Searching for the elusive graviton with solitary photons

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Outline

- Introduction
- Photon identification
- EM pointing algorithm
- Single photon selection and background estimation
- Results and Summary
Where is Gravity?

THE STANDARD MODEL

Fermions

<table>
<thead>
<tr>
<th>Quarks</th>
<th>3rd generation</th>
<th>2nd generation</th>
<th>1st generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>c</td>
<td>t</td>
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<td>d</td>
<td>s</td>
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<table>
<thead>
<tr>
<th>Leptons</th>
<th>3rd generation</th>
<th>2nd generation</th>
<th>1st generation</th>
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<tbody>
<tr>
<td>e</td>
<td>ν_e</td>
<td>ν_μ</td>
<td>ν_τ</td>
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<tr>
<td>μ</td>
<td></td>
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<tr>
<td>τ</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Force carriers</th>
<th>Bosons</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>γ</td>
</tr>
<tr>
<td></td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td>W</td>
</tr>
</tbody>
</table>

*Yet to be confirmed

Source: AAAS
We are way too familiar with the effects of gravity...

...but we don't yet understand it completely.
Gravity and the Standard Model

- Einstein's General Relativity good up to solar system scale.

- At larger scales the situation is not as clear.
  - Modified dynamics?
  - Dark Matter?

- Great efforts have been made to try to come up with a quantum description of gravity.
- Gravity is very weak, negligible in SM

\[
\frac{G_F}{G_N} \sim 10^{33}
\]

- Extrapolation defines the Planck energy scale:

\[
M_{\text{Pl}} \sim G_N^{-1/2} \sim 10^{19} \text{GeV}
\]

- Great jump in energy

\[
m_{\text{EW}} \sim 10^3 \text{GeV}
\]

Electroweak scale
**Hierarchy Problem, Naturalness, and Fine Tuning**

- **Naturalness**: belief that a small parameter in Nature can not be an accident. It must be associated with a symmetry.

- Additional contribution to the squared Higgs-boson mass:
  \[
  \delta m_H^2 = \kappa \Lambda^2 \quad (m_H \sim G_F^{-1/2})
  \]
  - \(\kappa\): constant parameter
  - \(\Lambda\): energy size of the quantum fluctuations

- Amount of fine tuning required for the SM to work at the Planck scale:
  \[
  \left(\frac{m_{EW}}{M_{Pl}}\right)^2 \sim 10^{-32}
  \]

- Analogy: balancing a pencil (\(R\) long), on its tip of length \(r\), where:
  - \(R\) ~ size of the solar system
  - \(r\) ~ 1 mm

- Supersymmetry and technicolor solve the problem.
**ADD (Arkani-Hamded, Dimopoulos, Dvali) Large Extra Dimensions**

- $m_{\text{EW}}$ the only fundamental scale in nature.
  - experimentally tested as opposed to $M_{\text{Pl}}$

- $n$ large extra spatial dimensions (LED).
  - **large compared to the electroweak scale**
  - gravity is diluted in large compactified volume.
  - SM particles bound to the 3D brane
  - localization is non trivial
  - compactification in a torus

- The greatness of the size of the extra volume $R$ conceals the smallness of the fundamental Planck scale $M_{D}$ $(4+n \ D)$, the result: the effective Planck scale $M_{\text{Pl}}$ $(4 \ D)$.

- **Hierarchy (fine tuning) problem is solved,**

- Constraints from astrophysics, cosmology, and table-top experiments (dark energy length scale!!) rule out $n = 2$.

**EW distance scale:**

\[1 \ \text{TeV}^{-1} \approx 10^{-19} \ \text{m}\]

\[M_{\text{Pl}}^2 = 8\pi M_{D}^{n+2} R^n\]

At $M_{D} = 1 \ \text{TeV}$:

- $n = 1 \Rightarrow R \sim 10^{13} \ \text{cm (solar system)}$
- $n = 2 \Rightarrow R \sim 1 \ \text{mm}$
- $n = 3 \Rightarrow R \sim 1 \ \text{nm}$
- $n = 7 \Rightarrow R \sim 1 \ \text{fm (proton)}$
Direct Graviton Production

- Kaluza Klein (KK) gravitons: towers of KK modes.

- Single graviton production suppressed by $1/M^2_{Pl}$. Large phase space compensates this suppression.

- We search for LED studying the exclusive photon ($\gamma$) + missing transverse energy (MET) channel.

- We generate the signal using PYTHIA, for $n = 2$ to $n = 8$, at $M_D = 1.5$ TeV.
Same Signature Backgrounds

Electroweak boson production:

\[ Z + \gamma \rightarrow \nu \bar{\nu} + \gamma \]

Irreducible physics background; an excess in events could also indicate the presence of anomalous ZZ\gamma or Z\gamma\gamma couplings.

\[ W \rightarrow e \nu \]

The electron is misidentified as a photon due to tracking inefficiency or hard bremsstrahlung.

\[ W + \gamma \rightarrow l \nu + \gamma \]

The charged lepton from a leptonic W boson decay is not detected.

W/Z + jet

The jet is misidentified as a photon.

Non-collision background:

Muons from the beam halo or cosmic rays undergo bremsstrahlung, producing an energetic photon.
The Apparatus: D0 Detector at the Tevatron

The Apparatus: D0 Detector at the Tevatron
Search for Large Extra Dimensions via Single Photon plus Missing Energy Final States at $\sqrt{s} = 1.96$ TeV

The Apparatus: D0 Detector at the Tevatron
The D0 Detector

The D0 Detector is a particle physics detector used in the study of high-energy collisions at the Fermi National Accelerator Laboratory. It contains several components, including:

- Calorimeters:负责探测和测量能量。
- Tracker: 负责探测和测量粒子的轨迹。
- Muon System: 负责探测和测量带电粒子。
- Beamline Shielding: 防止靶区外的粒子干扰。

图中显示了这些组件在D0 Detector中的布置方式。
Cells with **liquid Ar** as active medium. Uranium (EM+fine HD) and Cu/Steel (CC/EC coarse HD) as absorber.

- **Central Calorimeter (CC)** $|\eta| < 1.1$.
- **Endcap Calorimeters (EC)** $1.3 < |\eta| < 4$

### Table: Calorimeter Module Types

<table>
<thead>
<tr>
<th>Module Type</th>
<th>EM</th>
<th>Fine Had.</th>
<th>Coarse Had.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_{detector}$</td>
<td>±1.1</td>
<td>±1.0</td>
<td>±0.7</td>
</tr>
<tr>
<td>Absorber Material</td>
<td>Uranium 4</td>
<td>Uranium (1.7% Nb) 3</td>
<td>Copper 1</td>
</tr>
<tr>
<td>Readout Layers</td>
<td>0.1×0.1 (Layer 1, 2, 4) 0.05×0.05 (Layer 3)</td>
<td>0.1×0.1</td>
<td>0.1×0.1</td>
</tr>
<tr>
<td>Segmentation ($\Delta \eta \times \Delta \phi$)</td>
<td>10 $X_0$ (0.76 $\lambda_a$) 2, 2, 7</td>
<td>1.3, 1.0, 0.9 $\lambda_a$</td>
<td>3.2 $\lambda_a$</td>
</tr>
<tr>
<td>Radiation Lengths</td>
<td>Total $X_0$ 21</td>
<td>96</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Total $\lambda_a$ 0.76</td>
<td>3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Photon Identification

- Towers: cells close in $(\eta, \phi)$ space, that pass quality filters.

- Problematic cells are removed (hardware failures, electronic or uranium noise, liquid Ar contamination, non-collision events).

- Simple Cone Algorithm forms clusters with towers around seed towers (500 MeV) within $\Delta R < 0.4$

- Only clusters with $EM/(EM+HD) > 0.9$ and $p_T > 1.5$ GeV accepted.
Photon showers are narrow compared to hadronic ones.

\[ \text{iso} = \frac{E_{0.4}^{\text{tot}} - E_{0.2}^{\text{core}}}{E_{0.2}^{\text{core}}} - \alpha_{\text{lumi}} \]

\[ \text{iso} < 0.07 \]
**Photon Identification**

**SHOWER WIDTH:**

- EM showers narrower than jets.
- Calculate shower width in the azimuthal direction (transverse development).
- We use the shower width calculated at the 3rd EM layer.
- Individual cell energy and azimuthal angle position are used together with the total cluster energy and the energy-weighted azimuthal position of the cluster.

**Fine segmentation of the calorimeter provides additional information that can be used to discriminate backgrounds:**

- Energy fractions at each layer
- Cluster widths in the longitudinal direction.
Introduction

Results/Summary

γ Selection/Backgrounds

Non-collision/Pointing

Photon Identification

- SMT: doped silicon detectors, with barrel and disk configuration

- CFT: scintillating fibers arranged in 32 concentric layers with axial and stereo angles.

- TRACK ISOLATION:
  - Fake photon removal.
  - Scalar sum of the transverse momenta of all tracks in an annulus of $0.05 < \Delta R < 0.4$ around the cluster less than 2 GeV.

- ANTI-TRACK MATCH
  - non-converted photons do not have charged tracks.
  - no significant density of “hits on the road” in the SMT or CFT systems consistent with a track.
Located between solenoid magnet and the calorimeter, $|\eta| < 1.31$

There is a lead radiator between the CPS and the solenoid (0.9 $X_0$) of approximately 1 $X_0$.

Fast measurement of position and energy.

Three cylindrical layers of triangular extruded strips of scintillating plastic (WLS fibers embedded collect ionization energy in form of light)

WLS fiber split at $z = 0$

Each layer has 1280 strips

Axial layer: strips parallel to beam pipe

Stereo layers: $u$ and $v$ stereo angles of 23.774° and 24.016° with respect to $x$ layer
Photon Identification

- Single layer clusters (SLC's) formed from contiguous strips.
- Axial layer SLC's matched to u-v layer combinations to form 3D clusters.
- Energy and position of 3D clusters determined.
- Important combinatorial background (ghosts) taken care of by deghosting algorithm.
- Merging of clusters at $z = 0$ is done if necessary.
- Final EM clusters matched to CPS cluster in window of 0.1 x 0.1 in $(\eta, \phi)$ space.

### CPS Cluster Match

**Photon Identification**

- CPS match efficiency: 77% to 88%

---

**Summary:**

- Three body mass distribution for $Z \rightarrow e^+ e^- \gamma$
- CPS match efficiency: 77% to 88%

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**Photons with CPS match:**

- CPS efficiency vs Photon rapidity

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**Efficiency vs Photon rapidity:**

- CPS efficiency distribution

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**From data!**
Non-collision background: event display of a cosmic ray event

- Cosmic rays or halo particles can deposit energy in the calorimeter.
- This signature makes a perfect fake LED signal.
- Not too many handles to reject these events, just the photon as an actual physical object.
- Rejection of cosmic muons by timing signal in the muon scintillators and/or presence of characteristic pattern consistent with a cosmic muon.

![Event display of a cosmic ray event](image)

**Muon stub veto on cosmic ray muons**

- **Entries**: 300
- **Mean**: -0.3042
- **RMS**: 0.5974

![Muon stub veto on cosmic ray muons](image)
Non-collision background: event display of a cosmic ray event

- Cosmic rays or halo particles can deposit energy in the calorimeter.
- This signature makes a perfect fake LED signal.
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Non-collision background

Different components to the $\phi$ distribution, $p_T^\gamma > 50$ GeV, $E_T > 45$ GeV

- $\gamma$ sample data
- non-collision
- misidentified jets
- $e/\gamma$
- sum of histograms
EM cluster pointing algorithm calculates the direction of the EM shower.

It is based solely on the central preshower (CPS) and EM calorimeter clusters.

Energy-weighted centroid coordinates at each layer in the EM calorimeter are calculated.
EM Cluster Pointing Algorithm

- Fit of all five floor coordinates of the EM object and the CPS cluster to a straight line.

- Polar plane: *z position of vertex*.

- Azimuthal plane: distance of closest approach to the beam line (*DCA*). Resolution is about 2-3 cm.
### DCA Templates Construction

**non-collision template**
(widest DCA distribution):
events with no hard scatter (no reconstructed primary vertex or reconstructed tracks fewer than three), or from cosmic ray events.

**misidentified jets template**
(wider DCA distribution):
EM objects with reversed track isolation.

**e/γ template**
(narrow DCA distribution):
Obtained from sample of isolated electrons.

![DCA template graph](image)

From data!
Pointed Vertex

- Require at least one reconstructed interaction vertex consistent with the measured direction of the photon.
- Difference in the z-coordinate position less than 10 cm.
- Re-vertexing at high luminosities.

**Photon Candidates**

**Signal-like events**

**Non-collision events**

**Misidentified jets evts.**

*From data!*

![Graphs showing distributions of $\Delta Z_{\text{vtx}}$ for different categories: Photon Candidates, Signal-like events, Non-collision events, and Misidentified jets evts.](image)
**Pointed Vertex**

- Require at least one reconstructed interaction vertex consistent with the measured direction of the photon.
- Difference in the z-coordinate position less than 10 cm.
- Re-vertexing at high luminosities.

**Photon Candidates**

- **Backgrounds**
  - Require at least one reconstructed interaction vertex consistent with the measured direction of the photon.
  - Difference in the z-coordinate position less than 10 cm.
  - Re-vertexing at high luminosities.

**Signal-like events**

**BEFORE**

**DCA distribution, before |ΔZ_{min}|<10 cut**

- **Entries**: 1070
- **Mean**: 5.196
- **RMS**: 4.271

**Non-collision/Pointing**

**BEFORE**

**DCA distribution, before |ΔZ_{min}|<10 cut**

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Pointed Vertex

- Require at least one reconstructed interaction vertex consistent with the measured direction of the photon.
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**Photon Candidates**
- **Signal-like events**

**Non-collision/Pointing**

**Photon Candidates**

**Signal-like events**
Shower Shape

- EM objects from interaction region expected to deposit most of their energy in the 3rd layer of the EM calorimeter.
- Particles not from the interaction region deposit all their energy in the first EM layer.

```
EM4  EM3  EM2  EM1
CPS
Pb radiator
solenoid
Beam line
tracker
```

Non-collision, Energy Fraction at EM1

- From data!

Non-collision, Energy Fraction at EM3

- From data!
Require photon showers to deposit at least 10% of their total energy in the third layer of the EM calorimeter.
Require photon showers to deposit at least 10% of their total energy in the third layer of the EM calorimeter.
Require photon showers to deposit at least 10% of their total energy in the third layer of the EM calorimeter.
Shower Shape (H-Matrix)

- Additional quantity, in principle designed for electrons.
- Can be used loosely for photon identification to achieve some additional background rejection.
- Eight or seven variables can be used to construct a covariance matrix.
- The H-Matrix $\chi^2$ is calculated using the inverted covariance matrix, data, and the mean values from MC electron profile.
- A shower matching the MC profile will have low $\chi^2$.

**Variables x used:**
- Fractional energy in each of the EM layers.
- The total electromagnetic energy.
- The energy weighted shower width in z and azimuthal directions.
- The z vertex distribution.
The Photon sample

Photon selection:

- $p_T > 90$ GeV
- $MET > 70$ GeV, to guarantee no multijet background.
- No jets with $p_T > 15$ GeV to avoid large MET due to mismeasurement of jet energy.
- No muons and no energetic tracks in the event.

Most of signal-like events concentrated in this region (e/gamma) events + EM jets.

We use DCA templates to estimate these contributions.

Non-collision events + some misidentified jets

<table>
<thead>
<tr>
<th>hph_dca</th>
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</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>
We fit the DCA distribution in the photon sample to a linear sum of the three templates, fixing the contribution of the misidentified jets. Most of the signal is concentrated in this region.
Prediction of misidentified jets background

**photon sample**: number of events from misidentified jets $N_{\text{misid}}$ -> unknown.

**fake photon sample (inverted track isolation)**: number of events $N_{\text{fake}}$ -> known.

$N_{\text{misid}}$ can be predicted from the fake photon sample based on the rates at which jets, passing all other photon ID criteria, fail or pass the track isolation.

$N_{\text{misid}} = N_{\text{fake}} \times \frac{N_2}{N_1}$

---

EM + jet sample

fake (inverted track isolation) + jet: $N_1$

photon (track isolation) + jet: has $N_2$ *(from the fit)*

Events vs [cm]

- data
- misidentified jets
- $\mu/\gamma$
- sum of histograms
Remaining Backgrounds Estimation

\[ Z + \gamma \rightarrow \nu \bar{\nu} + \gamma \]

- Estimated from a sample of Monte Carlo (MC) events generated with PYTHIA.

\[ W + \gamma \rightarrow l \nu + \gamma \]

- Same selection requirements as for data plus correction factors to account for differences in simulation.

\[ W \rightarrow e \nu \]

- Estimated from data using a sample of isolated electrons. Same requirements as for the photon sample. The remaining number of events is scaled by:

\[
\left( 1 - \epsilon_{\text{trk}} \right) \frac{\epsilon_{\text{trk}}}{\epsilon_{\text{trk}}} \]

\( \epsilon_{\text{trk}} \): track reconstruction efficiency
Results

FINAL COUNTS

<table>
<thead>
<tr>
<th>Background</th>
<th>Number of expected events, combination (2.7 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \gamma \rightarrow \nu \bar{\nu} + \gamma$</td>
<td>29.5 ± 2.5</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>8.5 ± 1.7</td>
</tr>
<tr>
<td>Non-collision</td>
<td>6.6 ± 2.3</td>
</tr>
<tr>
<td>Misidentified jets</td>
<td>3.1 ± 1.5</td>
</tr>
<tr>
<td>$W + \gamma$</td>
<td>2.22 ± 0.3</td>
</tr>
<tr>
<td>Total Background Data</td>
<td>49.9 ± 4.1</td>
</tr>
<tr>
<td>Data</td>
<td>51</td>
</tr>
</tbody>
</table>

LIMITS

<table>
<thead>
<tr>
<th>$n$</th>
<th>Combination 2.7 fb⁻¹ observed (expected) cross section limit (fb)</th>
<th>Combination 2.7 fb⁻¹ observed $M_D$ lower limit (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>19.0 (14.6)</td>
<td>970 (1037)</td>
</tr>
<tr>
<td>3</td>
<td>20.1 (14.7)</td>
<td>899 (957)</td>
</tr>
<tr>
<td>4</td>
<td>20.1 (14.9)</td>
<td>867 (916)</td>
</tr>
<tr>
<td>5</td>
<td>19.9 (15.0)</td>
<td>848 (883)</td>
</tr>
<tr>
<td>6</td>
<td>18.2 (15.2)</td>
<td>831 (850)</td>
</tr>
<tr>
<td>7</td>
<td>15.9 (14.9)</td>
<td>834 (841)</td>
</tr>
<tr>
<td>8</td>
<td>17.3 (15.0)</td>
<td>804 (816)</td>
</tr>
</tbody>
</table>
Summary

✦ A search for the direct production of gravitons in association with single photons has been presented.

✦ Standard D0 photon identification is not enough to reject non-collision backgrounds for final states with just one single photon.

✦ The EM pointing algorithm has been proved to be an important tool to discriminate against these unwanted events.

✦ No evidence for the presence of LED has been found.

✦ Some of the ideas presented in this talk might be used in new hadron collider experiments (ATLAS in particular due to the fine segmentation of its calorimeter).
Shower Width Formulas

\[
\sigma_{r\phi} = \frac{\sum_{\text{cells}} E_i \times R^2 \times \sin^2 (\phi_c - \phi_i)}{E_C} < 16 \text{cm}^2
\]

\[
\phi_c = \frac{\sum_{\text{cells}} E_i \phi_i}{\sum_{\text{cells}} E_i}
\]

\[E_C: \text{energy of the cluster}\]
Centroid position calculation (f can be x, y, or z coordinates):

\[ f_{layerN} = \frac{\sum_{cells} w_{cell}^{layerN} f_{cell}}{\sum_{cells} w_{cell}^{layerN}} \]

\[ w_{cell}^{layerN} = \max \left\{ 0, \left[ w_0 + \ln \left( \frac{E_{cell}^{layerN}}{E_{total}^{layerN}} \right) \right] \right\} \]
### H-Matrix

**Covariance Matrix:**

\[
M_{ij} = \frac{1}{N} \sum_{n=1}^{N} (x_i^n - \bar{x}_i)(x_j^n - \bar{x}_j)
\]

**MC simulation**

**H-Matrix \( \chi^2 \):**

\[
X_{HM}^2 = \sum_{i,j=1}^{8} (x_i' - \bar{x}_i) H_{ij} (x_j' - \bar{x}_j)
\]

**Data**