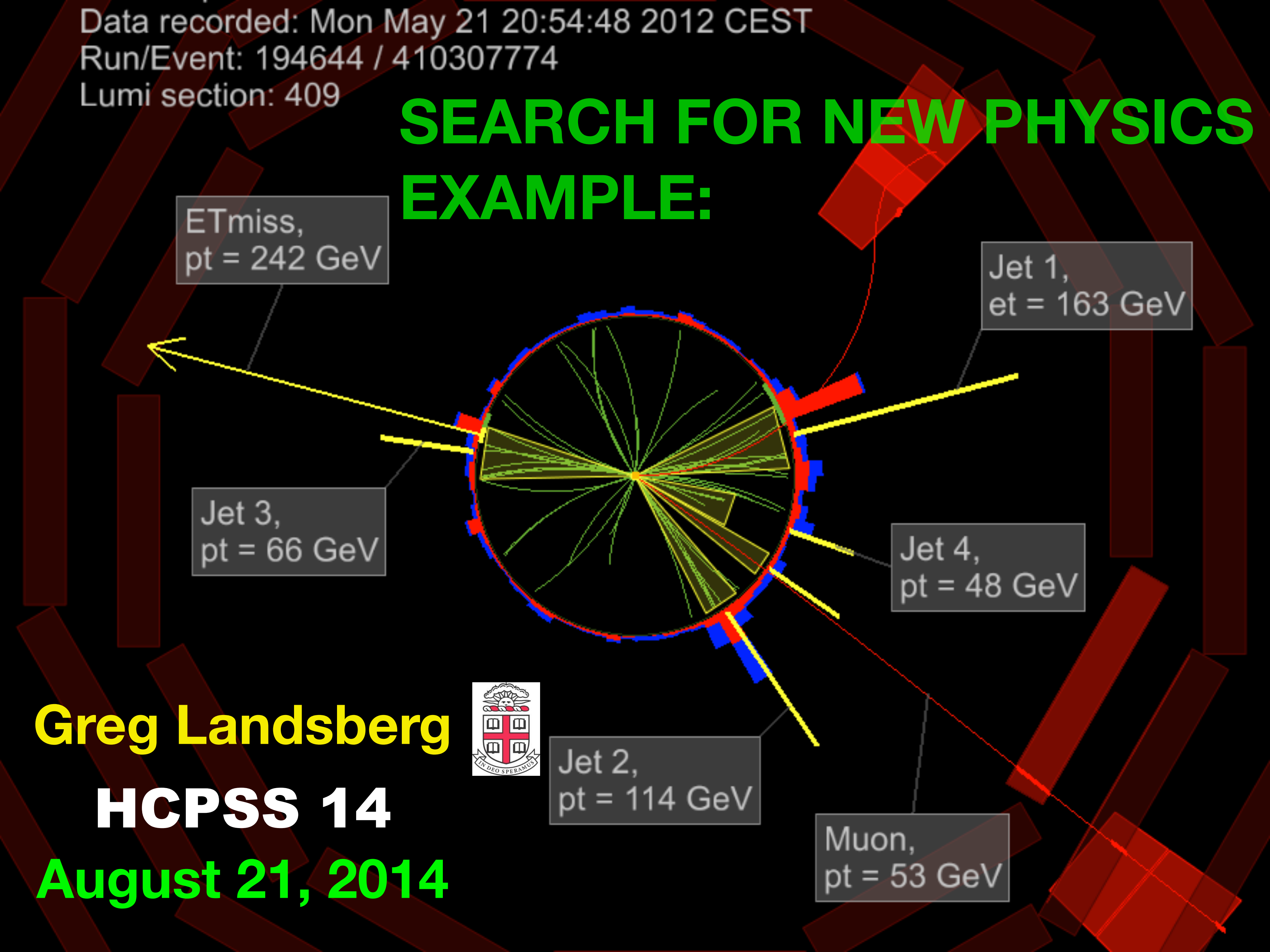
SEARCH FOR NEW PHYSICS EXAMPLE:



Greg Landsberg

HCPSS 14

August 21, 2014

Outline

- Motivation
- Physics
- Choosing the signature
- Signal simulation
- Event selection
- Backgrounds
- Analysis optimization
- Multivariate analysis vs. cut-based one
- Results
- Interpretation
- Next steps
- Conclusions

Motivation

MOTIVATION

Some people need more than others...

Why Motivate Yourselves?

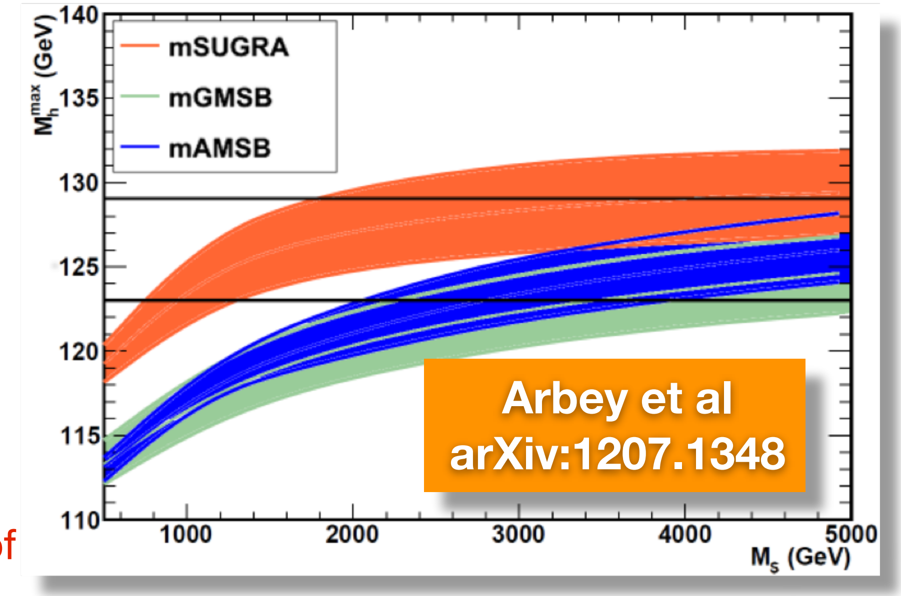
- Searching for new physics is not for lighthearted:
  - Some 200 searches have been done by the ATLAS and CMS Collaborations so far, and all came empty-handed
  - A likelihood for any given search to find something interesting is close to zero…
  - ..yet, the only way to find something is to keep looking!
- It's much easier to do the analysis if you are motivated
  - …not [just] by your advisor, but by the physics you are doing!
- Remember, every search is a potential discovery, and only if it fails, it becomes a limit setting exercise
- "Pier is a disappointed bridge" - James Joyce
  - Set out to build bridges, not piers!

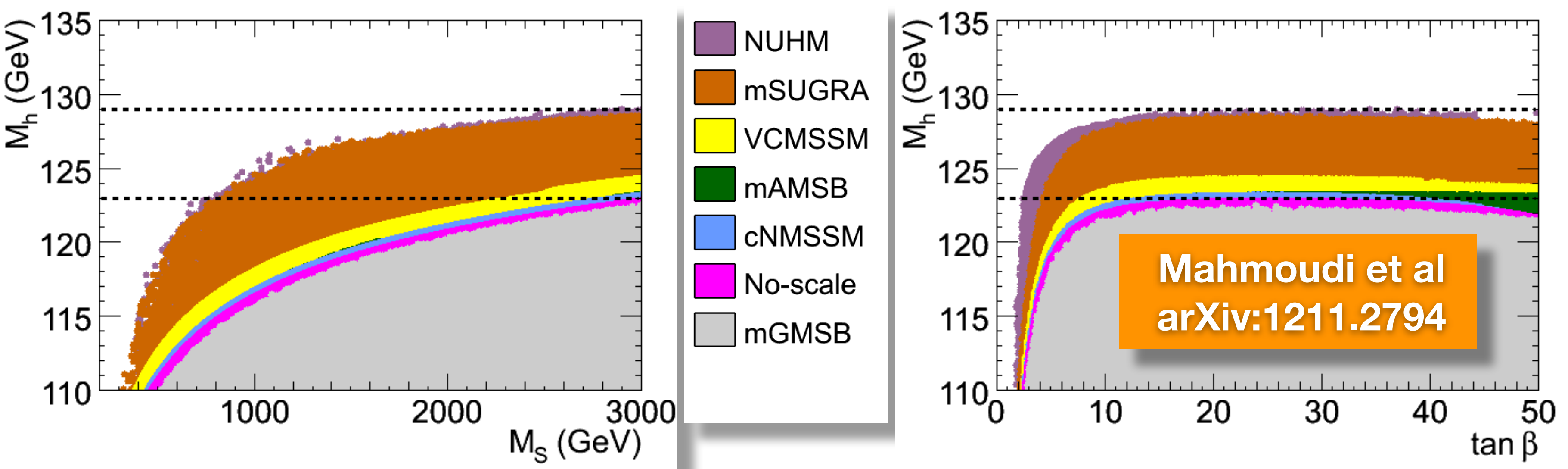
Looking for SUSY

- See more motivational details in Jessie Shelton's lectures:
  - What is SUSY?
  - Three SUSY miracles
  - Supersymmetric particle zoo
  - "Natural" SUSY
- SUSY and Higgs - the marriage made in heaven
  - What did we learn about SUSY in the aftermath of the Higgs discovery?

SUSY: the Higgs Aftermath

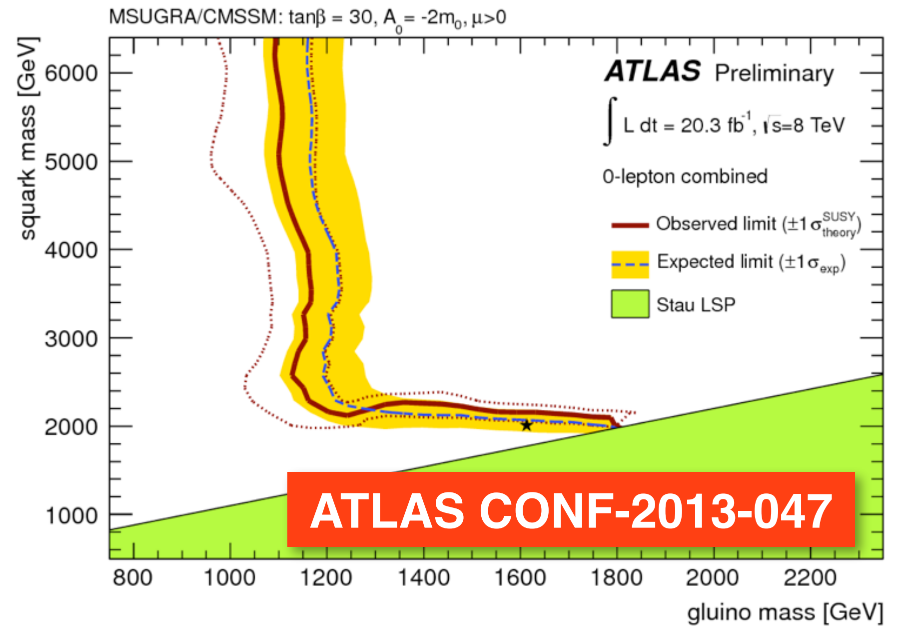
- A 125 GeV Higgs boson is challenging to accommodate in (over)constrained versions of SUSY, particularly for "natural" values of superpartner masses
  - Started to constrain some of the simpler models
- Big question: if SUSY exists, can it still be "natural", i.e. offer a non-fine-tuned solution to the hierarchy problem
  - If not, we would be giving up at least one of the three SUSY "miracles"

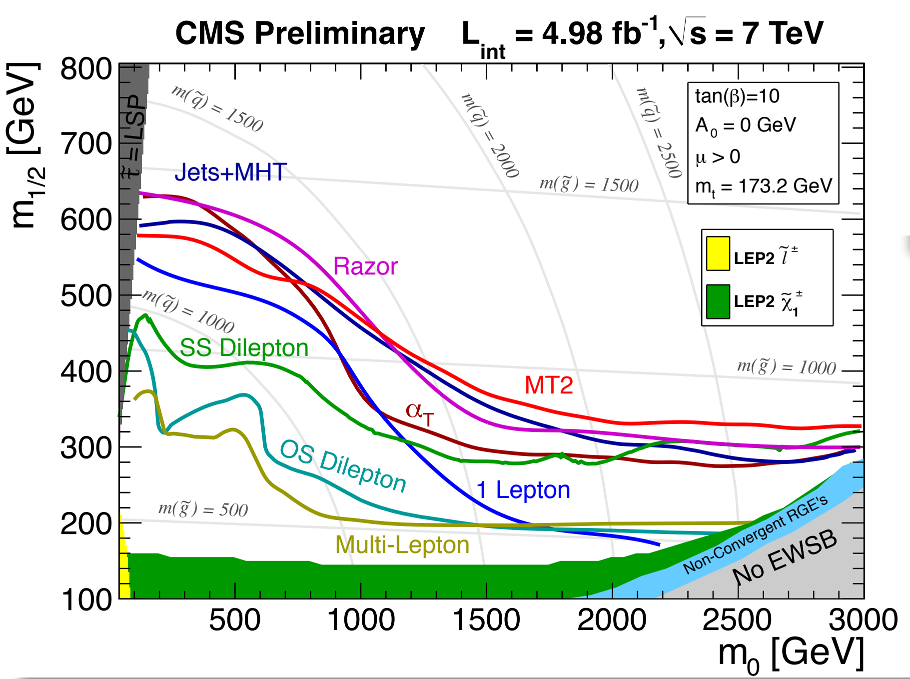




SuperSymmetry or SuperCemetery?

- Excluded squarks to ~2.0 TeV and gluinos to ~1.2 TeV - or did we?





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Read the fine print!

What SUSY Have We Excluded?

- We set strong limits on squarks and gluinos, and yet we have not excluded SUSY
  - Moreover, we basically excluded VERY LITTLE!
- We ventured for an "easy-SUSY" or "lazy-SUSY" and we basically failed to find it
  - So what? - Nature could be tough!
- What we probed is a tiny sliver of multidimensional SUSY space, simply most "convenient" from the point of view of theory
- All it takes to avoid these limits is to give up squark degeneracy!

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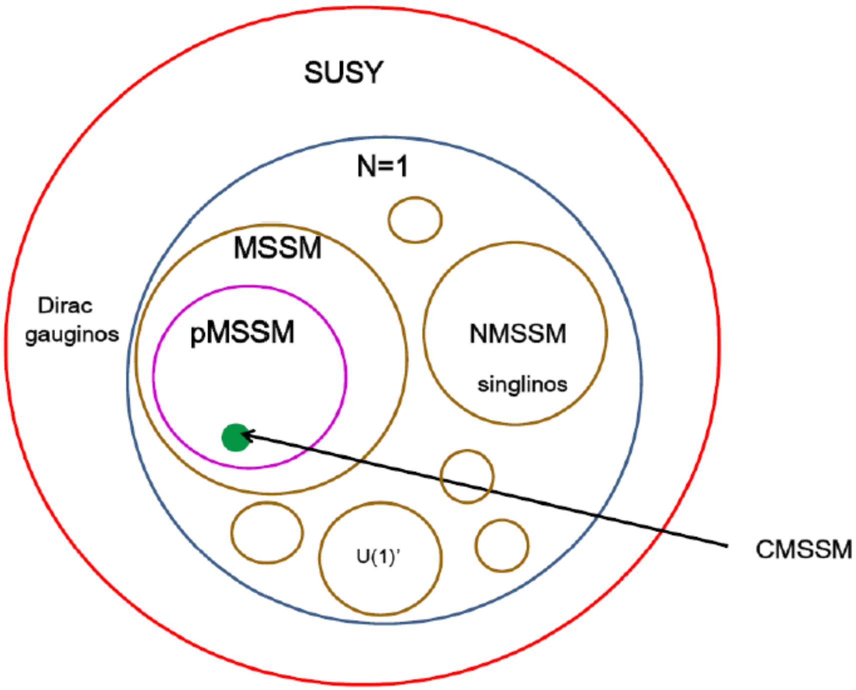
SUSY Theory phase space



T. Rizzo (SLAC Summer Institute, 01-Aug-12)

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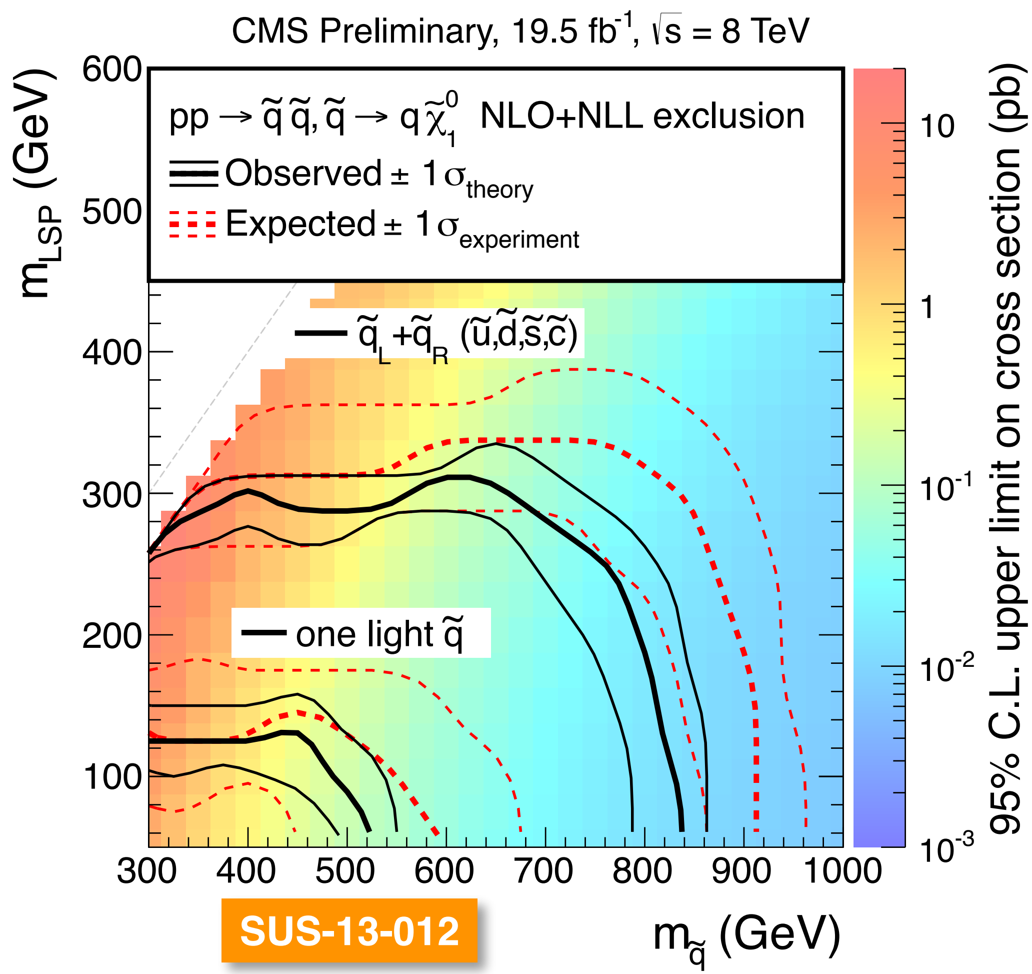

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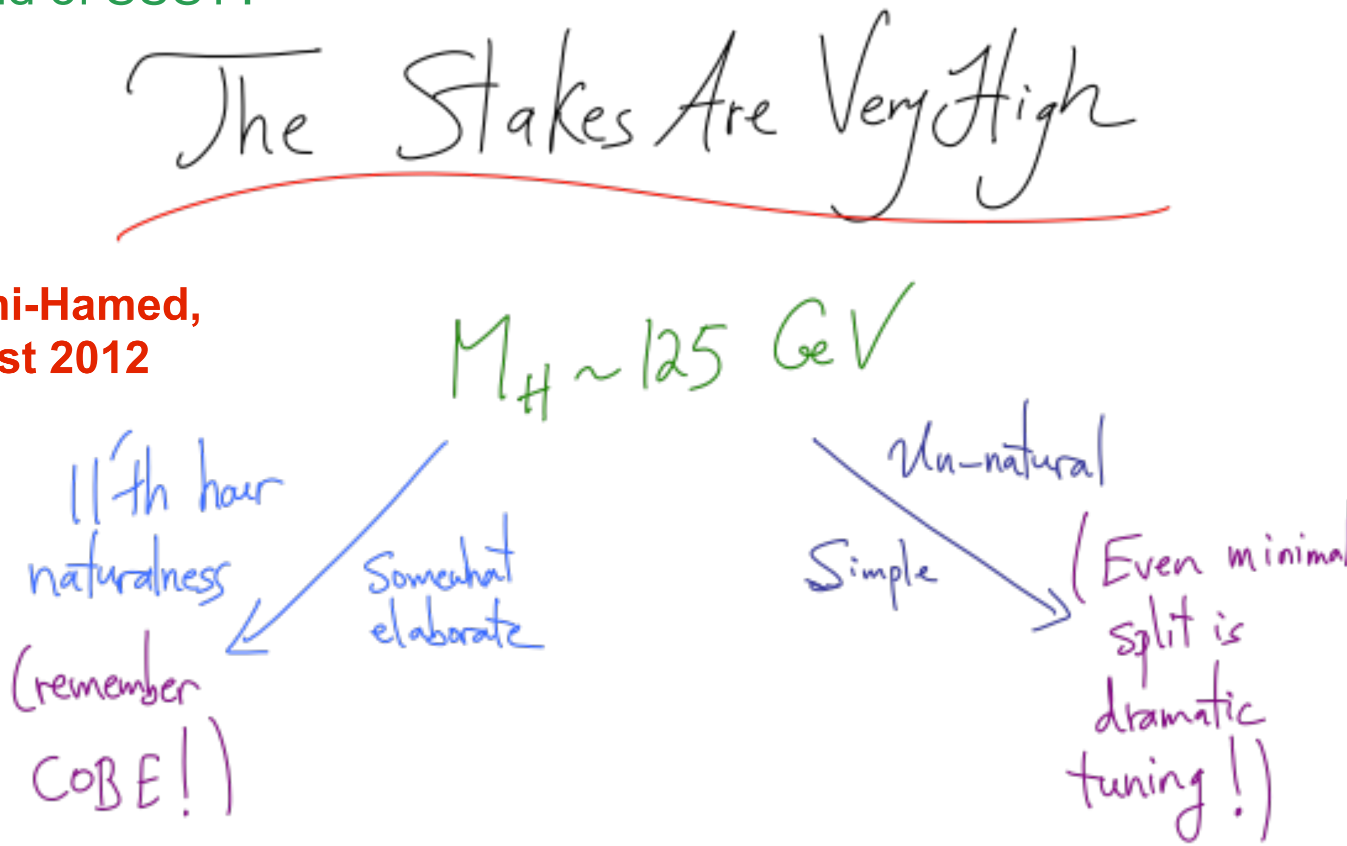
We are at a SUSY Crossroad

- Light 125 GeV Higgs boson strongly prefers SUSY as the fundamental explanation of the EWSB mechanism (via soft SUSY-breaking terms and radiative corrections)
- But what kind of SUSY?



Nima Arkani-Hamed, SavasFest 2012

Implies: light stops/sbottom, reasonably light gluinos and charginos/neutralinos

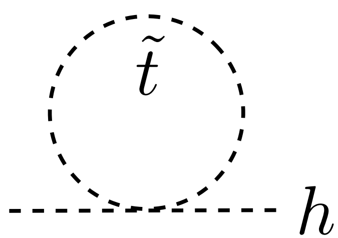
Likely: long-lived particles, light neutralino, multi-TeV Z′, ...

Fine-Tuning in (p)MSSM

- Fine-tuning: cancellation of two or more large numbers
- In pMSSM: $$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \frac{2}{\tan^2\beta}(m_{H_d}^2 - m_{H_u}^2) + \mathcal{O}(1/\tan^4\beta)$$

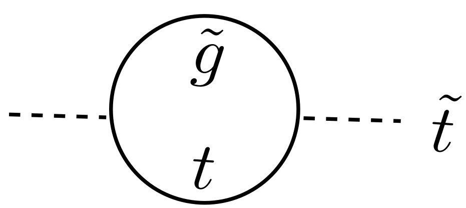
|μ| is small → light higgsinos

m^2_{Hu} is small → lights stops (at one-loop level) and gluinos (at two-loop level)



$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

stops

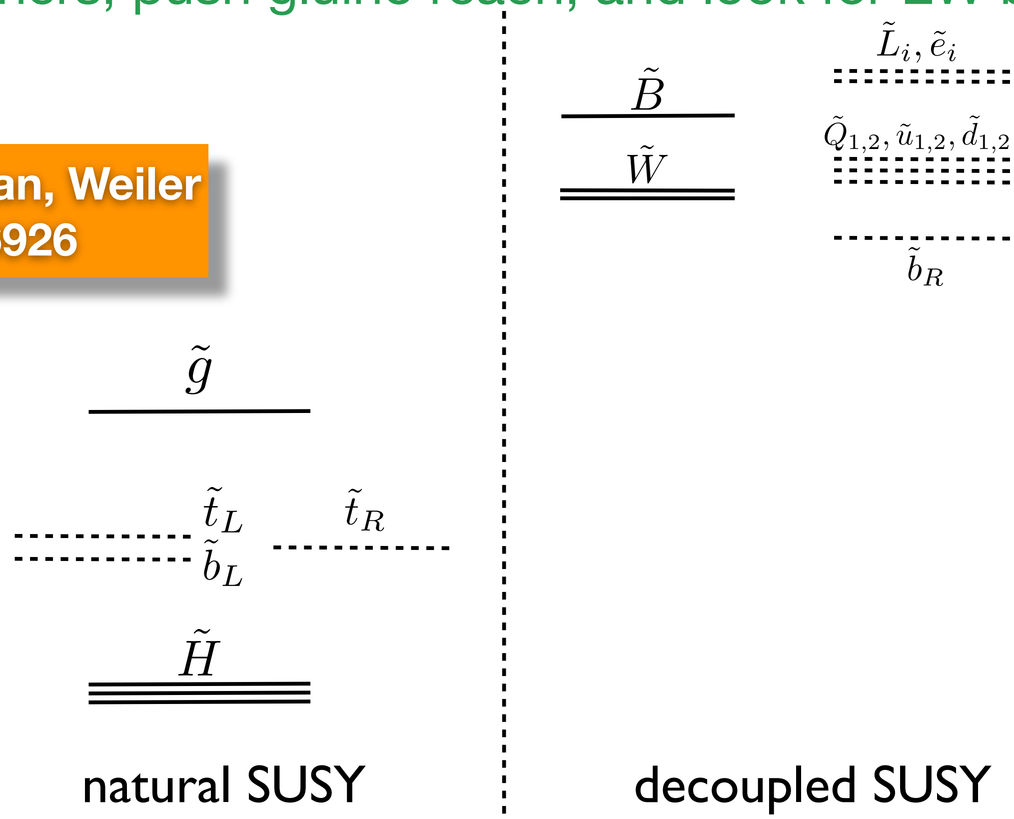


gluino-top loop drives the stop mass further up

Natural SUSY

- If SUSY is natural, we should find it soon:
  - And we most likely will find it by observing 3rd generation SUSY particles first!
- Requires shifting of the SUSY search paradigm: going for the third generation partners, push gluino reach, and look for EW boson partners

Papucci, Ruderman, Weiler
arXiv:1110.6926



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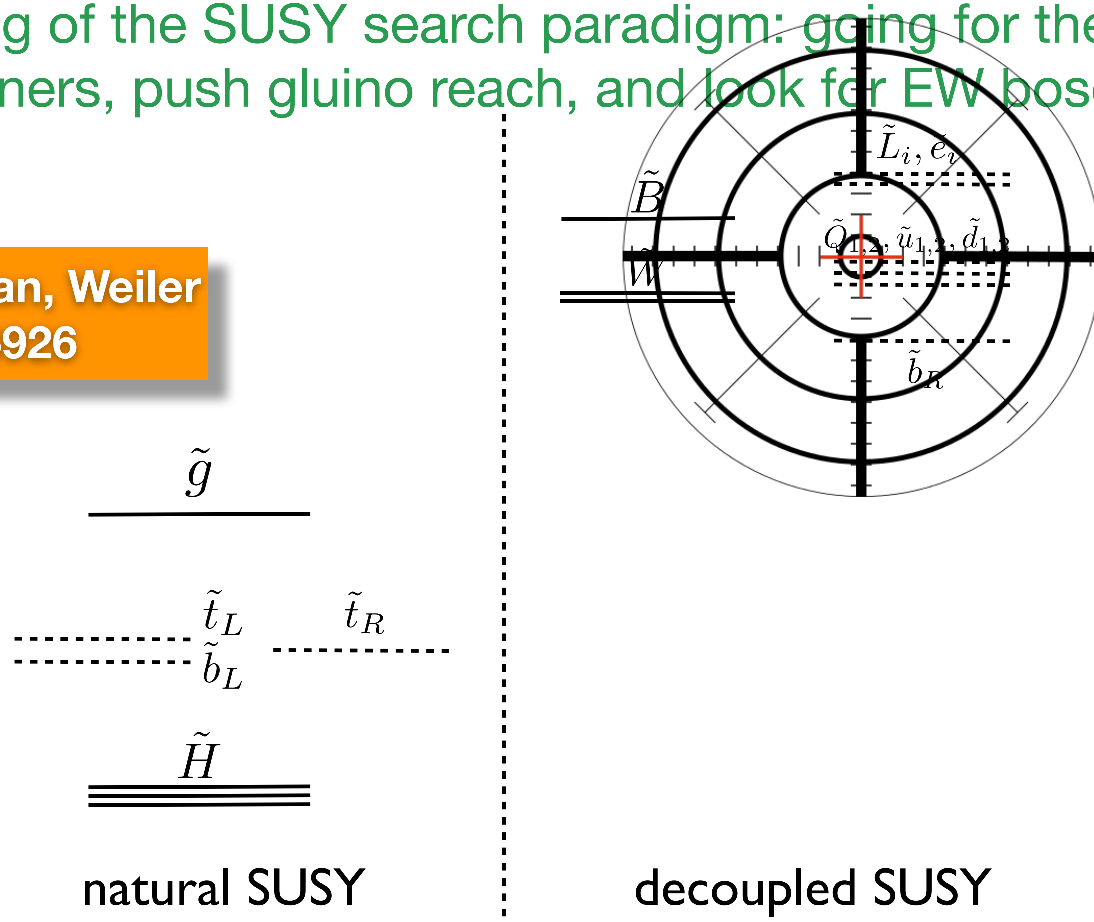

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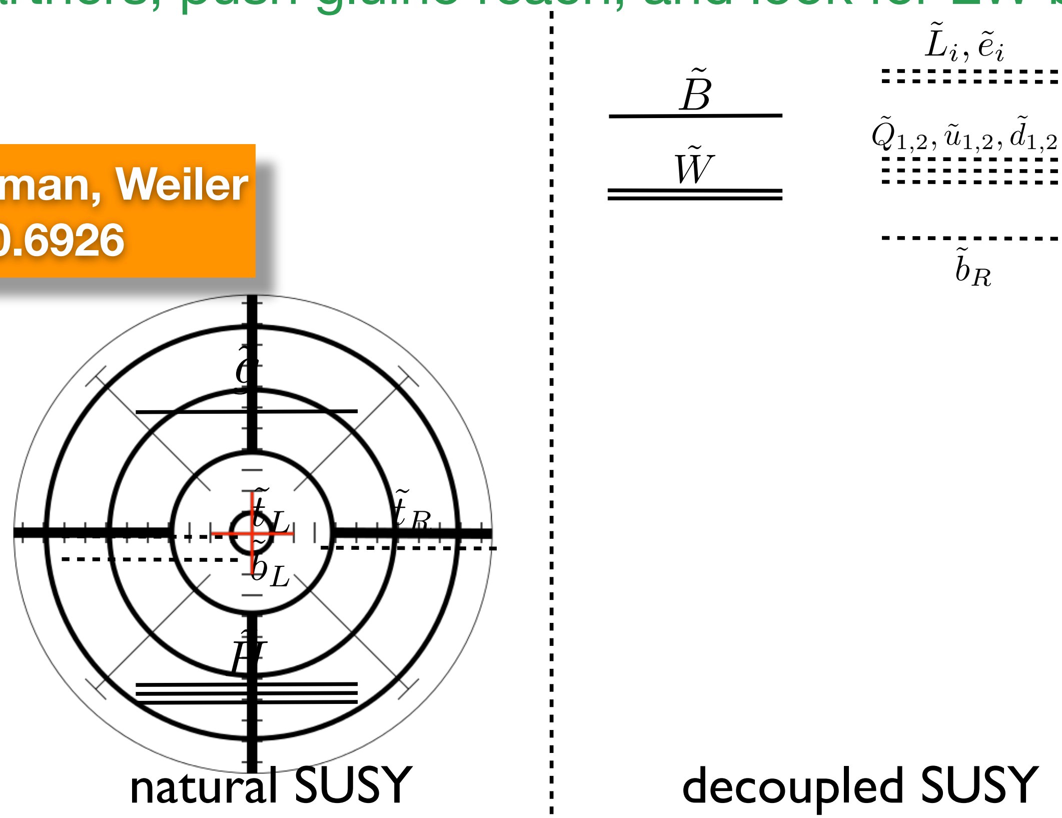
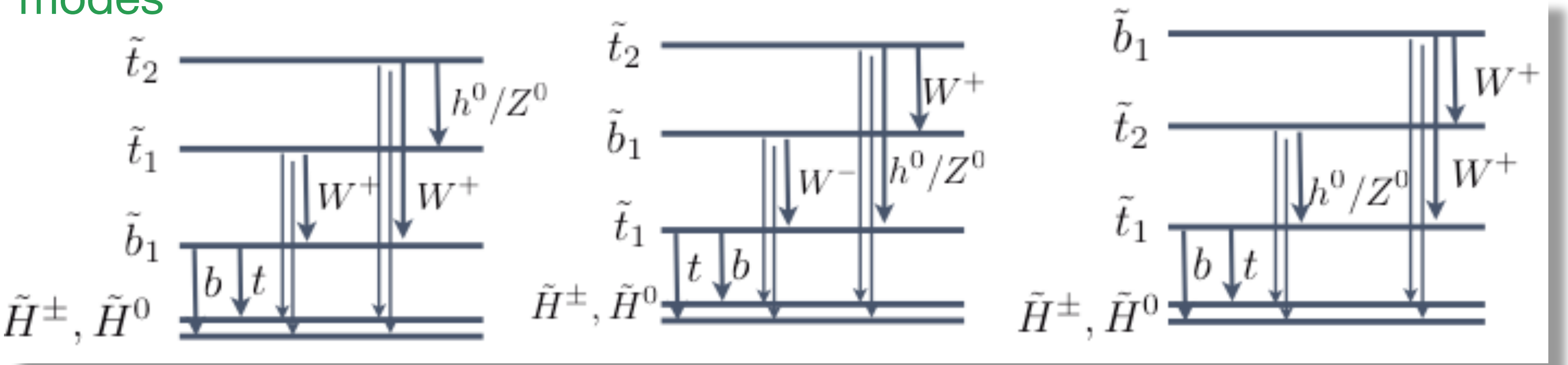


Natural SUSY Spectra

- Once we focus on natural SUSY, the spectra and the signatures become rather simple – almost like “simplified model spectra”
- Basically have to consider three types of spectra and related decay modes



Abbreviation	Decay mode	Conditions
T_t	$\tilde{t} \to t\chi^0$	$m_{\tilde{t}} > m_t + m_{\chi^0}$
T_b	$\tilde{t} \to b\chi^+ \to bW^+\chi^0$	$m_{\tilde{t}} > m_b + m_{\chi^+}$, $m_{\chi^+} > m_{\chi^0} + m_W$
$T_{b'}$	$\tilde{t} \to b\chi^+ \to bW^{+*}\chi^0$	$m_{\tilde{t}} > m_b + m_{\chi^+}$, $m_{\chi^+} < m_{\chi^0} + m_W$
$T_{t'}$	$\tilde{t} \to t^*\chi^0 \to bW^+\chi^0$	$m_{\tilde{t}} < m_t + m_{\chi^0}$, $m_{\tilde{t}} < m_{\chi^+} + m_b$
T_c	$\tilde{t} \to c\chi^0$	$m_{\tilde{t}} < m_t + m_{\chi^0}$, $m_{\tilde{t}} < m_{\chi^+} + m_b$
B_b	$\tilde{b} \to b\chi^0$	
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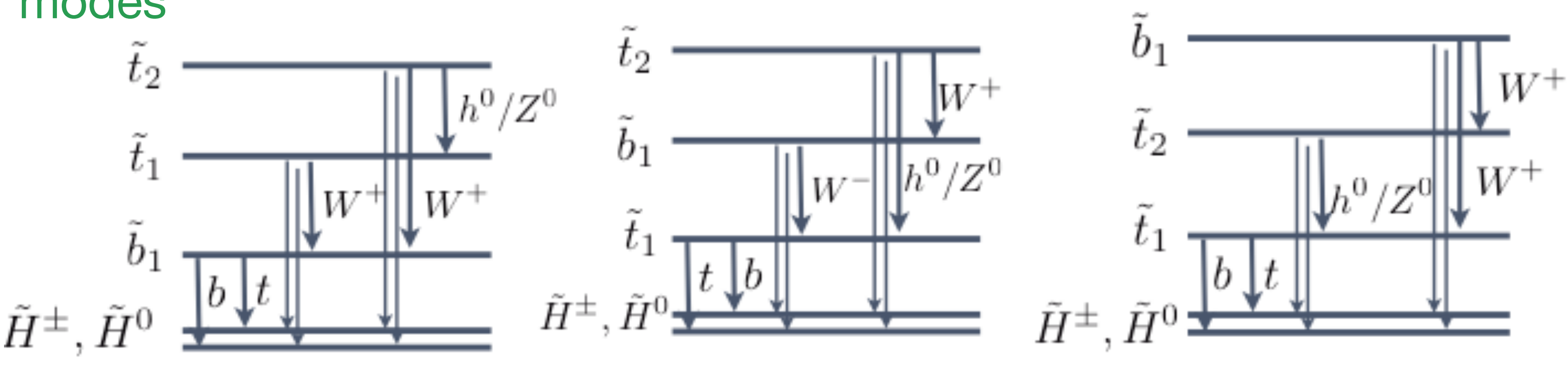

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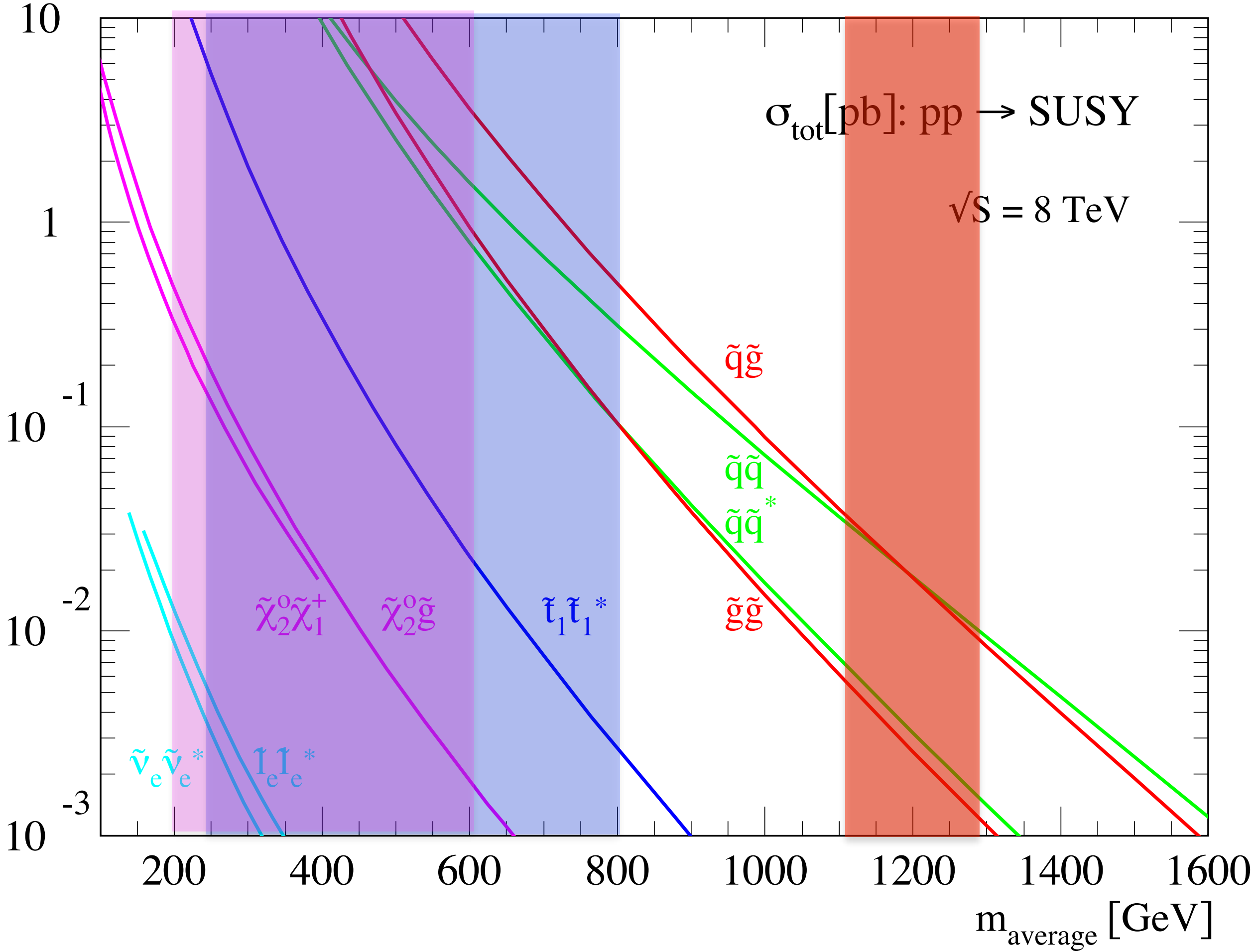
Natural SUSY Reach

- With $\int L dt \sim 20/fb^{-1}$ and 1 fb cross section produce 20 events; typically 1-10 events observed after acceptance/efficiencies

http://www.thphys.uni-heidelberg.de/~plehn/



$\tilde{g}\tilde{g}$: $M(\tilde{g}) \lesssim 1.3$ TeV

$\tilde{t}_1\tilde{t}_1$: $M(\tilde{t}_1) \lesssim 0.8$ TeV

$\tilde{\chi}\tilde{\chi}$: $M(\tilde{\chi}) \lesssim 0.6$ TeV

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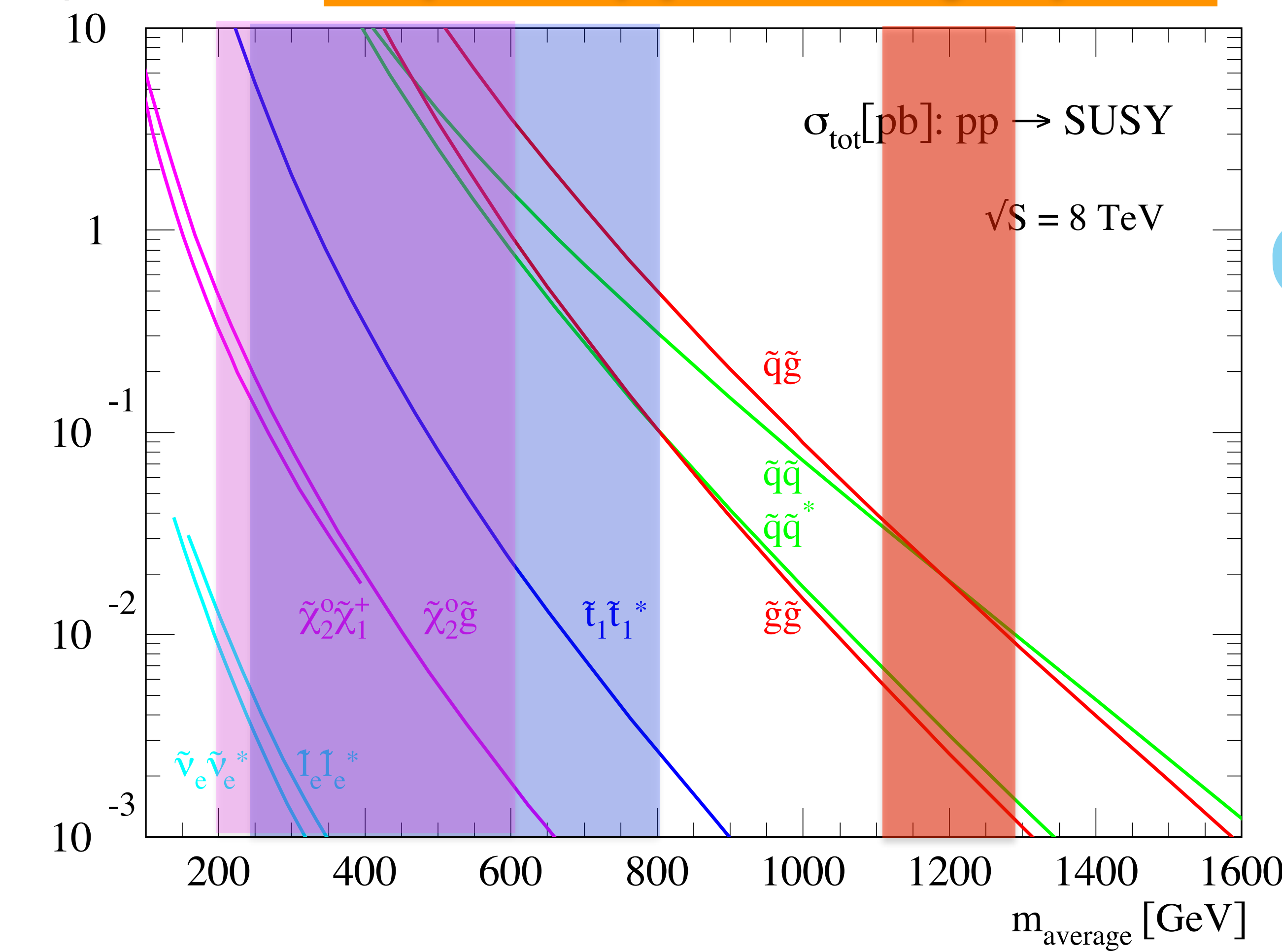

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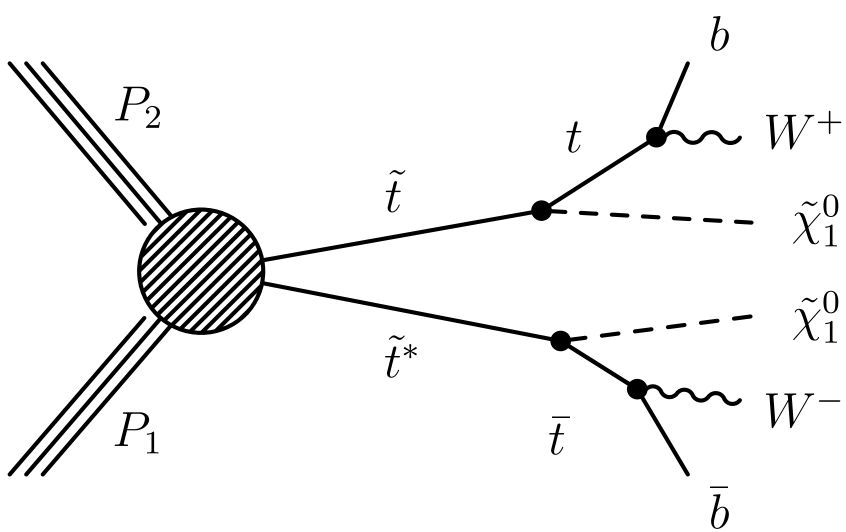
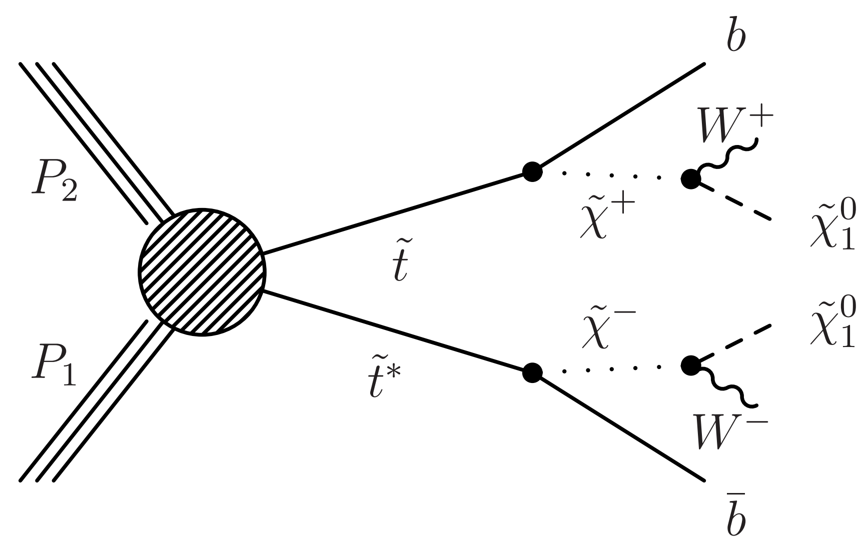
Physics: Stop Decays

Direct Stop Signatures

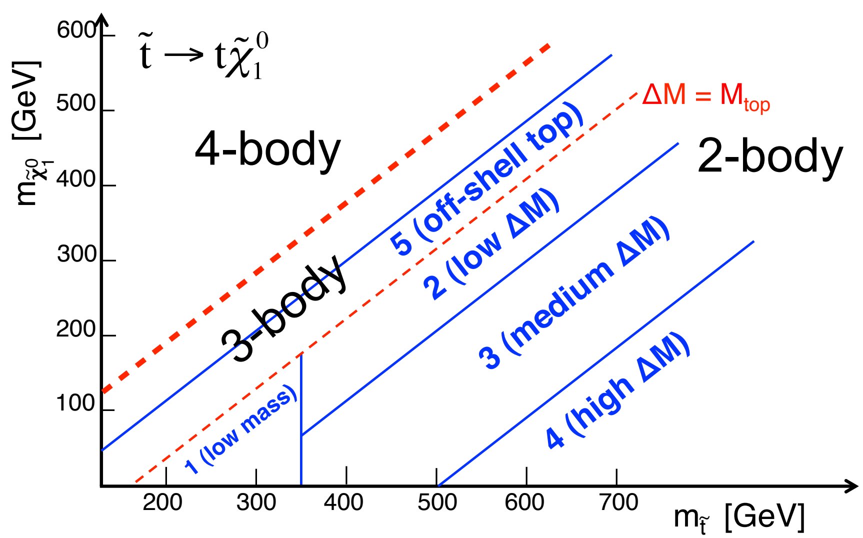
- We will model the stop pair production via a “Simplified Model Scenario”, i.e. zooming only on the light SUSY particles that matter for this process and assuming all other SUSY particles to be heavy
- Focus on just two Feynman diagrams representing relevant production and decay: $\tilde{t} \to t+\chi^0$ and $\tilde{t} \to b+\chi^+$
  - Both result in the same signature: $bbW^+W^-+ME_T$
  - N.B. this is the same signature as tt production (unless both W’s decay hadronically) - gives you an idea of the dominant background

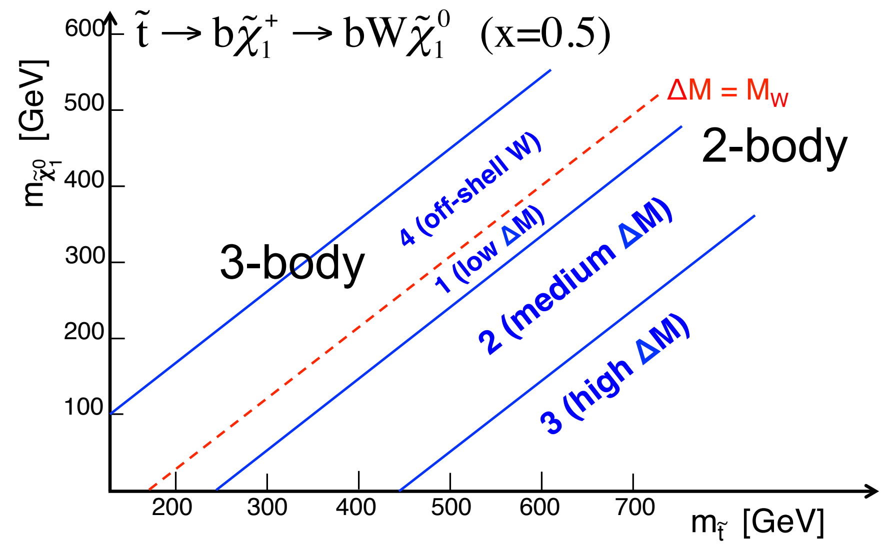




Kinematic Regions

- Depending on the mass differences between the stop and neutralino (chargino), several kinematic regions are defined:





- Different regions correspond to different challenges, so search strategy generally depends on the region
- Given that 4-body decays are enormously suppressed kinematically, the region $\Delta M < M_W$ in the $t\chi^0$ mode is usually covered by other channels, e.g. FCNC $\tilde{t} \rightarrow c\chi^0$ decay

Signal Simulation

Monte Carlo Samples

- One does have to rely on MC for estimating signal acceptance
  - Having signal MC is a prerequisite for any search analysis
  - This analysis uses MadGraph 5 LO generator, with up to two additional partons at the matrix element level in a grid of m(t) vs. $m(\chi^0)$
  - The decay of the stops and fragmentation are simulated with Pythia 6 generator, assuming 100% branching fraction in either the $t\chi^0$ or $b\chi^+$ final state
  - Both the 2-body and 3-body decays are considered; in the case of the $b\chi^+$ final state, an additional mass parameter is used: $m(\chi^+) = xm(t) + (1-x)m(\chi^0)$, with x = 0…1, which defines the chargino mass between the neutralino (x=0) and stop (x=1) masses
- One may or may not rely on MC for background estimates
  - Still, it's a good idea to have background MC samples generated
  - These are generated with a combination of LO generator MadGraph 5 and NLO generators Powheg and MC@NLO
  - In some cases (e.g., tt background) several generators are used for cross-checks

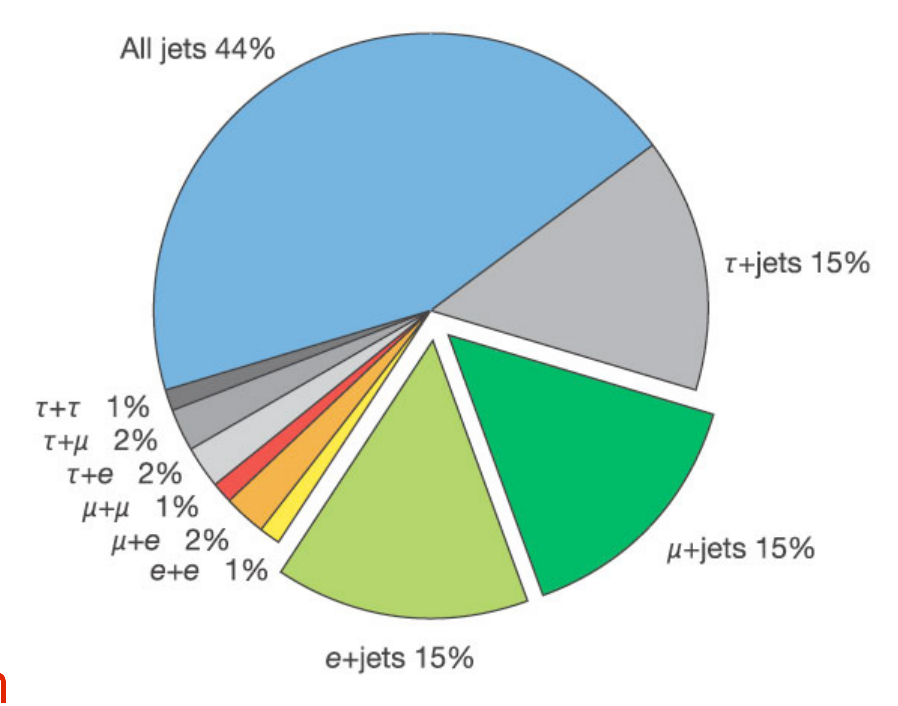
Parton Distribution Functions

- As usual, one has to interface MC generators with parton distribution functions (PDFs)
- Normally, one would like to match the order of the generator with the same order of the PDF set
- Thus, for MadGraph we use LO CTEQ6L1 set; for Powheg, we use CT10 NLO PDF set, and for MC@NLO we use CTEQ6M NLO PDF set
- Since Pythia is used for hadronization and fragmentation with all the generators, one has to patch matrix-element jets with the parton-shower jets, which is done using special prescription, to avoid double-counting
- The matching parameter defines minimum jet p_T for which the matrix elements are used to describe additional jet production; below this p_T (typically 20 GeV) the emission is described by parton showers
- All the cross sections are normalized to the best available predictions: NLO+NLL for the signal and NLO or NNLO for backgrounds

Signature

Single-Lepton Channel

- Now we need to figure out what's the best final state to pursue the search
- The final state depends on the W boson decay channels
  - All hadronic channel has the highest branching fraction, but backgrounds are huge
  - Dilepton channel is clean but the branching fraction is tiny
  - Tau channels are tough
  - Use single-lepton (e+jets, μ+jets) channels as a compromise between frequen



- The analysis I'm going to describe is CMS, arXiv:1308.1586

BROWN

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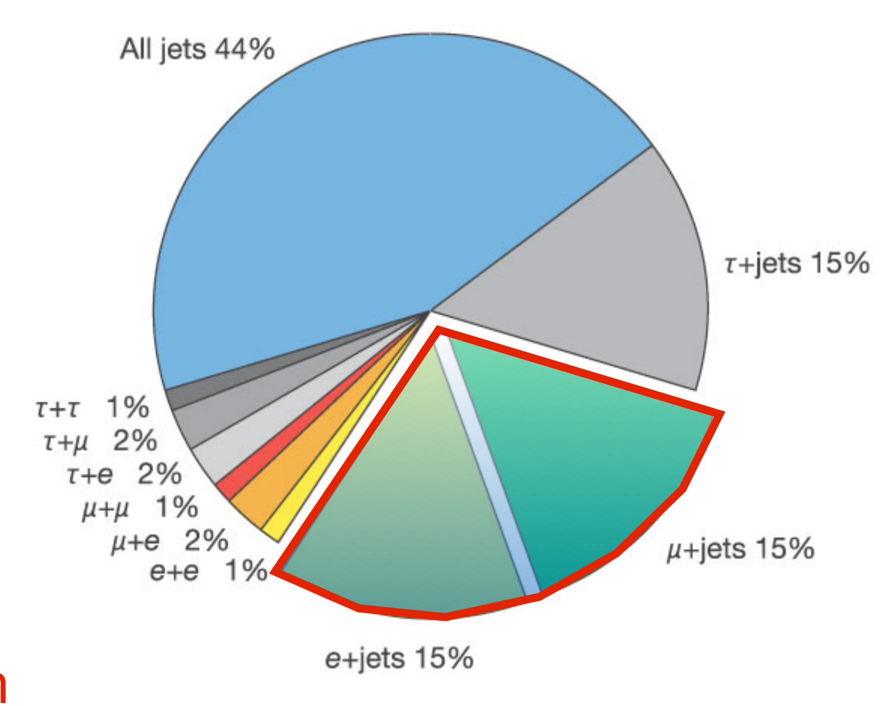

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Event Selection

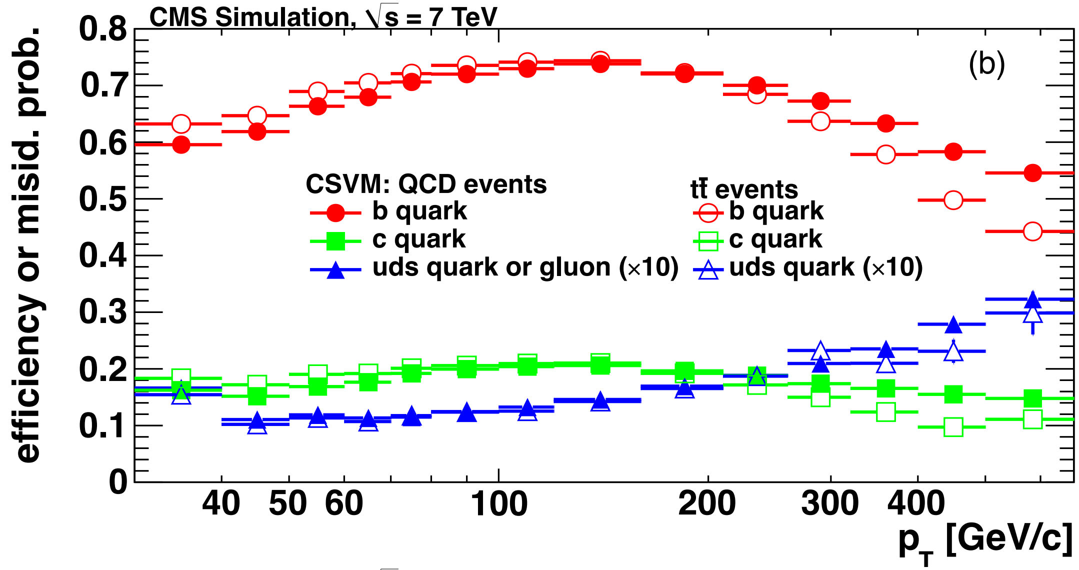
Preselection

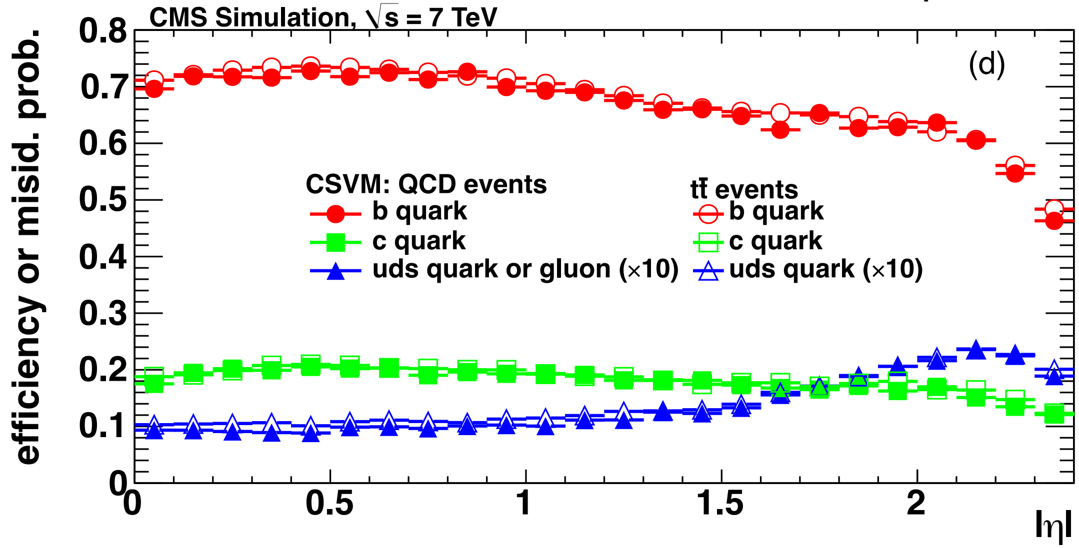
- Triggering is not an issue - standard top-quark triggers work just fine (single-electron or single-muon trigger with the thresholds of 27 and 24 GeV, respectively)
- One isolated electron ($p_T > 30$ GeV, $|\eta| < 1.44$) or muon ($p_T > 25$ GeV, $|\eta| < 2.1$)
  - Isolation is defined as a scalar p_T sum of all additional activity in a cone of R=0.3 around the lepton and is required to be 15% of the lepton p_T and less than 5 GeV
- Veto on a second isolated lepton ($p_T > 5$ GeV), including hadronically decaying τ-lepton ($p_T > 20$ GeV); also a veto on any additional isolated track w/ $p_T > 10$ GeV
  - Reduces background from dilepton tt decays
- At least 4 jets (anti-k_T algorithm with R = 0.5), with $p_T > 30$ GeV, $|\eta| < 2.4$
- At least one of them is tagged as a b-jet
  - Reduces W+jets background
- $ME_T > 100$ GeV
- All objects are reconstructed using CMS particle-flow algorithm, which combines the information from all the sub-detectors in an optimal way

BROWN

b-tagging

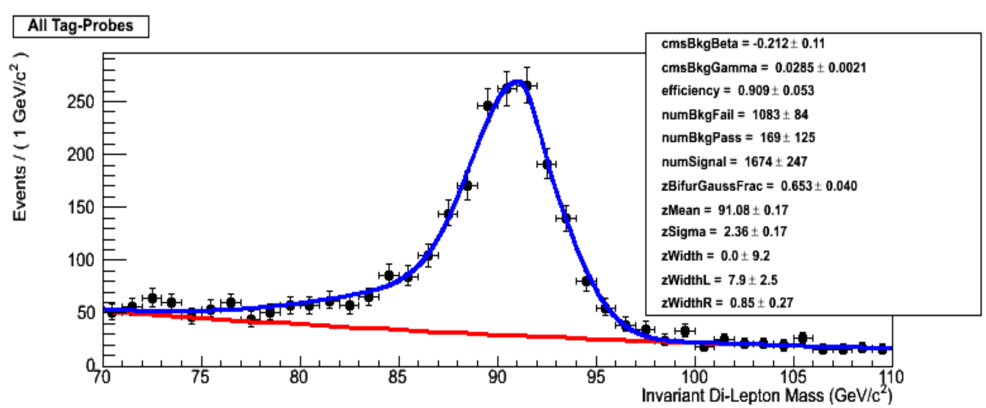
- Several algorithms are used to tag jets originating from b-quark fragmentation
  - Characterized by efficiency and purity
- CMS uses “combined secondary-vertex” (CSV) algorithm in most of the search analyses
  - Uses the significance of secondary vertex separation, when secondary vertices are found or uses individual tracks with large impact parameter when no secondary vertices are found
- Typical tagging efficiency is 60-70% with light-jet mis-ID rate of ~1%



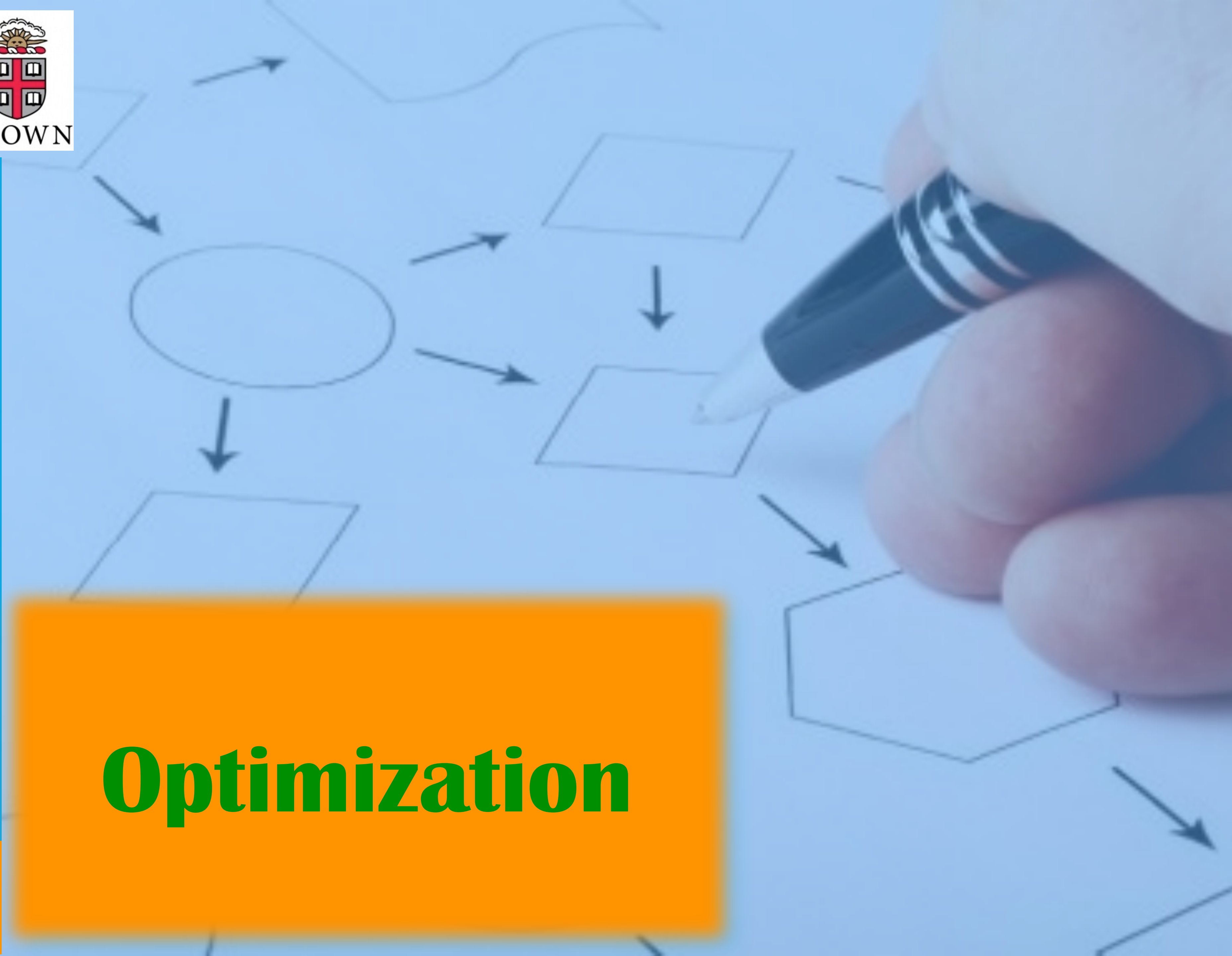


Efficiency Calculation

- “Tag-and-probe” method is used, utilizing Z(ee) and Z(μμ) events
- Look at the Z(ll) events, apply tight requirements on one lepton (“tag”) and very loose requirements on the other (“probe”)
- Estimate efficiency of standard requirements by counting the fraction of probe leptons passing these standard requirements
  - Fit for the number of events in the Z-peak, by subtracting the backgrounds



- Typical efficiency: 80%



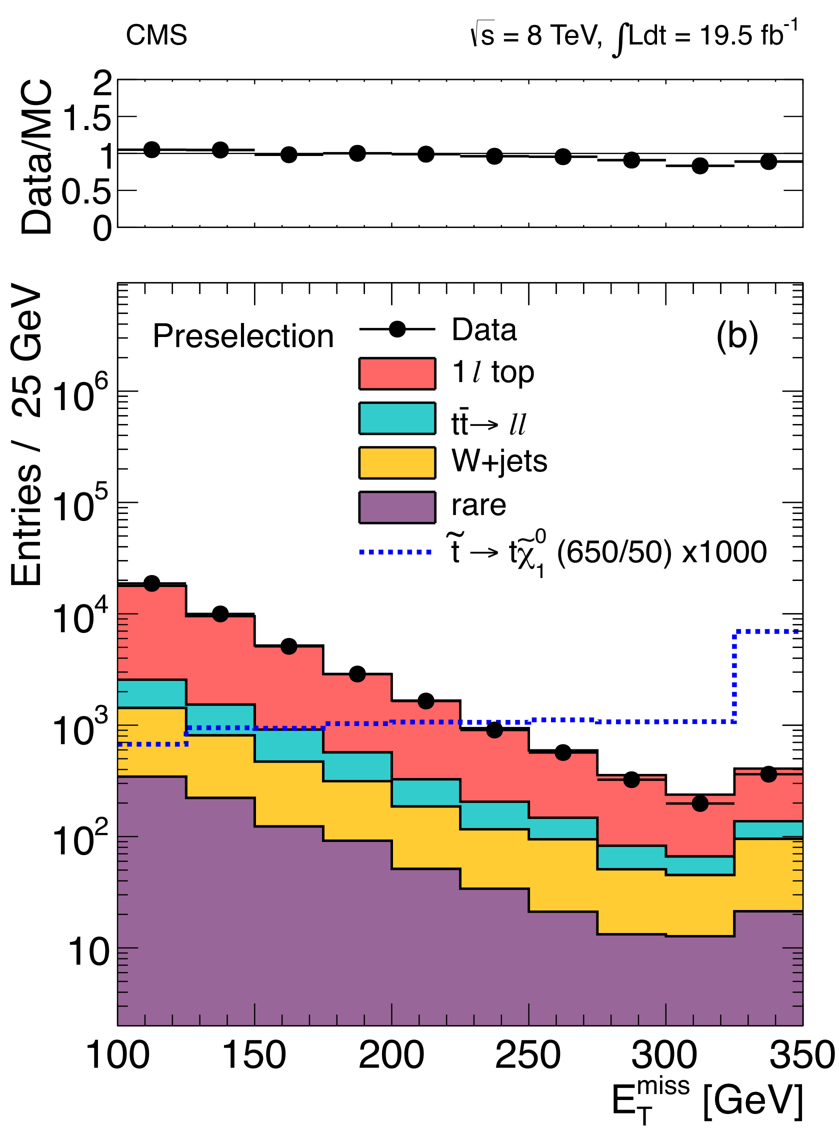
Optimization

Backgrounds

- In the regions of interest, there are four classes of backgrounds, in decreasing significance:
  - tt → ll + jets + ME_T, with a lost lepton (three undetected particles, similar to the signal)
  - tt → l + jets + ME_T, similar to the signal, but ME_T comes from a single neutrino; also some contribution from single-top-quark production
  - ttV, VV, VVV, tW - electroweak and other rare backgrounds
  - W+jets
  - Multijets with misidentified leptons (negligible)
- Use hybrid method for background determination: MC based, with validation and correction from control regions (CR)

Missing Transverse Energy

- Given that the signal signature has three invisible particles, while most of the backgrounds have one, ME_T is a good discriminating variable between the signal and background

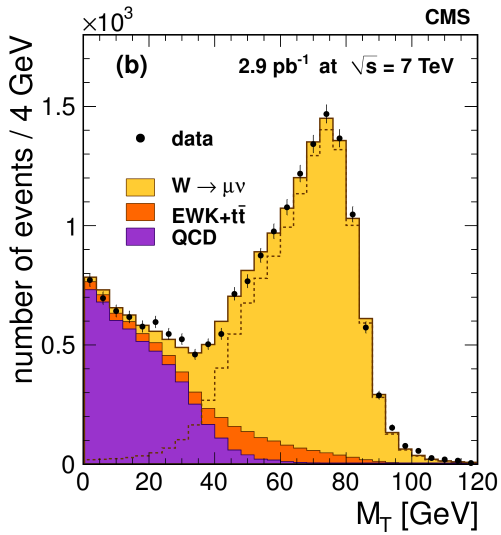


Transverse Mass

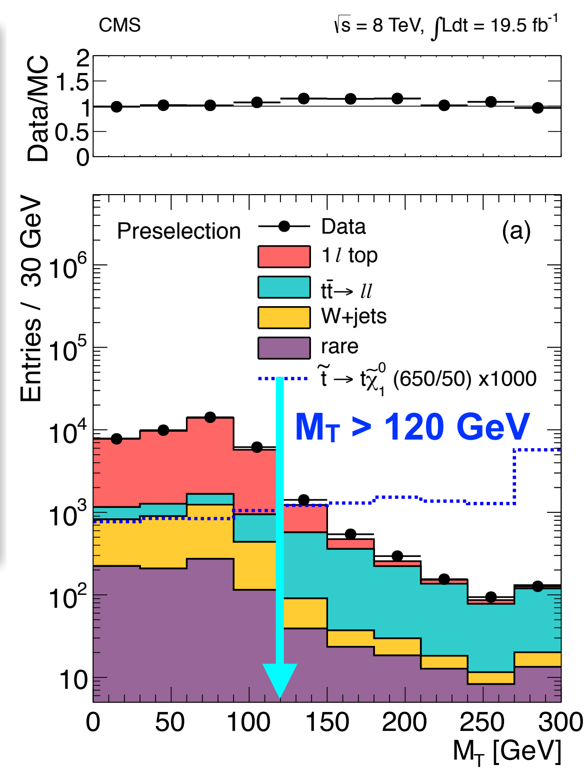
- Standard variable when dealing with signatures containing ME_T
- Classical example: W(lν)

$$M_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} \not{E}_{\mathrm{T}} (1 - \cos\Delta\phi)}$$

- Transverse mass is an approximation of the invariant mass in the case when the longitudinal momentum component is not available (e.g., due to a neutrino)
- Has a sharp Jacobian peak with a sharp falling edge at the true invariant mass m_W



M_T > 120 GeV requirement is used for signal selection



- Signal has different distribution in M_T, as it contains three invisible particles and therefore doesn't have a Jacobian peak at m_W

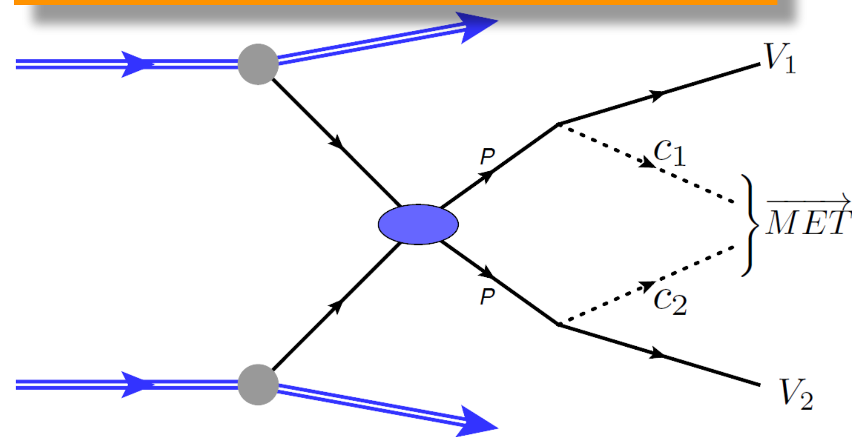
The M_{T2} Variable

- M_{T2}: ***"stransverse mass"*** - a generalization of the transverse mass in case of a pair of invisible particles
- For a simplified case of no extra jets and zero masses for visible and invisible systems:

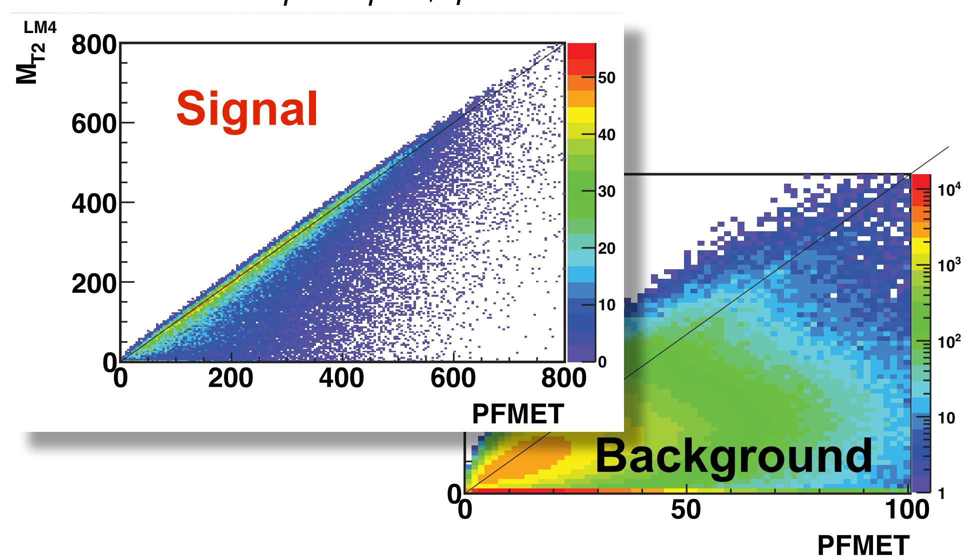
$$(M_{T2})^2 \simeq 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

  - $M_{T2} \sim ME_T$ for symmetric SUSY-like topologies
- M_{T2} kills QCD background very efficiently:
  - $M_{T2} \sim 0$ for dijets
  - $M_{T2} < ME_T$ in case of mismeasured dijets

Lesters & Summers, hep-ph/9906349

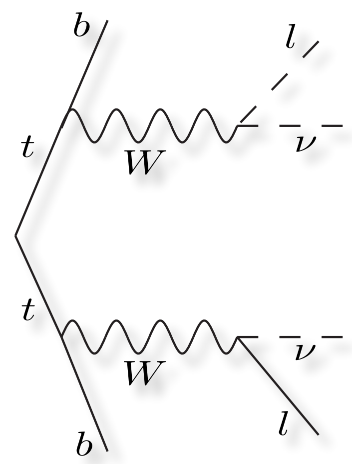


$$M_{T2} = \min_{p_T^{c1} + p_T^{c2} = \not{p}_T} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right]$$

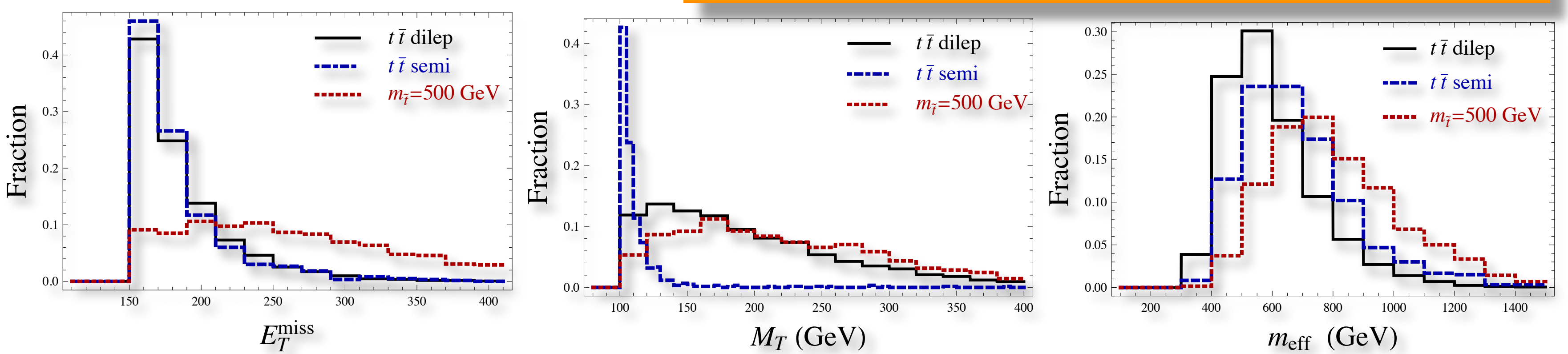


More M_{T2} Variables

- The main variable used in this analysis is a variation of M_{T2} variable, known as M^{W}_{T2} variable, which is the minimum mother mass compatible with all the decay products and on-shell constraints
- It is designed to specifically kill tt → ll+jets+ME_T background with a lost lepton
- This is a difficult background to deal with as it looks similar to the signal in other distributions, particularly in transverse mass M_T
- The trick of finding the right M_{T2} variable is how to partition the final state particle into visible and invisible states



Bai, Cheng, Gallicchio, Gu, arXiv:1203.4812

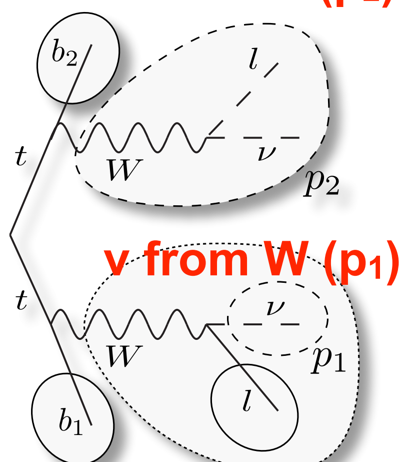


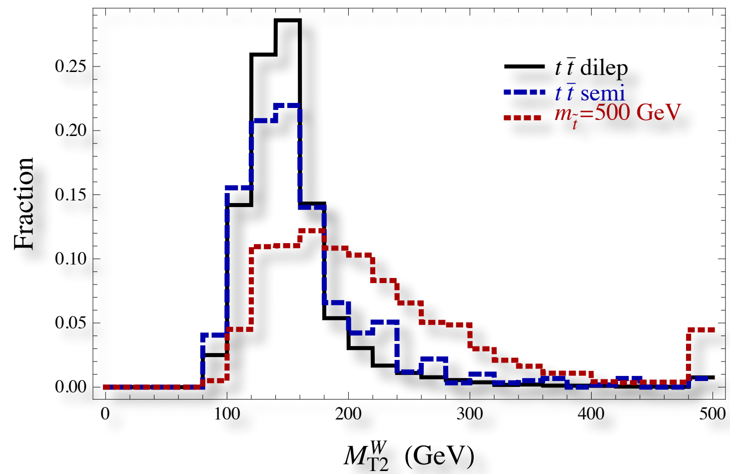
M^W_{T2} Variable

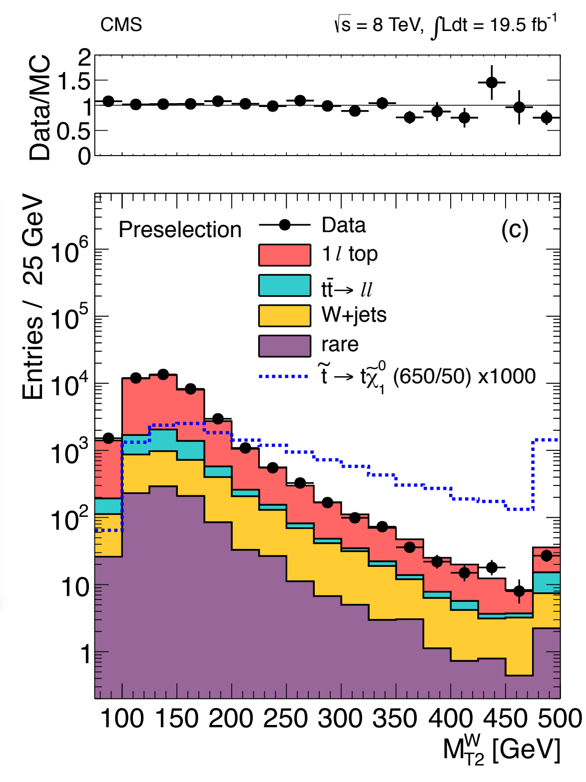
- Here is the definition of the M^W_{T2} variable designed to reconstruct tt events with a lost lepton:

$$M^W_{T2} = \min\left\{m_y \text{ consistent with: } \left[\begin{array}{r} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\text{miss}},\ p_1^2 = 0,\ (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b_1})^2 = (p_2 + p_{b_2})^2 = m_y^2 \end{array}\right]\right\}$$

- The tt events with lost lepton exhibit endpoint at $m_y = m_t$, while the signal has long tail





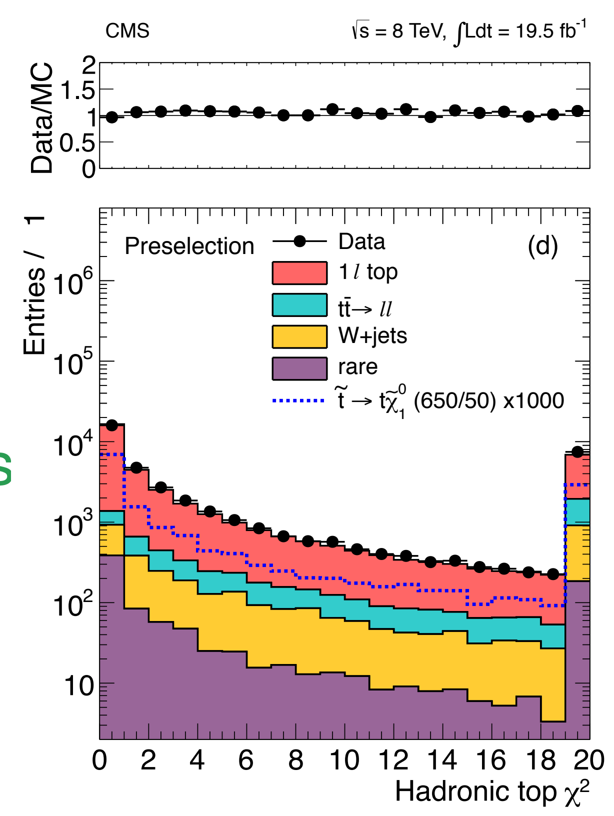


Kinematic Fit

- In the case when top quark in the $\tilde{t} \to t+\chi^0$ decay is on-shell (i.e., $m(\tilde{t}) > m_t + m(\chi^0)$) the three jets from the t → Wb → jjb decay should satisfy two mass constraints: $m(jj) \sim m_W$ and $m(jjb) \sim m_t$
- Construct a χ^2 variable for each allowed combination (which respects b-tag jet assignments)

$$\chi^2 = \frac{(M_{j_1 j_2 j_3} - M_{\rm top})^2}{\sigma^2_{j_1 j_2 j_3}} + \frac{(M_{j_1 j_2} - M_{\rm W})^2}{\sigma^2_{j_1 j_2}}$$

- Find the combination that minimizes the χ^2 ($\chi^2_{\rm min}$)
- The $\chi^2_{\rm min}$ should be small for backgrounds with hadronic top-quark decays; it should be larger for events w/o, e.g. W+jets background or dilepton tt with a lost lepton



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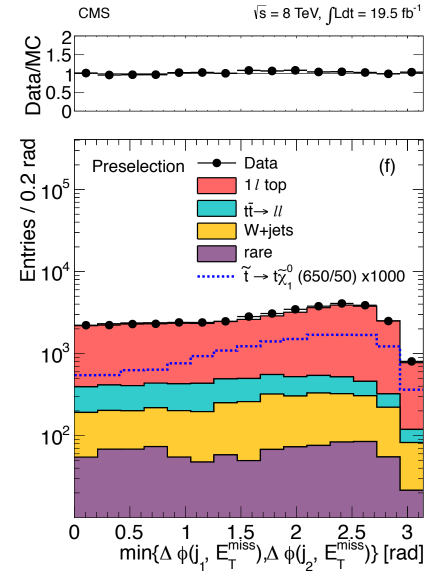
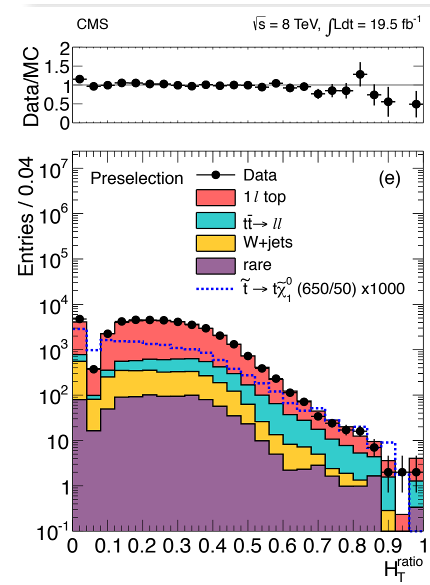
Topological Variables

- $\Delta\phi_{min}(ME_T, j_{1,2})$ - minimum azimuthal angle difference between the ME_T vector and two leading jets
  - Background tt events tend to be more back-to-back as the signal events; hence top quarks are more boosted for the background and $\Delta\phi_{min}$ tends to be smaller than for the signal events
- H_T ratio defined as the ratio of the scalar sum of p_T of jets in the same hemisphere than the ME_T vector to the total scalar sum of all jet p_T (H_T)
  - Tends to be smaller for the signal, as visible decay products recoil against the LSPs, so they tend to be opposite to ME_T





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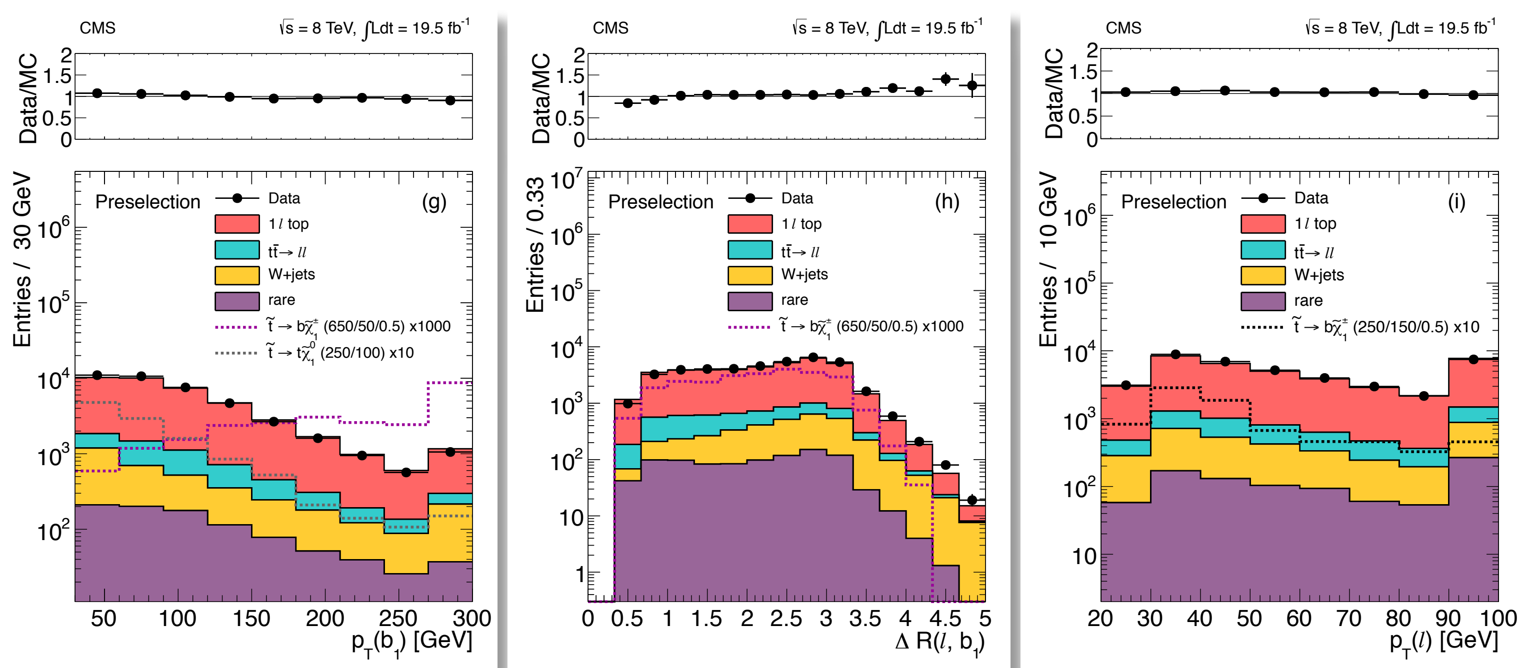
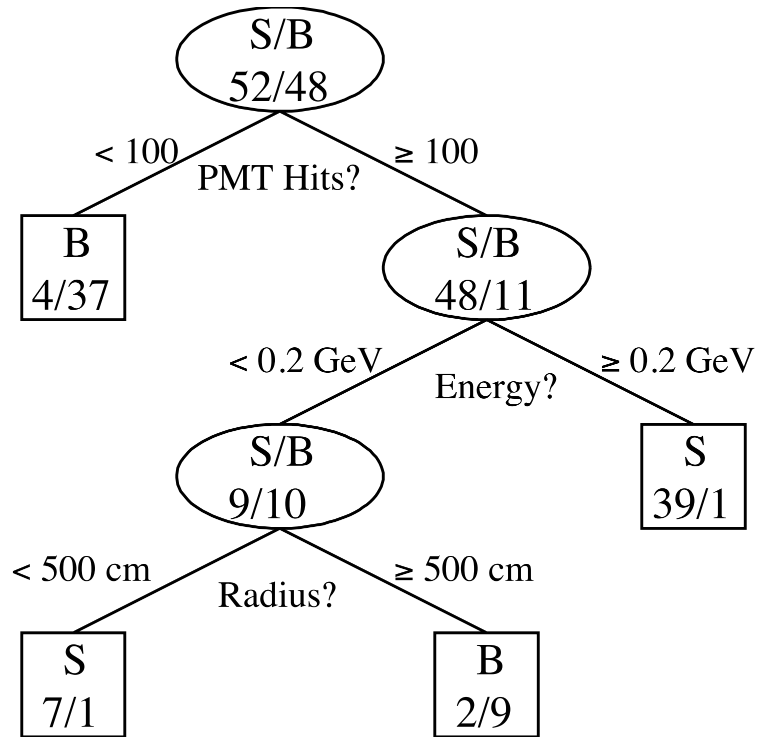
Topological Variables

- For the $\tilde{t} \rightarrow b+\chi^{+}$ decay, b-jet comes from the stop decay, while for the background, it comes from the top-quark decay; thus the b jet in general is harder for the signal
  - Conversely, for the $\tilde{t} \rightarrow t+\chi^{0}$ events in the 3-body region of the parameter space, b-jet is softer than for the tt background
  - Use leading b jet (b_1) p_T as a discriminant
  - Related variable is $\Delta R(l,b_1)$
- For a 3-body $\tilde{t} \rightarrow b+\chi^{+}$ decay ($m(\chi^{+}) - m(\chi^{0}) < m_W$), lepton p_T is softer and can be used as an additional discriminating variable



Optimization

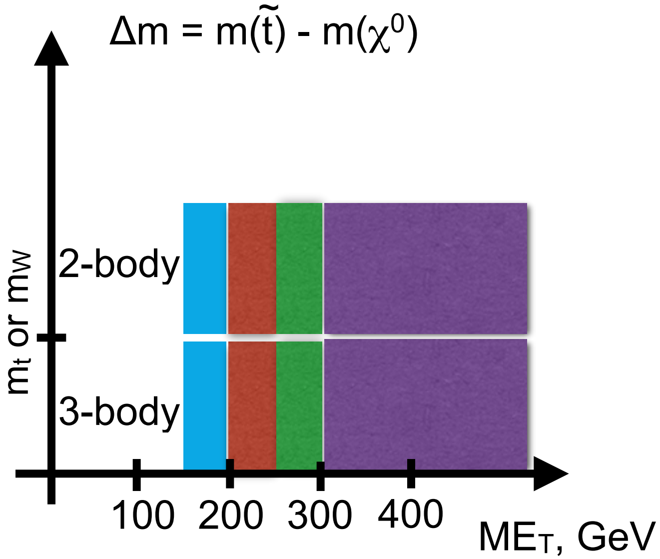
- A number of variables have discriminating power between the signal and various backgrounds
- No single variable is "winning"
- Variables are correlated
- Two approaches:
  - Simple cut-based approach, which treats each variable independently and puts a cutoff on each of them
  - Multivariate approach, when all the variables are combined in a likelihood reflecting how signal-like they are
    - Practical implementation as a boosted decision tree via TMVA Root package; trained on signal and backgrounds separately

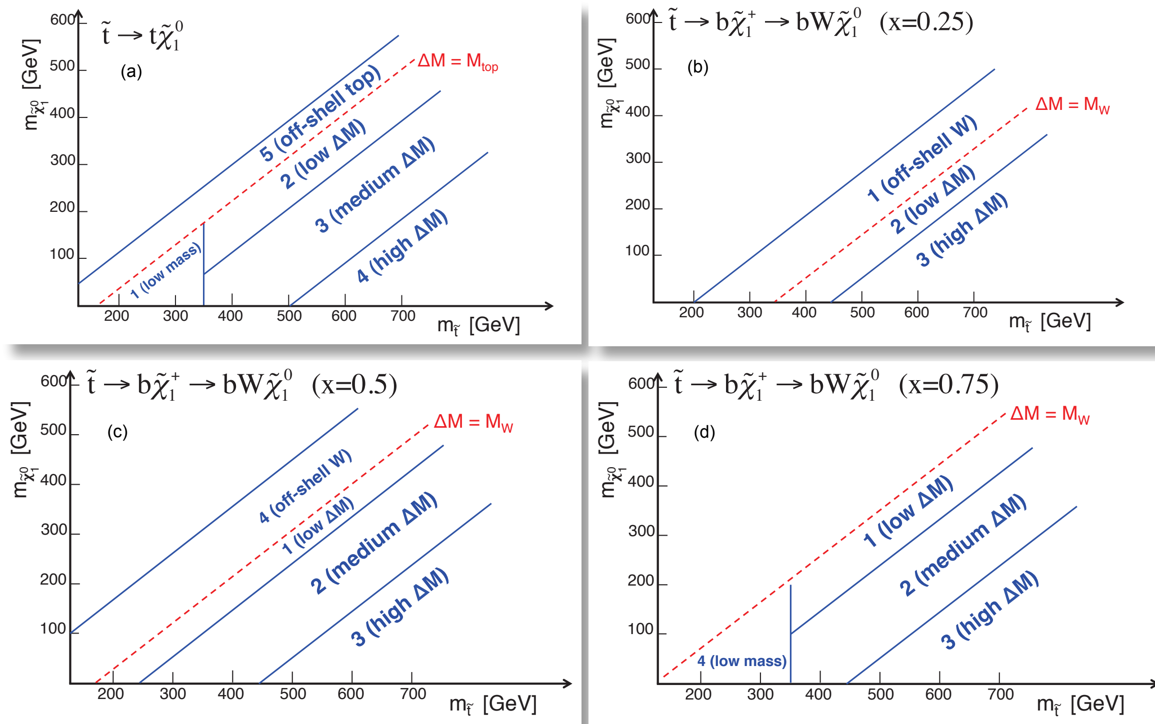


Signal Regions

✦ Cut-based analysis: 8 signal regions (SR) per channel

All SR require $M_T > 120$ GeV





✦ BDT analysis: signal regions based on the BDT output value; several networks are trained depending on the phase space probed

✦ Each BDT has single SR (BDT > x), except for $t\chi^0$, region 1 and $b\chi^+$, x = 0.5, region 2, each of which has 2 working points (tight and loose)

- 6 SR for $t\chi^0$ and 12 SR for the $b\chi^+$ analysis

Signal Selection

✦ The following selections are used for signal regions:

	$\tilde{t} \to t\tilde{\chi}^0_1$			$\tilde{t} \to b\tilde{\chi}^+$		
		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-tagged jet p_T (GeV)	(off-shell top)			yes		$>$100
$\Delta R(\ell$,leading b-tagged jet)				yes		
Lepton p_T (GeV)				(off shell W)		

✦ BDT analysis uses more inputs, in a more complete way and offers ~40% improvement in the sensitivity w.r.t. the cut-based analysis

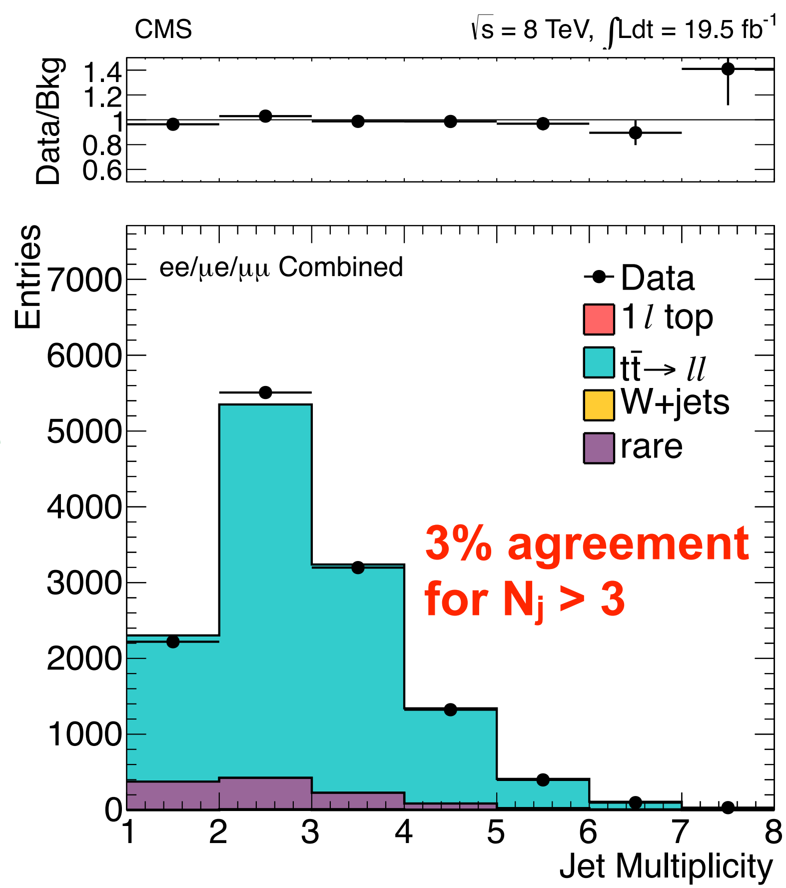
✦ The main result is therefore based on the BDT analysis, with the cut-based analysis used as a cross-check

Control Regions

- The analysis uses three control regions:
  - CR-2l requires 2 OS leptons
    - Dominated by tt dilepton events
  - CR-lt requires single lepton and an additional track or a hadronically decaying tau lepton
    - Dominated by the tt semileptonic and dilepton events
  - CR-0b requires no b-tagged jets
    - Dominated by the W+jets background
- CR do not include $M_T > 120$ GeV cut; use M_T distribution after BDT or cut-based selections as the test of accuracy of the background predictions and correct them if needed
- To minimize uncertainties from tt cross section, integrated luminosity, efficiency, etc., we normalize the MC-based predictions in the low-M_T region ($50 < M_T < 80$ GeV) after subtracting rare backgrounds, and then extrapolate to the $M_T > 120$ GeV signal region

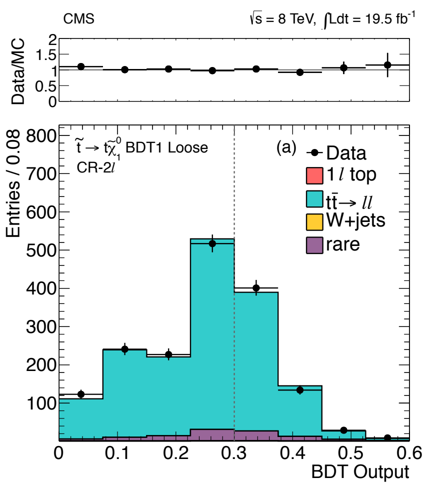
Validation I: ISR/FSR

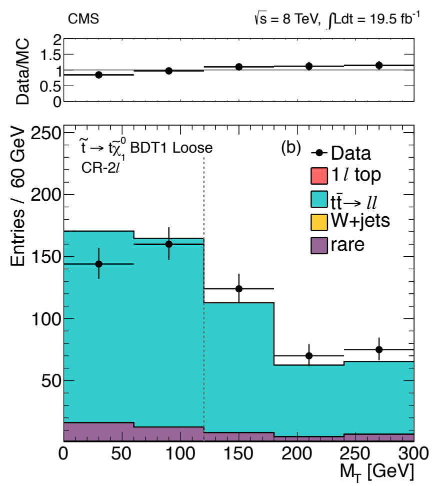
- The main background is from dilepton tt events; they only have two tree-level jets, both from b-quarks
- The preselection requires four or more jets with at least one b-tag
- Two extra jets for the dominant background must come from ISR or FSR - need to ensure correct modeling
- Test with a CR-2l control sample requiring two OS leptons and at least one b-tagged jet
- For the ee and μμ channels, require the dilepton mass away from the Z-peak



Validation II: tχ^0 BDT1 Loose

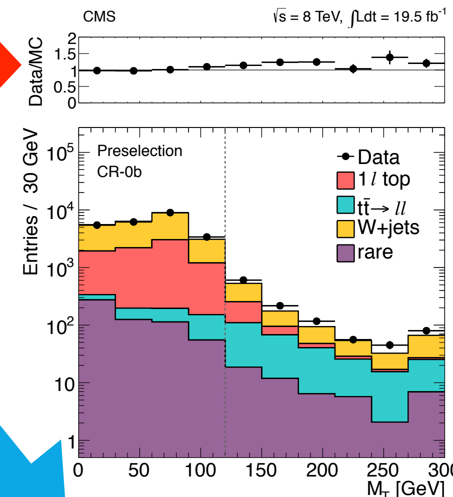
- ✦ Validation in the CR-2l,CR-lt, and CR-0b regions

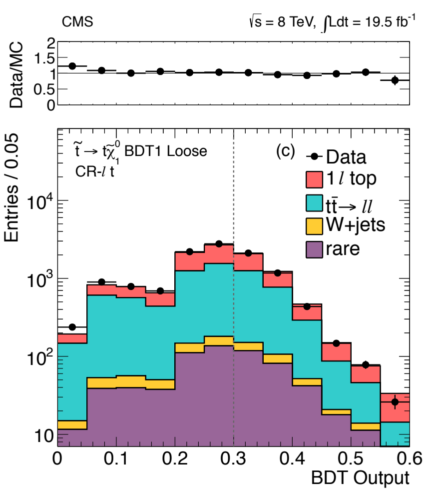


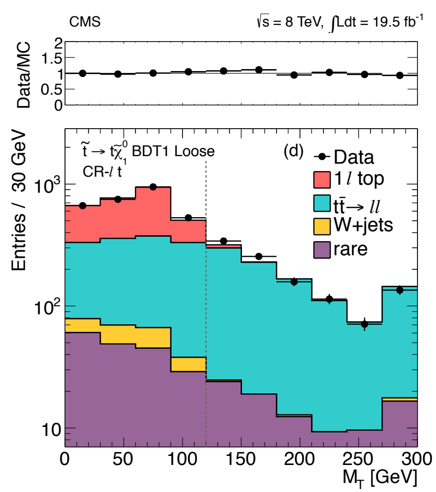


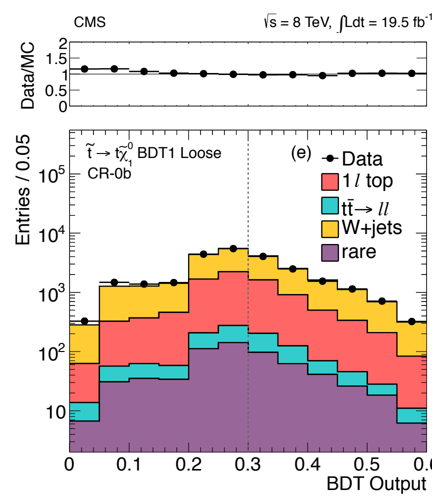
Originally, there is a slight trend in CR-0b in the W+jets data/MC difference; correct for it below

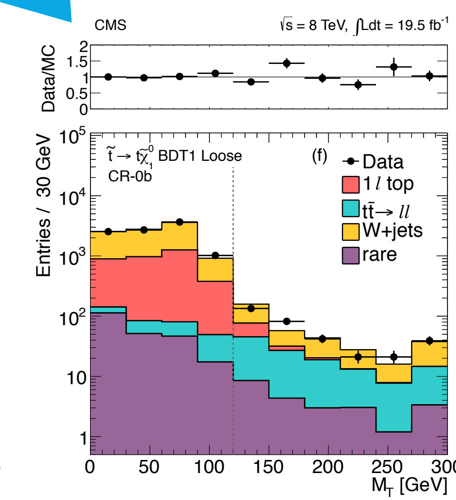
W+jets: x (1.2 ± 0.3)
Similar factor for single top background











5-70% agreement for various BDTs [large uncertainty where statistics are low]

Systematic Uncertainties

- Here are the main systematic uncertainties for the $t\chi^0$ analysis:

$\tilde{t} \to t\tilde{\chi}_1^0$

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

Results

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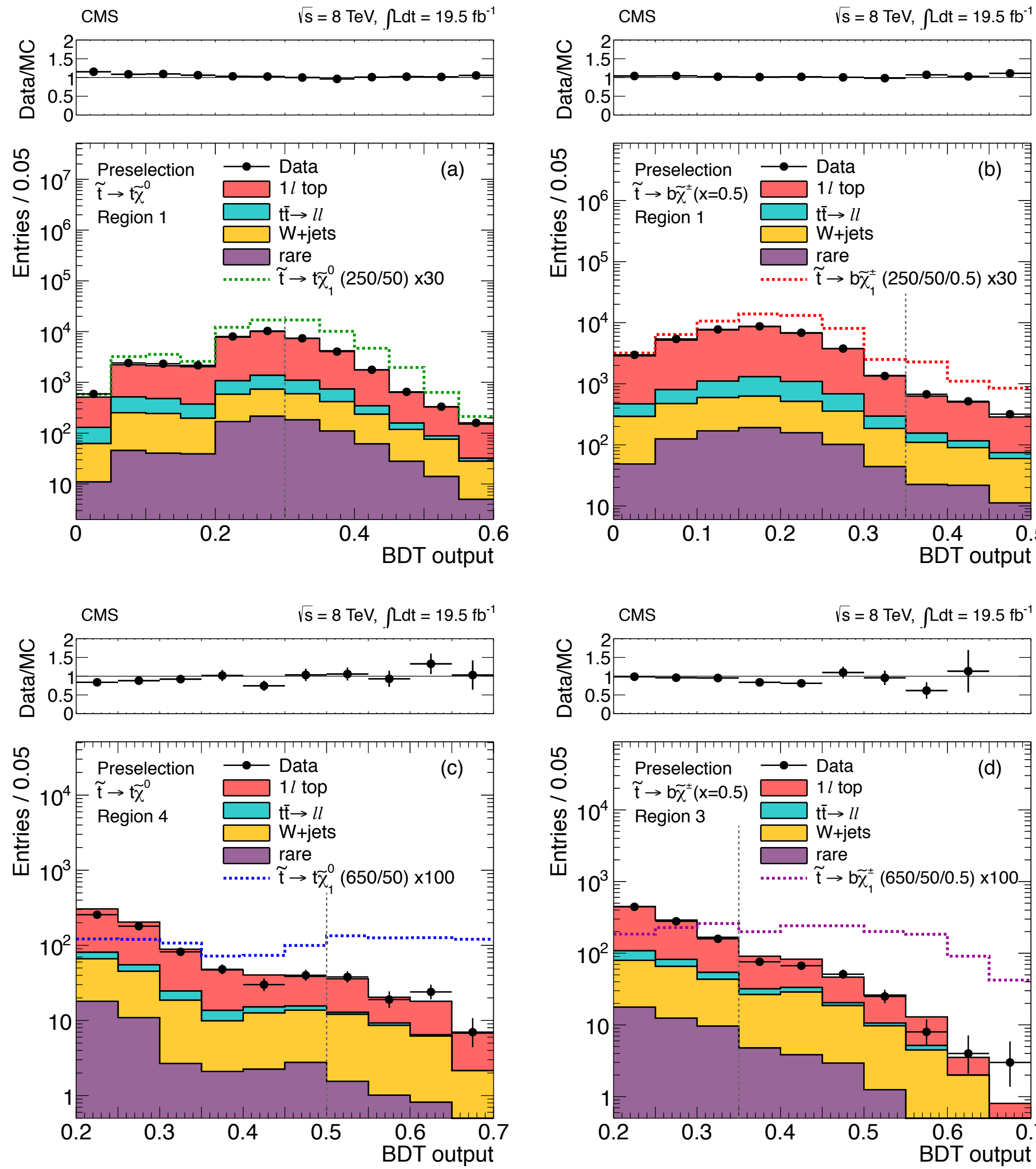
Results: Preselection

- After adjustments, based on data/MC comparison in the CR, the agreement in the signal region looks good
- The figure shows the agreements between the data and background predictions in the BDT output for four out of 16 BDTs used in the analysis
- Similar agreement is found for other BDTs
- Only event preselection is applied; no $M_T > 120$ GeV requirement used



Results: BDT, $t\chi^0$

- Here are the results of the counting experiment in all the signal regions:

$\tilde{t} \to t\tilde{\chi}^0_1$

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
Data	728	104	56	8	2	76
$\tilde{t} \to t\tilde{\chi}^0_1$ (250/50)	285 ± 8.5	50 ± 3.5	28 ± 2.6	4.4 ± 1.0	0.3 ± 0.3	34 ± 2.9
$\tilde{t} \to t\tilde{\chi}^0_1$ (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

Results: Cut-Based, $t\chi^0$

- Similar results in the eight SR for the cut-based analysis:

Sample	$E_T^{miss} > 150$ GeV	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 250$ GeV	$E_T^{miss} > 300$ GeV
		Low ΔM Selection		
$t\bar{t} \to \ell\ell$	131 ± 15	42 ± 7	17 ± 5	5.6 ± 2.5
1ℓ top	94 ± 47	30 ± 19	9 ± 6	3.1 ± 2.4
W + jets	10 ± 3	5 ± 1	2 ± 1	1.0 ± 0.4
Rare	16 ± 8	7 ± 4	4 ± 2	1.8 ± 0.9
Total	251 ± 50	83 ± 21	31 ± 8	11.5 ± 3.6
Data	227	69	21	9
$\tilde{t} \to t\tilde{\chi}_1^0$ (250/50)	108 ± 3.7	32 ± 2.0	12 ± 1.2	5.2 ± 0.8
$\tilde{t} \to t\tilde{\chi}_1^0$ (650/50)	8.0 ± 0.1	7.2 ± 0.1	6.2 ± 0.1	4.9 ± 0.1
		High ΔM Selection		
$t\bar{t} \to \ell\ell$	8 ± 2	5 ± 2	3.2 ± 1.4	1.4 ± 0.9
1ℓ top	13 ± 6	6 ± 4	3.0 ± 2.2	1.4 ± 1.0
W + jets	4 ± 1	2 ± 1	1.5 ± 0.5	0.9 ± 0.3
Rare	4 ± 2	3 ± 1	1.8 ± 0.9	1.0 ± 0.5
Total	29 ± 7	17 ± 5	9.5 ± 2.8	4.7 ± 1.4
Data	23	11	3	2
$\tilde{t} \to t\tilde{\chi}_1^0$ (250/50)	10 ± 1.1	4.6 ± 0.8	2.3 ± 0.5	1.4 ± 0.4
$\tilde{t} \to t\tilde{\chi}_1^0$ (650/50)	4.9 ± 0.1	4.7 ± 0.1	4.3 ± 0.1	3.7 ± 0.1

Results: BDT, bχ^+

- Also, no excess in the chargino channel BDT analysis:

$\tilde{t} \to b\tilde{\chi}^+$ $x = 0.25$

Sample	BDT1	BDT2	BDT3
$t\bar{t} \to \ell\ell$	18 ± 4	2.2 ± 1.3	1.2 ± 1.0
1ℓ top	10 ± 5	4.0 ± 1.8	1.5 ± 0.8
W + jets	3 ± 1	2.0 ± 0.7	0.7 ± 0.3
Rare	4 ± 2	1.6 ± 0.8	1.0 ± 0.5
Total	35 ± 6	9.8 ± 2.4	4.4 ± 1.4
Data	29	7	2
$\tilde{t} \to b\tilde{\chi}^+$ (450/50/0.25)	19 ± 2.9	11 ± 2.2	5.2 ± 1.5
$\tilde{t} \to b\tilde{\chi}^+$ (600/100/0.25)	8.8 ± 0.8	7.5 ± 0.8	5.6 ± 0.7

$\tilde{t} \to b\tilde{\chi}^+$ $x = 0.5$

Sample	BDT1	BDT2–Loose	BDT2–Tight	BDT3	BDT4
$t\bar{t} \to \ell\ell$	40 ± 5	21 ± 4	4 ± 2	6 ± 2	100 ± 16
1ℓ top	24 ± 10	15 ± 7	4 ± 3	4 ± 2	33 ± 12
W + jets	5 ± 1	5 ± 1	2 ± 1	3 ± 1	5 ± 1
Rare	8 ± 4	8 ± 4	3 ± 1	4 ± 2	8 ± 4
Total	77 ± 12	50 ± 9	13 ± 4	17 ± 4	146 ± 21
Data	67	35	12	13	143
$\tilde{t} \to b\tilde{\chi}^+$ (250/50/0.5)	45 ± 7.6	24 ± 5.2	5.7 ± 2.4	5.2 ± 2.6	55 ± 8.1
$\tilde{t} \to b\tilde{\chi}^+$ (650/50/0.5)	3.5 ± 0.4	9.5 ± 0.7	5.6 ± 0.5	8.3 ± 0.6	3.2 ± 0.4

$\tilde{t} \to b\tilde{\chi}^+$ $x = 0.75$

Sample	BDT1	BDT2	BDT3	BDT4
$t\bar{t} \to \ell\ell$	37 ± 5	9 ± 2	3.1 ± 1.3	248 ± 22
1ℓ top	17 ± 9	6 ± 5	1.6 ± 1.6	188 ± 70
W + jets	4 ± 1	4 ± 1	1.6 ± 0.6	22 ± 6
Rare	4 ± 2	4 ± 2	1.8 ± 0.9	20 ± 10
Total	61 ± 10	22 ± 6	8.1 ± 2.3	478 ± 74
Data	50	13	5	440
$\tilde{t} \to b\tilde{\chi}^+$ (250/50/0.75)	115 ± 13	21 ± 5.6	8.0 ± 3.7	518 ± 28
$\tilde{t} \to b\tilde{\chi}^+$ (650/50/0.75)	3.9 ± 0.4	8.4 ± 0.6	6.8 ± 0.6	5.5 ± 0.5

Results: Cut-Based, $b\chi^+$

- … or cut-based analysis:

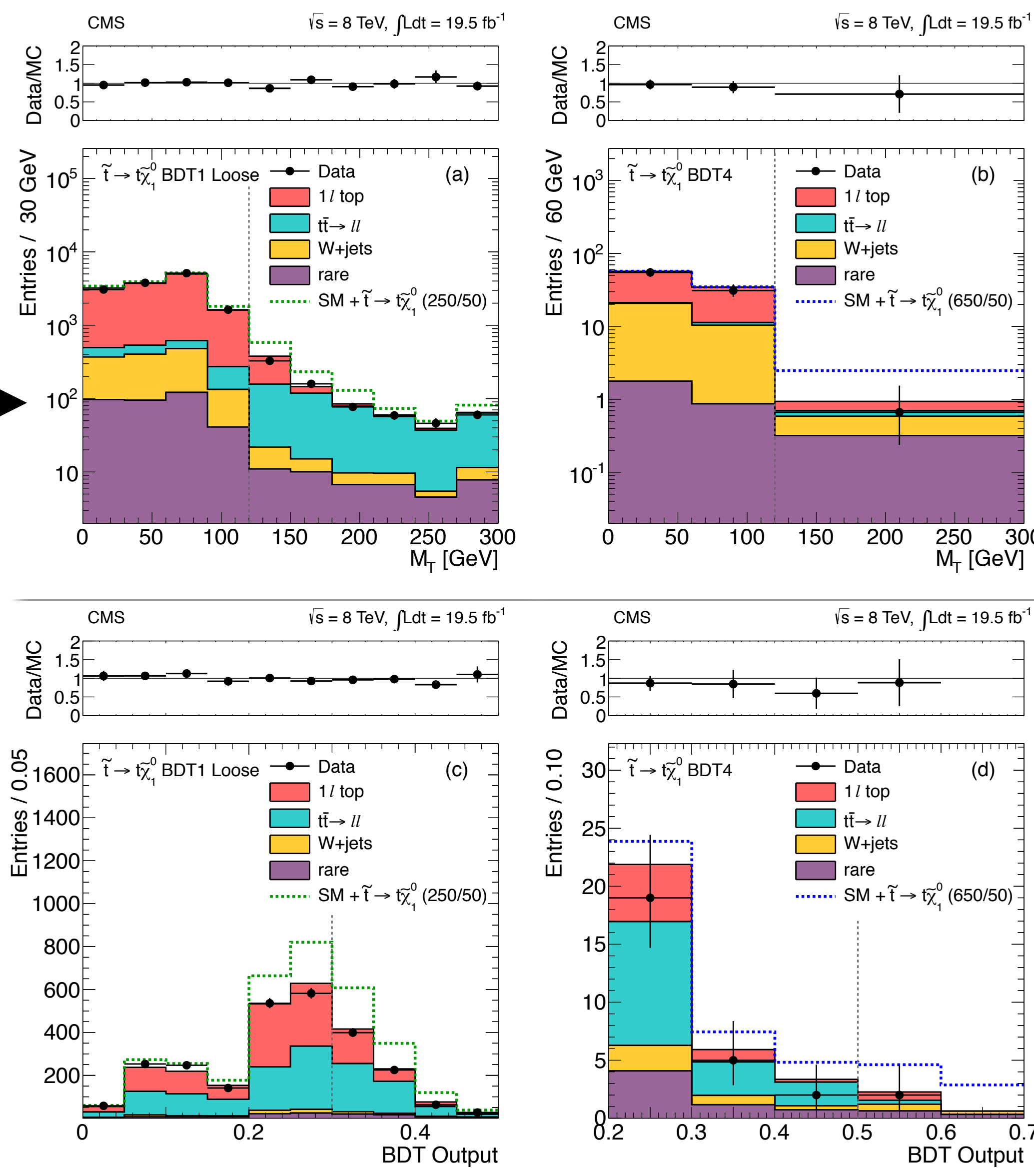
Sample	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 150$ GeV	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 250$ GeV
Low ΔM Selection				
$t\bar{t} \to \ell\ell$	875 ± 57	339 ± 23	116 ± 14	40 ± 9
1ℓ top	658 ± 192	145 ± 70	41 ± 24	14 ± 9
W + jets	59 ± 15	21 ± 5	8 ± 2	4 ± 1
Rare	70 ± 35	33 ± 17	16 ± 8	8 ± 4
Total	1662 ± 203	537 ± 75	180 ± 28	66 ± 13
Data	1624	487	151	52
$\tilde{t} \to b\tilde{\chi}^+$ (450/50/0.25)	47 ± 3.3	33 ± 2.7	19 ± 2.0	8.7 ± 1.4
$\tilde{t} \to b\tilde{\chi}^+$ (600/100/0.25)	15 ± 0.7	13 ± 0.7	11 ± 0.6	7.9 ± 0.5
$\tilde{t} \to b\tilde{\chi}^+$ (250/50/0.5)	419 ± 17	157 ± 9.9	52 ± 5.4	21 ± 3.4
$\tilde{t} \to b\tilde{\chi}^+$ (650/50/0.5)	14 ± 0.6	13 ± 0.5	11 ± 0.5	8.4 ± 0.4
$\tilde{t} \to b\tilde{\chi}^+$ (250/50/0.75)	854 ± 26	399 ± 18	144 ± 10	56 ± 6.4
$\tilde{t} \to b\tilde{\chi}^+$ (650/50/0.75)	17 ± 0.7	16 ± 0.6	13 ± 0.6	11 ± 0.5
High ΔM Selection				
$t\bar{t} \to \ell\ell$	25 ± 5	12 ± 3	7 ± 2	2.9 ± 1.5
1ℓ top	35 ± 10	15 ± 6	6 ± 3	2.7 ± 1.8
W + jets	9 ± 2	5 ± 1	2 ± 1	1.8 ± 0.6
Rare	9 ± 5	7 ± 3	4 ± 2	2.4 ± 1.2
Total	79 ± 12	38 ± 7	19 ± 5	9.9 ± 2.7
Data	90	39	18	5
$\tilde{t} \to b\tilde{\chi}^+$ (450/50/0.25)	30 ± 2.7	23 ± 2.3	15 ± 1.8	7.3 ± 1.3
$\tilde{t} \to b\tilde{\chi}^+$ (600/100/0.25)	11 ± 0.6	9.7 ± 0.6	8.4 ± 0.6	6.1 ± 0.5
$\tilde{t} \to b\tilde{\chi}^+$ (250/50/0.5)	37 ± 4.8	23 ± 3.8	11 ± 2.6	5.0 ± 1.7
$\tilde{t} \to b\tilde{\chi}^+$ (650/50/0.5)	11 ± 0.5	9.8 ± 0.5	8.6 ± 0.4	6.7 ± 0.4
$\tilde{t} \to b\tilde{\chi}^+$ (250/50/0.75)	32 ± 5.2	23 ± 4.4	11 ± 2.9	3.6 ± 1.4
$\tilde{t} \to b\tilde{\chi}^+$ (650/50/0.75)	9.2 ± 0.5	8.4 ± 0.5	7.5 ± 0.4	6.3 ± 0.4

BDT Outputs for $t\chi^0$ SR

- Here are the BDT outputs for the loosest (left column) and tightest (right column) SR:

M_T distribution after the BDT selection →

BDT distribution after the M_T > 120 GeV selection →

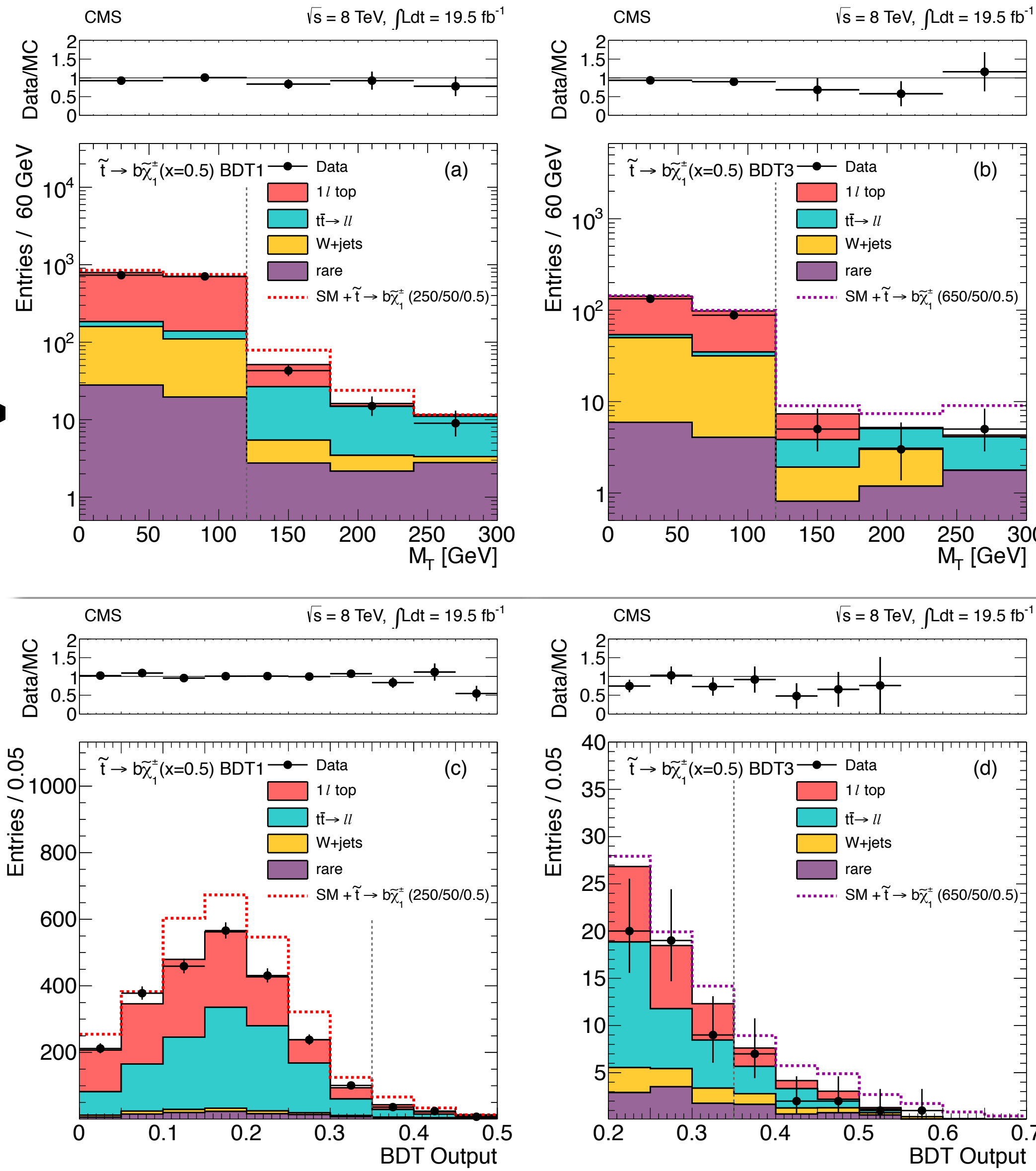


BDT Outputs for $b\chi^+$ SR

- Here are the BDT outputs for the loosest (left column) and tightest (right column) SR for the x = 0.5 case:

M_T distribution after the BDT selection

BDT distribution after the M_T > 120 GeV selection



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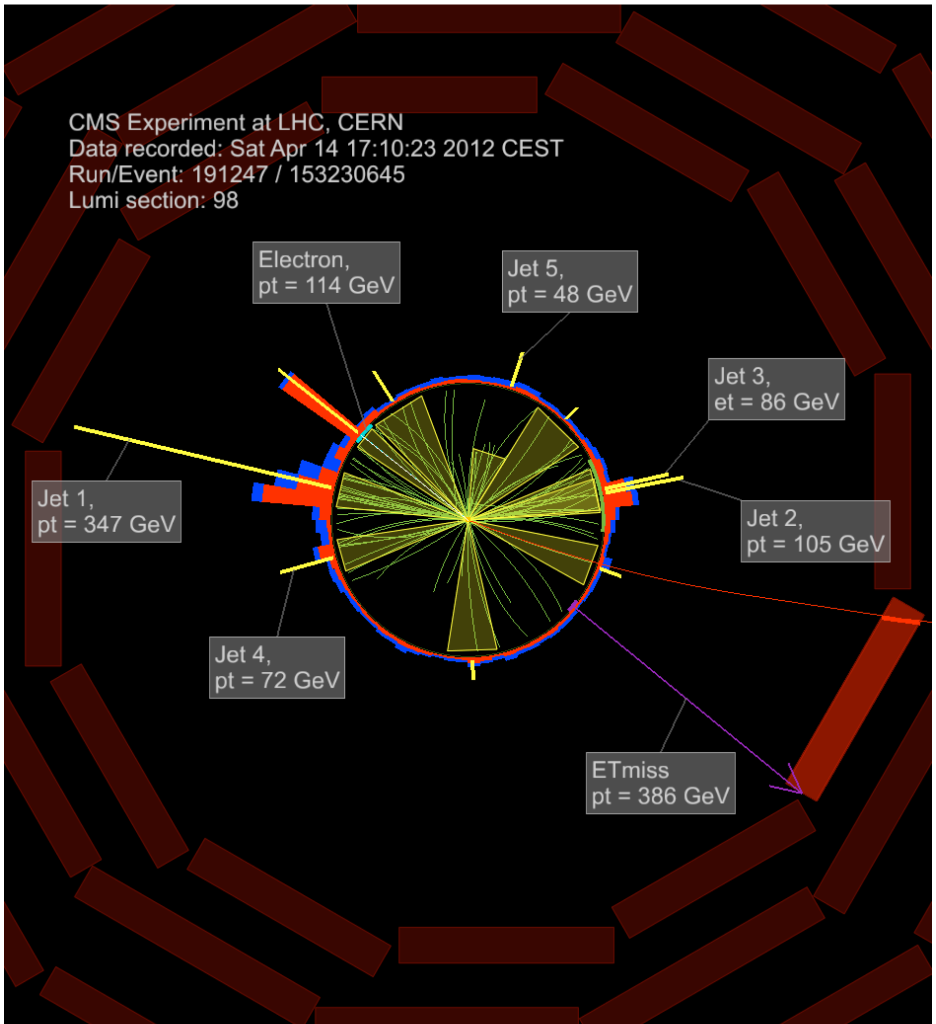
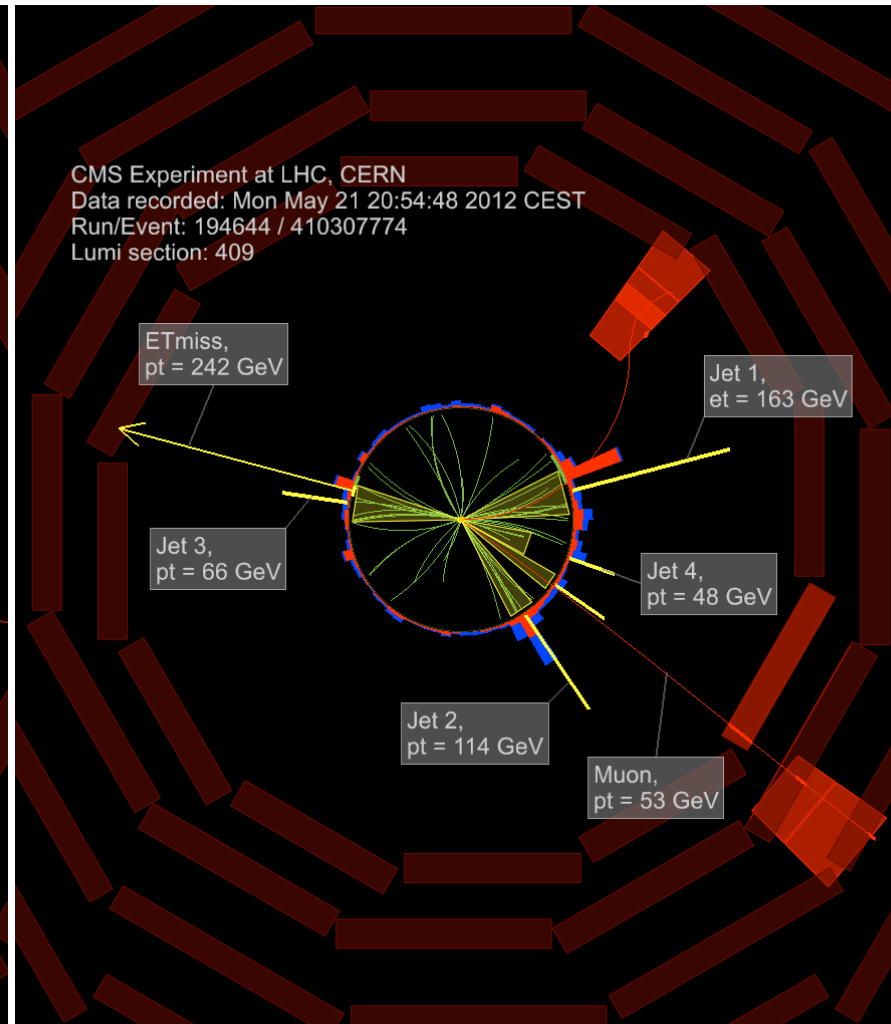
Candidate Events

- Here is how the signal would've looked like…

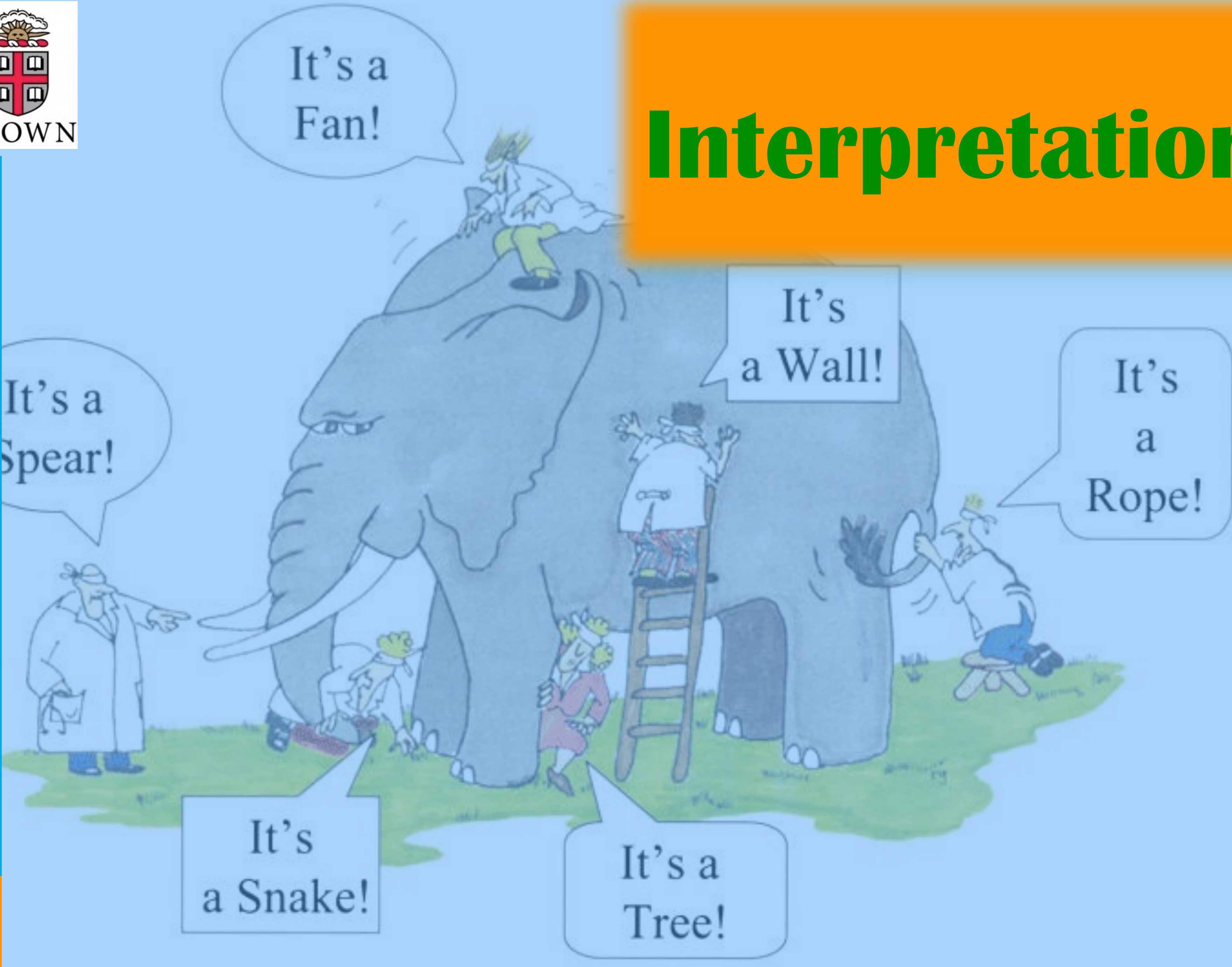




Results: Summary

- The data agree with the SM background prediction corrected for the data/MC discrepancies in the CR within 1.0-1.5 standard deviations in all the search regions, both for the cut-based and BDT analyses
- Having seen no evidence for stop production, we proceed in interpreting our results in terms of limits on the stop production cross section, as a function of the stop mass, neutralino mass, and the x parameter in case of the $b\chi^+$ decay channel
- The limits are set from the counting experiment in the most sensitive signal region for any given mass point
- In general could be improved by combining several search regions, but as the improvement is small (SR are largely overlapping) go for a simpler analysis
- Further improvement could generally be achieved by the shape-based analysis, but this requires a much more sophisticated treatment of the systematic uncertainties, not possible with the present statistics
- Will ultimately be used for Run 2, once statistics increase significantly

Interpretation



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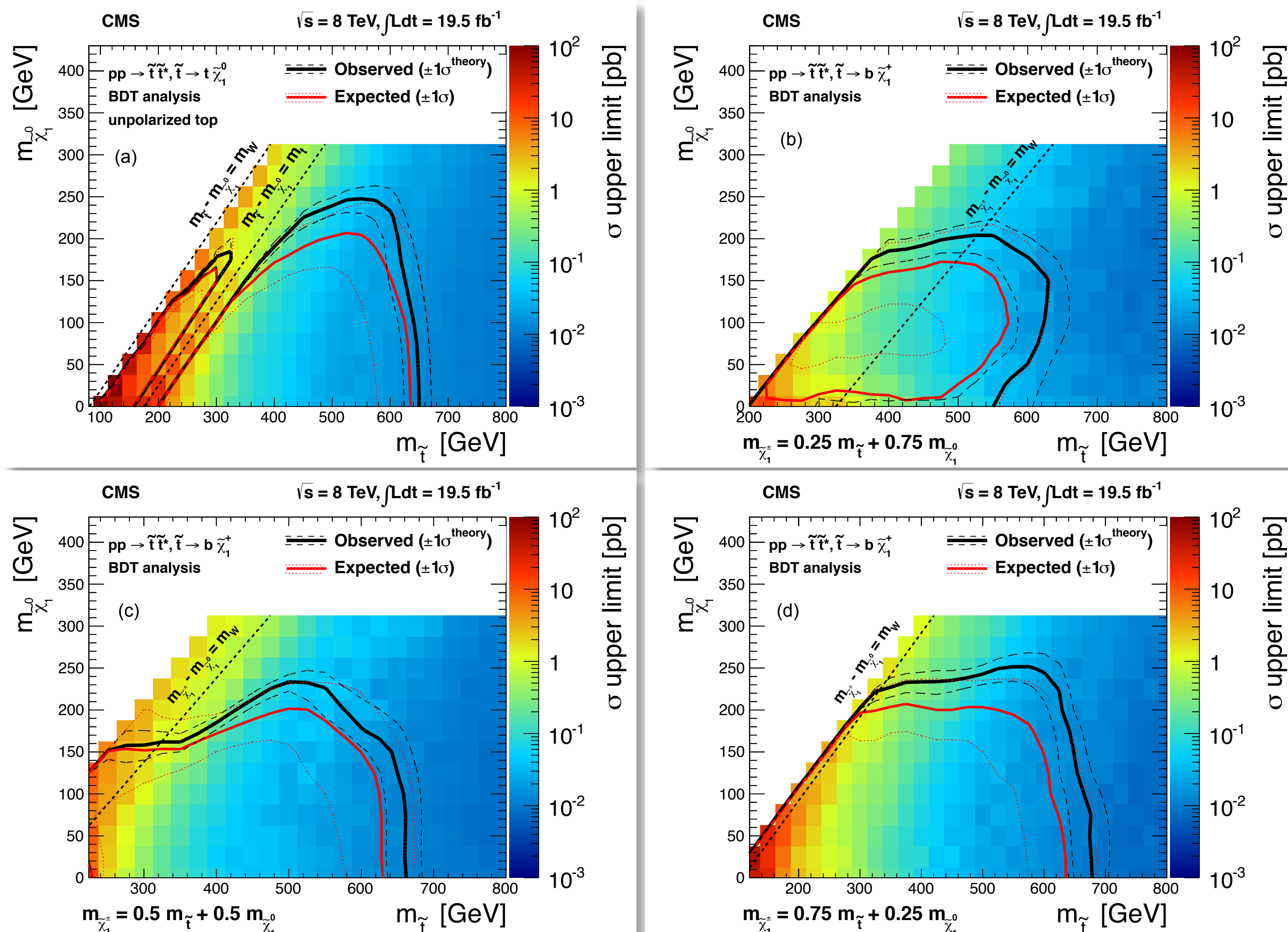
Interpretation

- Use the LHC-style CL_s method (see Daniel Whiteson's lectures) to set 95% CL limits
- Use standard convention of treating experimental and theoretical uncertainties:
  - Uncertainties are propagated into the limits via nuisance parameters, represented typically by log-normal distributions
  - Experimental uncertainties are shown as ±1 standard deviation band around the expected limits
  - Theoretical uncertainties (renormalization/factorization scale variation, PDFs, etc.) are shown as ±1 standard deviation band around the observed limits

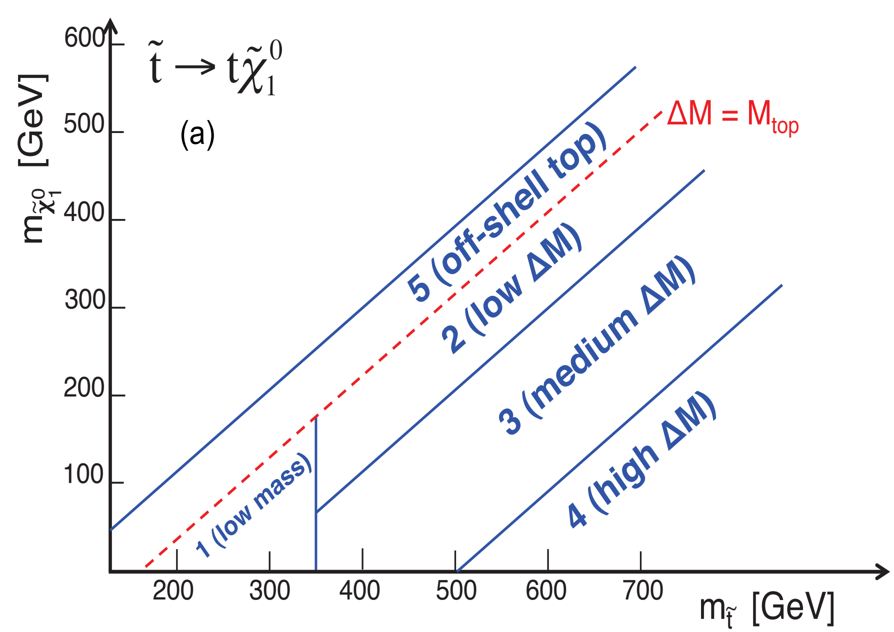
Limits

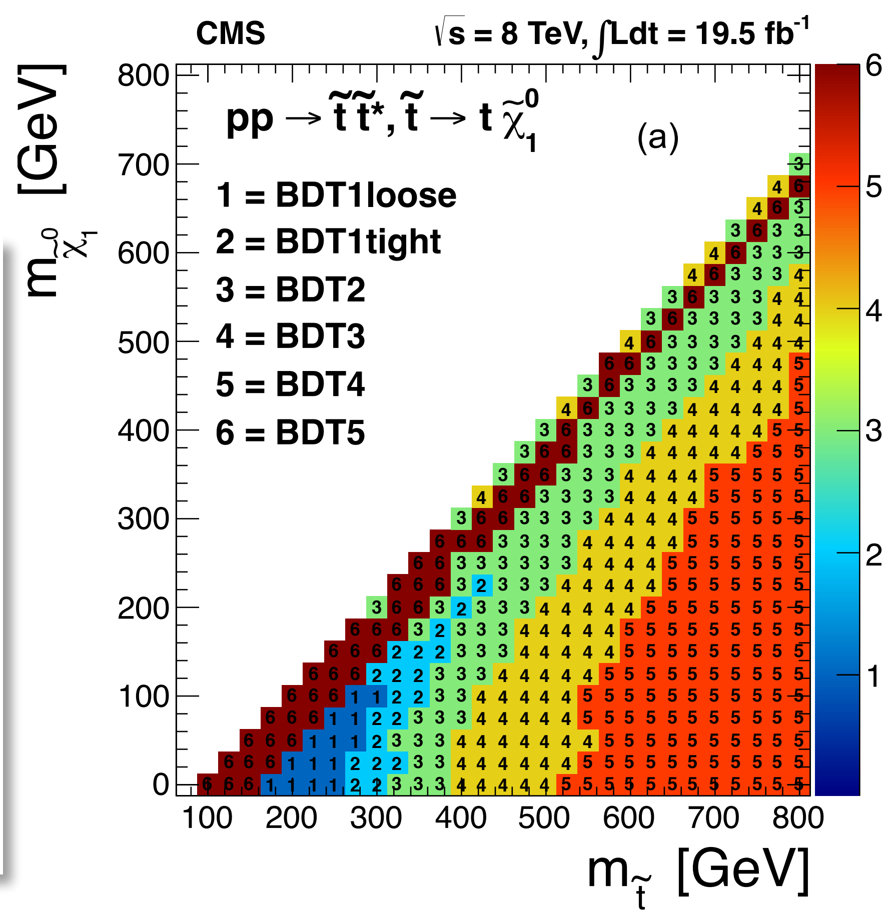
- Here are the limits in four scenarios studied:



Most Sensitive SRs

- Which region does the sensitivity come from?
- In most parts of the phase space the best SR matches the a priori optimization





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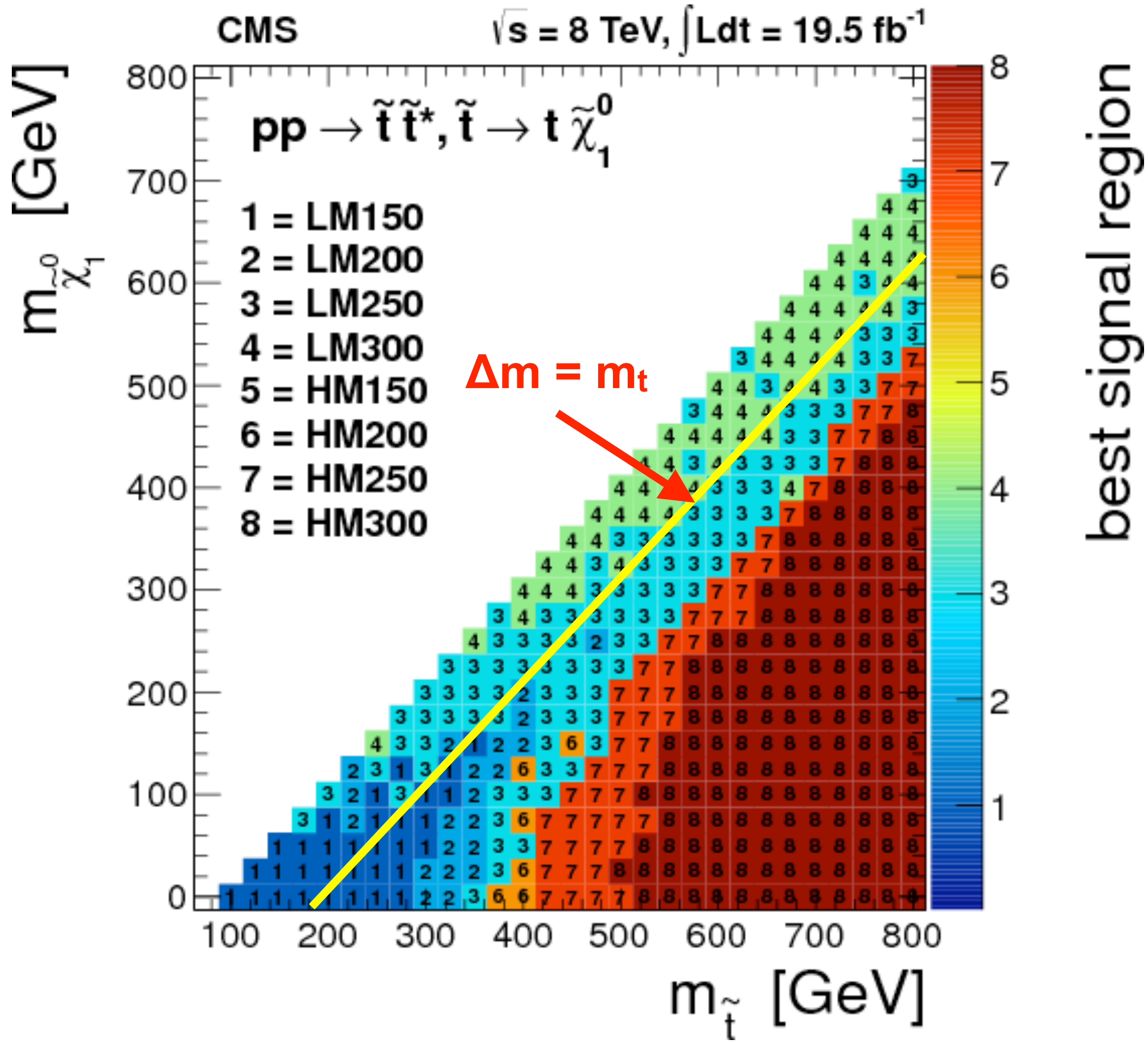
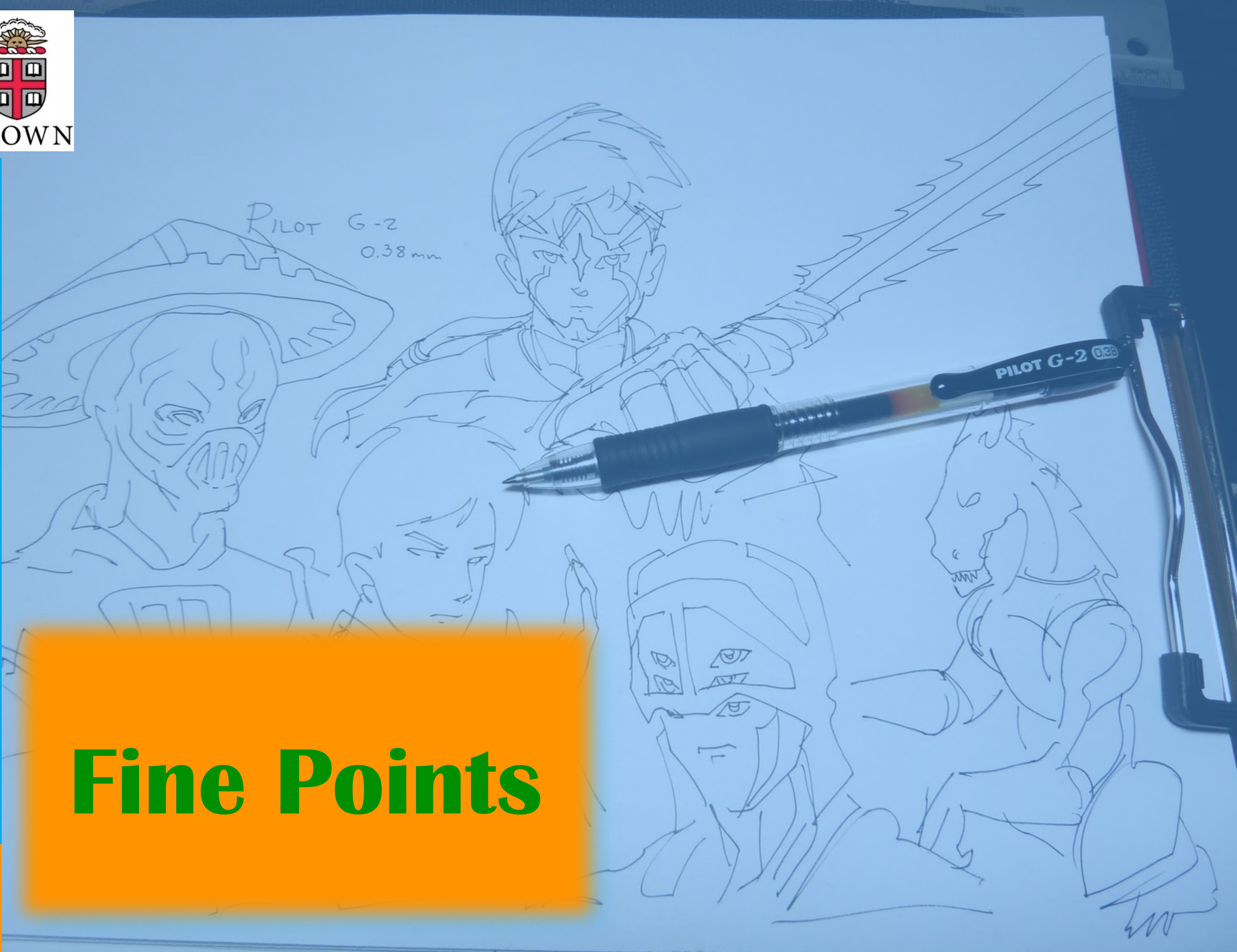
Most Sensitive SRs: Cut-Based

- ✦ Similar situation for the cut-based analysis:

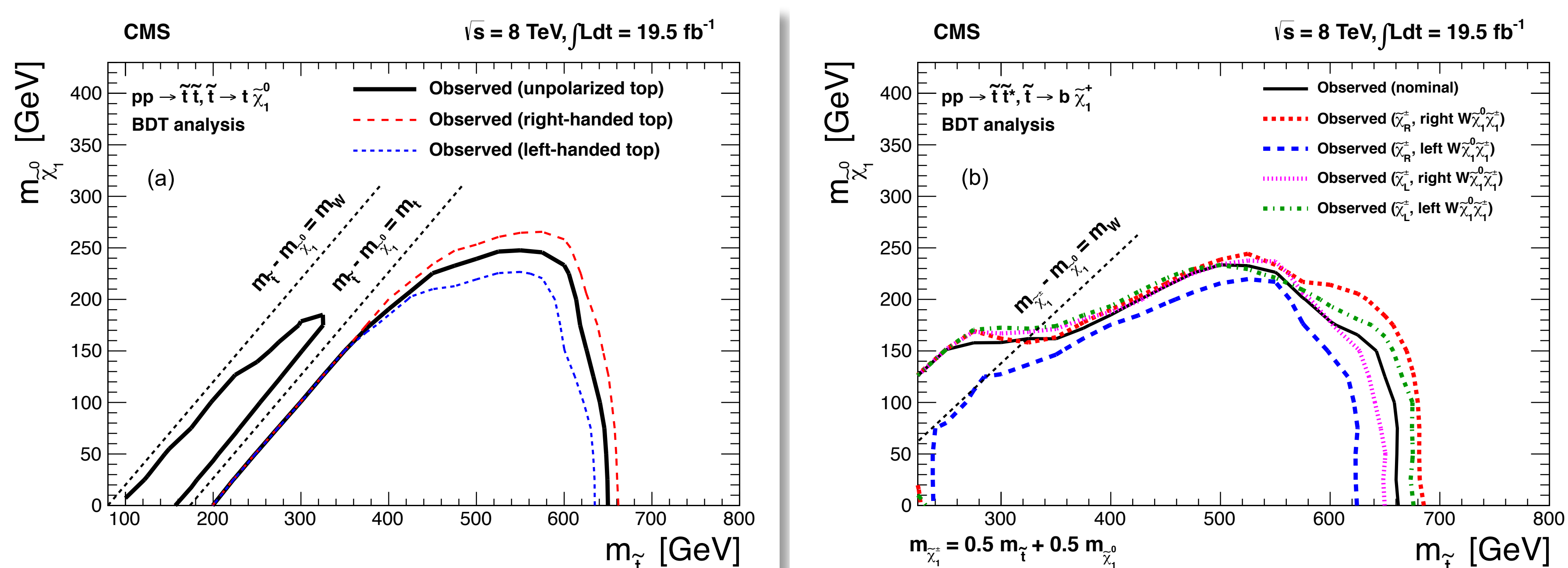


Fine Points



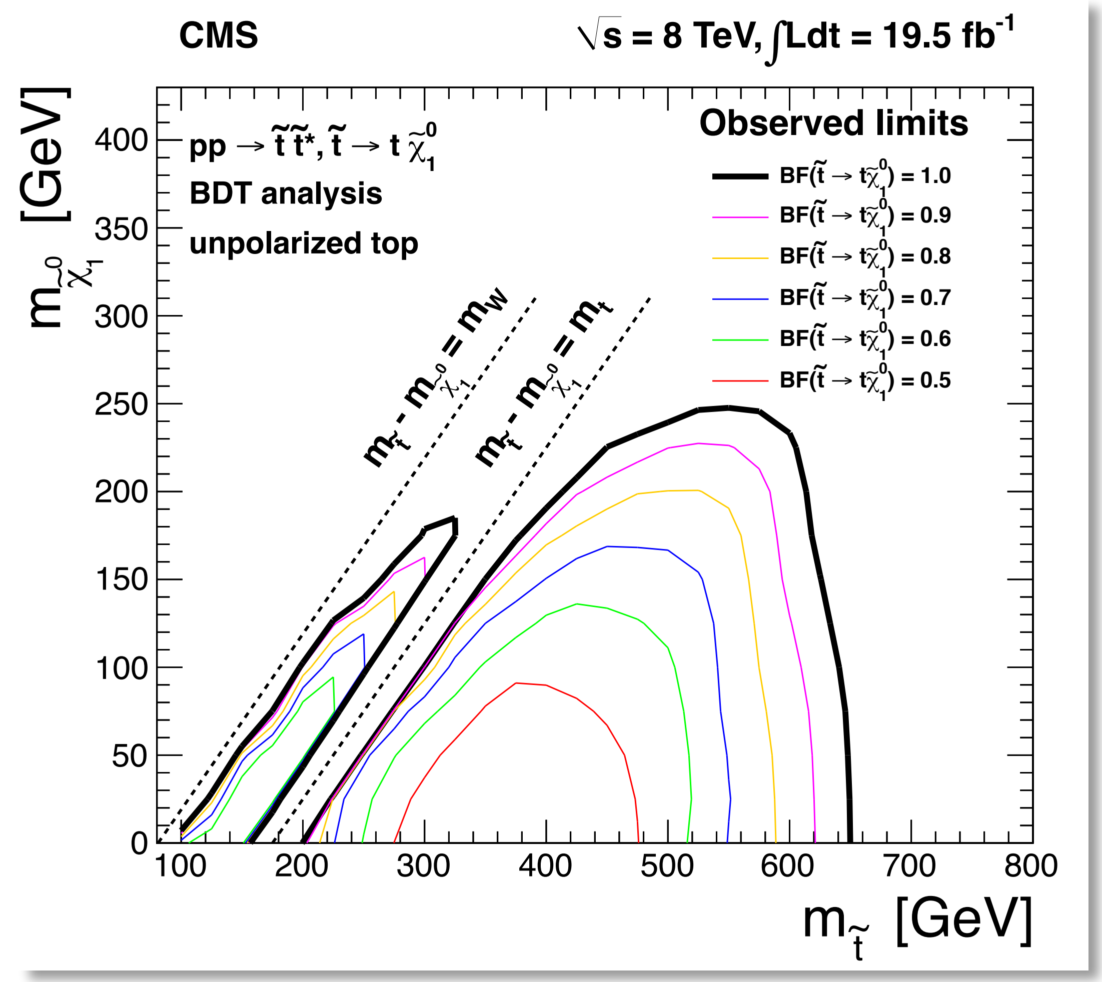
Fine Points: Polarization

- Top quark in the stop decay may be produced polarized
- The main limits correspond to the case of no polarization
- Important to study the effect of polarization
- The effect turns out to be not so large: 10-20 GeV in the limtis



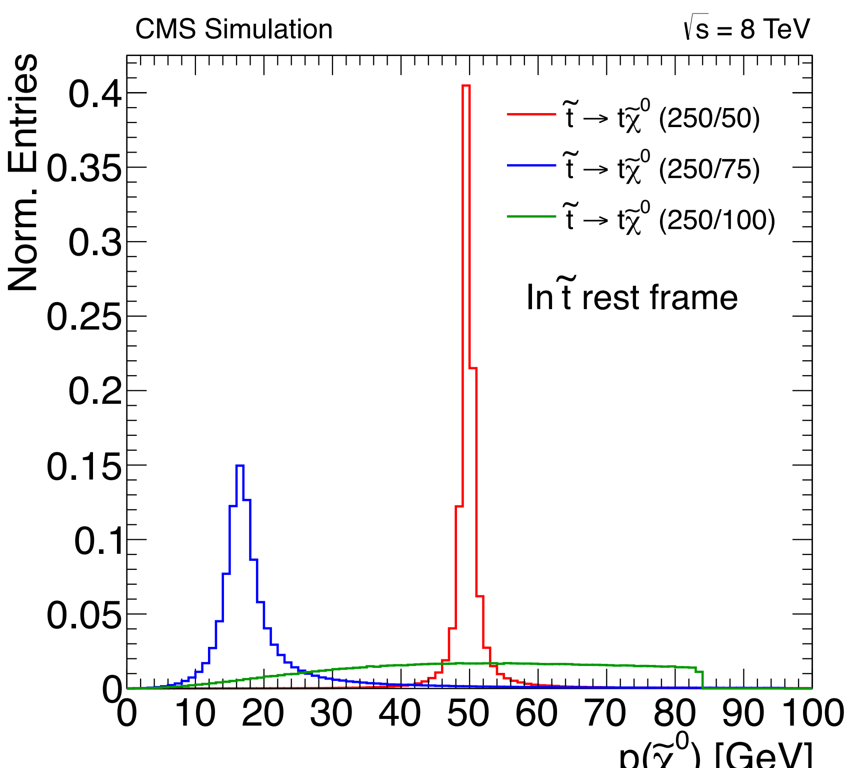
Fine Points: Branching Fraction

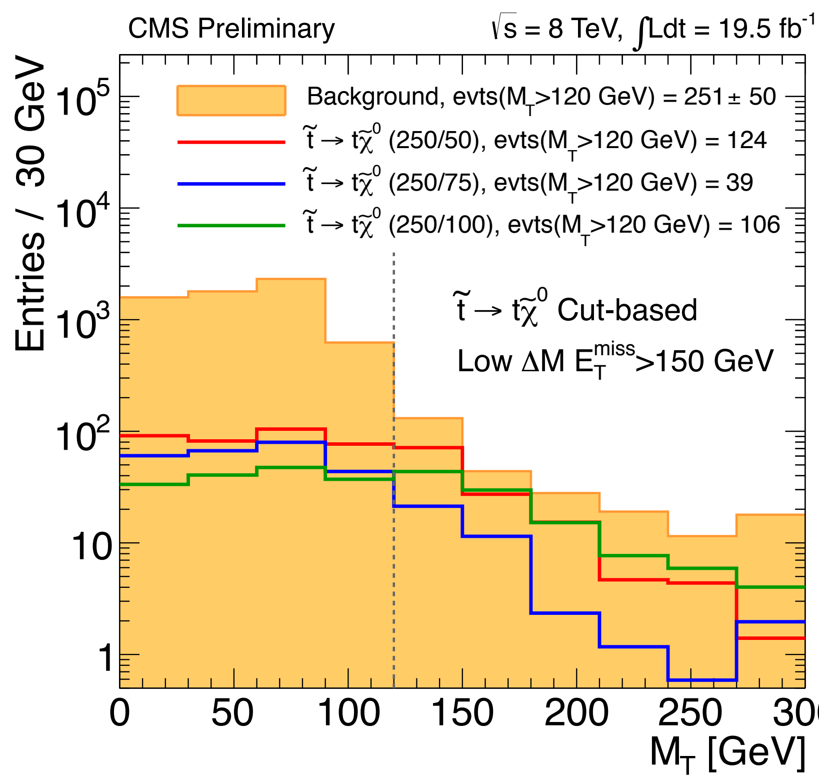
- What if $B(\tilde{t} \to t\chi^0)$ is less than 100%?
  - Conservative analysis, ignoring other stop decays



Fine Points: Sensitivity Near m_t

- Reduced sensitivity in region $\Delta m = m(\tilde{t}) - m(\chi^0) \sim m_t$
- Momentum of the χ^0 is reduced in the 'compressed' region → reduced source of ME_T which is the main discriminator from background
- Results in a reduced M_T acceptance





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Next Steps

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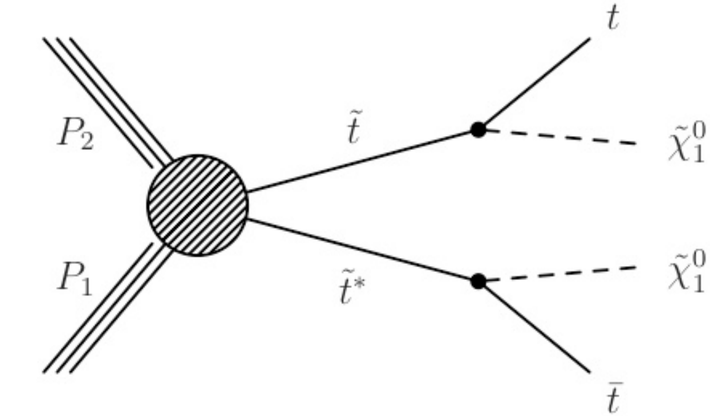
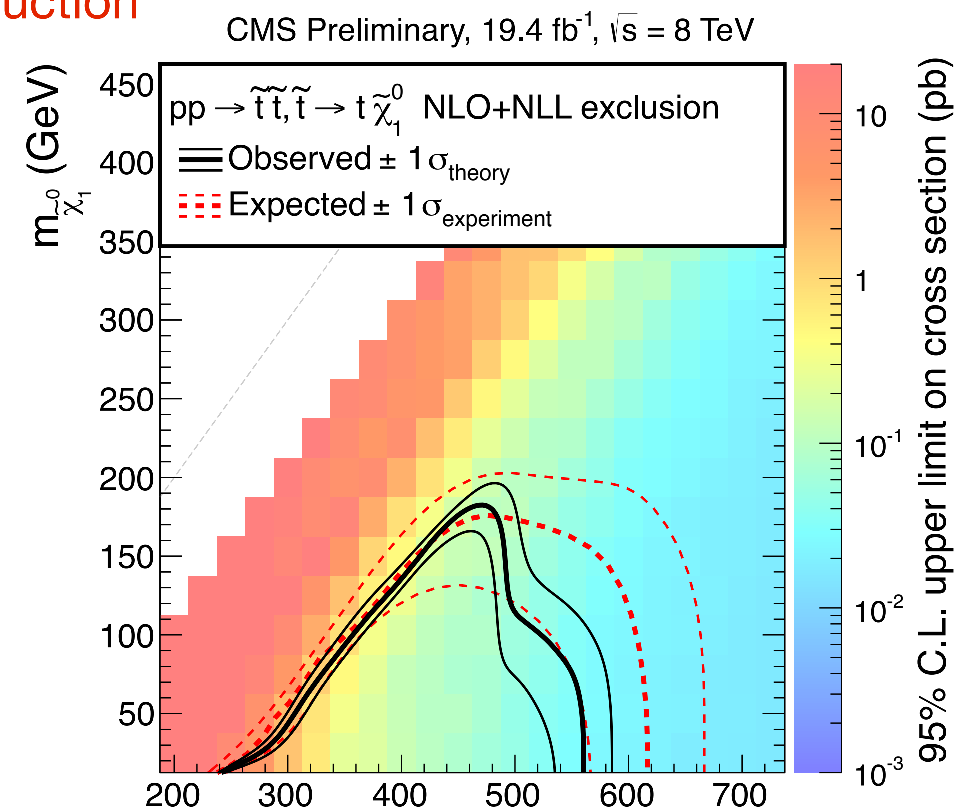
Direct Stop: All Hadronic

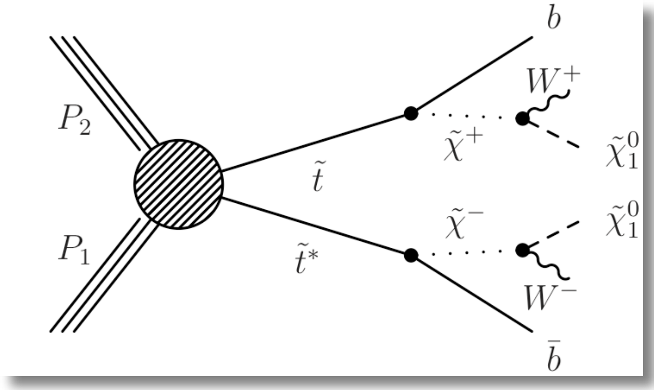
- ✦ This is quite sensitive, and yet the toughest channel at the LHC
- ✦ Simple reinterpretation of the existing analyses is not sensitive enough
- ✦ Requires a dedicated optimized tour-de-force analysis:
  - Top-quark full or partial reconstruction
  - W+jets and tt with τ_h and lost leptons (from W(μν)+jets with embedded τ_h), invisible Z decays (from Z(μμ)), and multijets (made negligible)

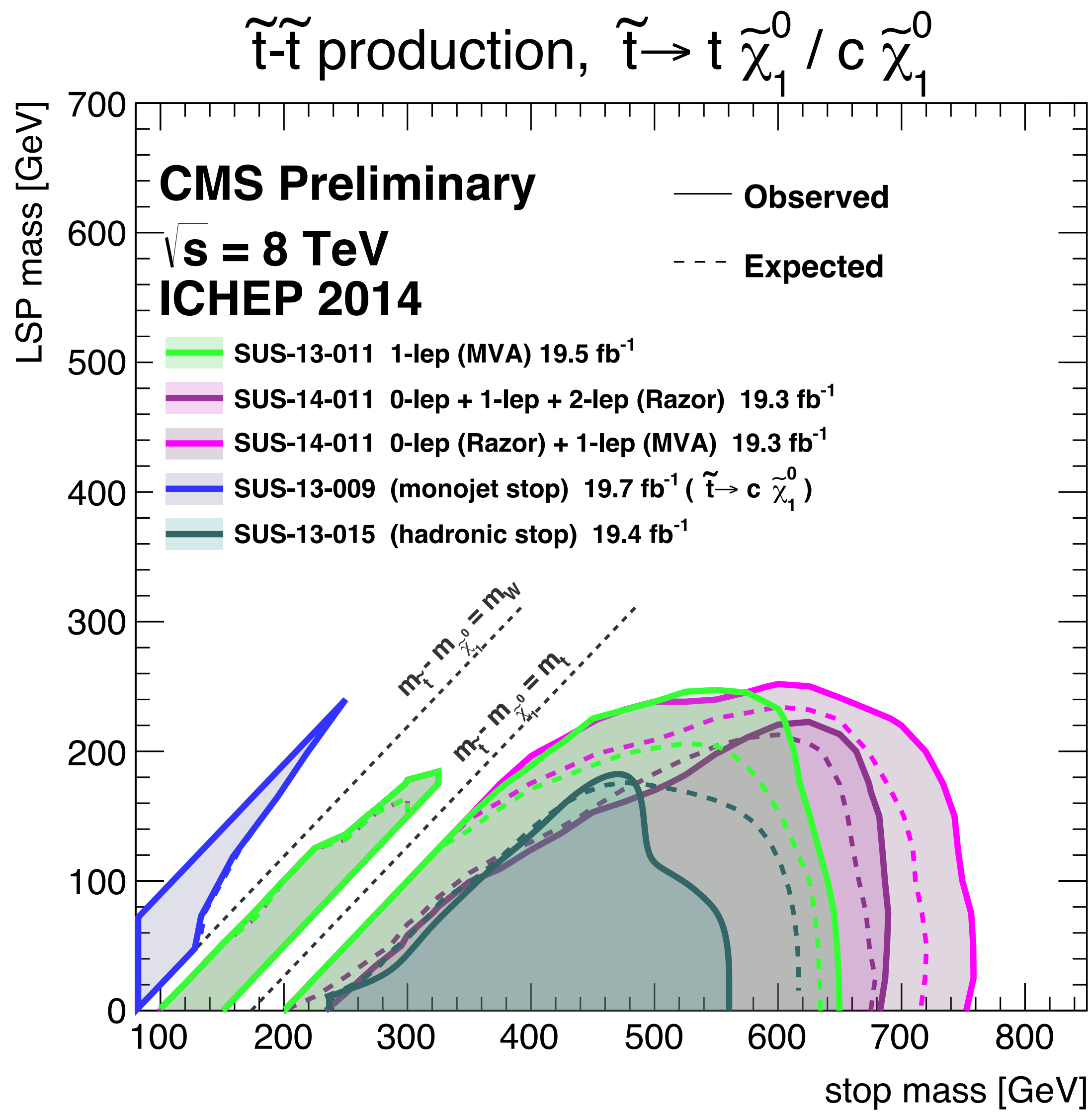




CMS PAS- SUS-13-015

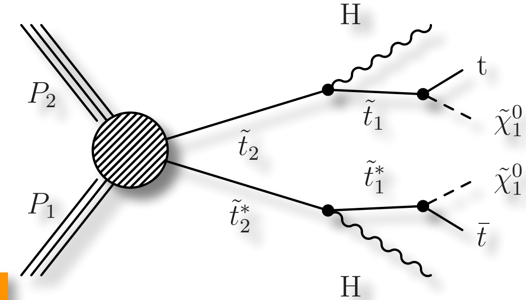
Direct Stop: Summary



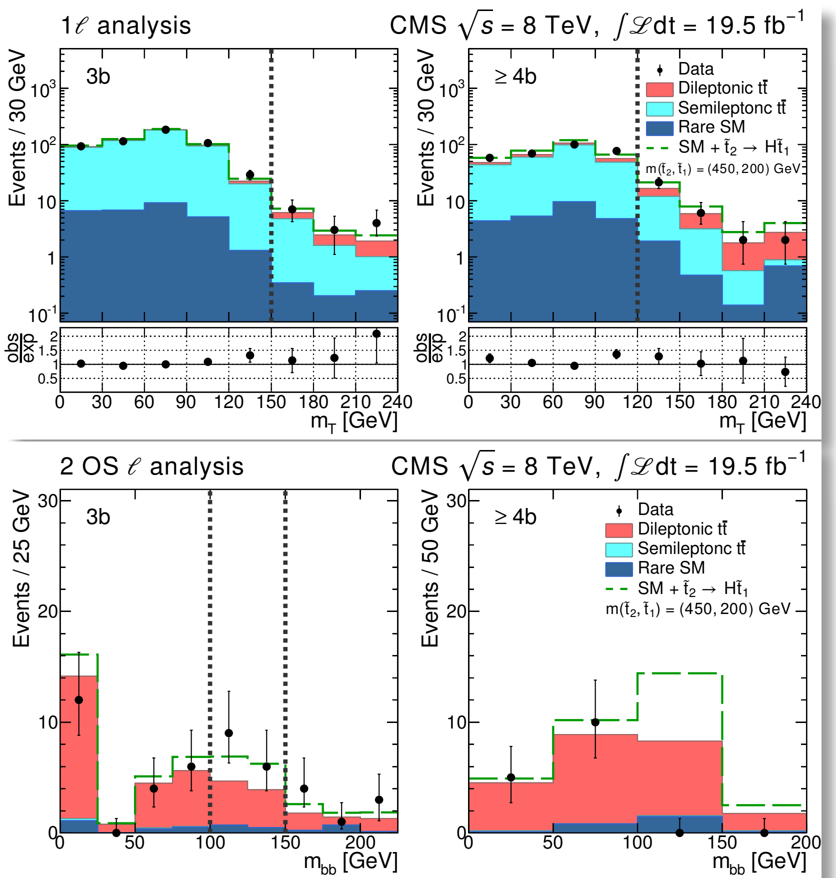


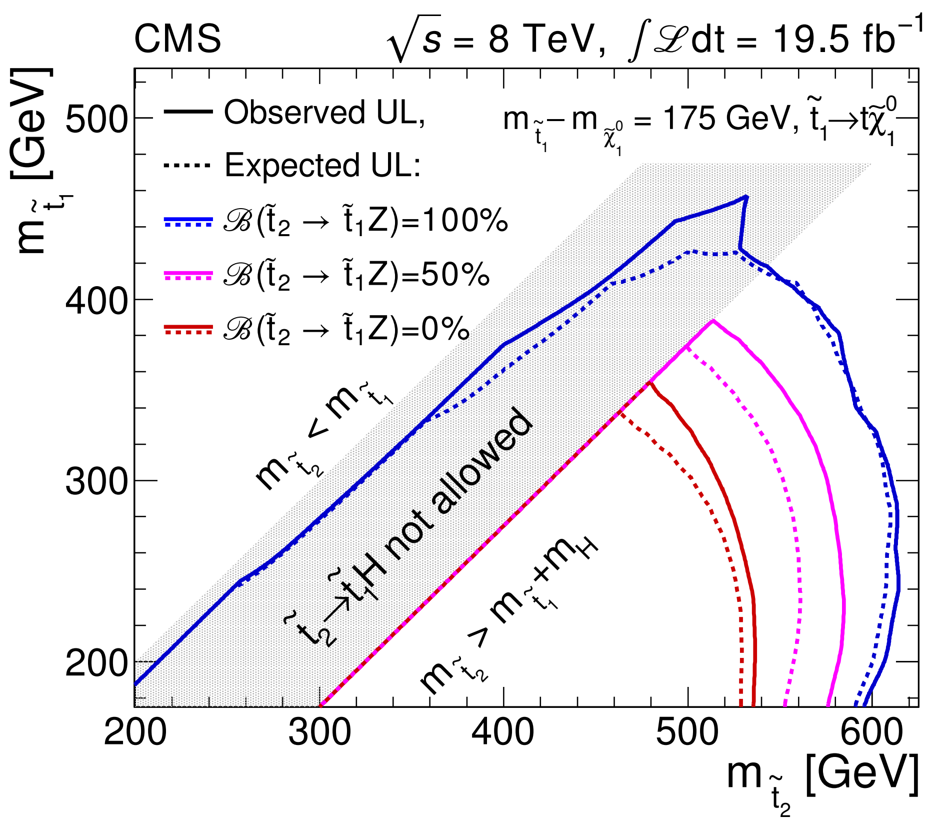
Stop Decays via Higgs/Z

- Probing compressed spectrum in the stop to top + neutralino decays by looking for the heavier stop production with the decay in the lightest stop and a Z or Higgs boson
- Results in additional boost of decay products probing $M(\tilde{t}_1) - M(\tilde{\chi}^0_1) \approx 175$ GeV



CMS, arXiv:1405.3886





Conclusions

- Direct stop pair production is a classic example of a sophisticated search analysis:
  - Well-motivated
  - Uses advanced kinematic variables
  - Uses both cut-and-count and modern multivariate techniques
  - Combines several channels
  - Offers high sensitivity to a broad class of models
- Unfortunately, the search came empty-handed, but it set stringent limits on stop production and covered large fraction of “natural” phase space
- The analysis will remain a flagship SUSY search in Run 2 and will either result in a discovery or significant limits on the very “natural” SUSY possibility!

Thank You!