Searches for top squark pair production with the CMS detector

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Overview

- Why would we look for top squarks?
- How would top squarks decay and how can we detect them?
- Looking for top squarks in the single-lepton final state
- Peek at difficult mass spectra
- Conclusions and outlook

Overview

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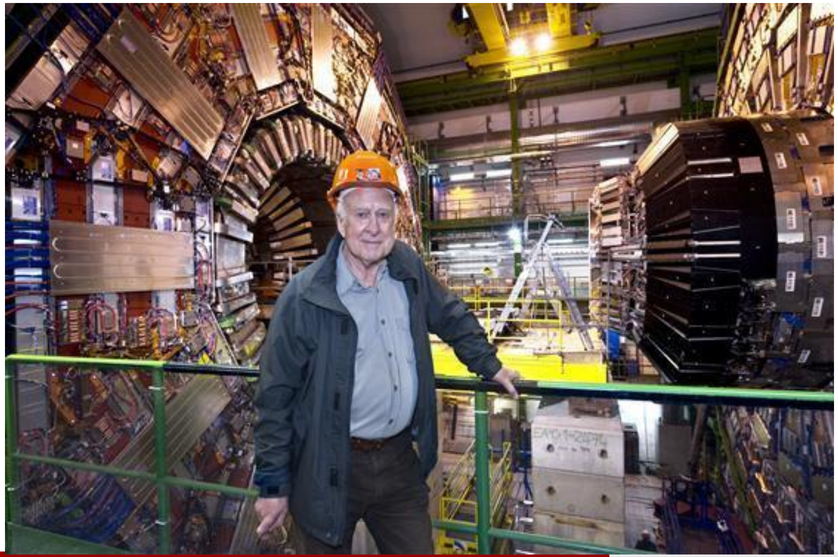
Motivation

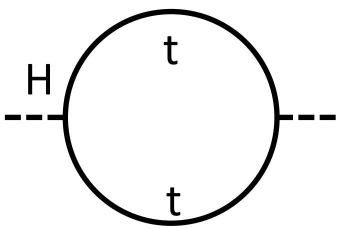


- In 2012 the Higgs was seen in the ATLAS and CMS detectors
  - Gives mass to other particles
- Led to detailed measurements of its properties, e.g. $m_H \approx 125$ GeV
- Irony: the mass of the Higgs not understood

Corrections to Higgs mass

- Quantum corrections to the Higgs boson mass become uncomfortably large in the Standard Model (SM)
  - Due to top quark loops

$$\Delta M_H^2 \sim |\lambda_t|^2 \left[-\Lambda_{UV}^2 + \frac{3}{2} M_t^2 \log(\frac{\Lambda_{UV}^2}{M_t^2}) \right]$$



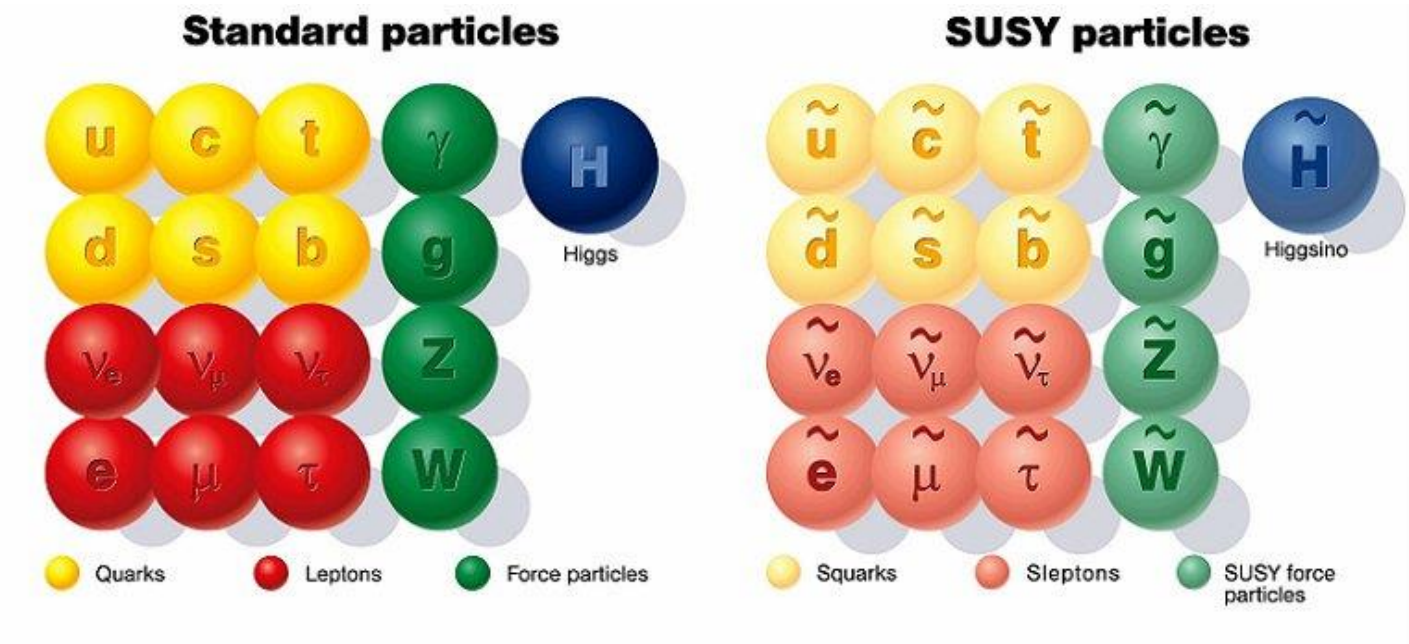
Λ_{UV} is SM cut-off, without new physics at Planck scale (10^{19} Gev)

  - $M_H^2 \quad = \quad M_{H,0}^2 \; + \; \Delta M_H^2$

    $O(10^4) = O(10^{38}) - O(10^{38})$
  - **Cancellation of 10^{-34}? Highly unlikely!**
    - Alternative: new symmetry (supersymmetry)

Supersymmetry (SUSY)

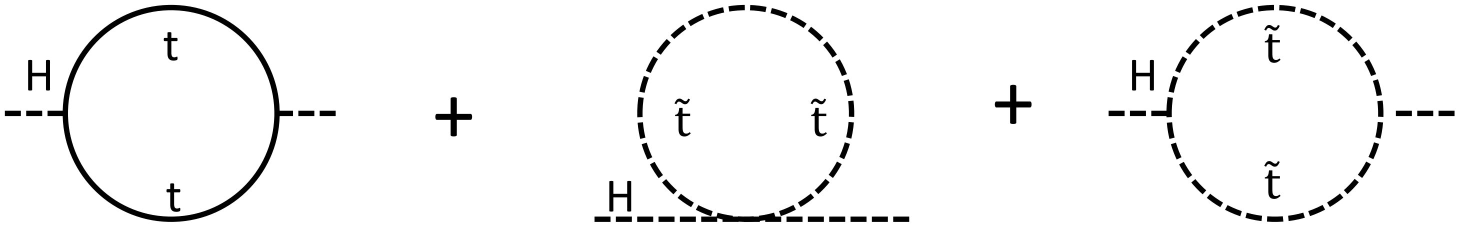
- New fundamental symmetry relating bosons with fermions. Thus, each SM particle has a SUSY partner
- Imposing R-parity conservation:
  - SUSY particles produced in pairs
  - Lightest SUSY particle (LSP) is stable neutral particle
    - **WIMP dark matter candidate!**



Solving the problem

- Quantum corrections to the Higgs boson mass become uncomfortably large in the Standard Model (SM)
  - Adding top squarks

$$\Delta M_H^2 \sim |\lambda_t|^2 \left[-\Lambda_{UV}^2 + \frac{3}{2} M_t^2 \log(\frac{\Lambda_{UV}^2}{M_t^2})) + \Lambda_{UV}^2 - \frac{3}{2} M_{\tilde{t}}^2 \log(\frac{\Lambda_{UV}^2}{M_{\tilde{t}}^2})) + \cdots \right]$$



- **Top squarks cancel the quadratic divergence**
- Left-over terms proportional to $M_t^2 - M_{\tilde{t}}^2$
  - Light stops make a more “natural” solution

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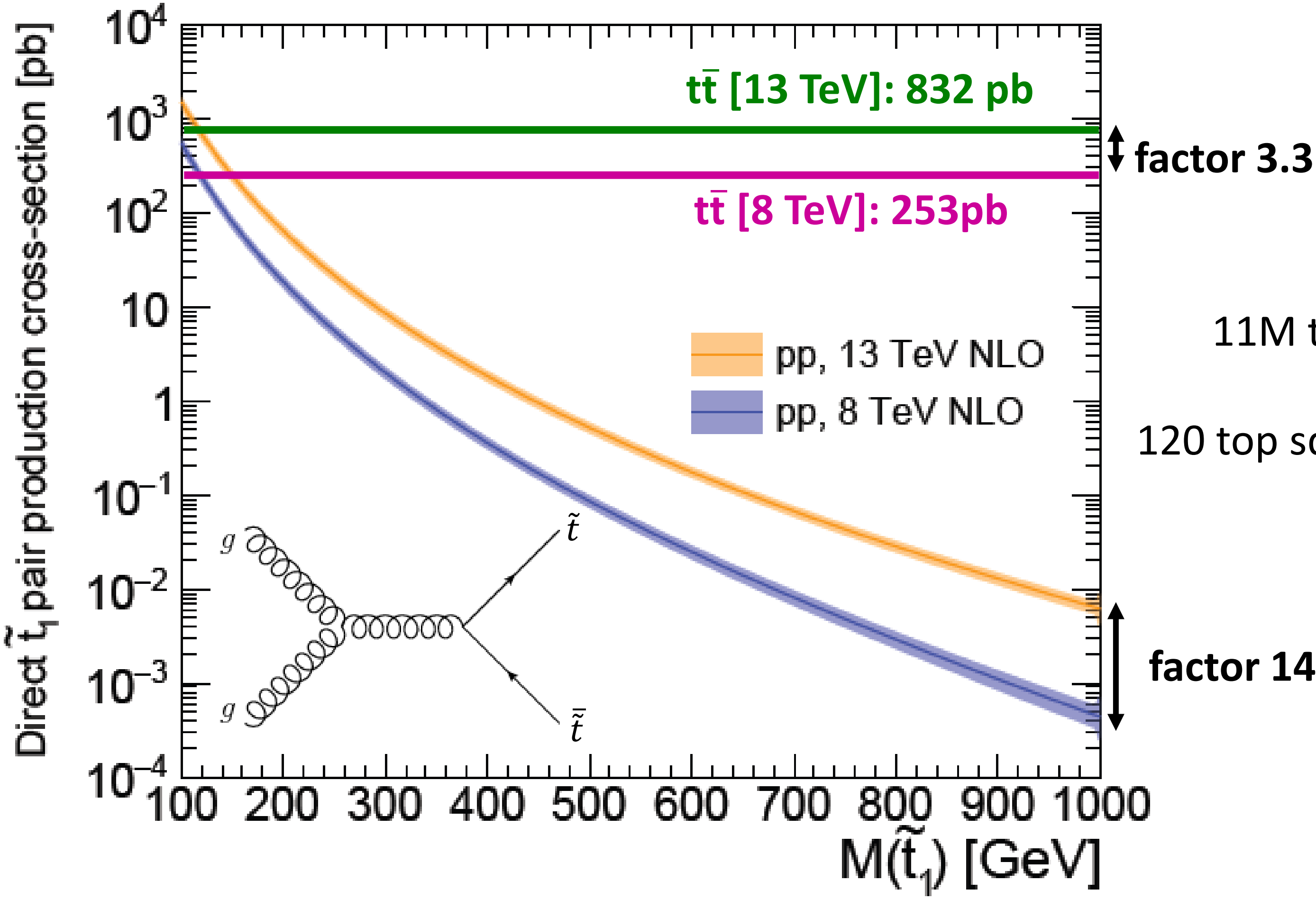
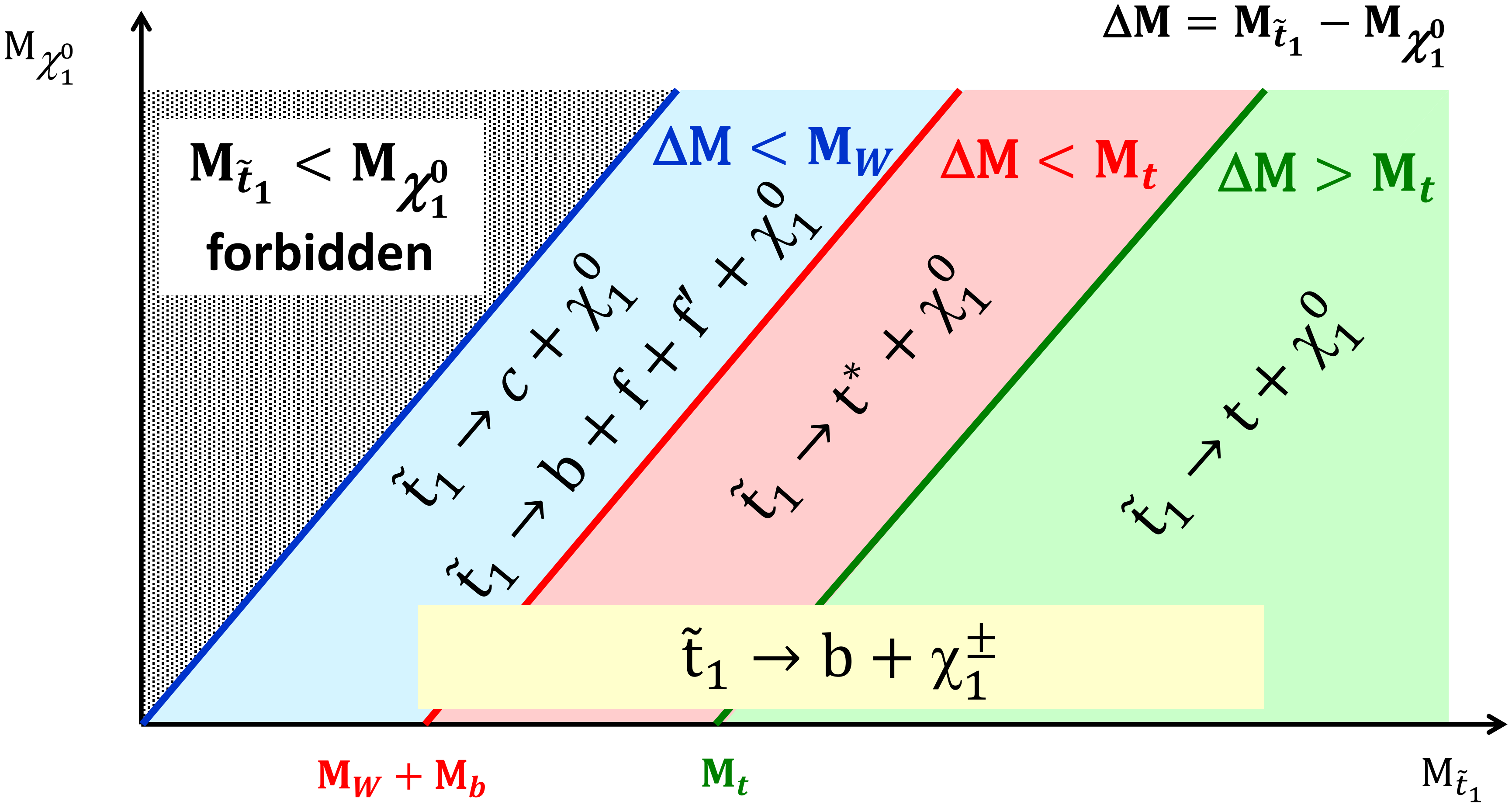
Top squark production

- For high top squark masses larger cross section increase than for main $t\bar{t}$ background



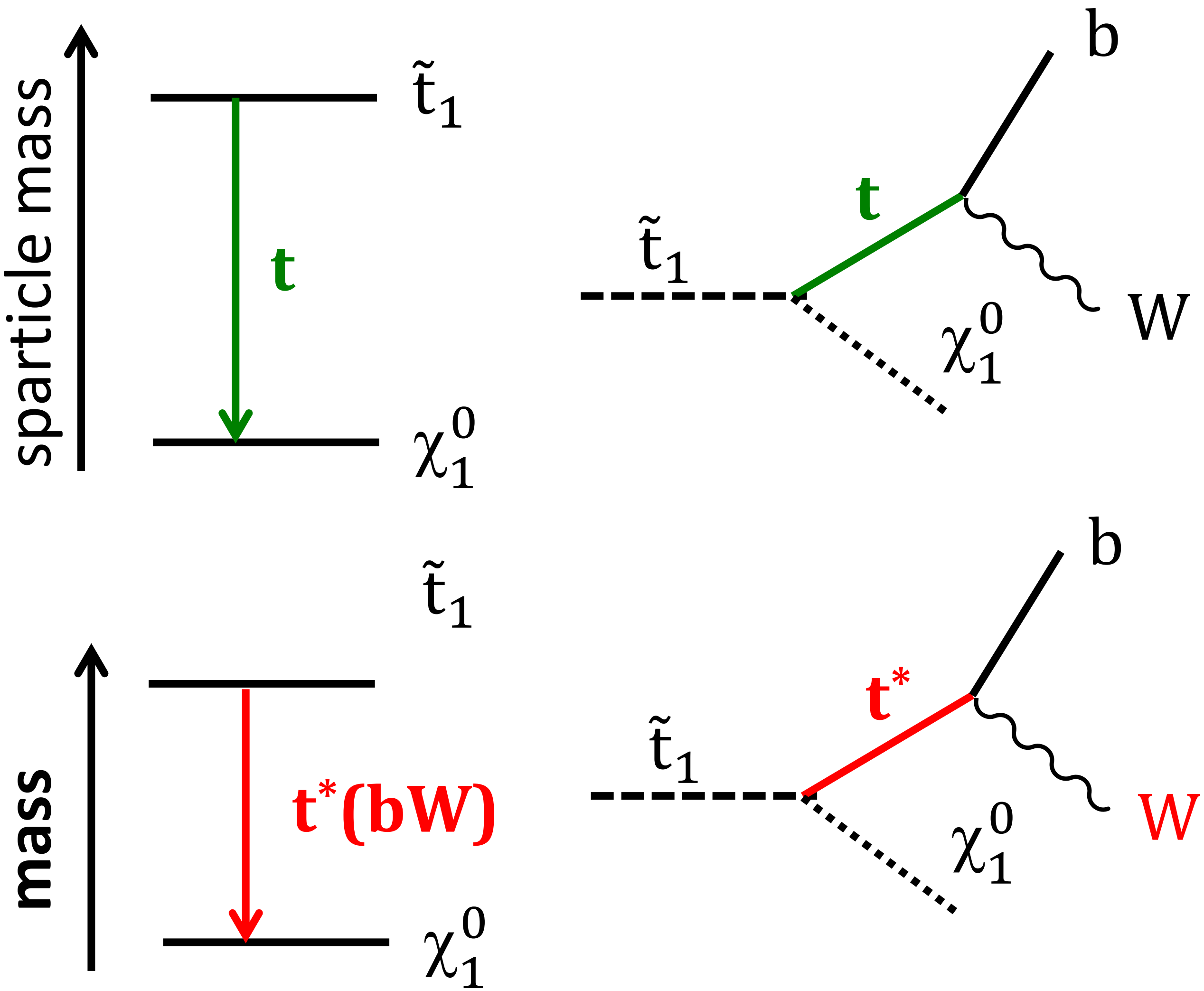
Top squark decay

- Rich spectrum of decay modes depending on SUSY mass spectrum and couplings



Top neutralino decay

- Top squark can decay to a top quark and a LSP



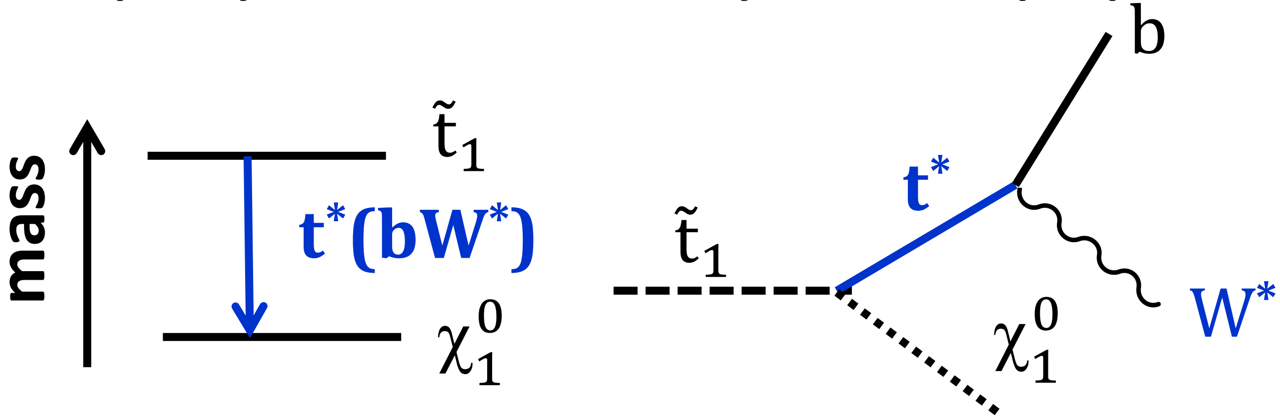
$\Delta M > M_t$

$\Delta M = M_{\tilde{t}_1} - M_{\chi_1^0}$

$M_W < \Delta M < M_t$

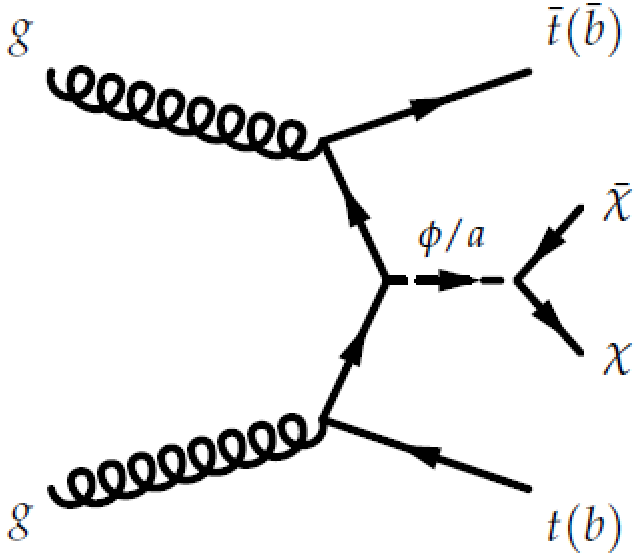
Top neutralino decay

- Top squark can decay to a top quark and a LSP



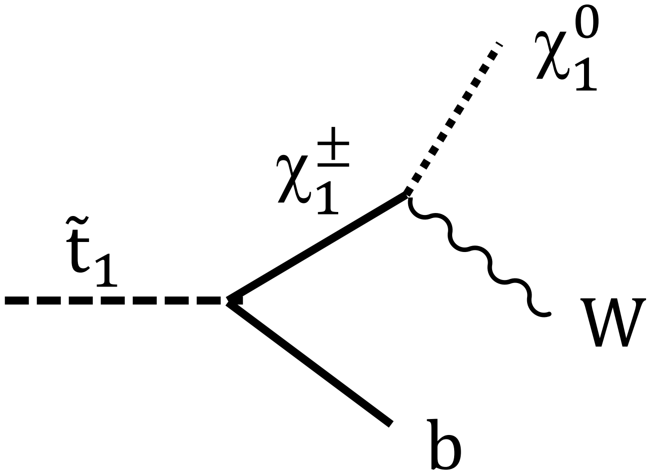
$\Delta M < M_W + M_b$

- Same final state can also target direct DM searches with low mass spin-0 mediator
  - In ATLAS same analysis used for both with optimized selection



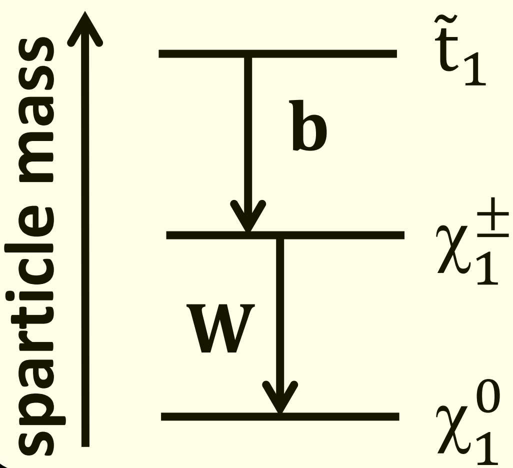
Bottom chargino decay

- Top squark can decay to a bottom quark and a chargino

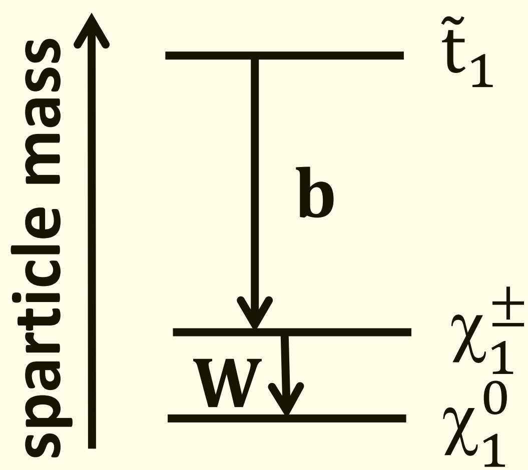


- Same particles in final state as top neutralino decay mode
  - BUT: sensitivity and best analysis depends a lot on mass spectrum

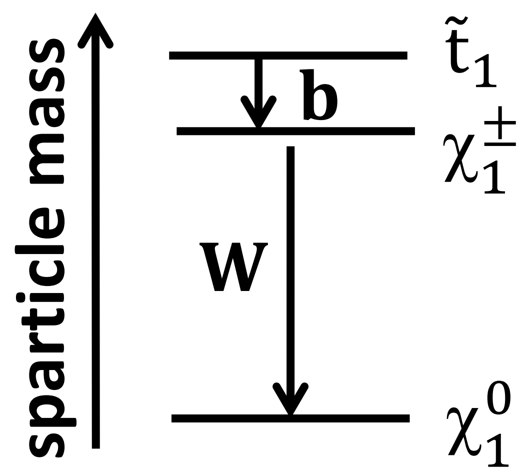
High-p_T b and W



Very soft W bosons

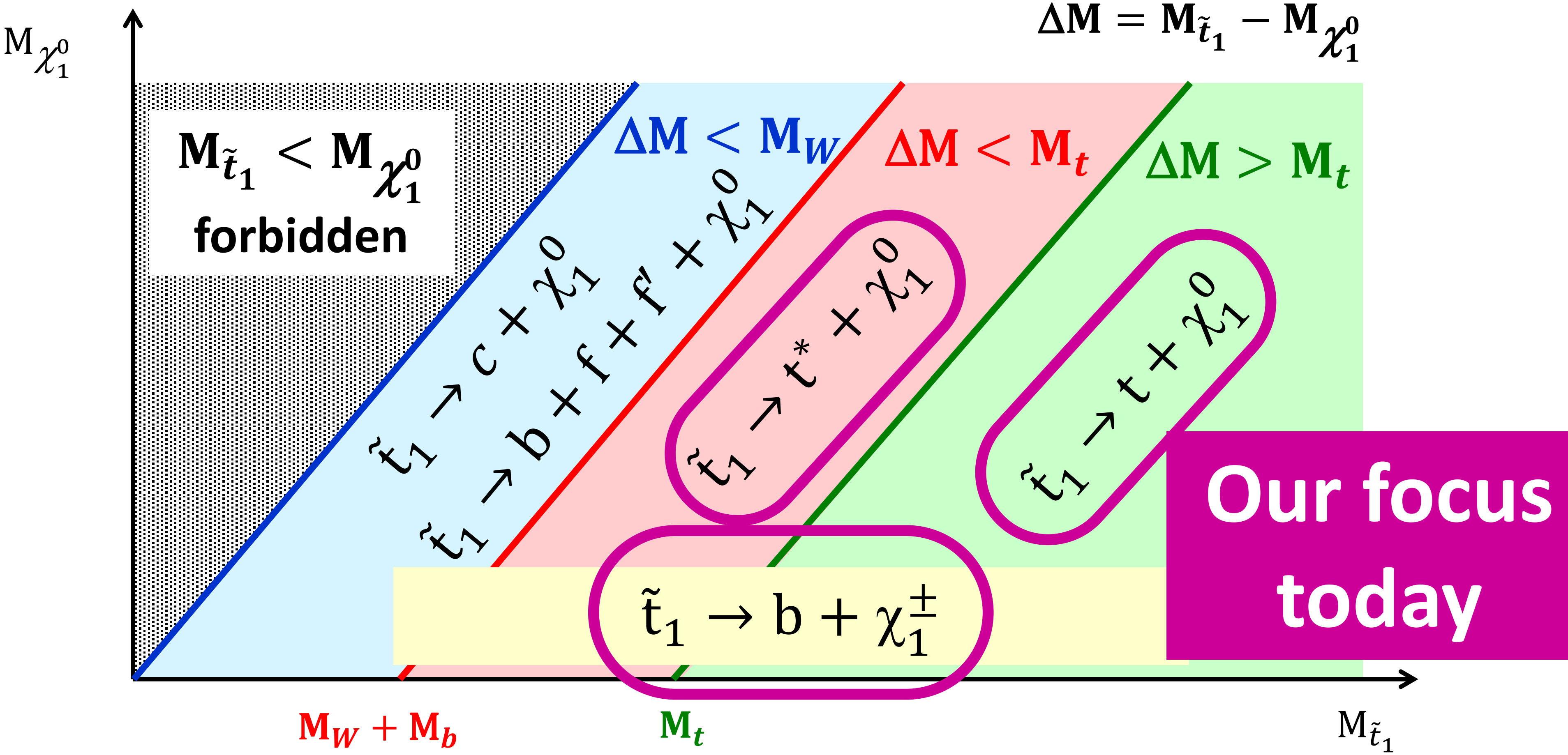


Very soft b-jets



Top squark decay

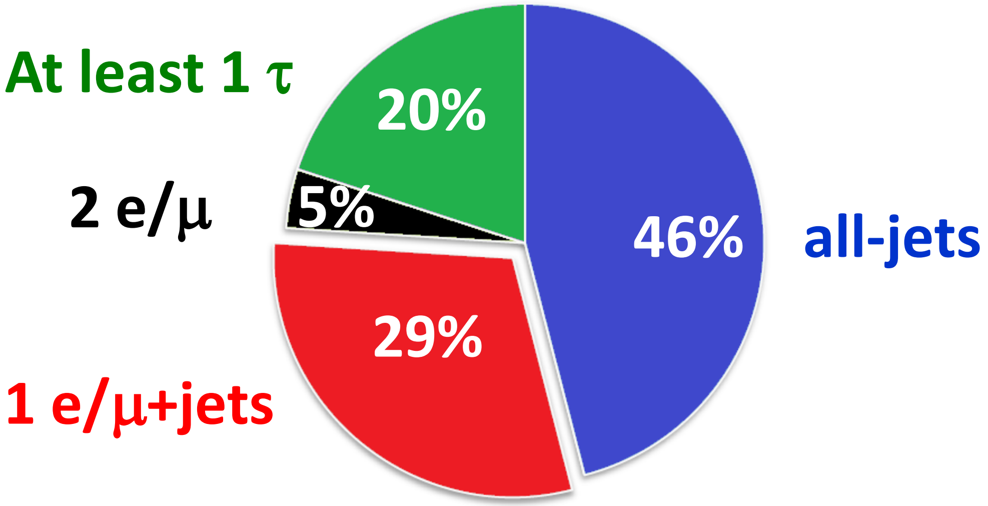
- Rich spectrum of decay modes depending on SUSY mass spectrum and couplings



Experimental signatures for pair production

- Final states (2 top squarks) have two on- or off-shell W bosons
  - Leads to 0, 1 or 2 leptons in the final state

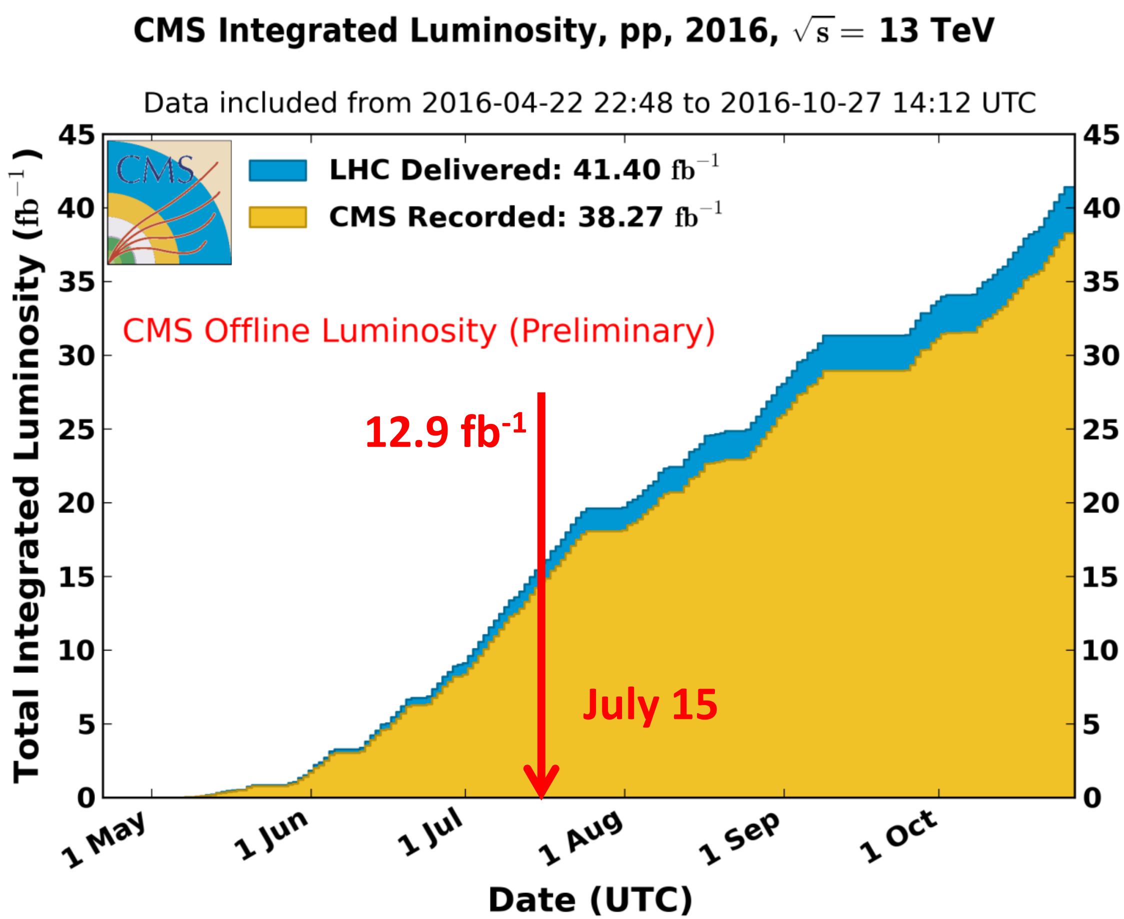
Without p_T or η requirements
~30% in the 1 e/μ final state
- **Refered to as single-lepton**



- $\tilde{t}_1 \rightarrow c + \chi_1^0$ a bit different
  - Target with mono-jet like search or use charm-tagging
- Alternative decays possible leading to lots of experimental signature:
  - Long-lived, R-parity violating, GSMB scenario's

Dataset

- Corresponding to the dataset for summer conference: 12.9 fb^{-1}
- Total 13 TeV dataset: ~38.3 fb^{-1} $_{(2016)}$ + 2.3 fb^{-1} $_{(2015)}$



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  - Rejecting backgrounds
    - 1l backgrounds
    - 2l backgrounds
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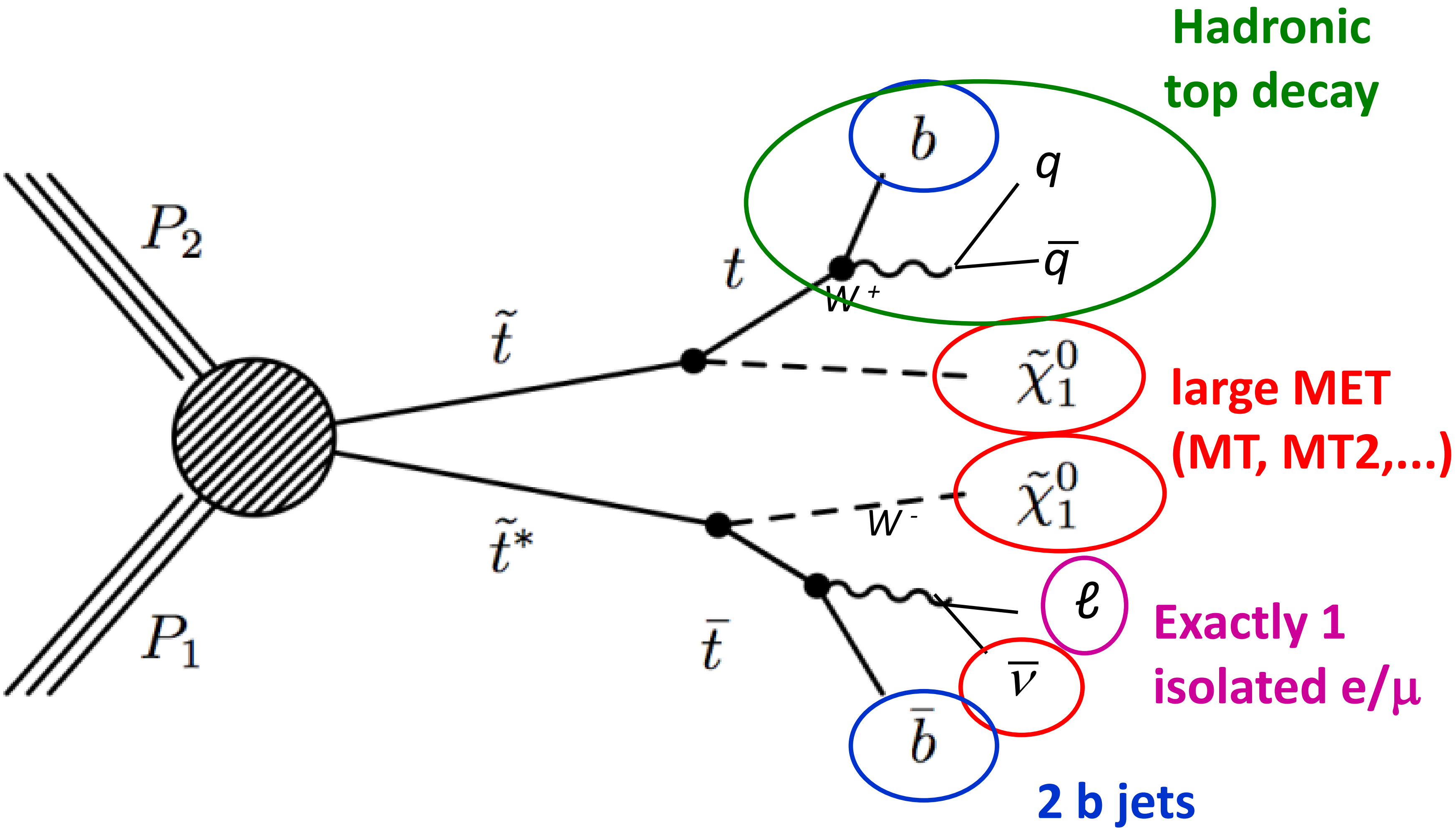
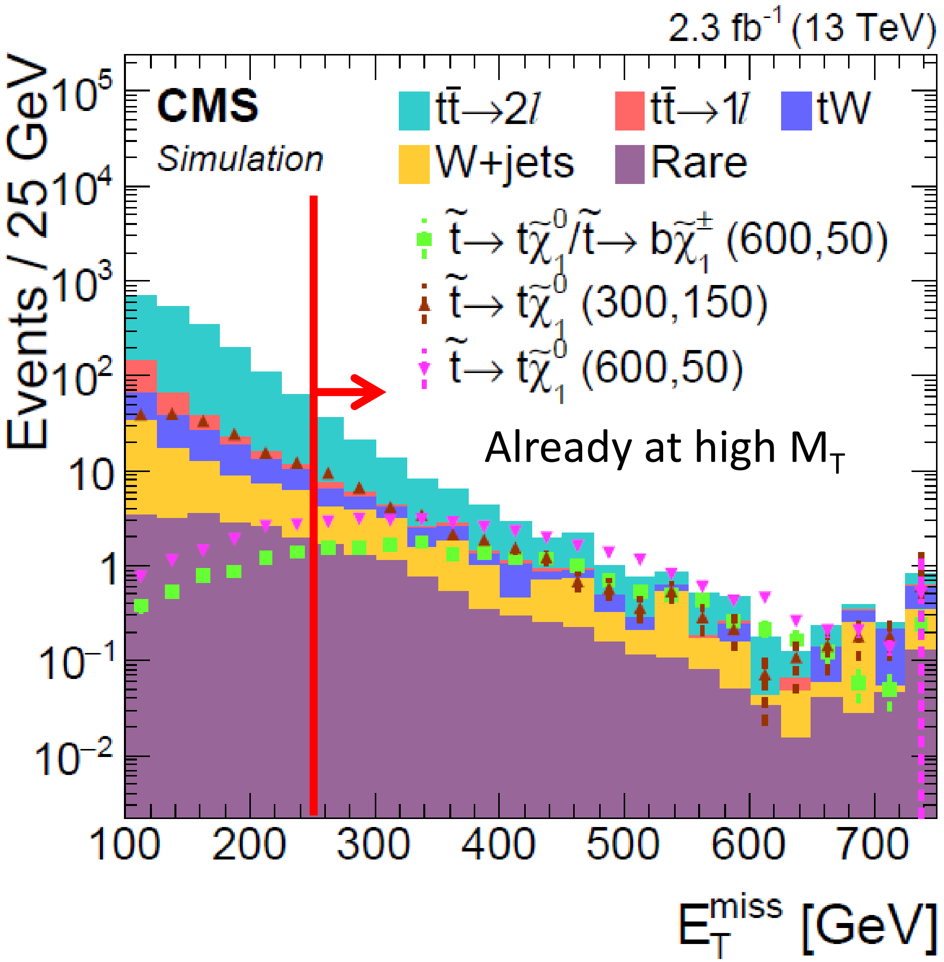
Both stops decay as $\tilde{t} \rightarrow t\chi_1^0$



Baseline selection

- Selection (trigger-inspired):
  - Exactly 1 electron or muon with p_T>20 GeV
  - MET>250 GeV
  - At least 1 b-tagged jet
- Main backgrounds:
  - 1ℓ $t\bar{t}$
  - W+jets
  - 2ℓ $t\bar{t}$
  - Single top
  - Dibosons, $t\bar{t}V$



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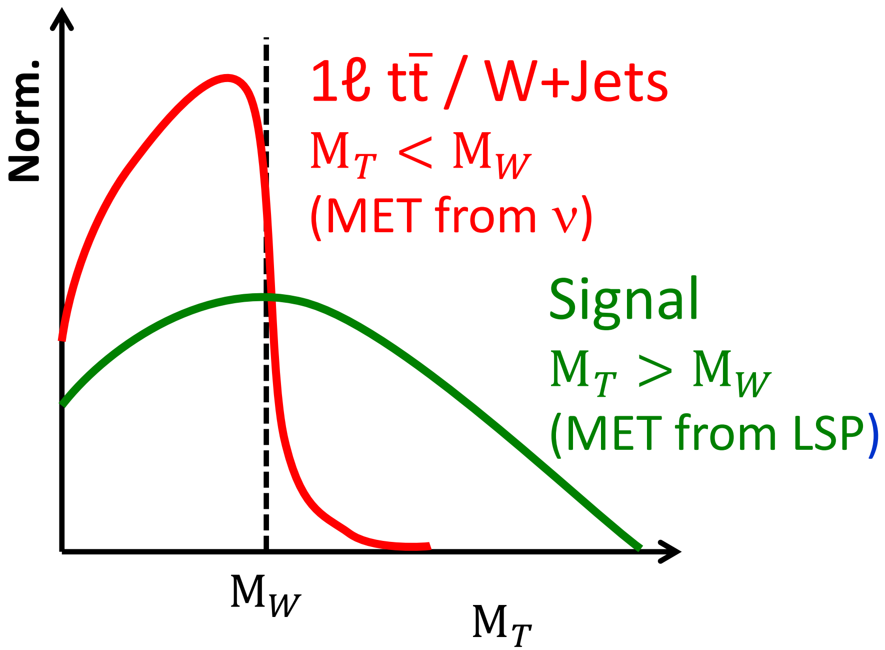
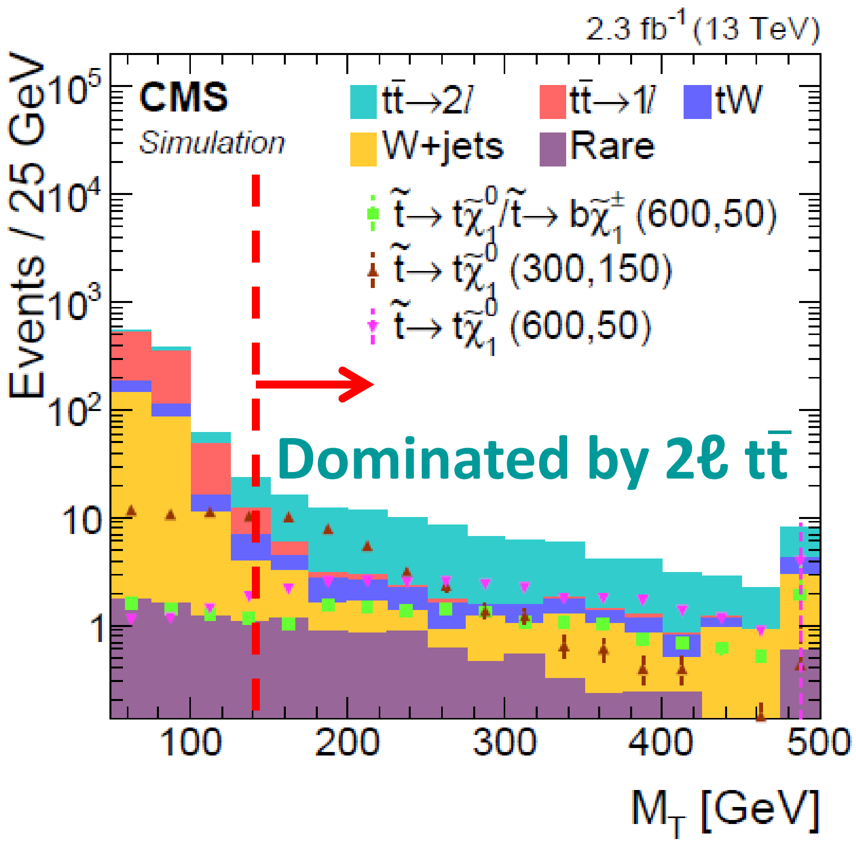
Killing the single-lepton background

- Largest two backgrounds are $t\bar{t}$ and W+Jets
  - No endpoint in transverse mass due to extra MET from LSPs

$$M_T(\ell,\nu)^2 = (E_T(\ell)+E_T(\nu))^2 - (\vec{p_T}(\ell)+\vec{p_T}(\nu))^2$$

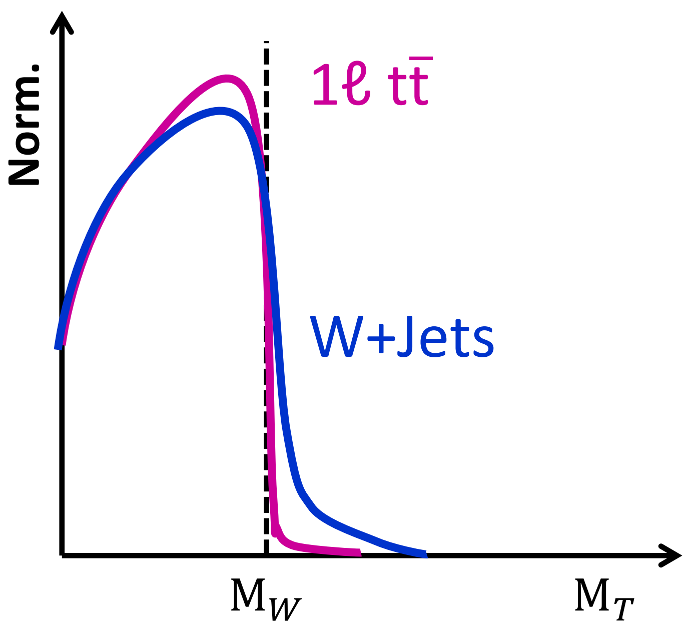
$$\rightarrow 2E_T(\ell)E_T(\nu)(1-\cos(\Delta\phi))$$

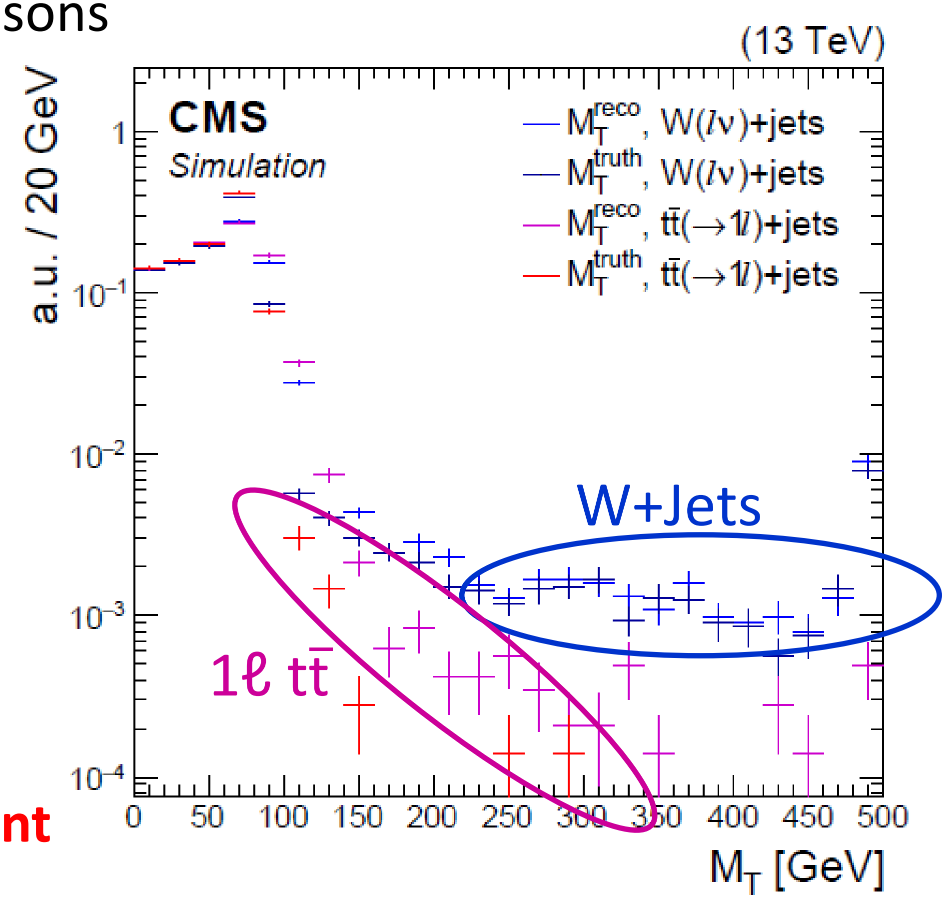




Killing the single-lepton background

- Transverse mass point more efficient for 1l $t\bar{t}$
  - Top mass imposes kinematic constraint on W mass
    - Tail for $t\bar{t}$ dominated by resolution effects, for W+Jets by off-shell W bosons





Reduce W+Jets with b-tag requirement

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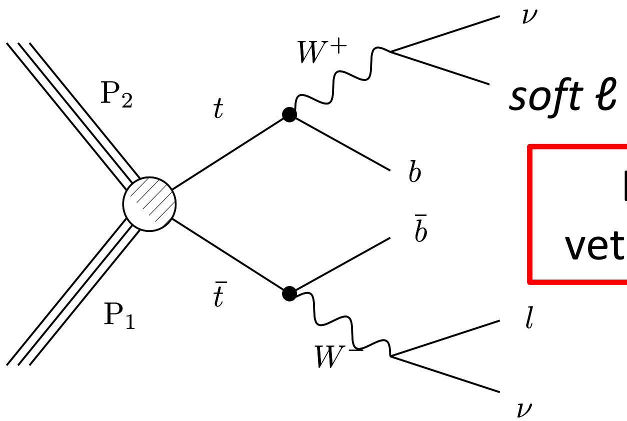
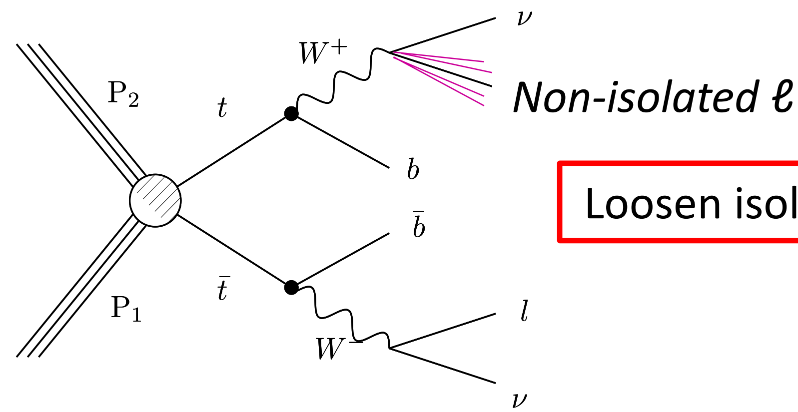
Removing dilepton backgrounds

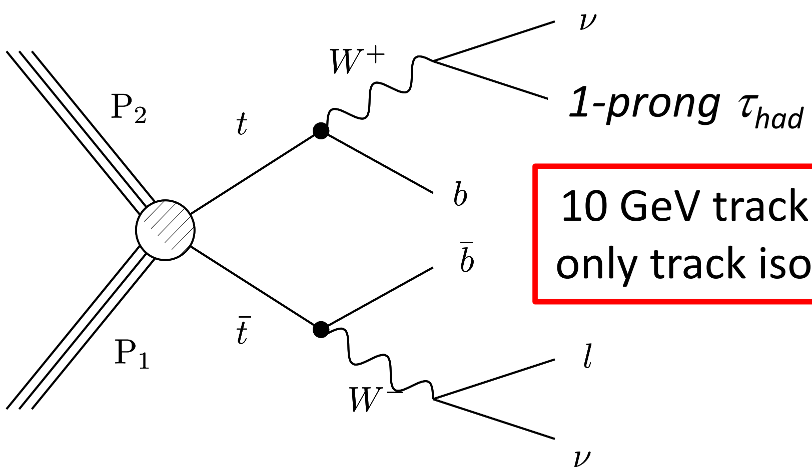
- After tight M_T cut dilepton backgrounds ($t\bar{t}$ and tW) dominate
  - Try to minimize this background by optimizing lepton vetoes



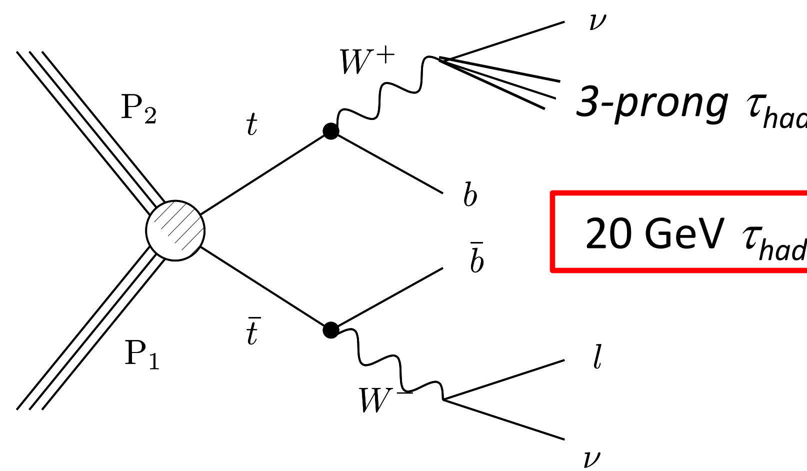
Lower p_T:
veto 5 GeV e/μ



Loosen isolation



10 GeV track veto:
only track isolation

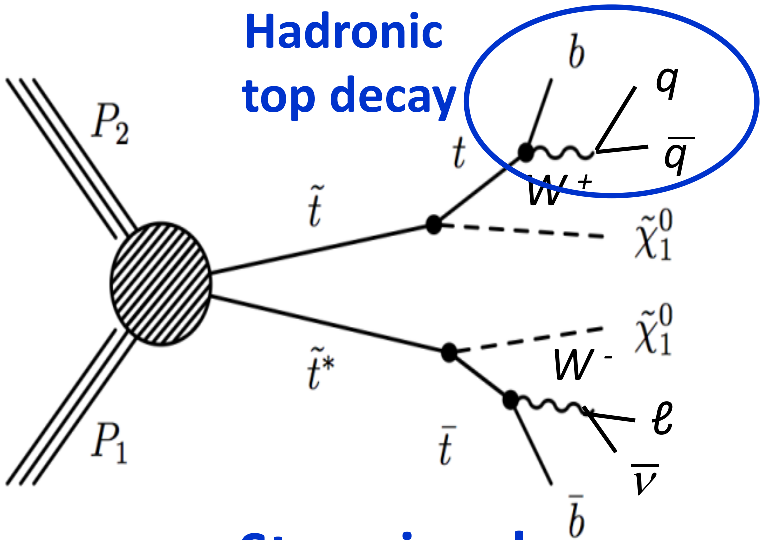


20 GeV τ_{had} veto

Hadronic top decays

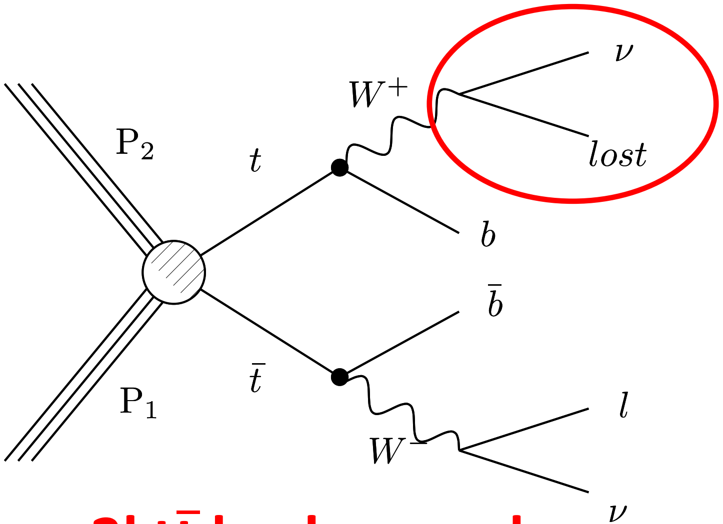
- Only signal has a hadronic top decay

Hadronic top decay



Stop signal

Misidentified leptonic top decay



2l $t\bar{t}$ background

- Require at least 4 jets
  - 3 for boosted scenario's when W jets will be merged
- Can be exploited further with (low-p_T) top tagger

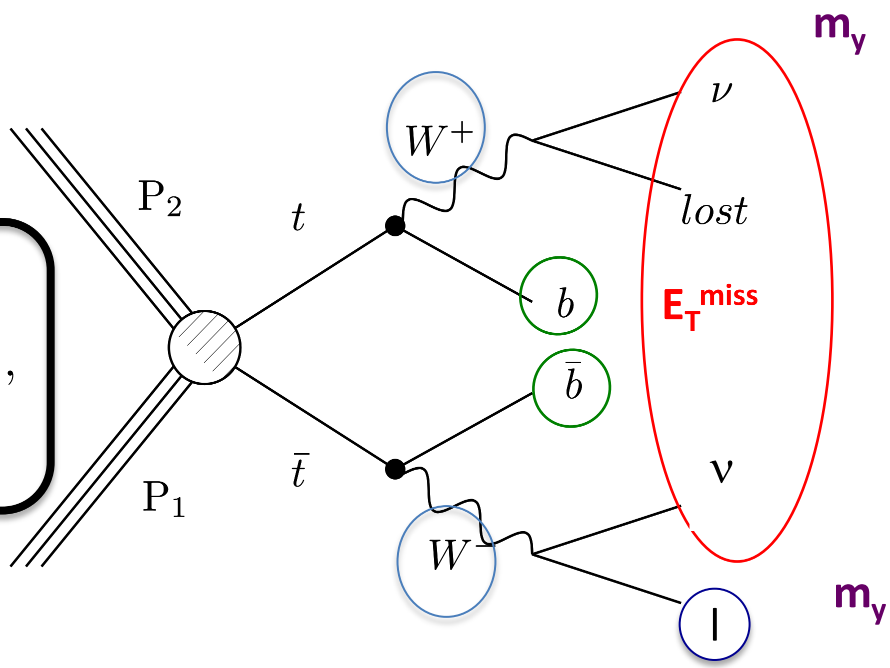
Attacking the dilepton background

- After tight M_T cut dilepton backgrounds ($t\bar{t}$ and tW) dominate
  - Target lost lepton background with dedicated variable

arXiv:1203.4813

M_{T2}^{W}: minimum mother particle mass compatible with W mass and MET constraints for 2l $t\bar{t}$ hypothesis

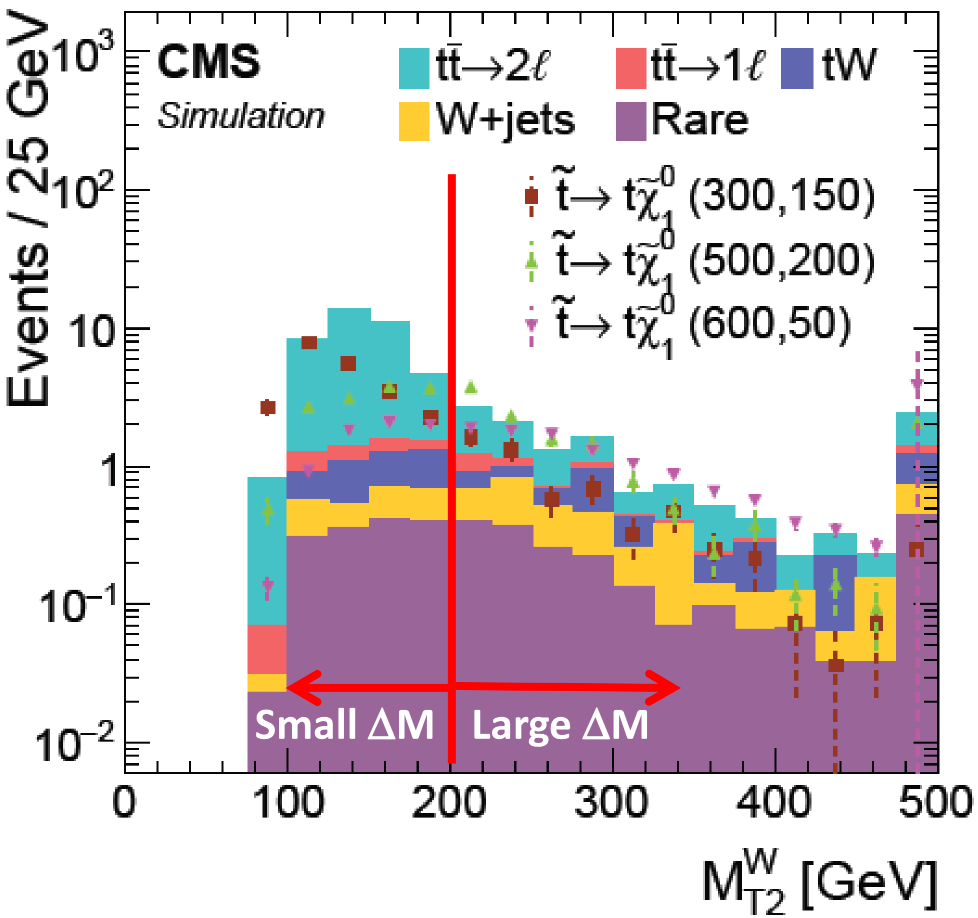
$$M_{\mathrm{T2}}^{\mathrm{W}} = \min\Big\{m_y \text{ consistent with } \big[p_1^2 = 0, \\ (p_1 + p_\ell)^2 = p_2^2 = M_W, \vec{p}_{\mathrm{T}}^{\,1} + \vec{p}_{\mathrm{T}}^{\,2} = \vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2, \big]\Big\}$$



Attacking the dilepton background

- After tight M_T cut dilepton backgrounds ($t\bar{t}$ and tW) dominate
  - Use M_{T2}^{W}: minimum mother particle mass compatible with W mass and MET constraints assuming 2l $t\bar{t}$

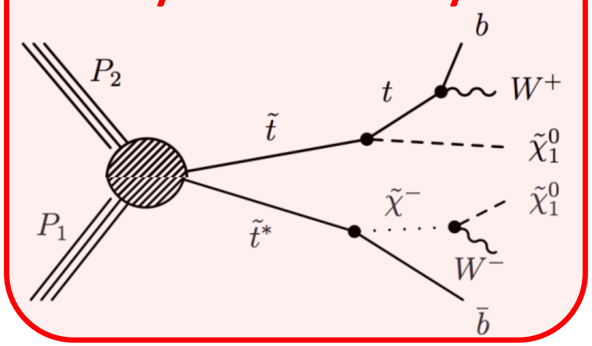
- Natural endpoint around 200 GeV
- Compressed mass points at low M_{T2}^{W}
- Tails for SM backgrounds due to different effects
  - tW does not obey mass constraint
    - Only 1 real b tag
  - Only 17% of 2l $t\bar{t}$ with high generator-M_{T2}^{W}
    - 9 %: overlap between jets
      - **Jet substructure?**
    - 56 %: one of the jets not in kinematic acceptance
      - **Loosen p_T cut (30 GeV) on jets?**
      - **Allow for missing a b-jet**
    - 18 %: wrong jet choice
      - **Investigated different algorithms to chose**



Modified topness

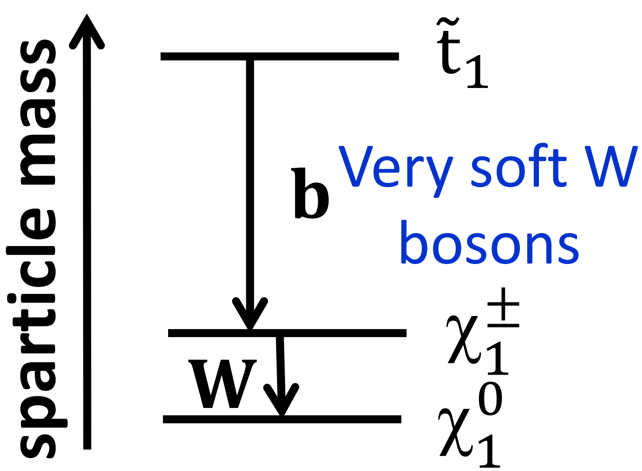
- Remove some of the background where one of the jets is not in the acceptance
  - Also helps for signal acceptance for asymmetric decays
  - Improved tW rejection

Asymmetric decays

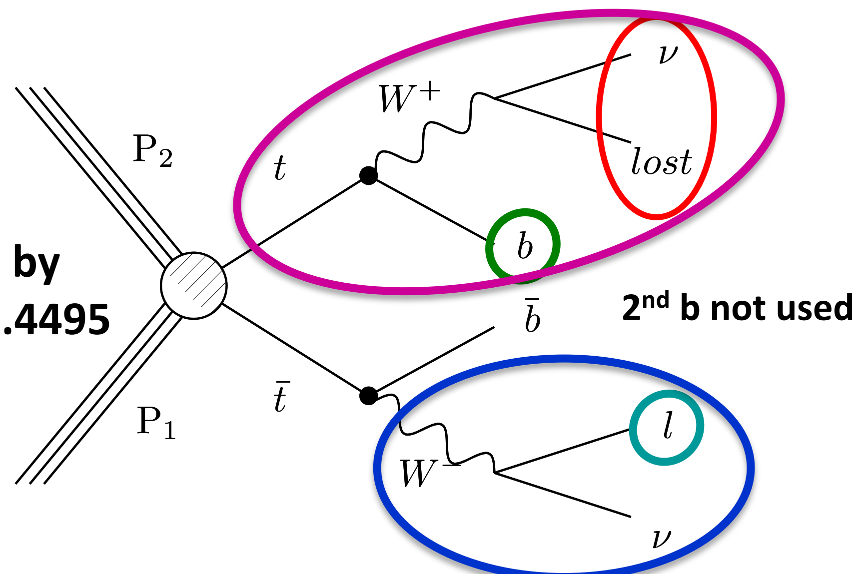


$$t_{\text{mod}} = \ln(\min S) \quad \text{with} \quad S(\vec{p}_W, p_{\nu,z}) = \frac{(m_W^2 - (p_\nu + p_\ell)^2)^2}{a_W^4} + \frac{(m_t^2 - (p_{b_2} + p_W)^2)^2}{a_t^4},$$

Constrained to M_W **Constrained to M_{top}**



Inspired by arXiv:1212.4495



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    - **Rare Standard Model processes**
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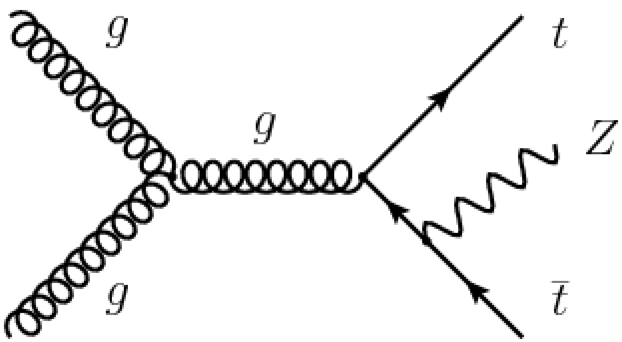
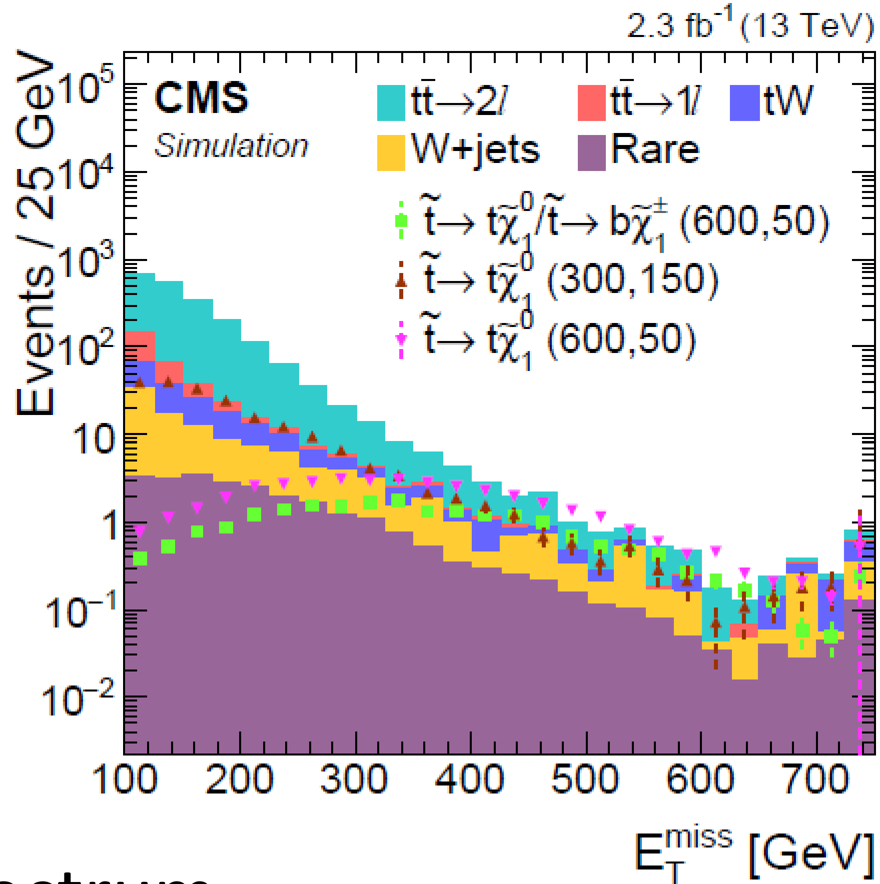
Rare SM backgrounds

- Rare SM backgrounds enter through $Z \to \nu\nu$ decays:
  - $t\bar{t}Z$:
    - Almost indistinguishable
    - Real MET, 2 b quarks, hadronic top decay



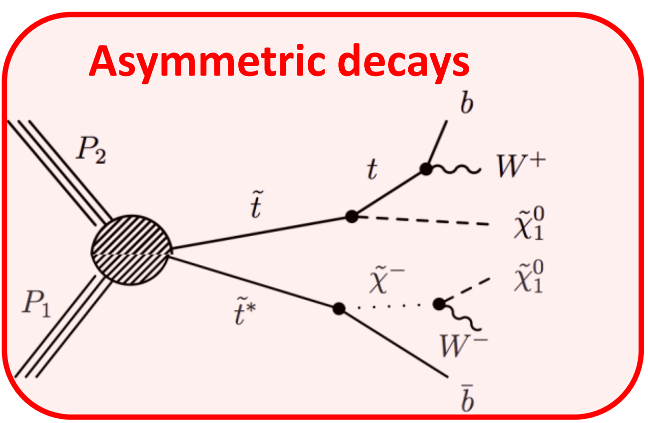


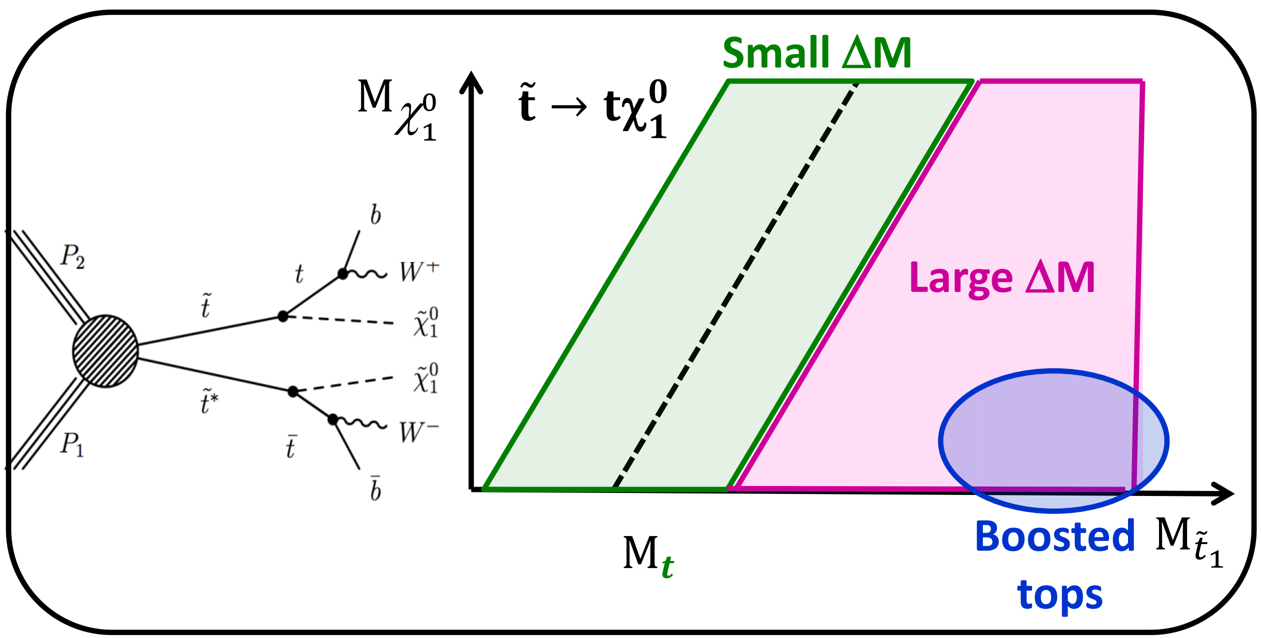
  - Also WZ, tqZ,...
- Use differences in MET spectrum

Selection summary

- Exclusive search regions designed to target specific regions
  - Extra gain due to statistical combination (low ΔM)

	N_{jets}	M_{T2}^{W} [GeV]	t_{mod}	E_T^{miss} [GeV]				
Asymmetric decays ←	$= 2$		> 6.4	250–350	350–450	> 450		
Boosted tops ←	$= 3$	> 200		250–350	350–450	450–550	> 550	
Small ΔM ←	≥ 4	≤ 200		250–350	350–450	> 450		
Large ΔM ←	≥ 4	> 200		250–350	350–450	450–550	550–650	> 650





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Background prediction

- Dominant background predicted in data-driven way
  - Use control regions very similar to signal region

	Exactly 1l	1l + veto lepton
0 b-tag	0b control region W+Jets dominated	
≥ 1 b-tag	↓ T_{N_b} Signal region ← T_{LL}	2l control region tt→2l dominated

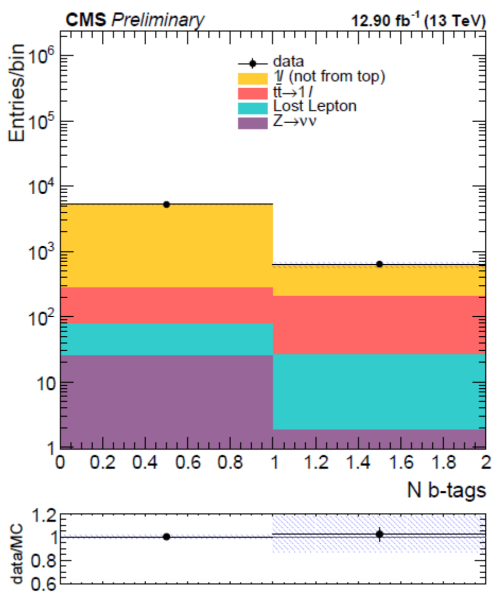
- Smaller backgrounds taken from simulation after estimating experimental and theoretical uncertainties
  - Rare SM backgrounds
    - First checks done to get normalization from 3l CR and distributions from ttγ
  - 1l $t\bar{t}$: dominated by MET resolution
  - W+Jets in low M_{T2}^{W} regions:
    - even 0b control region dominated by lost lepton background

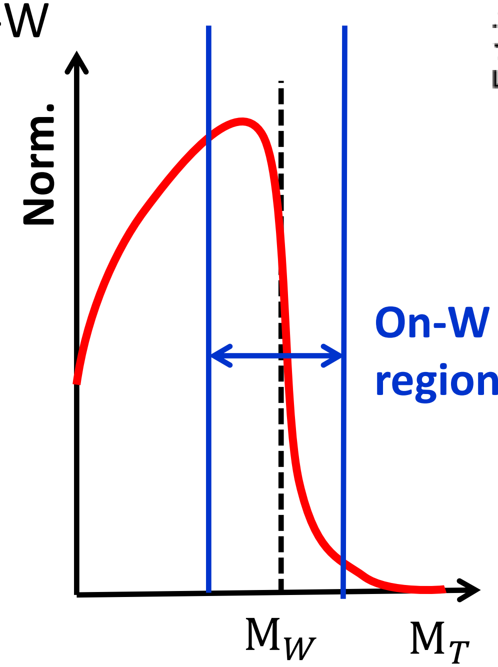
W+Jets background

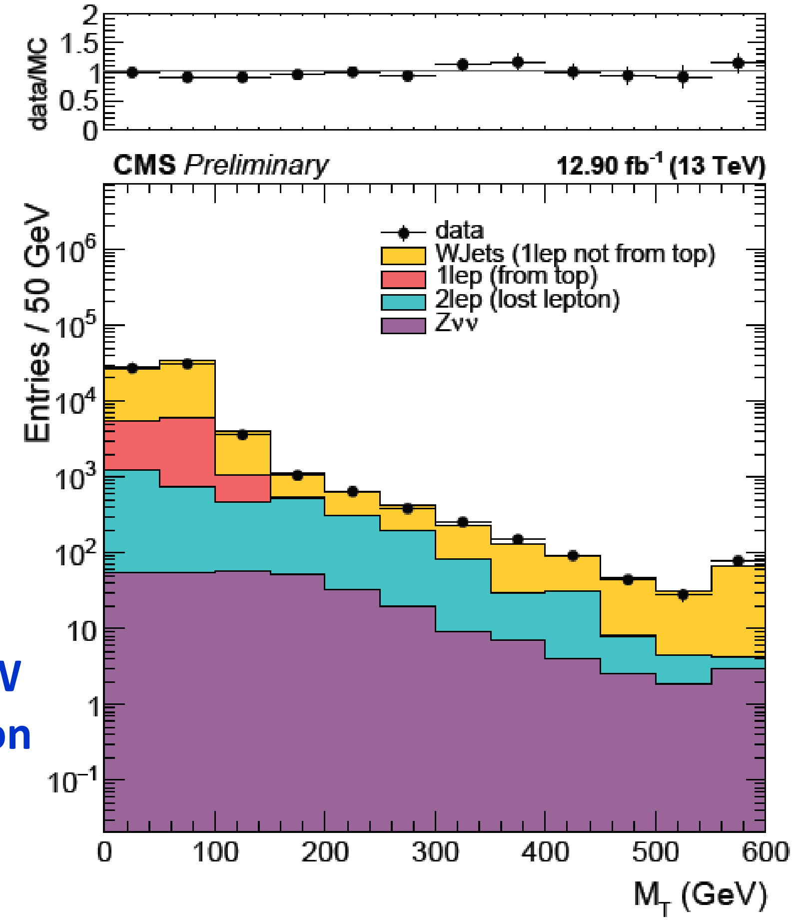
- Extrapolation in number of b-tagged jets

$$N^{\mathrm{pred}}_{\mathrm{W+jets}} = (N^{\mathrm{data}}_{N_b=0} - N^{\mathrm{non-W+jets}}_{N_b=0})\, T_{N_b}$$

- Most important systematic uncertainty for b-tag extrapolation:
  - b-tagging efficiency from data
  - Uncertainty for W+b(b) fraction
    - Control region on-W



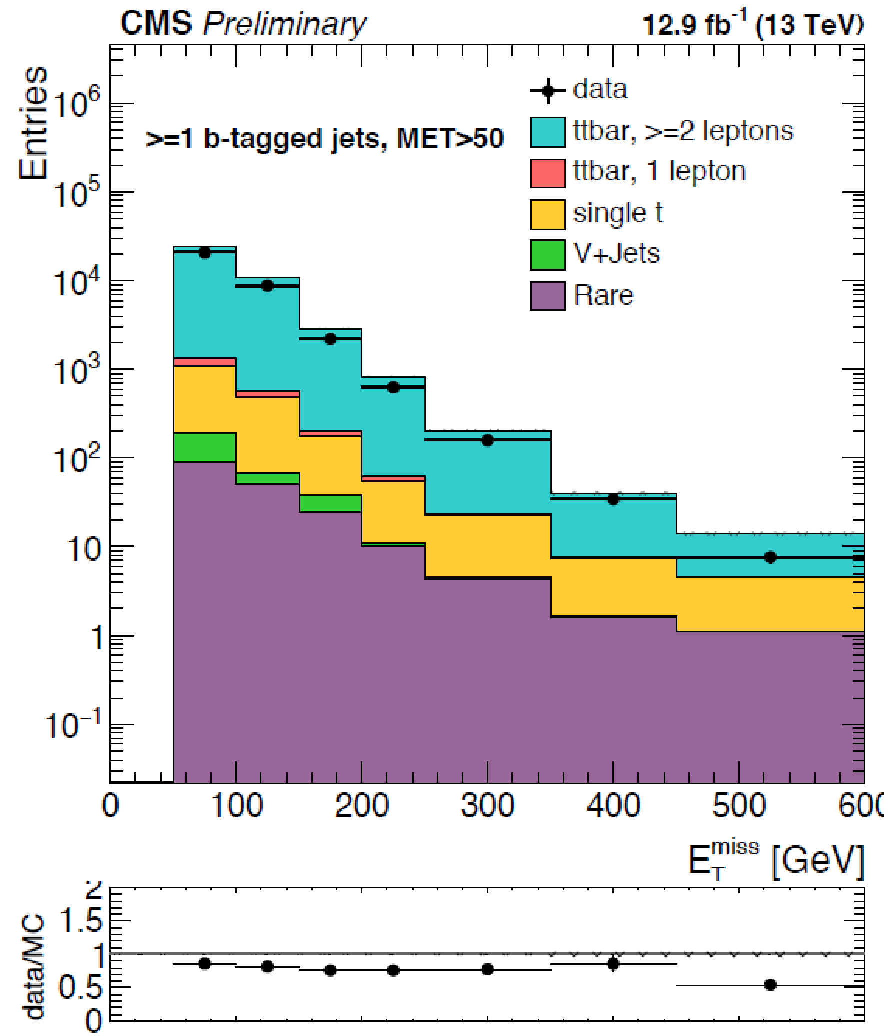




Lost lepton background

- Lost lepton background dominated by 2ℓ $t\bar{t}$, but also includes tW
  - Enters signal region when one lepton out of acceptance or not identified/isolated
- Normalize the estimate to a dilepton control region in data
  - Require extra e/μ (p_T>10 GeV)
  - Only extrapolate along the lost lepton category
    - Large statistical uncertainties, small systematic uncertainties

$$N_{lost\ \ell}^{Data,\ SR} = N_{\ell\ell}^{Data,\ CR} \times \frac{M_{lost\ \ell}^{MC,\ SR}}{M_{\ell\ell}^{MC,\ CR}}$$



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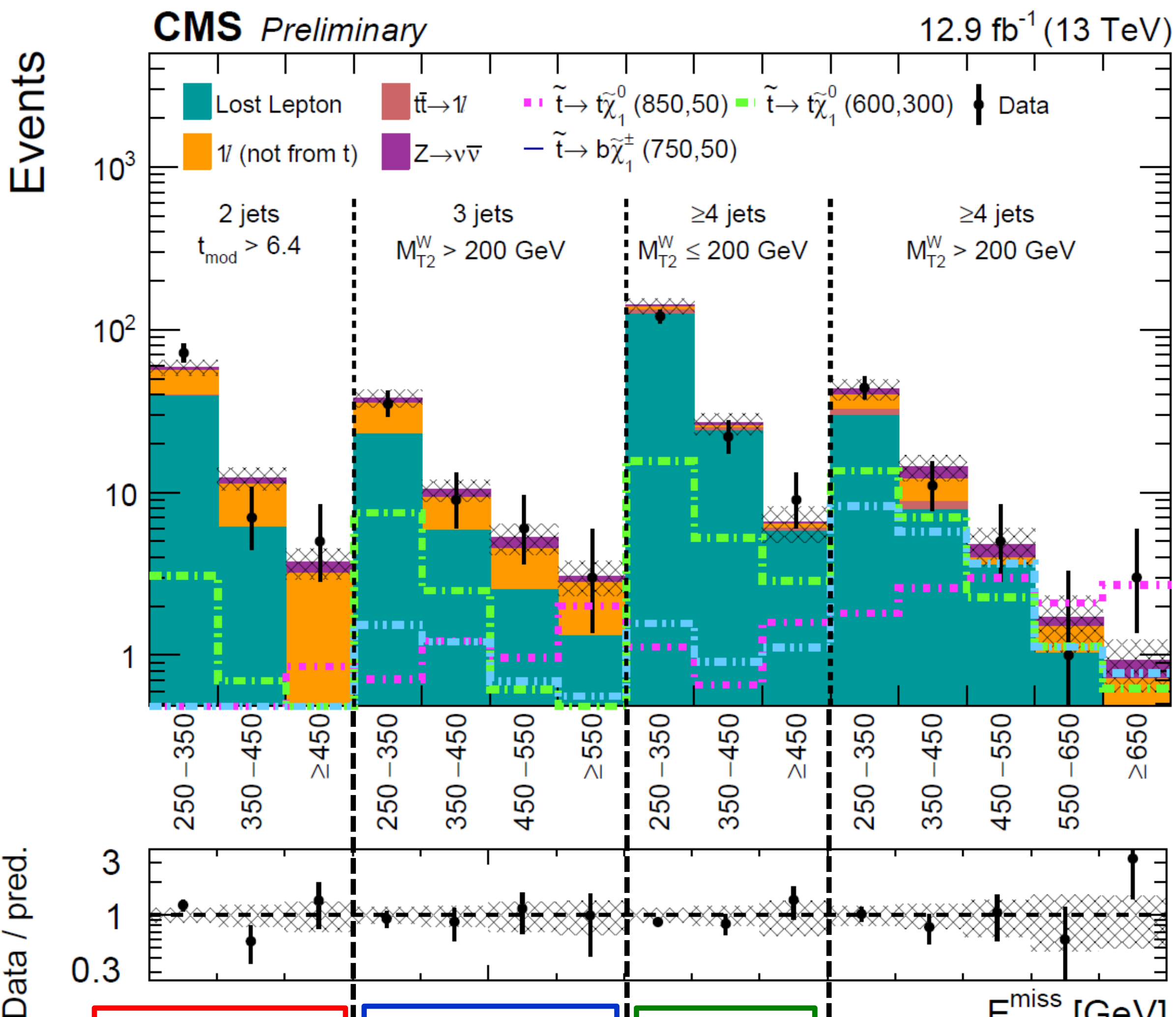
No excess observed



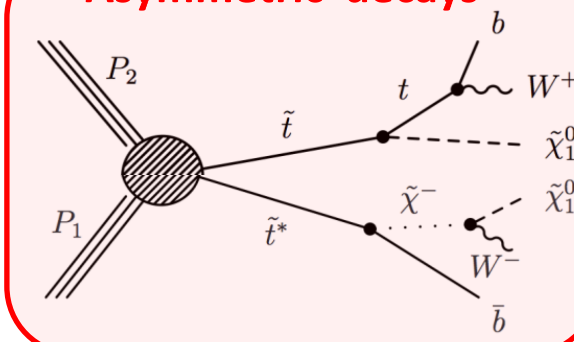
Asymmetric decays

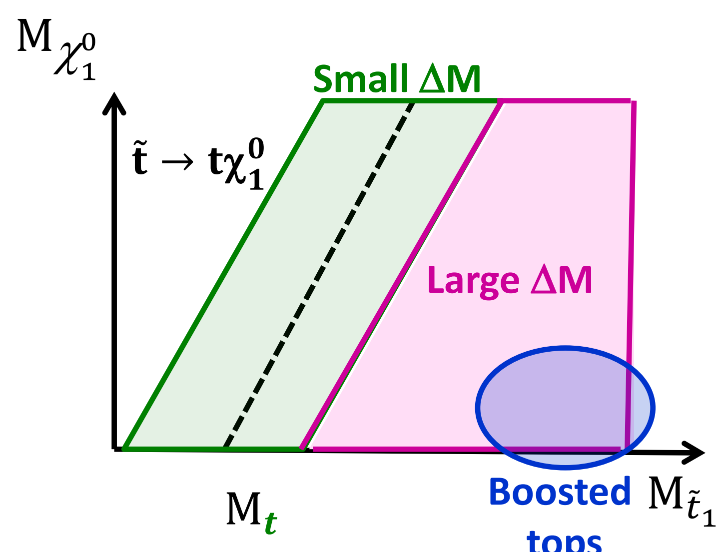
Boosted tops

Small ΔM

Large ΔM

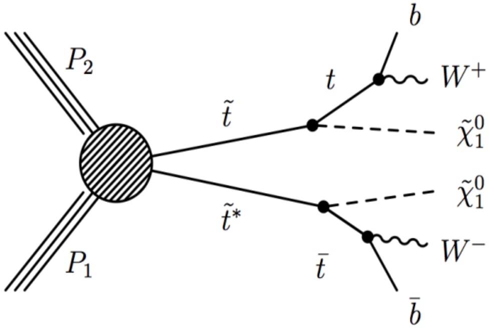
Asymmetric decays

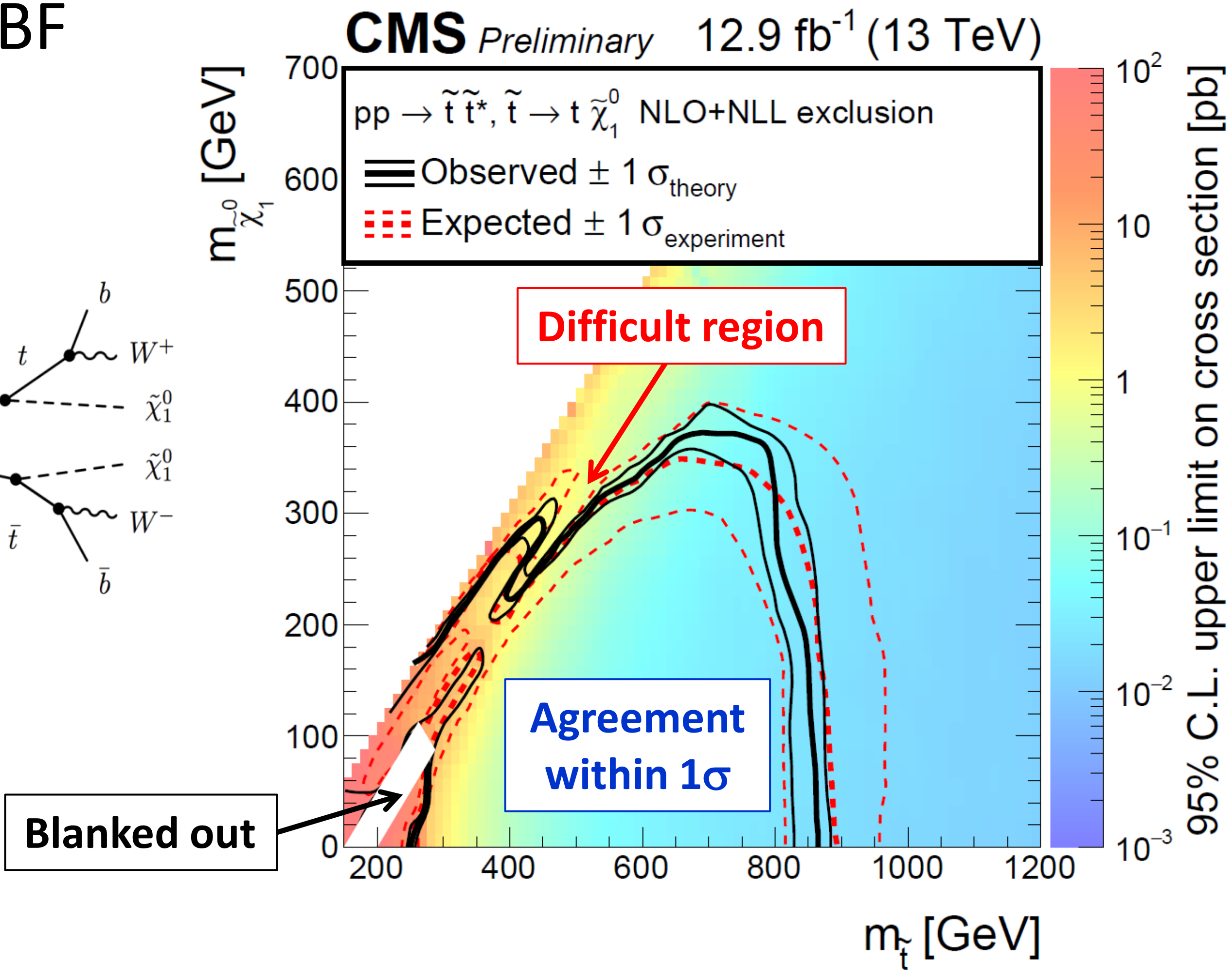




Interpretation

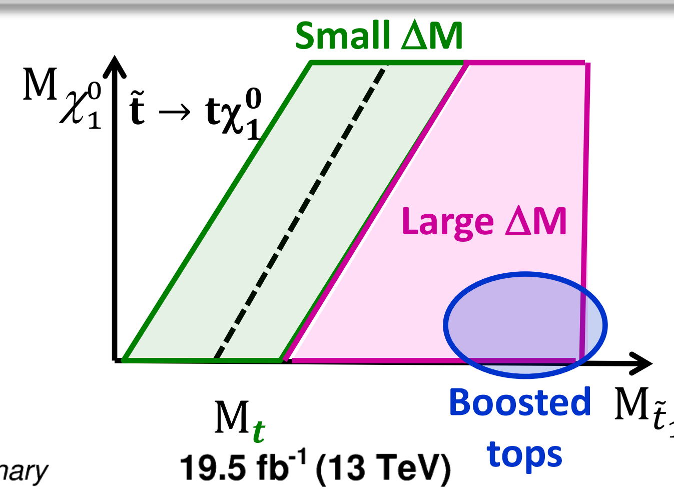
- Top squarks probed up to 870 GeV
  - 100% BF

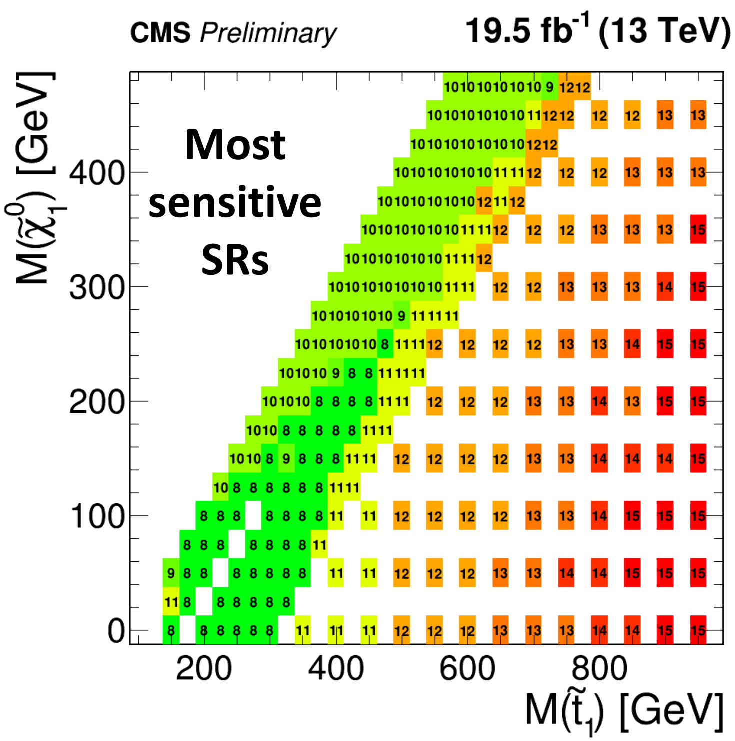


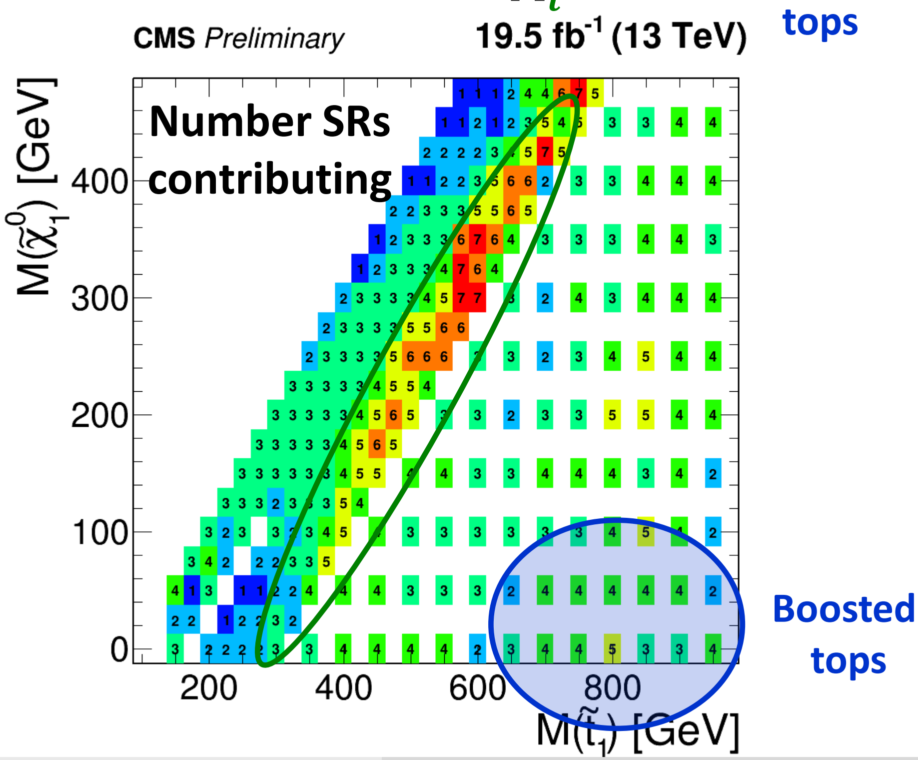


Interpretation

- Most sensitive search regions divided between small and large ΔM
- Small mass splittings get sensitivity from a large group of search regions
- High mass tops have extra contributions from boosted SRs



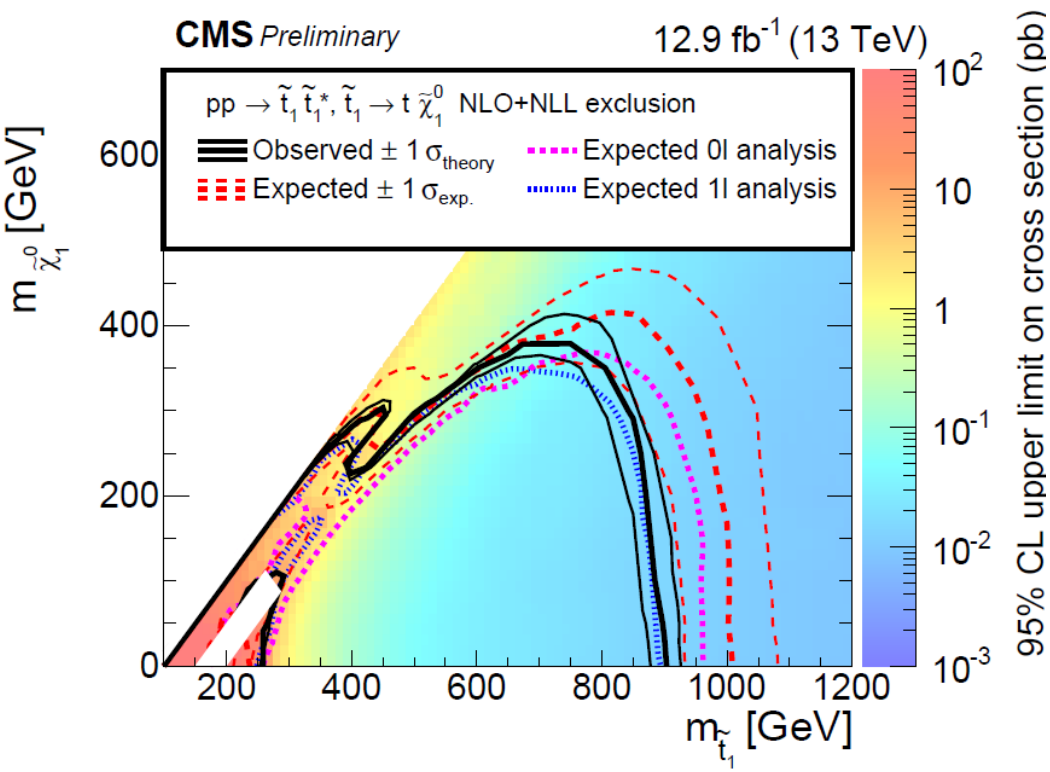


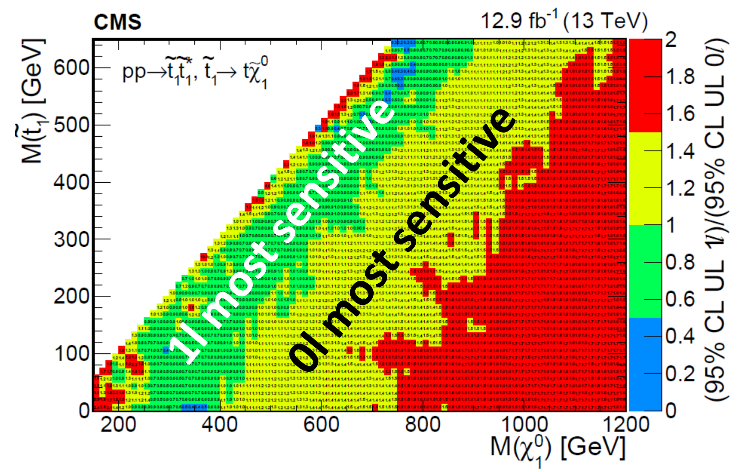


Complementarity with all-jets analysis

- To believe a new-physics discovery we will also want to see multiple decay modes
  - Higgs boson discovery both in ZZ and $\gamma\gamma$
- Make sure both analyses are fully disjoint, use same prescriptions for systematic uncertainties and statistical treatment

Breaking 1 TeV frontier!





For intermediate chargino: 1l always the most sensitive

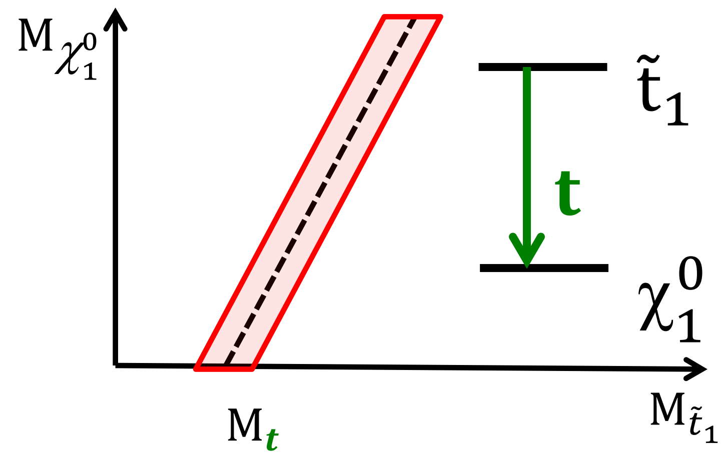
Overview

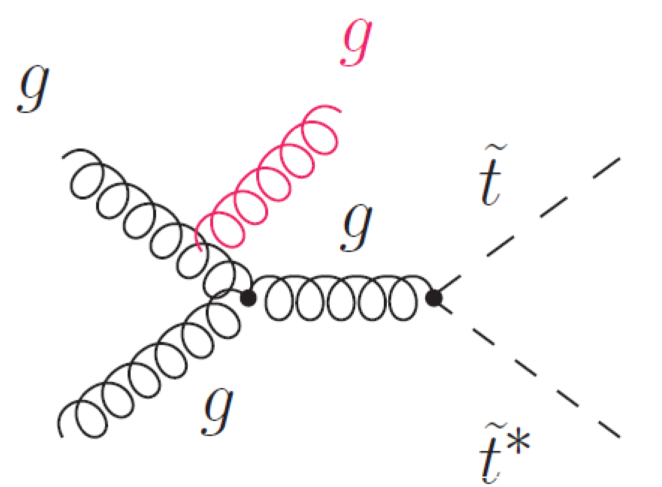
- Why would we look for top squarks?
- How would top squarks decay and how can we detect them?
- Looking for top squarks in the single-lepton final state
- **Peek at difficult mass spectra**
- Conclusions and outlook

Top mass corridor

- Most difficult area to target when $\Delta M = M_{\tilde{t}_1} - M_{\chi_1^0} = M_t$
  - In rest frame of top squark
    - $E_{\tilde{t}_1} = M_{\tilde{t}_1}$ and $|\vec{p}_{\tilde{t}_1}| = 0$
    - LSP also at rest: $E_{LSP} = M_{LSP}$ and $|\vec{p}_{LSP}| = 0$
  - After Lorentz boost:
    - $p_{T,LSP} = -\gamma v E_{LSP} = -\gamma v M_{LSP}$
    - $p_{T,\tilde{t}_1} = -\gamma v E_{\tilde{t}_1} = -\gamma v M_{\tilde{t}_1}$
  - Combining this information:
    - $p_{T,LSP} = \frac{M_{LSP}}{M_{\tilde{t}_1}} p_{T,\tilde{t}_1}$

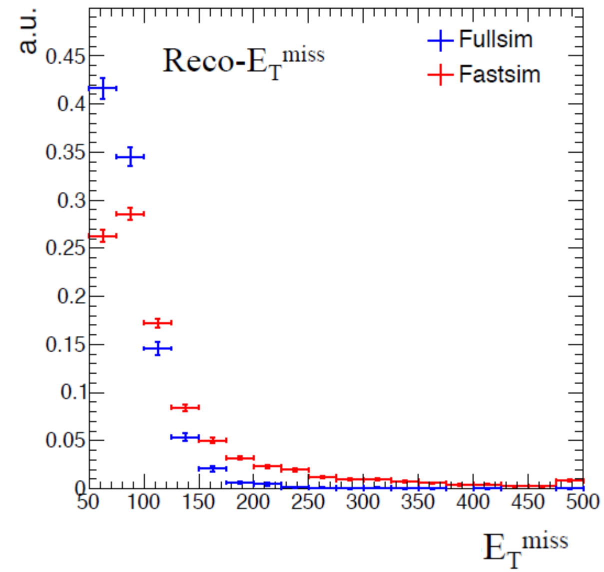
1. **Boosting the top squarks will lead to large MET**
2. **For $M_{LSP} \ll M_{\tilde{t}_1}$ impossible to get high MET**

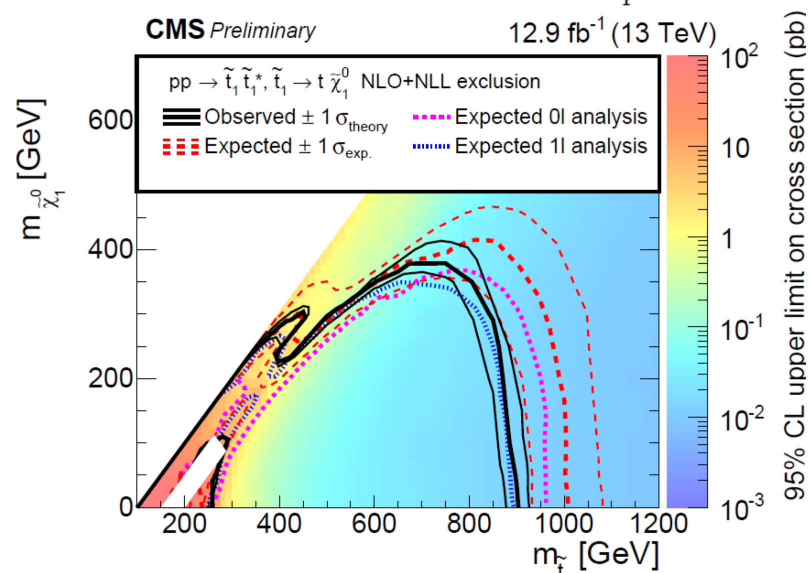




Top mass corridor

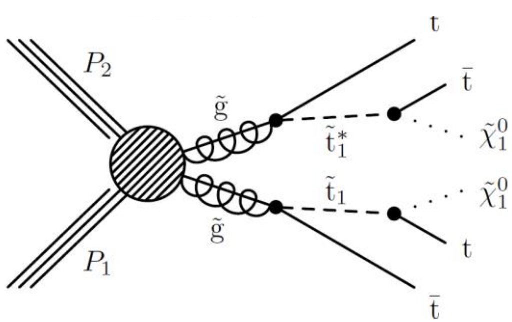
- Dedicated working group to focus on this region:
  - Study the sensitivity in more detail
    - Especially comparing LSP mass of 0 GeV with $t\bar{t}$ background
  - Signal modeling/simulation
    - Fast simulation had spurious high p_T jets and much worse MET resolution
- Still a few problems remaining:
  - Different MadGraph settings for background modeling
  - Strong dependence on polarization
- All these effects most sensitive for low LSP masses
- Conclusion:
  - New guidelines for FastSim usage
  - **Light LSPs still needs further study**

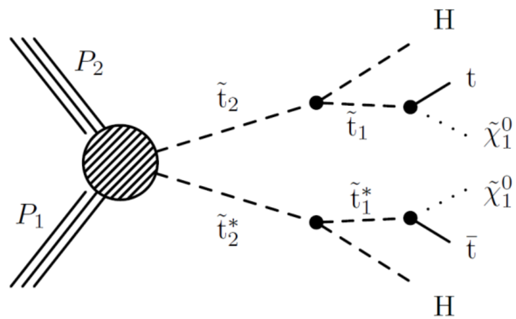


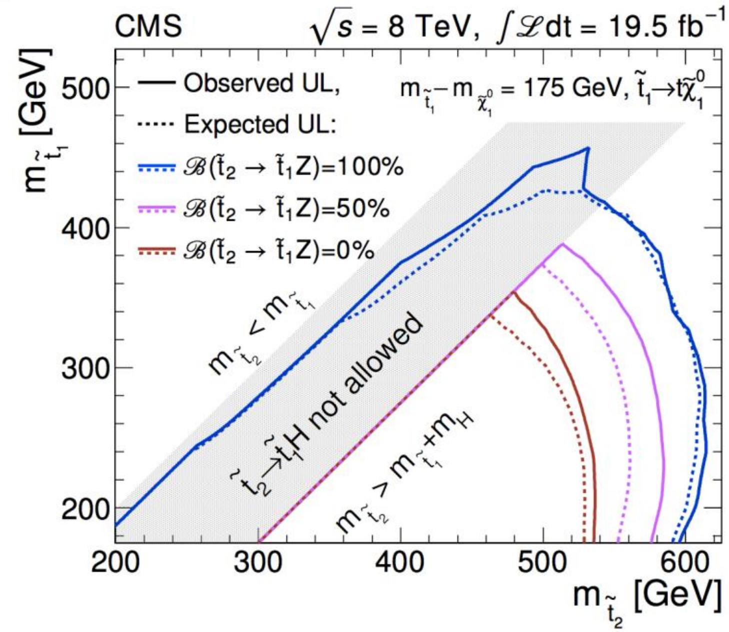


Other ways to target the top corridor

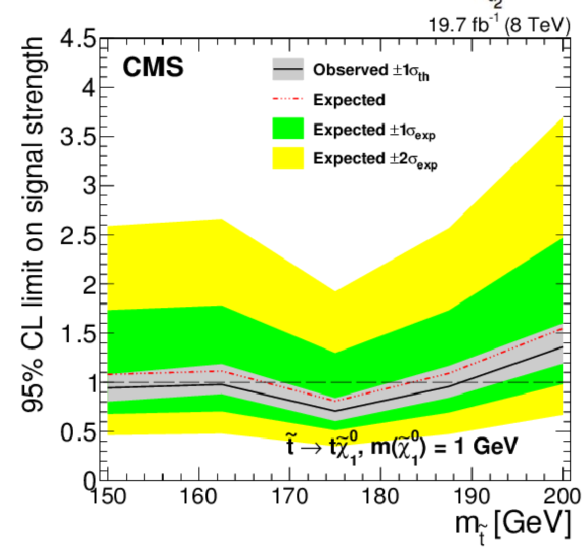
- Cascade decays
  - Gluinos or heavier stop partners







- Indirect search
  - Excess in $t\bar{t}$ cross section measurement
  - Measurement of spin correlations between the tops (e.g. Δϕ(l,l)) since top squarks have spin 0



Overview

- Why would we look for top squarks?
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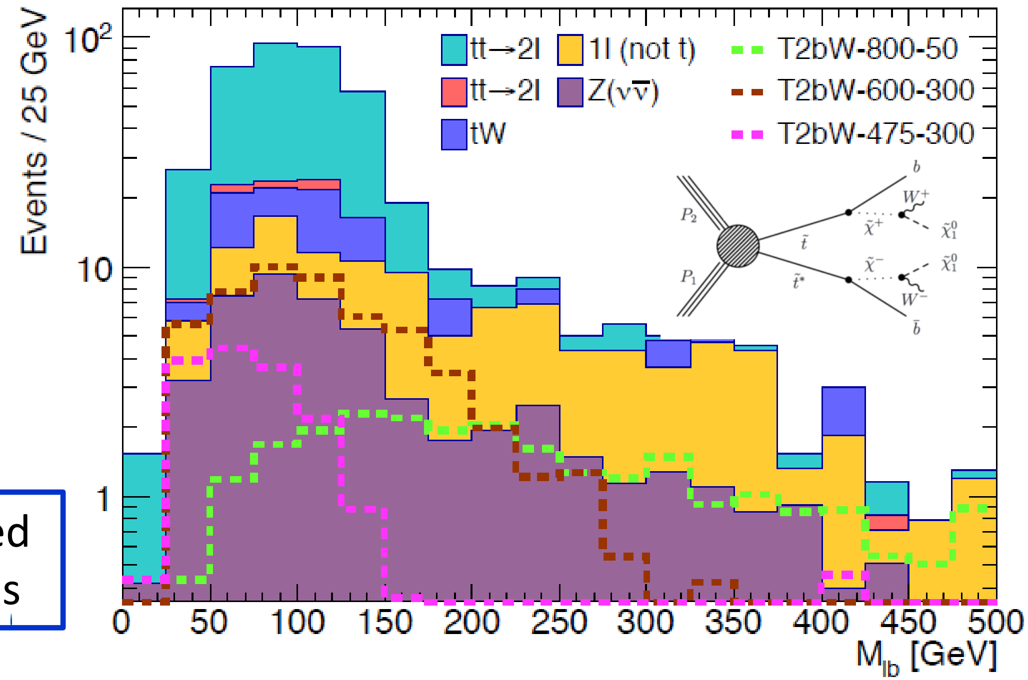
- Looking for top squarks in the single-lepton final state
- Peek at difficult mass spectra
- **Conclusions and outlook**

Possible improvements

- Search regions for decays with intermediate chargino
  - More energetic b jets
    - » Use b jet p_T, M(l,b), N_b=2 category,…
- Compressed mass splittings:
  - Ask for ISR jet activity
  - Use soft leptons

Dedicated analyses

- Better lost lepton background selection:
  - Start from modified topness
    - » Include detector resolution
    - » Use MET covariance matrix
    - » Softer jets



'theoretical width' parameters

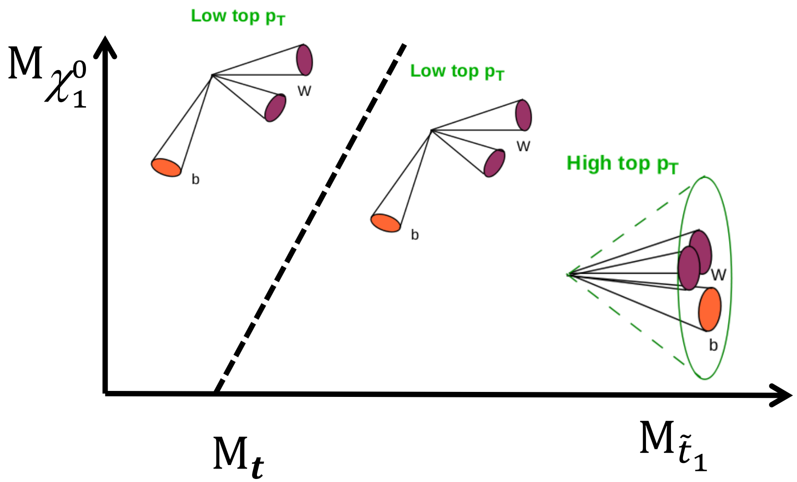
$$t_{\rm mod} = \ln(\min S) \quad \text{with} \quad S(\vec{p}_W, p_{\nu,z}) = \frac{(m_W^2 - (p_\nu + p_\ell)^2)^2}{a_W^4} + \frac{(m_t^2 - (p_{b_2} + p_W)^2)^2}{a_t^4},$$

Constrained to M_W

Constrained to M_{top}

Possible improvements

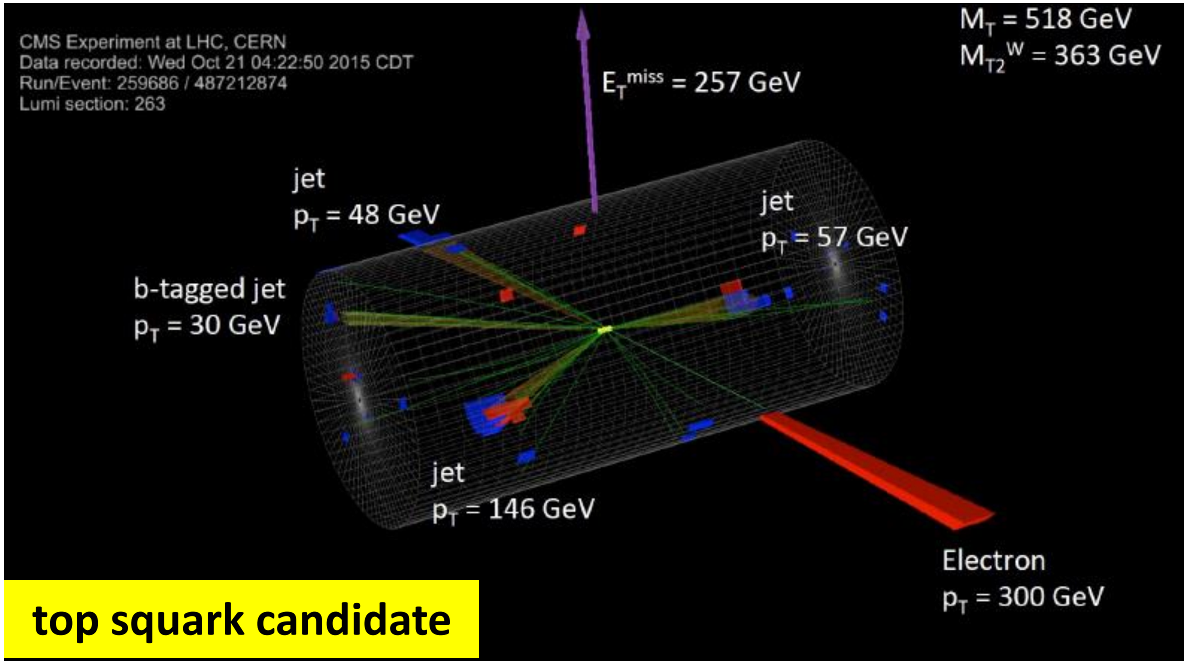
- Identifying hadronic top decays
  - Both boosted and resolved top quark decays
    - » Low p_T top tagging the most important!
  - Also crucial for all-hadronic top squark search



- Improve background prediction
  - Rare backgrounds
  - Current data-driven methods dominated by statistical uncertainties:
    - » Can we replace some by (smaller) systematic uncertainties?

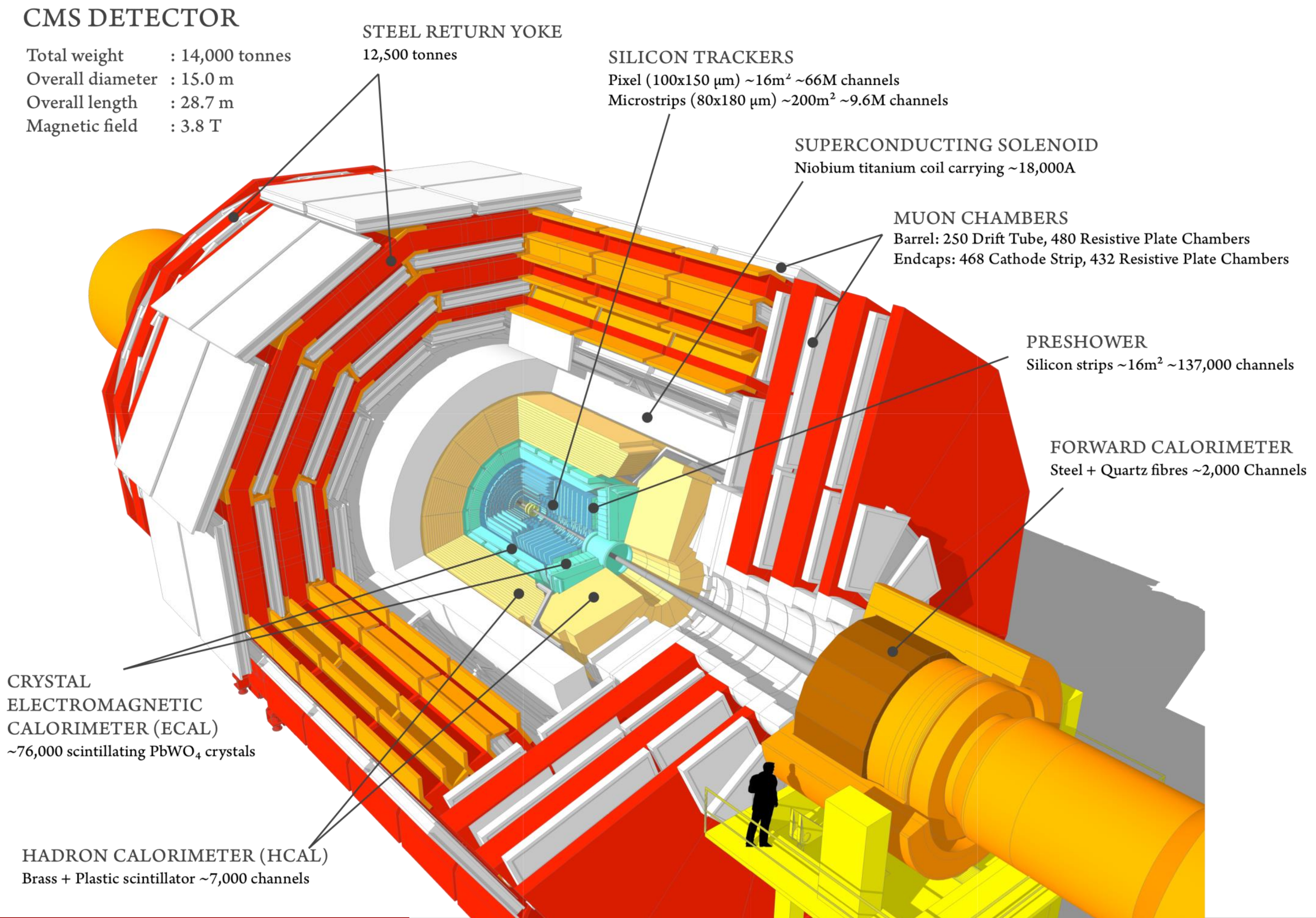
Conclusions

- Light top squarks provide a clean solution for the hierarchy problem
  - And connects nicely to dark matter searches
- With 12.9 fb^{-1} CMS puts stringent limits on top squark masses
  - Start probing 1 TeV mass top squarks
  - Full dataset 3 times larger
- Took a first look at possible improvements



Any questions?

Back-up


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

Other models