Searches for
QCD Instantons with ALFA Detector
feasibility study

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Recap QCD

Theory of Strong Interactions

- Hadron: particles that hold together due strong interaction
  - 2 Quarks: Meson ($q\bar{q}$)
  - 3 Quarks: Baryon (qqq or $\bar{q}\bar{q}\bar{q}$)
- Resonances: excited states of Hadrons

- Initially we had many hadrons and resonances
- Too many, for all of them to be fundamental particles
- Theory of QCD was able to explain all with proposing 6 quarks and 8 gluons
  - Quarks → fundamental particles behind all hadrons and resonances
  - Gluons → force carrier

Problems of Perturbative QCD

Limits of Perturbation theory

- Energy scale of Field Theory
  - High energy - short distance
  - Low energy - long distance

- Perturbation theory predicts behaviour only if done to the correct equilibrium (vacuum)
- At high energies, perturbative QCD works well
  - particles behave mostly freely (interact weakly)→ asymptotic freedom
- At low energies QCD too strong (system too far from equilibrium) → Perturbation theory not applicable
- We need non-perturbative approaches
  - example where pQCD breaks down: measurement of total pp cross section

Comparison of QCD and QED

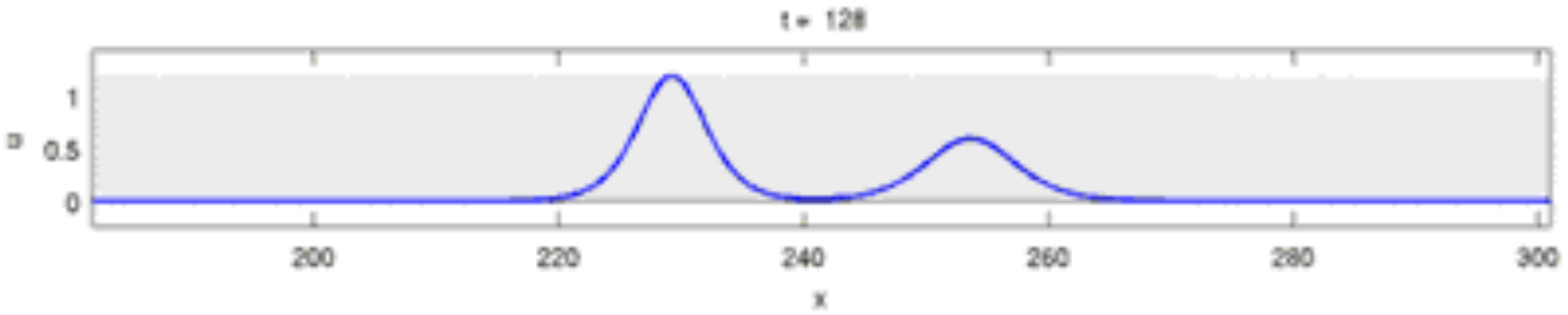
Difference in group and the implications

- QED symmetry group U(1) ↔ QCD symmetry group SU(3)
- QED electric charge (Q) ↔ QCD color charge (R,B,G)
- Gluons are analogues to photons and are massless
  - Gluons: color charge + no electric charge
  - photons: no color charge + no electric charge
- QED is Abelian → vacuum is trivial (unique)
- QCD is non-Abelian → vacuum is non trivial due to the presence of instantons

Soliton

Where is the Soliton? It's in solitonary confinement

- Solitons are wavepackets that are classical solutions with particle like properties
  - permanent form
  - localized within a region
  - can interact with other solitons
  - after interaction soliton keeps its form
    - they are robust → behave like standard initial/final (one particle) states

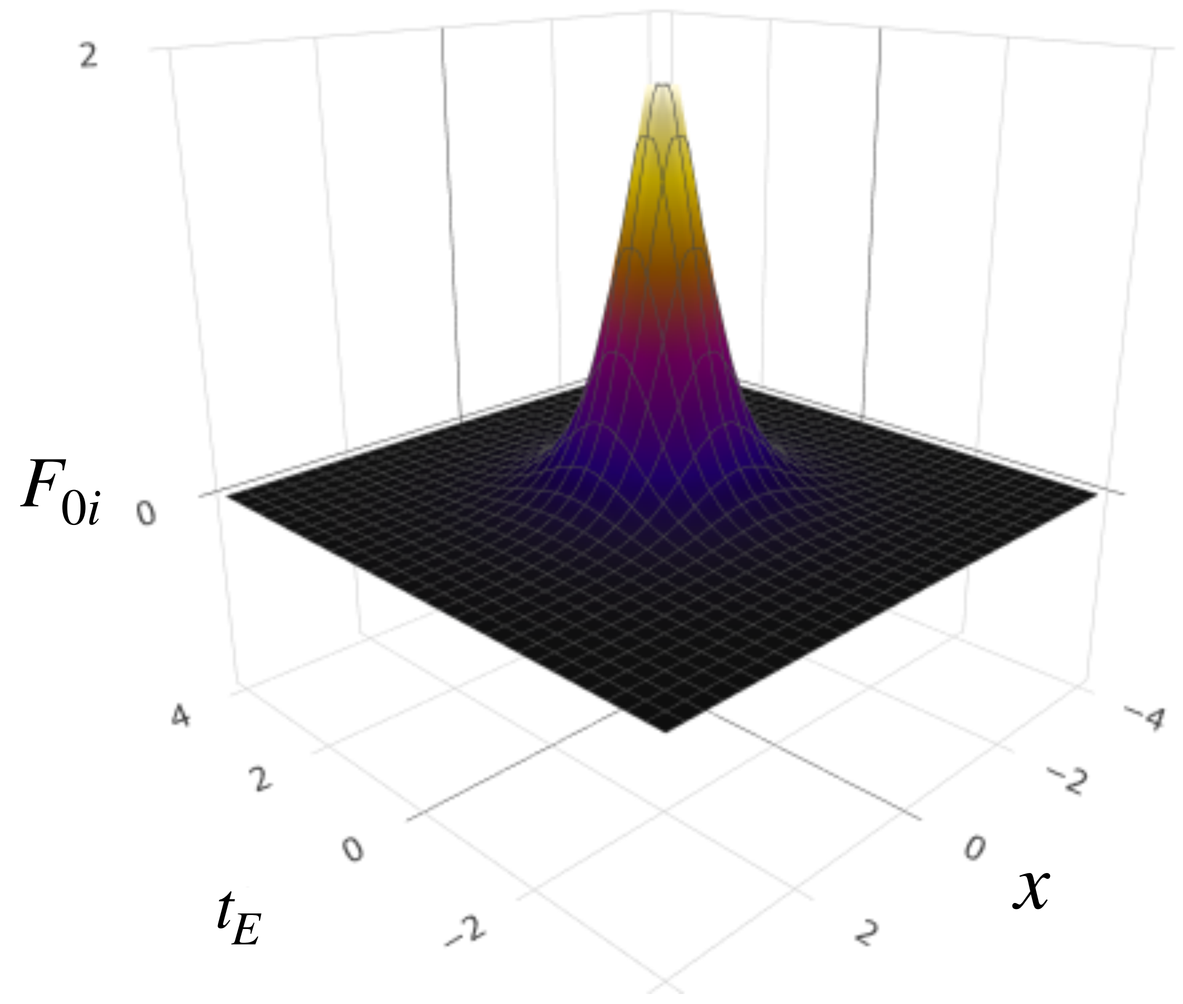


source: wikipedia

Instanton

The key part of this presentation

- Instantons are soliton solution with important caveat
  - they are solution in Euclidean spacetime
  - cannot exist forever in Minkowski time
  - Instanton appears only at one instant in time



source: Wikipedia

- they would predict processes not explainable in perturbation theory
  - would predict new QCD and EW processes violating symmetries

Instanton

What does Euclidean time mean

$$L = T - V$$

$$S = \int d\tau \left(\frac{1}{2} m \left(\frac{dx}{d\tau} \right)^2 - V \right)$$

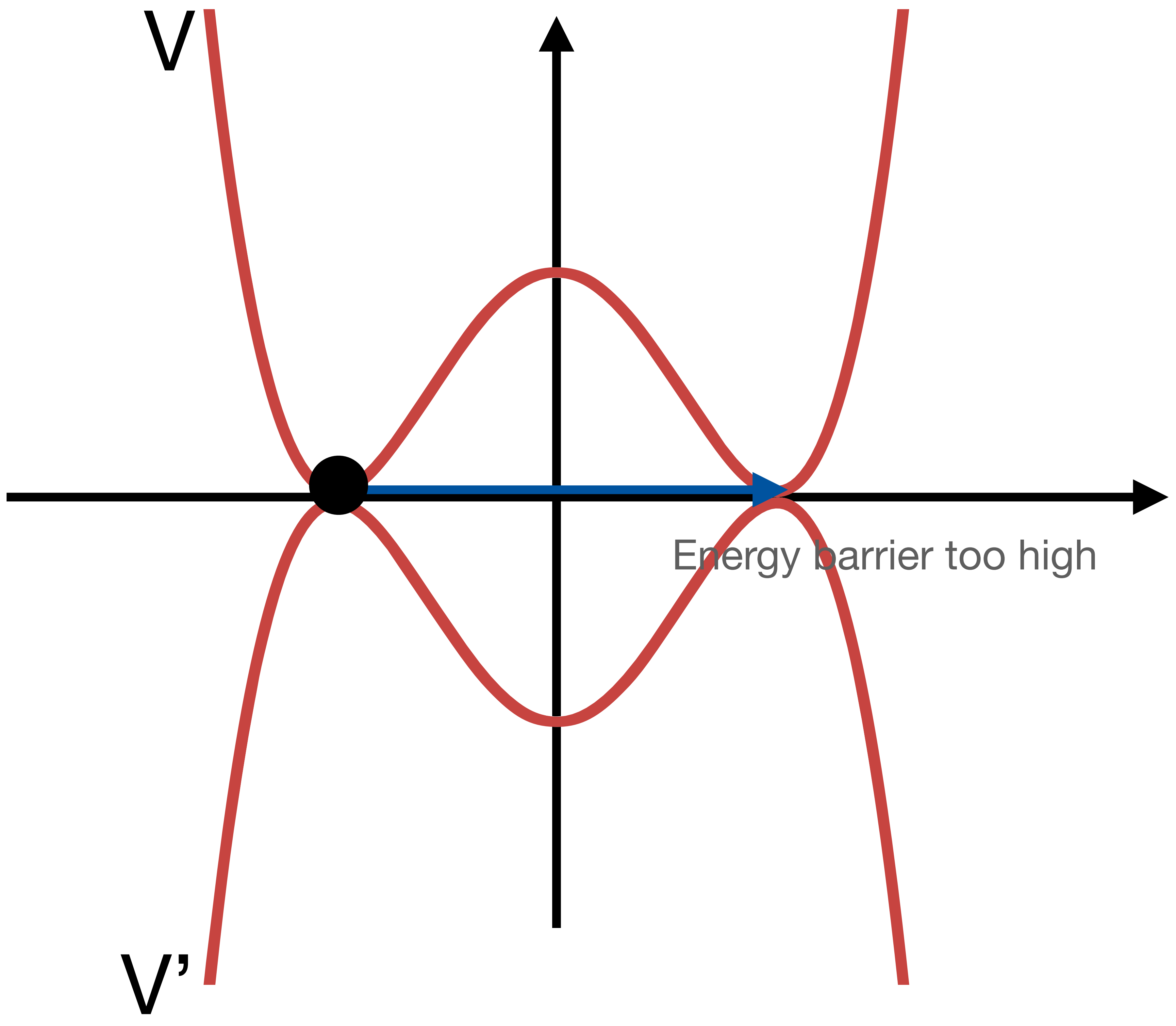
$$\tau = it$$

$$S = \int i\,dt \left(\frac{1}{2} m \left(\frac{dx}{dt} \right)^2 + V \right) = -iS_E$$

$$S_E = -\int dt \left(\frac{1}{2} m \left(\frac{dx}{dt} \right)^2 + V \right)$$

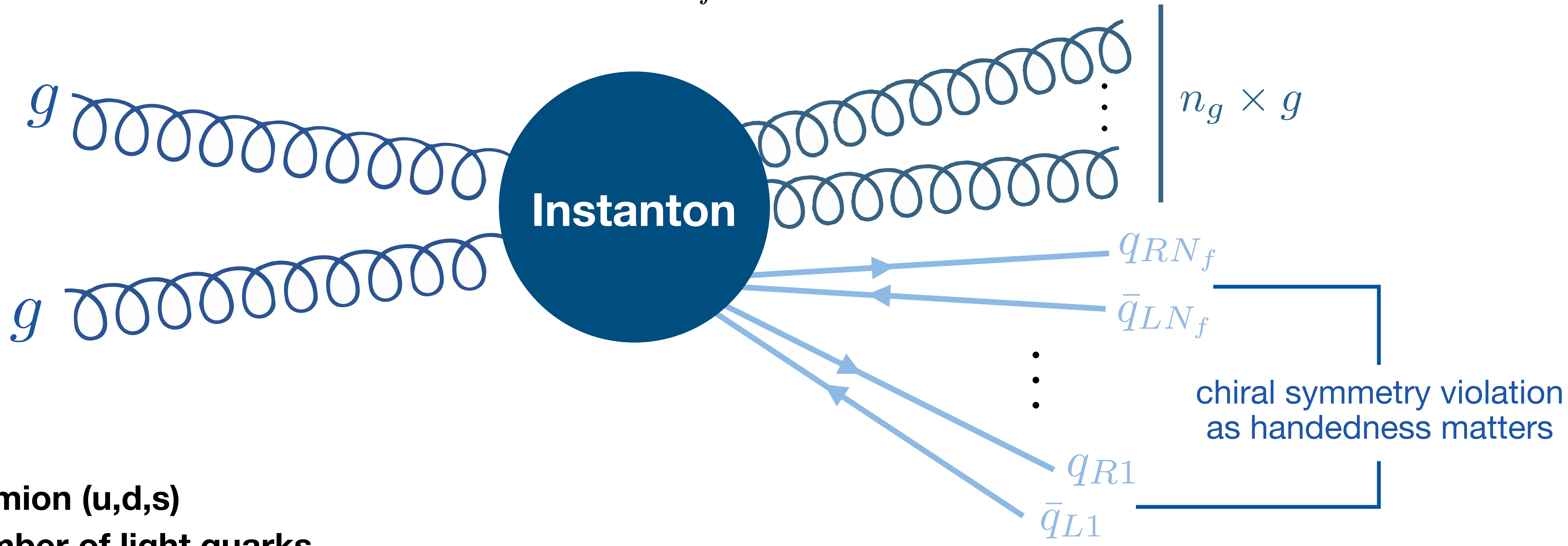
This is just a $S(T, V')$ with $V' = -V$

Time has lost meaning now → happens instantly



What process are we interested at the LHC?

$$g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})$$

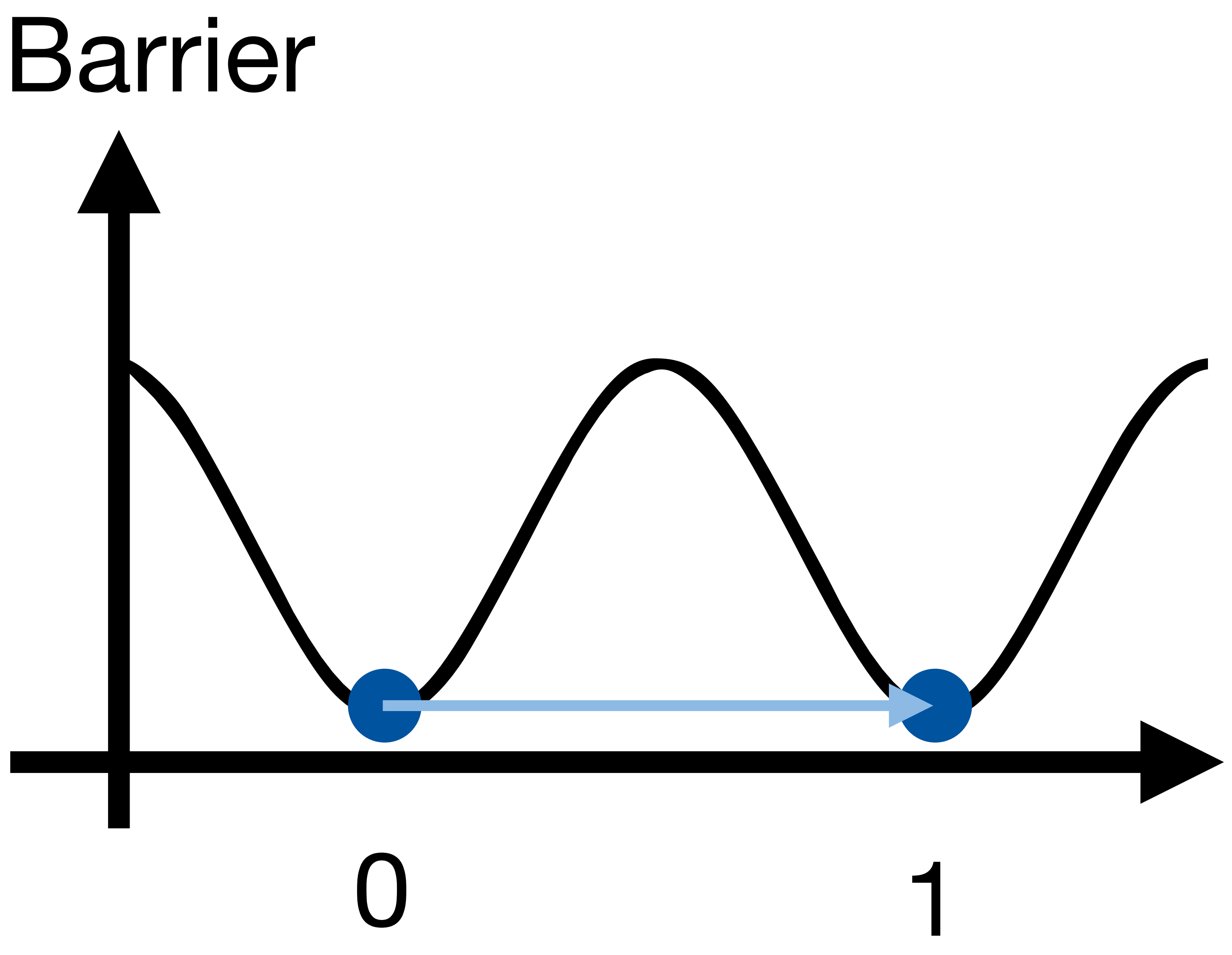


f: Fermion (u,d,s)
N_f: Number of light quarks

Implications of Instantons in QCD

They would be instantaneous game-changers!

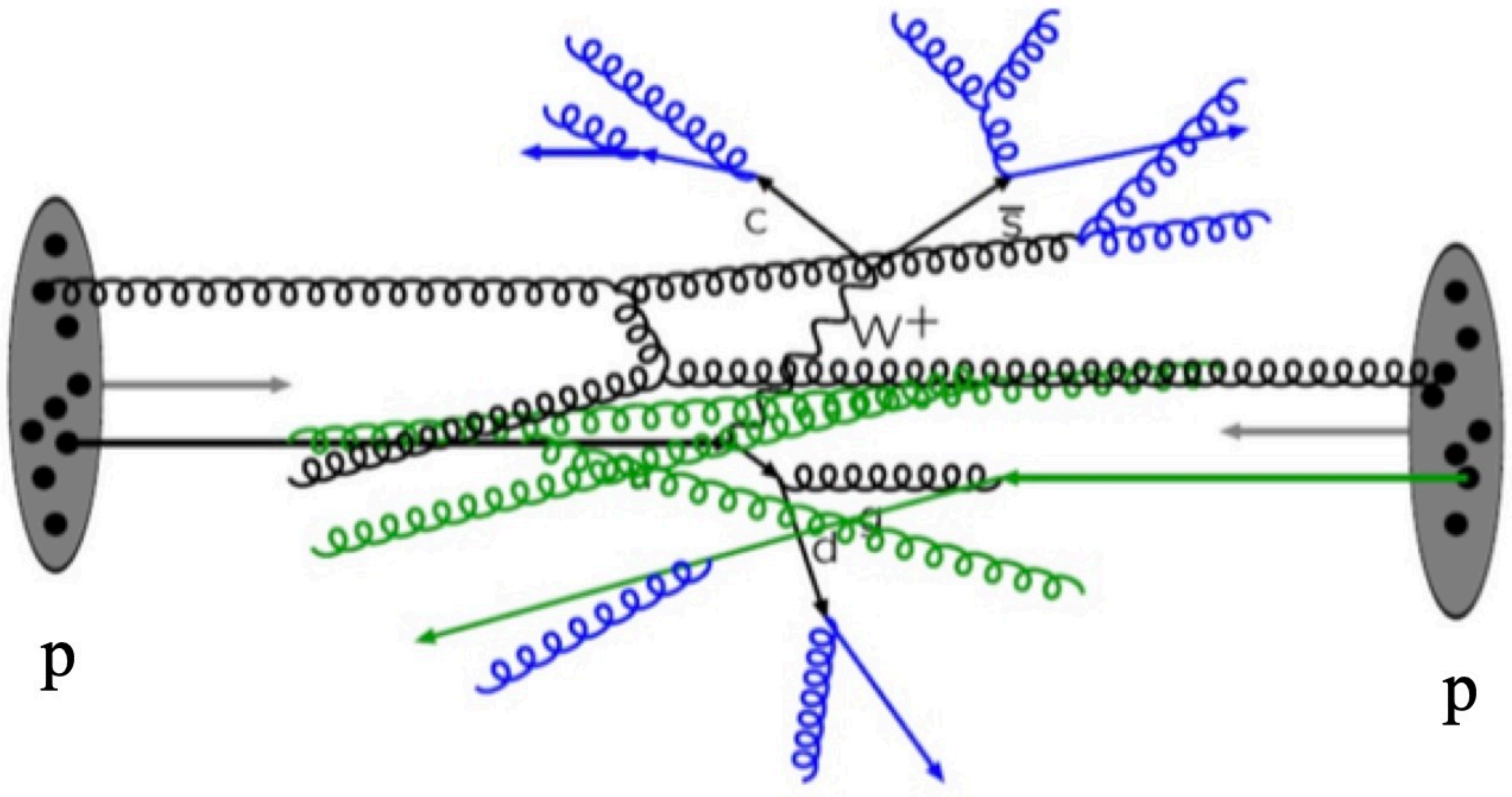
- Change in winding number is measurable indirectly
  - by violating "chiral symmetry"
- In perturbative approaches not possible
- Violation would be proof of
  - highly non-trivial structure of the QCD vacuum



$\Delta N_{\text{winding}} = 1$

How to detect Instantons at CERN

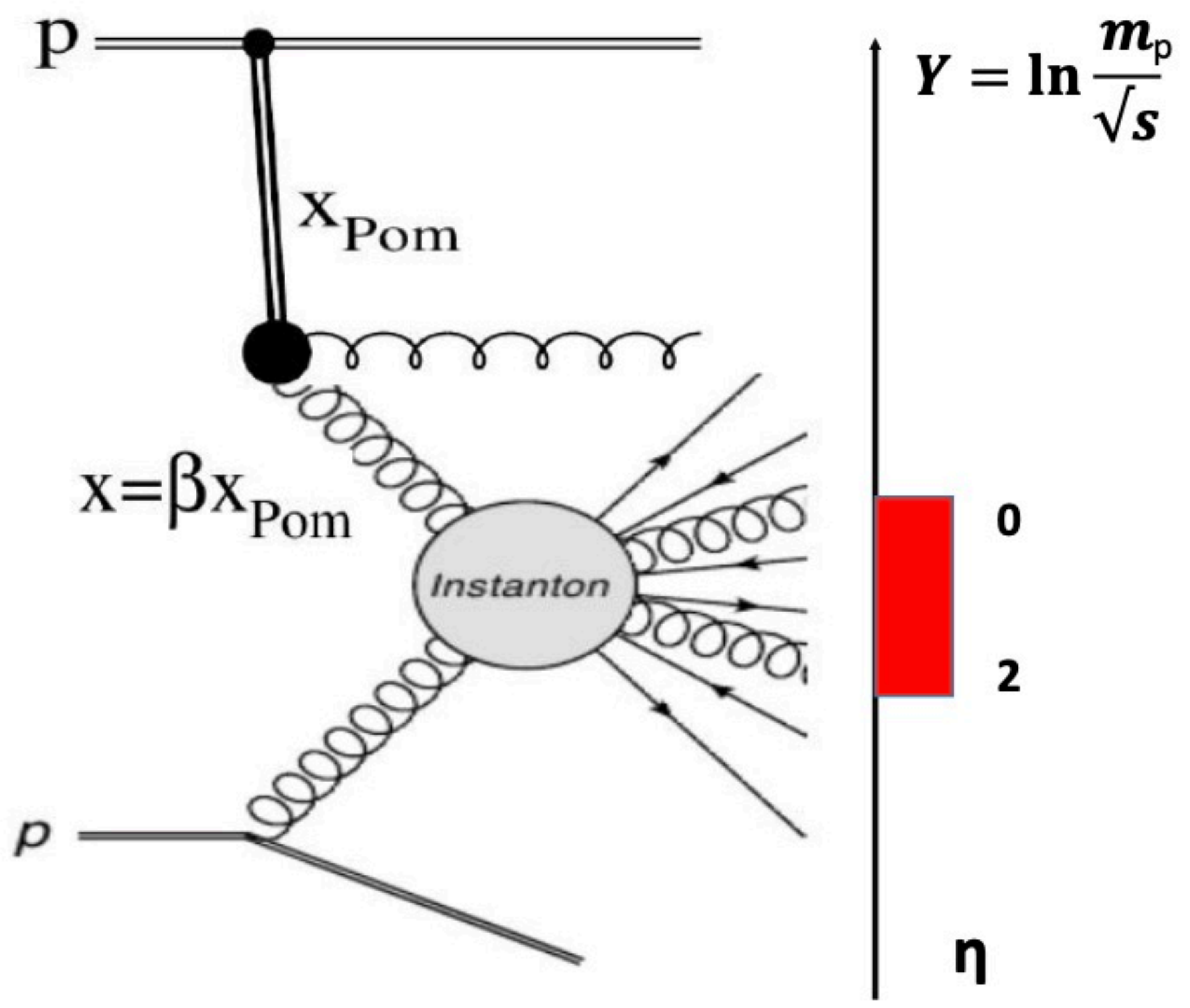
- Events with high gluon multiplicities will suppress signal
  - Dominated by Multiple Parton Interactions (MPI)
  - in pp collision several partons can interact at same time
  - more than one interaction → low chances for rapidity gaps



C. Charlot, LLR-École polytechnique, CNRS&IN2P3

How to detect Instantons at CERN

- Demand events with large rapidity gap[1-4]
  - gap in rapidity of proton and the secondaries
  - suppress background
- Rapidity gap is applied using central ATLAS/ALFA
  - **A**bsolute **L**uminosity **F**or **A**TLAS: Measure elastic proton-proton scattering at small angles
- My Tasks:
  - Estimate number of events detectable by ALFA based on theory
  - compare with data → maybe visit Stockholm afterwards



Instanton production in a diffractive process with an LRG [2104.01861]

Winding Number - Backup

Didn't expect to be that fast

- To the field configuration we can assign winding number N_{CS}
- Result will be integer
- Implies that pure gauge field configurations can be classified by a number
- configurations of different number cannot be deformed into each other