Anomalous Coupling Studies Using Proton Tagging at the LHC

Justin Williams

The University Of Kansas
Setting The Scene

The typical collision at the LHC includes parton interactions

“Hard” Scattering

initial-state radiation

final-state radiation

proton

underlying event

outgoing parton

proton

underlying event

outgoing parton
There’s a significant number of collisions that leave protons intact.
The physics program studies events giving intact protons in the forward regions.

- The CMS Precision Proton Spectrometer (PPS) and ATLAS Forward Proton detectors (AFP) provides an opportunity for new searches and measurements.
- Possibility of a very strong background suppression using intact protons.

**Outline**

1. Description of proton detection technology
2. Physics results
3. Prospects: Anomalous Couplings, Axion-Like Particles, Dark Matter, etc.
Proton Tagging at the LHC

One example of the experimental setup is CMS PPS

- Stations of detectors at ± 200 m from IP
- Multiple planes of detectors
- Measure x (and/or y) position → ξ of proton
- Timing detectors ~ 40 ps
Proton Measurement with Roman Pot detectors

Figure 2.14: The geometry of RP stations (only the first two planes/sensors of the 56-220-near unit are drawn). The proportions have been modified for graphical reasons, they are not to scale. The blue line marks the beam axis. The red arrows mark the offsets of sensors' centers from the package axes (slightly inclined dotted lines). The black marks the beam of the thin window (see Fig. 2.10). These devices are calibrated to give the distance between the face exposed to the beam of the thin window and the hit points in the near and far units of the station.

Since there is no significant magnetic field in the region of the CT–PPS RPs, the trajectory of particles passing through the silicon strip detectors is a straight line. In each RP (RP hereinafter operations, every alignment fill. The point where a proton is emitted, as sketched in Fig. 2.15. One may relate the momentum \( p^\ast \) of the outgoing proton to the nominal beam momentum

\[
p^\ast = p_{\text{nom}} (1 + x^\ast),
\]

where \( x^\ast \) is the momentum loss.

Proton acceptance in the detectors depends on the machine optics parameters: leading terms for "standard" LHC optics:

\[
\begin{align*}
\delta_x &\approx \frac{1}{2} \left( \frac{1}{2} y \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \frac{1}{2} \frac{y}{y_{\text{nom}}} \\
\delta_y &\approx \frac{1}{2} \left( \frac{1}{2} y \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \frac{1}{2} \frac{y}{y_{\text{nom}}}
\end{align*}
\]

\[\Theta_x \approx \frac{1}{2} \left( \frac{1}{2} y \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \frac{1}{2} \frac{y}{y_{\text{nom}}}
\]

\[\Theta_y \approx \frac{1}{2} \left( \frac{1}{2} y \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \left( \frac{1}{2} \frac{y}{y_{\text{nom}}} \right) \frac{1}{2} \frac{y}{y_{\text{nom}}}
\]

Proton transport description:

\[
X \left( p^\ast \right) = X \left( p_{\text{nom}} \right) + X \left( x^\ast \right)
\]

Optics

measured at RP

\[
\begin{pmatrix}
 x \\
 \Theta_x \\
 y \\
 \Theta_y \\
 \zeta
\end{pmatrix}
_{\text{RP}} =
\begin{pmatrix}
 v_x & L_x & m_{13} & m_{14} & D_x \\
 v'_x & L'_x & m_{23} & m_{24} & D'_x \\
 m_{31} & m_{32} & v'_y & L'_y & D'_y \\
 m_{41} & m_{42} & v'_y & L'_y & D'_y \\
 0 & 0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
 x^\ast \\
 \Theta_x^\ast \\
 y^\ast \\
 \Theta_y^\ast \\
 \zeta^\ast
\end{pmatrix}
\]

values at IP

The CMS+TOTEM 2016, \( \beta = 13 \) TeV

\[
\begin{pmatrix}
 X_{\text{nom}} \\
 \Theta_{x_{\text{nom}}} \\
 y_{\text{nom}} \\
 \Theta_{y_{\text{nom}}} \\
 \zeta_{\text{nom}}
\end{pmatrix}
\]
Roman Pot Technology

Roman Pots are the movable machinery that houses tracking detectors

Roman Pots

- Multiple planes of detectors
- Silicon or pixels
- Horizontal and vertical RPs
- Approach the beam at $\sim 1$ mm
- Designed to operate at standard running conditions
Introduction

Proton Tagging

Anomalous Couplings

Conclusion

Advantages of Roman Pot Technology

M. Trzebiński Photon-Photon @ ATLAS/AFP 7/19

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LHC beam
LHC beam
LHC beam

x
y
z

M. Trzebiński
Photon-Photon © ATLAS/AFP

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LHC beam

thin window and floor (300 µm)
Shadow of TCL4 and TCL5 collimators

LHC beam

Geometric acceptance:

Mass acceptance:

Thin window and floor (300 µm)
shadow of TCL4 and TCL5 collimators

Geometric acceptance:

Mass acceptance:

M. Trzebiński

Photon-Photon @ ATLAS/AFP
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diffractive protons

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shadow of TCL4 and TCL5 collimators

diffractive protons
thin window and floor (300 \( \mu \)m)

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Not reviewed, for internal circulation only

Advantages of Roman Pot Technology

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**Introduction**

**Proton Tagging**

**Anomalous Couplings**

**Conclusion**

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**Advantages of Roman Pot Technology**

- **Geometric acceptance:**
  - LHC beam
  - Diffractive protons
  - Thin window and floor (300 µm)

- **Mass acceptance:**
  - Geometric acceptance [%]
  - Proton relative energy loss, $\varepsilon$
  - Proton transverse momentum, $p_T$ [GeV]

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Photon-Photon © ATLAS/AFP

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shadow of TCL4 and TCL5 collimators

Geometric acceptance:

Mass acceptance:
shadow of TCL4 and TCL5 collimators

diffractive protons
thin window and floor (300 µm)

Geometric acceptance:

Mass acceptance:
Physics Results (PPS)

- First observation of the process at high mass using intact protons
- Observed 13 signal events (5.1σ) consistent with the SM expectation
- Performed at normal optics and pileup conditions
- Proof that the alignment, optics, trigger, proton tagging, etc are working
Anomalous Quartic Gauge Couplings

- Photon induced processes with intact protons in forward regions
- Exclusive processes with a very clean signal
- Proton tagging provides the best sensitivity to anomalous couplings
Motivations

- Warped Extra Dimensions solve hierarchy problem of the SM
- Predicted by Composite Higgs, Kaluza Klein, Extra Dimensional models
- Couplings can be probed independently of models
- Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13} \text{ GeV}^{-4}$ possible
Backgrounds

- Requesting two protons identified in forward detectors + two converted photons in central detector

- All backgrounds considered (DPE diphoton production, H→γγ, exclusive γγ production, dilepton + dijet misidentification, PU, Drell-Yan, ...)

- Pileup is the main source of background
Pile Up

- The LHC collides packets of protons
- PU causes background from particles generated at unrelated vertices
- For conditions of the LHC in 2016, can have up to 60 PU vertices
Dealing With Pile Up

\[ \gamma \gamma \]

\[ p \]

\[ p \]

\[ \zeta_1 = 10^{-12} \text{ GeV}^4 \]

\[ \zeta_1 = 10^{-13} \text{ GeV}^4 \]

\[ \zeta_1 = 10^{-12} \text{ GeV}^4 \]

\[ \zeta_1 = 10^{-13} \text{ GeV}^4 \]

\[ \mu = 50 \]

\[ \mu = 50 \]

\[ s = 14 \text{ TeV} \]

\[ L = 300 \text{ fb}^{-1} \]

JHEP 02, 165 (2015)
Dealing With Pile Up

<table>
<thead>
<tr>
<th>Cut / Process</th>
<th>Signal (full)</th>
<th>Signal with (without) f.f. (EFT)</th>
<th>Excl.</th>
<th>DPE</th>
<th>DY, di-jet + pile up</th>
<th>γγ + pile up</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.015 &lt; ξ_{1,2} &lt; 0.15, ( p_{T1,(2)} ) &gt; 200, (100) GeV]</td>
<td>65</td>
<td>18 (187)</td>
<td>0.13</td>
<td>0.2</td>
<td>1.6</td>
<td>2968</td>
</tr>
<tr>
<td>( m_{γγ} &gt; 600 ) GeV</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
</tr>
<tr>
<td>[ p_{T2}/p_{T1} &gt; 0.95,</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>80.2</td>
</tr>
<tr>
<td>(</td>
<td>Δφ</td>
<td>&gt; π - 0.01 ]</td>
<td>( √{ξ_1ξ_2}s = m_{γγ} ± 3% ]</td>
<td>61</td>
<td>16 (175)</td>
<td>0.09</td>
</tr>
<tr>
<td>(</td>
<td>y_{γγ} - y_{pp}</td>
<td>&lt; 0.03 ]</td>
<td>60</td>
<td>12 (169)</td>
<td>0.09</td>
<td>0</td>
</tr>
</tbody>
</table>

Virtually no background after selection cuts \(^1\)

\(^1\)JHEP 02, 165 (2015)
Comparison Of Limits

Expect up to 2 orders of magnitude improvements for 95% CL limits on aQGC with CT-PPS wrt to Run 1 CMS only results
Search For Axion-Like Particles

We can study the production of ALPs via photon exchange with intact protons

- Study the production of ALPs via photon exchange with intact protons
- Sensitivity is enhanced since ALP production rate increases with $m_{\gamma\gamma}$
- Proton tagging provides sensitivity that is competitive and complementary to other collider searches above 600 GeV
- Existing limits on ALP production\(^2\)

\(^2\) JHEP 1806 (2018) 131
Summary

- Proton tagging provides a broad physics program, from the study of proton structure to BSM physics.
- Proton tagging provides the best sensitivity to anomalous couplings.
- Measuring all final state particles gives a closed kinematic system.
- PPS and AFP have taken data during the LHC Run 2 that are currently being analyzed.
Questions?
Available Phase Space

Available Phase Space

LHC Run-II, pre-TS2
\( \beta^* = 0.4 \, \text{m} \)
\( \alpha_x = 370 \, \mu\text{rad} \)

\[
Y(\text{central system}) = \frac{1}{2} \log(\frac{\xi_1}{\xi_2})
\]

\[
m(\text{central system}) = \sqrt{s_{12} \xi_1 \xi_2} \, (\text{GeV})
\]

No acceptance
Acceptance in 210-N/F
Acceptance in 210-F
Double arm acceptance

Single- and double-arm acceptance
Physics observable: proton longitudinal momentum loss \( \vec{p}/p \) (GeV)

\[
(\xi_1 \xi_2)_{s(\text{central system})} = 2 \times 10^3 \times 10^4
\]

Single-arm tagging extends acceptance to low-mass, forward-region events

L. Forthomme (University of Kansas)

Physics results with the CMS-TOTEM Precision Proton Spectrometer — LHC Working Group on Forward Physics and Diffraction

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Standard Model $\gamma\gamma$ Exclusive Production

- QED process dominates at high $m_{\gamma\gamma}$
- Cross section is well known
- $W$ boson loop is the most significant at high $m_{\gamma\gamma}$

JHEP 02, 165 (2015)
Potential For Limits

Cross section scales as a function of the coupling values $\zeta_1, \zeta_2$

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s} \left( s^2 + t^2 + st \right)^2 \left[ 48 (\zeta_1)^2 + 40\zeta_1\zeta_2 + 11 (\zeta_2)^2 \right]$$

- Based on $9.41\text{ fb}^{-1}$ of data from 2016
- Assume signal and background obey a Poisson distribution
- Assume expected background is 0 and observed events is 0

$$\sqrt{48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2} \geq 5.8 \times 10^{-13}\text{ GeV}^{-4}$$
See talk by L. A. Hardland-Lang at PHOTON2019

- Cross section for ~ 100 GeV slepton pair CEP ~ fb ⇒ essential to take data during nominal high-luminosity LHC running.
- Question discussed in recent study: what are challenges/backgrounds in searching for such a signal via CEP?

LHC Searches for Dark Matter in Compressed Mass Scenarios:
Challenges in the Forward Proton Mode

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Abstract

We analyze in detail the LHC prospects at the center-of-mass energy of \( \sqrt{s} = 14 \) TeV for charged electroweakino searches, decaying to leptons, in compressed supersymmetry scenarios, via exclusive photon-initiated pair production. This provides a potentially increased

LHL, V.A. Khoze, M.G. Ryskin, M.
Tasevsky, JHEP 1904 (2019) 010