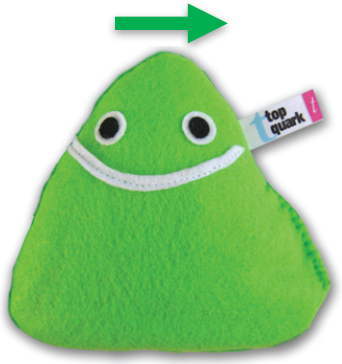


Search for top partners

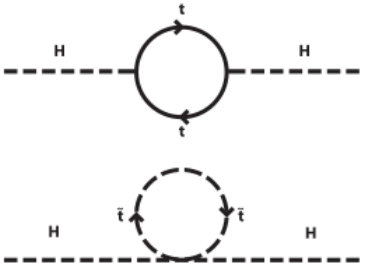
Bertrand Martin dit Latour
University of Bergen

on behalf of **ATLAS** and **CMS** collaborations

Rencontres de Blois 2016 – Particle Physics and Cosmology

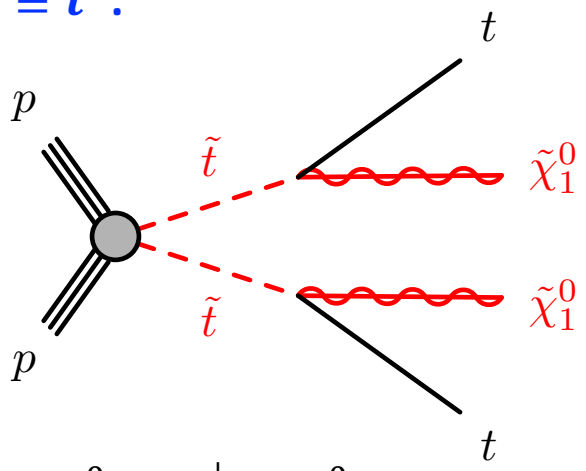
Scalar top partner

Top partners play a central role in **regulating Higgs mass radiative corrections** (**hierarchy problem**).



"Naturalness" favours **"light" top partners**.

In **supersymmetry**, **top partner** = **scalar top**. Here, **"** $\tilde{t}_1 \equiv \tilde{t}$ **".**



$\tilde{t} \rightarrow t\tilde{\chi}_1^0\ ,\ b\tilde{\chi}_1^{\pm}\ ,c\tilde{\chi}_1^0$

Vector-like top partner

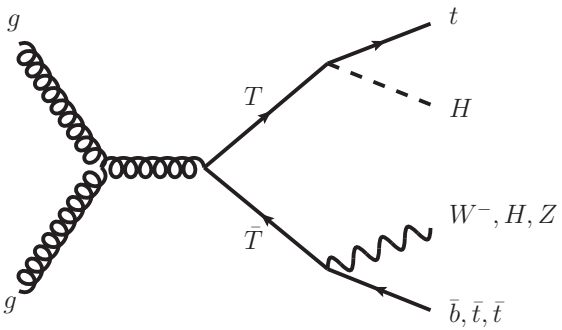
Exotics models (**Composite Higgs**, **Little Higgs**) predict **vector-like quarks**, with L/R chiral components transforming similarly under SU(2).

Heavy quarks can be:

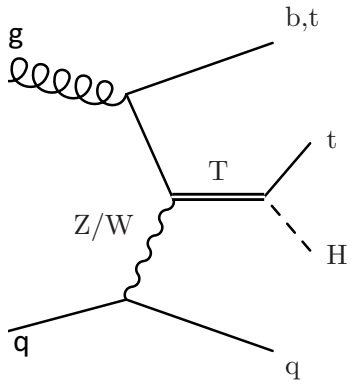
- **SU(2) singlets**: T, B
- **SU(2) doublets**: $\begin{pmatrix} T \\ B \end{pmatrix}, \begin{pmatrix} X \\ T \end{pmatrix}, \begin{pmatrix} B \\ Y \end{pmatrix}$

Electric charge: T=+2/3, B=-1/3, **X=+5/3, Y=-4/3**

Pair production via strong interaction



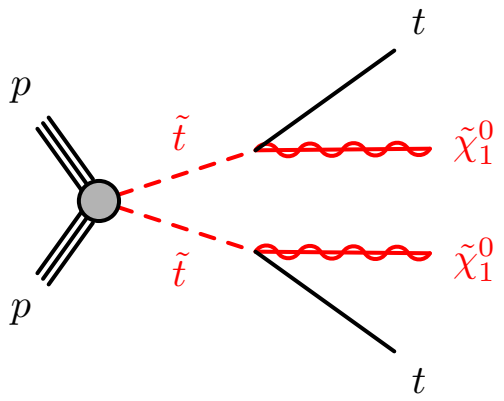
Single production via EW interaction

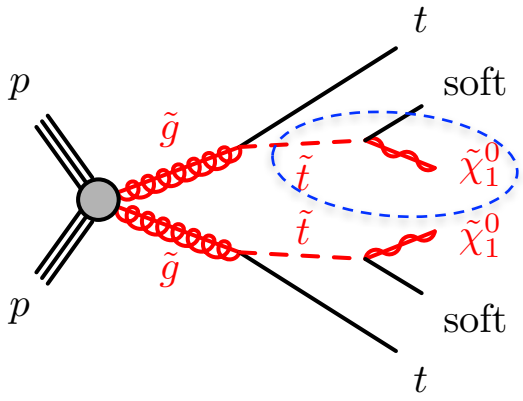


Searches for Supersymmetry

$\tilde{t}\tilde{t}$ search with 1 lepton

ATLAS-CONF-2016-007

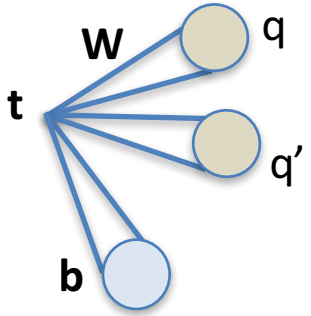




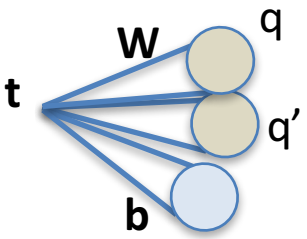
~ degenerate

E_T^{miss}, ≥4 jets, ≥1 b-jet, 1 e/μ

Backgrounds:
- **semileptonic $t\bar{t}$ and Wt**
- **$t\bar{t}$+Z($\nu\nu$)**, estimated from **$t\bar{t}$+γ**
- **W($\ell\nu$)+jets**



Resolved top

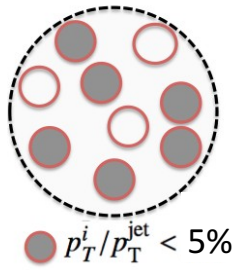


Boosted top

Small $\Delta m(\tilde{t}/\tilde{g}, \tilde{\chi}_1^0)$: resolved top.
Mass of 3 small-R jets compatible with hadronic top decay (χ^2)

Large Δm: boosted top.
Mass and p_T of large-R jet

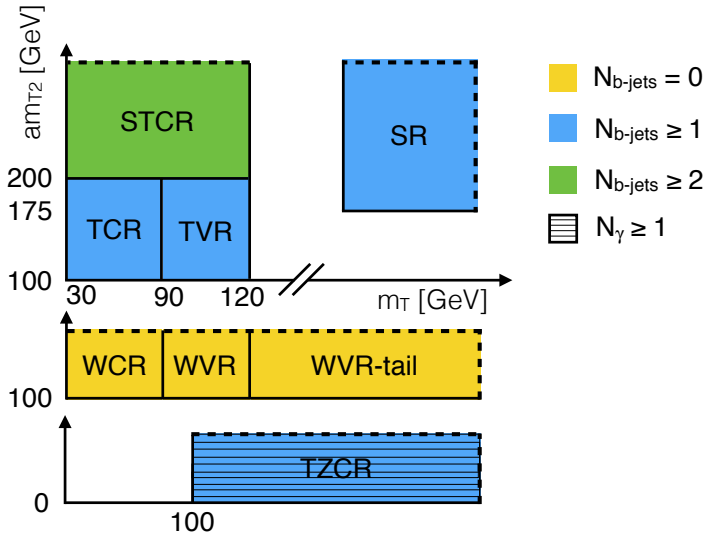
Large-R jets (R = 1, 1.2) **built from small-R jets.**



$\tilde{t}\tilde{t}$ search with 1 lepton

Common approach to all searches:

- **SR: signal region**
- **CR: control region** (signal free), to **normalize background to data**
- **VR: validation region**, to **check the extrapolation from CR to SR**

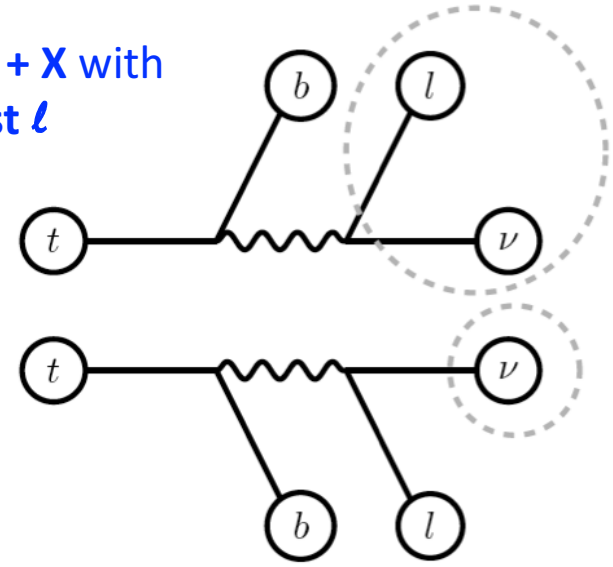


Discriminants:

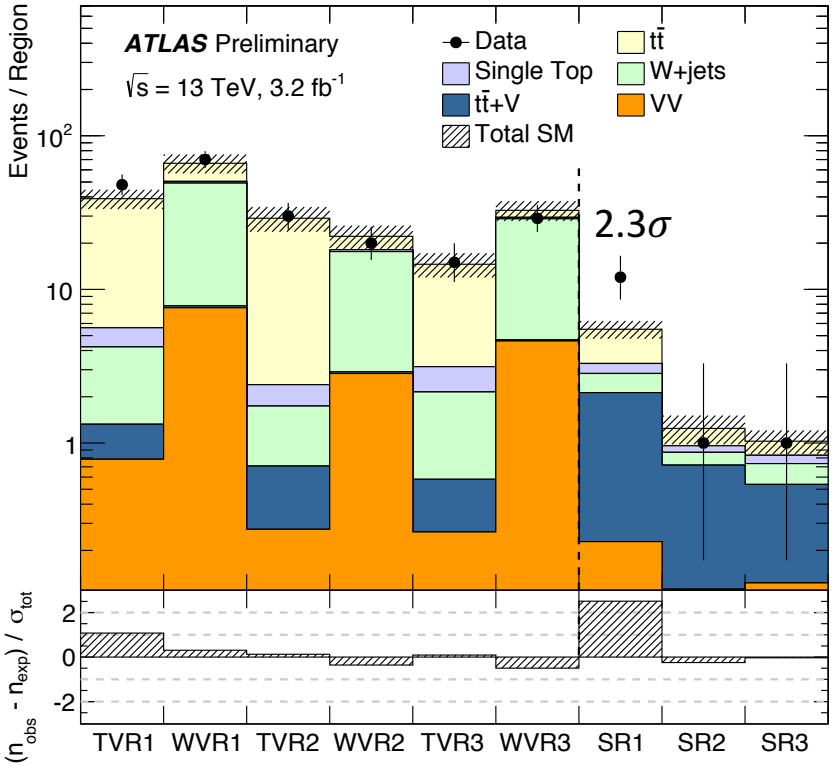
- **m_T**
- **topness** = χ^2 compatibility with $t\bar{t} \rightarrow \ell\ell'$+X with a lost ℓ
- **m_{T2} (am_{T2})** = generalization of **transverse mass** where **2 "particles" are not detected**.

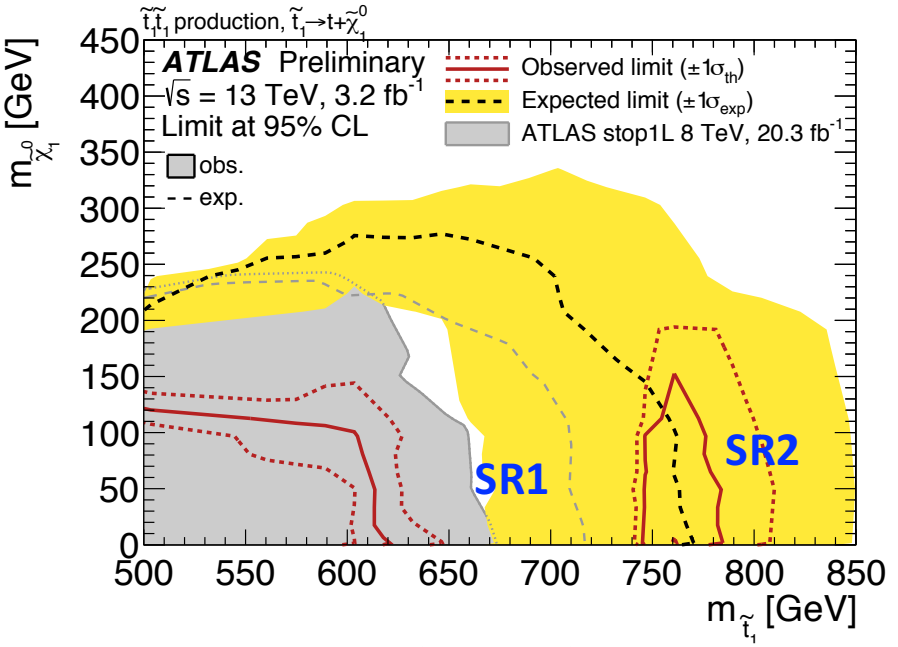
  Find **kinematics most compatible** with **assumed mass of invisible particles**.

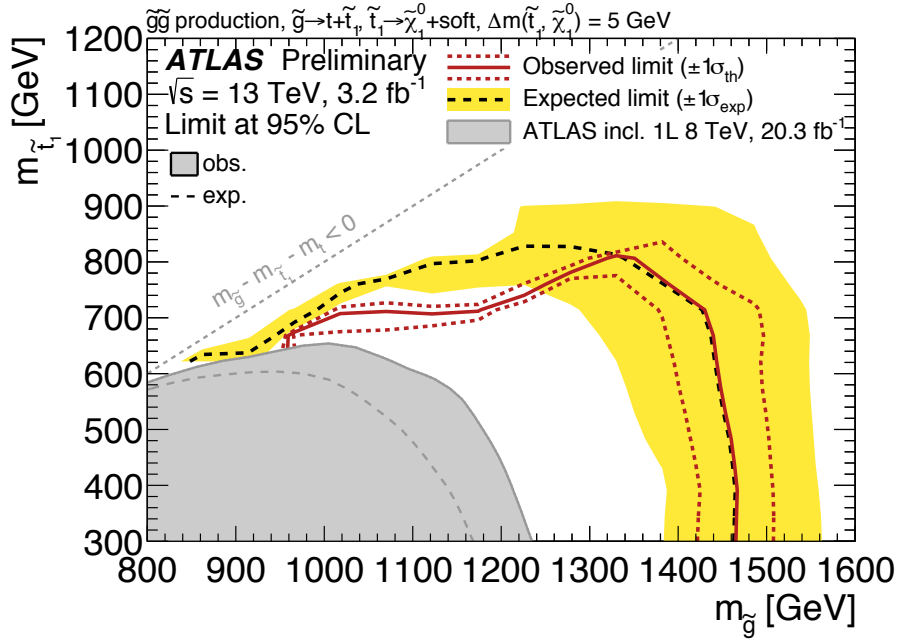
$t\bar{t} \rightarrow \ell\ell'$ + X with one lost ℓ



$\tilde{t}\tilde{t}$ search with 1 lepton







Alternative interpretations:

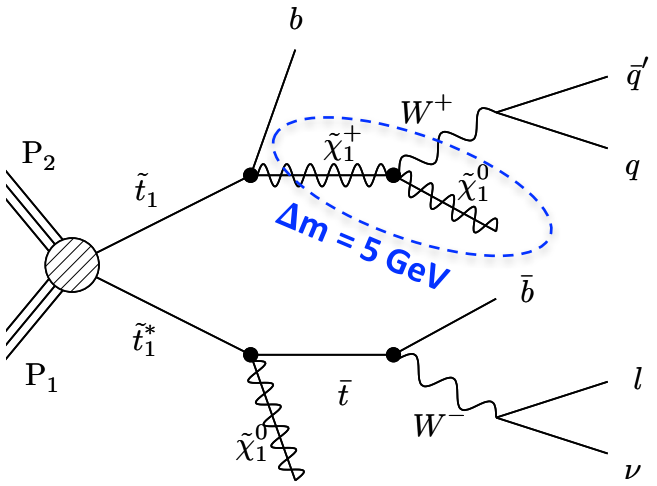
- **scalar leptoquarks**, **LQ → t ν**, using direct $\tilde{t}\tilde{t}$, massless LSP, unpolarized top
- **vector-like quark**, **T → t Z**, tH, Wb
  BR(T → tZ) < 0.90 at 95%CL for m_T=800 GeV

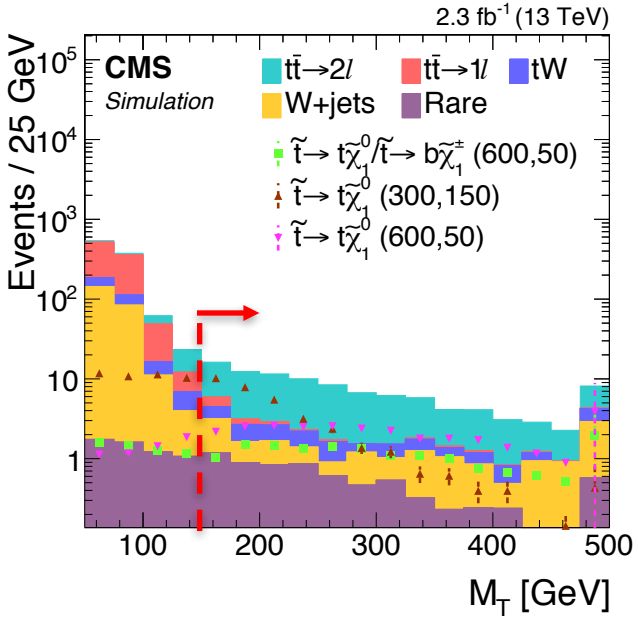
$\tilde{t}\tilde{t}$ search with 1 lepton

CMS-PAS-SUS-16-002

3 scenarios:

- **both** $\tilde{t} \to t\tilde{\chi}_1^0$
  4 jets, 2 b-jets, 1ℓ
- **both** $\tilde{t} \to b\tilde{\chi}_1^{\pm}$
  little sensitivity
- **mixed decay**
  2 b-jets, 1ℓ

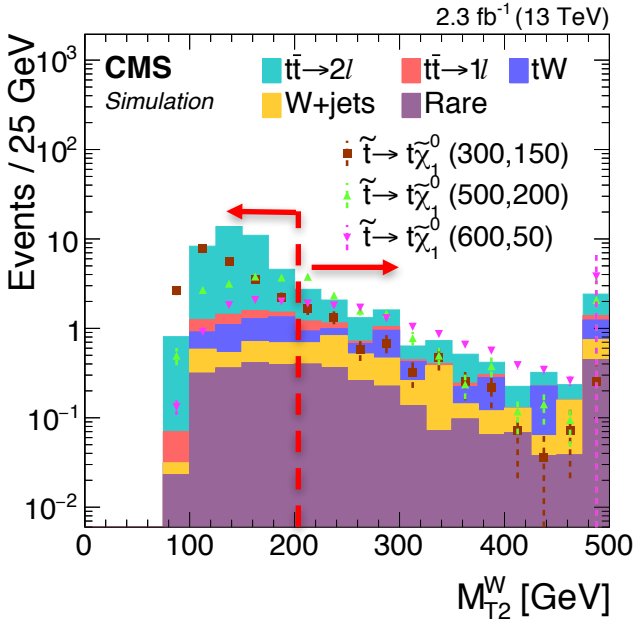




2-4 jets, ≥1 b-jet, 1ℓ, E_T^{miss}

Backgrounds:

- dileptonic $t\bar{t}$ with lost lepton, from 2ℓ CR
  discriminant:
  - m_{T2}^W (aka am_{T2}) for large $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$
  - else use modified "topness"
- semileptonic $t\bar{t}$, W($\ell\nu$)+jets
  discriminant: m_T

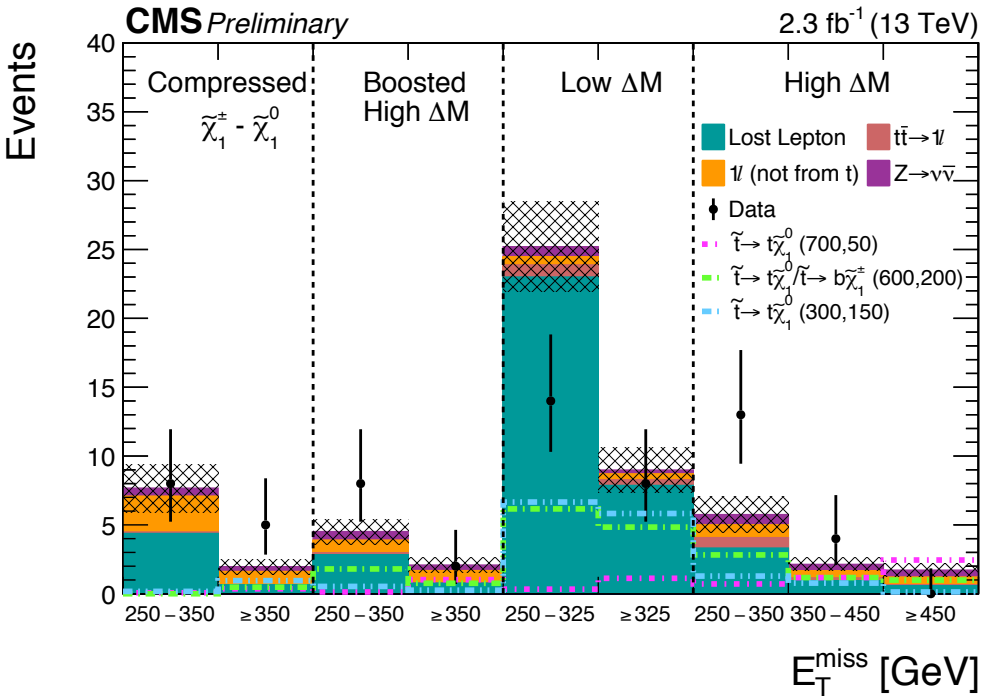


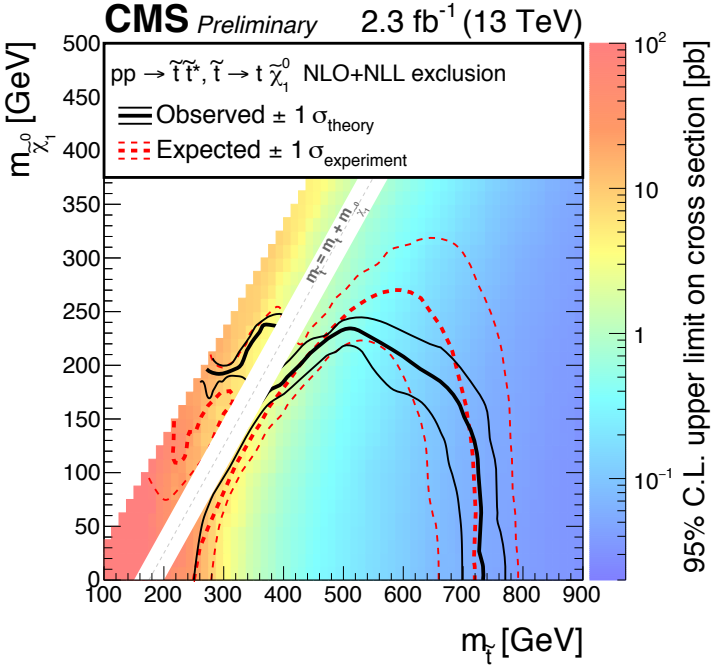
$\tilde{t}\tilde{t}$ search with 1 lepton

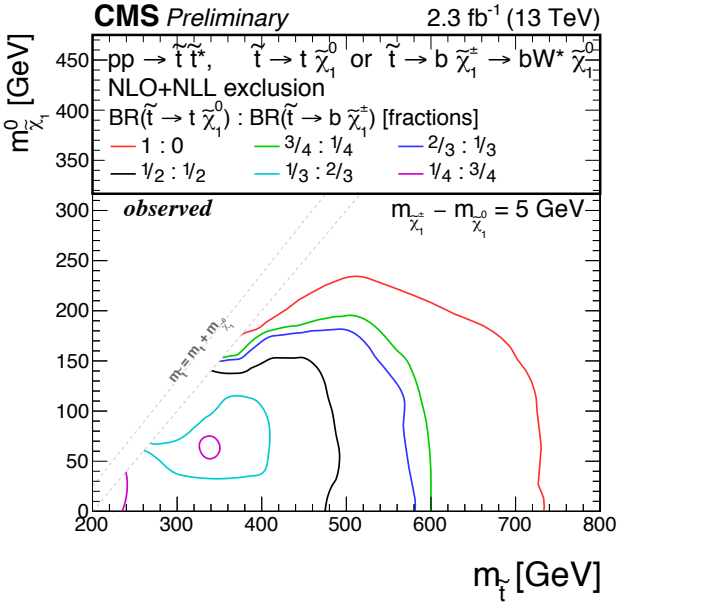
Signal regions binned in E_T^{miss}.
Data / SM agree within 2σ.

Limits derived for the 3 scenarios:
both $\tilde{t} \to t\tilde{\chi}_1^0$, both $\tilde{t} \to b\tilde{\chi}_1^{\pm}$, mixed,
assuming unpolarized top quark.

Limits also computed for BR $\neq$ 100%.

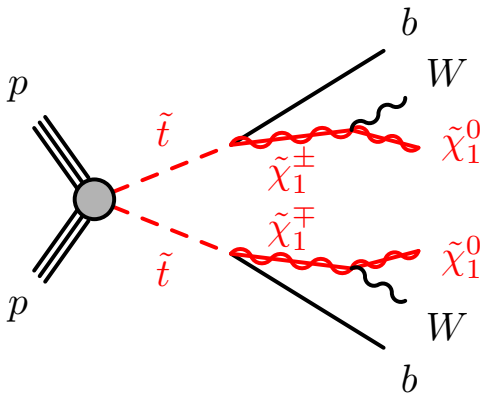






$\tilde{t}\tilde{t}$ search with 2 leptons

ATLAS-CONF-2016-009



2 opposite-charge leptons, 2 jets, E_T^{miss}

ee/$\mu\mu$ and **eμ**

Control regions for diboson and $t\bar{t}$.

Fake ℓ from "matrix method" (loose/tight ℓ).

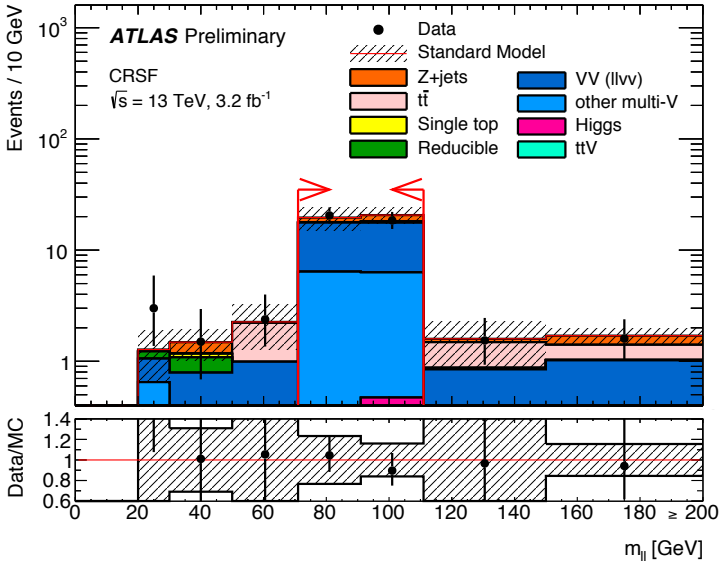
Discriminant:

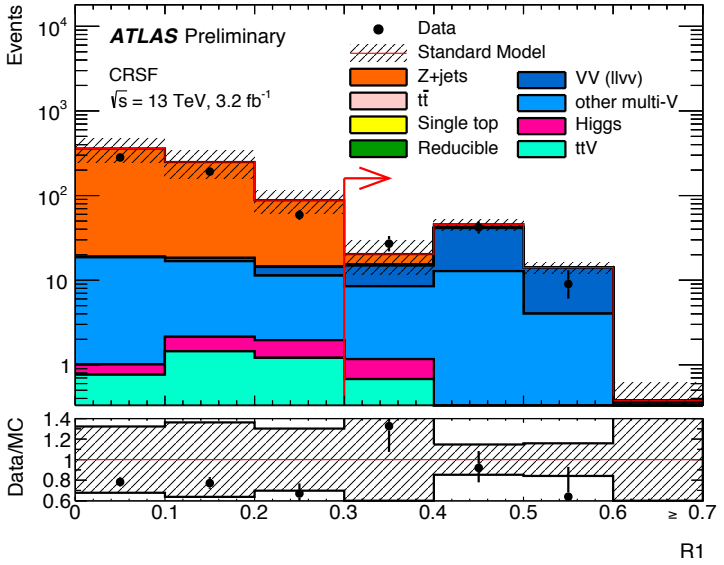
- **m_{T2}**, bounded by m_W for $t\bar{t}$ and WW. For $\tilde{t}$ decay, depends on $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$
- **E_T^{miss}/m_{eff} ratio**

$$R1 = \frac{E_T^{miss}}{E_T^{miss} + p_T(\ell_1) + p_T(\ell_2) + p_T(j_1) + p_T(j_2)}$$

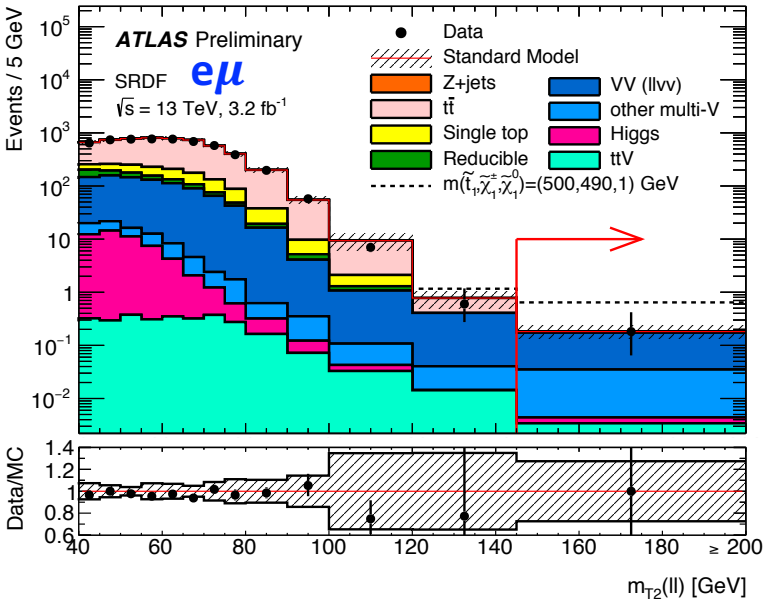
- **$m_{\ell\ell}$** (Z veto in ee/$\mu\mu$ SR)

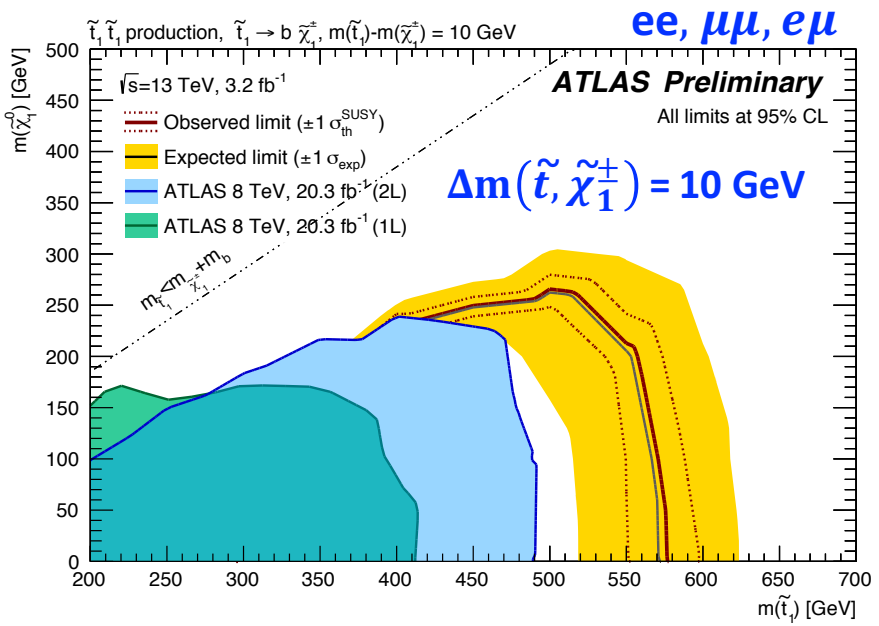
Diboson CR, ee, $\mu\mu$

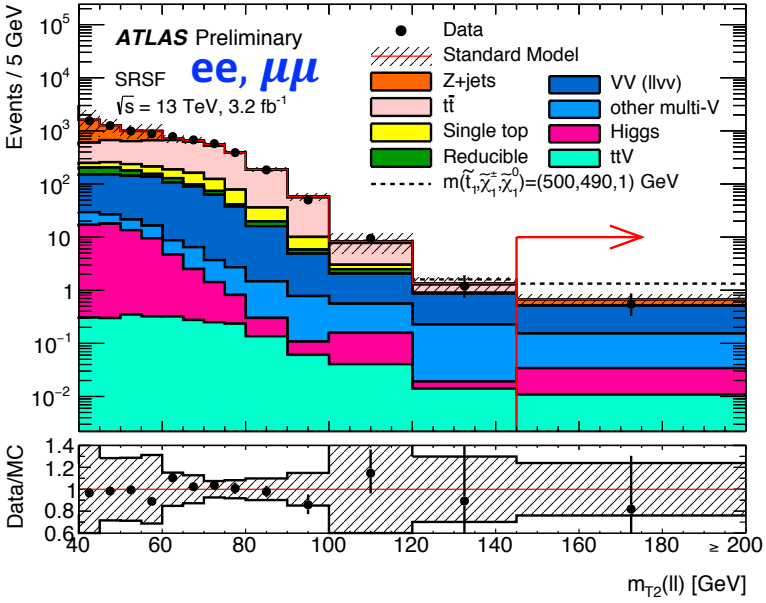


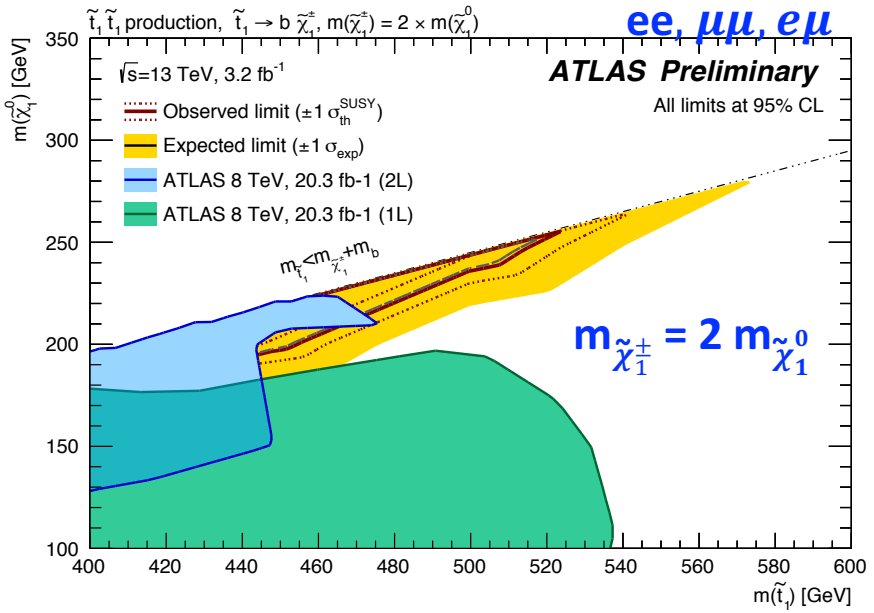


$\tilde{t}\tilde{t}$ search with 2 leptons



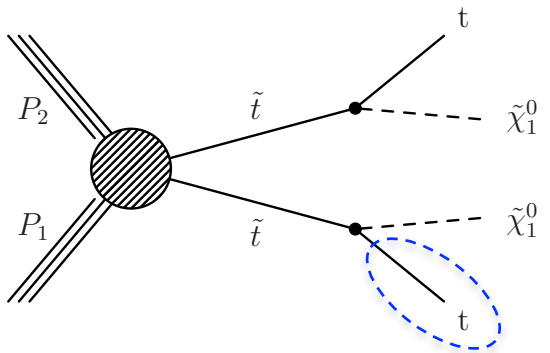




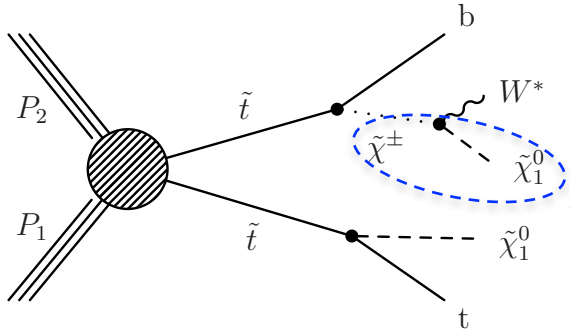


$\tilde{t}\tilde{t}$ all-hadronic search

CMS-PAS-SUS-16-007



on-/off-shell



$\Delta m = 5$ GeV

Large $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$

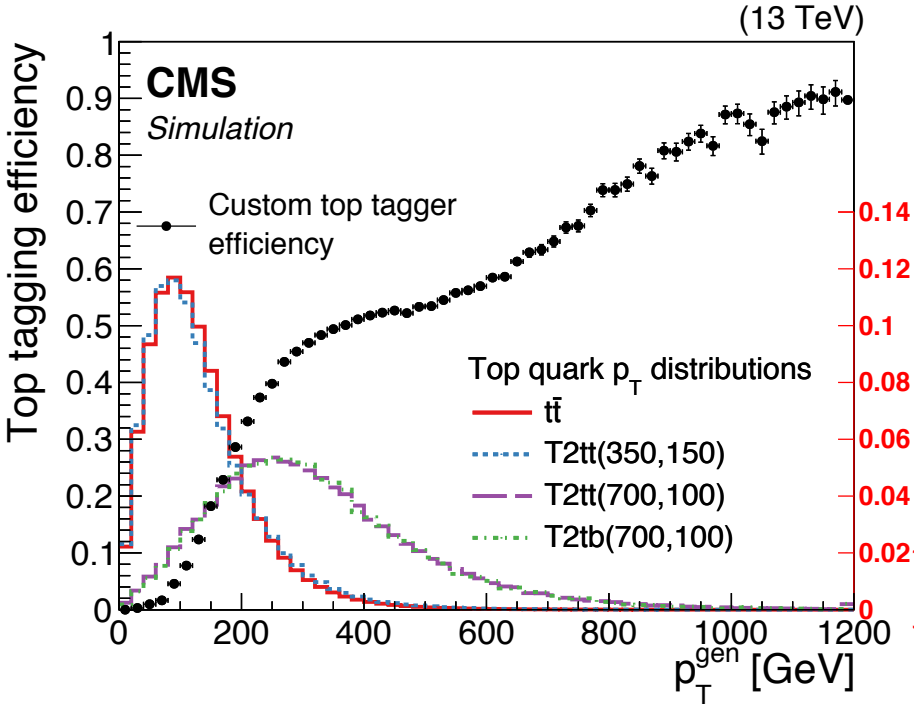
Top tagging uses **R=0.4 jets**.
3 jets within $\Delta R=1.5$, $m_{2j} \sim m_W$, $m_{3j} \sim m_{top}$,
or **2 jets** (**merged W**), or **1 jet** (**merged top**)

$t\bar{t}$, W($\ell\nu$)+jets with **lost lepton: 1μ CR**

W($\tau_h\nu$)+jets from **W($\mu\nu$)+jets** with **$\mu \leftrightarrow \tau$**

Z($\nu\nu$)+jets from **Z($\mu\mu$)+jets**

37 SRs binned in $N_{b\text{-jet}}$, N_{top}, m_{T2}, E_T^{miss}



$\tilde{t}\tilde{t}$ all-hadronic search

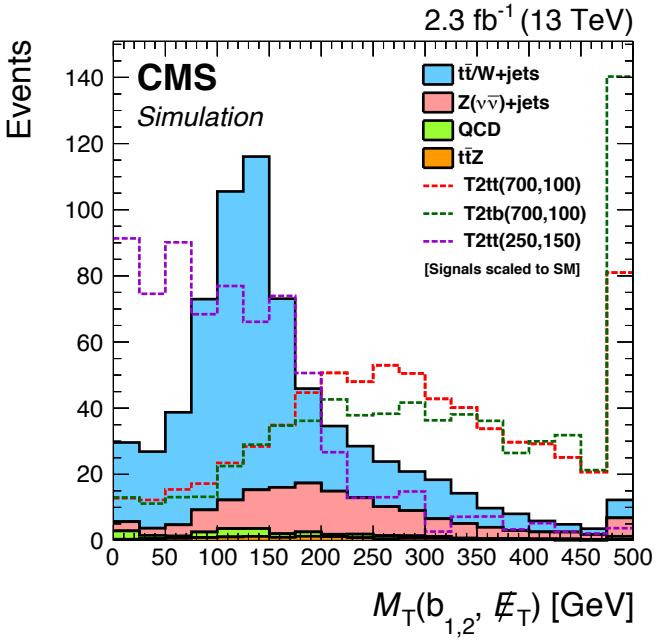
Small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$ and mixed decays:

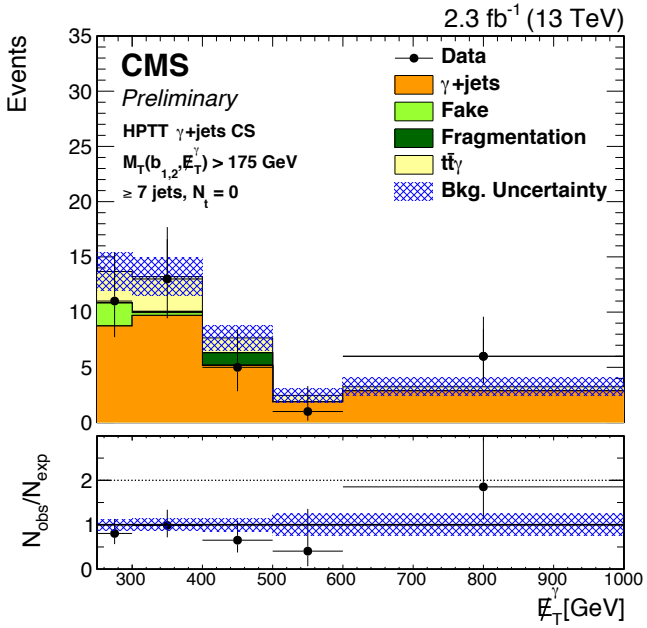
Top tagging: **R=0.8 jets** with sub-jet decomposition.
$\geq$3 sub-jets, $m_{jet} \sim m_{top}$, $m_{2subjet} \sim m_W$.

$t\bar{t}$ and **W($\ell\nu$)+jets** with **lost lepton**: **1ℓ CR**.
Extrapolation $1\ell \rightarrow 0\ell$ using MC.
Discriminant: **min $m_T(b_{1,2}, E_T^{miss})$**.

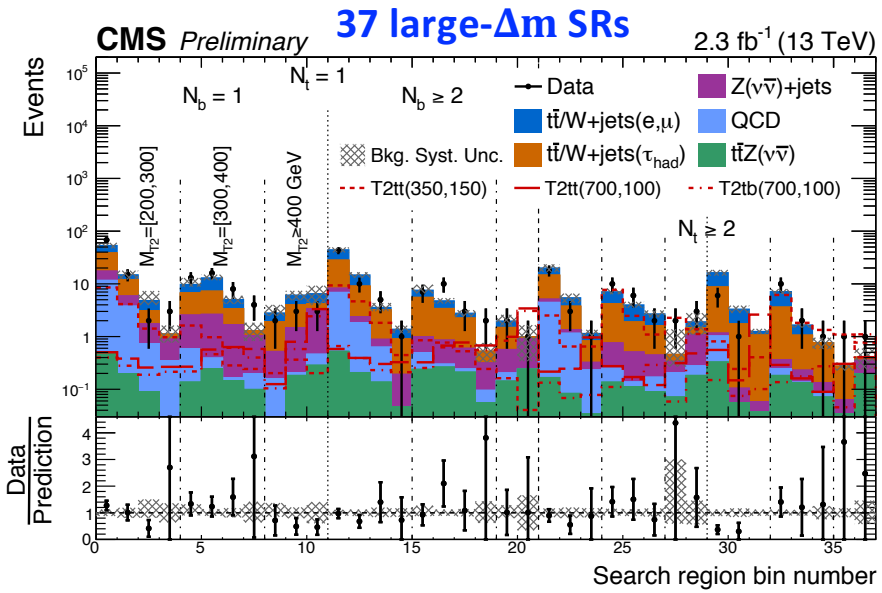
Z($\nu\nu$)+jets scaled with **Z($\mu\mu$)+jets**, and **E_T^{miss} shape correction** from **γ+jets**.

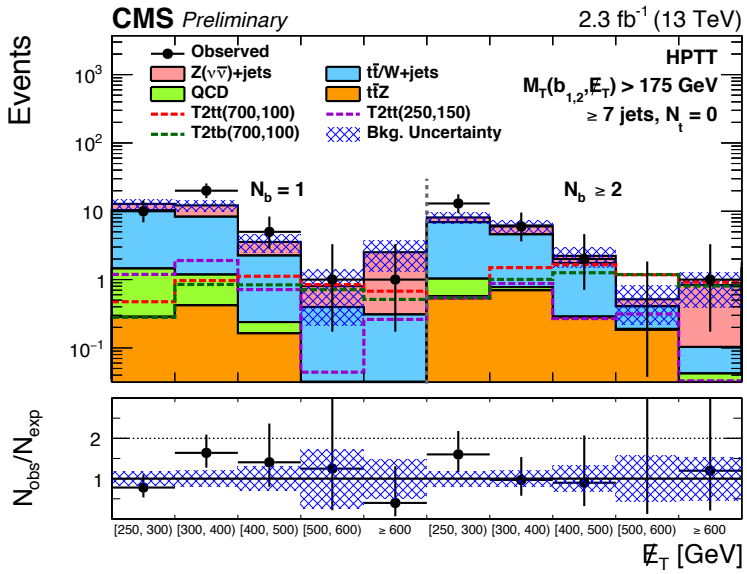
50 SRs binned in:
N_{jet}, $N_{b\text{-}jet}$, N_{top}, $m_T(b_{1,2}, E_T^{miss})$, E_T^{miss} .

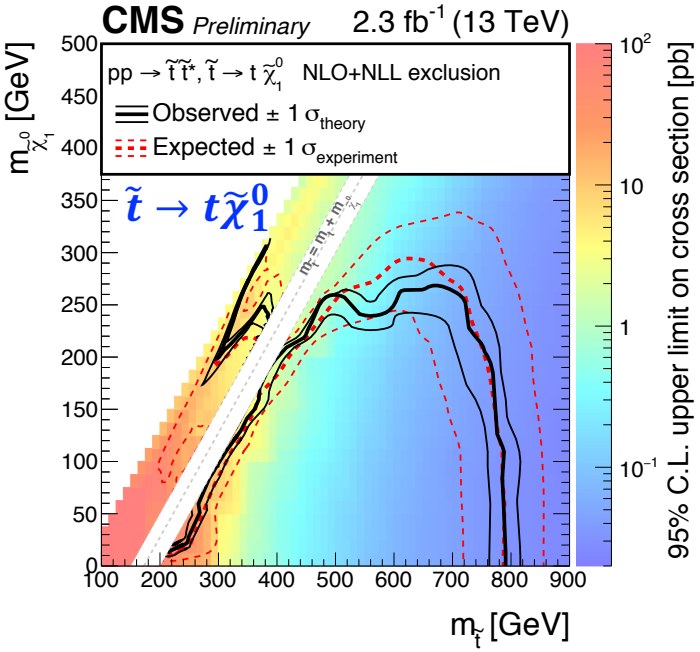


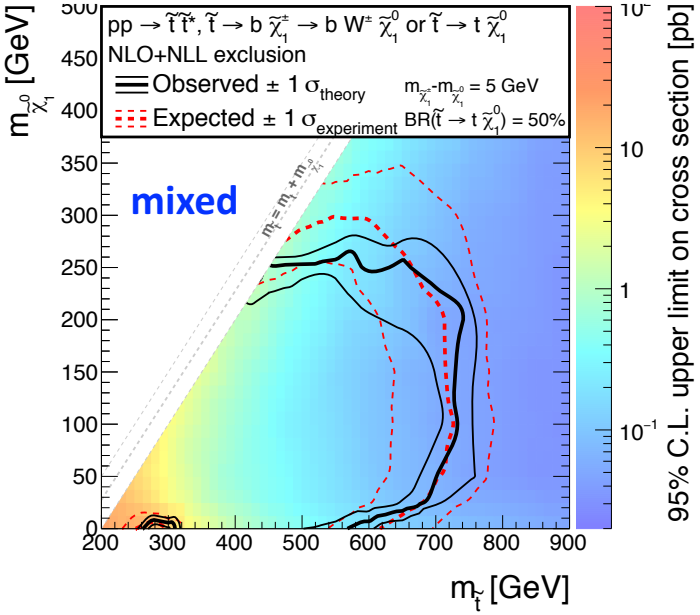


$\tilde{t}\tilde{t}$ all-hadronic search



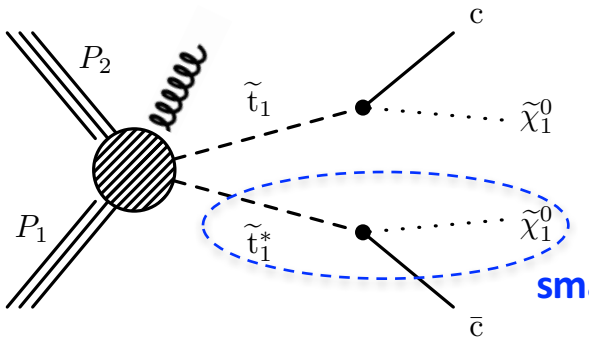






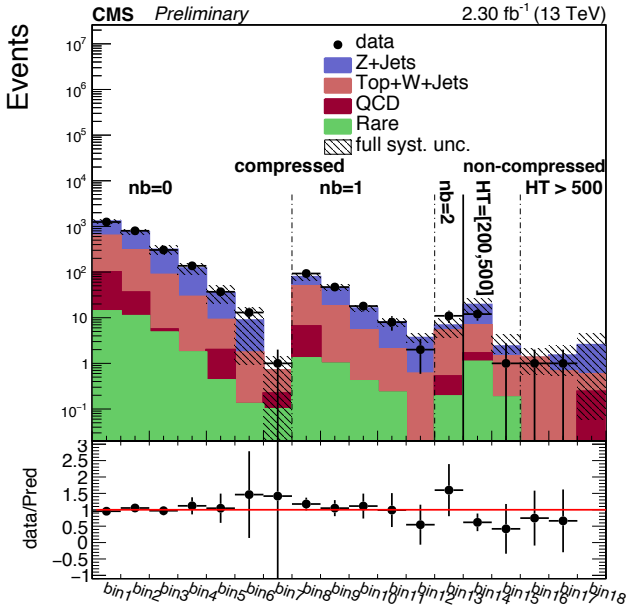
Search for $\tilde{t} \rightarrow c\tilde{\chi}_1^0$

CMS-PAS-SUS-16-001



Compressed scenario with **"ISR topology"**

small Δm

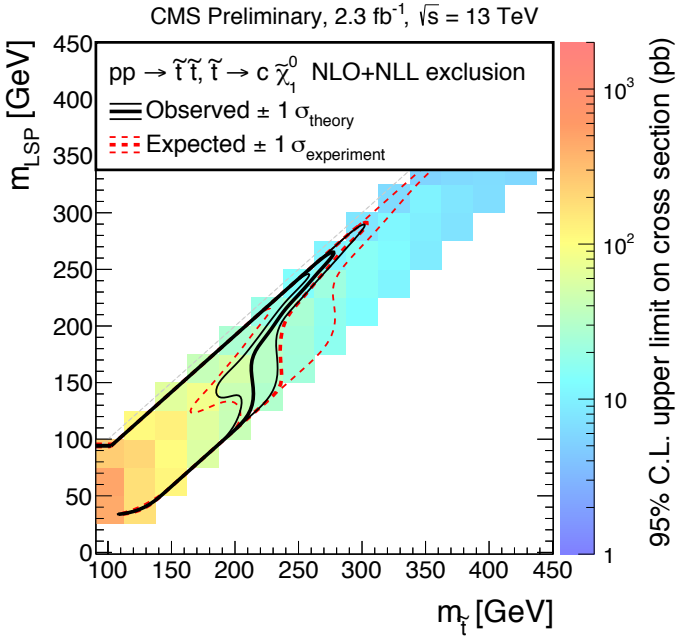


2-3 jets, 0-2 b-jets, large p_T^{jet1}, E_T^{miss}.
Veto against ℓ and isolated tracks (τ_h).

Backgrounds:

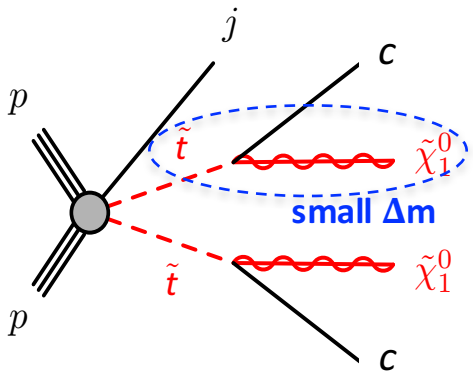
- **$Z(\nu\nu)$+jets**, estimated from $Z(\mu\mu)$+jets
- **semileptonic $t\bar{t}$** and **$W(\ell\nu)$+jets** with **lost lepton** scaled in 1ℓ CRs
- **QCD multi-jet**, estimated as (data – non-QCD) in inverted $\Delta\phi$(jet, E_T^{miss}) selection

Discriminants: $\Delta\phi$(jet1, E_T^{miss}), and min m_T(jet, E_T^{miss}) bounded by m_{top} for $t\bar{t}$.



Search for $\tilde{t} \rightarrow c\tilde{\chi}_1^0$

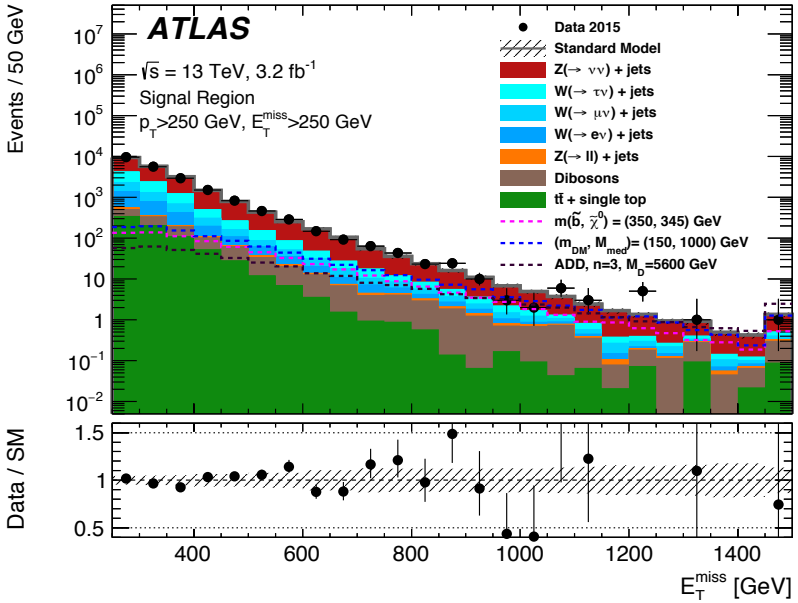
arXiv:1604.07773

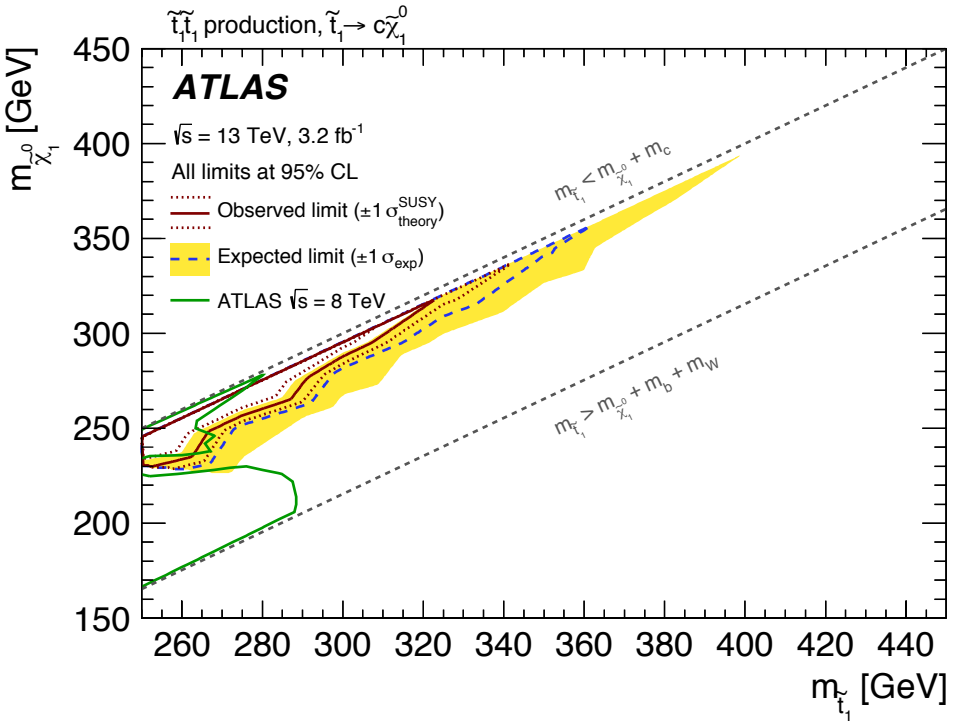


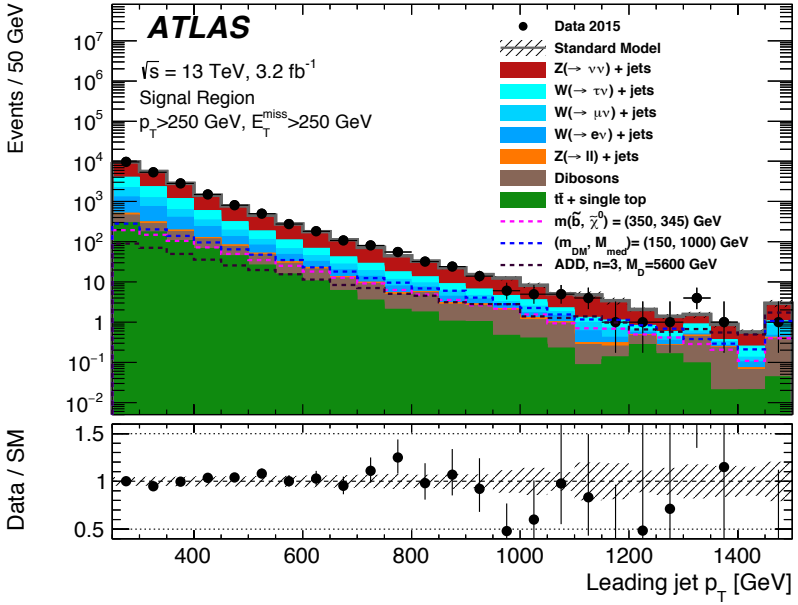
ISR topology, ≤4 jets, 0ℓ

SRs with increasing E_T^{miss}

Dominant background
Z($\nu\nu$)+jets scaled using
W($\mu\nu$)+jets CR







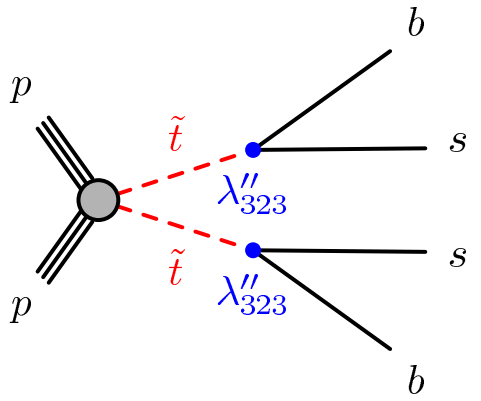
$\tilde{t} \rightarrow bs$ in RPV SUSY

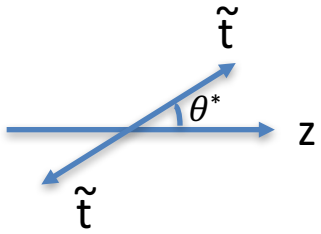
ATLAS-CONF-2016-022

R-parity violating term in superpotential $\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$.

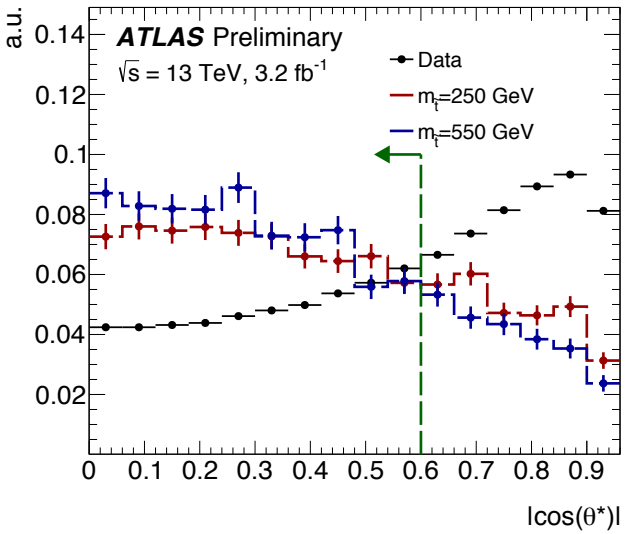
$\tilde{t} \rightarrow bs$ expected in minimal flavour-violation scenarios.

Search for **2 heavy pairs of close-by jets**, with **1 *b*-jet per pair**.

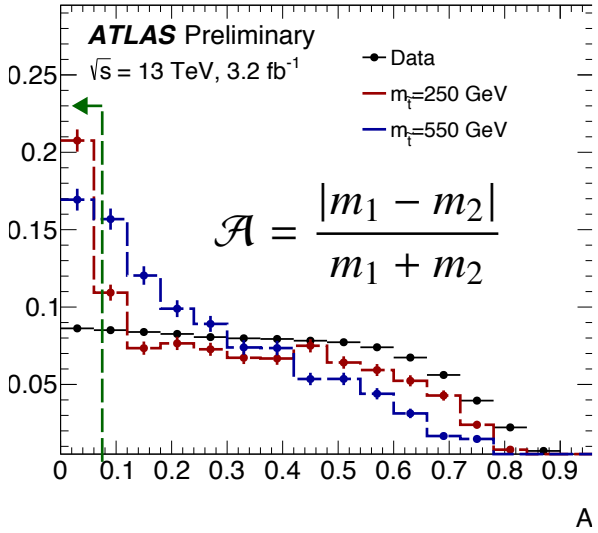




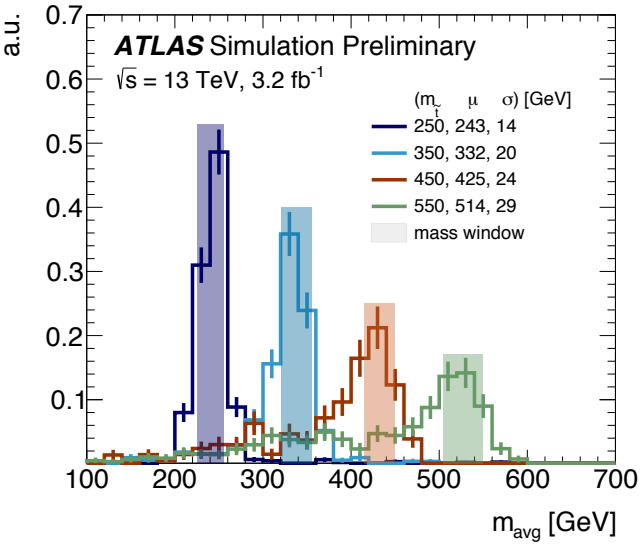
$|\cos(\theta^*)|$ in $\tilde{t}\tilde{t}$ frame



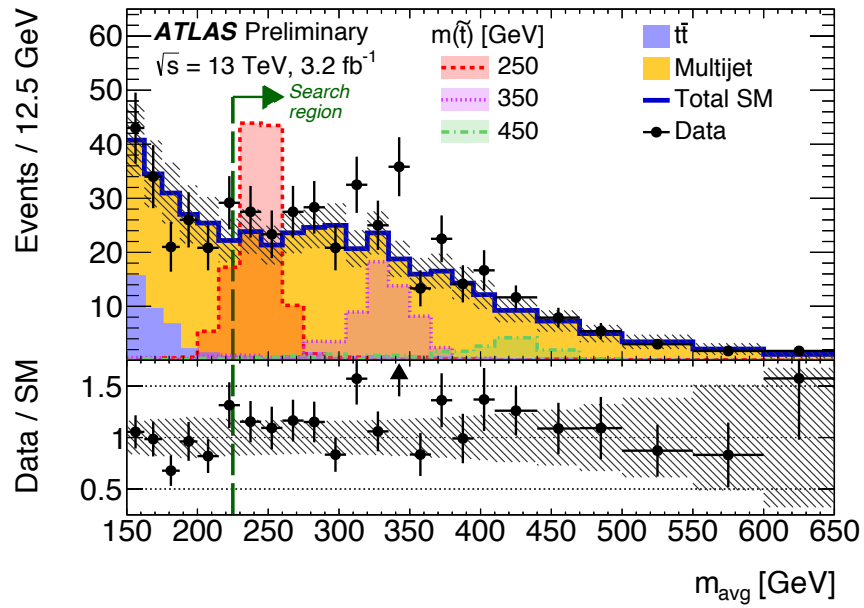
mass asymmetry

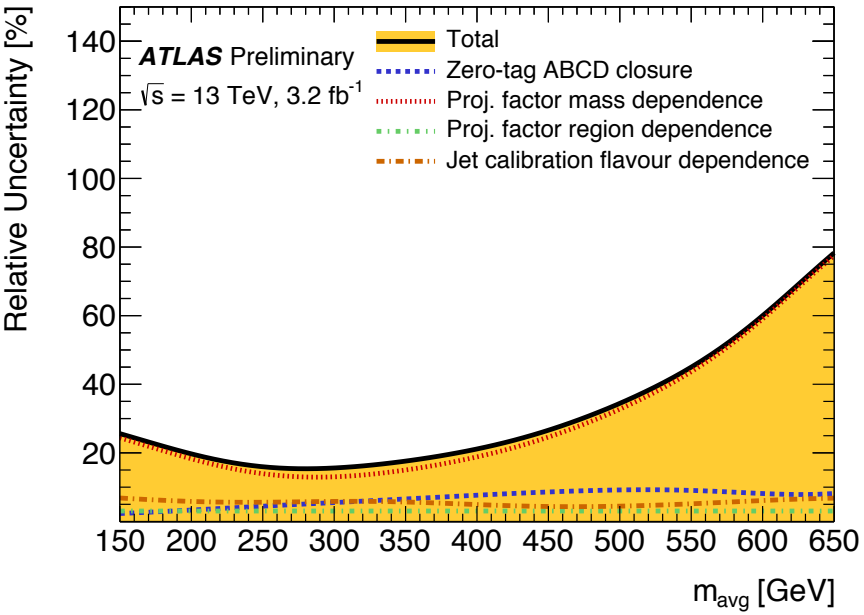


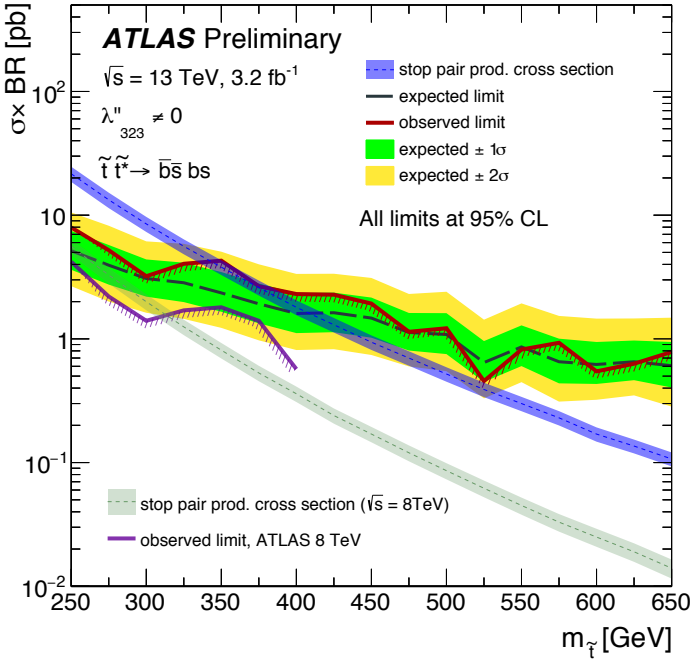
average mass



$\tilde{t} \rightarrow bs$ in RPV SUSY







Dominant uncertainty: constant vs m_{avg}-dependent projection factors. Uncertainty limited by CR statistics.

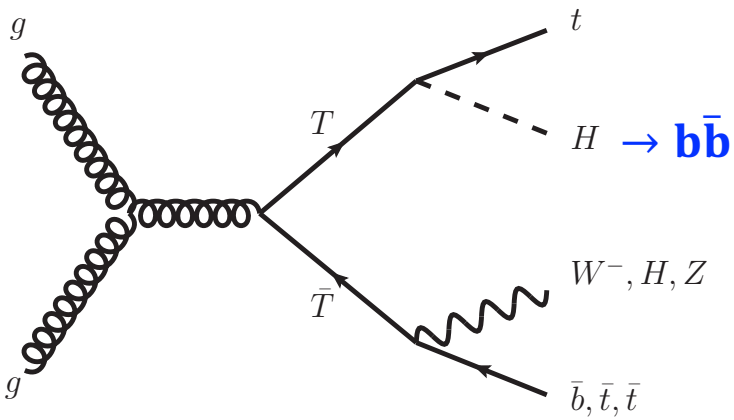
Observed (exp.) limit on stop mass: 345 (320) GeV.

ATLAS Run-1 observed limit: 320 GeV.

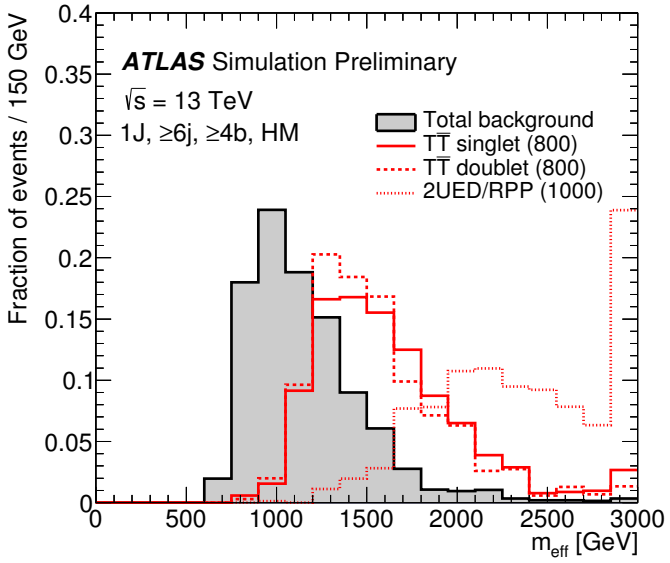
Exotic Searches

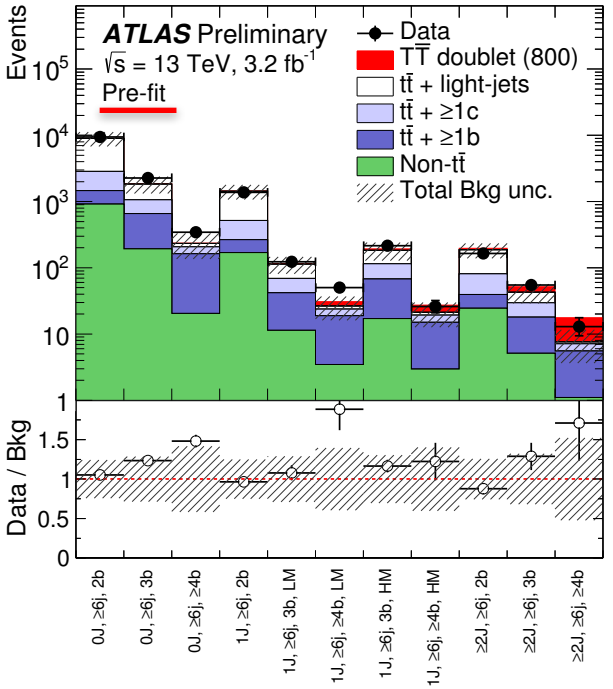
Vector-like T pair

ATLAS-CONF-2016-013



1 ℓ, ≥6 jets, ≥2 b-jets, E_T^{miss}





Tagging of **boosted top/Higgs**:
R=1.0 jets re-clustered from R=0.4 jets

Sensitive to T → $tH(b\bar{b})$, T → $tZ(b\bar{b})$.

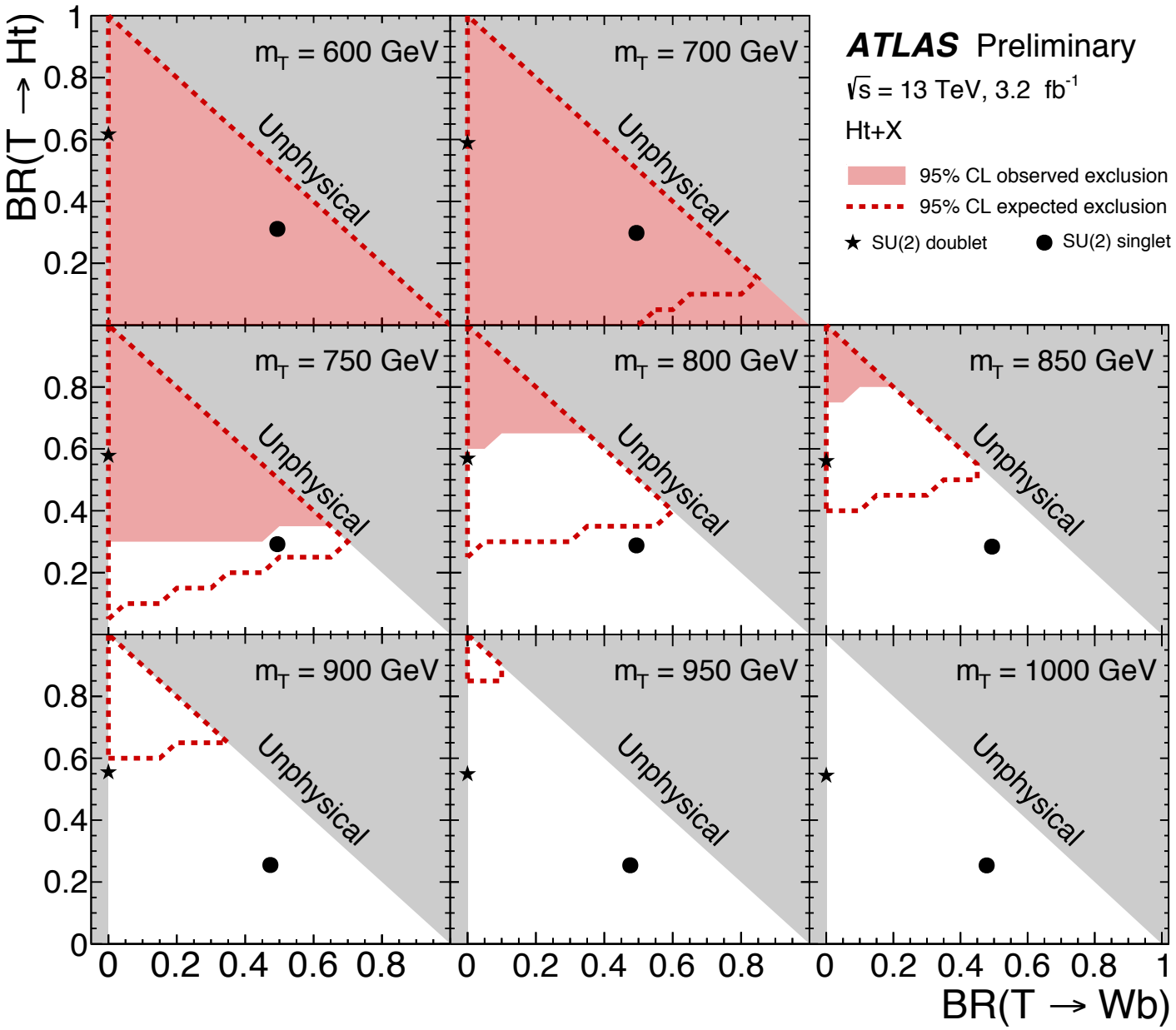
Background: $t\bar{t}$ + heavy-flavour jets

Discriminants: $m_{bb}^{\min \Delta R}$ (boosted H/Z)

effective mass = $\Sigma p_T^{jets} + p_T^{\ell} + E_T^{miss}$

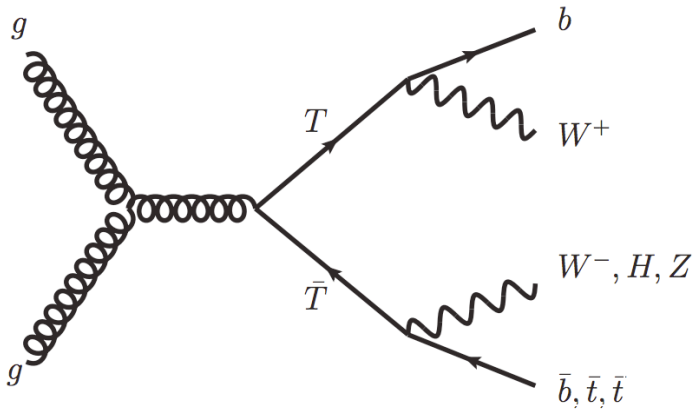
11 SRs binned in number of b-jet, large-R jet, $m_{bb}^{\min \Delta R}$

Vector-like T pair

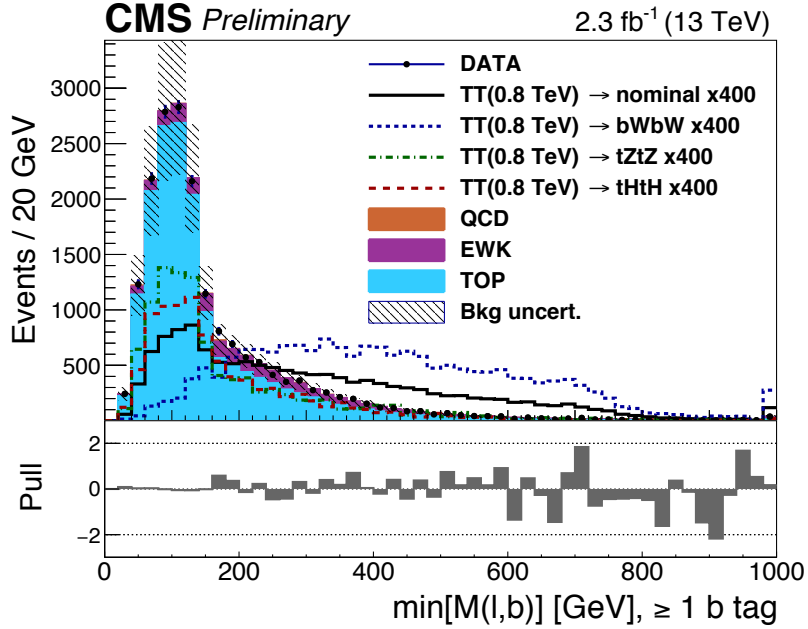


Vector-like T pair

CMS-PAS-B2G-16-002



1ℓ (from **top** or **T → W($\ell\nu$)b**), **≥3 jets, E_T^{miss}**



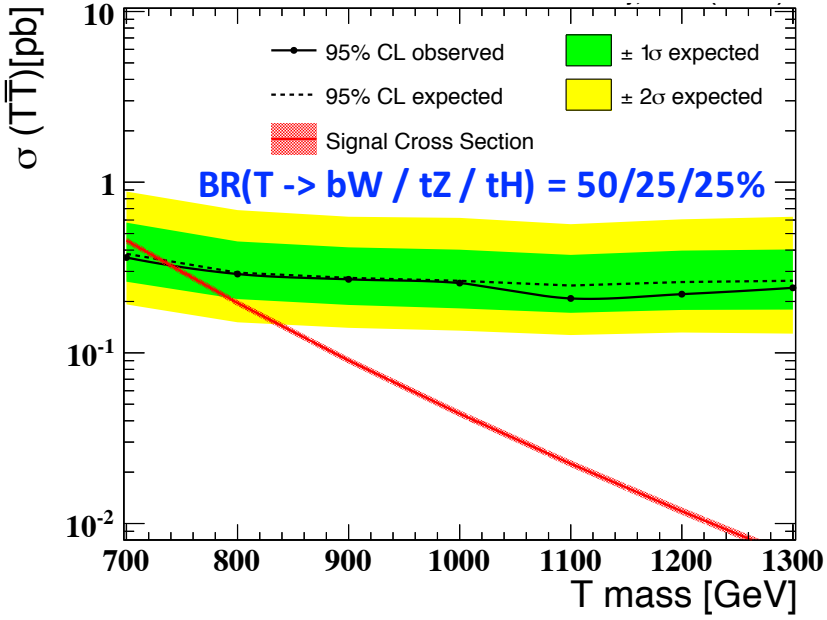
Backgrounds: $t\bar{t}$ and V+jets.

Discriminant with **sensitivity to T → Wb**: **min(M(ℓ,b-jet))**.

16 SRs binned in e/μ, number of **b-jets** and **W-tagged jets** (R=0.8).

Limits for several BR(T) assumptions.

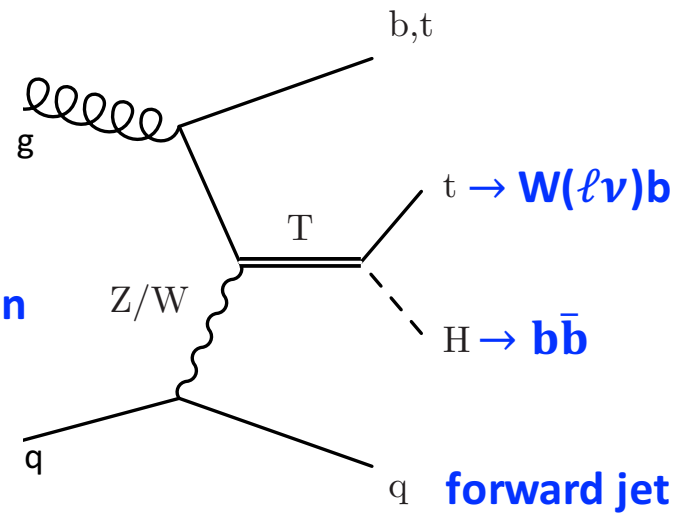
Stronger limits at large BR(T → Wb).

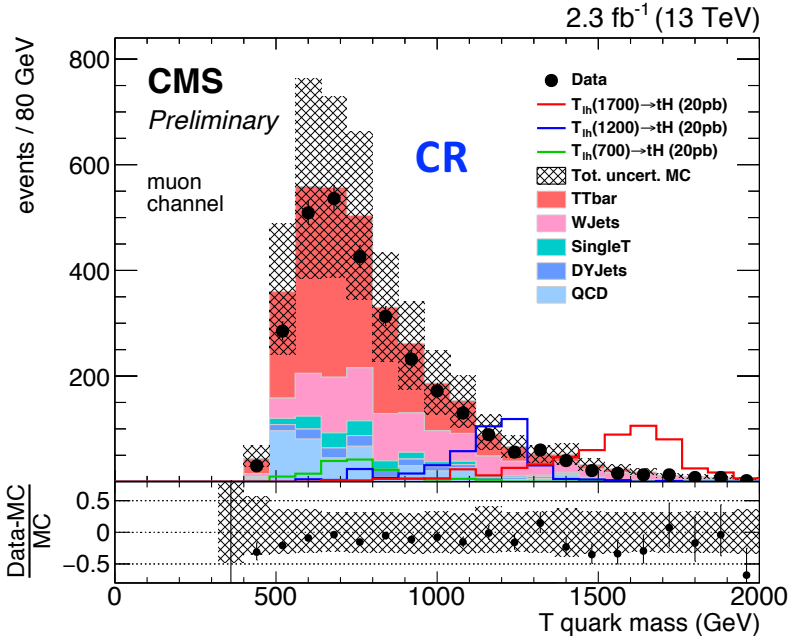


Single vector-like T

CMS-PAS-B2G-15-008

Single-T via
EW production



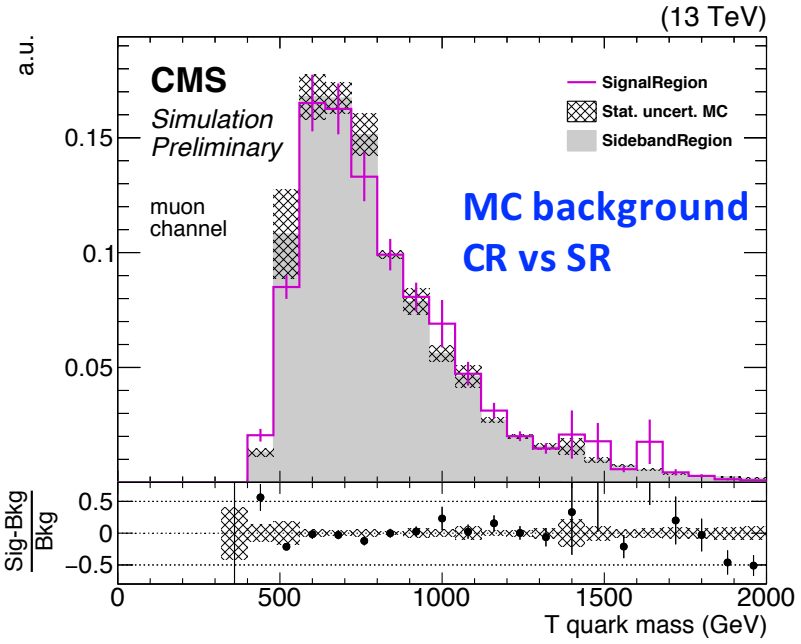


Higgs boson: **R=0.8 jet** with **2 b-tagged sub-jets**

Top quark: ℓ, $E_{x,y}^{miss}$, 1-2 jets **consistent with m_W, m_{top}** and **ΔR(top,H) expected for signal**.

Backgrounds: $t\bar{t}$ and W($\ell\nu$)+jets.
Modeled directly from data in **CR** with:

- 0 forward jet
- Higgs candidate with 1 b-tagged sub-jet

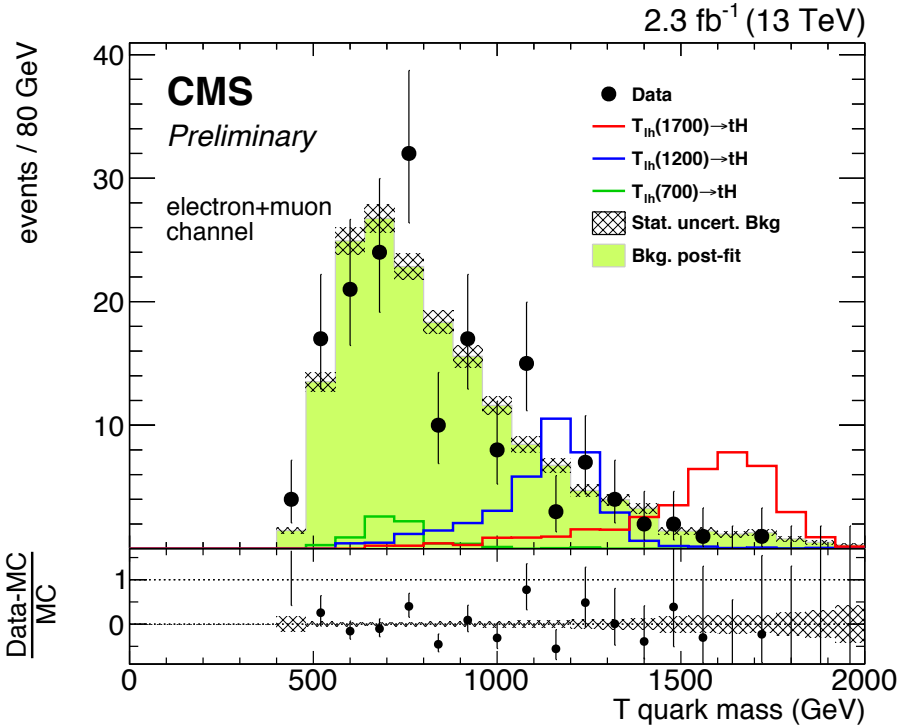


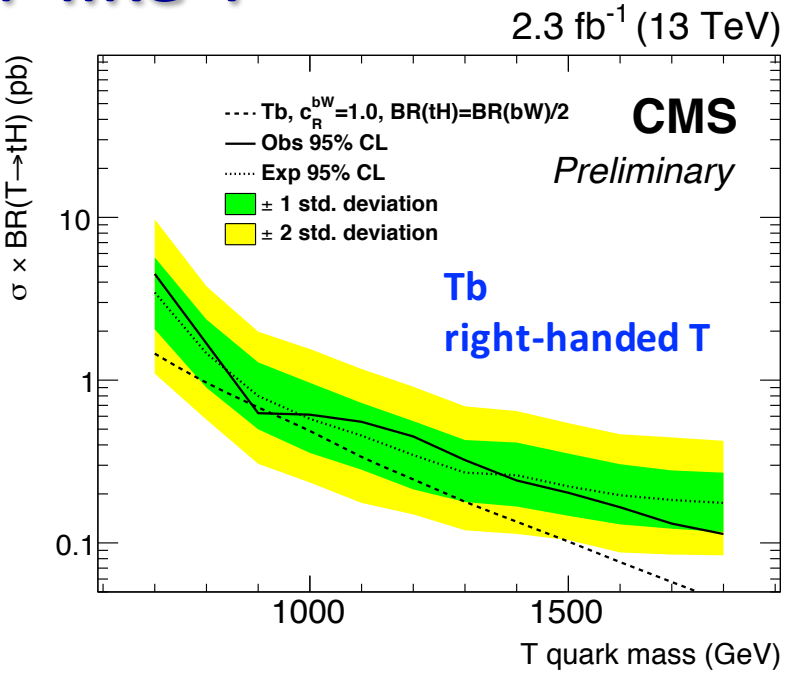
Single vector-like T

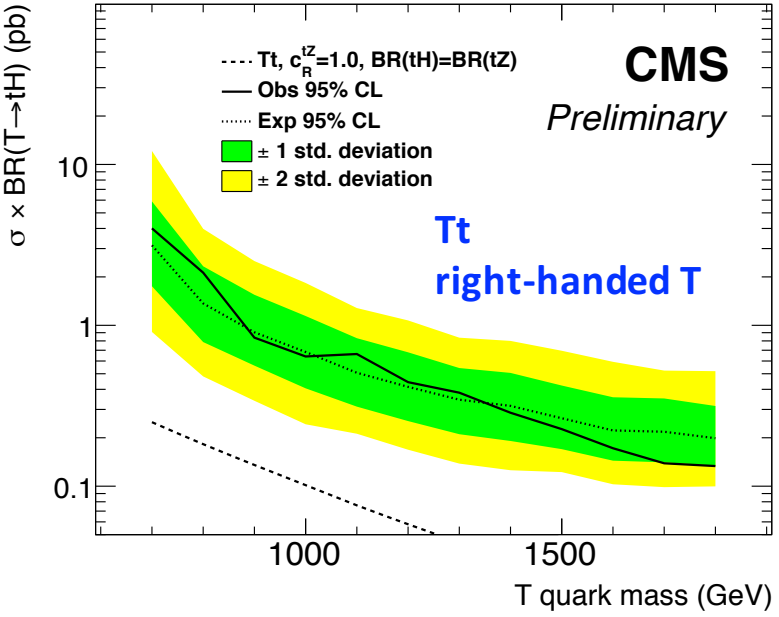
Mass of T candidate used to set limits for 2 scenarios:

"charged current" Tb production, with BR(T → bW , tZ , tH) = 50/25/25%

"neutral current" Tt production, with BR(T → tZ , tH) = 50/50%







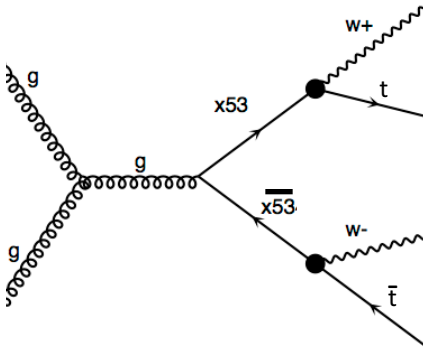
$X_{5/3}$

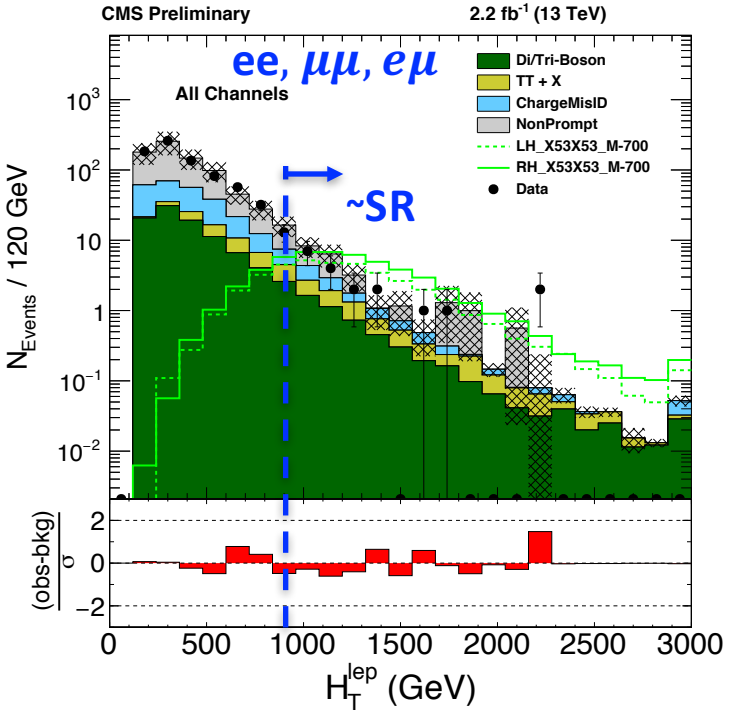
CMS-PAS-B2G-15-006

Top partner with **charge 5/3** in composite Higgs models.

$X_{5/3} \rightarrow W^+ t$, 100% BR.

Signatures:
same-sign dilepton, ℓ+jets.

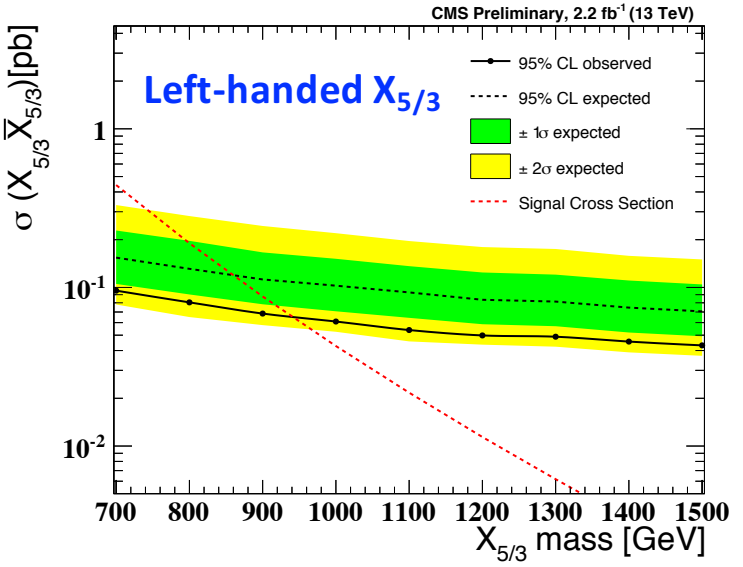




Backgrounds:

- **prompt same-sign $\ell\ell'$** (WZ, ZZ)
- **prompt opposite-sign $\ell\ell'$ + charge mis-id.**
  - charge mis-id. from Z(ee)+jets data
  - applied to opposite-sign selection
- **non-prompt leptons** (fake, non-isolated):
  - loose lepton selection
  - proba. for true/fake loose lepton to be tight

Discriminants: $m_{\ell\ell}$, $H_T^{lep} = \Sigma\, p_T^{jets} + \Sigma\, p_T^{\ell}$



Summary

ATLAS and **CMS** have already released **many results** for **top partner searches at 13 TeV**.

- **Scalar top in SUSY:**

  $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, $b\tilde{\chi}_1^{\pm}$, $c\tilde{\chi}_1^0$, bs

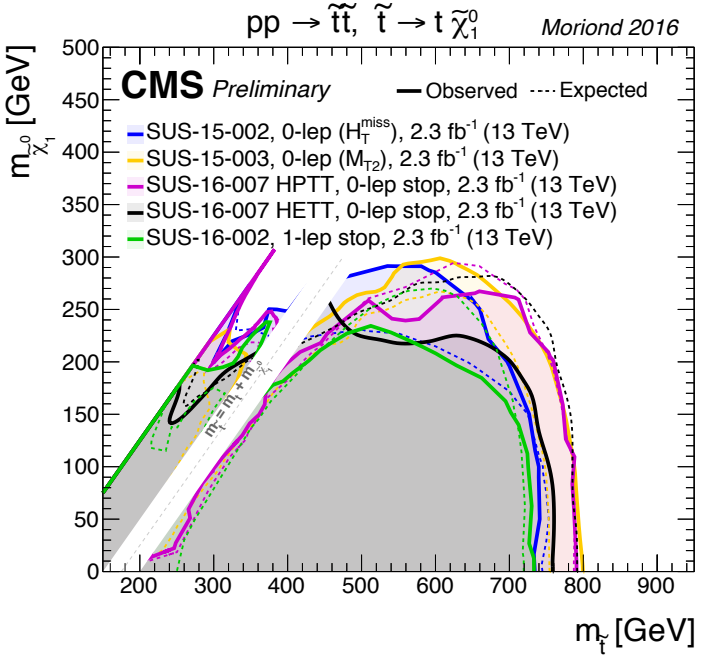
  Light stealth stop scenario still viable.

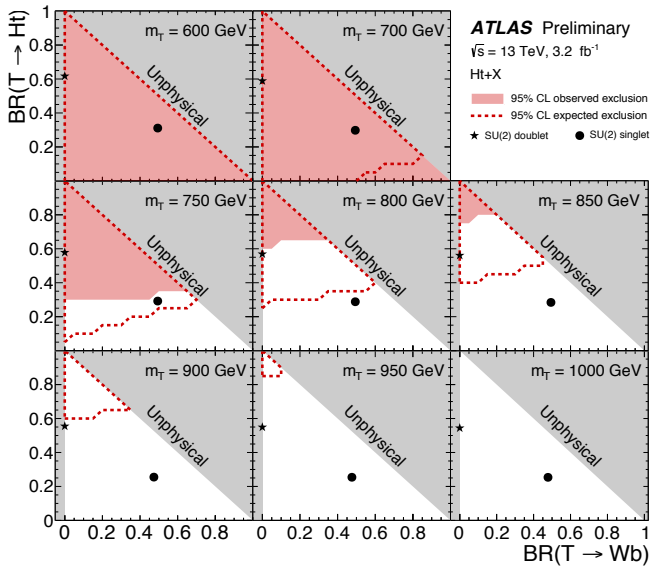
- **Vector-like top in exotic models:**

  $\mathrm{T} \rightarrow Wb$, tZ , tH and $X_{5/3} \rightarrow W^+t$

  Light stealth top scenario still viable.

Run-1 exclusion reach exceeded.





And this is just the beginning…

Exciting prospects for 2016!

References

SUSY

ATLAS $\tilde{t}\tilde{t}$ 1-lepton: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-007/

CMS $\tilde{t}\tilde{t}$ 1-lepton: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-002/

ATLAS $\tilde{t}\tilde{t}$ 2-lepton: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-009/

CMS $\tilde{t}\tilde{t}$ all-hadronic: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-007/

CMS $\tilde{t} \rightarrow c\tilde{\chi}_1^0$: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-001/

ATLAS $\tilde{t} \rightarrow c\tilde{\chi}_1^0$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2015-03/

ATLAS $\tilde{t} \rightarrow bs$: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-022/

EXOTICS

ATLAS TT: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-013/

CMS TT: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-16-002/

CMS Single-T: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-15-008/

CMS X53: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-15-006/

Backup

$\tilde{t}\tilde{t}$ search with 1 lepton

Common event selection	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons.
Jets	at least four signal jets, and $\lvert\Delta\phi(\mathrm{jet}_i, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert > 0.4$ for $i \in \{1,2\}$.
hadronic τ	veto events with a hadronic τ and $m_{T2}^{\tau} < 80\,\mathrm{GeV}$.

Variable	SR1	TCR1 / WCR1	STCR1
≥4 jets with p_{T} > [GeV]	(80 50 40 40)	(80 50 40 40)	(80 50 40 40)
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 260	> 200	> 200
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 14	> 5	> 5
m_{T} [GeV]	> 170	[30,90]	[30,120]
am_{T2} [GeV]	> 175	[100, 200] / > 100	> 200
topness	> 6.5	> 6.5	> 6.5
m_{top}^{χ} [GeV]	< 270	< 270	< 270
$\Delta R(b,\ell)$	< 3.0	–	–
$\Delta R(b_1, b_2)$	–	–	> 1.2
number of b-tags	≥ 1	≥ 1 / = 0	≥ 2

	SR2	TCR2 / WCR2	STCR2
≥4 jets with p_{T} > [GeV]	(120 80 50 25)	(120 80 50 25)	(120 80 50 25)
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 350	> 250	> 200
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 20	> 15	> 5
m_{T} [GeV]	> 200	[30,90]	[30,120]
am_{T2} [GeV]	> 175	[100, 200] / > 100	> 200
$\Delta R(b,\ell)$	< 2.5	–	–
$\Delta R(b_1, b_2)$	–	–	> 1.2
number of b-tags	≥ 1	≥ 1 / = 0	≥ 2
leading large-R jet p_{T} [GeV]	> 200	> 200	> 200
leading large-R jet mass [GeV]	> 140	> 140	> 0
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, 2^{\mathrm{nd}}\text{large-R jet})$	> 1.0	> 1.0	> 1.0

	SR3	TCR3 / WCR3	STCR3
≥4 jets with p_{T} > [GeV]	(120 80 50 25)	(120 80 50 25)	(120 80 50 25)
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 480	> 280	> 200
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 14	> 8	> 5
m_{T} [GeV]	> 190	[30,90]	[30,120]
am_{T2} [GeV]	> 175	[100, 200] / > 100	> 200
topness [GeV]	> 9.5	> 0	> 9.5
$\Delta R(b,\ell)$	< 2.8	–	–
$\Delta R(b_1, b_2)$	–	–	> 1.2
number of b-tags	≥ 1	≥ 1 / = 0	≥ 2
leading large-R jet p_{T} [GeV]	> 280	> 200	> 200
leading large-R jet mass [GeV]	> 70	> 70	> 70

Signal region	SR1	SR2	SR3
Observed	12	1	1
Total bkg	5.50 ± 0.72	1.25 ± 0.26	1.03 ± 0.18
$t\bar{t}$	2.21 ± 0.60	0.29 ± 0.10	0.20 ± 0.07
Single top	0.46 ± 0.39	0.09 ± 0.08	0.10 ± 0.09
W+jets	0.71 ± 0.43	$0.15^{+0.19}_{-0.15}$	0.20 ± 0.09
$t\bar{t} + W/Z$	1.90 ± 0.42	0.61 ± 0.14	0.41 ± 0.10
Diboson	0.23 ± 0.15	0.11 ± 0.07	0.12 ± 0.07
$t\bar{t}$ NF	1.10 ± 0.14	1.06 ± 0.14	0.80 ± 0.13
Single top NF	0.62 ± 0.46	0.65 ± 0.49	0.71 ± 0.42
W+jets NF	0.75 ± 0.12	0.78 ± 0.15	0.93 ± 0.12
$t\bar{t} + W/Z$ NF	1.42 ± 0.24	1.45 ± 0.24	1.46 ± 0.24
p_0	$0.01 (2.3\,\sigma)$	$0.50\ (0.0\,\sigma)$	$0.50\ (0.0\,\sigma)$
$N_{\mathrm{non-SM}}^{\mathrm{limit}}$ exp. (95% CL)	$6.4^{+3.2}_{-2.0}$	$3.6^{+2.3}_{-1.3}$	$3.5^{+2.2}_{-1.2}$
$N_{\mathrm{non-SM}}^{\mathrm{limit}}$ obs. (95% CL)	13.3	3.4	3.4

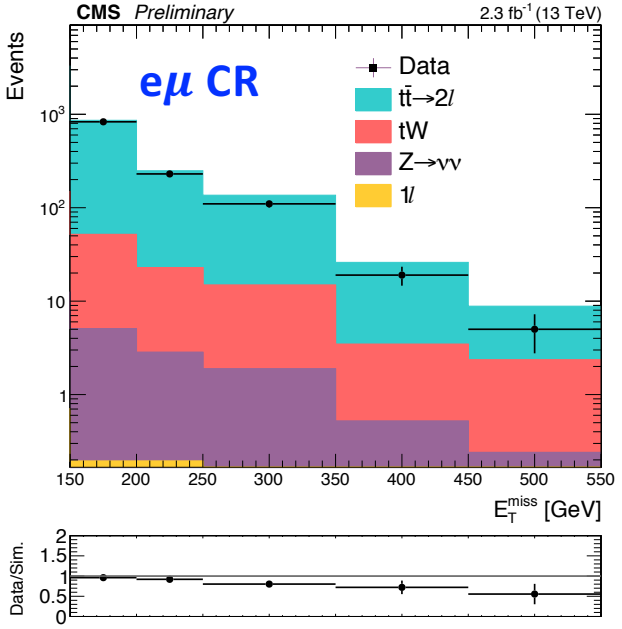
$\tilde{t}\tilde{t}$ search with 1 lepton

Lost-lepton background from **dilepton CR:**

$$N^{Data}_{lost-\ell} = N^{Data}_{2\ell} \times \frac{N^{MC}_{lost-\ell}}{N^{MC}_{2\ell}} \times \frac{N^{MC}_{lost-\ell}(NJ,\ E_T^{miss})}{N^{MC}_{lost-\ell}}$$

transfer factor $2\ell \rightarrow 1\ell$ — **extrapolation** inclusive → bin(N_{jet}, E_T^{miss})

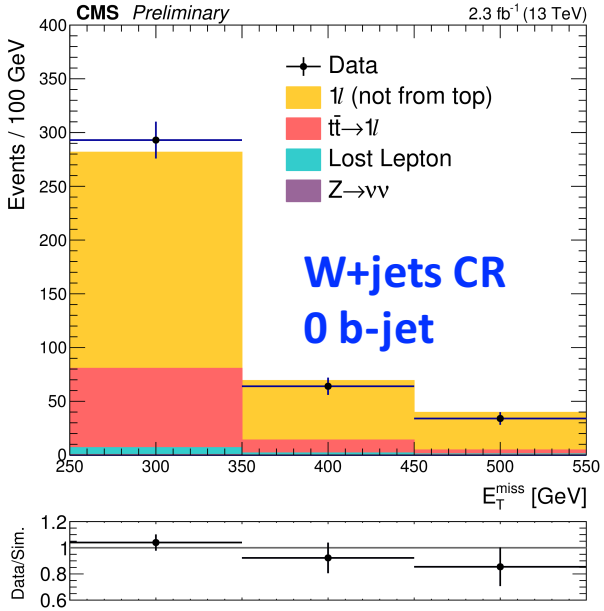
Corrections vs N_{jet} and E_T^{miss} **derived in eμ CR.**



W+jets background from **0 b-jet CR**:

$$N^{W+jets}_{SR,\geq 1\,btag} = (N^{data}_{CR,0\,btag} - N^{non-WJetsMC}_{CR,0\,btag}) \times TF_{E_T^{miss}} \times TF_{btag}$$

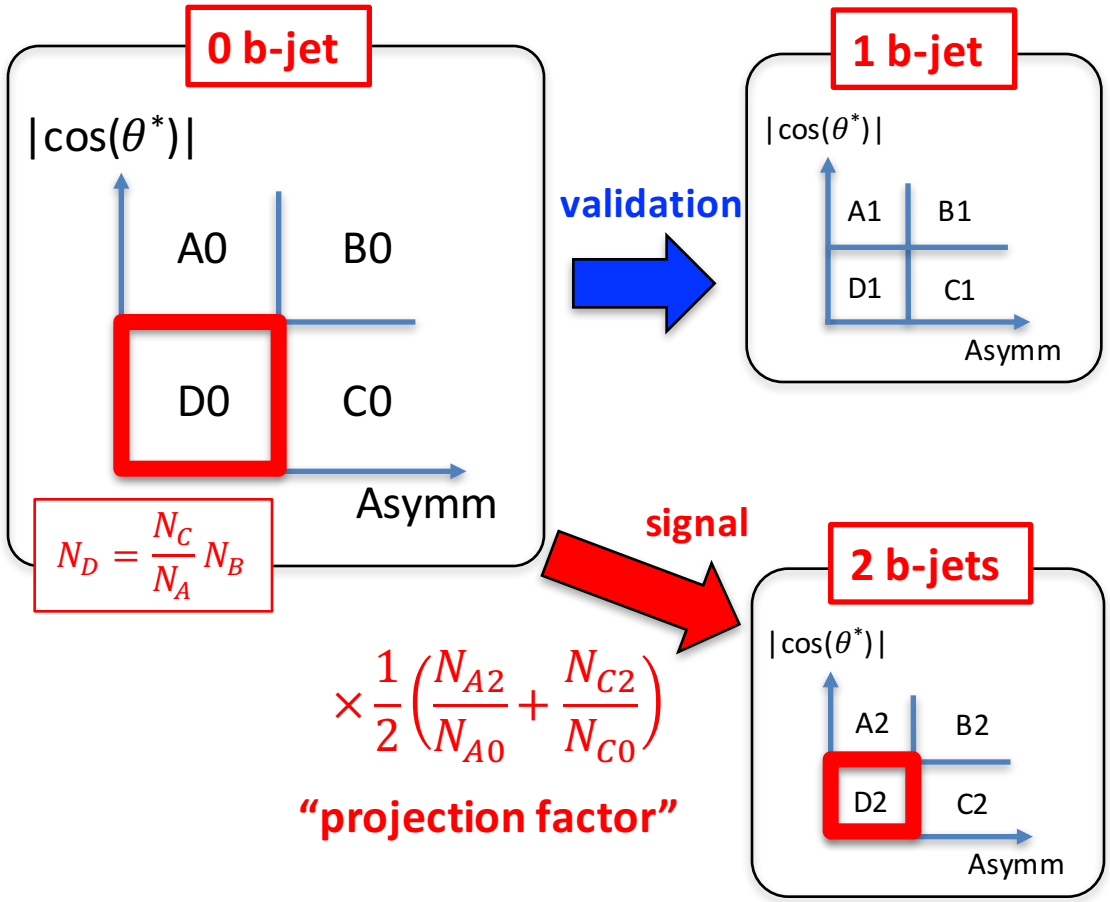
with 2 transfer factors to **extrapolate vs E_T^{miss} and $N_{b\text{-jet}}$**

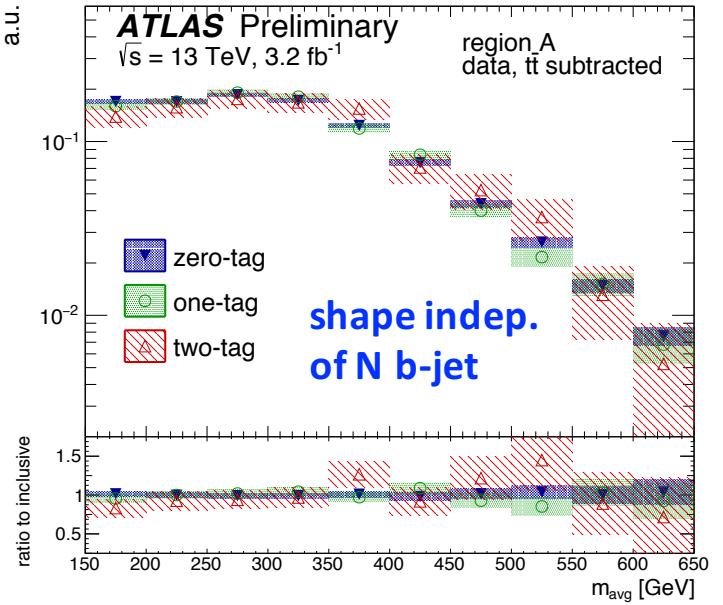


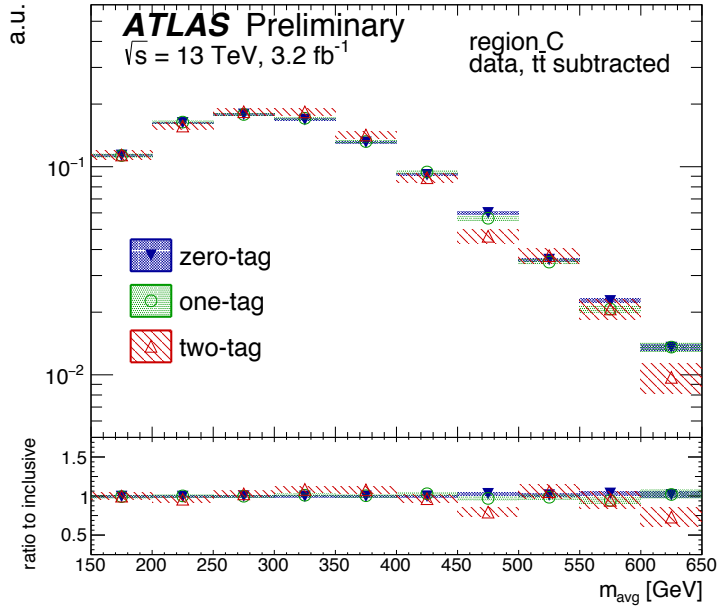
$\tilde{t} \rightarrow bs$ in RPV SUSY

Main background = multi-jets.
Estimated **from data** with **ABCD method**:

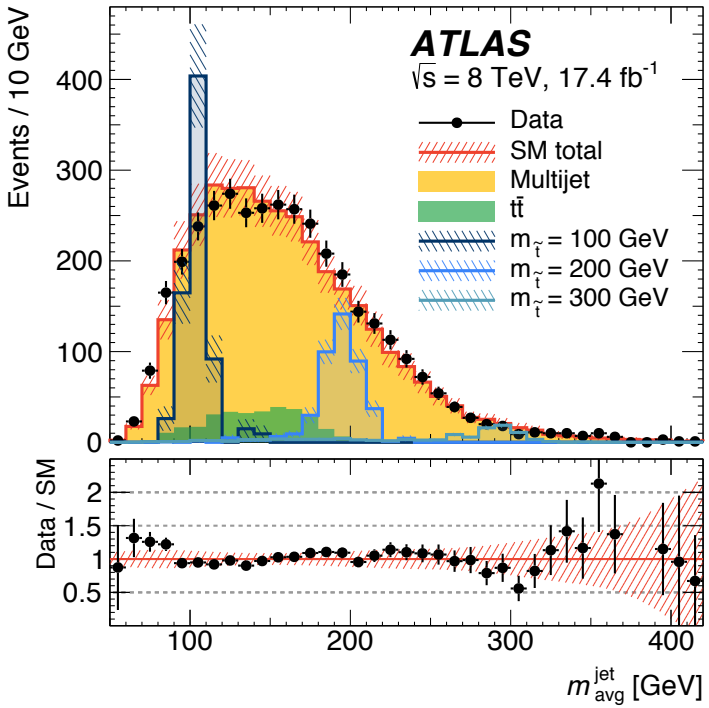
- shape and normalization from 0 b-jet
- extrapolation vs N *b*-jet

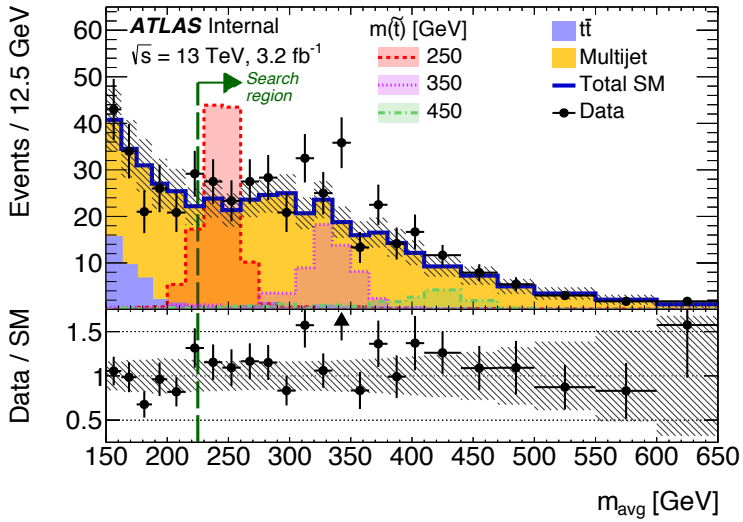


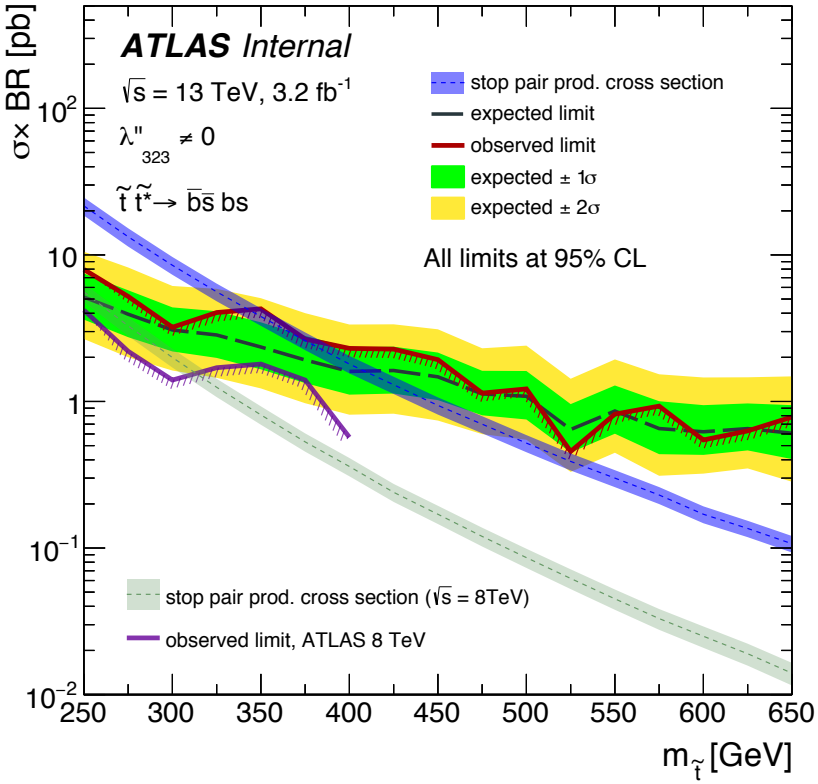




$\tilde{t}$ -> bs, Run-1 vs Run-2







Stealth $\tilde{t}$ via spin correlations

Phys. Rev. Lett. 114, 142001 (2015)