Hunting for QCD instantons

M.G. Ryskin (PNPI) June 2026

1. Instanton is the classical solution

It describes the transition between different QCD vacuums.

??? Do we have *many* vacuums in our QCD ???

2. QCD instanton signatures

large multiplicity $N \propto 1/\alpha_s(\rho)$

sphericity $S \to 1$

zero modes for light quarks (extra $s_R\bar{s}_L$, $c\bar{c}$ pairs)

3. background (MPI)

large size (ρ) – no good signature

small ρ – large M_{inst} but small $\sigma_{inst} \propto \exp(-2\pi/\alpha_s(\rho))$

4. Instanton in diffractive events (MPI suppressed)

5. Instanton via the spin-spin correlations

between two hyperons at NICA

(2104.01861)

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)

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

$\alpha_s = g^2/4\pi$, ρ= 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 $\mu, \nu = 1, 2, 3$

2. QCD is the non-abelian gauge theory with infinite number of vacuums.
The vacuums differ from each other by the gauge field slowly decreasing at large distances $x \to \infty$

Instanton/sphaleron describes the transition between different vacuums.

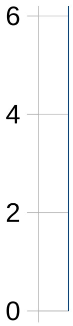
It is not known whether we have to admit *all* vacuums or we have to consider only the (gluon) fields which fall down sufficiently fast and thus to deal with only one vaccuum.
In the last case there will be **No** QCD instantons.

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.



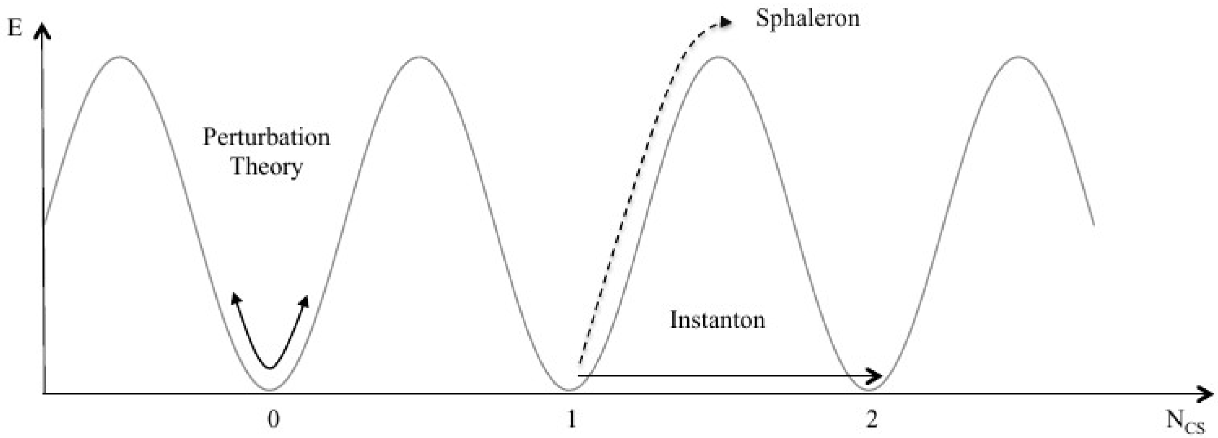


Figure 1. Instanton and Sphaleron processes in the topology of a Yang-Mills vacuum; energy density of the gauge field (y-axis) vs. winding number N_{CS} (x-axis).

Instanton has never been 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 signature

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

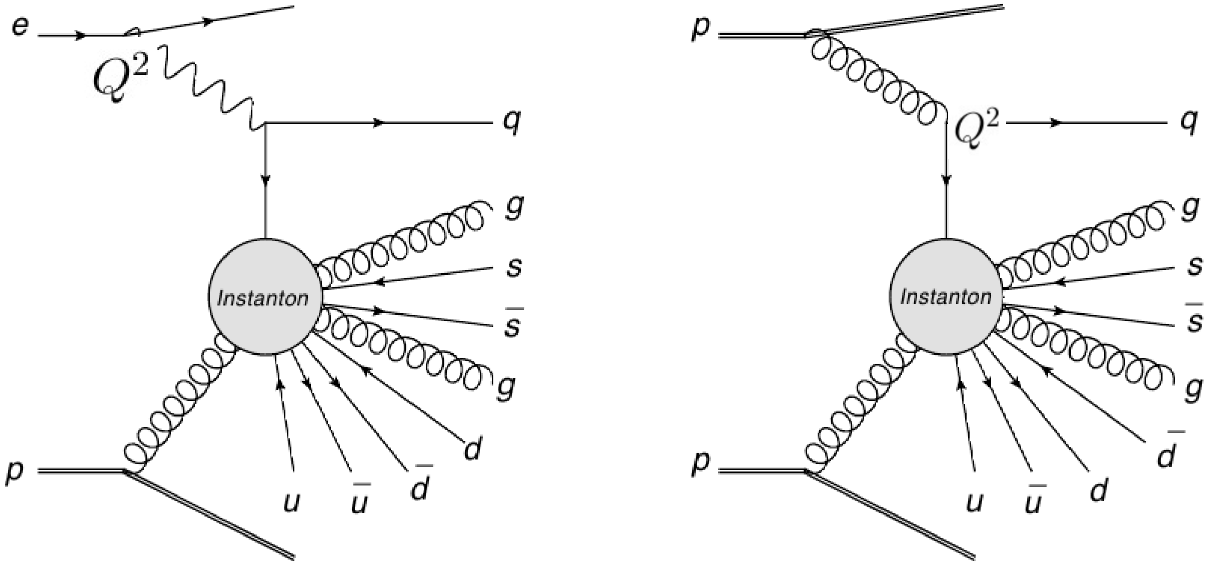


Figure 2. Depiction of a QCD Instanton processes in electron-proton (left) and proton-proton (right) collisions, where an external scale parameter Q' is required.

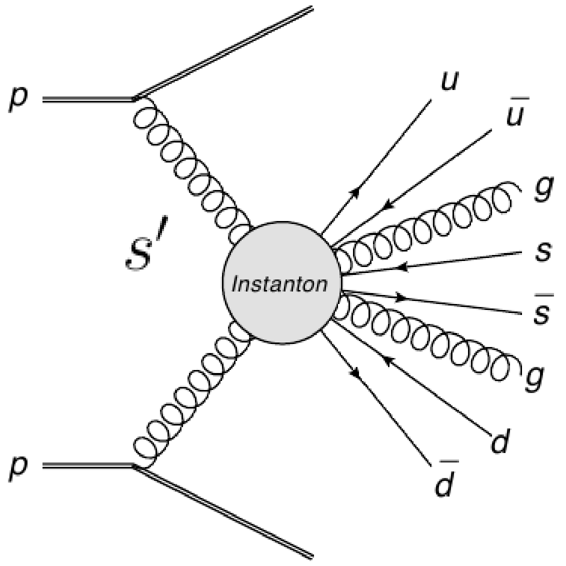
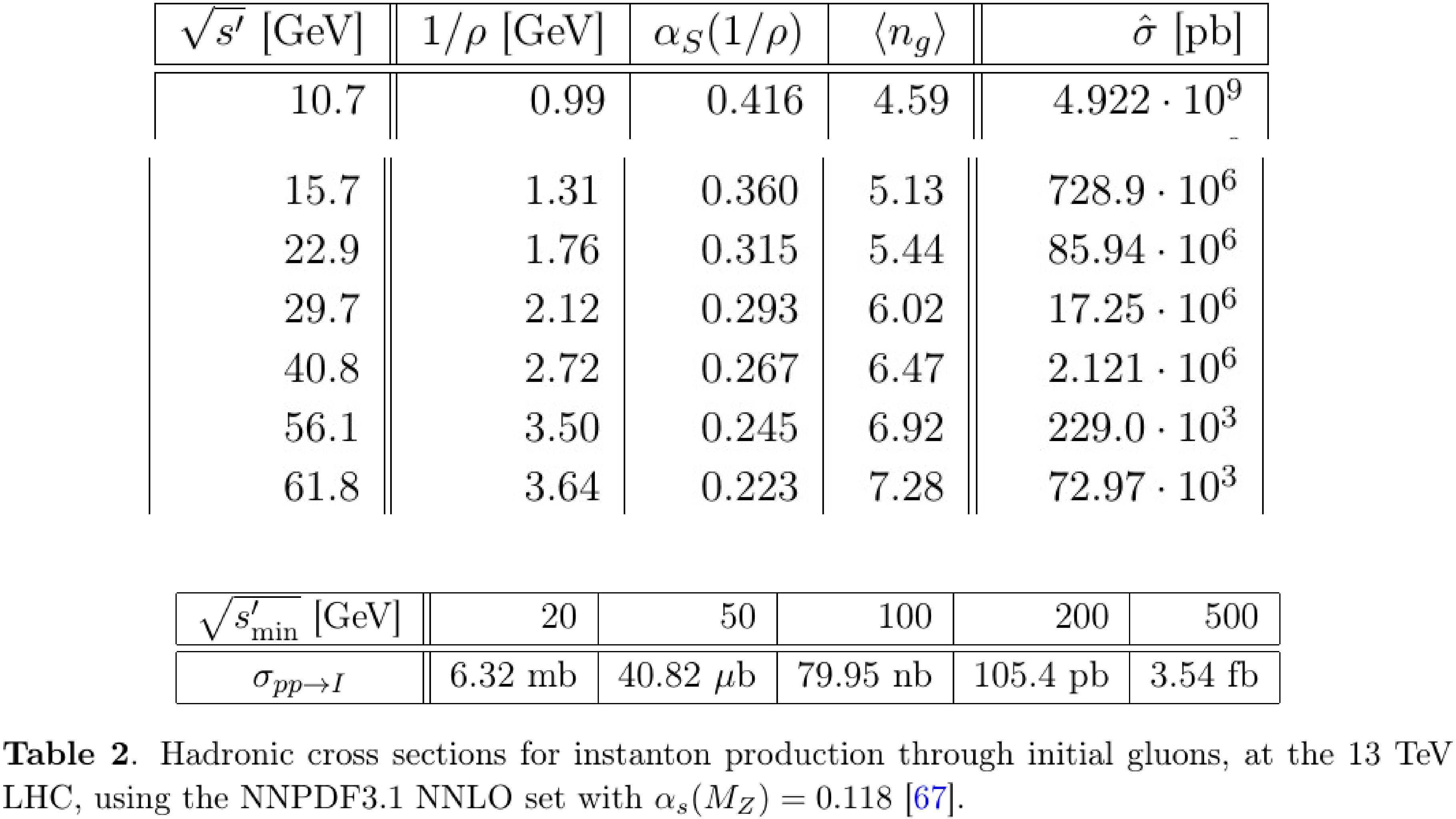


Figure 3. Depiction of a QCD Instanton processes in proton-proton (right) colli-

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.

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	$72.97 \cdot 10^3$

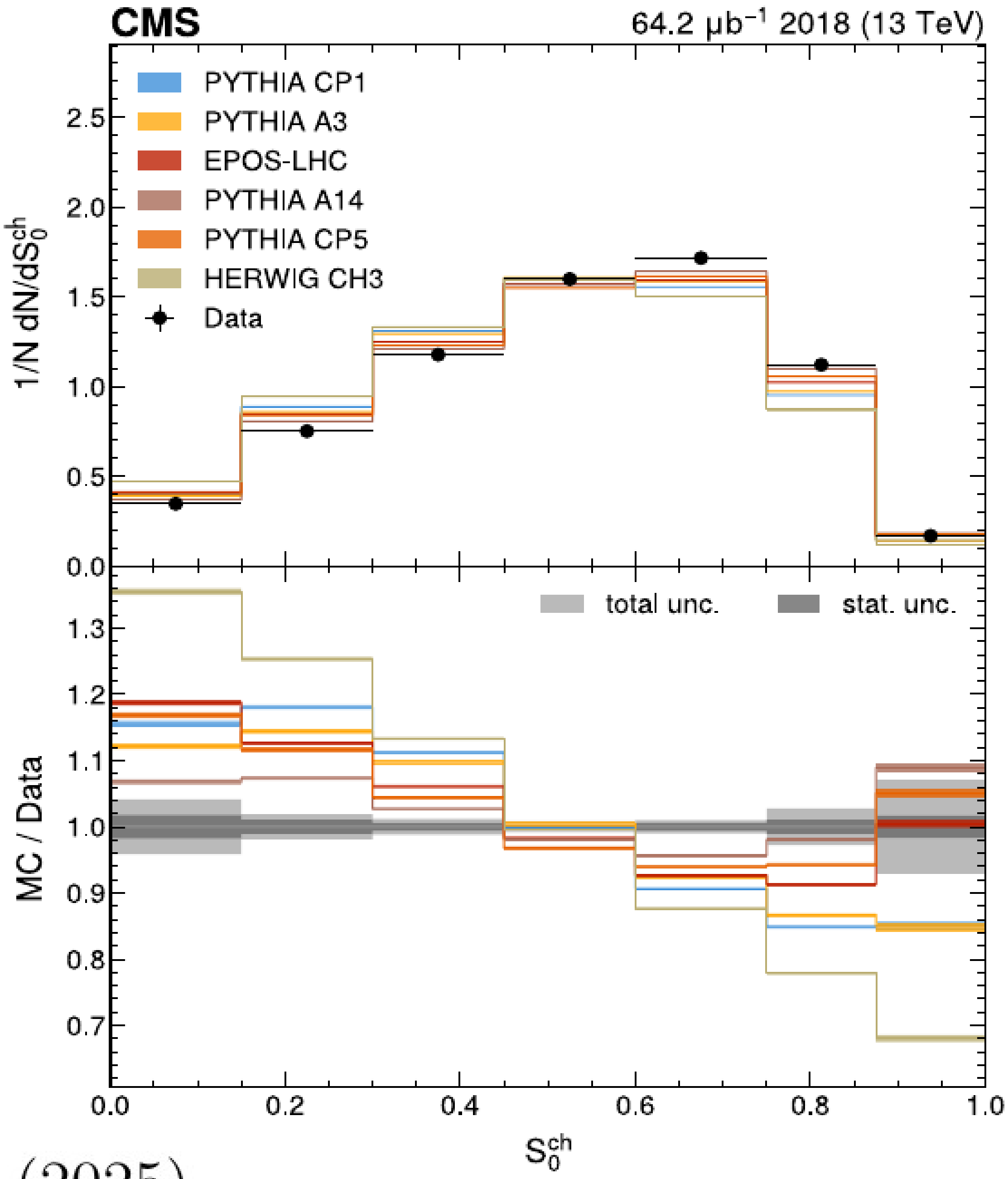
$\sqrt{s'_{\rm min}}$ [GeV]	20	50	100	200	500
$\sigma_{pp\to I}$	6.32 mb	40.82 μb	79.95 nb	105.4 pb	3.54 fb

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

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

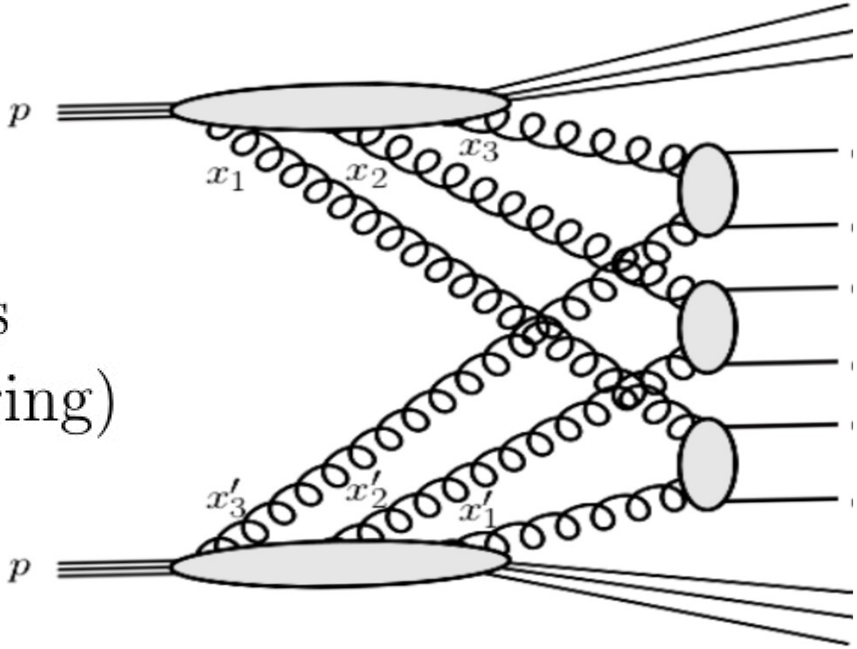
”data being more isotropic than any of the simulations.”



CMS PRD 112, 112006 (2025)

It was noticed by Bjorken that the large (~5%) branching of $\eta_c \to \eta\pi\pi$, $\eta'\pi\pi$ and $\bar{K}, K\pi$ decays, naturally produced via the 't Hooft instanton-induced interaction $L \sim (\bar{c}c)(\bar{u}u)(\bar{d}d)(\bar{s}s)$ can be considered as the experimental indication of the QCD instantanton presence.
(J.D. Bjorken, AIP Conf. Proc. 549(1), 211–229 (2000). arXiv:hep-ph/0008048)

Background



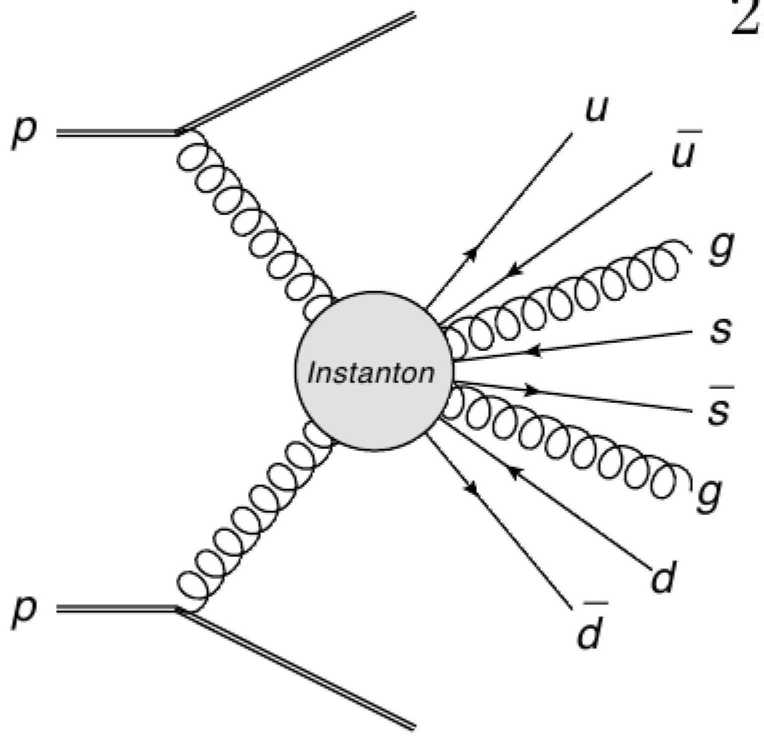
1. Multiple parton interactions (Double/Triple/... parton scattering)

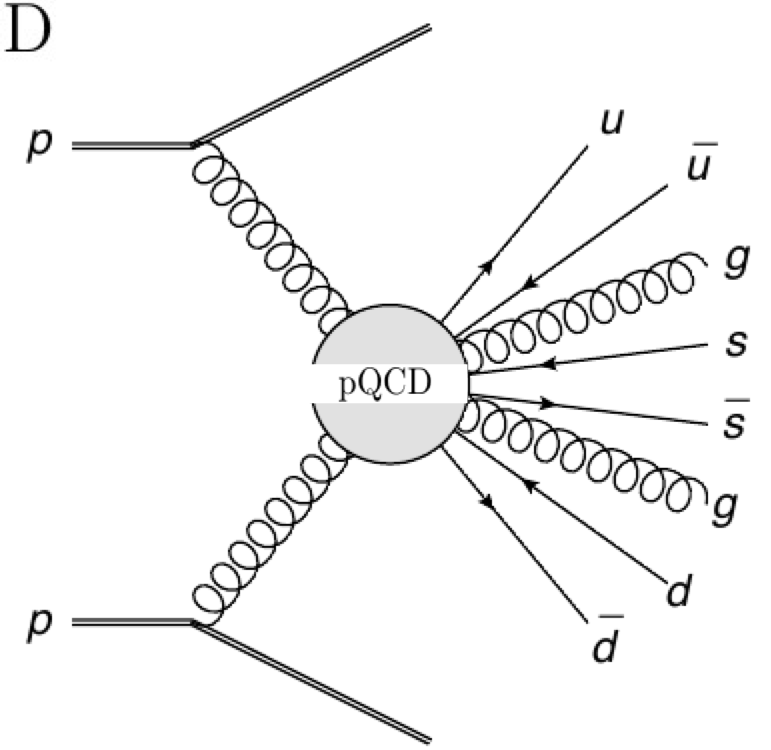
Large at small M_{inst}

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

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

2. pQCD





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

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

(hedgehog-like)

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

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

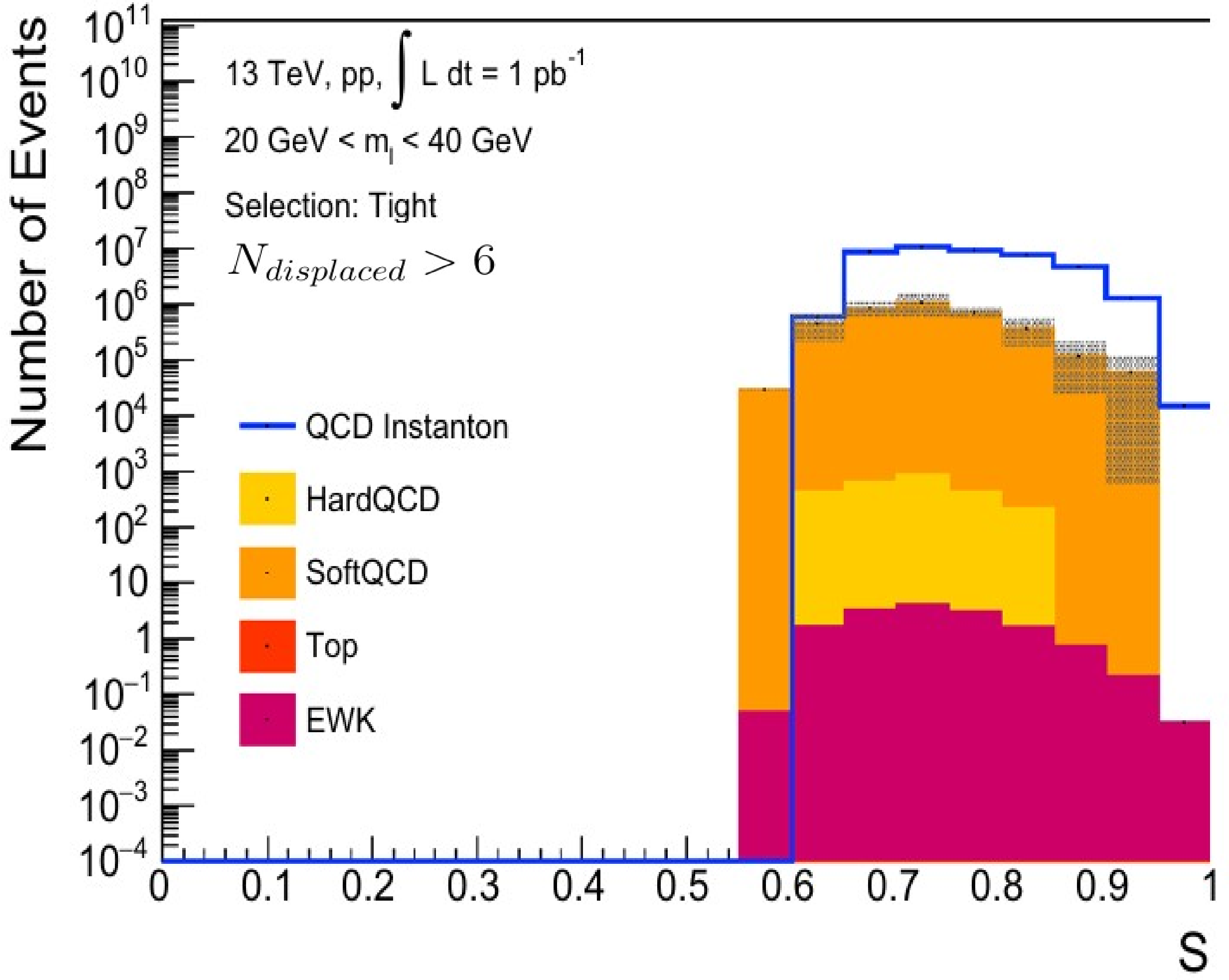
- Sphericity $S = (3/2)(\lambda_2 + \lambda_3)$ close to 1

$\lambda_1 > \lambda_2 > \lambda_3$ 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

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



S. Amoroso, D. Kar, M. Schott 2012.09120

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::

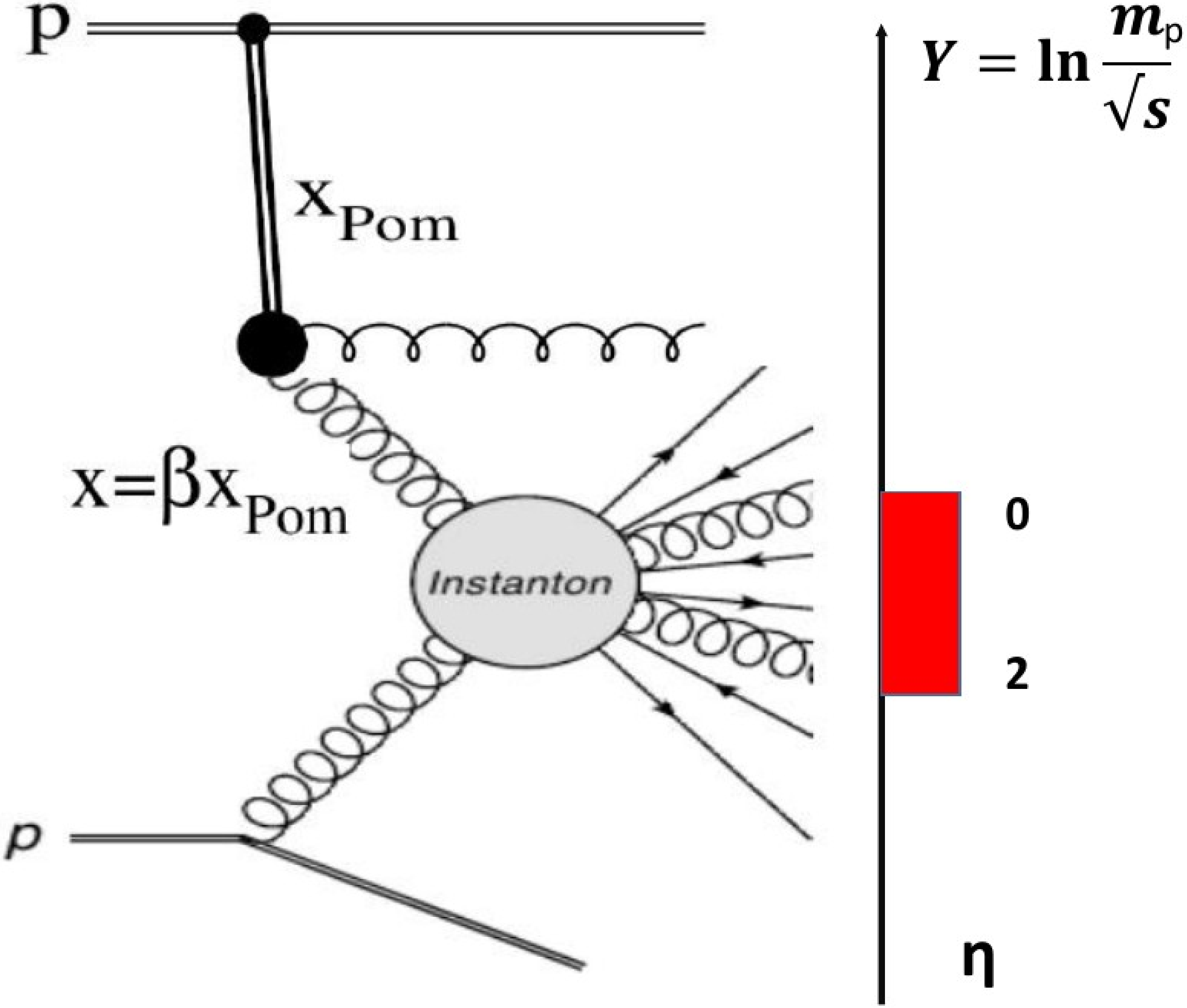
$N_{ch} > 20 \quad \sum_i E_{T,i} > 15$ **GeV**

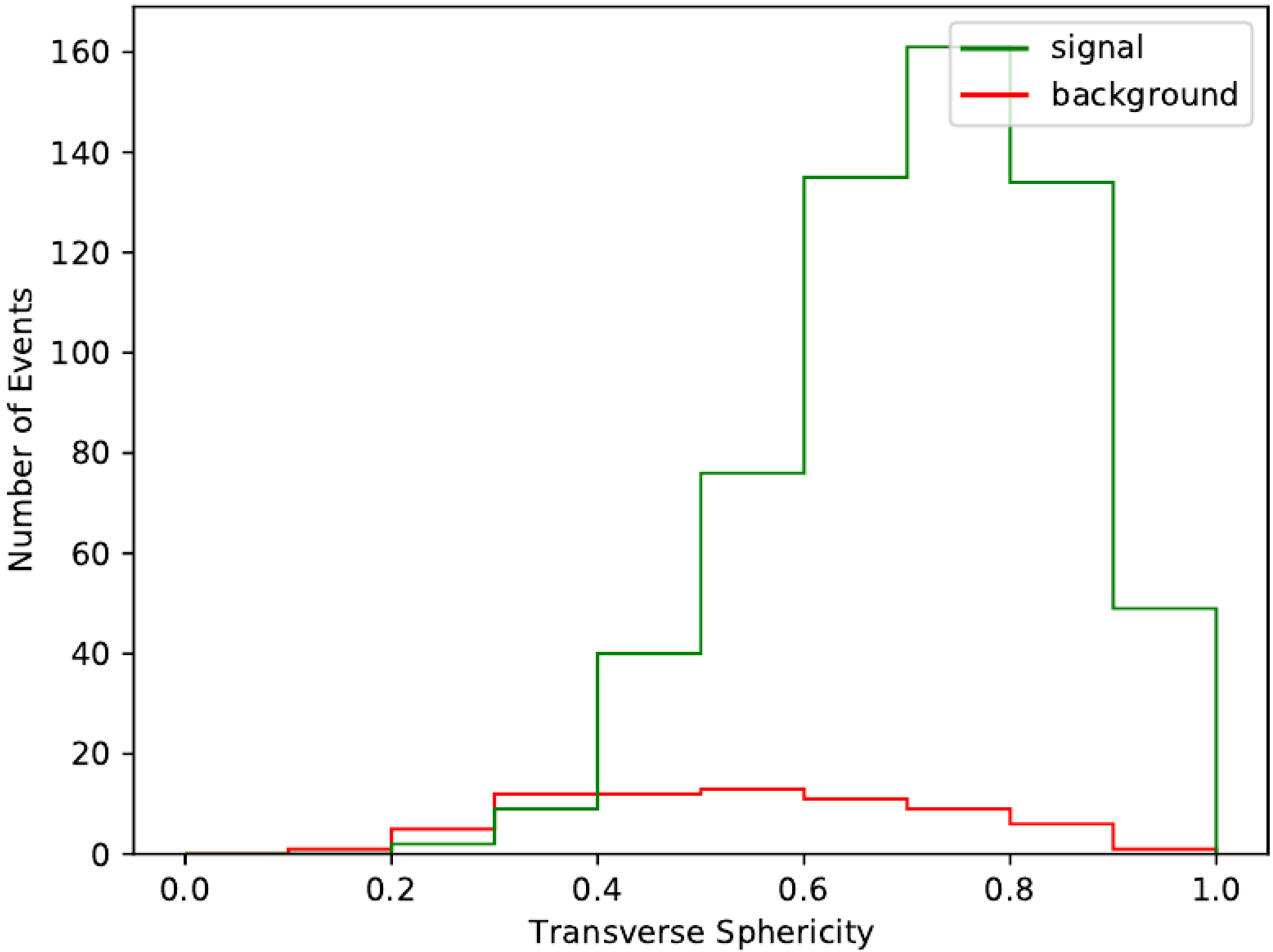
($0 < \eta < 2 \quad \mathbf{p}_{T,i} > 0.5$ **GeV**)

Trigger:
large N_{ch}
× LRG veto

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

(to exclude high E_T jets)


p
x_{Pom}
$x=\beta x_{Pom}$
Instanton
p
$Y = \ln \frac{m_p}{\sqrt{s}}$
0
2
η



$L = 1\ pb^{-1} \qquad 0.002 < \xi < 0.005$

Instanton induced spin-spin corr^n.

$$q_{Li} + q_{Lk} ==> I ==> n_g \cdot g + \sum_f (q_{Rf} + \vec{q}'_{Lf});\ i \neq k,\ \textbf{for}\ \vec{q}'\ f \neq i,\ f \neq k$$

$$q_R + q_R ==> \bar{I} ==> n \cdot g + \sum_f (q_{Lf} + \vec{q}'_{Rf}) \qquad n \sim 1/\alpha_s(\rho)$$

Instanton rearranges the Dirac sea.

One extra level of light left quark appears while the level of right quark goes upstairs to continuum spectra.

In the electroweak case, where the γ_5 anomaly is cancelled between the quarks and the leptons this leads to the *baryon charge non-conservation*.

In QCD this is the helicity non-conservation.

The idea is to exploit the Instanton induced spin-spin correlations. Indeed in terms of Feynman diagrams the instanton/sphaleron looks as the non-local vertex with n_g gluon and $2n_f$ fermion legs; n_f is the number of light quarks with $m_q < \rho$ (m_q is the curent quark mass, ρ is the instanton size).
That is 2 (quark + antiquark) legs for each light flavour. Instanton absorbs left quark and emits right quarks (absorbs right antiquarks and emits left antiquarks)

$$q_{Li} + q_{Lk} ==> I ==> n_g \cdot g + \sum_f (q_{Rf} + \bar{q}'_{Lf});\ i \neq k,\ \textbf{for } \bar{q}'\ f \neq i,\ f \neq k$$

$$q_R + q_R ==> \bar{I} ==> n \cdot g + \sum_f (q_{Lf} + \bar{q}'_{Rf}) \qquad n \sim 1/\alpha_s(\rho)$$

Strong instanton gluon field rearranges the Dirac basement.
One extra level of light left quark appears while the
level of right quark goes upstairs to continuum spectra.

This is connected with the γ_5 anomaly.

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In electro-week case where the γ_5 anomaly is canceled between the quarks and the leptons this leads to the *baryon charge non-conservation.*

In QCD this is the helicity non-conservation.

This can be checked experimentally by studying the spin-spin correlations, say in

$$p_\uparrow \ + \ p \ \to \ \Sigma \ + \ X$$

First at the quark level the instanton *doubles* the incoming polarization. Instead of one left u_L-quark it produces two right quarks - u_R and s_R. To distinguish the 'left' and 'right' quarks we need the weak interaction, that is the weak decay of Σ or Λ hyperons. (Another possibility is to produce the $\bar{\Lambda}\Lambda$ pair and to check that Λ is *right* while $\bar{\Lambda}$ is *left*.)

To confirm that it was the instanton/sphaleron we may observe a larger than usual (at this energy) multiplicity and a stronger energy ($\sqrt{s}$) dependence and/or the spin-spin correlation when the second beam is polarized (instanton absorbs two *left* quarks only).

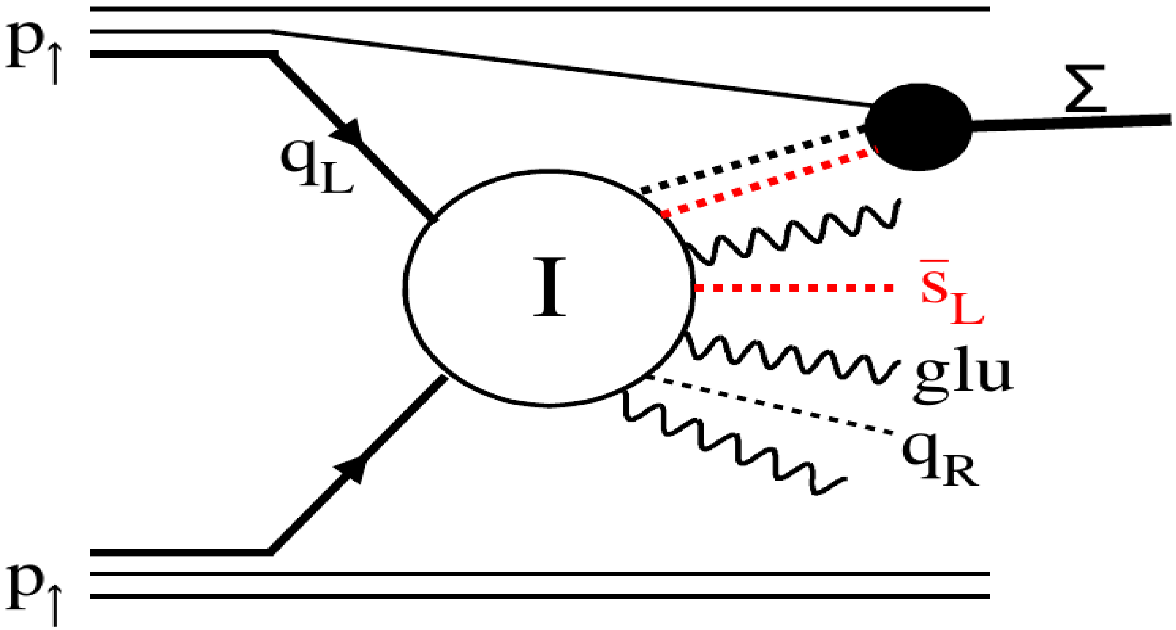
In QCD instanton vacuum models the typical instanton size $\rho \sim 0.3fm = 1/600$ MeV and the separation between the instantons is $R \sim 1fm$.

The cross section to create the $\rho = 0.3fm$ sphaleron is about

$$\rho^2 \cdot (\rho/R)^2 \times \text{ Ringvald factor} \sim 1mb$$

(see e.g. Tab.2 of 1911.09726)

However the probability to form the hyperon from these quarks is small. So I would expect $\sigma \sim 1$ μb.



A New Mechanism for Single Spin Asymmetries in Strong Interactions

JETP Lett. 72 (2000) 481

N.I. Kochelev

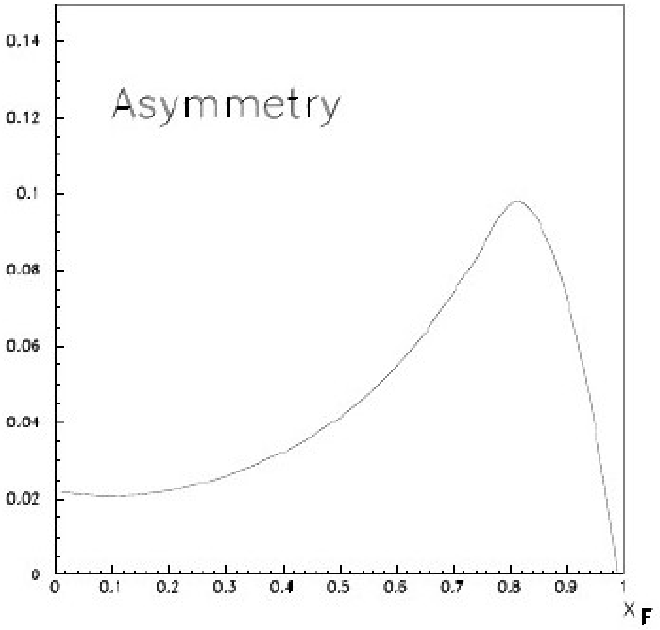


Figure 2: *The instanton contribution to the single spin asymmetry for pion production as a function of x_F.*

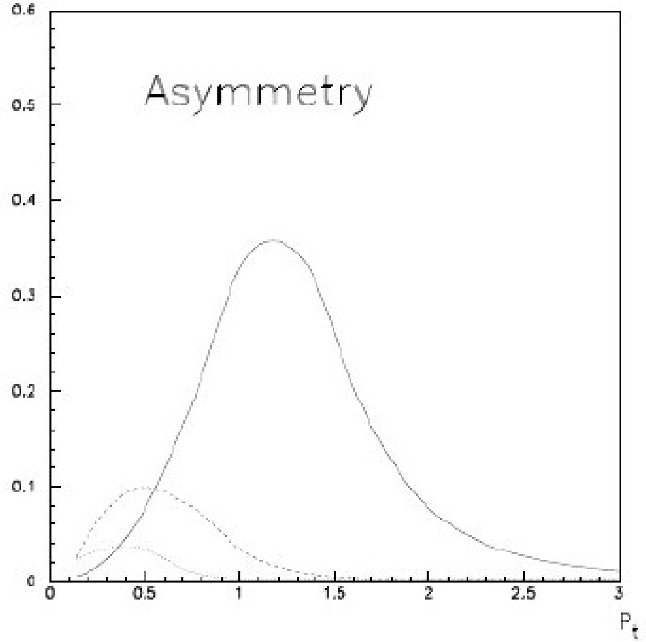
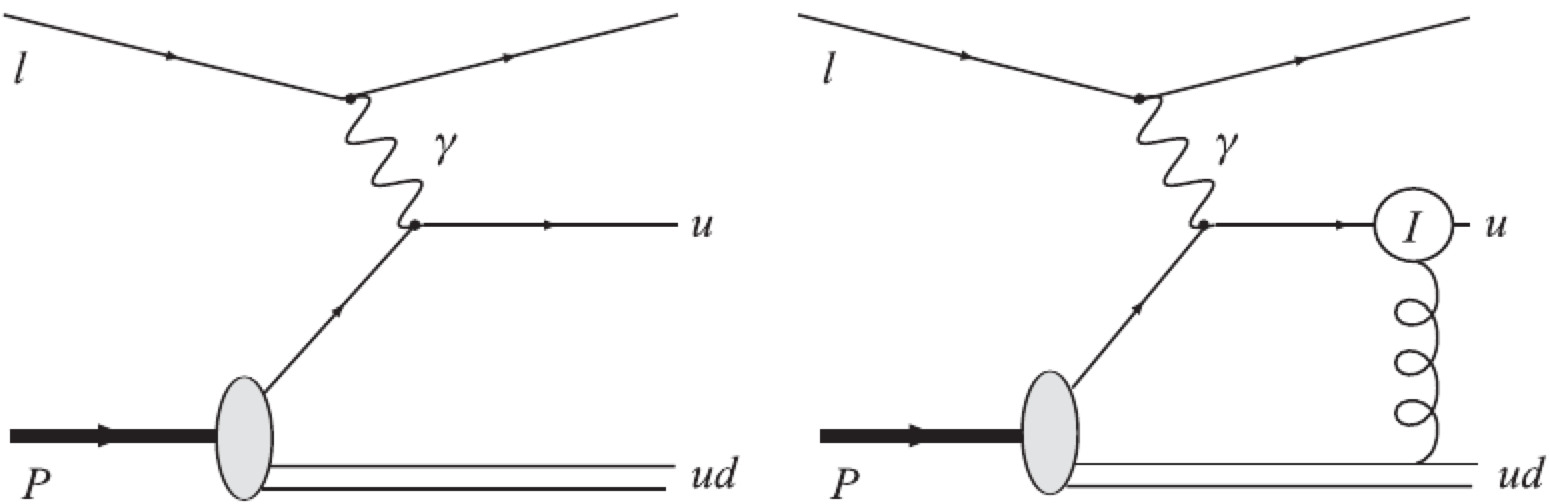


Figure 3: *The instanton contribution to the single spin asymmetry for pion production as a function of x_F and $p_t = |l_\perp|$. Solid line is for $x_F = 0.9$, dashed line is for $x_F = 0.6$ and dotted line is for $x_F = 0.3$.*

SINGLE SPIN ASYMMETRIES IN HIGH ENERGY REACTIONS AND NON-PERT. QCD EFFECTS

A. E. Dorokhov, N. I. Kochelev, W.-D. Nowak

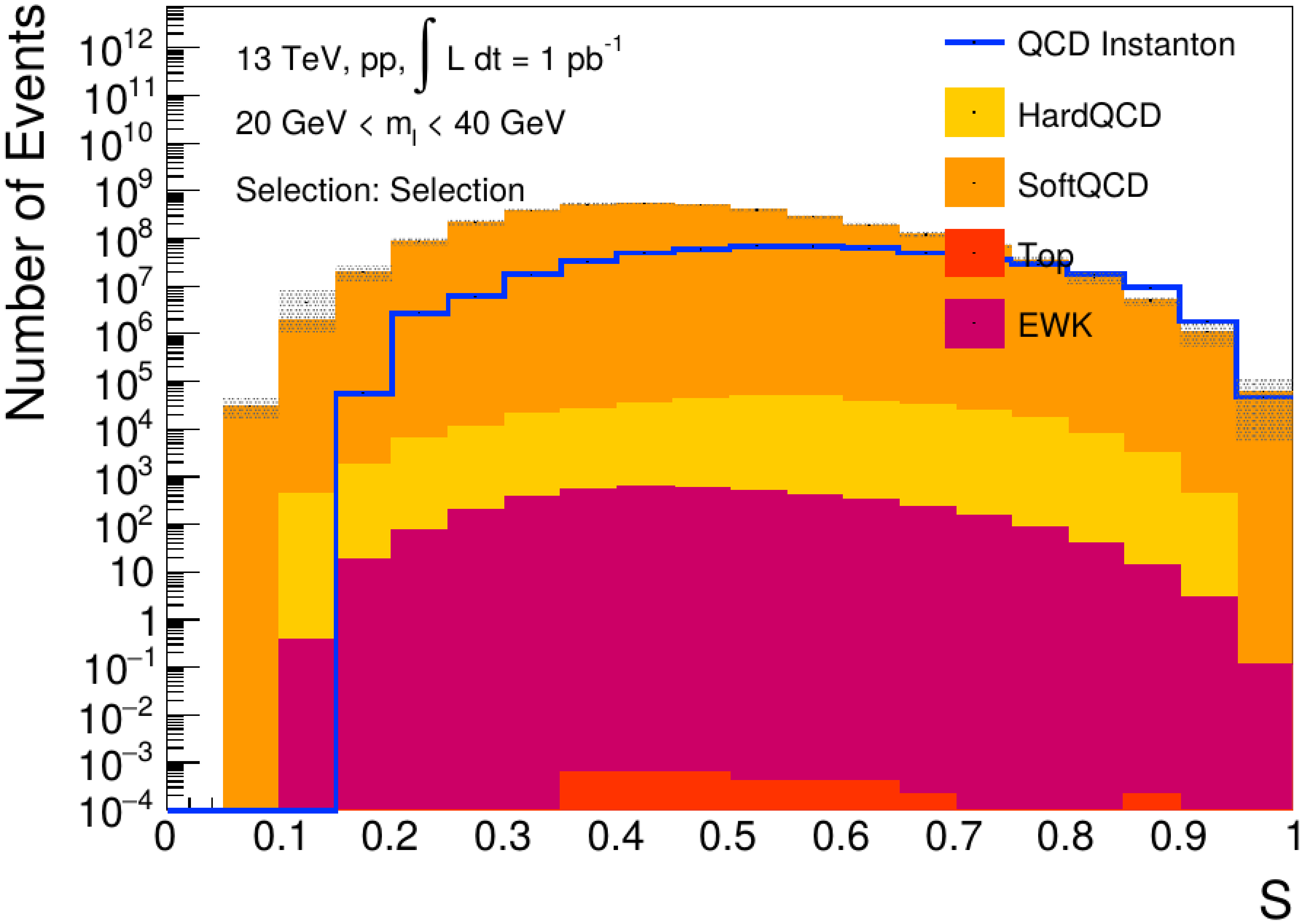
Phys.Part.Nucl.Lett. 6 (2009) 440-445 • e-Print: 0902.3165



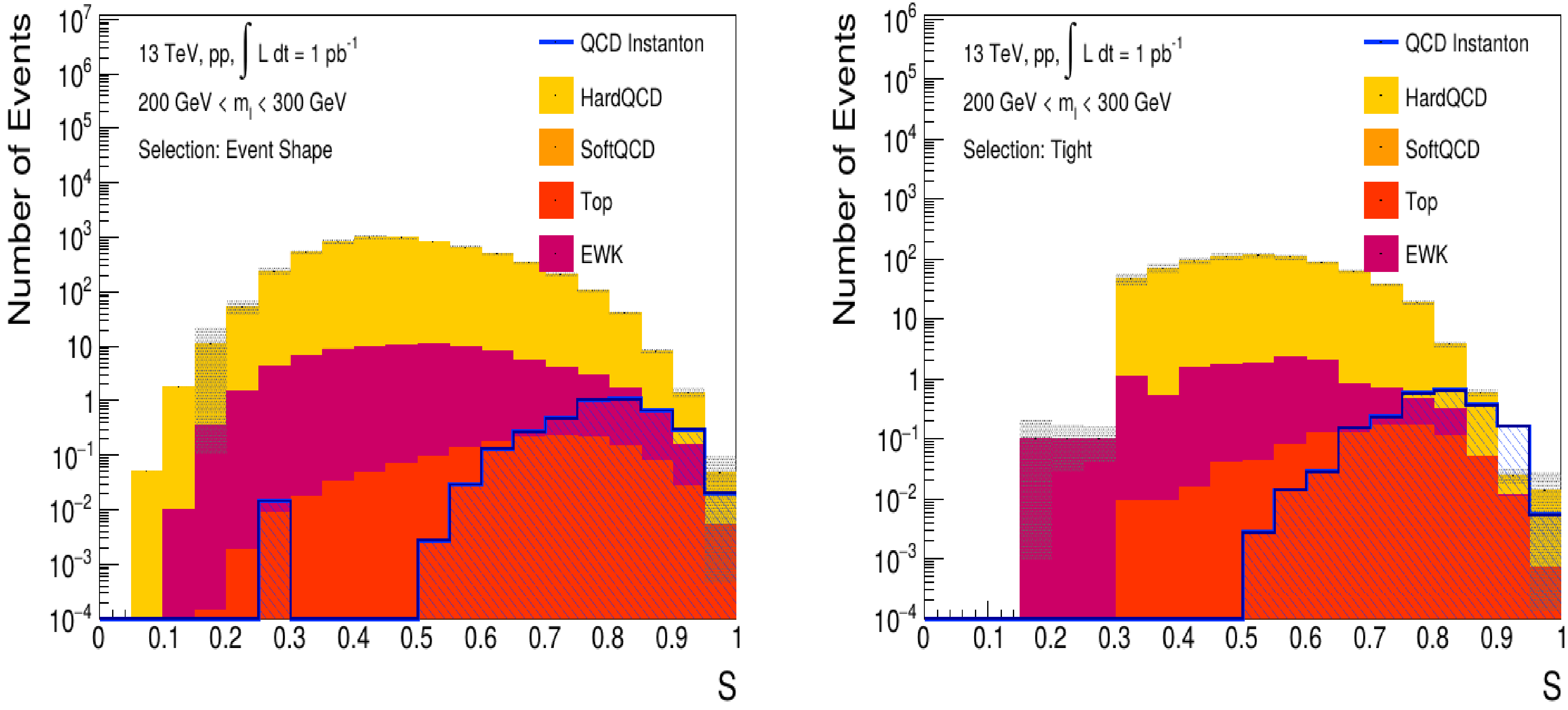
The diagrams giving rise to SSA in SIDIS. The symbol I denotes the instanton

QCD Instanton flips the quark spin !

THANK YOU



S. Amoroso, D. Kar, M. Schott 2012.09120



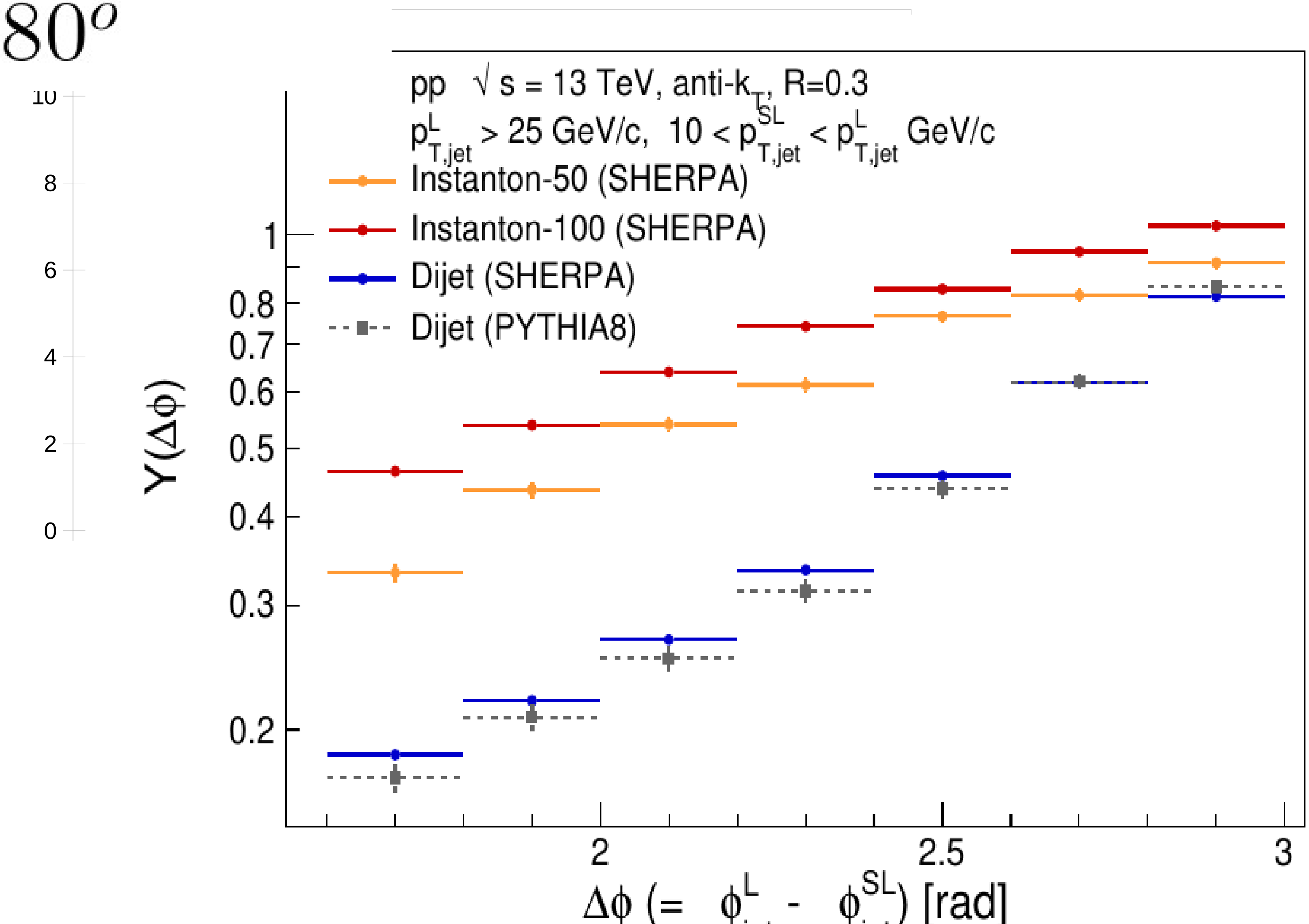
$$N_{displ} > 15$$

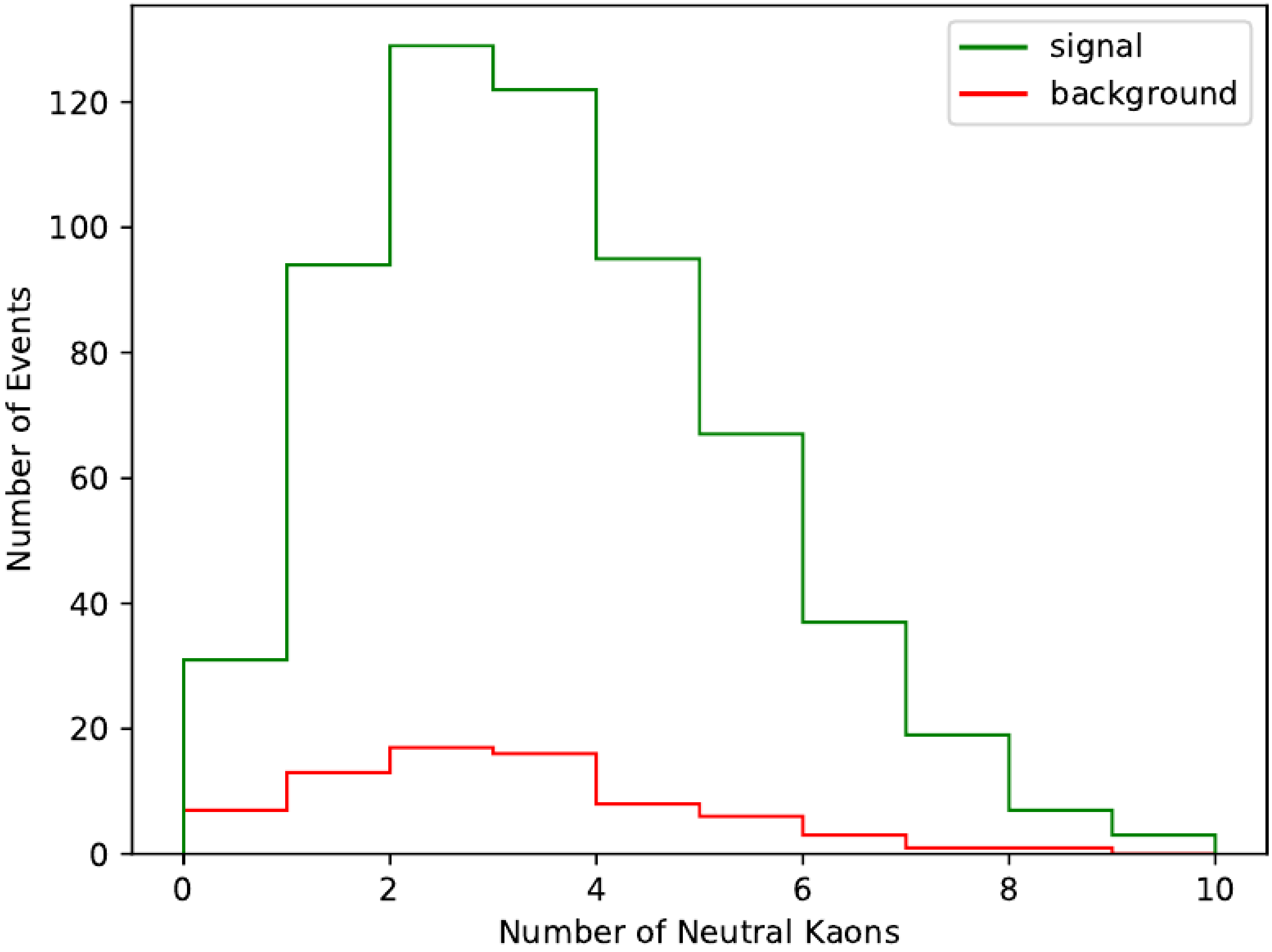
Simone Amoroso[a] Deepak Kar[b] Matthias Schott **2012.09120**

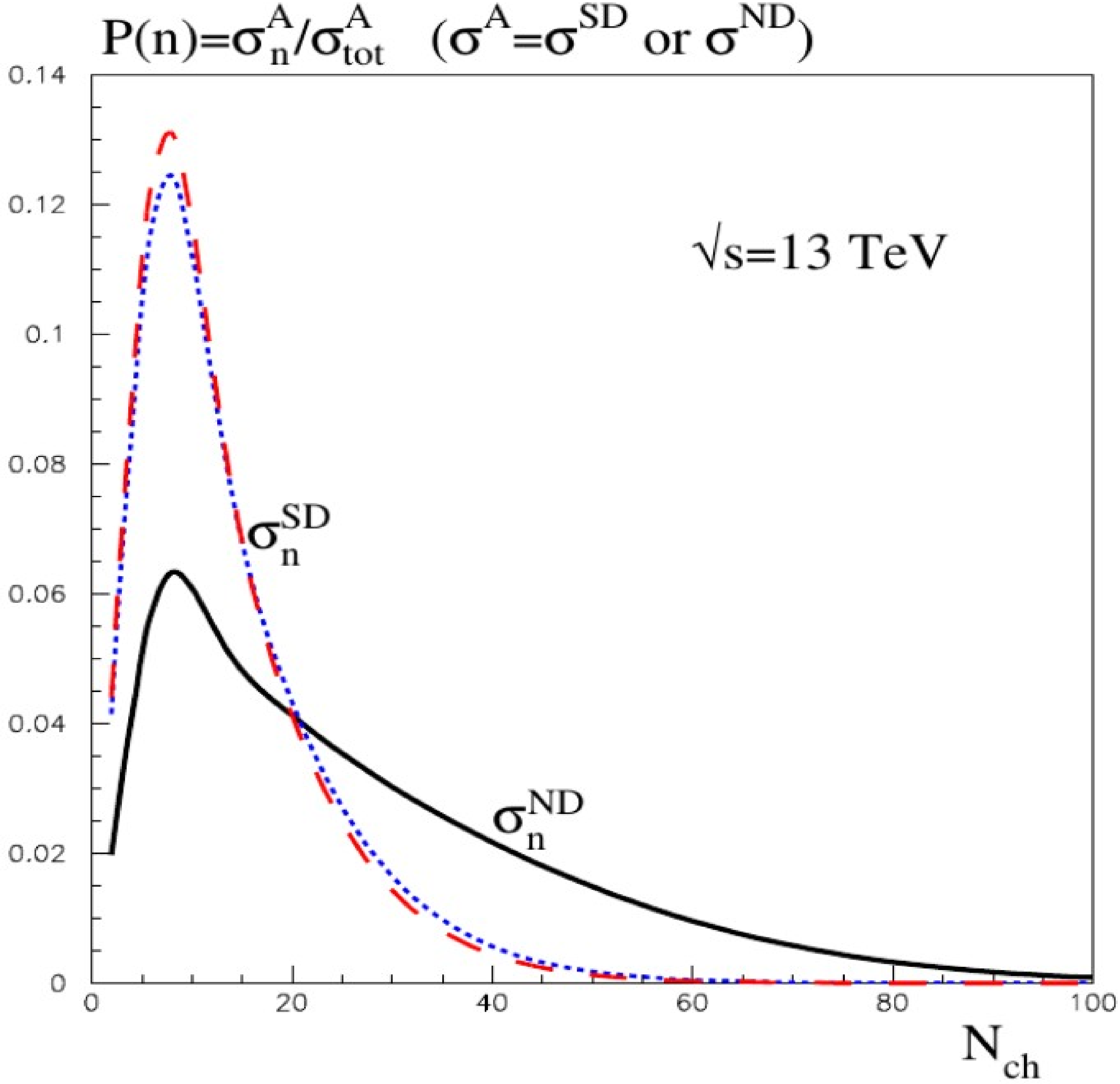
Sayak Guina, Swagatam Taha, Nihar Ranjan Sahooc, Sayantan Sharmaa, arXiv: 2604.20780

Not back-to-back

$\Delta\phi < 180^o$




signal
background
Number of Events
0
20
40
60
80
100
120
0
2
4
6
8
10
Number of Neutral Kaons



$P(n)=\sigma_n^A/\sigma_{tot}^A \quad (\sigma^A=\sigma^{SD} \text{ or } \sigma^{ND})$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
$\sqrt{s}$=13 TeV
σ_n^{SD}
σ_n^{ND}
N_{ch}

The statistical weight of size-ρ instanton is

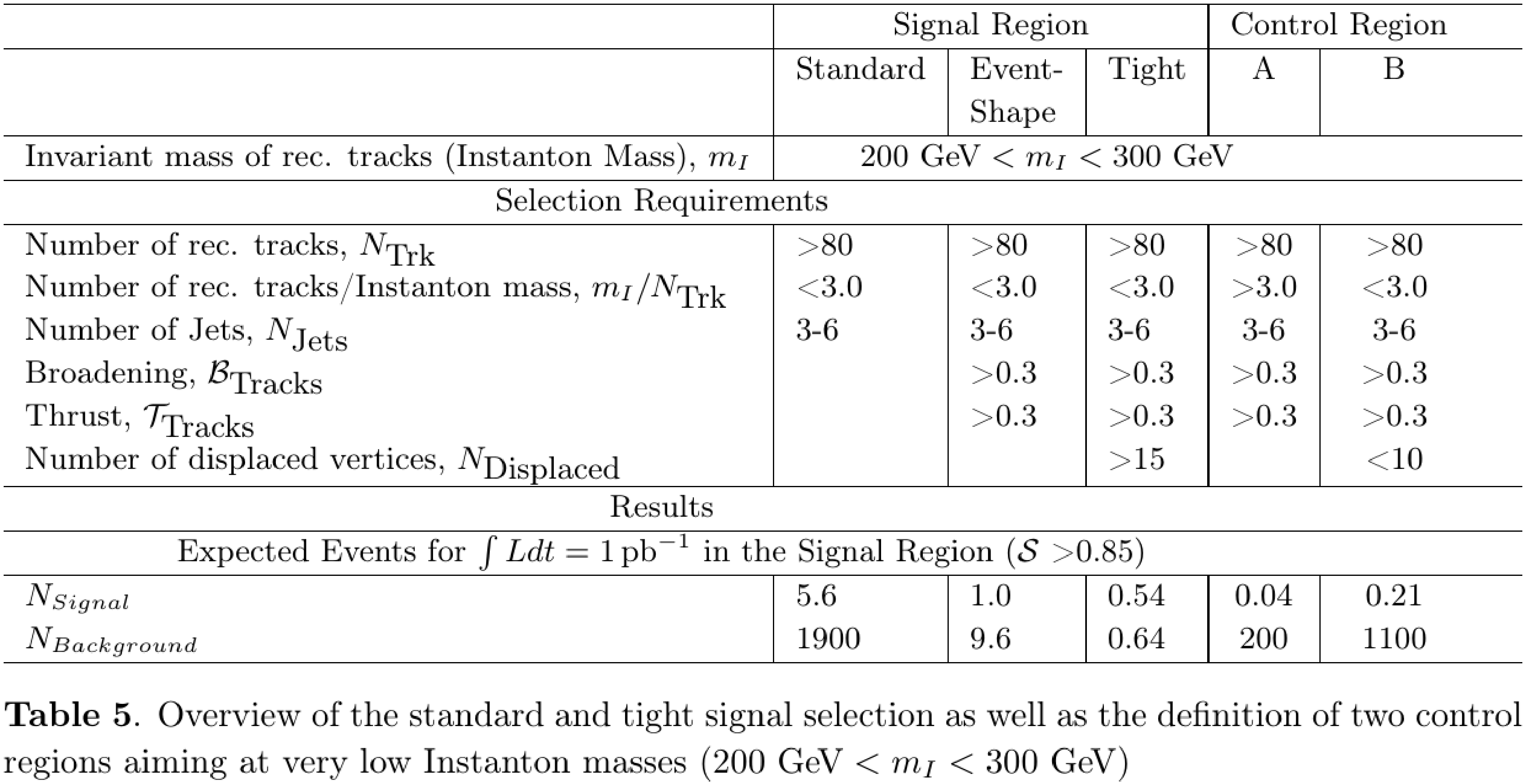
$$D(\rho,\mu_R)=\frac{\kappa}{\rho^5}\left(\frac{2\pi}{\alpha_s(\mu_R)}\right)^6(\rho\mu_R)^{b_0}$$

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

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

	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 $\int L dt = 1\,\text{pb}^{-1}$ 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 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, $\mathcal{B}_{\mathrm{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Thrust, $\mathcal{T}_{\mathrm{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Number of displaced vertices, $N_{\mathrm{Displaced}}$			>15		<10
Results					
Expected Events for $\int Ldt = 1\,\mathrm{pb}^{-1}$ 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 GeV $< m_I <$ 300 GeV)

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