QCD Instantons at the LHC

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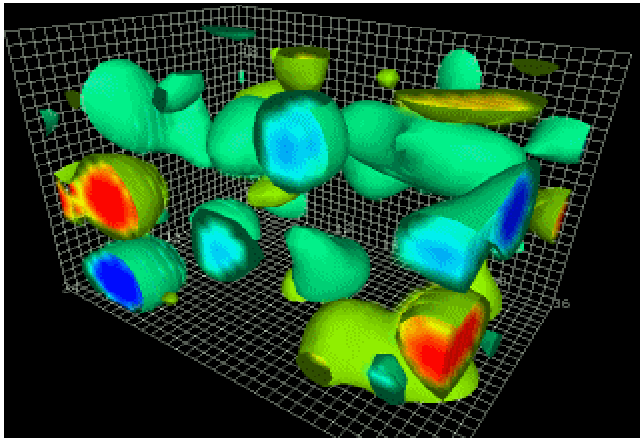
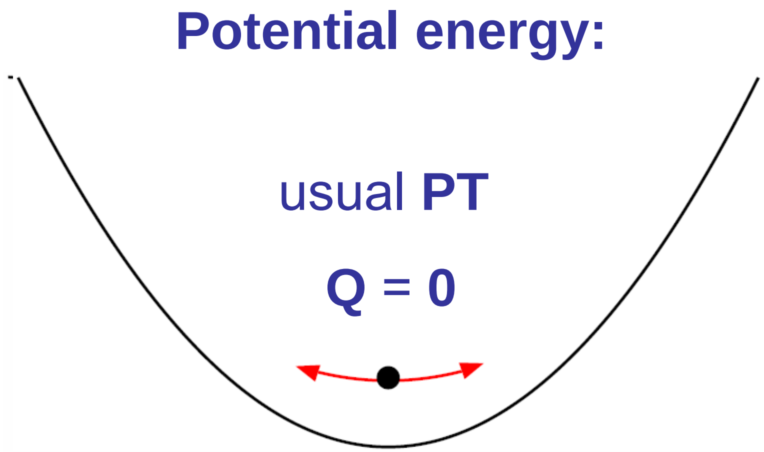
DESY

1. Introduction

- Huge effort to experimentally verify SM perturbation theory (**PT**) for hard processes..
- Yet 't Hooft '76: **hard** processes must exist that cannot be described by **PT,** despite α << 1! Induced by **topological** fluctuations of gauge fields.
- Rich vacuum structure of non-abelian gauge theories (QCD) ← Topology!
  Gauge fields carry an integer topological charge **Q = 0, ±1**,…↔ winding number

  Classical ground states energetically degenerate, but topologically distinct (fig)!





- (Anti) Instantons [Belavin *et al*. '75] ⟺ a **basic aspect** of the SM!
  explicitly known tunneling transitions between vacua differing by **Q = +1 (-1),**
  "instantaneous" in **time** and **space.**

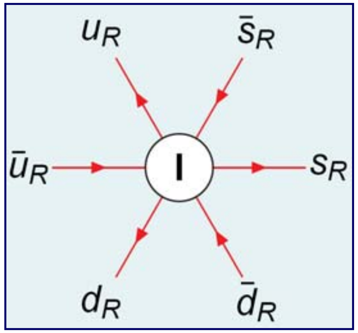
- **Theoretically**: QCD instantons known to play an important rôle in interface regime: partons → hadrons. E.g. chiral symmetry breaking, spectroscopy.. [Diakonov '96]

  Also: Instanton-driven gluon saturation at small x [F. Sch & Utermann '01-'04]
- **Yet… Direct experimental evidence for instantons still lacking!**
- **However:** [A. Ringwald & F. Sch. '94]

  Characteristic **short**-distance manifestation of instantons may be exploited for experimental search!

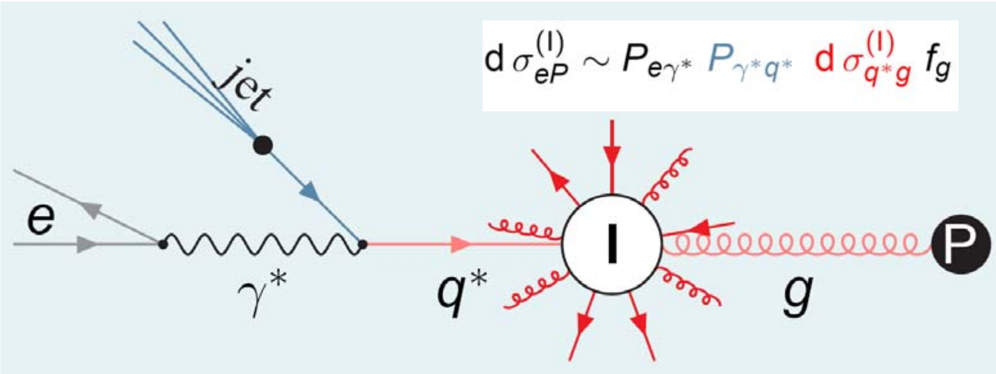
  - QCD I's induce hard, calculable, chirality-violating processes, forbidden in usual **PT** ! ['t Hooft '76]
  - Theoretical prediction of rate and characteristic event signature achieved in **DIS** (strict I perturbation theory) →

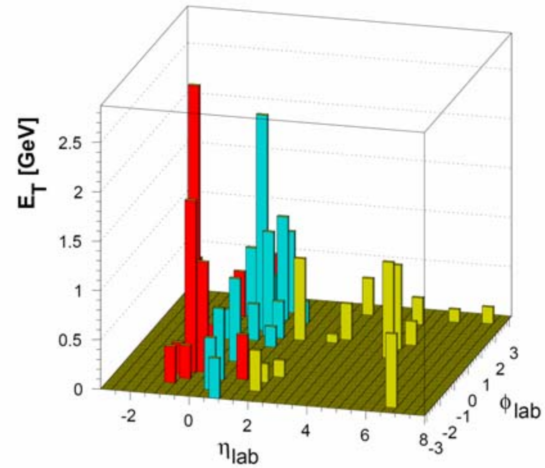
    rate in measurable range at **HERA**. [Ringwald & F. Sch. '94 - '01]
  - Two dedicated I-search experiments by **H1, ZEUS** **demonstrated** that required **exp. sensitivity is within reach**!



- Study in detail **discovery potential** for QCD instanton processes **@LHC!**
- Looking forward to data reanalysis in 2007 with ~750 pb^{-1} @ **HERA**!

1.1 Instantons at DESY





- A quick reminder:
- Extensive theoretical work
  Ringwald & F. Sch. **'94 - '01** & Moch (PhD '94-'97) & Utermann (PhD '00 – '03) & Petermann (PhD '04 – '07),
- Instanton Monte Carlo generator for HERA: **QCDINS [** Ringwald & F. Sch.] (fig. right)
- 2 instanton search experiments based on our work:

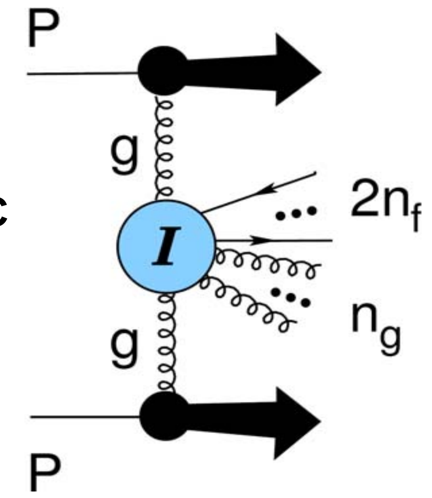
• **H1** $\left\{ \begin{array}{l} \int \mathcal{L}dt = \mathbf{21}\ \mathrm{pb}^{-1},\ \theta_{e^+} > 156^\circ,\ 0 < y < 0.6 \\ x > 10^{-3},\ \mathbf{10} \lesssim \boldsymbol{Q^2} \lesssim \mathbf{100}\ \mathrm{GeV}^2 \end{array} \right.$ • **ZEUS** $\left\{ \begin{array}{l} \int \mathcal{L}dt = \mathbf{38}\ \mathrm{pb}^{-1},\ y > 0.05 \\ x > 10^{-3},\ \boldsymbol{Q^2} \gtrsim \mathbf{100}\ \mathrm{GeV}^2 \end{array} \right.$

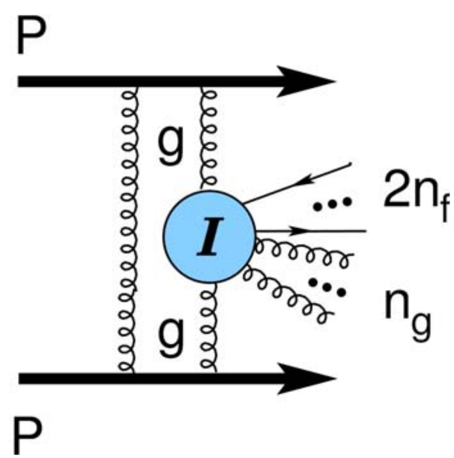
[**H1 Coll**., Eur.Phys. J. C 25 (2002) 495; **ZEUS Coll**., Eur. Phys. J. C 34 (2004)]

- While **H1** saw significant excess over **MC**'s in accord with our predictions, large remaining uncertainties from normal **DIS** event generators remained challenging…

2. Setting the stage for the LHC

- "Gold-plated" I - induced events **@LHC** ↔ best compromise between rate and bg-freedom!
- Very promising new method for bg-suppression **@HERA** & **@LHC** [Barakbayev, Boos, Lohrmann, Petermann & F.Sch. '06] in prep.
- Three main aspects to select dominant $I-$subrocess,
  1) counting powers of α_s and α_{em} ,
     - each external **non**-perturbative gluon: $\sigma \propto \frac{1}{\alpha_s}$
     - each external quark (**zero mode**): $\sigma \propto \mathcal{O}(1)$
  2) enhancements from parton densities
  3) subprocess dependent power-growth in $\hat{s} = E^2$, at lower energies for exlusive, exp-growth for inclusive processes!
- (1) & (2) → $g + g$ initial state strongly dominant as in usual **PT**
- Focus on general topology as in fig. (top). Interesting variant with 2 rapidity gaps and central "fireball" in fig. (bottom): "diffractive instanton" events…





2.1 Energy constraint

- The (inclusive) sum over multi-gauge boson final states is known to exponentiate,

$$\sigma^{(I)}_{\text{'t Hooft}} \sim \exp\left[-\frac{4\pi}{\alpha}\right] \quad \Rightarrow \quad \sigma^{(I)} \sim \exp\left[-\frac{4\pi}{\alpha} F_{\rm hg}\left(\frac{E}{m_{\rm sph}}\right)\right]$$

with the **"holy grail"** function $F_{\rm hg}$ and $0 \le F_{\rm hg} \le 1$, turning 't Hooft's tunneling factor (left) into a much weaker suppression (right), since $F_{\rm hg}\downarrow$ for E↑.

- The scale $m_{\rm sph}$ denotes the "sphaleron mass" (barrier height) for QFD and QCD:

$$m_{\rm sph} \approx \frac{3\pi}{4}\frac{1}{\alpha\,\rho_{\rm eff}} \approx \begin{cases} 4\frac{m_W}{\alpha_W} \approx 10\ \text{TeV} & (m_{\rm Higgs} \approx 115\ \text{GeV}) \quad \text{for QFD} \\ \mathcal{O}(1)\,\mathcal{Q} & (\ \text{virtuality}\ \mathcal{Q}) \quad \text{for QCD} \end{cases}$$

$\rho_{\rm eff}$ = effective instanton size

[Klinkhamer & Manton '84 (QFD); Ringwald & F. Sch '94 (QCD)]

- Resummation of gauge bosons (gluons) in final state via "valley approximation" & optical theorem. → [Yung '88]

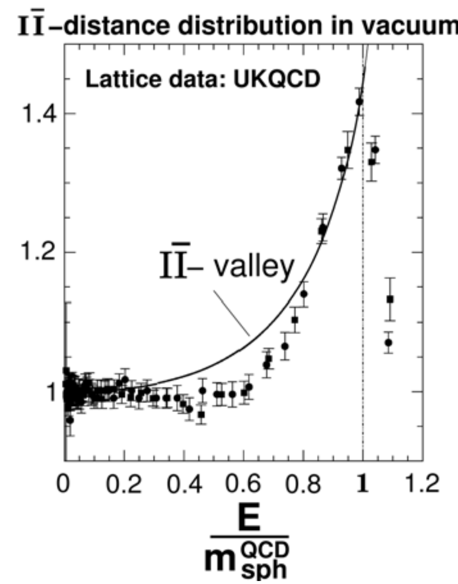
valley action $S^{I\bar{I}}_{\rm valley}$ formally known for all $\frac{E}{m_{\rm sph}}$ $\leftrightarrow$ $F_{\rm hg}$ "**known**"!
[Khoze & Ringwald '91, Verbaarschot '91]

Energy constraint

- **Crucial:** **when does the valley approximation break down??**

  2 direct, independent evidences for requirement: $\frac{E}{m_{\mathrm{sph}}} \leq \mathcal{O}(1)$

  QCD: [F. Sch. & Utermann '02]; QFD: [Rubakov, Rebbi *et al.* '03]

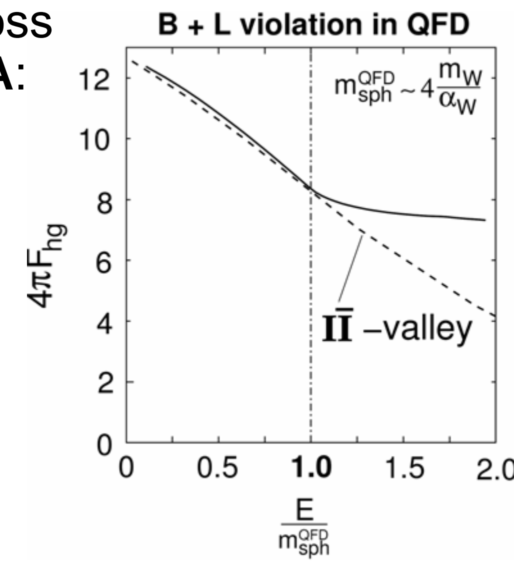


- This energy constraint is implemented in our LHC analysis.

  Since cross section increases with E until $E \approx m_{\mathrm{sph}}$, always work effectively near the "sphaleron"!

- Matches widely believed **"square root rule"** for instanton cross sections, which was also implemented for predictions **@HERA**:

$$E \text{ large} : \sigma^{(I)} \sim \sqrt{\sigma^{(I)}_{\text{'t Hooft}}} \sim \exp\left[-2\frac{\pi}{\alpha}\right], \text{ i.e. } F_{\mathrm{hg}} \to \frac{1}{2}$$

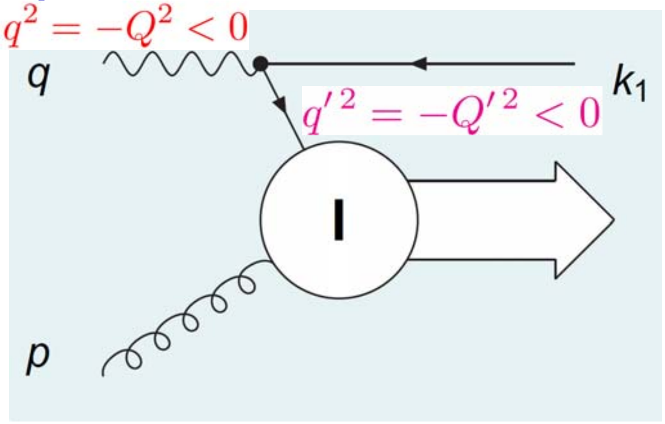


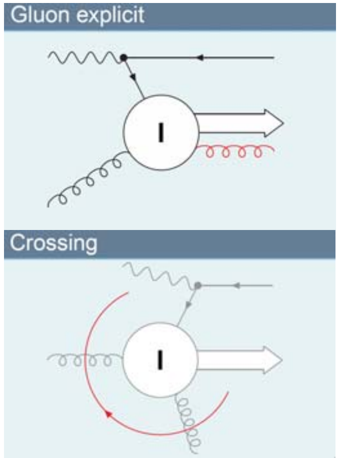
- **Note:** observability of B+L violation in QFD at the LHC would require **a far less conservative assumption**, i.e.

$$F_{\mathrm{hg}} \overset{E\to\infty}{\Rightarrow} 0$$

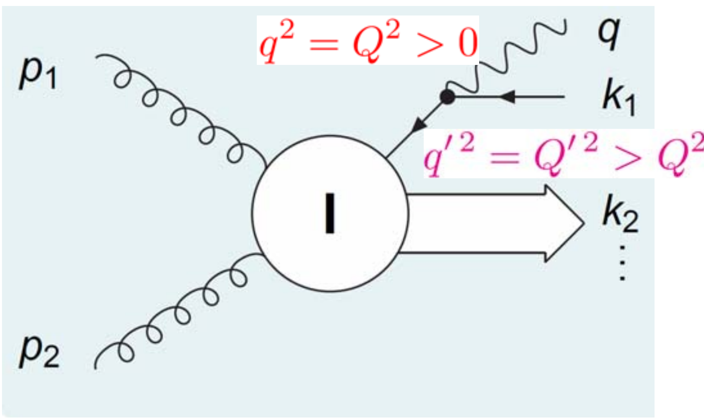
2.2 From HERA to the LHC by crossing

I-process @HERA





I-process @LHC



1 HERA variables

2 LHC variables

$-Q'^2 \equiv (q - k_1)^2 < 0$ $\Leftarrow$ **I - subprocess virtuality** $\Rightarrow$ $Q'^2 \equiv (q + k_1)^2 > 0$

spacelike **timelike**

$$x' \equiv \frac{Q'^2}{Q'^2 + s'} \in [0, 1] \qquad x' \equiv \frac{Q'^2}{Q'^2 - t'} \in [0, 1]$$

- **@HERA**: initial state, virtual $\gamma^*(Q)$

- **@LHC**: consider $\gamma(q_T), \gamma^*(Q)_{\to l^+l^-}, W^{\pm}(m_W)$ in final state together with a q-jet.

- **@HERA**, the I-subprocess virtuality Q'^2 **not** bounded by Q^2, hence need Q'^2 reconstruction and a respective cut!

  @LHC: $Q'^2 > Q^2$ kinematically! **Timelike virtuality** Q'^2 enforced in ***I*** – subprocess, by requiring a final state vector boson (fig)

$$\gamma(q_T), \gamma^*(Q)_{\to l^+l^-}, W^{\pm}(m_W) + \textbf{1 jet}$$

2.2 Event signature

- In I - rest system: **"fireball"** decaying isotropically to

$$n_f \cdot (q+\bar{q}) + \mathcal{O}\left(\frac{1}{\alpha_S}\right) \cdot g = \mathcal{O}(20) \text{ partons} \sim \mathcal{O}(60-80)$$ **hadrons**

- $u, \bar{u}, d, \bar{d}, s, \bar{s}$ **flavor "democracy"** in **each** event!

  strangeness $\Rightarrow K's, \Lambda's$

- Lego plot (η, φ, E_T) ⇒ **"I – band"**

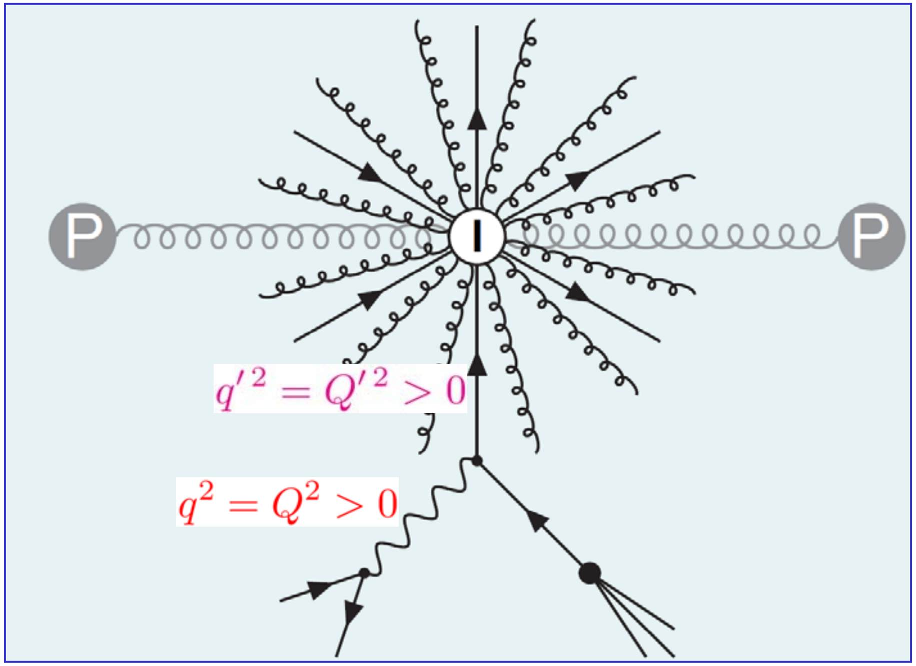
  Isotropy ⇒ small width $\Delta\eta = \pm 1$ in (pseudo-) rapidity η and isotropy in azimuth φ, large total E_T

- Every exclusive I-process grows initially with energy like a high power:

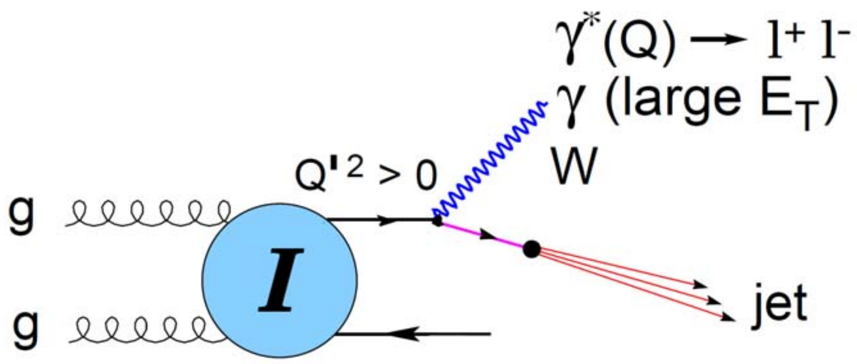
  $$\hat{\sigma} \sim \hat{s}^{\,3n_f+2n_g-5}$$

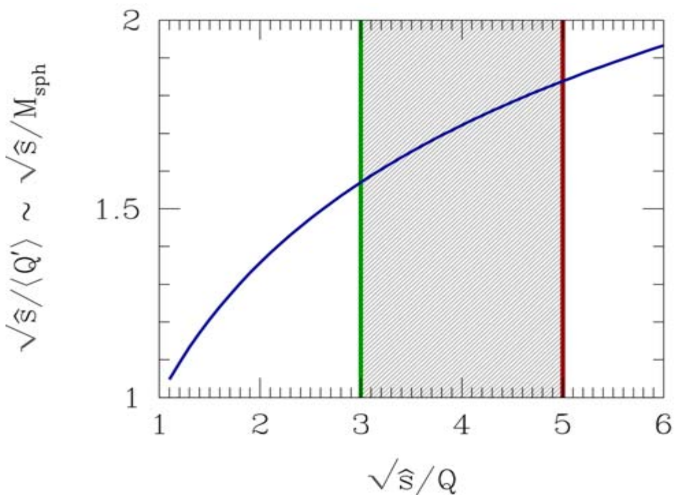
  (like a contact term)

"fireball" + vector boson + 1 jet



3. The simplest I-induced LHC process





- Like for **HERA**, idealized simplest I-process **@LHC**, $n_f = 1$ ⊕ no final-state gluons

  is very instructive (fig left)! Being **exactly calculable** in I-perturbation theory, many of its features remain valid after final state gluon resummation. Focus on such aspects.

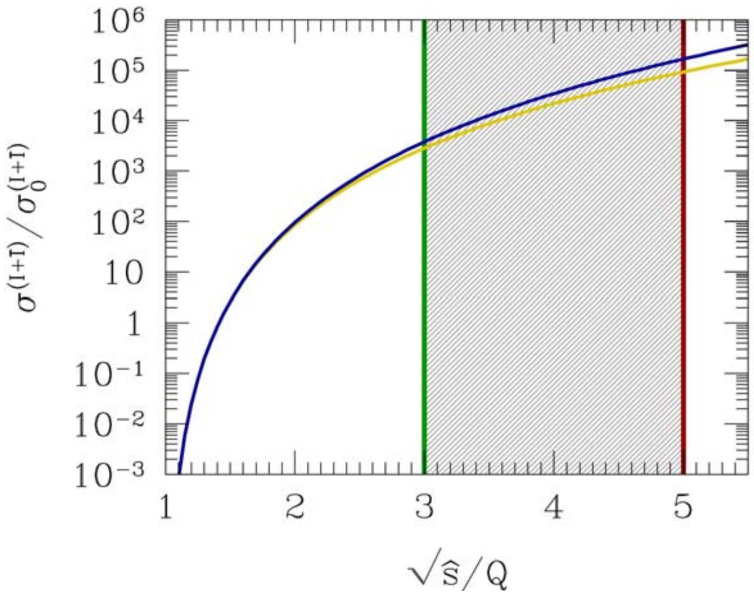
- Fig. right illustrates that **sphaleron mass** constraint may be characterized in terms of vector boson virtuality:

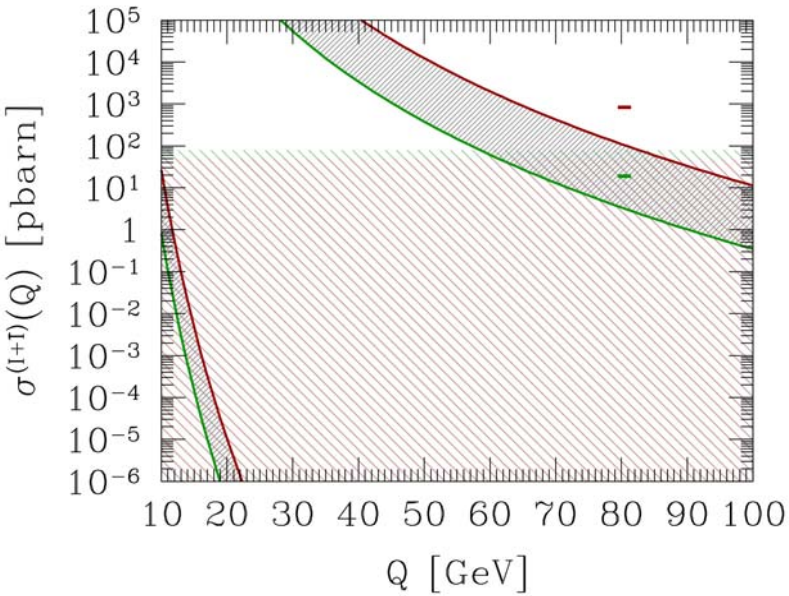
  $$3 \lesssim \frac{\sqrt{\hat{s}}}{Q} \lesssim 5 \Leftrightarrow \frac{\sqrt{\hat{s}}}{m_{\rm sph}} = \mathcal{O}(1) \text{ more/less conservatively}$$

  resulting from (known) form of Vqq' vertex in I-background!

- While rigorous calculation being still in progress, consider "poor man's" gluon resummation in terms of dominant effect: $F_{\rm hg} \to \frac{1}{2}$

3.1 Results



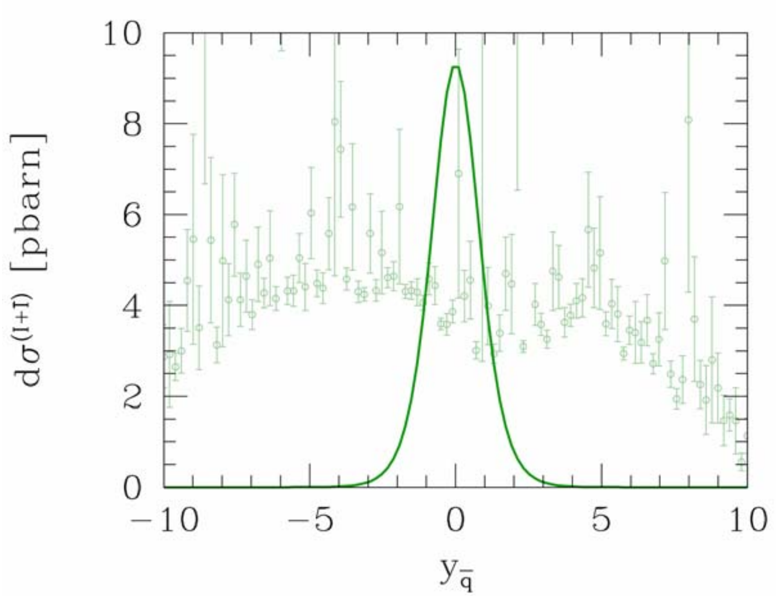


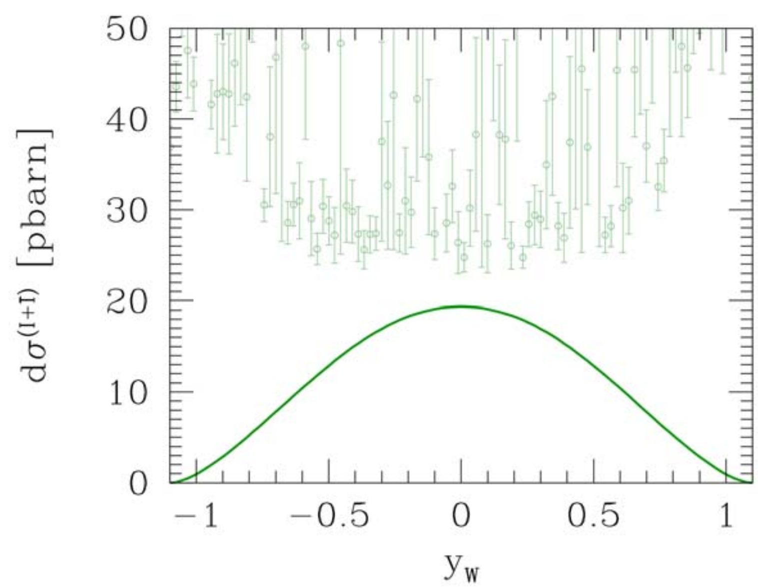
$g + g \Rightarrow \bar{q} + q + \gamma^*(Q)$ $\qquad$ $g + g \Rightarrow \bar{u} + d + W^+$ + cc

- Display a set of characteristic results for simplest processes and enhancements via "poor man's" gluon resummation that are expected to survive in fully realistic case.
- Fig. left: relative energy dependence and our two "sphaleron limits" (green, red lines)
- Fig. right: huge enhancement via "poor man's" gluon resummation. W final state not too small!

shaded region: normal, perturbative background, calculated with **Comphep**

Results

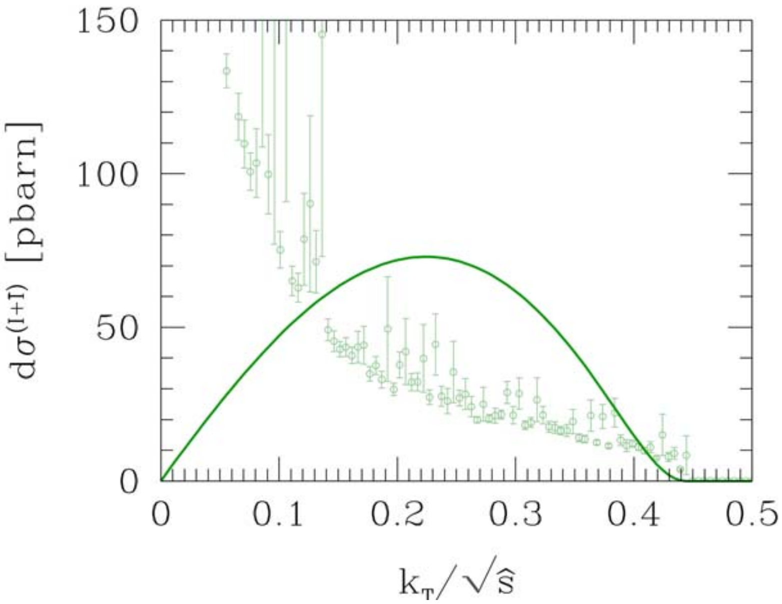


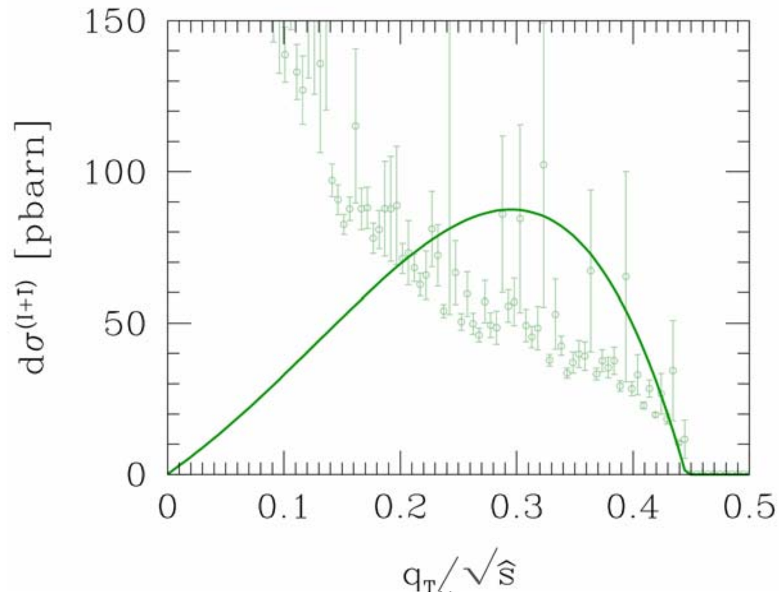


$$g + g \Rightarrow \bar{u} + d + W^{+}$$ + cc.

- **Rapidity distributions** for final state quark-jet and W, first for conservative "benchmark": $\sqrt{\hat{s}} = 3\, m_W$, and using "poor man's" gluon resummation.
- Normal SM background calculated with **Comphep**. "Errors" are Monte Carlo errors.
- Note: widths of rapidity profiles are uniformly ±1 unit, due to isotropy!
- Next: $\sqrt{\hat{s}} = 5\, m_W$: **signal / background improves a lot!**

Results





$$g + g \Rightarrow \bar{u} + d + W^{+}$$ + cc.

- **Transverse momentum distributions** for final state quark-jet and W, first for conservative "benchmark": $\sqrt{\hat{s}} = 3\, m_W$, and using "poor man's" gluon resummation.
- Normal SM background calculated with **Comphep**. "Errors" are Monte Carlo errors.
- Again for $\sqrt{\hat{s}} = 5\, m_W$: **signal / background improves a lot!**

4. Conclusions & Outlook

- Search for instanton processes concerns a **basic** non-perturbative aspect of QCD!
- Calculations for the “simplest I-induced LHC process”: **completed & promising**.
- Explicit gluon resummation via the “valley method” and (saddle point) integration over the 9 (!) collective instanton coordinates is difficult (**timelike** virtuality!) and still in progress.
- Yet, the presented “poor man’s” gluon resummation estimates give rise to optimism!
- **Higher “fireballness”** of I-events is expected compared to **HERA,** due to increased phase space @**LHC**!
- Important relations of I-predictions @**LHC** to those @**HERA** due to **crossing**.

Outlook:

- Explore new method of background suppression for LHC [Barakbayev, Boos, Lohrmann, Petermann & F.Sch. ‘06]
- With Tancredi Carli/CERN & friends: LHC observables…QCDINS@LHC (C++)…