Non-SUSY BSM Physics in CMS

Heraeus workshop, 19/10/2016

Matthias Mozer
The Standard Model
SUSY
The Physics Museum

1st Floor

- Objets d'art
- Egyptian Antiquities
- Greek, Etruscan, and Roman Antiquities
- Paintings
- Prints and Drawings

Non-SUSY BSM

Standard Model

SUSY
Non-SUSY BSM Results

CMS Preliminary

Heavy Gauge Bosons

Leptoquarks

RS Gravitons

23

CMS long-lived particle searches, lifetime exclusions at 95% CL.

Non-SUSY BSM Results

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Extra Dimensions
Why Extra Dimensions

- Hierarchy problem: Why is gravity so much weaker than EWK or QCD forces?
- EWK+QCD confined to three “normal” dimensions
- Graviton propagates in extra dimension(s)
- “Curled up” extra dimension prevents macroscopic effects

Extra space or time dimensions?
- spatial dimensions related to hierarchy
- time dimensions considered in cosmology
Classical Limits

- How large is „macroscopic“?
- Classic effect: gravitational force falls more quickly than $1/r^2$
- Measure with torsion pendulum
- Limits extra dimension size to $\lesssim 50 \ \mu m$
- Excludes simple models with one extra-dimension → but there may be more

[hep-ph/061184]
Warped Extra Dimensions

- Alternative (Randall-Sundrum):
  → salvage single extra-dimension by introducing a suitable metric
  \[ ds^2 = e^{-2k\gamma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \]

- Gravity localized at different position than other forces
  → different apparent strength due to “warp factor” \( e^{-2k\Delta y} \)

- Expect „tower“ of KK graviton resonances

- Entirely governed by two parameters:
  → „warp factor“ k
  → graviton mass M
RS-Graviton Searches

- Diphoton search (but also di-ele, di-mu)
- Used because:
  → high graviton BR
  → no secondary BR
  → low background
- 750 GeV "graviton"?
  → observed cross section not compatible with width (both governed by k)
  → no hint in di-leptons
- Not confirmed in 2016 data

2.7 fb\(^{-1}\) (13 TeV, 3.8 T)

[arxiv:1606.04093]
Bulk Graviton Searches

- Simple RS extra-dimension models have trouble with flavor-changing neutral currents (FCNC)

- Solution:
  → let other fields also propagate in fifth dimension
  → adjust profiles to set up “5th dim. GIM mechanism”

- Result:
  → coupling to light particles suppressed
  → search in WW, ZZ, HH, top-pairs

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[arxiv:1404.0102]
Example: ZZ

- $Z \rightarrow \ell\ell, qq, \nu\nu$
  - $\Rightarrow$ 6 different final states

- Example: ZZ $\rightarrow$ $\ell\ell qq$
  - $\rightarrow$ 2 leptons
    - same flavor, opposite charge
    - compatible with Z mass
  - $\rightarrow$ 2 jets
    - compatible with Z mass
  - $\rightarrow$ build invariant mass
  - $\rightarrow$ look for peak

- Add improvements to taste:
  - $\rightarrow$ kinematic fit
  - $\rightarrow$ use angular distributions to enrich spin-2 signals
  - $\rightarrow$ study jet shape to reject gluon jets (i.e. Z+jets background)
  - $\rightarrow$ …
Jet Merging

CMS, $L = 4.9\, fb^{-1}$ at $\sqrt{s} = 7\, TeV$

- Data (eejj, 0 btag)
- Background
- Z+jets Madgraph
- ZZ Pythia
- WZ Pythia
- t\bar{t} Madgraph
- RS1 $G_{xx} (M = 700\, GeV, \bar{k} = 0.10)$

[10.1016/j.physletb.2012.11.063]
Jet Merging

CMS, $L = 4.9\ fb^{-1}$ at $\sqrt{s} = 7\ TeV$

[10.1016/j.physletb.2012.11.063]

ATLAS Preliminary

$\bar{s} = 8\ TeV \int Ldt = 7.2\ fb^{-1}$

$Z \rightarrow ee$ Channel

Resolved Signal Region

Merged Signal Region

$M_{G^*}$ [GeV]

[ATLAS-Conf-2012-150]
Merged Decays

- Finding “fat jets” compatible with W/Z decay:
  → jet mass
  → jet substructure

- Jet mass:
  → sum of constituent 4-vectors
  → falling steeply for quark/gluon jets
  → W/Z hard to separate

- Sensitive to pile-up
  → increases light jet masses
  → smears out signal peak
  → try to aggressively remove pile-up
Substructure: N-subjettiness

average distance to closest of N subjet axis

\[ \tau_N = \frac{\sum_{i=1}^{M} p_{T,i} \min\{\Delta R_{i1}, \ldots, \Delta R_{iN}\}}{\sum_{i=1}^{M} p_{T,i} R_0} \]

small if N real subjets exist
large otherwise

→ use ratio \( \tau_2/\tau_1 \)
  small for W/Z
  large for QCD

W: 2-jet structure

QCD: diffuse/round
Does that really work?

- How to find hadronic W decays for validation?
- Look at top quark pairs
  → identify lepton + b-jet
  → a second top quark is likely in the event
Graviton Search with Boosted W/Z

- Mass-reach greatly extended by considering boosted decays
- How to improve further:
  → look at more decay channels
  → look at more lumi at higher energies
Results with Merged Decays

- Issue:
  - → many graviton decay channels
  - → multiply by boson decay channels
- Use stat. combination for optimal reach:
  - → low mass ZZ channels
  - → intermediate mass WW semi-leptonic
  - → high mass WW/ZZ all hadronic
Dark Matter
Why Dark Matter?

[wikipedia]
A New Particle?

Key characteristics:
→ not a baryon
→ “dark” (no color/electric charge)
→ long lived or stable
→ “cold”

Neutrinos only SM candidates
but probably too light/hot
A new particle?

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- BSM candidates → plenty!
A new particle?

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- Neutrinos only SM candidates but probably too light/hot

- BSM candidates
  - plenty!

- Potentially too plenty
  - signature driven searches
Detection Schemes

Direct Detection

[Diagram showing SM and DM connections]
Detection Schemes

Indirect Detection

Bubbles show energetic spectrum and sharp edges

Credit: NASA/DOE/Fermi LAT Collaboration et al.
Detection Schemes

Collider Production
Detection at the LHC

Protons go in

nothing comes out

SM

DM

SM

DM

SM

DM

SM

DM
EFT and Simplified Models

- Simplest Parameterization: Effective Field Theory
  - encode all dynamics in effective operators
  - small number of cases to consider
  - only valid if dynamics much heavier than probed scales

- Alternative: simplified models
  - Increased number of parameters (couplings, mediator mass, …)
  - Probes much larger model space
Monojets

- Typical search approach: Mono-X
  X = Jet, Z, H, …
Monojets

- Simple selection:
  → a jet
  → balanced by MET
Monojets

- Simple selection:
  - a jet
  - balanced by MET

- Backgrounds:
Monojets

- Simple selection:
  → a jet
  → balanced by MET

- Backgrounds:
  $Z \rightarrow \nu \nu + \text{jets}$
Background Estimates

12.9 fb⁻¹ (13 TeV)

CMS Preliminary

Events / GeV

Data / Pred.

Data
Z → ττ
W → ℓν
WW/ZZ/WZ
Top Quark
Z/γ → ℓ⁺ℓ⁻γjets
QCD
Higgs Invisible, m_H = 125 GeV
Axial-vector, M_{LH} = 1.6 TeV

[EXO-16-037]
Exclusion Limits

(a) Vector med, Dirac DM, $g_q = 0.25$, $g_{\chi_1} = 1$

(b) Axial-vector med, Dirac DM, $g_q = 0.25$, $g_{\chi_1} = 1$

[EXO-16-037]
Exclusion Limits

simplified model spec.

2 \cdot m_{DM} > m_{med}

cross section drops for heavier mediators

[EXO-16-037]
Comparison to Other Results

- Direct detection experiments
  - non-relativistic
  - $\Rightarrow$ cross section reduces to spin (in)dependent number (no mediator mass)
- Easier to do in simplified models than in EFTs
- LHC most competitive at low $m_{\text{DM}}$
  - $\rightarrow$ low energy transfer in elastic scattering (direct detection)
The Wider View

CMS Preliminary

Dark Matter Summary - ICHEP 2016

DM + jets/V(dφ)
g_{DM} = 1, g_{q} = 0.25

DM + γ
g_{DM} = 1, g_{q} = 0.25

DM + Z(Γ)
g_{DM} = 1, g_{q} = 0.25

DM + t
g_{DM} = 1, g_{q} = 0.25

DM + H(bb'/γγ)
m_{H} = 9000GeV; m_{DM} = 100GeV

DM + V(dφ)
g_{DM} = 1

DM + V(t)
g_{DM} = 1, g_{q} = 0.25

DM + V(γγ)
g_{DM} = 1, g_{q} = 0.25

DM + V(dφ)
g_{DM} = 1, g_{q} = 0.25

DM + V(t)
g_{DM} = 1, g_{q} = 0.25

DM + V(γγ)
g_{DM} = 1, g_{q} = 0.25

Observed limits at 95% CL for considered simplified models
Theory uncertainties not included
V = vector; AV = axial-vector
S = scalar; PS = pseudoscalar

Maximal excluded mass

EXO-16-037
13TeV, 12.9fb^{-1}

EXO-16-039
13TeV, 12.9fb^{-1}

EXO-16-038
13TeV, 12.9fb^{-1}

EXO-16-040
13TeV, 12.9fb^{-1}

EXO-16-012
13TeV, 2.3fb^{-1}

EXO-16-011
13TeV, 2.3fb^{-1}

EXO-16-037
13TeV, 12.9fb^{-1}

(a)

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Long Lived Particles
Long Lived Particles

What is „long“
→ travels measurably after creation ⇒ > $10^{-7}$s
→ avoid left-overs from Big-Bang ⇒ < $10^{14}$s

Why long lived, but not stable?
→ almost exact / slightly broken symmetry
→ small couplings
→ phase space suppression / near degenerate mass states

Not a coherent set of models
Driven by experimental considerations
Experimental Considerations

- How long is „long“?

- Decay in flight:
  → observe decay away from the collision point
  → charged: kinked tracks / disappearance
  → major issue is reconstruction of peculiar signatures

- Absorbed in Detector, decays later:
  → detector activity in absence of collisions

- Too long to observe the decay
  → covered by DM searches if neutral and not strongly interacting
  → otherwise treat effectively as stable
Experimental Considerations

CMS long-lived particle searches, lifetime exclusions at 95% CL

- RPV SUSY, $\tilde{t} \rightarrow b l, m(\tilde{t}) = 420$ GeV
  - 8 TeV, 10.7 fb$^{-1}$ (displaced leptons)

- $H \rightarrow XX (10\%), X \rightarrow ee, m(H) = 125$ GeV, $m(X) = 20$ GeV
  - 8 TeV, 19.6 fb$^{-1}$ (displaced leptons)

- $H \rightarrow XX (10\%), X \rightarrow \mu\mu, m(H) = 125$ GeV, $m(X) = 20$ GeV
  - 8 TeV, 20.5 fb$^{-1}$ (displaced leptons)

- GMSB BPSS, $\chi^0 \rightarrow \tilde{g} V, m(\chi^0) = 250$ GeV
  - 8 TeV, 19.7 fb$^{-1}$ (disp. photon conv.)

- GMSB BPSS, $\chi^0 \rightarrow \tilde{g} V, m(\chi^0) = 250$ GeV
  - 8 TeV, 19.1 fb$^{-1}$ (disp. photon timing)

- RPV SUSY, $m(\tilde{q}) = 1000$ GeV, $m(\chi^0) = 150$ GeV
  - 8 TeV, 16.5 fb$^{-1}$ (displaced dijets)

- RPV SUSY, $m(\tilde{q}) = 1000$ GeV, $m(\chi^0) = 500$ GeV
  - 8 TeV, 16.5 fb$^{-1}$ (displaced dijets)

- AMSB $\tilde{g} \rightarrow \chi^0 + \pi$, $m(\chi^0) = 200$ GeV
  - 8 TeV, 19.5 fb$^{-1}$ (disappearing tracks)

- cloud model R-hadron, $m(\tilde{q}) = 1000$ GeV
  - 8 TeV, 18.6 fb$^{-1}$ (stopped particle)

- AMSB $\chi^0, \tan(\beta) = 5, \mu > 0, m(\chi^0) = 600$ GeV
  - 8 TeV, 18.8 fb$^{-1}$ (tracker + TOP)

- AMSB $\chi^0, \tan(\beta) = 5, \mu > 0, m(\chi^0) = 200$ GeV
  - 8 TeV, 18.8 fb$^{-1}$ (tracker + TOP)
Experimental Considerations

- neutral
- charged
- any charge

- HSCP
- displaced dilepton
- displaced lepton
- displaced dijet
- displaced vertex
- displaced conversion
- BSM
- lepton
- quark
- photon
- anything

Not pictured: stopped particles
Decays in Flight

- Scenario:
  pair-produced neutral particle with long lifetime
decays to leptons

- Signature:
  Two lepton pairs
both vertices displaced from beamspot

- Origin:
  → RPV SUSY
  → Z’ with heavy majorana neutrinos

- Difficulty:
  → needs specialized track reconstruction
Displaced Leptons

**Striking Signature**

- Too close to the vertex
- Leave detector before decay

**Data**

- 19.6 fb\(^{-1}\) (8 TeV)

**Expected Limits**

- m_\(X\) = 20 GeV/c\(^2\)
- m_\(X\) = 50 GeV/c\(^2\)
- m_\(X\) = 150 GeV/c\(^2\)
- m_\(X\) = 350 GeV/c\(^2\)

**Observed Limits**

- m_\(H\) = 1000 GeV/c\(^2\)
Almost Stable

- **HSCP**
  - Heavy $\rightarrow$ slow
  - Stable $\rightarrow$ traverses detector
  - Charged $\rightarrow$ visible in tracker
  - Muon system

- Discriminating variables
  - $\rightarrow$ specific ionization $dE/dx$
    (tracker)
  - $\rightarrow$ time of flight $\beta^{-1}$
    (Muon system)

- Two categories
  - $\rightarrow$ $dE/dx + \beta^{-1}$
  - $\rightarrow$ $dE/dx$ only (avoid charge exchange reactions)
Almost Stable

[EXO-15-010]

2.5 fb⁻¹ (13 TeV)

CMS

No. of tracks / [2.4 (GeV) x 0.03 (MeV/cm)]

\( \frac{dE}{dx} = \frac{K m^2}{p^2} + C \)

\[ K = 2.468 \pm 0.009 \]

\[ C = 2.679 \pm 0.011 \]
Time of Flight

time delay from hits scatter in DT
BX change in RPC

$\delta t$
Results

Final selection:
\[ p_T > 65 \text{ GeV} \]
\[ |\Delta\phi| > 0.3 \]
Outlook

[technicolor]
Outlook

[leptoquarks]

[technicolor]
Outlook

[technicolor]

[hidden sectors]
Outlook

[composite leptons]  [hidden sectors]
Outlook

[extended gauge groups]

[composite leptons]  [hidden sectors]
Stopped Particles

- Charged particles may get stuck in the detector
  → needs to be reasonably slow (heavy particles won’t induce showers)
  → low speed common for heavy particles

- Most likely resting place
  → Calorimeters
  → Return Yoke

- Wait for decay
  → how to distinguish from collisions?
When to Look?

Abort gap for safe beam disposal: ⇒ guaranteed no interaction
Results

CMS

$E_g > 120$ GeV, $E_t > 150$ GeV

$E_{\text{jet}} > 70$ GeV

18.6 fb$^{-1}$ (8 TeV)

95% CL Limits:

- Observed
- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$

$\sigma_{\text{theory}} (m_g = 600$ GeV$)$

$\sigma_{\text{theory}} (m_t = 600$ GeV$)$