

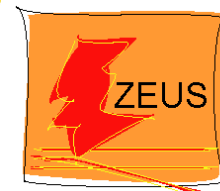
# Searches for QCD Instantons at HERA and EW Sphaleron Limits at LHC

Achim Geiser, DESY

Workshop on Topological Effects in the Standard Model, 18.12.2020



[Achim.Geiser@desy.de](mailto:Achim.Geiser@desy.de) member of



- Reminder: Why should we search for sphalerons/instantons?
- Experimental sphaleron searches at LHC
- Experimental instanton searches at HERA, old and new
- Some personal remarks
- Conclusions

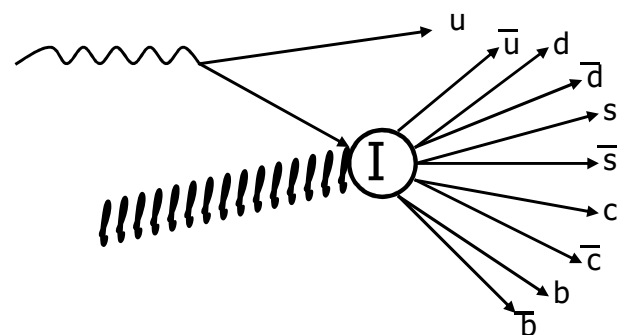
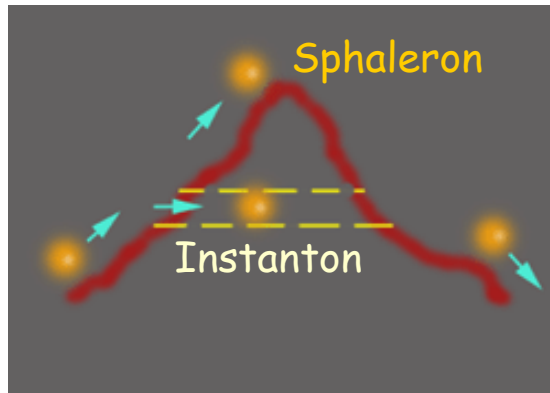
(also separate contribution to discussion session)

# Contribution to the antimatter puzzle from HERA and LHC?

- CP violation measured so far in SM not strong enough to explain matter-antimatter asymmetry
- way out: CP violation in neutrino oscillations and/or strong lepton number asymmetry in early universe.
- Standard Model predicts baryon and lepton number violation through so-called EW sphaleron process:  
converts e.g. 3 leptons into 3 baryons!
- rare process at very high energy -> not observed so far  
**search for them at LHC!**
- related process: QCD instantons
- **in principle observable at HERA!**

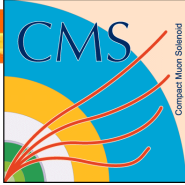
see  
also  
talks  
Khoze &  
Plätzer

see  
also  
talk  
Ringwald

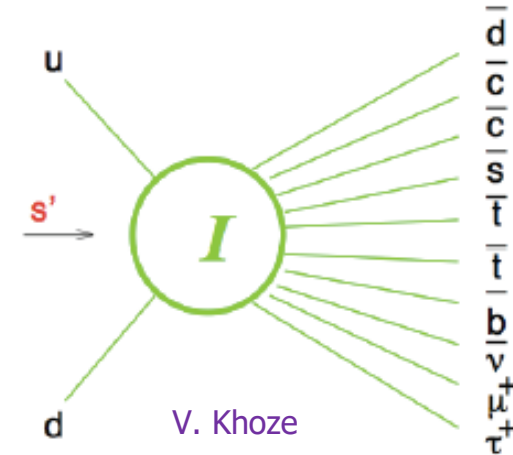


# Search for sphalerons in high multiplicity final states

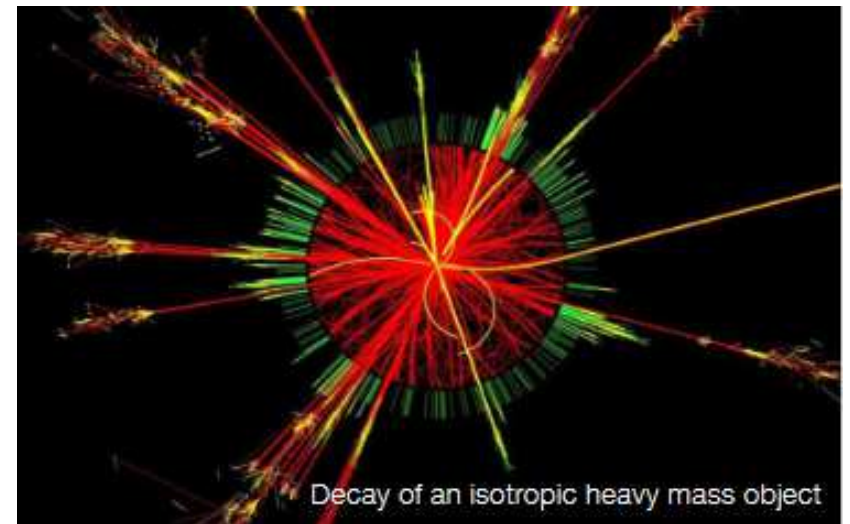
CMS, arXiv:1805.06013, JHEP



- Collect events with  $N$  objects above a given  $p_T$  threshold:  
jets, electrons, muons, and photons



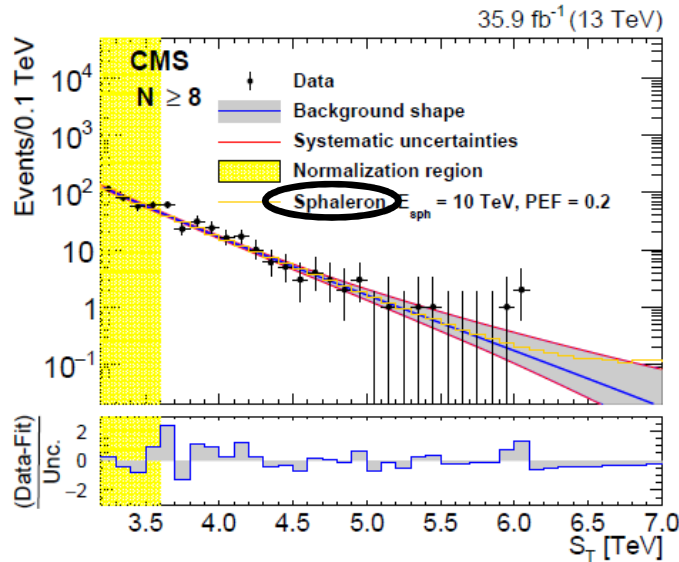
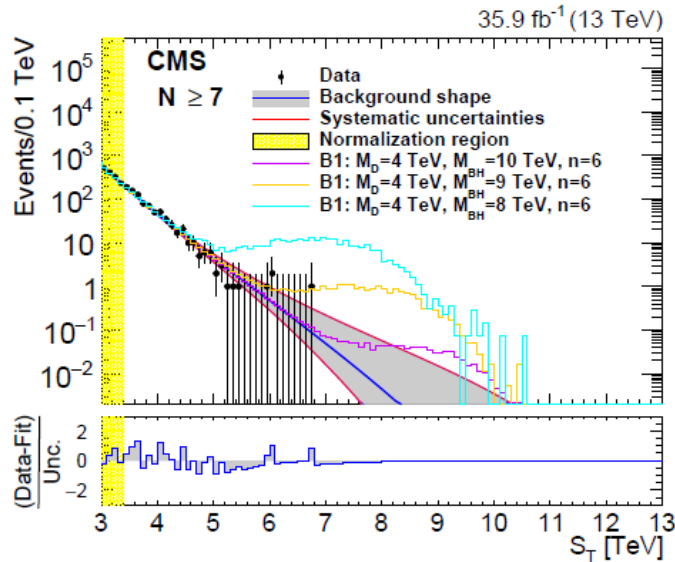
- Build
$$S_T = p_T^{\text{miss}} + \sum_{i=1}^N p_T^i$$
- Sphaleron: expect  $N+1 \geq 10, 11$  or  $12$   
 $S_T \sim 9 \text{ TeV}$



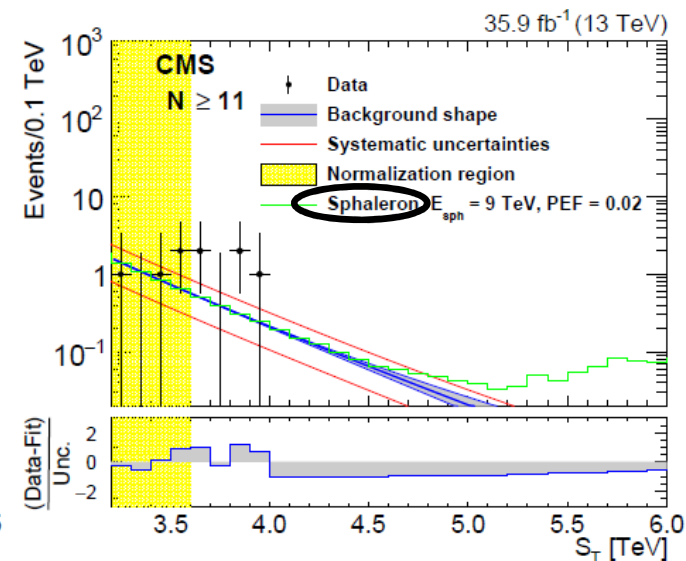
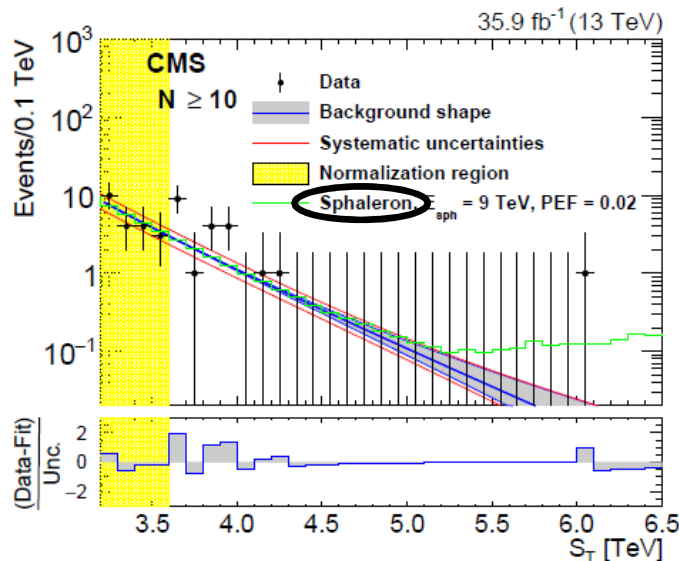
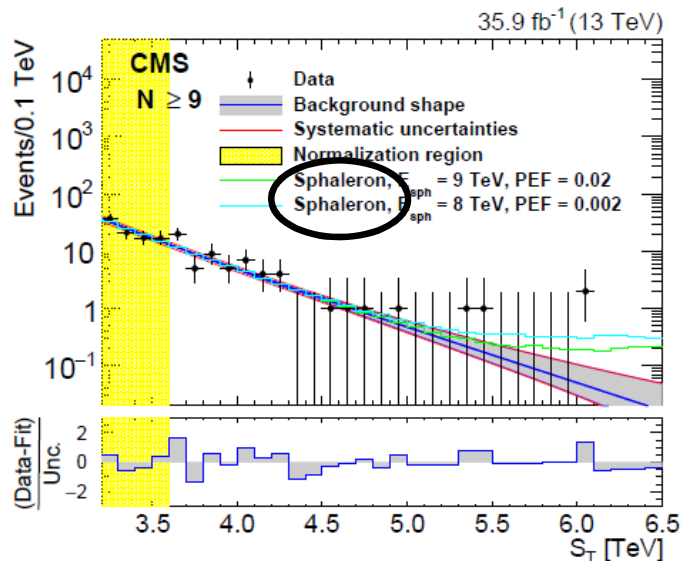
# Search for sphalerons in high multiplicity final states

arXiv:1805.06013, JHEP

see also Black Hole search, 2015 data, 2.3 fb<sup>-1</sup> arXiv:1705.01403, PLB



convert  
to limit



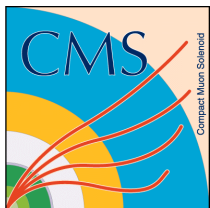
18.12.2020

Instantons at HERA, sphalerons at LHC



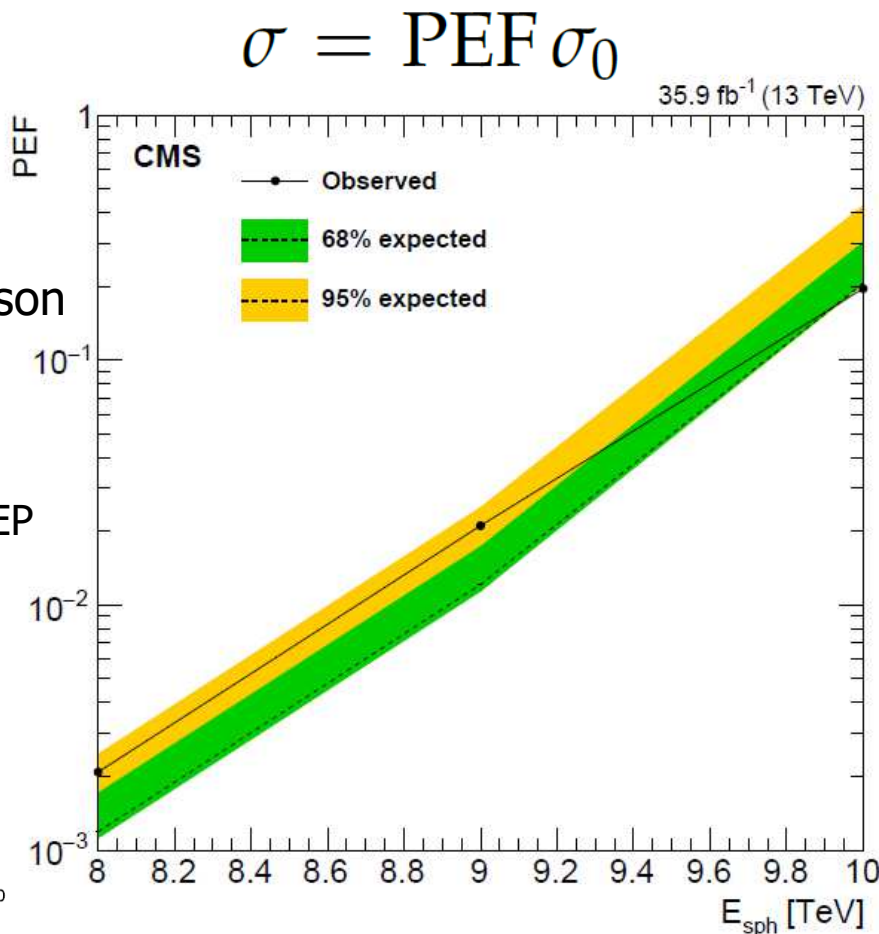
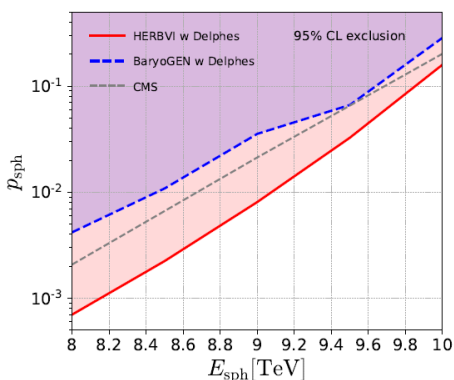
# Limit on EW sphaleron production

arXiv:1805.06013, JHEP



see also talk S. Sakurai

Recast for multi-boson  
final states  
Ringwald, Sakurai,  
Webber,  
arXiv:1809.10833, JHEP



sensitivity  
will increase  
by factor 6  
13 TeV  $\rightarrow$  14 TeV

Ellis, Sakurai,  
arXiv:1601.03654, JHEP  
(recast of BH search  
ATLAS 2015  
data, 3 fb $^{-1}$ ,  
arXiv:1512.01530, PLB)



Figure 12: Observed (solid curve) and expected (dashed black curve) 95% CL upper limit on the pre-exponential factor  $PEF$  of the sphaleron production as a function of  $E_{sph}$ . The inner (outer) band represents the  $\pm 1$  ( $\pm 2$ ) standard deviation uncertainty in the expected limit. The area above the solid curve is excluded by this search.

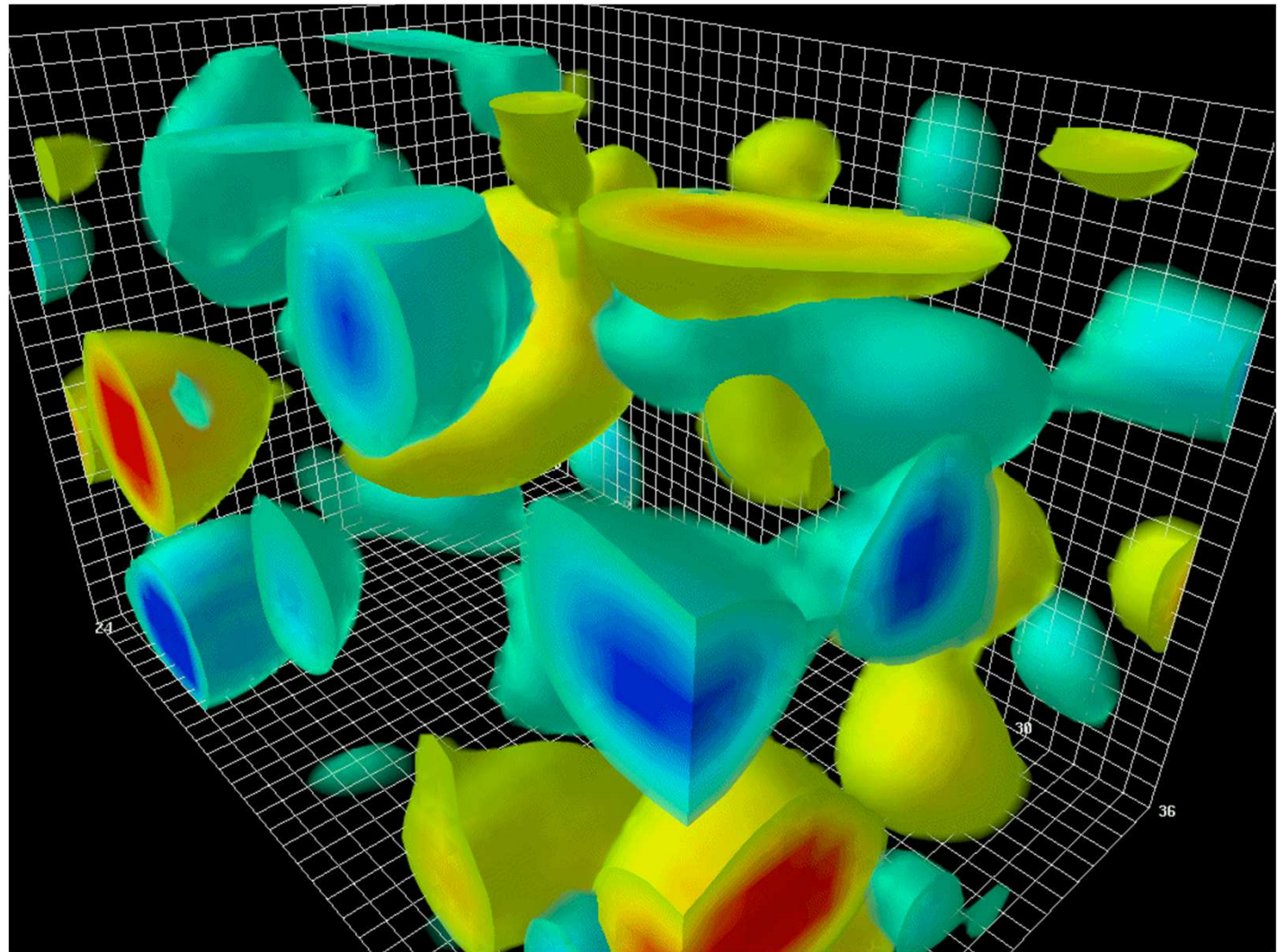
# Topological charge fluctuations (instantons) on the lattice

Derek B. Leinweber, <http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/>

QCD  
vacuum,

$\sim 3 \text{ fm}^3$

In lattice QCD,  
instantons are  
ubiquitous!



# Why/how to look for QCD instantons in ep collisions at HERA?

- **Chirality** (all left or all right)  
... difficult to access experimentally

- **Flavour democracy !?**

- **2 flavours:** pion propagation through instanton-antiinstanton hopping

$$u_L + \bar{d}_L \rightarrow u_R + \bar{d}_R \rightarrow u_L + \bar{d}_L \rightarrow \dots$$

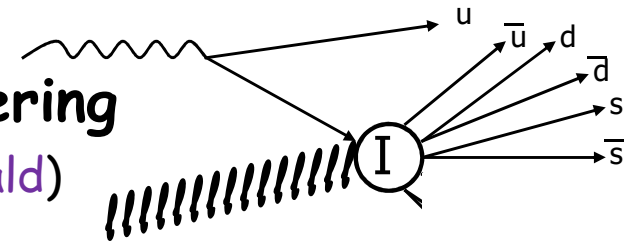
-> calculate pion mass on lattice

relates pion and proton masses  
-> understand mass of  
visible part of the universe

- **3 flavours:**

## light instantons in Deep Inelastic Scattering

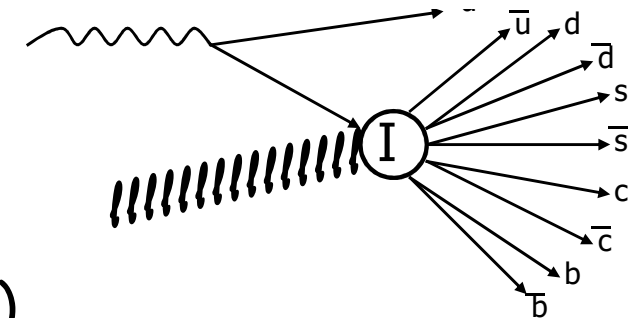
(DIS needed to provide virtuality, [see talk A. Ringwald](#))



- **4 or 5 flavours:** "new"

## "heavy" instantons in photoproduction

(minimum virtuality provided by heavy quarks)



- up to **6 flavours?**: LHC (see next talk)



## QCD-Instanton Induced Processes in DIS at HERA

see also presentation A Ringwald

### Event generator **QCDINS 2.0:**

[Gibbs,AR,F.Schrempp '95; AR,F.Schrempp '00]

- **Hard subprocess:**

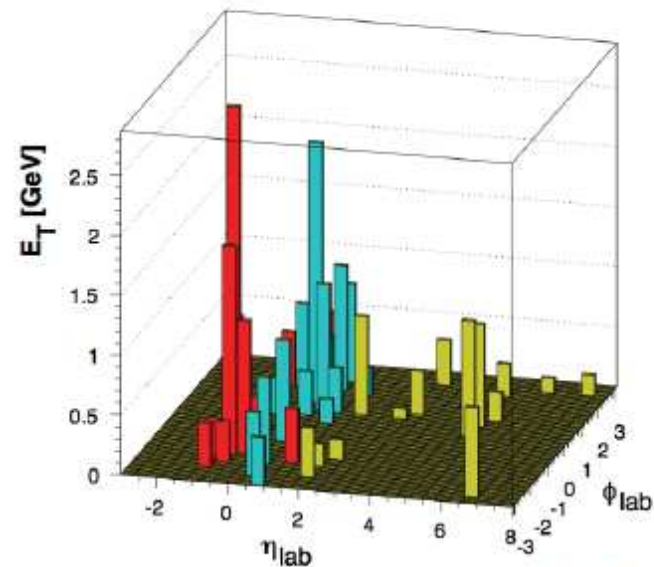
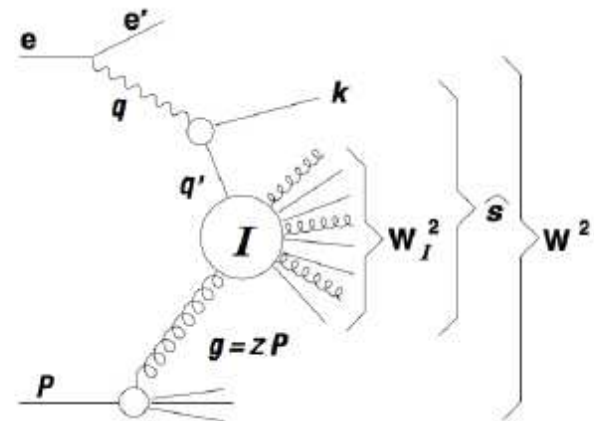
- isotropic in  $q'g$  CM
- flavour democratic
- large parton multiplicity

$$\langle n_q + n_g \rangle = 2 n_f - 1 + \mathcal{O}(1)/\alpha_s \gtrsim 8,$$

- **Parton shower (HERWIG)**

- **Hadronization (HERWIG or JET-SET)**

**QCDINS default:  $N_f=3$**



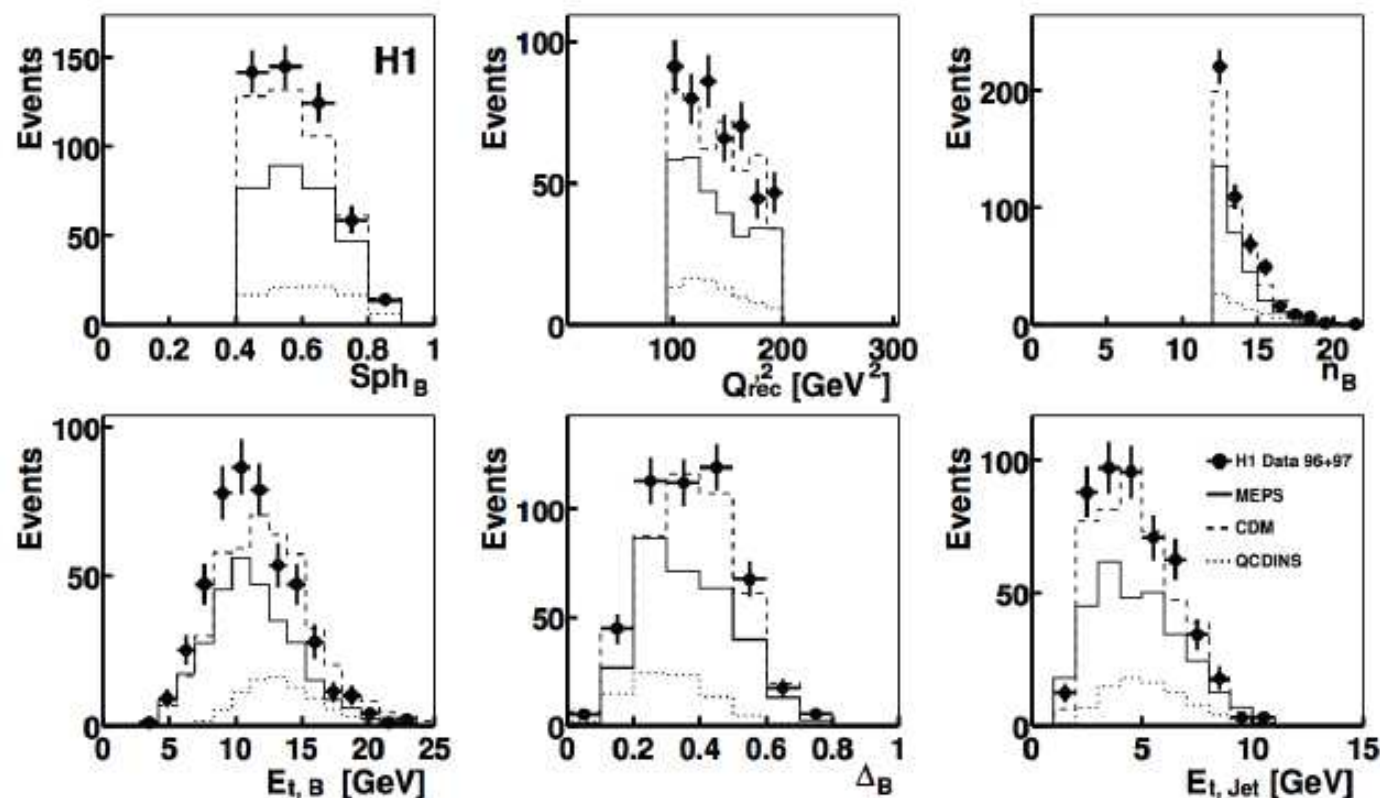


# QCD-Instanton Induced Processes in DIS at HERA



[H1, hep-ph/0205078](#), EPJ C 2002

- > Instanton-enriched samples by cuts on discriminating observables
- > Large uncertainties in predictions of standard DIS processes



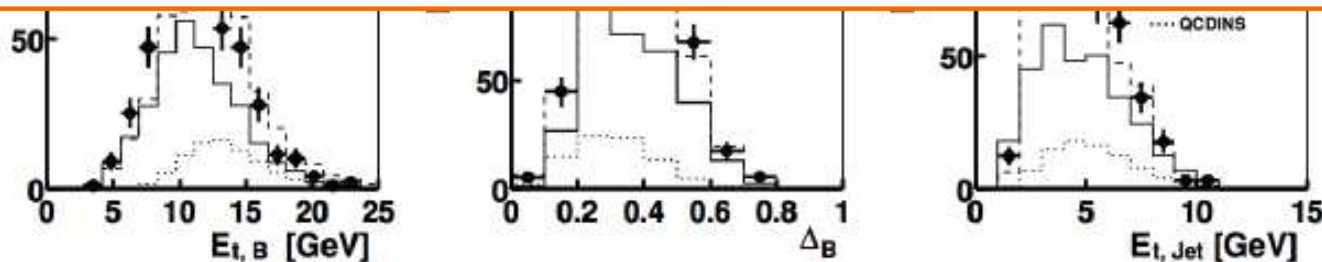
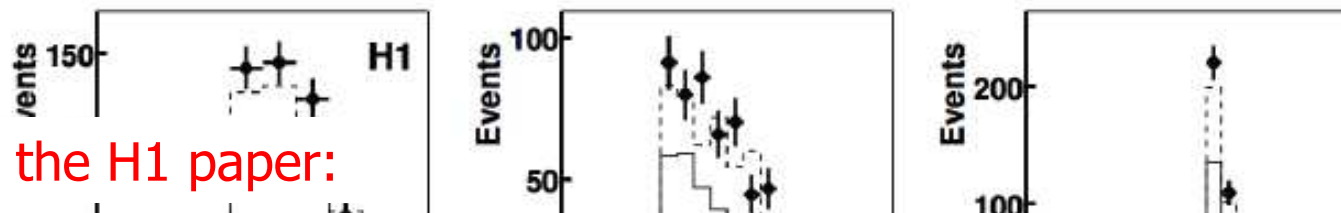
[H1 '02]



- > Instanton-enriched samples by cuts on discriminating observables
- > Large uncertainties in predictions of standard DIS processes

Quote from the H1 paper:

As said before, it is questionable whether the CDM and MEPS models are able to adequately describe the standard DIS background in this extreme corner of phase space, where only  $\sim 0.1\%$  of the events in the total sample of standard DIS events are expected. To be independent of the detailed modelling of the hadronic final state of DIS events, an additional upper limit is extracted where the expected standard DIS background is assumed to be zero. in the signal region



[H1 '02]

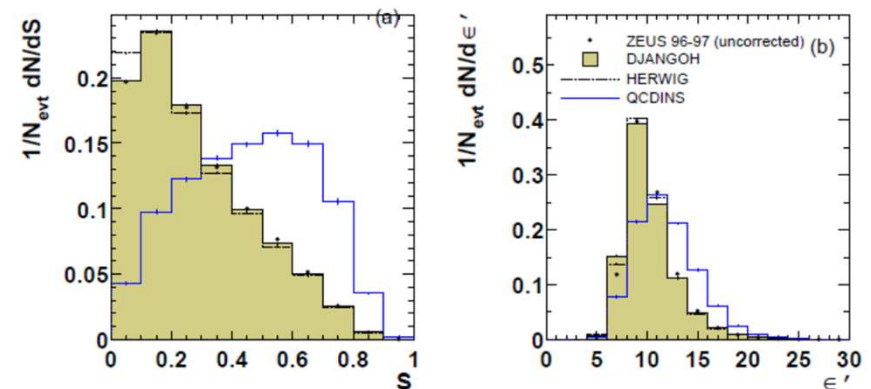
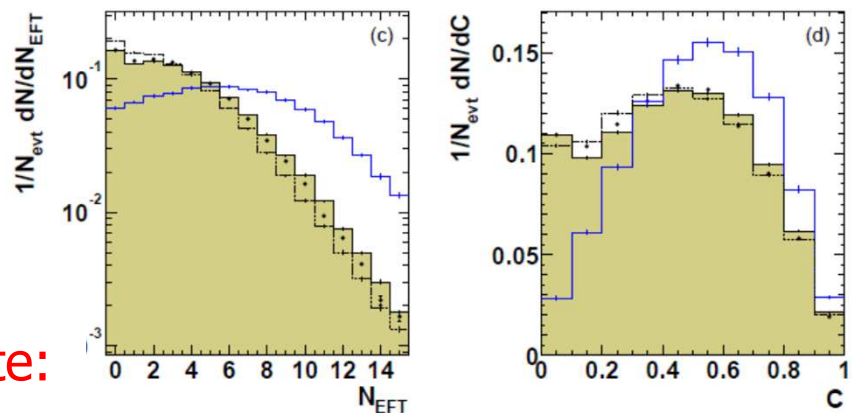
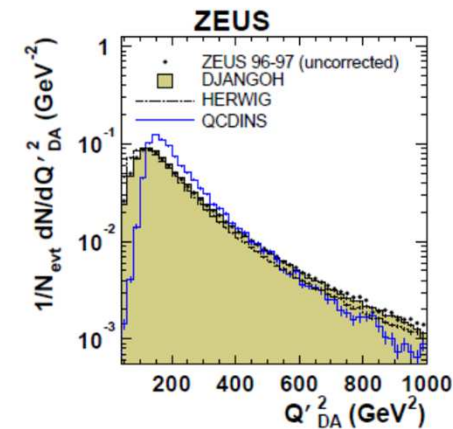
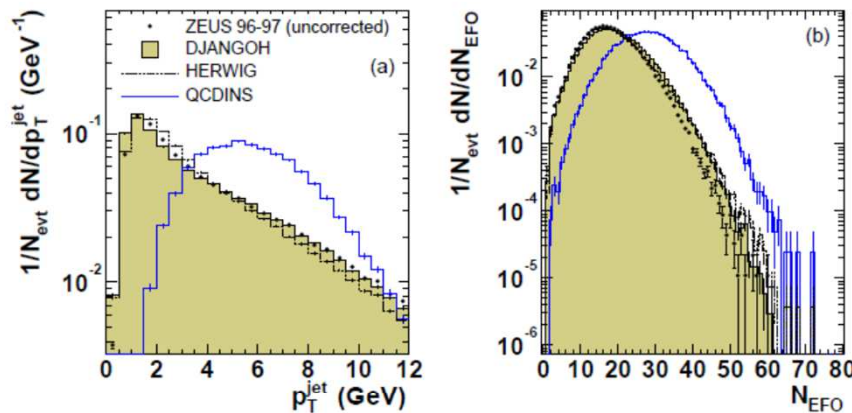
# QCD-Instanton Induced Processes in DIS at HERA



[ZEUS, hep-ex/0312048](#), EPJ C 2003

- Instanton-enriched samples by cuts on discriminating observables
- Large uncertainties in predictions of standard DIS processes

ZEUS



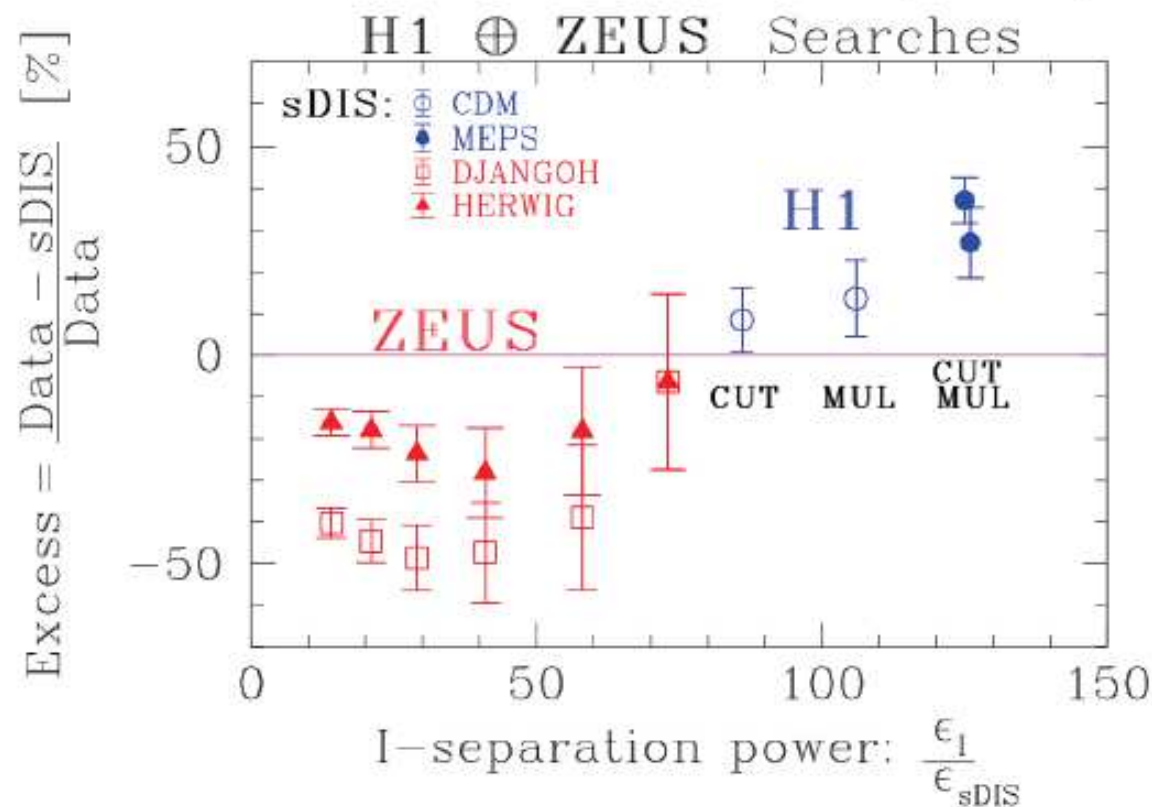
Quote:

Assuming that all data events belong to an instanton signal, a conservative background-independent upper limit on the instanton cross section of 26 pb at a 95% c.l. has been set, to be compared to the theoretically predicted cross section of 8.9 pb.



# QCD-Instanton Induced Processes in DIS at HERA

- > Instanton-enriched samples by cuts on discriminating observables
- > Large uncertainties in predictions of standard DIS processes
- > H1/ZEUS “excess” increases with separation power (ratio of efficiencies)



interpretation  
is strongly  
model dependent!

[F. Schrempp '04]





# QCD instantons at HERA II



H1, arXiv:1603.05567, EPJ C (2016)

instanton  
sensitive  
variables,  
  
build  
discriminant

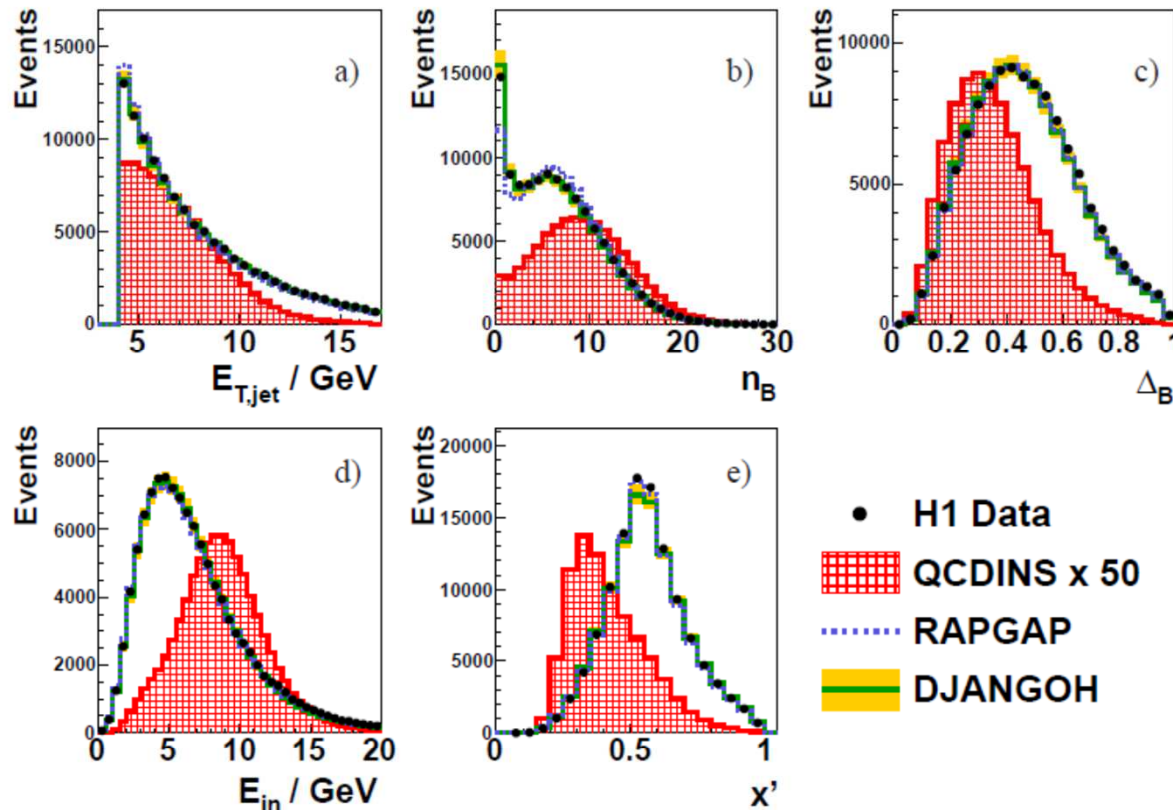
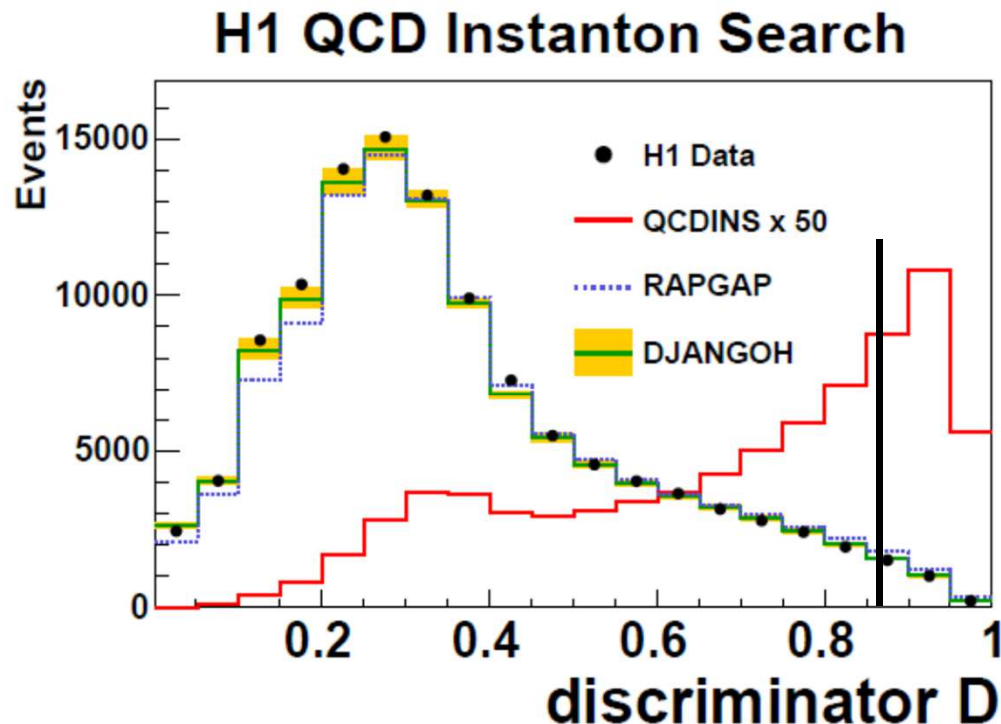


Figure 3: Distributions of the observables used in the multivariate analysis: (a) the transverse current jet energy  $E_{T,jet}$ , (b) the charged particle multiplicity in the instanton band  $n_B$ , (c) and (d) two variables measuring the azimuthal isotropy of the event,  $\Delta_B$  and  $E_{in}$ , respectively, and (e) the reconstructed instanton kinematic variable  $x'$ . Data (filled circles), the RAPGAP and DJANGO sDIS background predictions (dotted and solid lines) and the QCDINS signal prediction scaled up by a factor of 50 (hatched), are shown. The error band, shown only for DJANGO, represents the MC statistical and systematic uncertainties added in quadrature.

# "light" instantons at HERA II



arXiv:1603.05567, EPJ C (2016)



limits are  
calculated  
using the full  
range of the  
discriminator  
distribution

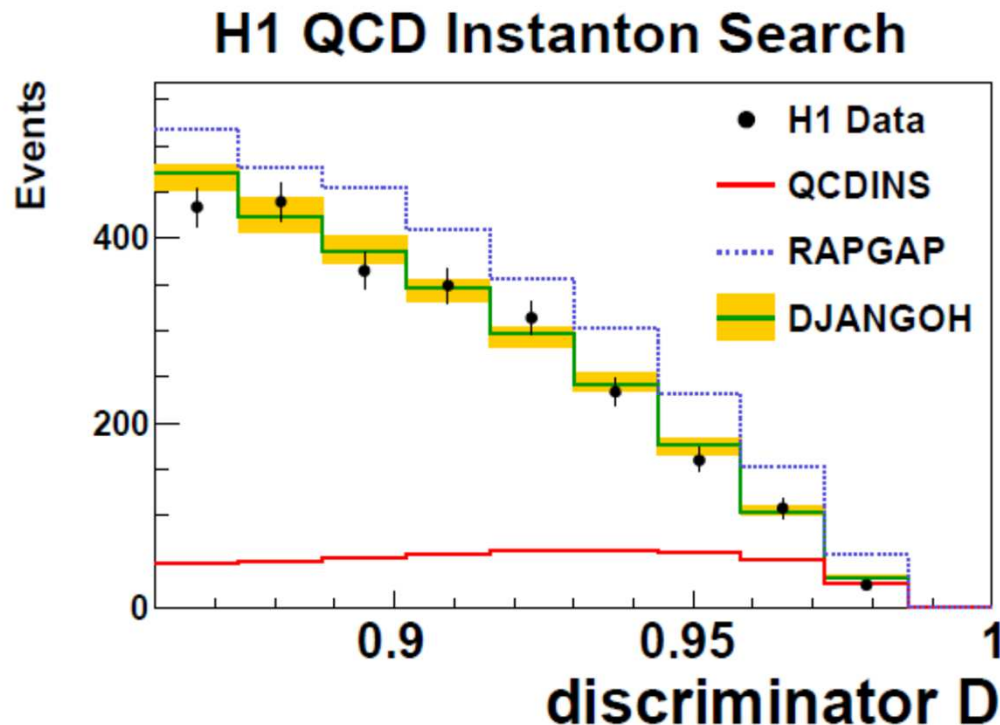
Figure 4: Distribution of the discriminator  $D$ . Data (filled circles), the RAPGAP and DJANGO sDIS background predictions (dotted and solid lines) and the QCDINS signal prediction scaled up by a factor of 50 (red line) are shown. The error band, shown only for DJANGO, represents the MC statistical and systematic uncertainties added in quadrature.

- The difference between the prediction from DJANGO and RAPGAP is assigned as model uncertainty of the background estimation, i.e. the difference between two background histograms in figure 4. This model uncertainty is large, 8 – 20% and 13 – 46%, for small  $D < 0.2$  and large  $D > 0.85$  values of the discriminator, respectively. For intermediate values of  $D$  it amounts to 0.3 – 8%.

# "light" instantons at HERA II



arXiv:1603.05567, EPJ C (2016)



"signal  
region"  
only

Figure 5: Distribution of the discriminator  $D$  in the signal region  $D > 0.86$ . Data (filled circles), the RAPGAP and DJANGO sDIS background predictions (dotted and solid lines) and the QCDINS signal prediction (red line) are shown. The error band, shown only for DJANGO, represents the MC statistical and systematic uncertainties added in quadrature.

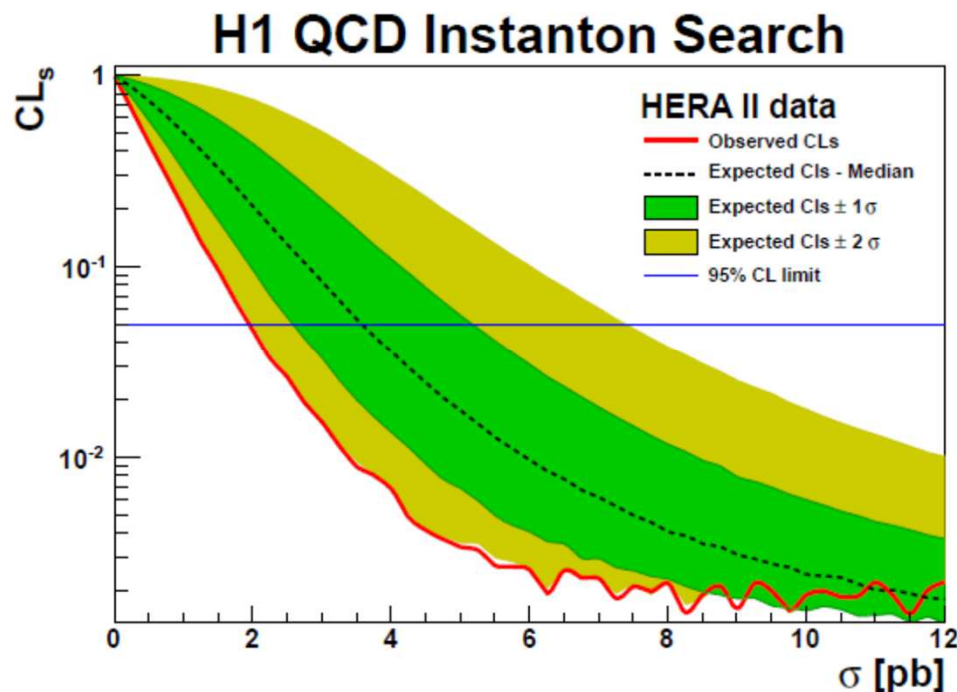
A signal region is defined for  $D > D_{cut} = 0.86$ , optimised for a determination of the instanton signal from event counting. The distributions of the expected instanton signal and of the background are shown in figure 5. No excess of events is observed and the DJANGO MC describes the data well, while the prediction of RAPGAP is systematically above the data.



# "light" instantons at HERA II



arXiv:1603.05567, EPJ C (2016)



convert  
to limit

Figure 7: Observed  $CL_s$  (solid line) as a function of the instanton cross section. The 95% CL limit is indicated by a horizontal line. The dark and light bands correspond to  $\pm 1\sigma$  and  $\pm 2\sigma$  fluctuations of the expectation (dashed line).

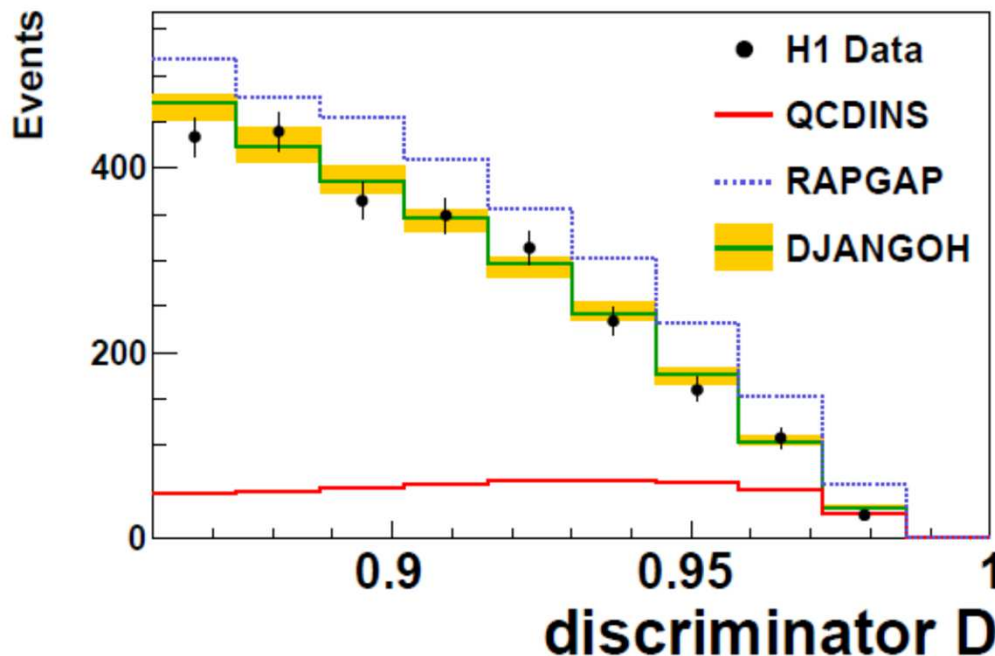
The QCD instanton model implemented in QCDINS, restricted to the kinematic region defined by  $x'_{\min} = 0.35$  and  $Q'^2_{\min} = 113 \text{ GeV}^2$ , predicts a cross section of  $10 \pm 3 \text{ pb}$ , and thus is excluded by the H1 data. Note that the cross section uncertainty of 30%, stemming from the variation of  $\Lambda_{\overline{MS}}^{(3)}$ , is already included in the observed limit of 2 pb.



# personal "recast" considerations

not a statement by any collaboration

## H1 QCD Instanton Search



MC: many "nonperturbative" parameters tuned to data including QCD instantons. (at low scales they are always there: see QCD lattice predictions)

for  $D > 0.86$ :

$$\text{RAPGAP} - \text{DJANGO} = \text{QCDINS!}$$

personal bet (obviously not yet a scientific statement): might be possible to retune "RAPGAP-like" MC with same size but opposite sign deviation from DJANGO (and data) such that QCDINS gives perfect fit.

-> H1 limit, while correct within the assumptions stated, might be strongly model dependent  
-> QCDINS prediction might not be excluded

# "Heavy flavour" instantons at HERA II

N. Stefaniuk, DESY-THESIS-2017-038 Appendix D, using ZEUS data

With the support of F. Schrempp, modified QCDINS to work for  $N_F=5$  also in photoproduction

(Diplom thesis D. Bot, DESY-THESIS-2008-014, in German)

photon virtuality  $\rightarrow$  incoming heavy quark virtuality

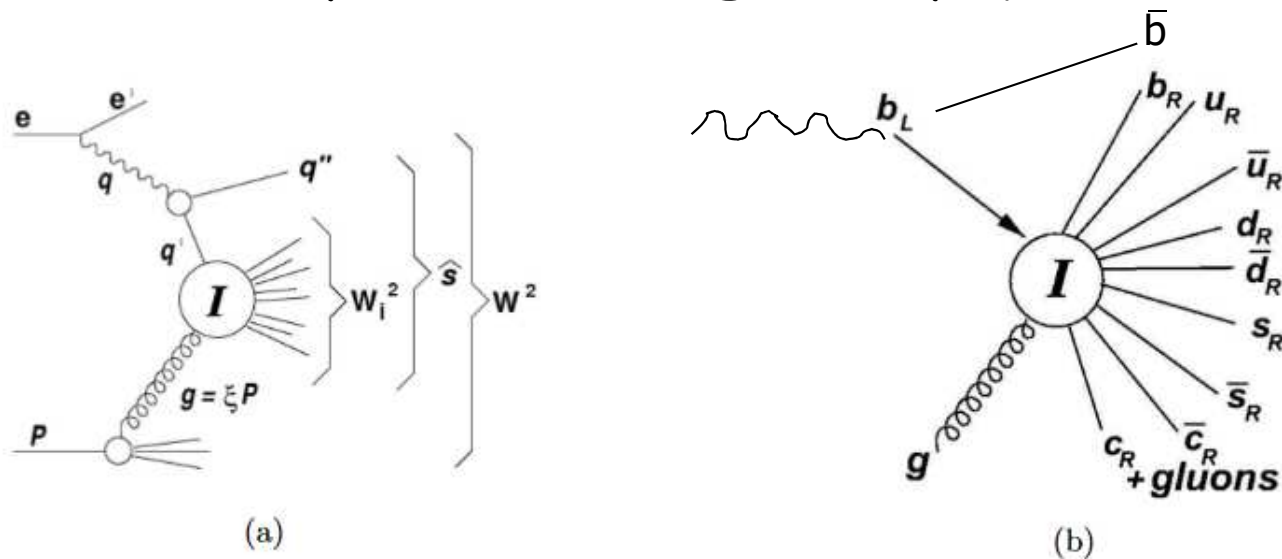


Figure 7.24: QCD instanton-induced events production diagram.

$\rightarrow$  correct kinematics, unknown normalization (mass effects)

"mass unsuppressed"  $N_F=5$  prediction:

16% of total  $b\bar{b}$  cross section  $\rightarrow$  try 8%  $\pm$  8%

# Dimuon mass spectrum, $b\bar{b} \rightarrow \mu\mu + X$

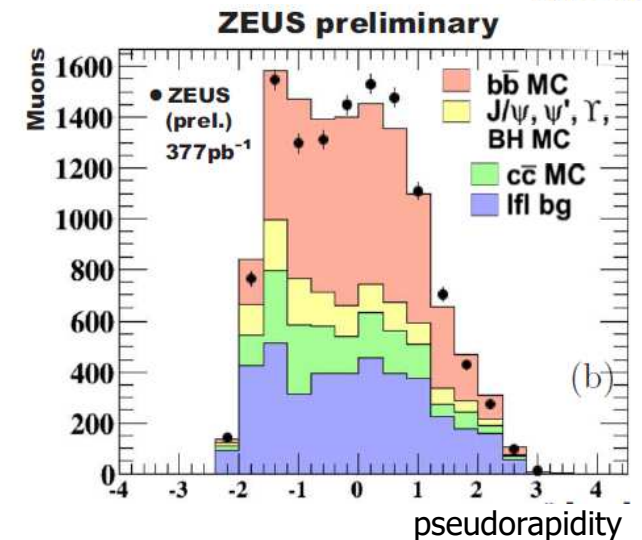
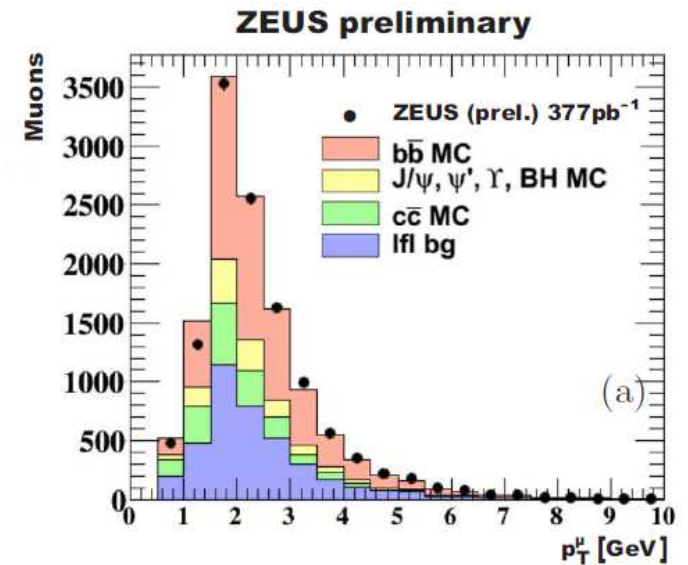
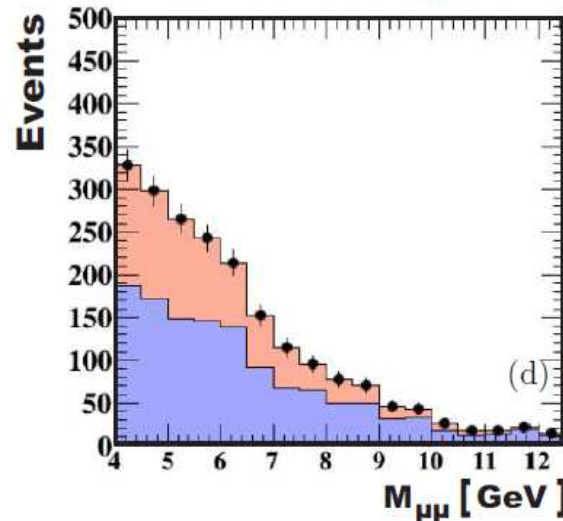
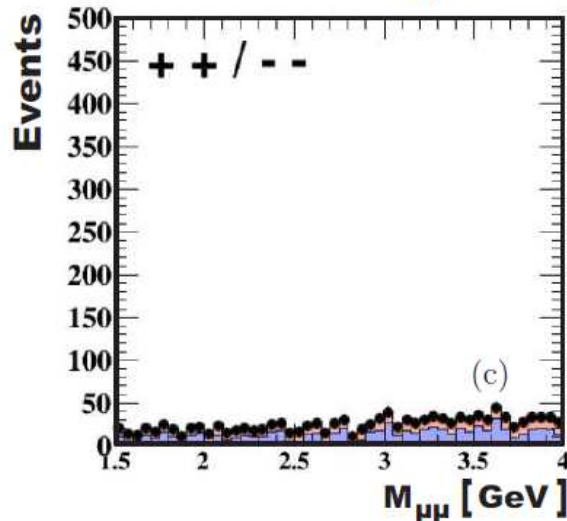
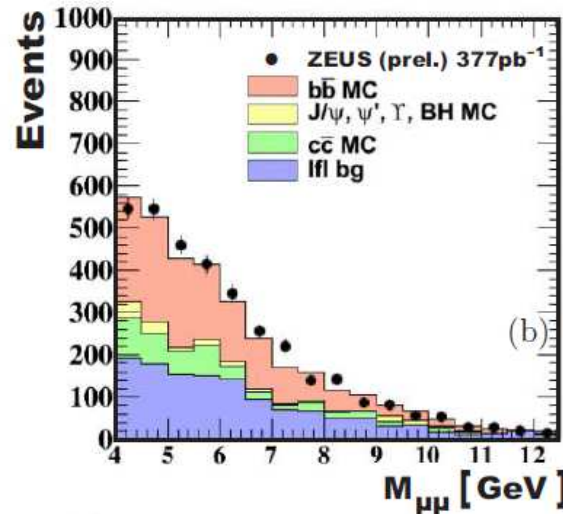
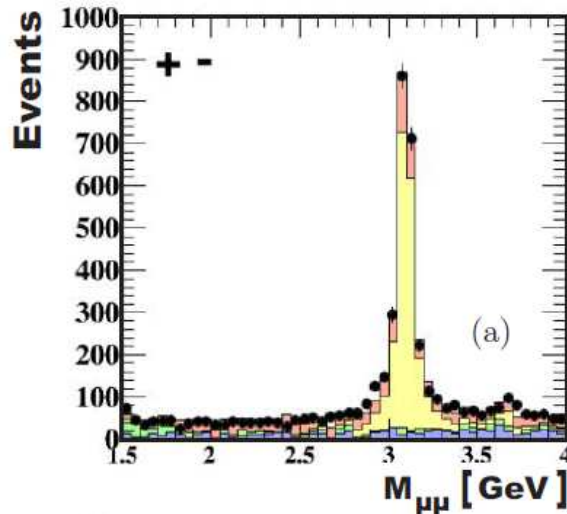


ZEUS-prel-18-006

very similar to HERA I analysis  
JHEP02 (2009) 032

**ZEUS preliminary**

**signal mainly nonisolated:**



# Heavy flavour instantons at HERA II

N. Stefaniuk, DESY-THESIS-2017-038 Appendix D, using ZEUS data

instanton-sensitive variables

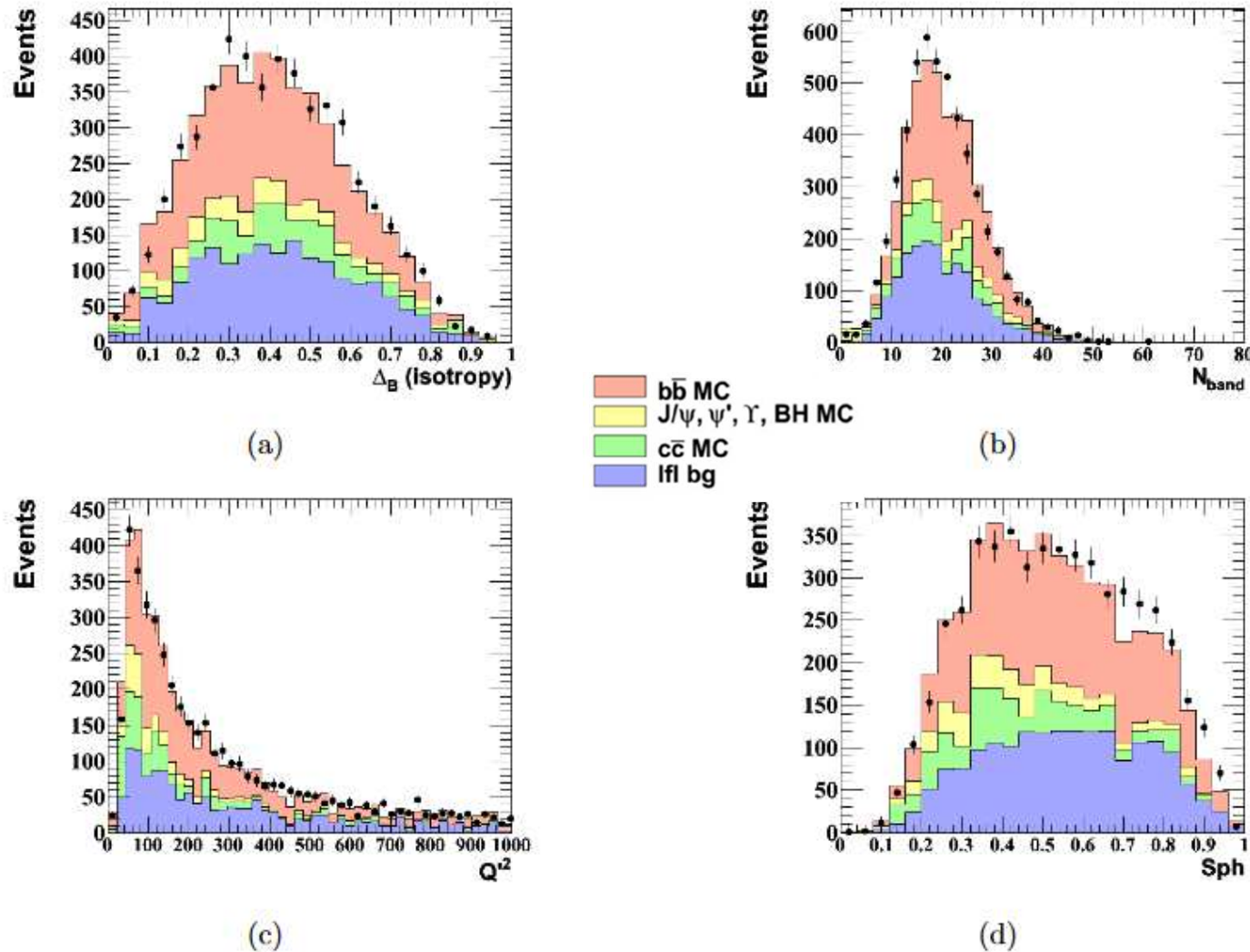
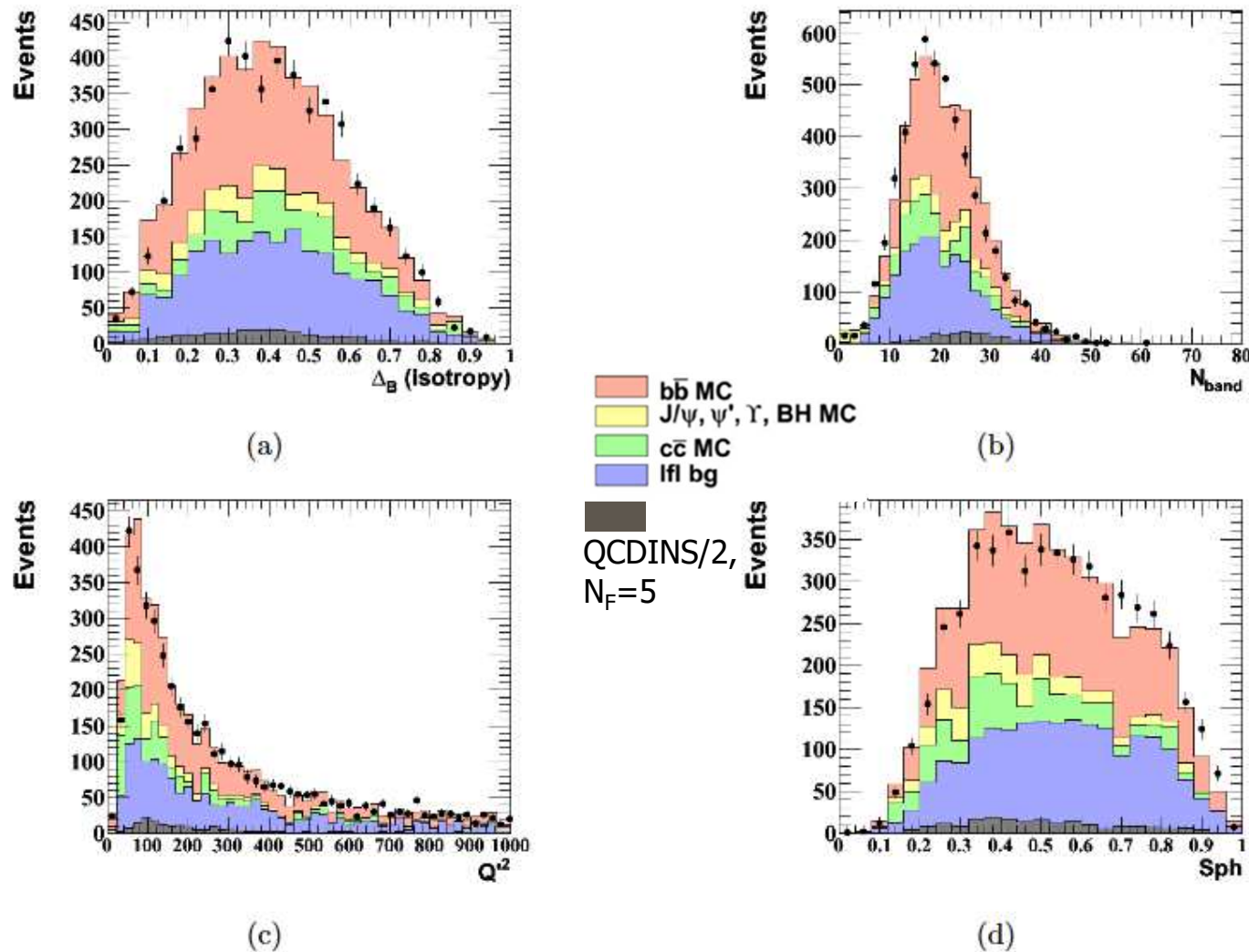


Figure 7.25: The isotropy(a), instanton band(b), quark virtuality(c) and sphericity(d) without instanton events included.



# Heavy flavour instantons at HERA II

N. Stefaniuk, DESY-THESIS-2017-038 Appendix D, using ZEUS data



no improvement  
->

no indication for  
sizeable instanton  
contribution

(qualitative only)

Figure 7.26: The isotropy(a), instanton band(b), quark virtuality(c) and sphericity(d) variables with instanton events included.

# Summary and conclusions

- electroweak sphalerons have not yet been observed  
needs new 100 TeV collider? (sensitivity at 14 TeV will be 6 times larger)  
-> **baryon/lepton number violation?** (within Standard Model !)  
-> **understand baryon number asymmetry in universe?**
- QCD instantons accessible at HERA energies with potentially sizeable cross sections      -> **understand QCD vacuum/visible mass of universe**  
H1 result excludes default QCDINS prediction
- results obtained so far for  $N_F=3$  or  $N_F=5$  not conclusive (in my opinion)  
-> **need to improve sensitivity on both theory and experiment side**
  - > reevaluate theoretical/MC tuning aspects?
  - > go for multiple flavour tagging ? (unfortunately statistics limited)
  - > helicity tagging unfortunately not statistically accessible at HERA  
-> **go for LHC?**      (next talk and discussion session)

# Backup

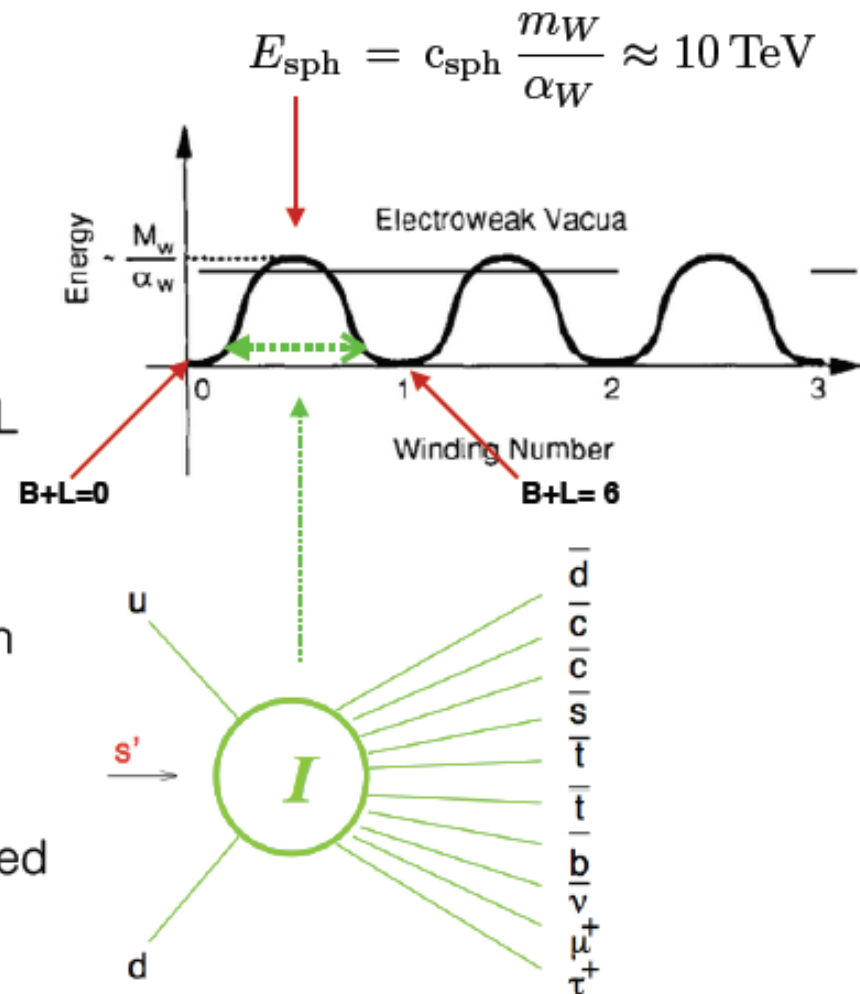




# 1. Baryon + Lepton number violation in the Standard Model

V. Khoze, 2014

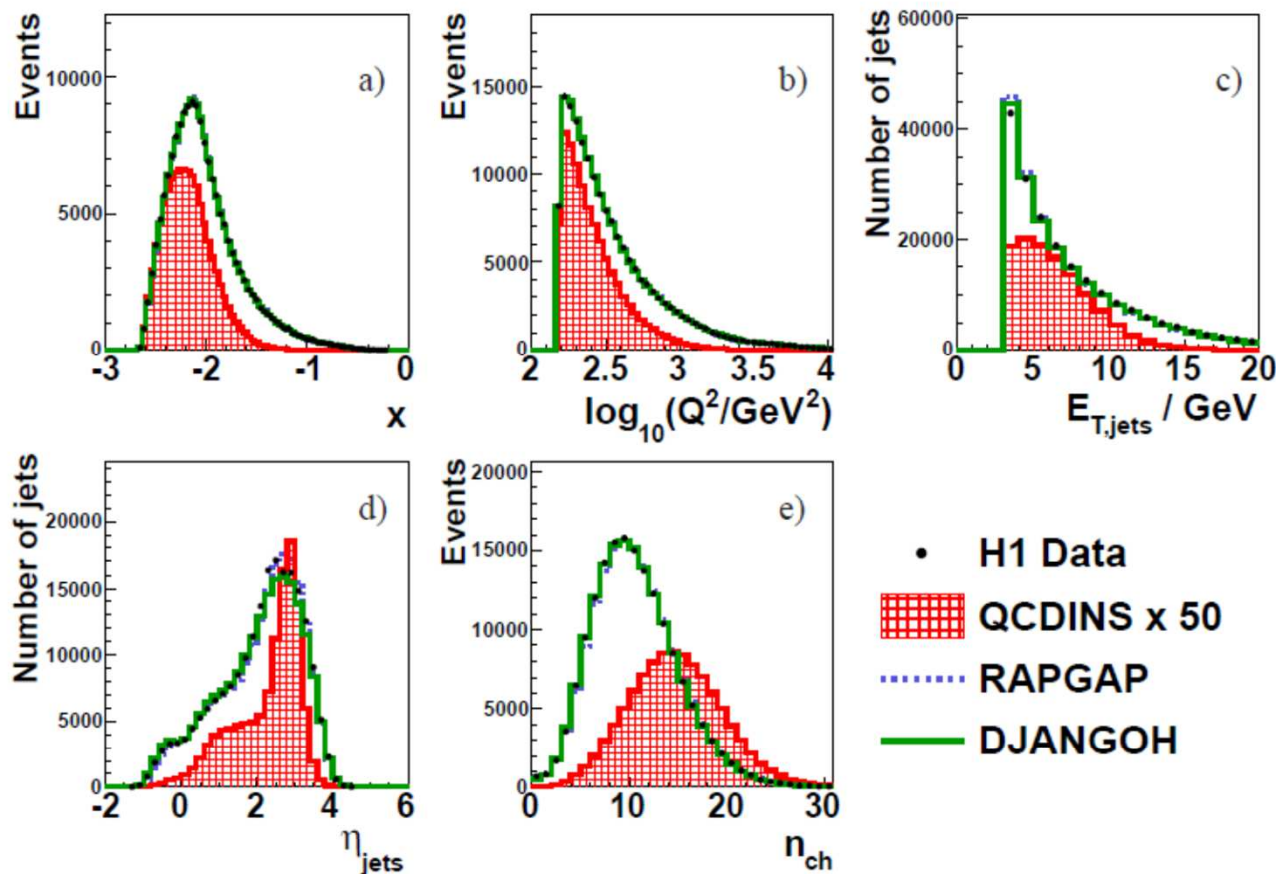
- Electroweak vacuum has a nontrivial structure (!) [SU(2)-sector]
- The saddle-point at the top of the barrier is the *sphaleron*. New EW scale  $\sim 10$  TeV
- Transitions between the vacua change B+L (result of the ABJ anomaly):  
 $\Delta(B+L) = 3 \times (1+1)$ ;  $\Delta(B-L) = 0$
- Instantons* are tunnelling solutions between the vacua. They mediate B+L violation
- $3 \times (1 \text{ lepton} + 3 \text{ quarks}) = 12$  fermions  
 12 left-handed fermion doublets are involved
- There are EW processes which are not described by perturbation theory!



$$q + q \rightarrow 7\bar{q} + 3\bar{l} + n_W W + n_Z Z + n_h H$$

need  $\sqrt{s} \sim 100 \text{ TeV}$  to produce with sizeable rate!

# QCD instantons at HERA II



control  
variables

Figure 2: Distributions of (a) the Bjorken-scaling variable  $x$ , (b) the photon virtuality  $Q^2$ , (c) the inclusive distribution of the transverse energy of the jets  $E_{T,\text{jets}}$ , (d) the pseudorapidity of the jets  $\eta_{\text{jets}}$  and (e) the charged particle multiplicity  $n_{\text{ch}}$ . Data (filled circles), the RAPGAP and DJANGO sDIS background predictions (dotted and solid lines) and the QCDINS signal prediction scaled up by a factor of 50 (hatched) are shown.

# Selection cuts and MC

ZEUS-prel-18-006

## data samples:

- **HERA II, 03-07,  $L \sim 377 \text{ pb}^{-1}$**

## event selection:

- **$\text{CAL } E_T > 8 \text{ GeV}$**  ( $\approx 2 m_b$  - missing neutrinos, proton remnant and DIS e cand. removed)
- cut on muon  $E_T$  fraction ( $0.1 < p_T^{\mu\mu}/E_T < 0.7_{\text{high m}} / 0.5_{\text{low m}}$ )
- $|z_{\text{vtx}}| < 30 \text{ cm}$ ,  $\sqrt{(x_{\text{vtx}}^2 + y_{\text{vtx}}^2)} < 3 \text{ cm}$ , muon  $p_T$  asym.  $< 0.7$ ,  $\Delta\eta^{\mu\mu} < 3$ , anti-cosmic cuts
- 'or' of muon, hadronic charm, and dijet triggers

## muon selection:

- **two muons,  $m^{\mu\mu} > 1.5 \text{ GeV}$**
- **$p_T^\mu > 0.75 \text{ GeV}$**  for high muon quality  $\geq 5$ ,  **$p_T^\mu > 1.5 \text{ GeV}$**  for low muon quality
- simplified for differential cross sections:  **$p_T^\mu > 1.5 \text{ GeV}$**  for both muons

## MC samples:

- **beauty and charm: RAPGAP** ( $Q^2 > 1 \text{ GeV}^2$ ) and **PYTHIA** ( $Q^2 < 1 \text{ GeV}^2$ )
- $J/\psi$ ,  $\psi'$ , Upsilon, Bethe-Heitler, each DIS/ $\gamma p$  from various generators
- $J/\psi$  ( $p_T$ ) and Upsilon ( $Q^2$ ) MCs reweighted to data distributions
- muon efficiency corrections applied (from independent data set)