QCD Instantons at Colliders

Based on [2010.02287] with Valya Khoze and Michael Spannowsky
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Motivation

- Prediction of the Standard Model.
- Better understanding of non-abelian gauge theories.
- Could be useful in understanding the QCD background.
- Related to the vacuum structure of the Standard Model.
- Also important in BSM theories such as SUSY.

The QCD vacuum

By looking at the form of the QCD field strength tensor, one can show that there are multiple degenerate vacua.

After Wick rotating we get maps from S^3 to $SU(3)$ which are characterised by $\Pi_3\left(S^3\right) \sim \mathbb{Z}$. The instanton is the tunneling solution between adjacent vacua

$$A^a_\mu = \frac{2}{g}\eta_{a\mu\nu}\frac{(x-x_0)_\nu}{(x-x_0)^2+\rho^2}$$

The Instanton process

The main instanton process is

$$g + g \to \sum_{i=1}^{N_f} \left(q_R^0 + \bar{q}_L^0 \right) + n_g\, g.$$

The number of fermions is determined by the Adler-Bell-Jackiw anomaly.

$$\partial_\mu j^\mu = \frac{N_f g^2}{16\pi^2} Tr \left(F_{\mu\nu} \tilde{F}_{\mu\nu} \right) \implies$$

$$\Delta Q_A = 2N_f \Delta Q_T$$

where

$$j^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi$$

Numerical results

The instanton cross section can be calculated through the use of the optical theorem

$$\sigma^{I}_{\text{tot}} = \frac{1}{s'}\text{Im}\mathcal{M}\left(p_1, p_2, -p_1, -p_2\right)$$

This is given by

$$\hat{\sigma}^{\text{inst}}_{\text{tot}} \simeq \frac{1}{E^2}\,\text{Im}\,\frac{\kappa^2\pi^4}{36\cdot 4}\int\frac{d\rho}{\rho^5}\int\frac{d\bar{\rho}}{\bar{\rho}^5}\int d^4R\int d\Omega\left(\frac{2\pi}{\alpha_s(\mu_r)}\right)^{14}$$

$$(\rho^2 E)^2(\bar{\rho}^2 E)^2\mathcal{K}_{\text{ferm}}(z)(\rho\mu_r)^{b_0}(\bar{\rho}\mu_r)^{b_0}$$

$$\exp\left(R_0 E - \frac{4\pi}{\alpha_s(\mu_r)}\mathcal{S}(z) - \frac{\alpha_s(\mu_r)}{16\pi}(\rho^2+\bar{\rho}^2)\,E^2\,\log\frac{E^2}{\mu_r^2}\right)$$

Numerical results

$\sqrt{\hat{s}}$	$\langle n_g \rangle$	$\hat{\sigma}_{\rm tot}^{\rm inst}$ [pb]
50	9.43	207.33×10^{3}
100	11.2	1.29×10^{3}
150	12.22	53.1
200	12.94	5.21
300	13.96	165.73×10^{-3}
400	14.68	13.65×10^{-3}
500	15.23	1.89×10^{-3}

Virtuality form factor

If any of the gluons entering the instanton vertex has a virtuality then we must include in the integral the factor, $e^{-Q\rho}$.

E [GeV]	$\langle n_g \rangle$	$\hat{\sigma}\,(gg \to I)$ [pb]
20	7.81	2.01×10^6
40	9.67	1.25×10^5
60	10.89	1.38×10^4
80	11.67	2.36×10^3
100	12.10	5.44×10^2
120	12.77	1.53×10^2
140	13.25	4.99×10^1

Shape variables

Instanton events produce many jets and so will not stand out from the QCD background.

We want to exploit the lack of angular dependence to search for the instanton signal so we define the transverse sphericity tensor:

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\mathbf{p}_i|^2}.$$

$$S = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$$

Looking for instantons with LHC data

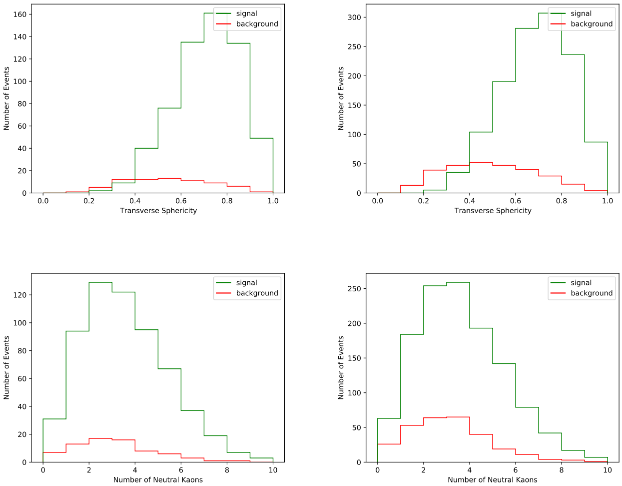
- ATLAS and CMS triggers are not sensitive to instantons, requiring single jets of $E_T > 360$ GeV or six jets of $E_T > 45$ GeV.
- However there is a potential search strategy using minimum bias data.
- We found that by examining events with 6 jets with $p_T > 10$ GeV and $\tau > 0.2$, we could obtain $s/\sqrt{b} \sim 50$, using the full 337 pb^{-1} dataset.
- There is also the potential to discover the instanton in existing Tevatron analyses.

Instantons with Large Rapidity Gaps

- Demanding the presence of large rapidity gaps is a useful way of searching for instantons as it suppresses the QCD background due to factors of $(S^2)^n$.
- We examined low mass instantons, $M_I > 20$ GeV.
- We found that by demanding:
  - $\sum E_T > 15$ GeV
  - $N_{ch} > 20$
  - a veto on the presence of charged particles with high p_T

We could obtain a set of events where signal exceeded background by a factor of 8.

Results


signal
background
Number of Events
Transverse Sphericity
signal
background
Number of Events
Transverse Sphericity
signal
background
Number of Events
Number of Neutral Kaons
signal
background
Number of Events
Number of Neutral Kaons

Summary

- Instanton processes are a good further test of the standard model.
- Instantons cannot be constrained by any existing analyses.
- We must search for instantons in minimum bias data as triggers are not sensitive.
- There are good kinematic regions existing in both usual searches and events with Large Rapidity Gaps where we have good sensitivity.