CMS Physics at the LHC
- Re-discovery to New Discovery -

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Oct 15, 2008
The LHC at CERN will provide the first proton-proton (pp) collisions in 2009. The smashing power is 7.1 times larger than that of the Tevatron at Fermilab (Batavia, IL, USA).
LHC First Beam

August 1, 2008
LHC magnets are super-cold (2 K).
(LHC magnets are fully commissioned.)

August 8, 2008
First Beam in LHC between IP2 and IP3
(or "Section 23")
Single-bunch beam with $5 \times 10^9$
protons was repeatedly injected,
totaling approximately
$1 \times 10^{13}$ protons

See a blue path
labeled as "B1"
in a schematic diagram below.

See four snap-shots
of beam profile:

August 22, 2008
First Particles at LHCb
The LHC synchronisation test
collided a beam of protons with a 28
tonne absorber 200m
away from LHCb,
producing a shower of particles. Some of
these particles reached the LHCb
experiment, where the tracks were
observed by a small
team of scientists.
The observation was
made with one
quarter of the LHCb
VELO detector
operational on Friday
22 August. Read
more.

September 5, 2008
CERN Press Release: CERN is safe!

September 10, 2008
Brief History of LHC First Beam Event
[CERN's Welcome Page]
[Pajama Party at Fermilab]

LHC: Record-breaking Proton-Proton Collider Machine

- ONE(1) hydrogen bottle to make the proton beams
- TWO(2) 27-km long vacuum pipes, 100 m below ground
- SEVEN(7) Tera-electron-Volts per beam.
  Beam 1 = clockwise (c.w.)
  Beam 2 = counter clockwise (c.c.w.)
- NINE THOUSAND (9,000) magnets (dipoles and RFs), working as one unit
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- 08:54: Counting down...
- 09:00: People, including Chi-Nhan Nguyen (Alexei’s postdoc, who just a night shift) and me, are waiting to the “Event.”
- 09:15: Address by Lyn Evans (LHC Project Leader since the LHC project was approved in 1984) in French
- 09:20: Address by Robert Aymer (Director General) in French (I only understood a single word “LHC” :("...

We were waiting for “beam injection octant by octant”. Lyn explained the beam monitor – it took 5 seconds to appear on the monitor due to after the beam (every 48 sec of pulse) was injected. The LHC project possible by combining different skills from scientists and engineers.

- 09:35: Proton beams (450 Giga-electron Volts or 450 GeV) to Point the ALICE detector is located.
- 09:30: Proton beams to Point 3
- 09:46: Proton beams to Point 5 (where the CMS detector is located) display of one of first–beam events seen at CMS.
- 09:55: Proton beams to Point 6
- 10:00: Address by Lyn Evans “optimization now and a full Beam One beams) circulation within one hour”
- 10:10: Proton beams to Point 7
- 10:14: Proton beams to Point 8 (where the LHCb detector is located
- 10:18: Proton beams to Point 1 (where the ATLAS detector is located
- 10:25 (3:25 am Central): Proton beams to Point 2 – A full circulation One (or blue beam) in clock–wise direction! → Amazingly smooth of approximately 10,000 magnets as one unit at the same time.

- 10:55: CERN Press Release
The CMS (21 m x 15 m x 15 m, 12,500 tonnes) is one of two super-fast & super-sensitive detectors, consisting of 15 heavy elements, collecting derbies from the collision and converting a visual image for us.
WHERE IS CMS?

"UNDERGROUND" EXPERIMENTS

Overall view of the LHC experiments.

(*) The TAMU group is a member of the CMS collaboration.
December 2006

Prof. Steve Hawking, visiting the CMS experimental site.

Lowering the 1st heavy element of the CMS detector.
blue and red dots and yellow lines are studied to figure out what happens in the collision!
LHC has ~ 20 times the luminosity of the Tevatron and 7 times the energy.

\[ \text{Rate} = \text{luminosity} \times \text{cross section} \]

CDF and D0 successfully found the top quark, which has a cross section \(~10^{-10}\) the total cross section.

A 500 GeV Higgs has a cross section ratio of \(~10^{-11}\), which requires great rejection power against backgrounds and a high luminosity.
\[ \sqrt{s} = 10 \text{ TeV} \ (\mathcal{L} = 50 \text{ pb}^{-1}) \text{ in 2009} \]

- Dominant processes - QCD & EWK
  - Re-discovery the Standard Model (SM) events at 10 TeV.

- TAMU group’s discovery program: Higgs and SUSY
**Typical Statistics for a 10 TeV Run**

- Assume $\mathcal{L} = 10 \text{ pb}^{-1}$, include acceptance, initial reconstruction and id efficiency
- “Establish” the SM cross sections and distributions

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
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<tr>
<td>min bias</td>
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<tr>
<td>Jet $\text{Et}&gt;25$</td>
<td>$3 \times 10^{10}$</td>
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<tr>
<td>Jet $\text{Et}&gt;140$</td>
<td>$3 \times 10^{6}$</td>
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<tr>
<td>$\gamma+\text{Jet Et}&gt;20$</td>
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<tr>
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<tr>
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<tr>
<td>$tt \rightarrow l\nu4q$</td>
<td>100</td>
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<tr>
<td>L for 1 month run (10^6 sec)</td>
<td>Integrated L</td>
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<tr>
<td>-------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>10^{23}</td>
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<td>L for 1 month run</td>
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<tr>
<td>10^{28}</td>
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<tr>
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<td>100 pb^{-1}</td>
</tr>
<tr>
<td>10^{33}</td>
<td>1 fb^{-1}</td>
</tr>
</tbody>
</table>
J/Psi Production

Largest cross section resonant dilepton state. Set momentum scale for tracker.
W Production

L = 10 pb⁻¹

CMS Preliminary

Events / 1 GeV

M_T (GeV/c²)

E_T (GeV)

Signal + Background

10pb⁻¹
SM Z – check mass scale, Z resolution/ width and FB asymmetry.

Use Z signal for “tag and probe” to get lepton efficiencies
The TAMU group (A. Safonov et al.) is a leader of tau-lepton-related electroweak physics program at CMS and sees \( Z \rightarrow \tau\tau \) is the necessary step to discover Higgs \( \rightarrow \tau\tau \).
B Tagging

Tracking alignment crucial.

Establish b tagging. Check with top pair events.
SUPERSYMMETRY (SUSY)

Nature may love this symmetry!

One of them is a neutralino. This is a leading candidate for the DM particle.
SUSY Signatures in CMS

- Many hard Jets
- Large missing energy
  - 2 LSPs
  - Many neutrinos
- Many leptons
- In a word Spectacular!
Assuming a conserved SUSY quantum number, the lightest SUSY particle (LSP) is stable. A neutral weakly interacting LSP escapes the detector. Dramatic event signatures (cascade to LSP → jets + Missing Et) and large cross section mean we will see an excess due to SUSY quickly, if it exists.
SUSY at 10 TeV

- $\sqrt{s} = 10$ TeV ($\mathcal{L} = 50$ pb$^{-1}$) in 2009
  - Still powerful for SUSY searches
SUSY and Cosmological Connection
DM Particle in SUSY

CDM = Neutralino (\( \tilde{\chi}_1^0 \))

\[ \Omega_{\chi_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle} dx \]

\[ \langle \sigma_{\text{ann}} v \rangle = \frac{\pi \alpha^2}{8 M^2} \]

WMAP 5: 23.3% (± 1.3%)

CMS Physics
DM Allowed Regions (Illustration)

- Higgs Mass ($M_h$)
- Branching Ratio $b \rightarrow s\gamma$
- Magnetic Moment of Muon

Co-annihilation Region

No CDM Candidate

CDM allowed region
Minimal Supergravity (mSUGRA)

SUSY model in the framework of unification:

\[ \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle} \text{ at } M_Z \]

4 parameters + 1 sign

- \( \tan \beta \) : \( \frac{\langle H_u \rangle}{\langle H_d \rangle} \) at \( M_Z \)
- \( m_{1/2} \) : Common gaugino mass at \( M_{\text{GUT}} \)
- \( m_0 \) : Common scalar mass at \( M_{\text{GUT}} \)
- \( A_0 \) : Trilinear coupling at \( M_{\text{GUT}} \)
- \( \text{sign}(\mu) \) : Sign of \( \mu \) in \( W^{(2)} = \mu H_u H_d \)

Key Experimental Constraints

- \( M_{\text{Higgs}} > 114 \text{ GeV} \)
- \( M_{\tilde{\chi}_1^+} > 104 \text{ GeV} \)
- \( 2.2 \times 10^{-4} < B(b \rightarrow s\gamma) < 4.5 \times 10^{-4} \)
- \( (g - 2)_\mu \) : \( \approx 3\sigma \) deviation from SM
- \( 0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129 \)
Proving $\Omega_{\text{SUSY DM}}$ in Inclusive Jets+$E_T^{\text{miss}}$

Excess in $E_T^{\text{miss}} + \text{Jets} + X$

$X = \text{Dilepton mass endpoint from } \chi_2^0 \text{ decay to reconstruct the SUSY masses}$

$X = ee, \mu\mu, \tau\tau$

$X = \tau\tau$

Co-annihilation

$\Delta M = 5-10 \text{ GeV}$

$\Omega_{\text{SUSY DM}} \equiv \Omega_{\text{CDM}}$

LM1 (Low Mass Case 1)

$\sigma = 55 \text{ pb}$

$M_{\tilde{g}} = 611$

$M_{\tilde{q}} = 559$

$\tilde{g} \to \tilde{q}\tilde{q} \to \tilde{\chi}_0^0 q\bar{q}$

$B(\tilde{\chi}_2^0 \to \tilde{\ell}\ell) = 11.2\%$

Nojiri, Polesselo, Tovey, JHEP 0603 (2006) 063

Arnowitt et al., PRL 100 (2008) 231802

Dilepton mass "edge" in the $\chi_2^0 \to ee/\mu\mu$ $\chi_1^0$ decays for reconstruction of SUSY Masses $\rightarrow \Omega$

Teruki Kamon Measurement of Dark Matter Relic Density at the LHC
[1] Established the CA region by detecting low energy $\tau$'s ($p_T^{\text{vis}} > 20$ GeV)

[2] Determined SUSY masses using:

- $M_{\tau\tau}$, Slope, $M_{j\tau\tau}$, $M_j$, $M_{\text{eff}}$

  e.g., $M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, M_{\tilde{\chi}^0_2}, M_{\tilde{\chi}^0_1})$

  Gaugino universality test at $\sim 15\%$ (10 fb$^{-1}$)

[3] Measured the dark matter relic density by determining $m_0$, $m_{1/2}$, $\tan\beta$, and $A_0$

  using $M_{j\tau\tau}$, $M_{\text{eff}}$, $M_{\tau\tau}$, and $M_{\text{eff}}^{(b)}$

  $\Delta \Omega_{\tilde{\chi}^0_1} h^2 / \Omega_{\tilde{\chi}^0_1} h^2 \approx 6\%$ (30 fb$^{-1}$)

[4] Working on non-minimal case...
TAMU group’s Particle Physics Cosmology (PPC) is unique at CMS.
✓ SUSY with $\tau$’s
✓ SUSY with $b$’s
✓ SUSY with $t$’s
✓ Extra Dimension
✓ ...