Electroweak baryon and lepton number violation at future hadron colliders

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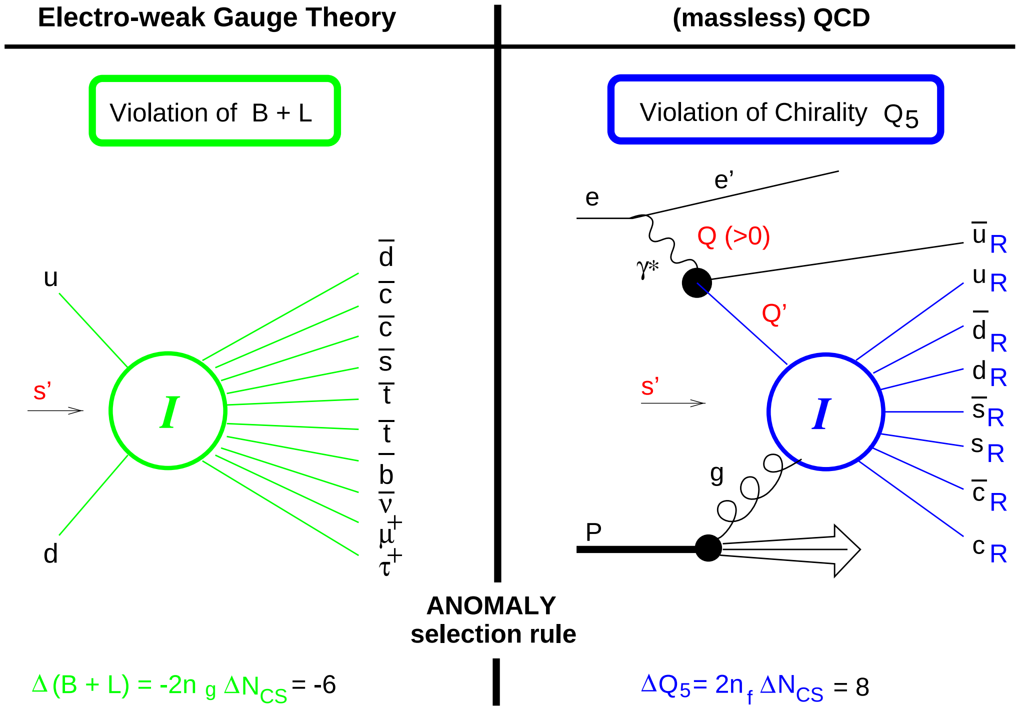
1. Introduction

- Standard Model of **electroweak** (**QFD**) and **strong** (**QCD**) interactions remarkably successfull

- There are processes that cannot be described by ordinary perturbation theory: [Adler '69; Bell,Jackiw '69; Bardeen '69]]

  B+L/**Chirality**-violating processes in **QFD**/**QCD**

- **Anomalous** processes induced by **topological fluctuations** of the non-abelian gauge fields, notably by **instantons** [Belavin *et al.* '75; 't Hooft '76]



- Topological gauge field fluctuations and associated anomalous processes play important role in
  - **QCD** in various **long-distance** aspects:
    - U$_A$(1) problem ($m_{\eta'} \gg m_\eta$) ['t Hooft '76]
    - SU(n_f) chiral symmetry breaking [Shuryak '82; Diakonov,Petrov '86]
  - **QFD** at **high temperatures**: [Kuzmin,Rubakov,Shaposhnikov '85]
    - Impact on baryon and lepton asymmetries of the universe

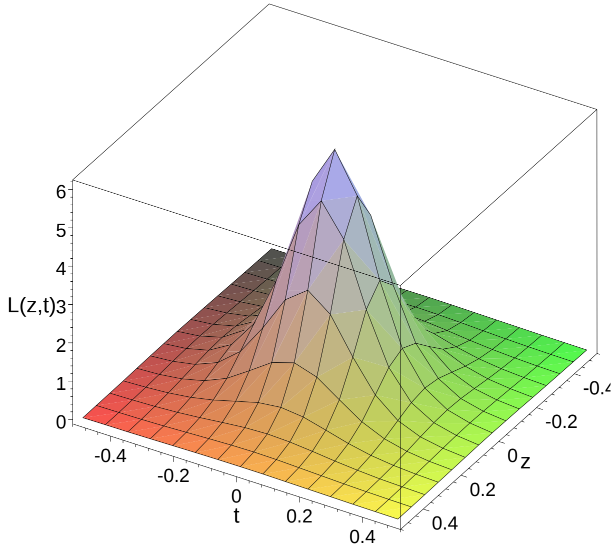
- Are they directly observable in **high energy reactions**?
  - **QFD**: Intense studies in early 1990s; inconclusive [AR '90; Espinosa '90; ...]
  - **QCD**:
    - **Hard QCD**-instanton induced events in **deep inelastic scattering**
      - reliably calculable and sizeable rate [Moch,AR,F.Schrempp '97; AR,F.Schrempp '98]
      - characteristic final state signature [AR,F.Schrempp '94–'01]
    - **Soft QCD**-instanton induced events might be responsible for the bulk of inelastic processes [E.Levin *et al.*; Shuryak *et al.*; F.Schrempp,Utermann '02]

- **Further content:**

  2. **Instanton-induced Hard Scattering Processes**
  3. **QCD-Instantons at HERA**
  4. **QFD-Instantons at VLHC?**
  5. **Conclusions**

2. Instanton-induced Hard Scattering Processes

Instantons:



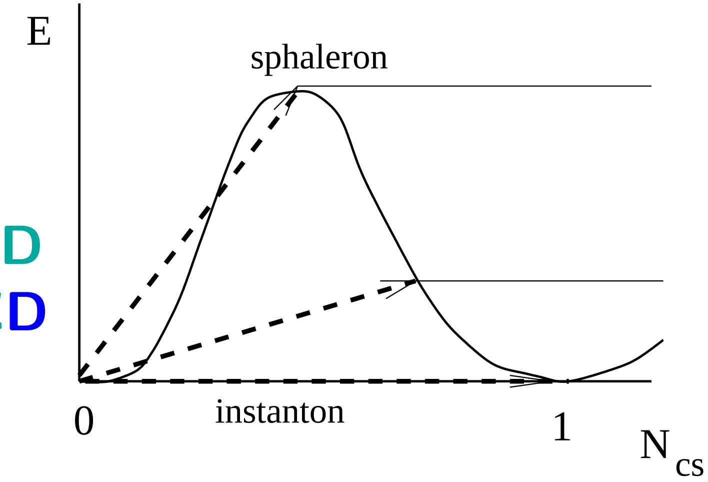
- Minima $A_\mu^{(I)}(x; \underbrace{\rho, U, x_0}_{\text{size,or.,pos.}}) \propto 1/g$ of Euclidean YM action [Belavin *et al.* '75; 't Hooft '76]

- **Tunneling transitions** between classically degenerate, topologically inequivalent vacua [Jackiw, Rebbi '76; Callan,Dashen,Gross '76]

  Sphaleron energy $\Rightarrow$ natural scale

$$M_{\rm sp} \sim \frac{\pi}{\alpha_g\, \rho_{\rm eff}} \sim \begin{cases} \pi \frac{M_W}{\alpha_W} \simeq 7.5\ \text{TeV} & \text{in } \textbf{QFD} \\ \mathcal{Q} & \text{in } \textbf{QCD} \end{cases}$$

[Klinkhamer,Manton '84; AR,F.Schrempp '94]



- Cross-sections rapidly growing below sphaleron scale; multiple emission of $\mathcal{O}(1/\alpha_g)$ gauge bosons [AR '90; Espinosa '90]

- Total cross-section grows exponentially

[McLerran,Vainshtein,Voloshin; ...; Khoze,AR '91; ...]

$$\hat{\sigma}_{\rm ff}^{(I_W)} \approx \frac{1}{m_W^2}\left(\frac{2\pi}{\alpha_W}\right)^{7/2} {\rm e}^{-\frac{4\pi}{\alpha_W} F_W(\epsilon)}$$

$$\epsilon \equiv \sqrt{\hat{s}}/(4\pi m_W/\alpha_W) \simeq \sqrt{\hat{s}}/(30\ {\rm TeV})$$

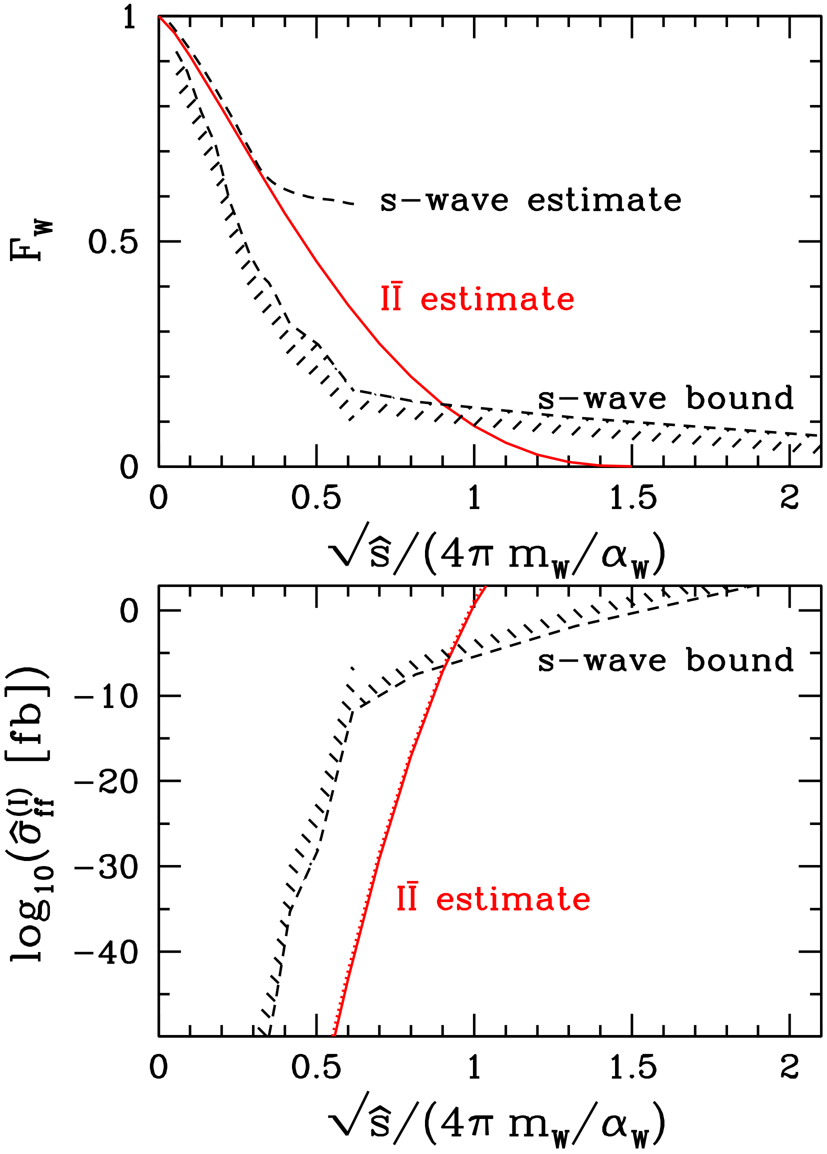
$$F_W(\epsilon) = 1 - \frac{3^{4/3}}{2}\,\epsilon^{4/3} + \frac{3}{2}\,\epsilon^2 + \mathcal{O}(\epsilon^{8/3})\,.$$

- For $\epsilon > 0.3 \div 0.75$ only estimates, educated guesses and bounds exist

[Khoze,AR '91; AR '02; Bezrukov *et al.* '03; AR '03]

$\Rightarrow$ Need future hadron collider or look for analogue **QCD** processes at **HERA**

[AR,F.Schrempp '94-'01]



Instanton-Antiinstanton Estimate

[AR,F.Schrempp '98]; also [Zakharov '90; Khoze,AR '91]

$$\hat\sigma^{(I)}_{\rm p_1p_2} \sim \int \mathrm{d}^4R \int_0^\infty \mathrm{d}\rho \int_0^\infty \mathrm{d}\overline{\rho}\, D(\rho)D(\overline{\rho}) \int \mathrm{d}U \mathrm{e}^{-\frac{4\pi}{\alpha_g}\Omega\left(U,\frac{R^2}{\rho\overline{\rho}},\dots\right)}\ \mathrm{e}^{\mathrm{i}(p_1+p_2)\cdot R - \sum_{i=1}^2 \sqrt{-p_i^2}\,(\rho+\bar\rho)}$$

- **Ingredients:**
  - Instanton-size distribution $D(\rho) \propto \mathrm{e}^{-2\pi/\alpha_g}$
  - $\Omega\left(U, R^2/(\rho\overline{\rho}), \dots\right)$:
    - ∗ Exponentiation of $\mathcal{O}(1/\alpha_g)$ final state gauge bosons [AR '90;Espinosa '90]
    - ∗ Anti-instanton-instanton interaction

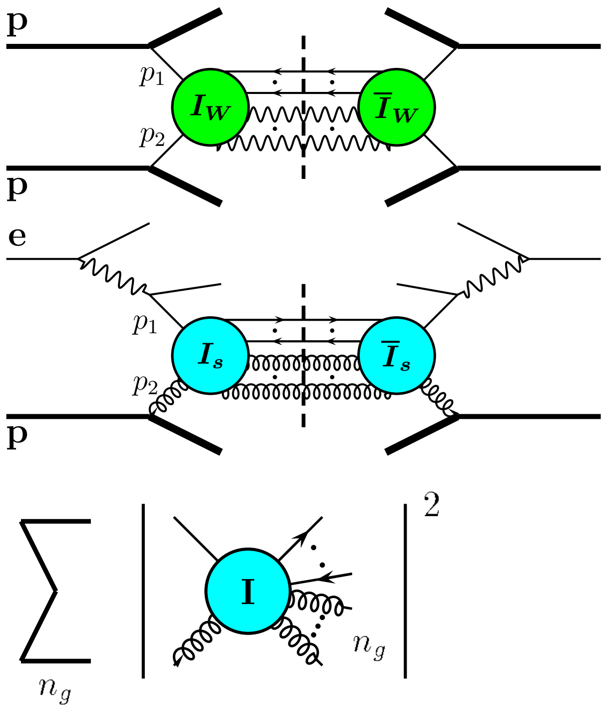
[Khoze,AR '91; AR,F.Schrempp '98]

- **General form:**

$$\hat\sigma^{(I)} \sim \mathrm{e}^{-\frac{4\pi}{\alpha_g}F_g(\epsilon)};\ \ \text{with } \epsilon = \sqrt{\hat s}/M_{\rm sp}$$

"Holy-Grail" function $F_g(\epsilon) \searrow$ for $\epsilon \nearrow$, with

$$0 < F_g(1) < F_g(0) = 1\,.$$



- **Saddle point evaluation:**

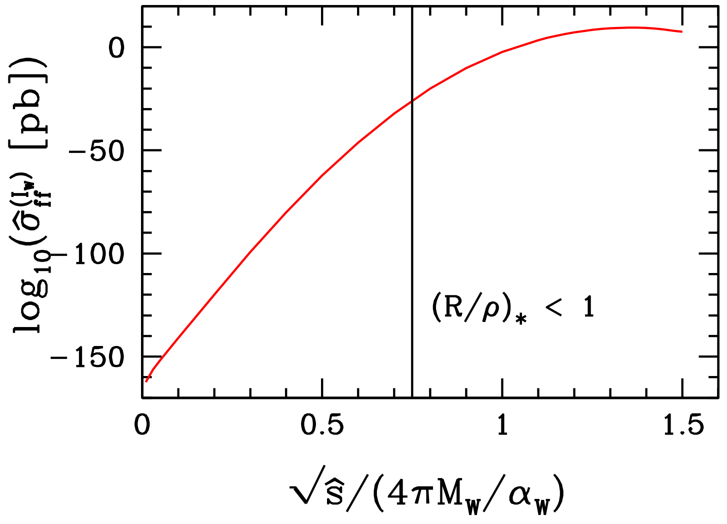
$$\hat{\sigma}^{(I)} \propto \mathrm{e}^{-\Gamma_*} \equiv \mathrm{e}^{-\frac{4\pi}{\alpha_g} F_g(\epsilon)} \,,$$

where

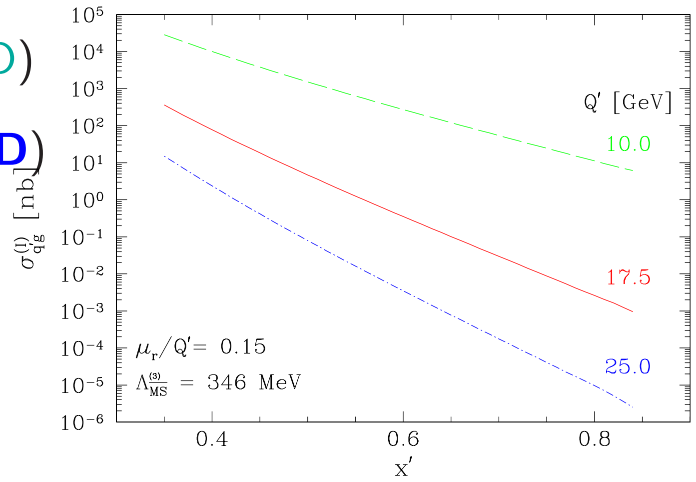
$$\epsilon \quad \equiv \quad \begin{cases} \sqrt{\hat{s}}/(4\pi M_W/\alpha_W) & (\mathbf{QFD}) \\ \sqrt{\hat{s}}/Q' \equiv \sqrt{1/x' - 1} & (\mathbf{QCD}) \end{cases}$$

is a scaled cm energy and

$$F_g = 1 + \Omega_g(1, \xi_*) + \begin{cases} -(\xi_* - 2)\, \frac{\partial}{\partial \xi_*} \Omega_g(1, \xi_*)_{|\xi_* = 2 + \left(\frac{R}{\rho}\right)^2_*} & (\mathrm{QFD}) \\ 0 & (\mathbf{QCD}) \end{cases}$$



[AR '02]



[AR,F.Schrempp '98,'00]

- Increasing $\epsilon \Rightarrow$ smaller $(R/\rho)_*$ probed $\Rightarrow$ cross-section grow due to attractive nature of Ω_g in perturbative semi-classical regime

- **s-Wave Bound:**

  [Bezrukov,Levkov,Rebbi,Rubakov,Tinyakov '03; AR '03]

  – Lower bound on holy grail function $F_W(\epsilon)$ by calculating

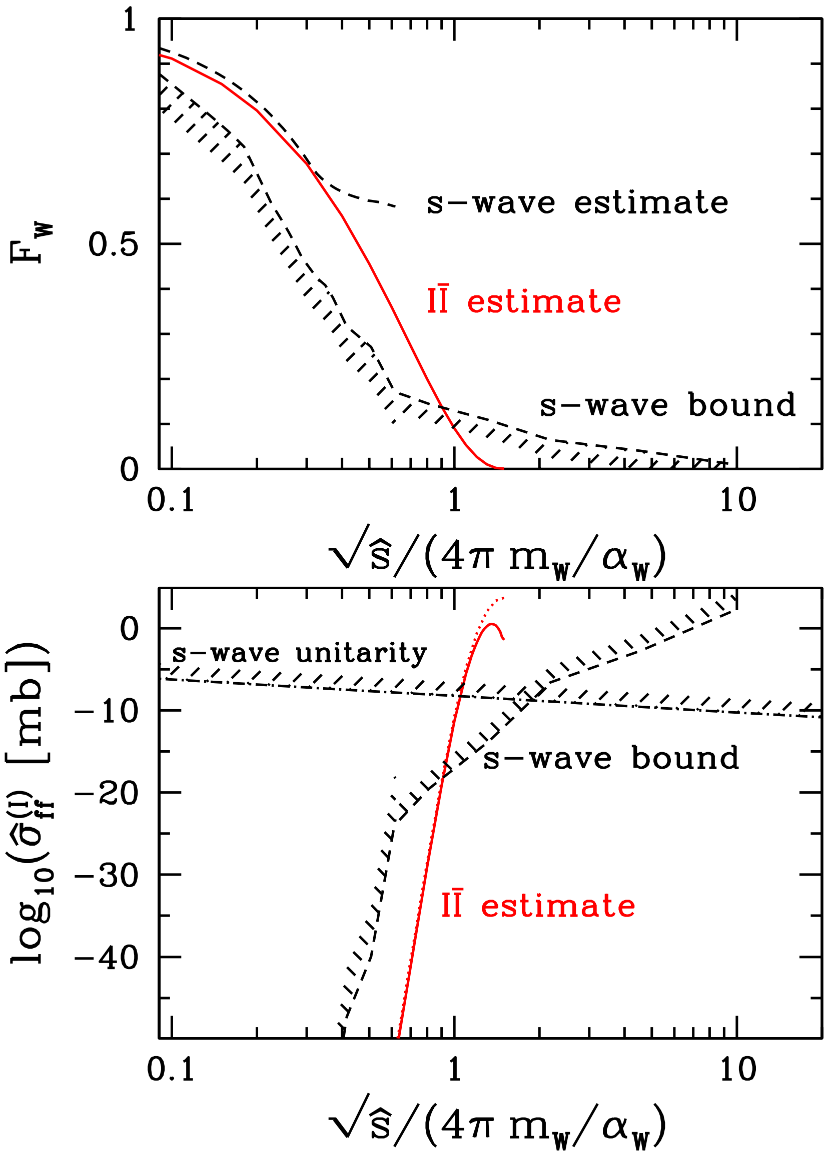
  $$n \equiv \frac{\tilde{n}}{\alpha_W} \xrightarrow{I_W} \text{all}$$

  processes semi-classically and extrapolating $\tilde{n} \to 0$

  – Considered only spherically symmetric configurations $\Rightarrow$ Bound applies only to s-wave scattering

  – Bound neither excludes observable cross-section at VLHC nor $\mathcal{O}(\text{mb})$ cross-section for cosmic neutrinos

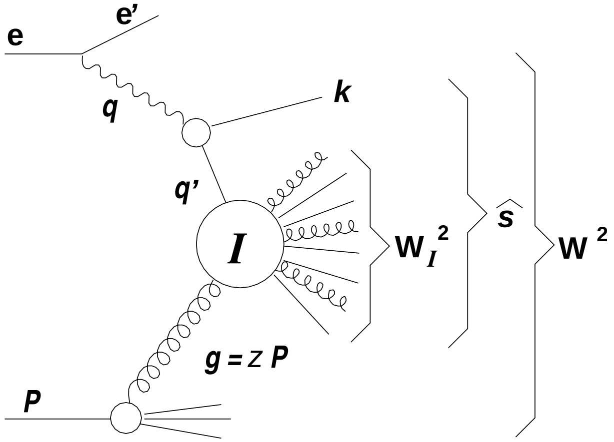
  – Latter requires substantial contribution from higher partial waves



3. QCD-Instantons at HERA

[AR,F.Schrempp '94–'01]

- **Kinematics:**



Deep-inelastic scattering variables:

$S = (e+P)^2$
$Q^2 = -q^2 = -(e-e')^2$
$x_{\rm Bj} = Q^2/\ (2P\cdot q)$
$y_{\rm Bj} = Q^2/\ (S\, x_{\rm Bj})$
$W^2 = (q+P)^2 = Q^2(1/x_{\rm Bj}-1)$
$\hat{s} = (q+g)^2$
$z = x_{\rm Bj}\ (1+\hat{s}/Q^2)$

Variables of instanton-subprocess:

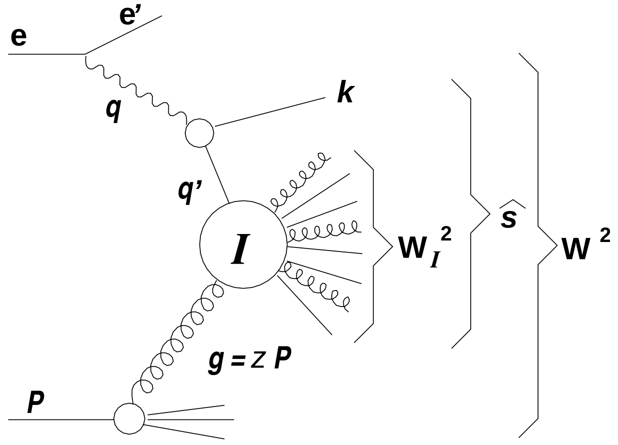
$Q'^2 = -q'^2 = -(q-k)^2$
$x' = Q'^2/\ (2\ g\cdot q')$
$W_I^2 = (q'+g)^2 = Q'^2(1/x'-1)$

- "Fiducial" kinematical region from lattice constraints: [AR,F.Schrempp '99;'01]

$$\left(\rho^* \Lambda_{\overline{\rm MS}}^{(0)} \lesssim 0.4, \frac{R^*}{\rho^*} \gtrsim 1.0\right) \Rightarrow \left(Q'/\Lambda_{\overline{\rm MS}}^{(n_f)} \gtrsim 30.8, x' \gtrsim 0.35\right)$$

Event generator **QCDINS 2.0:**

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

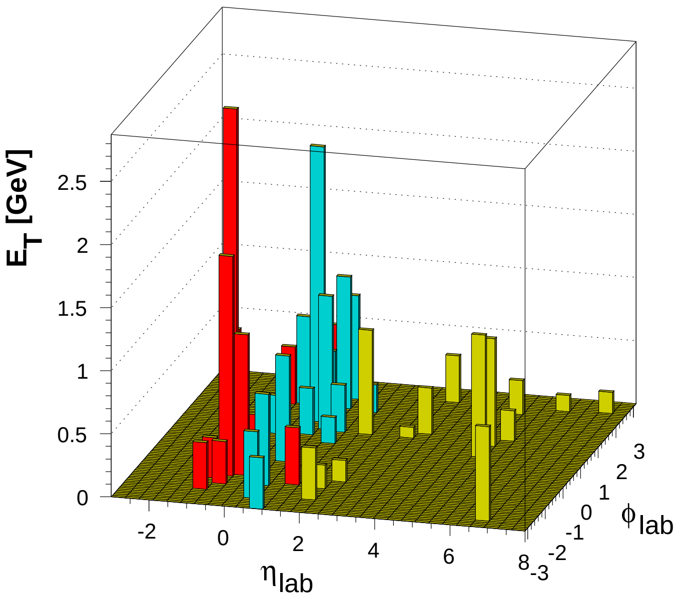


- **Hard subprocess:**
  - isotropic in $q'g$ CM
  - flavour democratic
  - large parton multiplicity

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

- **Parton shower** (**HERWIG**)

- **Hadronization** (**HERWIG** or **JETSET**)



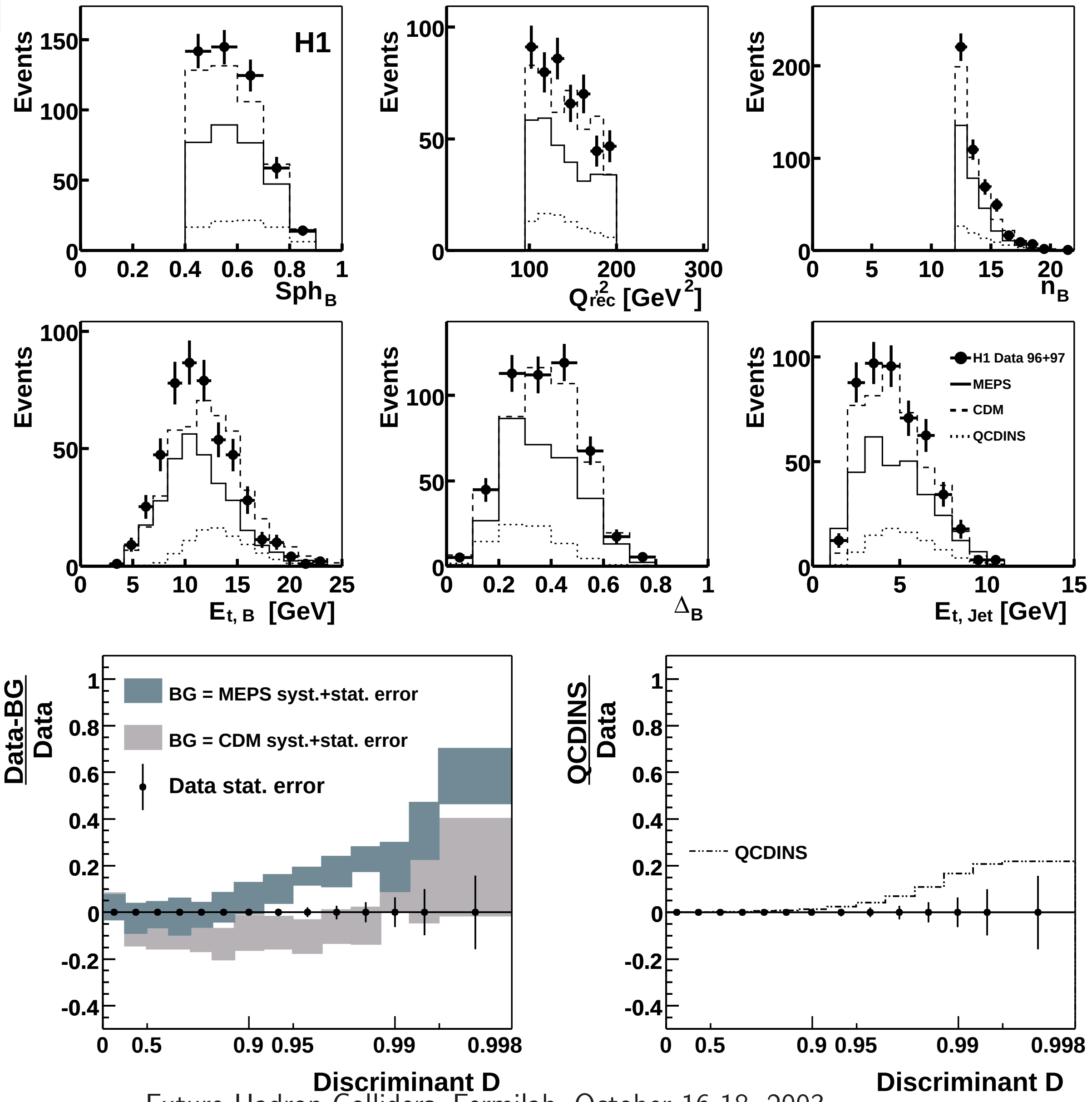
Dedicated search by H1 collaboration

[H1 collab. '02]

- Based on **QCDINS 2.0**, compared to **MEPS** and **CDM**
  - **Excess** with instanton-like topology, compatible with instanton signal
  - Statistical **significant** in comparison to **MEPS**
  - **Uncertainties** in background simulations?

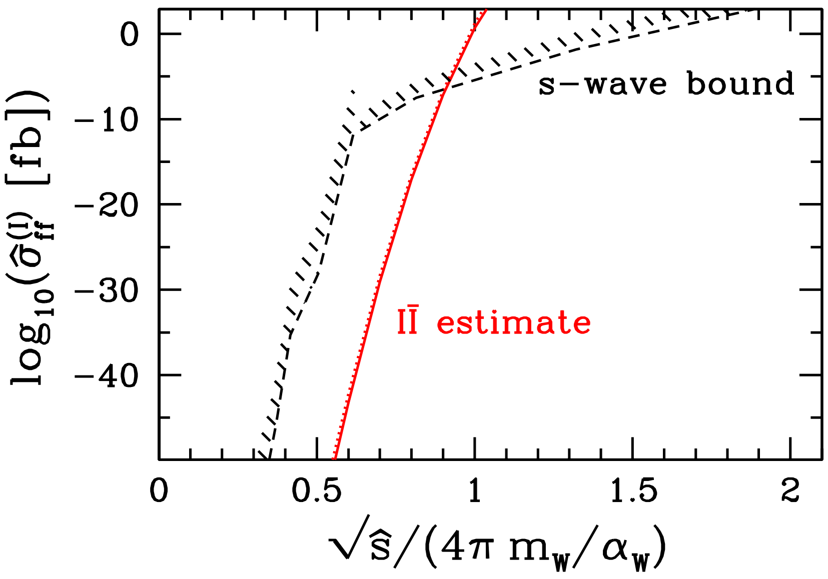
  $\Rightarrow$ **Upper limit on σ**

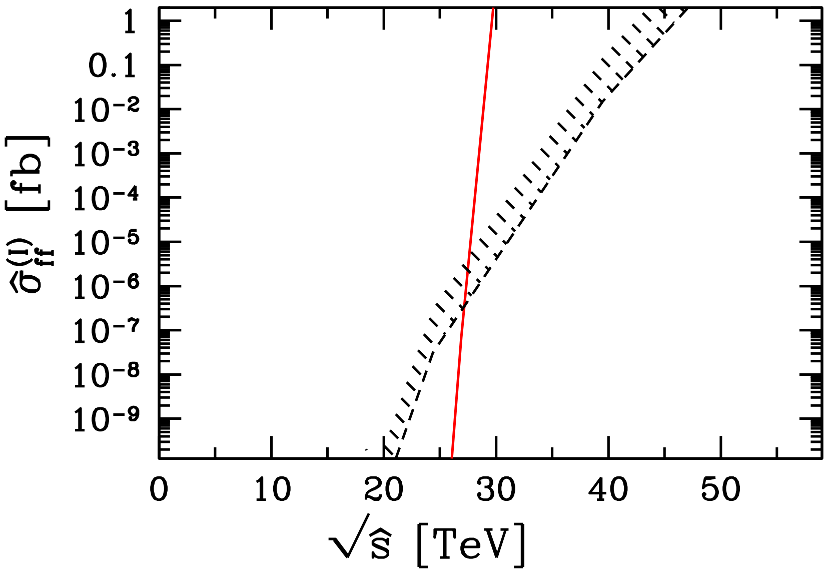
- Data do not exclude cross-section predicted for small $(R_*/\rho_*) \gtrsim 0.5$, as long as one probes small $\rho_* \ll 0.3$ fm



4. QFD-Instantons at VLHC?

- Lattice data as well as **H1** limit on small-size **QCD**-instantons suggest:
  - $I\bar{I}$ estimate reliable, as long as $(R/\rho)_* \geq 1$
  - For $(R/\rho)_* < 0.5 \div 1$, rapid growth, as implied by Ω, stops.
- Implications for **QFD**-instantons:
  - $(R/\rho)_* < 0.5 \div 1$ corresponds to $\epsilon < 0.75 \div 1.15$, $\sqrt{\hat{s}} < 22 \div 35$ TeV
  - At these energies, parton-parton cross-section estimates and bounds reach observable values





- **Estimate of $\sigma_{\rm pp}^{(I_W)}$**

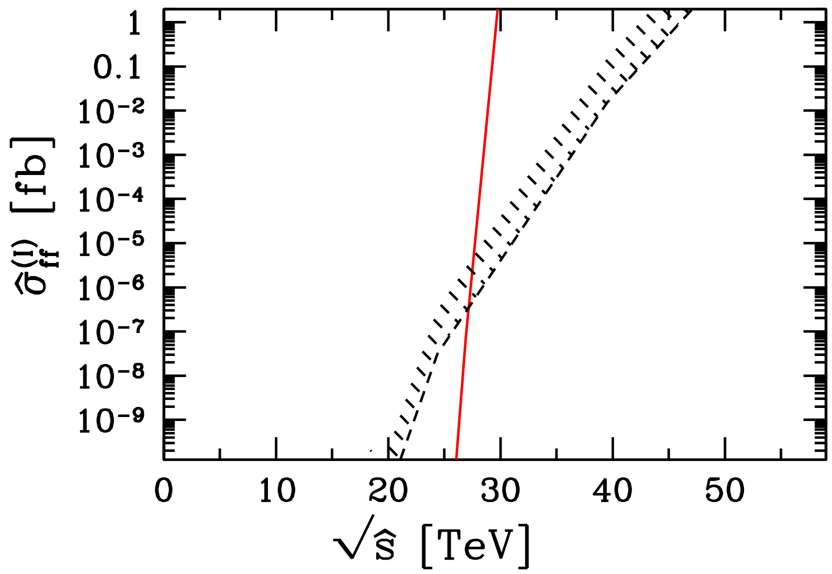
[AR,Tu (unpublished)]

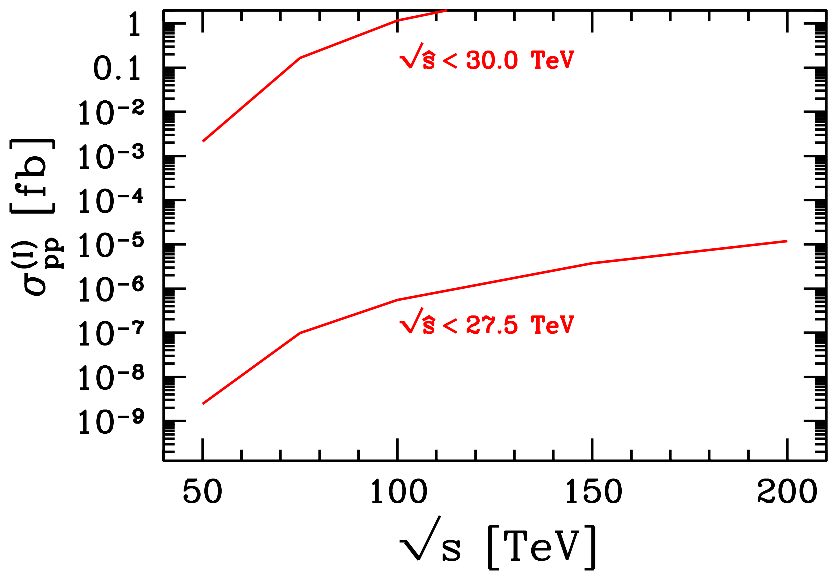
– **VLHC:**

$$\sqrt{s_{PP}} \approx 200\ \text{TeV}$$
$$\mathcal{L} \approx 6\cdot 10^2\ \text{fb}^{-1}\,\text{yr}^{-1}$$

– **Observable, $\gtrsim 10^{-3}$ fb**, if estimate valid/bound saturated up to $\sqrt{\hat{s}} \approx 28/35$ TeV.

$\Rightarrow$ Further study worthwhile





Phenomenology of QFD-instantons

[AR,F.Schrempp,Wetterich '91; Gibbs,AR,Webber,Zadrozny '94]

- No background from perturbative Standard Model processes by requiring
  - ≥ 4 identified charged e's or μ's
  - $E_T \geq$ several TeV
- **Event generator HERBVI:**

  [Gibbs,Webber '95]

  - B-violation cannot be established
  - **L-violation verifiable:** measure

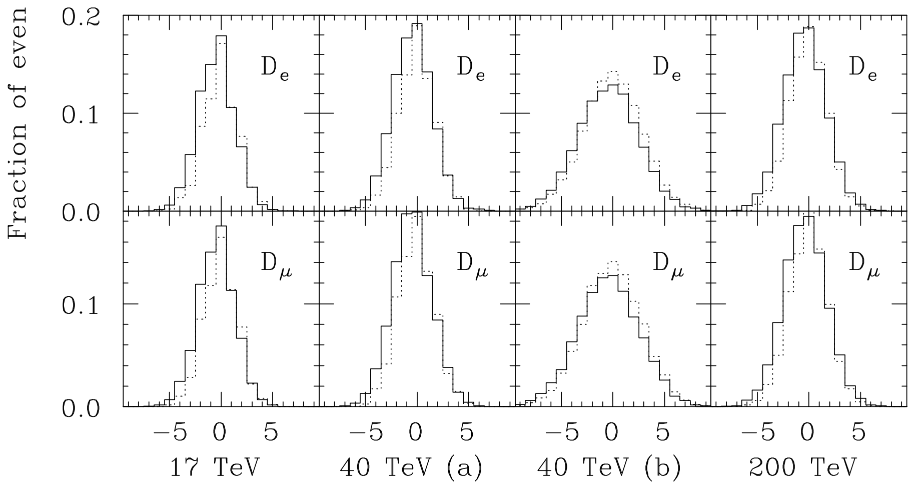
$$D_\ell = N_{\ell^-} - N_{\ell^+}\,;$$

need $\sim 10^3$ events

[Gibbs,AR,Webber,Zadrozny '94]

Simulations performed		
Energy (TeV)	n_B estimate	$\sqrt{\hat{s}_0}$ (TeV)
17	$1/\alpha_W$	5
40 (a)	$1/\alpha_W$	18
40 (b)	LOME	18
200	$1/\alpha_W$	18

[Gibbs,AR,Webber,Zadrozny '94]



5. Conclusions

- Opportunities to study **instanton-induced hard scattering processes**
- Need **future hadron collider** to explore **QFD** instantons and electroweak $B + L$ violation
- If cross-section exceeds even $\mathcal{O}(10\ \mathrm{nb/mb})$, first signs of electroweak sphaleron production may be/may already have been seen in neutrino nucleon scattering at **cosmic ray facilities and neutrino telescopes**

  [Morris,AR ‘94; Fodor,Katz,AR,Tu ‘03; Han,Hooper ‘03]

- Hard **QCD** instanton-induced deep-inelastic scattering processes

  $\Rightarrow$ can and are being probed presently at **HERA**
  – yield insight into fait of **QFD** instanton-induced processes at multi-TeV