# Discovering QCD Instantons at the LHC.

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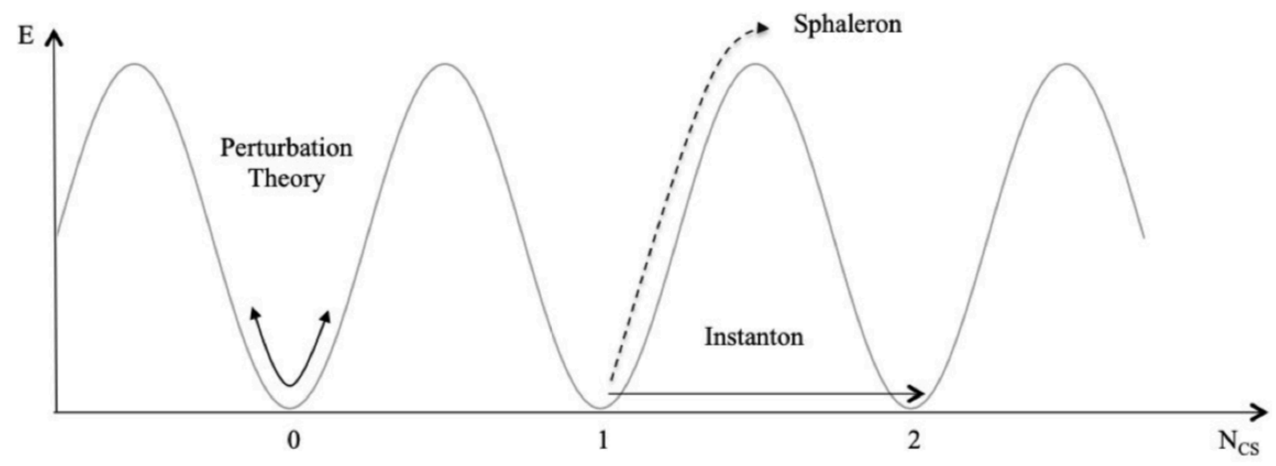
## 1 - Topological phenomena in the Standard Model

- Yang-Mills theories have a topologically non-trivial vacuum, and admit "tunnelling solutions" across different vacua which cannot be obtained through perturbation theory

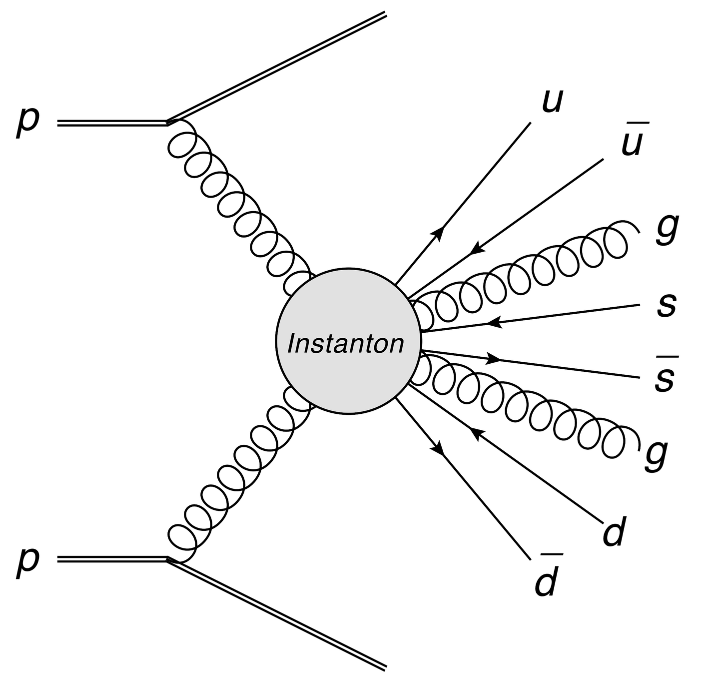



- First discovered by t'Hooft in the 70s, these ***Instantons*** are related to many low energy properties of QCD: chiral symmetry breaking, confinement, …
- Never been observed experimentally, ***can we search for Instantons at the LHC ?***

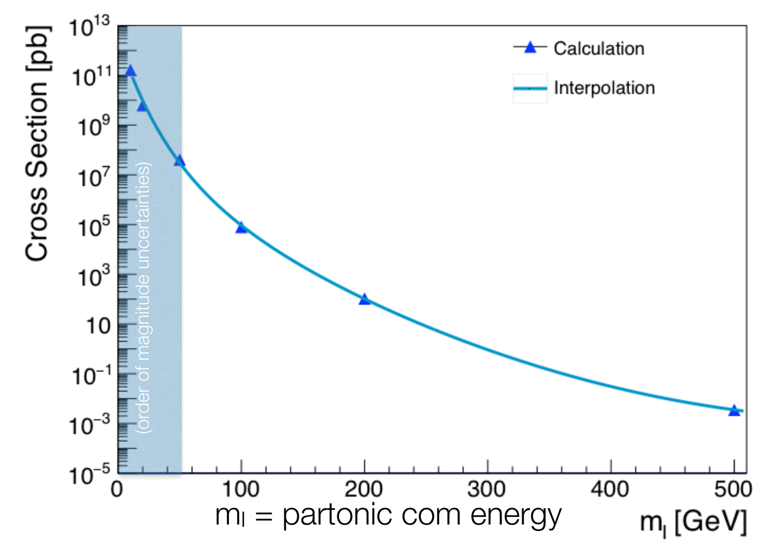
## 2 - Phenomenology of QCD Instantons at the LHC

- A QCD instanton transition in *pp* collisions would produce the following particle content:

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




- Exactly $2N_f$ fermions pairs of different chiralities
- An additional large number of gluons $N_g \sim 1/\alpha_S$
- Only gluon-initiated production considered, dominant due to PDFs at small-x

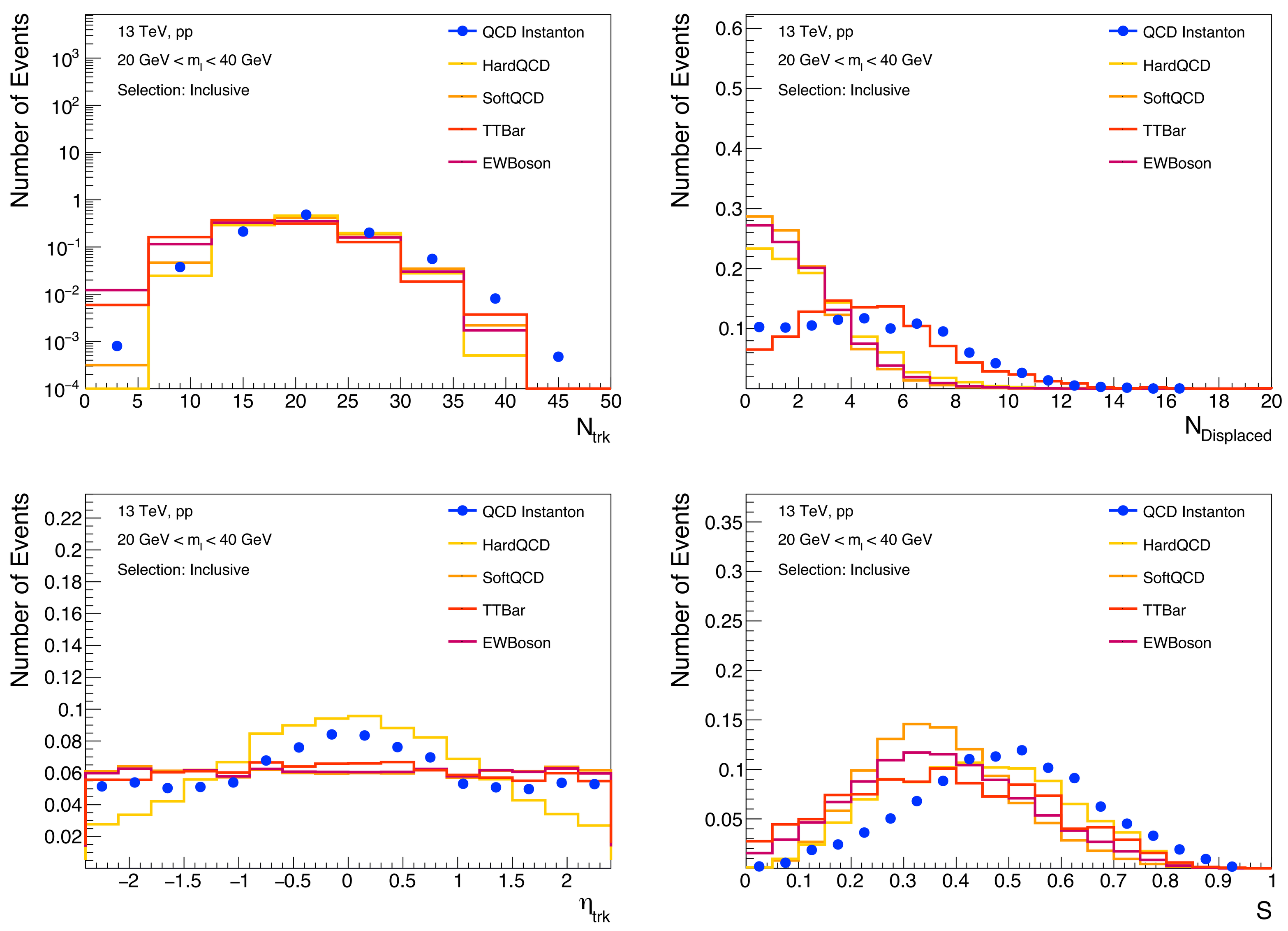



- Instanton cross-sections recently calculated in [1911.09726]
  - Using semi-classical approach valid in the weakly-coupled regime
  - Quickly drops with CoM energy
- Monte Carlo implementation of Instanton transitions in Sherpa
- High multiplicity of low energetic partons, a ***soft bomb*** final state
  - Large number of tracks and spherically symmetric events

## 3 - Analysis Strategy and Optimisation

- Developed possible analysis strategies to search for Instantons
  - SM backgrounds generated with Pythia8
  - Detector simulation with Delphes (ignoring Pile-Up)
- Three regimes identified, and separately optimised

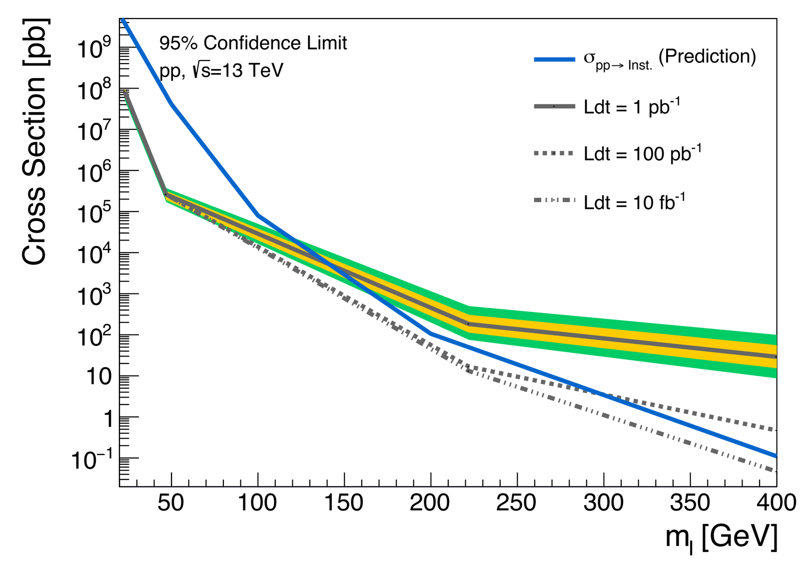
> - The soft QCD regime (20 < $m_I$ < 40 GeV and 40 < $m_I$ < 80 GeV)
>   - Large signal cross-sections, but large theory uncertainties
>   - Background dominated by soft QCD, no first principle description
> - The hard QCD regime (200 GeV < $m_I$ < 300 GeV)
>   - Instanton cross-sections are much smaller, events hard to trigger but more striking topologies
>   - Background dominated by (perturbative) QCD jet production, uncertainties at the level of several percent (known to NNLO)
> - The top-quark regime (300 GeV < $m_I$ < 500 GeV)
>   - In this high mass regime can also define signal regions dominated by top-quark pair production.
>   - Easier to model and to control using data regions



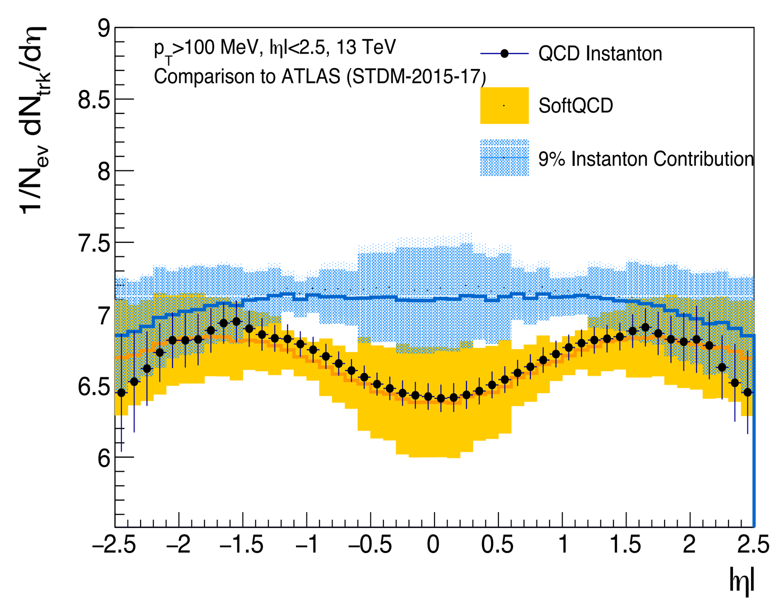

- At low masses the signal can be easily discriminated
  - Huge number of events, can use special datasets (low pile-up)
  - Signal selection based on track multiplicity, event shapes and displaced vertices (from C-/B-hadrons)
- Some complications arise at high-masses
  - Cross-section drops very quickly, but signal remains low-$p_T$
  - Need dedicated triggers for high-multiplicity low-$p_T$ jet events
  - But otherwise strong discrimination from jet-based event shapes

## 4 - Sensitivity and first limits

- Using our analysis results can now derive the expected 95% upper limits on the Instanton production cross-section
  - With 1 $pb^{-1}$ exclude the Instanton cross-section up to 150 GeV
  - Reaching ~250 GeV and 400 GeV with 100 $pb^{-1}$ and 10 $fb^{-1}$
- Even with small datasets can reach sensitivity to the predicted Instanton cross-sections




- Charged particle distributions are routinely measured at the LHC




- Recasted existing ATLAS 13 TeV measurement of low-$p_T$ charged particles [2012.09120]
- Background model from an envelope of Pythia, Herwig and Sherpa MC
- Excludes Instanton cross-sections:

$$\sigma_I < \; 2.1 - 6.4 \text{ mb}$$

## 5 - Summary and Outlook

- Intriguing possibility to ***discover QCD Instantons at the LHC***
  - Would open a new window into QCD dynamics
- LHC experiments have sensitive datasets already now
  - A track based analysis of event-shapes observables being the most promising approach at low Instanton masses
  - Sensitivity at higher Instanton masses only limited by the trigger
- For a convincing discovery more sophisticated approachesneeded
  - Look into particle composition, chirality imbalance (?)
  - Consider Instantons in single- and double-diffractive events

Based on "How to discover QCD Instantons at the LHC", arXiv:2012.09120