3RD GENERATION SUSY SEARCHES AT CMS

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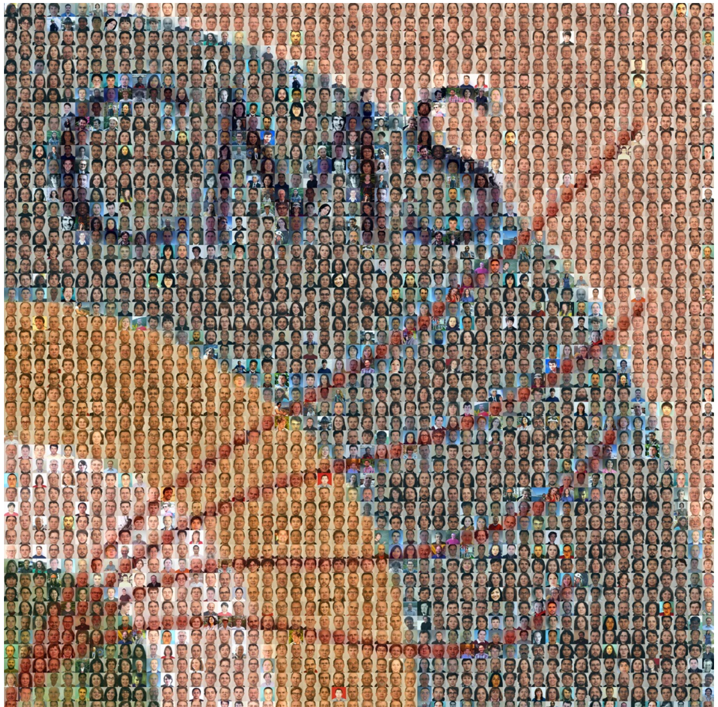
on behalf of the CMS collaboration



Focus of this talk

- There is a large effort in searches for third generation squarks.
  - They contribute in Higgs boson mass loop corrections.
  - ➢ Light 3rd generation squarks expected to be lighter than ≲1 TeV in many "natural" scenarios.
  - Due to large mixing they can be lighter than other squarks.

- In this talk, I will focus on interpretations in the simplest models for third generation squark searches.
  - Direct squark production with decays like $\tilde{q} \longrightarrow q\chi^0{}_1$
  - Gluino decays via virtual squark exchange: $\tilde{g} \longrightarrow q\bar{q}\,\chi^0{}_1$
- Several other models considering 3rd generation squarks are considered by CMS can be found in the backup of this talk.

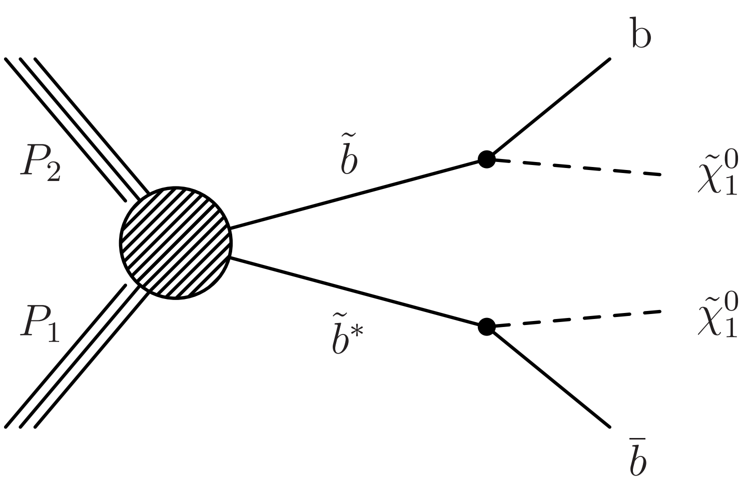
DIRECT PRODUCTION

Direct $\tilde{b}$ production

- I will focus here on the simple decay $\tilde{b} \longrightarrow b\, \chi^0{}_1$
  - Other sbottom decays like $\tilde{b} \longrightarrow t\, \chi^{\pm}{}_1$ can be found in the backup.

- Inclusive analyses are interpreted in this decay mode.
  - The M_{T2} analysis based on H_T, M_{T2}, and b-jet multiplicity

- Dedicated search for direct sbottom production.
  - I will quickly discuss this one.

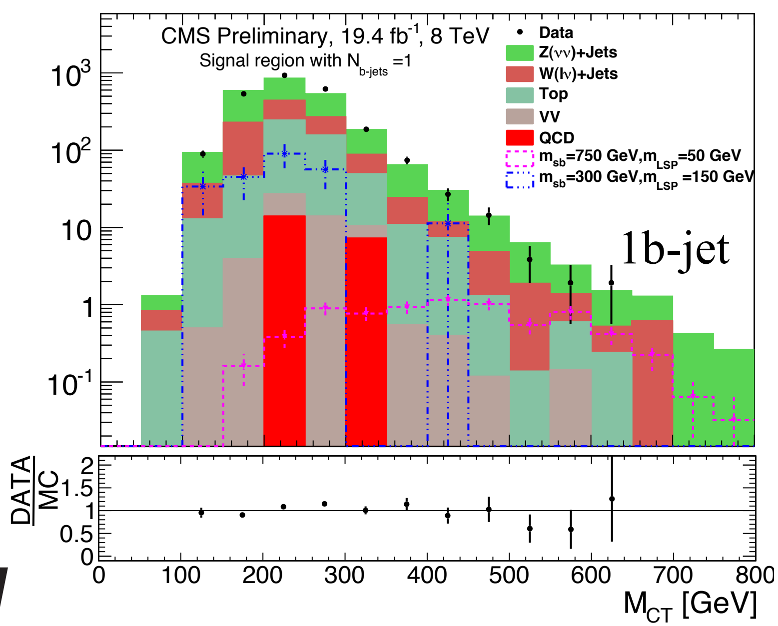


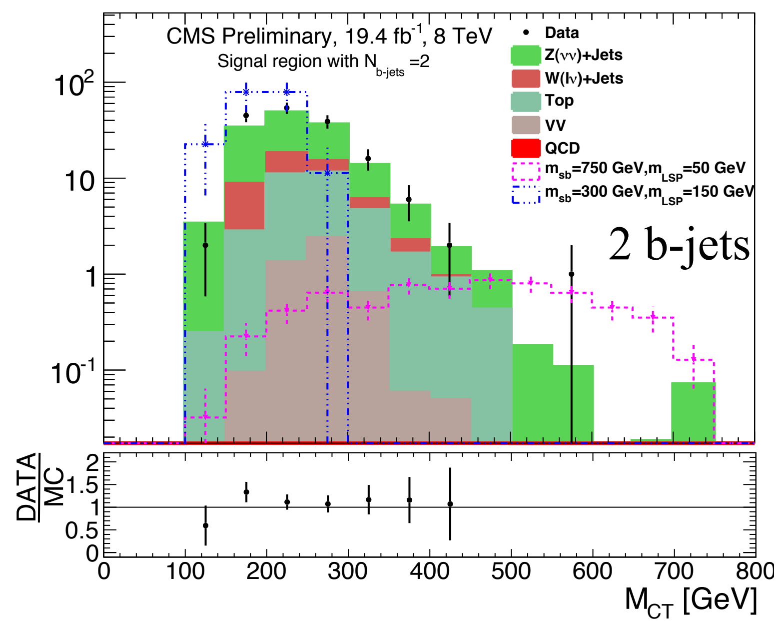
Direct $\tilde{b}$ production

- The dedicated direct sbottom search is based on events with exactly two jets with one or two b-jets, and no charged leptons.
- The signal discriminant is M_{CT}:

$$M_{\mathrm{CT}}^2 = \left[E_{\mathrm{T}}^{j1} - E_{\mathrm{T}}^{j2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,j1} - \vec{p}_{\mathrm{T}}^{\,j2}\right]^2$$

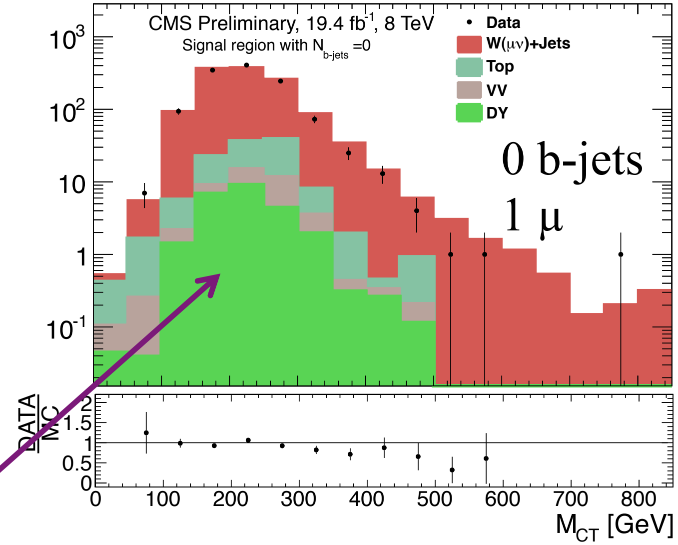
$$= 2 p_{\mathrm{T}}^{j1} p_{\mathrm{T}}^{j2}\left(1 + \cos\Delta\phi(j_1, j_2)\right)$$

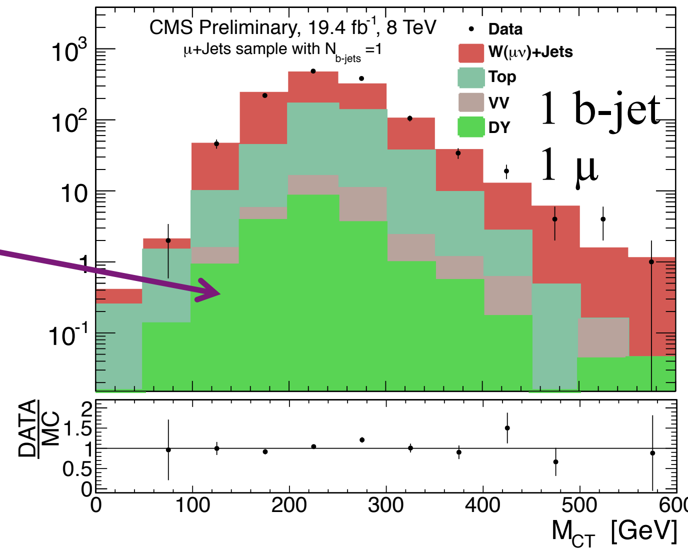




Direct $\tilde{b}$ production

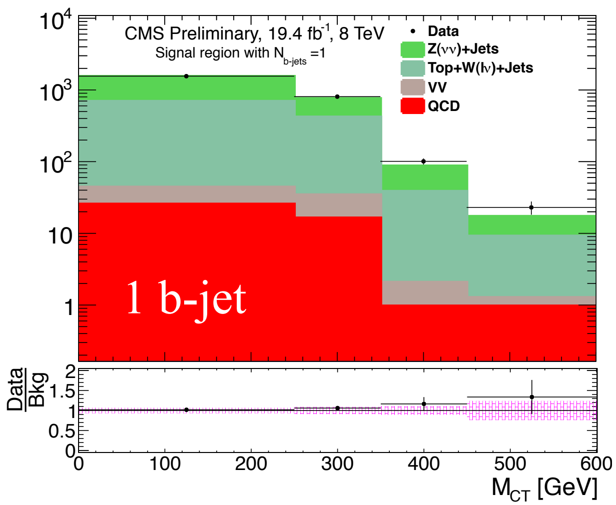
- The analysis as two important backgrounds:
  - Z+jets with $Z \longrightarrow \nu\bar{\nu}$
  - $W \longrightarrow l\bar{\nu}$ (W+jets and $t\bar{t}$+jets) decays with lost charged lepton
- Both backgrounds are estimated from the 1μ sample.
  - Use Z ↔ W correspondence for Z+jet estimation (add muon to E_T^{miss} vector).
    - Require 0 b-jet to reduce top contamination.
  - Use lepton efficiency in μ+jets events in b-enriched region for lost lepton prediction.

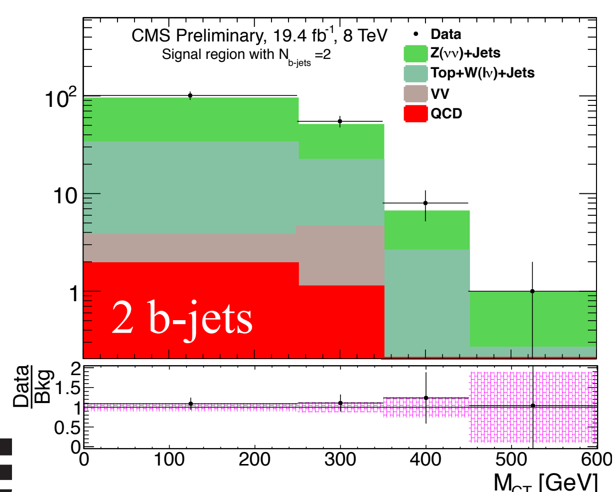




Direct $\tilde{b}$ production

- The analysis sees no significant excess in data over predicted background.





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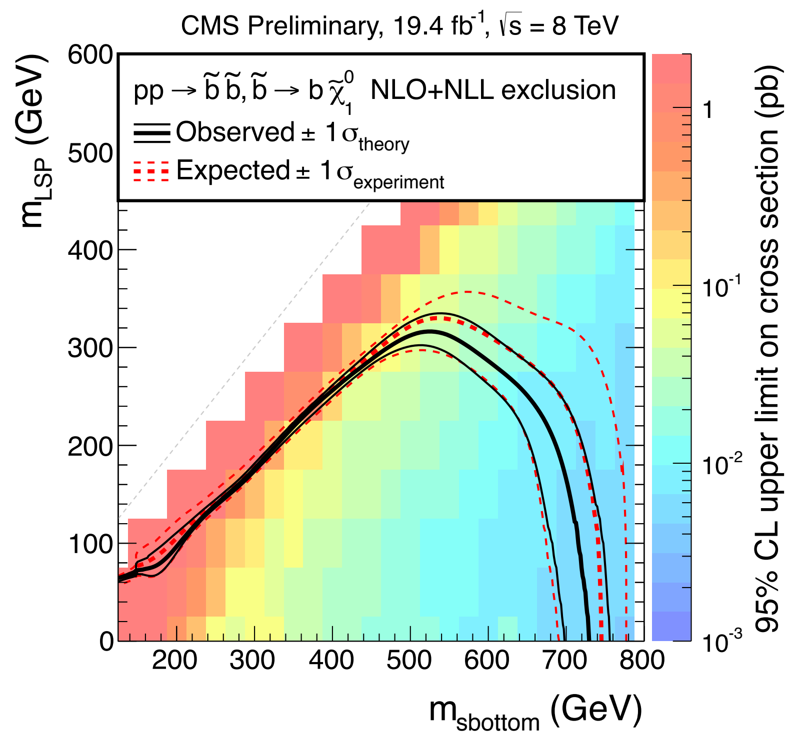

Direct $\tilde{b}$ production

- Mass limit using dedicated sbottom search

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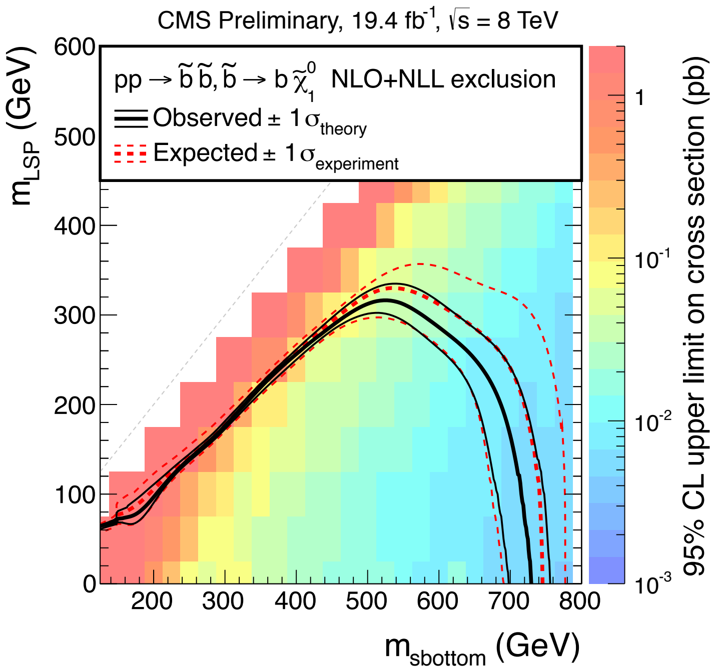

- Mass limit using inclusive M_{T2} analysis

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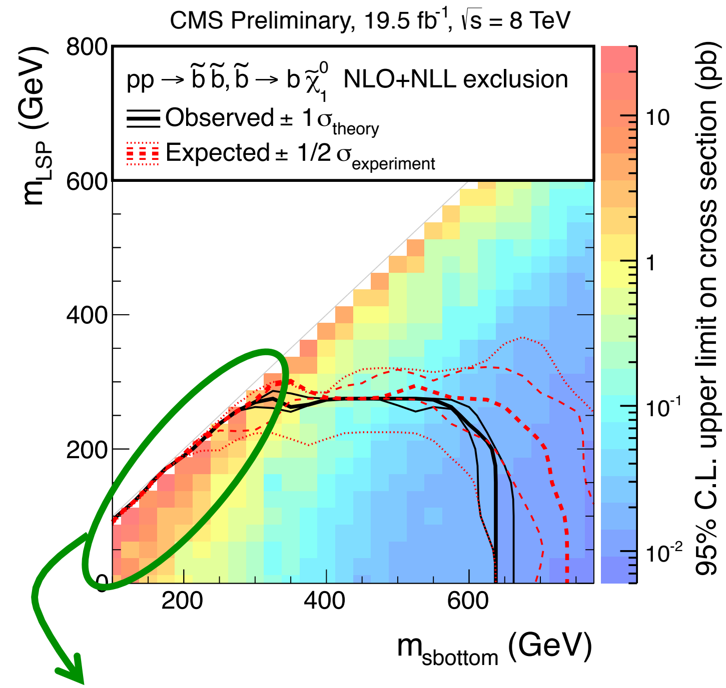


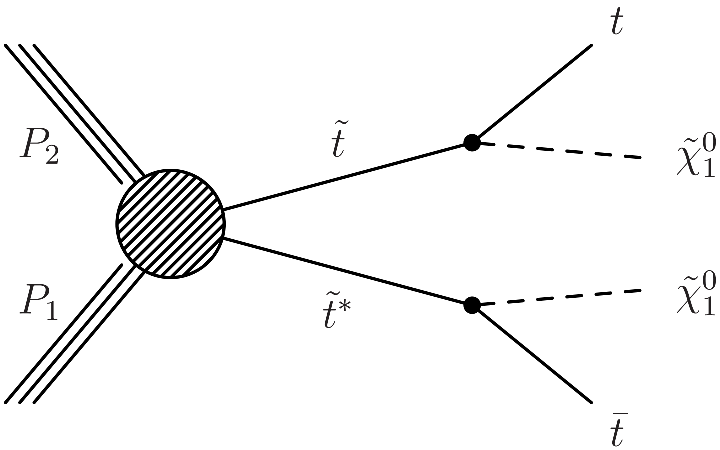
Higher sensitivity due to jet bins with ≥3 jets.

Direct $\tilde{t}$ production

- I consider here the simple decay $\tilde{t} \longrightarrow t\, \chi^0_1$
  - Other stop decays like $\tilde{t} \longrightarrow b\, \chi^\pm_1$, $\chi^\pm_1 \longrightarrow W^\pm \chi^0_1$ can be found in the backup.

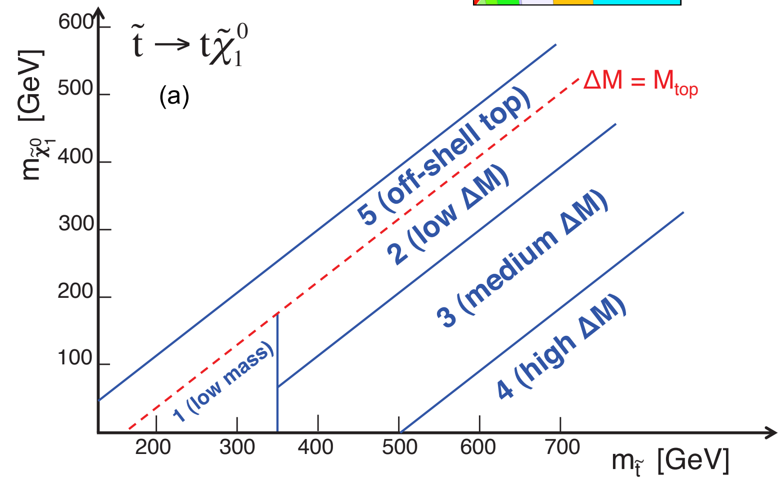
- CMS interprets several inclusive analyses in this decay mode.
  - The M_{T2} analysis based on H_T, M_{T2}, and b-jet multiplicity.
  - The Razor analysis based on R^2, M_R, lepton- and b-content.

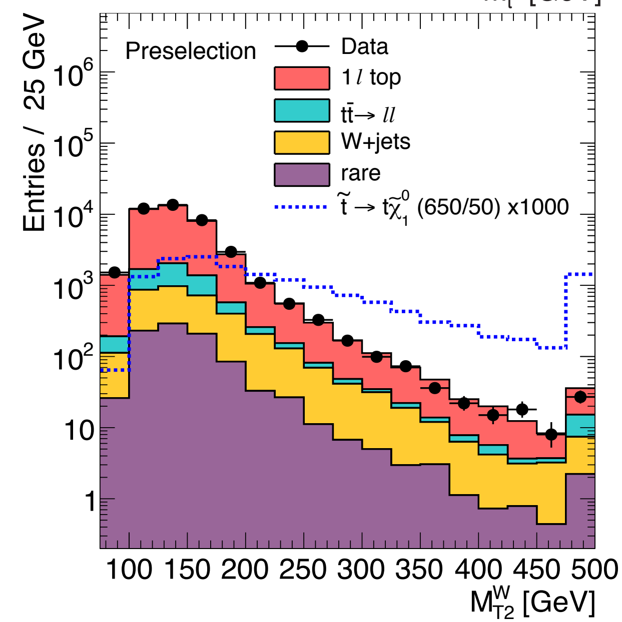
- CMS also has several dedicated search for direct stop production.
  - A all-hadronic stop search using top tagger.
  - A one lepton search using BDTs.
    - I will discuss this one as an example.



Direct $\tilde{t}$ production

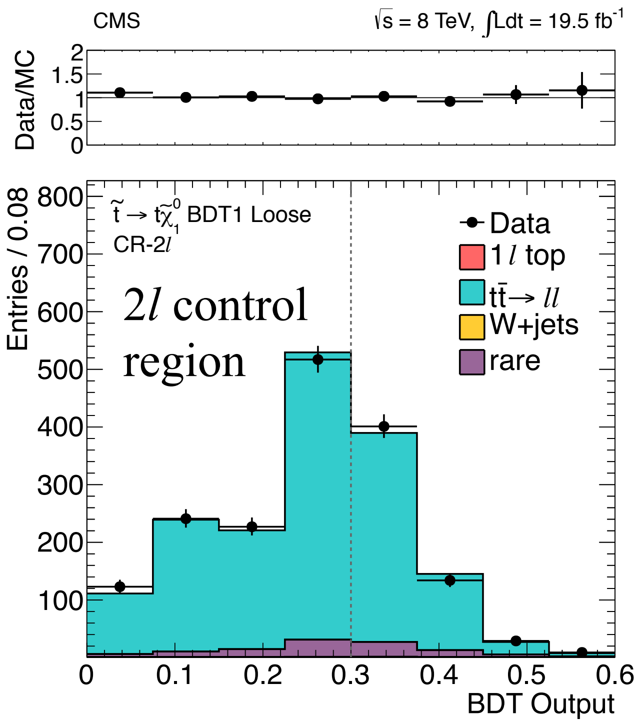
- The dedicated $1l$ analysis selects events with $1l$, ≥ 4 jets, ≥ 1 b-jet and $M_T(l, E_T^{miss}) > 120$ GeV
- Several BDTs are trained to discriminate SM backgrounds and the stop signal.
- The kinematic variables are:
  - E_T^{miss}
  - H_T^{ratio}
  - $\min\Delta\phi$(jet 1 or 2, E_T^{miss})
  - Leading b-jet p_T
  - Hadronic top χ^2 (mass fit)
  - M_{T2}^W

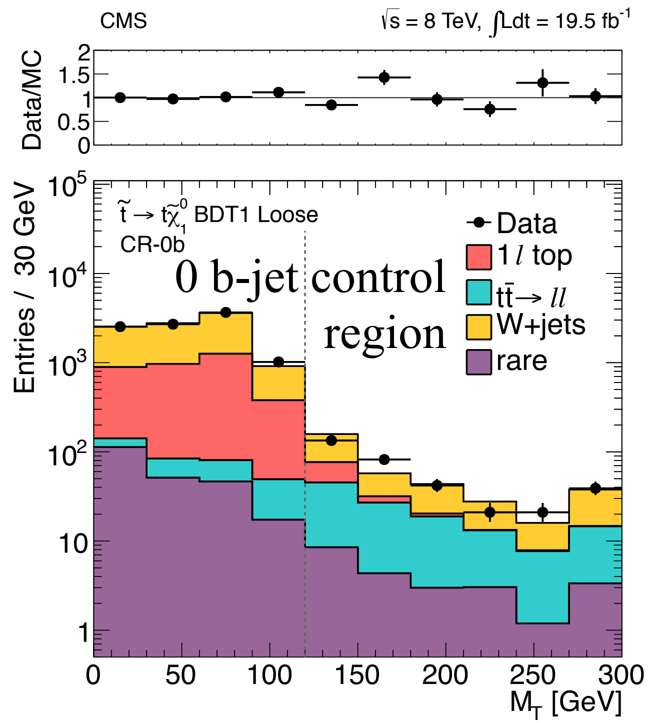




Direct $\tilde{t}$ production

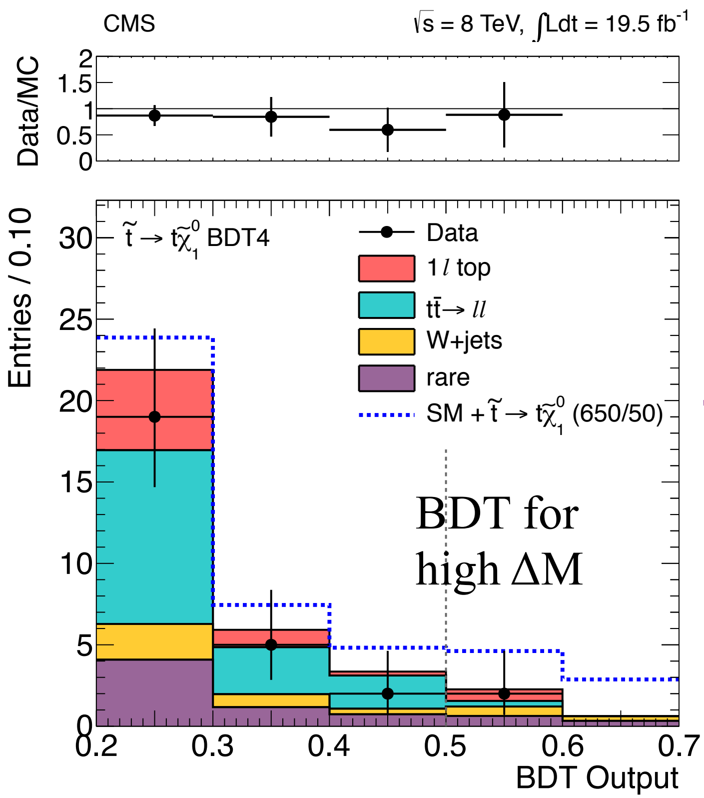
- Backgrounds are predicted using (corrected) simulation which is validated in data control regions





Direct $\tilde{t}$ production

- No excess over SM backgrounds observed.



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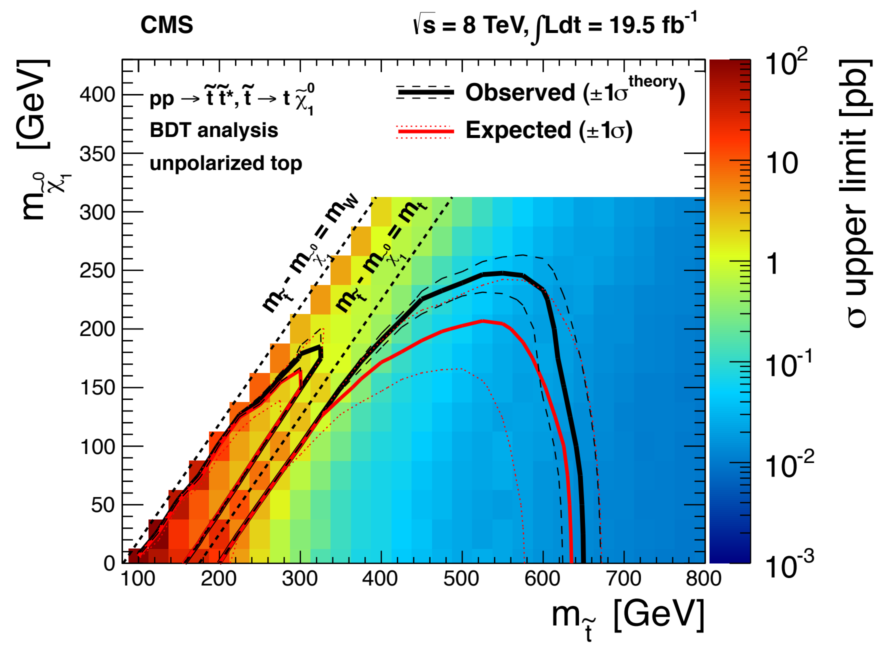


Other analyses have similar reach in on-shell top region, but are less sensitive in off-shell top region (⟶ backup).

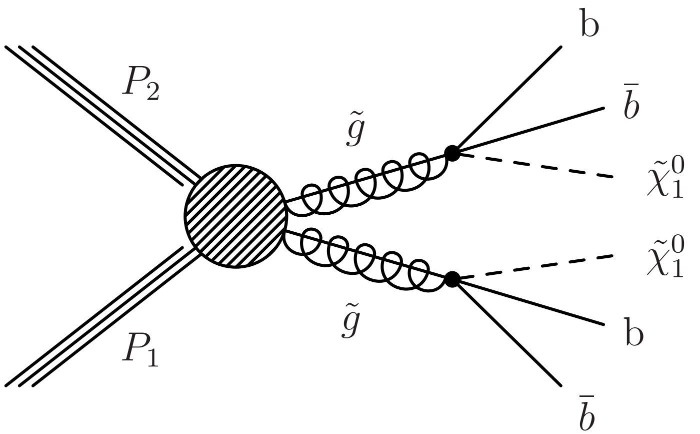
GLUINO-INDUCED PRODUCTION

Gluino decays via virtual $\tilde{b}$

- I discuss here $\tilde{g} \longrightarrow b\bar{b}\,\chi^0{}_1$
- This final state is purely hadronic.
  - Other decays like $\tilde{g} \longrightarrow \bar{b}\tilde{b}$, $\tilde{b} \longrightarrow t\,\chi^-{}_1$, $\chi^-{}_1 \longrightarrow W^-\chi^0{}_1$ can be found in the backup.

- All the inclusive hadronic searches with a b-jet selection are very sensitive to this decay.

- Searches are based on:
  1. E_T^{miss}, H_T, and b-jet multiplicity
  2. R^2, M_R, lepton- and b-content (‘Razor’ variables)
  3. M_{T2}, H_T, jet and b-jet multiplicity
     - I will show this analysis.

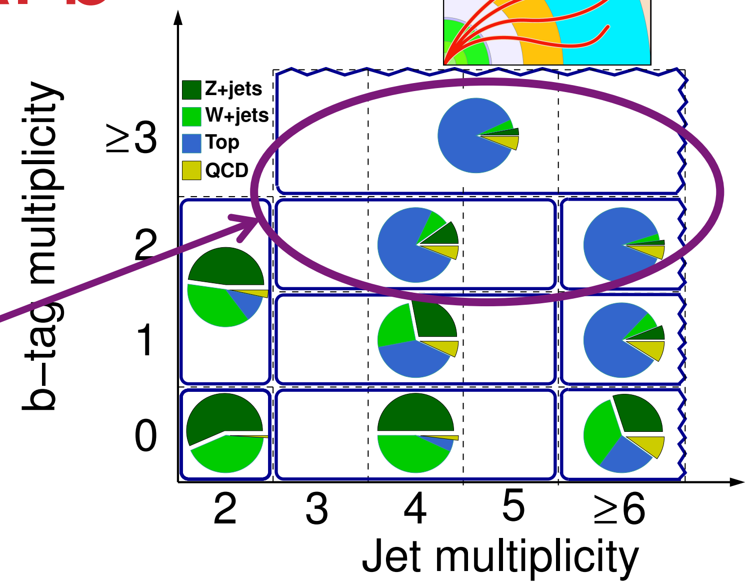


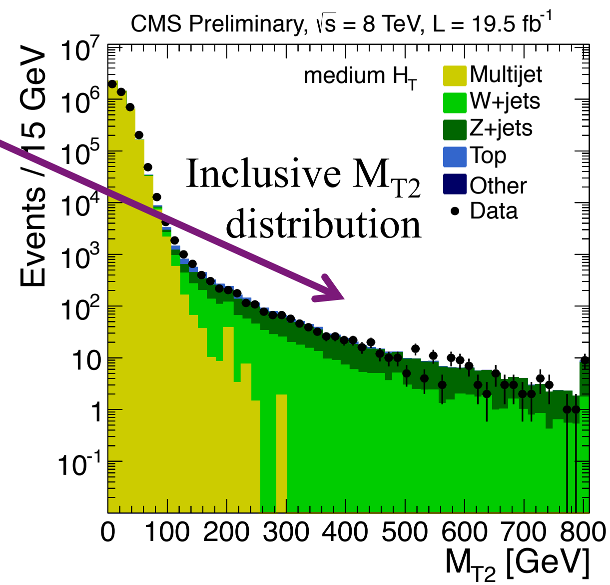
Gluino decays via virtual $\tilde{b}$

- One example: The M_{T2} analysis.
- The M_{T2} analysis is an all-hadronic analysis, rejecting events containing any charged lepton.
- This inclusive analysis contains a b-jet multiplicity binning.
  - The high b-jet bins (≥2 b-jets) are very sensitive to this model.
- The main signal discriminant is the M_{T2} variable.

$$M_{T2}(m_c) = \min_{\vec{p}_T^{\,c(1)}+\vec{p}_T^{\,c(2)}=\vec{p}_T^{\,miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)}\right)\right]$$

  - Especially strong in suppressing background due to jet energy mismeasurements.
  - High sensitivity for SUSY signals.



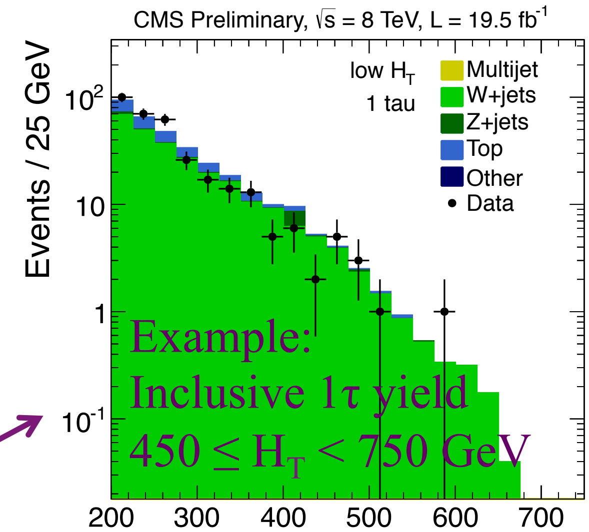


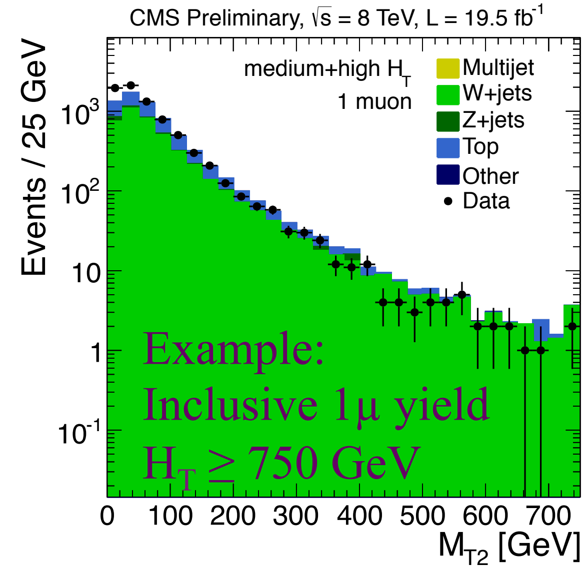
Gluino decays via virtual $\tilde{b}$

- From the previous upper plot, one observes that the main background is top, mainly $t\bar{t}$+jets.
  - Background due to E_T^{miss} from neutrino.
    - ➢ A charged lepton must be lost.

- Background is predicted using a data sample containing one charged lepton with $M_T < 100$ GeV.

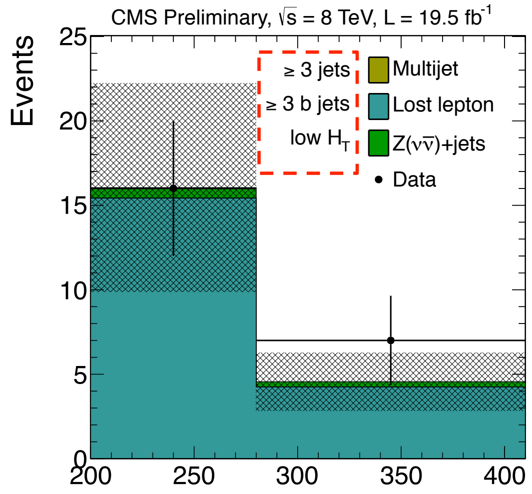
$$N_l^{lost} = (N_l^{reco} - N_l^{bg})\frac{1-\varepsilon_l}{\varepsilon_l \varepsilon_{M_T}}, \quad l = e,\mu,\tau_h$$

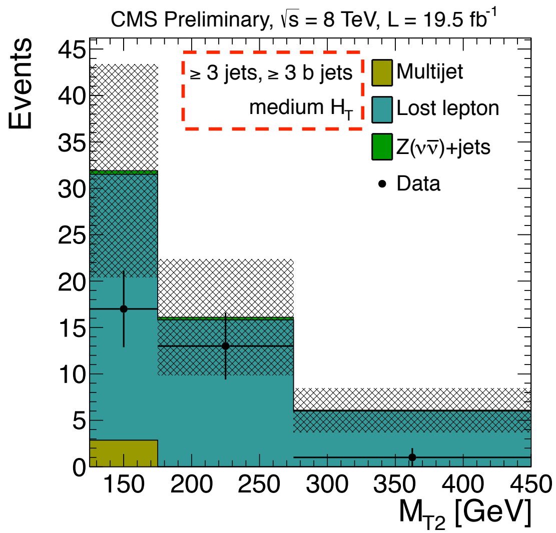




Gluino decays via virtual $\tilde{b}$

- Result: No excess over SM background prediction observed in data.





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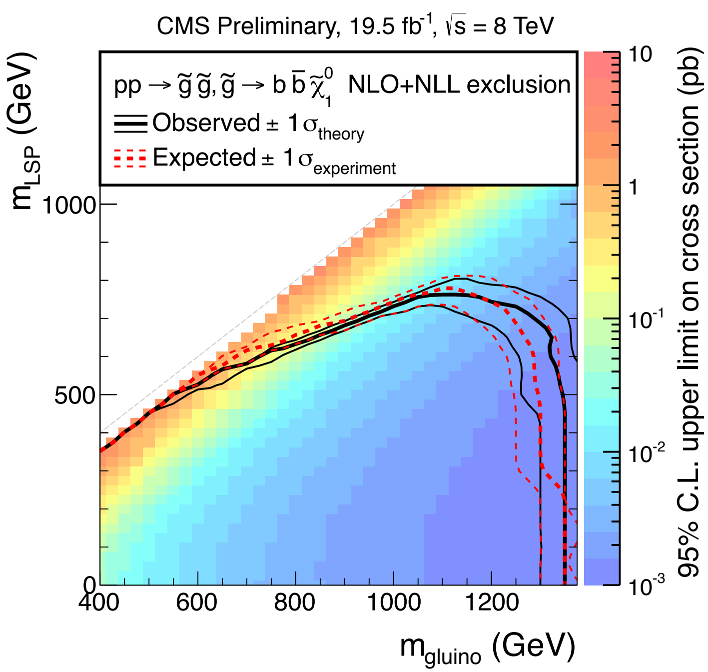
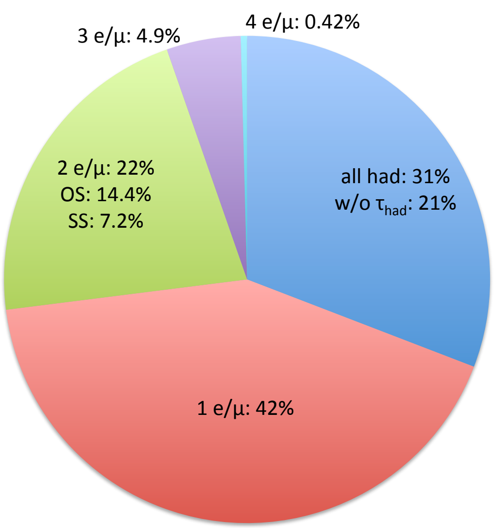
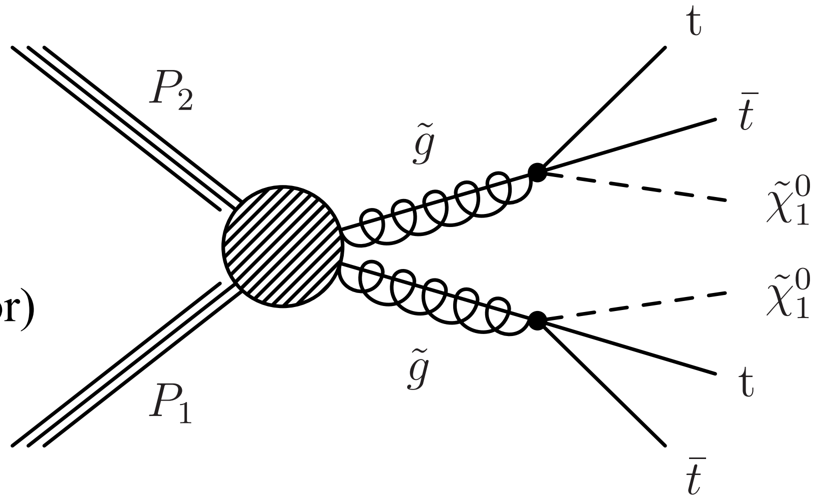


Other analyses interpreting this model have similar reach (⟶ backup).

Gluino decays via virtual $\tilde{t}$

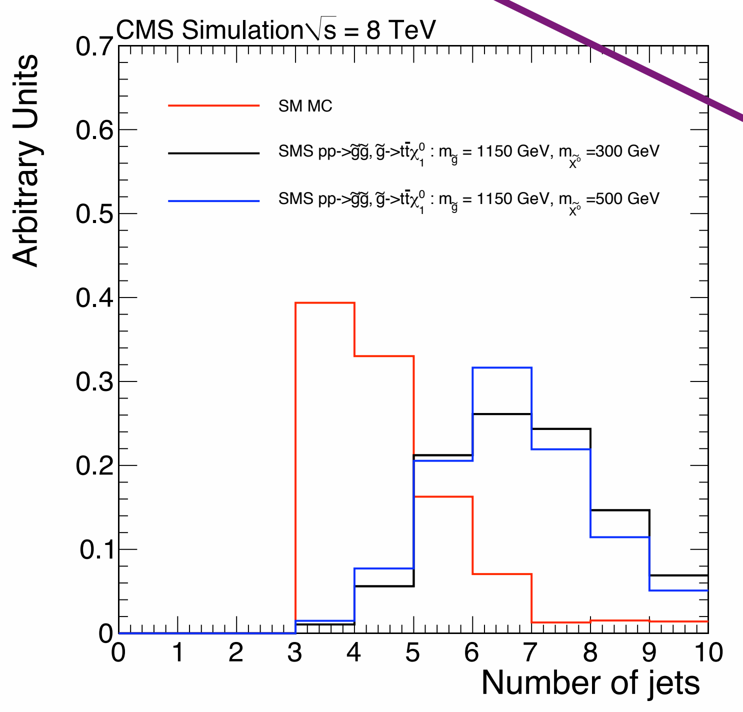
- I discuss here $\tilde{g} \longrightarrow t\bar{t}\,\chi^0_1$.
- This decays allow many different final states, and therefore many different analyses in CMS interpret their results in this final state.
  - Hadronic search: H_T, H_T^{miss}, and jet multiplicity
  - Hadronic search: H_T, E_T^{miss}, and b-jet multiplicity
  - Hadronic search: H_T, M_{T2}, jet and b-jet multiplicity
  - Single lepton search: high jet and b-jet multiplicity
  - Dilepton search: opposite sign leptons and high jet and b-jet multiplicity
    - I will discuss this analysis as an example.
  - Dilepton search: same sign leptons
  - 3-lepton search: with ≥1 b-jet
  - Multilepton search: inclusive
  - Inclusive search: M_R, R^2, lepton-content (Razor)

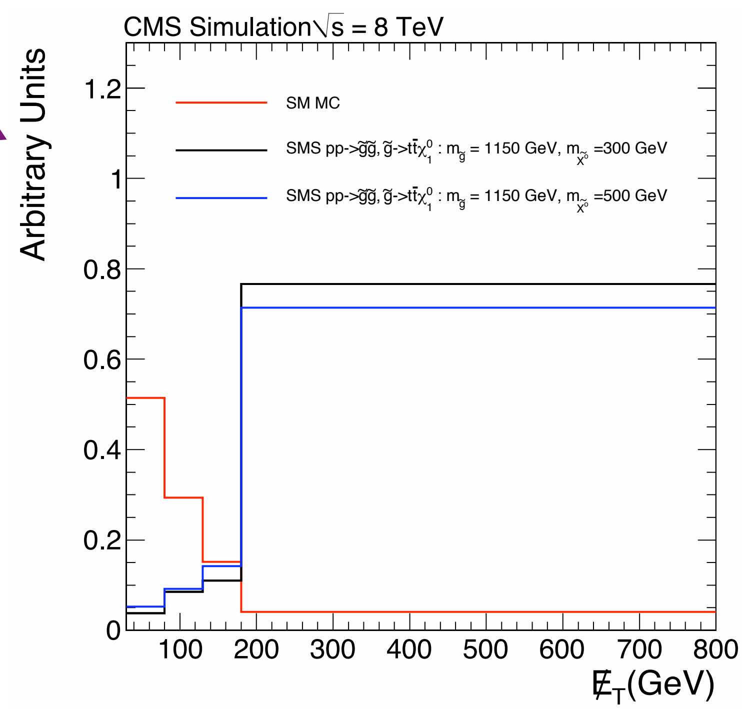




Gluino decays via virtual $\tilde{t}$

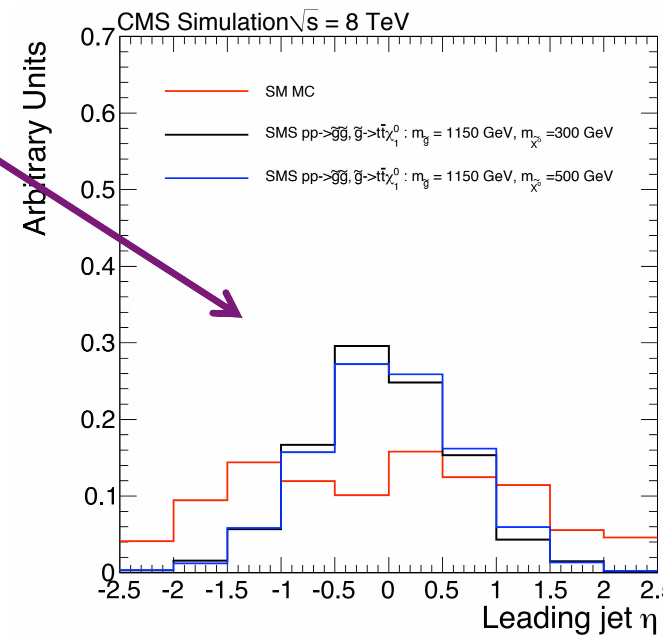
- An example: OS-dilepton search based on
  - Two OS leptons,
  - $N_{jets} \geq 5$, two of the central ($|\eta| < 1$)
  - $N_{b\text{-}jets} \geq 3$,
  - $E_T^{miss} > 180$ GeV.

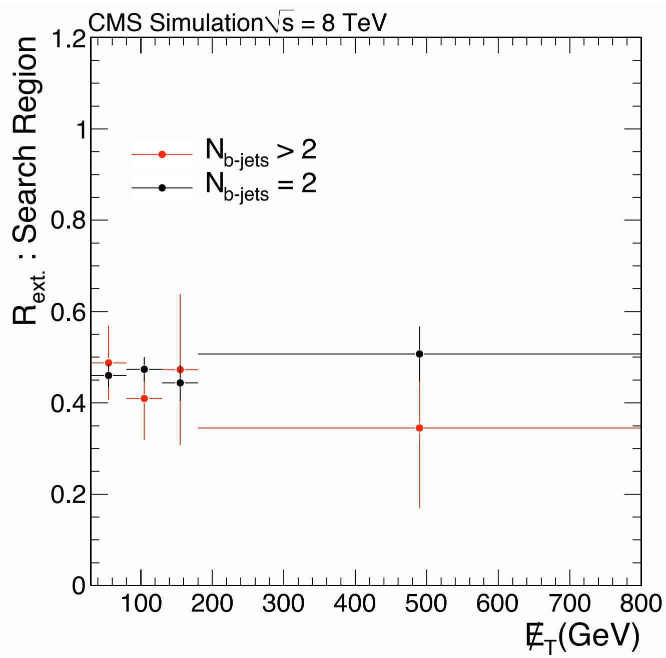




Gluino decays via virtual $\tilde{t}$

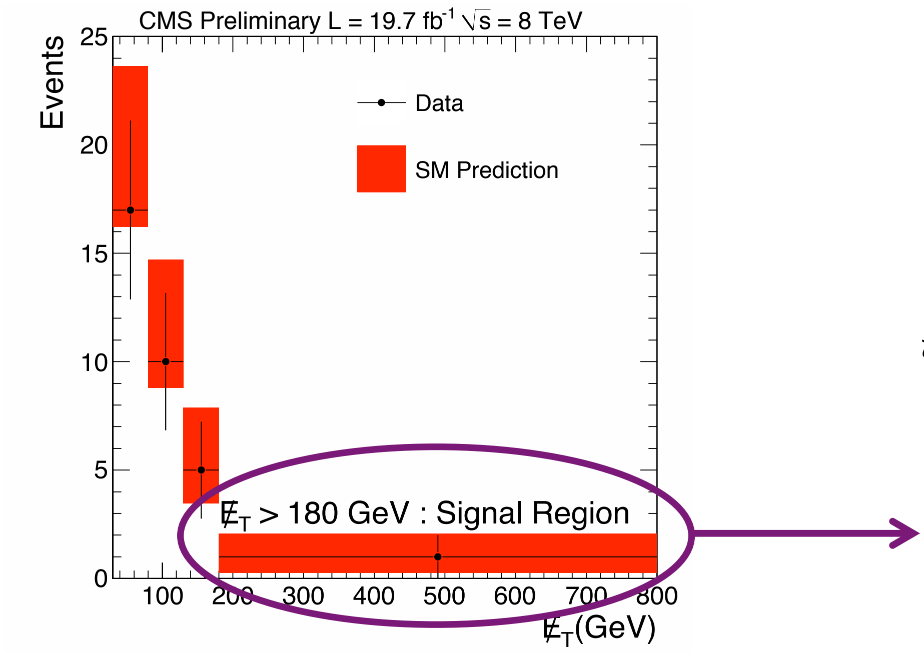
- Background is predicted from
  - Data control region with inverted jet |η| selection
    - Signal contamination < 10% for this model
  - Transfer factor obtained in data using events with exactly 2 b-jets





Gluino decays via virtual $\tilde{t}$

- No excess over SM prediction.



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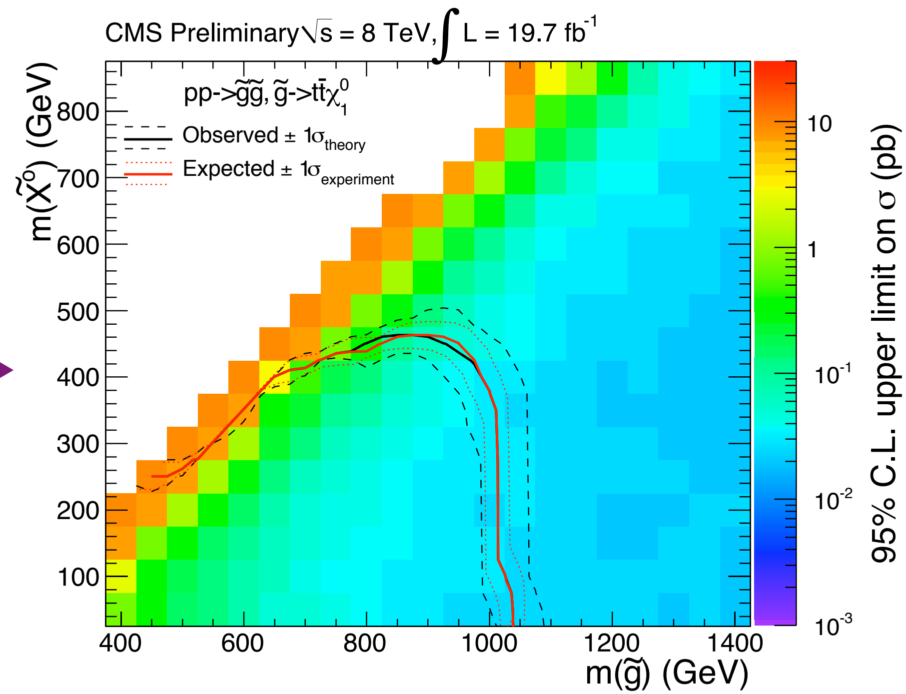
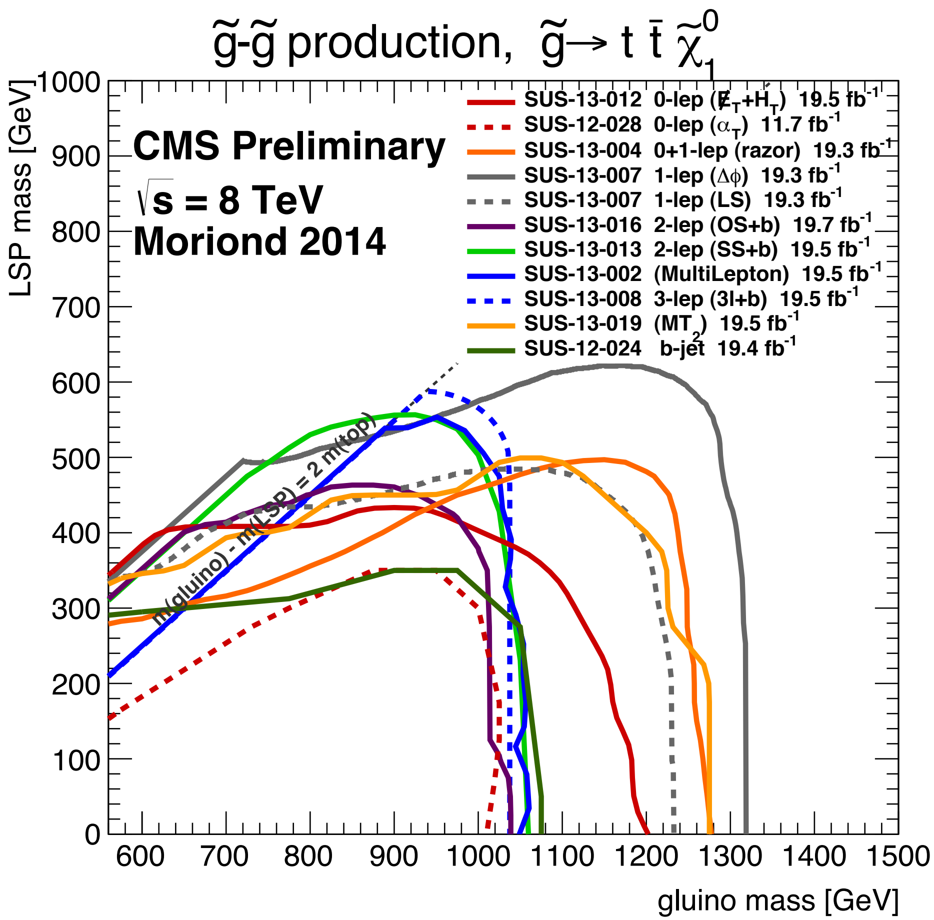


Gluino decays via virtual $\tilde{t}$

- Summary of all analyses' mass limits.



… and many more

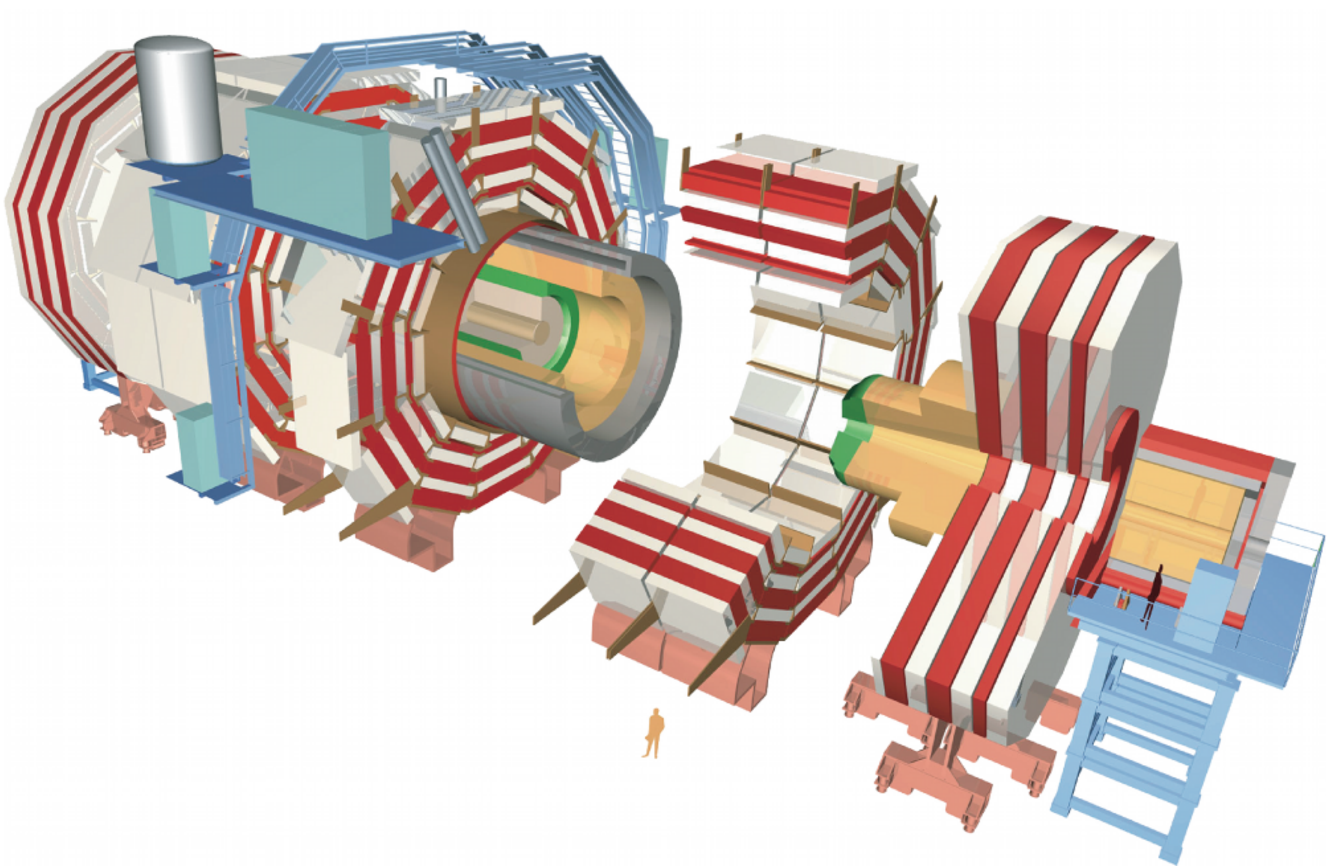
- CMS has even more analyses covering other models (all in the backup), e.g.
  - stop decays with RPV
  - extremely compressed spectra (e.g. $\tilde{t} \longrightarrow c\, \chi^0{}_1$)
  - $\tilde{t}_2 \longrightarrow \tilde{t}_1$ decays via Z or h radiation
  - $\tilde{g} \longrightarrow \bar{b}\tilde{b}$, $\tilde{b} \longrightarrow t\, \chi^-{}_1$, $\chi^-{}_1 \longrightarrow W^- \chi^0{}_1$
  - $\tilde{t} \longrightarrow b\, \chi^\pm{}_1$, $\chi^\pm{}_1 \longrightarrow W^\pm \chi^0{}_1$
  - …

- CMS's search program for 3rd generation squarks has been presented.
  - Both general SUSY searches and dedicated searches target this phase space within SUSY.

- No significant excess over Standard Model background observed in any analysis.

Backup

The CMS detector



Direct $\tilde{t}$ production

- Mass limit of the dedicated hadronic search using a top tagger.
- Mass limit of the inclusive M_{T2} analysis
- Mass limit of inclusive Razor analysis using 0-1 lepton events.

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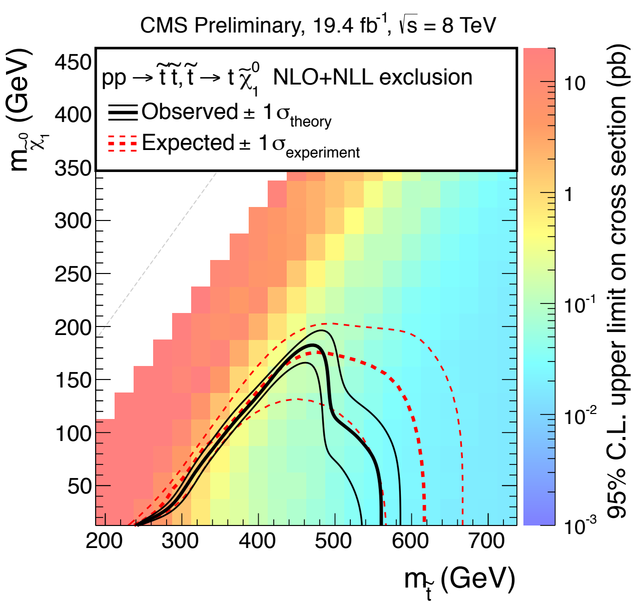
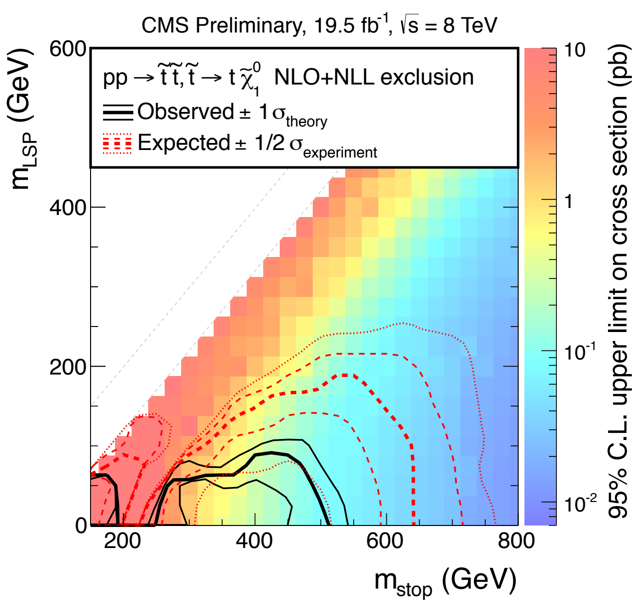
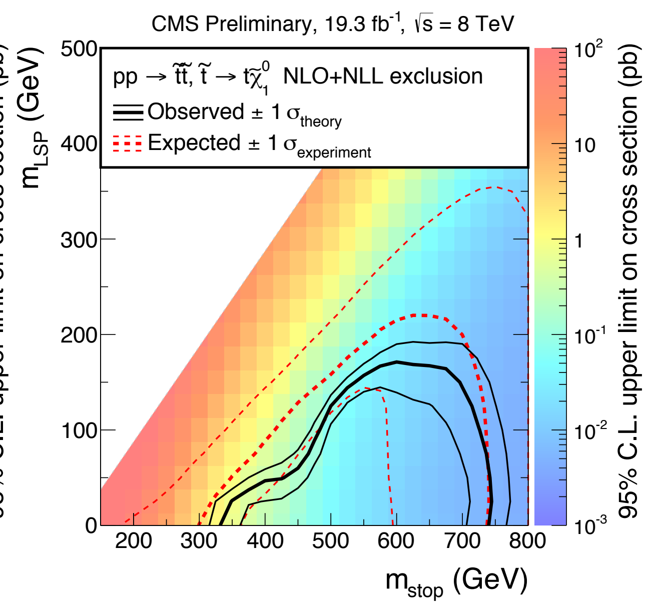
SUS-13-019

SUS-13-004







Gluino decays via virtual $\tilde{b}$

- Mass limit using the E_T^{miss}, H_T, #b-jet analysis.
- Mass limit using the Razor analysis.

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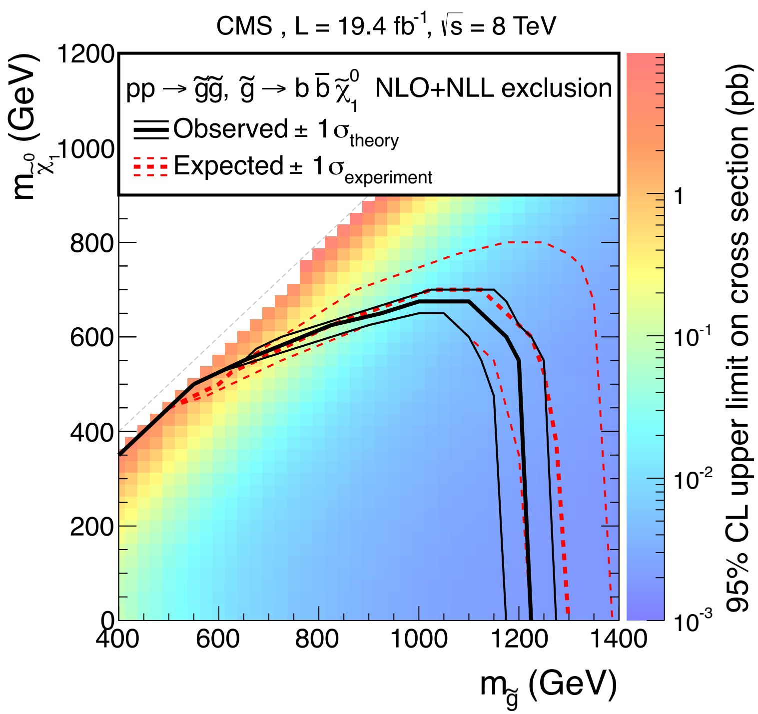

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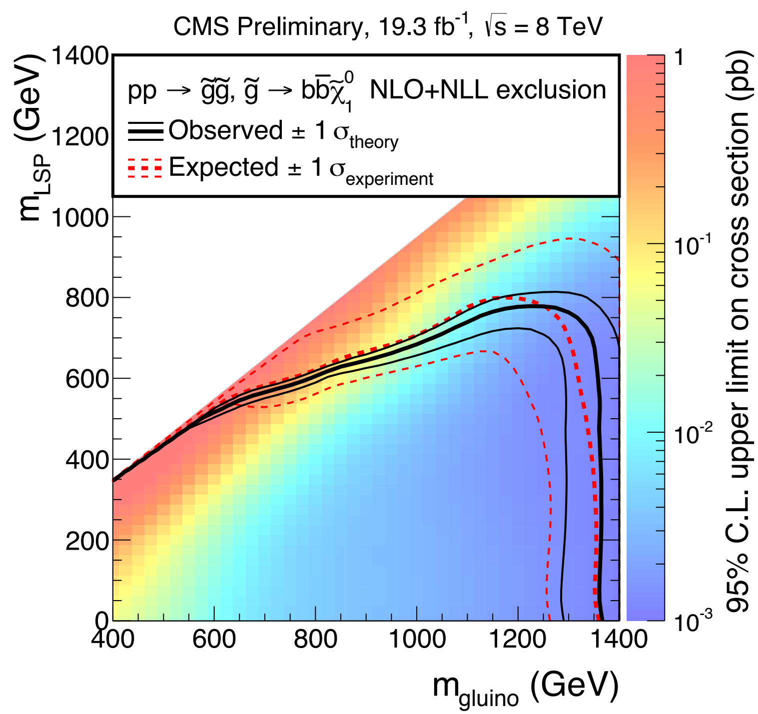
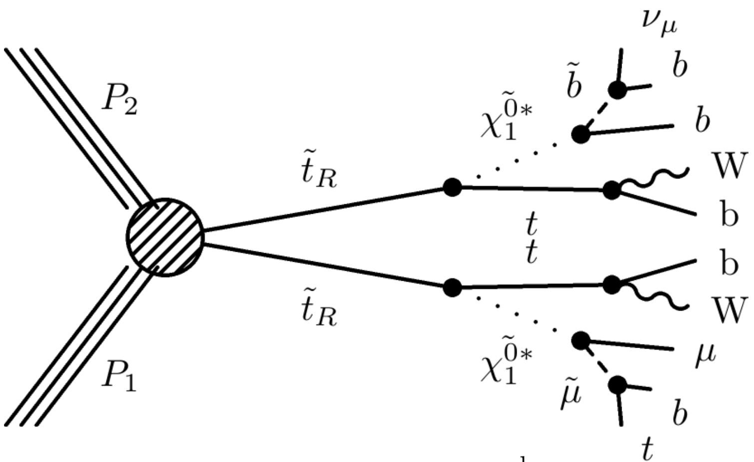
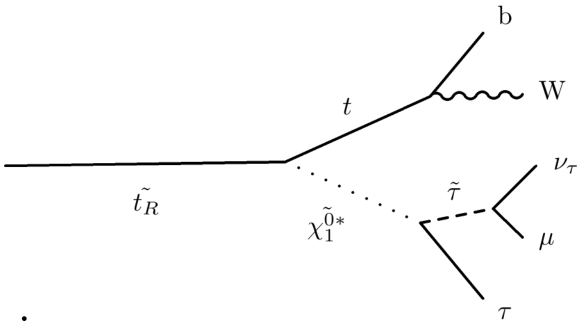
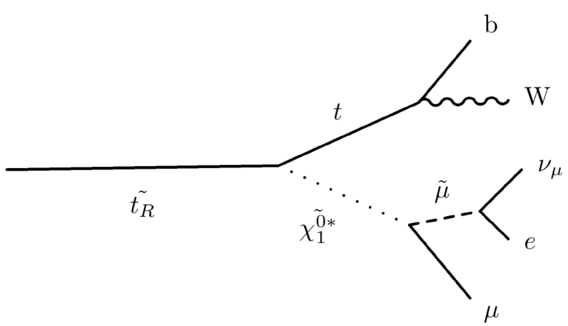


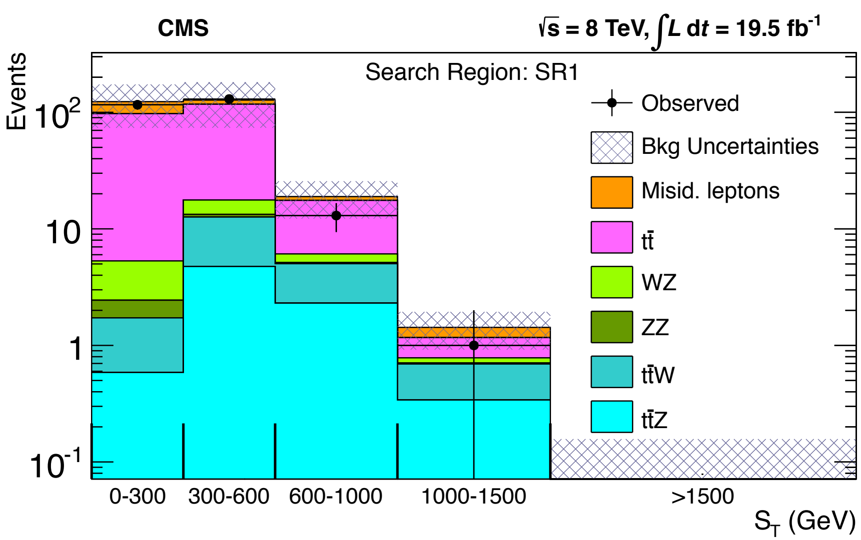
RPV models

- Different models of R-parity violation considered.
- Search is based on multilepton + b-jets final states, and high S_T.
- Background from dibosons and rare background obtained from simulation.
- Background due to non-prompt leptons estimated from data.









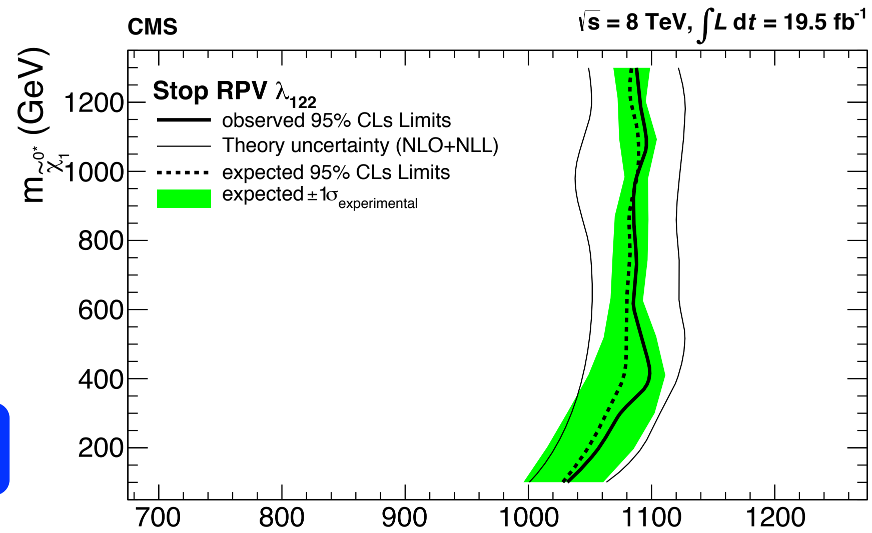
One search region:

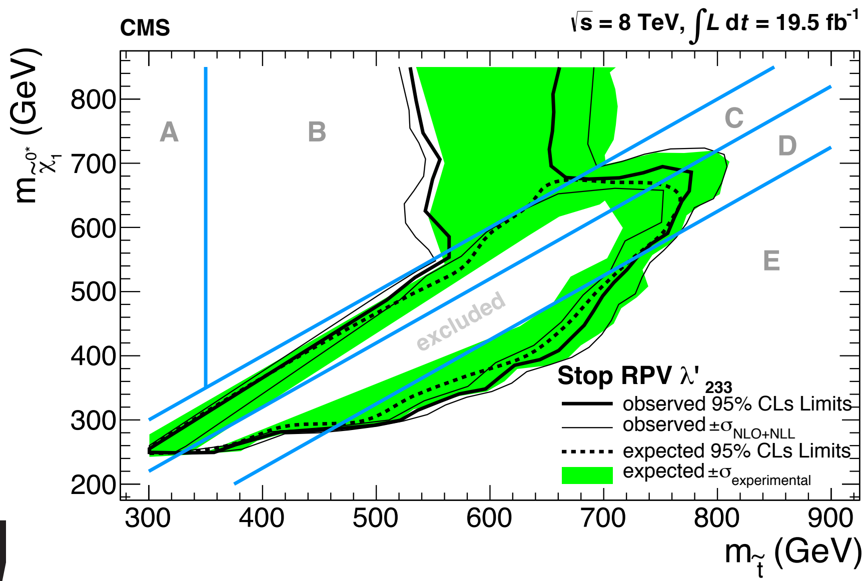
≥ 1 b-jet
3 e/μ
0 τ_h

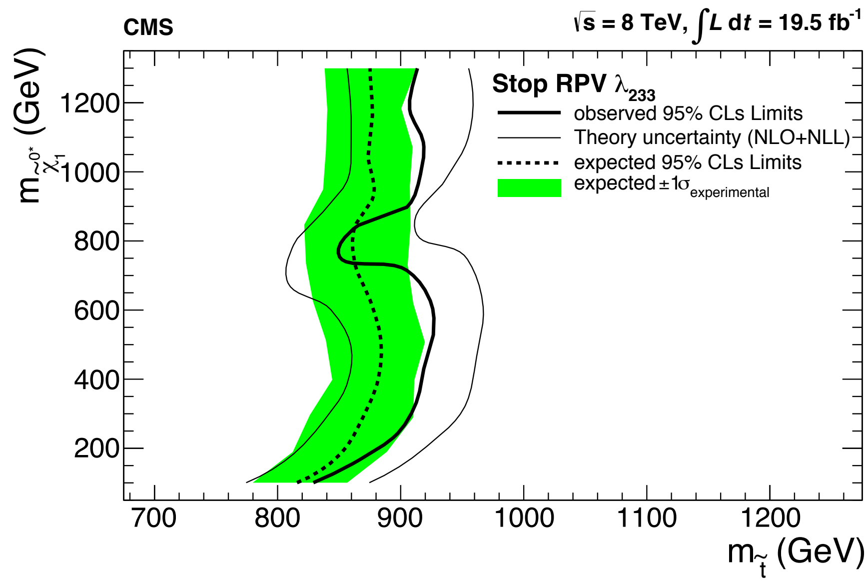
RPV models

- Interpretation

PRL 111, 221801 (2013)



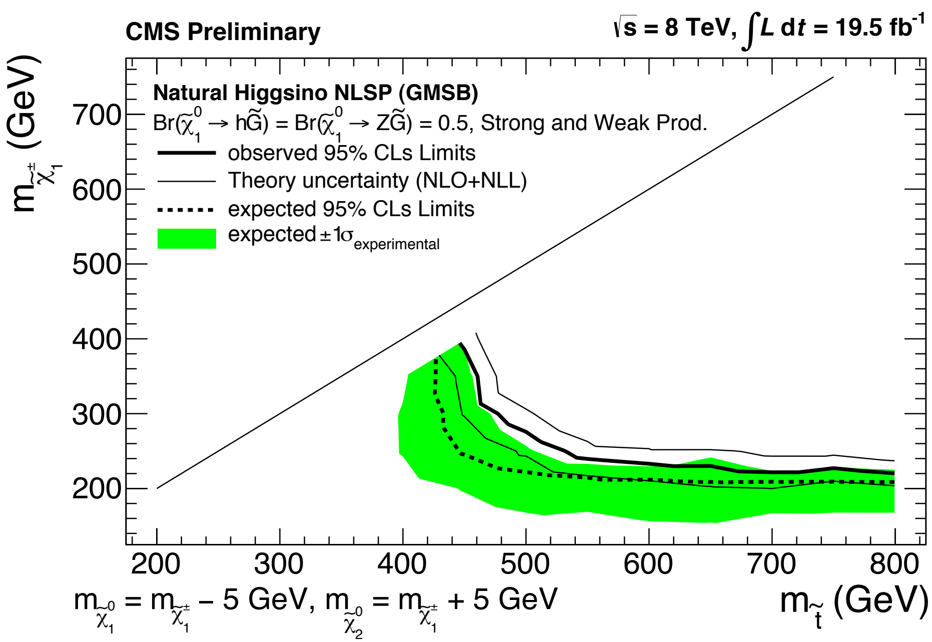


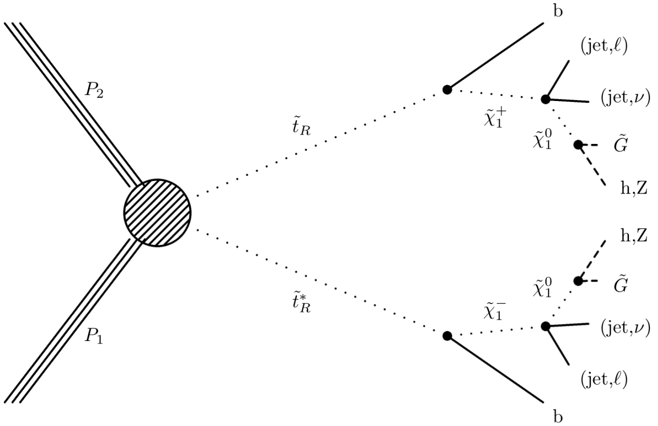


GMSB models

- The inclusive multilepton search interpret its result also in terms of GMSB including stop decays.

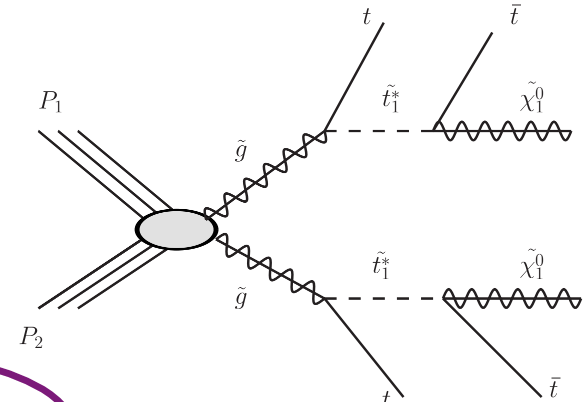
arXiv:1404.5801



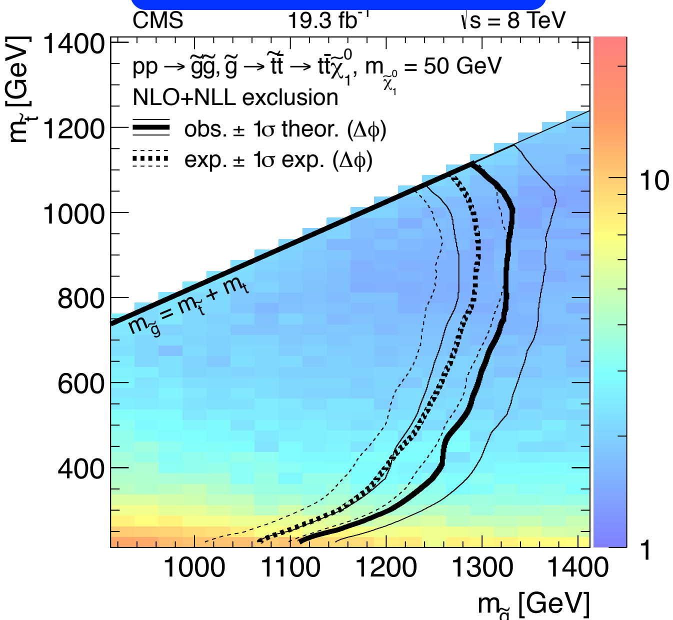


Gluino decays via real $\tilde{t}$

- Three analyses interpret their results in terms of $\tilde{g} \to \tilde{t}\,\bar{t},\ \tilde{t} \to t\,\chi^0{}_1$:
  - single lepton search
  - same-sign dilepton search
  - three lepton search



arXiv:1311.4937



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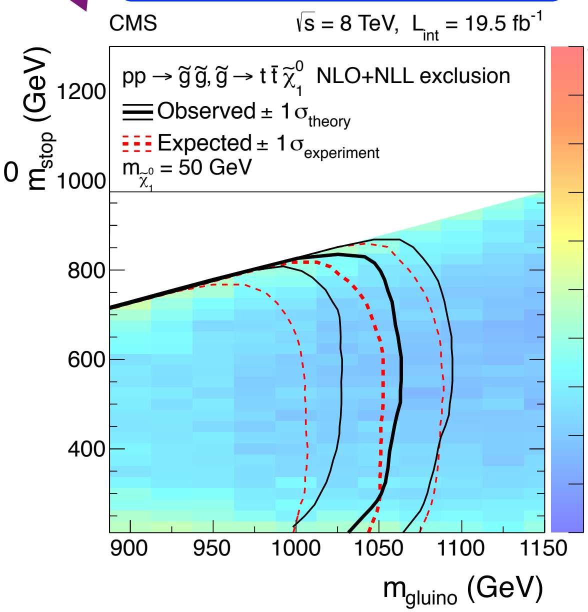
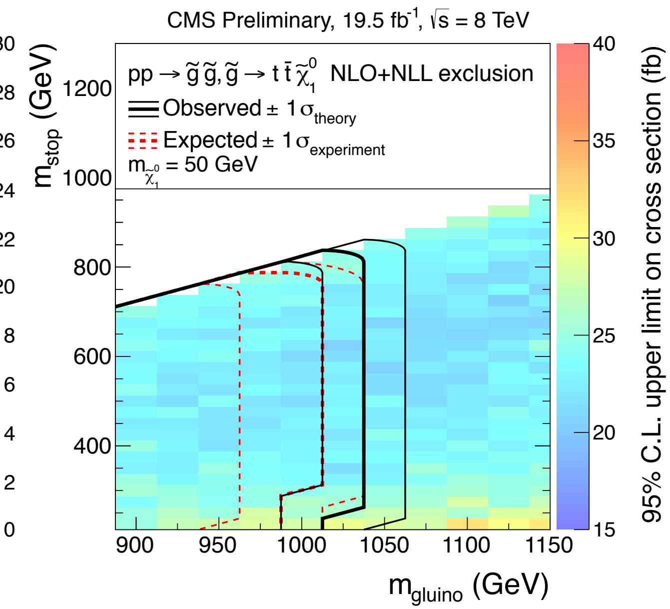
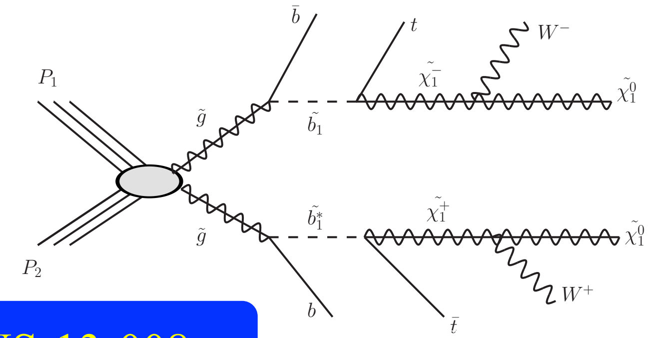


SUS-13-008



Gluino decays via $\tilde{b} \longrightarrow t\,\chi^{\pm}_1$

- Two analyses interpret their results in terms of
- $\tilde{g} \longrightarrow \tilde{b}\,\bar{b}$, $\tilde{b} \longrightarrow b\,\chi^{\pm}_1$, $\chi^{\pm}_1 \longrightarrow W^{\pm}\,\chi^0_1$:
  - same-sign dilepton search
  - three lepton search



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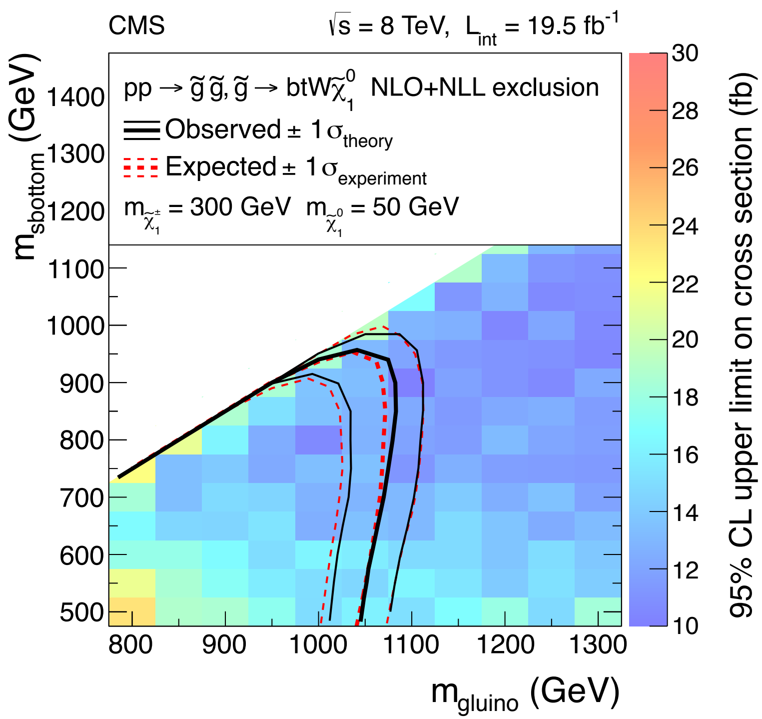
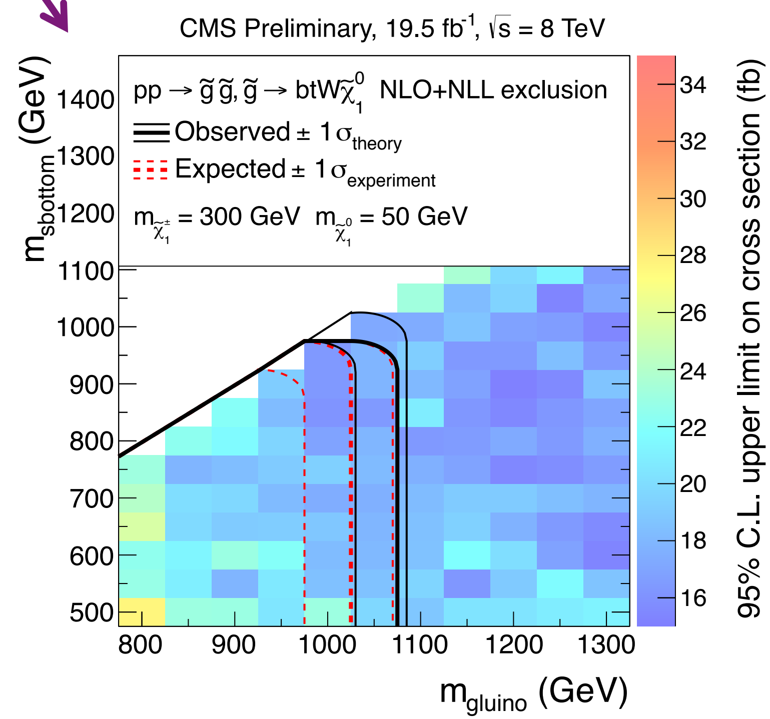
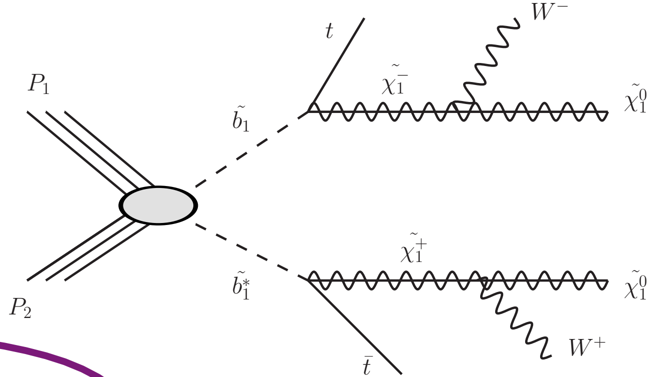


SUS-13-008

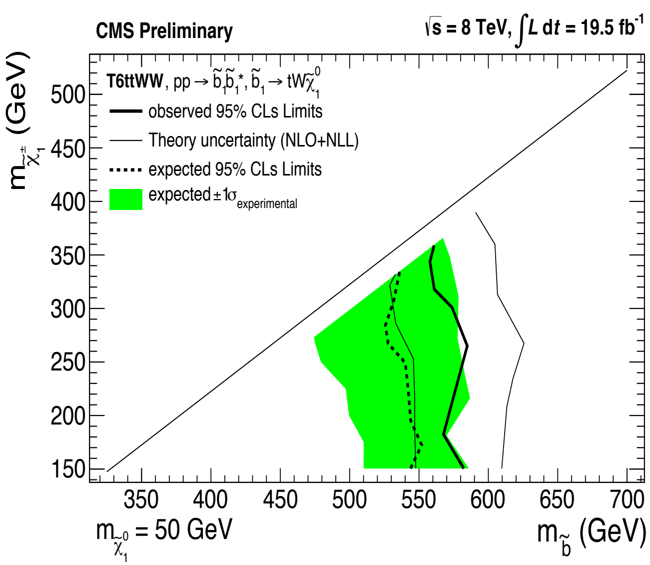


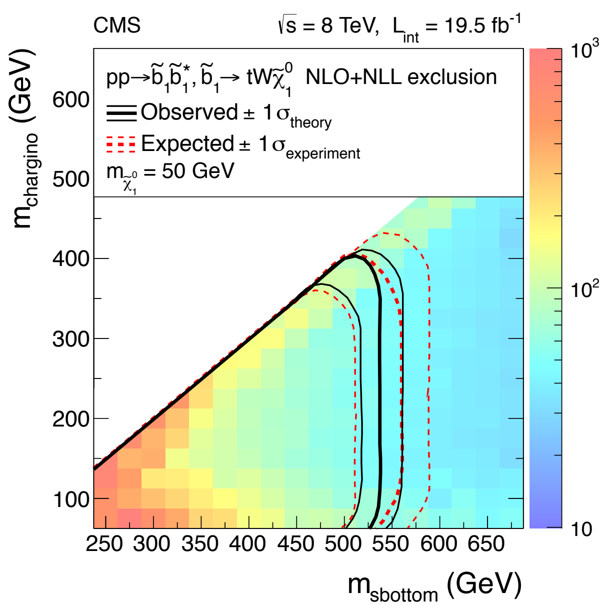
Direct $\tilde{b} \longrightarrow t\,\chi^{\pm}_{1}, \chi^{\pm}_{1} \longrightarrow W^{\pm}\,\chi^{0}_{1}$

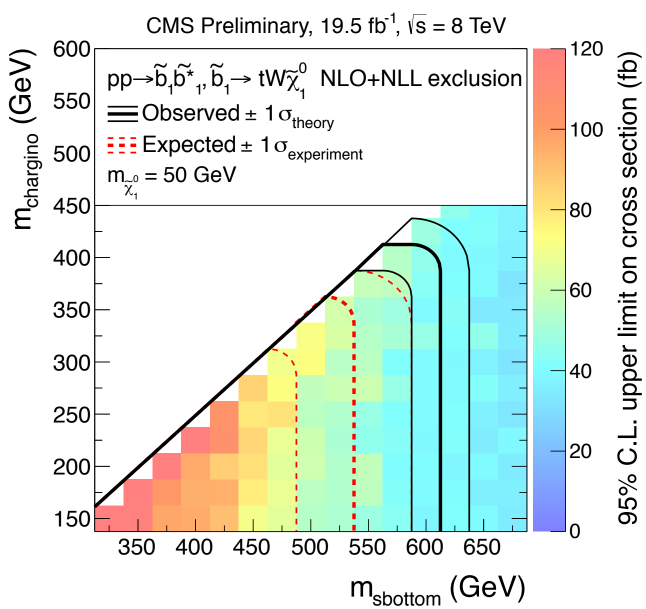
- Three analyses interpret their results in terms of $\tilde{b} \rightarrow t\,\chi^{\pm}_{1}, \chi^{\pm}_{1} \rightarrow W^{\pm}\,\chi^{0}_{1}$:
  - multilepton search
  - same-sign dilepton search
  - three lepton search



arXiv:1404.5801 | JHEP 01 (2014) 163 | SUS-13-008



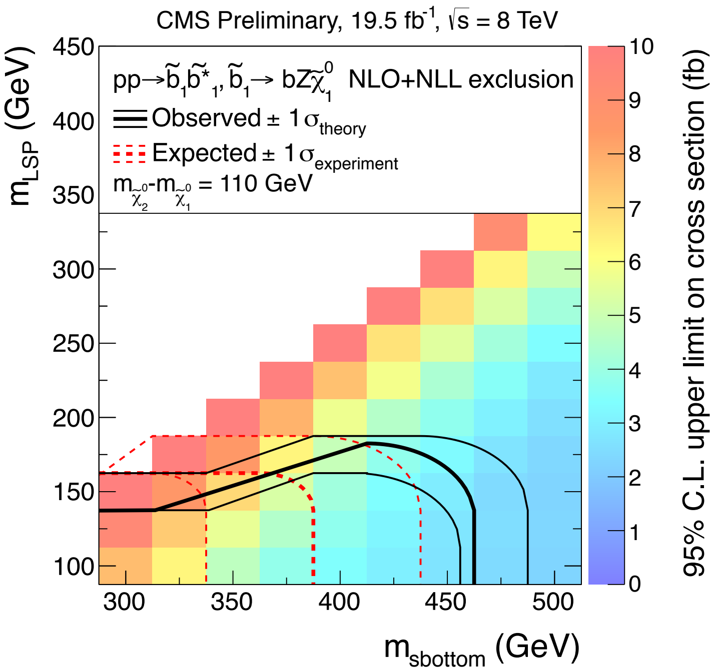


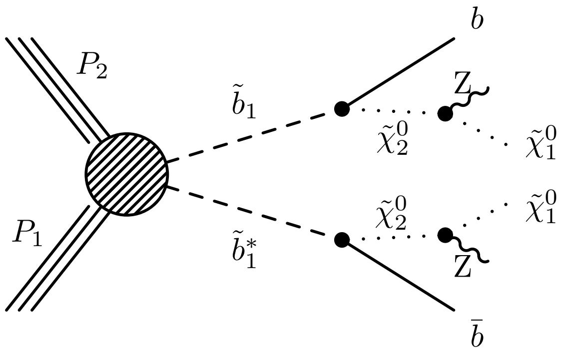


Direct $\tilde{b} \rightarrow b\, \chi^0_2, \chi^0_2 \rightarrow Z\, \chi^0_1$

- The three lepton search interpret their results in terms of $\tilde{b} \rightarrow b\, \chi^0_2, \chi^0_2 \rightarrow Z\, \chi^0_1$:

SUS-13-008

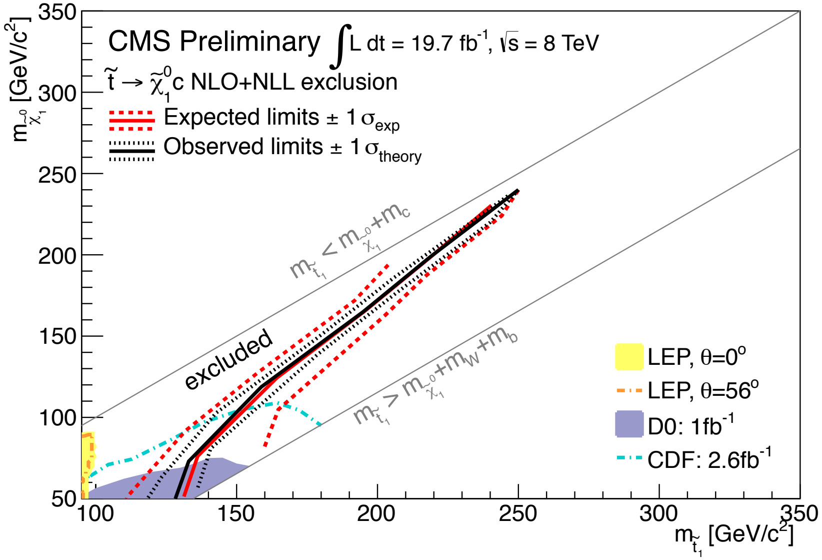




Direct $\tilde{t}$ production

- Mass limit of dedicated search for compressed spectra using monojet events.
  - In this spectra, with M(t)+M($\chi^0{}_1$) ≪ M($\tilde{t}$), the stop decays via the CKM matrix element to $\tilde{t} \longrightarrow c\, \chi^0{}_1$. The event is tagged by an ISR jet.

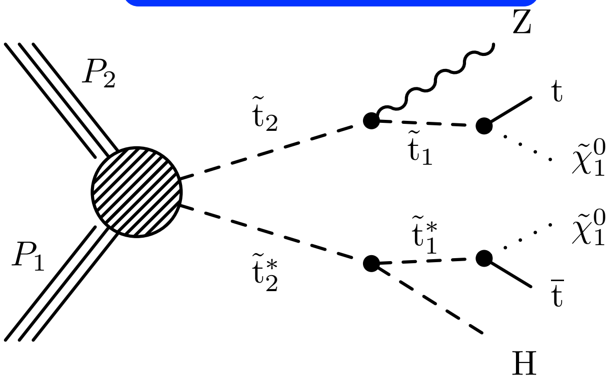
SUS-13-009

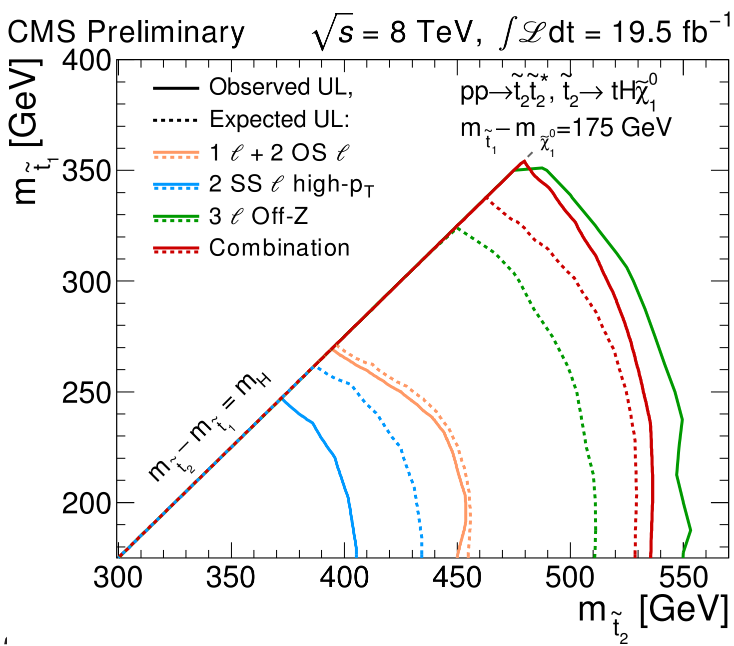


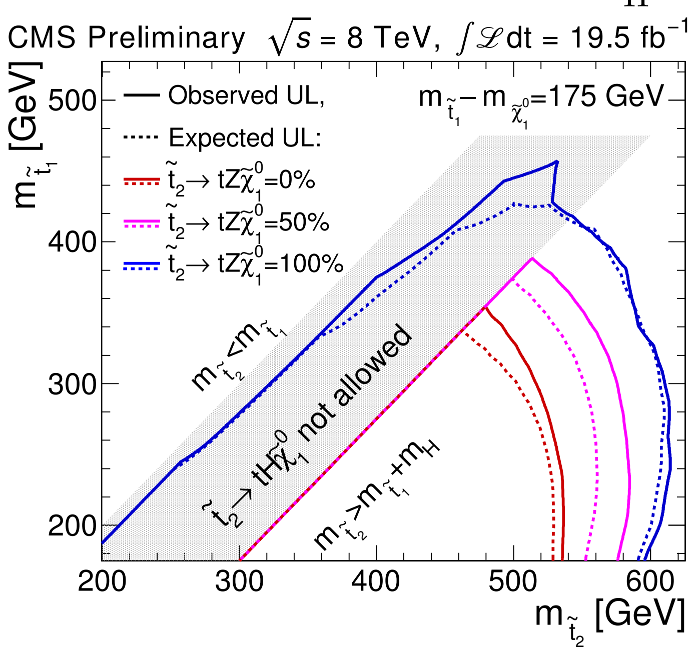
Direct $\tilde{t}_2 \rightarrow Z/h\, \tilde{t}_1$, $\tilde{t}_1 \rightarrow t\, \chi^0_1$

arXiv:1405.3886

- Three analyses interpret their results in terms of $\tilde{t}_2 \rightarrow Z/h\, \tilde{t}_1$, $\tilde{t}_1 \rightarrow t\, \chi^0_1$:
  - single and OS dilepton search
  - same-sign dilepton search
  - three lepton search

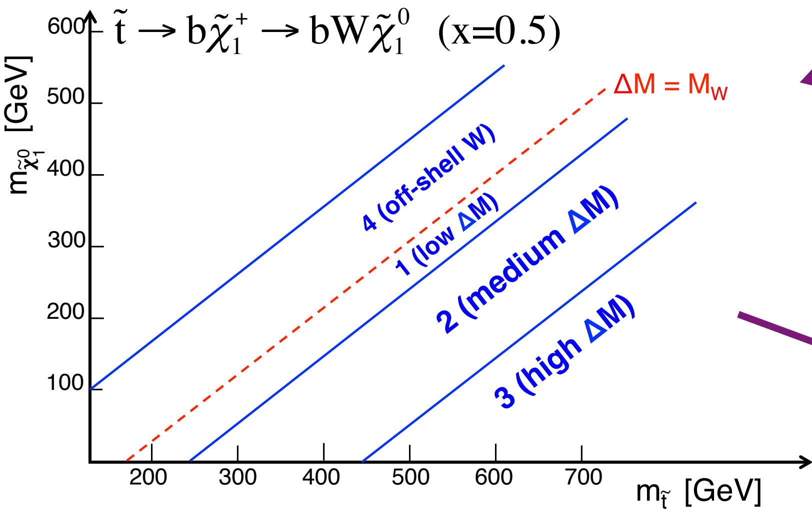


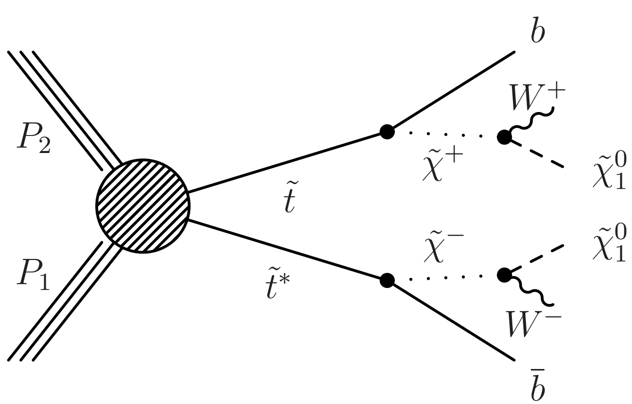




Direct $\tilde{t}_1 \longrightarrow b\,\chi^{\pm}_1,\ \chi^{\pm}_1 \longrightarrow W^{\pm}\,\chi^0_1$

- The dedicated single lepton stop search also optimizes on the stop decay via chargino.





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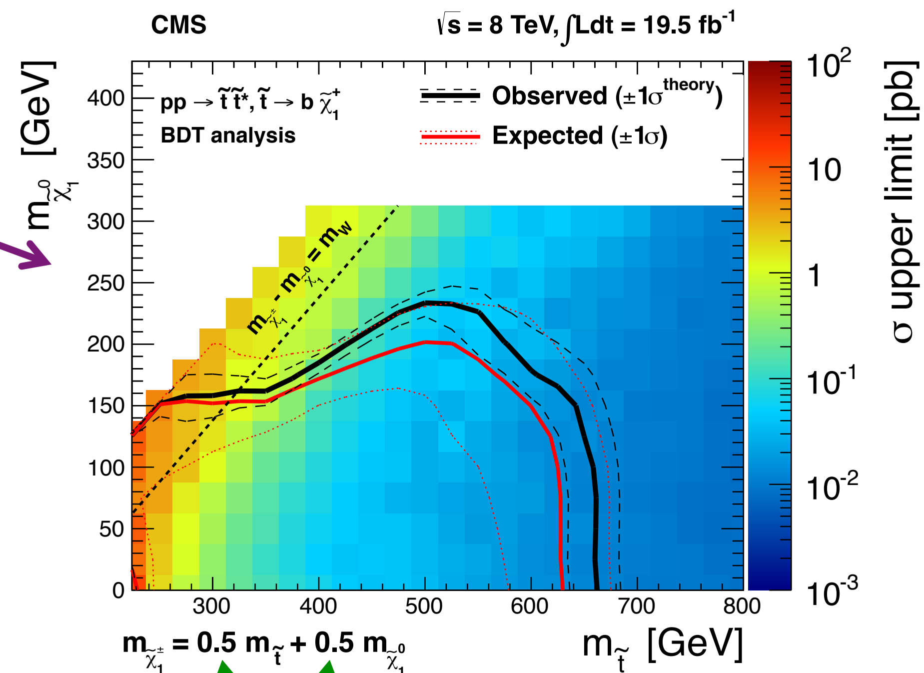
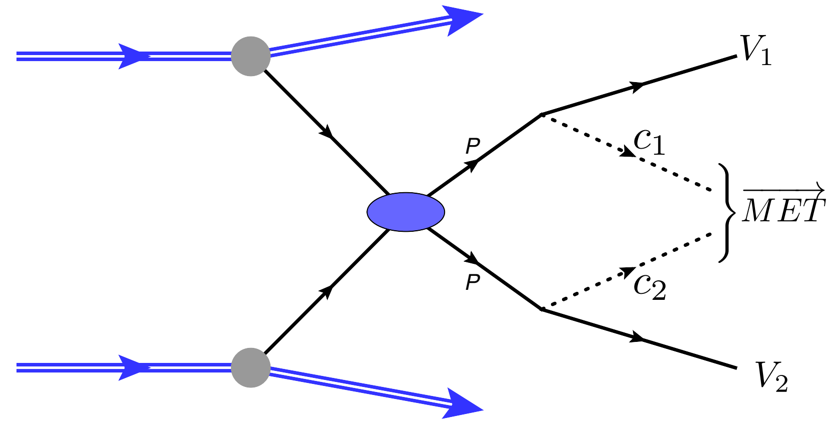


Also other mass relations are considered.

(see also PLB 463 (1999) 99, PRD 80 (2009) 074007)

M_{T2}

- M_{T2} is a generalization of the transverse mass with one unobserved particle for each chain.
  - If all masses are known, M_{T2} would have an endpoint at the parent mass.



$$M_{T2}(m_c) = \min_{\vec{p}_T^{\,c(1)}+\vec{p}_T^{\,c(2)}=\vec{p}_T^{\,miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)}\right)\right]$$

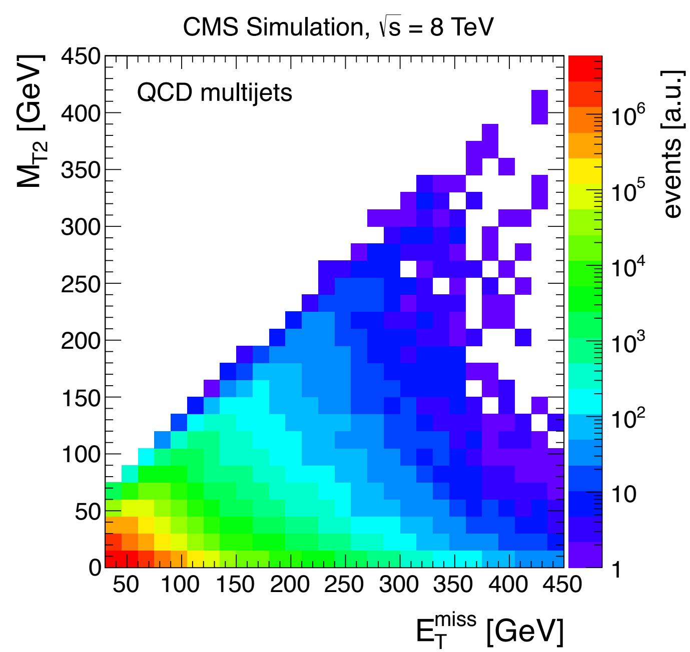
no ISR ↓ no masses

$$M_{T2}^2 = 2 p_T^{(1)} p_T^{(2)} (1 + \cos\phi_{1,2})$$

- $M_{T2} \approx E_T^{miss}$ for symmetric systems:

  $(E_T^{miss})^2 = (p_T^{(1)} - p_T^{(2)})^2 + 2p_T^{(1)}p_T^{(2)} (1 + \cos\phi_{12})$
- $M_{T2} = 0$ GeV for back-to-back systems

→ robust against jet energy mismeasurements



M_{CT}

(see also JHEP 04 (2008) 034, JHEP 03 (2010) 030, JHEP 06 (2008) 004)

- The contransverse mass is defined as

$$M_{CT}^2 = \left[E_T^{j1} - E_T^{j2}\right]^2 - \left[\vec{p}_T^{\,j1} - \vec{p}_T^{\,j2}\right]^2$$
$$= 2 p_T^{j1} p_T^{j2} \left(1 + \cos\Delta\phi(j_1, j_2)\right)$$

- It has an endpoint at

$$M_{CT}^{max} = \frac{M(\tilde{b})^2 - M(\tilde{\chi}_1^0)^2}{M(\tilde{b})}$$

- For massless jets, M_{CT} and E_T^{miss} are related via

$$\left(E_T^{miss}\right)^2 = \left(p_T^{j1} - p_T^{j2}\right)^2 + M_{CT}^2$$

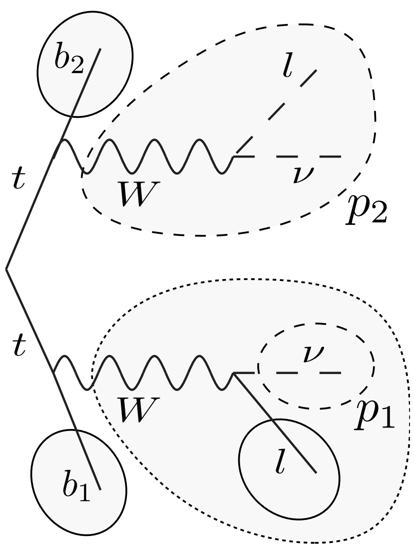
- Note: $M_{CT} = M_{T2}$ if
  - there is no transverse boost due to ISR,
  - the visible systems are massless and the test mass is set to zero.

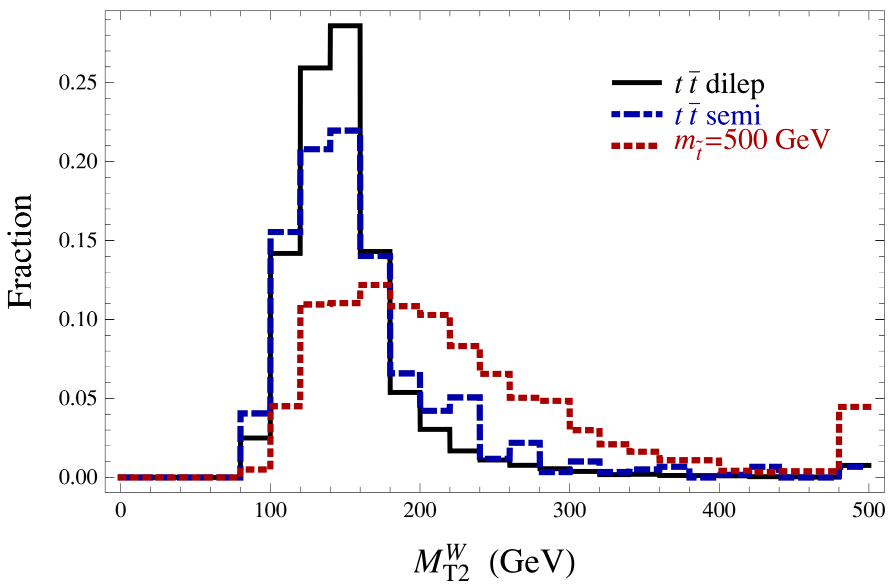
(see also JHEP 07 (2012) 110)

M_{T2}^{W}

- M_{T2}^{W} is motivated by the M_{T2} variable and defined as

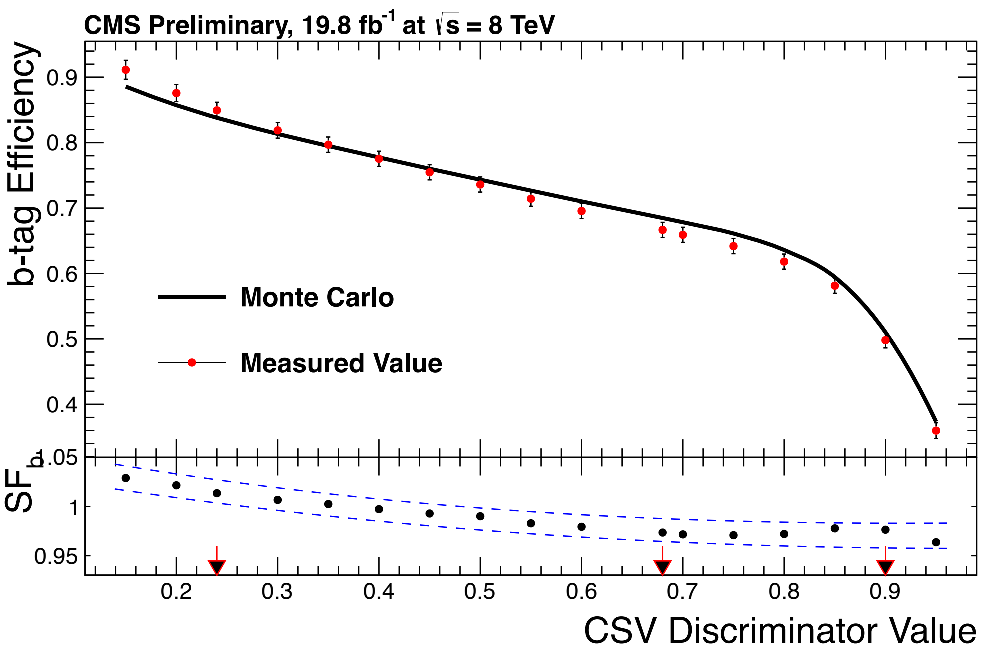
$$M_{T2}^{W} = \min\left\{ m_y \text{ consistent with } \left[\begin{array}{l} \vec{p}_T^{\,1} + \vec{p}_T^{\,2} = \vec{E}_T^{\text{miss}}, (p_1 + p_l)^2 = p_2^2 = M_W^2, \\ p_1^2 = 0, (p_1 + p_l + p_{b1})^2 = (p_2 + p_{b2})^2 = m_y^2 \end{array} \right] \right\}$$

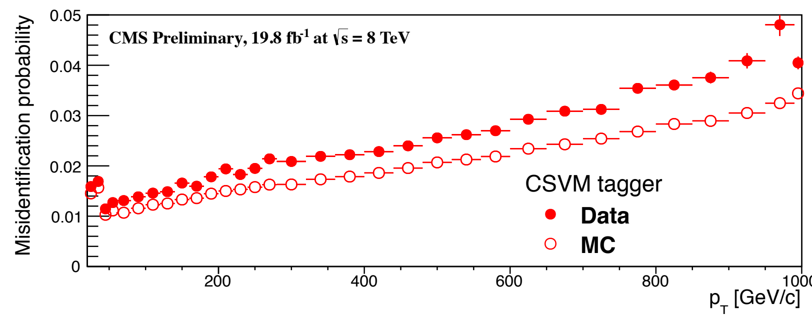


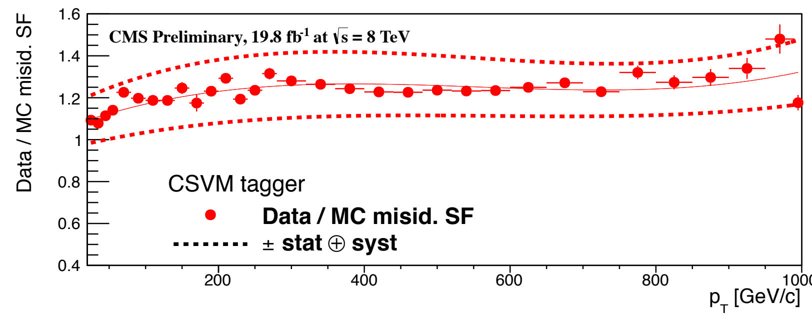


b-tagging at CMS

BTV-13-001







b-tagging at CMS

JINST 8 (2012) P04013