Search for Supersymmetry at CMS in all-hadronic final states

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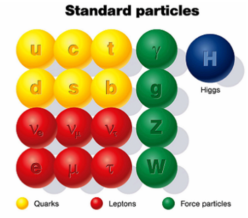
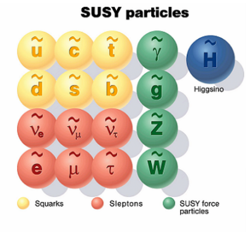
Introduction

- Motivation SUSY in all-hadronic final states
- Analysis $\sim 35\ \mathrm{pb}^{-1}$ of data recorded with CMS in 2010
- Three all-hadronic searches:
  - α_{T}-Search
  - Jets + $\not{H}_{\mathrm{T}}$-Search
  - Razor Anaysis
- Results

Motivation for SUSY





New Physics?

- Dark Matter in the Universe
- Hierarchy Problem
- Unification of Forces
- ...

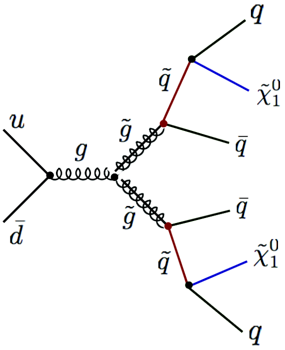
Supersymmetry (SUSY):

- Proposes symmetry between bosons and fermions: for each SM particle a SUSY-counter-particle
- Solves divergent loops on Higgs mass
- Unifies Strong and Electroweak force @ GUT

SUSY is a good candidate for new Physics

Motivation for SUSY in all-hadronic final states

Assume R-Parity (*) conserving Supersymmetry (SUSY)



- **Production**
  - Strong pair production of Squarks ($\tilde{q}$) and Gluinos ($\tilde{g}$) expected to dominate
- **Decay**
  - Lightest Supersymmetric Particle (LSP)
  - Jet Mult. $\sim$ Long/Short decay chain
  - Heavy/Soft Jets $\sim \Delta m$ ($\tilde{g}$,LSP)
- **Signatures**
  - Missing Transverse Momentum (LSP)
  - High-p_T Jets and Leptons (@ lower rate)
  - Long decay chain
    $\Rightarrow$ high visible momentum (Jets)
  - Short decay chain
    $\Rightarrow$ high missing momentum (LSP)

(*) Same holds for KK-parity in UED models and T-parity in Little Higgs models

Backgrounds: the key to discovery

- Backgrounds due to **Physics**
  - Standard Model Processes give the same signature as SUSY:
    - W, $t\bar{t}$, Z, QCD Multi-Jets
  - One cannot (yet?) rely on MC Predictions $\Longrightarrow$ Measure SM in Data
- Backgrounds due to **Detector Effects**
  - Detector Noise, mis-measurement of jets, ...generate fake MET
  - $\Longrightarrow$ need to understand the detector thoroughfully
- **Beam induced** backgrounds
  - Beam Gas interactions and Beam scraping
  - Beam Halo Muons and Cosmic Ray Muons
  - $\Longrightarrow$ Tag in Data + MC available

All-hadronic final states

- Very challenging background (both in amount and variety)
- Most sensitive search channel for strongly produced SUSY
- Several complementary search strategies in place

Complementary Search Strategies

Different Search Strategies:

- α_T**-Search:**
  - Simple and Robust Analysis, optimized for Early Discovery
  - Strong Background Rejection
  - Exclusive 2 Jets Search and Inclusive 3 Jets Search
  - Kinematic cut on α_T
- **Jets +** $\not{H}_T$**-Search:**
  - Inclusive Analysis, sensitive to any model yielding Jets + $\not{H}_T$
  - Analysis based on understanding of detector response in detail
  - Optimized for $\geq$ 3 Jets
- **Razor Search:**
  - Checks kinematic consistency
  - No explicit $\not{E}_T$ cut
  - Di-Jet + 0 or 1 lepton search

Overview

Important Observables in Hadronic Searches:

Jets: anti-k_T ($R = 0.5$) (AK5) Calo, TC, PF

HT: Scalar sum of Transverse Energy of jets:

$$\mathrm{HT} = H_T = \sum_i |\vec{p}_T(J_i)|$$

MHT: Jet based Missing Transverse Energy:

$$\mathrm{MHT} = \not{H}_T = |-\sum_i \vec{p}_T(J_i)|$$

Emphasis on Data-driven Background Estimates

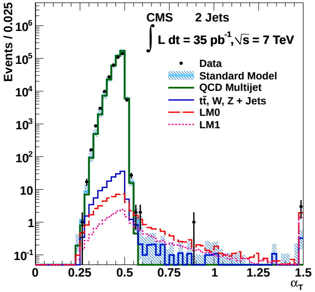
- Multiple Data driven methods used where possible
- Optimized for providing robust prediction of backgrounds

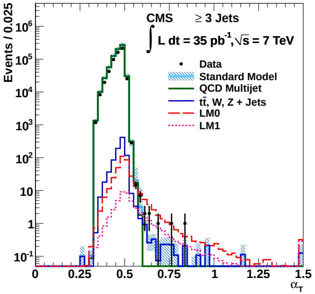
Results

- Comparison to LEP, TeVatron: limits in CMSSM
- Simplified Models, useful for model builders

α_T-Search (2010)

PLB 698 (2011) 196-218 --- arXiv:1101.1628





Event Selection

- AK5 Calorimeter Jets: $N \geq 2$, $p_T > 50$ GeV/c & $|\eta| < 3.0$
- Leading 2 Jets: $p_T > 100$ GeV/c, Leading Jet: $|\eta| < 2.5$
- Veto Isolated Leptons & Photons
- $H_T > 350$ GeV/c

Kinematic cut: α_T

Di-Jet system: $\alpha_T = \dfrac{E_T(J_2)}{M_T(J_1, J_2)}$

$E_T(J_i) \gg M_T(J_i)$:

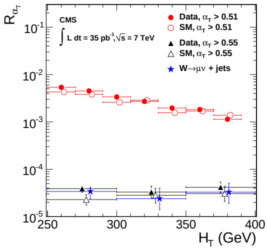
- $\alpha_T = 0.50$: Well measured & back-to-back
- $\alpha_T < 0.50$: Mismeasured & back-to-back
- $\alpha_T > 0.55$: Not back-to-back, genuine $\not{H}_T$

N-Jet system: $\alpha_T = \frac{1}{2}\dfrac{H_T - \Delta H_T}{M_T}$, $\Delta H_T = E_T(PJ_1) - E_T(PJ_2)$

α_T-Search

PLB 698 (2011) 196-218 --- arXiv:1101.1628

Inclusive background estimate



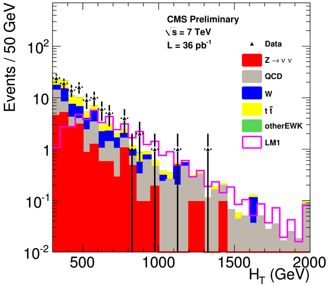
- 2 Control regions: HT250 and HT300
- $R_{\alpha_T} = \frac{N(\alpha_T > x)}{N(\alpha_T < x)}$
- $\alpha_T > 0.51$ dominated by QCD, decreases with H_T
- $\alpha_T > 0.55$ dominated by real $\not{E}_T$, Flat behaviour
- Final Selection QCD Free
- $R_R = \frac{R_{\alpha_T}(HT300)}{R_{\alpha_T}(HT250)} = \frac{R_{\alpha_T}(HT350)}{R_{\alpha_T}(HT300)}$
- Predicted: $N(HT350) = 9.4^{+4.8}_{-4.0}(\text{stat}) \pm 1.0(\text{syst})$
- Observed: $N(HT350) = 13$
- With *b*-tag: 1 Pred.: $0.33^{+0.43}_{-0.33}(\text{stat}) \pm 0.13(\text{syst})$

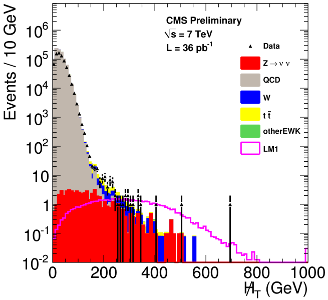
Independent EWK Background methods

- $N(W + \text{jets}, t\bar{t}) = 6.1^{2.8}_{-1.9}(\text{stat}) \pm 1.8(\text{syst})$ from $W(\mu\nu) + \text{jets}$
- $N(Z(\nu\nu) + \text{jets}) = 4.4^{+2.3}_{-1.6}(\text{stat}) \pm 1.8(\text{syst})$ from $\gamma + \text{jets}$ (see later)
- Total: $10.5^{+3.6}_{-2.5}$ in agreement with inclusive prediction $9.4^{+4.8}_{-4.0}(\text{stat}) \pm 1.0(\text{syst})$
- Further x-checks: $W(\mu\nu)$ from γ and $Z(\nu\nu)$ from $W(\mu\nu)$ all within agreement

Jets + $\not{H}_T$-Search

CMS-PAS-SUS-10-005





Baseline Selection

- AK5 PF Jets ≥ 3 & $H_T > 300$ GeV/c
  ($p_T > 50$ GeV/c and $|\eta| < 2.5$ jets)
- $\not{H}_T > 150$ GeV/c
  ($p_T > 30$ GeV/c and $|\eta| < 5.0$ jets)
- $|\Delta\varphi(\not{H}_T, J_{[1,2,3]})| > [0.5, 0.5, 0.3]$
- Veto Isolated Muons and Electrons

2 Search Regions:

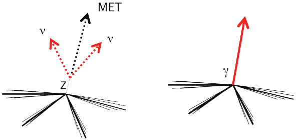
- High-$\not{H}_T$ Search $\Rightarrow$ LSP with high p_T
  baseline + $\not{H}_T > 250$ *GeV/c*
- High-H_T Search $\Rightarrow$ Jets with high p_T
  baseline + $H_T > 500$ *GeV/c*

- Data-driven Background Estimates
- MC shown for comparison

Jets + $\not\!\!H_T$-Search

CMS-PAS-SUS-10-005

Data-driven Prediction of $Z(\nu\nu)$ background using γ



$Z(\ell\ell)$ + jets is an **irreducible background**.
Photons and Z bosons are similar at high energy.
Removing the γ emulates the $\not\!\!H_T$ due to $Z(\nu\nu)$.
This method exploits the much higher statistics for γ + jets w.r.t. $Z(\mu\mu)$ + jets.

Z - γ Correspondence:

Z and γ are both vector bosons, but:

- Mass difference Photon - Z-boson
- Different Electroweak coupling

Global Correction Factor derived with detector simulation and reconstruction

- acceptance & selection
- data/mc scale factor

theory uncert. from LO/NLO

Isolated γ Selection

- γ ID from γ cross section measurement
- Indirect p_T cut due to $H_T > 150$ GeV/c req.
- Backgrounds from:
  - Neutral Mesons: π^0, η
  - Fragmentation γ
  - MisIdentified $e^{\pm}$

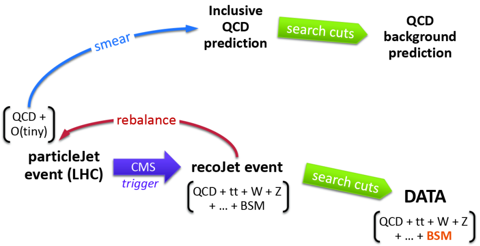
Contribution of the speaker to 2010 SUSY Searches in CMS

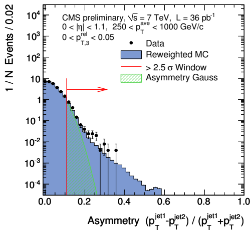
Jets + $\not{H}_T$-Search

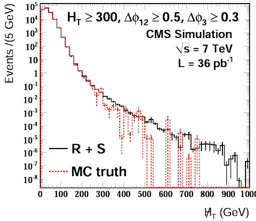
Data-driven Prediction of QCD background

The **Rebalance and Smear** (R&S) method relies on the in-depth knowledge of the **Jet Energy Resolutions**

- H_T trigger collects QCD Events
- Rebalance: unfold jets to balanced event
- Smear: smear jets with Jet Energy Resolutions
- Inclusive QCD Prediction ⇒ Search cuts

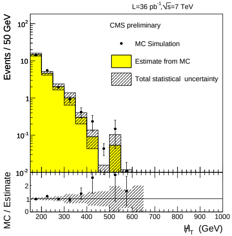






W and $t\bar{t}$ background

- Lepton out of kinematic or geometric acceptance
  $\Longrightarrow$ *Monte Carlo Simulation*
- Lepton not reconstructed or not isolated
  $\Longrightarrow$ *Reweight Lepton control sample with ϵ_{ID} and ϵ_{ISO} from T&P on μ+jets*
- Tau Lepton decays hadronically
  $\Longrightarrow$ *Substitute τ-jet for μ in μ+jets sample*



Summary Data-driven Predictions

Method	Baseline		High-$H\!\!\!/_T$ ($H\!\!\!/_T > 250$ GeV/c)		High-H_T ($H_T > 500$ GeV/c)	
$Z \to \nu\bar{\nu}$ from γ+jets	26.3	$\pm$4.8	7.1	$\pm$2.2	8.4	$\pm$2.3
$t\bar{t}/W \to e, \mu$+X lost-lepton method	33.0	$\pm$8.1	4.8	$\pm$1.9	10.9	$\pm$3.4
$t\bar{t}/W \to \tau_{hadr}$+X method	22.3	$\pm$4.6	6.7	$\pm$2.1	8.5	$\pm$2.5
QCD Rebalance+Smear method	29.7	$\pm$15.2	0.16	$\pm$0.10	16.0	$\pm$7.9
QCD factorization method	25.2	$\pm$13.4	0.4	$\pm$0.3	17.3	$\pm$9.4
Total data-driven background	111.3	$\pm$18.5	18.8	$\pm$3.5	43.8	$\pm$9.2
Observed in 36 pb^{-1} of data	111		15		40	
95% CL limit on signal events	40.4		9.6		19.6	

Razor-Search

CMS-PAS-SUS-10-009

Baseline Selection

- AK5 Calo Jets ≥ 2 ($p_{\mathrm{T}} \geq 30$ GeV/c, $|\eta| < 3.0$)
- No Electron and Muon Veto, no $\not{E}_{\mathrm{T}}$ req.
- Clustering of Jets in 2 *Mega-jets*, $\Delta\phi < 2.8$
- Event kin. consistent: Boost $\beta_{\mathrm{R}} < 0.99$
- Di-Jets Search $\Rightarrow$ Challenging QCD bkg

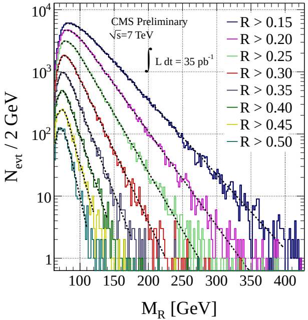
Razor kinematics

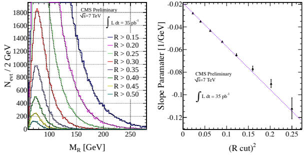
arXiv:1006.2727

- Pair production of Heavy Particles
- $M_{\Delta} = \dfrac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{q}}}$ (Mass Scale)
- M_{R} is event by event estimator of M_{Δ}
  - Peaks at Mass Scale, falls exponentially
- Razor variable $R = \dfrac{M_{\mathrm{T}}^{\mathrm{R}}}{M_{\mathrm{R}}}$ is discriminator
  - $M_{\mathrm{T}}^{\mathrm{R}}$ independent (transverse) estimator of M_{Δ}
  - $M_{\mathrm{T}}^{\mathrm{R}}$ uses kinematic information $\Delta\phi(J_1, J_2)$
  - R will remove most QCD dijet events
  - R th. shapes M_{R} in predictable way.

QCD Control Box

Prescaled Jet $p_{\mathrm{T}} > 15$ GeV/c Trigger



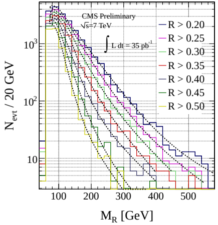


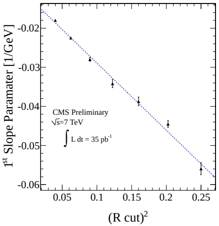
$f(x) = A \exp Sx \quad S = a + bR^2$

Razor-Search

CMS-PAS-SUS-10-009

$W(\mu\nu)$ + Jets





$S = a + bR^2$

Shape

$f(x) = A(\exp S_1 x + f \exp S_2 x)$

- 1^{st} component: ℓ as Jet
- 2^{nd} component: ℓ as ν

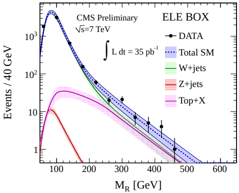
- MU and ELE box: x-check
- DATA/MC: $\rho(a,b)^{\text{DATA/MC}}_{1,2}$

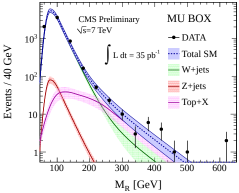
Normalization

- Non-QCD:
  MC Shape $\times \rho \times \sigma \times \epsilon \times \mathcal{L}$
  Renormalized in
  $125 < M_R < 175$ GeV
- QCD:
  QCD Control box with inverted ℓ isolation measured in $80 < M_R < 120$ GeV

Fits & Normalization @ low-M_R
Extrapolated to high-M_R-region

ELE and MU box





$R > 0.45$ and $M_R > 500$ GeV

R (0.45) / M_R (500)	Predicted	Observed
ELE box	0.63 ± 0.23	0
MU box	0.51 ± 0.20	3

Razor-Search

CMS-PAS-SUS-10-009

DATA in HAD box:

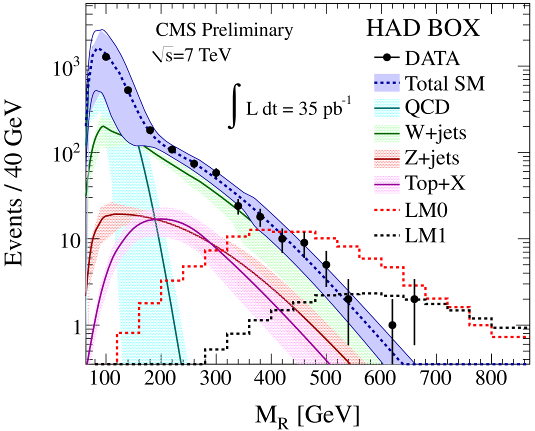
- H_T Trigger × Turn-on

Background in HAD box:

- Shapes same as in Lepton boxes
- $Z(\nu\nu)$ Shape from 2nd component W
- $Z(\ell\ell)$ Tag&Probe for $\rho(\epsilon)$
- Fit in $80 < M_R < 400$ GeV
- Final normalization from Lepton boxes
- Extrap. to high-M_R-region

Signal region in HAD box:

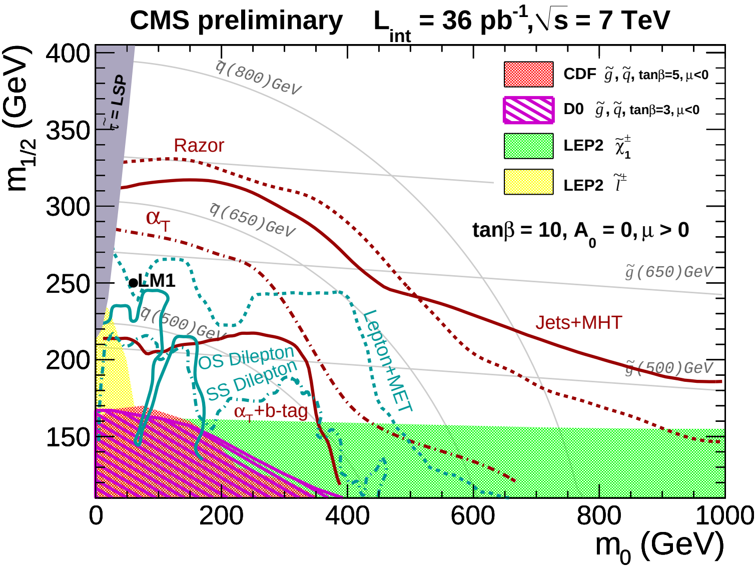
- $R > 0.5$ & $M_R > 500$ GeV
- Predicted: 5.5 ± 1.4
- Observed: 7



$R > 0.5$ and $M_R > 500$ GeV

M_R cut	Predicted	Observed
$M_R > 500$ GeV	5.5 ± 1.4	7

Comparison Different Search Strategies in CMSSM

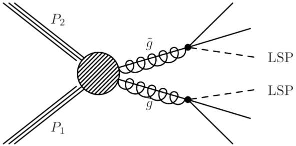


twiki ≫ CMSPublic/PhysicsResultsSUS

Simplified Model Spectra (SMS)

- Many models predict same signatures but depend dramatically on a large number of parameters:
  - Steeply falling PDF $\Longrightarrow$ Production at threshold (On Shell)
  - Discrete Symmetry $\Longrightarrow$ (Strong) Pair production
  - Decay dominated by Phase Space constraints

Can we characterize new physics in a way that allows comparison to any model?



$\Longrightarrow$ Simplified Models:

- small set of parameters: Masses, BR, σ
- scan the whole phase space $><$ LM Benchmarks

- Simplified Models for LHC New Physics Searches [hep-ph/1105.2838]
- Simplified Models for a First Characterization of New Physics at the LHC [PRD 79 075020 (2009)]

Combined Results in SMS

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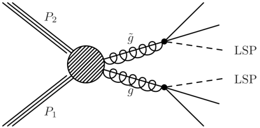
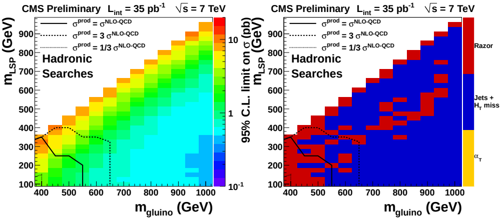
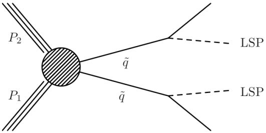
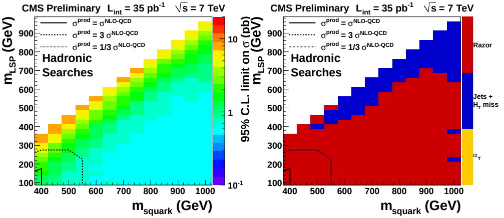
T1: gluino-gluino production





T2: squark-squark production





We provide all information needed to check your model in a PC-friendly way: ▸ twiki

Summary

- All CMS SUSY results publicly available at: `https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS`
- Three different Hadronic Searches for New Physics were presented
- $\sim 35\ \mathrm{pb}^{-1}$ of CMS data recorded in 2010 was analyzed

- Each of the Searches depends on Data-driven Background estimates
- No Excess of events was observed and results were interpreted in the context of Simplified Models
- Now $\sim 750\ \mathrm{pb}^{-1}$ recorded, expect new results for this summer!