Search for Supersymmetry in Boosted Topologies at CMS

SUSY 2017, Mumbai

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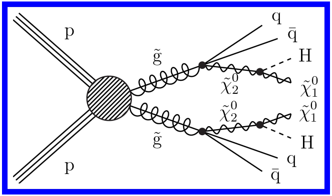
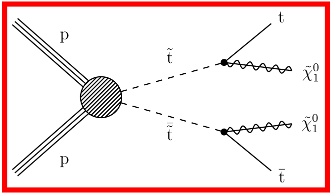
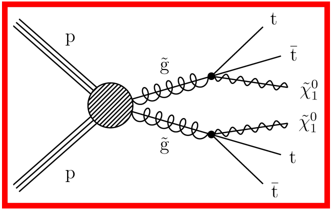
Dec 12, 2017

Scope of the Talk

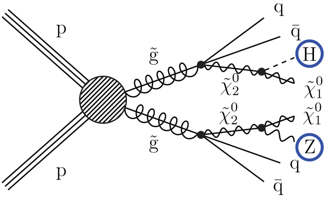
- Focus on two (**new!**) searches that make use of boosted objects
  - **Boosted Higgs**
    CMS-PAS-SUS-17-006
  - **(Boosted) Top quarks**
    CMS-SUS-16-050,
    arXiv:1710.11188
- Magnitude of boost depends on mass splittings
- Similarities:
  - **Strong production** (largest cross-section)
  - **Hadronic decay channels** (jets and missing transverse energy (MET) in final state)







- Several other SUSY searches target decays with **resolved** b-jets
  - See e.g. talk Inclusive search for SUSY in hadronic final states at CMS



→ **Explicitly targets boosted Higgs production**

- Take advantage of $H \to b\bar{b}$ branching fraction of $\approx 58\%$
- High p_T Higgs bosons lead to collimated b-quarks which can be **reconstructed as a single object**

→ Ensured by compressed mass splitting (e.g. $\Delta m(\tilde{g}, \tilde{\chi}_2^0) = 50\,\mathrm{GeV}$, $m(\tilde{\chi}_1^0) = 1\,\mathrm{GeV}$)

- Interpret results for models with H+H and H+Z, i.e. $\mathcal{B}(\tilde{\chi}_2^0 \to H) = 50\%$

1) Baseline Selection

- **Hadronic final states** (also motivated by trigger)
  - Cut on $N_{\text{Jets}} \geq 2$, $H_{\text{T}} > 600\,\text{GeV}$, $H_{\text{T}}^{\text{miss}} > 200\,\text{GeV}$
  - No isolated leptons or tracks
  - Reject if $H_{\text{T}}^{\text{miss}}$ is aligned with leading 4 jets ($\Delta\Phi$)
- **Boosted objects**
  - $E_{\text{T}}^{\text{miss}} > 300\,\text{GeV}$
  - **At least 2 AK8 Higgs candidate jets** with
    - $p_{\text{T}} > 300\,\text{GeV}$
    - Pruned jet mass m_{J} within $50\,\text{GeV}, 250\,\text{GeV}$

2) Signal: Higgs Tagging

- Use events with **1 or 2 Higgs tagged AK8 jets** (N_{Higgs})
  - Pruned jet mass m_{J} within $85\,\text{GeV}, 135\,\text{GeV}$
  - Have a double-b tag (loose WP, $\approx 75\%$ signal eff)
    - link: CMS-PAS-BTV-15-002

Jet Pruning

- Recluster jet
- Remove soft, large angle particles from the jet (often UE, PU)

→ Improves mass resolution

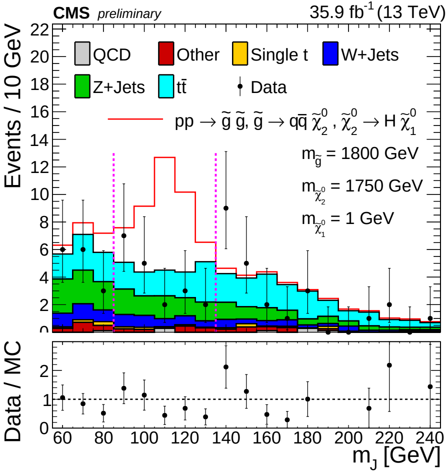
$b\bar{b}$ Tagging

- Based on MVA
- Compatibility of an AK8 jet coming from decay of two b-quarks
- Combines information from secondary vertices, tracks, τ-axes (N-subjettines axes)
- Explicitly doesn't use jet mass m_{J}

→ **More information in backup**

Boosted Higgs: Analysis Design

- Analysis designed as a **counting experiment**
  - $3 \times 2 =$ **6 search regions** ($E_T^{miss} \times N_{Higgs}$)
- **Plot**: Mass m_J of leading jet ($N_{Higgs} = 1, 2$)
  - $\rightarrow$ **Signal** can be seen as a resonance in m_J



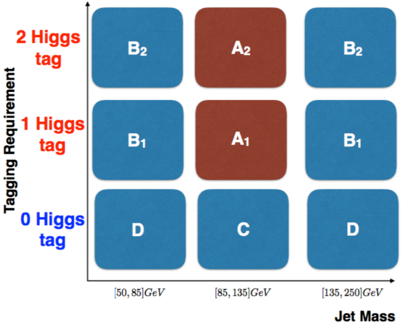
- Estimate the background using an '**ABCD**' method:
  - Use $\boldsymbol{m_J}$ **sideband and un-bb-tagged regions** (background dominated) to extrapolate to **signal region** $\boldsymbol{A_{1,2}}$
  - Measure $\kappa_{1,2}$ in MC to **correct for correlations** of the jet mass and the bb-tagging variables

→ Derive data/MC scalefactors (SFs) in **validation regions** to correct for relative composition of BGs

  - low-$\Delta\Phi$ (QCD)
  - single-lepton ($t\bar{t}$, W+jets)
  - single-photon ($Z(\nu\nu)$+jets)

  → SFs validated in signal sideband regions

- **Validity of ABCD method tested in data** in the validation regions



$$\boxed{A_{1,2} = B_{1,2} \cdot \frac{C}{D} \cdot \kappa_{1,2}}$$

Boosted Higgs: Results

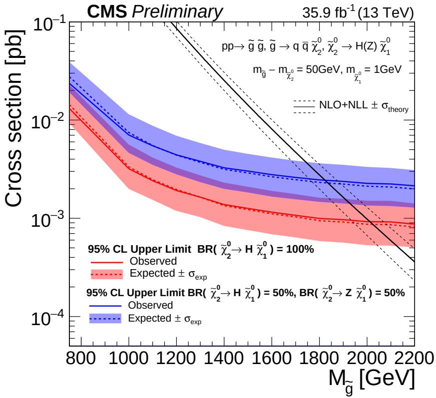
- Observed event yields are in statistical agreement with data-driven prediction of SM backgrounds

$\rightarrow$ **No evidence for SUSY**

N_{Higgs}	$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	κ	Predicted	Observed
1	$300-500$	0.98 ± 0.11	17.68 ± 3.85	15
1	$500-700$	0.86 ± 0.16	3.44 ± 1.47	2
1	> 700	0.86 ± 0.17	0.61 ± 0.45	1
2	$300-500$	0.73 ± 0.14	1.52 ± 0.57	1
2	$500-700$	0.43 ± 0.12	$0.09^{+0.08}_{-0.08}$	0
2	> 700	0.62 ± 0.30	$0.09^{+0.11}_{-0.09}$	0

- Compute upper limits on the gluino pair-production cross section
  - Contributions to sideband regions from signal modeled in likelihood fit
  - **T5HH: exclude $m_{\tilde{g}}$ up to 2010 GeV**
  - **T5ZH: exclude $m_{\tilde{g}}$ up to 1825 GeV**

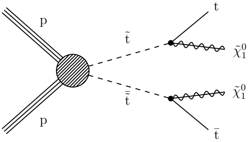
  (with the assumption of $\Delta m(\tilde{g}, \tilde{\chi}_2^0) = 50\,\mathrm{GeV}$, $m(\tilde{\chi}_1^0) = 1\,\mathrm{GeV}$)

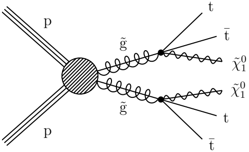


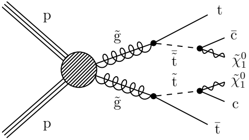
(Boosted) Top: Introduction & Analysis Setup

All-hadronic analysis using top-tagging

- **Jets+E_T^{miss} final states**
  - $N_{Jets} \geq 4,\ E_T^{miss} > 250\,\mathrm{GeV},\ H_T > 300\,\mathrm{GeV},\ N_b \geq 1$
  - Lepton and track vetoes
  - $\Delta\Phi(\text{jet}, E_T^{miss})$-cut on leading three jets
- **Top reconstruction**
  - $N_t \geq 1$ (customized top tagger)
  - $M_{T2} > 200\,\mathrm{GeV}$





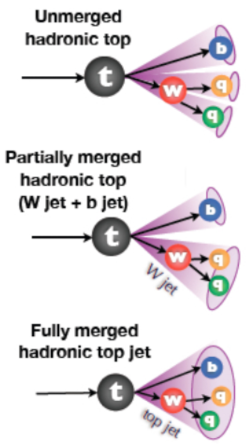


- Targeting large **variety of signal models**
  - $\rightarrow$ **84 search regions** binned in $N_t, N_b, E_T^{miss}, M_{T2}/H_T$
  - Also define **10 aggregate search regions** (simplifies re-interpretation etc.)
- **Customized** top-tagging algorithm
  - Designed for a good efficiency for a **large range of *t*-quark p_T** (boost depends on signal)
  - Uses AK4 and AK8 jets since *t*-jet can be **resolved** or **partially/fully merged**

1. Tag **fully merged** tops
   - **Standard** PUPPI AK8 **boosted top** (loose working point)

2. Tag **partially merged** tops (merged W-jet)
   - **Standard** PUPPI AK8 **boosted W** (loose working point)
   - **Combine with** nearby AK4 jet
   - Require mass to be consistent with $m(t)$ and ratio consistent with $m(W)/m(t)$

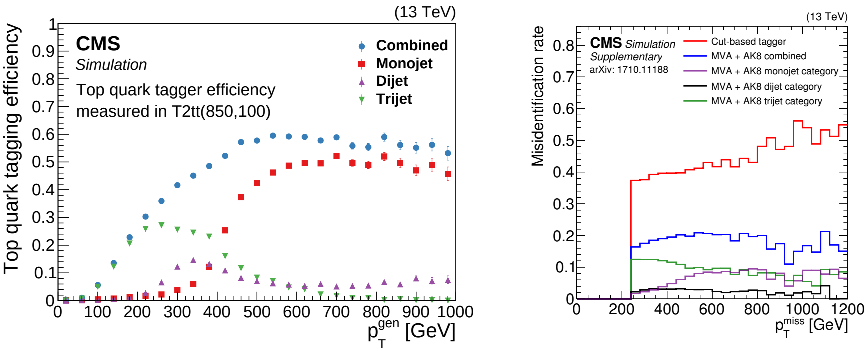
3. Tag **resolved** tops (**New!**)
   - Use **all combinations** of 3 AK4 jets (no more than 1 b-jet)
   - **Train MVA** on jet properties (p_{T}, mass of tri-jet and di-jet system, angular separation, CSV, QGL, etc.)
   - Optimized cut on MVA based on full limit-setting procedure



PUPPI (pileup per particle identification)

- Each particle is weighted by the probability to originate from the primary vertex before jet clustering

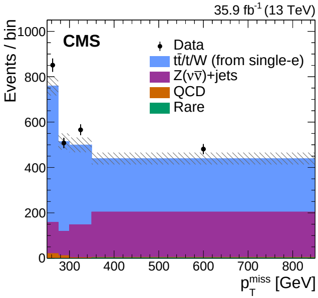
(Boosted) Top: Top Tagger (Performance)

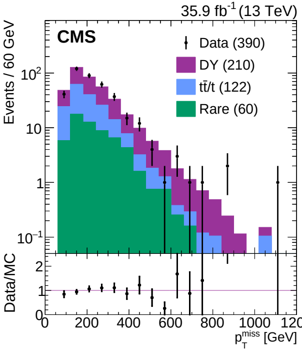


- **Left**: Performance of "Tight" working point in signal MC (T2tt)
  - **High efficiency** for a large range of t-quark p_T
  - Breakdown in the categories reveals important contributions
- **Right**: Misidentification rate of the top tagger in MC ($Z \to \nu\nu$)
  - Almost constant with an average of $\approx 20\%$
  - **Huge improvement** compared to previous (cut-based) version of tagger

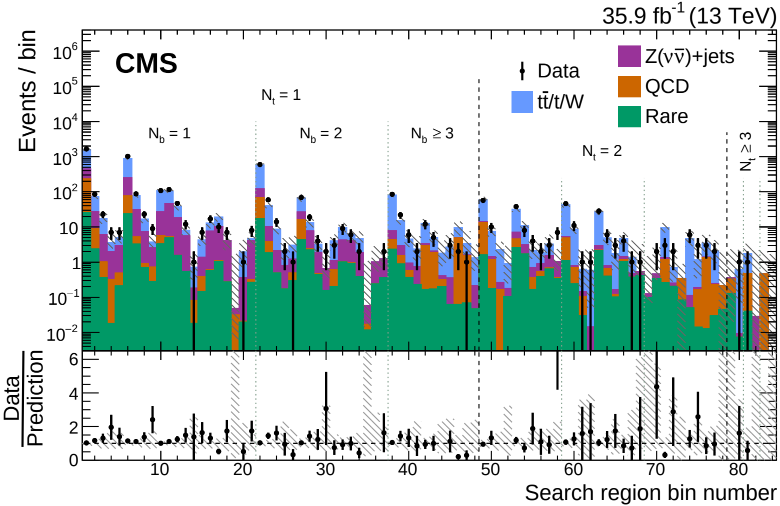
- **Most important backgrounds**: lost lepton and hadronic tau, as well as Z invisible
  1. $t\bar{t}$, W +jets: Data-driven approach using **translation factors**
     - Derive $\mathrm{TF} = N^{\mathrm{MC}}_{\mathrm{SR}} / N^{\mathrm{MC}}_{\mathrm{CR}}$ in MC (data/MC SFs applied)
     - Then estimate using data CR: $N_{\mathrm{SR}} = \mathrm{TF} \cdot N_{\mathrm{CR}}$
     - Use data sideband to validate approach **[top plot]**
  2. $Z(\nu\nu)$ +jets: Central value from **MC with data/MC corrections**
     - Derive SF(N_{Jets}) in "loose" ($DY \to \mu\mu$) CR and apply on ($Z \to \nu\nu$) MC **[bottom plot, after application of SF]**
     - Then adjust normalization in "tight" CR
     - Derive shape uncertainty based on "loose" CR after all corrections have been applied

→ Details on QCD, ttZ background estimation in backup





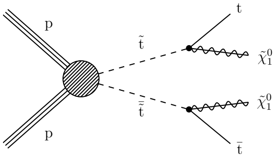
No statistically significant deviation between data and SM background observed

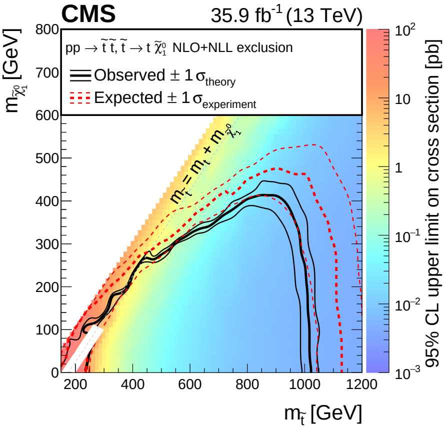


→ Results of aggregated Search Regions in backup!

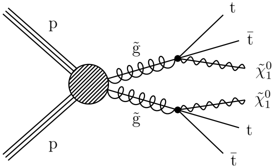
(Boosted) Top: Exclusion Limits **[more in backup]**

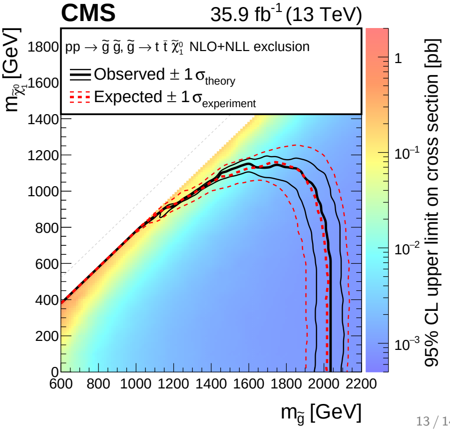
T2tt





T1tttt

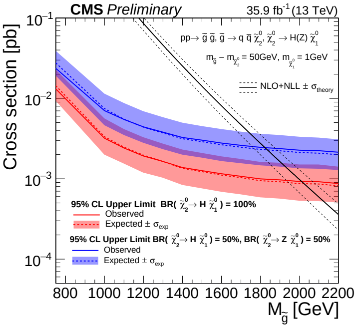


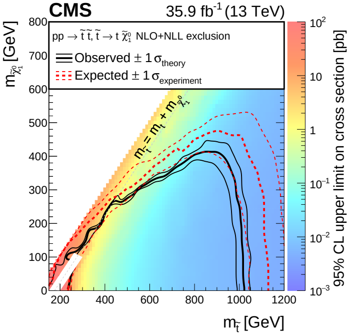


- Highlighted results from two (brand-new!) analyses with boosted final states with $35.9\,\mathrm{fb}^{-1}$ data collected by CMS
  - Both searches for Supersymmetry are performed in jets+MET final state, plus
    1. **boosted Higgs** (CMS-PAS-SUS-17-006, paper will be available soon)
    2. **(boosted) top quark** (link: arXiv:1710.11188)

  $\rightarrow$ No evidence for physics beyond the Standard Model found

- **Additional material for interpretation: link (boosted top)**

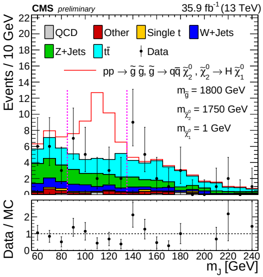




Backup

- Prediction can be done in data using the signal trigger:

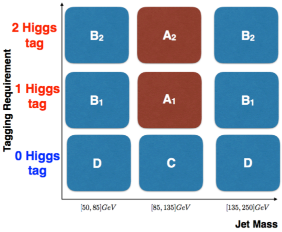
$$\boxed{A_{1,2} = B_{1,2} \cdot \frac{C}{D} \cdot \kappa_{1,2}}$$



- Based on assumption that the jet mass and the bb-tagging variables are un-correlated
  - But: **ratios** $\left(\frac{B_1}{D}, \frac{A_1}{C}, \ldots\right)$ **are sample dependent**

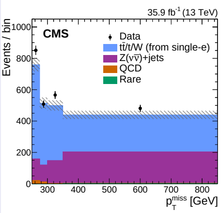
  → Derive correction for the effect:
  $$\kappa_{1,2} = A^{MC}_{1,2} / \left(B^{MC}_{1,2} \cdot \frac{C^{MC}}{D^{MC}}\right)$$
  - $\kappa_{1,2}$ calculated inclusively in all BG MC samples (but independently for all 6 SRs)

- **Derive data/MC SFs in validation regions to correct for relative composition of BGs**
  - Loosen cut on E_T^{miss} or $\Delta\Phi$ in case of low statistics
  - Generally no E_T^{miss} dependence observed so calculated inclusively
  - Single lepton validation region: derive SF as a function of E_T^{miss} and assign E_T^{miss} shape uncertainty in case of low statistics

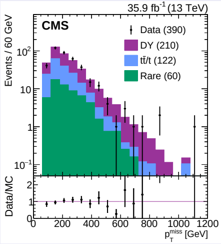


1. ***$t\bar{t}$, W +jets***: Data-driven approach using **translation factors**
   - Derive $\mathrm{TF} = N_{\mathrm{SR}}^{\mathrm{MC}} / N_{\mathrm{CR}}^{\mathrm{MC}}$ in MC (data/MC SFs applied)
   - Then estimate using data CR: $N_{\mathrm{SR}} = \mathrm{TF} \cdot N_{\mathrm{CR}}$
   - Use data sideband to validate approach
2. ***$Z(\nu\nu)$ +jets***: Central value from **MC with data/MC corrections**
   - Derive SF(N_{Jets}) in "loose" ($DY \to \mu\mu$) CR and apply on ($Z \to \nu\nu$) MC
   - Then adjust normalization based on "tight" DY CR
   - Derive shape uncertainty based on "loose" CR after all corrections have been applied
3. **QCD**: Data-driven approach using **translation factors**
   - Measure $\mathrm{TF} = N_{\mathrm{QCD}}^{\Delta\Phi} / N_{\mathrm{QCD}}^{\overline{\Delta\Phi}}$ in data in low $E_{\mathrm{T}}^{\mathrm{miss}}$ sideband region
   - Use MC to extrapolate to SR
   - Derive systematic uncertainty based on MC closure test
4. ***ttZ***: **MC**, validated in three-lepton CR

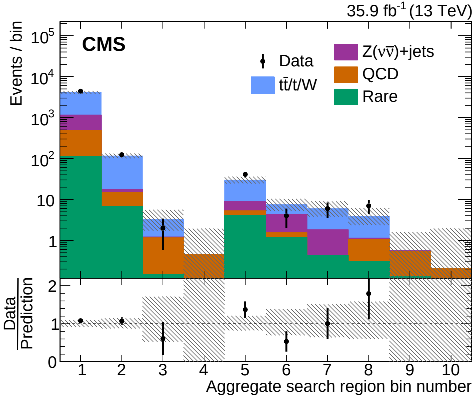
Validation of $t\bar{t}$, W +jets estimation in data sideband



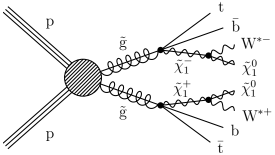
Data/MC in "loose" DY CR after application of SF(N_{Jets})



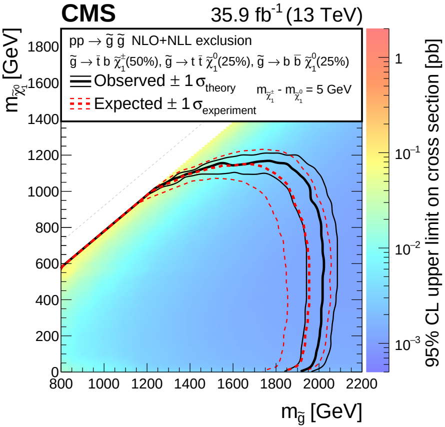
(Boosted) Top: Results (Aggregated Search Regions)



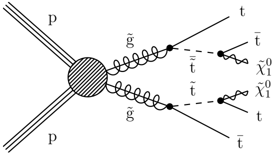
Region	N_t	N_b	m_{T2} [GeV]	p_T^{miss} [GeV]	Motivation
1	≥1	≥1	≥200	≥250	Events satisfying selection criteria
2	≥2	≥2	≥200	≥250	Events with $N_t \geq 2$ and $N_b \geq 2$
3	≥3	≥1	≥200	≥250	Events with $N_t \geq 3$ and $N_b \geq 1$
4	≥3	≥3	≥200	≥250	T5tttt; small $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ and $m_{\tilde{\chi}_1^0} < m_t$
5	≥2	≥1	≥200	≥400	T2tt; small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$
6	≥1	≥2	≥600	≥400	T2tt; large $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$
Region	N_t	N_b	H_T [GeV]	p_T^{miss} [GeV]	Motivation
7	≥1	≥2	≥1400	≥500	T1ttbb & T5ttcc; large $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
8	≥2	≥3	≥600	≥350	T1tttt; small $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
9	≥2	≥3	≥300	≥500	T1/T5tttt & T1ttbb; intermediate $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
10	≥2	≥3	≥1300	≥500	T1/T5tttt; large $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$

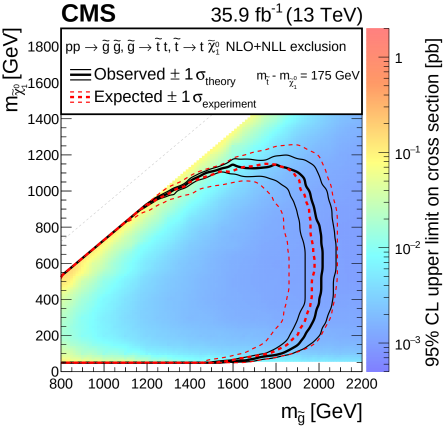


T1ttbb



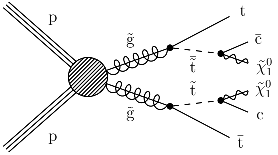
- Gluino decays via an off-shell top or bottom squark
  - $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0(25\%)$
  - $\tilde{g} \to b\bar{t}\tilde{\chi}_1^+$(or charge conjugate,50%)
  - $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0(25\%)$
- $\tilde{\chi}_1^+$ decays to LSP and off-shell W
- Provides sensitivity to mixed states of top and bottom quarks

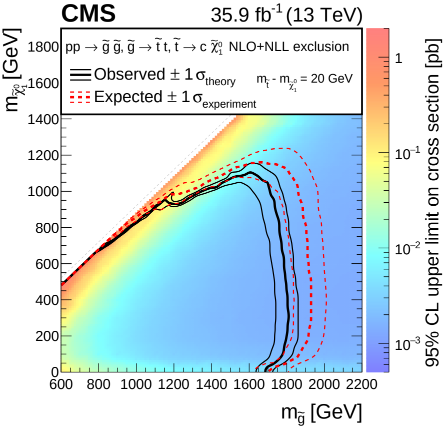




T5tttt

- Gluino decays via on-shell top squark
  - $\Delta m(\bar{t}, \tilde{\chi}^0_1) = 175\,\mathrm{GeV}$
- Provides sensitivity to a region that is difficult to probe with the T2tt model
  - Signal similar to $t\bar{t}$ events
- Area at the bottom is excluded due to high signal contamination
  - Statistical treatment of signal contamination becomes unreliable

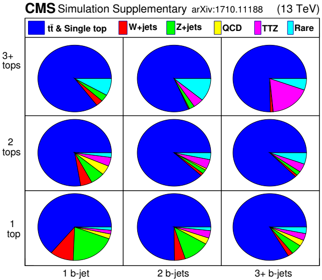


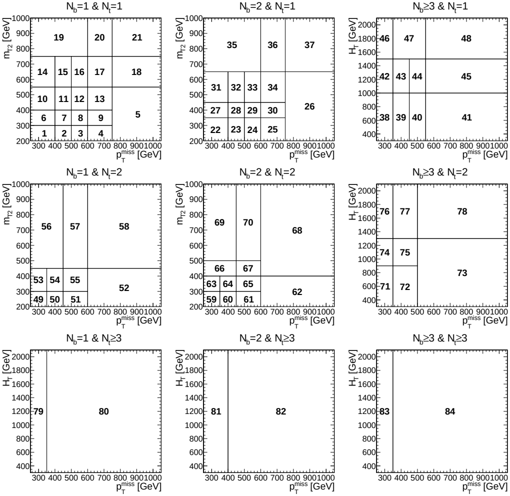


T5ttcc

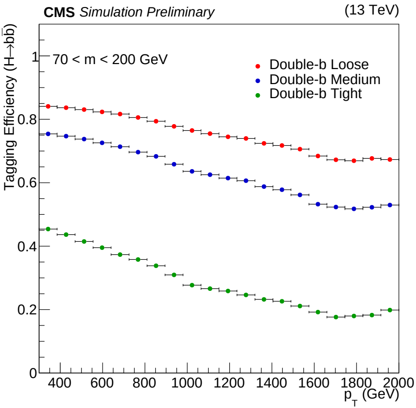
- Top squark decays to a charm quark and the LSP.
  - $\Delta m(\bar{t}, \tilde{\chi}_1^0) = 20\,\mathrm{GeV}$
- Provides sensitivity to scenarios in which the top squark is kinematically unable to decay to an on-shell top quark
  - Dominant decay mode of top squark in this case

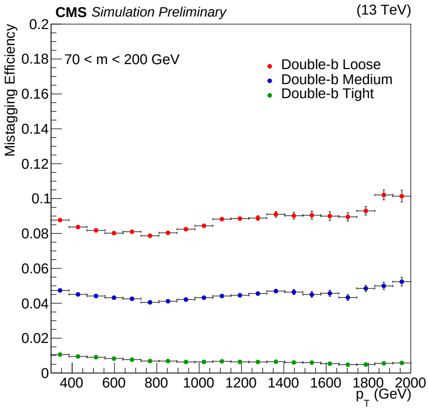
(Boosted) Top: Search Binning





CMS-PAS-BTV-15-002





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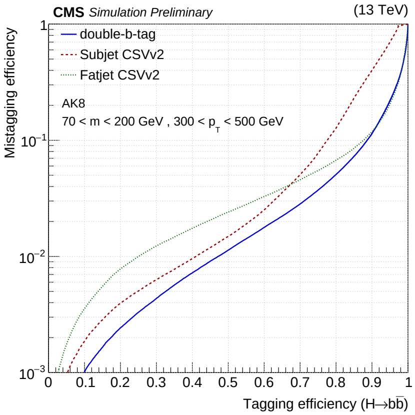

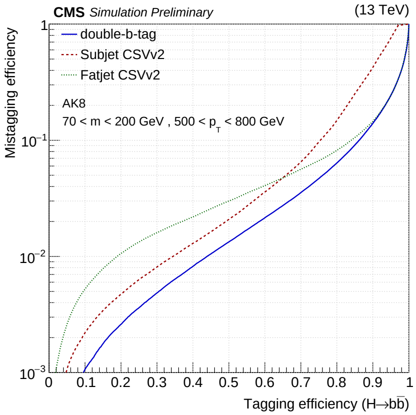

(Boosted) Higgs: Performance of $H \to b\bar{b}$ tagger

CMS-PAS-BTV-15-002