From diffraction to the search for extra-dimension at the LHC

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- Pomeron structure in terms of quarks/gluons
- Tests of BFKL resummation
- Photon exchanges processes and beyond standard model physics
- Anomalous quartic $\gamma\gamma\gamma\gamma$ couplings using intact protons
Diffraction at Tevatron/LHC

Kinematic variables

- $t$: 4-momentum transfer squared
- $\xi_1, \xi_2$: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken-x of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta \eta \sim \log 1/\xi_{1,2}$: rapidity gap
What is AFP/CT-PPS?

- Tag and measure protons at ±210 m: AFP (ATLAS Forward Physics), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Sensitivity to high mass central system, $X$, as determined using AFP: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements
**Hard diffraction at the LHC**

- **Dijet production**: dominated by $gg$ exchanges; $\gamma+\text{jet}$ production: dominated by $qg$ exchanges (C. Marquet, C. Royon, M. Saimpert, D. Werder, arXiv:1306.4901)


- **Three aims**
  - Is it the same object which explains diffraction in $pp$ and $ep$?
  - Further constraints on the structure of the Pomeron as was determined at HERA
  - Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement
Inclusive diffraction at the LHC: sensitivity to gluon density

- Predict DPE dijet cross section at the LHC in AFP acceptance, jets with $p_T > 20$ GeV, reconstructed at particle level using anti-$k_T$ algorithm
- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high $\beta$: multiply the gluon density by $(1 - \beta)^\nu$ with $\nu = -1, \ldots, 1$
- Possibility to measure Reggeon contribution by looking at dijet production at high $\xi$
- Dijet mass fraction: dijet mass divided by total diffractive mass ($\sqrt{\xi_1 \xi_2 S}$)

![Graph showing dijet cross section as a function of mass fraction with different values of $\nu$. The graph includes a 20% uncertainty bar and a standard (HERA Fit PDF).](image-url)
Inclusive diffraction at the LHC: sensitivity to quark densities

- Predict DPE $\gamma+\text{jet}$ divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quark density in Pomeron, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA
Measure the average $W$ charge asymmetry in $\xi$ bins to probe the quark content of the proton: 

$$A = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}$$

Test if $u/d$ is equal to 0.5, 1 or 2 as an example

A. Chuinard, C. Royon, R. Staszewski, JHEP 1604 (2016) 092
Looking for BFKL effects

- Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP): Evolution in $Q^2$
- Balitski Fadin Kuraev Lipatov (BFKL): Evolution in $x$

Aim: Understanding the proton structure (quarks, gluons)

$Q^2$: resolution inside the proton (like a microscope)

$X$: Proton momentum fraction carried away by the interacting quark
**Jet gap jet events in diffraction**

- Study BFKL dynamics using jet gap jet events in DPE

\[ \text{ratio} = \frac{\sigma(\text{DPE JGJ})}{\sigma(\text{DPE Jets})} \times \frac{\sigma(\text{DPE LO Jet++})}{\sigma(\text{DPE NLO Jet++})} \]

- 2nd leading jet $p_T > 20$ GeV
- $0.012 < \xi_{AFP} < 0.14$
- $\Delta \eta_j > 3.0$  \quad $|\eta_j| > 1.0$

\[ \int_{L dt} = 300 \text{ pb}^{-1} \]
Exclusive diffraction

- Many exclusive channels can be studied: jets, $\chi C$, charmonium, $J/\Psi$...
- Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton
- CMS/TOTEM has the possibility to discover/exclude glueballs at low masses: Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates
- Simulation of signal $f_0(1710) \rightarrow \rho^0\rho^0$ and non resonant $\rho^0\rho^0$
Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling

- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W = M_X > 1$ TeV$) = 5.9$ fb
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models Concentrate on $\gamma\gamma\gamma\gamma$ anomalous coupling in this talk
QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$

- Important to consider $W$ loops at high $m_{\gamma\gamma}$

- At high masses ($\sim 750$ GeV), the photon induced processes are dominant

**Conclusion:** Two photons and two tagged protons means photon-induced process
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

• Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F^{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F^{\rho\lambda} F^{\lambda\mu}$$

• $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charge particles

$$\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$$

where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle

This leads to $\zeta_1$ of the order of $10^{-14}$-$10^{-13}$

• $\zeta_1$ can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where $f_s$ is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$
Warped extra-dimensions

- Warped Extra Dimensions solve hierarchy problem of SM
- $5^{th}$ dimension bounded by two branes
- SM on the visible (or TeV) brane

- The Kaluza Klein modes of the graviton couple with TeV strength

\[ \mathcal{L}_{\gamma\gamma h} = f^{-2} h_{\mu\nu}^{KK} \left( \frac{1}{4} \eta_{\mu\nu} F_{\rho\lambda}^2 - F_{\mu\rho} F_{\rho\nu} \right) \]

- $f \sim \text{TeV}$
- $m_{KK} \sim \text{few TeV}$

- Effective 4-photon couplings $\zeta_i \sim 10^{-14} - 10^{-13} \text{ GeV}^{-2}$ possible

- The radion can produce similar effective couplings

- Which models/theories are we sensitive to using AFP/CT-PPS
- Beyond standard models predict anomalous couplings of $\sim 10^{-14}-10^{-13}$
- Work in collaboration with Sylvain Fichet, Gero von Gersdorff
One aside: what is pile up at LHC?

- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events
Search for quartic $\gamma \gamma$ anomalous couplings

- Search for $\gamma \gamma \gamma \gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...

\[ \sqrt{s} = 14 \text{ TeV} \]
\[ L = 300 \text{ fb}^{-1} \]
\[ \mu = 50 \]
\[ \zeta_1 = 10^{-12} \text{ GeV}^{-4} \]
\[ \zeta_2 = 10^{-13} \text{ GeV}^{-4} \]
Search for quartic $\gamma\gamma$ anomalous couplings

No background after cuts for $300 \text{ fb}^{-1}$ without needing timing detector information

Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb$^{-1}$)
High lumi: Search for quartic $\gamma\gamma$ anomalous couplings: Results from effective theory

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$300 \text{ fb}^{-1}$</th>
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<th>$300 \text{ fb}^{-1}$</th>
<th>$3000 \text{ fb}^{-1}$</th>
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<tbody>
<tr>
<td>pile-up ($\mu$)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>coupling ($\text{GeV}^{-4}$)</td>
<td>$\geq 1$ conv. $\gamma$ ($5\sigma$)</td>
<td>$\geq 1$ conv. $\gamma$ 95% CL</td>
<td>all $\gamma$ 95% CL</td>
<td>all $\gamma$ 95% CL</td>
</tr>
<tr>
<td>$\zeta_1$ f.f.</td>
<td>$8 \cdot 10^{-14}$</td>
<td>$5 \cdot 10^{-14}$</td>
<td>$3 \cdot 10^{-14}$</td>
<td>$2.5 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$\zeta_1$ no f.f.</td>
<td>$2.5 \cdot 10^{-14}$</td>
<td>$1.5 \cdot 10^{-14}$</td>
<td>$9 \cdot 10^{-15}$</td>
<td>$7 \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$\zeta_2$ f.f.</td>
<td>$2 \cdot 10^{-13}$</td>
<td>$1 \cdot 10^{-13}$</td>
<td>$6 \cdot 10^{-14}$</td>
<td>$4.5 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$\zeta_2$ no f.f.</td>
<td>$5 \cdot 10^{-14}$</td>
<td>$4 \cdot 10^{-14}$</td>
<td>$2 \cdot 10^{-14}$</td>
<td>$1.5 \cdot 10^{-14}$</td>
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- Unprecedented sensitivities at hadronic colliders: no limit exists presently on $\gamma\gamma\gamma\gamma$ anomalous couplings
- Reaches the values predicted by extra-dim or composite Higgs models
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way: $a \rightarrow \frac{a}{(1 + W_{\gamma\gamma}/\Lambda_{\text{cutoff}})^2}$ with $\Lambda_{\text{cutoff}} \sim 2 \text{ TeV}$, scale of new physics
- Full amplitude calculation leads to similar results: avoids using a form factor and parameters dependence of the results
- **Conclusion:** background free experiment
Removing pile up: measuring proton time-of-flight

- Measure the proton time-of-flight in order to determine if they originate from the same interaction as our photon
- Typical precision: 10 ps means 2.1 mm
Measuring the proton time-of-flight: the SAMPIC concept

- The general idea is to measure the signal created by the protons inside a quartz, diamond or Silicon detector.
- New electronics developed in Saclay/Orsay called SAMPIC that acquires the full waveform shape of the detector signal: about 3 ps precision!
- SAMPIC is cheap (∼10 Euros per channel) (compared to a few 1000 Euros for previous technologies)
Timing resolution vs delay

- Measure the RMS of the time difference between two pulses sent to SAMPIC vs delay using a pulse generator
- Flat resolution of $\sim 5$ ps vs delay: time resolution per channel of $\sim 3$ ps
The future: Application: Timing measurements in Positron Emission Tomography

- The holy grail: 10 picosecond PET (3 mm resolution)
- What seemed to be a dream a few years ago seems now to be closer to reality: Project that could benefit from the synergy between the different disciplines at the University of Kansas (physics, medicine, engineering, computing)
- Other possible application in drone technology: fast decision taking and distance measurement using laser
Conclusion

- Better constraints on gluon distribution in Pomeron, sensitivity to differences in quark distributions
- Jet gap jet events in diffraction: sensitivity to BFKL resummation effects, \( \sim 15-20\% \) of DPE jets are jet gap jet events!
- \( \gamma\gamma\gamma\gamma \) anomalous coupling studies
  - Exclusive process: photon-induced processes \( pp \rightarrow p\gamma\gamma p \) (gluon exchanges suppressed at high masses):
  - Theoretical calculation in better control (QED processes with intact protons), not sensitive to the photon structure function
  - “Background-free” experiment and any observed event is signal
  - NB: Survival probability in better control than in the QCD (gluon) case
- CT-PPS/AFP allows to probe BSM diphoton production in a model independent way: sensitivities to values predicted by extradim or composite Higgs models
- Look into other channels: \( WW, ZZ, Z\gamma \) (specially interesting), jet jet
Status of Yellow Report about LHC Forward Physics WG

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

  - Background and run plans: V. Avati, C. Royon
  - Monte Carlo: L. Harland-Lang
  - Soft Diffraction: V. Avati, T. Martin
  - Hard Diffraction: M. Ruspa, M. Trzebinski
  - Central Exclusive Production: M. Saimpert, L. Harland-Lang, V. Khoze
  - BFKL and saturation: C. Marquet, J. Bartels, H. Jung
  - Cosmic ray: T. Pierog
  - Heavy ions: D. Tapia Takaki
  - Detectors: J. Baechler, V. Avati