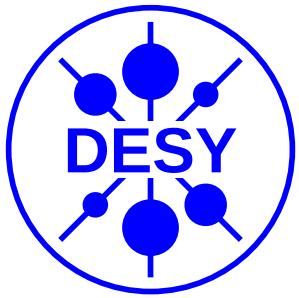
Search for QCD-Instantons at the LHC

Theoretical aspects

M. Petermann F. Schrempp



DESY, Theory Group, Hamburg

DESY Theory Workshop 2006

Overview

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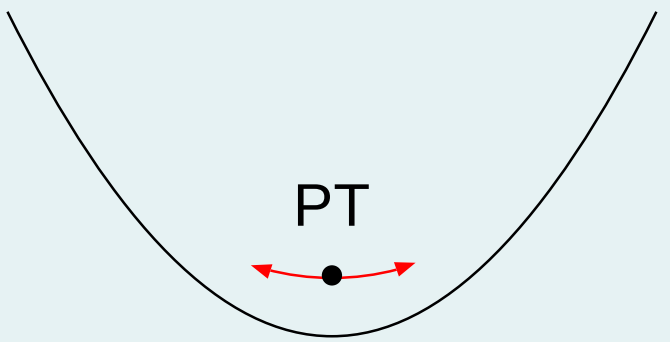
What are instantons?

Gauge potential



1. Ordinary perturbation theory (PT)
   - small vacuum fluctuations
   - cl. vacuum topologically degenerated $\Rightarrow$ winding number
   - potential wall $\Rightarrow$ sphaleron energy
   - no tunneling processes between vacua
2. Instantons (I)
   - special gauge field configurations $A^{(\mathrm{I})}$ of nonabelian gauge theories
   - certain classical solutions in Euclidean space time
   - carry factor $1/\sqrt{\alpha}$

[Belavin et al '75]

Tunneling processes between topologically distinguishable vacua with different winding number ['t Hooft '76]

Fundamental part of each nonabelian gauge theory like QCD or EW theory!

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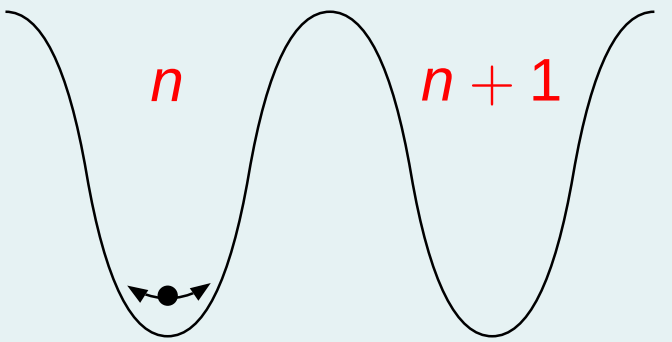

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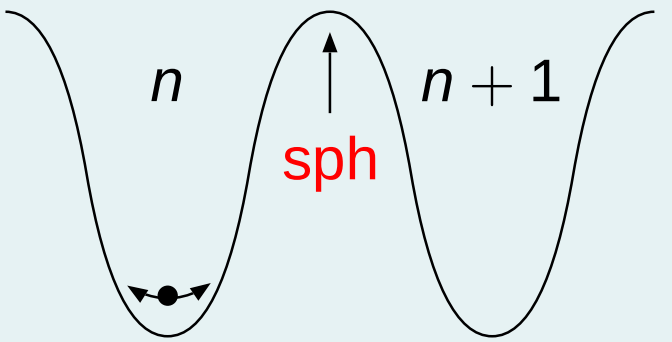

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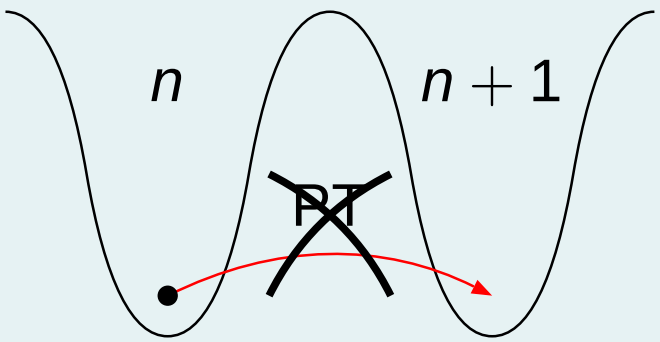

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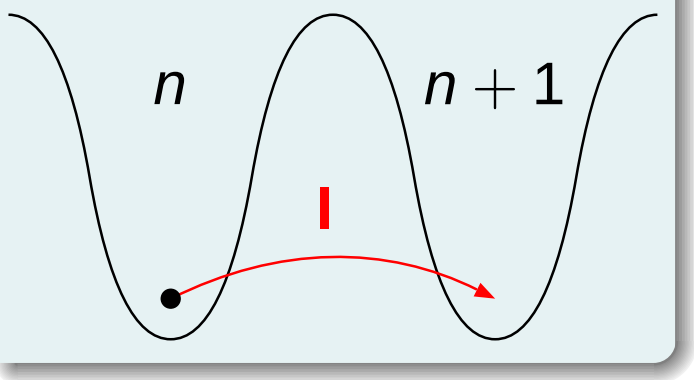

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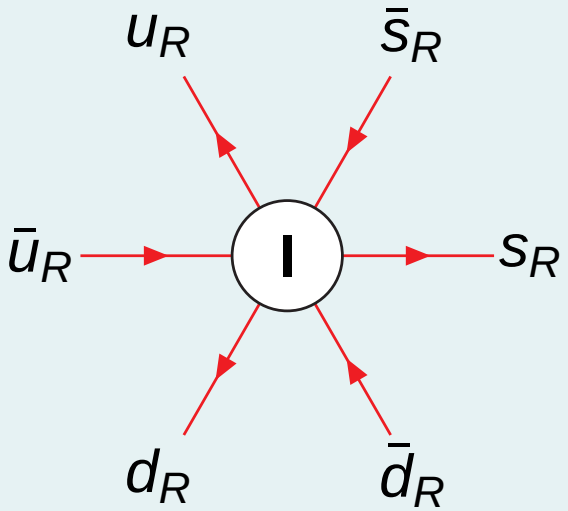
Physical impact in the SM

Chirality violation



1. Electroweak theory
   - $B + L$ violation
   - probably non measurable
2. QCD with light quarks
   - chirality violation
     $\Delta\chi = 2n_f \cdot Q_T$ (ABJ anomaly)
   - Q_T topological charge:
     PT: $Q_T = 0$, I: $Q_T = \pm 1$
     $\Rightarrow 2n_f$ quarks with equal helicity!
   - spontaneous χ symmetry breaking $\Rightarrow$ hadron masses

- play essential role for transition region between partonic and hadronic description.

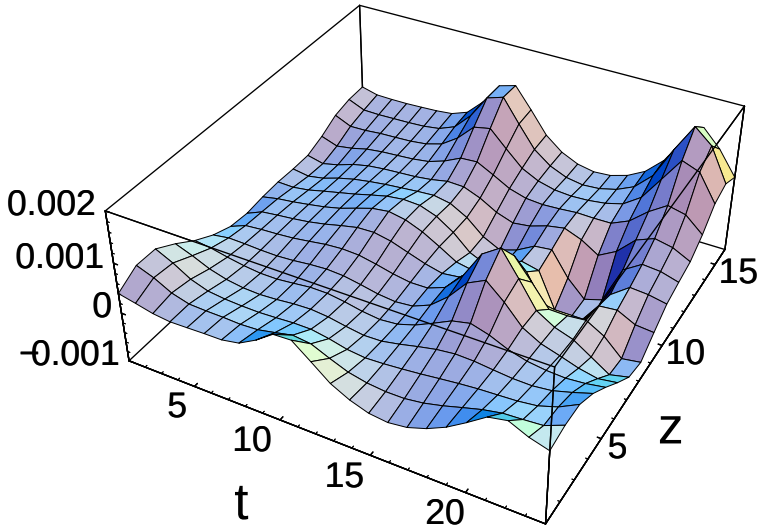
However, a direct experimental verification is still absent!

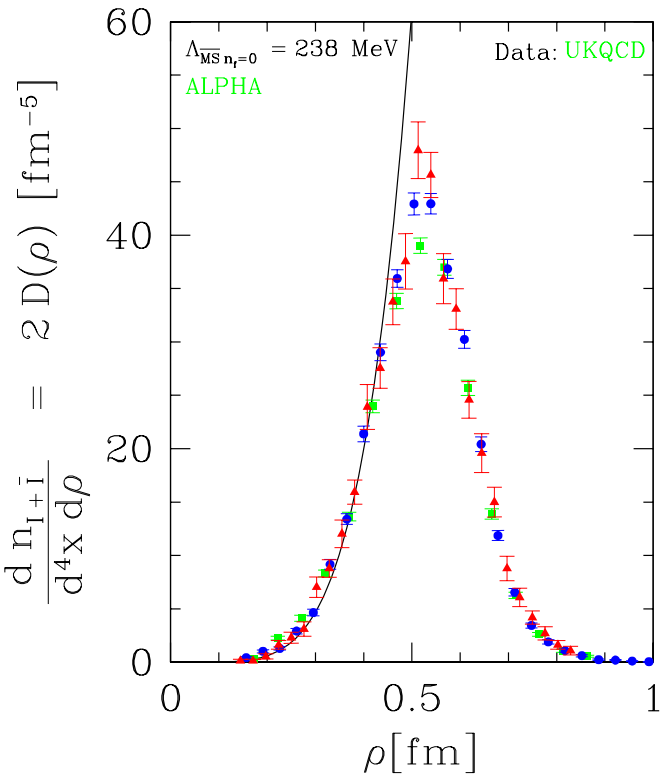
Ab initio methods

1 Lattice

- in principle always applicable
- ideal for pure gluodynamics
- Fig. lattice simulation of Q_T density
  $\Rightarrow$ instantons and anti instantons

[Chu et al '94]



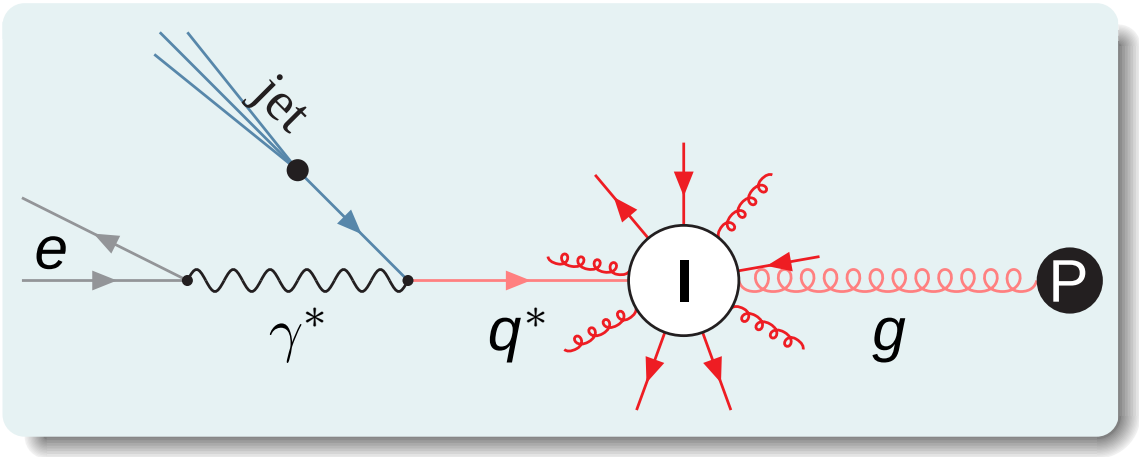


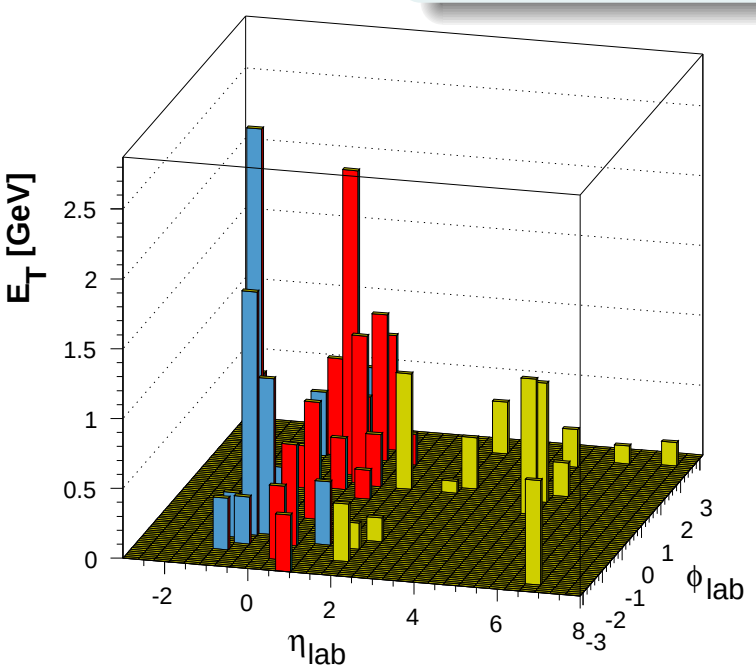
2 I-perturbation-theory

- PT with I-background field
- fluctuations around I-vacuum transition
- I-interactions between quarks and gluons
- needs large momentum transfers
  $\Leftrightarrow$ small instantons ($\rho < 0.35$ fm)
- I-size-distribution $D(\rho)$ (Fig. left)

[UKQCD Coll. '98; Ringwald, Schrempp '99]

Instantons at HERA

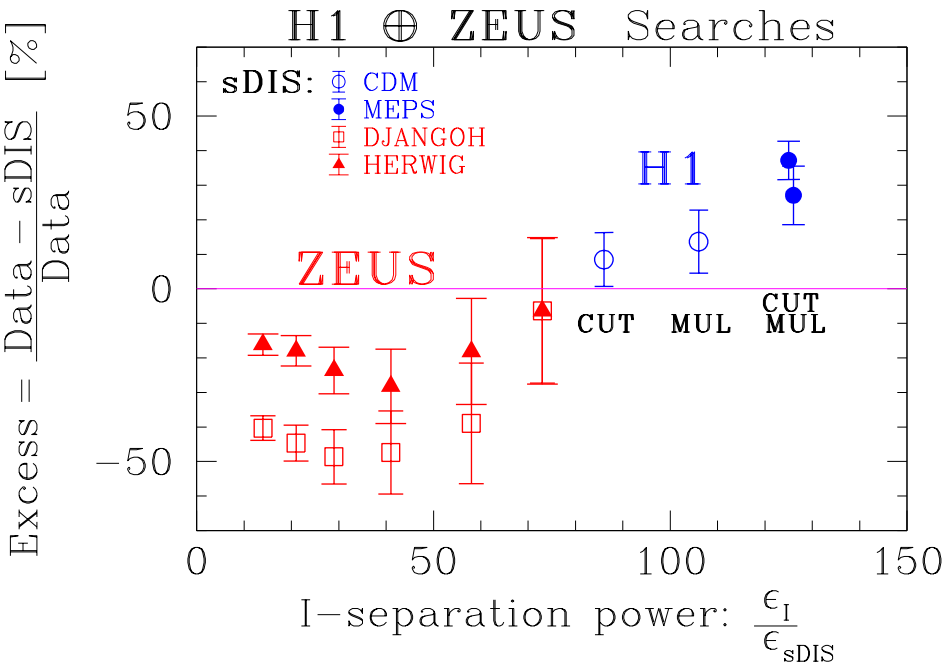




- eP collision with $E_{\text{cm}} \approx 318\,\text{GeV}$ ($\sim 30\,\text{GeV}$ und $\sim 900\,\text{GeV}$)
- virtual photon γ^* in initial state
- signature: jet plus narrow band in η
- factorization of cross section

$$\mathrm{d}\,\sigma^{(\mathrm{I})}_{eP} \sim P_{e\gamma^*}\; P_{\gamma^* q^*}\; \mathrm{d}\,\sigma^{(\mathrm{I})}_{q^* g}\; f_g$$

Experimental status



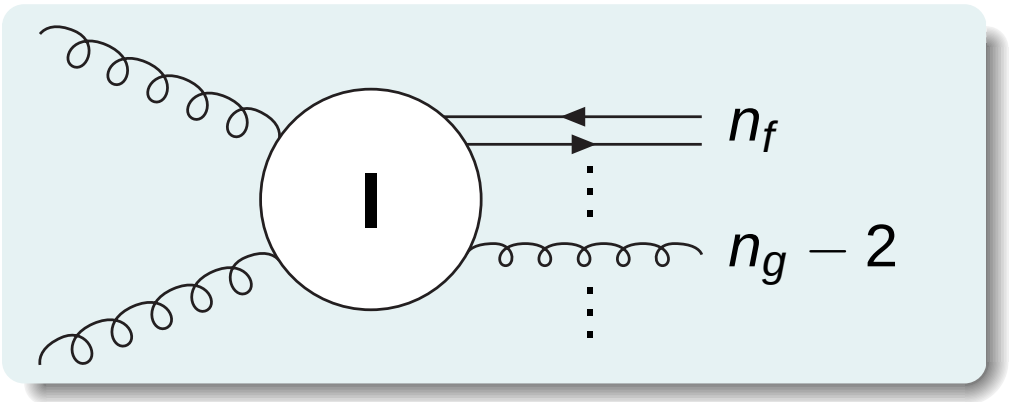
1. Data (HERA '96 until '97)
   - luminosity: $21/\text{pb}$ (H1), $38/\text{pb}$ (ZEUS)
   - excess vs. I-sep.-power
   - additional cuts at ZEUS
   - observable correlation!
2. HERA II (until 2007)
   - multiple luminosity $L_{'07} \gtrsim 500/\text{pb}$
   - possibility of sharper cuts

A study of the HERA II data seems to be very promising!

Leading I-process at the LHC

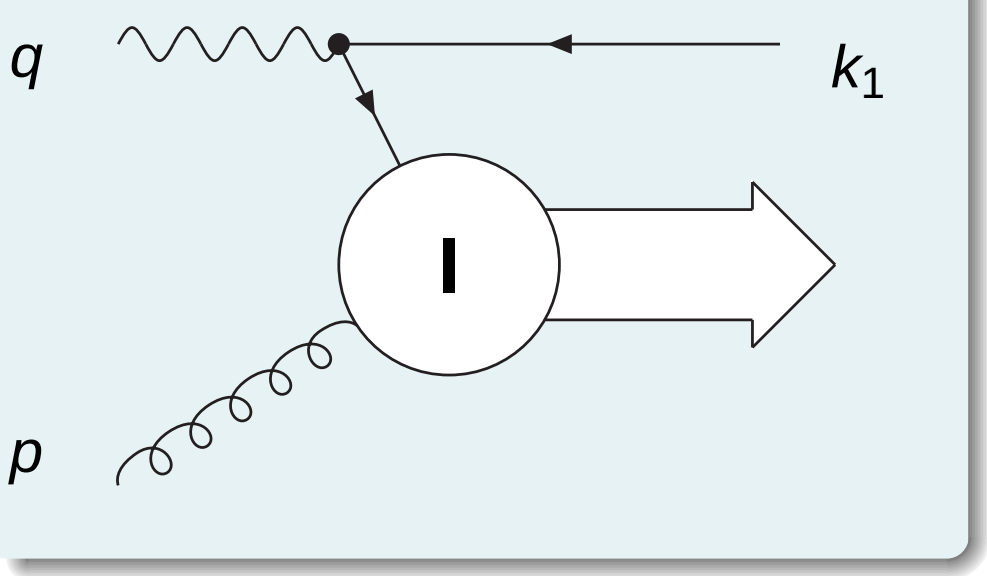
- PP-collision with $E_{\text{cm}} \approx 14\,\text{TeV}$
- initial state consist of quarks and gluons
- parton distribution prefers gluons
- additionally for non pert. gluon in I-background: $\sim \frac{1}{\alpha_s}$ in σ

  $\Rightarrow$ initial state with 2 gluons preferred
- final state with $n_f(q_R + \bar{q}_R)$ and $n_g - 2$ gluons



From HERA to the LHC via crossing

I-Prozess at HERA



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$$-Q'^2 \equiv (q - k_1)^2 < 0$$

$$x' \equiv \frac{Q'^2}{Q'^2 + s'} \in [0, 1]$$

2. LHC variables

$$Q'^2 \equiv (q + k_1)^2 > 0$$

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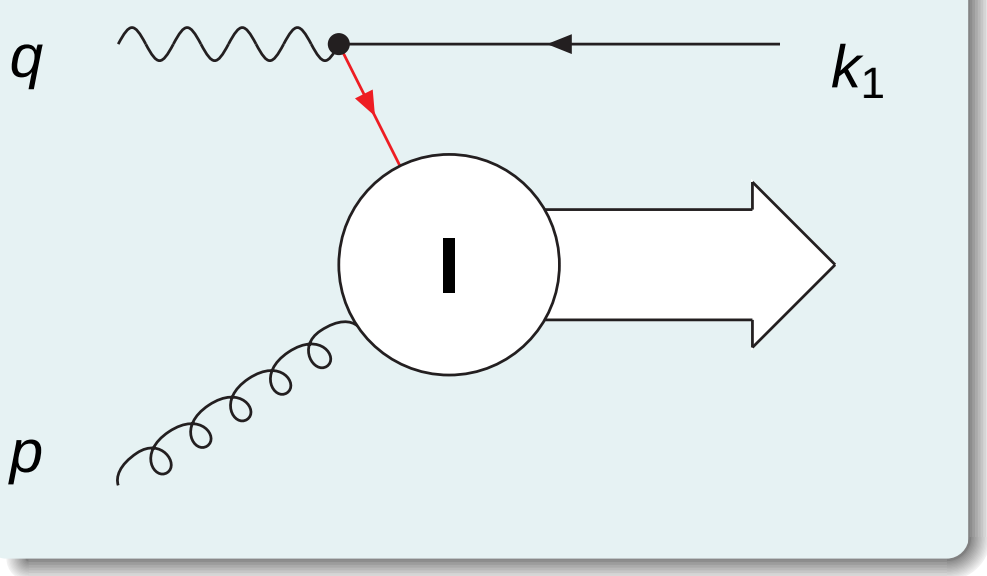
LHC process related to HERA by crossing
Virtuality is in the final state and time like
Emission of a virtual vector bosons with large P_T

From HERA to the LHC via crossing

Virtuality space like



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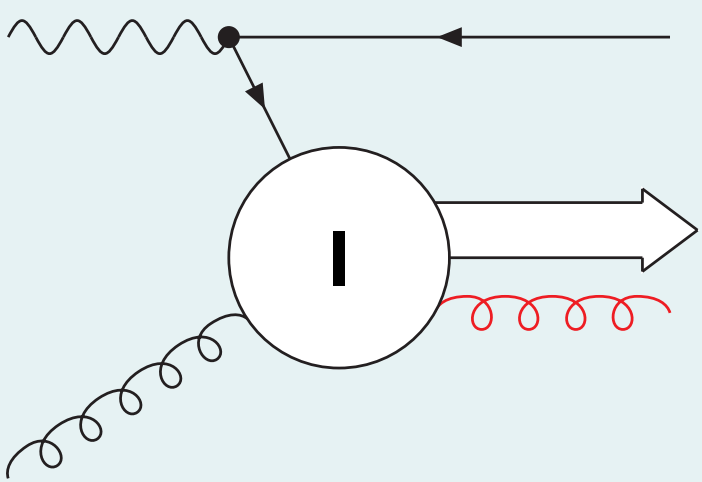
Gluon explicit



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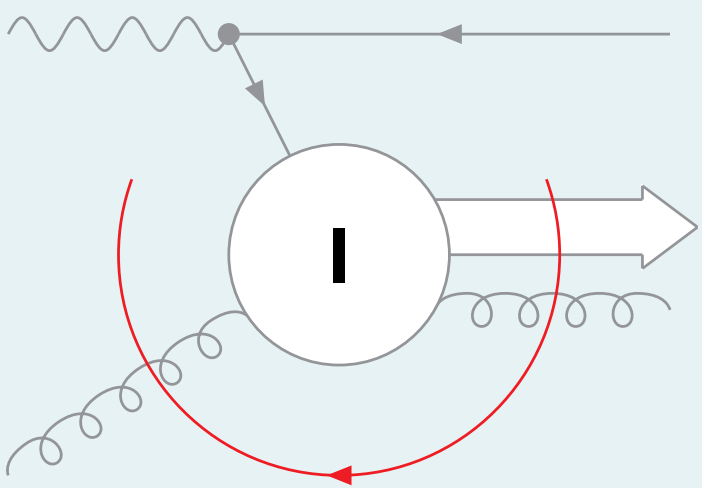

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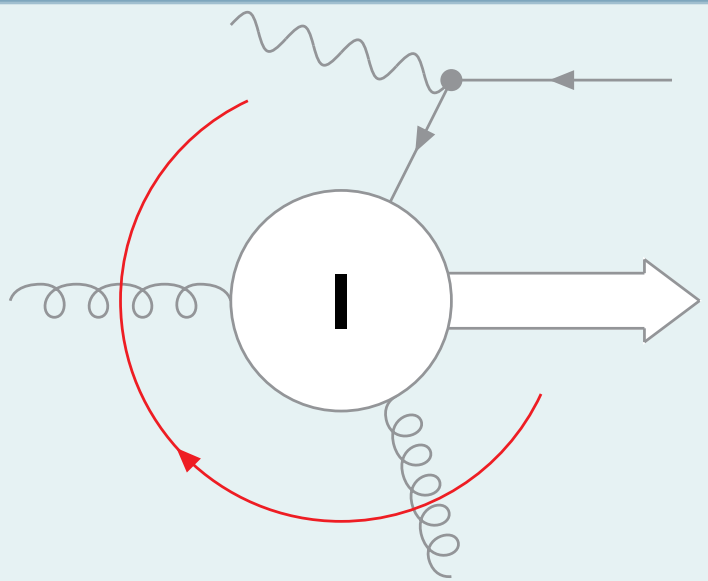

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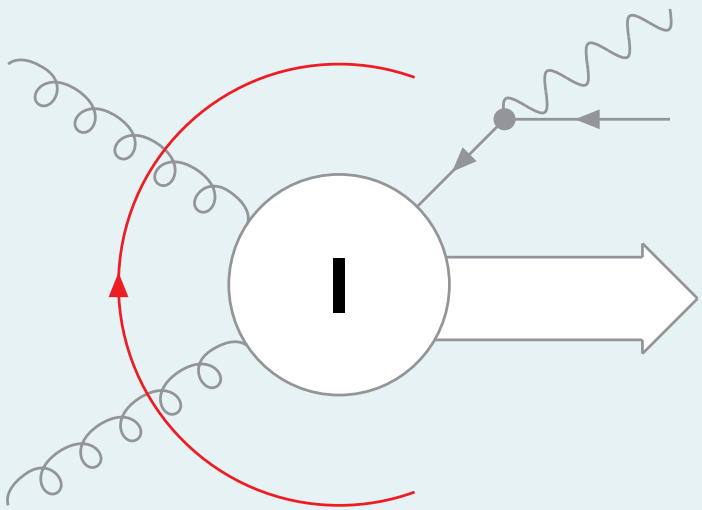

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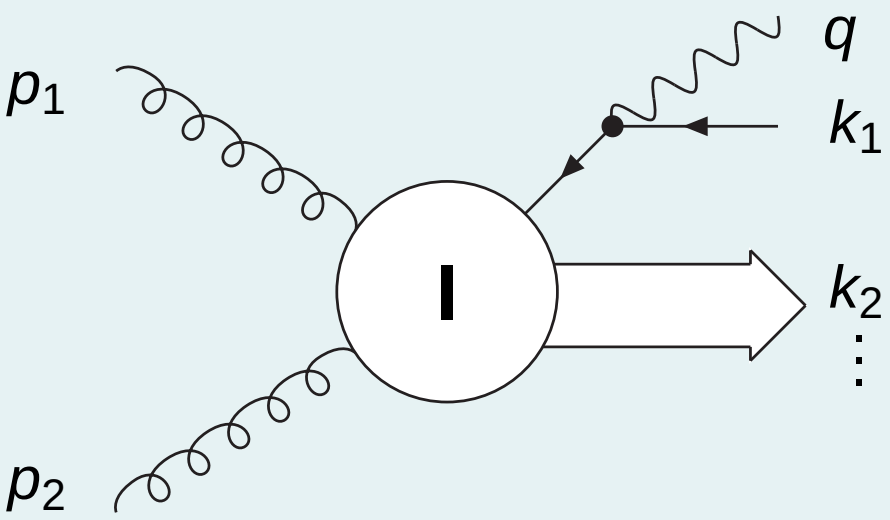

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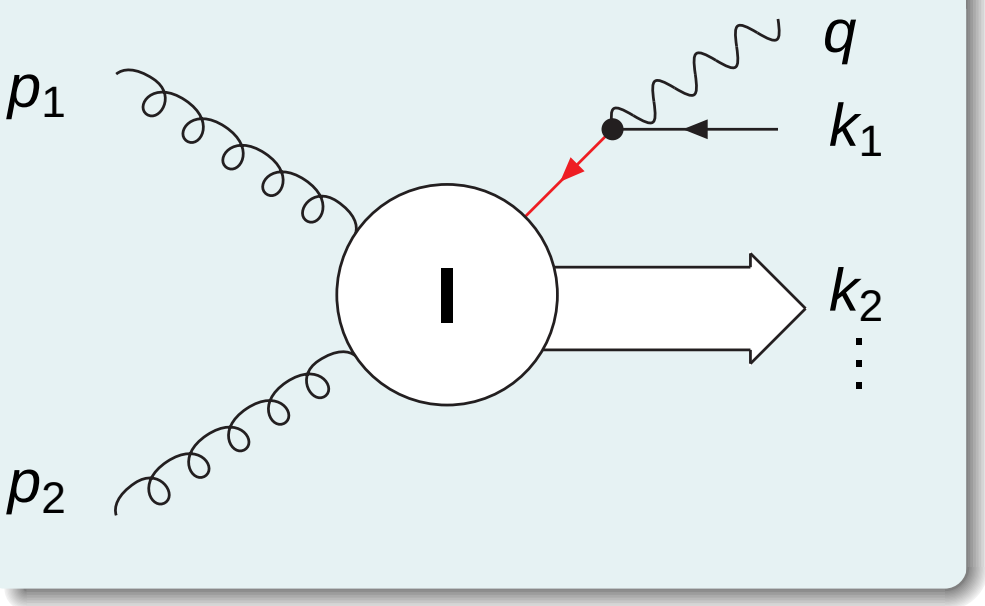

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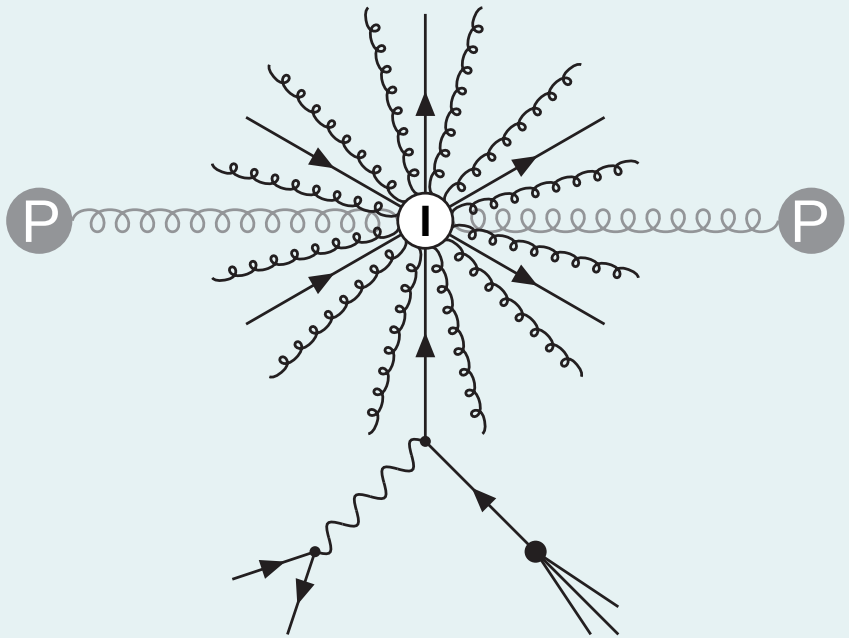
Expected signature at the LHC

- 3 light flavors: u, d and s
  $\Rightarrow$ 6 quarks and antiquarks
- $\mathcal{O}(1/\alpha_s) \sim 10$ gluons
- behave like contact term
  $\Rightarrow \hat{\sigma} \sim \hat{s}^{\,3n_f+2n_g-5}$
- momentum distribution isotropic
  $\Rightarrow$ narrow band in rapidity
- $Q', Q \geq 10\,\text{GeV} \Leftrightarrow \rho \leq 0.35\,\text{fm}$
  $\Rightarrow$ reconstruction by q-jet and (virtual) photon with high P_T

Fireball with jet and photon



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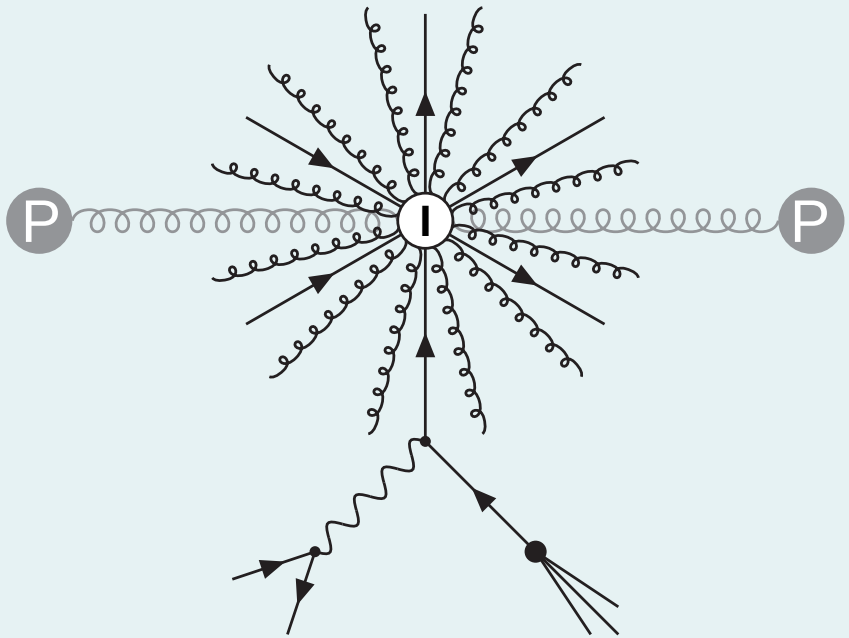

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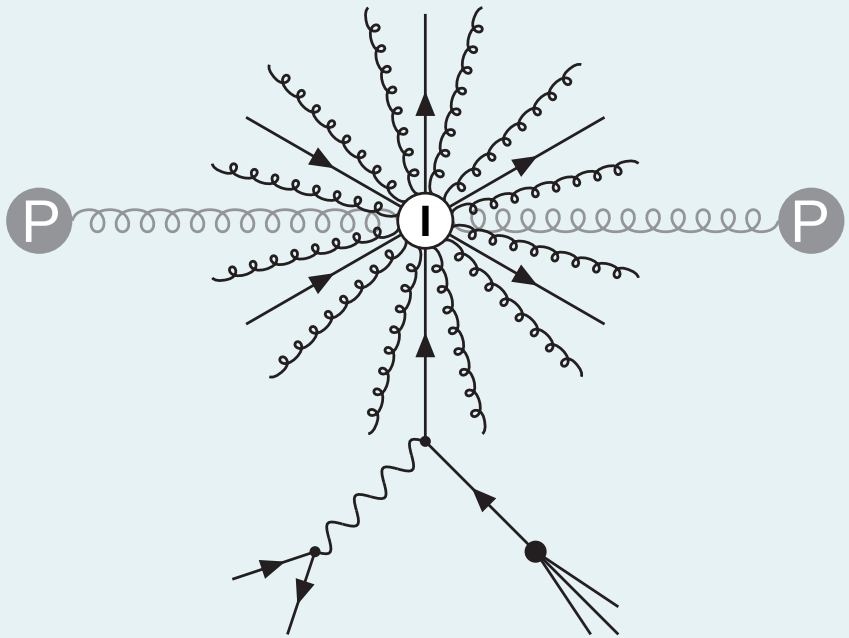

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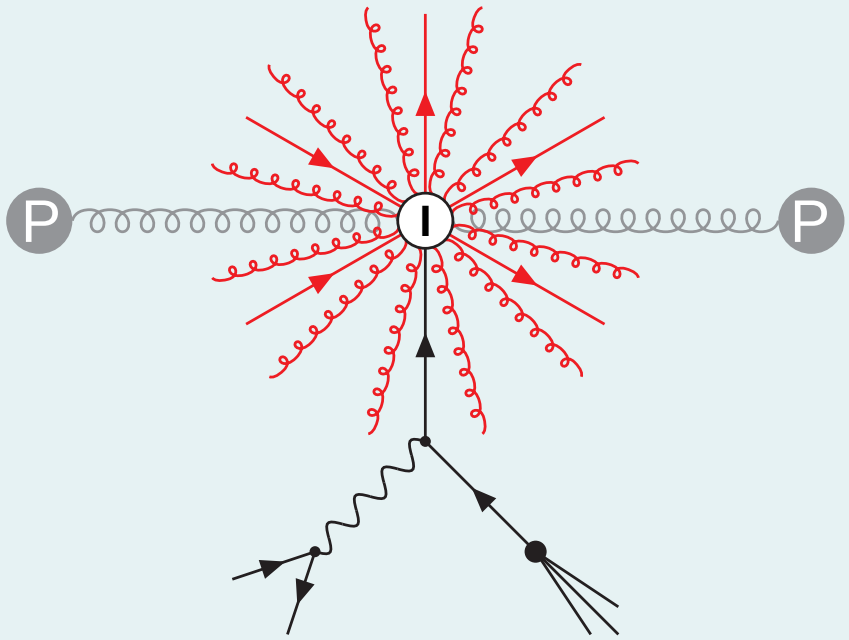

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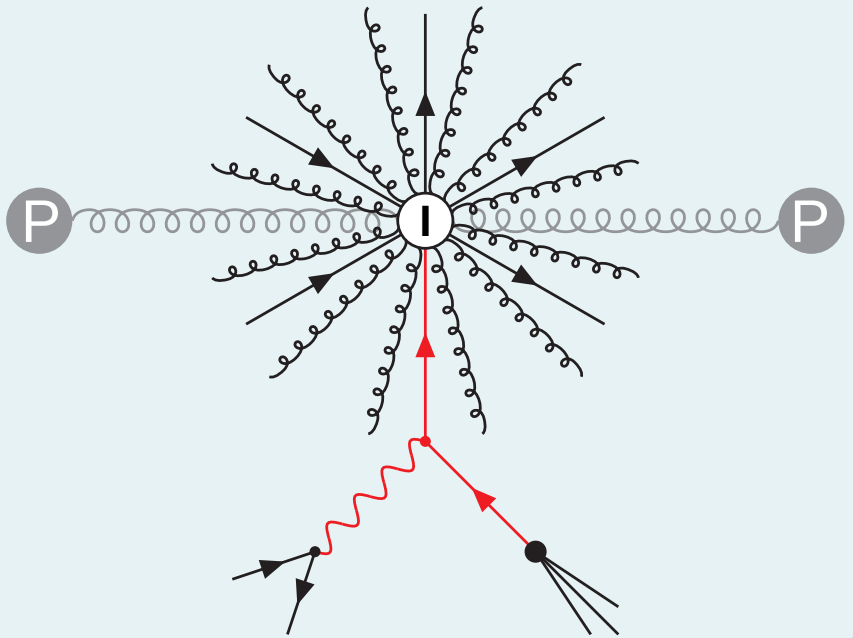

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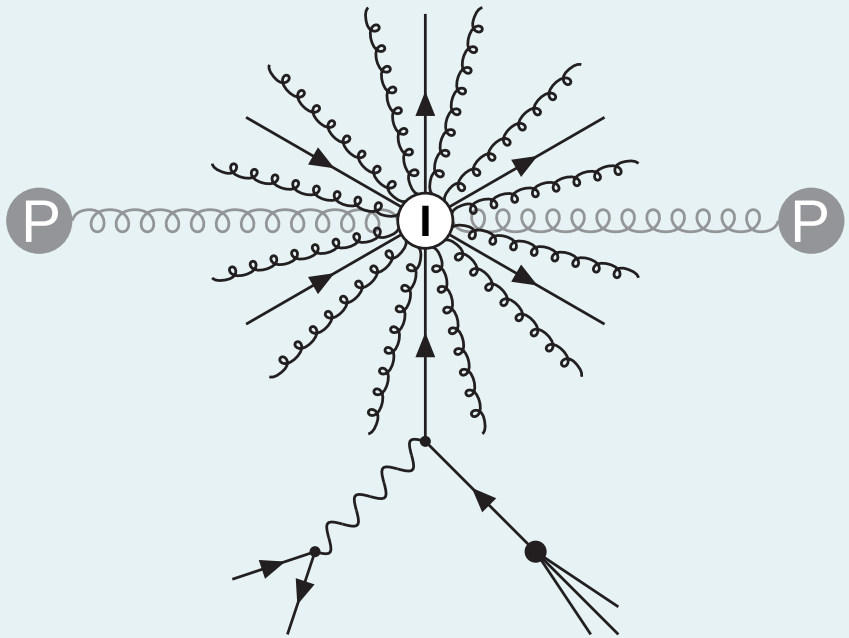

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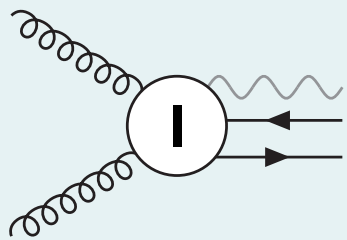
Simplest process—overwiev

- explicitly calculable $\rightarrow$ done!
- no extra gluons, $n_g = 2$
- just one quark-flavor, $n_f = 1$
- virtuality via radiated vektorboson, e.g. γ^* or W
- W radiation: factorization into $2 \rightarrow 2$ sub process and decay
- found nontrivial relation between processes at HERA and LHC



$$\hat{\sigma}_3^{(\mathrm{I})}(\hat{s}) \equiv \int \frac{\mathrm{d}\,x'}{x'} \int \frac{\mathrm{d}\,Q'^2}{Q'^2} \left[\frac{\mathrm{d}\,\hat{\sigma}_2^{(\mathrm{I})}}{\mathrm{d}\,x'} \left(x', Q'^2 \right) \right] \left[\mathcal{P} \left(x', \frac{Q'^2}{Q^2} \right) \right]$$

$$\mathcal{P}_{\mathrm{LHC}} \left(x', \frac{Q'^2}{Q^2} \right) = \int \frac{\mathrm{d}\,x}{x} P_{\mathrm{HERA}} \left(x' \leftrightarrow x, \frac{Q^2}{Q'^2} \right)$$

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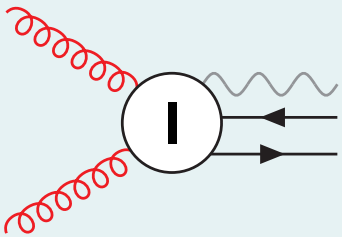

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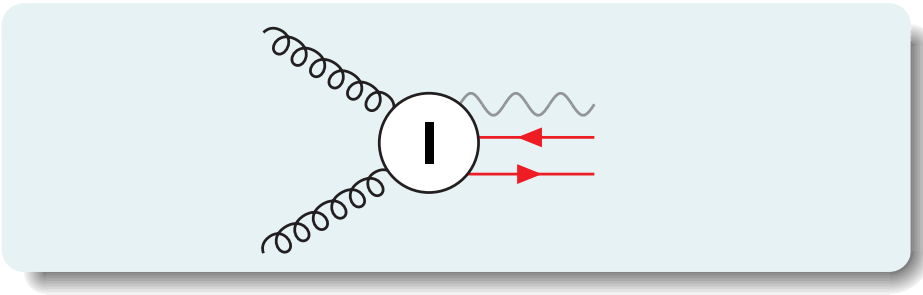

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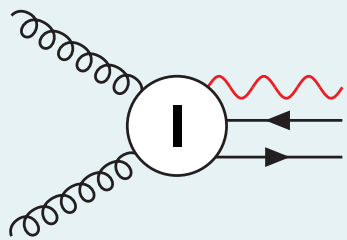

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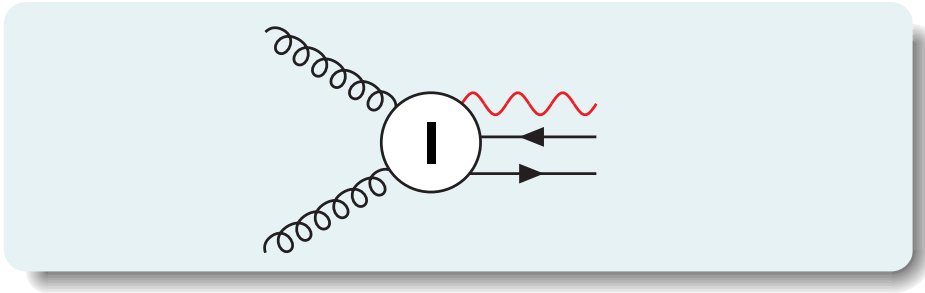

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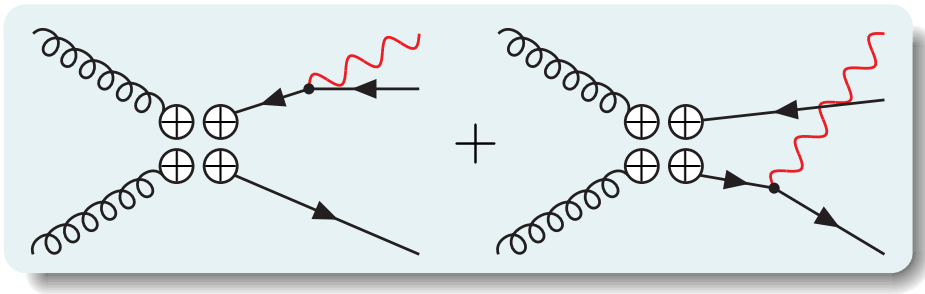

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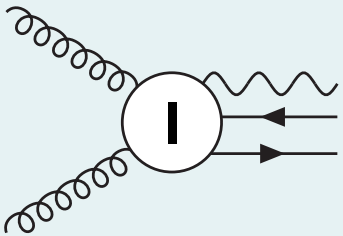

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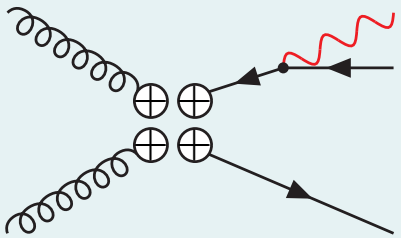

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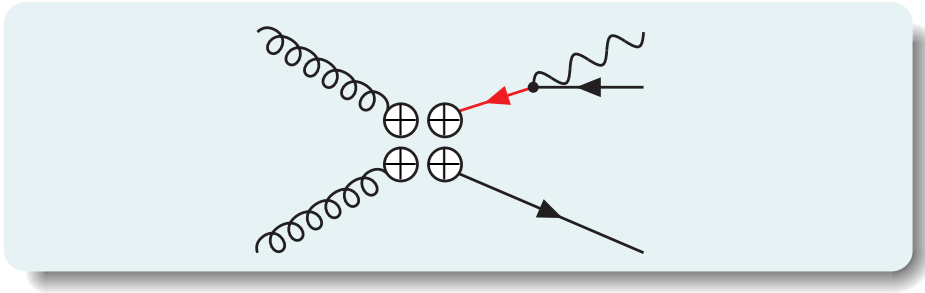

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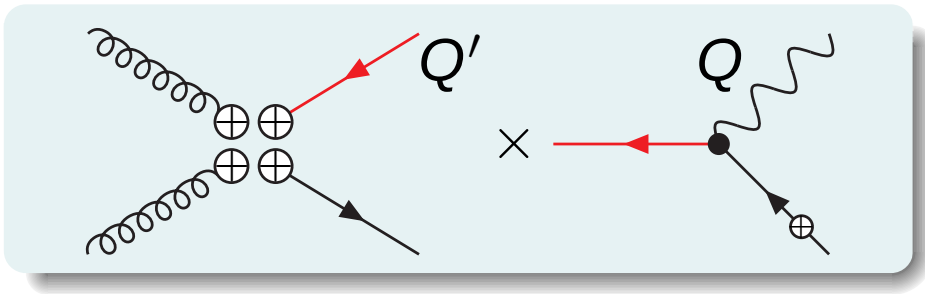

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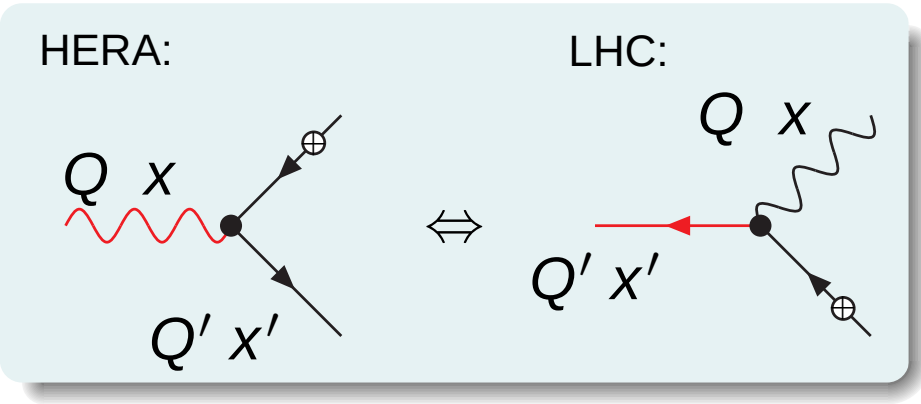

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Parton process: $g + g \xrightarrow{(\mathrm{I})} q + \bar{q} + \gamma^*$

$$\hat{\sigma}^{(\mathrm{I})}(\hat{s}; Q) \sim \frac{\left(\mathcal{R}^{(3)}_{\mu_r}(Q)\right)^2}{\alpha_s^2}\, \hat{s}^2 \times \left[1 + \mathcal{O}\left(\frac{Q^2}{\hat{s}}\right)\right]$$

- $\mathcal{R}^{(3)}_{\mu_r}(Q) \sim$ I-volume
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- η_q distribution (plot)
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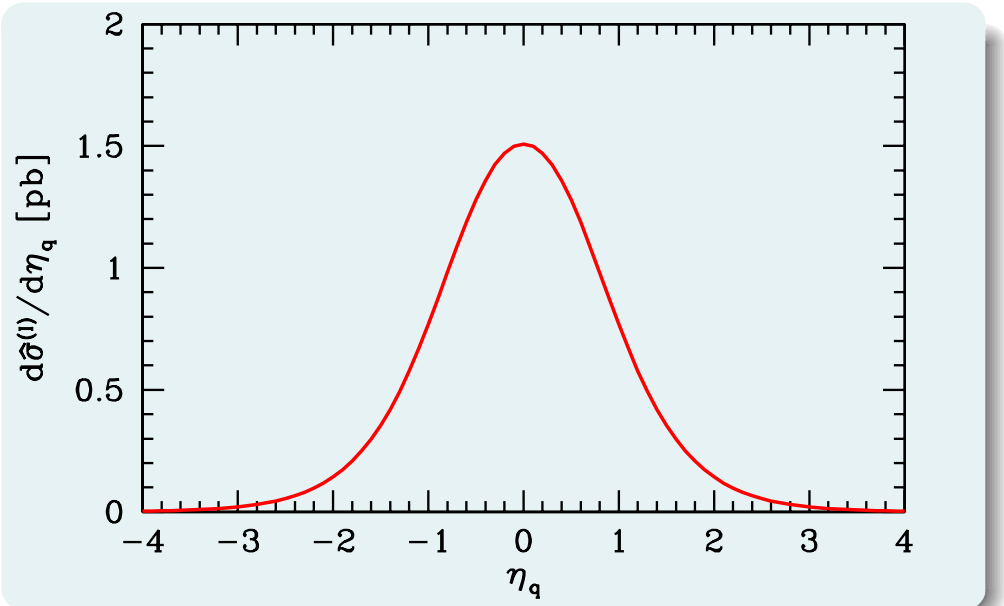

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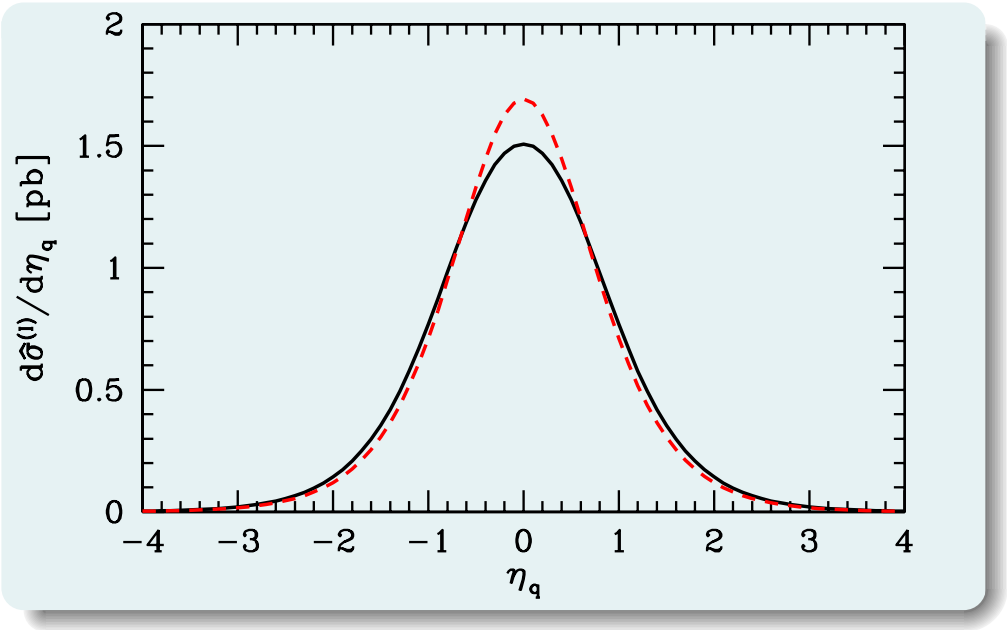

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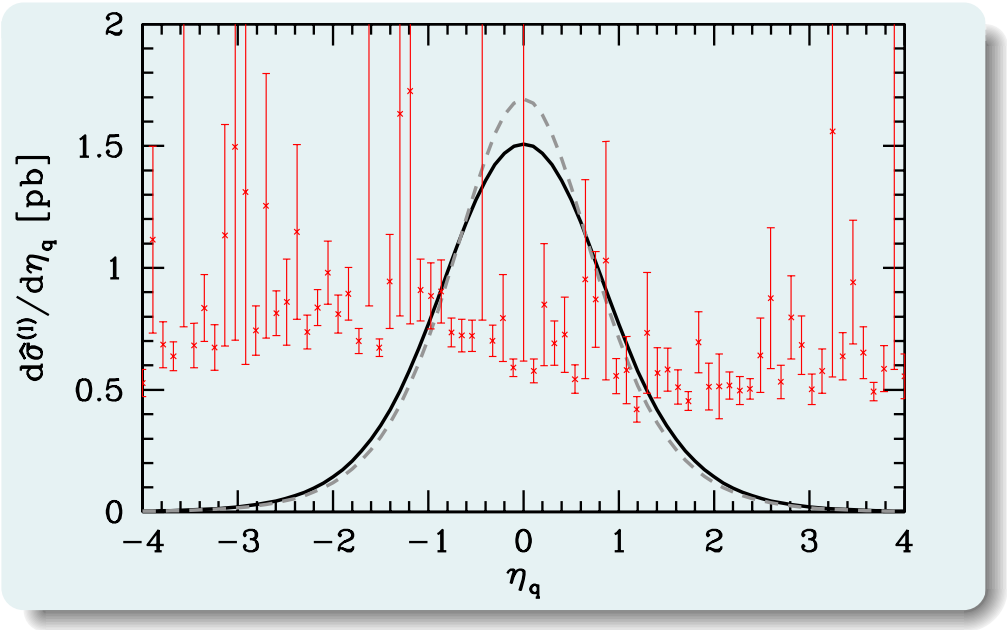

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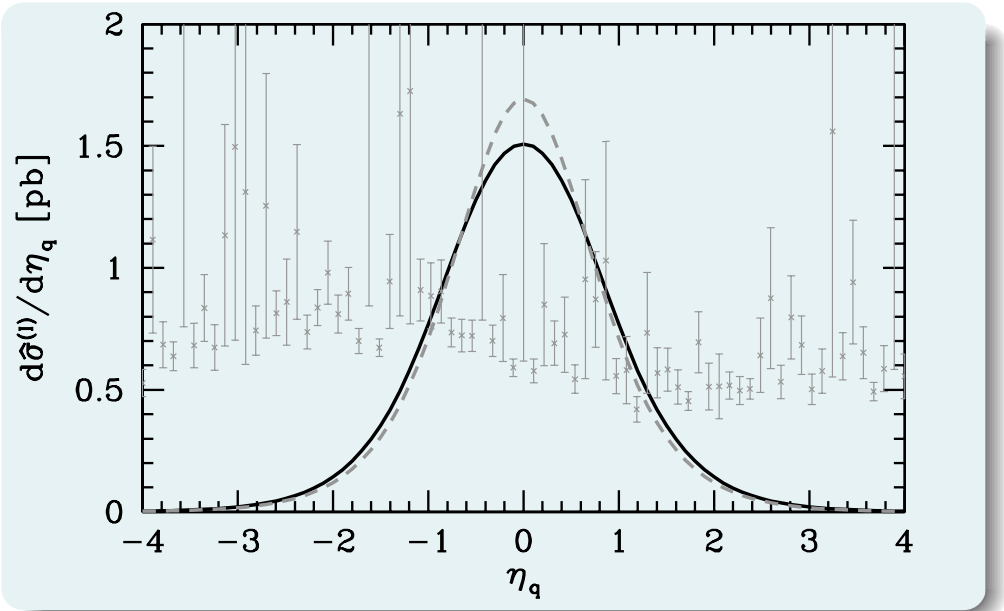

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Fireball signature apparent even for the simplest process!

Outlook

1. Complete simplest process
   - take final state gluons into account
     (valley-approximation, nontrivial because of the time like virtuality)
   - take all three light flavors into account
2. Push penomenological study
   - find proper cuts
   - find proper observables
3. Experimental verification!