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

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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

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Dark Matter

What is it?
• DM does not interact electromagnetically
• DM interacts gravitationally

Visual map
Why is it interesting?

• We do not see it…but we feel it
How do we find DM?

- Need to understand how it interacts with Universe
- Traditionally through a mediator
- Yields at least two new particles
Searching for DM

Direct Detection

Particle Colliders

Indirect Detection

Beyond the Standard Model (BSM) Physics

Standard Model

Dark Matter

LUX

CDMS

AMS

FERMI

GAPS

IceCube
How do we find it: @underground

- Through a nuclear recoil

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How do we find it: @Space

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

- Produced it through a mediator
DM at the LHC

- CMS/ATLAS experiments **not** designed for DM searches
DM searches at LHC

How do we find DM at the LHC?

• DM production gives MET signature
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:

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

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

\[
\text{MET}(Z \rightarrow vv) = - Z p_T
\]
How to discriminate signal against the background?

• Can fit the shape and look for signal
• Main background is from ZZ di-bosons
• Understanding ZZ di-boson pT is critical
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
DM+jet/V

Need good control of systematics

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In the SM, B(H→invisible) only 0.1%
Any significant deviation would indicate BSM
Signature: Large MET, Δφ(jj), veto ℓ/b-jets
  - C&C and shape fit of m(jj)
Main bkg: V+jets (95%)
Tag with forward jets+MET
Cross section ~4pb
Small background

Set limits: B(H→inv.)<0.37 (0.28) @95%CL

Shape: bkg-only fit in CRs+SR

ATLAS
13 TeV, 36 fb⁻¹

10^3

10^2

10

1

2 3 1 2 3 1 2 3 1 2 3 1 2 3

Events

e μν ee eν eν μν μν e ν ee μν μν
SR
Fake enriched W CR Z CR

Superimposed
- Data
- B + S, B_{inv}=1
B = syst,
all postfit

Stacked bkg.
- W (strong)
- Z (strong)
- W (EW)
- Z (EW)
- e fakes
- ℓℓ
- multijet

CMS
35.9 fb⁻¹ (13 TeV)

Pred. from b-only fit

Events / GeV
• DM search with $H(\rightarrow bb, \gamma\gamma)$
• Model dependent search
• $Z'$ 2HDM Model

• No significant excess
• Set limits for coupling $g=0.8$
Dark Matter

- Complementarity to direct/indirect searches
- DM particles:
  - interact via spin-0 & spin-1 mediators
  - are undetected (MET) recoiling against SM particle(s)
- Extensive program of mono-X searches (X=jet, γ, lepton, W, Z, t, tt, bb, H)
- No excess observed
- Interpretation through simplified models (DM and mediator masses, couplings to DM and SM)

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Experimental results

- Limits for given couplings between SM and DM interaction
- Competitive limits at low masses \( \text{wrt} \) other experiments

⇒ Collider results complement direct searches for low masses (<5-10 GeV)
Resonant searches

Among the highest dijet mass event recorded: $m_{jj} = 8.12$ TeV

Resonant Searches

$q \rightarrow e.g. Z', W' \rightarrow q$

$p_T = 3.8$ TeV

$p_T = 3.8$ TeV
BSM models predict new resonances

- BSMs predict resonances with spin 0, 1, 2

- Are quarks fundamental particles?
  - Excited quarks in models of compositeness

- Randall-Sundrum (RS) models
  - Spin-2 graviton (KK-particle)

- Heavy-Vector Triplets
  - Spin-1 resonance
  - Models based on strength of vector boson interactions

- Sequential SM
  - Z' and Z with same couplings to fermions
  - Width proportional to the mass

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New phenomena in di-jet events

- Searches up to high masses
- QCD predicts a smooth, monotonic decrease in dijet invariant mass
- Search for a localized excess
- No significant excess observed

ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]

Inclusive

- Data
- Background fit
- BumpHunter interval
- \( q^* \), \( m_{q^*} = 4 \text{ TeV} \)
- \( q^* \), \( m_{q^*} = 6 \text{ TeV} \)

\( q^* \), \( \sigma \times 10 \)

\( p \)-value = 0.89

ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]

Gaussian signals, inclusive

Exp. 95% CL upper limit for \( \sigma_X/m_X = 0\% \)
Obs. 95% CL upper limit for:
- \( \sigma_X/m_X = 0\% \)
- \( \sigma_X/m_X = 3\% \)
- \( \sigma_X/m_X = 5\% \)
- \( \sigma_X/m_X = 7\% \)
- \( \sigma_X/m_X = 10\% \)
- \( \sigma_X/m_X = 15\% \)
Searching for dilepton resonances

Dimuon candidate event:
Reconstructed mass of 2.4 TeV
Di-muon events

• Di-muon events: a re-discovery of the SM
High-mass dilepton resonances

• Search for dilepton (ee, μμ) resonance
Search for diboson 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)
Diboson resonances

- Many potential final states are possible
  - $WW/WZ$, $ZW/ZZ$, $VV$
- Hadronic channels with high sensitivity in high mass region

Boosted jets: Increasing transverse momentum, $p_T$
Jet grooming

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 $p_T^i/p_T^j < \text{cut removed}$)

“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→qq)**
  - n-subjettiness $\tau_{21}$: how consistent with 2 sub-jets
  - Categorization according to purity: high ($<0.35$) and high ($>0.35$)

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**arXiv:1707.01303**

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W, Z, H reconstruction (cont.)

- 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

![Graph showing $X \rightarrow VH \rightarrow q\bar{q}bb$ events]
Searching for diboson resonances

- No significant excess in any of the observed final states
- Exclusion limits: HVT models excluded up to 4.1 TeV, Spin-2 RS models up to 2.8 TeV
- Large improvements due to new methods for jet reconstructions and boson tagging
Search for multi-lepton final states

- Search for new heavy particles
  - Heavy fermions/scalars produced in association with ttbar
- 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 ($L_T$+MET)

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- 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
• 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 → ZV → llqq

• Search for resonances in Z → ee/μμ, V → 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

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• Search for a resonance decaying to WV in lepton+jet channel
• Categorization in $\tau_{21}$ and W/Z mass
• Sideband+transfer function for bkg estimate

• Similar sensitivity to $Z(\ell\ell)V(qq)$ search
• Excluded up to 1.1-3.1 TeV
**X→VH→ℓνqq**

- **Search for a resonance decaying to VH in leptonic channels**
  - $Z\rightarrowνν$: transverse mass $m_T(VH)$
  - $W→ℓν$: top control region
  - $Z→ll$: 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

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Combination of diboson searches

**Graphs:**

- **Left Graph:**
  - Title: Moriond 2018
  - Label: $\sigma_{95\%} [b(G_{bulk} \rightarrow ZZ)] [pb]$ vs $m_{G_{bulk}} [TeV]$.
  - Data points include:
    - Bulk Graviton ($k = 0.5$)
    - Observed
    - Median expected
    - 2l2v (B2G-16-023)
    - 2q2l (B2G-17-013)
    - 4q (B2G-17-001)
    - 2q2v (B2G-17-005)
  - Luminosity: 35.9 fb$^{-1}$ (13 TeV)

- **Right Graph:**
  - Title: Moriond 2018
  - Label: $\sigma_{95\%} [b(W \rightarrow ZZ)] [pb]$ vs $m_{W} [TeV]$.
  - Data points include:
    - HVT model B
    - Observed
    - Median expected
    - 2q2l (B2G-17-013)
    - 2q2v (B2G-17-005)
    - 2qlv (B2G-16-029)
    - 4q (B2G-17-001)
  - Luminosity: 35.9 fb$^{-1}$ (13 TeV)
Combination of resonance searches

- Combination of searches for heavy resonances decaying to boson and lepton final states
- Large gain in statistical combination
Resonance searches: Summary

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Leptoquarks

- Pair production of leptoquarks
  - Study $LQ \rightarrow b\tau$ final state
  - Can be interpreted in SUSY
- Main background from top quark pair events in different final states, determined from CRs
- Signal: use $M_{T2}$ (stransverse mass) and $s_T$ (scalar sum of $\tau$ and jet $p_T$) variables

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Heavy lepton resonances

- Two resonances in one process: $W \rightarrow NL$
- Off-shell $W$ decays to two new particles
- Signal selection:
  - OS and SS lepton pairs possible
  - two jets and MET
- Backgrounds from simulations and data CRs
Vector-like quarks

Motivation
- Simplest extension allowed in the quark sector
- Spin $\frac{1}{2}$ fermions with vector coupling
- Can mix with SM quarks and modify their couplings to the $W/Z/H$ bosons
- Sizeable mixing with 3rd family, $b$ and $t$

Properties
- Produced via strong and EWK interactions
- Mainly pair-produced
- Both CC and NC decay modes
VLQ searches

- Search for VLQ pair production decaying to WbWb
- Search in the **boosted regime**
- Can reconstruct the VLQ system

**Plot:**

- CMS
- Data
- \( \bar{t}t + \) jets
- Other backgrounds
- \( \sqrt{s} = 13.6 \text{ TeV} \), \( \bar{t}t \), \( m_t = 1300 \text{ GeV} \)
- Events/bin

**Diagram:**

- Dominant Bkg (top)
- VLQ signal
- Less boost vs high boost
Looking forward: PPS

- 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 \(~210\text{m}\) 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 \( \gamma \gamma \gamma \))

• Search for new BSM resonances

• Study of QCD in a new domain

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• **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
Roman Pot insertion

• Insertion procedure validated in 2016 by the LHC
  – Improvements carried out wrt earlier versions (RF shielding, cylindrical pots, ferrite, copper coating)

• Minimum distance of approach dramatically affects detector acceptance and physics reach

• A few mm (~15σ) from beam in nominal high-luminosity runs
  – Monitor beam losses, showers, interplay with collimators, beam impedance (heating, vacuum and beam orbit stability)
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**
  - AQGCs predicted in BSM theories
  - parameters: $a_0^{W/\Lambda^2}, a_c^{W/\Lambda^2}$

- **Deviations from SM can be large**
Exclusive Dileptons

- Study exclusive processes at the EWK scale
- Search for two-photon production of opposite charge lepton pair with forward proton tagging

Signal selected with:
- at least one proton tagged, muons, kinematic selection

Background: SD, DD, DY, dibosons, PU

JHEP 07(2018)153
Exclusive Dileptons (cont.)

- Correlation between the $\xi$ values in central system vs RP
- $12\mu\mu$, 8ee candidates observed ($>5\sigma$ over expected bkg)
- First observation of two-photon production of a lepton pair at this mass range
Expected limits @95%CL:

\[
\frac{a_0^W}{\Lambda^2} = 2 \times 10^{-6} \ (3 \times 10^{-6})
\]
\[
\frac{a_C^W}{\Lambda^2} = 7 \times 10^{-6} \ (10 \times 10^{-6})
\]
• Indirect search: neutral quartic gauge couplings (forbidden in SM) in $\gamma\gamma \rightarrow \gamma\gamma$
• Expect to provide best sensitivity at LHC
• Sensitive to axion-like particles
Prospects for Run3 and beyond

- More luminosity in a more challenging environment
- Will enhance the mass reach in the search for new particles
- Need to meet experimental challenges
  - Aging of detector, improve/adapt capability
  - Integrated luminosity: 300-3000/fb
  - Peak luminosity of $2 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$
  - Pileup will be ~150 or higher (Phase2)
  - Large radiation doses
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

(defunct) diphotons at PPS

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

Composite Higgs, anomalous gauge-Higgs couplings, excited leptons, technicolor, extra dimensions, axions, heavy exotic states, dark matter candidates, …?
HL-LHC upgrades

Luminosity of ~3000 fb^{-1} expected for HL-LHC

- **Tracking information in “L1 track-trigger”**
  - Tracker designed to enable finding all tracks w/ p_T > 2 GeV in < 4 µs
- **Tracker is all silicon but with much higher granularity, up to |η| = 4**
  - > 2 billion pixels and strips
- **High Granularity Endcap Calorimeters**
  - Sampling of EM showers: every ~ 1 λ (28 samples) w/ pixels, and every ~ 0.35 λ (24 samples) with pixels + scintillator to map 3D shower development
  - ~ 6 M channels in all
- **Precision timing to add a 4^{th} dimension to object reconstruction**
Future: HL-LHC upgrades

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ -10°

Muon systems
- New DT & CSC electronics
- New chambers 1.6 < η < 2.4
- Muon tagging 2.4 < η < 3

New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to η = 3.8

Beam radiation and luminosity
Common systems and infrastructure
Precision Timing Layer

• Time-of-flight precision ~30ps
  – $|\eta|<3$, $p_T>0.7$GeV
  – Crystal+SiPM: rad hard to $2\times10^{14}n_{eq}\text{cm}^{-1}$
• Provide ~x4-5 effective PU reduction
  – 15% merged vertices reduce to 1.5%
  – Low PU track purity of vertices recovered
• Showers timed to 30ps in calorimeters

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Summary

• Excellent consistency of SM but SM is incomplete

• Direct and indirect searches for New Physics
  – Collected ~150/fb @13 TeV in 2015-2018
  – ~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