QCD Instanton Hunting at the LHC

Instanton is the classical solution of QCD equations.

A.A.Belavin, A.M.Polyakov, A.S.Schwatz and Yu.S.Tyupkin,

Phys.Lett.**59B**, 85 (1975)

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

$\alpha_s = g^2/4\pi$, $\rho=$ instanton radius,

$\eta_{a\mu\nu} = 0$ for $\mu = \nu = 4$

$\eta_{a\mu\nu} = -\delta_{a\nu}$ for $\mu = 4$

$\eta_{a\mu\nu} = \delta_{a\nu}$ for $\nu = 4$

$\eta_{a\mu\nu} = \epsilon_{a\mu\nu}$ for $\mu, \nu = 1, 2, 3$

At $x \to \infty$ instanton is the pure gauge field

$$g\frac{\tau^a}{2}A_\mu^a \to iS\partial_\mu S^+$$

with $S = i\tau_\mu^+ x_\mu/\sqrt{x^2}$

However for $x \neq \infty$ it is the real transverse gluon field which describes the transition between two different (in gauge) QCD vacuums.

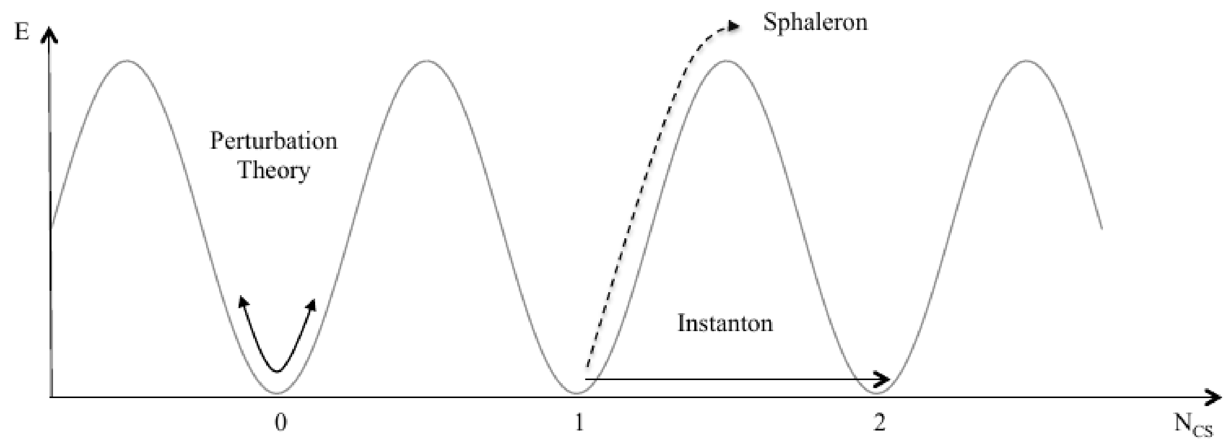


Figure 1. Instanton and Sphaleron processes in the topology of a Yang-Mills vacuum; energy density of the gauge field (y-axis) vs. winding number N_{CS} (x-axis).

Instanton was never observed

On another hand it is important in the theor. models of confinement and the chiral symmetry violation.
$< 0|G^a_{\mu\nu}G^a_{\mu\nu}|0 >\neq 0$

Instanton signatures:

- large multiplicity
- large 'Sphericity', $S \to 1$
- presence of an additional light $\bar{q}_R q_L$ pairs

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

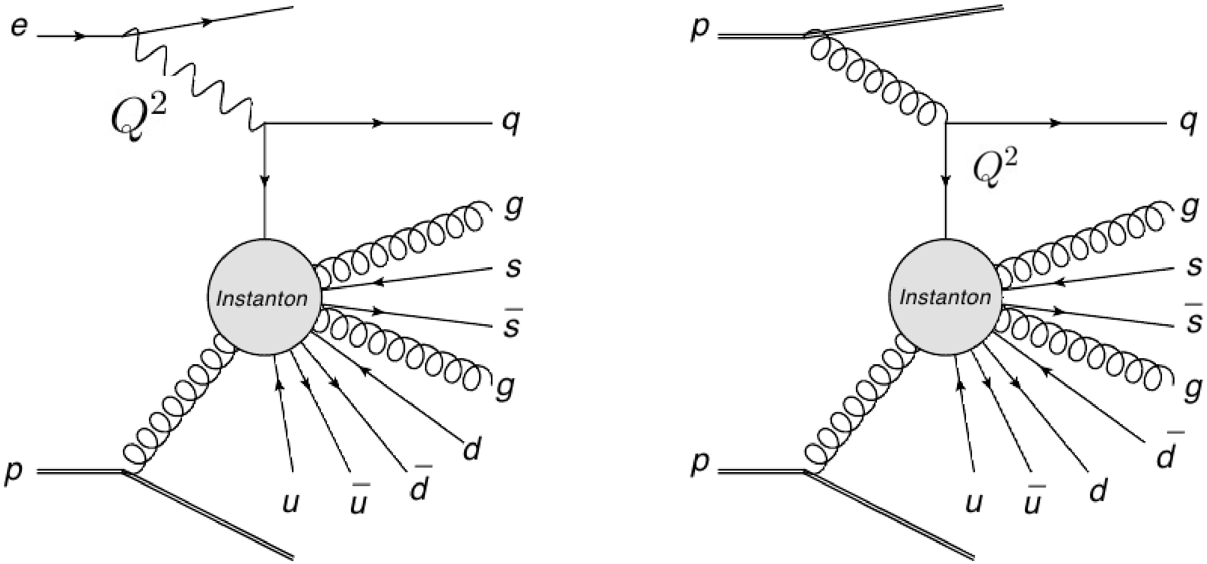


Figure 2. Depiction of a QCD Instanton processes in electron-proton (left) and proton-proton (right) collisions, where an external scale parameter Q' is required.

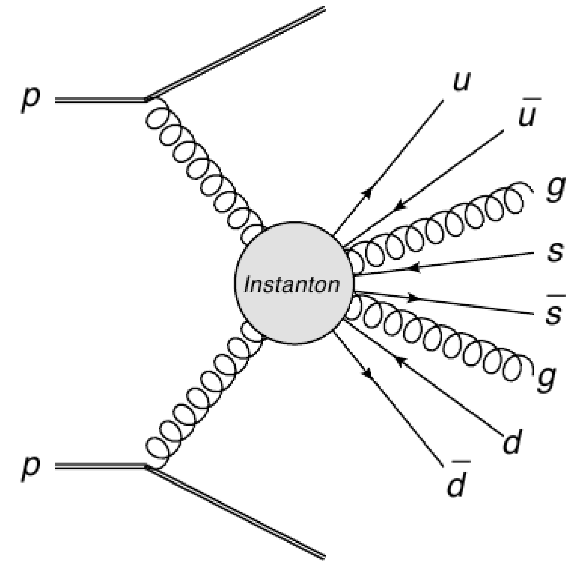


Figure 3. Depiction of a QCD Instanton processes in proton-proton (right) colli-

Instanton$\neq$ the particle (no peak in M_{inst})

It is a family of objects of different size, ρ, and orientations in Lorentz and colour spaces

The statistical weight of size-ρ instanton is

$$D(\rho, \mu_R) = \frac{\kappa}{\rho^5} \left(\frac{2\pi}{\alpha_s(\mu_R)} \right)^6 (\rho \mu_R)^{b_0}$$

where $(\rho\mu_R)^{b_0} = \exp(2S^I)$ $\qquad S^I = 2\pi/\alpha_s$

$\kappa = 0.0025 \exp(0.292 N_f) \sim 0.01$

Note infrared divergence at large ρ

Elementary $gg \to I + \ldots$ cross section at $\sqrt{s'} = M_{inst}$

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

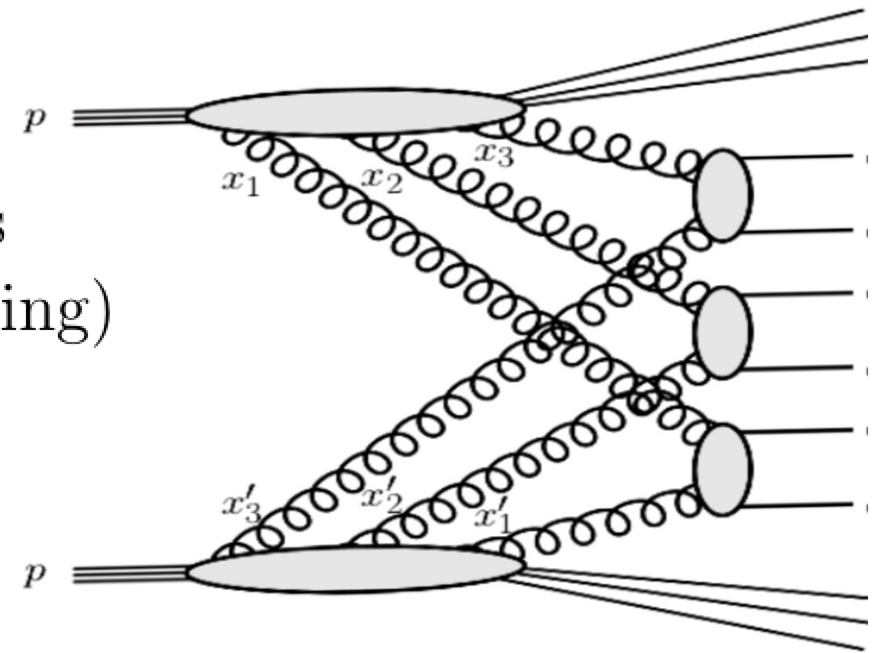
$\sqrt{s'_{\rm min}}$ [GeV]	20	50	100	200	500
$\sigma_{pp\to I}$	6.32 mb	40.82 μb	79.95 nb	105.4 pb	3.54 fb

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

$$\sigma(pp \to I) \sim 1/M_{inst}^7$$

Background



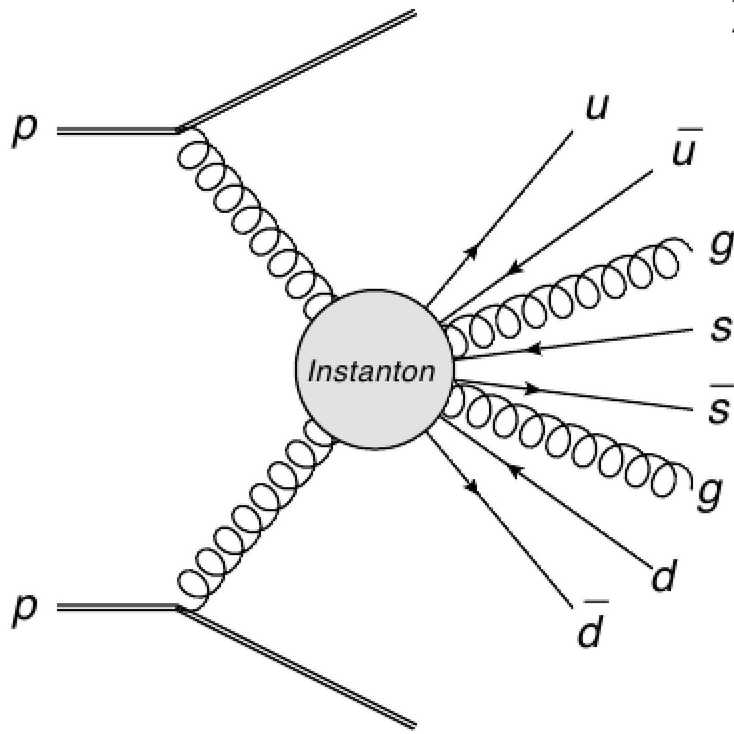
1. Multiple parton interactions
(Double/Triple/... parton scattering)

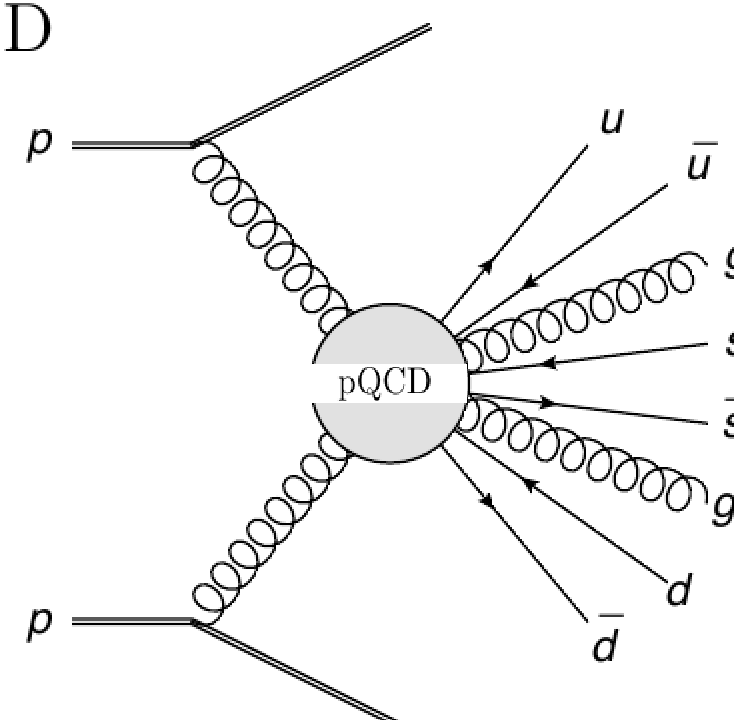
Large at small M_{inst}

$$\frac{d\sigma}{dp_1 ... dp_n} \sim \left(\frac{d\sigma}{\sigma_{eff} dp_1} \cdots \frac{d\sigma}{\sigma_{eff} dp_n} \right) \sigma_{eff}$$

$$\sigma_{eff} \sim 10 \text{ mb}$$

2. pQCD





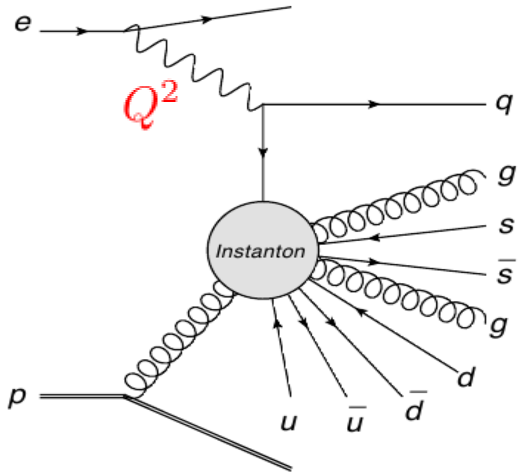
$$\sigma(gg \to N \cdot jets) \sim (16\pi/M_{inst}^2)\alpha_s^N$$

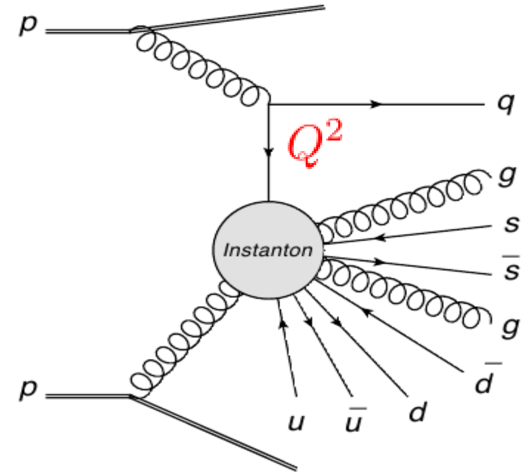
(hedgehog-like)

$$\sigma(pp \to I) \sim 1/M_{inst}^7$$

$$\sigma(gg \to Njets) \sim \sigma(gg \to I) \text{ at } M_{inst} > 200 \text{ GeV}$$

To choose M_{inst}:





a) To select Q^2 in DIS (or $q_{T,jet}$)
(A. Ringwald, F.Schrempp, PL B438 (1998) 217)

b) To select events with $\sum_i E_{T,i} > E_{cut}$
in some $\Delta\eta$ interval.

- Instanton event – large N_{ch} (due to N_{jets}) but not too large $\sum E_{T,i}$ since $(< k_t >\sim 1.5/\rho)$

- Sphericity $S = (3/2)(\lambda_2 + \lambda_3)$ close to 1

$\lambda_1 > \lambda_2 > \lambda_3$ are the eigenvalues of $S^{\alpha\beta}$

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

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

	Signal Region			Control Region	
	Standard	Event-Shape	Tight	A	B
Invariant mass of rec. tracks (Instanton Mass), m_I	20 GeV $< m_I <$ 40 GeV				
Selection Requirements					
Number of rec. tracks, N_{Trk}	$>$20	$>$20	$>$20	$>$15	$>$20
Number of rec. tracks/Instanton mass, m_I/N_{Trk}	$<$1.5	$<$1.5	$<$1.5	$>$2.0	$<$1.5
Number of Jets, N_{Jets}	=0	=0	=0	=0	=0
Broadening, $\mathcal{B}_{\text{Tracks}}$		$>$0.3	$>$0.3	$>$0.3	$>$0.3
Thrust, $\mathcal{T}_{\text{Tracks}}$		$>$0.3	$>$0.3	$>$0.3	$>$0.3
Number of displaced vertices, $N_{\text{Displaced}}$			$>$6		$<$4
Expected Events for $\int Ldt = 1\,\text{pb}^{-1}$ in the Signal Region ($\mathcal{S}$ $>$0.85)					
N_{Signal}	$1.1 \cdot 10^7$	$8.9 \cdot 10^6$	$5.9 \cdot 10^6$	$<$1	$6.8 \cdot 10^5$
$N_{Background}$	$6.2 \cdot 10^6$	$4.3 \cdot 10^6$	$1.8 \cdot 10^5$	$3 \cdot 10^5$.	$3.3 \cdot 10^6$

Table 3. Overview of the standard and tight signal selection as well as the definition of two control regions aiming at very low Instanton masses (20 GeV $< m_I <$ 40 GeV)

	Signal Region			Control Region	
	Standard	Event-Shape	Tight	A	B
Invariant mass of rec. tracks (Instanton Mass), m_I	$200\ \text{GeV} < m_I < 300\ \text{GeV}$				
Selection Requirements					
Number of rec. tracks, N_{Trk}	>80	>80	>80	>80	>80
Number of rec. tracks/Instanton mass, m_I/N_{Trk}	<3.0	<3.0	<3.0	>3.0	<3.0
Number of Jets, N_{Jets}	3-6	3-6	3-6	3-6	3-6
Broadening, $\mathcal{B}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Thrust, $\mathcal{T}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Number of displaced vertices, $N_{\text{Displaced}}$			>15		<10
Results					
Expected Events for $\int Ldt = 1\,\text{pb}^{-1}$ in the Signal Region ($\mathcal{S}$ >0.85)					
N_{Signal}	5.6	1.0	0.54	0.04	0.21
$N_{Background}$	1900	9.6	0.64	200	1100

Table 5. Overview of the standard and tight signal selection as well as the definition of two control regions aiming at very low Instanton masses ($200\ \text{GeV} < m_I < 300\ \text{GeV}$)

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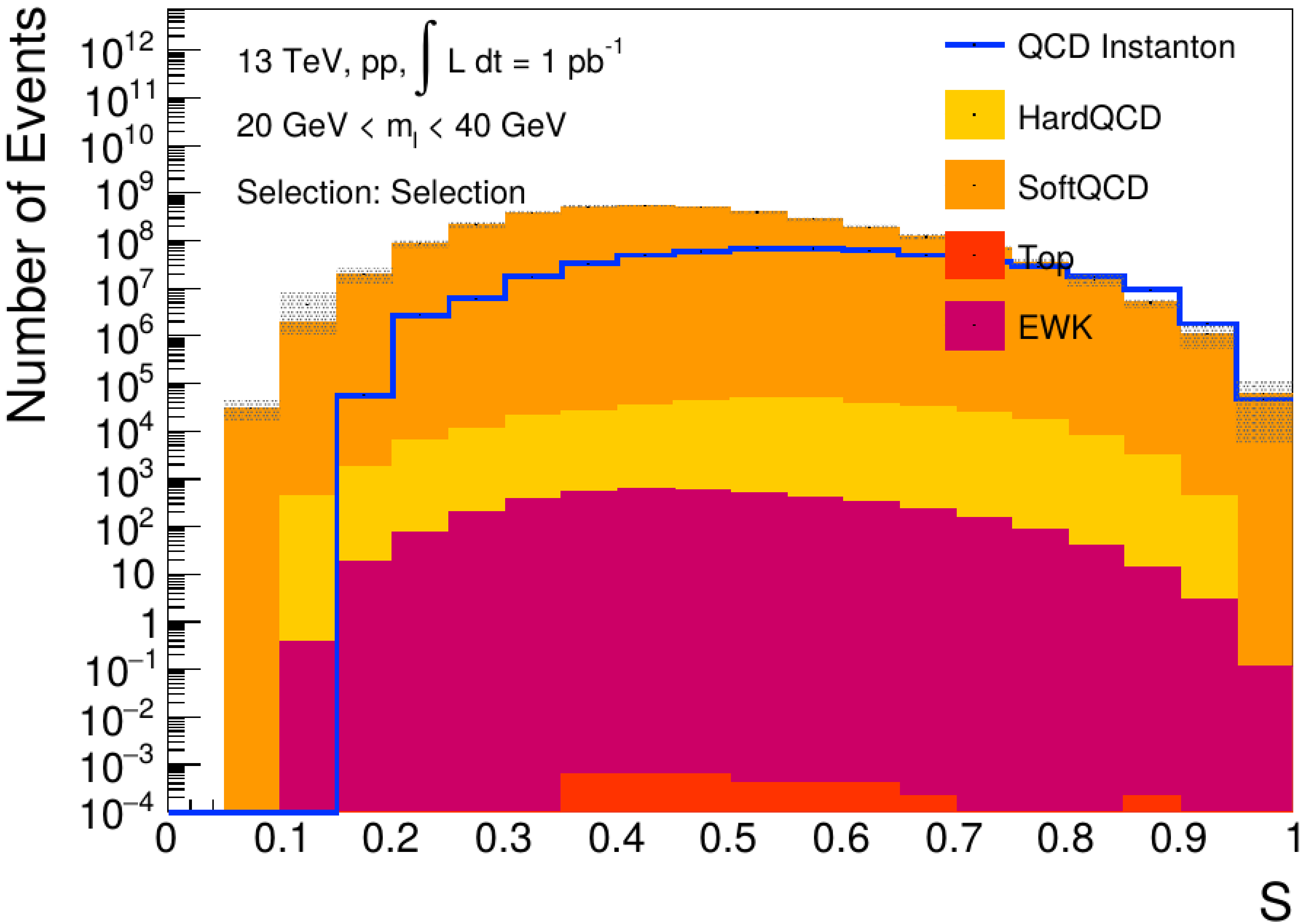
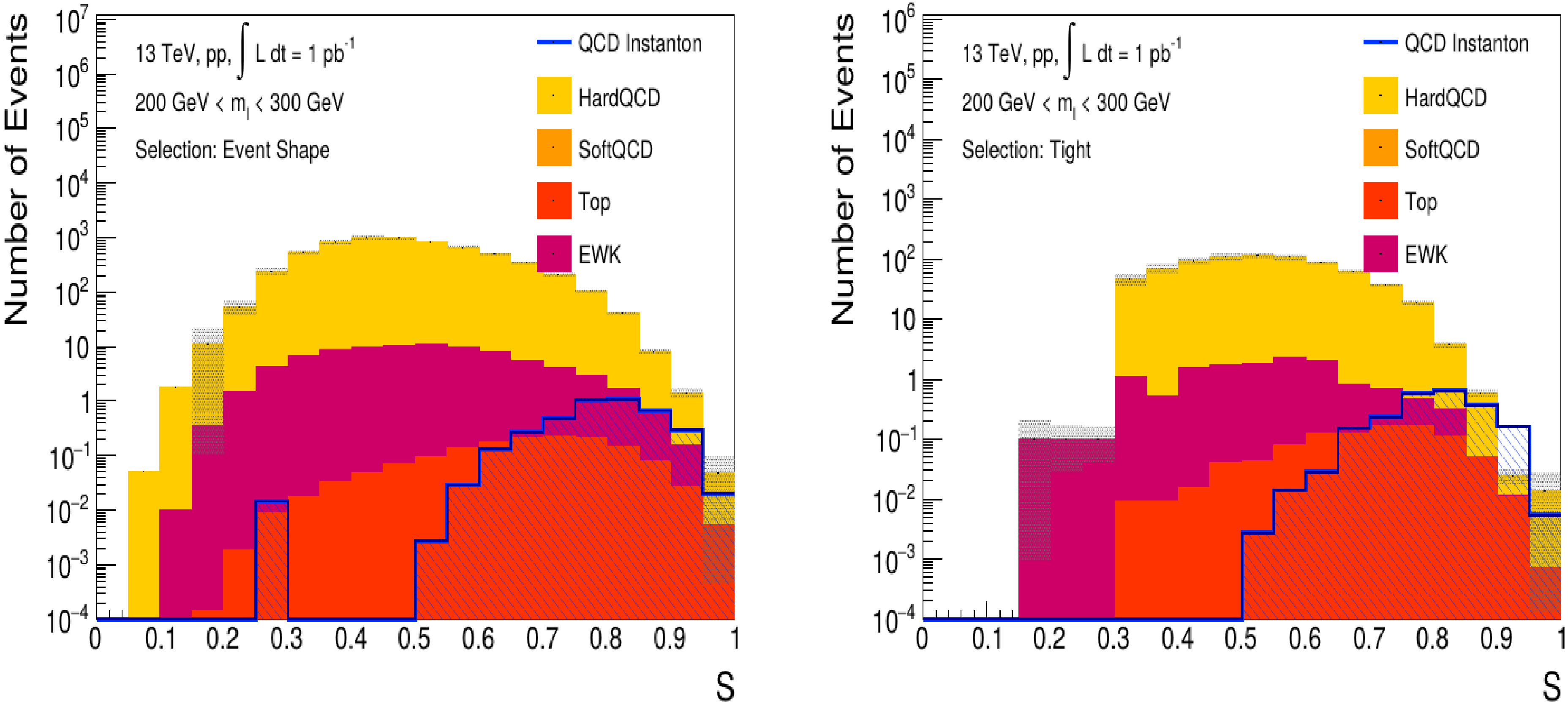


Number of Events
13 TeV, pp, ∫ L dt = 1 pb-1
20 GeV < m_l < 40 GeV
Selection: Selection
QCD Instanton
HardQCD
SoftQCD
Top
EWK
S


Number of Events
13 TeV, pp, ∫ L dt = 1 pb^-1
200 GeV < m_l < 300 GeV
Selection: Event Shape
QCD Instanton
HardQCD
SoftQCD
Top
EWK
S
Number of Events
13 TeV, pp, ∫ L dt = 1 pb^-1
200 GeV < m_l < 300 GeV
Selection: Tight
QCD Instanton
HardQCD
SoftQCD
Top
EWK
S

$N_{displ} > 15$

THANK YOU

At $x \to \infty$ instanton is the pure gauge field

$$g\frac{\tau^a}{2}A^a_\mu \to iS\partial_\mu S^+$$

with $S = i\tau^+_\mu x_\mu/\sqrt{x^2}$

However for $x \neq \infty$ it is the real transverse gluon field which describes the transition between two different (in gauge) QCD vacuums.