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Instanton production at the LHC

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with Frank Krauss & Matthias Schott 1911.09726 : JHEP (2020) and Dan Milne & Michael Spannowsky 2010.02287 : PRD (2021)

& with Valery A Khoze, Dan Milne and Misha Ryskin 2104.01861 : PRD (2021), 2111.02159 : PRD (2022)

QCD Instantons **2.1 QCD instantons** \mathcal{L} is the final state chirality, i.e. no left-handed quarks of opposite chirality, i.e. no left-handed quarks of opposite chirality, i.e. \mathcal{L}

Instanton-induced processes with 2 gluons in the initial state: for QCD the instanton field configuration involves the gluon component *A*inst t_{C} fermion components in the finite state. the fact that one-instanton fermion f and f

All light flavours of quark-antiquark pairs must be present. Light =>
$$
m_f \leq 1/\rho.
$$
\n
$$
g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})
$$
\n
$$
\sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})
$$
\ninstanton size arbitrary (tends to be large ~1/alpha_s)

Can also have quark-initiated processes e.g. : $g \cdot \frac{1}{2}$

state,

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

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

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

The amplitude takes the form of an integral over instanton collective coordinates. The classical result (leading order in the instanton perturbation theory) is simply: solutions of the Dirac equations.
In the porturbation theory) is simply: \mathbb{P} is a constant instanton instanton instanton instanton instanton instanton is,

semiclassical suppression
\n('t Hooft) factor by the instanton action
\n
$$
S_I = \frac{8\pi^2}{g^2} = \frac{2\pi}{\alpha_s(\mu_r)}
$$
\n
$$
A_{2 \to n_g + 2N_f} \sim \int d^4x_0 \, d\rho \, D(\rho) \, e^{-S_I} \left[\prod_{i=1}^{n_g + 2} A_{\text{LSZ}}^{a_i \text{inst}}(p_i, \lambda_i) \right] \left[\prod_{j=1}^{2N_f} \psi_{\text{LSZ}}^{(0)}(p_j, \lambda_j) \right]
$$

- the integrand: a product of bosonic and fermionic components of the instanton field configurations
- and *n*^f independent.
and mutually independent. • the factorised structure implies that emission of individual particles in the final state is uncorrel of the external legislature and momentum construction. T and a complementary over the integral over the integral over α in α in α • the factorised structure implies that emission of individual particles in the final state is uncorrelated

 \mathbf{X} $\sqrt{111/7}$ [this is correct at the LO in instanton pert. theory approximation] *a* port theory approvi [this is correct at the LO in instanton pert. theory approximation] *d*⇢ *D*(⇢) *eS^I*

We can also have can also have can also the called in the states are completed with ingle spitencity $\sum_{i=1}^{\infty}$ $\sum_{i=1}^{\infty}$ inductanton vertex \sim celection on final states at colliders with high sphere election on final states at colliders with high sphericity $\Gamma \leftrightarrow$ LO Instanton vertex -> selection on final states at colliders with high sphericity

The Optical Theorem approach

- Use the Optical Theorem:
- on an Instanton-Anti-instanton configuration
- Final states interactions effects
- Varying the energy E changes the Instanton-anti-Instanton separation R. At R=0 instanton and anti-instanton annihilate

VVK & Ringwald 1991

• Instanton — anti-instanton configuration has Q=0; it interpolates between infinitely \bullet instanton — anti-instanton comiguration nas $Q=0$, it interpolates between immittely
separated instanton—anti-instanton and the perturbative vacuum at R=0 section inst $\frac{1}{2}$ antial totation for the process Ω = Ω is to the optical theorem, and Ω \in in the background of an instanton–anti-instanton configuration, following the approach **z** it interpolates between infinitely

(anti)-instanton
sizes
separation

\n
$$
\simeq \frac{1}{s} \operatorname{Im} \int_0^\infty \frac{d\rho}{d\rho} \int_0^\infty \frac{4}{d\bar{\rho}} \int d^4 R \int d\Omega \ D(\rho) D(\bar{\rho}) \ e^{-S_{I\bar{I}}} K_{\text{ferm}} \times
$$
\n
$$
A_{LSZ}^{\text{inst}}(p_1) A_{LSZ}^{\text{inst}}(p_2) A_{LSZ}^{\text{inst}}(-p_1) A_{LSZ}^{\text{inst}}(-p_2),
$$
\n
$$
S_{I\bar{I}}(\rho, \bar{\rho}, R) = \frac{4\pi}{\alpha_s(\mu_r)} \hat{S}
$$
\ninstanton-anti-instanton
\ninstanton-anti-instanton
\nvector
\n(see next slide)

- Exponential suppression is gradually reduced at lower R (Energy-dependent) endent)
2 + p(*R*
	- no radiative corrs from hard initial states are yet included in this approximation $\overline{\mathbf{S}}$ irom nard ini al states are ve t included in this approximation \overline{R}

$$
\sigma_{\text{tot}}^{(\text{cl}) \text{inst}} = \frac{1}{s} \operatorname{Im} \mathcal{A}_4^{I\bar{I}}(p_1, p_2, -p_1, -p_2)
$$
\n
$$
\simeq \frac{1}{s} \operatorname{Im} \int_0^\infty d\rho \int_0^\infty d\bar{\rho} \int d^4 R \int d\Omega \ D(\rho) D(\bar{\rho}) e^{-S_{I\bar{I}}} \ \mathcal{K}_{\text{ferm}} \times
$$
\n
$$
A_{LSZ}^{\text{inst}}(p_1) A_{LSZ}^{\text{inst}}(p_2) A_{LSZ}^{\text{inst}}(-p_1) A_{LSZ}^{\text{inst}}(-p_2),
$$
\n
$$
S_{\langle \chi \rangle} \simeq 1 - 6/\chi^4 + 24/\chi^6 + \dots \quad \chi = \frac{R}{\rho}
$$
\n
$$
S_{\text{H}}(\rho, \rho, R) = \frac{4\pi}{\alpha_s(\mu_r)} S
$$
\n
$$
\text{Yung '88}
$$
\n
$$
\text{VVK & Ringwald '91}
$$
\n
$$
S_{\text{orbarschot '91}}
$$
\n
$$
S_{\text{orbarschot '91}}
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\n
$$
S_{\text{orbarschot '91}}
$$
\n
$$
S_{\text{d}} \qquad S_{\text
$$

$$
\sigma_{\text{tot}}^{(\text{cl})\text{ inst}} = \frac{1}{s} \operatorname{Im} \mathcal{A}_4^{I\bar{I}}(p_1, p_2, -p_1, -p_2)
$$
\n
$$
\simeq \frac{1}{s} \operatorname{Im} \int_0^\infty d\rho \int_0^\infty d\bar{\rho} \int d^4 R \int d\Omega \ D(\rho)D(\bar{\rho}) \ e^{-S_I\bar{I}} \ \mathcal{K}_{\text{ferm}} \times
$$
\n
$$
A_{LSZ}^{\text{inst}}(p_1) \ A_{LSZ}^{\text{inst}}(p_2) \ A_{LSZ}^{\text{inst}}(-p_1) \ A_{LSZ}^{\text{inst}}(-p_2),
$$
\n
$$
\downarrow
$$
\n
$$
\downarrow
$$
\n
$$
A_{LSZ}^{\text{inst}}(p_1) \ A_{LSZ}^{\text{inst}}(p_2) \ A_{LSZ}^{\text{inst}}(-p_1) \ A_{LSZ}^{\text{inst}}(-p_2),
$$
\n
$$
\downarrow
$$
\n
$$
\downarrow
$$
\n
$$
A_{LSZ}^{\text{inst}}(p_1) \ A_{LSZ}^{\text{inst}}(p_2) \ A_{LSZ}^{\text{inst}}(-p_1) \ A_{LSZ}^{\text{inst}}(-p_2) = \begin{bmatrix} 1 & \left(\frac{2\pi^2}{g} \rho^2 \sqrt{s'}\right)^4 e^{iR(p_1+p_2)} & \text{exp}\left(-Q(\rho+\bar{\rho})\right) \\ \frac{1}{36} & \left(\frac{2\pi^2}{g} \rho^2 \sqrt{s'}\right)^4 e^{iR(p_1+p_2)} & \text{exp}\left(-Q(\rho+\bar{\rho})\right) \\ \text{But the instanton size has not been stabilized.} \\ \text{in QCD - rho is a classically flat direction -\nneed to include and re-sum quantum corrections!\n
$$
\downarrow
$$
$$

a single light flavour (solid line). The dashed line is the dashed line is the large separation paper of ϵ

in the EW theory:

Exponential suppression is gradually reduced with energy [in the EW theory]

In QCD:

 P is the instanton size, the contribution of P is the instanton and the leading-order correction to the P propagator in the instanton background propagature the instanton back

$$
G_{\mu\nu}^{ab} (p_1, p_2) \rightarrow -\frac{g^2 \rho^2 s}{64\pi^2} \log(s) A_{\mu}^a (p_1) A_{\nu}^b (p_2)
$$

$$
p_1^2 = 0 = p_2^2, \quad 2p_1 p_2 = s \gg 1/\rho^2
$$

10 Rous bigher order oerrections in the bigh energy limit. relevant for the resumation of the coefficient in front of the instanton fields. The instanton fields in field *g* (*p*2) *der* corrections in the high-energy limit:
radiations in the high-energy limit: over all loop-level perturbative diagrams to order *N* involving the two initial-state vector bosons in the instanton background. The result is in the result is in the result is in the result is in the result of the result is in the result of the Include now higher order corrections in the high-energy limit:

$$
\sum_{r=1}^{N} \frac{1}{r!} \left(-\frac{g^2 \rho^2 s}{64\pi^2} \log(s) \right)^r A_{\mu}^a(p_1) A_{\nu}^b(p_2)
$$
 Mueller 1991

^µ (*p*1) *A^b*

Gab

$$
\left[\frac{\cdot}{e^{-(\alpha_s(\mu_r)/16\pi)\rho^2 E^2 \log E^2/\mu_r^2}} \right]
$$

Mueller 1991 Mueller 1991

 $+$

Combined effect of initial and final states interactions in QCD

$$
\hat{\sigma}_{\text{tot}}^{\text{inst}} \simeq \frac{1}{s'} \operatorname{Im} \frac{\kappa^2 \pi^4}{36 \cdot 4} \int \frac{d\rho}{\rho^5} \int \frac{d\bar{\rho}}{\bar{\rho}^5} \int d^4 R \int d\Omega \left(\frac{2\pi}{\alpha_s(\mu_r)} \right)^{14} (\rho^2 \sqrt{s'})^2 (\bar{\rho}^2 \sqrt{s'})^2 \mathcal{K}_{\text{ferm}}
$$
\n
$$
(\rho \mu_r)^{b_0} (\bar{\rho} \mu_r)^{b_0} \exp \left(R_0 \sqrt{s'} - \frac{4\pi}{\alpha_s(\mu_r)} \hat{\mathcal{S}}(z) - \frac{\alpha_s(\mu_r)}{16\pi} (\rho^2 + \bar{\rho}^2) s' \log \left(\frac{s'}{\mu_r^2} \right) \right)
$$
\nInstanton size is cut-off by partonic energy $\sim \sqrt{s}$

\nQuantum corrections this is what sets the effective QCD sphalrenon scale

\ninteractions

interactions

Basically, in QCD one can never reach the effective sphaleron barrier — it's hight grows with the energy. of the soluting in the comment of the scale of the scale in the scale of the scatch.
In the scale of the scattering process, and the scattering and the scale of the scale of the scale of the scale in the radiative corrections.

=> Among other things, no problems with unitarity.

This is the main idea of the approach:

[1] VVK, Krauss, Schott [2] VVK, Milne, Spannowsky

Combined effect of initial and final states interactions in QCD where we made use of the one-loop RG relation for the derivative of the running coupling, Jombined effect of initial and final states interactions in QCD $\,$ changes between the hard initial state gluons and the instantons [29]. Ininal states interactions in QCD

$$
\hat{\sigma}_{\text{tot}}^{\text{inst}} \simeq \frac{1}{s'} \operatorname{Im} \frac{\kappa^2 \pi^4}{36 \cdot 4} \int \frac{d\rho}{\rho^5} \int \frac{d\bar{\rho}}{\bar{\rho}^5} \int d^4 R \int d\Omega \left(\frac{2\pi}{\alpha_s(\mu_r)} \right)^{14} (\rho^2 \sqrt{s'})^2 (\bar{\rho}^2 \sqrt{s'})^2 \mathcal{K}_{\text{ferm}}
$$
\n
$$
(\rho \mu_r)^{b_0} (\bar{\rho} \mu_r)^{b_0} \exp \left(R_0 \sqrt{s'} - \frac{4\pi}{\alpha_s(\mu_r)} \hat{\mathcal{S}}(z) - \frac{\alpha_s(\mu_r)}{16\pi} (\rho^2 + \bar{\rho}^2) s' \log \left(\frac{s'}{\mu_r^2} \right) \right)
$$
\n
$$
\vdots
$$

exponent is (2.21) (note that we do not pull out the 4⇡*/*↵*s*(⇢) factor), 1. Extremise the function in the exponent: which is the function in the exponent.
look for a saddle-point in variables: ⇢˜ = *S*⁰ ()*,* (2.32)

 $\tilde{\rho}$

look for a saddle-point in variables:
\n
$$
\mathcal{F} = \rho \chi \sqrt{s} - \frac{4\pi}{\alpha_s(\rho)} \mathcal{S}(\chi) - \frac{\alpha_s(\rho)}{4\pi} \rho^2 s \log(\sqrt{s}\rho)
$$
\n
$$
\tilde{\rho} = \frac{\alpha_s(\rho)}{4\pi} \sqrt{s}\rho, \qquad \chi = \frac{R}{\rho} \qquad \text{Choice of the RG scale:}
$$
\n
$$
\mu_r = 1/\langle \rho \rangle = 1/\sqrt{\rho \bar{\rho}}
$$

all integrations using the steepest descent method evaluating the determinants or quadratic fluctuations around the saudie-point solution tot as the function of ^p*^s* are in good 2. Carry out all integrations using the steepest descent method evaluating the determinants of quadratic fluctuations around the saddle-point solution on the saddle-point solution

rs are very large — they compete with the semiclassical exponent which is very small! *u* defined in (2.31). 3. Pre-factors are very large — they compete with the semiclassical exponent which is very small! ⁴From the pomeron side the expected virtuality *Q*² ¹ ' *q*² the semiclassical exponent which is very small!

Results

Results for partonic cross-sections

 VVK, Krauss, Schott on the left is for eight *qq*¯ pairs in the final state, and the plot on the left is for ten *qq*¯ pairs. The

Results for partonic cross-section WVK, Milne, Spannowsky state. This sum can be uncovered by using the series expansion (2.31) of the exponent of

*x***32660000**

WK. Milne. Spannowsky

$$
\hat{\sigma}_{\text{tot}}^{\text{inst}}(E) = \frac{1}{E^2} \text{Im} \int_{-\infty}^{+\infty} dr_0 \, e^{r_0} \, G(r_0, E) \,, \qquad \langle n_g \rangle = \langle U_{\text{int}} \rangle
$$

$$
G(r_0, E) = \frac{\kappa^2 \pi^4}{2^{17}} \sqrt{\frac{\pi}{3}} \int_0^\infty r^2 dr \int_0^\infty \frac{dx}{x} \int_0^\infty \frac{dy}{y} \left(\frac{4\pi}{\alpha_s}\right)^{21/2} \left(\frac{1}{1 - \mathcal{S}(z)}\right)^{7/2} \mathcal{K}_{\text{ferm}}
$$

\n
$$
r = |\vec{R}|E,
$$

\n
$$
y = \rho \bar{\rho} E^2, \qquad x = \rho/\bar{\rho},
$$

\n
$$
\sum_{n_g=0}^\infty \frac{1}{n_g!} \left(U_{\text{int}}\right)^{n_g} \exp\left(-\frac{4\pi}{\alpha_s} - \frac{\alpha_s}{4\pi} \frac{x + 1/x}{4} y \log y\right).
$$

$$
\frac{4\pi}{\alpha_s(\langle \rho \rangle)} \simeq \begin{cases} \frac{4\pi}{0.32} - 2b_0 \log{(\langle \rho \rangle m_\tau)} & \text{: for } \langle \rho \rangle^{-1} \ge 1.45 \,\text{GeV} \\ \frac{4\pi}{0.35} & \text{: for } \langle \rho \rangle^{-1} < 1.45 \,\text{GeV} \end{cases}
$$

Total hadronic cross-sections for instanton processes are large p C.o.M. energies p*spp*¯ evaluated using Eq. (2.43). The minimal allowed partonic energy is *E*min = *s*ˆ [GeV] 50 100 150 200 300 400 500

$$
\sigma_{pp \to I} (\hat{s} > \hat{s}_{\min}) = \int_{\hat{s}_{\min}}^{s_{pp}} dx_1 dx_2 \quad f(x_1, Q^2) f(x_2, Q^2) \hat{\sigma} (\hat{s} = x_1 x_2 s_{pp})
$$

VVK, Milne, Spannowsky *x x* ix, ivinite

HOWEVER: If the instanton is recoiled by a high pT jet emitted from one of the initial state gluons => hadronic cross-section is tiny

\mathbf{r} GeV \mathbf{v} ್	310	350	Ω 010	400	450	500
$[{\rm pb}]$ $\hat{\sigma}^{\rm inst}_{\rm tot}$ L÷.	0.42×10^{-23}	1 O 1.35×10^{-7} $10 - 18$	\rightarrow 1.06×10^{-1} T 1	16 \sim $-$ 1.13×10	-10^{-16} 9.93 \checkmark $3.20 \wedge 10$	3.10×10^{-15}

Table 3. The instanton partonic cross-section recoiled against a hard jet with $p_T = 150$ GeV emitted from an initial state and calculated using Eq. (3.7) . Results for the cross-section are shown for a range of partonic C.o.M. energies $\sqrt{\hat{s}}$.

/ ∧ ∣ GeV^{\prime} \mathbf{C}	100	150	200	300	400	500
$\hat{\sigma}$ inst <u>ldql</u> $\sigma_{\rm tot}$	$\overline{ }$ ر $\times 10^{-7}$ $1.68\times$	1.20×10^{-9}	3.24×10^{-11}	1 Ω 1.84×10^{-13}	4.38×10^{-15}	2.38×10^{-16}

Table 4. The cross-section presented for a range of partonic C.o.M. energies $\sqrt{\hat{s}} = E$ where the recoiled p_T is scaled with the energy, $p_T = \sqrt{\hat{s}}/3$. recoiled p_T is scaled with the energy, $p_T = \sqrt{\hat{s}}/3$.

10 MVK, Milne, Spannowsky

Phenomenology

- QCD instanton cross-sections can be very large at hadron colliders.
- Instanton events are isotropic multi-particle final states [in CoM frame]. Event topology is very distinct - can use transverse sphericity & jet broadening event shapes. Also can look for c-cbar pairs in final states.
- Particles with large pT emitted from the instanton are rare. Especially hard to produce them at low partonic energies (for obvious kinematic reasons). They do not pass hight-pT triggers.
- At large (partonic) energies $[=> M_{\text{inst}}]$ instanton events can pass highpT triggers but have hopelessly suppressed cross-sections.
- Alternative approach 1: Examine data collected with minimum bias trigger [so no high-pT triggers!]
- Alternative approach 2: + Consider instanton production in diffractive processes looking for final states with large rapidity gaps.

Ginnal: VA Khoze, VVK, Dan coupling ↵*^s* decreases. Calculations presented in Section 5 (*cf.* Table 1) $\sqrt{111026}$, $\sqrt{111}$, Dall ivilitio, ivilsita Tyskiit. ZT040T00T due to the factor exp(*S^I*) = exp(2⇡*/*↵*s*(⇢)) in the amplitude. At smaller Signal: Singles of Nice, vviv, Dall willie, ivisital hysnic. 2 in VA Khoze, VVK, Dan Milne, Misha Ryskin: 210401861

values of ⇢ the instanton action *S^I* = 2⇡*/*↵*s*(⇢) increases since the QCD coupling ↵*^s* decreases. Calculations presented in Section 5 (*cf.* Table 1) Signal:

The cross-section of instanton production falls steeply with Minst mainly due to the factor $exp(-SI) = exp(-2\pi/\alpha_s(Q))$ in the amplitude. The cross-section of instanton production falls steeply with M_{inst} mainly due to the fact
exp($-\text{S}$ I) = exp($-\frac{2\pi}{\alpha_0}$ (o)) in the amplitude decretary *n* \overline{a}

$$
\hat{\sigma}_{\text{inst}} \propto M_{\text{inst}}^{-6}
$$
 M_{inst}^{-4} , at lower energies $20 - 30 \text{ GeV}$

 \overline{a} over a broad low-to-intermediate energy range (it becomes less steep, ˆinst / Background 1. N-minijets: (high transverse Sphericity final states) cally. For the perturbatively formed 'hedgehog' configuration of *N* final state

For the perturbatively formed the drehor' confi jets we would expect cally. For the perturbatively formed 'hedgehog' configuration of *N* final state For the perturbatively formed 'hedgehog' configuration of N final state perturbative QCD subprocess, *gg* ! *N*minijets, decreases only logarithmi-

$$
\sigma_{\text{pQCD}}(gg \to N \text{ jets}) \sim \frac{16\pi}{M^2} \left(\frac{N_c}{\pi} \alpha_s(M)\right)^N,
$$

where M سادة
تعليمات invariant energy of the pert signal will become negligible relative to the pu where $\frac{1}{2}$ denotes the perturbative invariant energy of the perturbative in t thand energy of the perturbatively formed clussametently large values of m_{inst} the mstanton \overline{p} where *M* denotes the invariant energy of the perturbatively formed cluster of minijets. Thus, at sufficiently large values of M_{inst} the instanton signal (5) will become negligible relative to the purely perturbative QCD

the set of minities. Thus, and the succiently succiently and the instanton instanton and the instanton instanton signal (5) will become negligible relative to the purely perturbative QCD In the regime of interest of moderately small *M*inst we face however anproduction (6). In the regime of interest of moderately small *M*inst we face however an-=> require M_inst < 200 GeV for instantons to dominate

Ginnal: VA Khoze, VVK, Dan coupling ↵*^s* decreases. Calculations presented in Section 5 (*cf.* Table 1) $\sqrt{111026}$, $\sqrt{111}$, Dall ivilitio, ivilsita Tyskiit. ZT040T00T VA Khoze, VVK, Dan Milne, Misha Ryskin: 210401861

values of ⇢ the instanton action *S^I* = 2⇡*/*↵*s*(⇢) increases since the QCD Signal:

The cross-section of instanton production falls steeply with Minst mainly due to the factor $exp(-SI) = exp(-2\pi/\alpha_s(Q))$ in the amplitude. **i**
a *d M***₆** *M***₆** decretary *n* \overline{a}

 $\hat{\sigma}_{inst} \propto M_{inst}^{-6}$ M_{inst}^{-4} , at lower energies \overline{a} a broad low-to-intermediate energy range (it becomes less steps) \overline{a} $M_{\rm inst}^{-4}$, at lower energies 20 – 30 GeV

Background 2 MPI Multi-parton inte inst, at lower energies 20 – 30 GeV). \overline{M} . \overline{M} parameter \overline{M} parameter \overline{M} parameter \overline{M} per ividiti-parton interactions Background 2. MPI Multi-parton interactions

On the other hand the dimensionless rate, *M*² pQCD, of a similar purely MPI backgrounds also have high transverse Sphericicity
Cand cally. For the perturbatively formed 'hedgehog' configuration of *N* final state and dominate over instantons at low M_inst < 200 GeV

 $=$ $>$ would require l $\frac{1}{2}$ => would require M_inst > 200 GeV for instantons to dominate: a conundrum!

where *M* denotes the invariant energy of the perturbatively formed clusto suppress ivini and wrille keeping low-mass <200 \,
The final state ealection with Large D use illial state selection with Large rid To suppress MPI and while keeping low-mass <200 GeV instanton contributions election with Large Rapidity Gaps *dE*² ¹ *...dE*² ⇠ $\overline{\mathbf{r}}$ *ef f dE*² apidit *ef f dE*² ◆ use final state selection with Large Rapidity Gaps

VA Khoze, VVK, Dan Milne, Misha Ryskin: 210401861

Instanton cross-sections are large, but one needs to be creative in separating instanton signal from large QCD background.

One such strates wie seerch for OCD instantone in diffractive events at the LHC: QCD background caused by multi-parton interactions can be Since Institute of Petersburg Nuclear Physics Institute, New York Institute, New Y with range rapidity gape ⁷ *b* Institute for Particle Physics Phenomenology, University of Durham, One such strategy is search for QCD instantons effectively suppressed by selecting events with large rapidity gaps

p

 1500 multi-intervalse and problems. use multi-jet cuts

> $F_{\rm eff}$ is instanton production in a difference production in a difference production in $F_{\rm eff}$ use low luminosity runs to avoid problems with large pile-up

Figure 3: Multiplicity distribution of charged hadrons produced in the events with the instanton (green) in comparison with the expected background (red).

The number of events is normalised to the integrated luminosity *L* = 1 pb¹ and

Figure 4: Distribution over the transverse sphericity S_T , Eq. (8), of the charged hadrons produced in the events with the instanton (green) in comparison with the expected background (red).

We have also considered central instanton production in diffractive events with two rapidity gaps:

Latest theoretical results look promising. More detailed phenomenological and ultimately experimental studies are needed and will hopefully follow. two LRGs. (a): (*gg*)+(*gg*) ! *Instanton* sub-process; (b): gluon-gluon fusion Latest theoretical results look promising. More detailed pheno denote gluon and quark jets while the dotted lines indicate the possibility of soft and one (a) or two (b) spectator jets. Pomerons are represented by thick double delalied prienomenological and dilimately

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with experimental strategies!

with experimental strategies! *IP* + *IP* ! (*gg*) + *g* + *g^s* ! *Inst* + *gs*, t collidars - naad to ha invantiva indices of the initial state gluons computed on the instanton configuration. General lesson: to see instantons at colliders - need to be inventive

[Extra slide] Theoretical uncertainties

- QCD Instanton rates are interesting in the regime where they become large lower end of partonic energies 20-80 GeV. The weak coupling approximation used in the semiclassical calculation can be problematic.
- What is the role of higher-order corrections to the Mueller's term in the exponent?
- Possible corrections to the instanton-anti-instanton interaction at medium instanton separations in the optical theorem approach.
- Non-factorisation of the determinants in the instanton-anti-instanton background in the optical theorem. (Instanton densities D (rho) do not factorise at finite R/rho \sim 1.5 - 2.)
- Choice of the RG scale $= 1$ /rho. (can vary by a factor of 2 or use other prescriptions to test. In Ref. [1] we checked that)
- A practical point for future progress is to test theory normalisation of predicted QCD instanton rates with data. [The unbiased un-tuned theory prediction looks promising.]