Exotica and Dark Matter searches

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- Introduction
- Dark matter
- Exotica searches
2012: A new boson discovery
Standard Model theory of everything?

- Discovery of the Higgs boson marks the triumph of the SM
- However, even with the inclusion of the Higgs boson, SM is an incomplete theory
Tests of the SM

CMS Preliminary

Production Cross Section, \( \sigma \) [pb]

- 7 TeV CMS measurement (L < 5.0 fb\(^{-1}\))
- 8 TeV CMS measurement (L < 19.6 fb\(^{-1}\))
- 13 TeV CMS measurement (L < 35.9 fb\(^{-1}\))

Theory prediction

CMS 95%CL limits at 7, 8 and 13 TeV

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Beyond the Standard Model

The SM answers many of the questions about the structure of matter. But SM is not complete; still many unanswered questions:

a) Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

b) What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

c) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

d) Why are there three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

e) How does gravity fit into all of this?
Dark matter and energy

• What is that accounts for 96% of the Universe? Nobody knows.
• It is one of the greatest mysteries of Science
What can we look for?

A crowded field. At the LHC we can search for some of these
How?

• Search for new phenomena
• Look for New Physics
• Indirect searches
  – precision measurements, event properties, etc.
• Direct searches
  – resonances, specific final states, model-(in)dependent searches, etc.
• Production and decay rates, event characteristics, advanced tools
Dark Matter

What is it?

• DM does not interact electromagnetically
• DM interacts gravitationally

Visual map

From P. Harris DM talk at Cern (July 2015)
Dark Matter (cont.)

Why is it interesting?
• We do not see it...
• ...but we feel it

Mass map

From P. Harris DM talk at Cern (July 2015)
Dark Matter (cont.)

How do we find DM?

• Need to understand how it interacts with Universe
• Traditionally through a mediator
• Yields at least two new particles
Stable(-ish) particles:
- Anti-nuclei
- Photons
- Anti-protons
- Positrons
- Neutrinos

BSM:
- Supersymmetry, neutralinos, gravitinos
- Extra-dimensions
- Axions(-like) particles
- Sterile neutrinos
Searching for DM

Particle Colliders

Direct Detection
- LUX
- CDMS

Indirect Detection
- AMS
- FERMI
- GAPS
- IceCube

Beyond the Standard Model (BSM) Physics

Standard Model

Dark Matter
How do we find it: @LHC

- Produced it through a mediator

![Diagram showing mediator and dark matter](image_url)
How do we find it: @underground

• Through a nuclear recoil
How do we find it: @Space

• Through annihilation
  – Cosmic rays from DM
How do we find it: @nearUniverse

- Back and forth, production and annihilation
- Measure density and set constraints

**Early Universe**

Relic density constraint
⇒ Direct searches less sensitive to low masses due to energy threshold on nuclear recoil.
Collider searches

Weakly interacting massive particles
• Effective field theory, simplified models

Model-dependent searches

Searches for particles stable within detector acceptance, sensitive to mediator mass
DM at the LHC

- CMS/ATLAS experiments not designed for DM searches
How do we find DM at the LHC?

- DM production gives MET signature
How do we find DM at the LHC?

- Mono-photon: Can also tag events with a photon
DM searches at LHC

How do we find DM at the LHC?

• Mono-V: Tag events with a boson
How do we find DM at the LHC?

- Mono-V with (pseudo-) scalars
  - Different production mechanisms
What are the backgrounds?

- \( Z \rightarrow \nu \nu \)
  - very similar to signal

Escapes detection
How to discriminate signal against the background?

• Look for high MET:

\[ MET = -\sum_{\text{All particles}} p_T \]

\[ MET(Z \rightarrow vv) = -Z \text{ recoil} + p_T(vv) \]

\[ MET(Z \rightarrow vv) = -Z p_T \]

Study hadronic recoil
How to discriminate signal against the background?

- Cut and count events or…
How to discriminate signal against the background?

• Can fit the shape and look for signal
Build a V-tagger

- Two jets are more collimated at high $p_T$
- At low $p_T$ jets are “resolved”
  - Focus on reconstructing di-jets with mass near $W$ mass
- At high $p_T$ get one “fat” jet
  - Focus on identifying one jet with mass near $W$ mass
- Use additional variables to improve discrimination
Main background is from ZZ di-bosons
Understanding ZZ di-boson $p_T$ is critical
DM+jets \((j/V/\gamma)\)

- Search focused on light mass region (100-300 GeV)
- Experimental challenges
  - Large QCD background
  - Triggers

hole in collider dijet searches

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DM+jets ($j/V/\gamma$): Motivation

- Search for $Z'$ leptophobic vector
- Strategy: $Z' \rightarrow q\bar{q}$
- Multijet topology with high-$p_T$ jet
- Look at jet substructure
- Search for "bump" in jet mass distribution

![Graph showing upper limit on $g_B$ (95% CL) vs. $M_{Z'}$ [GeV]]

CMS-EXO-16-030
DM+jets (j/V/γ): Analysis

• Signal region
  – $p_T > 500$ GeV
  – $\tau_{21}^{DDT} < 0.38$
  – lepton veto

• Soft drop mass $m_{SD}$: peaks at $Z'$ mass
  – removes soft wide-angle radiation from jet

• QCD background estimated from sideband regions in data

• $\tau_{21}^{DDT}$ n-subjettiness: consistency with 2-prong structure

• $\tau_{21}^{DDT}$ defines “pass” or “fail” sidebands
  – Use TF from fail to pass region
DM+jets ($j/V/\gamma$): Results

- Jet has 2-prong sub-structure
- Identify jet substructure using $\tau_{21}$
- Set limits on light $Z' \rightarrow q\bar{q}$ search (most sensitive at $<140$ GeV)

- Search for low-mass boosted dijet resonances
- Explores uncovered regions
- Limits in $Z'$ mass at low mass
DM+photon

• BSM theories predict events with photon+MET
• Small SM background
DM+jet/V

Need good control of systematics

DM search in mono-jet/V
DM+Higgs

- Generic search: $pp \rightarrow X + \text{MET}$
- Search for DM + $h(\rightarrow bb)$
- Model-independent search
  - Signature: $h(\rightarrow ZZ/bb/\gamma\gamma)+\text{MET}$
  - Simplified model with $Z'$ or pseudo-scalar Higgs $A(\rightarrow \chi\chi)$
- Signal events at large MET

DM particle ($\chi$): can be scalar or fermion

Pseudo-scalar Higgs $A$


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DM+Higgs (cont.)

- DM search with $H(\rightarrow bb, \gamma \gamma)$
- Model dependent search
- $Z'$ 2HDM model

- No significant excess
- Set limits for coupling $g=0.8$
BSM/SUSY searches

- Density of allowed supersymmetric models before and after Run 1
Experimental results

- Limits for given couplings between SM and DM interaction
- Competitive limits at low masses wrt other experiments
Experimental results (cont.)
Search for heavy resonances

- Heavy BSM resonances (>1TeV) may decay into SM bosons (W, Z, H)
- Several final states
- Experimental challenges
  - SM bosons decay mostly to quarks
  - Due to large Lorentz boost, decay products merge into single jet
  - Clustered within a large-cone jet (R=0.8)
- Look into jet substructure
  - Jet “grooming”: get rid of soft jet components from UE/pileup, keep constituents from hard scatter
  - Apply filters (mass drop, pruning, trimming)
Mass drop/filtering

• Identify approx. symmetric sub-jets (with smaller mass than sum)

Mass drop: define 2 sub-jets

Filtering: re-cluster j1, j2 constituents
Jet grooming (cont.)

“Trimming”
• Uses kT algorithm to make subjets (subjets with $p_T^i/p_T<\text{cut removed}$)

“Pruning”
• Recombine jet constituents, while veto wide-angle/softer constituents
W, Z, H reconstruction

• Grooming and jet mass
  – Pruning
  – soft drop (stable w/pileup, and
good jet mass resolution ~10%)

• Vector boson tagging ($V \rightarrow qq$)
  – $n$-subjettiness $\tau_{21}$: how consistent
    with 2 sub-jets
  – Categorization according to purity:
    high (<0.35) and high (>0.35)
• Higgs boson tagging ($H \rightarrow b \bar{b}$)
  – Double b-tagging
  – Exploit b-tagging to identify two b-quarks in same jet
  – Soft-lepton information
  – Combines tracking and vertexing in MVA
Diboson resonances

• Search for resonance: $X \rightarrow ZZ \rightarrow \ell\ell qq'$
• Use tools to identify jet substructure
  – N-subjettiness $\tau_{N}: \tau_{N} \sim 1/d_0 \Sigma pT$
  – Kinematic and flavor information to improve S-B separation
• Discriminant $Z+JJ$ (using MELA)
• Upper limits on resonant spin-0/spin-2 hypotheses
• Cross section limits $\sim 3-100 fb$
Heavy resonance: WH final state

- Search for massive resonance $W' \rightarrow WH$
- Distinctive features of BSM models, i.e. composite/little Higgs, technicolor, etc.
- Lepton+jet final state
- Use jet substructure/btag for $H \rightarrow bb$
- $2.2\sigma$ highest local significance at 1.8TeV

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Search for multilepton final states

- Type-III extension to SM
- Search for 3 or more lepton final states
- Pair production of $W/Z/H \rightarrow \Sigma\Sigma$
- Scalar sum of lepton $p_T (L_T)$
- Bin and count $(L_T + \text{MET})$
All hadronic resonance search with single ($qV$) or double ($VV$) $V$-tag
- At least 2 back-to-back jets $p_T > 200\,\text{GeV}$
- Categorization (jet mass, $\tau_{21}$)

Background estimation: “bump hunt” fit data with power law
**X \rightarrow VH \rightarrow qqbb**

- All-hadronic search for $V \rightarrow qq$ and $H \rightarrow bb$ resonances
  - Dedicated identification for $H \rightarrow bb$ (b-tagging)
- Use categories
  - V-jet mass ($W$ or $Z$), V-jet $\tau_{21}$ (high-purity, low-purity), H-jet (tight and loose b-tag)

*Similar topology and background estimate to VV resonance search*

*No significant excess found in data*

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X\rightarrow ZV \rightarrow llqq

- Search for resonances in $Z\rightarrow ee/\mu\mu$, $V\rightarrow qq$
- Clean final state (leptons)
  - Good mass resolution, good efficiency
- $\tau_{21}$ categorization (HP, LP)
- Parametrize main bkg ($Z+$jets), fit to data in sidebands, take shape from MC

- Data compatible with SM-only hypothesis
• Search for a resonance decaying to \( WV \) in leptonic channel
• Categorization in \( \tau_{21} \) and W/Z mass
• Sideband+transfer function for bkg estimate

• Similar sensitivity to \( Z(\ell)\nu qq \) search
• Excluded up to 2 TeV
Search for a resonance decaying to VH in leptonic channels
- $Z \rightarrow \nu\nu$: transverse mass $m_T(VH)$
- $W \rightarrow \ell\nu$: top control region
- $Z \rightarrow ll$: high-efficiency dilepton ID
- $H(bb)$ b-tagging

Sideband bkg prediction

Heavy vector triplet ($Z', W'$)
- $g_V, g_H (c_V, c_F)$: couplings

W/Z mass region
Combination of diboson searches

CMS Preliminary 2.2-2.6 fb⁻¹ (13 TeV) + 19.7 fb⁻¹ (8 TeV)

- $\sigma_{95\%}/\sigma_{\text{theory}}$
- $M_V$ (TeV)
- $M_{G_{\text{bulk}}}$ (TeV)

- Asympt. $\text{CL}_S$ Obs.
- Asympt. $\text{CL}_S$ Exp. ± 1σ
- Asympt. $\text{CL}_S$ Exp. ± 2σ
- $G_{\text{bulk}}$, $\kappa=0.5$
Di-muon events

- Di-muon events: a re-discovery of the SM

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Dilepton resonance

• Search for dilepton (ee, µµ) resonance

![Graphs showing CMS dielectron and dimuon data with different signal and background contributions.](image-url)
• Search for dilepton (ee, \(\mu\mu\)) resonance
Resonance searches: Summary

CMS Preliminary

Heavy Gauge Bosons

Excited Fermions

Leptoquarks

RS Gravitons

Multijet Resonances

Large Extra Dimensions

Compositeness
The Precision Proton Spectrometer is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions.

- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Project approved in Dec. 2014 by LHCC
- Data taking started in 2016 (full scope from 2017)
PPS physics motivations

- **Central Exclusive Production**
  - photon-photon collisions
  - gluon-gluon fusion in color singlet, $J^{PC}=0^+$

- **High-$p_T$ system in central detector, together with very forward protons in PPS**
  - momentum balance between central system and forward protons, provides strong kinematical constraints
  - Mass of central system measured by momentum loss of the two leading protons

- **Gauge boson production by photon-photon fusion and anomalous couplings ($\gamma\gamma WW$, $\gamma\gamma ZZ$, and $\gamma\gamma\gamma\gamma$)**

- **Search for new BSM resonances**

- **Study of QCD in a new domain**

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PPS detectors

• Tracking detectors
  – Goal: measure proton momentum
  – Technology: silicon 3D pixels (6 planes per pot)

• Timing detectors
  – Goal: identify primary vertex, reject “pileup”
  – $\sigma_{\text{time}} \sim 10\text{ps} \Rightarrow \sigma_z \sim 2\text{mm}$
  – Technology: silicon/diamond
Timing detectors

Use timing to reject pileup background

• Two scenarios studied:
  – 10ps and 30ps time resolution

• Baseline: solid state detectors

• Detector options investigated:
  – Diamond sensors
  – Fast silicon sensors (UFSD, HFS)

• Status:
  – Diamond and LGAD detectors installed
**WW production**

- **Study of process:** $pp \rightarrow pWWp$
  - Clean process: $W$ in central detector and "nothing" else, intact protons can be detected far away from IP
  - Exclusive production of $W$ pairs via photon exchange: QED process, cross section well known

- **Backgrounds:**
  - Inclusive $WW$, $\tau\tau$, exclusive two-photon $\gamma\gamma \rightarrow ll$, etc.

- **Events:**
  - $WW$ pair in central detector, leading protons in PPS

- **SM observation of WW events**

- **Anomalous coupling study**
  - AYGQCs predicted in BSM theories
  - Parameters: $a_0^W/\Lambda^2$, $a_c^W/\Lambda^2$

- **Deviations from SM can be large**
AQGC expected limits

Expected limits @95%CL:

\[
\frac{a_0^W}{\Lambda^2} = 2 \times 10^{-6} \ (3 \times 10^{-6}), \\
\frac{a_C^W}{\Lambda^2} = 7 \times 10^{-6} \ (10 \times 10^{-6}).
\]
BSM searches: resonances, etc.


CMS Experiment at the LHC, CERN
Data recorded: 2015-Sep-11 22:46:54.589056 GMT
Run / Event / LS: 256353 / 437637379 / 244

exclusive WW production

diphotons at PPS

$\sigma \sim 0.3 \text{fb}$ a few `clean' events with 20/fb

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Increased reach at 13 TeV

Predicted cross-section ratios

13 TeV with 2.2 fb$^{-1}$ potentially more sensitive than 8 TeV (19.8 fb$^{-1}$)
• Excellent consistency of SM but SM is incomplete
• Direct and indirect searches for New Physics
  – Collected ~40/fb @13 TeV in 2015/2016
  – ~300/fb to be collected in the next few years (up to LS3)
• Many studies performed with data collected so far
  – New dedicated algorithms being developed
  – Dark Matter, Exotica, signature-based searches
  – Other BSM searches
• Searches provide no hints for BSM yet