New Physics at the Energy Frontier

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University of Kansas

On behalf of ATLAS and CMS Collaborations

DPF2017, Fermilab, USA
Jul 31, 2017
A brief History of Achievements

- 1960
  - Parton observation in DIS and quark model - 1969

- 1970
  - $J/\psi$ discovery - 1974
  - $\tau$ discovery - 1976
  - B-quark discovery - 1977

- 1980
  - W and Z discovery - 1983

- 1990
  - Top quark discovery - 1995

- 2000
  - $\nu_t$ discovery - 2000

- 2010
  - Higgs boson discovery - 2012

- 2017

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A brief History of Achievements

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2017

- Higgs discovery and its properties
- Precision measurement of SM particles
- Measurements of rare B and D decays
- Precision measurement of CKM parameters
- Discovery of exotic Pentaquark, Tetraquark, $\omega_c^0 \rightarrow \Xi_c^+ + K^-$
(See Steven Blusk plenary talk on Wed, 2/8)
- Understanding of charm hadronization and nuclear effects in Pb-Pb/Pb-p collisions
Today I am going to give highlights of some of these questions at the Energy Frontier

- Are there any new symmetries beyond standard model that can also address mass hierarchy?
  - Supersymmetry
    - many variants and kind (MSSM, NMSSM, R-parity conserving, R-parity violating) of models
  - Global symmetry such as compositeness, extra dimension
    - Are there any additional new particles such as vector-like quarks, excited quarks, leptons, Higgs and gauge bosons?
  - Dark matter
    - non-SUSY DM models, lepto-quarks, dark/hidden sectors
  - Baryogenesis, leptogenesis
  - Strong Charge Parity
  - ...

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Outline

- What is required to discover new physics?
  - understanding SM backgrounds
  - tools and techniques
  - common procedures

- New Physics status
  - Supersymmetry
    - Strong and EWK processes
  - New heavy particles
    - VLQ, excited quarks, heavy bosons
  - Dark matter

- Prospectives of discovering NP at the HL-LHC

Disclaimer: Results from only ATLAS and CMS
Not in this talk: NP in Higgs sector, displaced vertices, composite Majorana neutrino, flavor physics, leptoquarks, composite Majorana neutrino.
Large Hadron Collider

7/8/13 TeV proton—proton collisions

ATLAS/CMS:
- 5 & 25 fb$^{-1}$/exp 2011-12 @ 7 & 8 TeV
- 36 fb$^{-1}$ (2015-2016) & 6 fb$^{-1}$ (2017) / exp @ 13 TeV
Standard Model Backgrounds

- Precise measurements of SM background is essential for accurate MC simulations

**Standard Model Production Cross Section Measurements**

**ATLAS Preliminary**
Run 1, 2 \( \sqrt{s} = 7, 8, 13 \) TeV

- **W+jets**
- **Z+jets**
- **t+jets**
- **H+jets**
- **tt+jets**
- **VV**
- **VVjj**
- **V+jets**
- **Vγγ**
- **VW**
- **Vγ**
- **W+jets**

**Theory**
- LHC pp \( \sqrt{s} = 7 \) TeV
  - Data 4.5 – 4.9 fb\(^{-1}\)
- LHC pp \( \sqrt{s} = 8 \) TeV
  - Data 20.3 fb\(^{-1}\)
- LHC pp \( \sqrt{s} = 13 \) TeV
  - Data 0.08 – 36.1 fb\(^{-1}\)

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Background Estimation

- Main backgrounds are mostly estimated from data
- Significant reduction in total systematic uncertainty due to detector response/simulations

![Diagram of validation regions and control regions with signal regions]

- Validation Region
- Control Region
- Signal Region

arXiv: 1410.1280
Background Estimation

- Main backgrounds are mostly estimated from data
- Significant reduction in total systematic uncertainty due to detector response/simulations

Validation Region

Control Region

\[ N_{\text{bkg}} = \frac{N_{\text{CR}}^{\text{data}}}{N_{\text{CR}}^{\text{mc}}} \times N_{\text{SR}}^{\text{mc}} \]

CR: 2l+0b+1W

VR: 2l+1bjet+0W

SR: 2l+1bjet+1W

Example:

CMS-PAS-B2G-17-07
Search Procedures

- Look for excesses over known backgrounds

*Example 1:* Search for vector-like quark $T^{2/3}$ by reconstructing its mass in high $S_T$ tails

$$S_T = l(p_T) + \sum P_T^{jets} + E_T^{Miss}$$
Search Procedures

- Divide and conquer, and leave no stone unturned
  - Multi-dimensional bins considering various discriminating observables

- Example 2: Search for SUSY in all-hadronic final states
  - Consider SRs categorized with respect to $N_{\text{jets}}$, $N_{\text{bjets}}$, $H_T$
  - Each region with a certain $H_T$ range is further split in terms of $M_{T2}$

\[
M_{T2} = p_T^{X(1)} \cdot \min \left( \frac{\max \left( M^{(1)}_T, M^{(2)}_T \right)}{p_T^{\text{miss}}} \right)
\]

- Great complexity of the current searches
- Model-independent upper limits
  ⇒ allows interpretations in other specific NP model(s)
Search Tools: Jet substructure

- Techniques focus on boosted final states where the whole heavy particle decay can be captured in a single jet
- SUSY signature: moderate boost
- Heavy vector-like quark and boson decays: large boost

Jet grooming and Wjet identification

Jet pruning and splitting

WJets

QCD

stops production through gluino decays with no leptons

ATLAS-CONF-2017-020
Search Tools: Re-tracking@ATLAS

- “Unconventional” signatures such as long-lived particles (LLP)
- Small medium decay lengths appears as displaced vertex (DV)
- Silicon-seeded Large-Radius Tracking (LRT) algorithm

ATLAS Simulation Preliminary
\( \sqrt{s} = 13 \text{ TeV} \)
Split-SUSY Model, \( \tilde{g} \rightarrow q\bar{q} \tilde{\chi}^0_1 \)
R-hadron: \( m(\tilde{g}) = 1200 \text{ GeV}, m(\tilde{\chi}^0_1) = 100 \text{ GeV}, \tau = 1 \text{ ns} \)

<table>
<thead>
<tr>
<th>Vertex reconstruction efficiency</th>
<th>Decaying Length</th>
<th>Disappearing (kink) track</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>0.001 mm</td>
<td>10 cm</td>
</tr>
<tr>
<td>0.8</td>
<td>0.3 cm</td>
<td>( \sim 1 \text{ m} )</td>
</tr>
<tr>
<td>0.6</td>
<td>0.1 cm</td>
<td>( \sim 10 \text{ cm} )</td>
</tr>
<tr>
<td>0.4</td>
<td>1 mm</td>
<td>( \sim 1 \text{ mm} )</td>
</tr>
<tr>
<td>0.2</td>
<td>10 mm</td>
<td>( \sim 10 \text{ mm} )</td>
</tr>
</tbody>
</table>

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The Higgs could indeed be the lightest of the SUSY-higgs goal here is to understand the qualitative trends, rather than guess the correct numerical values. The values were chosen more for their artistic value in Figure 8.

In the MSSM, there are 32 distinct masses corresponding to un sfermion mixing for the first two families assumed to be negligible. A complete set of Feynman rules for t gravitino. Above, we have explained how the masses and mixin

Table 8.1: The undiscovered particles in the Minimal Supers

Search for supersymmetric (SUSY) particles in their minimal forms.

The essential physics of supersymmetry breaking is not that the contribution to Higgs mass

\[ \delta m^2_H = \mu^2 \] (Higgnino)

\[ \delta m^2_H \propto \frac{3y_t^2}{8\pi^2} m_{\text{stop}}^2 \log(A/Q) \] (stops)

if \( \Delta \equiv 2 \frac{\delta m^2_H}{m_h^2} \); tuning \( \sim \frac{1}{\Delta} \)

Nathaniel Craig, EPS2017
Supersymmetry

Large number of searches both at ATLAS and CMS!

Typical mass limits for direct production:
- squarks > 1 TeV
- gluino > 2 TeV
- sleptons/chargino > 0.5-0.6 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

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Compressed Regions

Challenging to access!

- Example: direct stop pair production in multiple final states
  - $\text{top} + \text{LSP} \rightarrow 0\ell, 1\ell, 2\ell + \text{b-jets} + \text{E}_{T}^{\text{Miss}}$
  - $\text{charm} + \text{LSP}$

Jet substructure techniques are crucial!

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_b + m_W$

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_t$

2 body decay

$\text{stop} \rightarrow t + \text{LSP}$

3 body decay

$\text{top} + \text{LSP} \rightarrow 0\ell, 1\ell, 2\ell + \text{b-jets} + \text{E}_{T}^{\text{Miss}}$

4 body decay

$\text{charm} + \text{LSP}$

$\text{stop} \rightarrow c + \text{LSP}$
Third generation stops

Historical development!

Moriond 2014

Feb 2015

Moriond 2017

Similar developments happened at CMS at the same time

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Third generation stops

\[ pp \rightarrow \tilde{\tau}, \tilde{\tau} \rightarrow t \tilde{\chi}_1^0 \]  

**CMS Preliminary**  
- SUS-16-033, 0-lep \( (H_T^{\text{miss}}) \)  
- SUS-16-036, 0-lep \( (M_{T2}) \)  
- SUS-16-049, 0-lep stop  
- SUS-16-051, 1-lep stop  
- SUS-17-001, 2-lep stop  
- Comb. 0-, 1- and 2-lep stop

**ATLAS Preliminary**  
- SUS-16-034, 0-lep \( (H_T^{\text{miss}}) \)  
- SUS-16-036, 0-lep \( (M_{T2}) \)  
- SUS-16-049, 0-lep stop  
- SUS-16-051, 1-lep stop  
- SUS-17-001, 2-lep stop

**CMS equivalent for 4 body decays:** SUS-16-050 \( (0l+\text{top}) \), SUS-16-052 \( (1l+\text{compressed}) \)

**CMS equivalent for charm + \( E_T^{\text{miss}} \):** EXO-16-048

- For sbottom: Exclusion limits beyond 1 TeV in both experiments

See today’s BSM session @10:45  
Keisuke YOSHIHARA, Nathaniel PASTIKA  
Wednesday’s BSM session @10:45  
Leigh SCHAEFER (RPV)

**Status:** May 2017
Gluinos

- A spectacular number of regions scrutinized in 0, 1, or more lepton final states, in a variety of hypotheses

Typical limits on gluino $\sim 2$ TeV

$m(\tilde{g})$ [GeV] vs. $m(\tilde{\chi}_1^0)$ [GeV]

- R-Parity violation
- R-Parity conservation
Light squarks

- Searches are interpreted in terms of exclusion limits on the mass of squarks, considering sophisticated search regions.

Limits on light squarks $\sim 1$ TeV for direct decays [one-type only]

See today's BSM session@10:45 am
Kevin PEDRO, Frank JENSEN
Electroweak SUSY: chargino
Powerful exclusions in decays using multi-leptons final states

CMS-PAS-SUS-17-004

pp → \tilde{\chi}_2^0 \tilde{\chi}_1^\pm

35.9 fb^{-1} (13 TeV)

2 soft leptons: A region previously only reached by LEP (CMS-PAS-SUS-16-048)

See today’s BSM session@10:45: Frank JENSEN
BSM session@13:30: Joseph REICHERT, Elodie RESSEGUIE

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Electroweak SUSY: higgsino

Sensitivity to Gauge mediated SUSY breaking models

See today’s BSM session@13:30 : Basil SCHNEIDER
Electroweak SUSY: sleptons

- Powerful exclusions in decays via sleptons
  - **Best sensitivity**: left-handed stau of around 125 GeV and a massless LSP, with expected exclusion of 1.5 times the expected SUSY cross-section.

See today's BSM session@13:30: Elodie RESSEGUIE
Global Symmetry

Complementary to SUSY, with light fermionic partners & Higgs tuning

\[ \delta m^2_H \propto \frac{3y_t^2}{8\pi^2} m_T^2 \log(\Lambda/m_T) \]

Vector-like quarks:
Non-chiral matter and with its own mass, \( \mathcal{L}_M = -M \bar{\psi} \psi \)
Transforms under the same representation of the SM \( SU(3)_c \times SU(2)_W \times U(1)_{Y} \) gauge symmetry
\( \rightarrow \) has both left-handed and right-handed charged currents

Partner bosons:
\( Z', W' \) and \( G' \) appear as resonances in BSM Models

Nathaniel Craig, EPS2017

arxiv:1506.05110
Vector-like quarks

Produced either as in pair or as a single

Cross-section is independent of production mechanism

Cross-section dependents of ewk couplings and production mode

Decays and allowed combinations

<table>
<thead>
<tr>
<th>$Q_{\text{Ele.Charge}}$</th>
<th>Decays</th>
<th>I</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T^{2/3}$</td>
<td>$bW^+, tH, tZ$</td>
<td>1</td>
<td>2/3</td>
</tr>
<tr>
<td>$B^{-1/3}$</td>
<td>$tW^-, bH, bZ$</td>
<td>1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$X^{5/3}$</td>
<td>$tW^+$</td>
<td>2</td>
<td>1/6</td>
</tr>
<tr>
<td>$Y^{-4/3}$</td>
<td>$bW^-$</td>
<td>2</td>
<td>-5/6</td>
</tr>
<tr>
<td>$T^{7/6}$</td>
<td>$T, B, X$</td>
<td>3</td>
<td>2/3</td>
</tr>
<tr>
<td>$B, Y$</td>
<td>$T, B, Y$</td>
<td>3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Cross-section is independent of production mechanism
VLQ Searches

Pair Production in $1\ell + \text{jets} + E_T^{\text{Miss}}$

Single Production in all hadronic with $\geq 1$ fwd jet

**Extensive use of boosted jets!**

Mass exclusion limits up to 1.3 TeV

$\sigma \times \text{BR}$ exclusion limits up to 0.07-1.28 pb for B masses 700-1800 GeV

See Tuesday’s (01/08) BSM sessions at 13:30

Anthony BARKER, Rachitha MENDIS, Rizki SYARIF, Tyler MITCHEL, Erich SCHMITZ

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VLQ Searches

\( \mathbf{T}/\mathbf{B} \) in \( 1\ell + \text{jets} + \mathbb{E}_{\text{T}}^{\text{Miss}} \) using mass reconstruction

**Extensive use of boosted jets!**

arXiv:1707.03347

**Typical mass limits for singlet \( \mathbf{T}/\mathbf{B} \) pair production >1 TeV**

See Tuesday’s (01/08) BSM session talk by Joseph HALEY

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Resonances

- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, heavy higgs (A/H) ...
- New particle can decay into multiple final states:
  - dileptons, lepton+ $E_T^{\text{Miss}}$, dijets, $\gamma$+jets, dibosons (VV, $V\gamma$, $\gamma\gamma$), tt, tb ..

  Look for Jacobian-Peak in W-transverse mass, $M_T$

<table>
<thead>
<tr>
<th>Events</th>
<th>$\mu + E_T^{\text{Miss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$W\rightarrow l\nu$</td>
</tr>
<tr>
<td>$W'$</td>
<td>$t\bar{t}$</td>
</tr>
<tr>
<td>$Z/\gamma$</td>
<td>Diboson</td>
</tr>
</tbody>
</table>

  - arXiv: 1612.09274
  - arXiv: 1706.04786

- No significant deviation in data up to 2 TeV
- Simple SM extensions getting tightly constrained up to 4-5 TeV

See Tuesday's (01/08) BSM session
Norbert NEUMEISTER (Z', W', dijet)
Resonances

• Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, heavy higgs (A/H) …

• New particle can decay into multiple final states:
  - dileptons, lepton+ \( E_T^{\text{Miss}} \), dijets, \( \gamma+jets \), dibosons (VV, \( V\gamma \), \( \gamma\gamma \)), tt, tb ..

- \( Z' \) resonance in qq\( \bar{\text{q}} \) merged in 1 jet

Jet-substructure tools are fully exploited!

Sensitivity to \( Z' \) in [50-300] GeV (model dependent)

See Tuesday’s (01/08) BSM session
Alejandro GOMEZ, Norbert NEUMEISTER, Laser KAPLAN, Cristina Ana MANTILLA SUAREZ

Presented at EPS2017

• Excited quarks: \( m < 5.3 \) TeV
• ADD-Quantum black holes: \( m < 7.1 \) TeV
• RS-Quantum black holes: \( m < 4.4 \) TeV
Resonances

- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, heavy higgs (A/H) ...
- New particle can decay into multiple final states:
  - dileptons, lepton + \( E_T^{\text{Miss}} \), dijets, \( \gamma + \text{jets} \), dibosons (VV, \( V \gamma \), \( \gamma \gamma \)), \( tt \), \( tb \) ...

Sensitive to many model of NP, all final states explored: \( \rightarrow llqq, ll\nu\nu, vvqq, lvqq, qqqq, llll \) …

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**2016+Run1 legacy**

- 2.3-2.7 fb\(^{-1}\) (13 TeV) + 19.7 fb\(^{-1}\) (8 TeV)

**ATLAS** Preliminary \( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

95% C.L. exclusion limits

- HVT\(_A\) (\( g_v = 1 \))
- HVT\(_B\) (\( g_v = 3 \))

**probe 2 – 3 TeV mass range in all cases!**

More results: CMS-PAS-B2G-17-005

**See Tuesday’s (01/08) BSM session**

Manuel SILVA (\( \gamma \gamma \) resonance)

**Thursday’s (03/08) BSM session @10:45**

Caterina VERNIERI, Ines OCHOA, Yanchu WANG, Wei TANG
Dark Matter

The Indirect View

- **Simplified models**
  - 2 **new particles**: mediator and stable DM particle
  - **Mediator**: Vector, axial-vector, scalar or pseudoscalar
  - Rich phenomenology depends on mass of DM, mass of heavy mediator, and the value and type of the couplings
  - **Usually two free coupling constants**: $g_M$ and $g_{DM}$

- **Signatures at collider**
  - An object recoiling against large $E_T^{\text{Miss}}$
    - Mono-jet
    - Mono-photon
    - Mono-lepton
    - Mono-W/Z/H
    - Mono-top quark
    - tt/bb pair + DM
  - Boosted boson in association with ISR jet

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Dark Matter: Mono-jet

- Mono-jet: $E_T^{\text{Miss}}$ based signal regions with $E_T^{\text{Miss}} > 250$ GeV

Constrain backgrounds by fitting simultaneously in $W$, $Z/\gamma^*$, tt CRs $\Rightarrow$ systematic uncertainties reduces up to 40%

Variety of interpretations: DM models, SUSY stop in charm + $E_T^{\text{Miss}}$, extra dimensions

Model-dependent summary

ATLAS: arxiv:1704.03848

Similar background estimation in CMS mono-jet analysis (CMS-PAS-EXO-16-048)

See Thursday’s (03/08) BSM session CMS talk by Sonaina UNDLEEB
Dark Matter: di-jet

Di-jet resonance: one fat jet with $p_T > 500$ GeV

Model-dependent summary

Most sensitive limits up to date for leptophobic Z' mediator interacting between quarks and dark matter particles through an axial-vector current

Similar results for vector mediator
New Physics @ HL-LHC

- With luminosity of $7 \times 10^{34}$ Hz/cm$^2$ and a pileup of 200, both ATLAS and CMS foresee rebuilding the Tracker and Hadronic Calorimeter subsystems by 2025

Projections of $Z'$ in $l+$jets @ 13 TeV

![Graph showing projections of $Z'$ in $l+$jets at 13 TeV](image)

**CMS Preliminary Simulation**

**Z' with NWA**

**RS KK Gluon**

**CMS-PAS-FTR-16-005**

**Topcolour $Z'$ using full simulations**

**CMS-PAS-FTR-16-005**

Exclusion limits up to 4 TeV @ 3/ab

**ATL-PHYS-PUB-2017-002**

Exclusion limits up to 4 TeV @ 3/ab

Exclusion limits up to 4 TeV @ 3/ab
New Physics @ HL-LHC

- With luminosity of $7 \times 10^{34}$ Hz/cm$^2$ and a pileup of 200, both ATLAS and CMS foresee rebuilding the Tracker and Hadronic Calorimeter subsystems by 2025

**Mono-jet DM using Delphes Simulations**

**DM: Pseudo-scalar in jet+$E_T^{\text{miss}}$**

**DM: Axial-vector in jet+$E_T^{\text{miss}}$**

Maximum reach in mediator mass ($M_{\text{med}}$) $\approx 3$ TeV @ 3/ab

Reach in dark matter mass ($M_{\text{DM}}$) increases for high $M_{\text{med}}$ with better knowledge of systematic uncertainties.

Sadia Khalil, DPF, Fermilab, USA, Jul-Aug, 2017
• LHC has an **extensive program** for new physics at the energy frontier
• We have developed **sophisticated and ingenious techniques**
• Discovery potential for generic QCD-charged states (stops, gluino) is shrinking but new **opportunities lies at EWK scale**
• Global symmetries provide a suite of new particles to address mass hierarchy
• **Boosted jet substructure** techniques have allowed to probe DM, stops, VLQ, Z’/W’ in corner phase spaces that were not accessible at the LHC before
• **This is less than 10% of the LHC data compared to the expectation of Run2**
  • Many searches must yet be completed and/or will take long time
  • More data and ingenious theoretical guidance may lead to uncover the hidden nature of nature
Prediction is very difficult, especially if it's about the future.

— Niels Bohr —
**Long Lived Particles**

- What makes a particle long-lived?
  - **small couplings:** RPV decays, dark sector coupling
  - **small mass-splittings:** almost degenerate next-LSP
  - heavy messenger: $Z'$, split SUSY
  - hidden valley

**Displaced VERTEX**

- Dedicated re-tracking: Displaced Vertex from LLP
- Map based veto: Mask the detector material that is sensitive to tracks from $K^0_S$ and $\Lambda^0$

**Signal:** non-prompt gluino hadronize to meta-stable R-hadron that decays into SM q and LSP

**Probe lifetimes:** 0.02 - 10 ns

**Other searches with displaced jets, leptons:** EXO-16-003, EXO-16-022
Long Lived Particles

• What makes a particle long-lived?
  • small couplings: RPV decays, dark sector coupling
  • small mass-splittings: almost degenerate next-LSP
    heavy messenger: Z', split SUSY
  • hidden valley

Stopped objects: muons

Signal: LLP - gluinos, multiple charged massive particles that have late decays to muons

Custom trigger: record events out-of-time (50 ns) with pp collisions

Dedicated algorithm: Delayed StandAlone muon tracks

tDT: time at the point of closest approach to the IP measured by Drift Tubes in muon system

tRPC: RPC time for a track

CMS-PAS-EXO-17-004

\[ \beta^{-1} = \frac{c}{v} \propto \text{TOF of DT} \]

Major background:

• cosmic muons

probe lifetimes 100 ns → 10 days

See BSM session on Wed @ 13:30 am
Todd ADAMS

Sadia Khalil, DPF, Fermilab, USA, Jul-Aug, 2017
More on Resonances!

- **Jet-substructure tools are fully exploited!**
  - Spin-3/2 $t^*$ fermion
    - Pair: $t^*t^* \rightarrow tgtg \rightarrow q\bar{q}bg \ l\bar{v}bg$
    - Exclusion limits up to 1.2 TeV

- New resonances in $tt/tb$ production
  - combined $l+jets$ and all-hadronic final states

Similar results from ATLAS!

See Wednesday’s (02/08) BSM session: talk by Douglas BERRY
stops with top-tagging

- Top reconstruction improvements
- New pairing algorithm
- Use of W- & t-tag algorithms

arXiv: 1701.01954

CMS-PAS-SUS-16-050
Resonances

- Sensitive to many BSM scenarios: extra dimensions, new gauge bosons, higgs ...
- New particle can decay into multiple final states:
  - dileptons, lepton+ $E_T^{\text{Miss}}$, dijets, $\gamma$+jets, dibosons ($VV$, $V\gamma$, $\gamma\gamma$), $tt$, $tb$ ..

- No significant deviation in data up to 3 TeV ($Z'$)
- Similar results from CMS:
- Simple SM extensions getting tightly constrained!
**Dark Matter**

**Mono-top:**
- A boosted top-jet recoiling against $E_T^{\text{Miss}}$
- BDT based on substructure observables

**Mono-W/Z/H:**
- W/Z (leptonic or hadronic) recoiling against $E_T^{\text{Miss}}$

Other searches of DM + HF quarks: EXO-16-005, EXO-16-028, ATLAS-CONF-2016-086

Higgs: e.g. in $b\bar{b}$ or $\gamma\gamma$ final states

See Wednesday’s (02/08) DM session:
Yicheng GUO (VV), Chen ZHOU ($\gamma\gamma$), Efe YIGITBASI ($b\bar{b}$)
New Physics @ HL-LHC

- With luminosity of $7 \times 10^{34}$ Hz/cm$^2$ and a pileup of 200, both ATLAS and CMS foresee rebuilding the Tracker and Hadronic Calorimeter subsystems by 2025

Single VLQ, Tpq; $T \rightarrow tH$ in $\ell + jets$

**CMS**

*Preliminary Simulation*

- Expected
- 1 s.d.
- 2 s.d.
- $Tb$, $c_L^{bw}=0.5$, $\delta(T \rightarrow tH)=25$

**Delphes Simulations**

- Sensitive to EWK couplings!
- Expect improvement with new analysis techniques such as subjet b-tagging

Systematic uncertainties play an important role, with largest foreseen from top quark theory $x$-section, PDF, matrix-element $Q^2$ scale
Missing Transverse Energy

negative vector sum of energies of all final state particles
Jet Grooming

• **Pruning** - recluster. Throw out subjets requiring that each recombination satisfy

\[
\frac{\min(p_{T1}, p_{T2})}{p_{Tp}} > 0.1
\]
\[
\Delta R_{12} < 0.5 \times \frac{m_{\text{jet}}}{p_T}
\]

• **Soft drop** - decluster. Throw out subjets which do not satisfy

**Soft Drop Condition:**

\[
\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^\beta
\]
More taggers

**top-tagging**

Reconstruct the two B hadrons from the b and \( \bar{b} \) within the same fat jet

**H-tagging**

- Double tagger
  - \( \Delta R < 0.8 \)

**Boosted tautau-tagging**

CMS-DP-2016/038

- Mistag efficiency

- BTV-13-001, BTV-15-002

Sadia Khalil, DPF, Fermilab, USA, Jul-Aug, 2017
b-jets

- **Combined Secondary Vertex version 2** algorithm: secondary vertex and track-based lifetime informations
  - secondary vertex information is obtained with the Inclusive Vertex Finder algorithm
  - combines the variables with a neural network

weakly decaying b, c (b-c chain) and the principle of the TertiaryVertexTrackFinder TVTF.
• Need a “jet algorithm” to associate the charged/neutral hadrons in a spray to initial quarks and gluons

• Negative vector sum of energies of all final state particles