Experiments for Physics Beyond the Standard Model

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Search for Physics Beyond the SM at Colliders

- Introducing Physics Beyond the SM
- Search for New Resonances at the LHC
- Search for Supersymmetry at the LHC

Conclusions
Summary of the SM

Where we stand for now

**Passport**

- **Name:** « Standard Model » of Particle Physics
- **Date of Birth:** 1967
- **Parents:** S. Glashow, A. Salam, S. Weinberg
  - Birth certificates:
    - Nucl. Phys 22 (1961) 579
- **Pediatricians:** G. t’Hooft, M. Veltman
  - First pediatric examination: renormalizable (despite SSB)
- **Particle Content:**
  - Fermions: quarks & leptons (x3 generations)
  - Bosons:
    - Gauge: photon, W, Z, gluons
    - EWSB: Higgs
- **External Symmetries:**
  - Space-time structure: 3-D space, 1-D time, Minkowski metric
  - Poincaré group
    - Lorentz group: space-time rotation, boost
    - Space-time translation
- **Discrete Symmetries:** $C \cdot P \cdot T$
- **Internal Symmetries:** $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- **Visa exemptions:** particles dynamics from low energy up to the EWK scale
**Extending the Gauge Symmetries of the SM**

**Search for Grand Unified Theories**

- **New Particles**: $Z'$, $W'^\pm$, $LQ$, ...  
- **New Phenomena**: $Z - Z'$ mixing, $\sin^2 \theta_W$ (value and evolution), proton lifetime, ...

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**Passport**

- **Name**: « Grand Unified Theories »
- **Date of Birth**: 1974
- **Parents**:
  - S. Glashow, H. Georgi
  - J. Pati, A. Salam, ...
- **Birth certificates**:
  - Phys. Rev. Lett. 32 (1974) 438,
  - Phys. Rev. D10 (1974) 275-289, ...
- **Particle Content**:
  - Includes the SM
  - In addition:
    - Leptoquarks
    - Possible $Z'$ and/or $W'$
    - Possible $\nu_R$
- **Internal Symmetries**:
  - Ex. of Gauge groups:
    
    \[ G_{\text{GUT}} = E_6 \rightarrow SO(10) \times U(1)_Y \rightarrow SU(5) \times U(1)_Y \times U(1)_X \]

    \[ G_{\text{SM}} \ll \]

    \[ G_{\text{Pati-Salam}} = SU(4) \times SU(2)_R \times SU(2)_L \rightarrow SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_B-L \]

    \[ G_{\text{SM}} \times SU(2)_R \ll \]

- **Visa exemptions**: particles dynamics from low energy **up to the GUT scale**
Search for Supersymmetry

- New Particles: Higgs bosons ($A^0, H^0, H^\pm$), Super-partners ($\tilde{\ell}^\pm, \tilde{\nu}, \tilde{q}, \tilde{g},...$)
- New Phenomena: Dark Matter ($\tilde{\chi}_1^0$ or $\tilde{G}_{3/2}$), natural $M_h^{corr}$, quantum gravity,...
Search for $Z'$: Principles

- **Event Topology:** "Charged dilepton" ($\ell = e/\mu$), i.e. all visible decay products
- **Distinctive feature:** signal peaks at $M_{\ell^+\ell^-} \approx M_{Z'}$ over a smooth background (search for resonance)
- **Mass reconstruction:**
  - Easy if FS is only made of visible decay products
  - *In this case, one can rely exclusively on the Final State (FS)!*
  - Invariant mass for N-body decay:
    \[
    M = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{p}_i\right)^2}
    \] (1.a.)

- **Comments:**
  - Full Lorentz invariant
  - This is how the Z mass is measured at collider experiments
Search for New Resonances at the LHC

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  - Easy if FS is only made of visible decay products
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  - Invariant mass for 2-body decay:
    \[ M = \sqrt{2E_{\ell^+}E_{\ell^-} \left[ 1 - \cos(\alpha_{\ell^+,\ell^-}) \right]} \] (1.b.)

- Comments:
  - Full Lorentz invariant
  - This is how the $Z$ mass is measured at collider experiments
Search for $Z'$: Typical Analysis

- **Event Topology:** "Charged dilepton" ($\ell = e/\mu$)
- **Main background process:** $q\bar{q} \rightarrow \gamma^* / Z^* \rightarrow \ell^+\ell^-$ (aka Drell-Yan production)
- **Data sample:** $\int \mathcal{L}dt = 3.2 \text{ fb}^{-1}$ of ATLAS pp collisions at $\sqrt{s} = 13$ TeV (2015)
- **Event Selection:**
  - Trigger: di-electron with $p_T(e^\pm) > 17$ GeV & single muon with $p_T(\mu^\pm) > 26/50$ GeV
  - Offline: 2 OS-SF isolated leptons with $p_T > 30$ GeV
- **Final discriminant:** Dilepton Mass
- **Sensitivity to signal:** depends crucially on
  - Signal natural width: $\Gamma_{Z'}$ (model dependent)
  - Dilepton mass resolution: mainly resulting from $\frac{\sigma_{E}(e^\pm)}{E}(e^\pm)$ or $\frac{\sigma_{p}(\mu^\pm)}{p}(\mu^\pm)$

![Graphs showing Dielectron and Dimuon Invariant Mass Distributions](image-url)
Search for \( Z' \): Typical Analysis

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Search for \( W' \): Principles (1)

- **Event Topology:** \( 1\ell^\pm + \not{\! E}_T \)

- **Distinctive feature:** signal displays a Jacobian peak at \( M_T \approx M_{W'} \) over a smooth background (search for resonance)

- **Mass reconstruction:**
  - More complicated:
    - Can measure the full \( 4 - p \) of the charged lepton
    - But \( \nu \) escapes detection \( \Rightarrow \) both \( E(\nu) \) and \( p_z(\nu) \) are unknown!
    - Full event reconstruction: not possible!

- **Transverse mass for N-body decay:**

\[
M_T = \sqrt{\left( \sum_{i=1}^{N} E_{T_i} \right)^2 - \left( \sum_{i=1}^{N} \vec{p}_{T_i} \right)^2} \tag{2.a.}
\]

- **Ref:** V. Barger et al., Z.Phys. C21 (1983) 99

- **Comments:**
  - Not fully Lorentz invariant (only along longitudinal boosts)
  - This is how the W mass is measured at hadron collider experiments
Search for $W'$: Principles (1)

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\[
M_T = \sqrt{2p_T^{\ell^\pm} p_T^\nu [1 - \cos(\Delta \phi_{\ell^\pm},\nu)]}
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$$M_T = \sqrt{2p_T^{\ell^{\pm}} E_T \left[ 1 - \cos(\Delta \phi_{\ell^{\pm} E_T}) \right]}$$

(2.b.)

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  - Not fully Lorentz invariant (only along longitudinal boosts)
  - This is how the $W$ mass is measured at hadron collider experiments
Search for New Resonances at the LHC

Search for $W'$: Typical Analysis

- Event Topology: $\ell = e/\mu + \not{E}_T$
- Main background process: $q\bar{q} \rightarrow W^* \rightarrow \ell^\pm \nu$ (aka Drell-Yan production)
- Data sample: $\int L dt = fb^{-1}$ of CMS pp collisions at $\sqrt{s} = 13$ TeV (201?)
- Event Selection:
  - Trigger: $1 e^\pm$ w/ $p_T(e^\pm) > 105/115$ GeV or $1 \mu^\pm$ w/ $p_T(\mu^\pm) > 45/50$ GeV
  - Offline: 1 isolated $e^\pm/\mu^\pm$ (reject events w/ 2 leptons), $0.4 < \frac{p_T(\ell^\pm)}{\not{E}_T} < 1.5$
- Final discriminant: Transverse Mass
- Sensitivity to signal: depends crucially on
  - Signal natural width: $\Gamma_{W'}$ (model dependent)
  - Transverse mass resolution: resulting from $\frac{\sigma_{E_T}(e^\pm)}{E_T}$ or $\frac{\sigma_{p_T}(\mu^\pm)}{p_T}$ and $\frac{\not{E}_T}{E_T}$

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Experimtal Searches for Physics Beyond the Standard Model
Search for \( W' \): Typical Analysis

- **Event Topology:** \( \ell = e/\mu + \not{E}_T \)
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  - **Trigger:** 1 \( e^\pm \) w/ \( p_T(e^\pm) > 105/115 \) GeV or 1 \( \mu^\pm \) w/ \( p_T(\mu^\pm) > 45/50 \) GeV
  - **Offline:** 1 isolated \( e^\pm/\mu^\pm \) (reject events w/ 2 leptons), \( 0.4 \frac{p_T(\ell^{\pm})}{E_T} < 1.5 \)
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  - **Transverse mass resolution:** resulting from \( \frac{\sigma_E(e^{\pm})}{E_T} \) or \( \frac{\sigma_P(\mu^{\pm})}{p_T} \) and \( \frac{\not{E}_T}{E_T} \)

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Experimental Searches for Physics Beyond the Standard Model
Search for $W'$: Typical Analysis

- Event Topology: $\ell = e/\mu + \not{E}_T$
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  - Offline: $1$ isolated $e^\pm/\mu^\pm$ (reject events w/ $2$ leptons), $0.4 < \frac{p_T(\ell^\pm)}{\not{E}_T} < 1.5$
- Final discriminant: Transverse Mass
- Sensitivity to signal: depends crucially on
  - Signal natural width: $\Gamma_{W'}$ (model dependent)
  - Transverse mass resolution: resulting from $\frac{\sigma_F}{E}(e^\pm)$ or $\frac{\sigma_P}{p}(\mu^\pm)$ and $\frac{\sigma_{\not{E}_T}}{E}$

![Graph showing sensitivity to signal](image-url)
**Missing Transverse Momentum at Hadron Colliders**

**Definition:** (sum over visible particles)

- Ideally,
  \[
  \vec{p}_T \ = \ \sum_{i=1}^{\text{Invis. Part.}} \vec{p}_{T_i} = - \sum_{i=1}^{\text{Vis. Part.}} \vec{p}_{T_i}
  \]  (1)

- In practice,
  \[
  \begin{cases}
  p_x = - \sum_{j=1}^{\text{Reco. Objects}} p_{xj} - \sum_{j=1}^{\text{Soft Terms}} p_{xj} \\
  p_y = - \sum_{j=1}^{\text{Reco. Objects}} p_{yj} - \sum_{j=1}^{\text{Soft Terms}} p_{yj}
  \end{cases}
  \]  (2)

- Usual language and notations: "Missing Transverse Energy" \( (\vec{E}_x, \vec{y} \equiv \vec{p}_{x, y}) \)
  \[
  \begin{cases}
  E_T = \sqrt{E_x^2 + E_y^2} \\
  \phi(E_T) = \text{Atan} \left( \frac{E_y}{E_x} \right)
  \end{cases}
  \]  (3)
Restriction to the transverse plane for $\vec{E}_T$

- At hadron hadron colliders the kinematics of the hadron collision is fully known (4-momenta of hadrons is known)
- However since these are not elementary, there are two (correlated) parts in the collision

'Hard Scatter': violent collision of 2 partons (quarks or gluons); **of interest to us**

'Underlying Event': debris of hadrons (plus possible secondary Hard Scatter); **a background for us**
Restriction to the transverse plane for $\not{E}_T$

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$P(p_1) = (E = 7000, p_x = 0, p_y = 0, p_z = 7000) \text{ GeV}, \ P(p_2) = (7000, 0, 0, -7000) \text{ GeV}, \ \Rightarrow \sqrt{s} = 14 \text{ TeV}$
Restriction to the transverse plane for $\vec{E}_T$

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\[
P(q_1) = (x_1 \cdot 7000, 0, 0, x_1 \cdot 7000) \text{ GeV},
\]
\[
P(q_2) = (x_2 \cdot 7000, 0, 0, -x_2 \cdot 7000) \text{ GeV} \implies \sqrt{s} = \sqrt{x_1 x_2} \sqrt{\hat{s}} \approx 0.1\text{-few TeV}
\]
At hadron hadron colliders the kinematics of the hadron collision is fully known (4-momenta of hadrons is known)

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often $x_1 \neq x_2$ BOTH UNKNOWN $\Rightarrow$ possible boost along $\pm z$-axis

$0 < x_i < 1$, 
### Restriction to the transverse plane for $E_T$

- At hadron hadron colliders the kinematics of the hadron collision is fully known (4-momenta of hadrons is known)

- However since these are not elementary, there are two (correlated) parts in the collision
  
  - "Hard Scatter": violent collision of 2 partons (quarks or gluons); **of interest to us**
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Even though $(E, \vec{p})$ conservation fully holds, we do not know the partonic Initial State (I.S.)
### Restriction to the transverse plane for $\mathbf{E}_T$

- At hadron hadron colliders the kinematics of the hadron collision is fully known (4-momenta of hadrons is known)
- However since these are not elementary, there are two (correlated) parts in the collision
  - "Hard Scatter": violent collision of 2 partons (quarks or gluons); **of interest to us**
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All we know is

$$p_{x_i}^{l.S.} \approx 0 \text{ and } p_{y_i}^{l.S.} \approx 0$$
Restriction to the transverse plane for $\vec{E}_T$

- At hadron hadron colliders the kinematics of the hadron collision is fully known (4-momenta of hadrons is known)
- However since these are not elementary, there are two (correlated) parts in the collision
  - "Hard Scatter": violent collision of 2 partons (quarks or gluons); of interest to us
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Therefore we can only apply $\vec{p}$ conservation in the TRANSVERSE PLANE
Reminders about Supersymmetry

- **Definition:**
  \[ Q|S >= |S \pm 1/2 > \]  
  \[ \begin{cases} 
  Q|B >= |F > \\
  Q|F >= |B > 
  \end{cases} \] (5)

- **MSSM:** “Minimal Supersymmetric Standard Model”
  - \( \mathcal{N} = 1 \) (SUSY is a broken symmetry)
  - \( G_{MSSM} = G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \)
  - Minimal particle content (but with 5 Higgs bosons, not 1)
### Reminders about Supersymmetry

- **R-Parity:**
  \[
  R_P = (-1)^{L+2S+3B} \tag{6}
  \]
  \[
  \begin{cases}
  R_P = +1(\text{SM}) \\
  R_P = -1(\text{SUSY})
  \end{cases} \tag{7}
  \]

- **$R_P$ Conservation (RPC):**
  - SUSY particles are pair-produced
  - any SUSY particle decays into SM particles + a lighter SUSY particle
  - $\Rightarrow$ the lightest SUSY particle (LSP) is STABLE
  - The proton lifetime not excluded by data (Super-Kamiokande experiment)
  - In gravity-mediated SUSY breaking models, $\tilde{\chi}_1^0$ is the LSP
  - $\tilde{\chi}_1^0$ interacts weakly Rightarrow invisible in LHC detectors
  - $\tilde{\chi}_1^0$ is massive
  - Hence it’s an excellent candidate for Cold Dark Matter (DM)
Extending the Space-Time Symmetries of the SM

**SUSY Mass Spectrum**

- Full SUSY models depend on 19 (SM) + 105 (soft-SUSY breaking) free parameters.
- Once these parameters are set:
  - Masses: of all SUSY particles can be calculated.
  - Couplings: of all SUSY particles can be calculated.
  - These masses & couplings determine how:
    - the Sparticles are produced.
    - the Sparticles decay.
    - the Sparticles (long-lived and LSP) interact in the detectors.

![Graph showing the mass spectrum and resolution for SUSY particles.](image)
Extending the Space-Time Symmetries of the SM

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Extending the Space-Time Symmetries of the SM

**SUSY Strong Production at LHC**
- Shortname: "SUSY QCD"
- Sparticles:
  - $1^{st}$ & $2^{nd}$ generation squarks $\tilde{q}$: scalar $u$, scalar $s$,...
  - $3^{rd}$ generation squarks $\tilde{Q}$: stops ($\tilde{t}_1, \tilde{t}_2$), sbottoms ($\tilde{b}_1,\tilde{b}_2$)
  - gluinos $\tilde{g}$
- Cross section: $\sigma(pp \rightarrow \tilde{q}\tilde{q}/\tilde{g}\tilde{g})_{LO} \propto \alpha_3^2$

**SUSY EWK Production at LHC**
- Shortname: "SUSY EWK"
- Sparticles:
  - sleptons:
    - charged (staus, smuons, selectrons $\tilde{\ell}^\pm$
    - neutral (sneutrinos $\tilde{\nu}$)
  - "electroweakinos":
    - charginos $\tilde{\chi}_1^{\pm}$
    - neutralinos $\tilde{\chi}_1^{0}, \tilde{\chi}_2^{0}$
- Cross section: $\sigma(pp \rightarrow \tilde{\ell}^\pm \tilde{\nu}/\tilde{\chi}_1^{\pm} \tilde{\chi}_2^{0})_{LO} \propto \alpha_2^2$
Extending the Space-Time Symmetries of the SM

**SUSY Strong Production at LHC**

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**SUSY EWK Production at LHC**

- **Shortname:** "SUSY EWK"
- **Sparticles:**
  - sleptons: charged (staus, smuons, selectrons $\tilde{\ell}^\pm$), neutral (sneutrinos $\tilde{\nu}$)
  - "electroweakinos": charginos $\tilde{\chi}_1^\pm$, neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0$...
- **Cross section:** $\sigma(pp \rightarrow \tilde{\ell}^\pm \tilde{\nu}/\tilde{\chi}_1^\pm \tilde{\chi}_2^0)_{LO} \propto \alpha_2^2$
Decay of Strong SUSY Particles

- **State-of-the-art theory prediction:**
  - Matrix Elements (MEs): \( \sigma_{NLO} \) (Next-to-Leading Order: "1-loop" QCD corrections)
  - Resummation: \( \sigma_{NLL} \) (Next-to-Leading Logs)

![Graph showing SUSY particle cross-sections](image)
State-of-the-art theory prediction:

- Matrix Elements (MEs): $\sigma_{NLO}$ (Next-to-Leading Order: "1-loop" QCD corrections)
- Resummation: $\sigma_{NLL}$ (Next-to-Leading Logs)
Extending the Space-Time Symmetries of the SM

Decay of Strong SUSY Particles

Decay of EWK SUSY Particles
Extending the Space-Time Symmetries of the SM

Decay of Strong SUSY Particles

Decay of EWK SUSY Particles
Relation between Decay Chain & Search Topology

- Simple example:
  squarks pair production searched for in the acoplanar $2j + E_T$ event topology

- General case: $(n)j + (m)\ell^\pm + (p)\gamma + E_T$ event topology
  - with different jet flavours: $b - jets$, $c - jets$, $\tau - jets$, $LF - jets$ ($LF$: u/d/s/g)
  - $\ell^\pm$ stands for $e^\pm$ or $\mu^\pm$
**Relation between Decay Chain & Search Topology**

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  - $\ell^\pm$ stands for $e^\pm$ or $\mu^\pm$
Search for squarks & gluinos: Specific Variables

- Event Topology: products \((n)j + (m)\ell^\pm + \not{E}_T\) \((p \neq 0\) for GMSB\)
- No obvious distinctive features over the large QCD background
- Usual Angular Variables:

\[
\begin{align*}
  y &= \frac{1}{2} \log \frac{E+p_z}{E-p_z} \\
  \eta &= -\log \left( \tan \frac{\theta}{2} \right) \\
  \Delta R &= \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \\
  \Delta \phi_{\text{min}}(\text{jets}, \not{E}_T)
\end{align*}
\]
Search for squarks & gluinos: Specific Variables

- Effective Mass:

\[ M_{\text{eff}} = \sum_{i=1}^{N} p_{T_i}^{\text{jets}} + p_{T_i}^{\text{leptons}} + E_T \] (9)

- Not Lorentz invariant
- But, sensitive to mass scale
- \( pp \to \tilde{g} + \tilde{q} \): \( M_{\text{eff}} \text{Min}(M_{\tilde{g}}, M_{\tilde{q}}) \)
- Yet, not precise and slightly biased


Search for \( Z' \rightarrow t\bar{t} \)
Search for squarks & gluinos: Specific Variables

- **S**transverse Mass:
  - Partly Lorentz invariant (only along longitudinal boosts)
  - Sensitive to mass difference
  - In practice end-points are difficult to measure (smearing, background, pile-up,...)

\[
M_{T2} \left[ \text{vis}^{(A)}, \text{vis}^{(B)} | M_{\chi}^{\text{trial}} \right] =
\min_{\vec{F}_T = \vec{E}_T} \gamma^{(A)} + \gamma^{(B)} \max \left[ M_T (\vec{p}_T^{\text{vis}(A)}, \vec{E}_T | M_{\chi}^{\text{trial}}), M_T (\vec{p}_T^{\text{vis}(B)}, \vec{E}_T | M_{\chi}^{\text{trial}}) \right]
\]

\[
M_T^{2(A)} = M_T^{2(A)} + M_T^{2(\chi A)} + 2 \left[ E_T^{(A)} E_T^{(\chi A)} - \vec{p}_T^{(A)} \vec{p}_T^{(\chi A)} \right]
\]

\[
M_{T2} \leq M_{\text{Parent}} \text{ and } M_{T2}^{\text{Edge}} \approx M_{\text{Parent}}
\]

( provided \( M_{\chi} = M_{\chi_1} \) )

---

Steve Muanza  
**Expermintal Searches for Physics Beyond the Standard Model**
Search for squarks & gluinos: Specific Variables

**Stransverse Mass:**
- Partly Lorentz invariant (only along longitudinal boosts)
- Sensitive to mass difference
- In practice end-points are difficult to measure (smearing, background, pile-up, ...)

\[
M_{T2}\left[\text{vis}^{(A)}, \text{vis}^{(B)}|M_{\chi}^{\text{trial}}\right] =
\min_{\not{\tau}_T=\not{\tau}_T+\not{\tau}_T} \max \left[ M_T(\not{p}_T^{\text{vis}(A)}, \not{E}_T^{(A)}|M_{\chi}^{\text{trial}}), M_T(\not{p}_T^{\text{vis}(B)}) \right]
\]

\[
M_T^{2(A)} = M^{2(A)} + M^{2(\chi_A)} + 2 \left[ E_T^{(A)} E_T^{(\chi_A)} - \not{p}_T^{(A)} \not{p}_T^{(\chi_A)} \right]
\]

\[
M_{T2} \leq M_{\text{Parent}} \quad \text{and} \quad M_{T2}^{\text{Edge}} \approx M_{\text{Parent}}
\]

( provided \( M_{\chi} = M_{\chi_1}^{0} \))
Search for squarks and gluinos: Typical $M_{T2}$-based Search

- Event Topology: "$(n_{LF})j + (n_b)j + (0)\ell^\pm \not{E_T}$"
- Main background process: $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, $W^\pm(\rightarrow \ell^\pm \nu) + \text{jets}$, $t\bar{t}$ and QCD
- Data sample: $\int \mathcal{L}dt = 19.5 \text{ fb}^{-1}$ of CMS pp collisions at $\sqrt{s} = 8 \text{ TeV}$ (2012)
- Event Selection: $H_T = \sum_{i=1}^{N_j} p_{T_i}$
  - Trigger: $H_T > 650 \text{ GeV}$ OR $\not{E_T} > 150 \text{ GeV}$ OR $H_T > 350 \text{ GeV}$ AND $\not{E_T} > 100 \text{ GeV}$
  - Offline: 2 jets with $p_T > 100 \text{ GeV}$ and $|\eta| < 3.0$
    - $H_T > 750 \text{ GeV}$, OR $H_T > 450 \text{ GeV}$, AND $\not{E_T} > 200 \text{ GeV}$
    - suppress QCD: $\Delta \phi_{\text{min}}(\text{jets}, \not{E_T}) > 0.3 \text{ rad}$
- Final discriminant: events are clustered into 2 fat jets, $M_{T2} > 100 - 200 \text{ GeV}$

![Event topology and H_T cuts](image-url)
Search for Physics Beyond the SM at Colliders
Conclusions
Introducing Physics Beyond the SM
Search for New Resonances at the LHC
Search for Supersymmetry at the LHC
Search for SUSY at the LHC

Event Topology: 

\( (n_{LF})j + (n_b)j + (0)\ell^\pm \not{E_T} \)

Main background process: 

- \( Z(\rightarrow \nu\bar{\nu}) + \text{jets} \)
- \( W^\pm(\rightarrow \ell^\pm \nu) + \text{jets} \)
- \( t\bar{t} \) and QCD

Data sample: \( \int \mathcal{L} \, dt = 19.5 \, fb^{-1} \) of CMS pp collisions at \( \sqrt{s} = 8 \, TeV \) (2012)

Event Selection: 

\( H_T = \sum_{i=1}^{N_j} p_T^i \)

- Trigger: \( H_T > 650 \, GeV \) OR \( \not{E_T} > 150 \, GeV \) OR \( H_T > 350 \, GeV \) AND \( \not{E_T} > 100 \, GeV \)
- Offline: 2 jets with \( p_T > 100 \, GeV \) and \( |\eta| < 3.0 \)

\( H_T > 750 \, GeV \), OR \( H_T > 450 \, GeV \), AND \( \not{E_T} > 200 \, GeV \)

suppress QCD: \( \Delta \phi_{min}(\text{jets}, \not{E_T}) > 0.3 \, rad \)

Final discriminant: events are clustered into 2 fat jets, \( M_{T2} > 100 - 200 \, GeV \)
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Search for squarks and gluinos: Typical $M_{T2}$-based Search

- Event Topology: "$ (n_{LF})j + (n_b)j + (0)\ell^{\pm} E_T^- $"
- Main background process: $Z(\rightarrow \nu\bar{\nu}) + \text{jets}, W^{\pm}(\rightarrow \ell^{\pm}\nu) + \text{jets}, t\bar{t} \text{ and QCD}$
- Data sample: $\int L dt = 19.5 \text{ fb}^{-1}$ of CMS pp collisions at $\sqrt{s} = 8 \text{ TeV}$ (2012)
- Event Selection: $H_T = \sum_{i=1}^{N_j} p_{T_i}$
  - Trigger: $H_T > 650 \text{ GeV}$ OR $E_T^- > 150 \text{ GeV}$ OR $H_T > 350 \text{ GeV}$ AND $E_T^- > 100 \text{ GeV}$
  - Offline: 2 jets with $p_T > 100 \text{ GeV}$ and $|\eta| < 3.0$
    - $H_T > 750 \text{ GeV}$, OR $H_T > 450 \text{ GeV}$, AND $E_T^- > 200 \text{ GeV}$
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Search for Supersymmetry at the LHC

Search for SUSY at the LHC

Event Topology: 

\[ \text{Event Topology: } (n_{\text{LF}})j + (n_{\text{b}})j + (0)\ell^\pm \slashed{E}_T \]

Main background process: 

\[ Z(\to \nu \bar{\nu}) + \text{jets}, \ W^{\pm}(\to \ell^\pm \nu) + \text{jets}, \ t\bar{t} \text{ and QCD} \]

Data sample: \( \int \mathcal{L} dt = 19.5 \text{ fb}^{-1} \) of CMS pp collisions at \( \sqrt{s} = 8 \text{ TeV} \) (2012)

Event Selection: 

\[ H_T = \sum_{i=1}^{N_j} p_T_i \]

- Trigger: \( H_T > 650 \text{ GeV} \) OR \( \slashed{E}_T > 150 \text{ GeV} \) OR \( H_T > 350 \text{ GeV} \) & \( \slashed{E}_T > 100 \text{ GeV} \)
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Final discriminant: events are clustered into 2 fat jets, \( M_{T2} > 100 - 200 \text{ GeV} \)
Dilpeton Mass Edge:
- Lorentz invariant
- Sensitive to mass difference
- Very accurate

\[ pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow 3\ell^\pm + \not{E}_T \]

2-body DK:

\[
M_{\ell^+\ell^-}^{\text{max}} = M_{\tilde{\chi}_2^0} \times \sqrt{\left(1 - \frac{M_{\ell^\pm}^2}{M_{\tilde{\chi}_2^0}^2}\right) \left(1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\ell^\pm}^2}\right)}
\]

\[ (13) \]

3-body DK:

\[
M_{\ell^+\ell^-}^{\text{max}} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}
\]

\[ (14) \]


**Figure:** \( \tilde{\chi}_2^0 \) 2-body (top) and 3-body (bottom) leptonic decay
Search for Direct Production of Electroweakinos: Specific Variables

- **Dilpeton Mass Edge:**
  - Lorentz invariant
  - Sensitive to mass difference
  - Very accurate
  
  \[ pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow 3\ell^\pm + \not\!E_T \]

- **2-body DK:**
  \[ M_{\ell^+\ell^-}^{\text{max}} = M_{\tilde{\chi}_2^0} \times \sqrt{\left( 1 - \frac{M_{\ell^+}^2}{M_{\tilde{\chi}_2^0}^2} \right) \left( 1 - \frac{M_{\ell^-}^2}{M_{\tilde{\chi}_2^0}^2} \right)} \]
  \[ (13) \]

- **3-body DK:**
  \[ M_{\ell^+\ell^-}^{\text{max}} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \]
  \[ (14) \]


**Figure:** \( \tilde{\chi}_2^0 \) 2-body (top) and 3-body (bottom) leptonic decay
Search for Direct Production of Electroweakinos: Specific Variables

- **Integral Charge Asymmetry:**
  - Statistical variable (not event variable)
  - Sensitive to mass scale
  - Moderately accurate
  - Almost model-independent (relies on PDFs)
  - \( pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to 3\ell^\pm + \not\!E_T \)
  - \[
  A_C = \frac{N_{\ell^+} - N_{\ell^-}}{N_{\ell^+} + N_{\ell^-}}
  \] (15)

- Enables to measure \( M_{\tilde{\chi}_1^\pm} + M_{\tilde{\chi}_2^0} \)

- Complementary of other techniques that access mass differences

  Evolution of \( A_C \) is driven by the DGLAP evolution of the PDFs and parametrized as follows:

  \[
  A_C[M_{\tilde{\chi}_1^\pm} + M_{\tilde{\chi}_2^0}] = \sum_{i=0}^{N} A_i \times \left[ \log \left[ \log \left( M_{\tilde{\chi}_1^\pm} + M_{\tilde{\chi}_2^0} \right) \right] \right]^i
  \] (16)

Search for Direct Production of Electroweakinos: Specific Variables

- **Integral Charge Asymmetry:**
  - Statistical variable (not event variable)
  - Sensitive to mass scale
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  - Sensitive to mass scale
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  \[
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  \]

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  A_C = \frac{N_{\ell^+} - N_{\ell^-}}{N_{\ell^+} + N_{\ell^-}} \quad (15)
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  \]

Search for SUSY at the LHC

Search for chargino-neutralino pairs: Typical Search → Link
Search for Physics Beyond the SM at Colliders

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Search for SUSY at the LHC

**Search for chargino-neutralino pairs: Typical Search**

- **Event Topology:** "3ℓ⁺⁻ + ℋ_T"
- **Main background process:** \( W^{\pm}(\rightarrow ℓ^{\pm}ν) + Z(\rightarrow ℓ^+ℓ^-) \)
- **Data sample:** \( \int \mathcal{L} dt = 36.1 \text{ fb}^{-1} \) of ATLAS pp collisions at \( \sqrt{s} = 13 \text{ TeV} \) (2015-2016)
- **Event Selection:**
  - **Trigger:** dilepton
  - **Offline:**

<table>
<thead>
<tr>
<th>( m_{S\Phi\Omega} ) [GeV]</th>
<th>( E_T^{miss} ) [GeV]</th>
<th>( p_T^{\ell_3} ) [GeV]</th>
<th>( n_{non-b-tagged\ jets} )</th>
<th>( m_T^{min} ) [GeV]</th>
<th>( p_T^{\ell\ell} ) [GeV]</th>
<th>( p_T^{jetl} ) [GeV]</th>
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<td>&lt;81.2</td>
<td>&gt; 130</td>
<td>20–30</td>
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<td>&gt; 110</td>
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<td></td>
<td>SR3-slep-a, SR3-slep-b</td>
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<td>20–50</td>
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<td>≥ 1</td>
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<td>70</td>
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Search for Physics Beyond the SM at Colliders

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Search for SUSY at the LHC

Search for chargino-neutralino pairs: Typical Search

![Graph showing search for chargino-neutralino pairs](Link)
### Search for Physics Beyond the Standard Model

**Conclusions**

- Search for Physics Beyond the SM at Colliders
- Search for New Resonances at the LHC
- Search for Supersymmetry at the LHC

### Search for SUSY at the LHC

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#### Search for chargino-neutralino pairs: Typical Search

<table>
<thead>
<tr>
<th>Signal channel</th>
<th>Region</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{exp}}$</th>
<th>$\langle\varepsilon\sigma\rangle_{\text{obs}}^{95}[\text{fb}]$</th>
<th>$S_{\text{obs}}^{95}$</th>
<th>$S_{\text{exp}}^{95}$</th>
<th>$p(s=0)$</th>
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<td>SF-loose</td>
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<td>9.8 ± 2.9</td>
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<td>$6.8^{+2.9}_{-1.3}$</td>
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<td>slep-e</td>
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<td>$3.6^{+1.3}_{-0.5}$</td>
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</tbody>
</table>
Search for SUSY at the LHC

Search for challino-neutralino pairs: Typical Search

\[ \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to \tilde{\ell}_L \tilde{\ell}_L (\ell \bar{\nu}) \text{ or } l \nu \tilde{\ell}_R \tilde{\ell}_R (\nu \bar{\ell}) \rightarrow l \nu \tilde{\chi}_1^0 \tilde{\ell}_R (\nu \bar{\ell}) \tilde{\chi}_1^0 \]

**ATLAS**

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

All limits at 95% CL

- Observed limit \( (\pm 1 \sigma_{\text{Theory}}) \)
- Expected limit \( (\pm 1 \sigma_{\text{exp}}) \)

ATLAS 8 TeV arXiv:1402.7029
Search for SUSY at the LHC

Search for chargino-neutralino pairs: Typical Search

\[ \tilde{\chi}^\pm_1 \tilde{\chi}^0_2 \rightarrow W \tilde{\chi}^0_1 Z \tilde{\chi}^0_1 \]

ATLAS

\[ \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \]

All limits at 95% CL

Observed limit (\( \pm 1 \sigma_{\text{Theory}} \))

Expected limit (\( \pm 1 \sigma_{\text{exp}} \))

ATLAS 8 TeV arXiv:1403.5294

Steve Muanza

Experimental Searches for Physics Beyond the Standard Model
### ATLAS and CMS Latest Limits

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
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*Search for BSM at the LHC*