Search for SUSY events with off-time photons

Candidato: Daniele Franci

Relatori:
Prof. Egidio Longo
Dott. Daniele del Re
Prof. Shahram Rahatlou
Introduction

✓ Long-lived particles as evidence of new physics
  ➞ Predicted by many scenarios beyond the Standard Model
  ➞ Possible early discoveries (clear signature, high cross-section)
  ➞ Focus on neutral long-lived particles decaying into photons

✓ Algorithm for lifetime measurement
  ➞ Model-independent approach
  ➞ Based on ECAL response to high-$P_T$ photons

✓ Gauge Mediated Supersymmetry Breaking analysis
  ➞ Neutralino as Next to Lightest Supersymmetry Particle
  ➞ Neutralino is neutral and (potentially) long-lived
  ➞ Neutralino decay: $\chi \Rightarrow G + \gamma$
Zero vs non-zero lifetime

Zero lifetime

Non-zero lifetime

A segmented and projective detector is considered
Zero vs non-zero lifetime

Zero lifetime
- Photon generated at the interaction point (IP)
- EM shower develops along the crystal axis
- Limited lateral size of the energy deposit

Non-zero lifetime
- Photon generated at the secondary vertex
- Non-zero angle ($\delta$) between shower and crystal axis
- Energy deposit spread over many crystals

Pointing photon
- Photon generated at the interaction point (IP)
- EM shower develops along the crystal axis
- Limited lateral size of the energy deposit

Off-pointing photon
- Photon generated at the secondary vertex
- Non-zero angle ($\delta$) between shower and crystal axis
- Energy deposit spread over many crystals
Zero vs non-zero lifetime

Zero lifetime

- Arrival time compatible with that of a relativistic particle from the IP

Non-zero lifetime

- Arrival time sensibly increases with parent particle lifetime
- $\Delta T \sim O(\text{ns})$
CMS Electromagnetic Calorimeter (ECAL)

- **Cylindrical structure**
  - Central **barrel** ($|\eta|<1.479$)
  - Two **endcaps** ($1.479<|\eta|<3$)

- **75K PbWO$_4$ crystals**

- **0.5% resolution for $\gamma/e$**

- **$\eta = -\log(\tan[\theta/2])$**

**ECAL barrel crystals**
- Length: 23 cm ($\sim 26 \times X_0$)
- Front face: 2.2×2.2 cm$^2$ ($R_M \times R_M$)
- Fast light response: 5-15 ns

**PbWO$_4$**

- Molière radius 2.2 cm
- Radiation length 0.89 cm
The Compact Muon Solenoid Detector

Total weight: 12500 T
Overall diameter: 15.0 m
Overall length: 21.5 m
Magnetic field: 4 Tesla

CMS

ECAL
The Large Hadron Collider

- Proton-proton collisions
- 27 Km long
- Nominal $\sqrt{s} = 14$ TeV
  (7 TeV during low lumi phase)
- Four experiments
- $\sim 50$ pb$^{-1}$ recorded
Signal reconstruction in ECAL

When a photon reaches an ECAL crystal:

- Photon starts an electromagnetic shower inside the crystal
- Scintillation light collected by photodetectors
- Signal amplified and shaped by the front-end electronics
- Pulse digitized at 40 MHz (i.e. 25 ns)

From pulse shape:

- Energy $\propto A_0$
- Time $\propto T_0$
Photon reconstruction

✓ Shower not fully contained by a single crystal
✓ Lateral energy leaks
✓ Cluster of adjacent crystals

Several clustering algorithms are used in CMS:

⇒ Energy fully recovered ($E_{CLU} = \sum E_i$)
⇒ Precise position measurement
⇒ Time from the hottest crystal
Identification of neutral, long-lived decays into high-$P_T$ photons relies on:

1. ECAL time measured from the $\gamma$-cluster

2. Studies about the shape of the $\gamma$-cluster
ECAL timing can distinguish between in-time/off-time $\gamma$

$\sqrt{T_{REC}} = $ ECAL measured time
$\sqrt{T_{TRUE}} = X+\text{photon time of flight (calculated from MC)}$

$\sigma_t \sim 200 \text{ ps}$
$c*\sigma_t \sim 6 \text{ cm}$
Cluster shape described by the covariance matrix

$$\text{COV}_{\eta\phi} = \begin{pmatrix} S_{\eta\eta} & S_{\eta\phi} \\ S_{\phi\eta} & S_{\phi\phi} \end{pmatrix} \quad \text{with} \quad S_{\mu\nu} = \sum_{i=1}^{N} w_i (\mu_i - \langle \mu \rangle) (\nu_i - \langle \nu \rangle)$$

✓ Eigenvectors: principal axes of the energy distribution
✓ Eigenvalues: energy spread along the principal axes
Cluster major axis

Major axis used to identify off-pointing photon
- Elliptical shape for OP photon clusters
- Larger $S_{\text{major}}$ than the pointing case
- $S_{\text{major}}$ related to the angle of incidence $\delta$

\[
\sin(\delta) = \sqrt{S_{\text{major}} - 0.31} / 1.75
\]
Selection of long-lived decays in the $S_{\text{major}}$ vs $T_{\text{REC}}$ plane:

$\Rightarrow S_{\text{major}} > 0.4$

$\Rightarrow T_{\text{REC}} > 0.8 \text{ ns}$
Commissioning of time and cluster shape

$\sqrt{s} = 7$ TeV; $L = 1.2$ pb$^{-1}$

- Data
- $\gamma$+Jet
- QCD

$\sigma(t_1-t_2) = \frac{N}{A_{\text{eff}}/\sigma_n} \oplus \sqrt{2 \sigma C}$

- $N = 29.5 \pm 0.4$ ns
- $C = 0.33 \pm 0.02$ ns

- $N = 51.2 \pm 0.6$ ns
- $C = 0.23 \pm 0.05$ ns
After long-lived selection, photon momentum can be determined using:

1. **Energy**: from cluster reconstruction ($E_{CLU} = \sum E_i$)
2. **Angle $\delta$**: from $S_{\text{major}}$
3. **Angle $\alpha$**: from covariance matrix

$\alpha =$ angle between major axis and $\Phi$ (azimuth) direction of the ECAL surface

$$\tan \alpha = \frac{(S_{\eta\eta} - S_{\phi\phi}) + \sqrt{(S_{\eta\eta} - S_{\phi\phi})^2 + 4S_{\eta\phi}^2}}{2S_{\eta\phi}}$$
Determination of decay path

Photon direction extracted from momentum calculation

\((P_x, P_y, P_z) \leftrightarrow (E_{CLU}, \sin(\delta), \alpha)\)

\(\delta\)

\(\text{IP} = \text{Interaction Point}\)
Determination of decay path

Photon direction extracted from momentum calculation
\((P_x, P_y, P_z) \leftrightarrow (E_{CLU}, \sin(\delta), \alpha)\)

Decay vertex extracted from ECAL time calculation
\(\text{Decay path} = \overline{\text{IP-DV}}\)

\(= \text{Interaction Point}\)
\(= \text{Decay Vertex}\)
For each long-lived decay, decay path is determined:
- Strong linear correlation between reco and true value
- Decay path uncertainty $\sim 18 \text{ cm}$
Average decay path can be related to particle lifetime $c\tau$
Gauge Mediated Supersymmetry Breaking (GMSB) analysis
Supersymmetry: possible scenario beyond the Standard Model

- Each SM particle has a SUSY counterpart (sparticle)
- Theory invariant under particle\sparticle \rightleftharpoons \text{sparticle} transformation

Conservation of R-parity $R=(-1)^{3\,(B-L)+2s}$

- Sparticles produced in pairs
- Two decay chains composed by particles and sparticles
- Stable and neutral lightest SUSY particle (LSP) at the end of the chains
The Gauge Mediated Supersymmetry Breaking model is considered:

- Gravitino $\tilde{G}$ is the LSP
- Gravitino + photon produced by neutralino decay: $\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$

Process studied at the LHC:

\[ p + p \Rightarrow 2 \text{ chains} \Rightarrow 2\tilde{\chi}_1^0 + X \Rightarrow 2\tilde{G} + 2\gamma + (X) \]

Phenomenology determined by:

- $\Lambda \Leftrightarrow$ neutralino mass
- $C_{\text{grav}} \Leftrightarrow$ neutralino lifetime
  - $C_{\text{grav}} = 1 \rightarrow$ prompt decay
  - $C_{\text{grav}} > 1 \rightarrow$ long-lived decay

7 TeV scenario considered
Experimental signature

= Interaction Point
Experimental signature

Two high-$P_T \gamma$

✓ $cT \approx 0 \Rightarrow$ in-time $\gamma$
✓ $cT > 0 \Rightarrow$ off-time $\gamma$

= Interaction Point
Experimental signature

Two high-\(P_T\) \(\gamma\)
- \(\checkmark \) \(cT \sim 0\) \(\Rightarrow\) in-time \(\gamma\)
- \(\checkmark \) \(cT > 0\) \(\Rightarrow\) off-time \(\gamma\)

Two undetectable \(\tilde{\gamma}\)
- \(\checkmark\) Energy imbalance
- \(\checkmark\) Missing \(E_T\)

= Interaction Point
Experimental signature

- Two high-\(P_T\) \(\gamma\)
  - \(cT \sim 0 \Rightarrow \text{in-time } \gamma\)
  - \(cT > 0 \Rightarrow \text{off-time } \gamma\)

- Two undetectable \(\tilde{G}\)
  - \(\checkmark \) Energy imbalance
  - \(\checkmark \) Missing \(E_T\)

- Many high-\(P_T\) quarks
  - \(\checkmark \) High jet multiplicity

\(\star = \text{Interaction Point}\)
SM backgrounds

QCD events:
- Large cross section
- Fake photons from jets
- Mis-identified MET

Rejected by $\gamma$ isolation and MET

Photon+Jet:
- Real photon in the final state
- Mis-identified MET
- Low jet multiplicity

Rejected by jet multiplicity

t $\bar{t}$ events:
- Fake photons from electrons
- Real MET from neutrinos
- High jet multiplicity

Rejected by $\gamma$ isolation
Analysis strategy

Event selection

\{ 
\text{at least one photon} \Rightarrow \text{high } P_T, \text{ isolated} \\
\text{high jet multiplicity} \Rightarrow N_{\text{jet}} \geq 3 
\}

\text{MET} \text{ and } T_{\text{REC}} \text{ used to extract signal yield in a likelihood fit}
Results

✓ Analysis aims at establishing 95% CL limits on neutralino mass
✓ Scan over $\Lambda$ vs $C_{\text{grav}}$ parameters plane
✓ Mass limit $>200$ GeV with 200 pb$^{-1}$ for different lifetimes
✓ Well above the current limit of 149 GeV established by CDF
✓ Detailed studies about the systematics ongoing

Monte Carlo only

Monte Carlo only

Theoretical cross-section

Upper limit @ 95% CL

Excluded @ 95% CL

L=200 pb$^{-1}$
✓ Algorithm for lifetime measurement of neutral, long-lived particles decaying into photons
  ➡ Measurement of arrival time with ECAL
  ➡ Study about the shape of γ-cluster

✓ GMSB model analysis
  ➡ Neutral, long-lived neutralino decaying into photon
  ➡ ECAL time and missing $E_T$ used to extract signal yield in a likelihood fit
  ➡ Expected neutralino mass limit >200 GeV for different $c\tau$
  ➡ Detailed studies on systematics ongoing

Analysis publication planned for Winter 2010
Backup slides
Identification of photon conversions

Photon conversions: large $S_{\text{major}}$ regardless of the angle of incidence ⇒ fake off-pointing signature

$\alpha$ angle can identify conversions
Determining $\beta_x$

Velocity of long-lived particle can be related to $\gamma$ energy

$\Rightarrow$ Model-dependent distribution