Exotics @ CMS

CMS Physics Program 2011

Measurements
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions

Searches
- Higgs
- SUSY
- Exotics

Jim Brooke (Univ. of Bristol)
CMS Physics Program 2012

**Measurements**
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions

**Searches**
- Higgs
- SUSY
- Exotics

![Graph showing S/(S+B) weighted events vs. m_{\gamma\gamma} (GeV)](image)

### Factory Toy

- CMS \( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \)
- CMS \( \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \)

Data
- S+B Fit
- B Fit Component

\[ \sigma_1 \pm \sigma_2 \]

Unweighted Events / 1.5 GeV

1500
1000
500
0

110 120 130 140 150

m_{\gamma\gamma} (GeV)
Exotics @ CMS

CMS Physics Program post-2012

Measurements
- QCD
- Electroweak
- Heavy flavour
- Heavy Ions
- Higgs

Searches
- Higgs
- SUSY
- Exotics
Exotics @ CMS

Measurements
QCD
Electroweak
Heavy flavour
Heavy Ions
Higgs

Searches
Higgs
SUSY
Exotics

Searches for everything other than Higgs & SUSY
Exotics @ CMS

Measurements
QCD
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Higgs
SUSY
Exotics

Searches for everything other than Higgs & SUSY
Why Search for Exotics?

Leave no stone unturned
Why Search for Exotics?

Leave no stone unturned

- Large Extra Dimensions
- Glueballs
- Hidden Valleys
- R-hadrons
- Colorons
- Quirks
- Unparticles
- Leptoquarks
- Dark photons
- Microscopic black holes
- Stringballs
- Monopoles
- Compositeness
How to Search for Exotics

- Search for broad excess or resonance
  - Familiar final states: $e^+e^-$, $\mu^+\mu^-$, $bb$, dijet, $e+$MET, $\mu+$MET, top-like ...
  - Unexpected: $e+$jet, $\mu+$jet, $e+\mu$, high multiplicities, ...

- Measure properties of particles directly
  - anomolous dE/dx, timing, weird tracks, displaced vertices, etc.
  - (Obviously they need to be at least meta-stable for this...)

- Exotic decay modes of known particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time

RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→lljj), k=0.5

Bulk RS Gravitons

SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lv)
SSM W'(WZ→lvll)
SSM W'(WZ→4j)

Heavy Gauge Bosons

dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-

Excited Fermions

e* (M=Λ)
μ* (M=Λ)
q* (ag)
q* (qv)
b*
coloron(jj) x2
coloron(4j) x2
 gluino(3j) x2
gluino(jjb) x2

Multijet Resonances

Long-Lived Particles

Dark Matter

Compositeness

Large Extra Dimensions

CMS Preliminary

Sadly, we only have limits
What we (don’t) know

M. Strassler

Jim Brooke (Univ. of Bristol)
Large Hadron Collider
Compact Muon Solenoid

Muon Barrel
- DT, RPC

Muon Endcap
- CSC, RPC

ECAL
- PbWO$_4$

HCAL
- Brass/scintillator

Magnet
- 4T

Tracking
- Si pixel + strips

HF
- Iron/quartz
Integrated Luminosity

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹

2011 dataset
7 TeV ~5fb⁻¹

2012 “ICHEP” dataset
8 TeV ~4fb⁻¹

2012 full dataset
8 TeV ~20fb⁻¹
Familiar Final States
Familiar Final States

**Di-lepton**

\[ M_{\mu\mu} = 1.824 \text{ TeV} \]

**Lepton + \( E_T^{\text{miss}} \)**

\[ m_T = 2.31 \text{ TeV} \]
- Perform “bump hunts” in
  - Dilepton invariant mass spectrum
  - Lepton+ $E_T^{\text{miss}}$ $m_T$ distribution

- Background shapes taken from MC and normalised to control regions in data
Familiar Final States

- No evidence for a signal 😞
- Set limits on a variety of BSM physics
  - $Z'_\text{SSM}$, $Z'_\Psi$, $W'_\text{SSM}$, $W'_{KK}$

- Alternative interpretation of lepton + $E_T^{\text{miss}} \rightarrow W + E_T^{\text{miss}}$

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Dark Matter Signatures
Dark Matter

Lepton+MET final state is a signature of W+invisible, eg. $W\chi^0\chi^0$

DM production characterised using effective field theory with vector or axial-vector couplings

For $W+$MET search:
DM couplings to $u$ and $d$ may be different.
Interference characterised through parameter $\xi$
For $M_\chi > 100$ GeV, AV has lower cross-section than V. The $m_T$ distribution falls more steeply for $\xi = +1$. 

CMS Simulation

CMS Simulation

CMS-PAS-EXO-13-004

Monolepton

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Set limits on $\sigma \cdot BF$ as function of DM mass, for $V$ and $AV$, $\xi = -1, 0, +1$
Monojet

Single jet can result from initial state radiation
jet_1 \ p_T > 110 \text{ GeV}, \eta < 2.4
\ N_{\text{jet}} \ (30 \text{ GeV}) < 3
\ \Delta\phi(j_1,j_2) < 2.5
lepton veto : e, \mu \ (10 \text{ GeV}), \tau \ (20 \text{ GeV})
Perform a counting experiment for several $E_T^{miss}$ thresholds
Direct DM Searches


Search for galactic halo WIMPs interacting with matter in the lab

Edelweiss II [44] (dark yellow line), CDMS II [45] (green line), ZEPLIN-III [46] (magenta line), CDMSlite [47] (dark green line), XENON10 S2-only [20] (brown line), SIMPLE [48] (light blue line) and XENON100 100 live-day [49] (orange line), and 225 live-day [50] (red line) results. The inset (same axis units) also shows the regions measured from annual modulation in CoGeNT [51] (light red, shaded), along with exclusion limits from low threshold re-analysis of CDMS II data [52] (upper green line), 95% allowed region from CDMS II silicon detectors [53] (green shaded) and centroid (green x), 90% allowed region from CRESST II [54] (yellow shaded) and DAMA/LIBRA allowed region [55] interpreted by [56] (grey shaded). Results sourced from DMTools [57].
Indirect DM Searches


Observe a gamma-ray excess from galactic centre in the Fermi-LAT data

Compare observed spectrum with DM annihilation model

$\chi^0\chi^0 \rightarrow b\bar{b}$, $m_\chi = 35.25$ GeV
Indirect DM Searches

*Phys. Rev. D 89, 042001 (2014)*

**Fermi-LAT**
Gamma-ray data from 25 dwarf spheroidal galaxies

Set limits on DM co-annihilation cross-section

Expectation from primordial DM abundance:
\[ \sim 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \]
Dark Matter Searches

All these searches probe the same interaction...

Use the effective field theory to convert limits on $\sigma(pp \rightarrow \chi^0\chi^0)$ to limits on $\sigma(\chi^0$-nucleon) and compare with direct detection expts (scattering)
DM-nucleon Limits

Convert limits on $\sigma$.BF to limits in $\Lambda$-$M_\chi$ plane

Mono-lepton $V$

Mono-jet AV
DM-nucleon Limits

Also have results for:
- monolepton AV, monojet (V, S), monophoton (V, AV), monotop (V, S), tt+MET

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Caveat

- Several papers discuss validity of the effective field theory
  - eg Buchmuller, Dolan, McCabe: arXiv:1308.6799
  - EFT is only valid for high mediator mass
  - (Also, valid region has $\Gamma_{\text{med}}/m_{\text{med}} > 1$)

- Collider limits on $\sigma(\chi^0\text{-nucleon})$
  - Need to be taken with a pinch of salt!

- Proposal from paper above
  - Present limits using simplified models
  - Parameters: $m_{\text{med}}, m_\chi, g_q, g_\chi, \Gamma_{\text{med}}$

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Diagram:

- 95% exclusion contour
- Would need to also better characterize dependence on couplings.
  - This could be done by defining some benchmark scenarios.
  - Would also need to look at other operators/diagrams (of course).

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Diagram:

- $g_{u,d} = g_{\text{DM}} = 1$
- $g_{u,d} = g_{\text{DM}} = 0.5$
- XENON100
- LHC monojet

Limits:

- Direct Detection
- Collider

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Long Lived Particles
Long Lived Particles

- Long lifetimes are common in the SM
  - Constrained interactions + potential barrier

- We should expect them in BSM scenarios!
  - Split SUSY, GMSB, RPV, ....

Displaced Dileptons
Displaced Dileptons

Simulated

$H^0 \to X^0 X^0 \to \mu^+ \mu^- e^+ e^-$

Characterise $X^0$ decay with track impact parameters ($d_0, z_0$) and decay length ($L_{XY}$)
Require good tracking efficiency for high impact parameter tracks

Tracking efficiency measured from cosmics
Displaced Dileptons

CMS Simulation $\sqrt{s} = 8$ TeV

- $\mu^+\mu^-$
- Efficiency
- $m_\Psi = 1000$ GeV, $m_{\tilde{X}} = 350$ GeV
- $m_\Psi = 400$ GeV, $m_{\tilde{X}} = 50$ GeV
- $m_\Psi = 1000$ GeV, $m_{\tilde{X}} = 148$ GeV

- ECAL $E_T(1,2) > 40.25$ GeV
- Track $p_T(1,2) > 26$ GeV
- Track RelIso < 0.1 (0.04 < R < 0.3)
- Track $|d_0/\sigma_d| > 12$
- Secondary vertex $\chi^2$/dof < 10
- $\Delta \phi > \pi/2$

- $e^+e^-$
- Efficiency
- $m_\Psi = 1000$ GeV, $m_{\tilde{X}} = 350$ GeV
- $m_\Psi = 400$ GeV, $m_{\tilde{X}} = 50$ GeV
- $m_\Psi = 1000$ GeV, $m_{\tilde{X}} = 148$ GeV

- ECAL $E_T(1,2) > 40.25$ GeV
- Track $p_T(1,2) > 36.21$ GeV
- Track RelIso < 0.1 (0.04 < R < 0.3)
- Track $|d_0/\sigma_d| > 12$
- Secondary vertex $\chi^2$/dof < 10
- $\Delta \phi > \pi/2$
Azimuthal separation between dilepton momentum vector and displaced vertex vector

Signal at small values - define control region with \( \Delta \phi > \pi/2 \)

Background populates signal and control regions equally
Data and MC in control region: $\Delta \phi > \pi/2$
Excluded region

CMS Preliminary $\sqrt{s} = 8$ TeV L = 19.6 fb$^{-1}$

CMS Preliminary $\sqrt{s} = 8$ TeV L = 20.5 fb$^{-1}$

ee data
- Signal ($|\Delta \Phi| < \pi/2$)
- Control ($|\Delta \Phi| > \pi/2$)

$|d_0|/\sigma_d$ vs. Number of events with $|d_0|/\sigma_d > x$

$|d_0|/\sigma_d$ vs. Difference (control-signal)

Tail cumulative distributions in control and pseudo-signal regions
(i.e. minimum transverse impact parameter significance $|d_0/\sigma_d| < 6$)

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Transverse impact parameter distributions in the signal region ($\Delta\phi < \pi/2$)
Limits on exotic decays of $H_{125}$!
Displaced Dijets
Select events with two jets with good tracks and a common secondary vertex

- Jet $p_T(1,2) > 60$ GeV, $\eta < 2$
- Vertex $\chi^2$/dof < 5

Remainder of selection based on 3 orthogonal criteria

1. Jet 1: N prompt tracks, “prompt energy fraction”
2. Jet 2: N prompt tracks, “prompt energy fraction”
3. Vertex/cluster likelihood discriminant (based on four variables)

Background estimation then based on an extended ABCD using these 3 criteria
Displaced Jets

CMS Simulation, $\sqrt{s} = 8$ TeV

Simulated

$H^0 \rightarrow X^0 X^0 \rightarrow qqqq$

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Background estimates:

<table>
<thead>
<tr>
<th>$L_{XY}$</th>
<th>$&lt; 20,\text{cm}(\text{low})$</th>
<th>$&gt; 20,\text{cm}(\text{high})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>prompt tracks</td>
<td>$\leq 1$</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>prompt energy fraction</td>
<td>$&lt; 0.15$</td>
<td>$&lt; 0.09$</td>
</tr>
<tr>
<td>vertex/cluster disc.</td>
<td>$&gt; 0.9$</td>
<td>$&gt; 0.8$</td>
</tr>
<tr>
<td>expected background</td>
<td>$1.60 \pm 0.26(\text{stat.}) \pm 0.51(\text{syst.})$</td>
<td>$1.14 \pm 0.15(\text{stat.}) \pm 0.52(\text{syst.})$</td>
</tr>
</tbody>
</table>

Table 1: Predicted background and the number of observed candidates for optimised selections.

Cross-check in control region with inverted missing hits requirement:

- $L_{XY} < 20\,\text{cm}$
- $L_{XY} > 20\,\text{cm}$
Displaced Jets

Signal event in low $L_{XY}$ category

Signal event in high $L_{XY}$ category

CMS-PAS-EXO-12-038
Limits for a selection of signal hypotheses
Stable Massive Particles
Stable Massive Particles

- Identify a (meta)-stable charged particle as it traverse the detector

- Examples
  - R-hadrons
  - Long lived stau
  - Vector-like confining gauge theories

- SMP signature
  - High momentum
  - Highly ionising
  - Long time-of-flight

- Special case of strongly interacting R-hadrons
  - Nuclear interactions with material may change flavour
  - Neutral $\leftrightarrow$ Charged
  - Multiple analyses:
    - “Tracker-only”, “TOF-only”, “Tracker+TOF”
High momentum

Highly ionising

Long TOF

Plots from *Phys. Lett. B 713 (2012) 408*
Mass reconstruction
- Approximate Bethe-Bloch formula before minimum
- Extract parameters by fitting to the proton line
- Search for tracks with high mass

Plots from CMS-PAS-EXO-10-004
- Standard interpretation in terms of gluino, stop, stau (GMSB)
  - Inc. “charge suppressed” model of R-hadron nuclear interactions (any interaction results in a neutral R-hadron)
  - Different fractions of gluino/gluon initial states

**95% CL limit on σ (pb)**

**Tracker only**

- Theoretical Prediction
  - gluino (NLO+NLL)
  - stop (NLO+NLL)
  - stau, dir. prod. (NLO)
- μ = 2e/3 (LO)

**Tracker + TOF**

- Theoretical Prediction
  - gluino (NLO+NLL)
  - stop (NLO+NLL)
  - stau, dir. prod. (NLO)
- μ = 2e/3 (LO)

**TOF-only**

- Theoretical Prediction
  - gluino (NLO+NLL)
  - stop (NLO+NLL)
- μ = 1e (LO)

**Paper includes combined 7 TeV (5 fb⁻¹) + 8 TeV (19 fb⁻¹) result**
Limits on DY production of charged particles with $Q \neq 1$

- Neutral under SU(3) and SU(2)$_L$, only couple to Z and photon

*Paper includes combined 7 TeV (5 fb$^{-1}$) + 8 TeV (19 fb$^{-1}$) result*
The analysis is sensitive to large fraction of SUSY parameter space

Acceptances for results on previous slides are estimated using full GEANT simulation
  Detector effects are important and complex (e.g., amount of material traversed)
  This is impractical for parameter space scans

Instead parameterise acceptance as function of individual particle properties
  This is valid for lepton-like particles
  Use large full simulation samples to parameterise acceptance of Tracker+TOF analysis in bins of $p_T$, $\beta$, $\eta$
  Use this to re-cast Tracker+TOF result for any given model
SMPs in pMSSM

Chargino mass/lifetime exclusion map
pMSSM = 19 parameter SUSY model
Other Long Lived Searches
Stopped SMPs

Highly ionising particles may stop in the detector
Search during periods of no collisions
Trigger includes a “no collision” condition using BPTX monitors
Searching for a neutral long lived particle (eg $X^0$) that decays to photon + invisible particle (eg $G$)

Reconstruct photon direction from conversions

Use ECAL signal time to estimate TOF

Use cluster shape in ECAL
Displaced Photons

This experiment (4.9 fb⁻¹)

CMS 4.9 fb⁻¹

√s = 7 TeV

This experiment (4.9 fb⁻¹)

Expected

observed

CDF with \( \gamma + \not{E}_T + \text{Jets} \) (2.6 fb⁻¹)

D0 with prompt \( \gamma + \not{E}_T \) (6.3 fb⁻¹)

ATLAS with prompt \( \gamma + \not{E}_T \) (4.8 fb⁻¹)

Neutralino Mass [GeV] vs. Neutralino Proper Decay Length [mm]

Neutralino lifetime [cm]

Cross section [pb]

Production Cross Section [pb]

\( \tau = 1 \text{ mm} \), \( \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \)

Theoretical LO cross-section

Observed 95% CL upper limit

Expected 95% CL upper limit

Expected \( \sigma_1 \pm \)

Observed limits

Expected limits

± 1σ expected limit

± 2σ expected limit

CMS Preliminary, \( \int dt = 2.1 \text{ fb}^{-1} \)

ECAL time + cluster shape

GMSB \( \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \)

M_{m} = 2\Lambda, \tan(\beta) = 15

N_{m} = 1, \mu > 0

Conversions
Exotic Higgs Decays
Exotic Higgs Decays

- We know there must be BSM physics
- We know Higgs bosons couple to mass
- $H_{125}$ is one of the least well measured SM particles...

We should be looking for exotic decay modes!

See arXiv:1312.4992 for comprehensive survey
Exotic Higgs Decays

- **SM modes**
  - $H_{125} \rightarrow \mu\mu, H_{125} \rightarrow ee$

- **h125 $\rightarrow \gamma + \text{MET}$$^1$

- **H $\rightarrow$ invisible**
  - VBF, Z(II)H, Z(bb)H, monojet, ttH

- **Charged H**
  - $H^{+/−} \rightarrow cs, cb, tb, \tau \nu$

- **H$_{125}$ $\rightarrow$ XX $\rightarrow$ $\gamma\gamma\gamma\gamma$**

- **LFV in H $\rightarrow$ $\mu\tau$**

- **2HDM**
  - $H \rightarrow h_{125}h_{125}, A \rightarrow Zh_{125} \rightarrow$ multi-leptons, $\gamma$
  - $A \rightarrow Zh(125) \rightarrow llbb$
  - heavy H $\rightarrow$ ZA $\rightarrow llbb$
  - heavy H $\rightarrow$ ZA $\rightarrow ll\tau\tau$

- **NMSSM**
  - $H_2 (125) \rightarrow H_2H_1 \rightarrow 4\tau$
  - $H \rightarrow a_1a_1 \rightarrow 4\mu$
  - $H_3 \rightarrow H_2(125)H_1(60-125) \rightarrow bbbb$
  - $H_2(125) \rightarrow a_1a_1 \rightarrow YYYYY$
  - $H_1 \rightarrow YY$
  - $H_2(125) \rightarrow H_1H_1 \rightarrow 4\tau, 2\tau2b, 2\mu2b, 4b$

- **MSSM**
  - $H \rightarrow hh \rightarrow \gamma\gamma bb$
Invisible Higgs

Invisible decay modes are well motivated by the existence of dark matter!

Already have indirect limits from fits to visible decay modes

We search in ZH and vector boson fusion production modes

- With $Z \rightarrow ll$ and $Z \rightarrow bb$ final states
VBF jet topology

\[ p_T > 50 \text{ GeV}, \text{fwd-bkwd}, \Delta \eta_{jj} > 4.2, M_{jj} > 1100 \text{ GeV}, \Delta \phi_{jj} < 1.0, 30 \text{ GeV CJV} \]

\[ E_T^{\text{miss}} > 130 \text{ GeV} \]
Invisible Higgs

Limits on $\sigma \times \text{BF}$ and $\sigma \times \text{BF}/\sigma_{\text{SM}}$

$\text{BF}(H_{125} \rightarrow \text{inv}) < 0.65 \text{ obs (0.49 exp)}$
Combination of Z(\text{ll})H and Z(b\bar{b})H

\text{BF}(H_{125}\rightarrow\text{inv}) < 0.81 \text{ obs (0.83 exp)}
Invisible Higgs

CMS

Combination of VBF and ZH, $H \rightarrow$ invisible

$\sqrt{s} = 8$ TeV (VBF + ZH)
$L = 18.9-19.7$ fb$^{-1}$

$\sqrt{s} = 7$ TeV (Z(ll)H only)
$L = 4.9$ fb$^{-1}$

95% CL limits

- Observed limit
- Expected limit

Expected limit (1σ)
Expected limit (2σ)

$\sigma \times B(H \rightarrow \text{inv})/\sigma_{SM}$

$BF(H_{125} \rightarrow \text{inv}) < 0.58$ obs (0.44 exp)

Future plans: combination with indirect limits!
Invisible Higgs

Combination of VBF and $ZH, H \rightarrow$ invisible
\[\sqrt{s} = 8.0 \text{ TeV}, L = 18.9-19.7 \text{ fb}^{-1} \ (VBF+ZH)\]
\[\sqrt{s} = 7.0 \text{ TeV}, L = 4.9 \text{ fb}^{-1} \ (ZH)\]

$B(H \rightarrow \text{inv}) < 0.51 \ @ \ 90\% \ CL$

$m_H = 125 \text{ GeV}$

CMS
Try to leave no stone unturned!

Search for new physics using a wide range of methods
- Familiar final states & unfamiliar final states
- Directly detect particles with anomolous properties
- Exotic decays of 125 GeV Higgs!

No signals yet...
- Hope for some hints in Run 2