Searches for Exotica with CMS

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• Introduction to Searches
• Searches for New Physics
  • Searching SUSY (short)
  • Vector-like particles
• Resonance searches
• Dark Matter searches
• Exotic new particles
• Specific LFV Searches
• Summary
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015

Run-2 starts

Many analyses presented today based on full 2016 data sample

2016 luminosity > Run-1 luminosity
Recent LHC News: Beam is back

First test collisions in the experiments on Thursday last week

- Machine expected next week to start up with collisions (this weekend?)
- Expect to collect ~ $90 \text{ fb}^{-1}$ in 2017-2018 $\rightarrow$ around $130 \text{ fb}^{-1}$ total in Run-2
- CMS is ready to collect data
**Physics Beyond the Standard Model?**

A Higgs at 125 GeV
Precise measurements of the top quark and the Higgs mass

We also know that:

New Physics inevitable?
But at which scale/energy?

But Where Is Everybody?

N. Arkani-Hamed

Searches!!
New Physics?

New Gauge Bosons?  Supersymmetry  ZZ/WW resonances?  Technicolor?

Extra Dimensions?  Black Holes???  Little Higgs?  Hidden Valleys?

What stabilizes the Higgs Mass? Many ideas, not all viable any more
A large variety of possible signals. We have to be ready for that
Searches for BSM Physics

• First Searches at the LHC (2010-2012)
  – Supersymmetry with MET plus jets, lepton(s), photons
  – Extra Dimensions and black holes, heavy resonances (in electrons, muons, taus, jets), leptoquarks, excited leptons and quarks, 4th generation, a few very exotic signatures (R-hadrons)…

• Evolved Searches (2013-…)
  – Supersymmetry on third generation squarks, compressed spectra, stealth SUSY, EWKinos, VBF processes…
  – Higgs in decays or as study object, vector-like quarks, boosted objects, long lived particles, fractional charges…
  – More dedicated Dark Matter searches!

• We are now fully engaged in the analyses at 13 TeV…
  Strategy is a combination of the above!
Supersymmetry? Examples:

No significant signal to date

Within the context of the SMS:
Exclude with gluino masses $\sim 2100$ GeV for neutralino masses up to 800 GeV
November ’16 on the web page of The Economist (!?!):

Exotica Searches so far

Next: New analyses since March 2017
Vector-like Quark Pair Production

Cancelling quadratic divergences to the Higgs mass... Hierarchy problem

Using kinematic reconstruction in lepton+jets final states

Vector-like quarks Relevant eg in composite Higgs models

Mass limits of 1295 (1275) GeV excluded at 95% for T (Y)

T charge 2/3  
Y charge -4/3
Search for Top Quark Partners

Mass Limits of 1.30 (1.32) TeV excluded at 95% for left (right)-handed couplings
Vector-like Quark Production Overview

Updated summary plots on mass and cross section limits
Search for $X \rightarrow H H \rightarrow 4b$

- Higgs produced with $p_T > 1$ TeV: boosted regime
- Search for double b-tagged “fat” dijets resonance

Limits on bulk gravitons and radions (RS model)
Eg for a mass scale $\Lambda_R$ of 3 TeV, exclude radions 970-1450 at 95% CL
Right Handed Heavy Neutrinos and W Bosons

EXO-16-045

Search in 2 jets and 2 lepton final states

Limits on $M_{WR}$ extend to 3.5 (3.3) TeV in the muon (electron channel)

Similar for the electron final state channel
Search for Light Vector Resonances

Bump hunting in dijets produced with an ISR jet or high $p_T$ jet to give the trigger

Sensitivity ‘beats’ the old UA2 result, going now below 140 GeV
Mild excess around 115 GeV observed: $2.9\sigma$ ($2.2\sigma$) global (local) significance

EXO-17-001

- Jet with $p_T>360$ GeV
- $H_T > 800/900$ GeV
The Generic Dark Matter Connection

Use effective theory or better simplified models to relate measurements to Dark Matter studies.

- **Mono-jets**: Generally very powerful
- **Mono-photons**: First used for dark matter searches
- **Mono-Ws**: Distinguish dark matter couplings to u- and d-type of quarks
- **Mono-Zs**: Clean signature
- **Mono-Tops**: Couplings to tops
- **Mono-Higgs**: Higgs-portals

arXiv:1407.8257
arXiv:1411.0535
‘Mono-jets’ for ED and Dark Matter Searches

EXO-16-048

Search for new physics in final states with an energetic jet or boosted hadronically decaying vector bosons

Dark matter in Fermion portal model

Dark matter in non-thermal model

More DM limits given in the summary plots
Search for Large Extra Dimensions

Mono-jet final state + Missing $E_T$ (ADD)

$p_T$ jet > 100/250 GeV
MET > 250 GeV

Limits on $M_D$ between 6 and 10 TeV

Lower limit on the Planck Scale versus number of extra dimensions

Monojets searches are typically the among the most sensitive ones.

EXO-16-048
Search using $Z + \text{MET}$ final states

EXO-16-052

Search for Dark Matter, Extra Dimensions, Invisible Higgs

Dark Matter
Search: $E_{T\text{miss}} > 100 \text{ GeV} + Z$ boson

Invisible Higgs
Search for dark matter produced in association with a Higgs boson decaying in two photons

EXO-16-054

Limits on Two-Higgs Doublet Z’ signals 900 GeV
Baryonic Z’ signals 800 GeV
Dark Matter Searches: Evolution

- Dark Matter hunt is one of the new main physics goals for the LHC!
- New developments with Simplified Models, allow including many more search channels such as dijets (aka “In Search for the Mediator”)

A promise for future studies
Comparison with Direct Detection

Axial-vector mediator and Spin dependent direct limits

Vector mediator and Spin independent direct limits

More reliable comparisons with direct detection results now possible via the SMS method

90% CL limits

LHCP 2017
Dark Matter Search Summary Plots
Excitement in December 2015: CMS & ATLAS

-> Some excitement on a mild observed excess in both experiments for a diphoton mass of around 750 GeV
-> About 500 papers explaining a new particle 😊

Statistical fluctuation? A new resonance? ???

Moriond: CMS: 3.4σ ! ATLAS up to 3.9σ !! (local significances)

A totally unexpected new particle???

December 2015: $X \rightarrow \gamma\gamma$ 750 GeV?

So, not for this time, but a sign of new physics can be found any time now

We need only one significant deviation of the Standard Model to show the way!

August 2016: The excess is NOT seen in the new data from 2016!

EXO-15-004

EXO-16-027

Spin-0 analysis

RIP
Search for high mass Zγ Resonances

EXO-17-005

In the wake of the (mild) 750 GeV diphoton excess in 2015...

-> A search in the Zγ channel

Combining leptonics and hadronic Z decay channels

No sign of a new resonance – especially not at 750 GeV 😊
Searches for Long Lived Particles

Increasing interest and effort:
Look for unusual signals in the detector from long-lived particles

- Example displaced Jets: search for pair-produced long-lived decays to four jet final states.

Present coverage?
Heavy Stable Ionizing Particles

Detection techniques used for (multiple/fractional) heavy stable charge particles

- Abnormal energy loss (\(\text{d}E/\text{d}x\))
- Slower than speed of light (low \(\beta\)) via time of flight measurements with the muon system

### Time of flight

\[
\frac{1}{\beta} = 1 + \frac{c\delta t}{L}
\]

### EXO-16-036
Search for long lived particles that stop in the detector and decay into jets after some time, non-coincident with pp collisions.

- 586 hours trigger lifetime in 2016 included in this search.
- Searches for long lived gluinos and stops (R-hadrons)
- 13 events observed in 2016 -> consistent with background

Limits on $M_{\text{stop}} < 744$ GeV and $M_{\text{gluino}} < 1385$ GeV 95% CL for lifetimes from 10 µsec to 1000s
New Physics in Rare Decays?

Analysis of the $B^0 \rightarrow K^* \mu^+ \mu^-$ decay (LHCb)

LHCb: arXiv:1512.04442
CMS: BPH-15-008

Mass of the $\mu\mu$ system

Angular observable

2.9$\sigma$ for each point
3.7$\sigma$ naive combination
Search for LFV Violating Decaying Resonances

• Search for high mass $X \rightarrow e\mu$ resonances
• No signal observed. Result interpreted in RPV SUSY

Limits range from 1.1 to 3.3 TeV, depending on mode parameters.
Search for LFV Decays: $H \rightarrow \mu\tau$

Recall: Results from the 8 TeV

- Comparable sensitivity from all channels
- $B(H \rightarrow \mu\tau) < 1.51\%$ at 95$
\sigma$

- Large improvement of previous limits
- Background-only p-value of 0.010 (2.4 $\sigma$)
  - Best fit
  $B(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$

Mild excess giving a 2.4$\sigma$ effect in Run-1... What about 2016 data?
Search for LFV Decays: $H \rightarrow \mu \tau, \epsilon \tau$

Breaking News: The 2016 data does NOT show an excess

<table>
<thead>
<tr>
<th>$H \rightarrow \mu \tau$</th>
<th>$H \rightarrow \epsilon \tau$</th>
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</thead>
<tbody>
<tr>
<td>Observed (Expected) limits (%)</td>
<td>Observed (Expected) limits (%)</td>
</tr>
<tr>
<td>$M_{col}$-fit</td>
<td>BDT-fit</td>
</tr>
<tr>
<td>$&lt;0.51 (0.49)%$</td>
<td>$&lt;0.25 (0.25)%$</td>
</tr>
<tr>
<td>$&lt;0.72 (0.56)%$</td>
<td>$&lt;0.61 (0.37)%$</td>
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HIG-17-001

☹ It would Have been Nice...
Search for LFV Decays: $H \rightarrow \mu\tau, e\tau$

LHC measurements overview
Interpreting these constraints in terms of LFV Yukawa coupling limits
Many More Searches...

- Heavy fermions EXO-16-001
- Leptoquarks EXO-16-007
- See-saw type III EXO-17-006

- Black Holes: arXiv:1705.01403
- Di-jets / data scouting EXO-14-005
- Mono-top EXO-16-017
A General Search View!

Model independent search
- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Rates (exclusive classes) as expected for 19.7 fb$^{-1}$ for CMS →muons, electrons, photons, MET

Analysis ongoing for 13 TeV
Summary: Searches at the LHC

- The LHC has entered a new territory. The experiments are heavily engaged in searches for new physics with the high statistics 13 TeV data samples.
- No sign of new physics yet in these first analyses of the 13 TeV. Previous mild excesses have not been confirmed. No sign of LFV signals at present: \( H \rightarrow \mu \tau \) not confirmed with 2016 data.
- Special efforts on Supersymmetry searches continuing and a more systematic covering of dark matter searches emerging.
- New exotic channels are being explored further: More systematic approach for eg long lived particle searches.
- The LHC is continuing to explore the Terascale. We have much data to look forward to: it will only take on significant deviation to show the way!!

And maybe one day soon: