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

VALERY KHOZE
(IPPP, Durham University)

30 years on

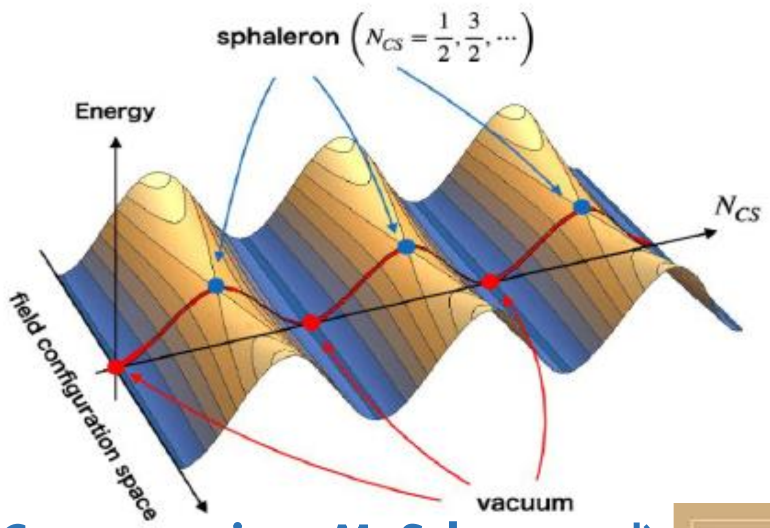
V. A. Khoze, V. V. Khoze, D. L. Milne and M. G. Ryskin, PRD 104, 05401; 105,03600

ISMD 2023 Gyöngyös, Hungary

MOTTO

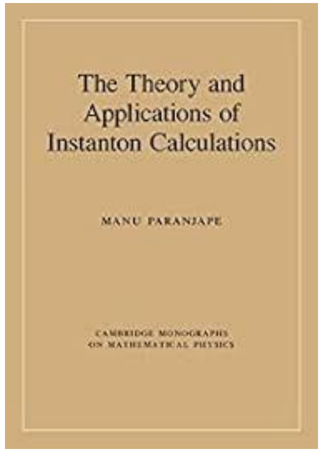
DO NOT COME TO TALK,
COME TO INTERACT

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 :

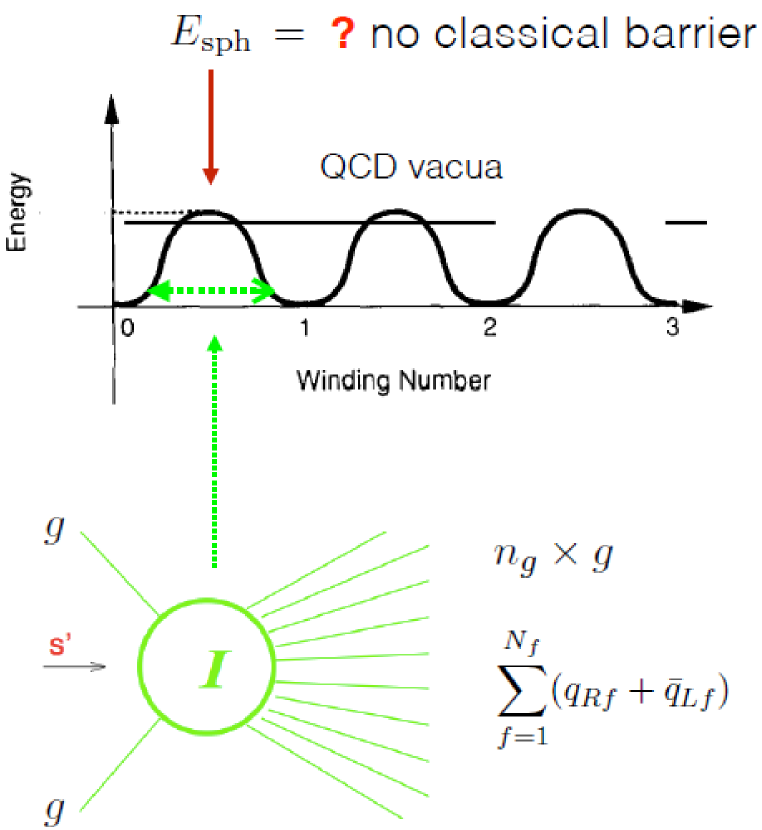
V.V. Khoze, F. Krauss, M. Schott, 1911.09726 : JHEP

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.

2



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

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

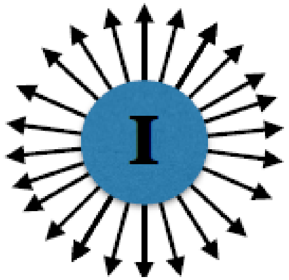
(about 1800 titles)

one of the biggest challenges for particle physics to date

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

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

Instanton signatures:



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

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

'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

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

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

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

$m_f \leq 1/\rho.$

instanton size

arbitrary (tends to be large ~1/alpha_s)

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

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

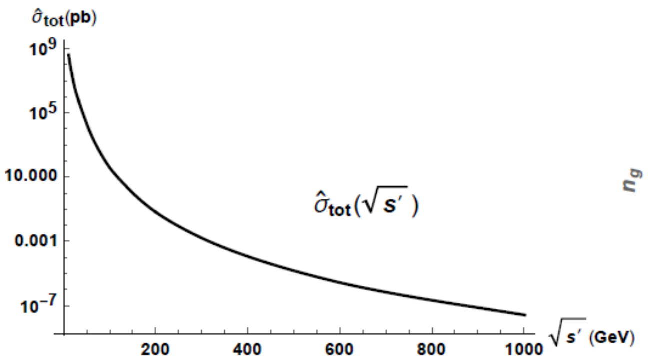
$$u_L + d_L \to n_g \times g + u_R + d_R + \sum_{f=1}^{N_f - 2} (q_{Rf} + \bar{q}_{Lf})$$

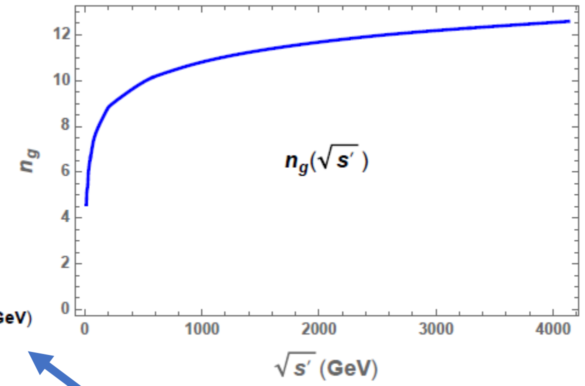
Instanton size is cut-off by partonic energy $\sim \sqrt{s}$ this is what sets the effective QCD sphalrenon scale

Quantum corrections due to in-in states interactions

Mueller 1991

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

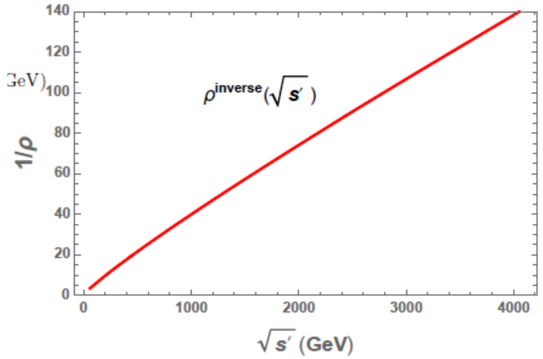




partonic cross-sections

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

Quantum corrections
due to in-in states
interactions

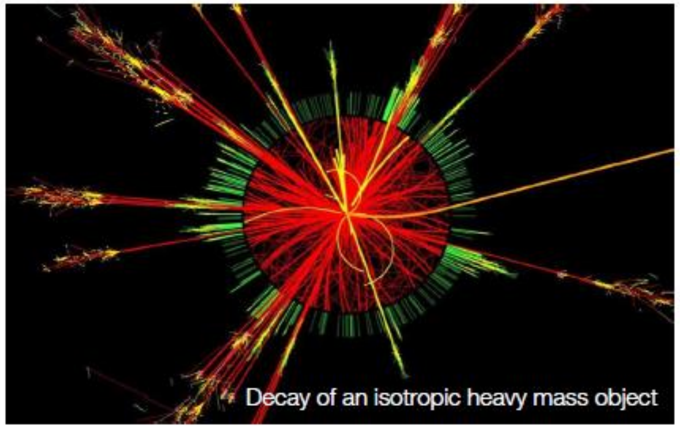


Small instanton masses-large rates, but difficult to distinguish from soft QCD activity (+ PU 'complications' at high lumi).
A large mass-striking multijet signature, but a very low rate.
The S/B ratio falls very rapidly with I-mass increasing –a higher chance of observing the signal in the low-mass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

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



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

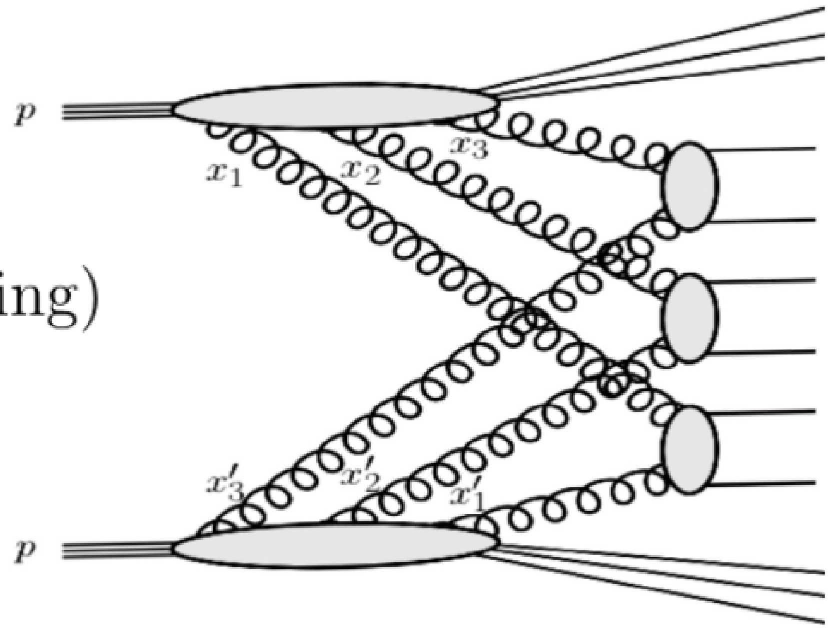
$$\sigma(pp \to I) \sim M_{\rm inst}^{-6}$$

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

Background

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

Large at small M_{inst}



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

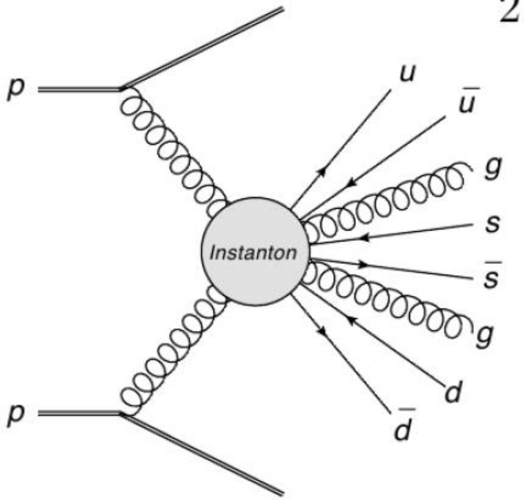
$d\sigma/dE_i^2 \sim \pi\alpha_s^2/E_i^4$ $\sigma_{eff} \sim$ 10 mb

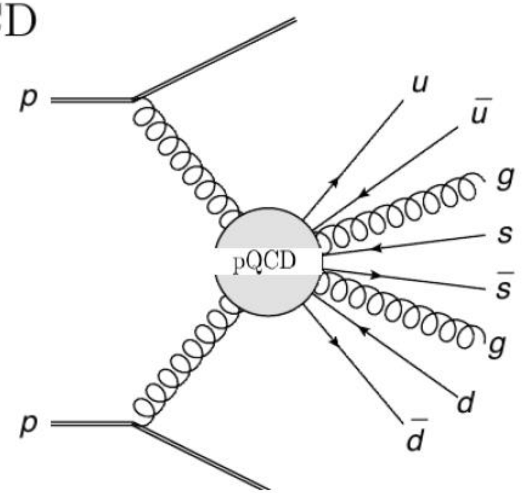
E_i denotes the transverse energy of a jet in the i dijet system,

$S^2 \leq 0.1$. 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.

- 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)

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

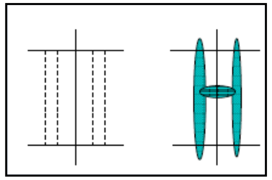
- extra $(\bar{s}s)$ pair of strange particles

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

Semiclassical Double-Pomeron Production of Glueballs and η′

Edward Shuryak and Ismail Zahed

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



UA8 and double-Pomeron production

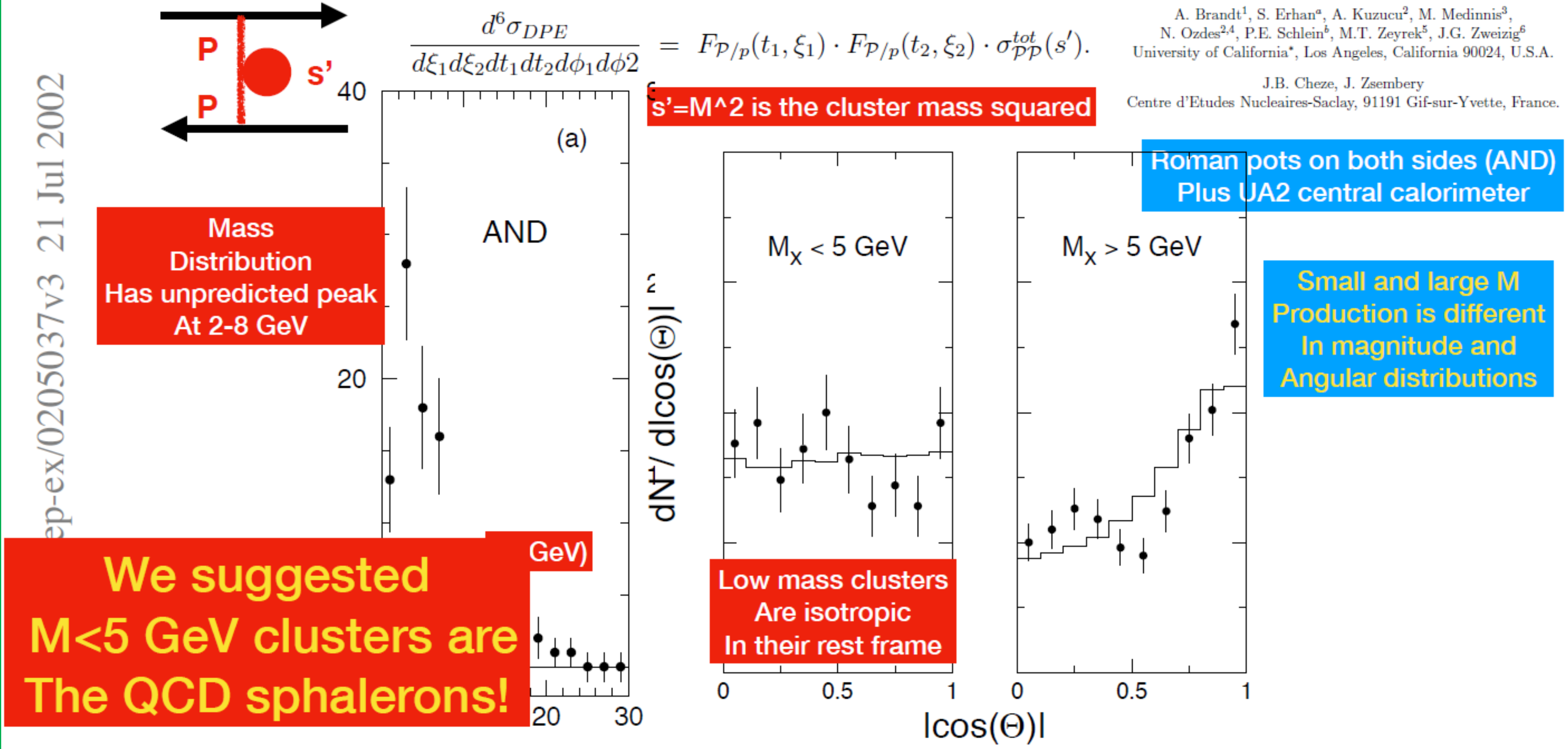
$$\frac{d^6\sigma_{DPE}}{d\xi_1 d\xi_2 dt_1 dt_2 d\phi_1 d\phi 2} = F_{\mathcal{P}/p}(t_1,\xi_1)\cdot F_{\mathcal{P}/p}(t_2,\xi_2)\cdot\sigma^{tot}_{\mathcal{P}\mathcal{P}}(s').$$

A Study of Inclusive Double–Pomeron–Exchange in $p\bar{p}\to pX\bar{p}$ at $\sqrt{s}=630$ GeV

A. Brandt[1], S. Erhan[a], A. Kuzucu[2], M. Medinnis[3], N. Ozdes[2,4], P.E. Schlein[b], M.T. Zeyrek[5], J.G. Zweizig[6]
University of California[*], Los Angeles, California 90024, U.S.A.

J.B. Cheze, J. Zsembery
Centre d'Etudes Nucleaires-Saclay, 91191 Gif-sur-Yvette, France.

hep-ex/0205037



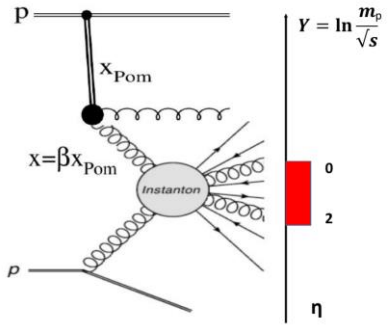
It may make sense to repeat this measurement at the LHC/RHIC ?

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 ($\xi = x_{Pom} \le 0.01$), or by observing no hadron activity in the forward calorimeters.

Low Luminosity run (no PU)

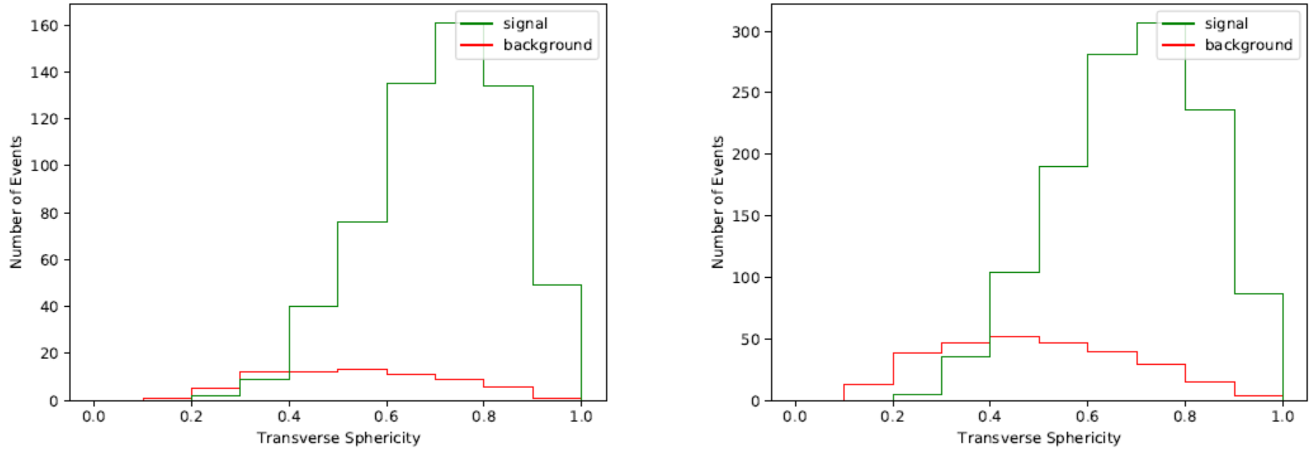


Figure 4: Distribution over the transverse sphericity S_T, Eq. (8), of the charged hadrons produced in the events with the instanton (green) in comparison with the expected background (red). The selection criteria used are the same as those described in Fig. 3

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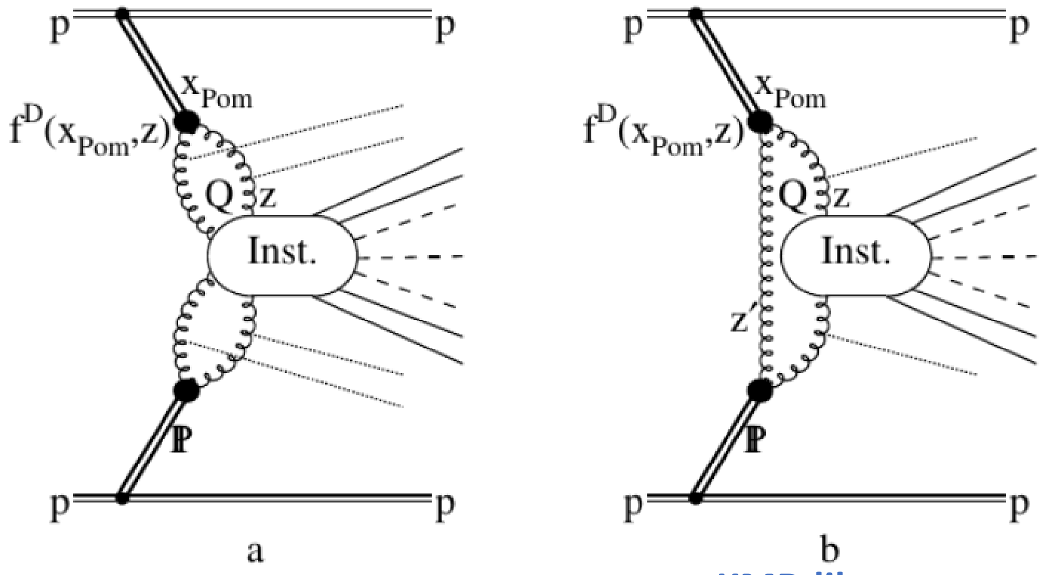
- It is shown that by imposing appropriate cuts on final states we can select the kinematical region where the I-signal exceeds BG by a factor of at least 2.5. At $\sum_i E_{T,i} > 15$ GeV, $N_{ch} > 20$ measured within the $0 < \eta < 2$ the rate is expected to be large enough to measure Instanton production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



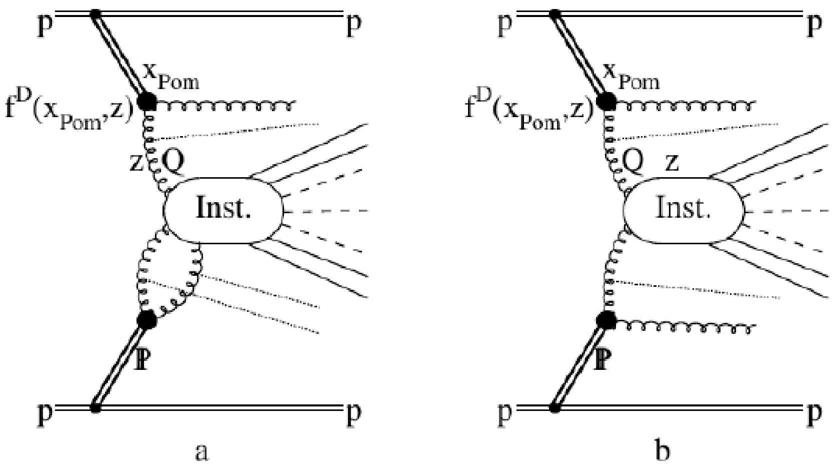
KMR-like

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

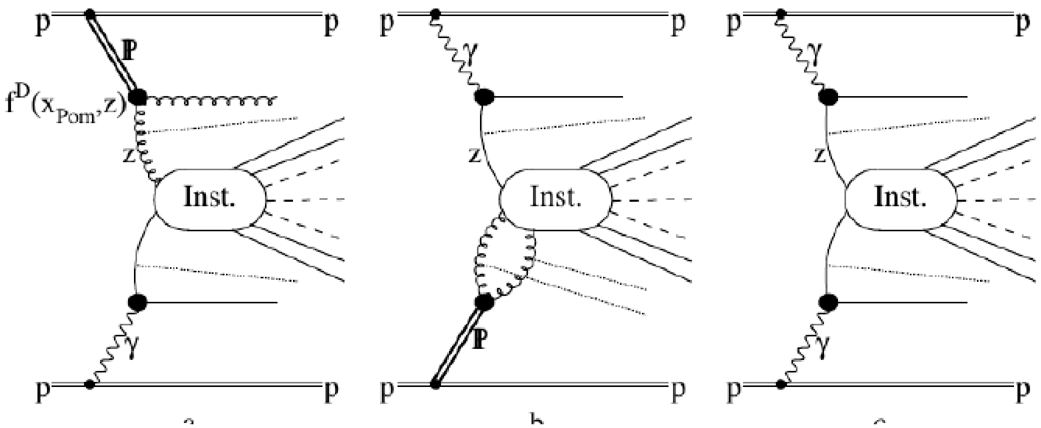


Dominant

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

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

Fig.3



HIC

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

UPC-no PU nightmare

L. Harland-Lang et al

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

CENTRAL PRODUCTION

- 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.

Summary

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

Goal of this analysis is extension of previous theory studies:

- Higher masses (M_{inst} > 60 GeV, M_{inst} > 100 GeV)
- Inclusion of multi-parton interactions
- Inclusion of detector effects
- Inclusion of pile-up effects

Single-tag approach:
S/B ~ 2.1 (>60 GeV) or 2.3 (>100 GeV) at generator level deteriorate to S/B~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 <μ> (20 and 50). There combinatorial effects are big and overwhelm the signal.

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

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).
- 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


THANK YOU

BACKUP

DIS HERA data seem to exclude the low range of expectations

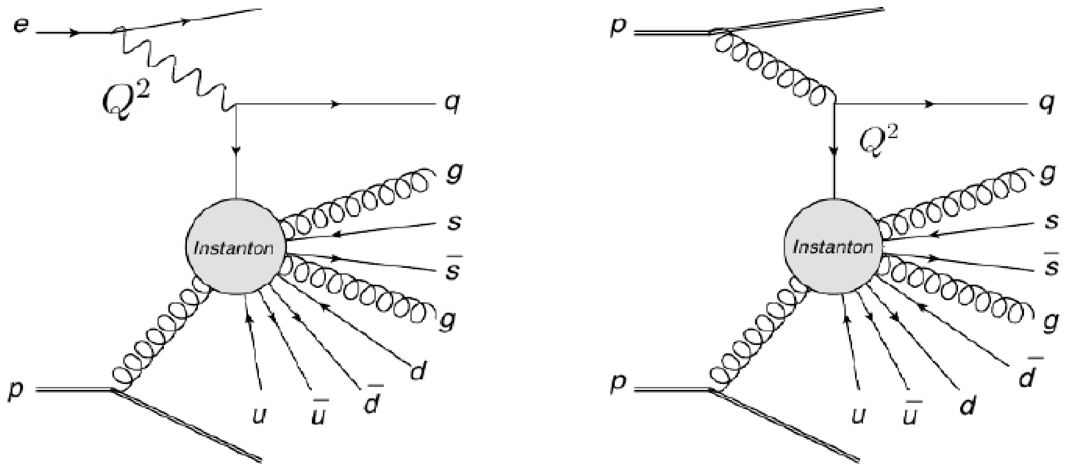


Figure 2. Depiction of a QCD Instanton processes in electron-proton (left) and proton-proton (right) collisions, where an external scale parameter Q' is required.

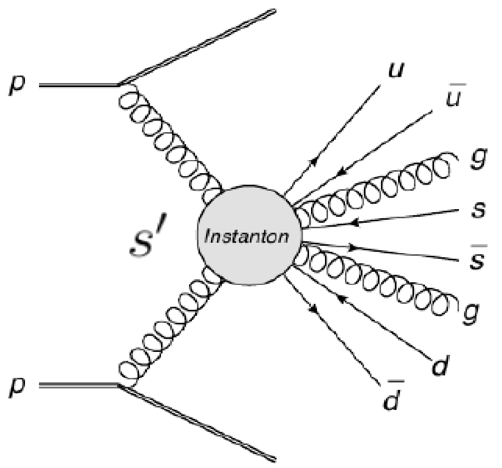


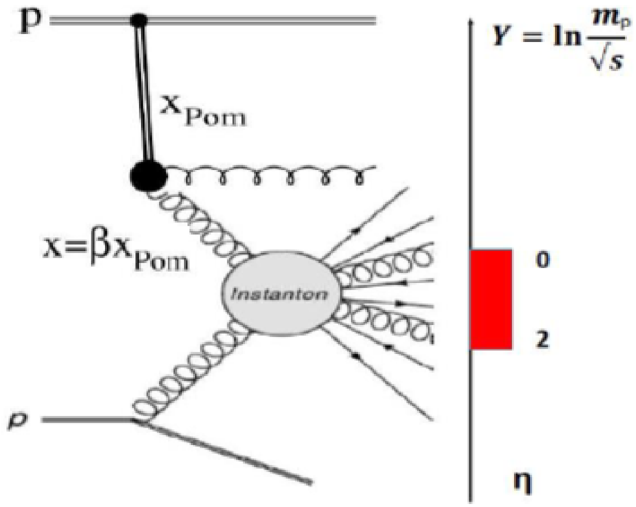
Figure 3. Depiction of a QCD Instanton processes in proton-proton (right) colli-

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

IN REAL LIFE



Instanton produced in Single Diffraction:

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

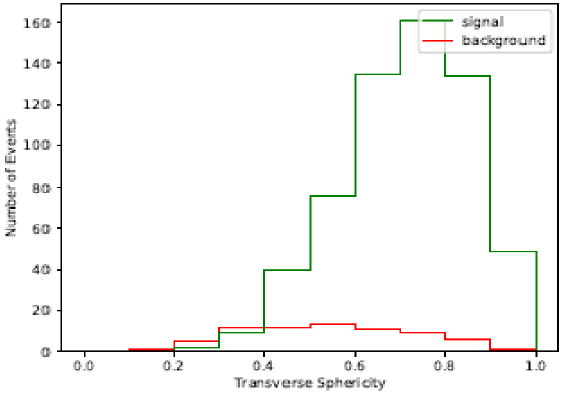
g+g → n_gx g + $\sum_{f=1}^{N_f}(q_{Rf}+q_{Lf})$:

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

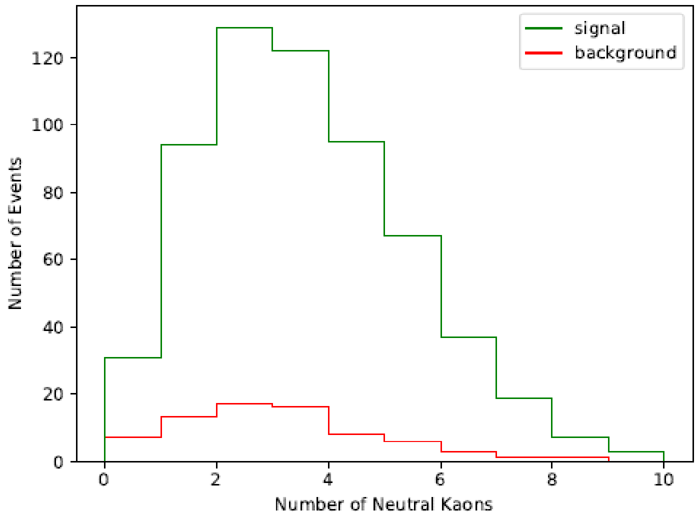
1. High particle multiplicity
2. No high-pt jets
3. Large density of E_T

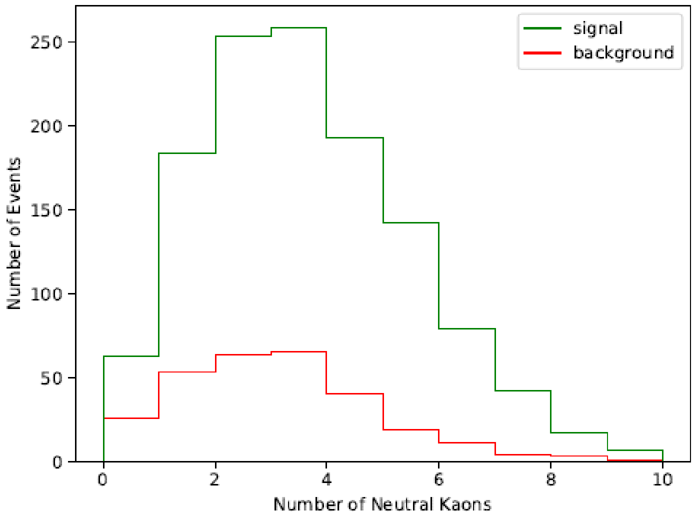
Suppress gluons from Pomeron with too large x (where gluon PDF rapidly decreases with incr. x)
→ focus on 0<η<2 (tagged proton has η<0)

Main background: underlying event. Multi-parton interactions shown to be suppressed theoretically in 2104.01861 for 20<M_{inst}<60 GeV



Check the impact of MPI at particle level.
What about detector effects? Pile-up? Look at M_{inst}>60 GeV
→ 2208.14089





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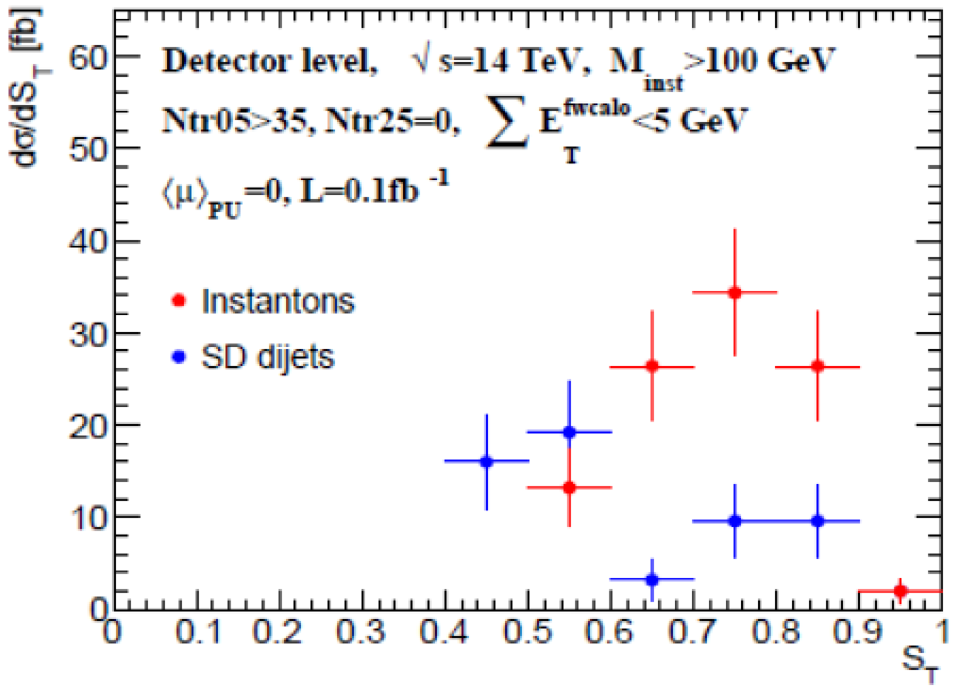
- Even with these rather strong cuts in place, the expected instanton cross-section remains sufficiently large (~ 1 nb) to effectively produce and probe QCD instantons at the LHC, at low luminosity runs, avoiding pile-up problems.

Single-tag: results at detector level



Hunting for higher S/B:

M_{inst} > 100 GeV for μ=0:

S/B ~1.5 for N_{tr05} > 35 ∧ N_{tr25} = 0 ∧ $\sum E_T^{fwcalo}$ < 5 GeV
but too few signal events survive