HUNTING FOR QCD INSTANTONS AT THE LHC IN THE FORWARD PROTON MODE

VALERY KHOZE
(IPPP, Durham University)
MOTTO

DO NOT COME TO TALK, COME TO INTERACT
Recently—a renewal of interest, initiated by the experimental LHC community (M. Schott et al)

Currently focus mainly on searches for the BSM phenomena

While the existence of topological effects within the Standard Model, such as QCD instantons or electroweak Sphaleron signatures is well known, it is far from clear, how they can be experimentally observed.

Instantons describe quantum tunneling between different vacuum sectors of the QCD and are arguably the best motivated yet experimentally unobserved nonperturbative effects predicted by the Standard Model.

Recent calculations of Instanton-induced processes in pp collisions:

V.V. Khoze, F. Krauss, M. Schott, 1911.09726 : JHEP
V.V. Khoze, D. Milne, M. Spannowsky, 2010.02287 : PRD
QCD Instantons

- Yang-Mills vacuum has a nontrivial structure
- *Instantons* are tunnelling solutions between the vacua.
- At the classical level there is no barrier in QCD. The *sphaleron is a quantum effect*
- Transitions between the vacua change chirality (result of the ABJ anomaly).
- All light quark-anti-quark pairs must participate in the reaction.
- Not described by perturbation theory.

\[
E_{\text{sph}} = ? \quad \text{no classical barrier}
\]

Sphaleron-transition on top of an energy barrier
Instantons have never been observed experimentally, however, they are playing very important role in the theoretical models of confinement and chiral symmetry breaking.

- a possible solution to the axial $U(1)$ problem

\[ < 0 | G^a_{\mu\nu} G^c_{\mu\nu} | 0 > \neq 0 \]

**Instanton signatures:**

- large multiplicity \( N_{jet} \sim 1/\alpha_s(\rho_{inst}) \) \( E_T \sim 1/\rho_{inst} \)

- large 'Sphericity', \( S \rightarrow 1 \)

- presence of an additional light \( \bar{q}_R q_L \) pairs

(in particular pair of strange (or charm. for the small size instanton) quarks)

**Instanton ≠ the particle (no peak in \( M_{inst} \))**

It is a family of objects of different size, \( \rho \), and orientations in Lorentz and colour spaces

**Extended objects in space-time**

Effectively – a family of new multiparton vertices in Feynman diagrams
Instanton-induced processes with 2 gluons in the initial state:

All light flavours of quark-antiquark pairs must be present. Light \( \Rightarrow \)

\[ g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf}) \]

arbitrary
(tends to be large \( \sim 1/\alpha_s \))

\[ m_f \leq 1/\rho. \]

\[ \uparrow \]

instanton size

Can also have quark-initiated processes e.g.:

\[ u_L + \bar{u}_R \rightarrow n_g \times g + \sum_{f=1}^{N_f-1} (q_{Rf} + \bar{q}_{Lf}) , \]

\[ u_L + d_L \rightarrow n_g \times g + u_R + d_R + \sum_{f=1}^{N_f-2} (q_{Rf} + \bar{q}_{Lf}) \]

\[ \ldots \]

Instanton size is cut-off by partonic energy
this is what sets the effective QCD sphalrenon scale

\[ \sim s^{\frac{1}{2}} \]

Quantum corrections due to in-in states interactions

Mueller 1991
Small instanton masses-large rates, but difficult to distinguish from soft QCD activity (+ PU ‘complications’ at high lumi).
A large mass-striking multijet signature, but a very low rate.
The S/B ratio falls very rapidly with l-mass increasing —a higher chance of observing the signal in the low-mass range.
Elementary $gg \rightarrow I + \ldots$ cross section at $\sqrt{s'} = M_{\text{inst}}$

<table>
<thead>
<tr>
<th>$\sqrt{s'}$ [GeV]</th>
<th>$1/\rho$ [GeV]</th>
<th>$\alpha_s(1/\rho)$</th>
<th>$\langle n_g \rangle$</th>
<th>$\hat{\sigma}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.7</td>
<td>0.99</td>
<td>0.416</td>
<td>4.59</td>
<td>$4.922 \cdot 10^9$</td>
</tr>
<tr>
<td>15.7</td>
<td>1.31</td>
<td>0.360</td>
<td>5.13</td>
<td>$728.9 \cdot 10^6$</td>
</tr>
<tr>
<td>22.9</td>
<td>1.76</td>
<td>0.315</td>
<td>5.44</td>
<td>$85.94 \cdot 10^6$</td>
</tr>
<tr>
<td>29.7</td>
<td>2.12</td>
<td>0.293</td>
<td>6.02</td>
<td>$17.25 \cdot 10^6$</td>
</tr>
<tr>
<td>40.8</td>
<td>2.72</td>
<td>0.267</td>
<td>6.47</td>
<td>$2.121 \cdot 10^6$</td>
</tr>
<tr>
<td>56.1</td>
<td>3.50</td>
<td>0.245</td>
<td>6.92</td>
<td>$229.0 \cdot 10^3$</td>
</tr>
<tr>
<td>61.8</td>
<td>3.64</td>
<td>0.223</td>
<td>7.28</td>
<td>$72.97 \cdot 10^3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sqrt{s'_{\text{min}}}$ [GeV]</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{pp \rightarrow I}$</td>
<td>6.32 mb</td>
<td>40.82 $\mu$b</td>
<td>79.95 nb</td>
<td>105.4 pb</td>
<td>3.54 fb</td>
</tr>
</tbody>
</table>

Table 2. Hadronic cross sections for instanton production through initial gluons, at the 13 TeV LHC, using the NNPDF3.1 NNLO set with $\alpha_s(M_Z) = 0.118$ [67].

V.V. Khoze, F. Krauss, M. Schott, 1911.09726

$$\sigma(pp \rightarrow I) \sim M_{\text{inst}}^{-6}.$$  

Note infrared divergence at large $\rho$ (small $M_{\text{inst}}$)
Background

1. Multiple parton interactions
   (Double/Triple/... parton scattering)

Large at small $M_{\text{inst}}$

$$\frac{d\sigma}{dE_1^2...dE_n^2} \sim \left( \frac{d\sigma}{\sigma_{\text{eff}}dE_1^2} \cdots \frac{d\sigma}{\sigma_{\text{eff}}dE_n^2} \right) \sigma_{\text{eff}}$$

$$\frac{d\sigma}{dE_i^2} \sim \pi\alpha_s^2/E_i^4 \quad \sigma_{\text{eff}} \sim 10 \text{ mb}$$

$E_i$ denotes the transverse energy of a jet in the $i$ dijet system.

Thus the probability to observe $n$ additional branches in LRG events is suppressed by the factor $(S^2)^n$. Events with an LRG mainly occur at large values of $b_\perp$. 

$S^2 \leq 0.1.$
Thus, at sufficiently large values of $M_{\text{inst}}$ the instanton signal will become negligible relative to the purely perturbative QCD background.
- Instanton event - large $N_{ch}$ (due to $N_{jets}$) but not too large $\sum E_{T,i}$

- Sphericity $S = (3/2)(\lambda_2 + \lambda_3)$ close to 1
  $\lambda_1 > \lambda_2 > \lambda_3$ are the eigenvalues of $S^{\alpha\beta}$

$$S^{\alpha\beta} = \frac{\sum p_i^\alpha p_i^\beta}{\sum |p_i^2|}$$

- extra ($\bar{s}s$) pair of strange particles

$$g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})$$

(dijet events lead to sphericity of $S = 0$)
We suggested
M<5 GeV clusters are
The QCD sphalerons!

s’=M^2 is the cluster mass squared

Roman pots on both sides (AND) Plus UA2 central calorimeter
Small and large M Production is different In magnitude and Angular distributions

It may make sense to repeat this measurement at the LHC/RHIC ?
Searching for the Instanton as a multiparticle cluster/fireball with a mass \( \sim 20-60 \) GeV in events with an LRG

- LRG can be detected either by detecting the leading forward proton with beam momentum fraction, \( x_L = 1 - \xi \), very close to 1 (\( \xi = x_{Pom} \leq 0.01 \)), or by observing no hadron activity in the forward calorimeters.
It is shown that by imposing appropriate cuts on final states we can select the kinematical region where the I-signal exceeds BG by a factor of at least 2.5. At $\sum_i E_{T,i} > 15 \text{ GeV}, N_{\text{ch}} > 20$ measured within the $0 < \eta < 2$ the rate is expected to be large enough to measure Instanton production in the events with LRG at low luminosity.

Even with these rather strong cuts in place, the expected instanton cross-section remains sufficiently large ($\sim 1 \text{ nb}$) to effectively produce and probe QCD instantons at the LHC, at low luminosity runs, avoiding pile-up problems.
Central Instanton Production

\[ pp \rightarrow p + IP + IP + p \rightarrow p + X + p, \]

Detecting two outgoing protons would allow placing an upper limit on Instanton mass.

only a small part of the finally produced hadron state will avoid detection (‘hermiticity’)

dominates
Full set of analytical formulas for the partonic processes, calculated for the first time

For a reasonable instanton mass $M_{\text{inst}} \gtrsim 50$ GeV

$$\sigma_{pp \to l}^{(2b)} \sim \text{hundreds of pb}$$

$\alpha_{em}^2 \sim 10^{-4}$

UPC-no PU nightmare

L. Harland-Lang et al
It is shown that for a instanton mass $M_{\text{inst}} \geq 50$ GeV the expected central production cross sections for the instanton-induced processes are of the order of picobarns in the pure exclusive case and increase up to hundreds of pb when the emission of spectator jets is allowed.

The $x$-sections are encouragingly large and under favourable background conditions there is a tantalising chance that QCD instanton effects can either be seen or ruled out.

The expected experimental signature for the instanton-induced process in the central detector is a large multiplicity and transverse energy ($\sum_i E_{T_i}$) in relatively small rapidity interval ($\delta y \simeq 2 - 3$ and large sphericity $S > 0.8$ of the event.)
Summary

Recent theory papers on searches for QCD instanton of low masses ($20 < M_{\text{inst}} < 60 \text{ GeV}$) at LHC are encouraging.

Goal of this analysis is extension of previous theory studies:
- Higher masses ($M_{\text{inst}} > 60 \text{ GeV}$, $M_{\text{inst}} > 100 \text{ GeV}$)
- Inclusion of multi-parton interactions
- Inclusion of detector effects
- Inclusion of pile-up effects

Single-tag approach:
S/B $\sim 2.1$ (>60 GeV) or 2.3 (>100 GeV) at generator level deteriorate to S/B $\sim 0.6-0.7$ or 0.4 at detector level. Track reconstruction efficiencies and resolutions seem to be responsible.

Double-tag approach:
Since production cross section is 80x smaller than for SD, we have to consider larger values of $<\mu>$ (20 and 50). There combinatorial effects are big and overwhelm the signal.

19/09/2022

Marek Tasevsky

Search for QCD instantons in SD/CD
Potential improvements

1. Instanton-dedicated L1 triggers
2. Adding time information to central or forward region
3. Identify $c$-quark jets in the final state
The direct experimental observation of Instanton-induced processes would be a real breakthrough in particle physics.

QCD instanton cross-sections can be very large at hadron colliders (lower end of partonic energies 20-80 GeV).

An existing lack of evidence by no means leads to the conclusion that QCD instanton “does not exist”, but rather that their actual production rate is on the low end of predictions.

Potential for large sources of theoretical uncertainties covering orders of magnitude. A practical point for future progress is to test theory normalization of predicted instanton rate with data.

Searches for the signal in non-diffractive events are very challenging: modeling the detailed final state, background suppression, and separation from the possible SM and BSM sources of the “hedgehog-like” events. Events with a large pT signature are too rare.

Diffraction (single tag, CEP) promises some attractive advantages: cleaner signal, suppressed ‘standard’ backgrounds (MPI).

Currently, after accounting for the detector effects the distributions are sufficiently washed out, and it becomes quite challenging to extract the pure instanton signal. On top of this, the PU background turns out to be large, especially for the case with two tagged protons requiring work at lower luminosities.
Strong need for enthusiastic experimental experts to join the efforts, addressing such issues as detector effects, PU at high luminosity, and timing resolution.....

(Marek Tasevsky et al)

One of the main obstacle currently – PU at high luminosity

Possible directions for further studies

- Feasibility of searches for moderate mass Instantons in UPC
- Using good timing from Central Detectors for both ST and DT events.
- Identification of charm quark jets in the final state
Conclusion
BACKUP
DIS HERA data seem to exclude the low range of expectations.

**Figure 2.** Depiction of a QCD Instanton processes in electron-proton (left) and proton-proton (right) collisions, where an external scale parameter $Q'$ is required.

**Figure 3.** Depiction of a QCD Instanton processes in proton-proton (right) collisions.

a) To select $Q^2$ in DIS (or $q_{T,\text{jet}}$)  

b) To select events with $\sum_i E_{T,i} > E_{\text{cut}}$

*If the instanton is recoiled by a high $p_T$ jet emitted from one of the initial state gluons => hadronic cross-section is tiny*
In Real Life

Instanton produced in Single Diffraction:

- Detect a proton in AFP on one side (e.g. $\eta<0$) (large rapidity gap not required)

$$g+g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{R_f} + q_{L_f})$$

Final state: multi-particle cluster (or a fireball) containing a large number of isotropically distributed gluon (mini)jets accompanied by $N_f$ light-quark jets

1. High particle multiplicity
2. No high-pt jets
3. Large density of $E_T$

Suppress gluons from Pomeron with too large $x$ (where gluon PDF rapidly decreases with incr. $x$)

→ focus on $0<\eta<2$ (tagged proton has $\eta<0$)

Check the impact of MPI at particle level.
What about detector effects? Pile-up? Look at $M_{\text{inst}}>60$ GeV

→ 2208.14089
It is shown that by imposing appropriate cuts on final states we can select the kinematical region where the I-signal exceeds BG by a factor of at least 2.5. At \( \sum_i E_{T,i} > 15 \text{ GeV}, N_{ch} > 20 \) measured within the \( 0 < \eta < 2 \) the rate is expected to be large enough to measure Instanton production in the events with LRG at low luminosity.

Even with these rather strong cuts in place, the expected instanton cross-section remains sufficiently large (\( \sim 1 \text{ nb} \)) to effectively produce and probe QCD instantons at the LHC, at low luminosity runs, avoiding pile-up problems.
Single-tag: results at detector level

Hunting for higher S/B:

\( M_{\text{inst}} > 100 \text{ GeV} \) for \( \mu = 0 \):

\( \text{S/B} \sim 1.5 \) for \( N_{\text{tr05}} > 35 \wedge N_{\text{tr25}} = 0 \wedge \sum E_T^{\text{fwdcalo}} < 5 \text{ GeV} \)

but too few signal events survive