Instanton-Induced Processes
An Overview

F. Schrempp, DESY

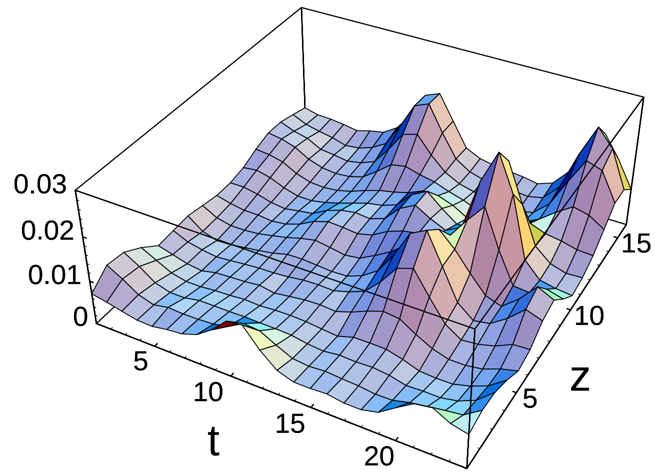
Copy available via WWW:

http://www.desy.de/~t00fri/talks.html

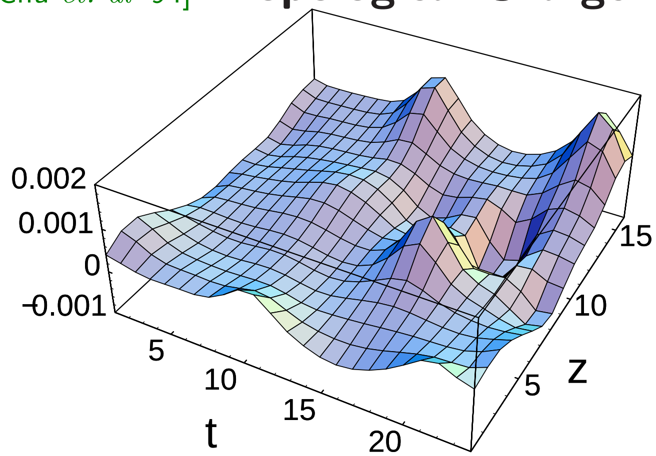
– *HERA and the LHC* workshop, DESY, Hamburg, June 2004 –

1. Setting the Stage

Lagrange Density



[Chu *et. al* '94] Topological Charge



- **Instantons:** a **basic aspect** of **QCD**

  [Belavin *et al* '75, 't Hooft '76]

Non-perturbative fluctuations of gluon fields with typical **size** $\langle\rho\rangle \approx \mathbf{0.5}$ **fm**; "instantaneous" in time and space

- Associated with non-trivial topology of **QCD** vacuum; I's ($\overline{I}$'s) carry conserved, topological charge $+1(-1)$
- **Theoretically:** Play an important rôle in interface region between partonic and hadronic description of strong int's
- **Direct experimental evidence for instantons lacking until now!**

♣ However,. . . [Ringwald & F. Sch. '94]
Characteristic **short** distance manifestation of instantons may be exploited for experimental search:

♢ I's induce hard, precisely known, **chirality-violating** processes, forbidden in usual perturbative **QCD** ! (⇔ ABJ-Anomaly) ['t Hooft '76]

♣ Theoretical prediction of rate and characteristic event signature achieved in **DIS** (strict I-perturbation theory) ⇒ rate in measurable range at **HERA**! [Ringwald & F. Sch. '94 - '01]

♣ **Great opportunity** in **DIS** at **HERA** for discovering I-induced processes: Two dedicated search experiments **H1 & ZEUS**, hope for **HERA2**!

(Sect. 2)

♣ What about **LHC**?? Theory? Expt? ⇒ Outline of **new, ongoing project** **(Sect. 3)**

On the other hand: Important theoretical challenge:

♣ Understanding the impact of **larger**-size instantons on **high-energy** processes:

Diffraction: [Kharzeev, Kovchegov & Levin '00; Shuryak *et.al* '00 -'02; F. Sch. & Utermann '02]

Small-x Saturation: [F. Sch. '01; F. Sch. & Utermann '02 - '04, Shuryak *et.al* '03]⇒ **(Sect. 4)**

Intriguing result: **"Color Glass Condenstate"** ⇔ **QCD** -**Sphaleron** state!

Plan

1. **Setting the Stage**
2. **Small Instantons in Deep-Inelastic Scattering (DIS)**
   2.1 Instanton-Perturbation Theory
   2.2 Status of Searches at **HERA**
3. **Study of the Discovery Potential at the LHC**
   3.1 Outline of the Project
4. **Instanton-Driven Saturation at Small x**
5. **Conclusions**

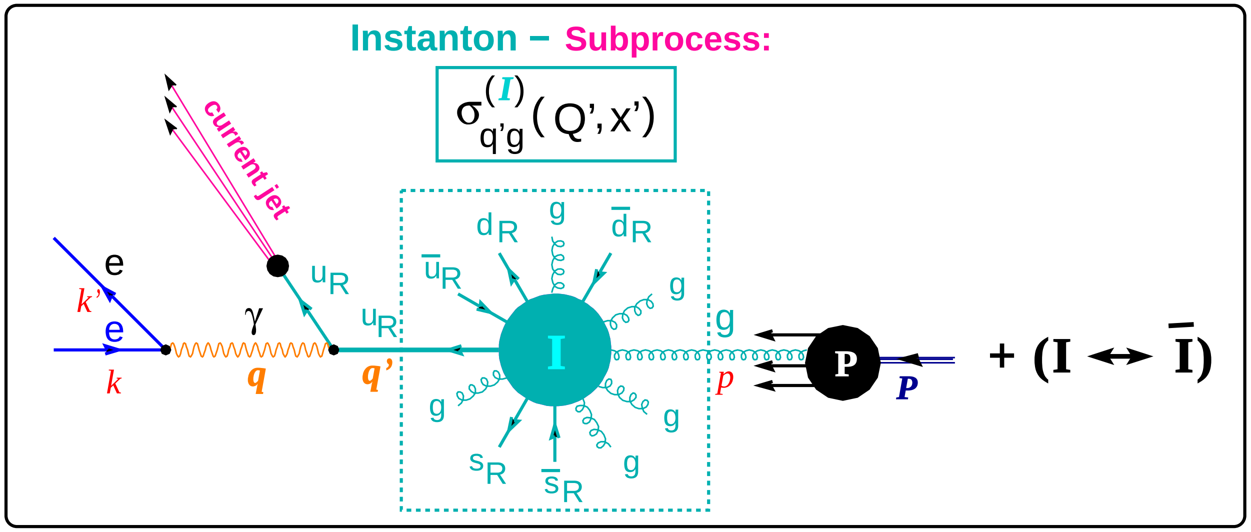
2. Small Instantons in Deep-Inelastic Scattering (DIS)

2.1 Instanton-Perturbation Theory

[Ringwald & F. Sch., Phys. Lett **B438** (1998) 217, Moch, Ringwald & F. Sch., Nucl. Phys. **B507** (1997)]

- ***I*-perturbation theory:** { dilute gas of $\boldsymbol{I}$'s and $\overline{\boldsymbol{I}}$'s, small α_s, light quarks with $\mathrm{m}_q \cdot \rho_{\mathrm{eff}} < 1$

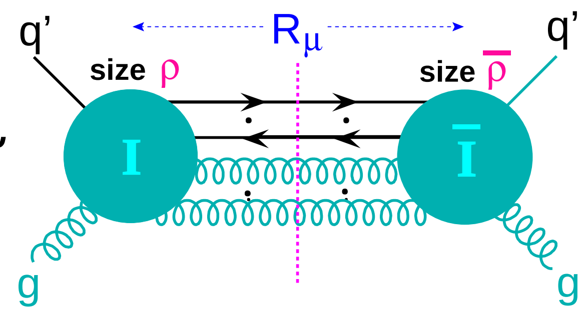
- Leading, $\boldsymbol{I}$-induced, **chirality-violating** process in **deep-inelastic** regime of $e^{\pm}\mathrm{P}$ scattering:



- Factorization in Bjorken limit of $\boldsymbol{I}$-subprocess variables $\boxed{(Q'^{\,2}, x')}$:

  large $Q'^{\,2} = -q'^{\,2} > 0;\quad x' = \frac{Q'^{\,2}}{2p\cdot q'} \leq 1$ fixed

$$\frac{d\sigma_{\mathbf{HERA}}^{(I)}}{dx'dQ'^2} \simeq \frac{d\mathcal{L}_{q'g}^{(I)}}{dx'dQ'^2} \cdot \boldsymbol{\sigma_{q'g}^{(I)}(Q',x')}$$

$\sigma_{q'g}^{(I)} \sim$ 

- Differential luminosity, $d\mathcal{L}_{q'g}^{(I)}$: number of $q'g$ collisions per eP collision
  $\Leftrightarrow$ integrals over the various known flux factors.

- **Essential instanton**-dynamics in total cross-section $\boldsymbol{\sigma_{q'g}^{(I)}(Q',x')}$ of $\boldsymbol{I}$-subprocess! (Fig.)

- As observable, $\sigma_{q'g}^{(\boldsymbol{I})}(Q',x')$ involves **integrations** over $\boldsymbol{I}$ & $\boldsymbol{\overline{I}}$-**"collective coordinates"**,

$\boldsymbol{I}$-size $\boldsymbol{\rho}$, $\boldsymbol{\overline{I}}$-size $\boldsymbol{\overline{\rho}}$, $\boldsymbol{I\overline{I}}$-distance 4-vector $\boldsymbol{R_\mu}$,
and $\boldsymbol{U} = \boldsymbol{I\overline{I}}$ relative color orientation

$$\sigma_{q'g}^{(\boldsymbol{I})} = \int d^4\boldsymbol{R}\, e^{i(p+q')R} \int_0^\infty d\boldsymbol{\rho} \int_0^\infty d\boldsymbol{\overline{\rho}}\; e^{-(\rho+\overline{\rho})Q'}\; \boldsymbol{D(\rho)D(\overline{\rho})} \int d\boldsymbol{U}\, e^{-\frac{4\pi}{\alpha_s}\boldsymbol{\Omega}\left(\boldsymbol{U},\frac{\boldsymbol{R}^2}{\rho\overline{\rho}},\frac{\overline{\rho}}{\rho}\right)} \{\ldots\}$$

Two crucial quantities of $\boldsymbol{I}$-calculus: $\boldsymbol{D(\rho)}$ = $\boldsymbol{I}$-size distribution, $\boldsymbol{\Omega}\left(\boldsymbol{U},\frac{\boldsymbol{R}^2}{\rho\overline{\rho}},\frac{\overline{\rho}}{\rho}\right)$ = $\boldsymbol{I\overline{I}}$-interaction

◇ **Known** in I-perturbation theory, formally for $\alpha_s(\mu_r)\,\ln(\mu_r\rho) \ll 1$ and $\frac{R^2}{\rho\overline{\rho}} \gg 1$.

◇ $D(\rho)_{I-\text{pert.}} \propto \rho^{6-2/3n_f+\mathcal{O}(\alpha)}$ generically spoils calculability of I-observables, since $(\rho, \overline{\rho})$-integrals badly diverge for large ρ!

♣ **Exception** in **DIS**, due to **hard scale** Q': despite growth of $D(\rho)_{I-\text{pert.}} \Rightarrow$ "form factor" $\exp(-Q'(\rho+\overline{\rho}))$ insures **small** $(I, \overline{I})$'s with $(\rho, \overline{\rho}) \lesssim \frac{1}{Q'}$

♣ For (large) $Q' \neq 0$, all collective coordinate integrations in $\sigma^{(I)}_{q'g}$ via unique **saddle point**:

U^* $\Leftrightarrow$ most attractive color orientation

$$\rho^* = \overline{\rho}^* \sim \frac{4\pi}{\alpha_s(\frac{1}{\rho^*})}\,\frac{1}{Q'}; \qquad \frac{R^{*\,2}}{\rho^{*\,2}} \overset{Q'\ \text{large}}{\sim} 4\frac{x'}{1-x'} \qquad \vec{R}^* \approx 0$$

◇ $\Rightarrow$ indeed, for **large** Q' and **small** $(1-x')$: dilute gas $\Leftrightarrow \frac{R}{\rho} \gg 1$ of small I's $\Leftrightarrow \rho \sim \frac{1}{Q'}$!

Crucial Impact of Lattice Results

[Ringwald & F. Sch., Phys. Lett. **B 459** (1999) 249; **B 438** (1998) 217; **B 503** (2001) 331]

$D(\rho)$ and $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$: Link **DIS results** with **lattice** observables in **QCD** vacuum!

Region of validity of I-perturbation theory in (Q', x') from re-analysis of high-quality lattice 'data' for **QCD** $_{n_f=0}$ [UKQCD, Smith & Teper, '98]

- $\approx$ **parameter-free** comparison of I-size and $I\overline{I}$-distance distributions with I-perturbation theory versus (ρ, R):
- $\Lambda_{\overline{\rm MS}}^{(n_f=0)} = (238 \pm 19)$ MeV with small error also from **lattice** [ALPHA-Collaboration '99]!
- **Results:** I-perturbation theory **quantitatively** valid for

$$\left.\begin{array}{lcl} \rho \cdot \Lambda_{\overline{\rm MS}}^{(n_f=0)} & \lesssim & 0.42 \\ R/\rho & \gtrsim & 1.05 \end{array}\right\} \overset{\text{saddle point}}{\Rightarrow} \left\{\begin{array}{lcl} Q'/\Lambda_{\overline{\rm MS}}^{(n_f)} & \gtrsim & 30.8, \\ x' & \gtrsim & 0.35, \end{array}\right.$$

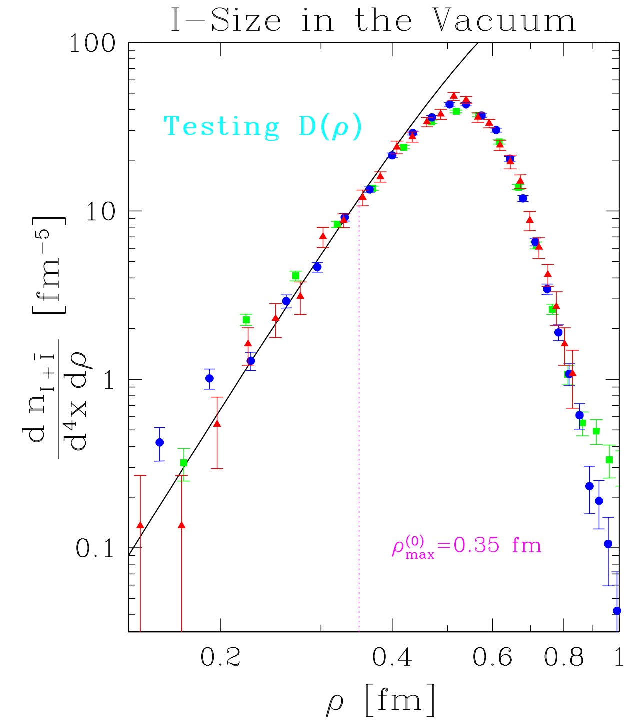
- Good **agreement** of lattice results with I-perturbation theory very interesting by itself!

$\boldsymbol{I}$-Size Distribution:

$$\frac{\mathrm{d}\, n_{I+\bar{I}}}{\mathrm{d}^4x\, \mathrm{d}\rho}\Big|_{\textbf{UKQCD}} \overset{?}{\simeq} 2\, D(\rho)_{\boldsymbol{I}-\text{pert.}}$$

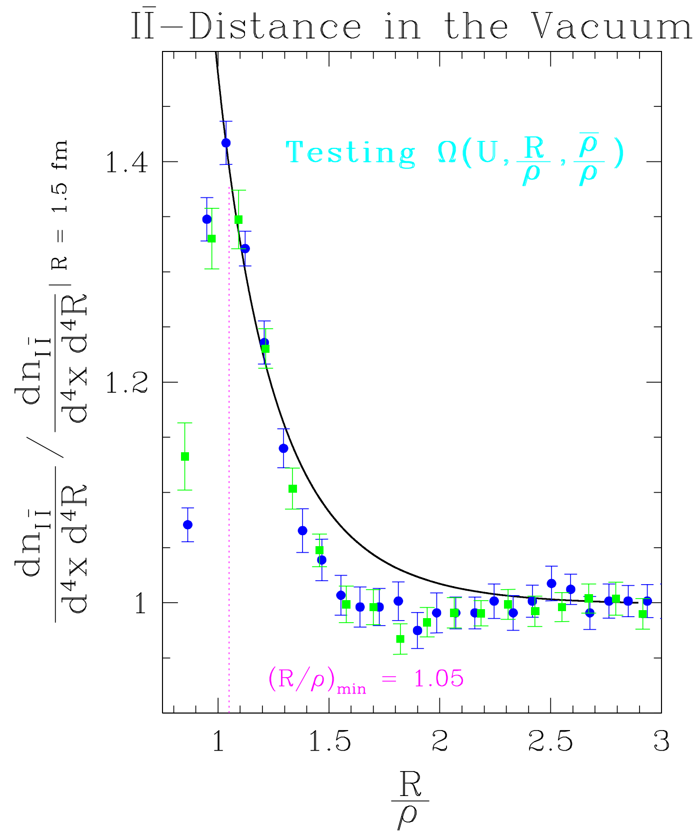
Parameter-free **agreement** in shape **and** normalization, for $\rho \cdot \Lambda_{\overline{\rm MS}}^{(n_f=0)} \lesssim 0.42$

Almost independent of renormalization scale μ_r, for large range of μ_r (2-loop RG-invariance!)



$\boldsymbol{I\bar{I}}$-Distance Distribution:

$$\frac{\mathrm{d}\, n_{I\bar{I}}}{\mathrm{d}^4x\, \mathrm{d}^4R}\Big|_{\textbf{UKQCD}} \overset{?}{\simeq} N \int_0^\infty d\rho \int_0^\infty d\bar{\rho}\; D(\rho)\, D(\bar{\rho}) \times \int dU\, e^{-\frac{4\pi}{\alpha}\, \Omega_{\rm valley}\left(U, \frac{R^2}{\rho\bar{\rho}}, \frac{\bar{\rho}}{\rho}\right)}$$

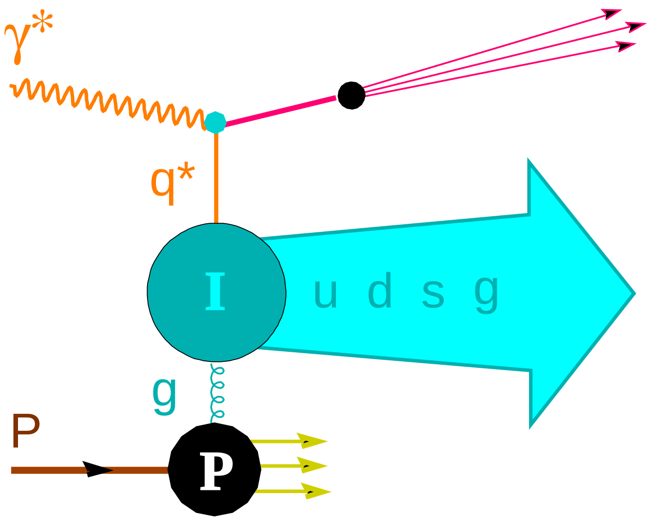


Good **agreement** with known $\boldsymbol{\Omega}_{\rm valley}$[Khoze & Ringwald '91; Verbaarschot '91] for $R/\rho \gtrsim 1.05$, using $D(\rho) = \boldsymbol{D(\rho)}_{\rm lattice}$

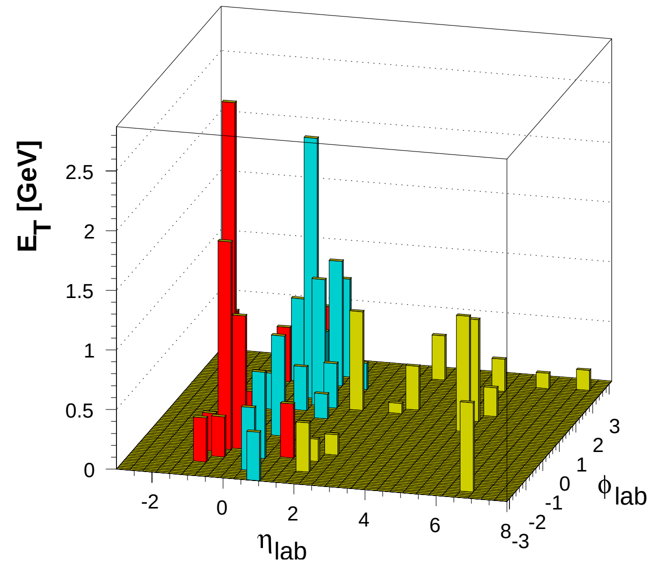
Characteristic Final-State Signature

Indispensable Tool: Monte-Carlo generator package for simulation of instanton events at **HERA**: **“QCDINS 2.0”**

[Gibbs, Ringwald & F. Sch. ’95, Ringwald & F. Sch, Comp. Phys. Com. **132** (2000) 267 (**long-wite-up**)]



- **current jet**
- **“band”-region:** $\Leftrightarrow$



In I-rest system: **“Fireball”** decaying **isotropically** into

$$n_f \cdot q + n_f \cdot \overline{q} + \mathcal{O}(\frac{1}{\alpha_s}) \cdot g =$$

$\mathcal{O}(10)$ **partons!**

◇ Large total E_t	◇ Large multiplicity
◇ “u, d, s flavour democracy”: **Strangeness** $\Rightarrow K's, \Lambda's$	◇ No further jets

2.2 Status of Searches at HERA (H1, ZEUS)

[**H1 Coll.**, Eur.Phys. J. **C 25** (2002) 495; **ZEUS Coll.**, Eur. Phys. J. **C 34** (2004) 255].

- **H1** $\left\{ \begin{array}{l} \int \mathcal{L}dt = \mathbf{21}\ \text{pb}^{-1},\ \theta_{e^+} > 156^\circ,\ 0 < y < 0.6 \\ x > 10^{-3},\ \mathbf{10} \lesssim \boldsymbol{Q^2} \lesssim \mathbf{100}\ \text{GeV}^{\mathbf{2}} \end{array} \right.$

- **ZEUS** $\left\{ \begin{array}{l} \int \mathcal{L}dt = \mathbf{38}\ \text{pb}^{-1},\ y > 0.05 \\ x > 10^{-3},\ \boldsymbol{Q^2} \gtrsim \mathbf{100}\ \text{GeV}^{\mathbf{2}} \end{array} \right.$

Challenges:

- Reconstructing variables (Q'^2, x') of $\boldsymbol{I}$-subprocess & implementing theoretical fiducial cuts (**lattice!**)

		H1	ZEUS
$Q^2 \gtrsim \mathbf{113}$ GeV^2	?	no	yes
$Q'^2 \gtrsim \mathbf{113}$ GeV^2	?	yes	yes
$x' \gtrsim 0.35$	?	no	no

- Large uncertainties due to different event generators, used for **sDIS**-background! $\Leftarrow$ **main** remaining problematics

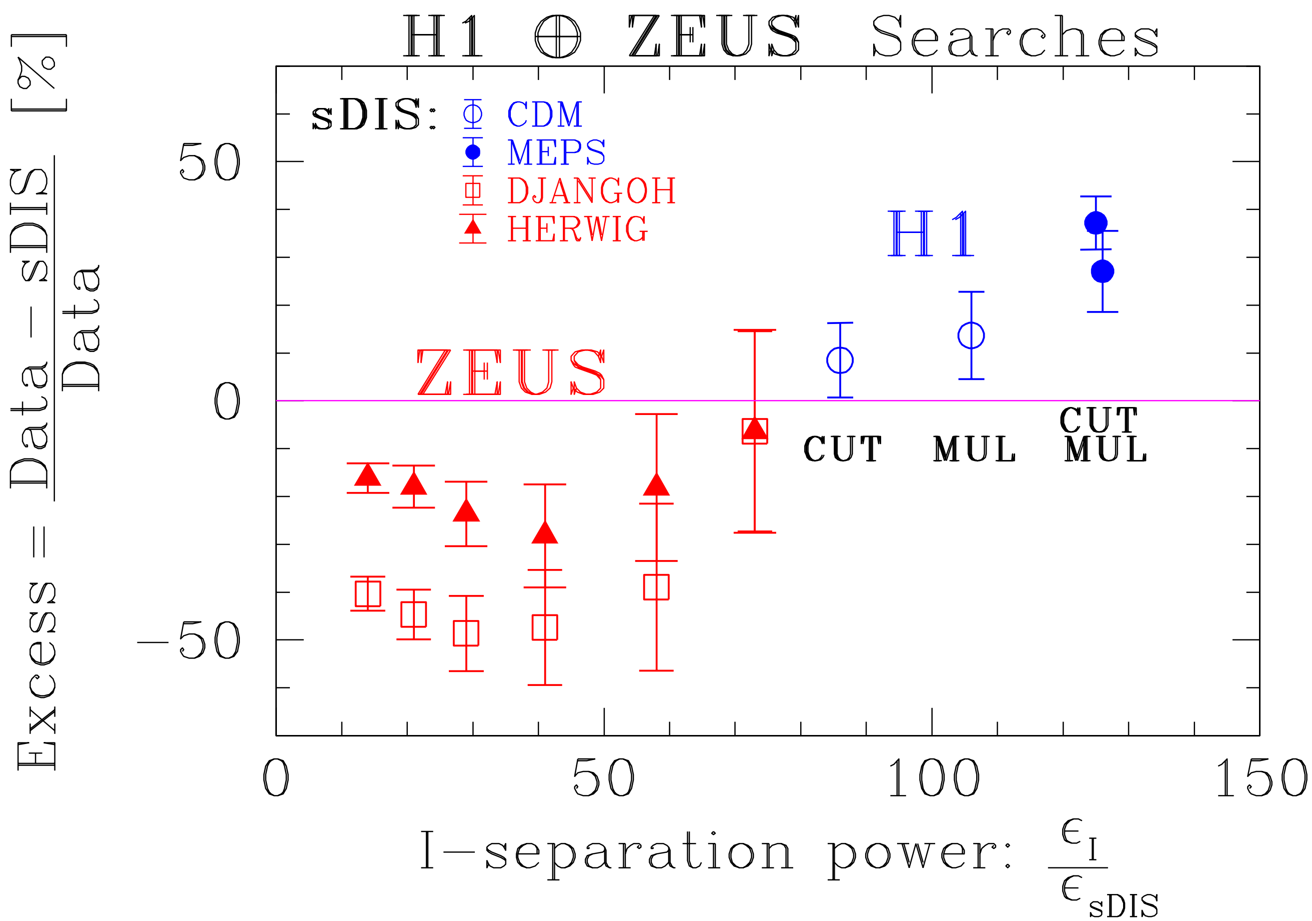
- $\boldsymbol{I}$-enriched data samples by cutting on several **optimized** discriminating observables

- using highest possible $\boldsymbol{I}$-separation power $= \frac{\epsilon_{\boldsymbol{I}}}{\epsilon_{\text{sDIS}}}$ $\epsilon_{\boldsymbol{I}} \gtrsim 5 - 10\%$.

- Both combinatorial cuts and various multivariate discrimination techniques $\Leftarrow$ **best!**

Results:

- A **theorist's** "unified plot" of the **H1** and **ZEUS** "excess" versus I-separation power!



- Hope for **HERA2** to push towards higher I-separation power!
- 95%-CL upper limits on I-induced cross sections factor $\mathbf{4-5}$ above our predictions.
- **Conclusion:** I-searches remain **challenging** but required sensitivity within reach!

3. Study of the Discovery Potential at the LHC

3.1 Outline of the Project

Members:
- **TH** : **Maik Petermann** (PhD-thesis) & F. Sch.
- **Exp** : Tancredi Carli/CERN & "friends?"

Challenges:

- Attempt to do a **broad study**, focussing both on **TH** & **EXP** aspects.

Theory:

- Single out & calculate optimal/leading $\boldsymbol{I}$**-subprocess** at the **LHC** within I-perturbation theory. Clearly, a gluon + gluon initial state! Rate enhanced by factor $\propto \frac{1}{\alpha_{\text{e.m.}}\,\alpha_s}$ w.r.to **HERA**, **but**
- need to enforce (quark) virtuality into I-induced **final state** to make I-perturbation theory work:

  interesting possibility: fragmentation of **outgoing** q**'s** from I-subprocess into $\mathbf{1}$ or $\mathbf{2}$ W**'s or** γ**'s with high** $E_\perp$.

  Good signature $\oplus$ low background!?

Exp :

- Adapt our **QCDINS** MC to **LHC** & work out characteristic signatures, best observables, fiducial cuts . . . !⇐ further help most welcome!!
- Find a good trigger!
- Incorporate years of **experience** from **HERA** searches!

4. Instanton-Driven Saturation at Small x

[F. Sch., J. Phys. G **28** (2002) 915;
F. Sch. & Utermann, Phys. Lett. **B543** (2002) 197; Acta Phys. Polon. **B33** (2002) 3633;
Proc. *SEWM 2002*, hep-ph/0301177; hep-ph/0401137.]

Why Instantons?

- Strong rise of gluon density towards $x \to 0$ (**HERA**) $\to$ **novel regime of QCD** :
  α_s **small** but gluon density **large** $\to$ breakdown of usual p**QCD**!

- **Expectation:** Non-linear interactions among many **overlapping** gluons $\to$ dampening of rise $\to$ gluon density **saturates**

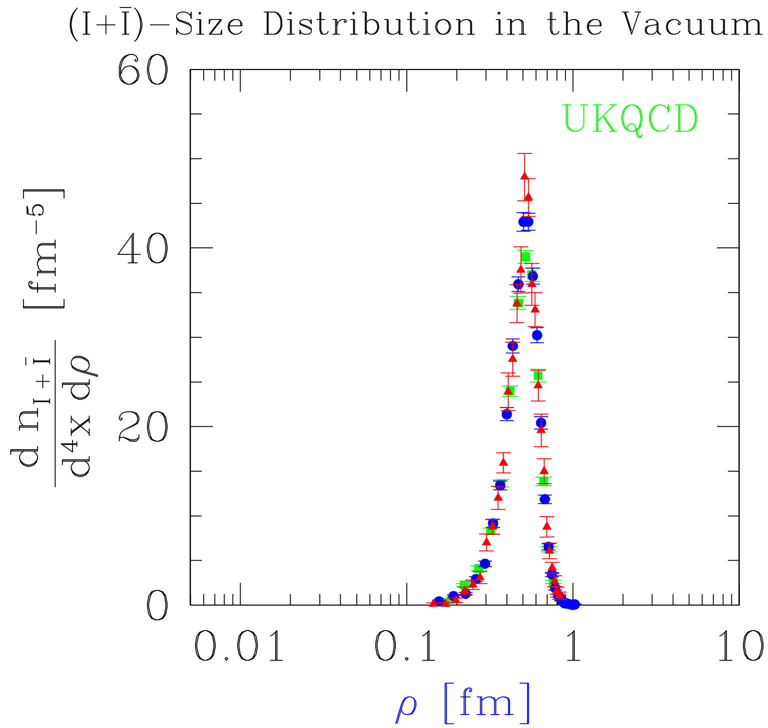
- **Saturation state** $\Leftrightarrow$ **"colour-glass condensate"** **[McLerran *et al* '01]:**

  New, dense state of (gluonic) matter, i.e. multi-gluon state of
  high occupation number $\to$ classical, strong color field $A_\mu \propto \frac{1}{\sqrt{\alpha_s}}$

- In this environment, **instantons** come to mind naturally:
  - ◇ Non-perturbative approaches indicated. Simpler than **huge** pQCD resummations?!
  - ◇ $\boldsymbol{I}$-interactions naturally involve many non-perturbative gluons, multiplicity $\langle n_g \rangle \propto \frac{1}{\alpha_s}$!
  - ◇ $\boldsymbol{I}$'s $\Leftrightarrow$ Explicitly known, classical & strong gluon fields ($A_\mu^{(\boldsymbol{I})} \propto \frac{1}{\sqrt{\alpha_s}}$)

◇ At **high**-energies ($x \longrightarrow 0$), **larger** I-sizes are probed!

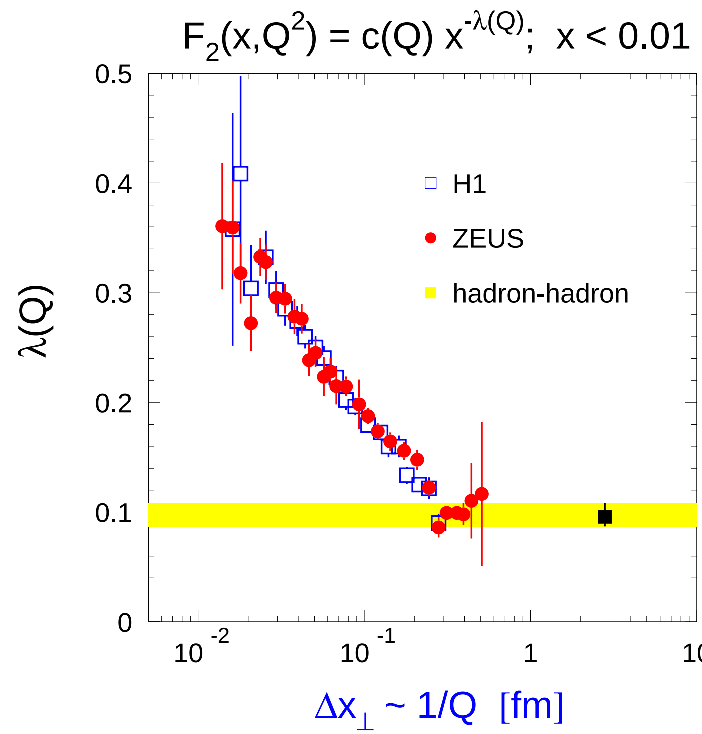
$\Rightarrow$ Sharply defined average I-size $\langle\rho\rangle \approx \mathbf{0.5}$ fm becomes **conspicuous** scale! $\Leftarrow$ **Lattice**, (Fig. top)



◇ **Coincidence (!)** with ($\perp$) resolution $\Delta x_\perp \sim 1/Q$, where small-x rise of $\boldsymbol{F_2}$ abruptly **increases** with **falling** $\boldsymbol{\Delta x_\perp}$! (Fig. bottom), [data from A. Levy].

Background **instantons** **"resolved"** for $\boldsymbol{\Delta x_\perp \lesssim \langle\rho\rangle}$!

◇ From I-**perturbation theory in DIS**: I-contribution grows strongly towards smaller x and Q^2 [A. Ringwald & F. Sch. '94, '98]



◇ **Central questions**:

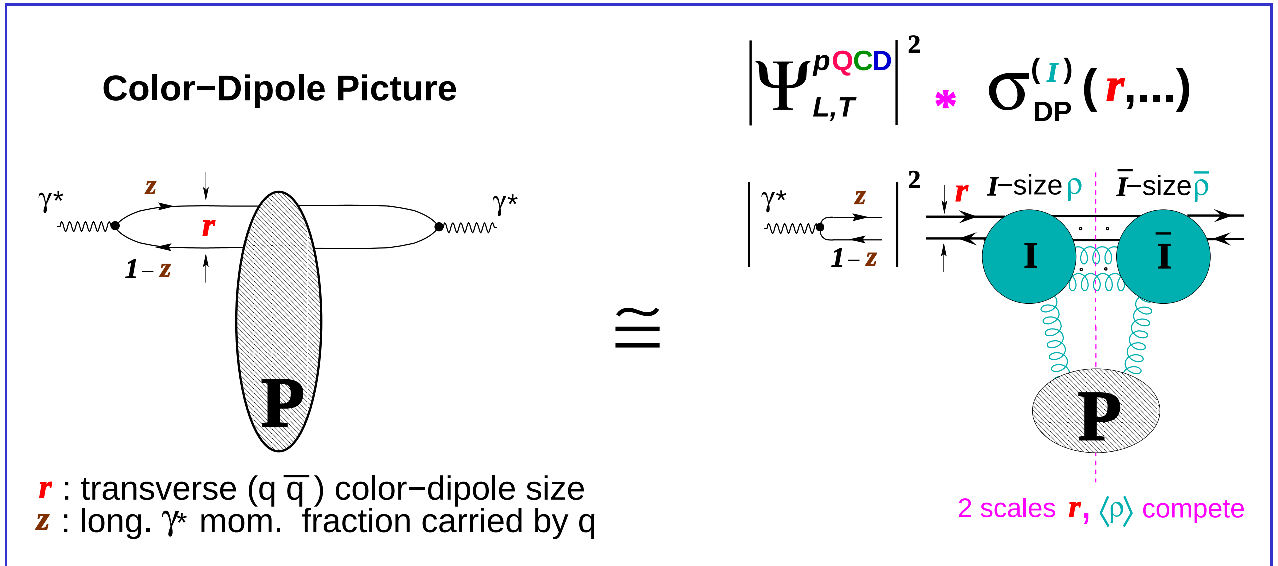
♣ Does saturation occur in an I- background?

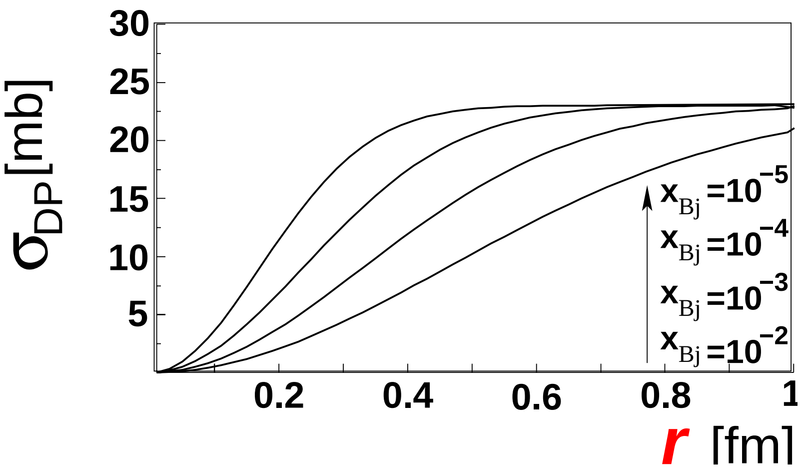
♣ Is the saturation **scale** connected with $\langle\rho\rangle$?

♣ "**colour-glass condensate**" $\Leftrightarrow$ **QCD** -**sphaleron** state??

From I-Perturbation Theory to Saturation

- *Starting point:* **DIS** regime, i.e. large $Q^2 \oplus$ **cuts**, such that I-perturbation theory holds.
- Transform our published **DIS** results on I-induced processes into **Color Dipole Picture** via variable and 2d Fourier transformations (Fig. left).





- **Guiding Question:** Can a background **instanton** of size $\approx \langle\rho\rangle$ give rise to a saturating, geometrical form? $\Big\}$ $\sigma^{(I)}_{\rm DP}(r,\ldots) \overset{r \gtrsim \langle\rho\rangle}{\sim} \pi\langle\rho\rangle^2$

  while respecting colour transparency, if **dipole area** $\pi r^2 \lesssim$ **instanton area** $\pi\langle\rho\rangle^2$

- *Next:* Carefully increase size r of $q\bar{q}$ colour-dipole towards hadronic dimensions with the help of **lattice data:** $D(\rho)_{I\text{-pert.}} \Rightarrow D(\rho)_{\rm lattice}$ for $\rho \gtrsim 0.35$ fm; $\Omega_{\rm valley} \Rightarrow \Omega_{\rm lattice}$ for $\frac{R}{\langle\rho\rangle} \lesssim 1.05$

- **Fiducial cuts become unnecessary!** Everything stable & finite.

- *Simplest Illustration:* $\gamma^* + g \overset{(I)}{\Rightarrow} q_R + \overline{q}_R$: **no final-state** gluons; only 1 **flavour**.

  ◇ ***I****-perturbation theory in* **DIS**: [Moch, Ringwald & Schrempp, Nucl. Phys. **B507** (1997) 134]

$$\sigma_{L,T}^{\gamma^* P}(x, Q^2) = \int_x^1 \frac{d\,\hat{x}}{\hat{x}} \left(\frac{x}{\hat{x}}\right) \boldsymbol{G}\left(\frac{x}{\hat{x}}, \mu^2\right) \int d\,t\, \frac{d\hat{\sigma}_{L,T}^{\gamma^* g}}{d\,t}(\hat{x}, t, Q^2)$$

e.g. $$\frac{d\,\hat{\sigma}_L^{\gamma^* g}}{d\,t} \overset{(I)}{=} 2\,\pi^3 \frac{e_q^2}{Q^2} \frac{\alpha_{\rm em}}{\alpha_s} \left[\hat{x}(1-\hat{x})\sqrt{tu}\,\frac{\mathcal{R}(\sqrt{-t})-\mathcal{R}(Q)}{Q^2+t} - (t \leftrightarrow u)\right]^2$$

$\boldsymbol{\mathcal{Q}^2 = \{Q^2, -t, -u\}}$ with $\mathcal{Q}\,\langle\rho\rangle$ **"large"**

◇ Resolution dependent **length** scale $\mathcal{R}(\mathcal{Q}) = \frac{\pi^2}{2} \int_0^\infty d\rho\, D(\rho)\rho^5\, (\mathcal{Q}\rho)\mathrm{K}_1(\mathcal{Q}\rho)$,
key to continuation towards $\mathcal{Q}\,\langle\rho\rangle \Rightarrow \mathbf{0}$!

– If $\mathcal{Q}\langle\rho\rangle$ **large**, $\Rightarrow$ $(\mathcal{Q}\rho)\mathrm{K}_1(\mathcal{Q}\rho) \sim e^{-\mathcal{Q}\rho}$ suppresses big-size $\boldsymbol{I}$'s $\Rightarrow \mathcal{R}(\mathcal{Q})$ **finite** and strict $\boldsymbol{I}$-perturbation theory with $D \Leftrightarrow D(\rho)_{\boldsymbol{I}\text{-pert.}}$ **applicable!**

– For $\mathcal{Q}\langle\rho\rangle \Rightarrow \mathbf{0}$ and $D \Leftrightarrow D(\rho)_{\rm lattice}$ $\mathcal{R}(\mathbf{0}) = \frac{\pi^2}{2}\int_0^\infty d\rho\, D_{\rm lattice}(\rho)\rho^5 = \mathcal{O}(1\mathrm{fm})$ **finite**

◇ *Results in Color Dipole Picture:*

As intuitively expected: observe an interplay of the 2 crucial scales $\boldsymbol{r}$ & $\langle\rho\rangle$!

$\frac{r^2}{\langle\rho\rangle^2} \ll 1$: $\left(|\,\Psi_{L,T}\,|^2\,\sigma_{\rm DP}\right)^{(I)} \Rightarrow$ exponentially **small** (color transparency)

$\frac{r^2}{\langle\rho\rangle^2} \approx 1$: strong rise of $\sigma_{\rm DP}^{(I)}(\mathbf{r},\ldots)$ starts **flattening out!**

$$\frac{r^2}{\langle\rho\rangle^2} \gg 1: \quad \left(|\,\Psi_{L,T}\,|^2\,\sigma_{\rm DP}\right)^{(I)} \approx |\,\Psi_{L,T}^{\rm pQCD}\,|^2 \underbrace{\frac{\pi^3}{3\,\alpha_s}\,x\,G(x,\mu^2)\,\left[\pi\,\mathcal{R}(0)^2\right]}_{\sigma_{\rm DP}^{(I)}\ \textbf{saturates!}}$$

- $\mathcal{R}(0) = \kappa^{(I)} \cdot \langle\rho\rangle$ determined by structure of I-ensemble in **QCD -vacuum**: $\langle\rho\rangle$ and **I-packing fraction $\kappa^{(I)}$** = fraction of space-time volume occupied by I's

- Indeed, a saturating, **geometrical** form, with **saturation scale $\approx \langle\rho\rangle$!**

- I-driven, saturated dipole cross section of **hadronic size** $\mathcal{O}(\frac{1}{\alpha_s}\pi\langle\rho\rangle^2) = \mathcal{O}(10\text{ mb})$; $\sigma_{\rm DP}^{(I)} \propto \frac{1}{\alpha_s}$ signals non-perturbative origin.

Color Glass Condensate $\Leftrightarrow$ QCD -Sphaleron state?

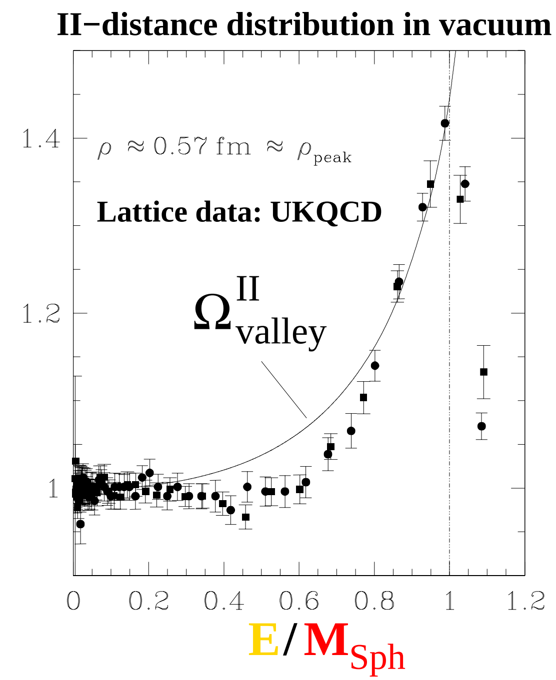
- *Now, focus on realistic process:* $\gamma^* + g \stackrel{(I,\overline{I})}{\Rightarrow} n_f\,(q_{\rm R} + \overline{q}_{\rm R}) +$ **gluons** $+\ (I \Leftrightarrow \overline{I}, \mathrm{R} \Leftrightarrow \mathrm{L})$

- **Changes in $\sigma_{DP}^{(I)\,\text{gluons}}$?** $\Omega^{I\bar{I}}_{\text{valley}} \neq 0$ known!, $\Leftrightarrow$ resummation of **final-state** gluons $\Rightarrow$ extra integrals over $I\bar{I}$-distance R_μ and $E_{q'g} = \sqrt{(q'+p)^2}$

  - In **saturation regime**: $\rho \approx \langle\rho\rangle$ $\Leftrightarrow$ **peaked** $D(\rho)_{\text{lattice}}$ $\Rightarrow$ d^4R-integral dominated by **new** saddle point, $R^*_\mu\left(\frac{E_{q'g}}{M_{\text{Sph}}}\right)$!
  - Mass M_{Sph} of **QCD -"Sphaleron** state" as scale for the I-subprocess energy $E_{q'g}$!
  - $M_{\text{Sph}} \equiv$ height of potential barrier separating vacua with **winding number** $|\Delta n| = 1$:

    $E^{\text{pot}}_{|\Delta n|=\frac{1}{2}}$: $M_{\text{Sph}} \approx \frac{3\pi}{4}\frac{1}{\alpha_s}\frac{1}{\langle\rho\rangle} \approx 2-3$ GeV [Ringwald & F. Sch. '94; Diakonov & Petrov '94]
  - **QCD -Sphaleron** configuration, a semi-classical, coherent **multi-gluon state**!

- **Map** the variable in **lattice data** of $I\bar{I}$-distance distribution $\frac{R}{\langle\rho\rangle} \Rightarrow \frac{E_{q'g}}{M_{\text{Sph}}}\left(\frac{R^*}{\langle\rho\rangle}\right)$ exploiting the above saddle point! $\Rightarrow$
- Form of $\Omega^{I\bar{I}}_{\text{valley}}$ valid right up to **Sphaleron-peak**! (Fig.)
- **Maximum at $E_{q'g} \approx M_{\text{Sph}}$!** $\rightarrow$ (Fig.)
- With **final-state gluons**: $(E_{q'g}, R_\mu)$ integrals **dominated** by **Sphaleron peak**, and again, $\sigma_{DP}^{(I)\,\text{gluons}} \propto \pi\mathcal{R}(0)^2$ saturates



5. Conclusions

- **Instantons** as non-perturbative, topological fluctuations of the gluon fields, are a **basic feature** of **QCD** . Discovery of I-induced processes would be of fundamental significance.

- Summarized existing, systematic theoretical and phenomenological investigation of the "discovery potential" at **HERA**: calculable rate in measurable range; event signature!

- Summarized status of 2 dedicated experimental searches (**H1** & **ZEUS**): major difficulty: large differences of **sDIS** generators in I-signal region!

- **HERA2** (still) offers a great opportunity . . . looking ahead to the **LHC**, broad study under way!

- Important theoretical challenge: Understanding the impact of **larger**-size instantons on **high-energy** processes: **Small-x Saturation**!

  ♣ Saturation does occur in an I- background.
  ♣ The saturation **scale** connected with the I-size $\langle \rho \rangle$
  ♣ "**colour-glass condensate**" ⇔ **QCD** -**sphaleron** state.

- **Open & interesting:** x-dependence of saturation scale? Geometrical scaling . . .
  Phenomenology!