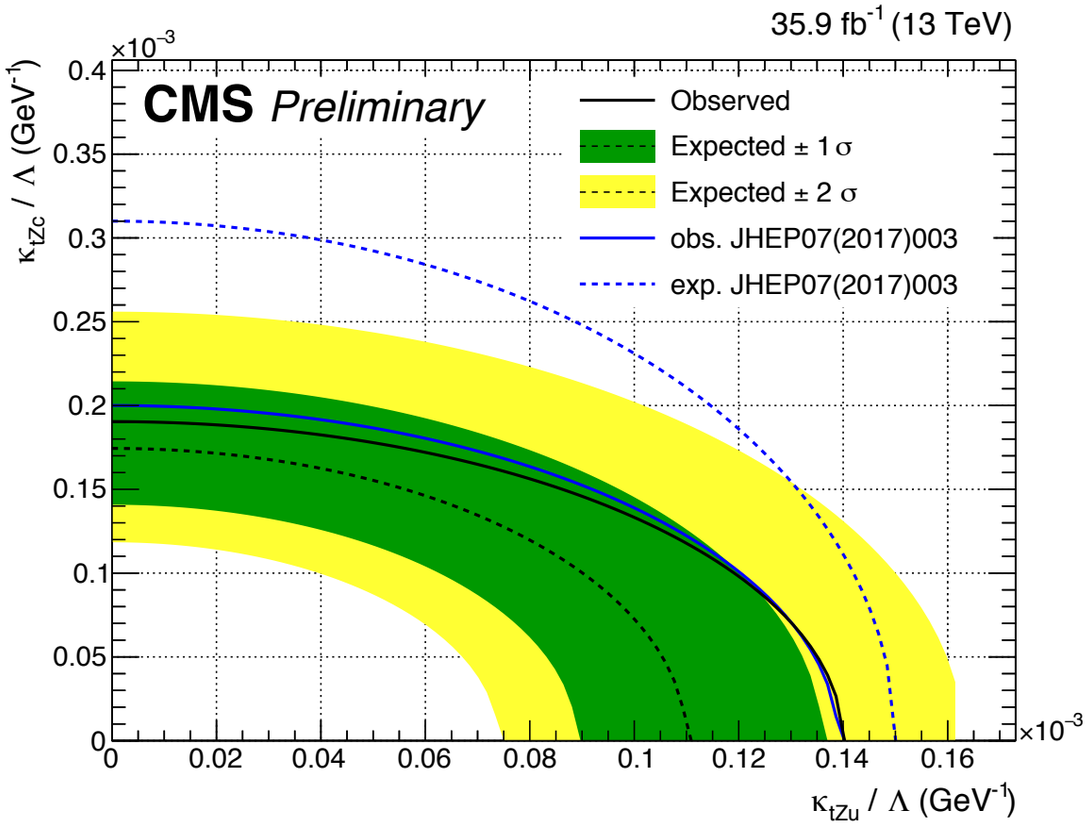
Limits on off-diagonal Yukawa couplings:

$$\lambda_{tqH} = (1.92 \pm 0.02) \times \sqrt{\mathcal{B}} \quad \Rightarrow \sqrt{\lambda_{tcH}^2 + 0.92\lambda_{tuH}^2} < 0.090$$

Limits on FCNC couplings @ scale Λ:

$$\mathcal{L}_{\mathrm{FCNC}}^{tZq} = \sum_{\mathrm{q=u,c}} \left[\frac{\sqrt{2}}{4} \frac{g}{\cos\theta_{\mathrm{W}}} \frac{\kappa_{\mathrm{tZq}}}{\Lambda} \bar{t}\sigma^{\mu\nu} \left(f_{\mathrm{Zq}}^{\mathrm{L}} P_{\mathrm{L}} + f_{\mathrm{Zq}}^{\mathrm{R}} P_{\mathrm{R}} \right) \mathrm{q} Z_{\mu\nu} \right] + h.c.$$

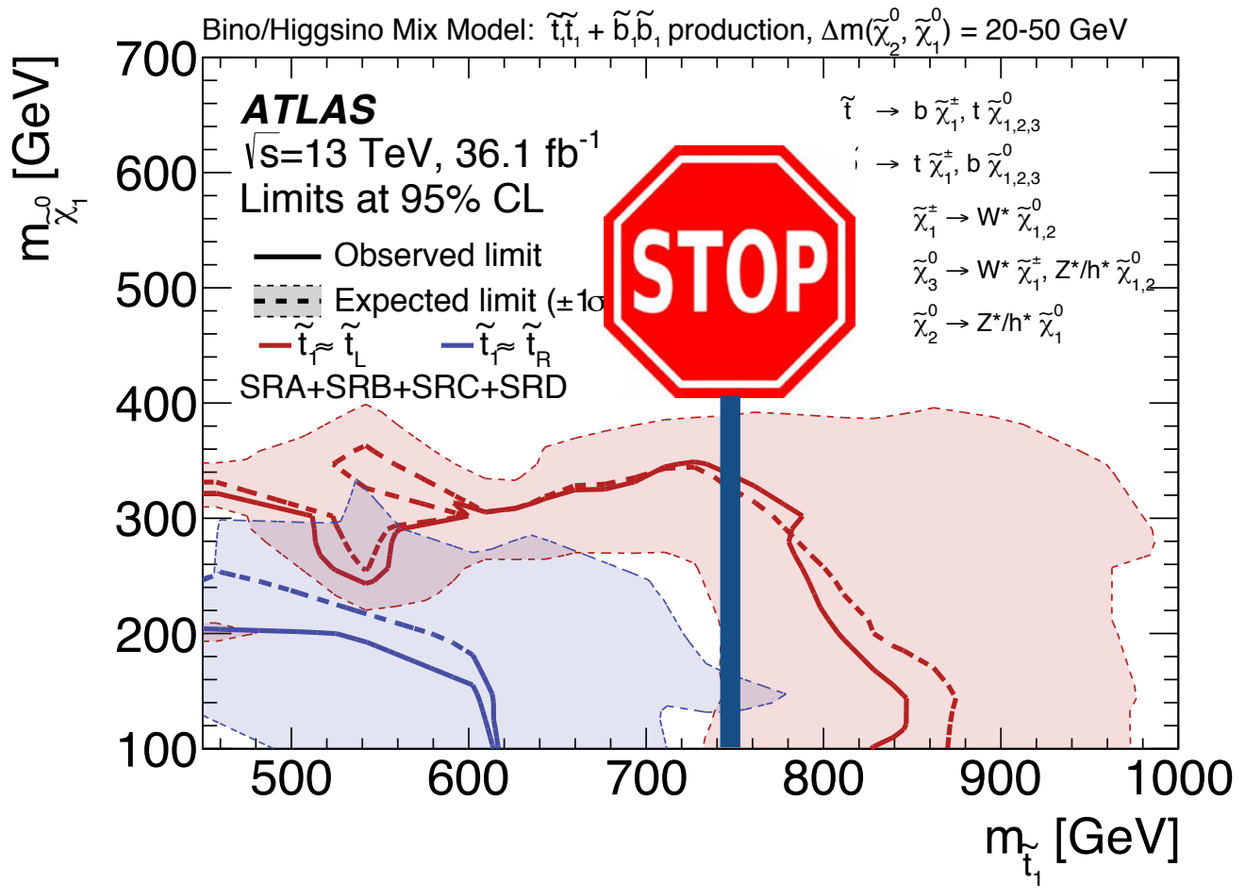




Closing Remarks

***Top quark* plays a key role in many BSM searches**

- Great deal of efforts in ATLAS+CMS to look for *t*- and *b*-quark super-partners
  - a small fraction presented today, through the 0L and 1L workhorses
  - only stringent limits so far, but we're not yet at the end of the journey…
- Limits on DM+HF models nicely complement direct-detection experiments
- Searches for rare top processes/decays start to show sensitivity for BSM rates

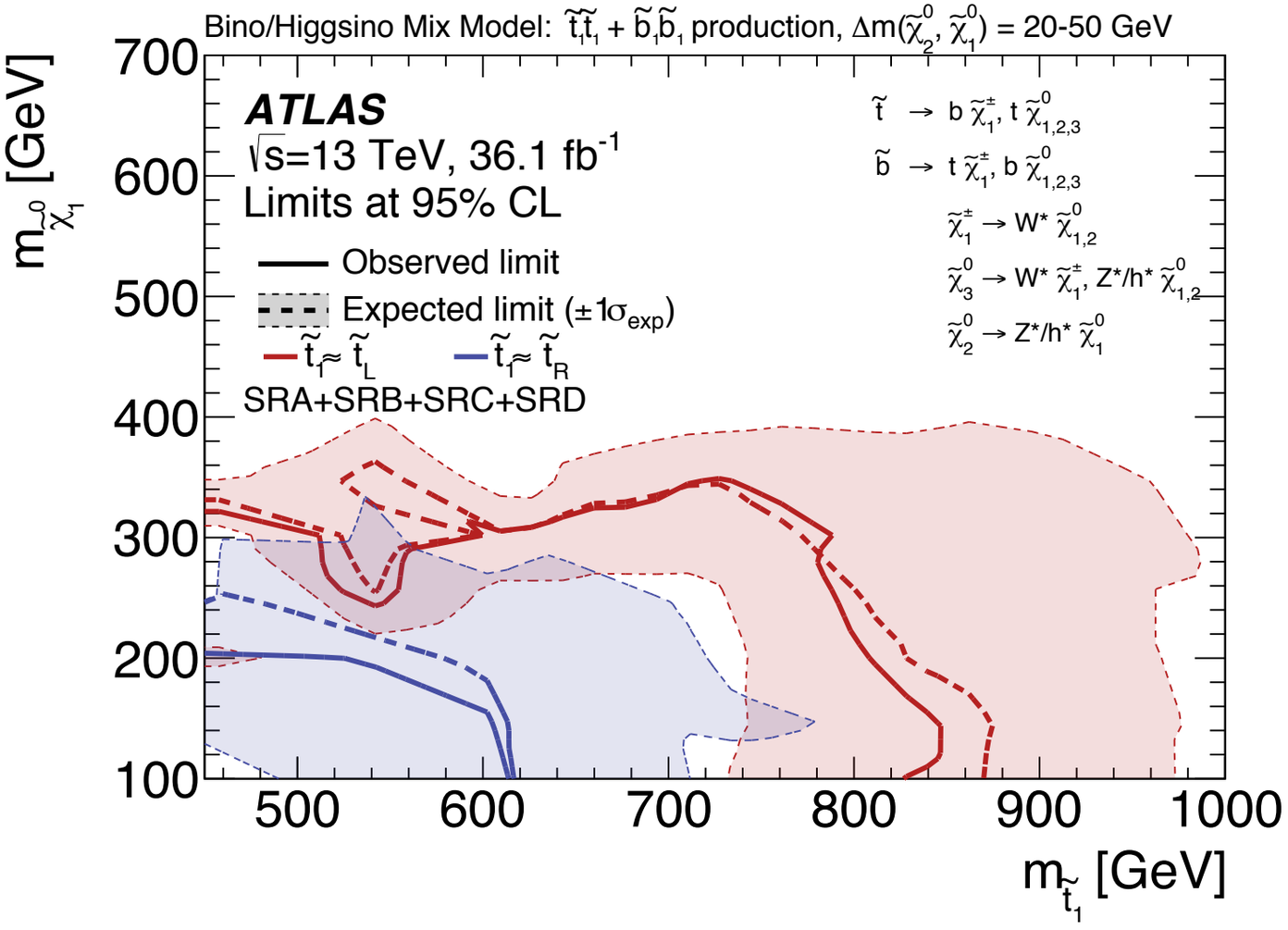


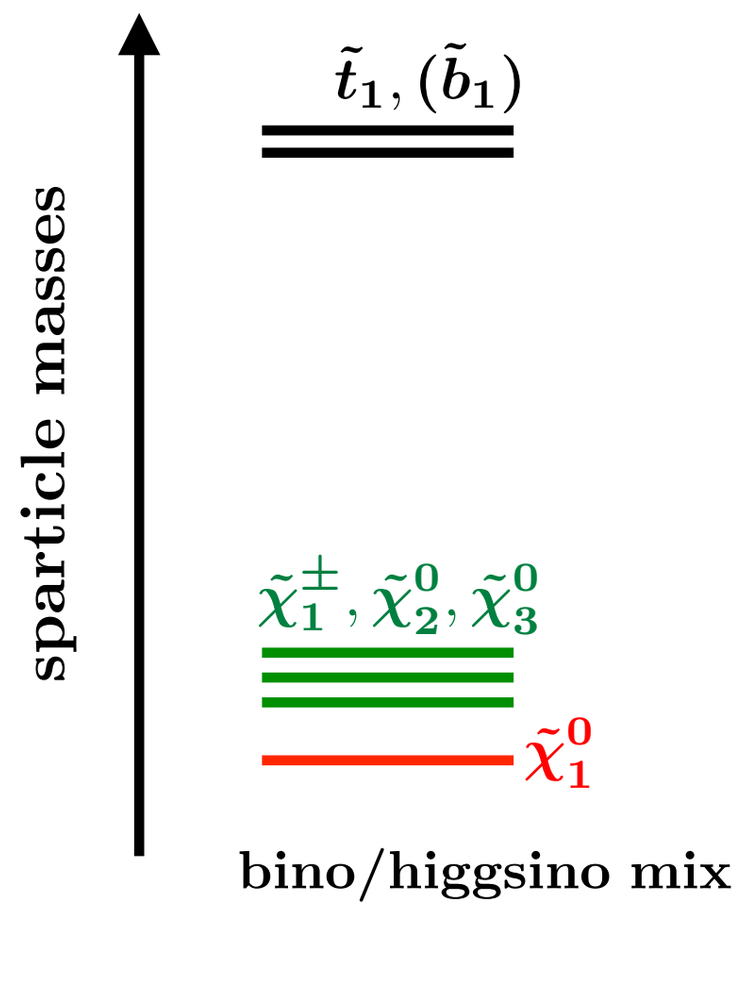
Spares

JHEP 12 (2017) 085
arXiv:1711.11520

"Well-Tempered" LSP

The 'well-tempered neutralino' [69] scenario seeks to provide a viable dark-matter candidate while simultaneously addressing the problem of naturalness by targeting an LSP that is an admixture of bino and higgsino. The mass spectrum of the electroweakinos (higgsinos and bino) is expected to be slightly compressed, with a typical mass-splitting between the bino and higgsino states of 20–50 GeV. A pMSSM signal model is designed such that only a low level of fine-tuning [70, 71] of the pMSSM parameters is needed and the annihilation rate of neutralinos is consistent with the observed dark-matter relic density[5] ($0.10 < \Omega h^2 < 0.12$) [72].





JHEP 10 (2017) 005

Stop 0L, CMS: Strategy (II)

Trigger on $\not{E}_T$ (offline: >250 GeV), veto events with isolated leptons

Low Δm

$N_{jets}\geq 2$, $N_t=N_W=0$, $m_T(\not{E}_T,\text{b-jet})<175$ GeV

one ISR jet, $p_{T,ISR}> 300$ GeV, $\Delta\phi(\not{E}_T,ISR)>2$, …

53 search regions

High Δm

$N_{jets}\geq 5$, $N_{b\text{-}tag}\geq 1$, $\Delta\phi(\not{E}_T,j_{1..4})\geq 0.5$

51 search regions

Table 2: Summary of the 53 non-overlapping search regions that mainly target low Δm signal. The low Δm baseline selection is $N_j \geq 2$, $p_T^{miss} \geq 250$ GeV, no leptons, $N_t = N_W = N_{res} = 0$, $m_T^b < 175$ GeV (when applicable), $|\Delta\phi(j_1, \vec{p}_T^{miss})| \geq 0.5$, $|\Delta\phi(j_{2,3}, \vec{p}_T^{miss})| \geq 0.15$, and an ISR jet with $p_T^{ISR} \geq 300$ GeV, $|\eta| \leq 2.4$, $|\Delta\phi(j_{ISR}, \vec{p}_T^{miss})| \geq 2$, and $S_{\not{E}_T} \geq 10\sqrt{\text{GeV}}$.

N_j	N_b	N_{SV}	p_T^{ISR} [GeV]	p_T^b [GeV]	p_T^{miss} [GeV]
2–5	0	0	≥500	—	450–550, 550–650, 650–750, ≥750
≥6		0			450–550, 550–650, 650–750, ≥750
2–5		≥1			450–550, 550–650, 650–750, ≥750
≥6		≥1			450–550, 550–650, 650–750, ≥750
≥2	1	0	300–500	20–40	300–400, 400–500, 500–600, ≥600
		0	300–500	40–70	300–400, 400–500, 500–600, ≥600
		0	≥500	20–40	450–550, 550–650, 650–750, ≥750
		0	≥500	40–70	450–550, 550–650, 650–750, ≥750
		≥1	≥300	20–40	300–400, 400–500, ≥500
≥2	≥2	≥0	300–500	40–80	300–400, 400–500, ≥500
≥2			300–500	80–140	300–400, 400–500, ≥500
≥7			300–500	≥140	300–400, 400–500, ≥500
≥2			≥500	40–80	450–550, 550–650, ≥650
≥2			≥500	80–140	450–550, 550–650, ≥650
≥7			≥300	≥140	450–550, 550–650, ≥650

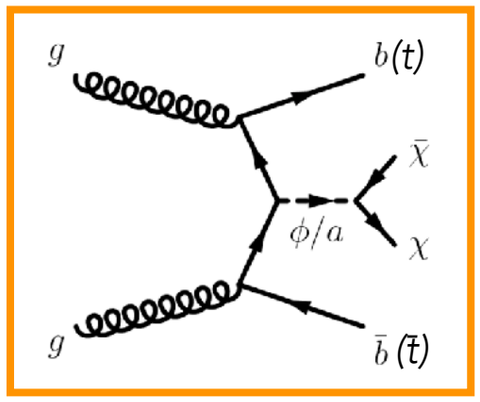
Table 1: Summary of the 51 non-overlapping search regions that mainly target high Δm signal. The high Δm baseline selection is $N_j \geq 5$, $p_T^{miss} \geq 250$ GeV, no leptons, $N_b \geq 1$, and $\Delta\phi_{1234} \geq 0.5$.

N_j	N_t	N_W	N_{res}	N_b	p_T^{miss} [GeV]
			$m_T^b < 175$ GeV		
≥7	≥0	≥0	≥1	1, ≥2	250-300, 300-400, 400-500, ≥500
			$m_T^b \geq 175$ GeV		
≥7	0	0	0	1, ≥2	250-350, 350-450, 450-550, ≥550
≥5	≥1	0	0	1	550-650, ≥650
	0	0	≥1		250-350, 350-450, 450-550, 550-650, ≥650
	≥1	≥1	0		≥550
	0	≥1	≥1		250-350, 350-450, 450-550, ≥550
≥5	1	0	0	≥2	550-650, ≥650
	0	1	0		250-350, 350-450, 450-550, 550-650, ≥ 650
	0	0	1		250-350, 350-450, 450-550, 550-650, ≥650
	1	1	0		≥550
	0	1	1		250-350, 350-450, 450-550, ≥550
	1	0	1		250-350, 350-450, ≥450
	≥2	0	0		≥250
	0	≥2	0		≥250
	0	0	≥2		≥250

Eur. Phys. J. C 77 (2017) 845
Eur. Phys. J. C 78 (2018) 18
arXiv:1711.11520

arXiv:1801.08427

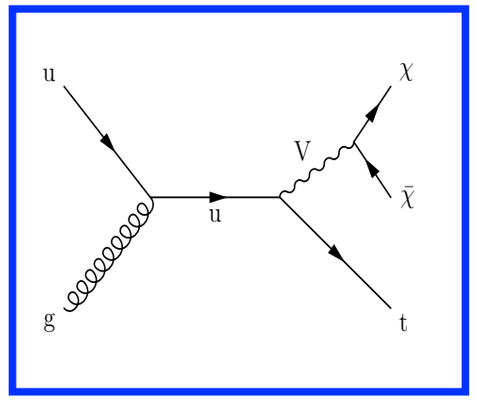
DM+Heavy Flavor(s) (HF)



WIMP(s) via mediators: *spin-0 ϕ/a* or *vector V*

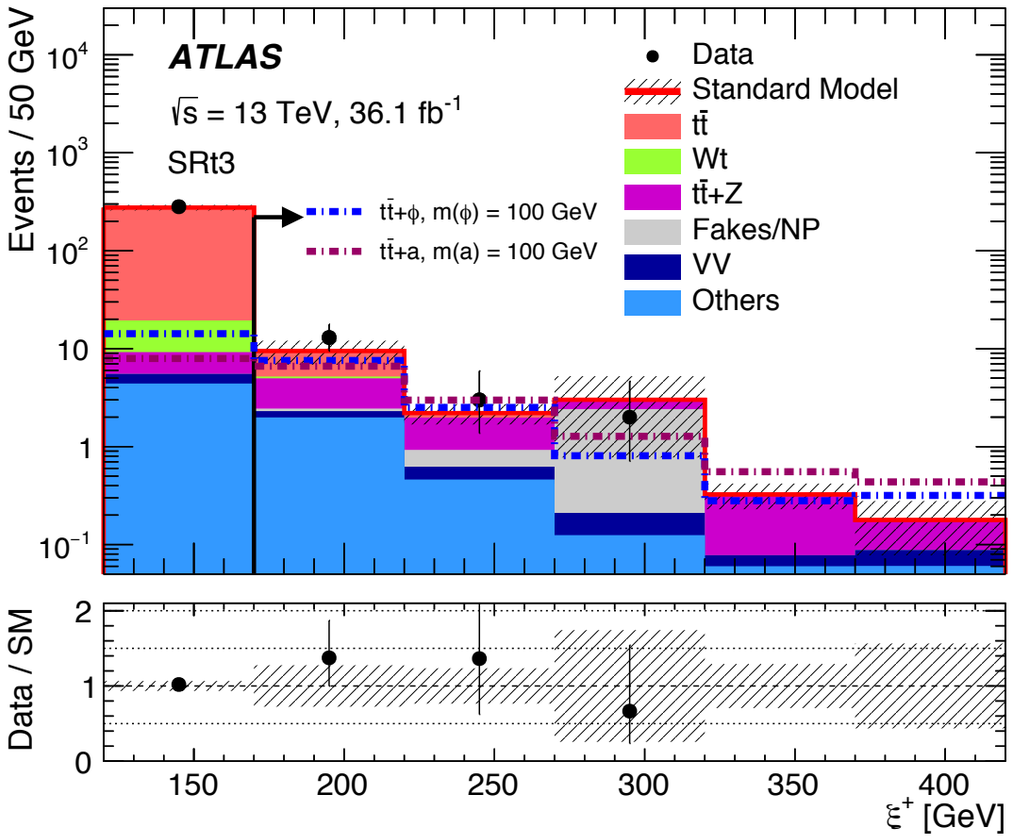
Minimal Flavor Violation: Yukawa-type ϕ/a-SM couplings

Monotop: flavor-violating V-quark couplings

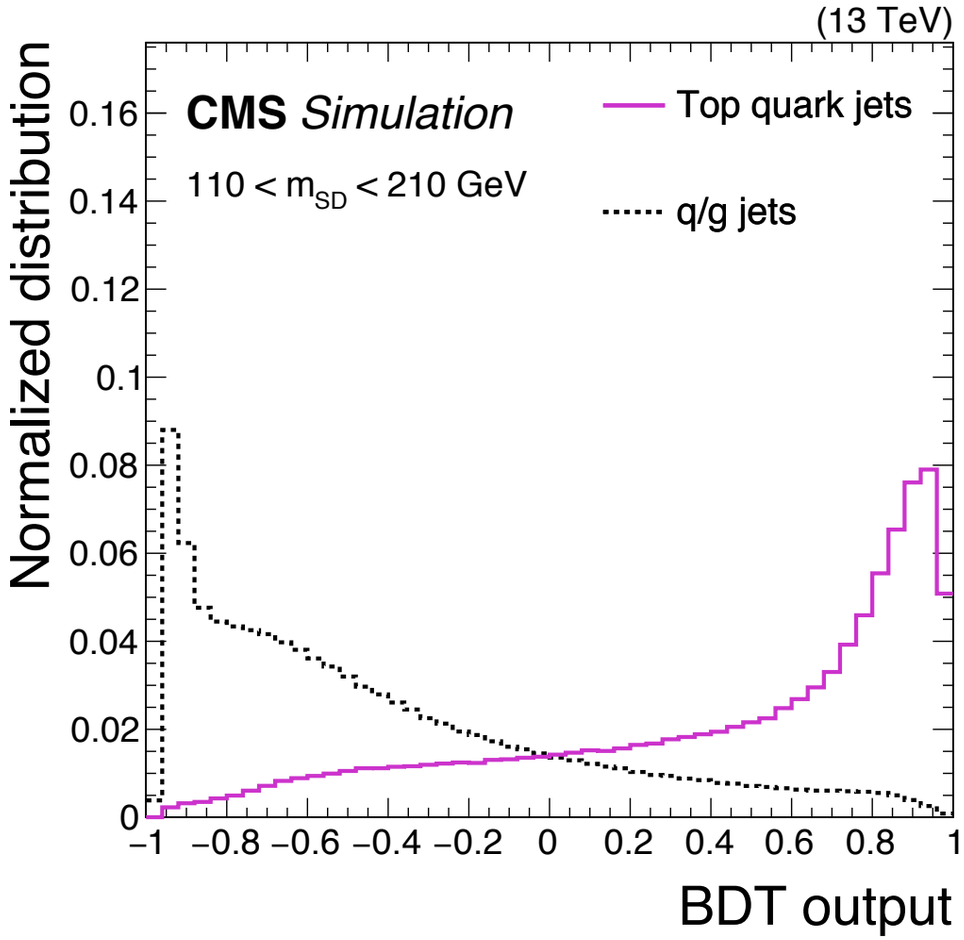


ATLAS: tailored kinematic variables

$\xi^{+} = m_{\mathrm{T2}}^{\ell\ell} + 0.2 \cdot E_{\mathrm{T}}^{\mathrm{miss}}$ large tail created by $\chi\chi$



CMS: exploit top reconstruction



Eur. Phys. J. C 77 (2017) 845
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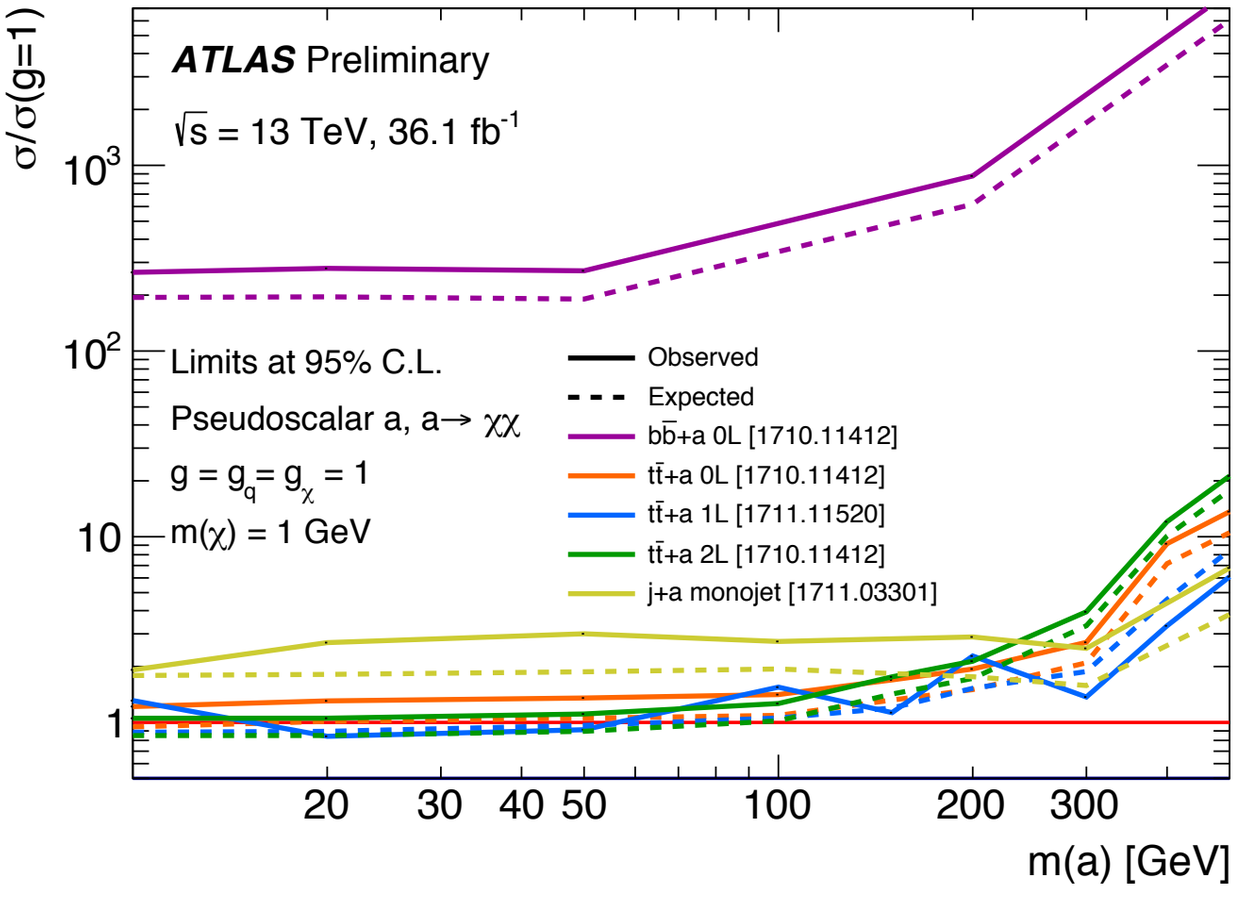
DM+HF: Limits

95% CL exclusion limits on Dirac DM and (pseudo)scalar mediators

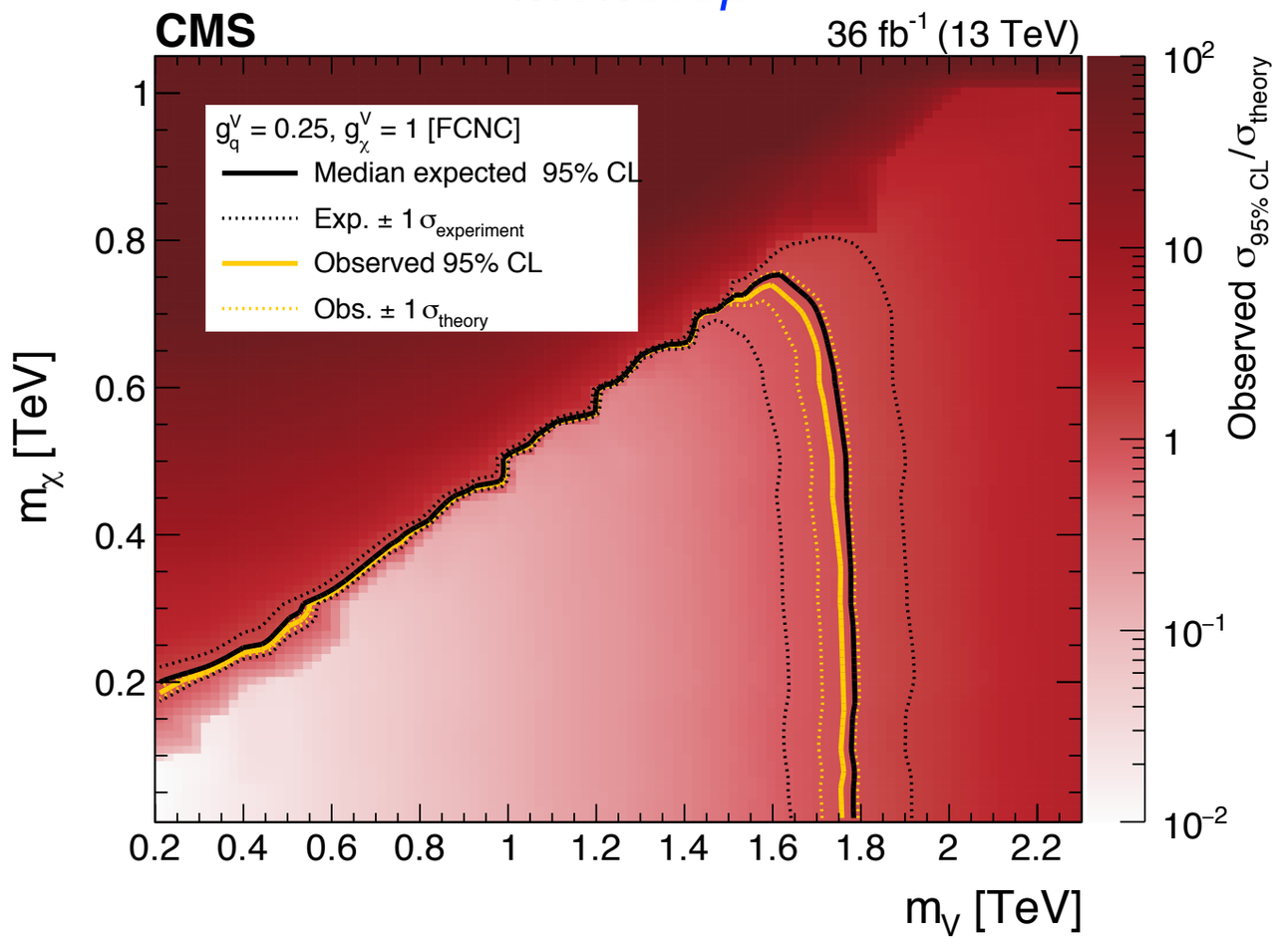
Scalar mediators ϕ masses excluded between 10-50 GeV (g=1, m(χ)=1 GeV)

Vector mediators with flavor-violating couplings excluded up to 1.8 TeV ($g_{q,V}$=0.25, $g_{\chi,V}$=1)

DM + $t\bar{t}$ ($b\bar{b}$)



Monotop



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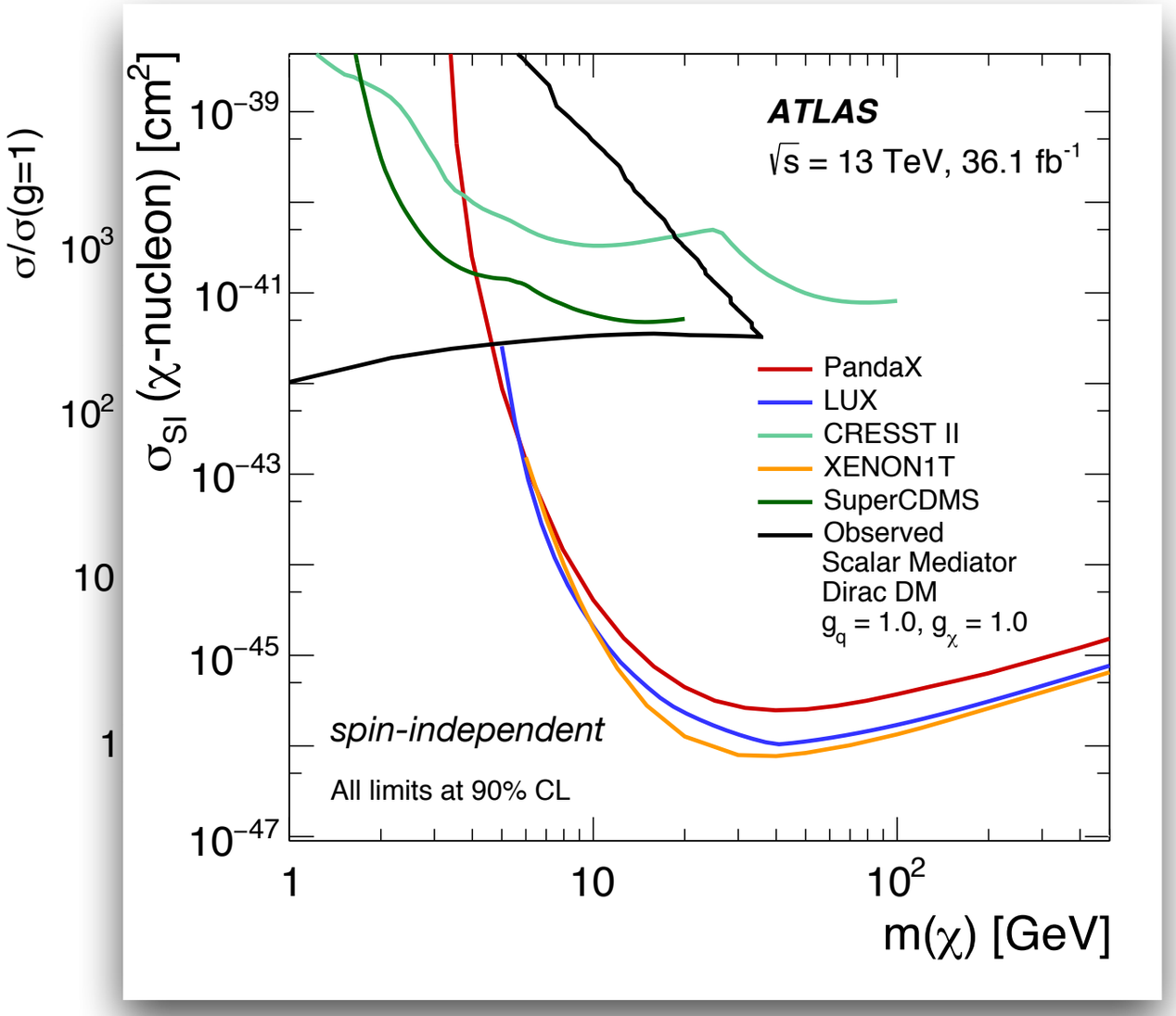

Monotop