u c s b High Energy Physics

Searching for top squarks at CMS

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UC Santa Barbara

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Outline

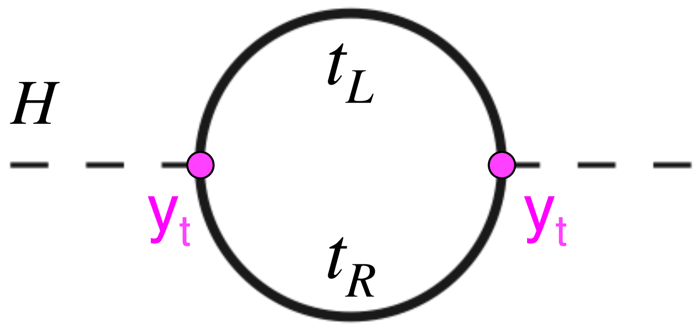
- Why searching for top squarks (stops)
- Top squarks production and decay
- Search in lepton+jets mode at CMS
- Limitations
- Conclsions and prospects

SUSY…..

Hierarchy problem, naturalness

$$\Delta m_H^2 \sim |y_t|^2 \left[-\Lambda_{UV}^2 + \frac{3}{2} m_t^2 \log\left(\frac{\Lambda_{UV}^2}{m_t^2} \right) \right]$$

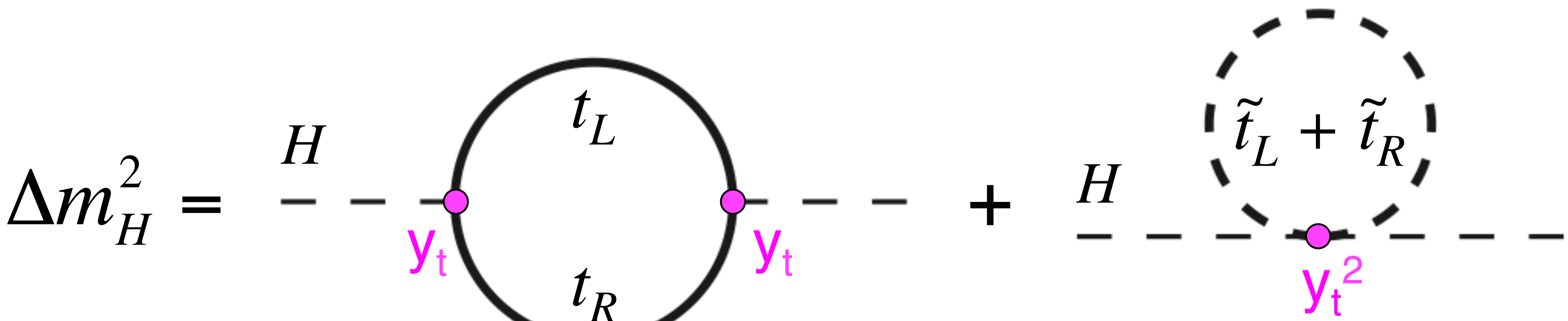
$$\Delta m_H^2 =$$



- In SM enormous radiative corrections to M_{higgs}: $\Delta m^2 \approx \Lambda^2_{UV}$

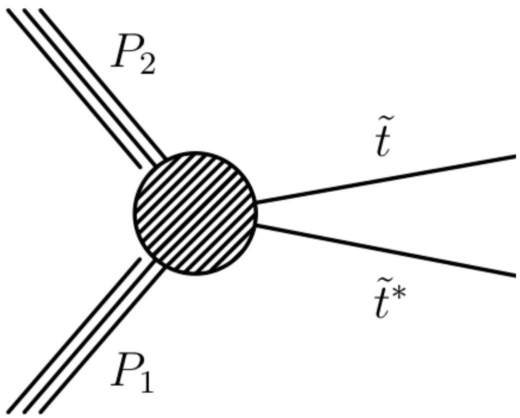
SUSY solution

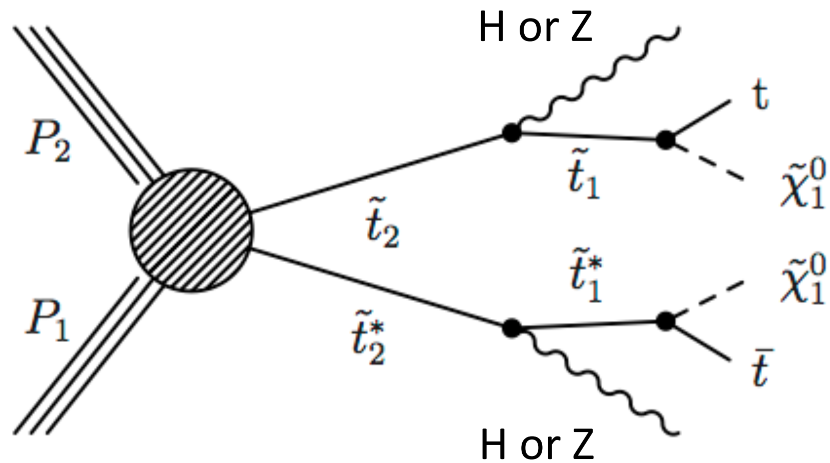
$$\Delta m_H^2 \sim |y_t|^2\left[-\cancel{\Lambda_{UV}^2} + \frac{3}{2} m_t^2 \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right) + \cancel{\Lambda_{UV}^2} - m_{\tilde{t}}^2 \log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}\right) + \ldots\right]$$

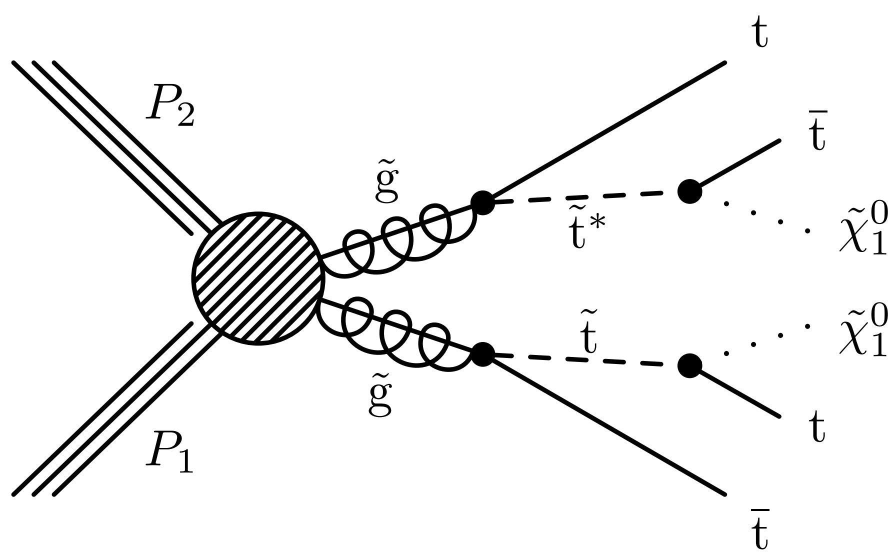


- In SM enormous radiative corrections to M_{higgs}: $\Delta m^2 \approx \Lambda^2_{UV}$
- Stop loop cancels Λ^2_{UV} term, adds $\approx m^2_{stop}$ term
- **Light stops (≤ 0.5-1 TeV) needed for "natural" (not fine-tuned) solution to hierarchy problem**

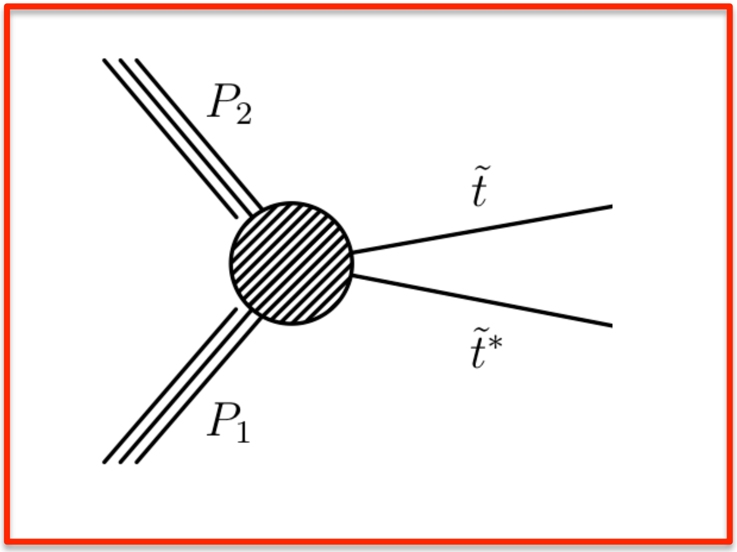
Top squark production processes



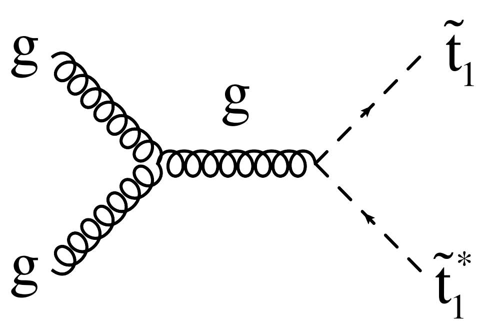




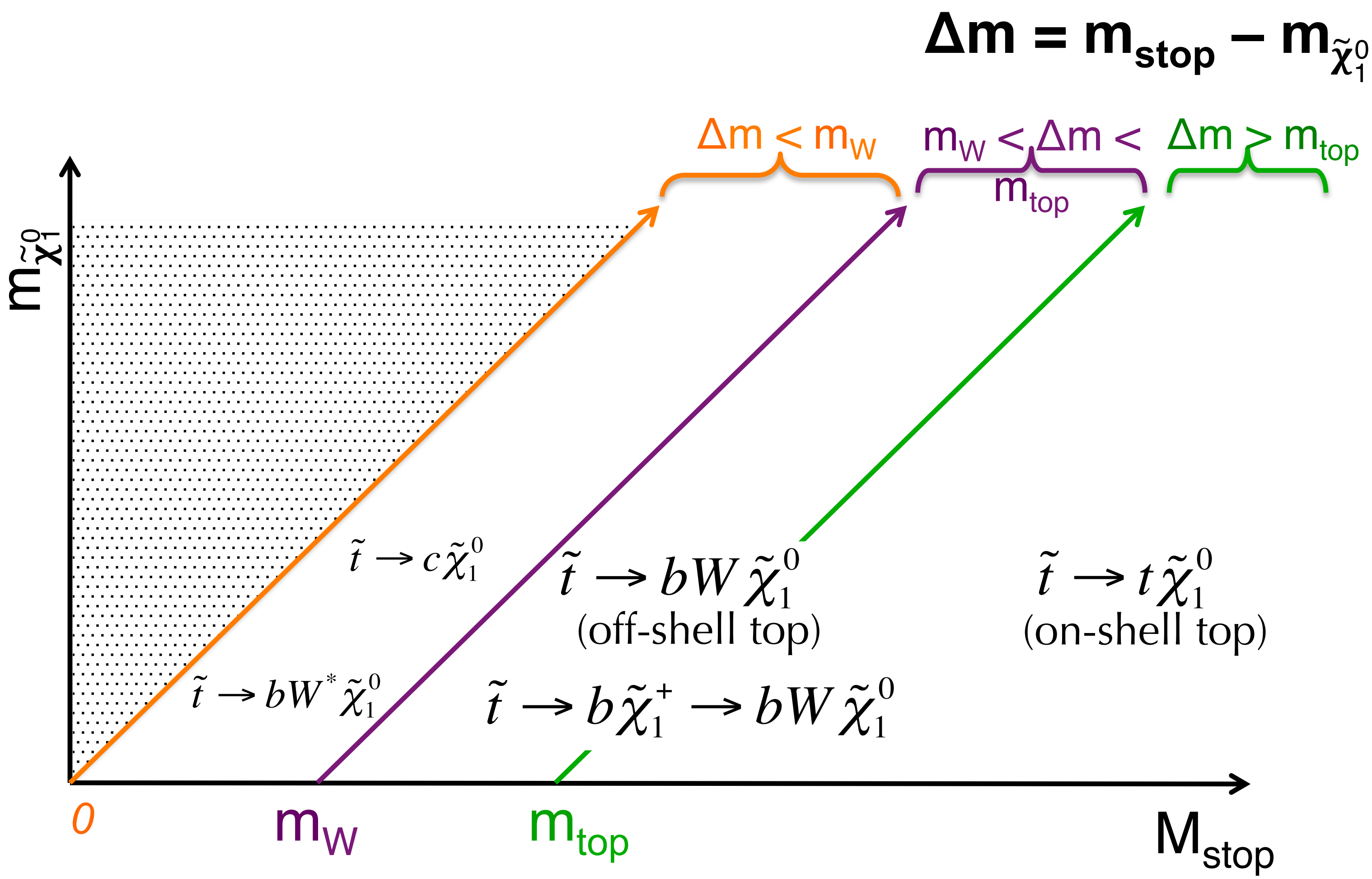
Top squark production processes



Will concentrate on pair production.

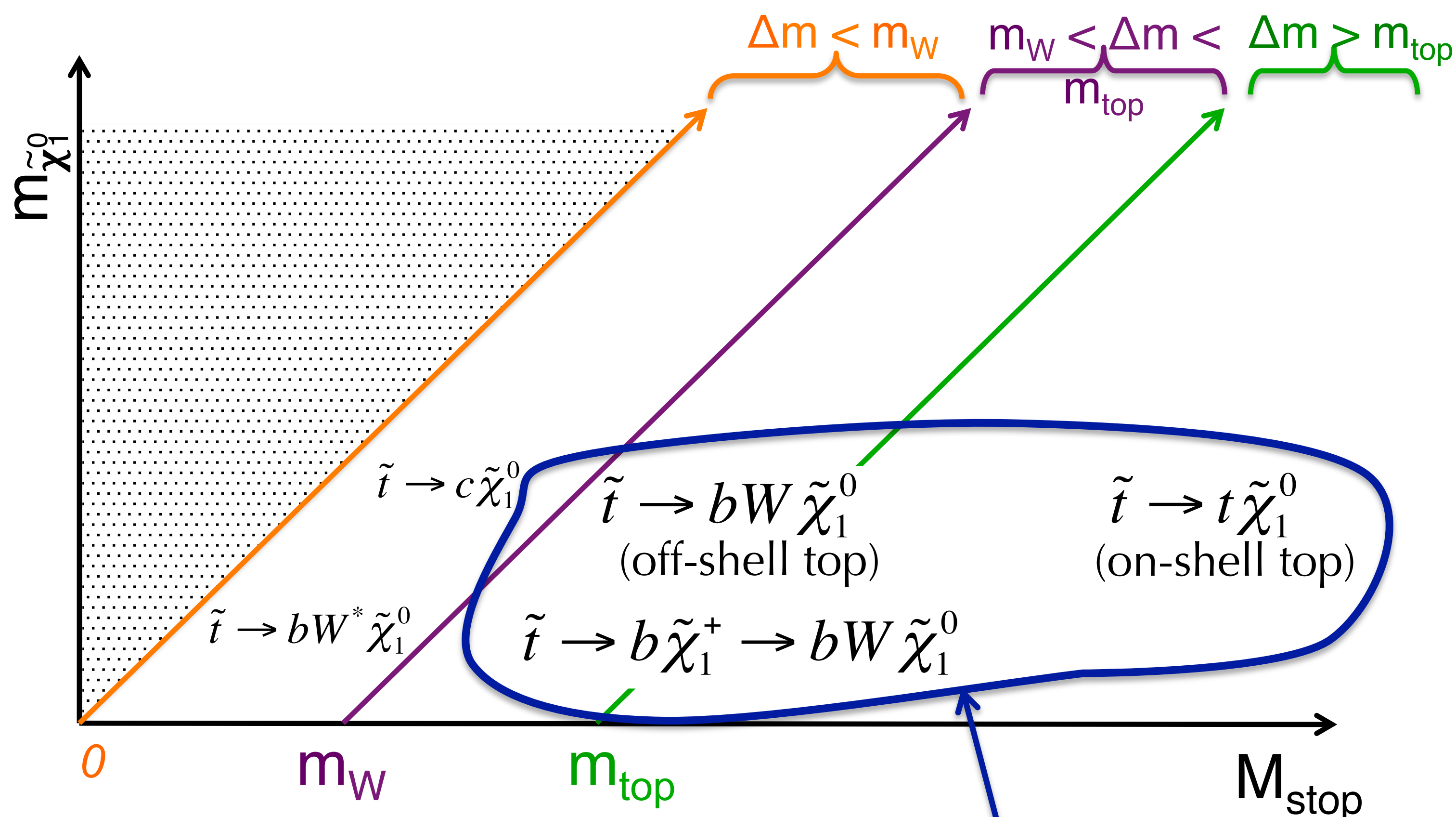


Top squark decay modes (RPC)



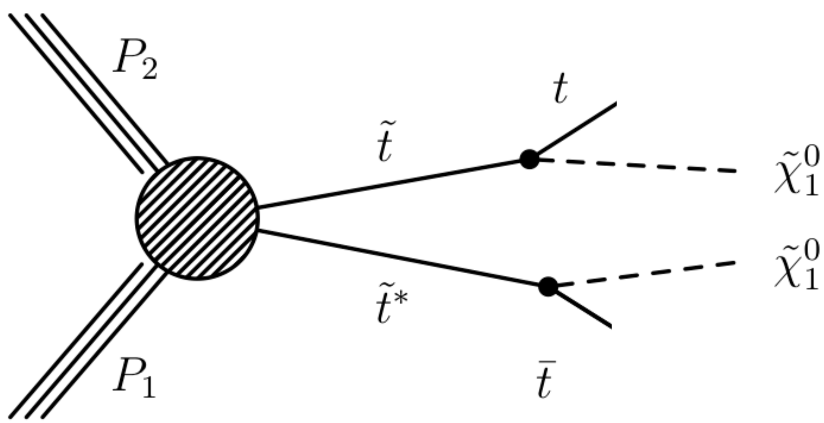
Top squark decay modes (RPC)

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

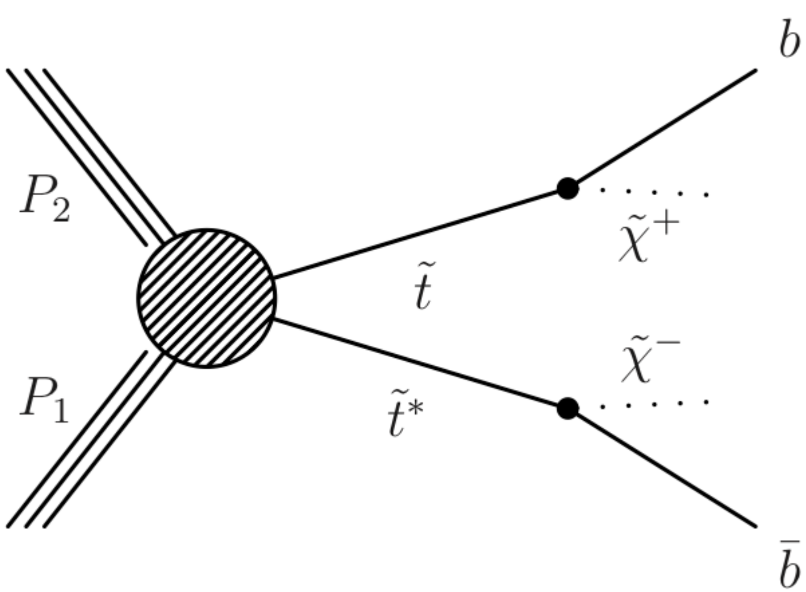


I will talk about these

Top squark decay modes

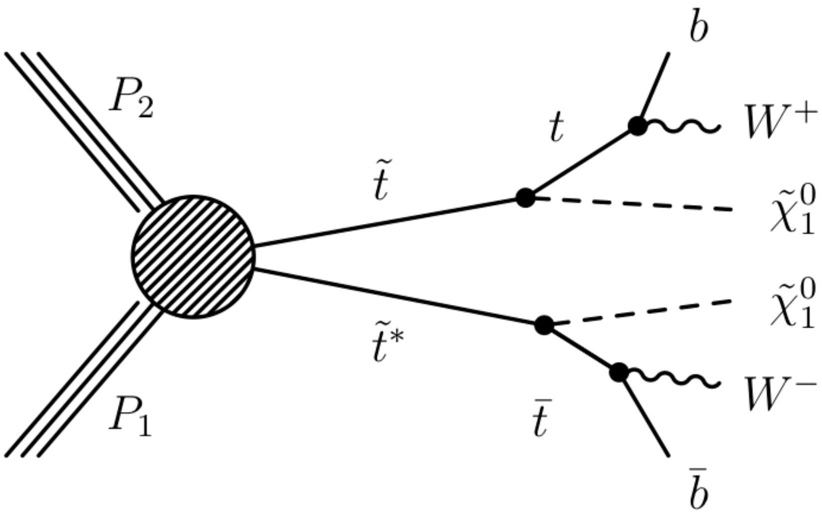


top-neutralino mode



b-chargino mode

Top squark decay modes



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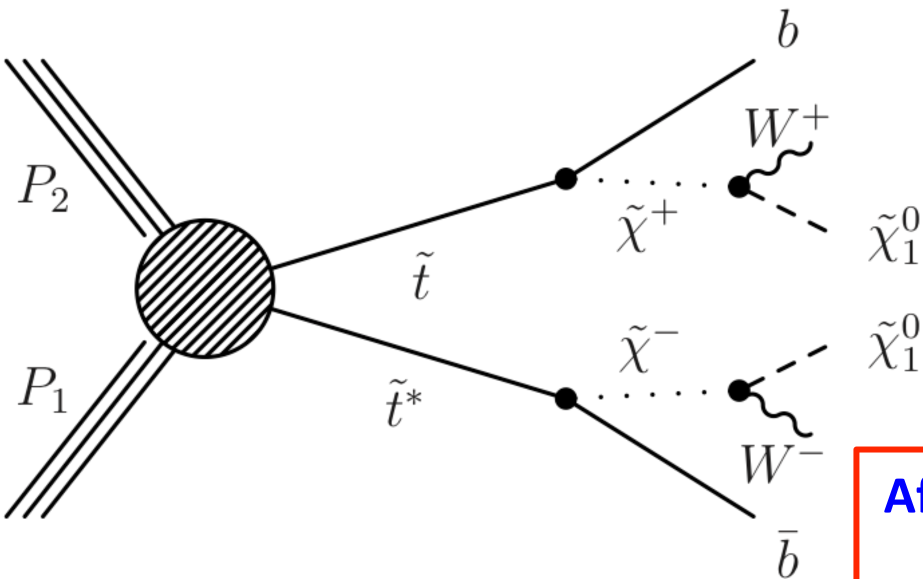

b-chargino mode

After top or chargino decay the final state particles are the same

Signal and background, general considerations

- Signal is "ttbar + MET"
  - MET from neutralinos
- Background is ttbar
  - Also: W+jets, single-top, rare processes (eg: ttbarW)
- Can look in three channels:
  - 0 leptons
  - 1 lepton
  - 2 leptons

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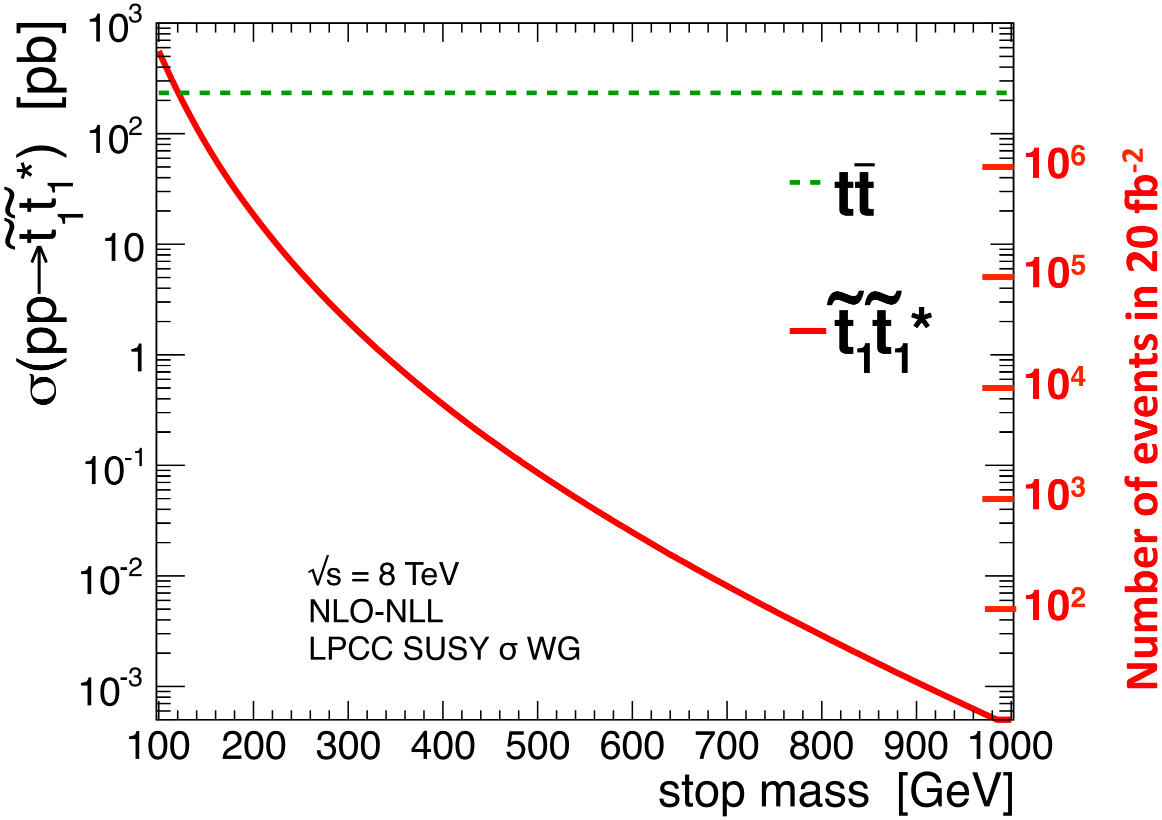
  - 1 lepton ← **This talk EPJC 73 (2013) 2677**
  - 2 leptons

What is the challenge?



The ttbar cross-section is enormous!

Lepton-MET Transverse mass (M_T)

- In semileptonic ttbar, MET is from ν from W→lν
  - → M_T is bound by M_W
- In signal events, MET is from ν from W→lν **and** from two LSPs
  - →M_T easily extend past M_W

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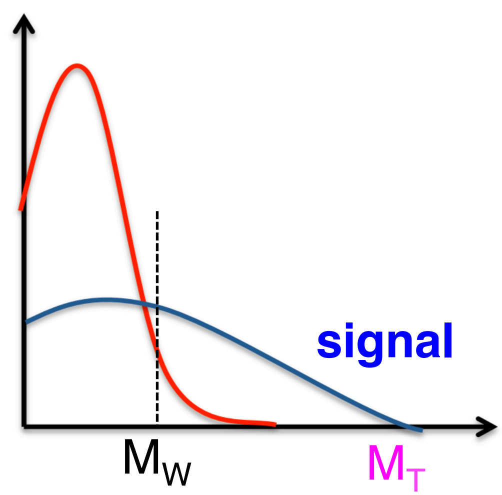

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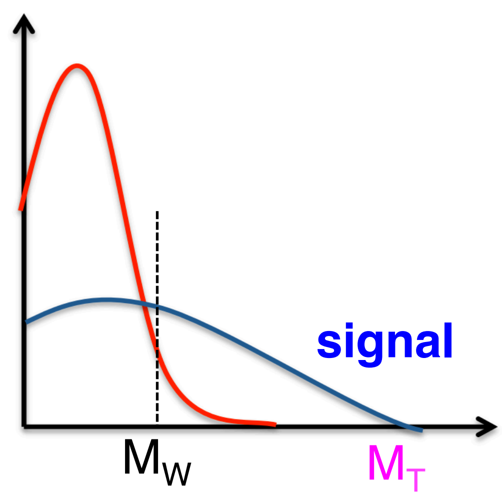
It's a cake walk!

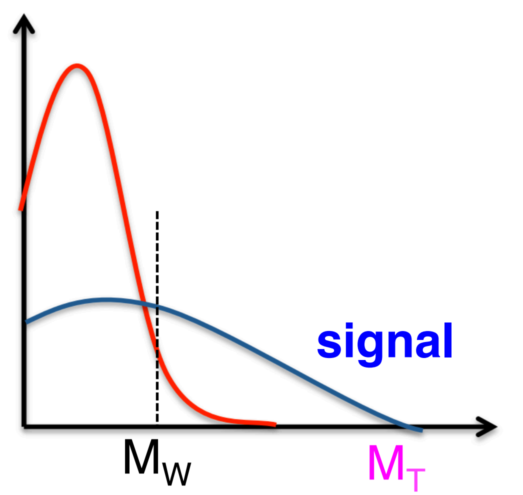


Lepton-MET Transverse mass (M_T)

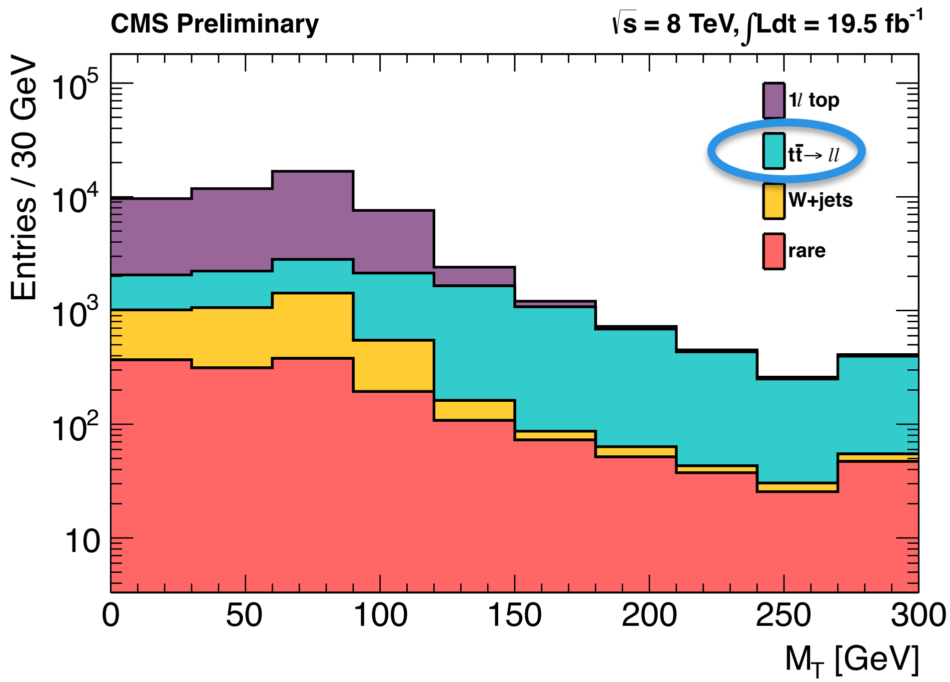
- In semileptonic ttbar, MET is fro… from W→lν
  → M_T is bound by M_W
- In signal events, ME… W→lν **and** from two LSPs…
  → M_T ea… M_W

Not so fast!!!

It's a cake walk!



M_T for lepton+MET+4 jets



M_T tail dominated by ttbar → dileptons

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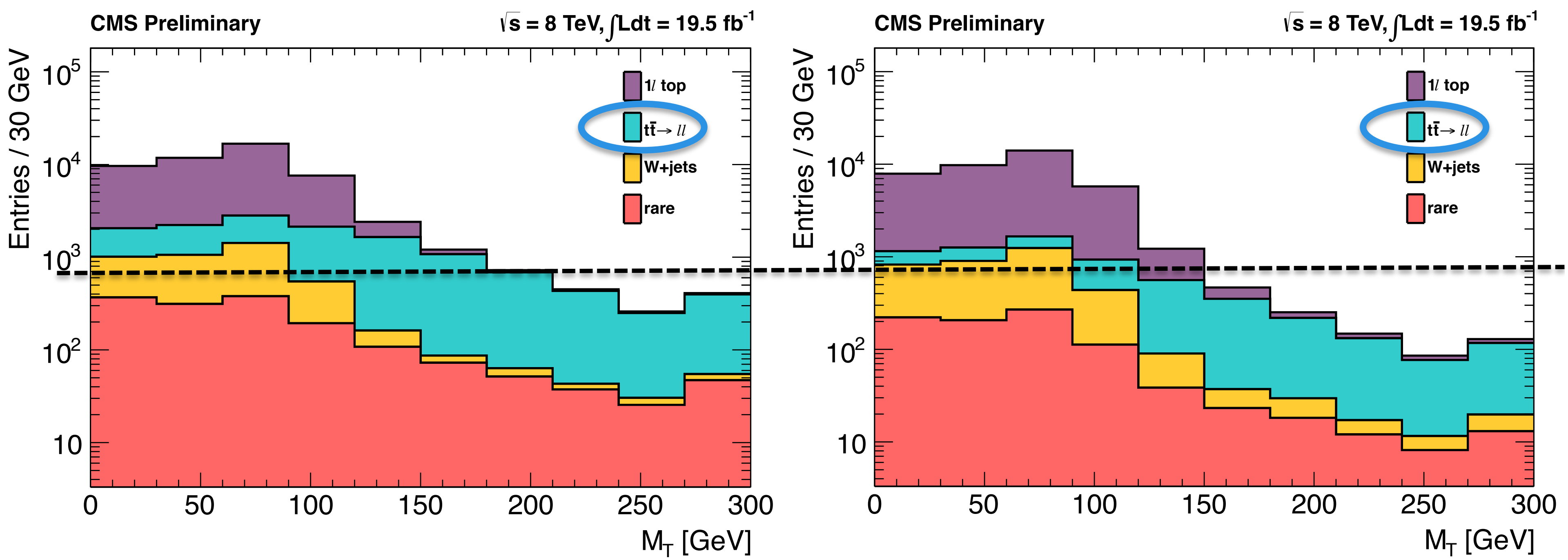


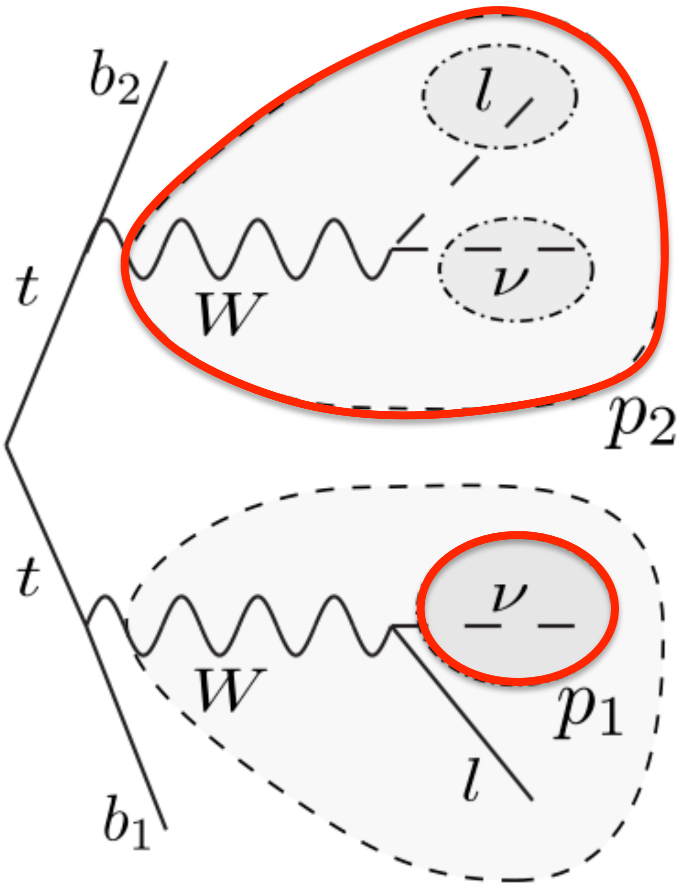
M_T tail dominated by ttbar → dileptons

"Aggressive" 2nd lepton veto helps, but does not solve problem completely

Kinematical Variables

It is clear that more kinematical information in addition to MET and M_T is needed to beat down the background

MT2W: a variable against dileptons



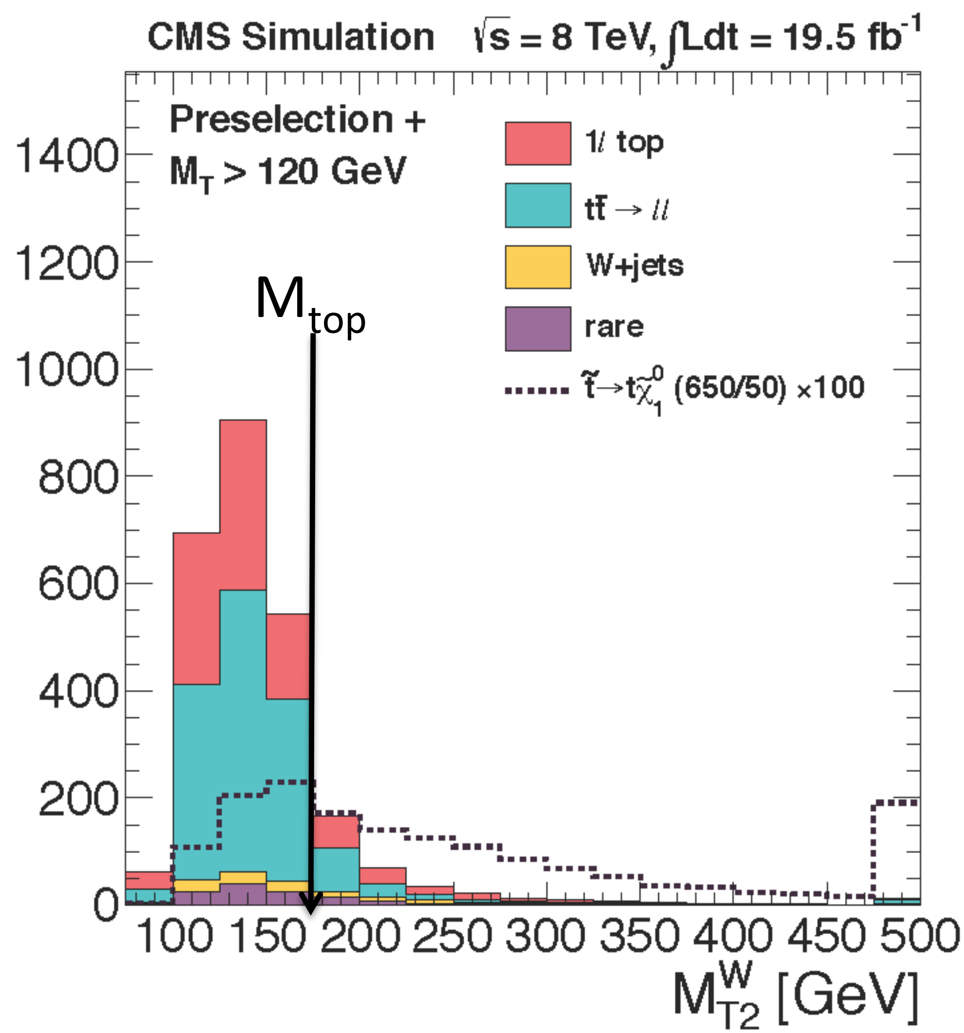
— = “missing” particles

MT2W is the minimum “mother” mass compatible with all P_T and invariant mass constraints

Bai, Cheng, Gallichio, Gu
JHEP 07 (2012) 110

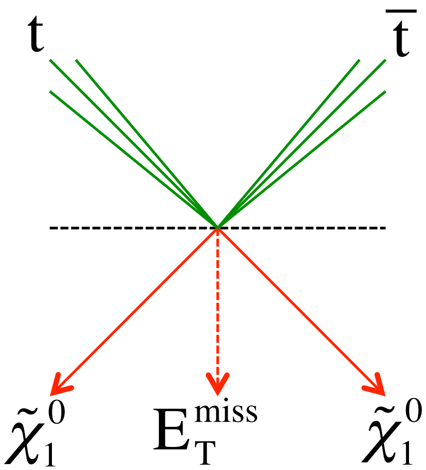
$$M_{T2}^{W} = min\left\{m_y \text{ consistent with: } \left[\begin{array}{c} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{mis}, p_1^2 = 0, (p_1 + p_l)^2 = p_2^2 = M_W^2, \\ (p_1 + p_l + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array}\right]\right\}$$

MT2W works very well!



Correlation btw MET and had. activity (part 1)

Many signal events look like this:



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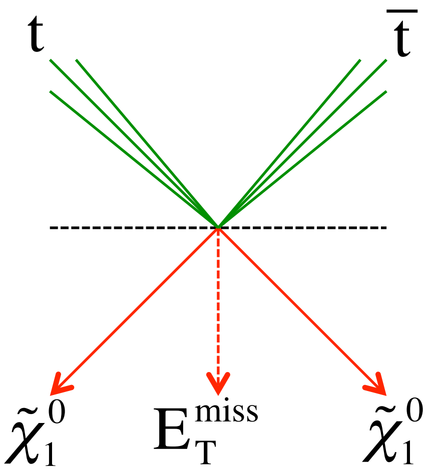
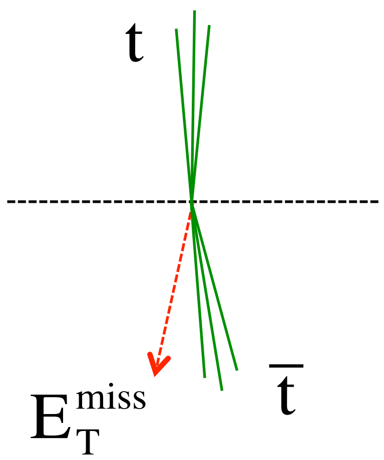


Most background events look like this:



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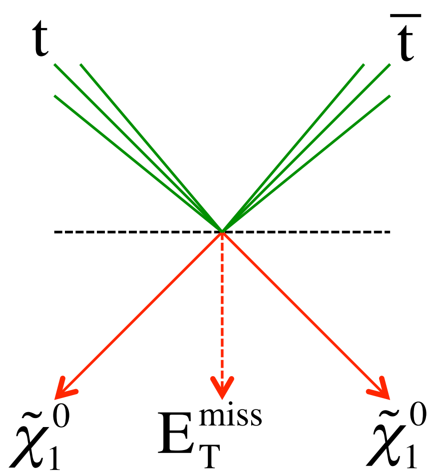

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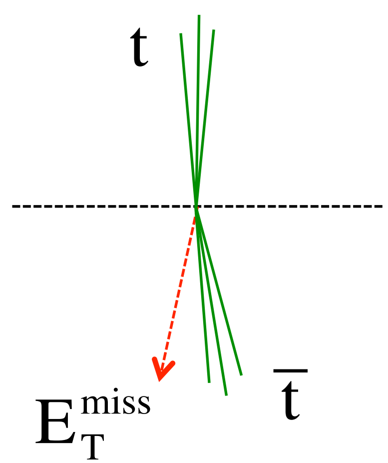
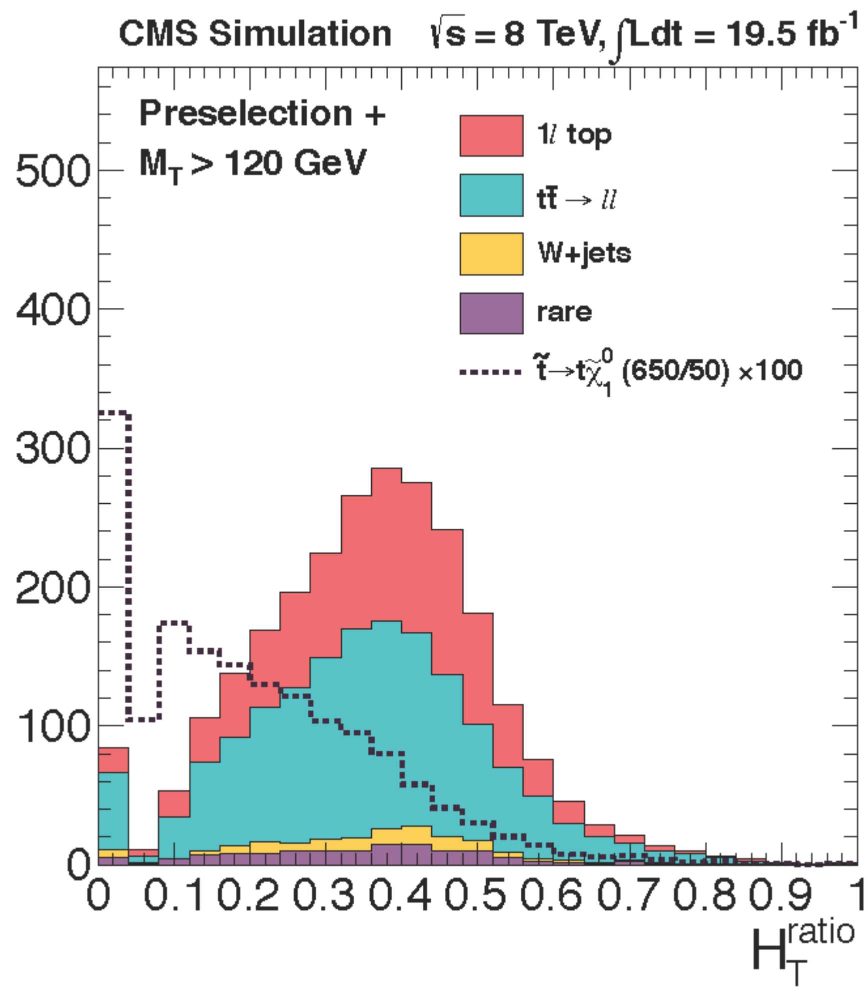


The fraction of H_T in same hemisphere as the MET is a useful variable



Correlation btw MET and had. activity (part 2)

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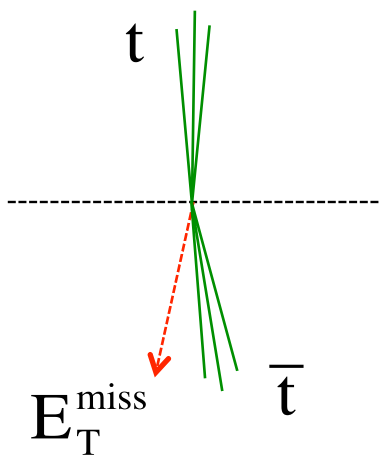

Suggests use of global event shape variables, eg, sphericity, thrust…..

Correlation btw MET and had. activity (part 2)

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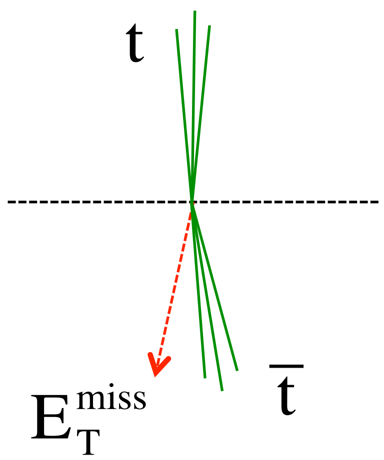
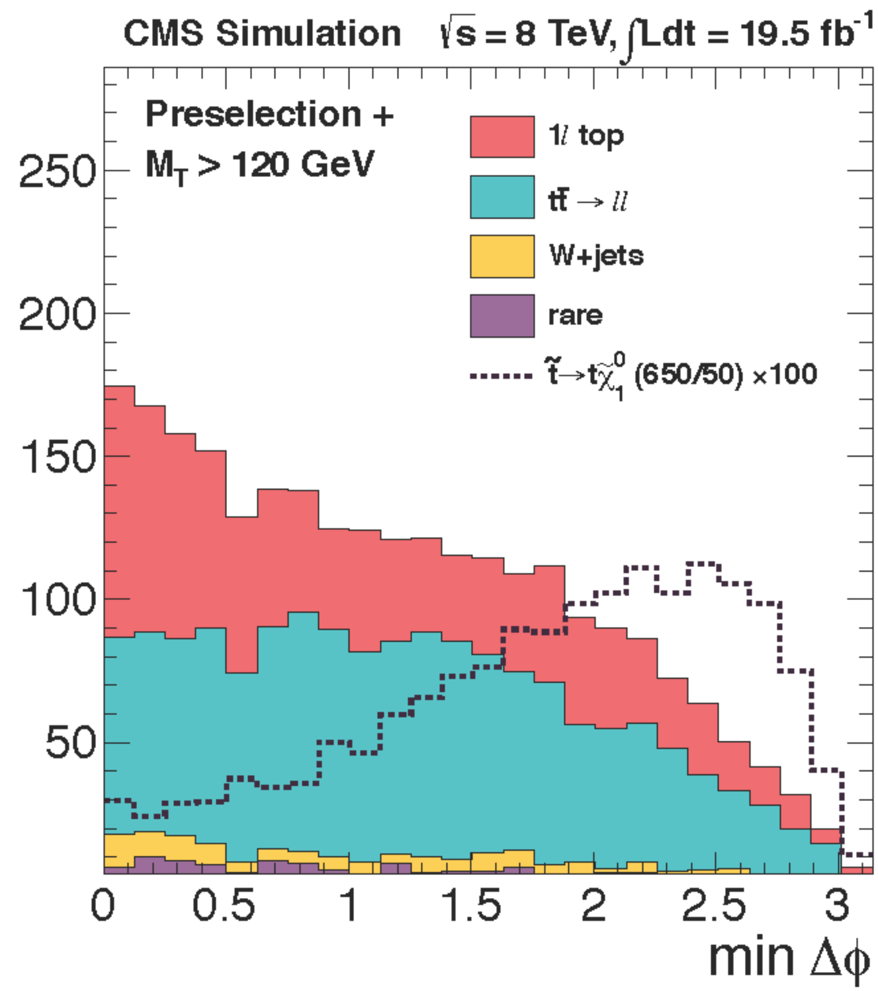
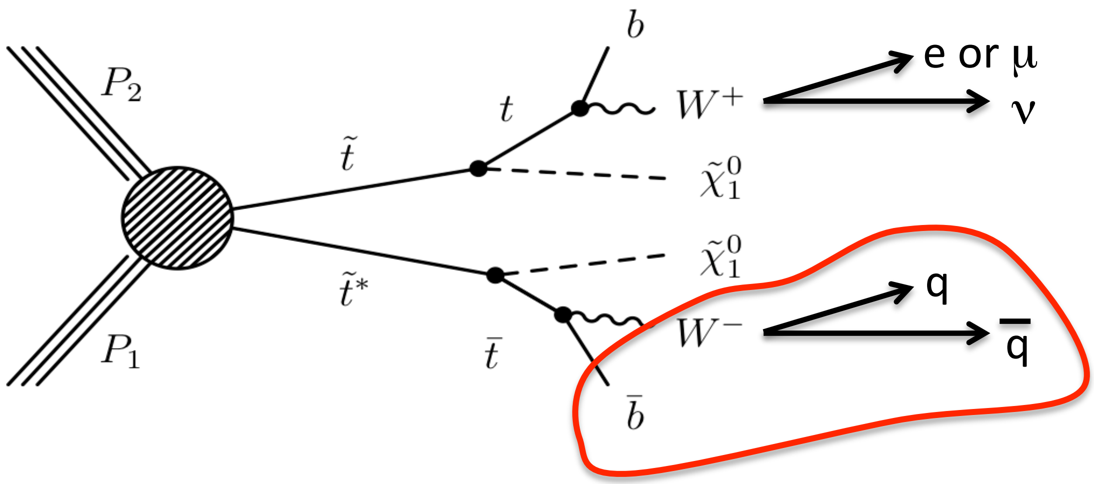


Suggests use of global event shape variables, eg, sphericity, thrust…..

To our surprise: simple variable
min[Δϕ(jet$_1$,MET), Δϕ(jet$_2$,MET)]
works the best



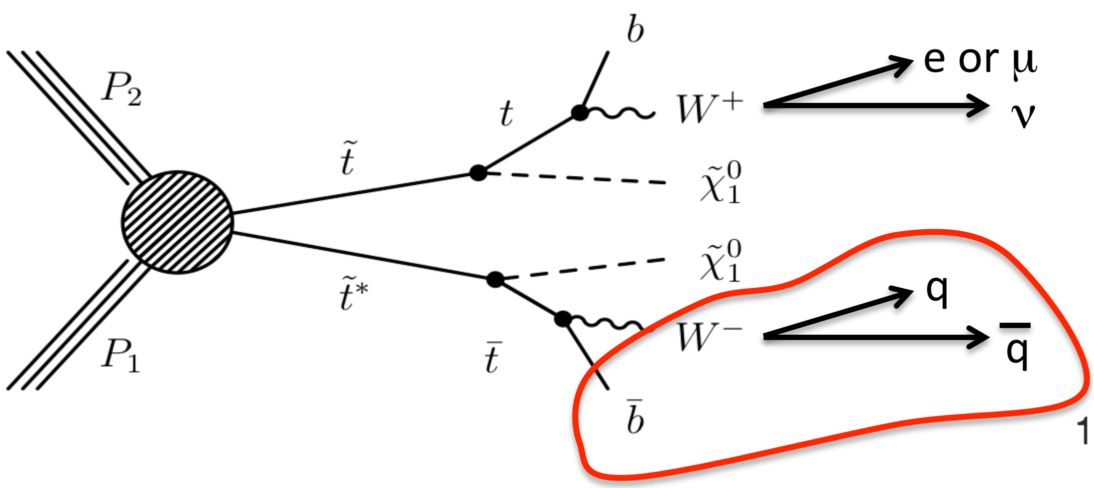
Hadronic top mass reconstruction



top-neutralino mode

- Signal has hadronically decaying top
- Main BG (dileptons) does not

Hadronic top mass reconstruction



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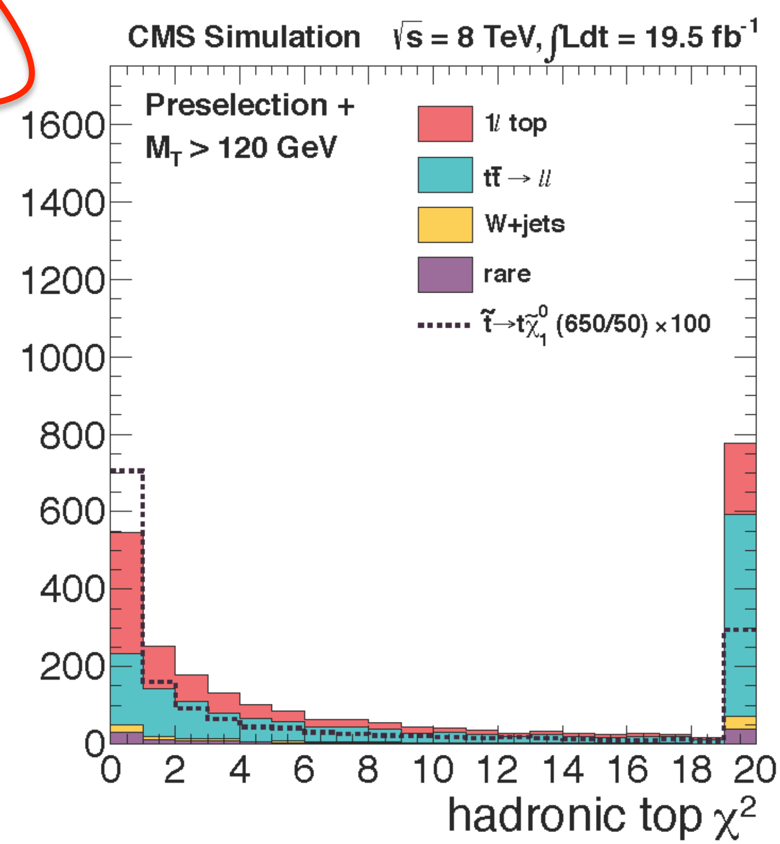
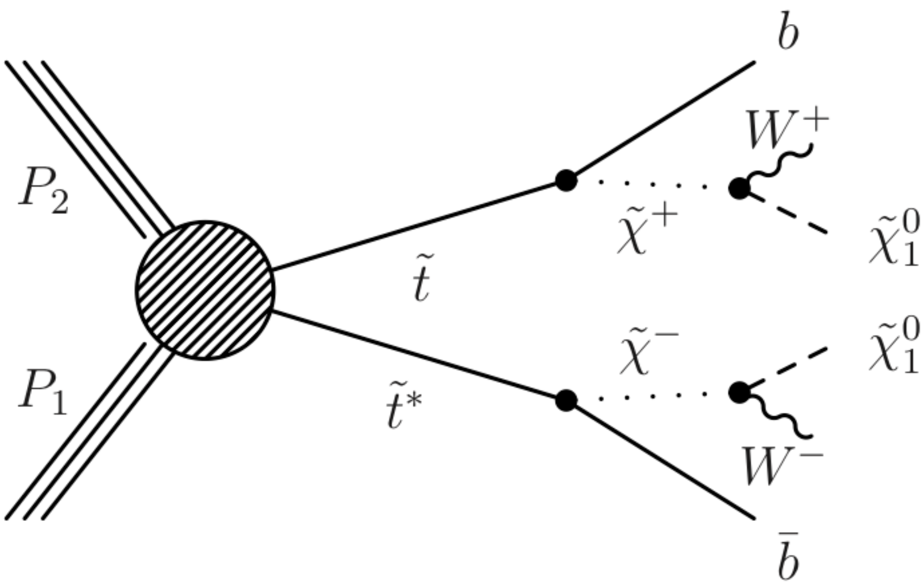


- Signal has hadronically decaying top
- Main BG (dileptons) does not

→ Build 3-jet χ^2 to hadronic top hypothesis

b-quark properties



b-chargino mode

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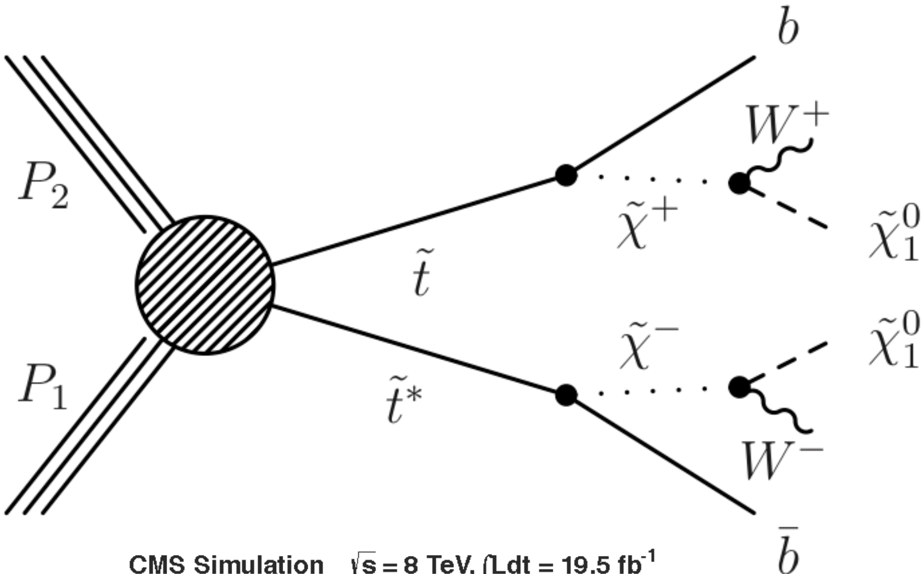
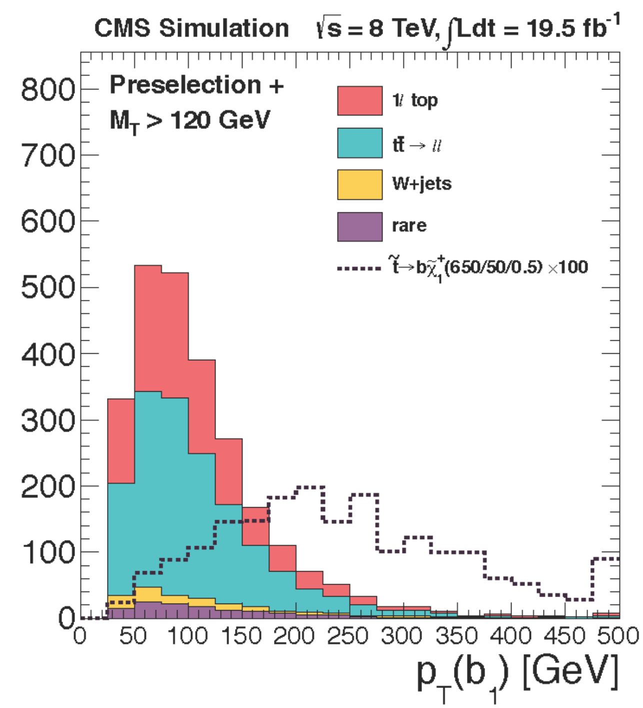
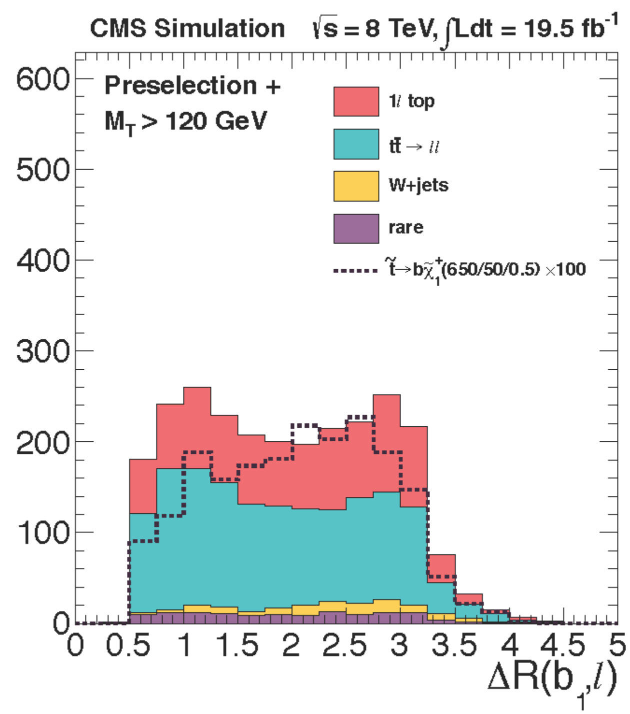


b-chargino mode

Obviously kinematical properties of b-quarks are different depending on whether the b's come from top decay (BG) or directly from stop decay (signal)





Search strategy in a nutshell

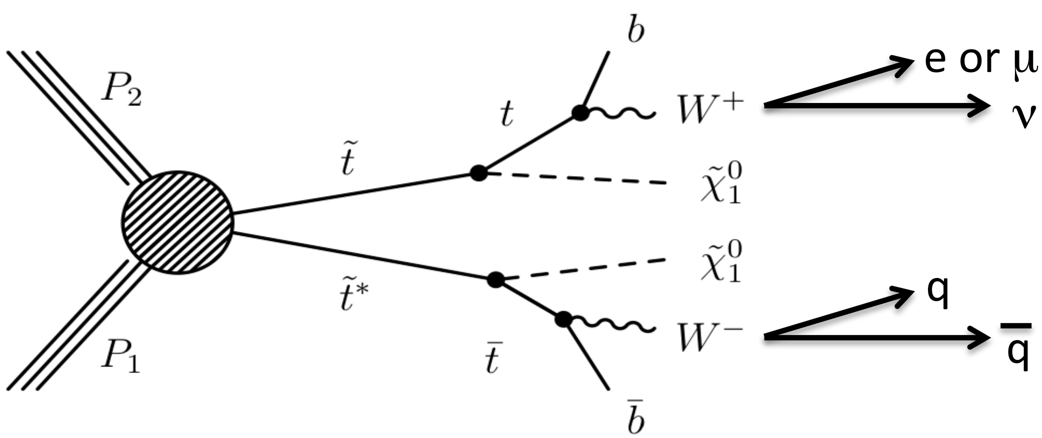
Signal Selection

- Start with a lepton + jets preselection
- Kill as many ttbar→dileptons as possible
- Use kinematical variables to reduce background
  - Cut-and-count
  - Multivariate
- Different "signal regions" to cover as much phase space as possible

Background Determination

- From Monte Carlo
- Calibrate/correct Monte Carlo with "control regions"

Signal Selection: Preselection



- **1 isolated e or μ, P_T > 30 GeV**
- **≥ 4 jets, P_T > 30 GeV, $|\eta|$ < 2.4**
- **at least one btagged jet**
- **MET > 100 GeV**
- **2nd lepton veto**

Signal Selection: dilepton veto

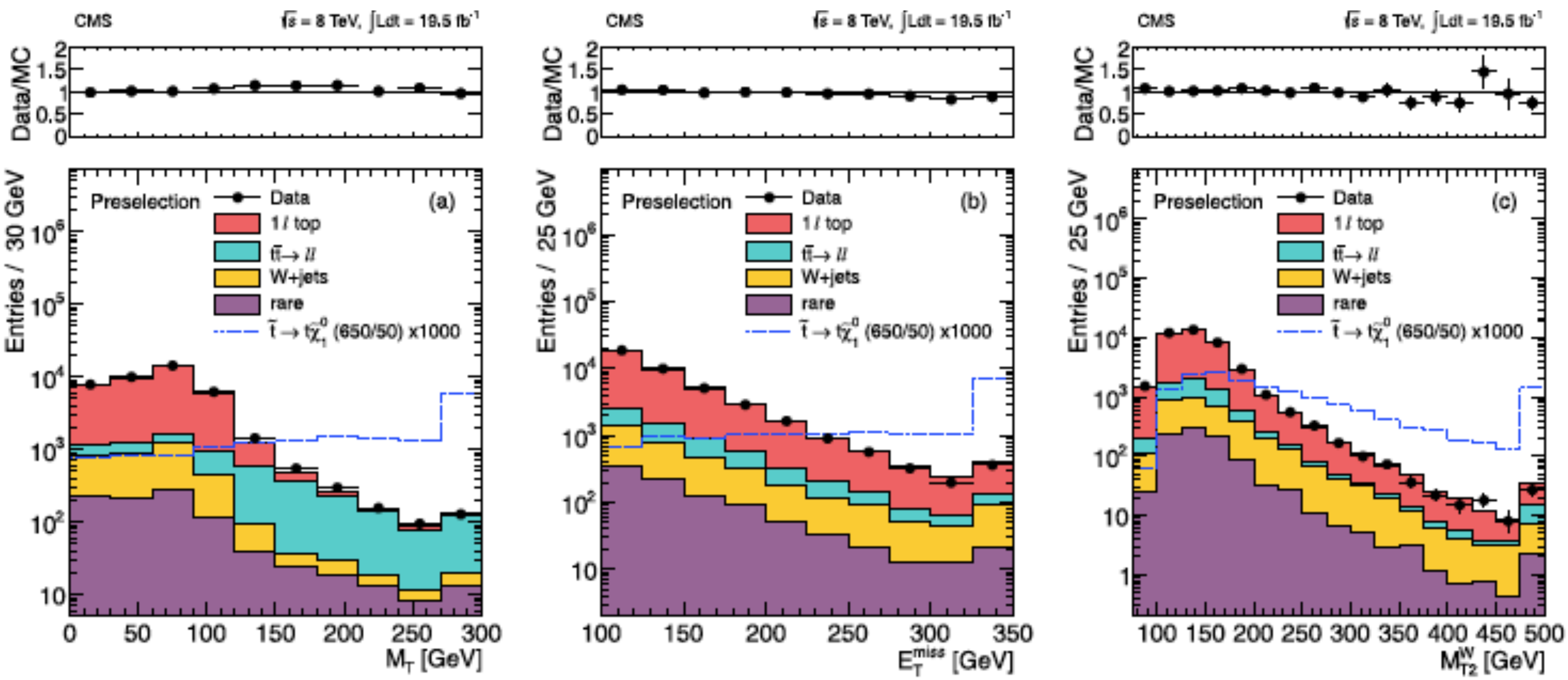
- Veto events with one isolated track P_T > 10 GeV
  - Also catches $W \rightarrow \tau \rightarrow \pi\nu$
- If the track passes very loose electron or muon ID requirements, lower the P_T cut to 5 GeV and loosen the isolation further
- Veto events with identified hadronic τ candidates of P_T > 20 GeV
  - Catches some multiprong tau decays

Signal Selection: cut-and-count vs. multivariate

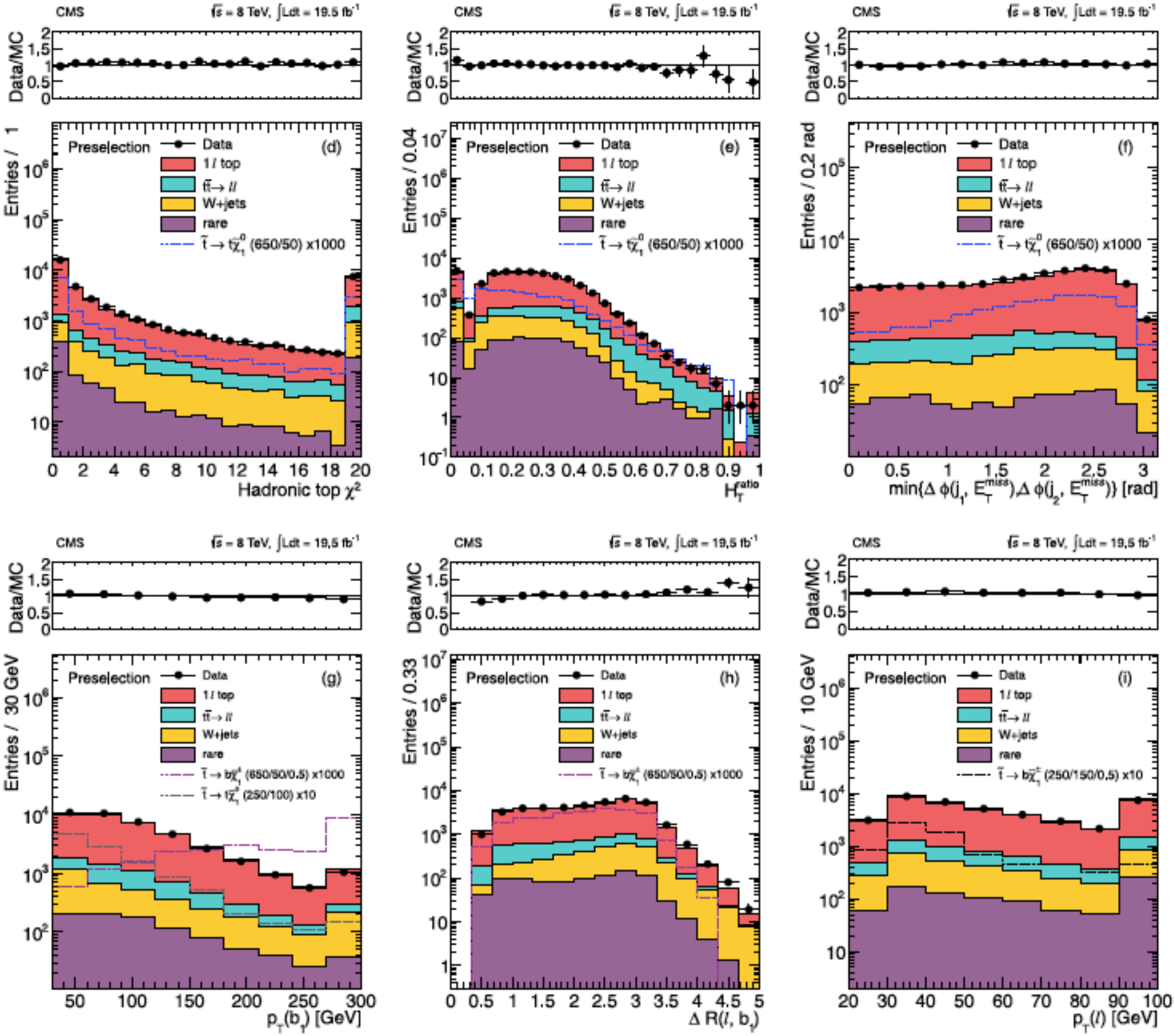
- Multivariate analysis has "ultimate sensitivity"
- "Cut-and-count" arguably more robust
- More importantly: cut-and-count less sensitive to model details. (Will come back to that)

<u>Do both analyses in parallel</u>

Kinematical quantities well understood



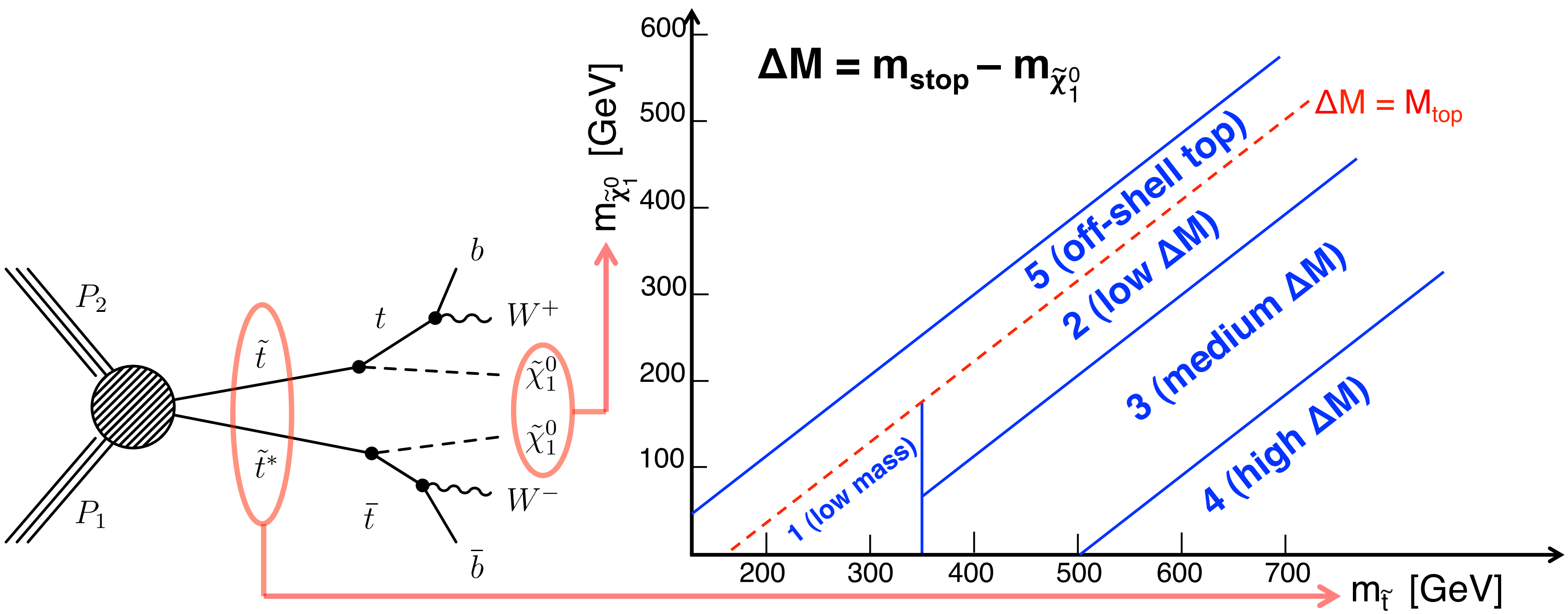
After preselection


CMS
√s = 8 TeV, ∫Ldt = 19.5 fb⁻¹
Data/MC
Preselection
Data
1 l top
tt̄→ ll
W+jets
rare
t̃ → tχ̃⁰₁ (650/50) x1000
(d)
Entries / 1
Hadronic top χ²
(e)
Entries / 0.04
H_T^ratio
(f)
Entries / 0.2 rad
min(Δ φ(j₁, E_T^miss),Δ φ(j₂, E_T^miss)) [rad]
(g)
Entries / 30 GeV
t̃ → bχ̃⁺₁ (650/50/0.5) x1000
t̃ → tχ̃⁰₁ (250/100) x10
p_T(b₁) [GeV]
(h)
Entries / 0.33
Δ R(l, b₁)
(i)
Entries / 10 GeV
t̃ → bχ̃⁺₁ (250/150/0.5) x10
p_T(l) [GeV]

Signal Region Selection

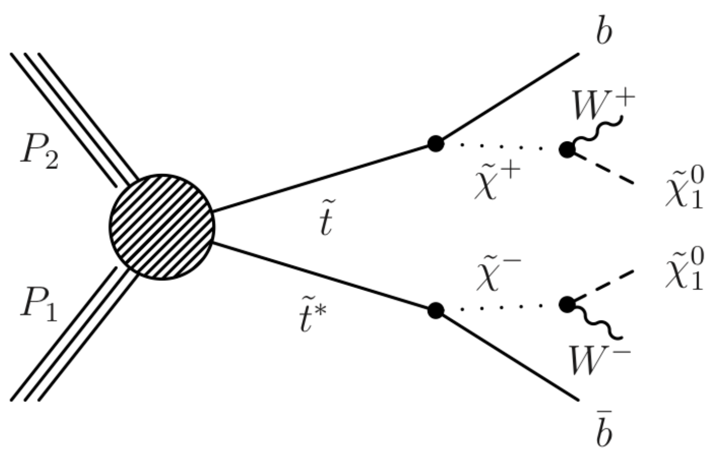
- Cross-section and kinematical properties of signal vary widely as a function of stop mass
- Must introduce different signal regions to target different corners of phase space

top-neutralino mode

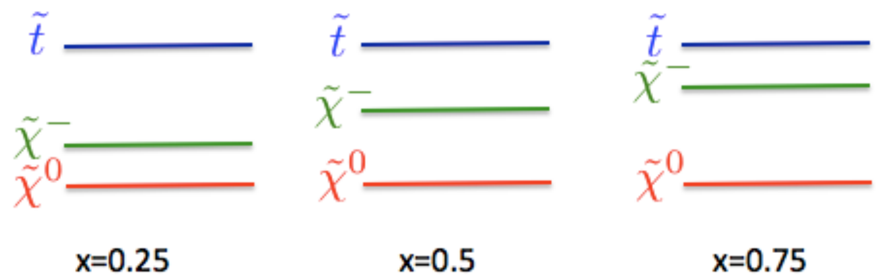


Kinematics depend on ΔM → train 5 different BDTs

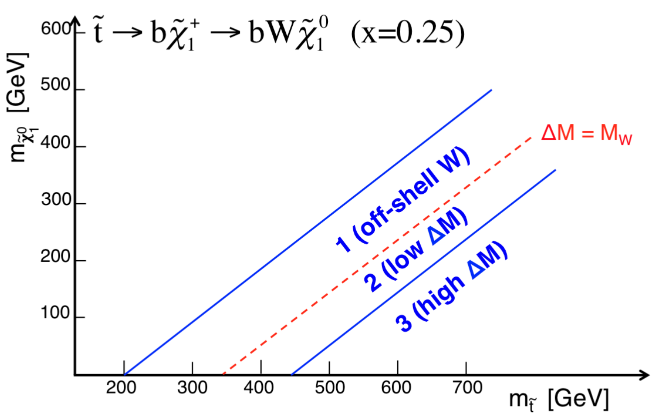
b-chargino mode

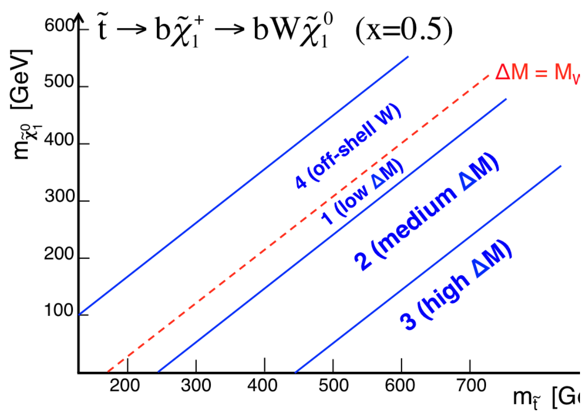


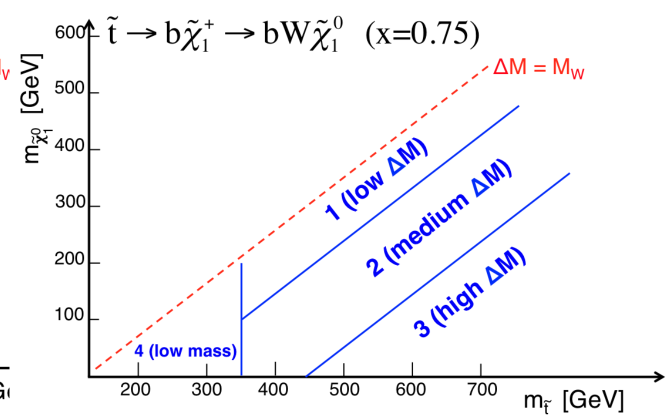
Consider 3 mass spectra:



ΔM = M(chargino)- M(LSP)







Kinematics depend on x,ΔM → train 11 different BDTs

Signal regions summary

	$\tilde{t} \to t\tilde{\chi}_1^0$			$\tilde{t} \to b\tilde{\chi}_1^+$		
		cut-based			cut-based	
Selection	BDT	Low ΔM	High ΔM	BDT	Low ΔM	High ΔM
E_T^{miss}(GeV)	yes	$> 150, 200, 250, 300$	$> 150, 200, 250, 300$	yes	$> 100, 150, 200, 250$	$> 100, 150, 200, 250$
M_{T2}^W (GeV)	yes		> 200	yes		> 200
min $\Delta\phi$	yes	> 0.8	> 0.8	yes	> 0.8	> 0.8
H_T^{ratio}	yes			yes		
hadronic top χ^2	(on-shell top)	< 5	< 5			
leading b-jet p_T (GeV)	(off-shell top)			yes		> 100
$\Delta R(\ell$,leading b-jet)				yes		
lepton p_T				(off shell W)		

- **We end up with 18 (BDT) and 16 (cut-and-count) signal regions (SRs)**
- **M_T > 120 GeV cut common to all SRs (not in BDT)**

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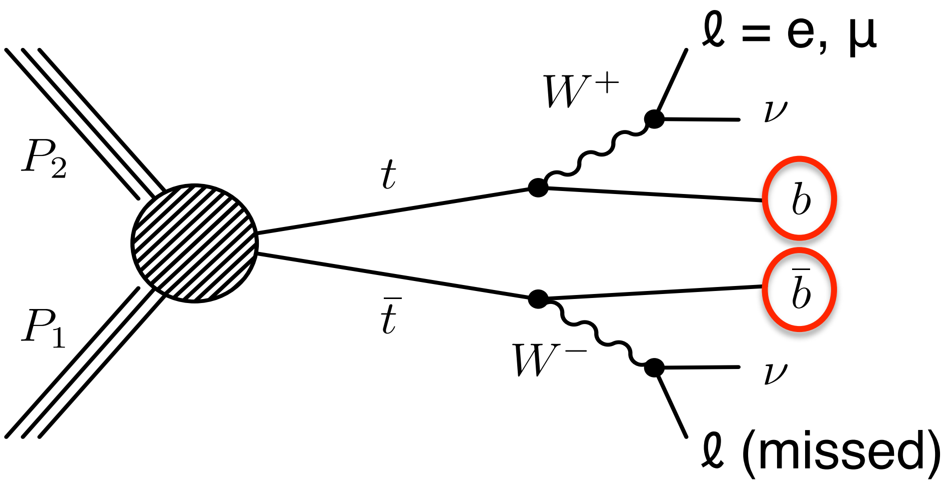
Control Regions (CR)

Define CRs to test the MC modeling of individual variables or even the full event selection on BG-enriched samples

1. **CR with bveto**
   - Enriched in W+jets.

2. **CR with 2nd well-identified lepton or isolated track**
   - Enriched in ttbar→dileptons

Modeling of initial state radiation (ISR)



- Main background: ttbar → dileptons
- Only two jets

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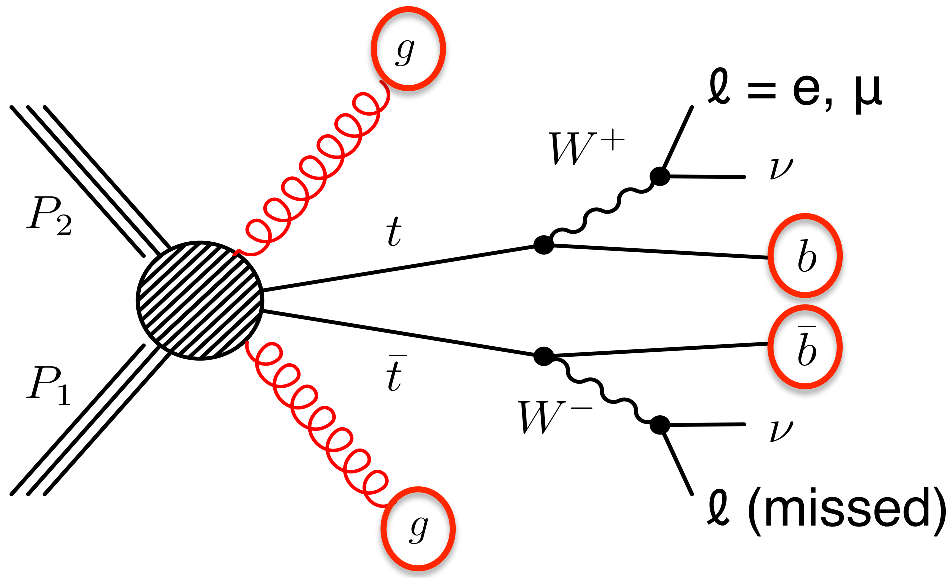
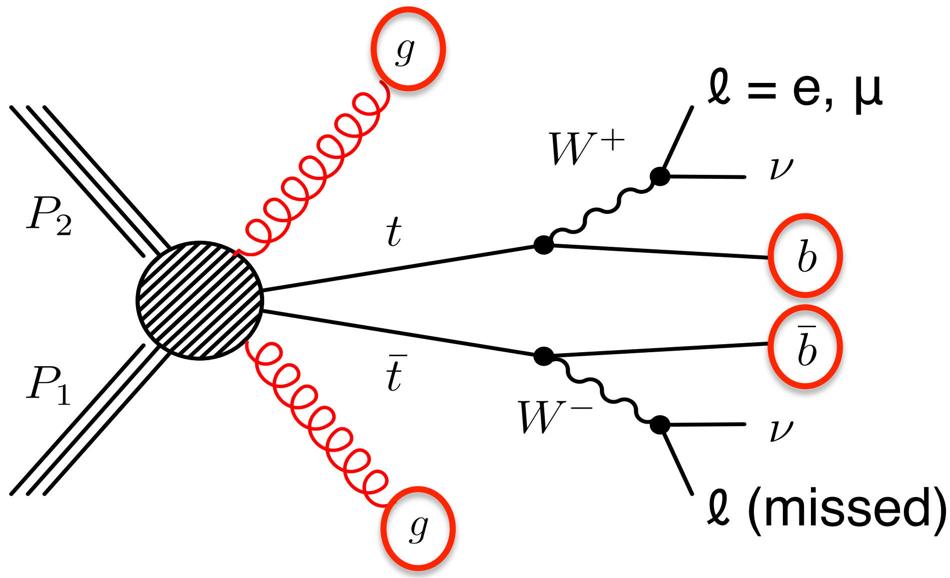
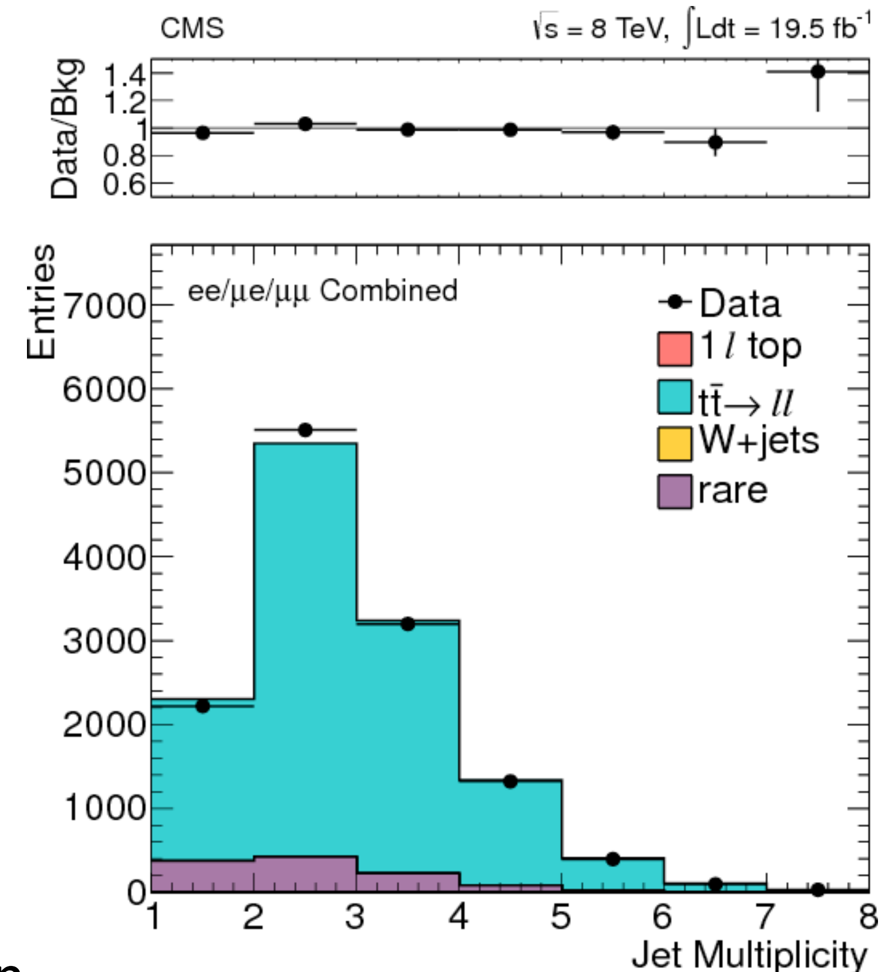


- Main background: ttbar → dileptons
- Only two jets
- Need 2 jets from ISR to pass selection

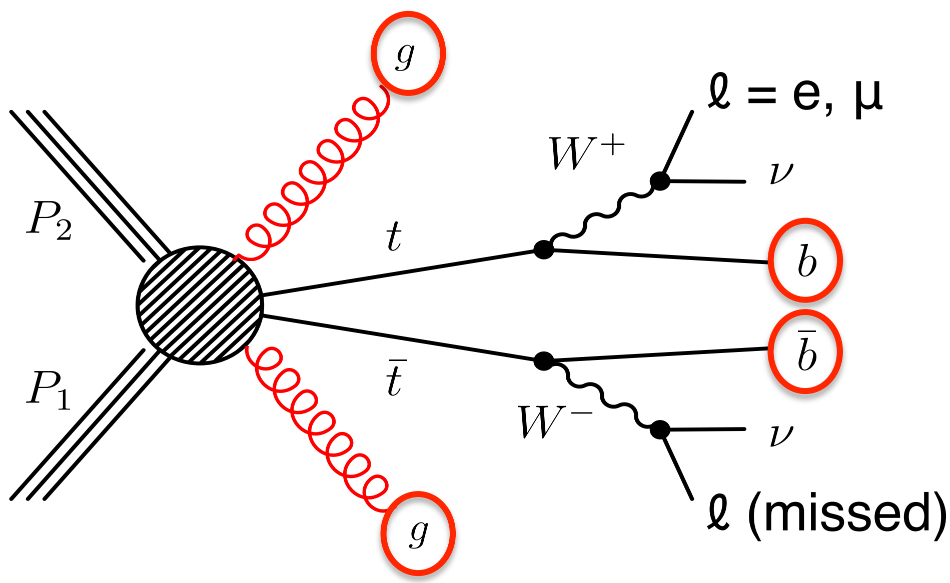
Modeling of initial state radiation (ISR)

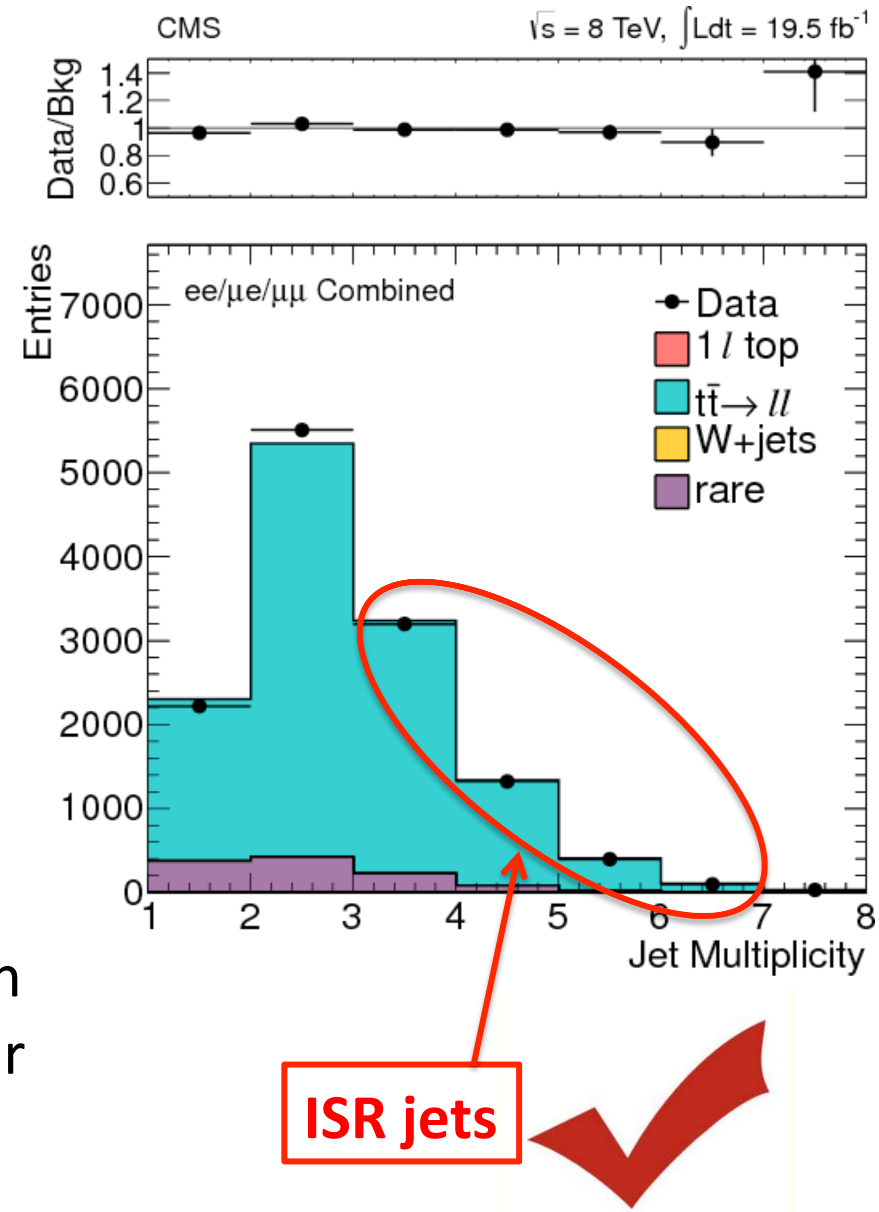




- Main background: ttbar → dileptons
- Only two jets
- Need 2 jets from ISR to pass selection
- Check jet multiplicity in dilepton ttbar

Modeling of initial state radiation (ISR)





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- Only two jets
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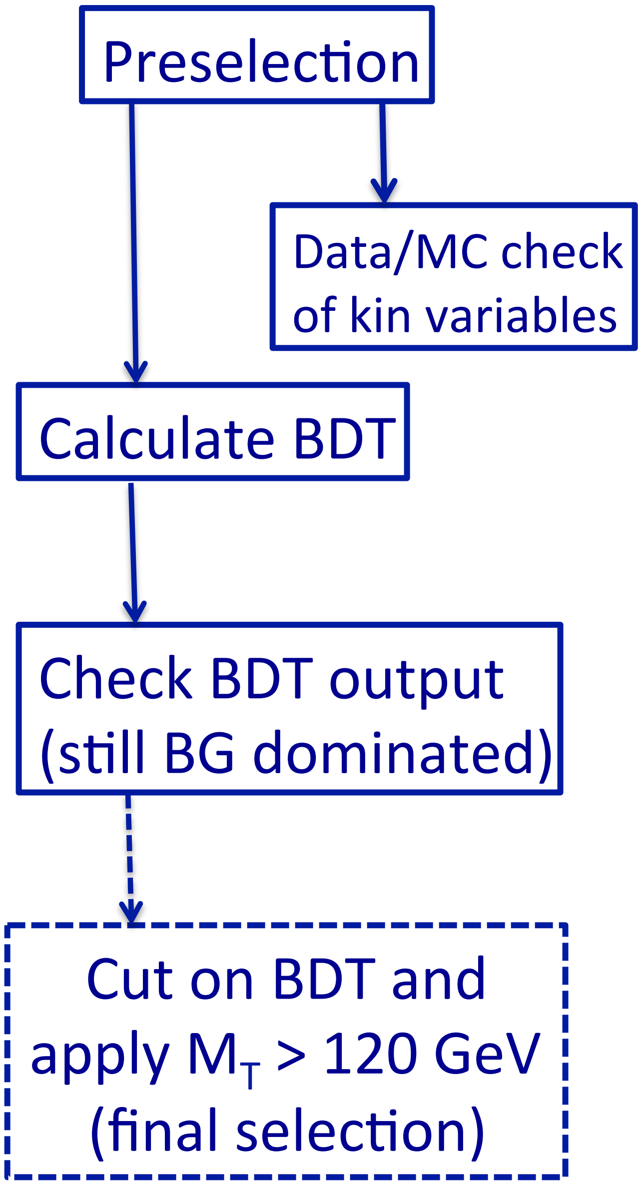
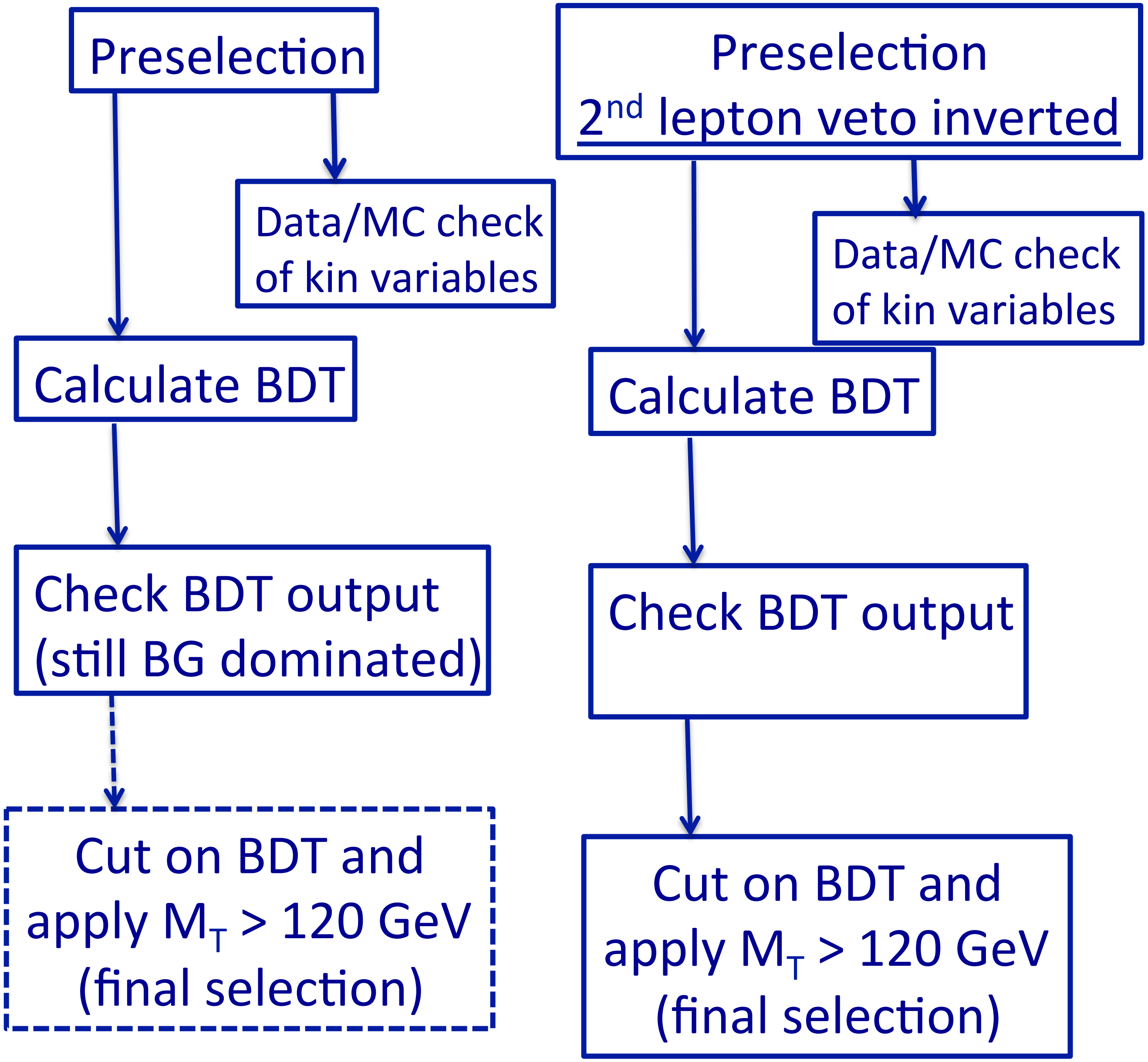
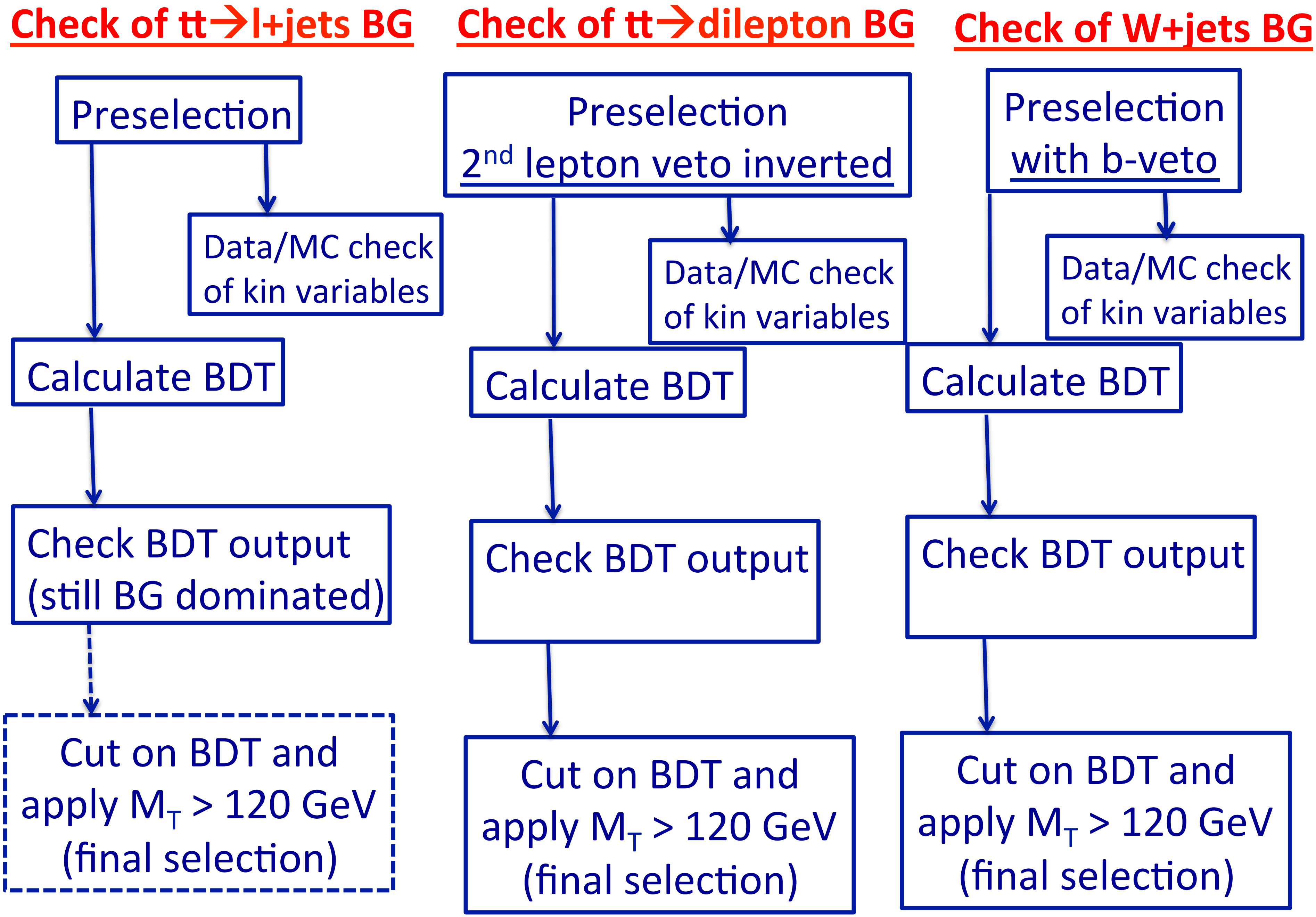
Check of tt→l+jets BG

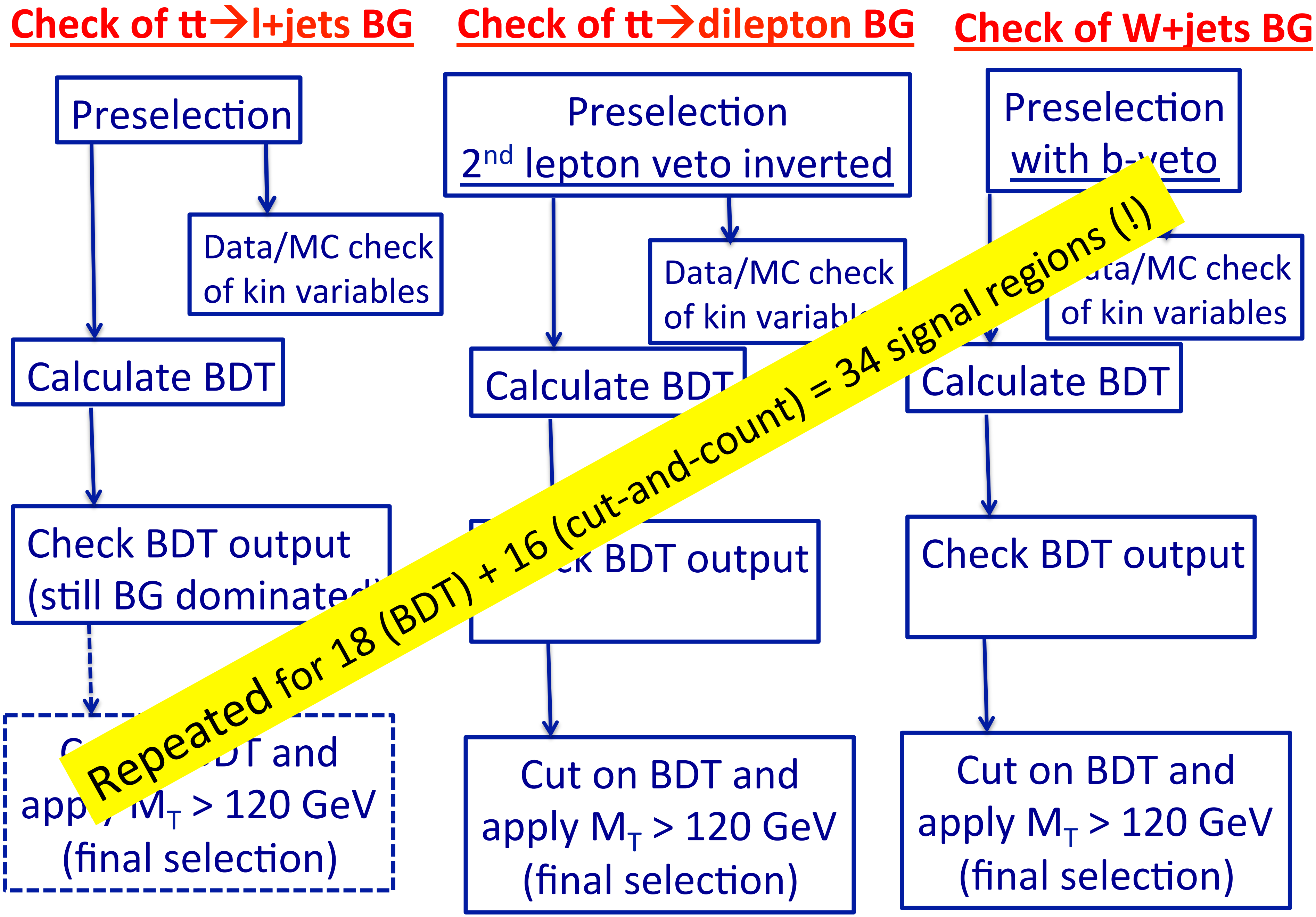


Check of tt→l+jets BG

Check of tt→dilepton BG




Check of tt→l+jets BG
Preselection
Data/MC check of kin variables
Calculate BDT
Check BDT output (still BG dominated)
Cut on BDT and apply M_T > 120 GeV (final selection)
Check of tt→dilepton BG
Preselection
2nd lepton veto inverted
Data/MC check of kin variables
Calculate BDT
Check BDT output
Cut on BDT and apply M_T > 120 GeV (final selection)
Check of W+jets BG
Preselection
with b-veto
Data/MC check of kin variables
Calculate BDT
Check BDT output
Cut on BDT and apply M_T > 120 GeV (final selection)



Check of tt→l+jets BG
Check of tt→dilepton BG
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Calculate BDT
Check BDT output
Cut on BDT and
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(final selection)
apply M_T > 120 GeV
(final selection)
Repeated for 18 (BDT) + 16 (cut-and-count) = 34 signal regions (!)

Some examples of these checks

Check of tt→l+jets BG

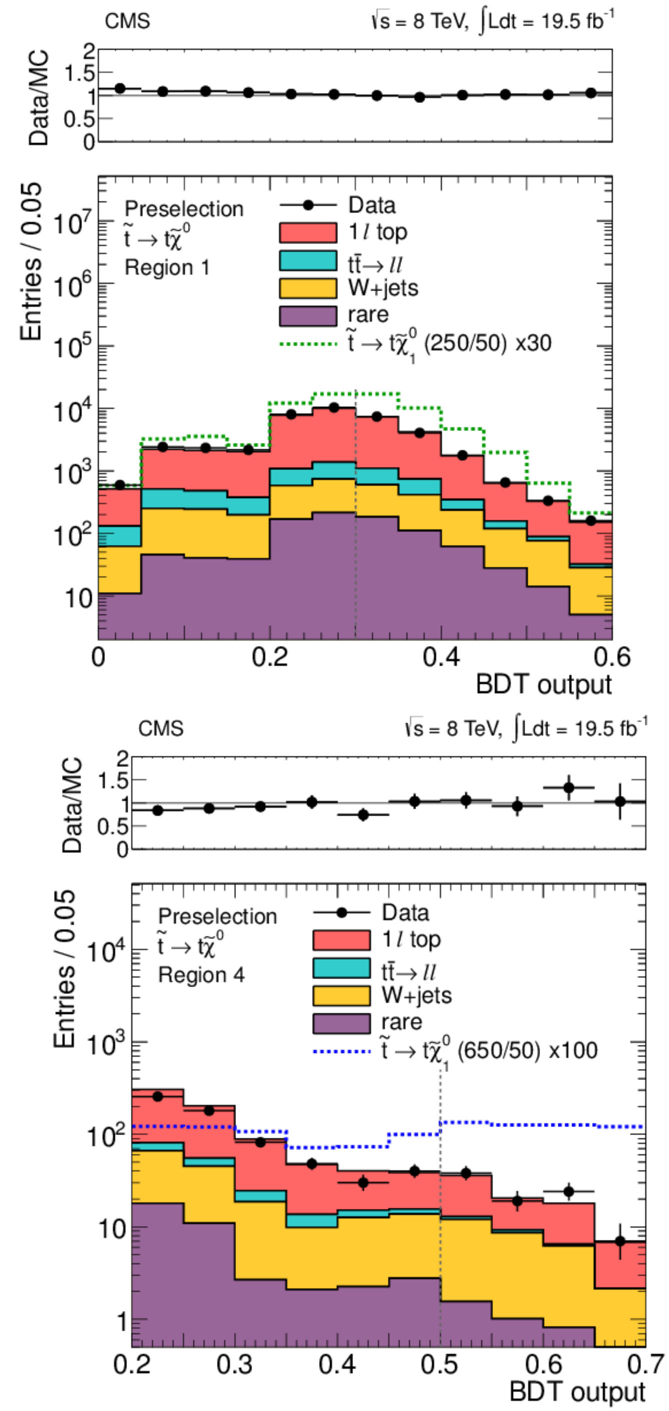
Preselection

Data/MC check of kin variables

Calculate BDT

Check BDT output (still BG dominated)

Cut on BDT and apply M_T > 120 GeV (final selection)



Check of tt→dilepton BG

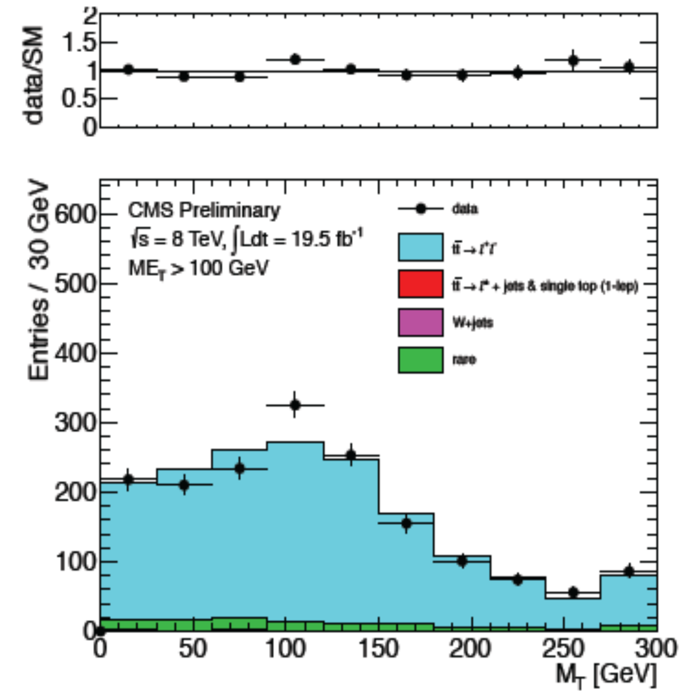
Preselection
2nd lepton veto inverted

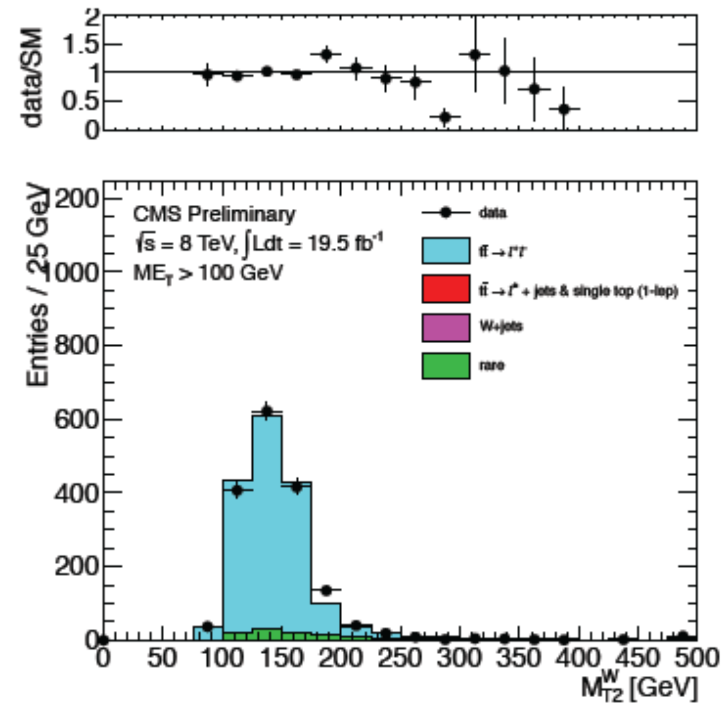
Data/MC check of kin variables

Calculate BDT

Check BDT output

Cut on BDT and apply $M_T > 120$ GeV (final selection)





Check of tt→dilepton BG

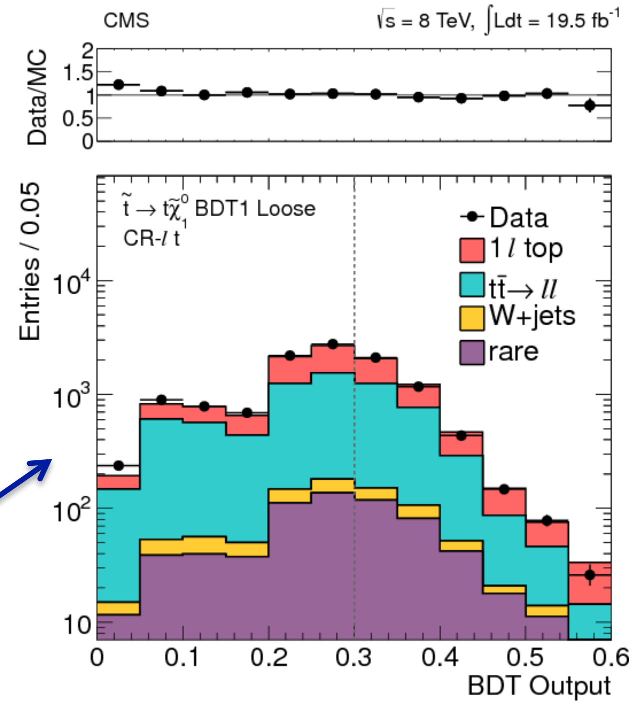
Preselection
2nd lepton veto inverted

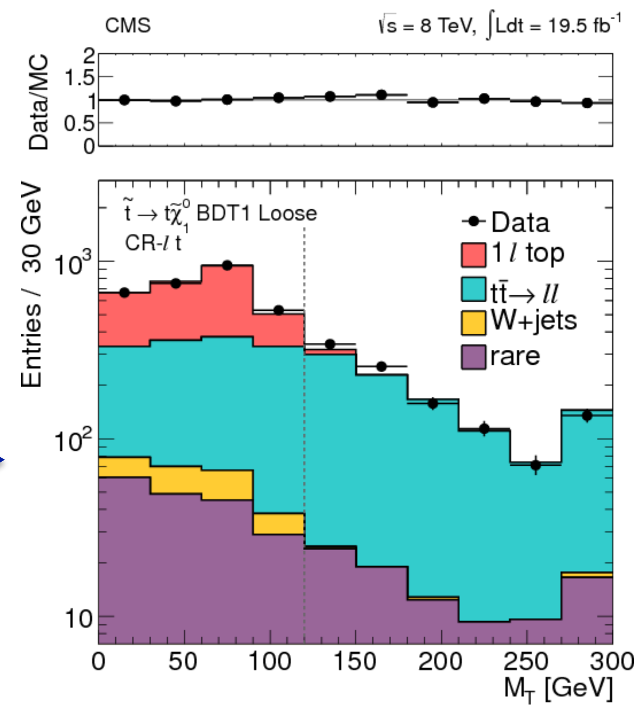
Dta/MC check of kin variables

Calculate BDT

Check BDT output

Cut on BDT and apply $M_T > 120$ GeV (final selection)





Next: the one check that does not look so great

Check of W+jets BG

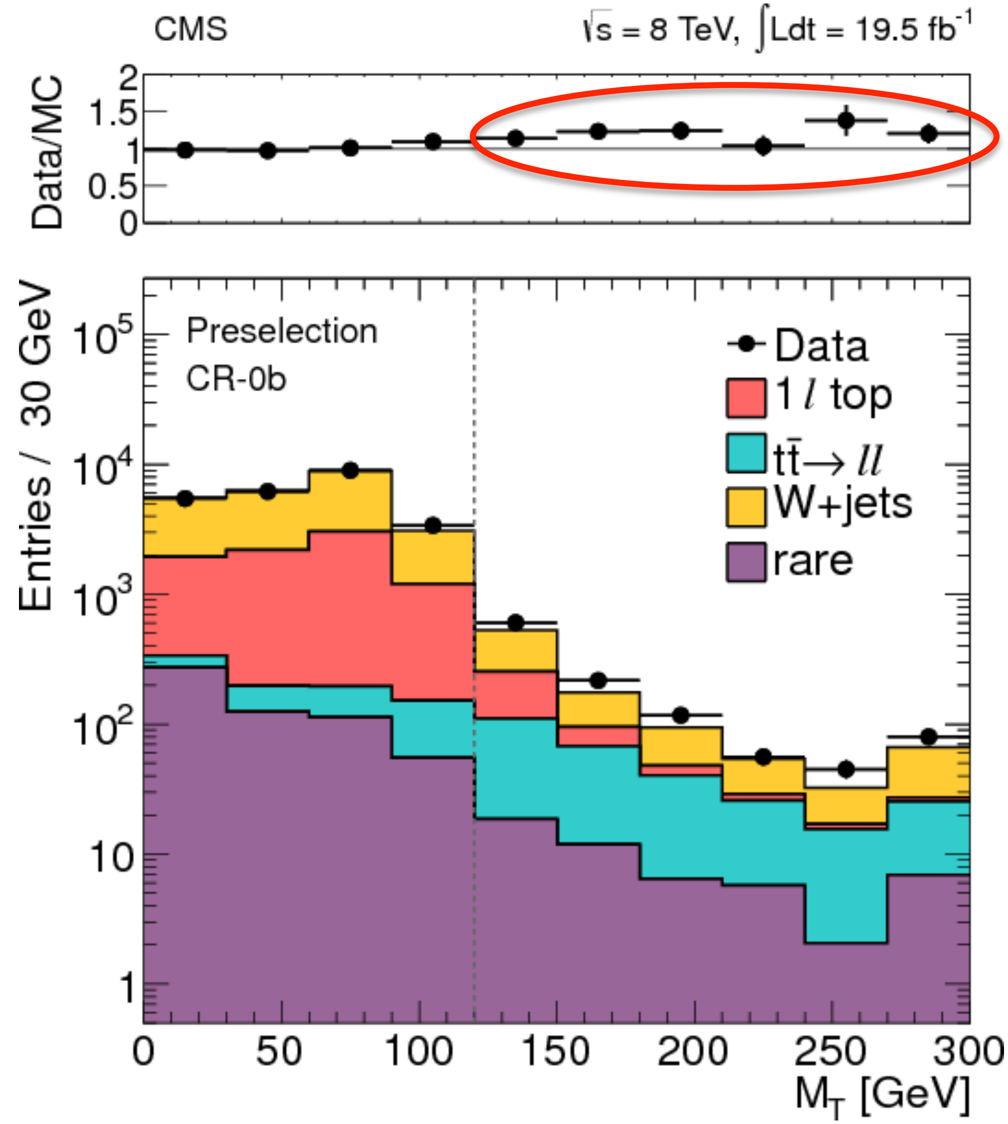
Preselection with b-veto

Data/MC check of kin variables

Calculate BDT

Check BDT output

Cut on BDT and apply M_T > 120 GeV (final selection)



MC does not get MET resolution right!

Issue with MET resolution

- **Effect on M_T measured in W+jets, corrected via scale factor ~ 1.2 ± 0.3**
  - Relatively painless
- **Affects ttbar→l+jets also**
- **Transferring scale factor to ttbar → l+jets not straightforward**
  - eg: the effect of "real" tails in M_T due to off-shell W's is very different in pp→W^* vs. t→W^*b

- **One of the main sources of systematics**

Systematics on background

Example: top-neutralino BDT analysis (uncertainties in %)

$\tilde{t} \to t\tilde{\chi}_1^0$						
Sample	BDT1–Loose	BDT1–Tight	BDT2	BDT3	BDT4	BDT5
M_T-peak data and MC (stat.)	1.0	2.1	2.7	5.3	8.7	3.0
$t\bar{t} \to \ell\ell$ N_{jets} modeling	1.7	1.6	1.6	1.1	0.4	1.7
$t\bar{t} \to \ell\ell$ (CR-ℓt and CR-2ℓ tests)	4.0	8.2	11.0	12.5	7.2	13.8
2nd lepton veto	1.5	1.4	1.4	0.9	0.3	1.4
$t\bar{t} \to \ell\ell$ (stat.)	1.1	2.8	3.4	7.0	7.4	3.3
W + jets cross section	1.6	2.2	2.8	1.7	2.7	2.2
W + jets (stat.)	1.1	1.9	2.0	4.6	10.8	5.2
W + jets SF uncertainty	8.3	7.7	6.8	8.1	9.7	8.6
$1-\ell$ top (stat.)	0.4	0.8	0.8	1.4	4.4	1.2
$1-\ell$ top tail-to-peak ratio	9.0	11.4	12.4	19.6	28.5	9.1
Rare processes cross section	1.8	3.0	4.0	8.1	15.7	0.7
Total	13.4	17.1	19.3	27.8	38.4	20.2

Systematics on background

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Total	13.4	17.1	19.3	27.8	38.4	20.2

Uncertainties due to MET resolution: as high as ~ 30%

Systematics on background

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Statistics of dilepton control region tests: ~ 4 - 14%

Systematics on background

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Rare processes cross section	1.8	3.0	4.0	8.1	15.7	0.7
Total	13.4	17.1	19.3	27.8	38.4	20.2

Misc. MC statistics: ~ 4 - 11%

Systematics on background

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Total	13.4	17.1	19.3	27.8	38.4	20.2

In the tight signal regions "rare" process matter

Systematics on background

Example: top-neutralino BDT analysis (uncertainties in %)

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Rare processes cross section	1.8	3.0	4.0	8.1	15.7	0.7
Total	13.4	17.1	19.3	27.8	38.4	20.2

Total uncertainty: ~ 13 – 40%

Expectations

Example: top-neutralino BDT analysis (number of events)

$\tilde{t} \to t\tilde{\chi}_1^0$						
Sample	BDT1–Loose	BDT1–Tight	BDT2	BDT3	BDT4	BDT5
$t\bar{t} \to \ell\ell$	438 ± 37	68 ± 11	46 ± 10	5 ± 2	0.3 ± 0.3	48 ± 13
1ℓ top	251 ± 93	37 ± 17	22 ± 12	4 ± 3	0.8 ± 0.9	30 ± 12
W + jets	27 ± 7	7 ± 2	6 ± 2	2 ± 1	0.8 ± 0.3	5 ± 2
Rare	47 ± 23	11 ± 6	10 ± 5	3 ± 1	1.0 ± 0.5	4 ± 2
Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
$\tilde{t} \to t\tilde{\chi}_1^0$ (250/50)	285 ± 8.5	50 ± 3.5	28 ± 2.6	4.4 ± 1.0	0.3 ± 0.3	34 ± 2.9
$\tilde{t} \to t\tilde{\chi}_1^0$ (650/50)	12 ± 0.2	7.2 ± 0.2	9.8 ± 0.2	6.5 ± 0.2	4.3 ± 0.1	2.9 ± 0.1

Good sensitivity across broad mass range

Results

Example: top-neutralino BDT analysis (number of events)

$\tilde{t} \to t\tilde{\chi}_1^0$						
Sample	BDT1–Loose	BDT1–Tight	BDT2	BDT3	BDT4	BDT5
$t\bar{t} \to \ell\ell$	438 ± 37	68 ± 11	46 ± 10	5 ± 2	0.3 ± 0.3	48 ± 13
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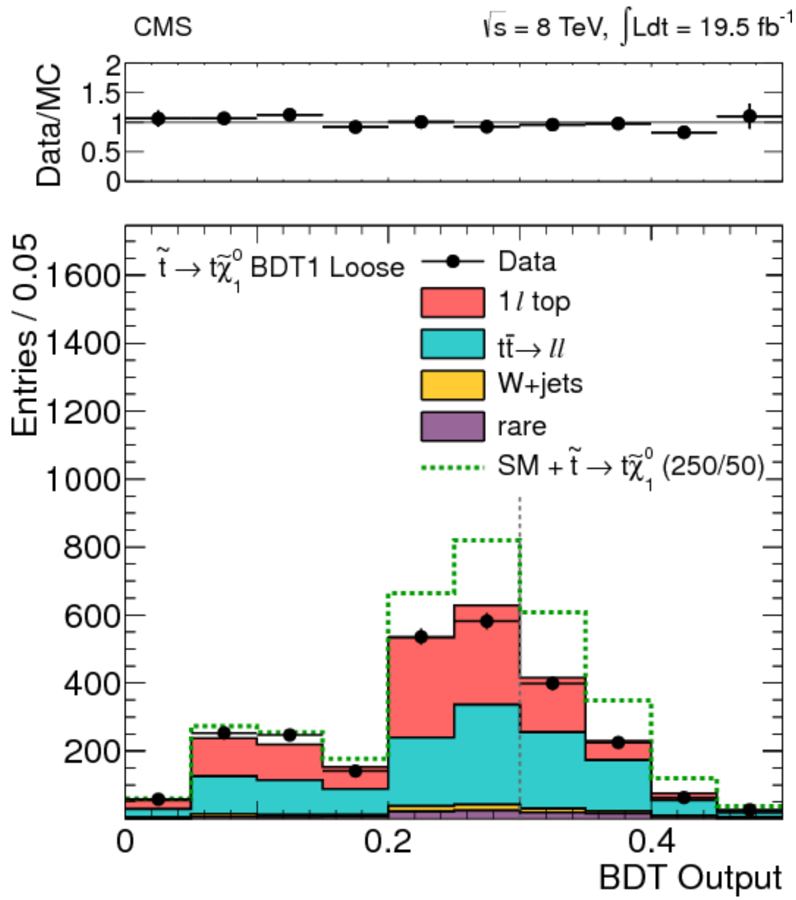
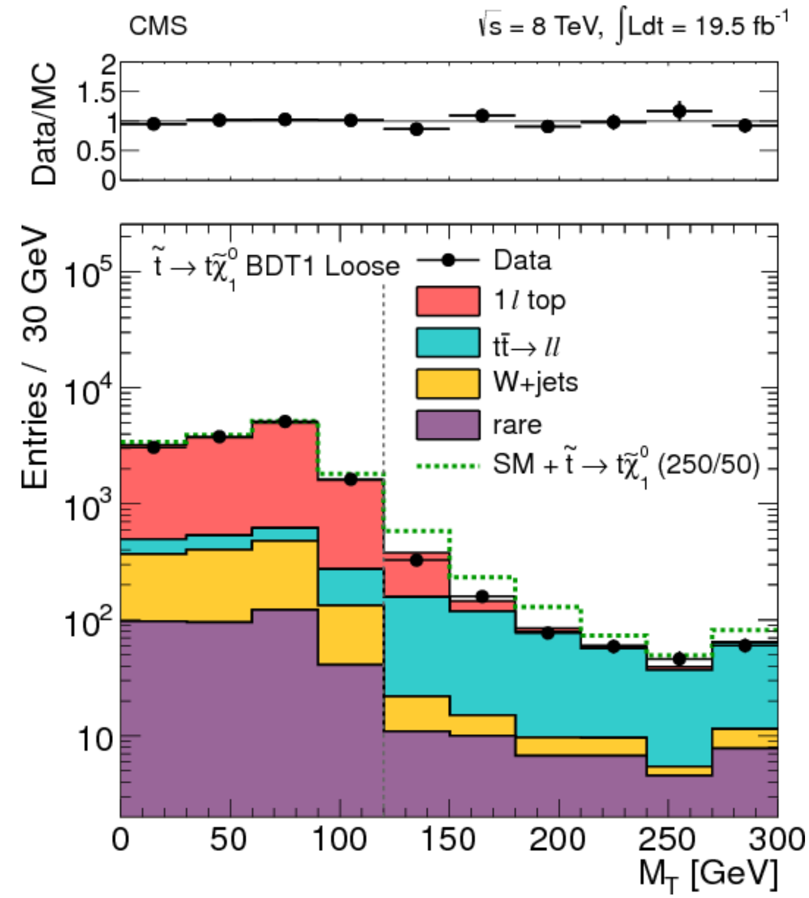
W + jets	27 ± 7	7 ± 2	6 ± 2	2 ± 1	0.8 ± 0.3	5 ± 2
Rare	47 ± 23	11 ± 6	10 ± 5	3 ± 1	1.0 ± 0.5	4 ± 2
Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76

No excess anywhere

Example BDT and M_T distributions



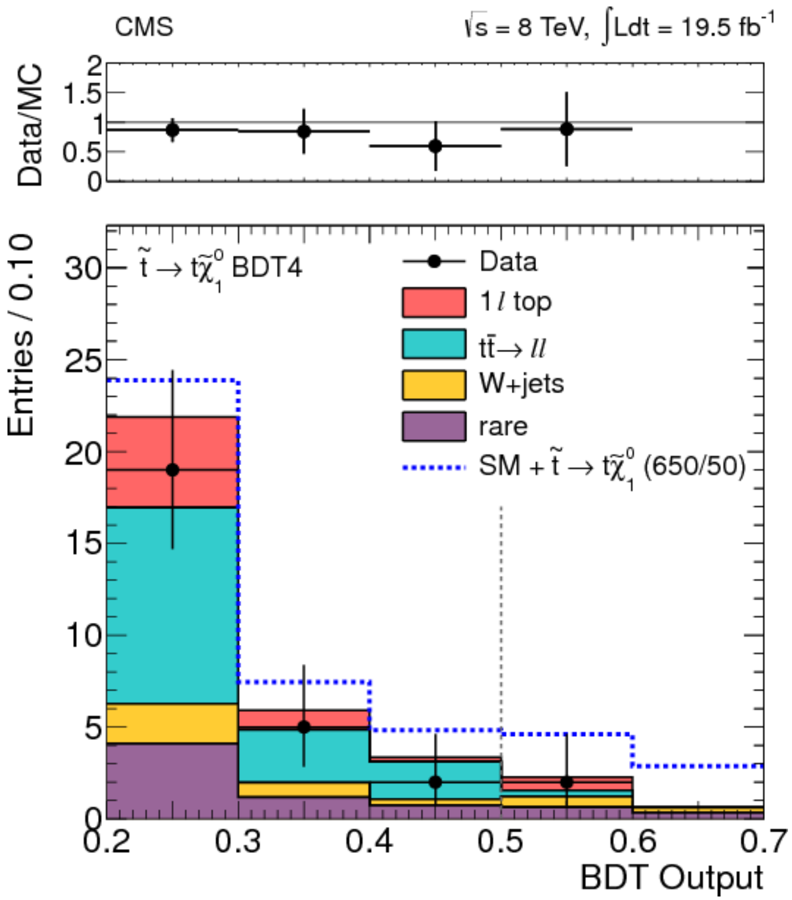
BDT with cut at M_T > 120 GeV



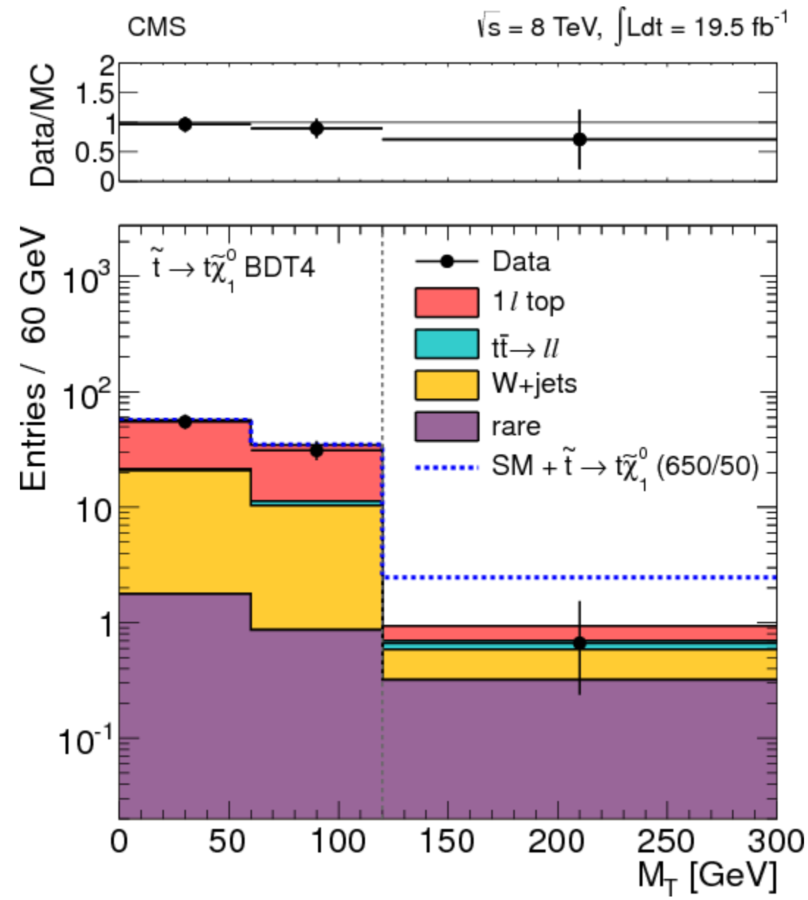
M_T with cut on BDT (BDT > 0.3)

Looks OK

Example BDT and M_T distributions



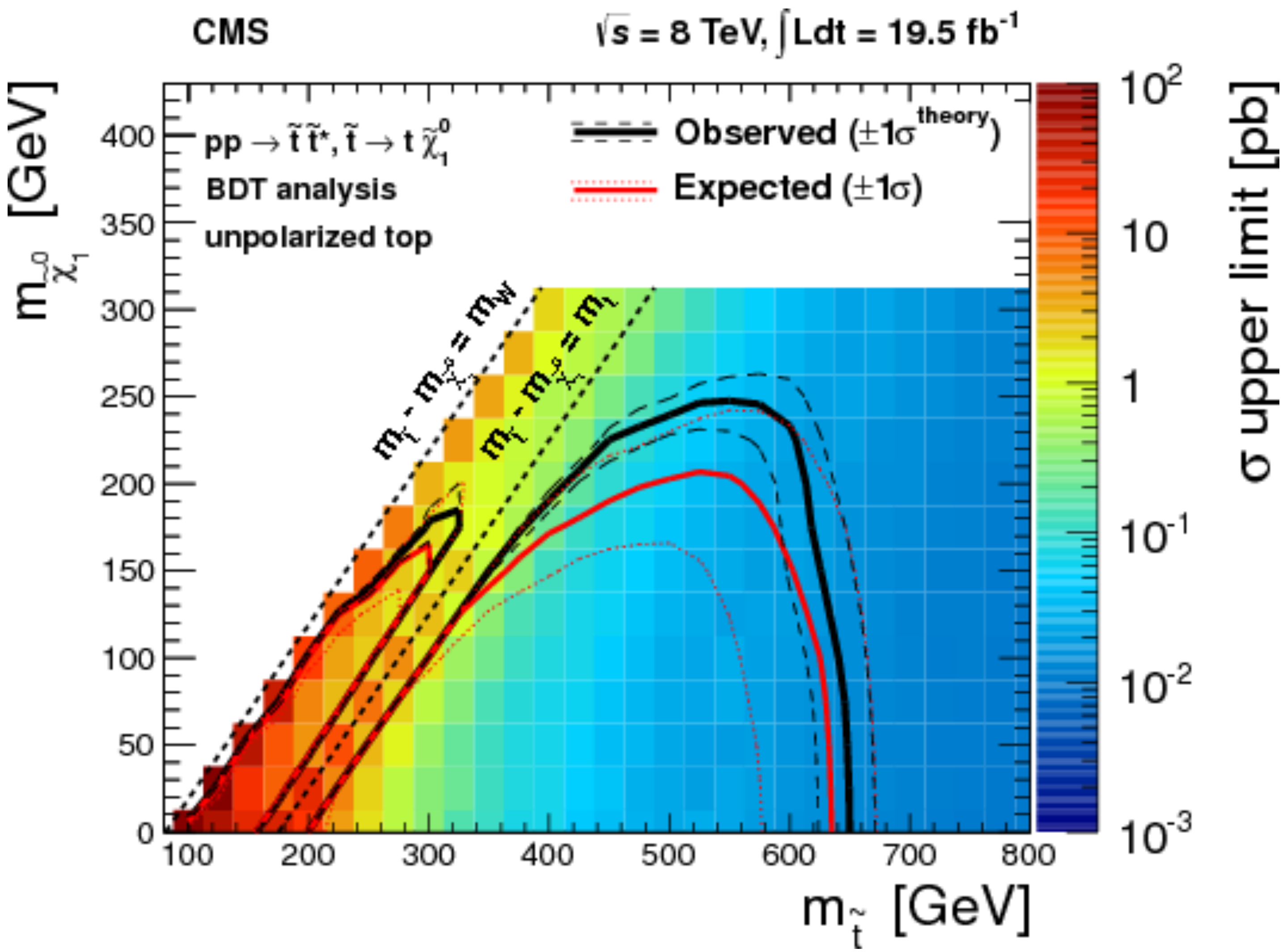
BDT with cut at M_T > 120 GeV



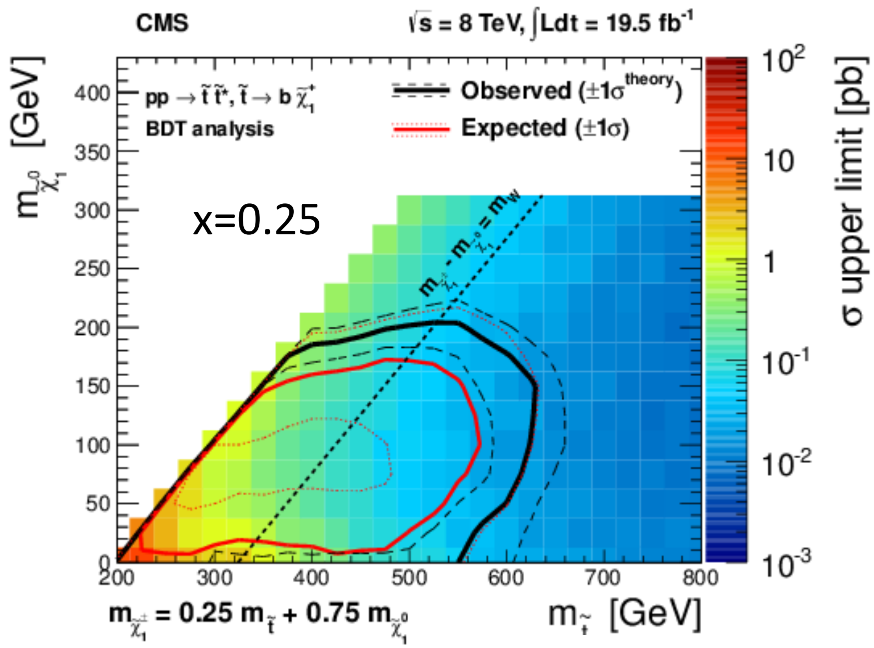
M_T with cut on BDT (BDT > 0.5)

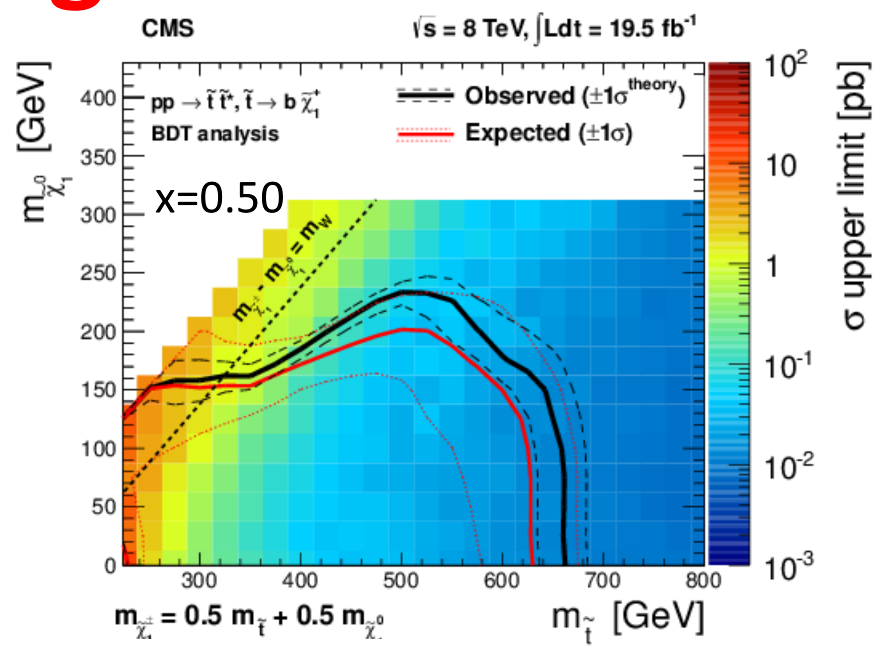
Looks OK

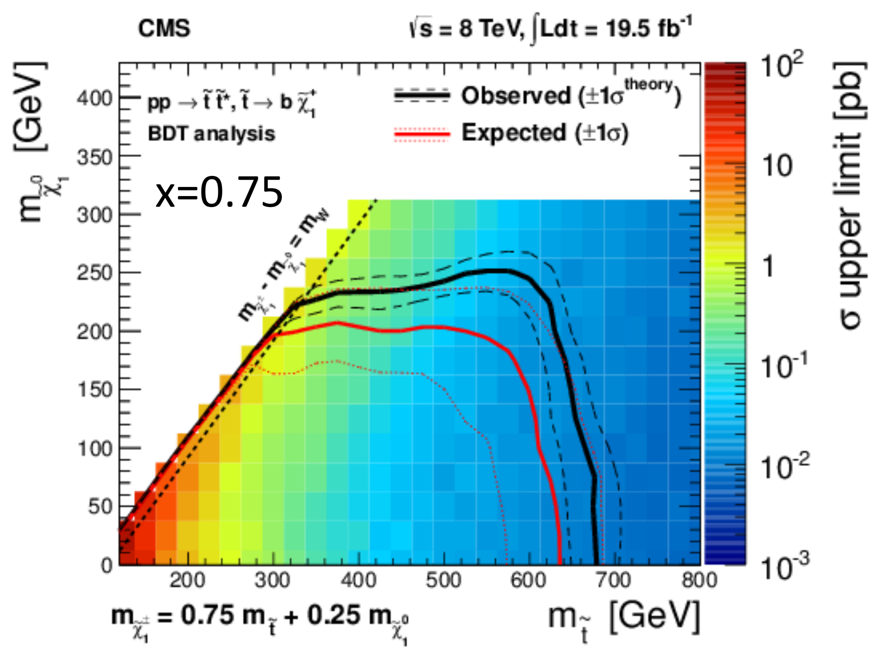
Limits: top-neutralino mode



Limits: b-chargino mode

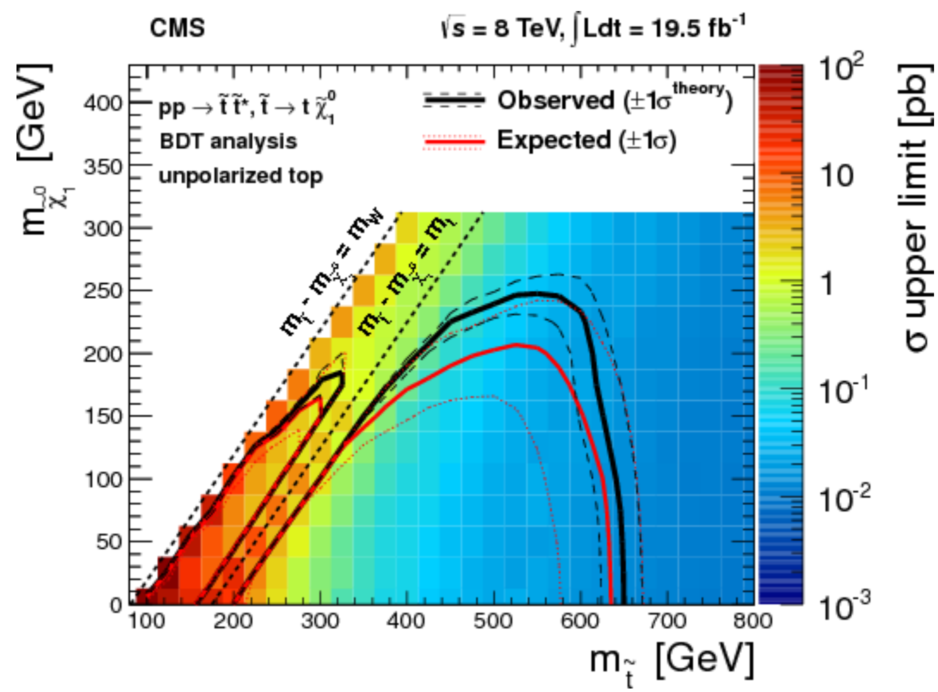




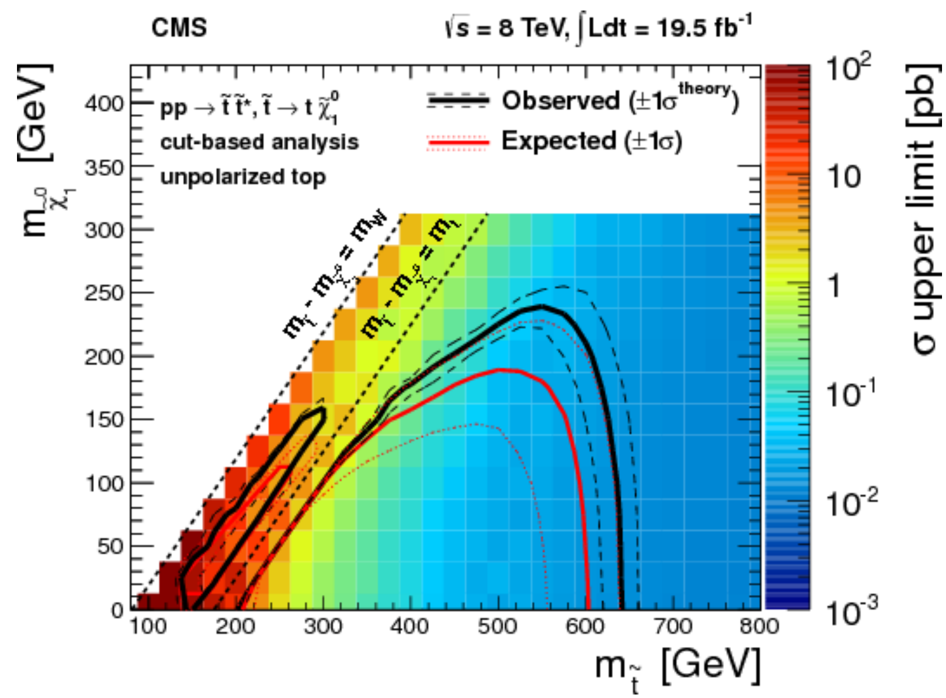


Cut-and-count limits a little worse

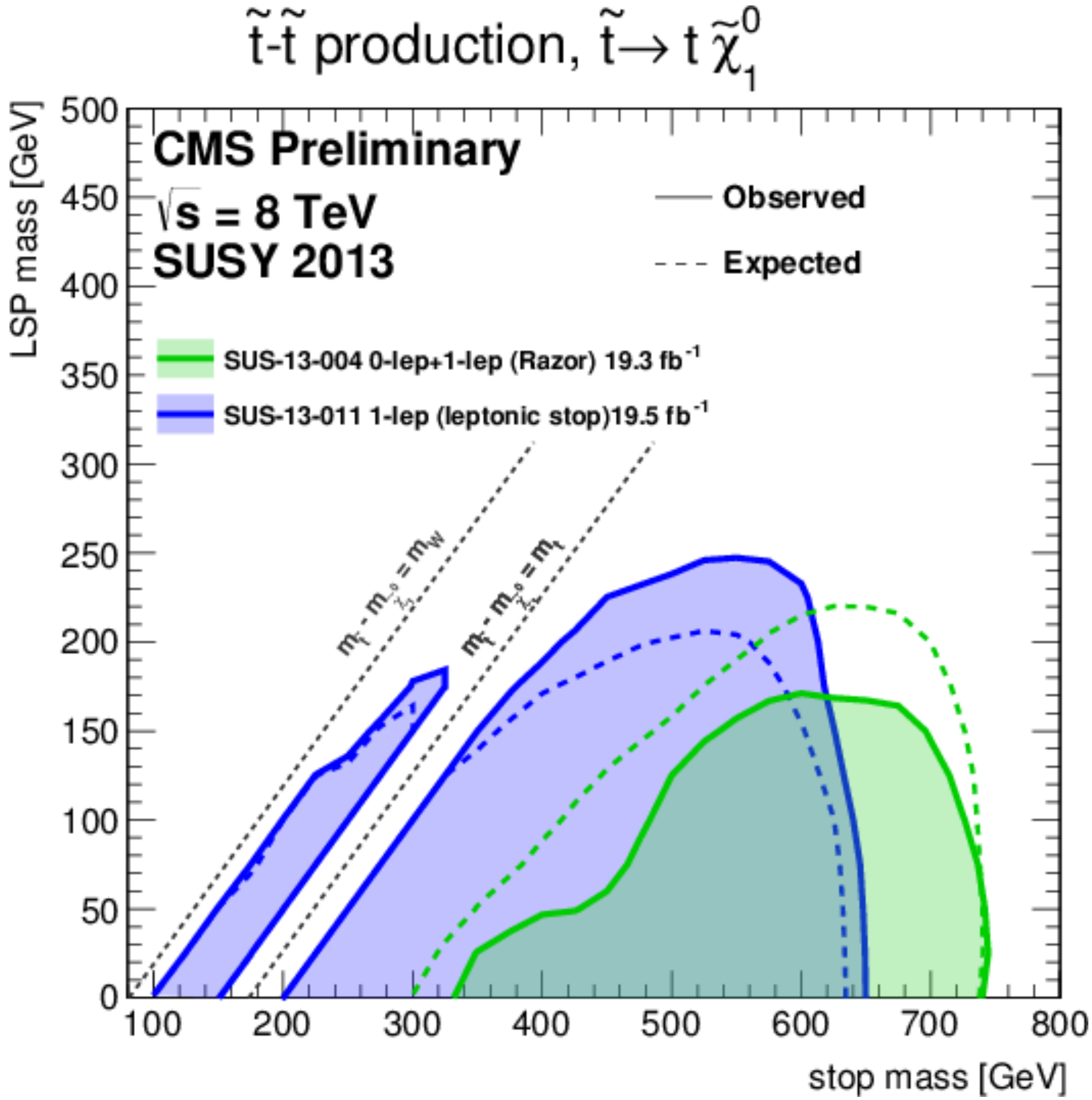
BDT exclusion region



Cut-and-count exclusion region



Comparison with generic 0-lepton search



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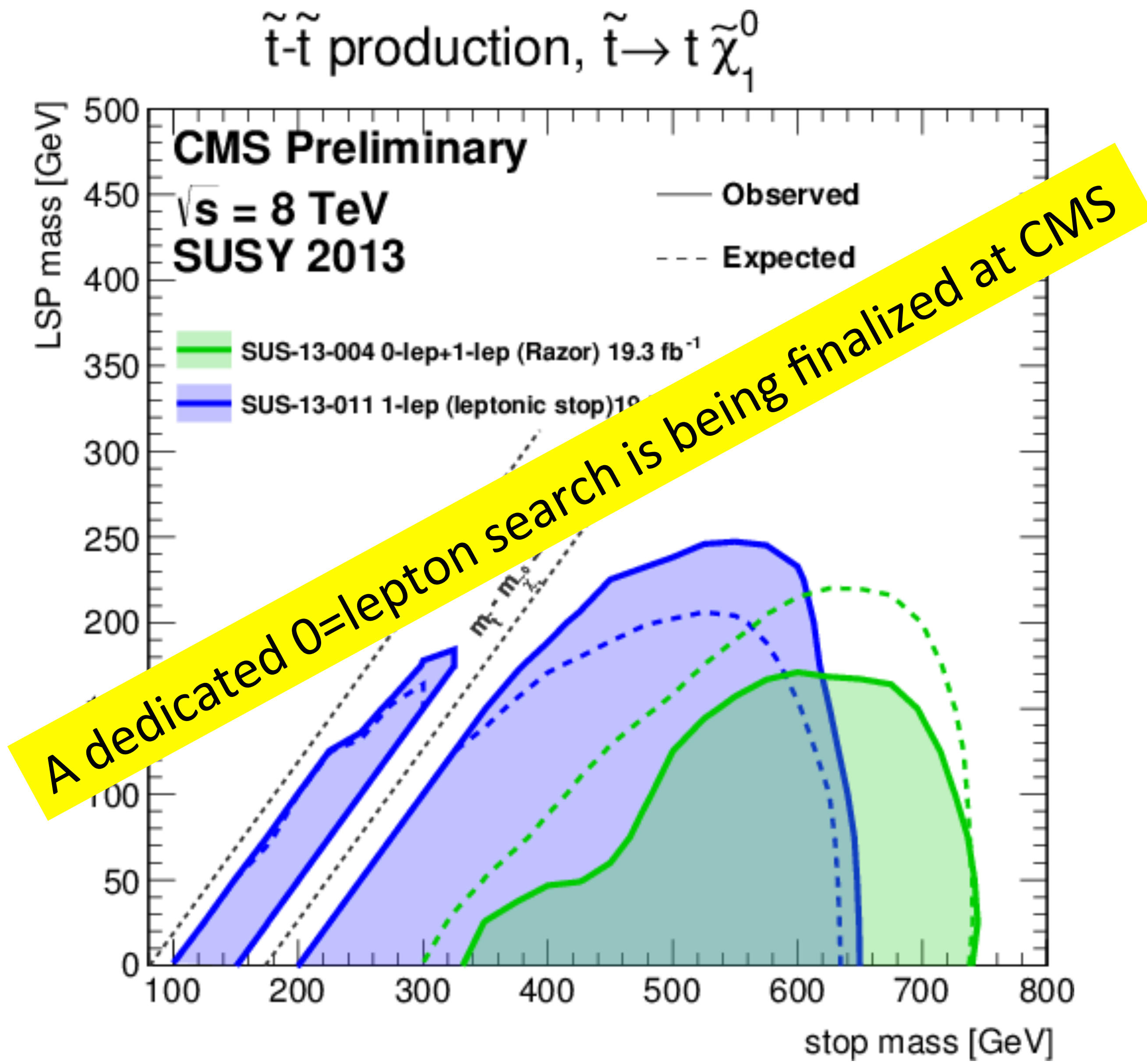
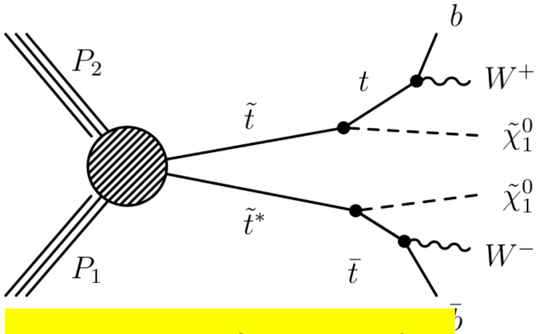


Some (slightly) dirty laundry

Polarization in stop decays



top-neutralino mode

The stop_1 and stop_2 are linear combinations of stop_L and stop_R

$$\tilde{t}_1 = \cos\theta_t \, \tilde{t}_L + \sin\theta_t \, \tilde{t}_R \, ,$$ ← Lighter stop

$$\tilde{t}_2 = -\sin\theta_t \, \tilde{t}_L + \cos\theta_t \, \tilde{t}_R \, ,$$ ← Heavier stop

The LSP is a mixture of wino, bino, higgsino

$$\tilde{N} = (\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0) \qquad \tilde{\chi}_j^0 = \sum_{k=1}^{4} N_{jk} \tilde{N}_k \, .$$

The top chirality in stop_1 decay depends on stop mixing **and** neutralino mixing. It is easy to see why:

LSP	Allowed stop decays	Why
$\tilde{\chi}_1^0 = \tilde{B}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_R \tilde{\chi}_1^0$	U(1) couples L to L and R to R
$\tilde{\chi}_1^0 = \tilde{W}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0$	SU(2) only acts on L
$\tilde{\chi}_1^0 = \tilde{H}_d^0$	none	Only couples to down-type
$\tilde{\chi}_1^0 = \tilde{H}_u^0$	$\tilde{t}_L \to t_R \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_L \tilde{\chi}_1^0$	Higgs couple L to R (mass term)

Bottom line: polarization of top is complicated function of susy parameters

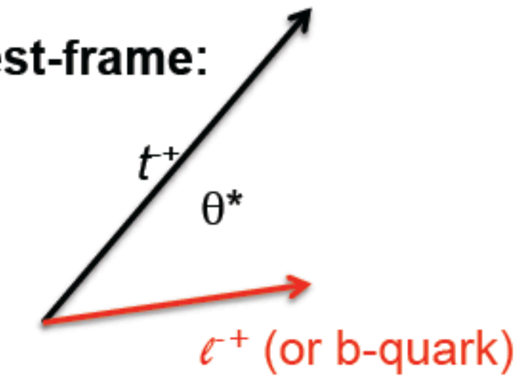
Why does top polarization matter?

Top polarization:

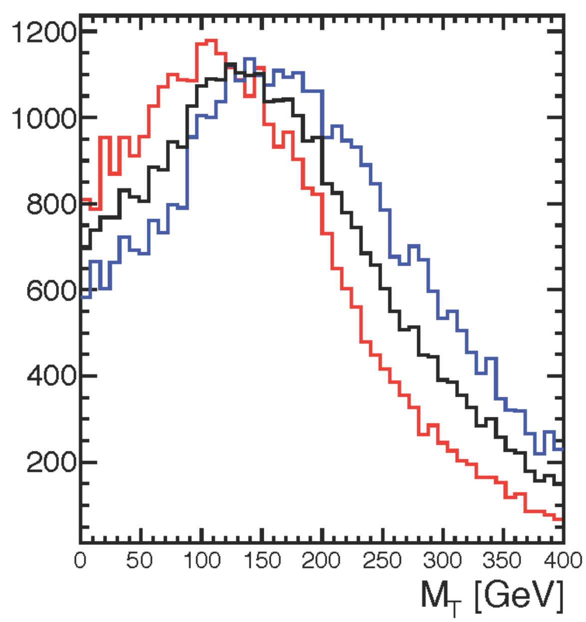
$$\frac{1}{N}\frac{dN}{d\cos\Theta^*} = \frac{1}{2}(1 + P\alpha\ \cos(\Theta^*))$$

- Where P is the polarization of the top
- α the “analyser quality”, which is 1 for leptons (and -0.41 for b quarks)

In top rest-frame:



Right handed tops have higher P_T leptons → higher transvese mass → better acceptance



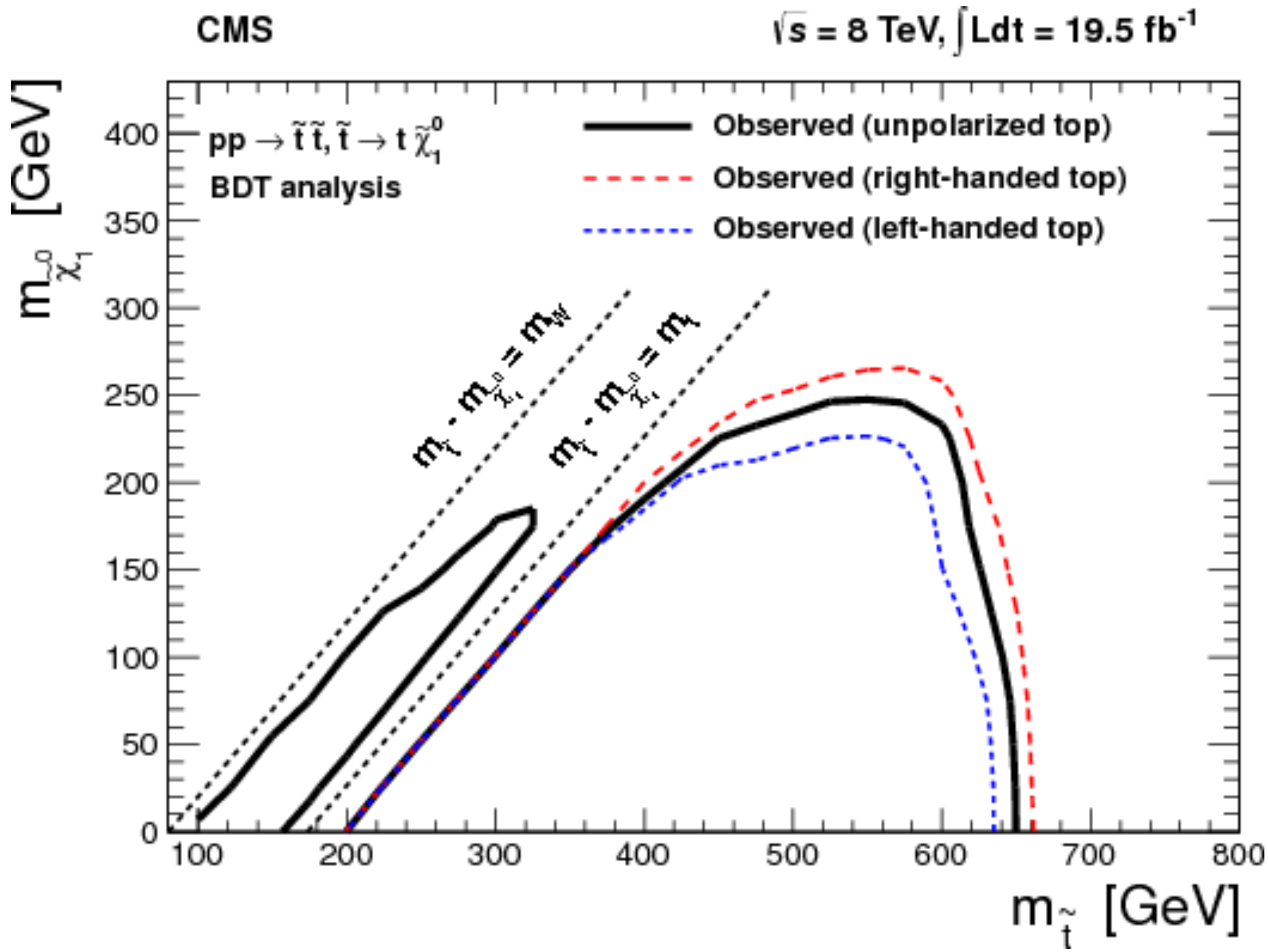
M_T distributions for M_{stop}=450 GeV M_{LSP} = 25 GeV

Right-polarized top

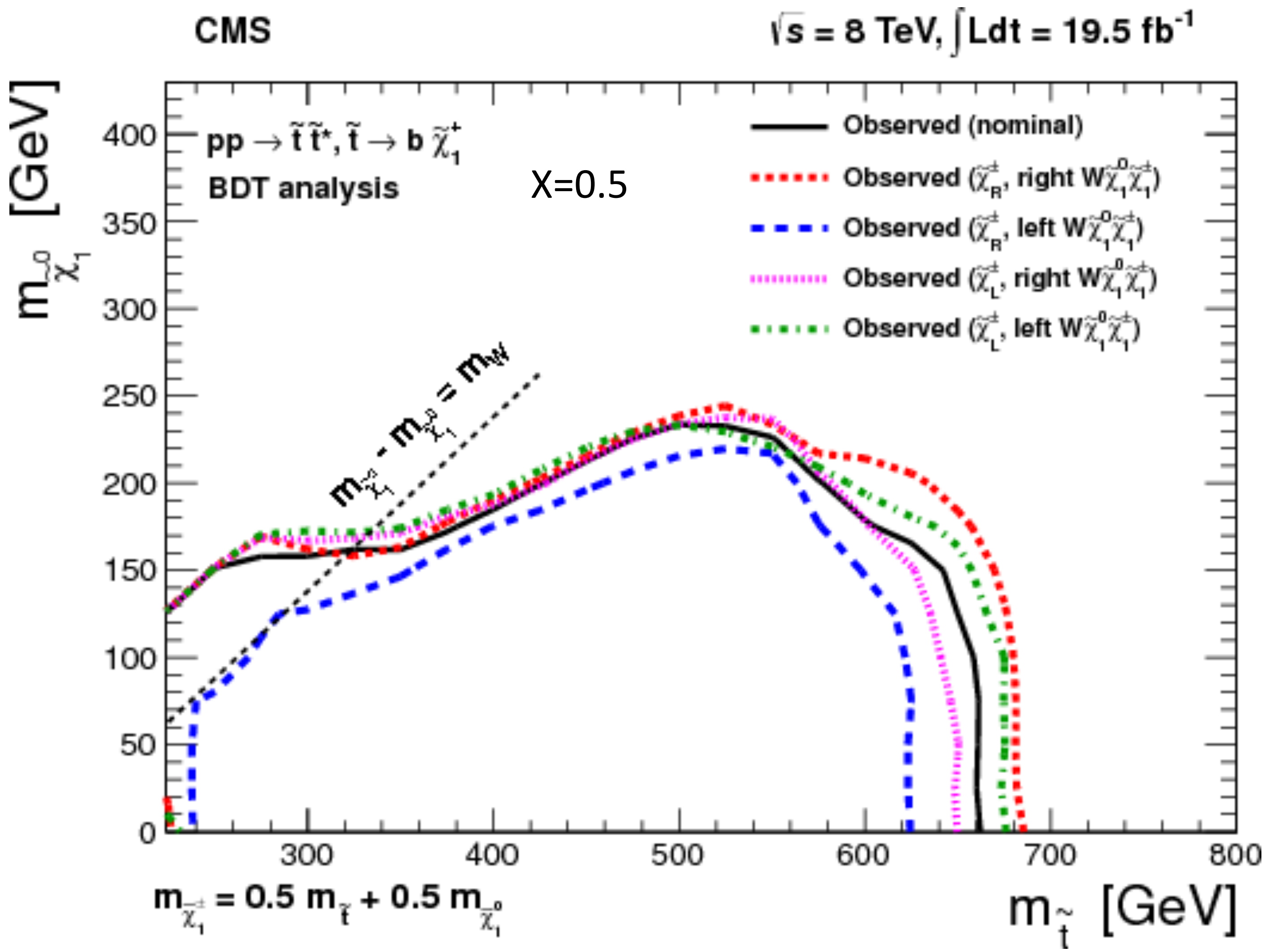
Unpolarized top

Left-polarized top

Limits for different polarization assumptions

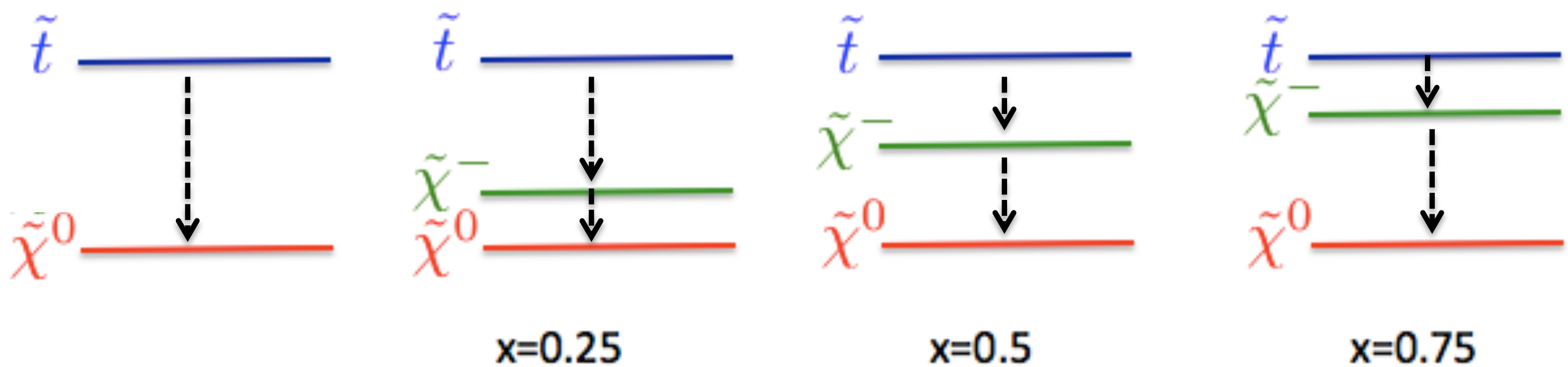


For the chargino mode is even more complicated



What about "mixed" channels?

- **So far: Only considered models with following decay chains, where <u>both</u> stops decayed the same way**
  – ie: branching ratios = 100%



- **What about branching ratio ≠ 100% ?**
  – **ie: the two stops can decay in two different ways**

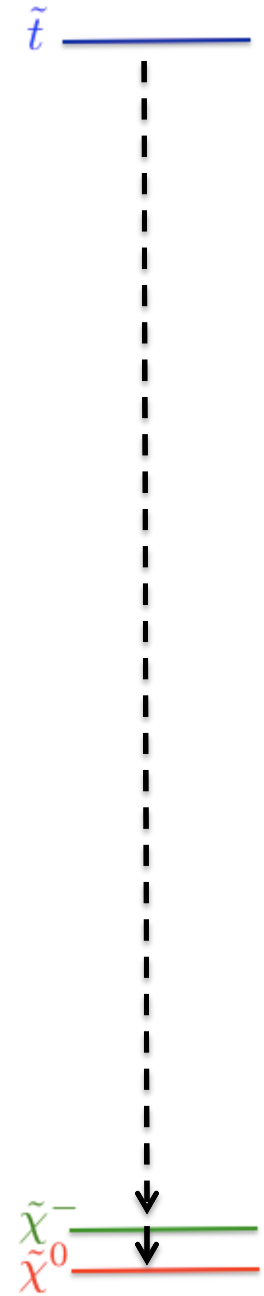
Mixed Decays

- The cut-and-count analysis is generic enough that it should have about the same sensitivity for mixed and unmixed decays
- <u>This is one of the reasons why the cut-and-count analysis is crucial!</u>

- **<u>But there is an important loophole</u>**

Mixed decay loophole: nearly degenerate chargino-LSP

- If one of the stop quarks decays through the chargino, this analysis has <u>no sensitivity</u>
- This is because the SM particles in the chargino decay are so soft that are not detectable → not enough jets



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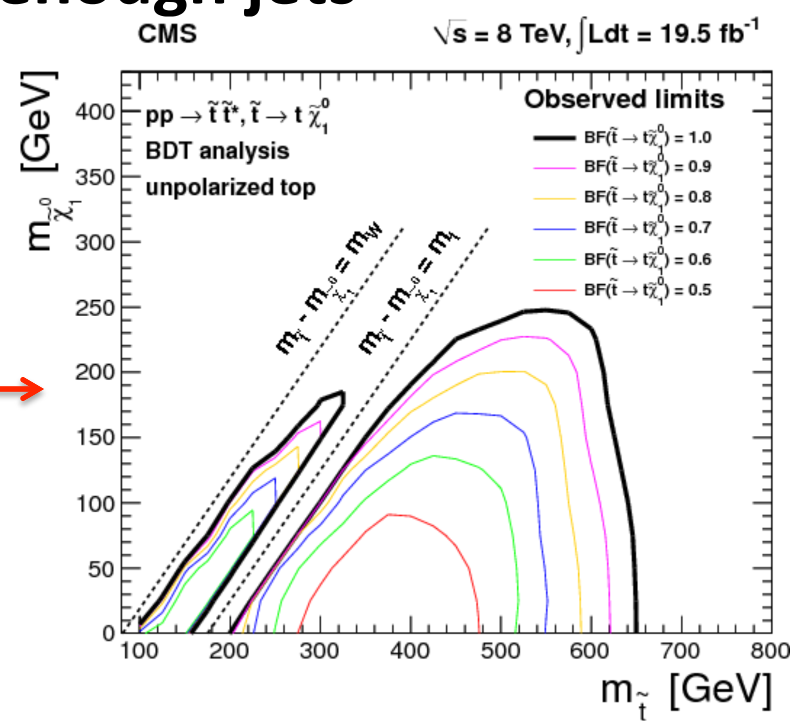
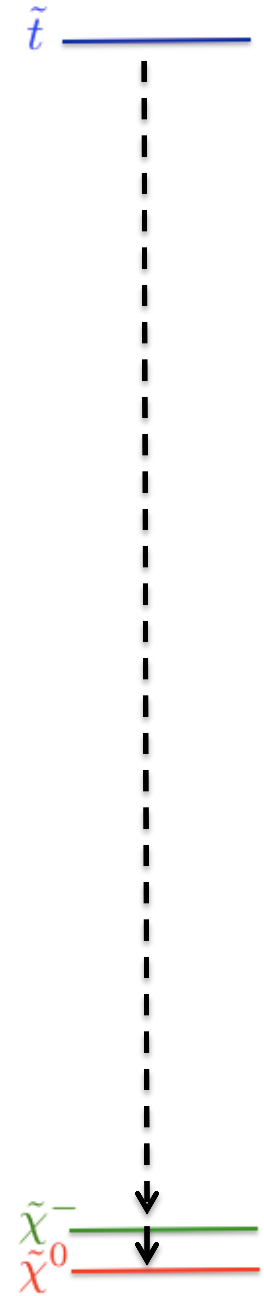
Significant degradation in sensitivity





Mixed decay loophole: nearly degenerate chargino-LSP

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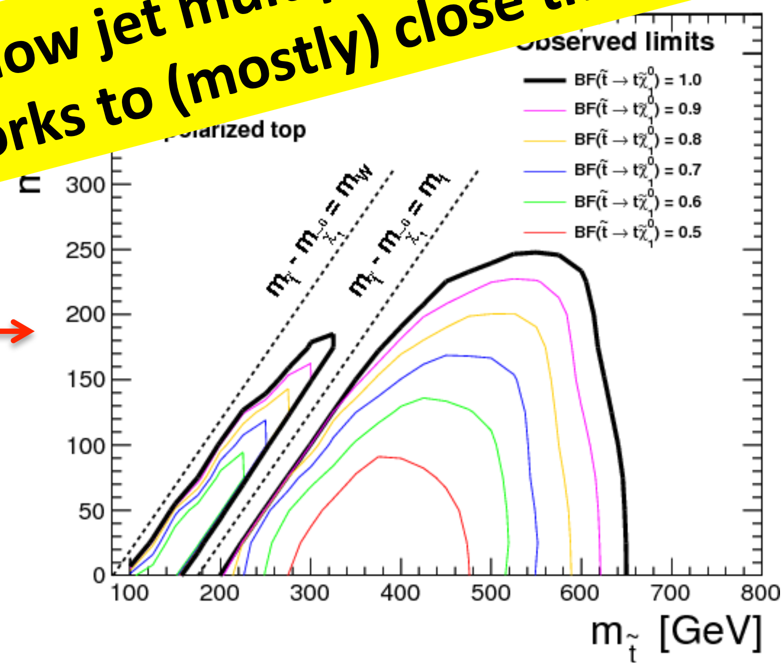
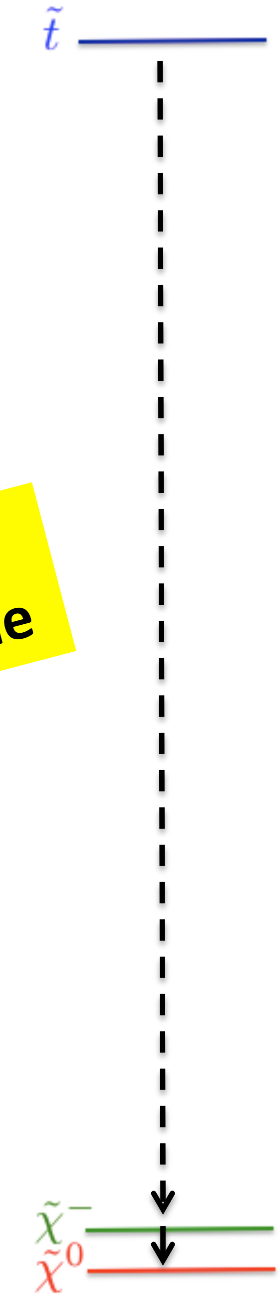
Combination with low jet multiplicity fully hadronic search is in the works to (mostly) close this loophole

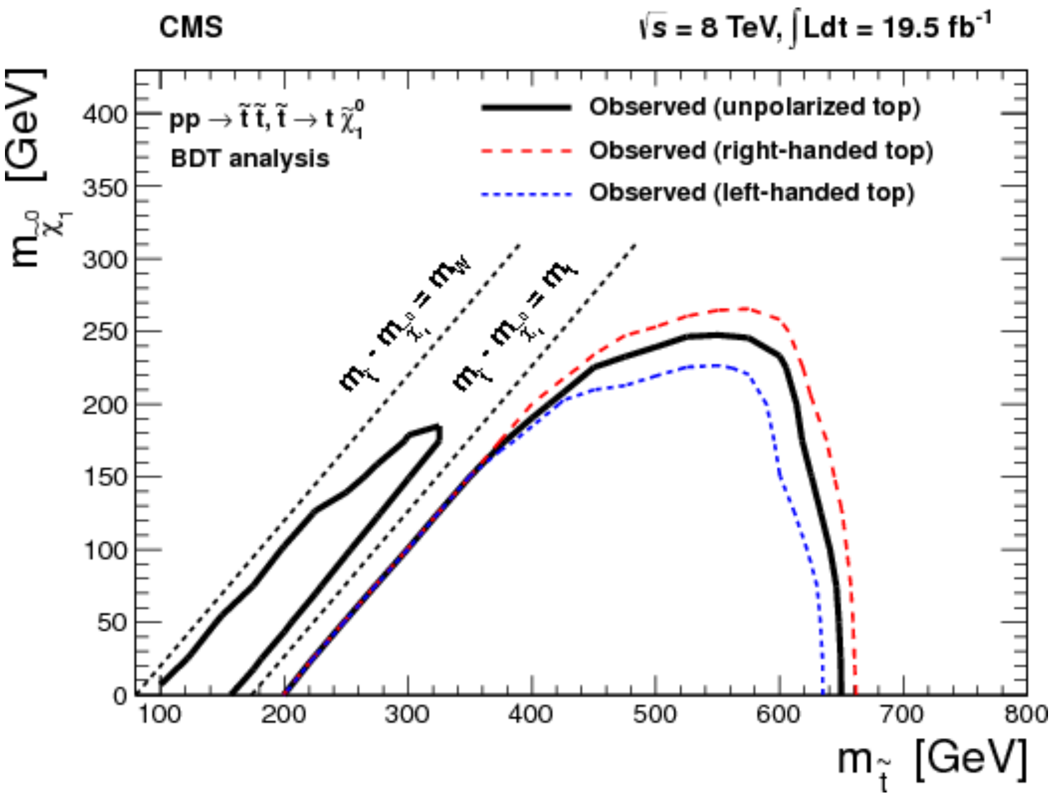
Significant degradation in sensitivity



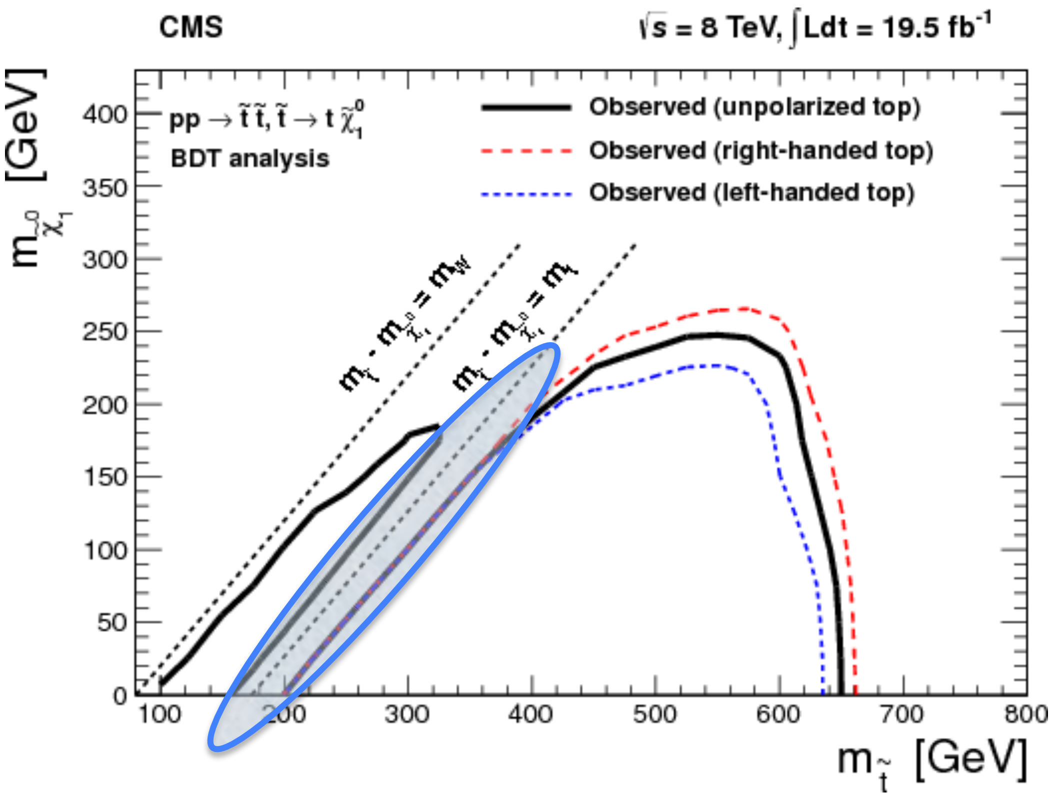


End of (slightly) dirty laundry

The hole in sensitivity



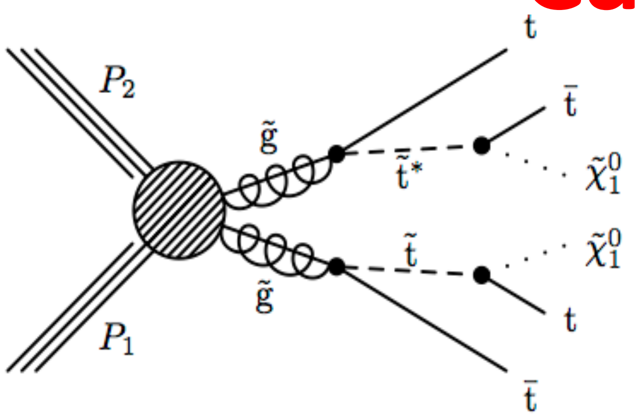
The hole in sensitivity

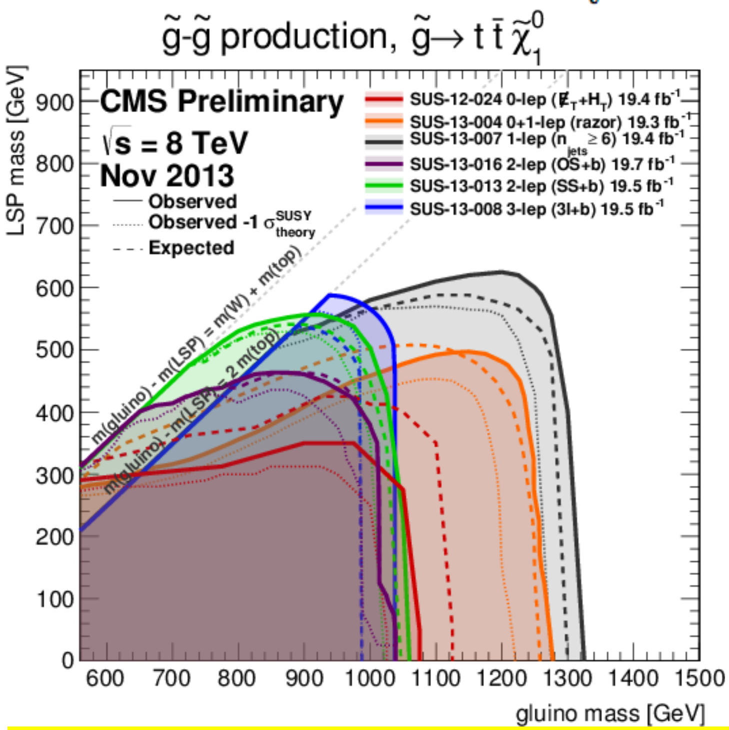


<u>Three ways of addressing it</u>

1. Cascade decays
2. Top cross-section constraints
3. Boosted events

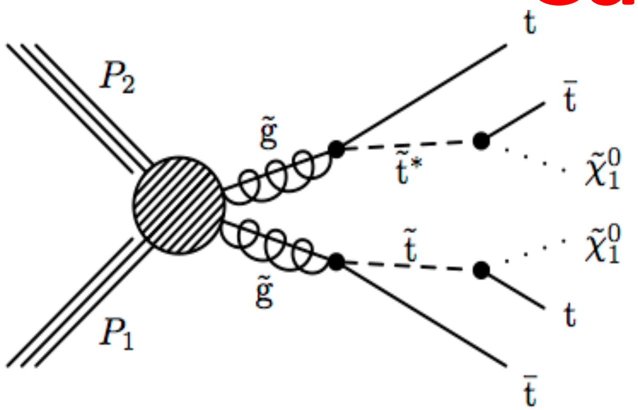
Cascade decays

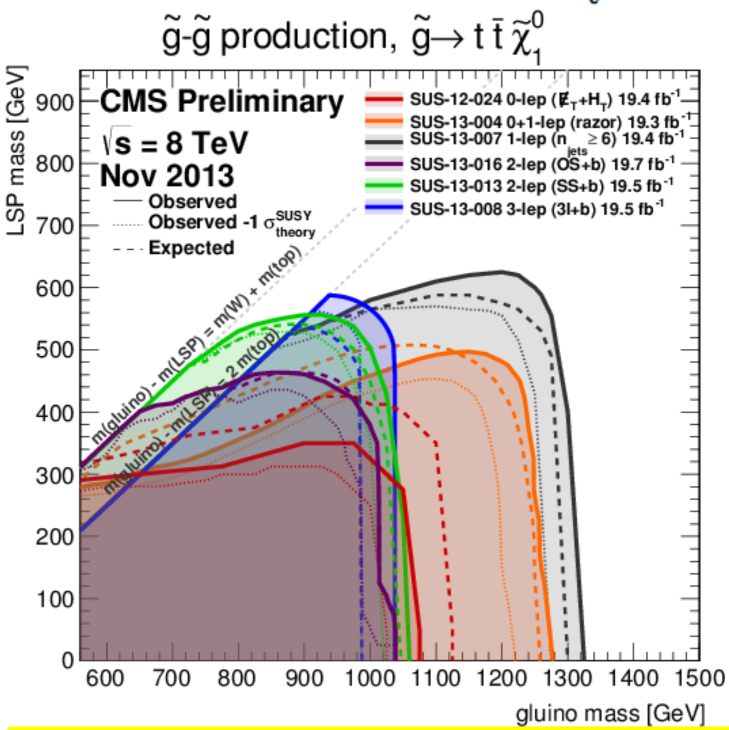


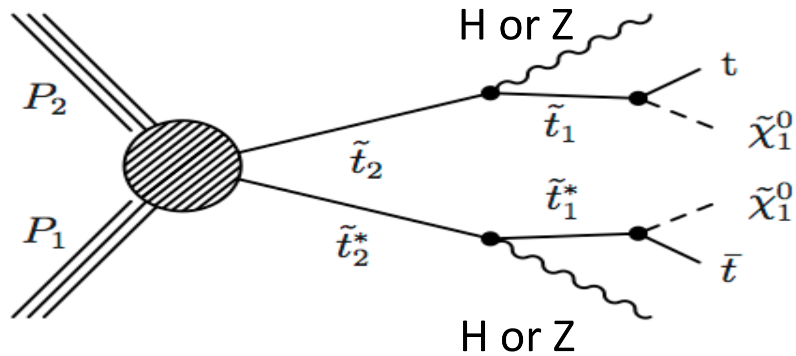


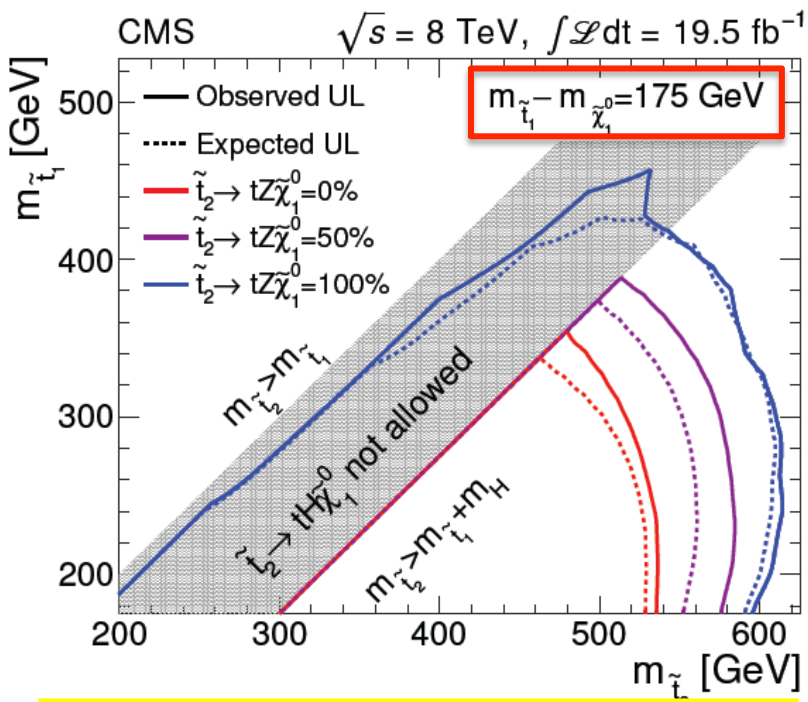
Hole is closed for 100% BR if gluino mass below ~ 1.3 TeV

Cascade decays





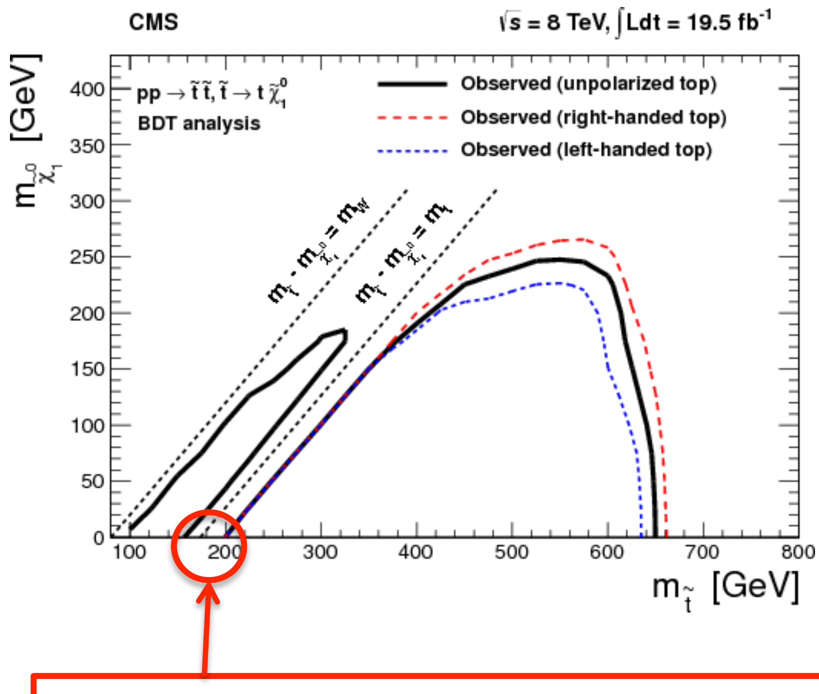




Hole is closed for 100% BR if gluino mass below ~ 1.3 TeV

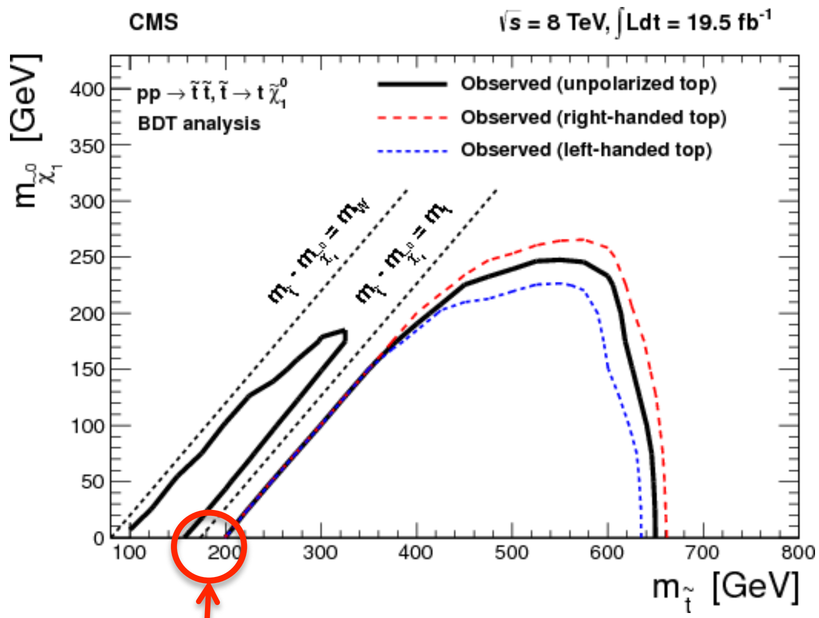
Hole is ~ closed for stop$_2$ mass below ~ 550-600 GeV

Precision ttbar cross-section measurement



Would increase measured σ(ttbar) by ~ 15%
NNLO theory Δσ ~ 6%
Experiment Δσ ~ 4%

Precision ttbar cross-section measurement



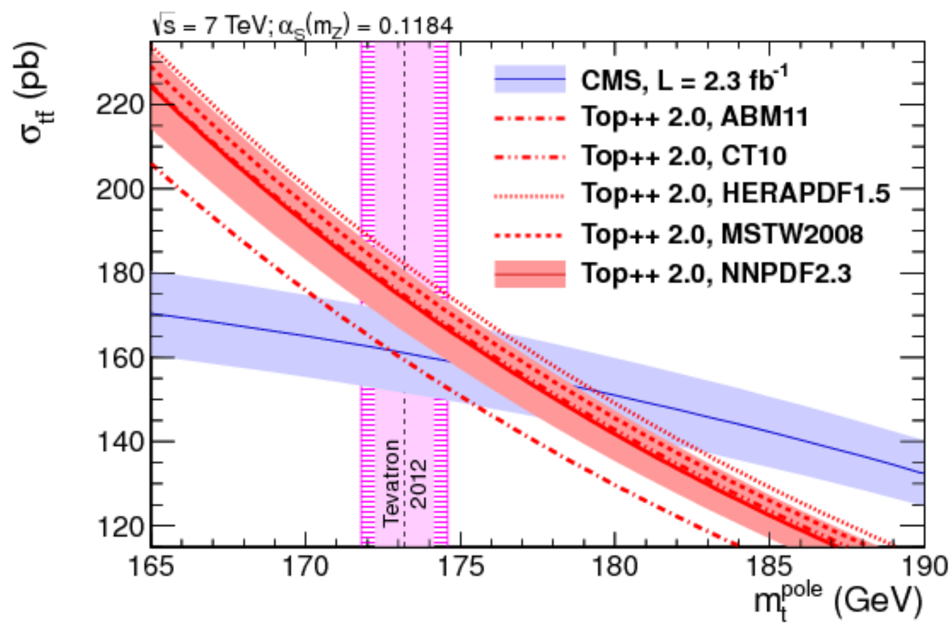
Would increase measured σ(ttbar) by ~ 15%
NNLO theory Δσ ~ 6%
Experiment Δσ ~ 4%

Problem:

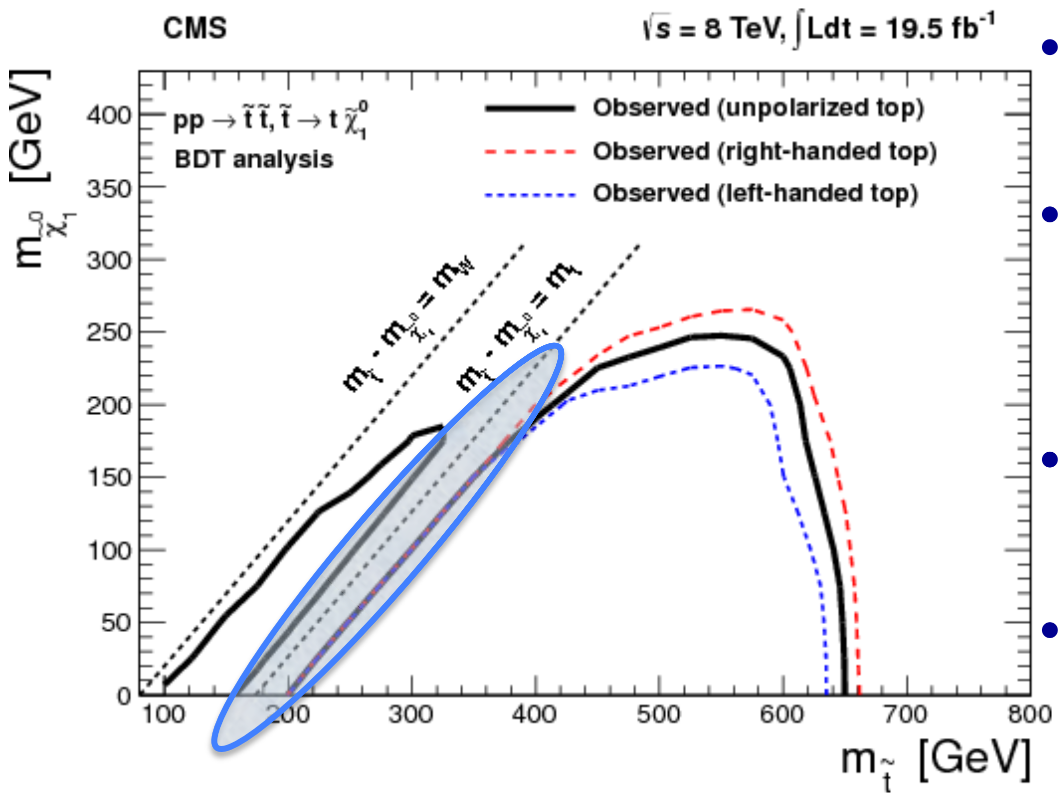
Such light stop would have also biased top mass measurement in unknown way.

Theory and expt σ(ttbar) depend on M_{top}

Situation not clear!



Boosted Events



- Design event selection for events recoiling against ISR
- ISR boost → momentum to LSP which is ~ at rest in stop rest frame
- Looks like we can get ~ 2σ sensitivity
- To be combined with dilepton mode for ~ 3σ sensitivity

Conclusions

- No sign of stop quarks at CMS
  - Atlas has similar results
- These null searches are beginning to be a serious challenge for the natural SUSY concept
- There remain loopholes, even for relatively light top squarks
  - Some of them are being addressed with current data
- The higher energy data to be collected starting next year will extended the (exclusion) sensitivity to > 1 TeV