Searching for Supersymmetry at the LHC

Jeffrey D. Richman (UC Santa Barbara)

Colloquium, Department of Physics, University of New Mexico, Albuquerque, November 7, 2014
F.A.Q.s
ABOUT THE
HADRON COLLIDER

Q: How does the Hadron Collider work?
A: You didn't even understand eleventh-grade math, so why are you asking?

Q: How many miles of pipes and whatnot are in it?
A: A bajillion.

Q: How much did it cost?
A: Forty squillion.

Q: What would happen if I went inside it?
A: Just. Don't.

Q: What does this thing do?
A: Don't touch that.

Q: What would happen if you, like, put a cat inside it?
A: I don't know.

Q: If I concentrate ultra-hard, will I ever be able to understand it?
A: No.
Outline

• Overview: mass scales
• What is supersymmetry?
• The Higgs, SUSY, and “naturalness”
• The LHC and CMS
• Searching for dark matter, scalar quarks, gluinos,...
• Prospects for Run 2 and beyond
• Conclusions

Drawing courtesy Sergio Cittolin

CMS PUBLIC SUSY RESULTS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Most results use 19.5 fb^{-1} (√s =8 TeV).
Key mass scales in particle physics

- **Electroweak scale**
  - $t$: 172 GeV
  - $W$: 80.4 GeV
  - $Z$: 91.2 GeV
- **Generational puzzle**
  - Hadronic mass scale
    - $\tau$: 1777 MeV
    - $\mu$: 106 MeV
    - $\tau$: 939.6 MeV
    - $\mu$: 938.3 MeV
- **Fragmentation puzzle**
  - $\nu$: 0.511 MeV
  - $\nu$: 1.27 GeV
  - $\nu$: 80.4 GeV
  - $\nu$: 91.2 GeV
- **Dark matter?**
  - $M$: 1.27 TeV
  - $M$: 1.07 TeV

**Si band gap:** $\approx 1.1$ eV

**Masses**
- $M(e) = 0.511$ eV
- $M(\mu) = 106$ MeV
- $M(\tau) = 1777$ MeV
- $M(p) = 939.6$ MeV
- $M(n) = 938.3$ MeV
- $M(u) = 2.5$ MeV
- $M(c) = 1.27$ GeV
- $M(t) = 172$ GeV
- $M(W) = 80.4$ GeV
- $M(Z) = 91.2$ GeV
- $M(H) = 125$ GeV

**Planck mass**

$$M_{\text{Planck}} \approx 10^{18} \text{ GeV}$$
Key mass scales in particle physics

- **SUSY?**
- **Dark matter?**
- **New gauge bosons?**

The LHC is a tool to explore the electroweak scale and beyond.

Si band gap: ≈ 1.1 eV  
\( m(\nu) \approx 0.1 \text{ eV?} \)  
\( m(\tilde{\gamma}) \approx 2 \text{ TeV?} \)  
\( M_{\text{Planck}} \approx 10^{18} \text{ GeV} \)
Symmetries in particle physics

- Theories of particle physics are built around a set (group) of assumed symmetry transformations that leave the action invariant.

\[ S = \int \mathcal{L} \, d^4x \rightarrow S' = S \]

under specified group of transformations acting on fields or coordinates

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>Symmetry operation</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacetime symmetries</td>
<td>Poincaré group: act on spacetime coords</td>
<td>Laws of physics are invariant under Poincare xfs; cons. of ( P, J ), etc.</td>
</tr>
<tr>
<td>Continuous global symmetries</td>
<td>e.g., U(1) phase xf’s</td>
<td>Conservation of charge (additively conserved quantum numbers)</td>
</tr>
<tr>
<td>Gauge (local) symmetries</td>
<td>SU(3)_c × SU(2)_L × U(1)_Y is gauge group of SM</td>
<td>Specify the form of interactions; predict specific gauge fields</td>
</tr>
<tr>
<td>Discrete symmetries</td>
<td>C, P, T, CP, CPT</td>
<td>Matter-antimatter relations, parity, time-reversal, etc.</td>
</tr>
</tbody>
</table>
Matter, antimatter, and CPT

- Dirac relativistic wave equation (1928): extra, “negative-energy” solutions.
- Positron interpretation confirmed by C.D. Anderson (cosmic ray experiment) at Caltech.

\[ a \rightarrow \bar{a} : \quad q_a = -q_{\bar{a}}, \quad m_a = m_{\bar{a}}, \quad \tau_a = \tau_{\bar{a}} \]

(CPT)

Author lists were shorter back in 1933...

March 15, 1933

Physical Review

Volume 43

The Positive Electron

Carl D. Anderson, California Institute of Technology, Pasadena, California

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

On August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no
Supersymmetry transformations

• SUSY xf’s map fermionic and bosonic degrees of freedom onto each other, e.g., $e^- (s = 1/2) \rightarrow \tilde{e}^- (s = 0)$

• $Q$ = generator of SUSY transformation

$$Q |s\rangle = |f\rangle$$

Q must be fermionic in character!

- boson (J=0 or J=1)
- fermion (J=1/2)

• The charges (interaction couplings) are unchanged.

• Doubles the numbers of degrees of freedom in the particle spectrum (but CPT did that too!)

• Unlike CPT, don’t see SUSY partners with same masses as SM $\Rightarrow$ if SUSY exists, it must be broken.
Particle content of the SM

Quarks: spin-1/2
- $u$: up
- $c$: charm
- $t$: top
- $d$: down
- $s$: strange
- $b$: bottom

Leptons: spin-1/2
- $e^-$: electron
- $\mu^-$: muon
- $\tau^-$: tau
- $\nu_e$: electron neutrino
- $\nu_\mu$: muon neutrino
- $\nu_\tau$: tau neutrino

Gauge bosons: spin-1
- Strong force: $g$, gluon (8)
- EM force: $\gamma$, photon
- Weak force: $Z^0$, $W^+$, $W^-$

Higgs boson: spin-0
- $H$, Higgs boson

And field vacuum expectation value

Quarks: spin-1/2
- $u$, up
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Higgs boson: spin-0
- $H$, Higgs boson

And field vacuum expectation value
Simple (naïve) SUSY spectrum

squarks: spin-0

<table>
<thead>
<tr>
<th>Squark</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>(\tilde{u})</td>
</tr>
<tr>
<td>Charm</td>
<td>(\tilde{c})</td>
</tr>
<tr>
<td>Top</td>
<td>(\tilde{t})</td>
</tr>
<tr>
<td>Down</td>
<td>(\tilde{d})</td>
</tr>
<tr>
<td>Strange</td>
<td>(\tilde{s})</td>
</tr>
<tr>
<td>Bottom</td>
<td>(\tilde{b})</td>
</tr>
</tbody>
</table>

scalar quark

sleptons: spin-0

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Symbol</th>
<th>Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selectron</td>
<td>(\tilde{e}^-)</td>
<td>Electron sneutrino</td>
</tr>
<tr>
<td>Smuon</td>
<td>(\tilde{\mu}^-)</td>
<td>Muon sneutrino</td>
</tr>
<tr>
<td>Stau</td>
<td>(\tilde{\tau}^-)</td>
<td>Tau sneutrino</td>
</tr>
<tr>
<td>Electron sneutrino</td>
<td>(\tilde{\nu}_e)</td>
<td></td>
</tr>
<tr>
<td>Muon sneutrino</td>
<td>(\tilde{\nu}_\mu)</td>
<td></td>
</tr>
<tr>
<td>Tau sneutrino</td>
<td>(\tilde{\nu}_\tau)</td>
<td></td>
</tr>
</tbody>
</table>

Gauginos: spin-1/2 “-ino” \(\rightarrow J=1/2\)

<table>
<thead>
<tr>
<th>Force</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>(\tilde{g})</td>
</tr>
<tr>
<td>EM</td>
<td>(\tilde{\gamma})</td>
</tr>
<tr>
<td>Weak</td>
<td>(\tilde{Z}^0)</td>
</tr>
<tr>
<td></td>
<td>(\tilde{W}^+)</td>
</tr>
<tr>
<td></td>
<td>(\tilde{W}^-)</td>
</tr>
<tr>
<td></td>
<td>(\tilde{H})</td>
</tr>
</tbody>
</table>
Scalar SUSY particles and chiral multiplets

- The SM is a **chiral theory**: the L and R chiral projections of the fermion fields have different EW interaction quantum numbers.
  - L projections are SU(2)_L doublets \( \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \), \( u_R \), \( d_R \)
  - R projections are SU(2)_L singlets
- Each chiral projection of a SM fermion has SUSY scalar partner (preserving degrees of freedom).

![Diagram of fermion and scalar partners]

- partner of the R-handed \( e^- \); has J=0, no helicity.
SUSY spectrum in gauge/higgs sector (MSSM)

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$\tilde{W}^-$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$Z$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$H$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$h$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$H^+$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$H^-$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$A$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

Gauginos = SUSY partners of SM gauge bosons
Higgsinos = SUSY partners of higgs bosons
Neutralinos = mix of neutral gauginos and higgsinos
Charginos = mix of charged gauginos and higgsinos
EWKinos = term that denotes neutralinos or charginos

The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.

If lightest neutralino is LSP, then can be dark matter candidate.

Mixing
The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.
<table>
<thead>
<tr>
<th>Sector of MSSM</th>
<th>Number of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model parameters</td>
<td>18</td>
</tr>
<tr>
<td>1 Higgs parameter, analogous to Higgs mass in SM</td>
<td>1</td>
</tr>
<tr>
<td>Gaugino/higgsino sector</td>
<td>5</td>
</tr>
<tr>
<td>Gaugino/higgsino sector – CP violating phases</td>
<td>3</td>
</tr>
<tr>
<td>Squark and slepton masses</td>
<td>21</td>
</tr>
<tr>
<td>Mixing angles to define squark and slepton mass eigenstates</td>
<td>36</td>
</tr>
<tr>
<td>CP violating phases</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>124</strong></td>
</tr>
</tbody>
</table>

In cMSSM, SUSY is described by just 4 continuous real params + 1 sign.
Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world’s most powerful particle accelerator, as well as a $6 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

...ouch.
Why are we still looking for SUSY?

<table>
<thead>
<tr>
<th>Hierarchy problem</th>
<th>Unification of couplings</th>
<th>Dark matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>~$10^{18}$ GeV</td>
<td>SM (no SUSY)</td>
<td>Atoms: 4.6%</td>
</tr>
<tr>
<td>Planck scale</td>
<td></td>
<td>Dark matter: 24%</td>
</tr>
<tr>
<td>(quantum gravity)</td>
<td>SM (no SUSY)</td>
<td>Dark energy: 71.4%</td>
</tr>
<tr>
<td>Separation of scales</td>
<td>MSSM</td>
<td>SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.</td>
</tr>
<tr>
<td>is stabilized by SUSY.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~$10^2$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electroweak scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unstable in SM)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Higgs and the Gauge Hierarchy Problem

• Evidence is very strong that the new particle discovered at $m \approx 125$ GeV is a/the Higgs boson, with the quantum numbers $J^{PC} = 0^{++}$ (scalar).

• Assuming that it is an *elementary scalar* particle, the Higgs mass is subject to enormous shifts due to short distance quantum corrections.

• These corrections pull the Higgs mass up to a high physical scale, e.g., the Planck scale!

\[ \text{f = SM fermion, e.g., top quark} \]

\[ \text{S = SUSY scalar partner, e.g., top squark} \]

SUSY amplitudes tame the quantum corrections!
“Natural SUSY endures”: the current fashion

Only part of the SUSY spectrum can be constrained by naturalness considerations.

M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926

natural SUSY  decoupled SUSY
Large Hadron Collider

C = 27 km (16.9 mi)

$E_{CM} = 2E(\text{beam}) = 8 \text{ TeV (Run 1), 13 TeV (Run 2)}$
LHC ring: 2 separate magnetic “highways”

- CMS Experiment, (Cessy, France)
- LHCb Experiment
- ATLAS Experiment
- Alice Experiment

- 9300 magnets, including 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)
Proton beam

Detector to observe outcome of the proton-proton collisions.
CMS DETECTOR

- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE

12,500 tonnes

SILICON TRACKERS

- Pixel (100x150 μm): 16m² ~66M channels
- Microstrips (80x180 μm): 200m² ~9.6M channels

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying ~18,000A

MUON CHAMBERS

- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER

Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)

~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)

Brass + Plastic scintillator ~7,000 channels
Working on the CMS detector
Installing CMS muon readout electronics
Installing muon readout electronics

Superconducting solenoid (6m diameter):
B-field (3.8 T) parallel to beam axis

Endcap detectors  Central barrel detectors
CMS Silicon-Strip Tracker Inner Barrel Detector
CMS Electromagnetic Calorimeter (ECAL)

- Barrel/Endcap: 61,200 / 2×7,324 PbWO₄ crystals
- Rad-hard, very fast (80% of light in 25 ns) \( \frac{\sigma_E}{E} \approx 0.8\% - 0.4\% \) (\( E \approx 25 - 200 \) GeV)
- 25.8 and 24.7 \( X_0 \); about 1 \( \lambda_0 \) (\( X_0 = 0.89 \) cm)
- Barrel inner radius: 129 cm (operates in B field!)
- Low light yield (30 \( \gamma/\text{MeV} \)); use avalanche photodiodes
- Coverage: \( |\eta| < 1.479 \) (barrel), 1.479\( < |\eta| < 3.0 \) (endcap)

Crystal face: 22 × 22 mm\(^2\)
Length: 230 mm
Beam Pipe at LHC Point 5
Proton-proton collision in CMS: animation
Proton-proton collisions

Top-quark pair production via gluon-gluon fusion.

Top-quark pair production via quark-antiquark annihilation.

Broad range of CM energies for parton-parton collision. A priori, we don’t know the Lorentz boost to this rest frame!
Huge QCD cross section: pp → jets

Di-jet mass = 764 GeV

Jet $p_T$ resolution: 15% for $p_T=10$ GeV, 8% for $p_T=100$ GeV, 4% for $p_T=1$ TeV
$H \rightarrow ZZ^*, \ Z \rightarrow \mu^+\mu^-, \ Z^* \rightarrow \mu^+\mu^-$

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86

$4\mu+\gamma$ Mass: 126.1 GeV

$(Z_1) E_T : 8 \text{ GeV}$

$\mu^-(Z_1) p_T : 28 \text{ GeV}$

$\mu^+(Z_2) p_T : 6 \text{ GeV}$

$\mu^+(Z_1) p_T : 67 \text{ GeV}$

$\mu^-(Z_2) p_T : 14 \text{ GeV}$

7 TeV DATA
Higgs boson $\rightarrow$ two $Z$ bosons $\rightarrow$ 4 leptons

$\sqrt{s} = 7 \text{ TeV}: L = 0.0 \text{ fb}^{-1}$
Higgs boson $\rightarrow$ two $Z$ bosons $\rightarrow$ 4 leptons

Can calculate the Lorentz-invariant mass of a system in any reference frame!
An example of a “natural” SUSY model (“NM3”)

\[ m_h = 125 \text{ GeV} \]
Dark matter: 24%
Dark energy: 71.4%

An example of a “natural” SUSY model (“NM3”)

Strongly interacting sector:
• Particles with color (QCD) charge.
• Large production cross section if mass is not too high.
An example of a “natural” SUSY model (“NM3”)

Electroweak sector:
- EM/weak interactions
- Major impact on decays of colored particles
- Generally low production cross sections, but may have lower masses.
- LSP lives here!

Lightest Supersymmetric Particle (LSP)
Big themes: production and decays

Strong production

Stop pair production

Electroweak production

LHC SUSY Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections
Big themes: production and decays

Exploring $\sigma = \sim 1$ fb $\rightarrow \sim 1$ pb

LHC SUSY Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

arXiv:1206.2892
Measurements of SM processes in CMS

Typical SUSY cross sections: ~few fb to hundreds of fb

Di-boson production

Top-quark production

Higgs production

Production Cross Section, $\sigma$ [pb]

0.1 pb = 100 fb

Feb 2014

CMS Preliminary

7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit

Typical SUSY cross sections: ~few fb to hundreds of fb
Formulating SUSY – a short history

CMS Preliminary \( L_{\text{int}} = 4.98 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \)

\[
\tan(\beta) = 10 \\
A_0 = 0 \text{ GeV} \\
\mu > 0 \\
m_t = 173.2 \text{ GeV}
\]

\[
m(\tilde{g}) = 1500 \\
m(\tilde{q}) = 2000 \\
m(\tilde{q}) = 2500
\]

\[
m(\tilde{g}) = 1000 \\
m(\tilde{g}) = 500
\]

\[
t = 7 \text{ TeV} \\
\alpha_T
\]

\[
\text{Multi-Lepton} \\
\text{1 Lepton} \\
\text{OS Dilepton} \\
\text{SS Dilepton} \\
\text{Razor} \\
\text{Jets+MHT}
\]

\[
t = 7 \text{ TeV} \\
\alpha_T
\]

\[
\text{Non-Convergent RGE's} \\
\text{No EWSB}
\]
Results for gluino pair production with $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1$

$M(\tilde{\chi}^0_1)$
Mass of LSP

Maximum gluino mass limit at minimum LSP mass.

$M(\tilde{g})$
Mass of pair-produced particle

Increasing mass splitting $\Rightarrow$ increasing MET

Decreasing cross section
Gluino pair production and decay to stop

Signature: 4 top quarks + $p_T^{\text{miss}}$
LSPs are unobserved: cannot reconstruct mass peaks!
Open letter to the group of radioactive people at the
Gauverein meeting in Tübingen.

Copy

Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more
detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta
spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and
the law of conservation of energy. Namely, the possibility that in the nuclei there could exist
electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion
principle and that further differ from light quanta in that they do not travel with the velocity of
light. The mass of the neutrons should be of the same order of magnitude as the electron mass and
in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make
sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such
that the sum of the energies of neutron and electron is constant.

Now called neutrinos!
Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment $\mu$. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then $\mu$ is probably not allowed to be larger than $e \cdot (10^{-13}\text{ cm})$.

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr. Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

[Translation: Kurt Riesselmann]
b-quark identification using displaced decay vertices

Secondary vertices
- top-right:
  
  3D flight distance (value / significance) = 6.2 mm / 43
  
  \[ m_{SV} = 2.9 \text{ GeV}, \quad p_T = 25.7 \text{ GeV}, \quad \chi^2 / \text{ndof} = 6.3 / 5 \]

- bottom left:
  
  3D flight distance (value / significance) = 8.6 mm / 55
  
  \[ m_{SV} = 3.1 \text{ GeV}, \quad p_T = 17.2 \text{ GeV}, \quad \chi^2 / \text{ndof} = 15.9 / 3 \]
Anatomy of a background: ttbar

Extremely common background in NP searches.
- looks like low-mass SUSY!
- large real MET from neutrinos in leptonic decays.
- high jet multiplicity, including b jets.

1. EVENT ENVIRONMENT
- Effects of pileup: isolation, jets, MET, vertices
- Underlying event.

2. PRODUCTION
- pT distributions of t and tbar (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of t and tbar

3. DECAY CHAIN
- W polarization
- Final-state radiation
- Decay branching fractions
Most "SUSY-like" process in SM: $pp \rightarrow t\bar{t}$

Candidate event for process

$pp \rightarrow t\bar{t}$

$t \rightarrow bW^+; \quad W^+ \rightarrow e^+ \nu_e$

$\overline{t} \rightarrow \overline{b}W^-; \quad W^- \rightarrow q_1\overline{q}_2$

Missing momentum vector from neutrino
Generic hadronic SUSY search using MHT

- **Signature:** Jets + MHT; events with leptons are vetoed
  - Jets: \( \geq 3 \) jets with \( p_T > 50 \text{ GeV} \), **no b-tagging**.
  - Veto event if MHT vector is \( \approx \)aligned with any of 3 leading jets.

- **Bin data in**
  - \( H_T \)
  - missing \( H_T \) (MHT)
  - Jet multiplicity (3—5, 6—7, \( \geq 8 \) jets)

- **Background estimation:** largely data driven.

\[ H_T = \sum_{j=\text{jets}} \left| \vec{p}_T^j \right| \]

\[ \mathcal{H}_T = \left| \vec{H}_T \right| = - \sum_{j=\text{jets}} \vec{p}_T^j \]

- **ttbar with** \( W \rightarrow l \nu \)
- **W \rightarrow l \nu + \text{jets}**

- **ttbar with** \( W \rightarrow \tau (\rightarrow h) \nu \)
- **W \rightarrow \tau (\rightarrow h) \nu + \text{jets}**

Control sample: Single-lepton + jets + MHT

- **Z \rightarrow \nu \nu + \text{jets}**

Control samples:
- \( \gamma + \text{jets} \),
- \( Z(\mu\mu) + \text{jets} \)

- **QCD multijet events**
  - MHT \( \sim \) aligned with high \( p_T \) jet.

Control sample:
- Multijets with re-balance and smear procedure
Distribution in bins of $N(\text{jets})$, $H_T$, and $H_T$.

CMS SUS-13-012

Distribution in bins of $N(\text{jets})$, $H_T$, and $H_T$.

CMS Preliminary, $L = 19.5$ fb$^{-1}$, $\sqrt{s} = 8$ TeV

$H_T$ : 0.8-1.0 TeV

$H_T$ : 1.0-1.2 TeV

- Data
- $Z \rightarrow \nu\bar{\nu} + \text{Jets}$
- $W/t\bar{t}(e/\mu + \nu)+\text{Jets}$
- $W/t\bar{t}(\tau_+ + \nu)+\text{Jets}$
- QCD

Total uncertainty on measured background

Statistical interlude

• Consider the bin with
  – \( N(\text{observed}) = 9 \) events
  – \( N(\text{background}) = 0.8 \pm 1.7 \) events

• First, let’s ignore the uncertainty on the background. What is the probability for a Poisson with \( \mu=0.8 \) to fluctuate to at least 9 events?
  – \( \text{Prob}( n \geq 9 \mid \mu = 0.8 ) = 1.8 \times 10^{-7} \)

  Have we discovered new physics?

• NO! The uncertainty is crucial!
  – \( \text{Prob}( n \geq 9 \mid \mu = 0.8 \pm 1.7) \approx 0.15 \)

• This example highlights the importance of quantifying the uncertainties on the SM backgrounds.

See CMS PAS SUS-13-012, Table 1, p. 10
Njets: 6-7
HT: 500-800 GeV
MHT>450 GeV
Search for generic jets and MET: results

- Simplified model exclusion plots

  1. Compute excluded cross section for each model in param space
  2. Compare to reference cross section to see if model excluded
     - Assume 100% branching fraction for stated process!

CMS Preliminary, 19.5 fb$^{-1}$, $\sqrt{s} = 8$ TeV

- Gluino pair production
  - Signal efficiency increases away from diagonal
  - Excluded $\sigma$ falls
  - Decreasing production cross section

- 95% C.L. upper limit on cross section (pb)
Search for generic jets and MET: results

- **Simplified model exclusion plots**
  
  1. Compute excluded cross section for each model in param space
  2. Compare to reference cross section to see if model excluded
     - Assume 100% branching fraction for stated process!

As before, weak limit with reduced number of squarks!
The famous neutralino dilepton cascade

Opposite-sign, same flavor leptons

The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production.

$$m_{\ell^+\ell^-}(\text{max}) = \sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)} / m_{\tilde{\ell}}$$
Search for SUSY in opposite sign dileptons

$m_{\ell^+\ell^-} > 20$ GeV, $N(\text{jets}) \geq 2$ ($p_T > 40$ GeV)

\[ E_T^{\text{miss}} > 150 \text{ GeV} \]
Search for SUSY in opposite sign dileptons

Fit opposite sign dilepton mass distribution to shapes from (1) Flavor Symmetric (FS) background, Drell Yan, and signal.

**Signal contribution (2.4σ local significance).**
Search for SUSY in opposite-sign dileptons

Central leptons
|\eta_{lep}|<1.4

\geq 1\ forward\ lepton
1.6<|\eta_{lep}|<2.4

2.6\sigma\ excess\ (not\ significant)

0.3\sigma\ excess
Interactions of neutralinos with matter

- Above: direct dark matter detection processes: doesn’t have to be SUSY!
- Use crossing to get \( q + \bar{q} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0 \)
- How to see \( q + \bar{q} \rightarrow \) invisible?

\[ q \rightarrow \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_1^0 \rightarrow h, H \]
\[ q \rightarrow \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_1^0 \rightarrow \tilde{q} \]
\[ q \rightarrow \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_1^0 \rightarrow Z \]

Initial-state radiation
mediator on-shell or off shell
Signature for dark matter at the LHC

**Signature:** Jet or photon from initial-state radiation (ISR) + large missing transverse momentum

**Dominant background:** \( Z(\rightarrow \nu\nu) + \text{jets} \)

...don’t want to rely on MC modeling of initial-state radiation
There are lots of monojet events in the data!

$\ptmiss^m = 914 \text{ GeV}$
We can predict the contribution from $Z + 1$ jet

$$\sum_{i=e,\mu,\tau} B(Z \rightarrow \nu_i \bar{\nu}_i) \approx 6$$

$$\frac{B(Z \rightarrow \mu^+ \mu^-)}{B(Z \rightarrow \mu^+ \mu^-)} \approx 6$$
Searching for dark matter: monojet search results

- **MET > 250 GeV**
- **1 central jet, pT>110 GeV.**
- **2nd softer jet allowed, not back-to-back.**
- **Remarkable that QCD is so well controlled.**
- **Veto events with leptons**
- **Z→νν is dominant background; predict from Z→μμ control sample.**

![Graph showing monojet search results](chart.png)
Searching for dark matter: monojet search results

**Graphs:**
- Left graph: 
  - **Label:** $\chi$-Nucleon Cross Section [cm$^2$]
  - **X-axis:** $M_\chi$ [GeV]
  - **Y-axis:** $10^{-46}$ to $10^{-36}$
  - Key results:
    - CMS, 90% CL, 7 TeV, 5.0 fb$^{-1}$
    - CMS, 90% CL, 8 TeV, 19.7 fb$^{-1}$
    - LUX 2013
    - Spin Independent
    - Scalar
    - CDMS II
    - XENON 100
    - SIMPLE 2012
    - COUPP 2012
    - SuperCDMS
    - CDMSlite

- Right graph: 
  - **Label:** $\chi$-Nucleon Cross Section [cm$^2$]
  - **X-axis:** $M_\chi$ [GeV]
  - **Y-axis:** $10^{-46}$ to $10^{-36}$
  - Key results:
    - CMS, 90% CL, 7 TeV, 5.0 fb$^{-1}$
    - CMS, 90% CL, 8 TeV, 19.7 fb$^{-1}$
    - IceCube $W^+W^-$
    - LUX 2013
    - SIMPLE 2012
    - COUPP 2012
    - W$^+$
    - Super-K $W^+$
  - Symbols:
    - **Red dots** for Spin Dependent
    - **Blue line** for Axial-vector operator
    - **Green line** for Spin Independent
  - Equations:
    - Spin Independent: $\propto \frac{|\chi\gamma_\mu \chi_5|^2}{4\Lambda^2}$
    - Axial-vector operator: $\propto \frac{(\chi_\mu \gamma_5 \chi)(\chi_\mu \gamma_5 \chi)}{\Lambda^2}$
Relative parton luminosities: 13 TeV vs. 8 TeV

rations of LHC parton luminosities: 13 TeV / 8 TeV

1350 GeV gluinos: x30
1000 GeV gluinos: x20
750 GeV squarks: x9
350 GeV $X^+X^0$: x3
top pairs: x4

$gg \rightarrow X$
$qg \rightarrow X$
$\sum q_i\bar{q}_i \rightarrow X$

MSTW2008NLO
LHC long-term plan

Several upgrades planned:

LHC:
- splice consolidation
- injector upgrade cryogenics P4
- HL-LHC installations

LS1:
- “Phase 0” Detector consolidation
- 8 TeV
- L\textsubscript{int} \approx 75-100 fb\textsuperscript{-1}
- 70% nominal luminosity

LS2:
- CMS Pixel Upgrade “Phase 1”
- 13 - 14 TeV
- > 1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}
- ~ 3 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}

LS3:
- “Phase 1” Upgrade
- “Phase 2” Upgrade
- ~ 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}
- L\textsubscript{int} = 3 \text{ ab}^{-1}
- (with lumii leveling)

2012 - 2023:
- “Phase 0” Detector consolidation
- CMS Pixel Upgrade “Phase 1”
- “Phase 1” Upgrade
- “Phase 2” Upgrade

Event Rate written to tape:
- 150Hz
- 1000Hz
- 10000Hz
“Once you have a collider, every problem starts to look like a particle.”
Backups
Search for neutralino/chargino production

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} \)
ICHEP 2014

Observed
Expected

SUS-13-006  19.5 fb\(^{-1} \)
SUS-14-002  19.5 fb\(^{-1} \)

Neutralino mass = chargino mass [GeV]