Exotic Summary

Shih-Chieh Hsu
University of Washington
Aug 9 2016
• Many Big Questions beyond the SM to be answered at TeV scale
• Big Ideas highly constrained from theory and observed phenomena

Wolfgang Adam's talk

Florenzia Canelli's talk

Scope of this talk
• Quite often the same big idea probed by different signatures
  • It’s crucial to search all complementary signatures

Plan of this talk

1. Dark Matter
   - Minimal Dark Matter

2. Resonance
   - Top Partner
   - W/Z'

3. Unconventional Signatures
   - SUSY
   - Extended Higgs Sector
   - Compositeness, Extra dimensions

Search Signatures for Big Ideas
A large number of contributions to this talk:
- 6 parallel sessions, 22 talks and 16 posters
- 2 submitted papers, 45 new conf. notes
- Selected (2016 or First) results as examples to illustrate key points
- More results are linked below and in the backup slides

### Exotic Contributions at a Glance

ICHEP Preliminary

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<td>long-lived</td>
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1. Dark Matter
**Collider Dark Matter Interpretation**

- ATLAS/CMS searches assuming that DM is a WIMP

![Diagram showing DM coupling to SM](image)

- DM interpretation using simplified model to avoid EFT validity concerns

![Diagram showing simplified model](image)

**Run1**

- Direct detection (WIMP-nucleon scattering)
- Indirect detection (WIMP annihilation)

**Run2**

- Collider searches (WIMP pair production)

Direct mediator searches contributing to DM interpretations

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Steven Schramm (Université de Genève)

Searches for Dark Matter in ATLAS

August 5, 2016 2 / 14

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Steven Schramm's talk

Shin-Shan Yu's talk

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arXiv:1507.00966
ET\text{miss}+X \text{ a.k.a. Mono-X}

- X from ISR jet, b, t, γ, W, Z
- X from mixing with mediator
- X from pair ed \bar{t}t, \bar{b}b

ATLAS

\text{Preliminary}

2 b-tags

\text{Resolved}

200 400

\text{Data/Pred}

0.5 1 1.5

600 800 1000 1200

\text{Data}
• Key observables - imbalanced transverse momentum $E_{T}^{miss}$

• Irreducible background: $Z(\nu\nu)$+jets

  • jets might be mis-reconstructed as $b$-jets, $\gamma$, $W$, $Z$

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**ET$^{miss}+$jet**

![Graph of ET$^{miss}+$jet](image1)

**ET$^{miss}+t$**

![Graph of ET$^{miss}+t$](image2)

**ET$^{miss}+bb/\bar{t}\bar{t}$**

![Graph of ET$^{miss}+bb/\bar{t}\bar{t}$](image3)
Boosted jet substructure technique is used in hadronic W/Z/H
- No significant excess observed so far
- DM mass exclusion up to \( \sim 550 \) GeV
- Vector Mediator mass exclusion up to 1.95 TeV
2. Resonance

- Why 'di2photon searches'
- Fully reconstructed resonances: simplest way to discover new particles
- Statistically significant peak over a smooth background
- Experimentally robust
- Small systematics
- Difficult for unknown backgrounds to mimic
  ⇒ simple yet striking signature!

Number of events $m_{\gamma\gamma}$

Interest of dijet data scouting

- Should be detected also in dijets
- Standard analysis not sensitive to masses below 1.2 TeV
- "Data scouting" sensitive to lower dijet mass
- 8 TeV results are public, no observed excesses
- Needed also at 13 TeV, very interesting

The production at LHC is allowed!

Final states with high $p_T$ photons:
- Generally low background at hadron colliders
- Good mass resolution

Many theoretical models

Spin20
Spin22

Entries
Heavy Resonances

Neutral Charge

- dilepton
  - $e, \mu$
  - $\tau$

Charged

- $M_x$
  - $l$
  - $v$

New fermions
  - top partners

W(Z,H)

Dilepton:
- disphoton
- diboson
- $Z\gamma$

Dijet:
- quark
- gluon

Top:
- W
- b

Courtesy S. Rahatlou
Z’ dilepton

ATLAS Highest dielectron invariant mass
2.38 TeV

ET = 889 GeV

ET = 868 GeV
Di-Lepton

Same Flavor Opposite Sign (ee, μμ, ττ)

- Dominant background: Model independent shape-based (W+jets, QCD) in the dielectron channel
- Isolated e/mu with pT > 35/53 GeV

Lepton Flavor Violation (eμ, eτ, μτ)

- Same Sign (ee, μμ): \(Z_{SSM}^{3\% \text{ width}} > 4 \text{ TeV}\)
- Same Sign (ee, μμ): \(Z'_{0.5\% \text{ width}} > 3.36 \text{ TeV}\)

- RPV (\(\lambda_{311}^{I} = \lambda_{132}^{I} = \lambda_{231}^{I} = 0.2\)) > 3.3 TeV
- RBH (n=6) > 4.5 TeV

\[\text{Observed limit} \quad \text{Expected limit}\]

\[\text{Data} \quad \text{Preliminary}\]

\[\text{leptons} \quad \text{jets} \quad \text{bkg events}\]

\[\text{SR} \quad \text{Fitted bkg events}\]

2015

2016
Lepton+ET^{\text{Miss}}

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV}, \ 13.3 \text{ fb}^{-1} \]
\[ W' \rightarrow e\nu \text{ selection} \]

- Data
- W (2 TeV)
- W (3 TeV)
- W (4 TeV)
- Top quark
- Multijet
- Z/\gamma^* (4 TeV)
- Diboson

**2016**

\[ \text{Data / Bkg} \]

2015

SSM \( W' > 4.74 \text{ TeV} \)

SSM \( W' > 3.3 \text{ TeV} \)
the highest dijet invariant mass
7.7 TeV
Background modeled by parametrized function for search

\[ f(x) = \rho_1 (1 - x)^p x \]

<table>
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<tr>
<th>Model</th>
<th>95% CL Exclusion limit</th>
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<td>Quantum black holes, ADD</td>
<td>8.7 TeV</td>
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<tr>
<td>(BLACKMAX generator)</td>
<td>8.7 TeV</td>
</tr>
<tr>
<td>Excited quark</td>
<td>5.6 TeV</td>
</tr>
<tr>
<td>( W' )</td>
<td>5.5 TeV</td>
</tr>
<tr>
<td>( W^* )</td>
<td>2.9 TeV</td>
</tr>
<tr>
<td>( W^* )</td>
<td>3.3 TeV</td>
</tr>
<tr>
<td>Contact interactions (( \eta_{LL} = +1 ))</td>
<td>12.6 TeV</td>
</tr>
<tr>
<td>Contact interactions (( \eta_{LL} = -1 ))</td>
<td>19.9 TeV</td>
</tr>
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\( b^* \) (BR(b*→ bg)=0.85) > 2.3 TeV
\( Z' \) > 1.5 TeV
The lowest mass (down to 100 GeV) probed by boosted dijet final state
A broad mass - leptophobic Z’ coupling parameter space constrained by combining various dijet channels.
Combined with DM Interpretation

- Complementary searches by **mono-X** and **dijet**
- Dijet searches cover a broad mediator mass range
- Results highly depend on choice of coupling parameters

\[ \mathcal{L} = g_q \bar{q} \gamma^\mu q Z^\prime_\mu \]

**DM Simplified Model Exclusions**

**ATLAS Preliminary**

August 2016

\[
\begin{align*}
\text{DM Mass [TeV]} & \quad \text{Mediator Mass [TeV]} \\
0 & \quad 0 \\
0.2 & \quad 0.2 \\
0.4 & \quad 0.4 \\
0.6 & \quad 0.6 \\
0.8 & \quad 0.8 \\
1 & \quad 1 \\
1.2 & \quad 1.2 \\
1.4 & \quad 1.4 \\
1.6 & \quad 1.6 \\
\end{align*}
\]

- **Axial-vector mediator, Dirac DM**
  - \( g_q = 0.25, g_{DM} = 1 \)
  - \( g_q = 0.1, g_{DM} = 1.5 \)
Non-trivial interference in gg to $t\bar{t}$ production between SM and type-II 2HDM

Reinterpretation of 8TeV analysis with addition of boosted channel

ATLAS Simulation Preliminary
\$\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$

S+I after det. sim. and event sel.
m$_{t\bar{t}} = 500$ GeV, $\tan \beta = 9.00$

$\sin(\beta - \alpha) = 1$

Powheg+Pythia6

ATLAS Preliminary
\$\sqrt{s} = 8$ TeV, $\int L dt = 20.3$ fb$^{-1}$

Data 2012
A+$tt(S+I)<7$

$tt$

$\tan \beta = 0.7$

Pre-fit background

First Results

$\tan(\beta)>0.8$

$\tan(\beta)>0.5$
Michael Anthony Buttignol's talk

- **Hadronic W' tb**
  - Only right-handed interaction searched for
  - W'\text{R} resonance with narrow width (3%)
  - Top-tagging (AK8 jets): (0.3% mistag)
  - B-tagging (AK4 jets): loose WP (10% mistag)
- **Event selection**
  - \(\geq 2\) high-\(p_T\) jets,
  - 1 t-tagged AK8 jet,
  - 1 b-tagged AK4 jet with \(m_{SD}\) < 70 GeV,
  - \(|\Delta\phi(j_1, j_2)| > \pi/2\) rad,
  - \(|\Delta y(j_1, j_2)| < 1.3\)

- **QCD multijet estimated from data**

---

**M_{tb} distribution (postfit)**

\[ \text{M}_{tb} \text{ distribution (postfit)} \]

- CMS Preliminary
- 2.55 fb^{-1} (13 TeV)

\[ \text{M}_{tb} \] (e channel, 2 b-tags)

- CMS Preliminary
- 12.9 fb^{-1} (13 TeV)

\[ W'_{\text{R}}: [1\sim 2] \text{ TeV} \]

\[ W'_{\text{R}}: [1\sim 2.67] \text{ TeV} \]

---

**Note:** pull = (data-background)/\(\sigma\)

- B2G-16-009
- 08/06/2016
- ICHEP 2016 / M. Buttignol

- B2G-16-017
- 08/06/2016
- ICHEP 2016 / M. Buttignol

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**W'_{\text{R}}**: [1\sim 2] TeV

**W'_{\text{R}}**: [1\sim 2.67] TeV
VLQ - Spin 1/2, colored, charged particles with both left- and right-handed coupling to charged currents.

- **pair production** through QCD - dominant in low mass
  Most channels have been updated with 2015 data
- **single production** through EWK coupling - dominant in high mass (model dependent)
  New results shown below.

\[ m(T/Y, \sqrt{c_L^2 + c_R^2} = 1/\sqrt{2}) > 1.44 \text{ TeV} \]

\[ m_T(C(bW)=1, BR(tZ)=0.25) > 1.37 \text{ TeV} \]
• Search for VV/Vh/hh resonance in *leptonic/hadronic* decay channels using **large-R jets with jet substructure techniques**

```
VV/Vh/hh Resonance

Z(\ell\ell)V  Z(\nu\nu)V  W(\nu\ell)V  VV(JJ)

Z(\ell\ell)h  Z(\nu\nu)h  W(\nu\ell)h  V(J)h  hh
```

- \ell: lepton
- \nu: neutrino
- J: jet
- b: bottom quark
Z(\ll)V

Z(vv)V

W(lv)V

VV(JJ)

ATL-CONF-2016-082

ATL-CONF-2016-082

ATL-CONF-2016-062

ATL-CONF-2016-055

B2G-16-010

B2G-16-020

Z(\ll)h

Z(vv)h

W(lv)h

V(J)h

hh

ATL-CONF-2016-083

ATL-CONF-2016-049

B2G-16-008

2015

2015

2015

2015

2016

2016

2016

Preliminary

CMS
Revisit diboson excesses in Run1

**ATLAS**

*Excesses not confirmed in Run2*

Run1

**Excesses not confirmed in Run2**

Run1

**ATLAS Preliminary**

13 TeV, 3.2 fb^{-1}

WZ selection

**ATLAS**

13 TeV, 3.2 fb^{-1}

WW selection

**CMS**

13 TeV, 3.2 fb^{-1}

**JHEP12(2015)055**

m= 2TeV

3.4σ local

2.5σ global

**EPJC 76 (2016) 237**

m=1.8 TeV

2.9σ local

1.9σ global

**ATL-CONF-2016-055**

2015+2016

**B2G-16-003**

2015
- RS Graviton mass limit up to 2 TeV
- HVT $W'$ mass limit up to 2.4 TeV
- a joint interpretation of $VV/Vh$ channel
Diphoton

$E_T, \eta, \phi, E_{Tiso} = 346$ GeV, $-1.26, 2.26, -0.76$ GeV.

$E_T, \eta, \phi, E_{Tiso} = 334$ GeV, $-0.52, -0.84, 5.44$ GeV

$m_{\gamma\gamma} = 728$ GeV

the Heaviest invariant mass

2.2 TeV

$E_T = 1.1$ TeV

$E_T = 1.1$ TeV

ATLAS EXPERIMENT

Run Number: 302956, Event Number: 2656107838
Date: 2016-06-29 14:32:52 CEST
Significant excesses observed in 2015 data

**Diphoton in 2015**

**Significance in 2015**

- m = 750 GeV (Γ/M = 6%)  
  3.9σ (local)/2.1σ (global)  
  \[ \rightarrow 3.4σ \text{ (local)/}~2σ \text{ (global)} \] reprocessing

- m = 760 GeV (Γ/M = 1.4 × 10^{-4})  
  2.9σ (local)/<1σ (global)  
  \[ \rightarrow 3.4σ \text{ (local)/}<1.6σ \text{ (global)} \] 2015+8 TeV

**purity ~90%**

**mass resolution (~750 GeV) <1%**

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**16th April 2016 – 20:32 13**

The uncertainty on the purity corresponds to the impact of the relative normalization of the reducible background, the impact of the parton-level mass interval, are taken into account, uncorrelated from bin to bin.

- MC statistical uncertainties, which are ranging from but fully correlated across the full mass range. These sources are the shape of the reducible background,

• D states \[ 7.2. \text{Functional form approach} \]

- Validation of functional form and uncertainty from simulation + variations above + jet, jet+jet shape from control regions,

•shape from DIPHOX NLO parton level calculation, re-weight Sherpa full-sim \[ D \]

- Systematics smaller than 30% of statistical error and decreasing with mass

- To predict the shape of the photon+jet and dijet backgrounds, control samples where one or two of the diphoton events generated with \[ D \]

= \[ D \](local)/~2σ (global)

\[ \rightarrow 3.4σ \text{ (local)/}~2σ \text{ (global)} \] reprocessing

Bruno Lenzi (CERN)

Chiara Rovelli’s talk

PRL 117(2016) no.5, 051802
Significance in 2015+2016:

\( m=710 \, \text{GeV} \) (\( \Gamma/M=10\% \))

2.3\( \sigma \) (local)/\(<1\sigma \) (global)

\( m=760 \, \text{GeV} \) (\( \Gamma/M=1.4\times10^{-4} \))

\(<1\sigma \) (local)
Resonance search summary

- Up to 25% mass limit increase by extending 2015 to 2016
- 50% of the analyses updated to Run2
3. Unconventional Signatures
Unconventional Signatures

- Long-lived particles
- Multiple-charged particles

MoEDAL

LHCb

Detector subsystems
- Low-threshold NTD array (z/β > 5)
- High-charge catcher NTD array (z/β > 50)
- TimePix radiation background monitor
- Monopole trapping detector

The 7th LHC experiment, located at IP8
- ~70 members, 25 institutes

MoEDAL probes messengers of new physics which are inaccessible to other LHC experiments.

Direct HIP/monopole detection at colliders (3)
1) General-purpose detectors
2) Nuclear-track detectors
3) Induction technique
   - Expect monopole-nucleus binding energy ~100 keV (Rept. Prog. Phys. 69, 1637 (2006), arXiv:hep-ex/0602040)
   - Persistent current after passage through superconducting coil

LHCb: a general-purpose detector in the forward direction
- Tracking system
- ECAL
- HCAL
- MUON
- VELO
- RICH
- Magnet

JINST 3 (2008) S08005
IntJModPhys A30 (2015) 1530022

Pieter David (Nikhef)

Electroweak-scale exotica with LHCb
ICHEP 2016

J. Antonelli      ICHEP 2016, Aug 6th

Not pictured:
- stopped particles

J. Antonelli      ICHEP 2016, Aug 6th
Complementary searches from LHCb and ATLAS/CMS to extend proper lifetime coverage:
- LHCb: \(O(10^{-5}) \sim O(10^{-2})\) m
- ATLAS: \(O(0.1) \sim O(100)\) m

LHCb-PAPER-2016-014 (in preparation)
• No excess found in the data

**Lepton jet:** collimated jet-like structures containing e/μ/pions

**Displaced e-μ pair:** large transverse impact parameter \(d_0\) for analysis
Magnetic Monopoles

Cross section limits versus magnetic charge

Probe magnetic charge $|g| > 1.5g_D$ (up to 4 $g_D$) for the first time at the LHC

Probe masses $> 2500$ GeV (up to 3500 GeV) for the first time at the LHC

Magnetic monopole masses $> 2500$ GeV
Magnetic monopole charge $|g| > 1.5g_D$ (up to 4 $g_D$)

ATLAS magnetic monopole mass

| $|g|$ | $g_D$ |
|------|------|
| spin-1/2 | 1340 |
| spin-0   | 1050 |

For comparison

ATLAS 8 TeV ($\sigma =$ 1340 ± 1050 GeV) (arXiv:1509.08059)

arXiv:1604.06645
• LHC experiments conducting BSM searches in broad and complementary signatures

• Known excesses (Diboson in Run1 and Diphoton in 2015) not confirmed using 2016 data

• No new significant excesses observed. Set new frontier scale:
  • Contact Interaction energy: 25.2 TeV
  • ADD BH mass: 9.55 TeV
  • $W'$ mass: 4.74 TeV
  • Dark photon lifetime: 2.5~100 mm (dark photon 400 MeV)
  • Magnetic charge: $|g|>1.5g_D$ (up to 4 $g_D$)

• More data to come - Stay tuned!
Backup
New Results for ICHEP

• ATLAS Exotics:
  • 18 conf notes; 1 submitted paper
  • https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  • https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Summer2016-13TeV

• CMS Exotics:
  • 22 conf. notes; 1 submitted paper
  • https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

• CMS Beyond 2 Generations:
  • 5 conf. notes submitted for ICHEP
  • https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

• LHCb Results
  • 1 conf. notes
  • https://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.html
Amazing Performance from LHC

• Record breaking luminosity in 2016!
• Most selected results updated with 2015+2016 13TeV data
  • 2016 data (~13 fb⁻¹): comparable statistics w.r.t. Run1 in all system mass
  • Results expected to surpass all Run1 sensitivity

---

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-08-07 05:35 UTC

- 2010, 7 TeV, 45.0 fb⁻¹
- 2011, 7 TeV, 6.1 fb⁻¹
- 2012, 8 TeV, 23.3 fb⁻¹
- 2015, 13 TeV, 4.2 fb⁻¹
- 2016, 13 TeV, 21.1 fb⁻¹

- Run1

2015

2016

ratios of LHC parton luminosities: 13 TeV / 8 TeV

- gg
- Σqq
- qg

J. Stirling

20.3 fb⁻¹ (run-I, 8 TeV) / 3.2 fb⁻¹ (run-II winter, 13 TeV) = 6.3

20.3 fb⁻¹ (run-I, 8 TeV) / 13.3 fb⁻¹ (now, 13 TeV) = 1.5

Mx=4 TeV x67 (qq)

MSTW2008NLO

WJS2013
Shin-Shan Eiko Yu

**Summary Of All Mono-X Channels**

- No excess observed
- Vector/Axial mediator mass up to 1.95 TeV excluded
- (Pseudo) scalar mediator mass up to (430) 100 GeV

**Mono-Jet/Jets/Hadronic W And Z**

2016 data

Vector Mediator

- No excess observed
- Vector/Axial mediator mass up to 1.95 TeV excluded
- (Pseudo) scalar mediator mass up to (430) 100 GeV

Pseudo-scalar Mediator

**DM Mass Exclusions**

*Dark Matter Summary - ICHEP 2016*

- DM + jets/V(ν) ($g_{DM} = 1$, $g_{ν} = 0.25$)
- DM + γ ($g_{DM} = 1$, $g_{γ} = 0.25$)
- DM + Z(0,τ) ($g_{DM} = 1$, $g_{τ} = 0.25$)
- DM + Z(τ,τ) ($g_{DM} = 1$, $g_{τ} = 0.25$)
- DM + H(γγ/γν) ($g_{DM} = 1$, $g_{ν} = 0.25$)
- DM + jets/V(ν) ($g_{DM} = 1$, $g_{ν} = 0.25$)
- DM + δ (ν) ($g_{DM} = 0.25$, $g_{δ} = 1$)
- DM + δ (τ) ($g_{DM} = 0.25$, $g_{δ} = 1$)
- DM + δ (t) ($g_{DM} = 0.25$, $g_{δ} = 1$)
- DM + δ (tt) ($g_{DM} = 0.25$, $g_{δ} = 1$)

**Exclusion Limits**

- Observed exclusion 95% CL
  
  **DM Mass Exclusions**

- Observed exclusion 95% CL

**Model Exclusions**

- CMS Preliminary
  
  **Vector Mediator**

- CMS Preliminary
  
  **Scalar Mediator**

**DM-nucleon scattering cross sections**

- BR($h(125) → invisible) < 0.44$ (0.56 expected)
- Results recast to limits on SI/SD DM-nucleon scattering cross sections

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**Axial-vector Mediator**

- Dirac DM ($g_{ν} = 0.25$, $g_{DM} = 1$)
- Observed exclusion 95% CL

**Scalar Mediator**

- Observed exclusion 95% CL

**DM-nucleon scattering cross sections**

- 12.9 fb$^{-1}$ (13 TeV)

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**CMS DM Summary**
• Using jet substructure techniques to search in lepton+jet and full hadronic jet channels.

\[ Z'_{TC2} \text{ (1.2\% width)} > 2.2 \text{ TeV} \]
\[ Z'_{TC2} \text{ (3\% width)} > 3.2 \text{ TeV} \]
The largest combined significance

\[ m = 1.6 \text{ TeV (narrow width)} \]
\[ 2.4 \sigma (\text{local})/<1\sigma (\text{global}) \]

\[ m = 0.9 \text{ TeV (1.4x10}^{-4} \text{ width)} \]
\[ 2.2 \sigma (\text{local})/<1\sigma (\text{global}) \]