Saturation and Diffraction at the LHC and the EIC

by ECT*, Trento/I 27 Jun-1 July 2022

HUNTING FOR QCD I… N THE FORWARD

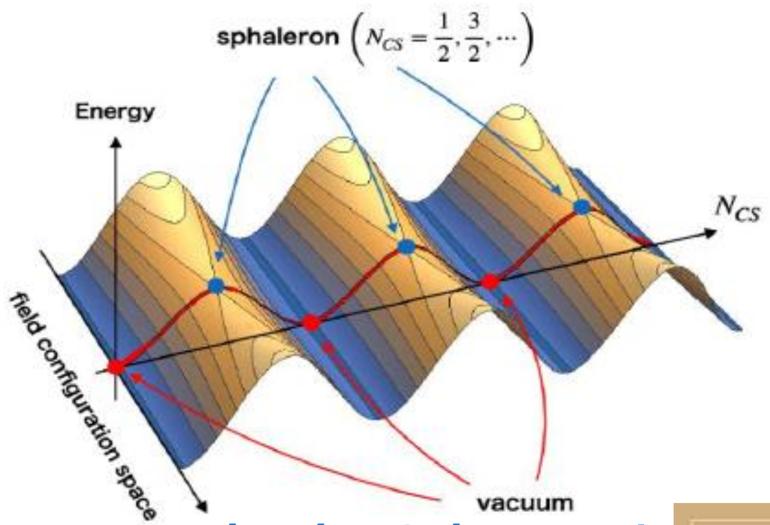
Work in Progress
(Testing the waters)

…ity)

30 years on

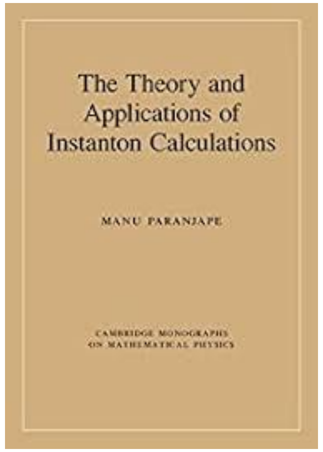
V. A. Khoze, V. V. Khoze, D. L. Milne and M. G. Ryskin, PRD 104, 05401 105,03600

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

Recently **–a renewal of interest, initiated by the experimental LHC community (M. Schott et al)**



Belavin, Polyakov, Schwarz,Tyupkin, 1975

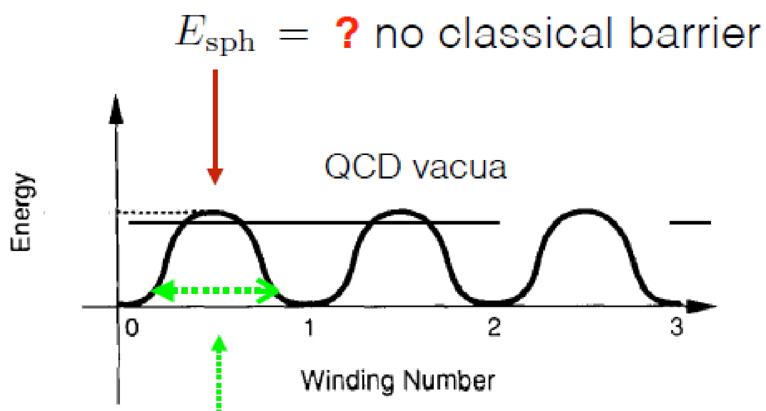
Instantons describe quantum tunneling between different vacuum sectors of the QCD and are arguably the best motivated yet experimentally unobserved nonperturbative effects predicted by the Standard Model.

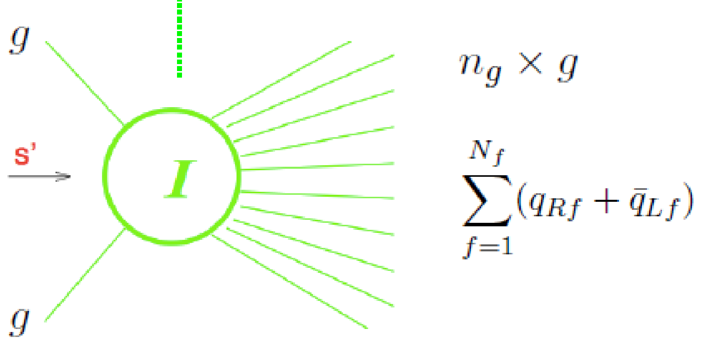
Recent calculations of Instanton-induced processes in pp collisions : V.V. Khoze, F. Krauss, M. Schott, 1911.09726 : JHEP

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.





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

2

Sphaleron-transition on top of an energy barrier

Instanton-induced processes with 2 gluons in the initial state:

All light flavours of quark-antiquark pairs must be present. Light =>

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

$m_f \leq 1/\rho.$

instanton size

arbitrary
(tends to be large ~1/alpha_s)

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

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

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

Instanton size is cut-off by partonic energy $\sim \sqrt{s}$
this is what sets the
effective QCD sphalrenon scale

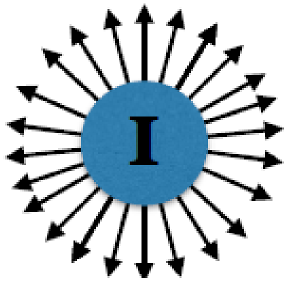
Quantum corrections
due to in-in states
interactions

Mueller 1991

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

$< 0|G^a_{\mu\nu}G^a_{\mu\nu}|0 > \neq 0$



one of the biggest challenges for particle physics to date

Instanton signatures:

LO Instanton vertex -> selection on final states at colliders with high sphericity

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

'soft bombs' –high-multiplicity spherically symmetric distributions of relatively soft particles

- 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)

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

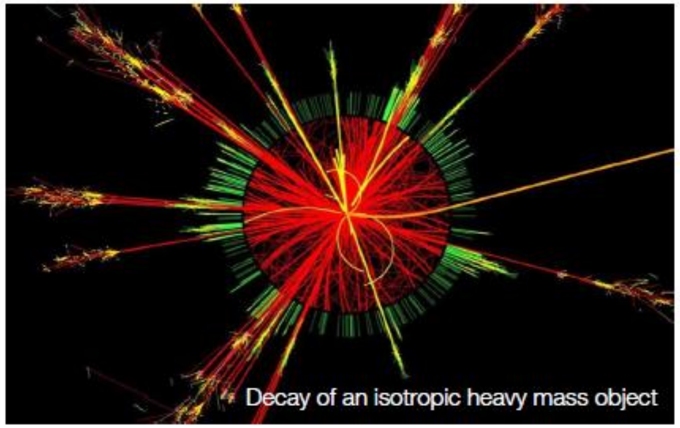
Extended objects in space-time

Effectively –a family of new multiparton vertices in Feynman diagrams

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	$72.97 \cdot 10^3$

Now in SHERPA



$\sqrt{s'_{\min}}$ [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

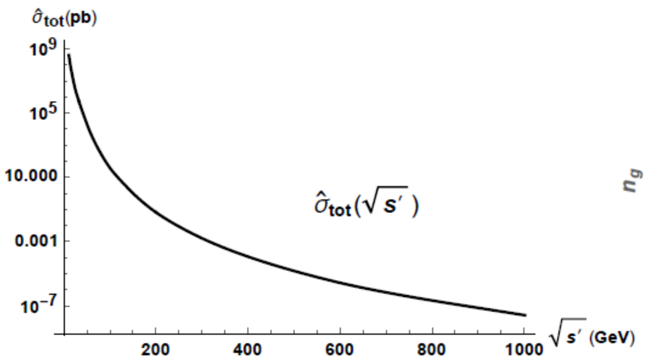
Table 2. Hadronic cross sections for instanton production through initial gluons, at the 13 TeV LHC, using the NNPDF3.1 NNLO set with $\alpha_s(M_Z) = 0.118$ [67].

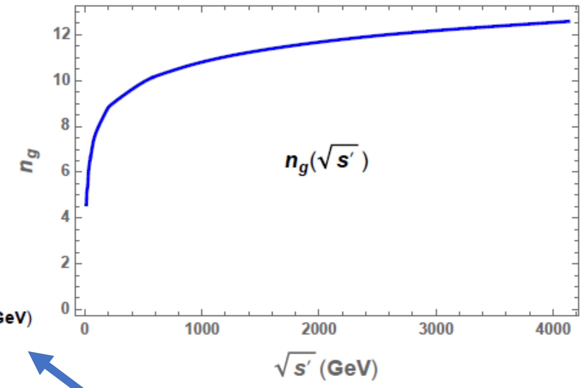
V.V. Khoze, F. Krauss, M. Schott, 1911.09726

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

Note infrared divergence at large ρ (small M_{inst})

VVKhoze,Krauss,Schott-2020
VVKhoze,Milne,Spannowsky-2021

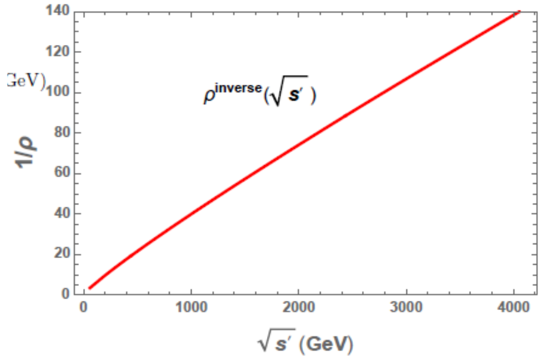




partonic cross-sections

Instanton size is cut-off by partonic energy $\sim \sqrt{s}$
this is what sets the
effective QCD sphalerenon scale

Quantum corrections
due to in-in states
interactions

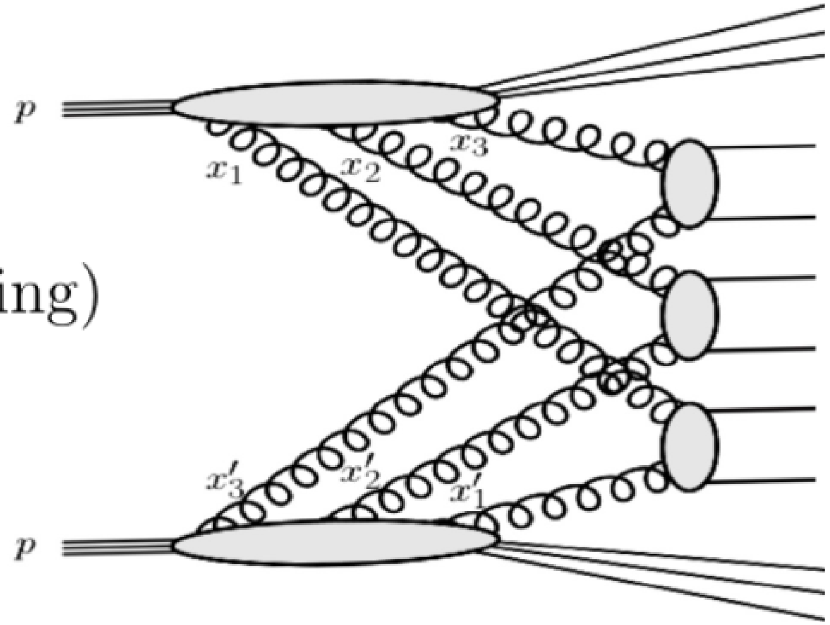


Small instanton masses-large rates, but difficult to distinguish from soft QCD activity (+ PU 'complications' at high lumi).
A large mass-striking multijet signature, but a very low rate.
The S/B ratio falls very rapidly with I-mass increasing –a higher chance of observing the signal in the low-mass range.

Background

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

Large at small M_{inst}



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

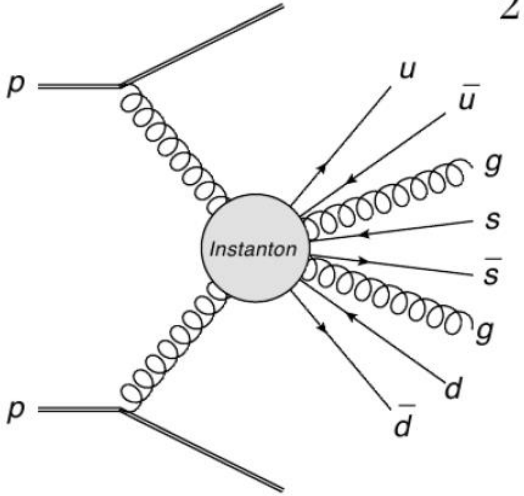
$d\sigma/dE_i^2 \sim \pi\alpha_s^2/E_i^4$ $\qquad \sigma_{eff} \sim$ 10 mb

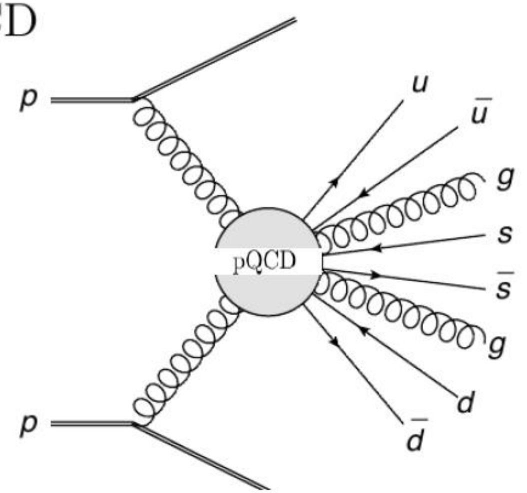
E_i denotes the transverse energy of a jet in the i dijet system,

$S^2 \leq 0.1$. 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 value of b_t,

2. pQCD





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

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

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

Thus, at sufficiently large values of M_{inst} the instanton signal will become negligible relative to the purely perturbative QCD background.

DIS HERA data seem to exclude the low range of expectations

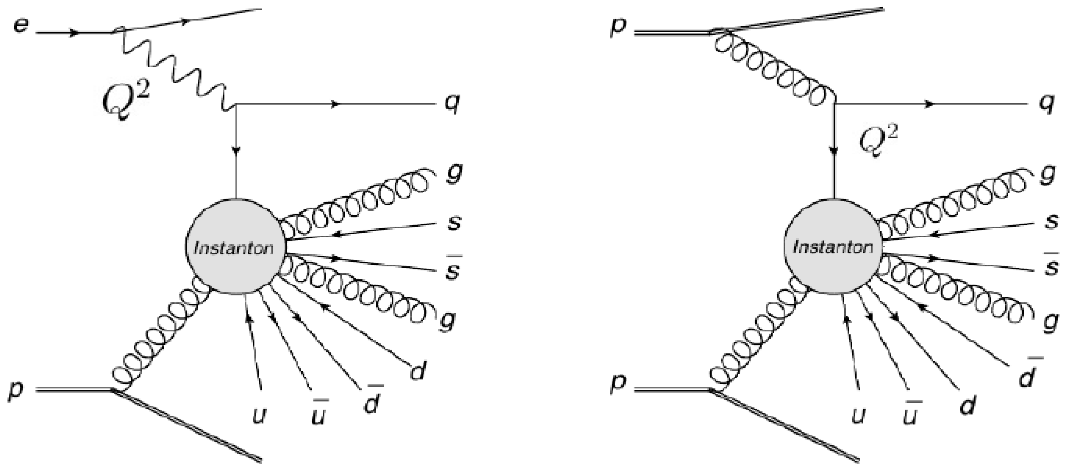


Figure 2. Depiction of a QCD Instanton processes in electron-proton (left) and proton-proton (right) collisions, where an external scale parameter Q' is required.

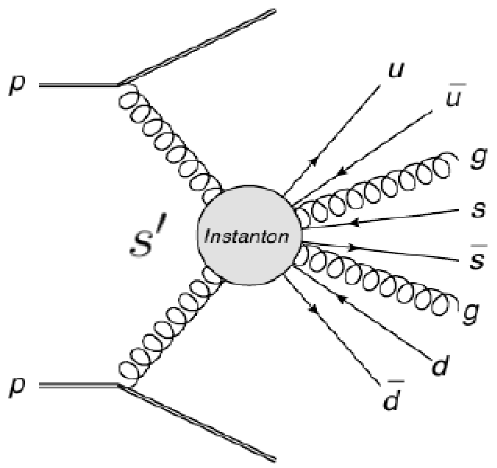


Figure 3. Depiction of a QCD Instanton processes in proton-proton (right) colli-

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

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

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

- 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

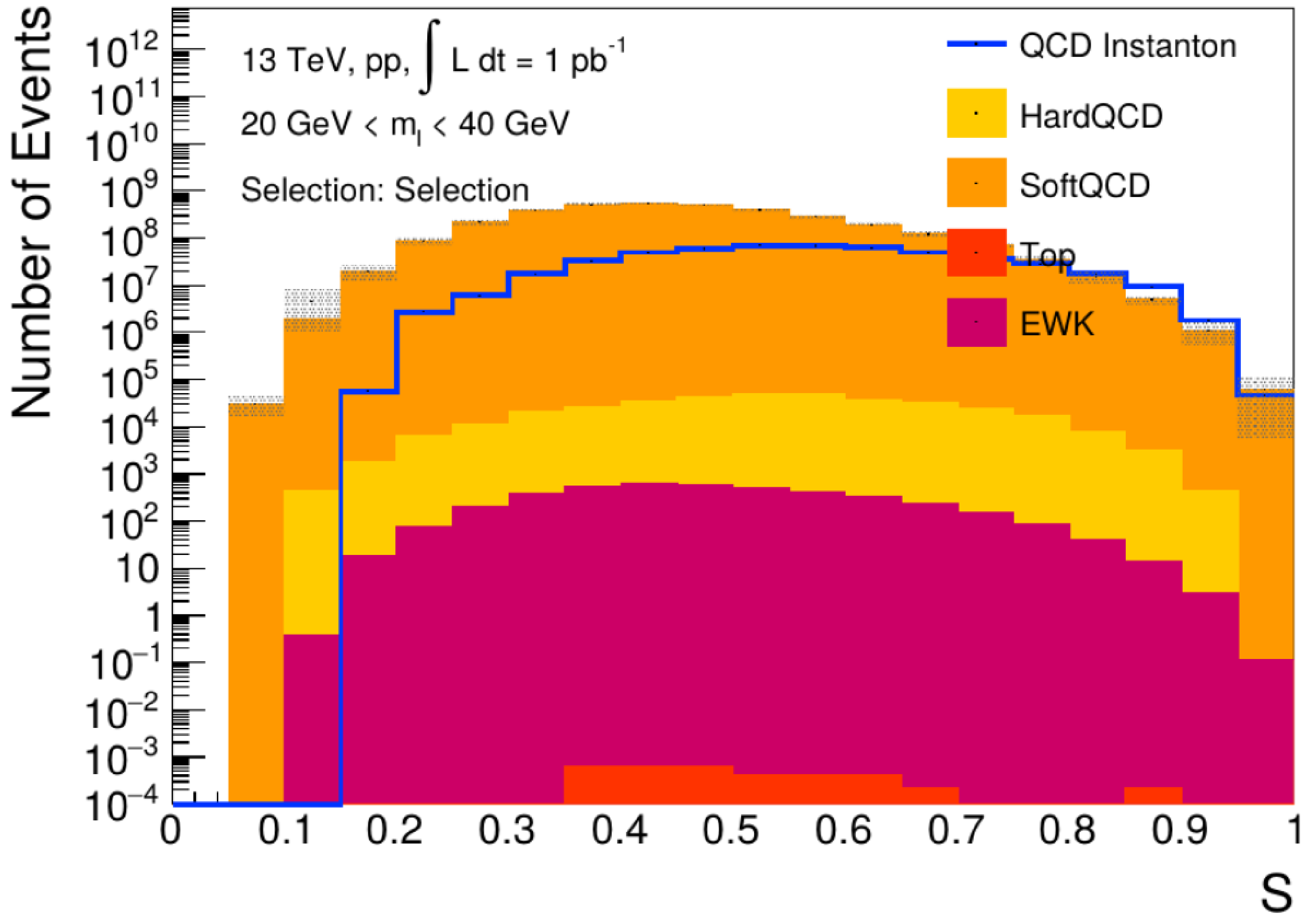
$\lambda_1 > \lambda_2 > \lambda_3$ are the eigenvalues of $S^{\alpha\beta}$

(dijet events lead to sphericity of S = 0)

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

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

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



Simone Amoroso[a] Deepak Kar[b] Matthias Schott[c] 2012.09120

First limits based on existing LHC Minimum Bias data

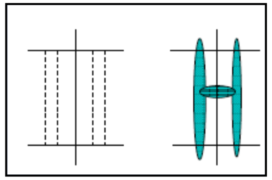
Instanton signal samples have been produced with a modified version of the SHERPA

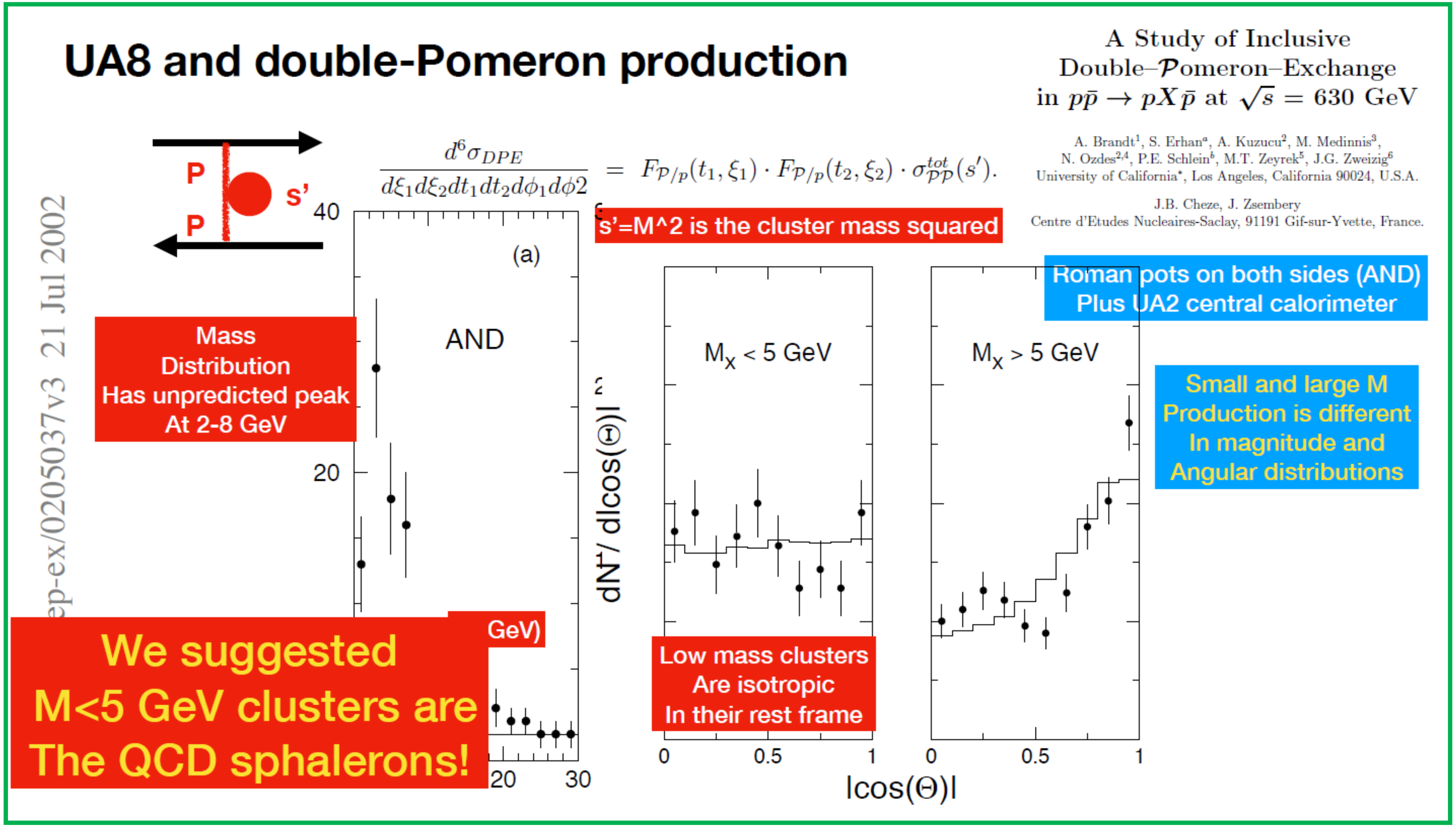
BG *softQCD* processes in the PYTHIA used as baseline.
simulated through the Delphes framework
no PU

Semiclassical Double-Pomeron Production of Glueballs and η'

Edward Shuryak and Ismail Zahed

(Phys.Rev.D 68 (2003) 034001)

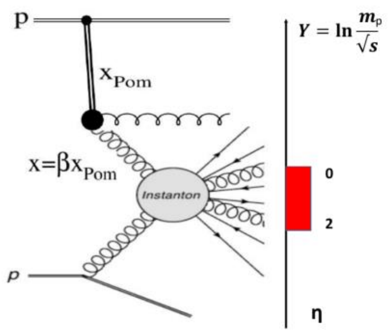




Instanton in diffractive events

V. A. Khoze, V. V. Khoze, D. L. Milne and M. G. Ryskin, PRD 104, 054013
105,036008

Lower background since
No multiparton interactions



Event selection::

$N_{ch} > 20 \quad \sum_i E_{T,i} > 15$ **GeV**

$(0 < \eta < 2 \quad \mathbf{p}_{T,i} > 0.5$ **GeV**$)$

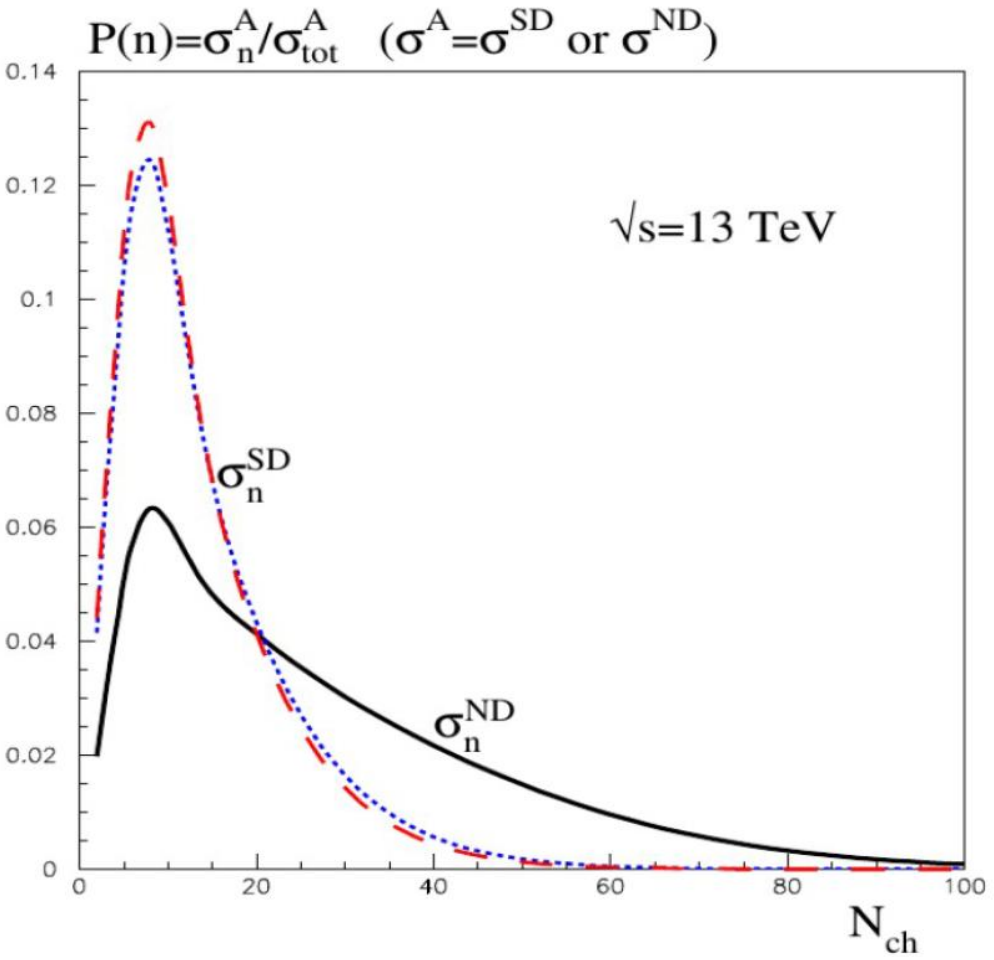
No charged at $-2 < \eta < 2$ **with** $p_T > 2$ **GeV**

(to exclude high E_T **jets)**

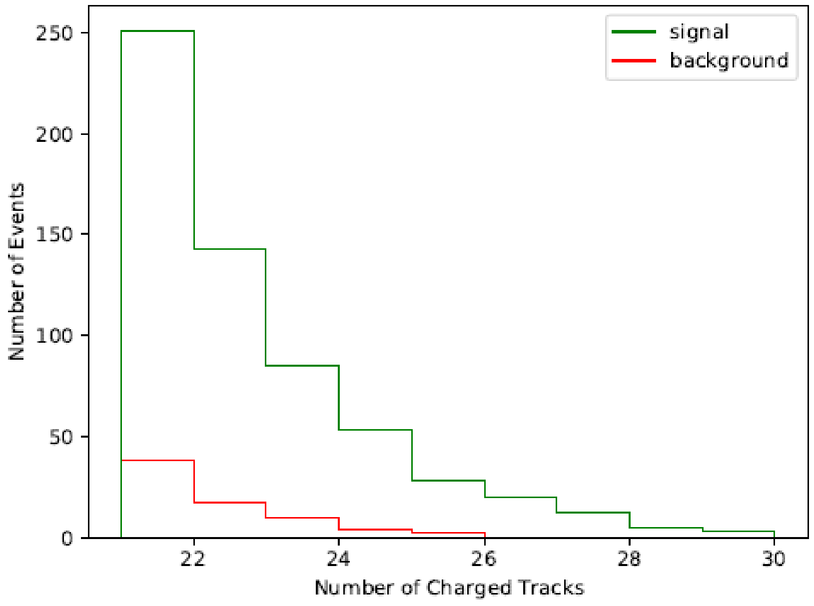
use low luminosity runs to avoid problems with large pile-up

Searching for the Instanton as a multiparticle cluster/fireball with a mass ~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.



; the instanton of mass 30 GeV produces about 17 jets (9 gluons plus 4 light $\bar{q}q$ pairs). The energy of each jet $E_{Ti} \sim 1/\rho \sim 2$ GeV. After hadronization in such an event we expect about 40-60 particles. The large multiplicity can be used as the main (or additional) trigger to select the events of interest.



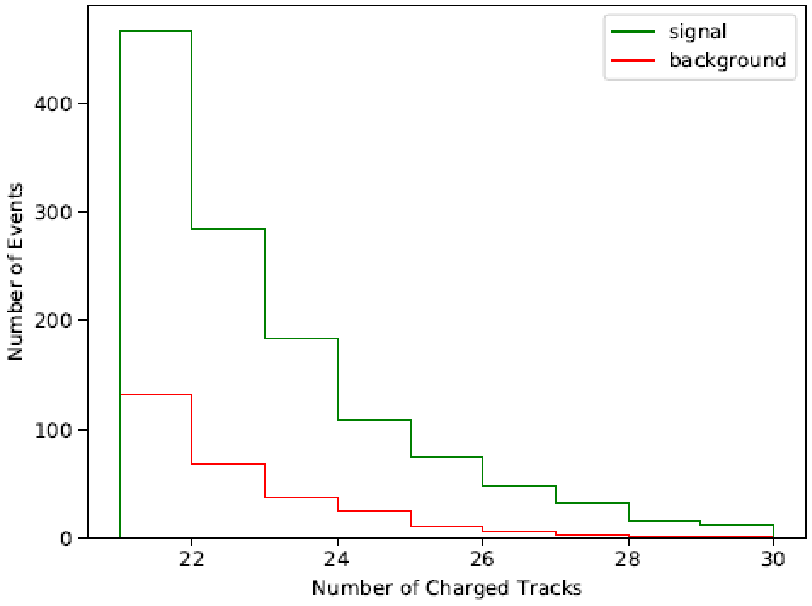


Figure 3: Multiplicity distribution of charged hadrons produced in the events with the instanton (green) in comparison with the expected background (red). The number of events is normalised to the integrated luminosity $L = 1\,\mathrm{pb}^{-1}$ and $\Delta \ln(x_{Pom}) = 1$ interval. We required events to have $\sum_i E_{T,i} > 15$ GeV and $N_{ch} > 20$, summing only over charged particles in the region $0 < \eta < 2$ with $p_T > 0.5$ GeV, with an additional constraint that there is no charged particle in this region with $p_T > 2$ GeV (left figure), or no charged particle in the region $-2 < \eta < 2$ with $p_T > 2.5$ GeV (right figure).

Low Luminosity run (no PU)

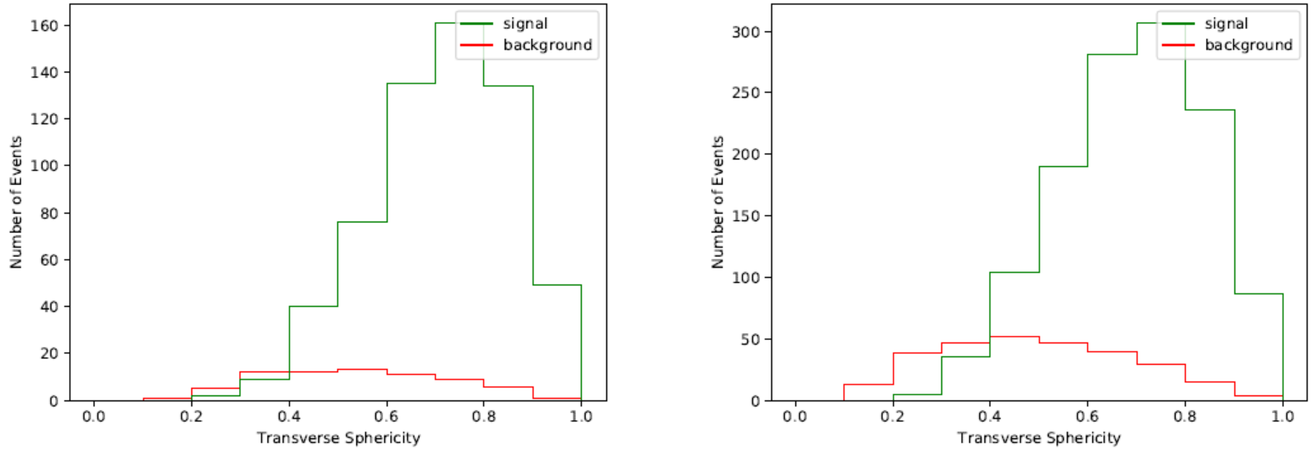


Figure 4: Distribution over the transverse sphericity S_T, Eq. (8), of the charged hadrons produced in the events with the instanton (green) in comparison with the expected background (red). The selection criteria used are the same as those described in Fig. 3

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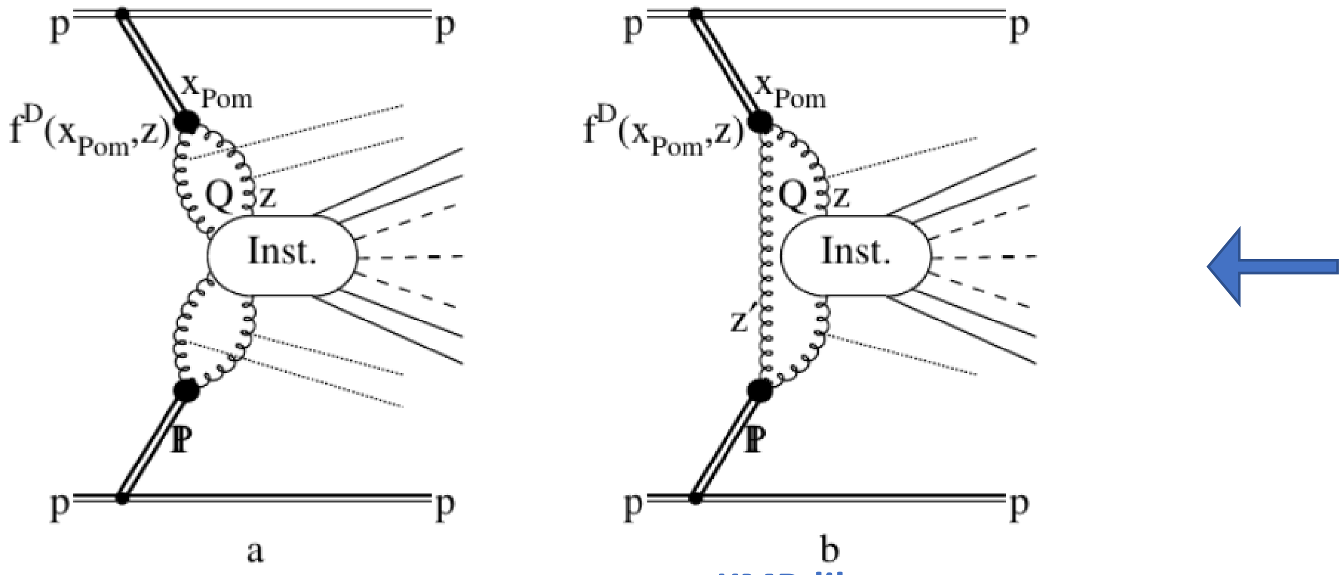
- It is shown that by imposing appropriate cuts on final states we can select the kinematical region where the I-signal exceeds BG by a factor of at least 2.5. At $\sum_i E_{T,i} > 15$ GeV, $N_{ch} > 20$ measured within the $0 < \eta < 2$ the rate is expected to be large enough to measure Instanton production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

- Even with these rather strong cuts in place, the expected instanton cross-section remains sufficiently large (~ 1 nb) to effectively produce and probe QCD instantons at the LHC, at low luminosity runs, avoiding pile-up problems.

Central Instanton Production

$$pp \rightarrow p + I\!\!P + I\!\!P + p \rightarrow p + X + p\,;$$

Fig.1



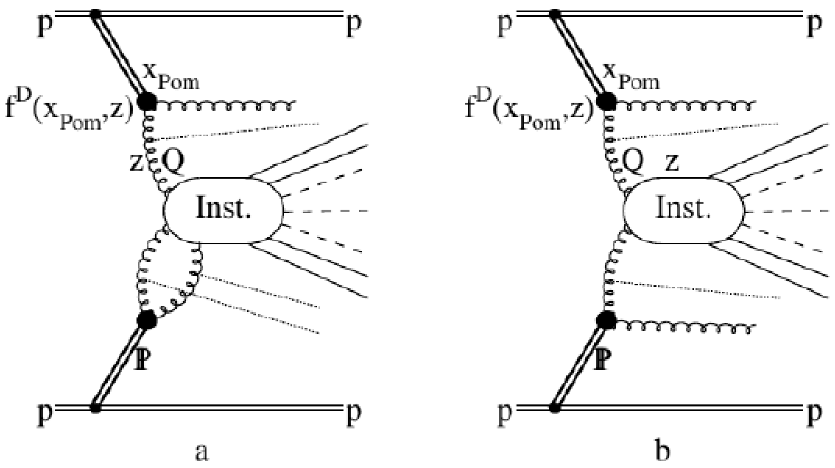
KMR-like

dominates

★ 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 detectio ('hermiticity')

Fig.2

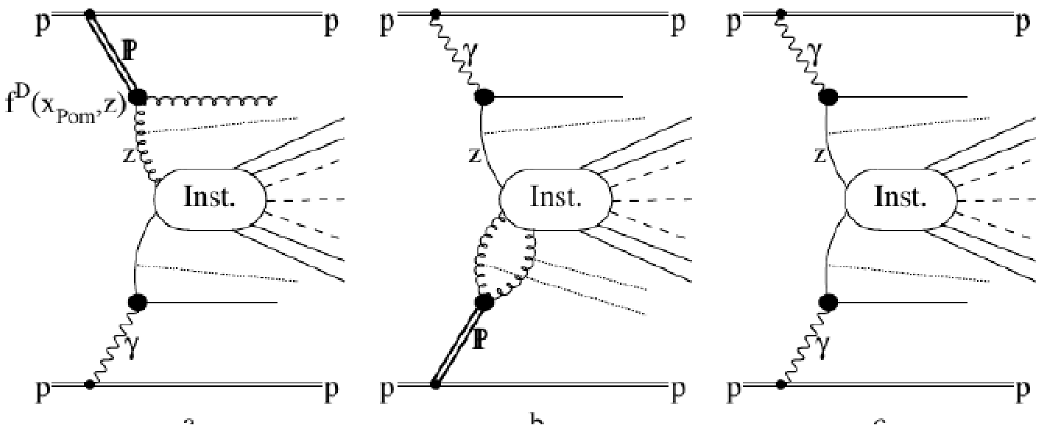


Dominant

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

$\sigma^{(2b)}_{pp\to I}$ ~ hundreds of pb

Fig.3



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

UPC-no PU nightmare

L. Harland-Lang et al

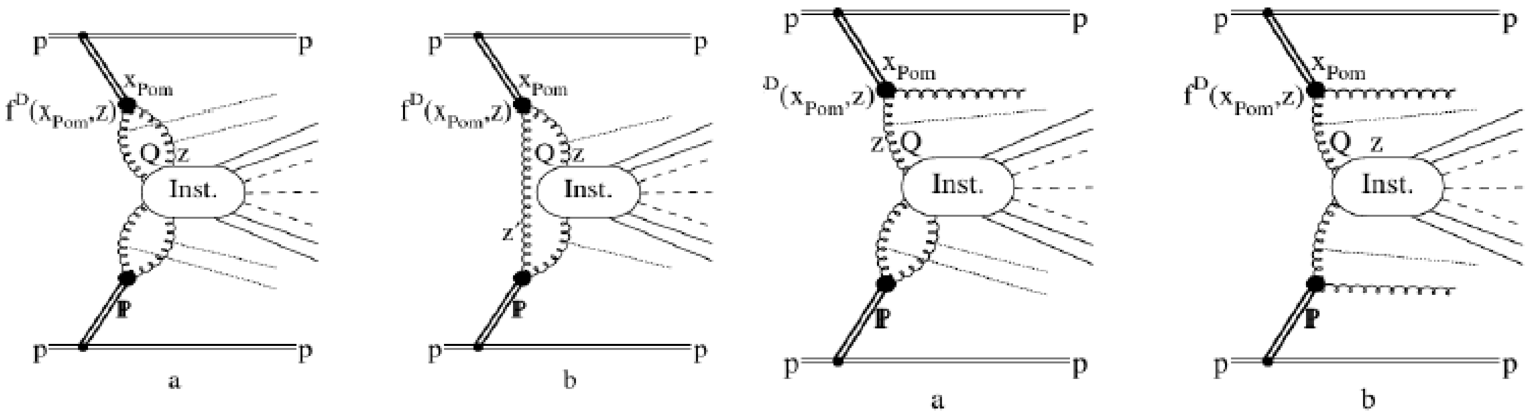
HIC

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

M_{inst} [GeV]	$d\sigma_{pp}^{(1a)}$[pb]	$d\sigma_{pp}^{(1b)}$[pb]	$d\sigma_{pp}^{(2a)}$[pb]	$d\sigma_{pp}^{(2b)}$[pb]	$d\sigma_{pp}^{(2b)}$, $Q_t > 20$GeV
15	13.3	$4.56{\cdot}10^{4}$	$3.72{\cdot}10^{3}$	$1.83{\cdot}10^{5}$	-
35	$6{\cdot}10^{-3}$	$1.69{\cdot}10^{2}$	8.10	$2.28{\cdot}10^{3}$	$1.99{\cdot}10^{-3}$
55	$3.82{\cdot}10^{-5}$	3.27	$1.19{\cdot}10^{-1}$	$8.96{\cdot}10^{1}$	$2.95{\cdot}10^{-3}$
75	$8.8{\cdot}10^{-7}$	$1.61{\cdot}10^{-1}$	$4.72{\cdot}10^{-3}$	7.06	$1.70{\cdot}10^{-3}$
95	$4.27{\cdot}10^{-8}$	$1.38{\cdot}10^{-2}$	$3.42{\cdot}10^{-4}$	$8.58{\cdot}10^{-1}$	$7.26{\cdot}10^{-4}$
115	$3.37{\cdot}10^{-9}$	$1.74{\cdot}10^{-3}$	$3.68{\cdot}10^{-5}$	$1.39{\cdot}10^{-1}$	$2.80{\cdot}10^{-4}$
135	$3.77{\cdot}10^{-10}$	$2.86{\cdot}10^{-4}$	$5.29{\cdot}10^{-6}$	$2.75{\cdot}10^{-2}$	$1.04{\cdot}10^{-4}$

Table 1: Instanton cross-sections at the 14 TeV LHC. The differential cross-sections for the process in Figs.1a, 1b and 2a, 2b, given by Eqs. (5.1) and (5.2), are computed for a range of instanton masses M_{inst}.

$x_{I\!P1} = x_{I\!P2} = 0.03$ integrated over z.



CENTRAL PRODUCTION "PROPONENT'S" SUMMARY

- It is shown that for a instanton mass $M_{inst} \geq 50$ 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 ($\sum_i ET_i$) in relatively small rapidity interval ($\delta y \simeq 2-3$ and large sphericity $S > 0.8$ of the event.

CONCLUSION

- 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).
- By imposing appropriate cuts on final states in SD we can select the kinematical region where the I-signal exceeds BG by a factor of at least 2.5. The rate is expected to be large enough to measure Instanton production in the events with a single proton tag.
- Searches for Instantons with $M_{inst} \geq 50 \text{ GeV}$ in the CEP mode would require measurements with 420m stations (PPS, AFP)

- 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)

The main obstacle currently – PU at high luminosity

Conclusion

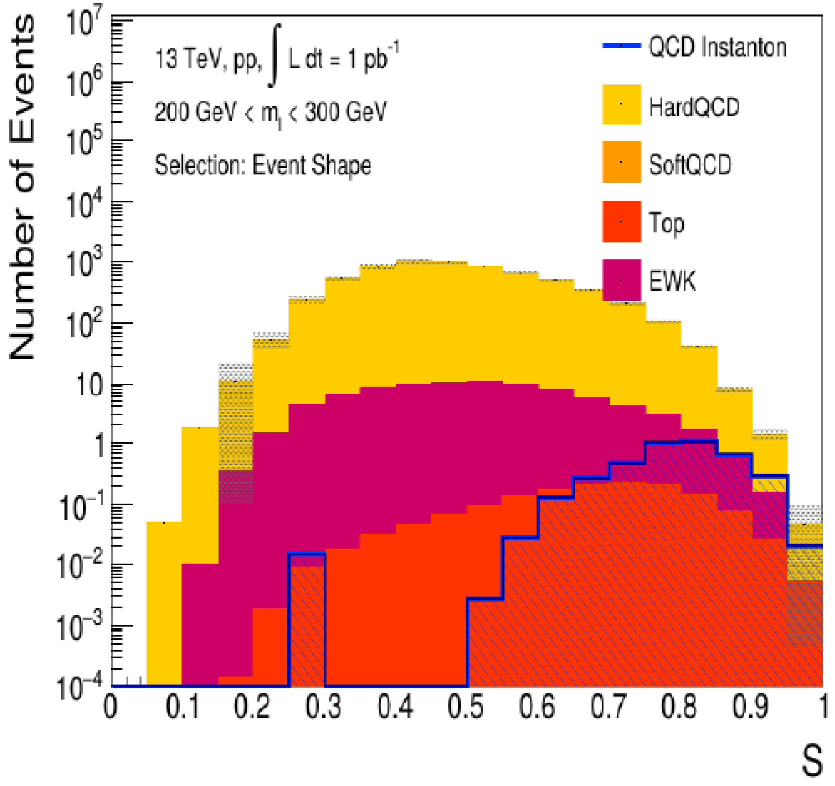

THANK
YOU

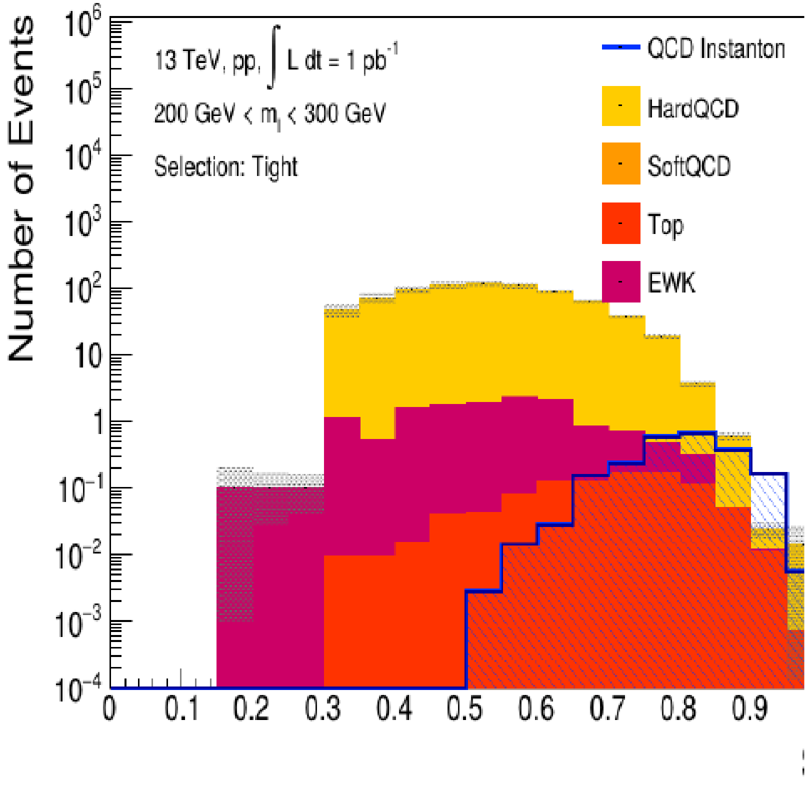
BACKUP

	Signal Region			Control Region	
	Standard	Event-Shape	Tight	A	B
Invariant mass of rec. tracks (Instanton Mass), m_I	200 GeV $< m_I <$ 300 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 $\int L dt = 1\,\text{pb}^{-1}$ 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 contro egions aiming at very low Instanton masses (200 GeV $< m_I <$ 300 GeV)

Simone Amoroso[a] Deepak Kar[b] Matthias Schott 2012.09120



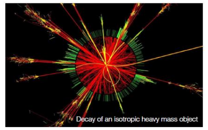


$$N_{displ} > 15$$

First limits based on existing LHC Minimum Bias data

Simone Amoroso[a] Deepak Kar[b] Matthias Schott 2012.0912

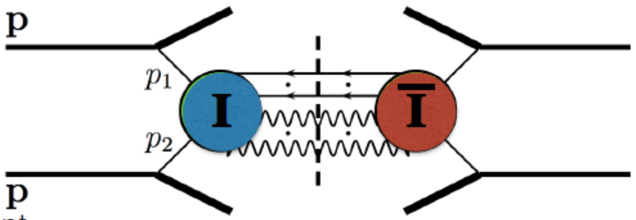
Hedgehog-like QCD background not accounted for (yet)

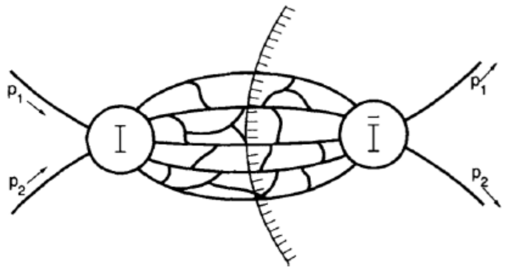


The Optical Theorem approach: to include final state interactions

$$\hat{\sigma}_{\text{tot}}^{\text{inst}} = \frac{1}{E^2}\,\text{Im}\,\mathcal{A}_4^{I\bar{I}}(p_1, p_2, -p_1, -p_2)$$

- Cross-section is obtained by |squaring| the instanton amplitude.
- Final states have been instrumental in combatting the exp. suppression.
- Now also the interactions between the final states (and the improvement on the point-like I-vertex) are taken into account.





V.V.Khoze, A.Ringwald-1991

Total hadronic cross-sections for instanton processes are large

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

V.V..Khoze,F.Krauss, M.Schott-1911.0977
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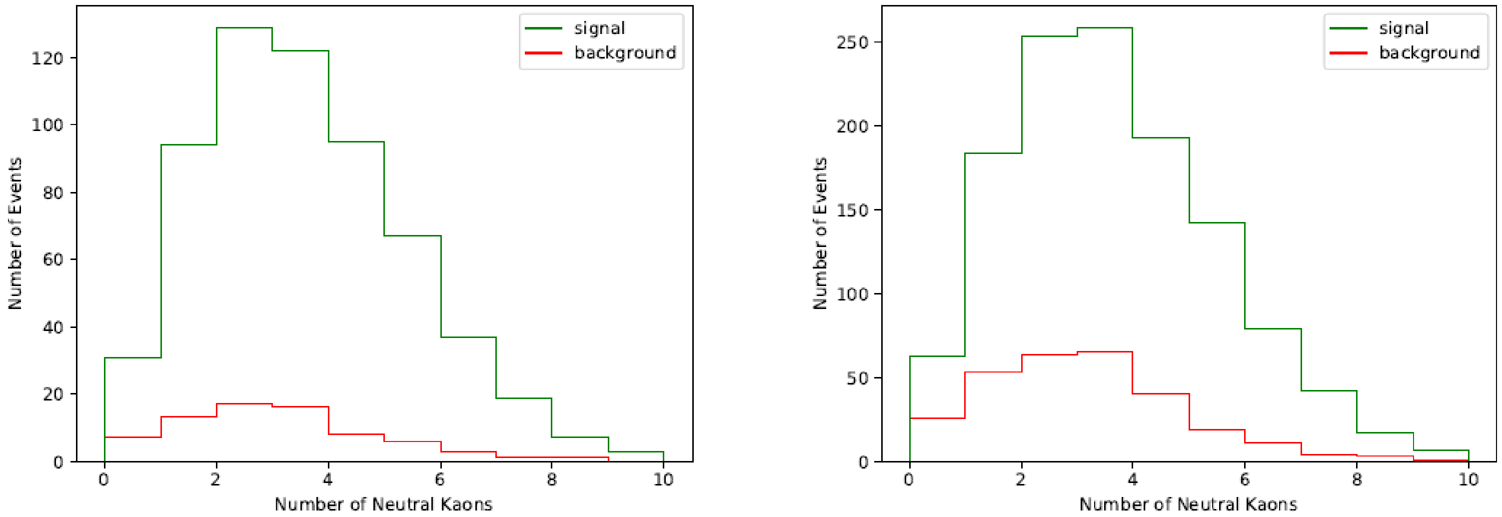
practical approach: vary minimal E

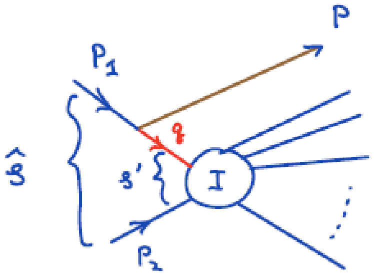
$E_{\min}$ [GeV]	50	100	150	200	300	400	500
$\sigma_{p\bar{p}\to I}$ $\sqrt{s_{p\bar{p}}}$=1.96 TeV	2.62 μb	2.61 nb	29.6 pb	1.59 pb	6.94 fb	105 ab	3.06 ab
$\sigma_{pp\to I}$ $\sqrt{s_{pp}}$=14 TeV	58.19 μb	129.70 nb	2.769 nb	270.61 pb	3.04 pb	114.04 fb	8.293 fb
$\sigma_{pp\to I}$ $\sqrt{s_{pp}}$=30 TeV	211.0 μb	400.9 nb	9.51 nb	1.02 nb	13.3 pb	559.3 fb	46.3 fb
$\sigma_{pp\to I}$ $\sqrt{s_{pp}}$=100 TeV	771.0 μb	2.12 μb	48.3 nb	5.65 nb	88.3 pb	4.42 pb	395.0 fb



- 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 $\sum_i E_{T,i} > 15$ 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 (~ 1 nb) to effectively produce and probe QCD instantons at the LHC, at low luminosity runs, avoiding pile-up problems.

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



$Q^2 = -q^2 = \sqrt{\hat{s}}\, p_T$

$s' = (q+p_2)^2 = \hat{s} - 2Q^2$

A virtual log

$\Rightarrow e^{-Q\rho}$ ← form factor.

↑ cuts-off low-energy range.

Mueller corr-s cuts-off high-energy range (as before.)

$$\exp\left(-Q(\rho+\bar{\rho})\right) = \exp\left(-\frac{Q}{E}\sqrt{y\,(x+1/x+2)}\right)$$

$\sqrt{\hat{s}}$ [GeV]	310	350	375	400	450	500
$\hat{\sigma}^{\text{inst}}_{\text{tot}}$ [pb]	3.42×10^{-23}	1.35×10^{-18}	1.06×10^{-17}	1.13×10^{-16}	9.23×10^{-16}	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 $\sqrt{\hat{s}}$.

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