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Search for SUSY in hadronic final states using M_{T2}

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Outline

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- Introduction
  - CMS @ LHC
  - Supersymmetry
  - The M_{T2} variable
- History
- Search strategy
- Background estimation
- Results
- Exclusion limits
- Summary

CMS @ the LHC

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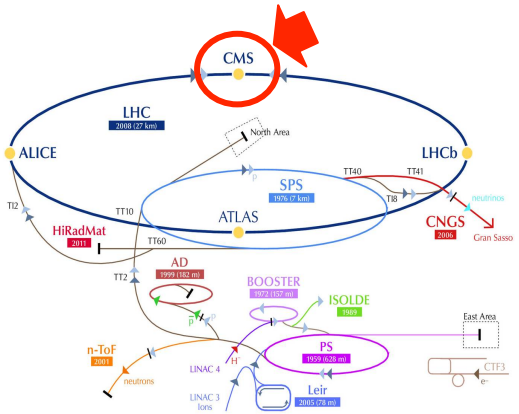
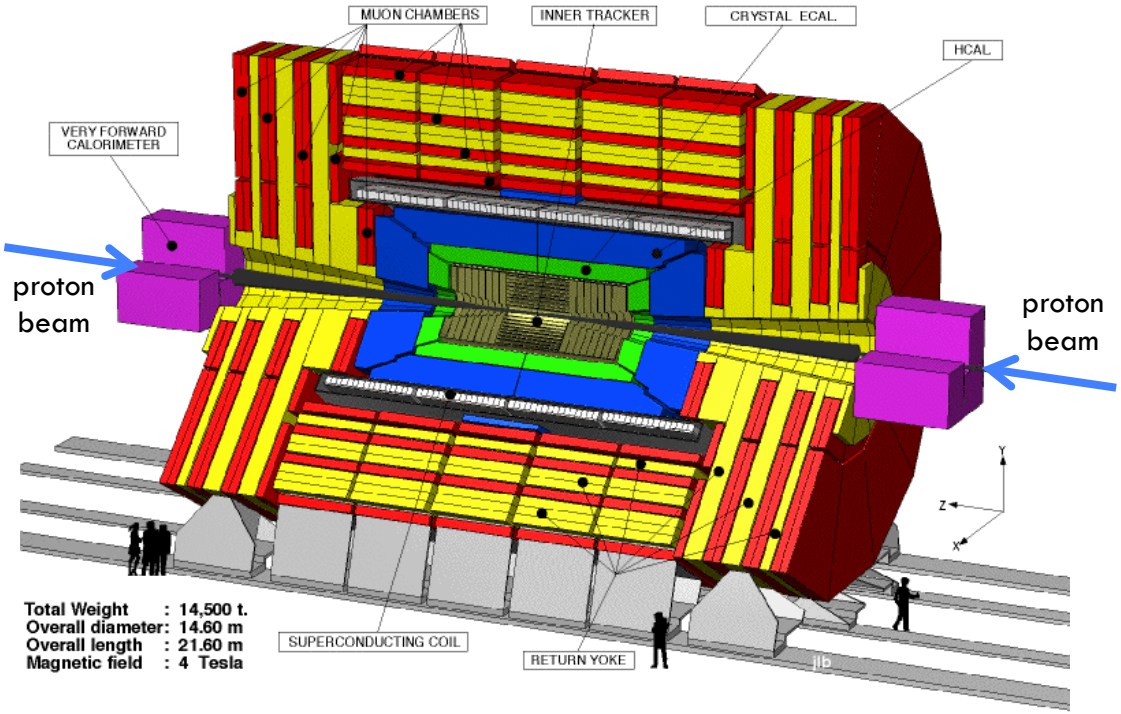


CERN Accelerator Complex



Compact Muon Solenoid

Supersymmetry

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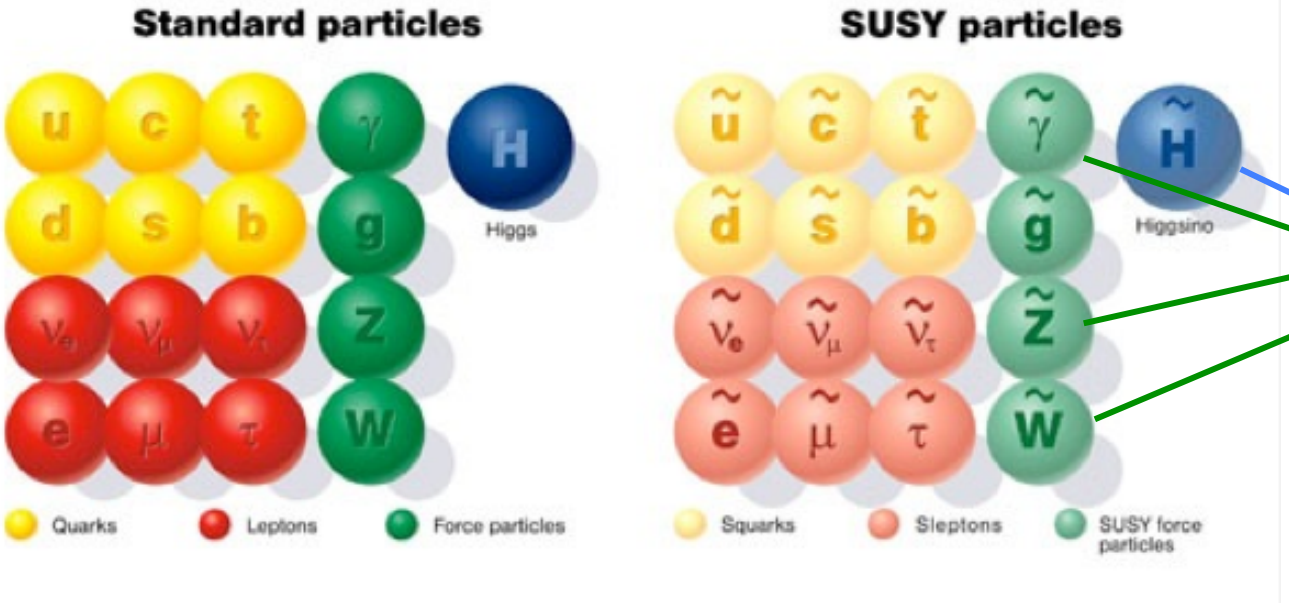

- Neutralinos: χ^0_i ($i = 1, \ldots, 4$)
- Charginos: $\chi^\pm_i$ ($i = 1, 2$)

- New fundamental (*broken*) symmetry
  - ➢ $Q\,|\text{fermion}\rangle = |\text{boson}\rangle$ & $Q\,|\text{boson}\rangle = |\text{fermion}\rangle$

    - ✓ Would stabilize mass hierarchy problem
    - ✓ Would facilitate GUT
    - ✓ Would provide candidates for Dark Matter
    - ✓ …

Topology of a SUSY event

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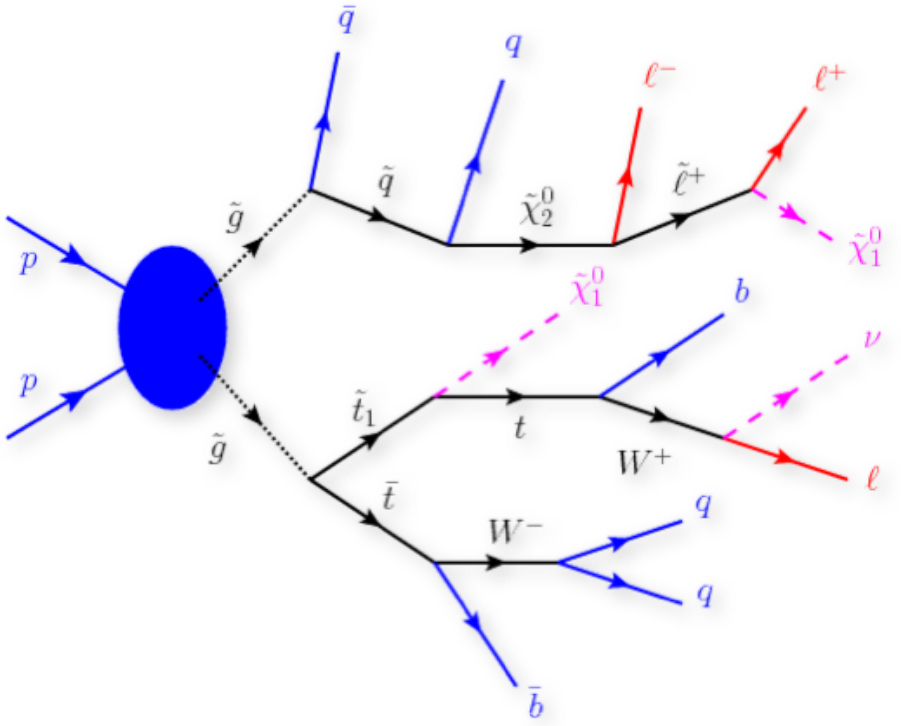
How to look for SUSY?

- Large energy release
- Large number of **jets**
- Large E_T^{miss}
- Low momentum **leptons**



⇒ Search for **jets + E_T^{miss}** + leptons

The M_{T2} variable

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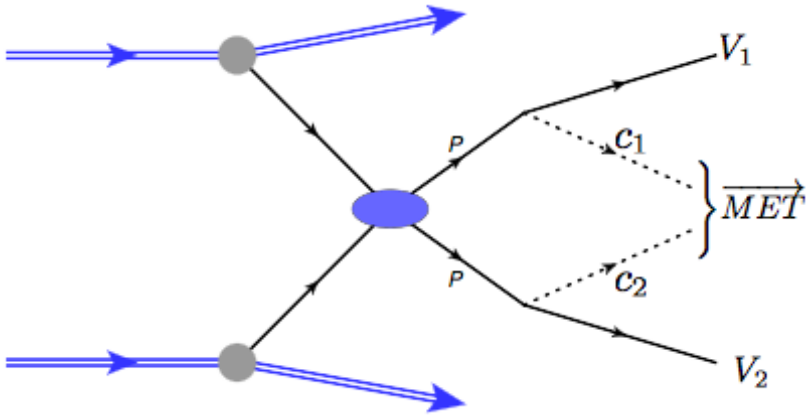
- **Generalization of transverse mass M_T** to case of **two** decay chains with an **un**observed particle each

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

  - ✓ If all masses are known, M_{T2} will have an **endpoint** at the parent mass

- **Division** of events into **two massless pseudo-jets**



* Bibliography: arXiv: hep-ph/9906349, hep-ph/0907.2713

The M_{T2} variable

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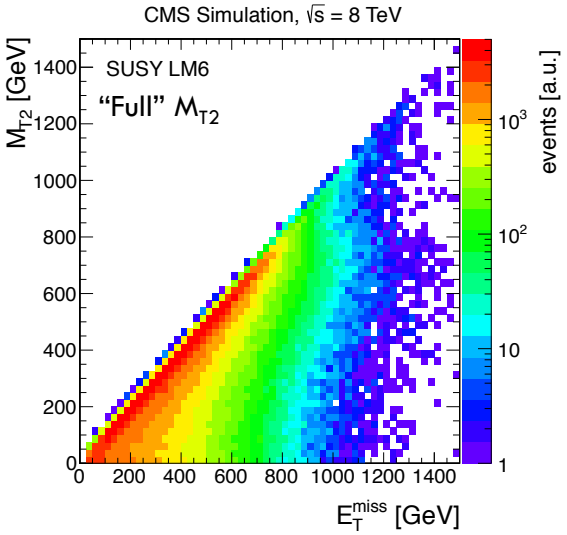
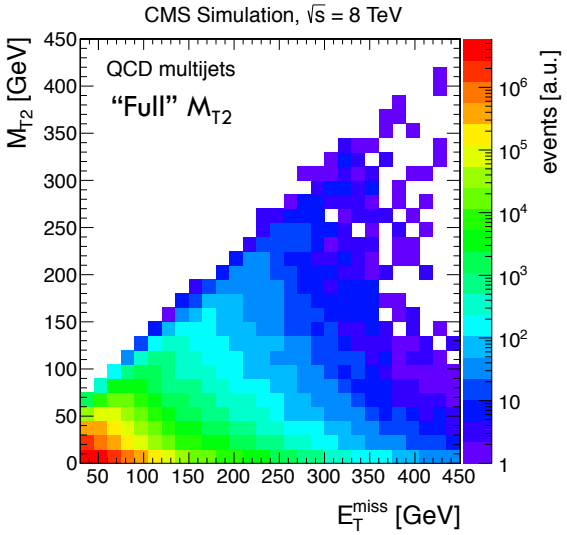
- Virtue of M_{T2} becomes evident for the simplified case of:
  - ✓ **zero masses**
  - ✓ **no ISR**

$$\Rightarrow \quad M_{T2}^2 = 2p_T^{V_1} p_T^{V_2} (1+\cos\phi_{1,2})$$





- **SUSY**-like events:
  - ✓ $M_{T2} \lesssim E_T^{miss}$
- **Multijet**-like events:
  - ✓ $M_{T2} \rightarrow 0$

* $E_T^{miss\,2} = (p_{T1} - p_{T2})^2 + 2p_{T1}p_{T2}(1+\cos\phi_{1,2})$

History @ 7 TeV

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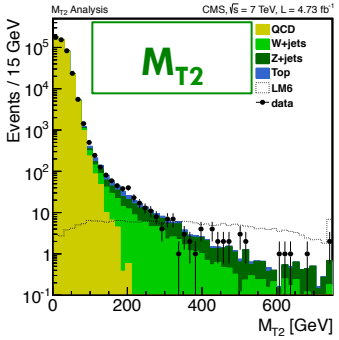
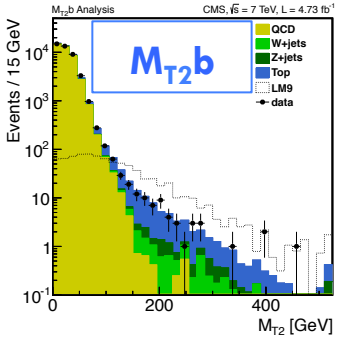
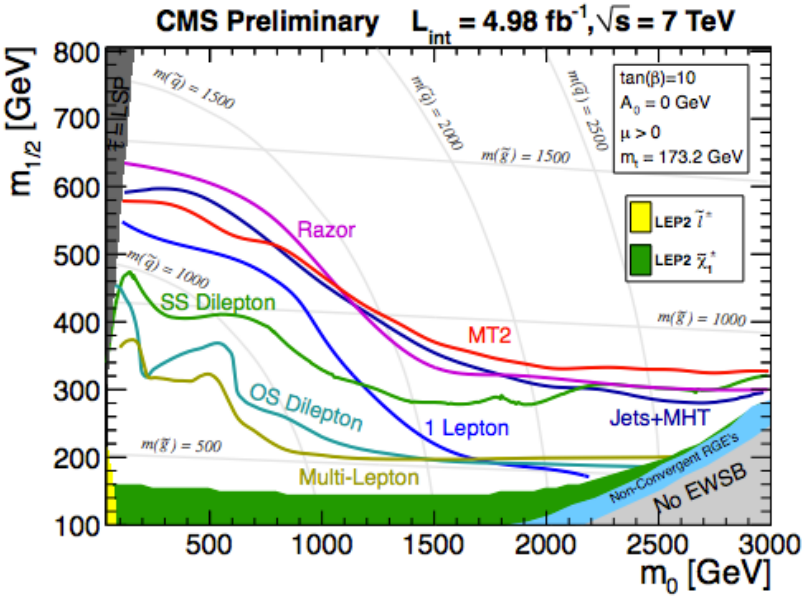
- **Publication**: J. High Energy Physics 1210 (2012) 018





CMS Exclusion Limits



- **Two** mutually **not exclusive** analyses (with H_T > 750 GeV)
  1. M_{T2} , with N(jets) ≥ 3
  2. M_{T2}**b**, with N(jets) ≥ 4 & N(**b**-jets) ≥ 1

The search strategy @ 8 TeV

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- ✓ This search is a development of the published 7 TeV analysis
- ✓ The 7 TeV analysis did **not** see any significant excess over the Standard Model background

Two way optimization

Inclusive M_{T2} analysis

- Combining former M_{T2} and M_{T2}**b**
- Have high granularity of the search region
- Access large phase space

M_{T2} Higgs analysis

- New analysis optimized for the search of a light Higgs boson within a SUSY decay chain
- Exploit Higgs decay into $b\bar{b}$

Inclusive M_{T2} analysis

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General Strategy

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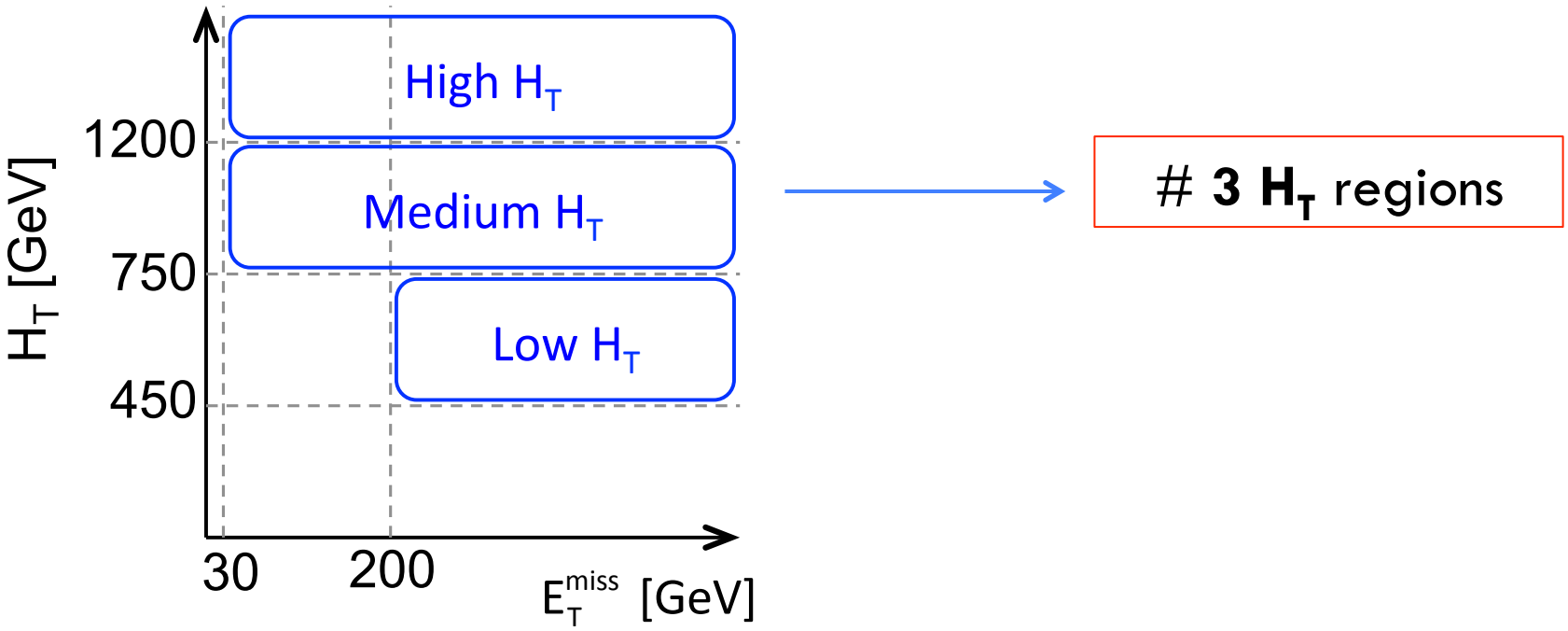
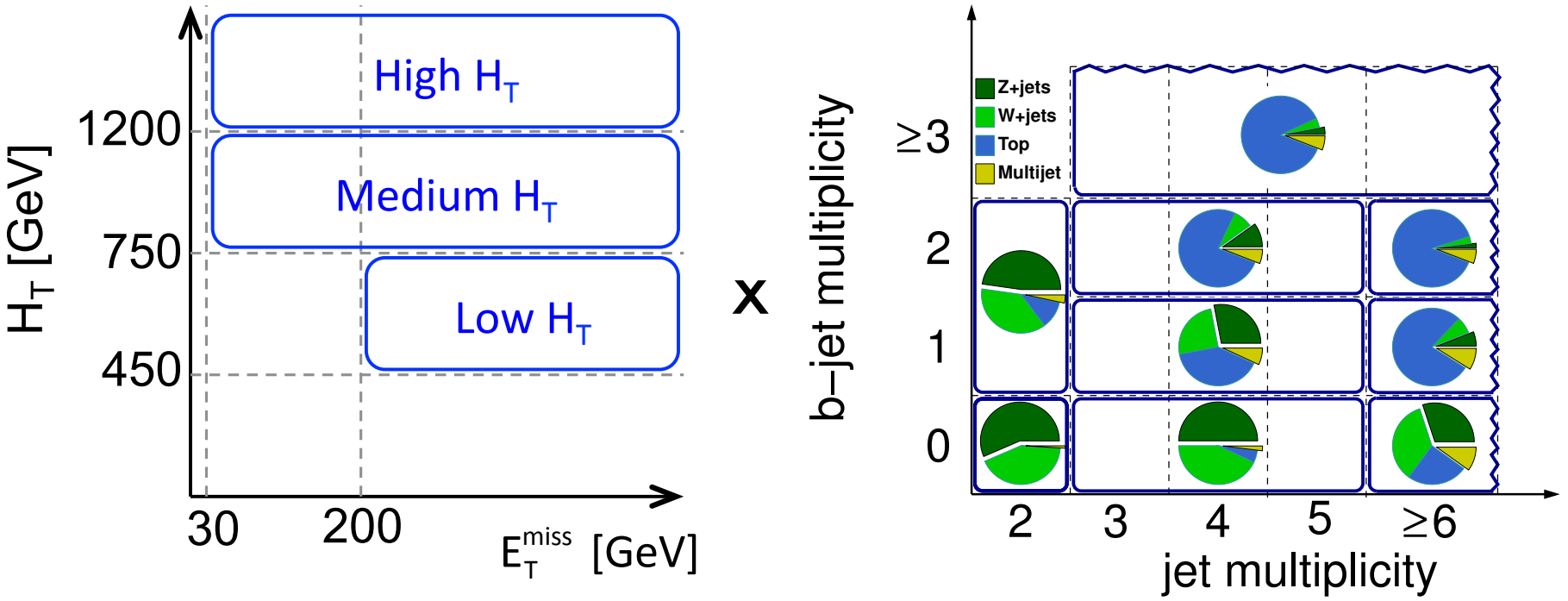
- Select a large phase space in H_T - E_t^{miss} plane
  - **Three H_T regions** are selected



General Strategy

- Select a large phase space in H_T - E_t^{miss} plane
- Consider separately different **jet & b-jet multiplicities**



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- Select a large phase space in H_T - E_t^{miss} plane
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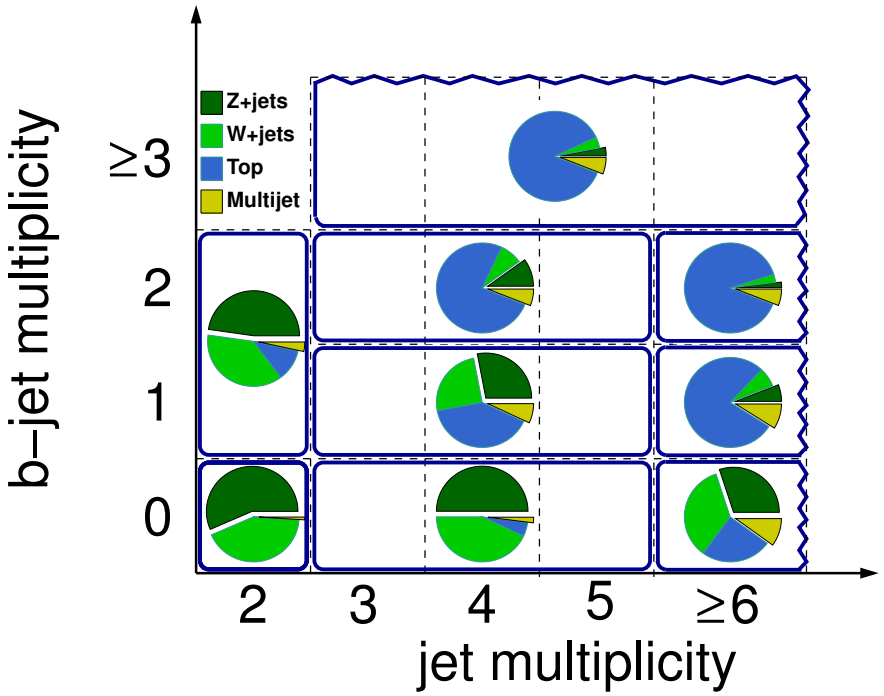
➢ **Sensitivity** to:

- ❑ **Direct squark** production
- ❑ **Direct gluino** production
- ❑ **1st/2nd & 3rd generation**



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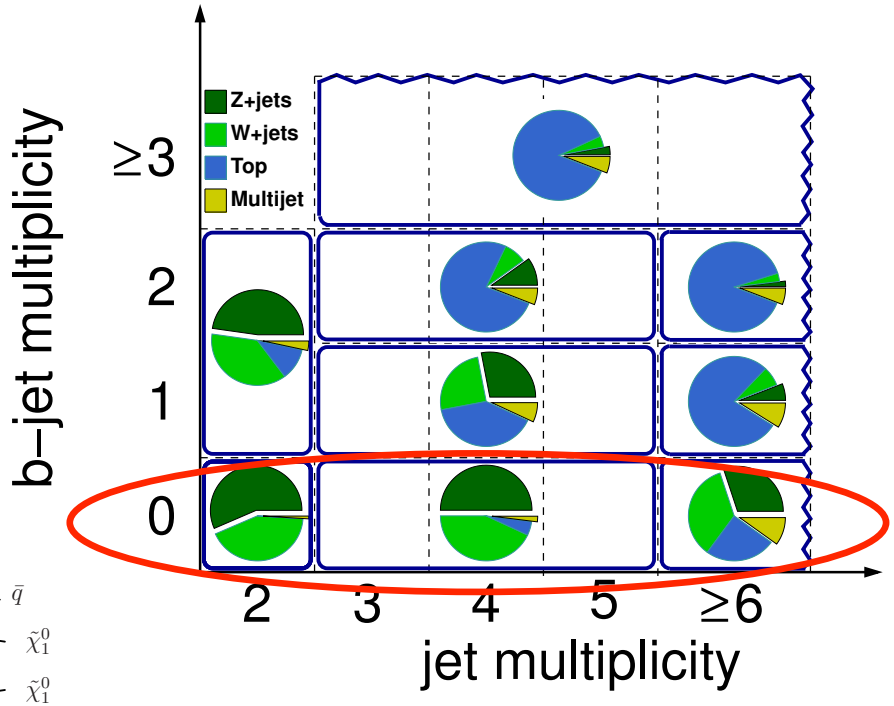

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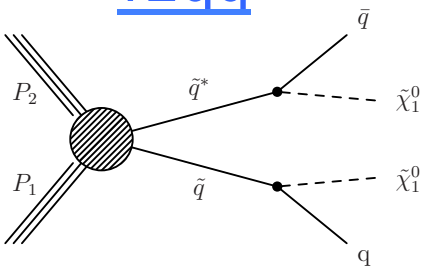

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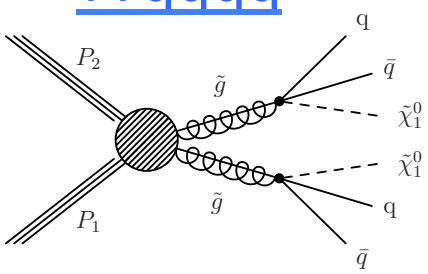

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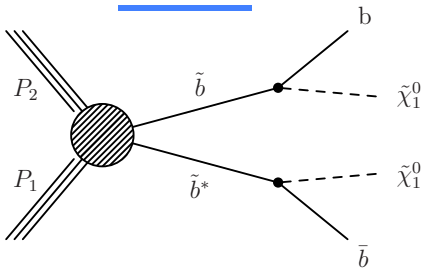
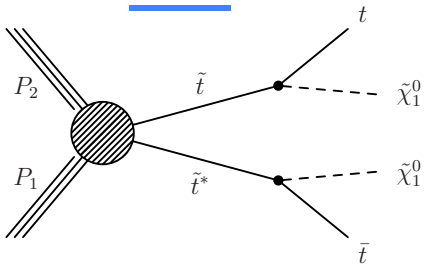
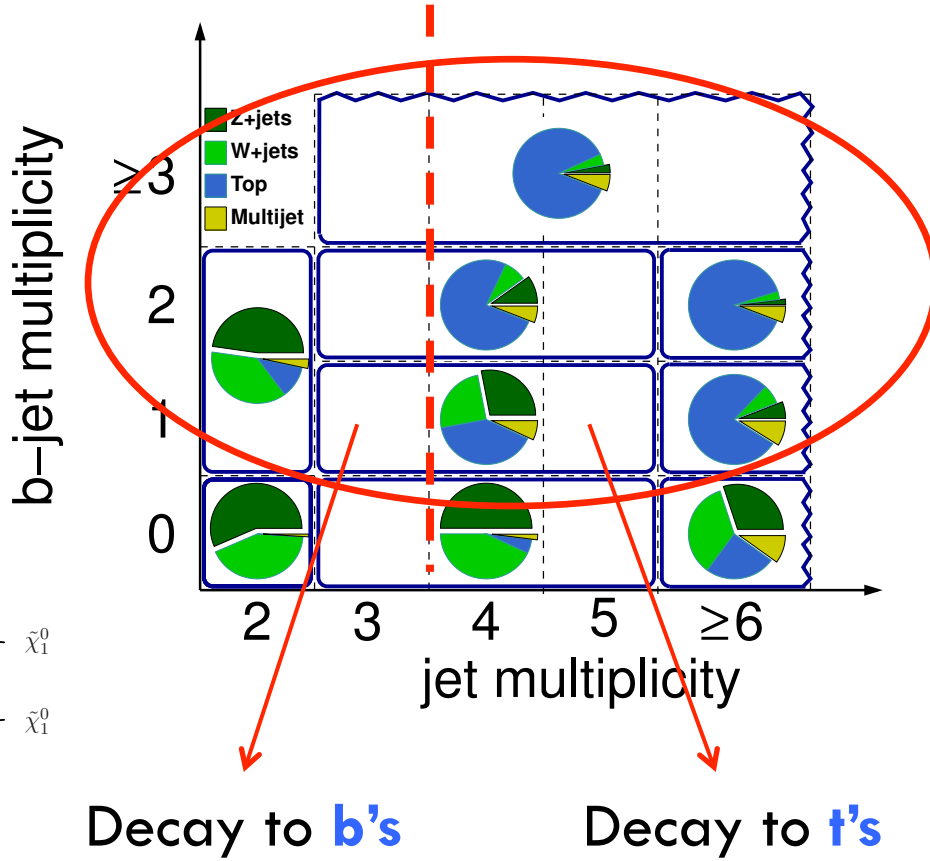
T2bb



T2tt





General Strategy

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- Select a large phase space in H_T - E_t^{miss} plane
- Consider separately different **jet & b-jet multiplicities**

➢ **Sensitivity** to:

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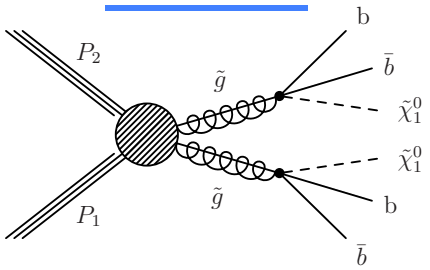
- ❑ **1st/2nd & 3rd generation**

T1bbbb



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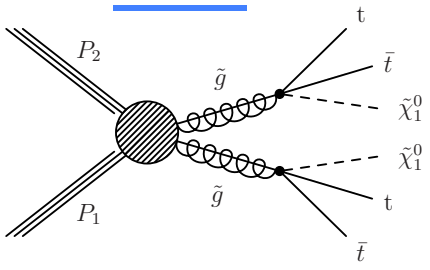
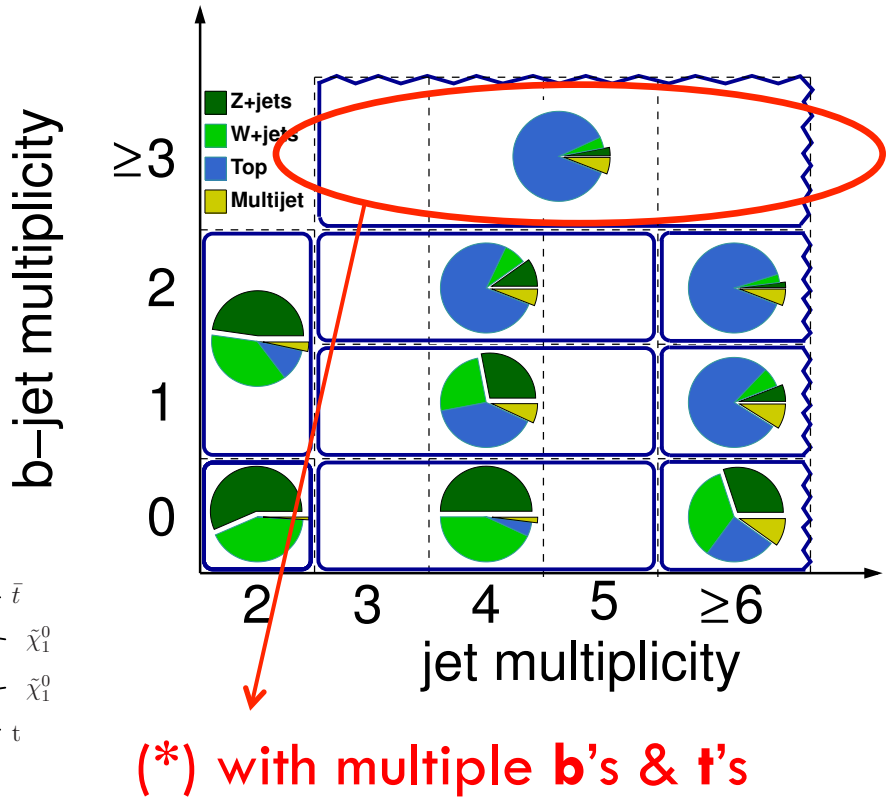
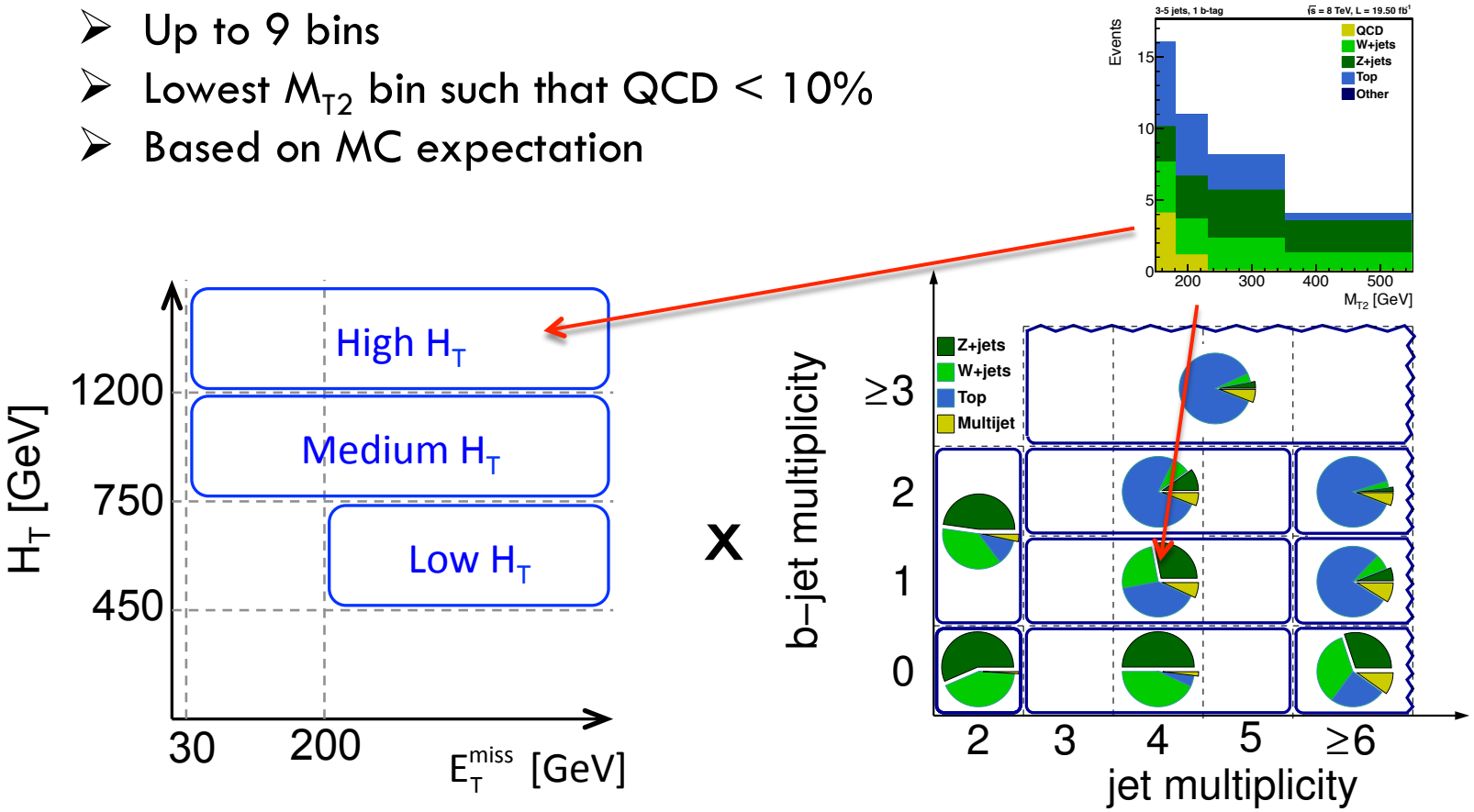




(*) with multiple **b**'s & **t**'s

General Strategy

- Finally, in each region **M_{T2} distribution** divided in adjacent **bins**
  - Up to 9 bins
  - Lowest M_{T2} bin such that QCD < 10%
  - Based on MC expectation



- See BACKUP for exact binning!

M_{T2} Higgs analysis

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Motivation – SUSY Higgs?

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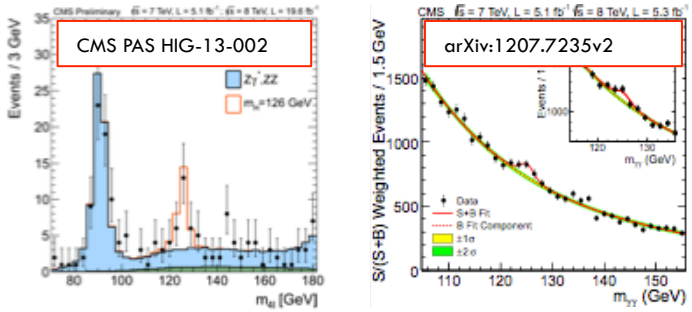
- Light Higgs boson was observed, with $M(h^0) \simeq 125$ GeV



➢ Could it be a light SUSY Higgs boson?

- ✓ In the MSSM, five Higgs bosons are foreseen: h^0, H^0, A^0, H^+, H^-
- ✓ If SUSY exists, the observed Higgs boson is likely to be the lightest SUSY Higgs boson (h^0). In fact, SUSY predicts $M(h^0) < 135$ GeV
- ✓ h^0 may be produced at the end of a cascade of SUSY particles
- ✓ If SUSY is observed, this search may confirm whether the observed Higgs boson is compatible with the lightest SUSY Higgs boson, or not

Models of interest

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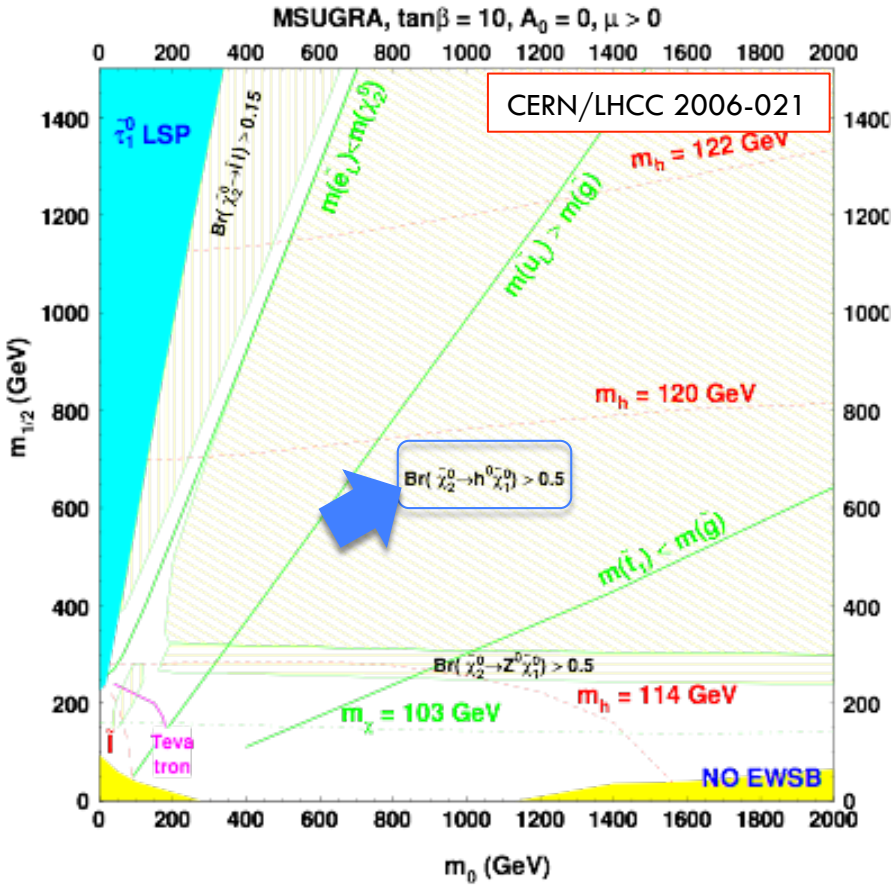
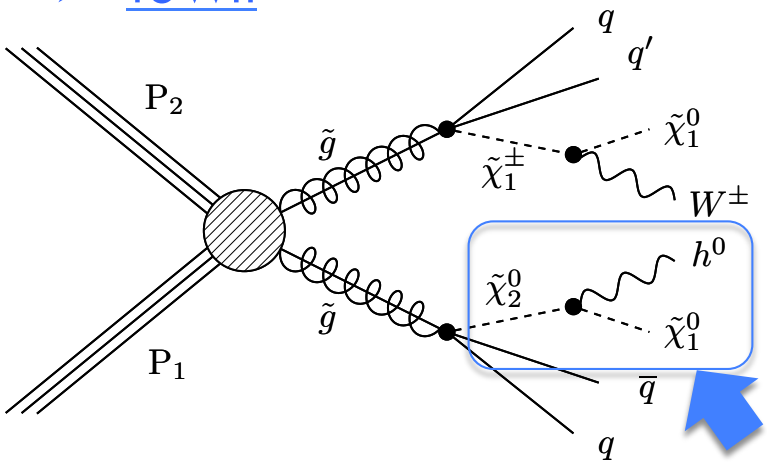


- Look at Simplified Models with **one h^0**
  - T5Wh



- Exploit main h^0 decay, $h^0 \to b\bar{b}$

➢ Asymmetric decays with **one** h^0 may be dominant

✓ Models with symmetric decays (i.e., with 2 h^0) also exist...

General Strategy

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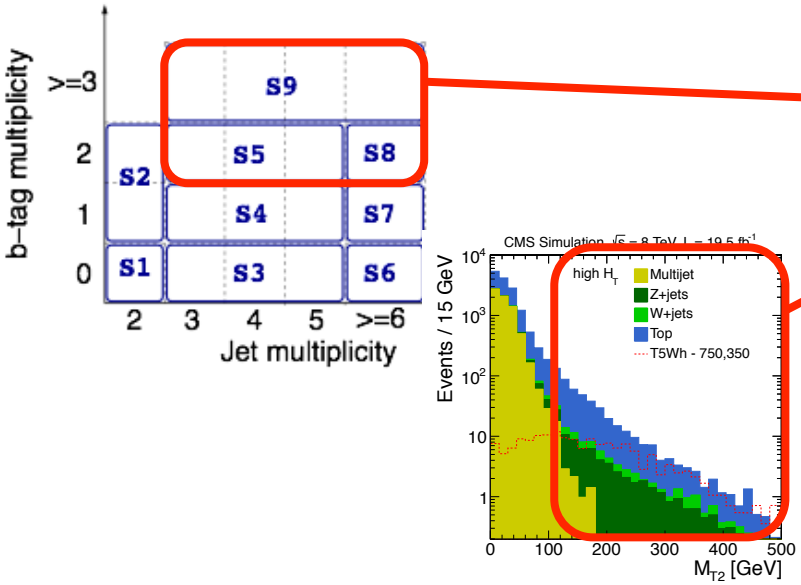
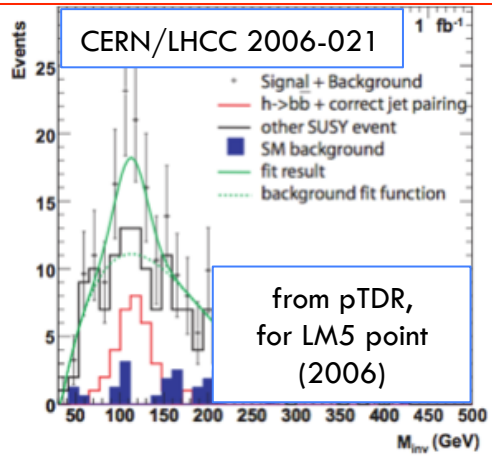
- Search **not orthogonal** wrt. inclusive M_{T2} analysis
- ➢ **Optimization** of inclusive M_{T2} analysis
  - ✓ Select phase-space of interest
    - High jet & b-jet multiplicity, high M_{T2} …
  - ✓ **Select b-pair**



Higgs Invariant Mass



Background estimation – Summary

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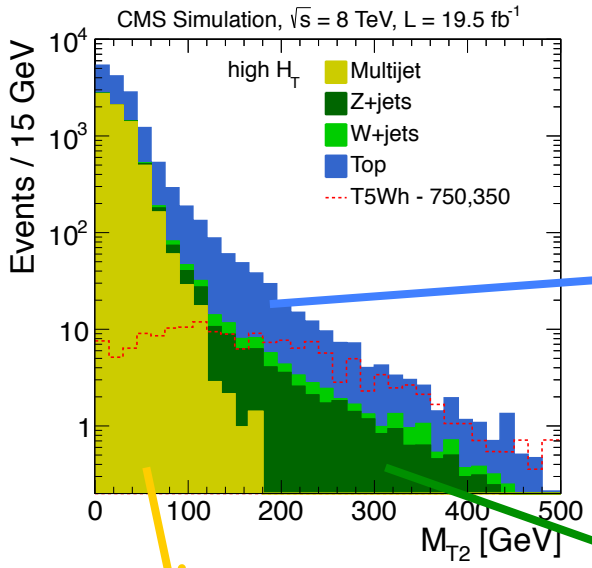

Top & W(lν)+jets

- ✓ Real E_T^{miss}
- ✓ Mostly rejected by lepton veto
- ✓ **Signal-like** if charged lepton **lost**
  - Acceptance
  - Identification & Isolation
- ✓ Probability to lose a lepton
- ➢ **1-lepton** events used for prediction

QCD multijet

- ✓ **No** real E_T^{miss} ⇒ small M_{T2}
- ✓ Larger M_{T2} in case of **mis-**measured jets
- ✓ **Mis**-measured jets aligned with E_T^{miss}
- ➢ Correlation **min Δϕ(jets, E_T^{miss})** vs **M_{T2}** used for prediction

Z(νν)+jets

- ✓ Large E_T^{miss} ⇒ **Signal-like** event
- ➢ **γ + jets** events used for prediction
- ✓ Photon p_T added to E_T^{miss}
- ✓ Mimic Z(νν) + jets events

Results

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- ✓ For 19.5 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV

Inclusive M_{T2} analysis

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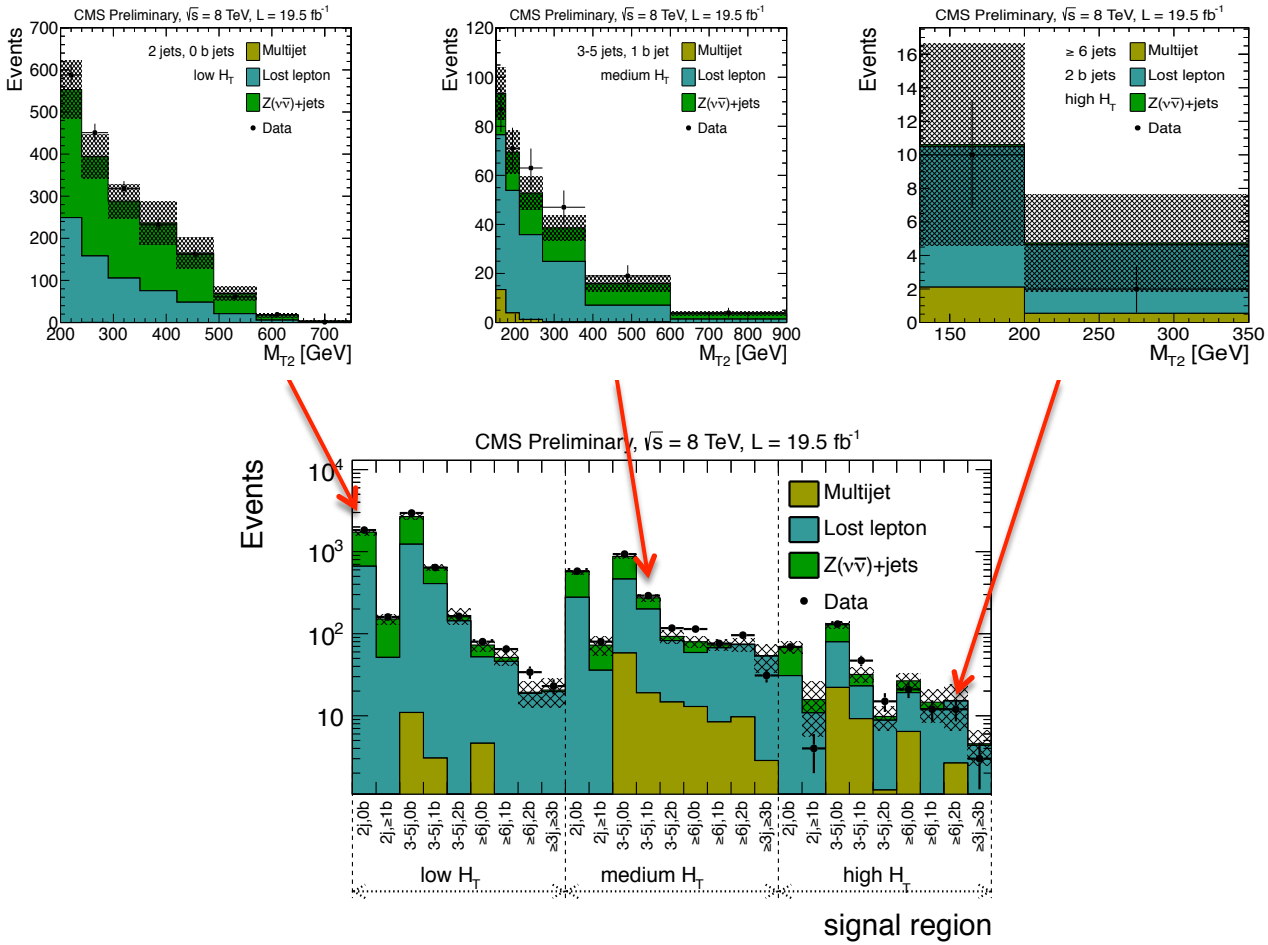
✓ Looking for an excess in M_{T2} tail



M_{T2} Higgs analysis

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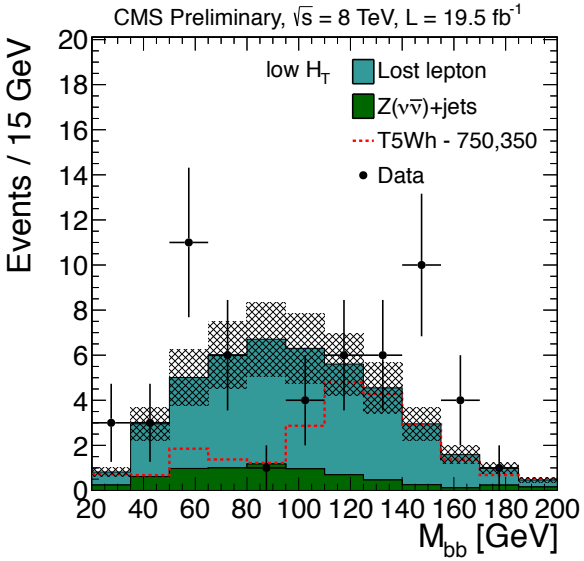
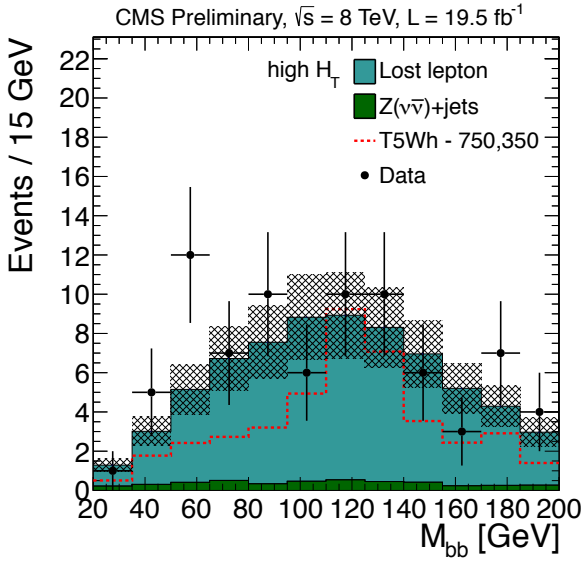
✓ Looking for a peak in M_{bb} distribution





Channel	Lost lepton	$Z(\nu\bar{\nu})$+jets	Total background	Data
low H_T	37.1 ± 9.0	6.9 ± 6.9	44.0 ± 11.3	55
high H_T	64.8 ± 16.4	4.4 ± 4.4	69.2 ± 17.0	81

Exclusion limits

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- ✓ For a selection of Simplified Models

Inclusive M_{T2} analysis

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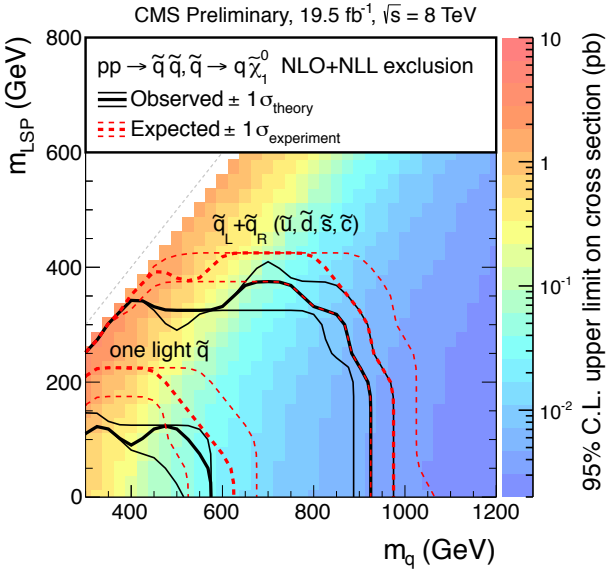

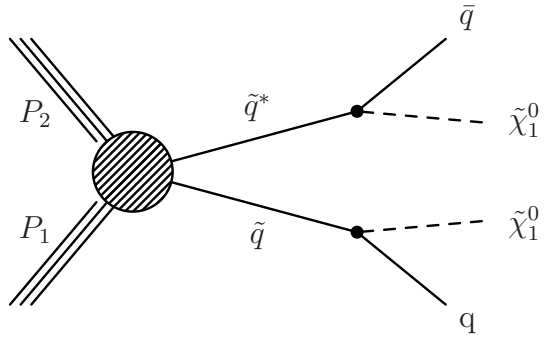

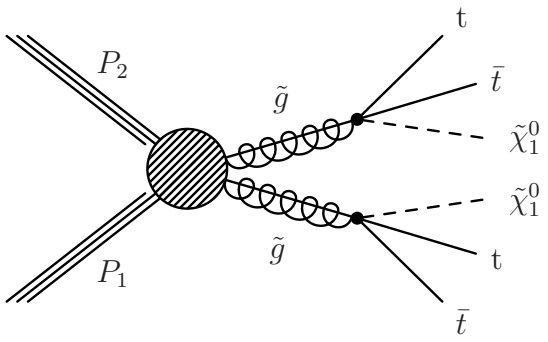

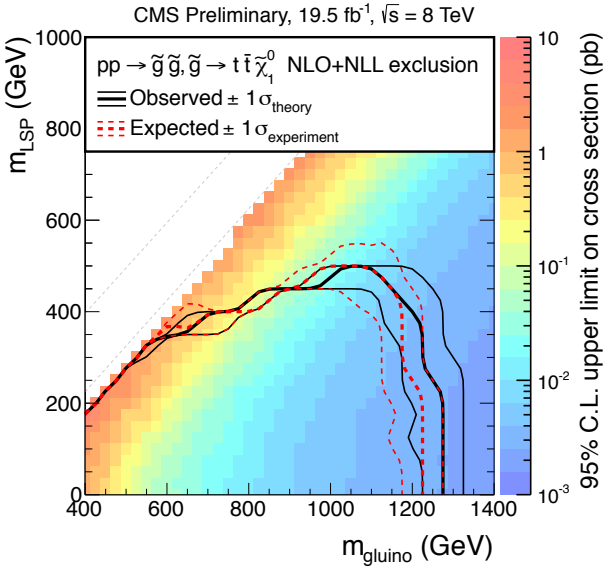

M_{T2} Higgs analysis

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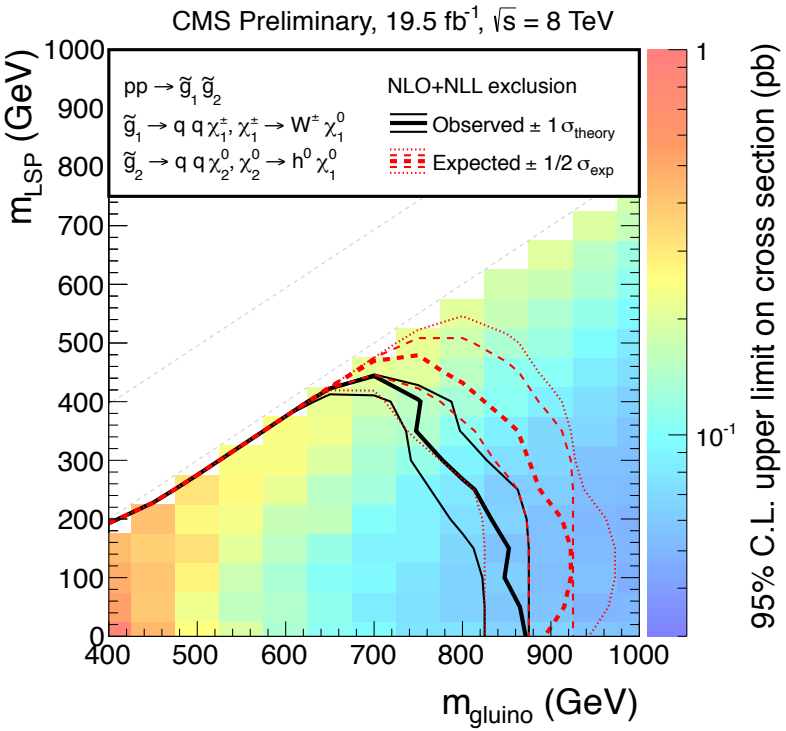

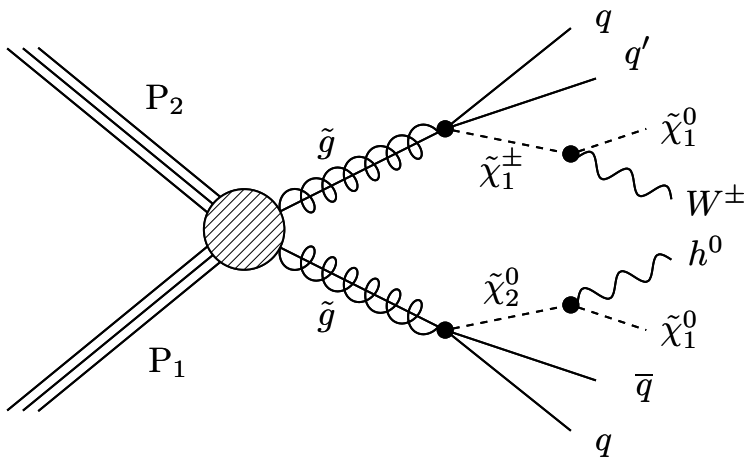

Summary

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- A search for SUSY using M_{T2} as a discovery variable was motivated and presented
- An optimized search for $h^0 \rightarrow b\bar{b}$, with h^0 produced within SUSY cascades, using M_{T2} for background rejection and M_{bb} as a discovery variable, was also motivated and presented
- Results and exclusion limits for a selection of models were shown

The end.

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THANK YOU!

BACKUP

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Documentation

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- CMS Physics Analysis Summary
  http://cms-physics.web.cern.ch/cms-physics/public/SUS-13-019-pas.pdf
- Public TWiki
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13019
- CADI Entry
  http://cms.cern.ch/iCMS/analysisadmin/viewanalysis?id=1180&field=id&value=1180&name=MT2%20all%20hadronic

The Large Hadron Collider

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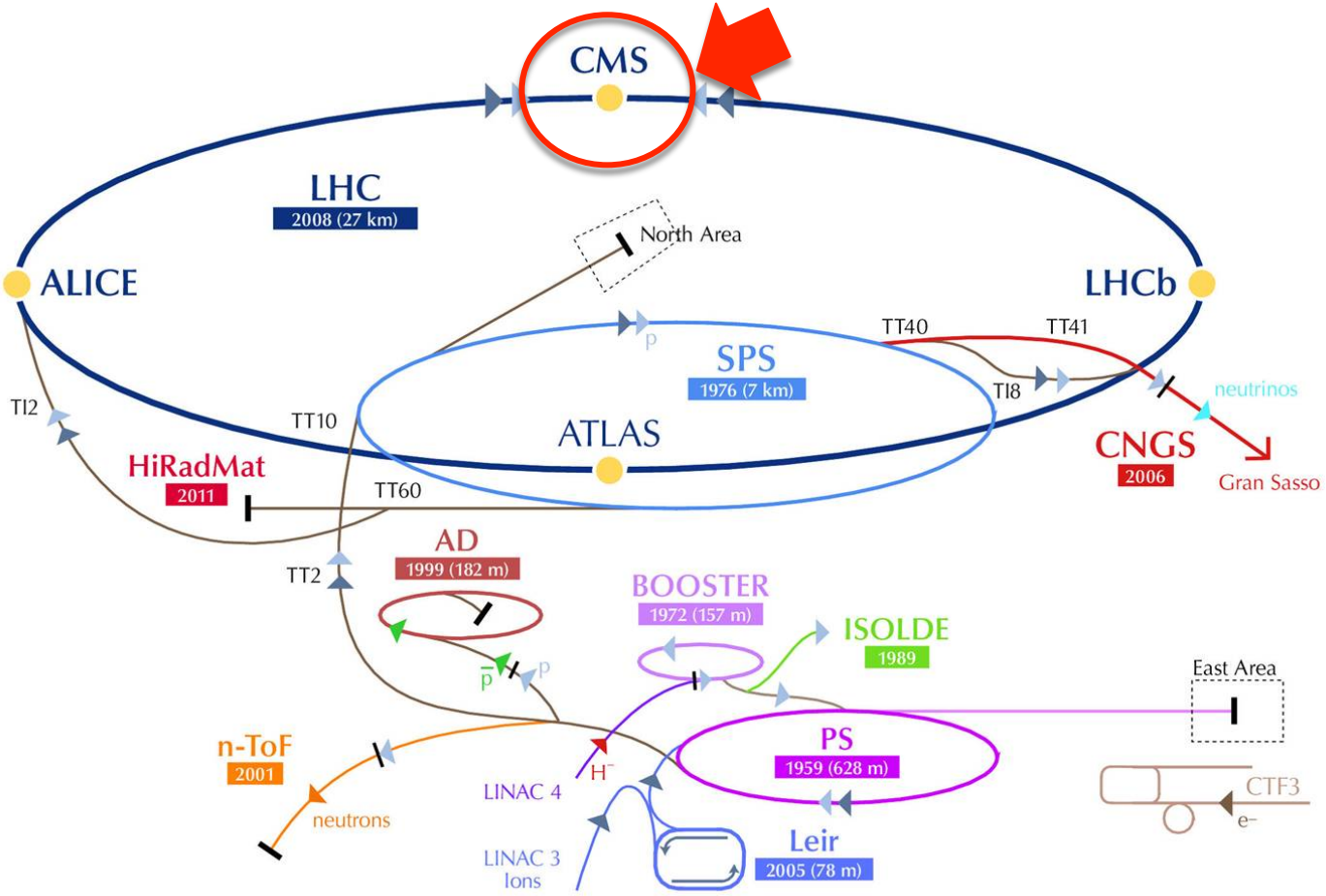
CERN Accelerator Complex



Inclusive M_{T2} binning

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	low H_T region			medium H_T region			high H_T region	
	M_{T2} bin [GeV]			M_{T2} bin [GeV]			M_{T2} bin [GeV]	
2 jets, 0 b jets	200-240 240-290 290-350	350-420 420-490 490-570	570-650 ≥ 650	125-150 150-180 180-220	220-270 270-325 325-425	425-580 580-780 ≥ 780	120-150 150-200 200-260	260-350 350-550 ≥ 550
2 jets, ≥ 1 b jets	200-250 250-310	310-380 380-450	450-550 ≥ 550	100-135 135-170	170-260 260-450	≥ 450	100-180 ≥ 180	
3-5 jets, 0 b jets	200-240 240-290 290-350 350-420	420-490 490-570 570-650 ≥ 650		160-185 185-215 215-250 250-300	300-370 370-480 480-640 640-800	≥ 800	160-185 185-220 220-270 270-350	350-450 450-650 ≥ 650
3-5 jets, 1 b jets	200-250 250-310	310-380 380-450	450-550 ≥ 550	150-175 175-210	210-270 270-380	380-600 ≥ 600	150-180 180-230	230-350 ≥ 350
3-5 jets, 2 b jets	200-250 250-325	325-425 ≥ 425		130-160 160-200	200-270 270-370	≥ 370	130-200 ≥ 200	
≥ 6 jets, 0 b jets	200-280 280-380	≥ 380		160-200 200-250	250-325 325-425	≥ 425	160-200 200-300	≥ 300
≥ 6 jets, 1 b jets	200-250 250-325	≥ 325		150-190 190-250	250-350 ≥ 350		150-200 200-300	≥ 300
≥ 6 jets, 2 b jets	200-250 250-300	≥ 300		130-170 170-220	220-300 ≥ 300		120-200 ≥ 200	
≥ 3 jets, ≥ 3 b jets	200-280	≥ 280		125-175	175-275	≥ 275	1≥ 125	

Inclusive M_{T2} analysis – Strategy

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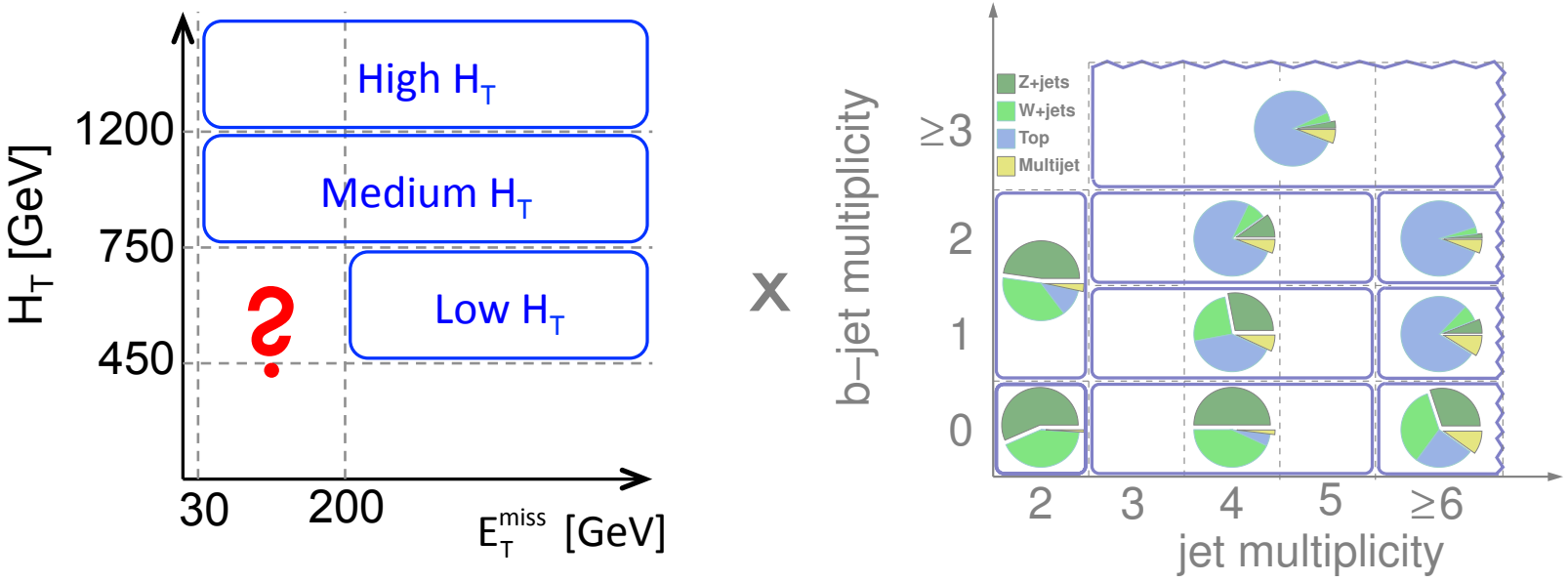
- Finally, in each region **M_{T2} distribution** divided in adjacent **bins**
  - Up to 9 bins
  - Lowest M_{T2} bin such that QCD < 10%
  - Based on MC expectation



- See BACKUP for exact binning!

Triggers

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- **Three** different **triggers** are used to access a large phase space, in the $\mathbf{H_T - E_T^{miss}}$ plane
  1. HLT $\mathbf{H_T > 650\ GeV}$
     - Fully efficient @ $H_T >$ **750 GeV**
  2. HLT $\mathbf{E_T^{miss} > 150\ GeV}$

  +

  3. HLT $\mathbf{H_T > 350\ GeV}$ & $\mathbf{E_T^{miss} > 100\ GeV}$
     - Fully efficient @ $H_T >$ **450 GeV** & $E_T^{miss} >$ **200 GeV**

Logical 'OR'

Event Selection

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1. **450** < H_T/GeV < **750** & E_T^{miss} > **200** GeV
2. H_T > **750** GeV & E_T^{miss} > **30** GeV

Trigger-driven

Safety Threshold for M_{T2} computation

Event Selection

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1. $450 < H_T/\text{GeV} < 750$ & $E_T^{miss} > 200$ GeV
2. $H_T > 750$ GeV & $E_T^{miss} > 30$ GeV

- **N(jets) ≥ 2,** with **p_T(2nd** leading jet) **> 100 GeV**

Event Selection

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1. **450 < H_T/GeV < 750** & **E_T^{miss} > 200 GeV**
2. **H_T > 750 GeV** & **E_T^{miss} > 30 GeV**

- **N(jets) ≥ 2**, with **p_T(2^{nd} leading jet) > 100 GeV**
- **Lepton veto** (e, μ, τ_{had})
  - ➢ Rejection of large fraction of W+jets & TTbar contribution

Event Selection

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1. **$450 < H_T/\text{GeV} < 750$** & **$E_T^{miss} > 200$ GeV**
2. **$H_T > 750$ GeV** & **$E_T^{miss} > 30$ GeV**

- **N(jets) ≥ 2**, with **p_T(2nd** leading jet**) > 100 GeV**
- **Lepton veto** (e, μ, τ_{had})
- **min Δφ (4 leading jets, E_T^{miss}) > 0.3**
  - ➢ Rejection of QCD multijet **mis**-measurements

Event Selection

1. $450 < H_T/\text{GeV} < 750$ & $E_T^{miss} > 200$ GeV
2. $H_T > 750$ GeV & $E_T^{miss} > 30$ GeV

- **N(jets) ≥ 2**, with **p_T(2nd leading jet) > 100 GeV**
- **Lepton veto** (e, μ, τ_{had})
- **min Δφ (4 leading jets, E_T^{miss}) > 0.3**
- **$|H_T^{miss} - E_T^{miss}| < 70$ GeV**
  - Limit p_T from *upstream* decays
  - Avoid broadening of M_{T2}

Upstream momentum

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- The **upstream transverse momentum** (UTM) biases the shape of M_{T2} distribution

  - Introduce a cut on $|H_T^{miss} - E_t^{miss}|$ to limit bias

$$|\vec{E}_{\mathrm{T}}^{\mathrm{miss}} - \vec{H}_{\mathrm{T}}^{\mathrm{miss}}| = \sqrt{\left(\sum_{\text{jets, leptons, } \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}} p_x\right)^2 + \left(\sum_{\text{jets, leptons, } \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}} p_y\right)^2}$$

    - H_T^{miss} = vectorial p_T sum of **selected** jets, e's and μ's

$p_T > 20$ GeV

Upstream momentum

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- The **upstream transverse momentum** (UTM) biases the shape of M_{T2} distribution

  - Introduce a cut on $|H_T^{miss} - E_t^{miss}|$ to limit bias

$$|\vec{E}_{\mathrm{T}}^{\mathrm{miss}} - \vec{H}_{\mathrm{T}}^{\mathrm{miss}}| = \sqrt{\left(\sum_{\text{jets, leptons, } \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}} p_x\right)^2 + \left(\sum_{\text{jets, leptons, } \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}} p_y\right)^2}$$

  - ✓ Expected to be **small** if:
    - ❖ **NO** hard objects failing selection (acceptance, ID)
    - ❖ **NO** **un**-clustered energy (**soft** jets, $p_T < 20$ GeV)

  - ✓ $|H_T^{miss} - E_t^{miss}| < 70$ GeV ⇒ -10% of QCD multijet

M_{T2} Higgs analysis – Selection

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✓ In **addition** to inclusive event selection

- N(jets) ≥ 4
- N(**b**-jets) ≥ 2, medium CSV tag & p_T(**b**-jet) > 20 GeV
  - ➢ Select phase-space of interest

- M_{T2} > 200 GeV @ **low H_T** (i.e., H_T < 750 GeV)
- M_{T2} > 125 GeV @ **high H_T** (i.e., H_T > 750 GeV)
  - ➢ Background rejection (QCD multijet especially)

➢ **b-pair selection**

- $\Delta R(b_1, b_2) < 1.5$

b-pair selection

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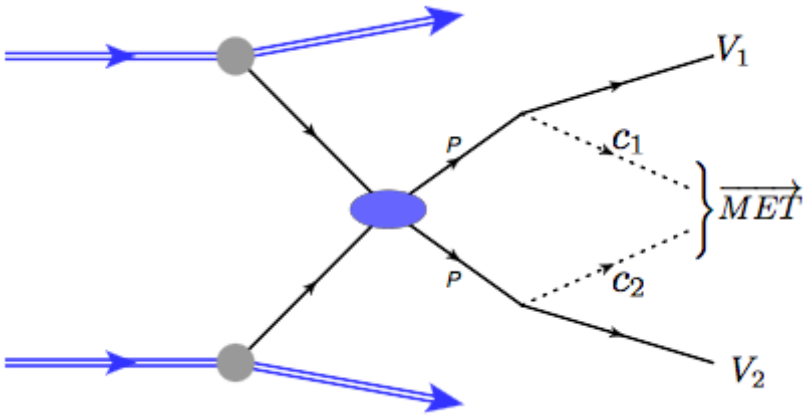
- A hemisphere algorithm is used to separate two visible systems
  - ➢ Each decay chain should cluster into one hemisphere



Working point:

- ➢ Look at b-jets within **same** hemi
- ➢ Select b-pair as the closest in **ΔR**
  - ✓ Maximize **purity**
- ➢ If no b-pair with ΔR < 1.5, then look at **opposite** hemi
  - ✓ Maximize **efficiency**

* $\Delta R^2 = \Delta\Phi^2 + \Delta\eta^2$

Multijet estimate

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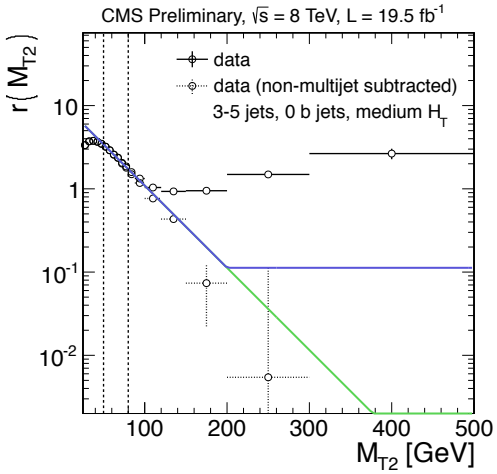
- **QCD multijet** in signal region in case of **mis**-measured jets, due to fake E_t^{miss}

➢ Use a factorization method:

$$r(M_{T2}) = \frac{N(\min\Delta\phi(\text{jets}, E_T^{miss}) \geq 0.3)}{N(\min\Delta\phi(\text{jets}, E_T^{miss}) \leq 0.2)} = \exp(a - b \cdot M_{T2}) + c$$

✓ **a** & **b** from fit to data in $50 < M_{T2} < 80$ GeV

✓ **c** from **$r(M_{T2} = 200$ GeV)**



Lost lepton method

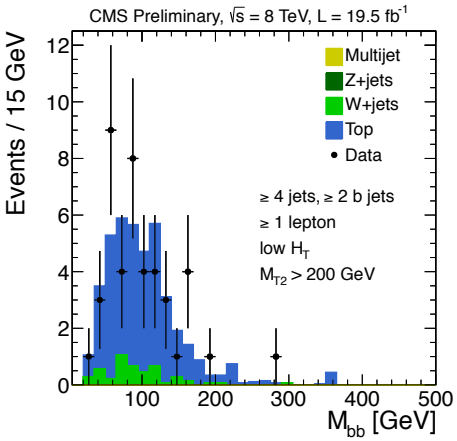
- **Top** & **W + jets** in signal region if **W→ lν**, and **charged lepton lost**

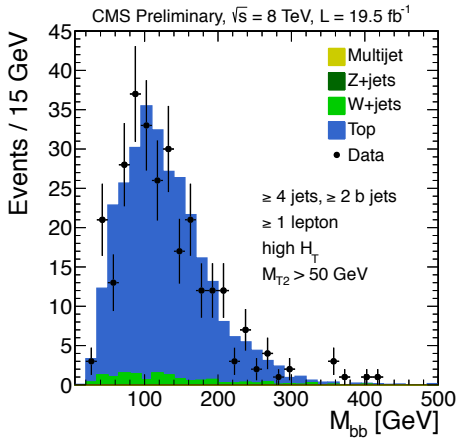
➢ Probability (ε_l) to **lose** leptons, due to:

- Acceptance
- Identification & Isolation

$$\Rightarrow \quad N_l^{lost} = (N_l^{reco} - N_l^{bg}) \frac{1-\varepsilon_l}{\varepsilon_l}$$

M_{bb} in lepton control region:





Z(νν)+jets estimate

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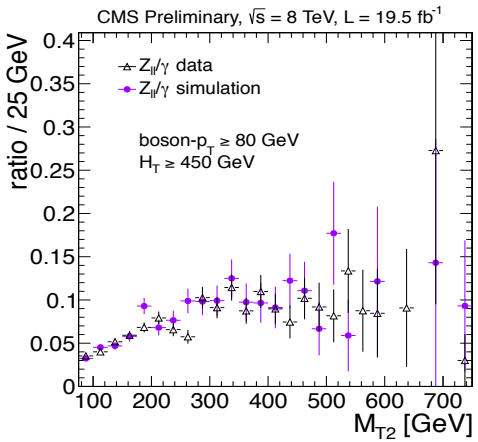
- **Z(νν) + jets** in signal region as irreducible background

➢ Use **γ + jets** for prediction

✓ $\mathbf{p_T^{\gamma}}$ added to $\mathbf{E_T^{miss}}$ to mimic **Z(νν)**

$$\Rightarrow \boxed{N_{Z(\nu\nu)} = R^{MC}(Z(\nu\nu)/\gamma) \cdot N_{\gamma}^{Data}}$$

➢ Validate $\mathbf{R^{MC}(Z(\nu\nu)/\gamma)}$ using **Z(ll)** data



Systematics

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- An extensive list of **normalization and shape systematics** considered, in both the M_{T2} inclusive analysis and the M_{T2} Higgs analysis

Process	Source/Region	Effect	Shape
Multijet	$M_{T2} < 200$ GeV	10-50%	–
	$M_{T2} \geq 200$ GeV	50-100%	–
$W(l\nu)$+jets and Top	Lost-lepton method	10-65%	–
	b-tagging scale factor	–	x
	Jet energy scale	–	x
	Matching scale	–	x
	Renormalization and factorization scale	–	x
	p_T MC NLO uncertainty	–	x
$Z(\nu\bar{\nu})$+jets	Systematics on $Z(\nu\bar{\nu})/\gamma$ ratio (0-1 b jets)	20-30%	–
	Systematics on $1b/0b$ ratio from Z_{ll} (1 b jet)	10-75%	–
	Statistics from γ+jets data (0-1 b jet)	5-100%	–
	simulation (≥ 2 b jets)	100%	–
Signal	Luminosity uncertainty	2.6%	–
	Trigger efficiency	1%	–
	Parton distribution functions	5-15%	–
	b-tagging scale factor	5-40%	x
	Jet energy scale	5-40%	x
	p_T MC NLO uncertainty	10-20%	x