Searches for signatures of supersymmetry with the $\alpha_T$ variable at CMS

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Outline

- Supersymmetry searches at the LHC
- The $\alpha_T$ hadronic search for supersymmetry
  - Analysis strategy and methods
  - LHC Run 1 $\alpha_T$ supersymmetry search results
- Supersymmetry in LHC Run 2
  - Opportunities and challenges
- The $\alpha_T$ analysis in Run 2
  - Trigger and analysis developments
Signatures of supersymmetry (SUSY)

- Supersymmetric particles share the same couplings as their SM counterparts
  - Dominant production mechanism at the LHC is strong production of squarks and gluinos
  - → Hadronic final states

- If R-parity, \( R_p = (-1)^{3(B-L)+2S} \), is conserved:
  - → Sparticles are pair-produced and decay to sparticle-particle pairs in cascades
  - → The lightest supersymmetry particle (LSP) is stable

- This leads to the typical SUSY event signature for hadronic final states:
  - High-\( p_T \) jets, large jet multiplicities and b-jets
  - Large scalar sum of hadronic energy, \( H_T \)
  - Missing transverse energy (MET) from the LSP
The Compact Muon Solenoid (CMS)

- General purpose detector with large rapidity coverage, $|\eta| < 5$
- Hermetic design provides precise measurement of MET

- Two-level trigger system
  - Hardware: Level-1 trigger (L1)
  - Software: High level trigger (HLT)

- Particle flow (PF) reconstruction
  - Measurement of sub-detectors are combined to individually reconstruct particles
The $\alpha_T$ analysis

- An inclusive hadronic search for supersymmetry (SUSY) with the CMS experiment
  - Event signature: Jets and MET

- Eliminate QCD with the use of the dimensionless kinematic $\alpha_T$ variable
  - $\alpha_T \equiv \frac{E_T^{j_2}}{M_T} \quad M_T = \sqrt{H_T^2 - \hat{H}_T^2}$

- Utilise three discriminating variables: $H_T$, $N_{\text{Jet}}$, $N_{\text{b}}$
  - Categorise signal model topology and better control of backgrounds

- Robust and inclusive search with low-thresholds
  - Provides sensitivity to a large range of SUSY models

\[ \alpha_T = 0.5 \quad \text{Jet} \quad \text{Jet} \]

\[ \alpha_T < 0.5 \quad \text{Jet} \quad \text{Jet} \]

\[ \alpha_T > 0.5 \quad \text{LSP} \quad \text{LSP} \]

\[ \text{QCD} \]

\[ \text{Mismeasurement} \]

\[ \text{Signal} \]

\[ \alpha_T > 0.5 \]

\[ \alpha_T < 0.5 \]

\[ \alpha_T = 0.5 \]
Data driven background estimation

- SM backgrounds with genuine MET remain after $\alpha_T$ selection
  - $t\bar{t}$, $W +$ jets and $Z +$ jets

- Estimate backgrounds using three kinematically similar data control samples
  - $\mu +$ jets, $\mu\mu +$ jets and $\gamma +$ jets
  - Neglect $\mu$, $\gamma$ to emulate background topologies

- Translation factors predict background contamination in signal region from yields in the control samples and MC modelling

- Validate procedure with closure tests using translation factors between control samples
Run 1 results

- Latest published result 11.7 fb\(^{-1}\) at 8 TeV: [arXiv:1303.2985](https://arxiv.org/abs/1303.2985)

- No excess above SM background expectation is observed
  - Set limits on 6 models with simplified model interpretations
  - **Production**: Gluino and squark pairproduction **Decay**: Light flavour, sbottoms and stops

  ![Simplified model diagram](image)

  - From the 6 model interpretations achieve 95\% CL on maximum mass exclusion:
    - **Gluinos**: 950-1125 GeV
    - **Light squarks**: 750 GeV (450 GeV single light squark)
    - **Sbottoms**: 600 GeV

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Coverage of SUSY searches in Run 1

- Current searches at the LHC have set strong limits for large mass splittings.
- The limits for models with small ‘compressed’ mass splittings however are considerably weaker:
  - Challenging due to low visible energy in final state
- Acceptance to compressed spectra can be achieved by exploiting ISR:
  - ISR boosts soft decay products into trigger acceptance
- $\alpha_T$ has extended acceptance to compressed spectra by exploiting ISR and lower trigger thresholds:
  - Analysis of full 18.5 fb$^{-1}$ 8 TeV dataset currently undergoing approval
Supersymmetry in Run 2

- In LHC Run 2 the centre of mass energy will far exceed what was achieved in Run 1
  - $\sqrt{s} = 8 \text{ TeV} \rightarrow 13 \text{ TeV}$

- This will yield a large increase in the production cross section of massive objects
  - Relatively small for Higgs
  - Potentially very large for SUSY

- Run 2 will bring a large boost to sensitivity of SUSY searches
  - Gluinos will be of particular interest in early data

Higgs:
- Mass: 125 GeV
- $\sigma = 2 \times \sigma(8 \text{ TeV})$

Stops:
- $\sim 750 \text{ GeV}$
- $\sigma = 5-10 \times \sigma(8 \text{ TeV})$

Gluinos:
- $\sim 1.4 \text{ TeV}$
- $\sigma = 20-35 \times \sigma(8 \text{ TeV})$
Triggering in Run 2

- In Run 1 $\alpha_T - H_T$ cross triggers enabled low analysis thresholds to be utilised
  - Inefficiencies at low-$H_T$ a result of Level-1 thresholds

<table>
<thead>
<tr>
<th>Offline $H_T$ region (GeV)</th>
<th>Offline $\alpha_T$ threshold</th>
<th>L1 seed (L1_?)</th>
<th>Trigger (HLT_?)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$200 &lt; H_T &lt; 275$</td>
<td>0.65</td>
<td>DoubleJetC64</td>
<td>HT200_AlphaTop57</td>
<td>$81.8^{+0.4}<em>{-0.4}$ $78.9^{+0.3}</em>{-0.4}$</td>
</tr>
<tr>
<td>$275 &lt; H_T &lt; 325$</td>
<td>0.60</td>
<td>DoubleJetC64</td>
<td>HT200_AlphaTop57</td>
<td>$95.2^{+0.3}<em>{-0.4}$ $90.0^{+1.2}</em>{-1.3}$</td>
</tr>
<tr>
<td>$325 &lt; H_T &lt; 375$</td>
<td>0.55</td>
<td>DoubleJetC64 OR HTT175</td>
<td>HT300_AlphaTop53</td>
<td>$97.9^{+0.3}<em>{-0.3}$ $95.6^{+0.9}</em>{-1.0}$</td>
</tr>
<tr>
<td>$375 &lt; H_T &lt; 475$</td>
<td>0.55</td>
<td>DoubleJetC64 OR HTT175</td>
<td>HT350_AlphaTop52</td>
<td>$99.2^{+0.2}<em>{-0.2}$ $98.7^{+0.5}</em>{-0.7}$</td>
</tr>
<tr>
<td>$H_T &gt; 475$</td>
<td>0.55</td>
<td>DoubleJetC64 OR HTT175</td>
<td>HT400_AlphaTop51</td>
<td>$99.8^{+0.1}<em>{-0.3}$ $99.6^{+0.2}</em>{-0.7}$</td>
</tr>
</tbody>
</table>

- The $\alpha_T$ analysis aims to maintain the same trigger acceptance in Run 2, however will be more challenging:
  - Increase in beam energy: $\sqrt{s} = 8$ TeV $\rightarrow$ 13 TeV – QCD cross section increase $\times 2$
  - Reduced bunch spacing: 50 ns $\rightarrow$ 25 ns – Collision rate increase $\times 2$
  - Average pileup 20 $\rightarrow$ 40 will result in a degradation in reconstruction performance

- Developments in triggering aim to mitigate these problems
  - Doubling of high level trigger output bandwidth – Stored data rate $\times 2$
  - Improved pileup subtraction: HLT and Level-1
  - Improved reconstruction: Particle flow, improved calorimeter algorithms
Improvements for the Level-1 trigger

- In Run 2 thresholds on the Level-1 $H_T$ need to be increased to control trigger rate
  - Trigger is still fully efficient for models with large mass splittings
  - Lower efficiency for compressed models which typically populate lower-$H_T$ regions
  - Require new triggers to select these signatures

- Studied new topological Level-1 triggers to suppress QCD whilst retaining signal
  - Veto events with large $\Delta \phi$ separation between leading jets
  - Enables a large reduction in the trigger $H_T$ threshold

- Significant improvement in trigger efficiency for compressed models for new L1 trigger
  - Implemented in hardware and software for CMS-wide trigger studies

<table>
<thead>
<tr>
<th>Signal model ($N_{\text{jet}} = 2$)</th>
<th>Current L1 trigger efficiency</th>
<th>New L1 trigger efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2cc</td>
<td>0.60</td>
<td>0.94</td>
</tr>
<tr>
<td>T2qq</td>
<td>0.63</td>
<td>0.95</td>
</tr>
<tr>
<td>T2tt</td>
<td>0.53</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Run 2 trigger optimisation

- Trigger selection is a multi-dimensional problem
  - Large combination of potential $\alpha_T - H_T$ trigger thresholds and pre-filters with rate constraints
  - Require high efficiency for a range of signal models and analysis selections

- Reduce complexity with $\alpha_T$, $H_T$ parameterised efficiency-rate curves

- QCD pileup is a serious challenge in controlling trigger rates (expect 40 simultaneous interactions)

- Investigating methods for controlling QCD rate in the trigger
  - Implementation of a second jet threshold provides increase in performance relative to 2012 selection

- Trigger selections for Run 2 are currently in the process of being finalised
Run 2 analysis developments

- Transition to particle flow (PF) jet reconstruction with charged hadron pileup subtraction (CHS)
  - Provides improved jet resolution and performance in high-pileup environments
  - Reduced jet radius parameter ($\Delta R = 0.4$) mitigates pileup energy contamination within clustered jets

- Improved event reconstruction and analysis selections to increase analysis acceptance

- Better control of systematics with additional control samples and closure tests
  - Addition of $e +$ jets, $e e +$ jets control samples

- Extend sensitivity to compressed models and monojet-like signatures (DM)
  - Relax second jet threshold to increase acceptance to compressed models

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Compressed model

$H_T > 200, \alpha_T > 0.65$
The $\alpha_T$ analysis is an inclusive and robust search utilising low thresholds to probe a range of SUSY models

- Has set stringent limits on sparticle production for several supersymmetric models with new limits on compressed models to be released soon

Run 2 offers many opportunities for SUSY searches

- New energy frontier provides a large increase in the production rate of heavy particles

The environment in Run 2 however will be challenging

- Latest trigger developments aim to provide the same acceptance as in Run 1
- Analysis developments aim to extend model coverage even further

Eagerly awaiting the start of Run 2

- Run 2 should be particularly sensitive to natural SUSY
- Quickly improve limits (or discover) natural (non-compressed) SUSY
Backup
Supersymmetry

- Supersymmetry is the last available extension to the Poincare symmetry group
  - Space-time symmetry between fermions and bosons → Superpartners to SM particles

Stability of proton motivates conservation of R-parity: $R = (-1)^{3(B-L)+2S}$
  - SM particles: $R = +1$, SUSY particles: $R = -1$
  - Conservation of R-parity implies:
    - Sparticles are produced and annihilate in pairs
    - The lightest supersymmetric particle (LSP) is stable
  - SUSY signatures → Jets, leptons, photons and MET

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SUSY solutions to SM problems

- Unification of gauge coupling constants at GUT scale
  - Introduction of SUSY particles enables unification at $\sim 10^{15}$ GeV

- Supersymmetry provides candidates for dark matter
  - LSP is weakly interacting and stable (conservation of R-Parity)

- Provides a solution to the hierarchy problem
  - Cancellation of quadratic diverges to radiative corrections of the Higgs mass
  - Higgs (125 GeV) discovery motivates focus on natural SUSY
    - $\sim$1 TeV gluino, $\sim$500 GeV 3rd generation squarks and an LSP
Run 1 event selection

- **Jet selection**
  - Jet $E_T > 50$ GeV, $|\eta| < 3$
  - Leading jet: $|\eta| < 2.5$
  - Second jet threshold: $E_T > 100$ GeV, reduced for low-$H_T$
  - Forward jet: No jets with $E_T > 50$ GeV and $|\eta| > 3$

- **Event categorisation**
  - Eight $H_T$ bins: Two 50 GeV bins in range: $275 < H_T < 375$ GeV, five bins 100 GeV in the range: $375 < H_T < 875$ GeV and an open bin: $H_T > 875$ GeV
  - Two jet bins: $2 \leq N_{jet} \leq 3$, $N_{jet} \geq 4$
  - Five b-jet bins: $N_b = 0, 1, 2, 3, \geq 4$

- **$\alpha_T$ threshold scaled with $H_T$ to control QCD**
  - Low $H_T$: $\alpha_T > 0.65$, High $H_T$: $\alpha_T > 0.55$

- **Event vetoes**
  - MHT/MET > 1.25
  - Dead ECAL: Jets in proximity to dead calorimeter regions
  - Isolated $e/\gamma$ $p_T > 10$ GeV
  - Isolated $\mu > 25$ GeV
Analysis backgrounds

- QCD
  - Fake missing energy from detector and acceptance effects
  - Jets below threshold
  - Calorimeter effects

- W + Jets
  - Leptonic decay with lepton outside acceptance/below threshold
  - Hadronic tau decay

- Z + Jets
  - $Z \rightarrow$ Invisible, irreducible background

- $t\bar{t}$
  - Leptonic decay with lepton outside acceptance/below threshold
  - Hadronic tau decay

- Residual backgrounds
  - Single-top, diboson production
$\alpha_T$ Run 1 limits

CMS, 11.7 fb$^{-1}$, $\sqrt{s} = 8$ TeV

**T1qqqq**

**T2qq**
$\alpha_T$ Run 1 limits

CMS, 11.7 fb$^{-1}$, $\sqrt{s} = 8$ TeV

T2bb

T2tt
$\alpha_T$ Run 1 limits

**Diagram 1:**
- Process: $pp \rightarrow g\bar{g}, g \rightarrow t\bar{t}\chi_1^0$; $m(t) >> m(g)$
- Expected Limit $\pm 1\sigma$ exp.
- $\sigma^{\text{NLO+NLL}} \pm 1\sigma$ theory
- CMS, 11.7 fb$^{-1}$, $\sqrt{s} = 8$ TeV

**Diagram 2:**
- Process: $pp \rightarrow g\bar{g}, g \rightarrow b\bar{b}\chi_i^0$; $m(b) >> m(g)$
- Expected Limit $\pm 1\sigma$ exp.
- $\sigma^{\text{NLO+NLL}} \pm 1\sigma$ theory
- CMS, 11.7 fb$^{-1}$, $\sqrt{s} = 8$ TeV

**Diagrams:**
- T1tttt
- T1bbbb
CMS Run 1 limits
Potential reach in Run 2

- In LHC Run 2 the centre of mass energy of will exceed Run 1
  - \( \sqrt{s} = 8 \text{ TeV} \rightarrow 13 \text{ TeV} \)
  - Large increase in the production cross section of massive objects

- Considering current limits and parton scaling alone can provide a naïve estimate of reach with 10 fb\(^{-1}\) at 13 TeV:
  - \( m_{\text{gluino}} = \sim 1.4 \text{ TeV} \rightarrow \sim 1.9 \text{ TeV} \)
  - \( m_{\text{stop}} = \sim 750 \text{ GeV} \rightarrow \sim 950 \text{ GeV} \)
  - Reach is weaker for compressed spectra
Pileup

- 8 TeV event with 29 simultaneous interactions
Triggering at the LHC

- The LHC presents several major challenges to the trigger system
  - **High collision rate** – CMS measures 40 Million events per second, at 1 MB per event this corresponds to ~40 TB/s
  - **Pileup** – 40 overlapping collisions per event
  - **pp collider** – Messy environment, high particle fluxes

- Events are predominantly QCD events of little interest
  - Require a trigger system with huge suppression to reject QCD but retain signal
  - Higgs cross section $10^{10}$ smaller than QCD

![Graph showing Inelastic QCD and Higgs production rates at different energy scales.](Graph.png)
The CMS trigger system

- CMS utilises a two-level trigger system to perform event selection

- Level-1 trigger (L1 trigger)
  - Custom electronics perform a coarse reconstruction of the event (3.2 μs)
  - Only perform reconstruction of calorimeter and muon systems
  - **Rate reduction:** 40 MHz → 100 kHz (1:400)

- High level trigger (HLT)
  - Computer farm (10,000’s of cores) perform a more complete reconstruction (~300 ms)
  - Full detector reconstruction, pileup-subtraction, simple tracking algorithm
  - **Rate reduction:** 100 kHz → ~1 kHz (1:100)