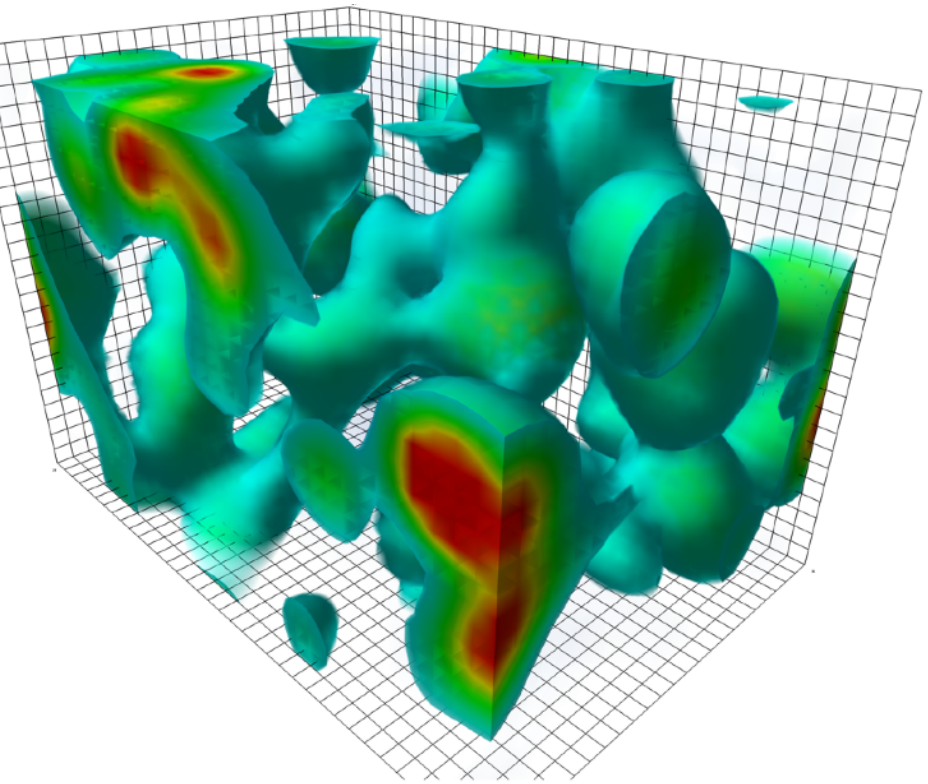

How to discover QCD Instantons at the LHC

ISMD2021

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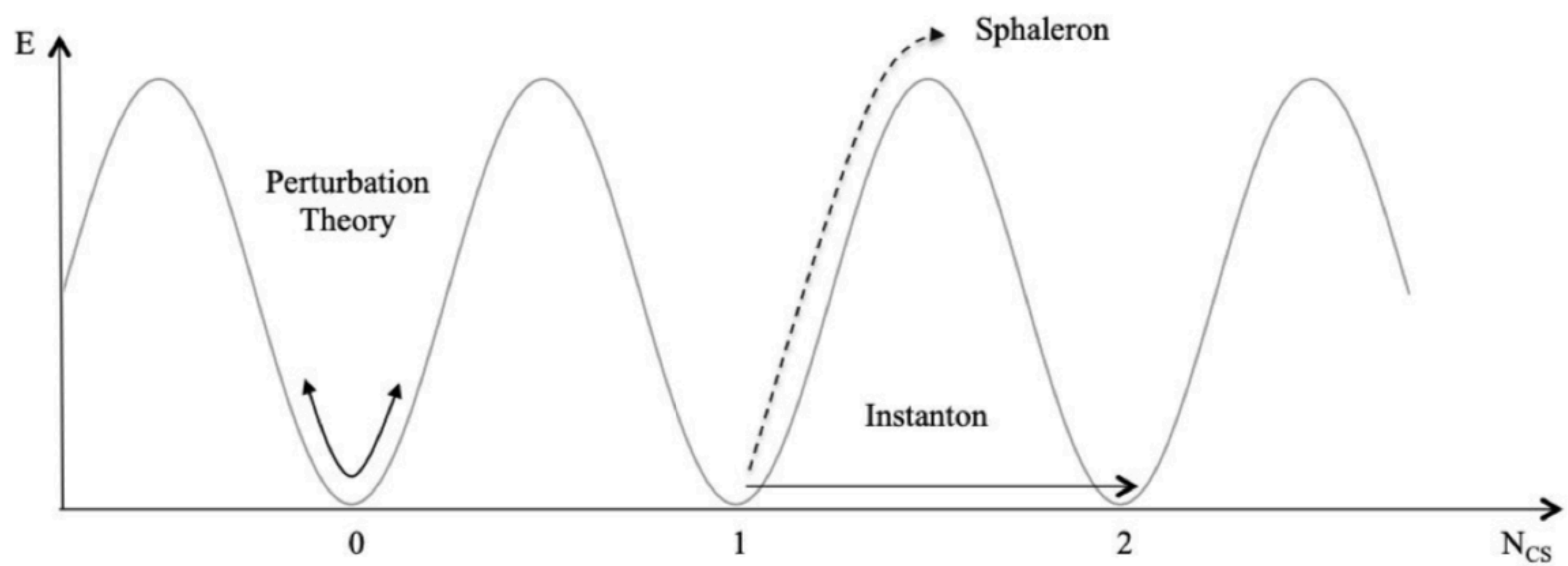
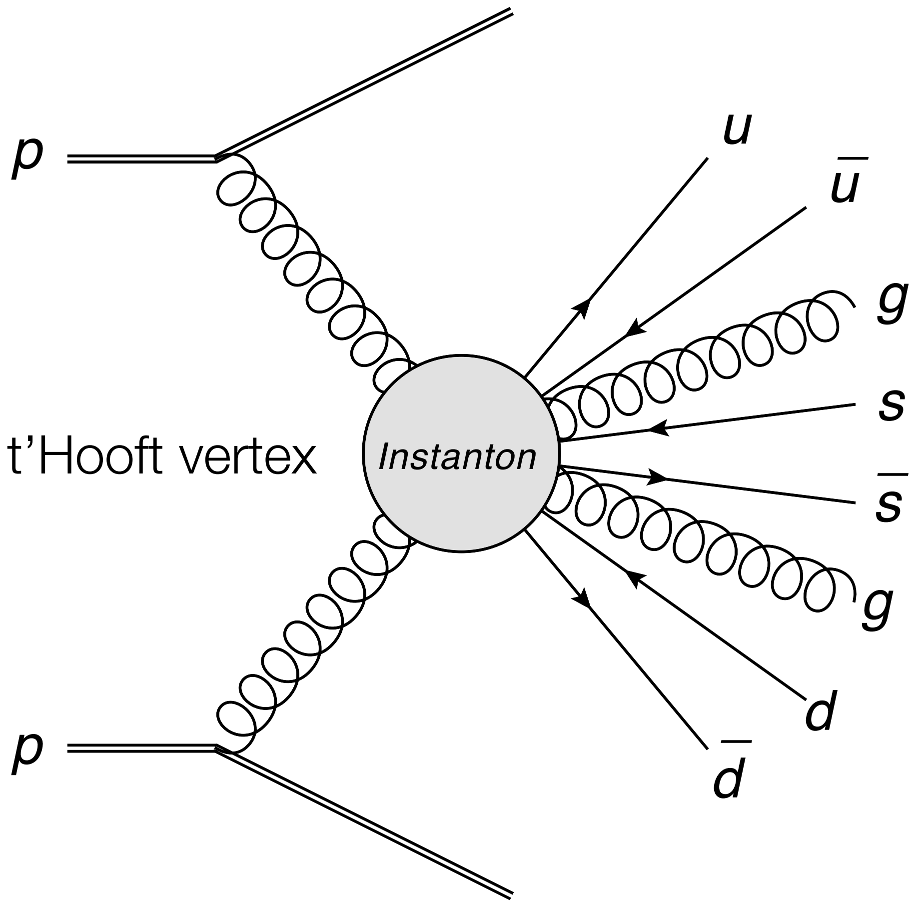
Introduction

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



- These “Instanton” solutions were first discovered by t’Hooft in the 70s, and are related to many low energy properties of QCD: chiral symmetry breaking, confinement, …
- Never been directly observed experimentally, ***can we search for them at the LHC ?***

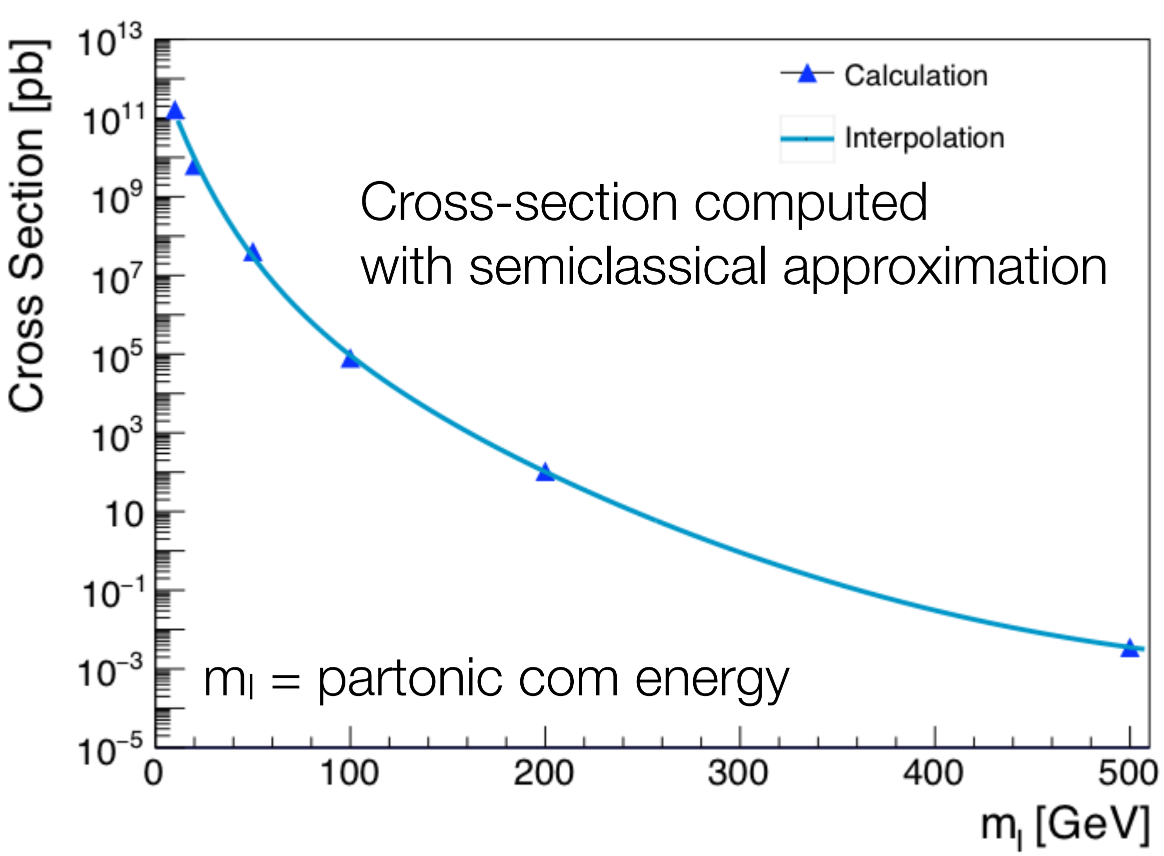
QCD Instantons at colliders



- An Instanton transition should give rise to $2N_f$ fermion pairs of different chiralities, and an additional number of gluons

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

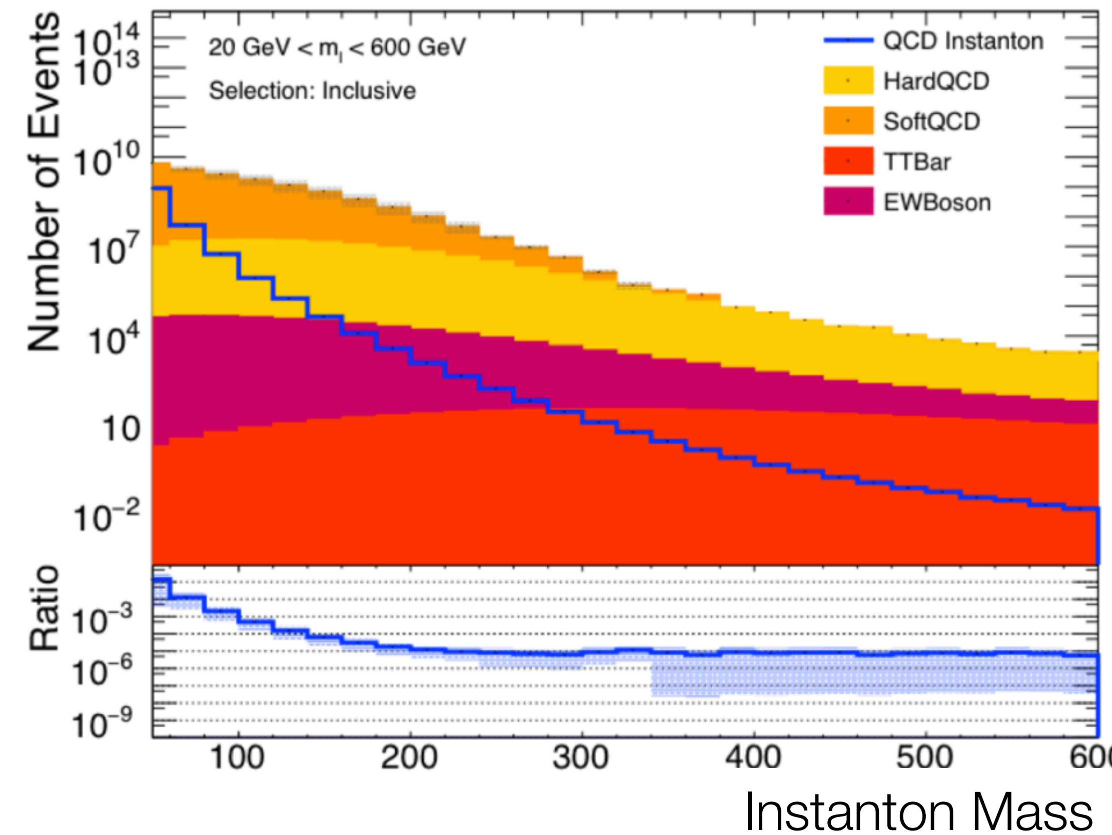
- At colliders, interested in small-size (high-energy) Instantons

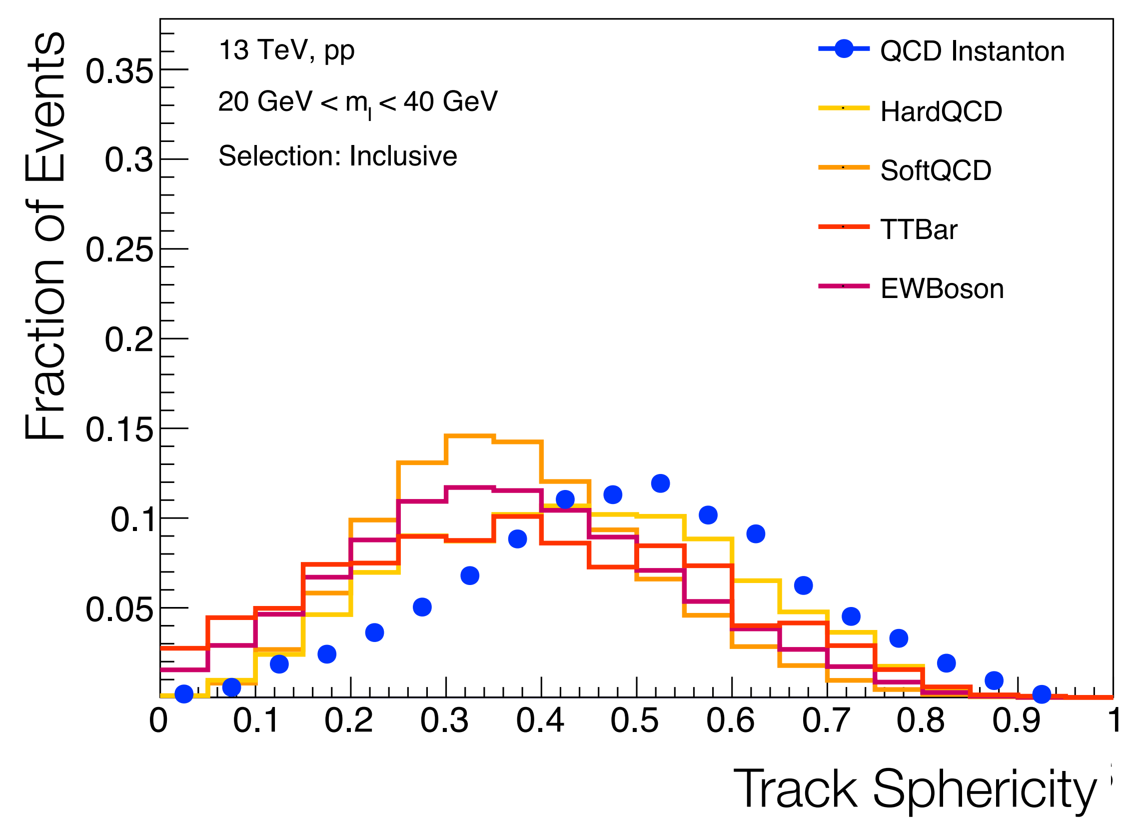


- First searched for in *ep* collisions at HERA in the late 90s https://arxiv.org/abs/hep-ph/9609445
- Very recently predictions for *pp* collisions became available https://arxiv.org/abs/1911.09726
- CERN-Th workshop last December https://indico.cern.ch/event/965112/

Low-mass search

- At low masses (m_I < 100 GeV), cross-sections are very large
  - Even the highly prescaled MBTS triggers should give sensitivity
  - But signal cross-section is also very uncertain at low masses
- Expect a high multiplicity of low energetic partons, a ***soft bomb***
  - Large number of tracks and spherically symmetric events
  - Background dominated by soft QCD processes, hard to simulate reliably
  - A signal selection can be based on the track multiplicity, event shapes and displaced vertices (c-/b-hadrons)



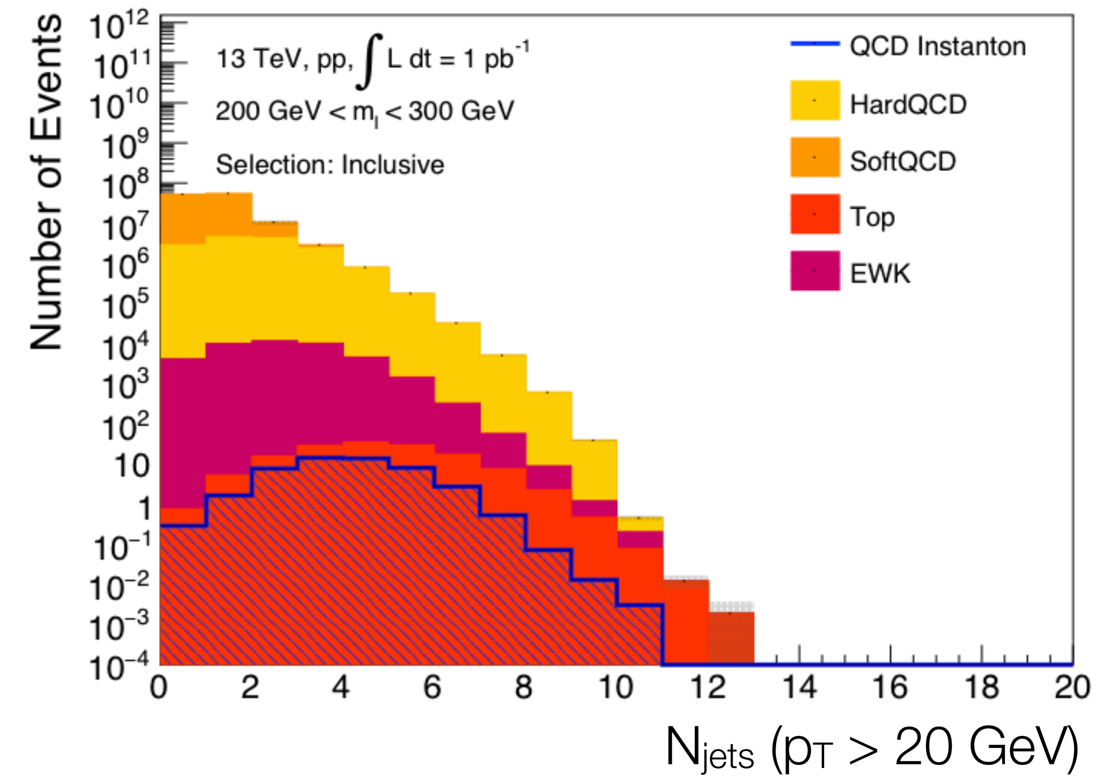


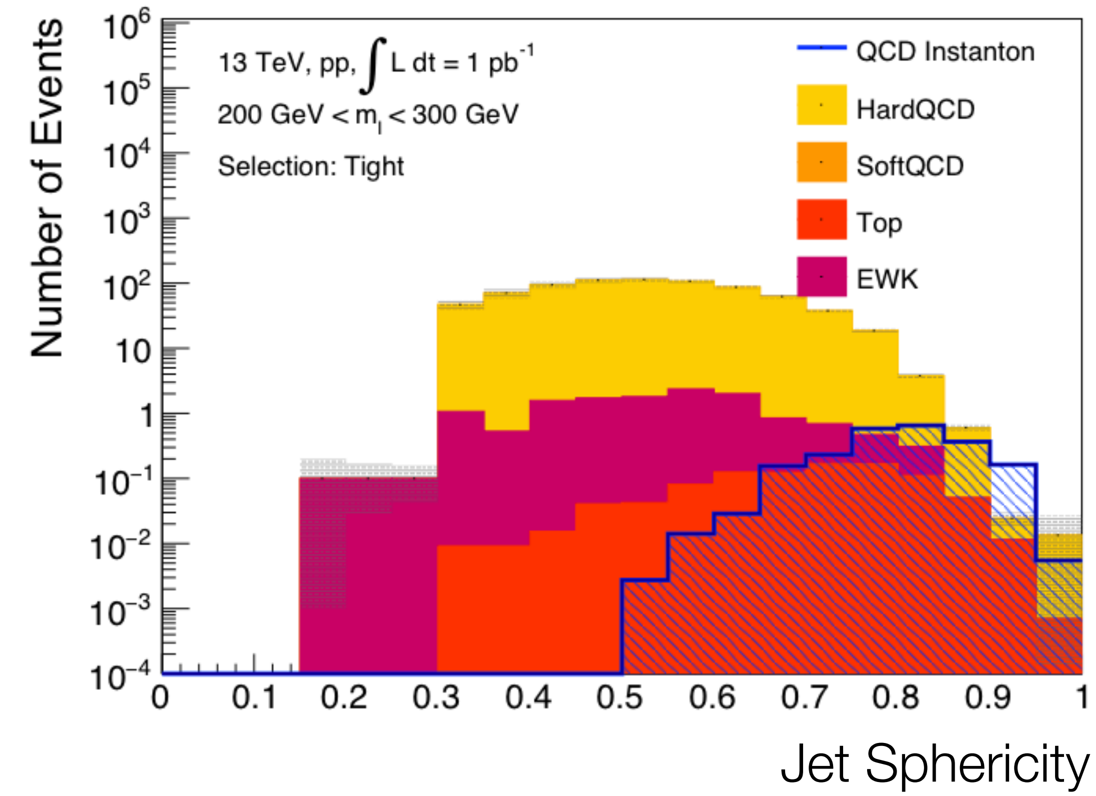
https://arxiv.org/abs/2012.09120

High-mass search

- At higher masses (m_l > 100 GeV) the Instanton cross-sections are o(pb) and high p_T jets can be reconstructed
  - Dominant backgrounds from multi-jets and top production calculable in perturbative QCD
  - A dedicated signal selection can achieve a signal/bkg. ~ 1

- Triggering is however a challenge.
  - Might benefit from dedicated low-p_T multi jet (topological?) triggers or dedicated runs to collect enough statistics





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Conclusions

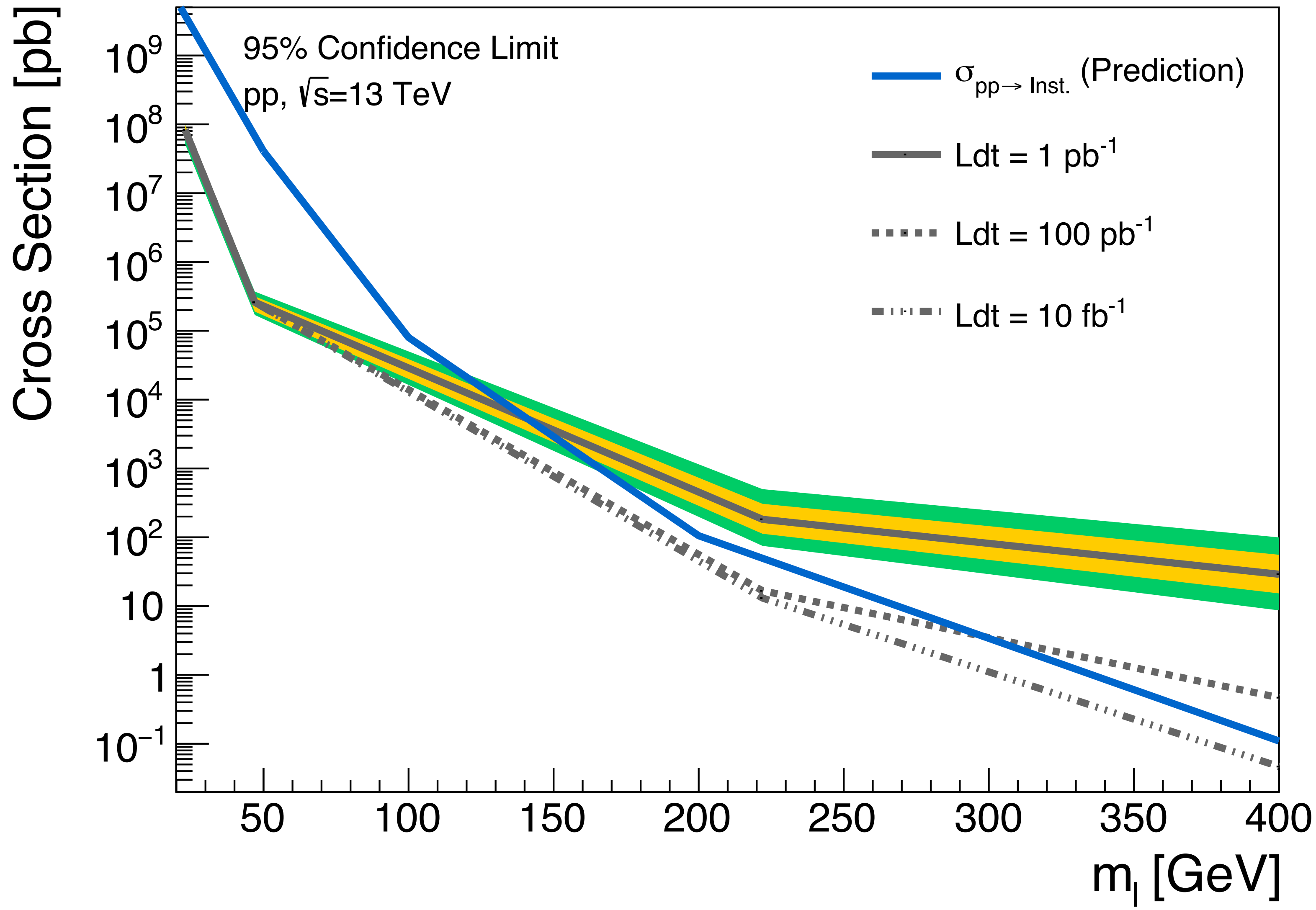
- The discovery of QCD Instanton induced processes would confirm of one of the last unobserved predictions of the SM
- A certain breakthrough in our understanding of the theory

- LHC can already search for Instanton processes
  - A low mass search can reach sensitivity for the predicted cross-section, limited by our understanding of soft QCD models
  - High mass needs dedicated triggers/runs to collect enough statistics

- For a convincing discovery more sophisticated approaches are needed to unambiguously characterise the candidate events
  - Particle composition (expect more strange, heavy-flavor)
  - Per-event chirality imbalance to measure chirality violation

Backup

Expected reach



[2012.09120]

- We can now derive the expected 95% upper limits on the Instanton
  - With 1 pb^{-1} can exclude there nominal cross-section up to 150 GeV
  - Reach~250 GeV and > 400 GeV with 100 pb^{-1} and 10 fb^{-1}
- Interesting limits even if the cross-sections are only valid to within a couple order of magnitudes

Can we tune the instanton away?

[2012.09120]

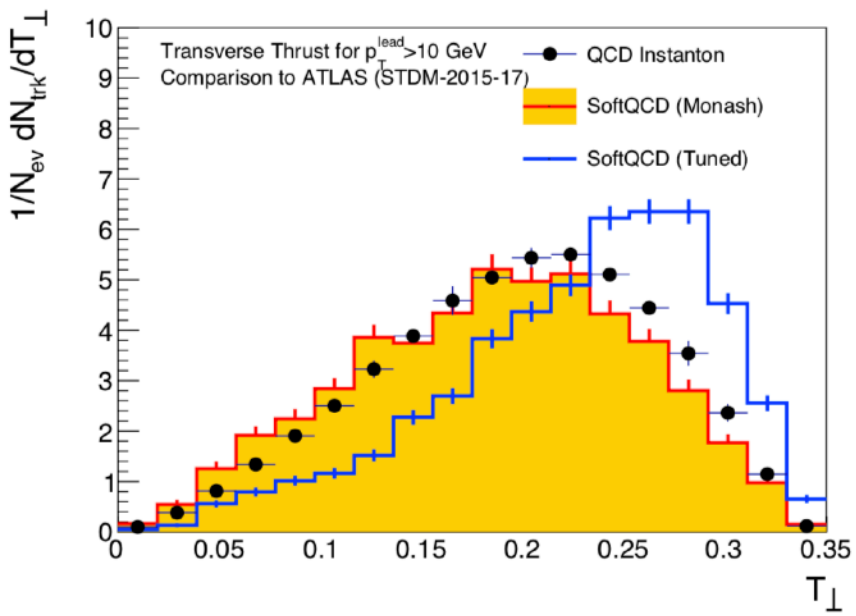


Figure 19. Predicted distribution of the event thrust of the Monash *softQCD* tune of Pythia8 as well as a modified version with significantly enhanced multiple parton interaction probability (MPI:alphaSvalue = 0.150) in comparison to the measurement at 13 TeV of the ATLAS Collaboration [50]

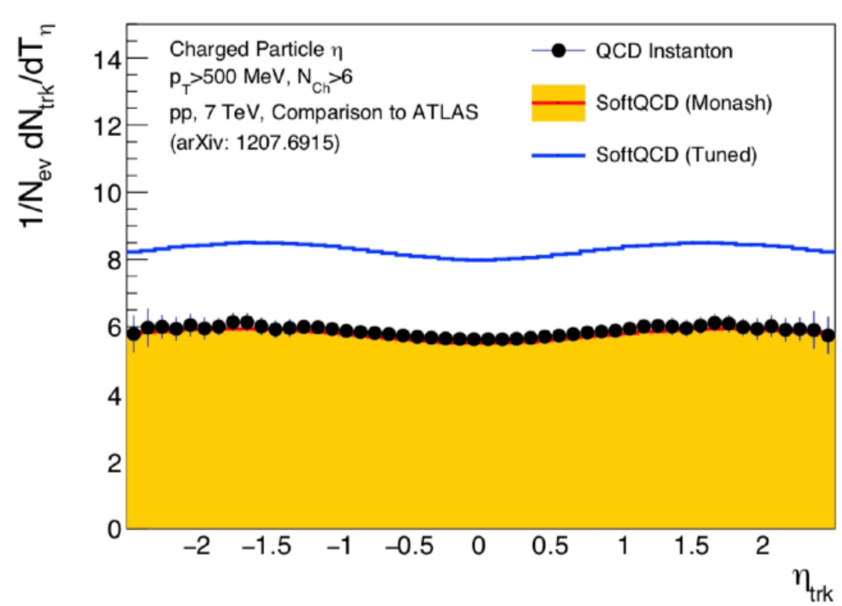
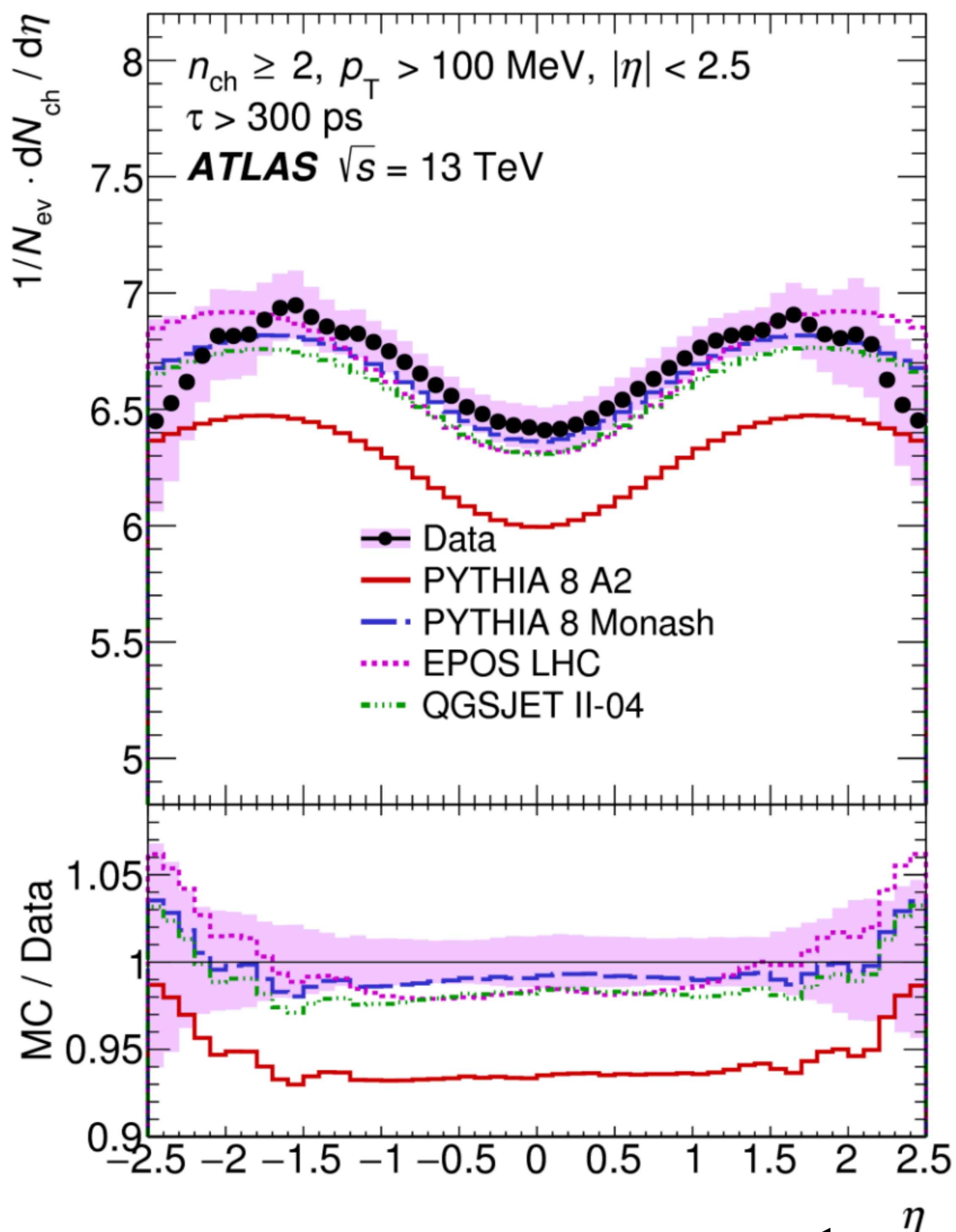


Figure 20. Predicted distribution of the charged particle spectrum vs. η of the Monash *softQCD* tune of Pythia8 as well as a modified version with significantly enhanced multiple parton interaction probability (MPI:alphaSvalue = 0.150) in comparison to the measurement at 7 TeV of the ATLAS Collaboration [48]

- Modelling of soft QCD processes relies on models fitted to data
  - Could this procedure have fitted the Instanton away?
- Simple test within Pythia of trying to reproduce a more Instanton like configuration. Possible but not describing data anymore
- More thorough tests obviously welcome

Recasting existing data

Eur. Phys. J. C 76 (2016) 502.



9M events, 151 μb^{-1}

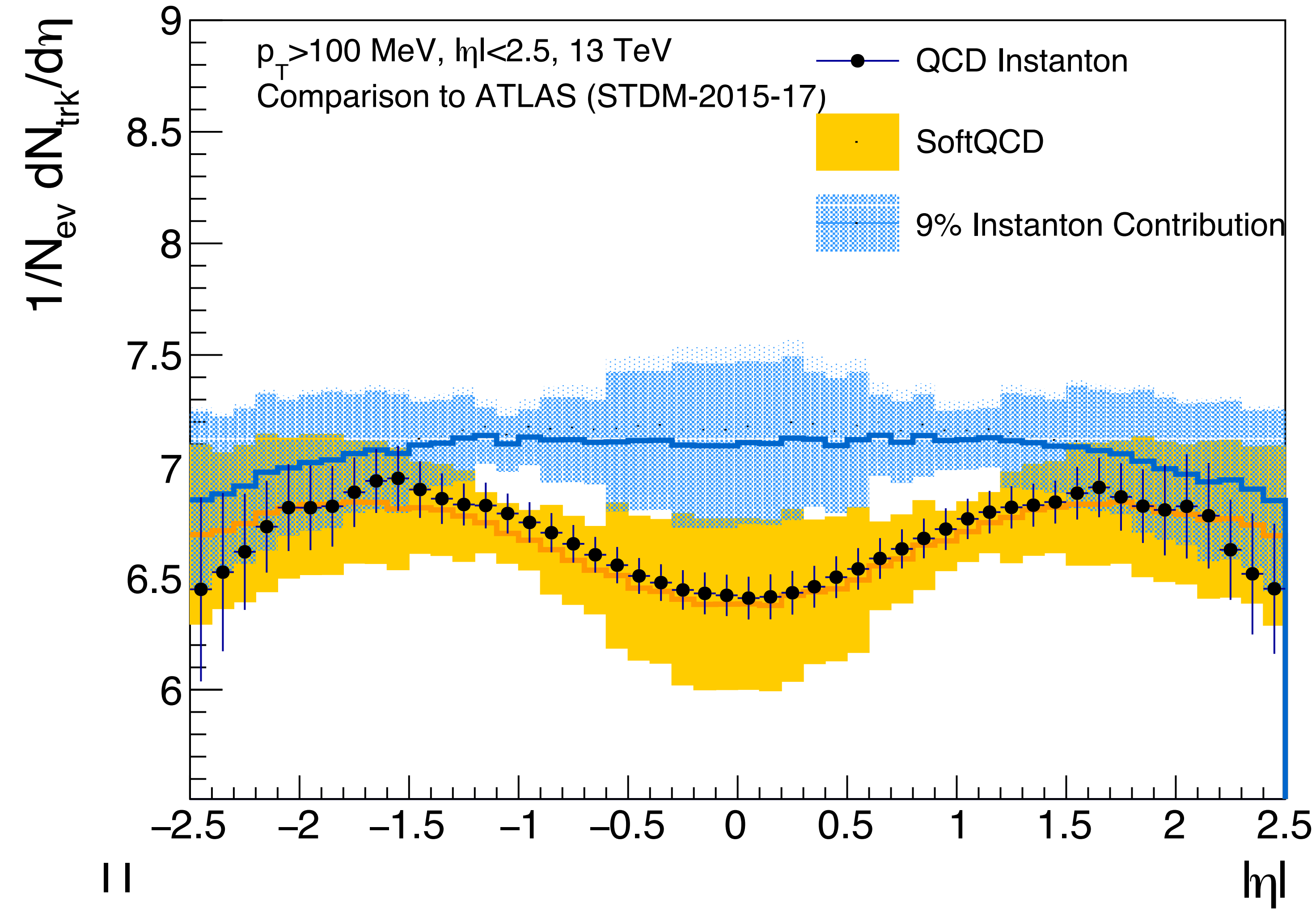
- ATLAS 13 TeV measurement of charged particles in Minimum Bias events
  - Track pT requirement of 100 MeV
- Nch/Nevt prediction depends on the total cross-section models
- But the η dependence is consistently well described
- We have seen the Instanton would predict a much more central distribution for this observable
- Can we already constrain Instanton production using this data?

A first limit

- We have passed our Pythia8 and Instanton signal events through the Rivet implementation of the analysis selection
- Signal added to the softQCD background with a scaling factor μ
  - Background uncertainty from comparison of Pythia/H7/Sherpa
  - Signal uncertainty from comparison of Sherpa/H7
- Scaling fitted to data to derive a 95% CL limit

[2012.09120]

  - Different correlation assumed for the bkg



- For a $\sigma = 71\mu b^{-1}$ and a signal efficiency of ~90%, exclude cross-sections:

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

Search strategies [2012.09120]

- The soft QCD regime (20 <m_I< 40 GeV and 40 <m_I< 80 GeV)
  - Very large signal cross-sections, but approaching the regime where cross-sections might not be anymore reliable
  - Background dominated by soft QCD, described by phenomenological models fitted to data with large uncertainties
  - Two regions to exploit the different fall-off of the cross-section for Instantons and softQCD as a function of mass
- The hard QCD regime (200 GeV <m_I< 300 GeV)
  - Instanton cross-sections are much smaller, and events hard to trigger but events look more striking
  - Background dominated by (perturbative) QCD jet production Known to NNLO, uncertainties at the level of several percent
- The top-quark regime (300 GeV <m_I< 500 GeV)
  - In this high mass regime can also try to find regions dominated by top-quark pair production.
  - Can use semi-/dileptonic decays in data as control regions

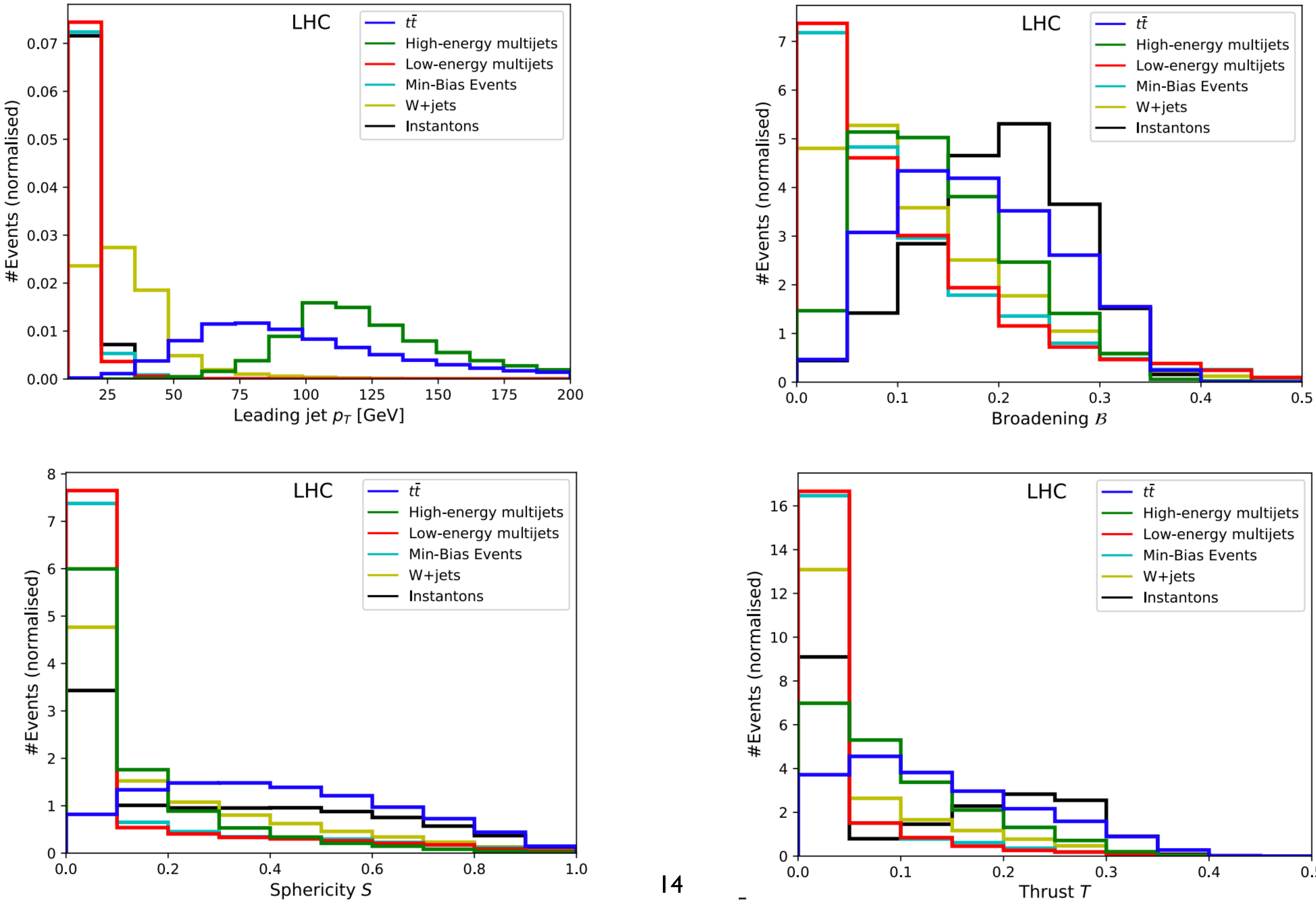
Signal simulation

- Relies on the process implementation in Sherpa [1911.09726]
  - Partonic cross-sections from tabulated calculation
  - Minimal $\sqrt{s'}$ fixes the factorisation scale $\mu_F = 1/\rho$
  - Instanton decay products consist of $q\bar{q}$ pairs as long as:
    - Quark mass smaller than partonic energy
    - Total Instanton mass smaller than partonic energy
  - An additional Poisson distributed number of gluons is added as long as total mass is below the parsonic energy
  - Particles are decayed isotropically in their rest frame and boosted back to the lab frame
- Likely ignores dependence of the active flavours on the instanton size/partonic energy
- Implementation in Herwig7 exists, but lacking partonic cross-section dependence

Jet Observables

[2010.02287]

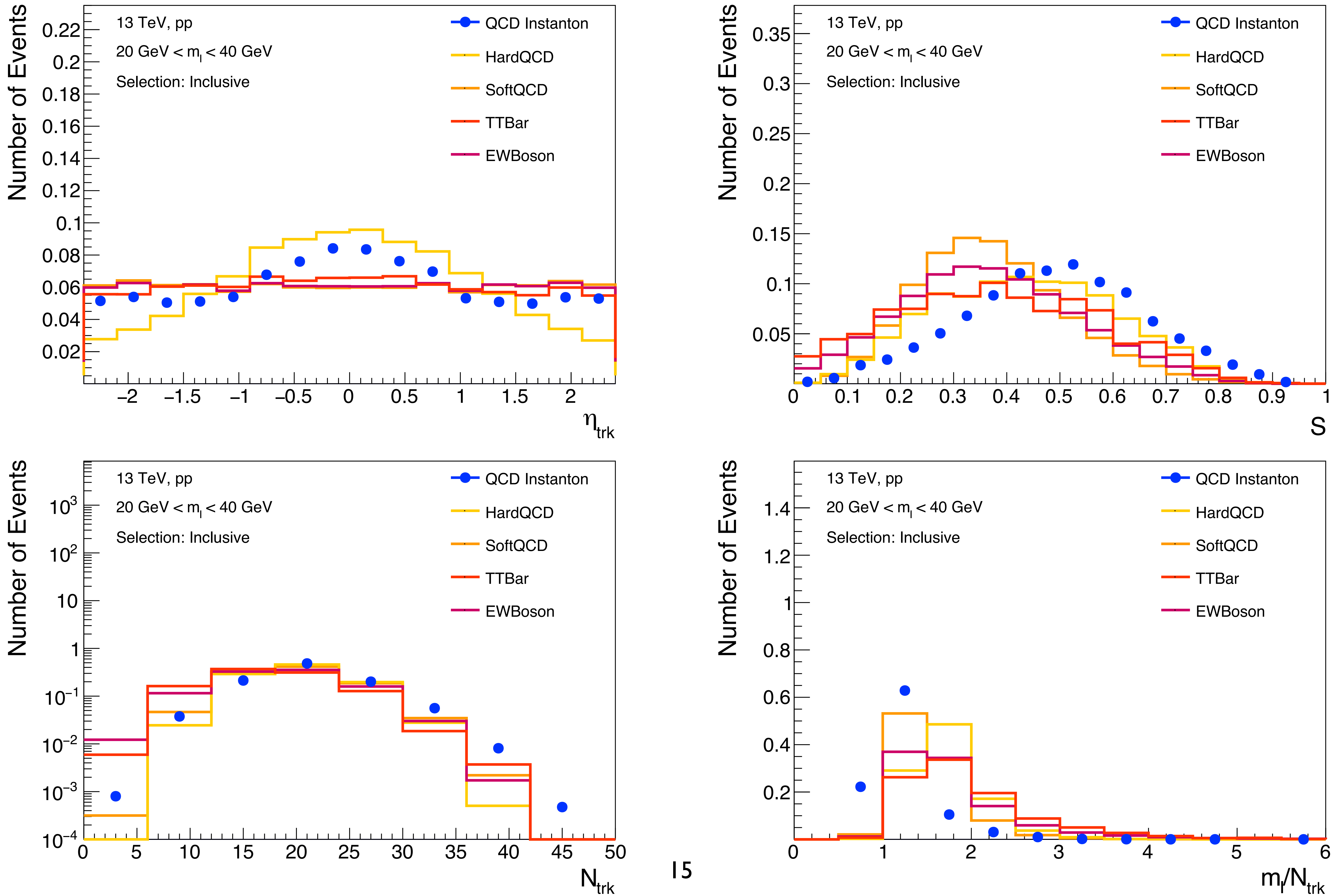
anti-k_T jets, R=0.4, p_T>10 GeV



Track observables

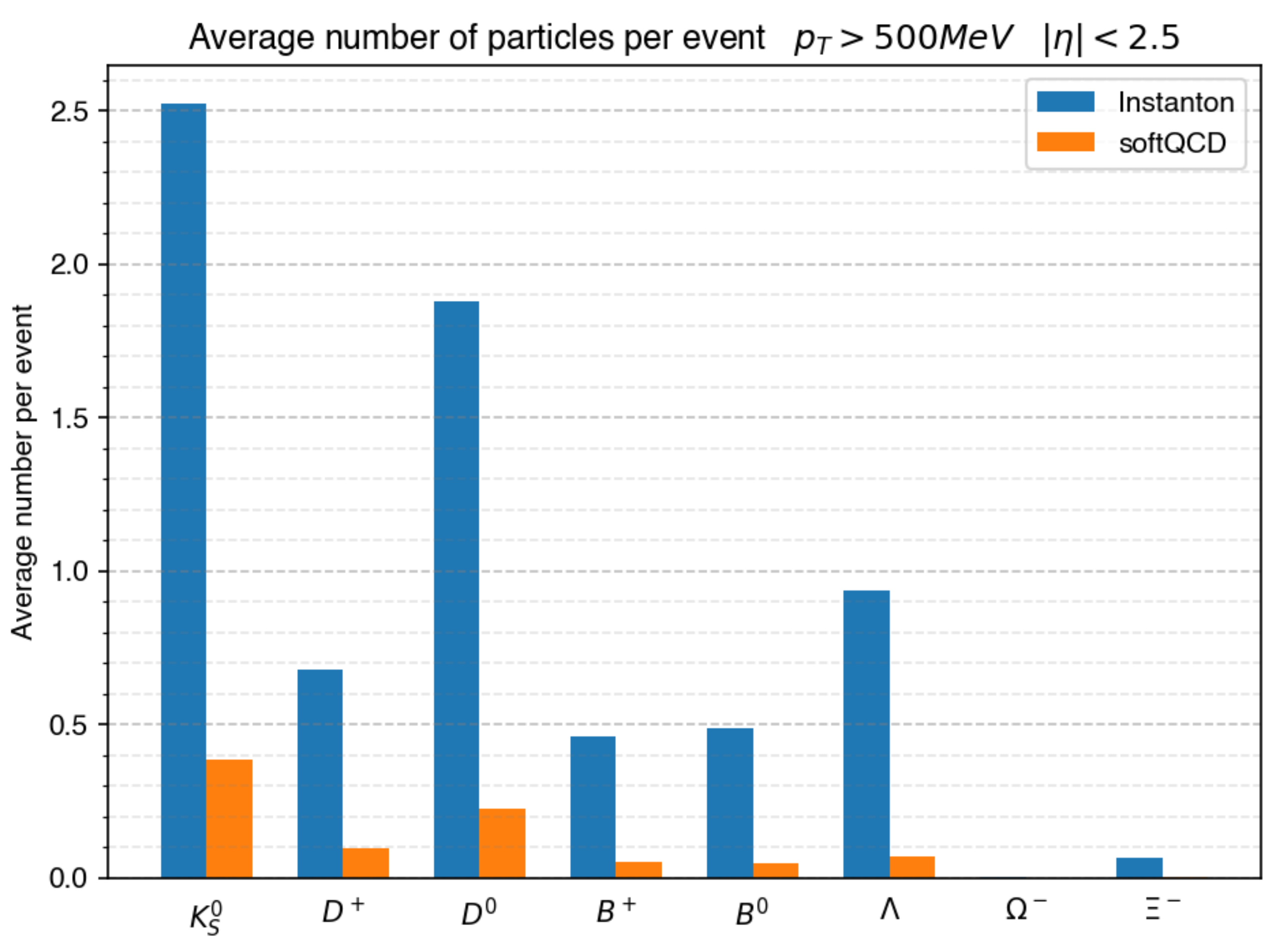
[2012.09120]

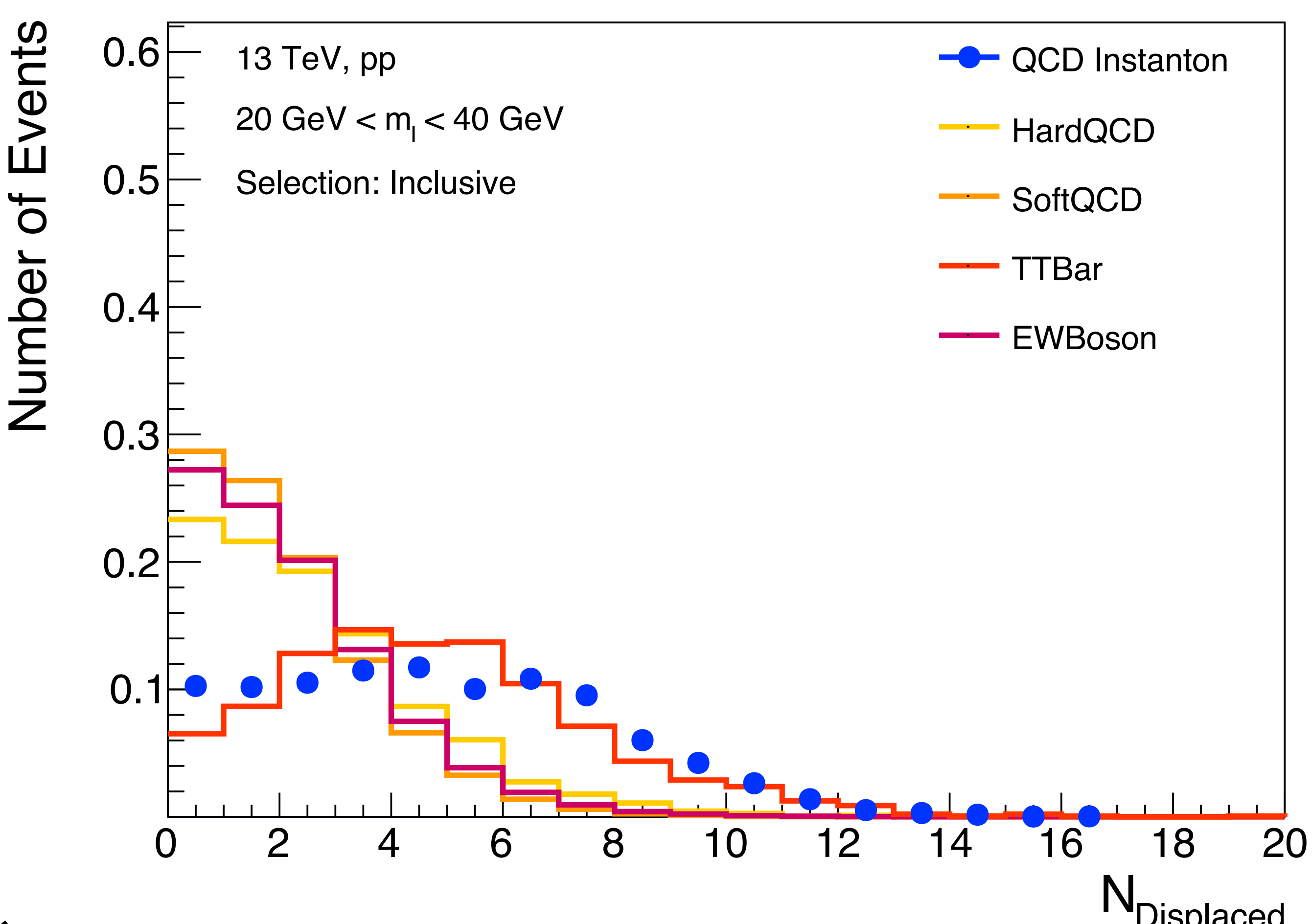
tracks p_T>500 MeV, $|\eta|$<2.5



Particle composition

- we should expect a different particle composition of the instanton events
  - We see a somewhat larger fraction of strange, charm and bottom particles in Instanton events than in QCD
  - Also larger number of displaced tracks, similar to the expectation for ttbar production (b-quarks?)

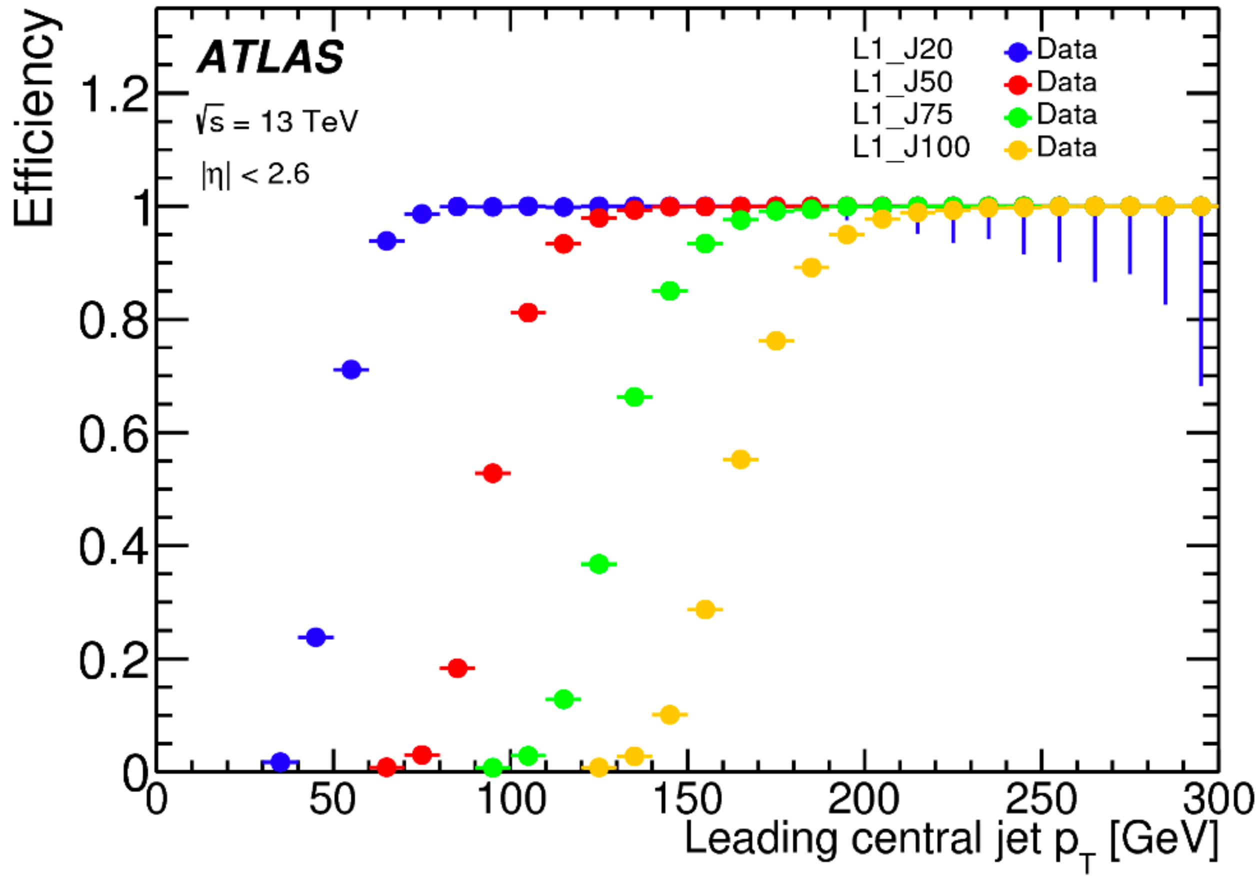


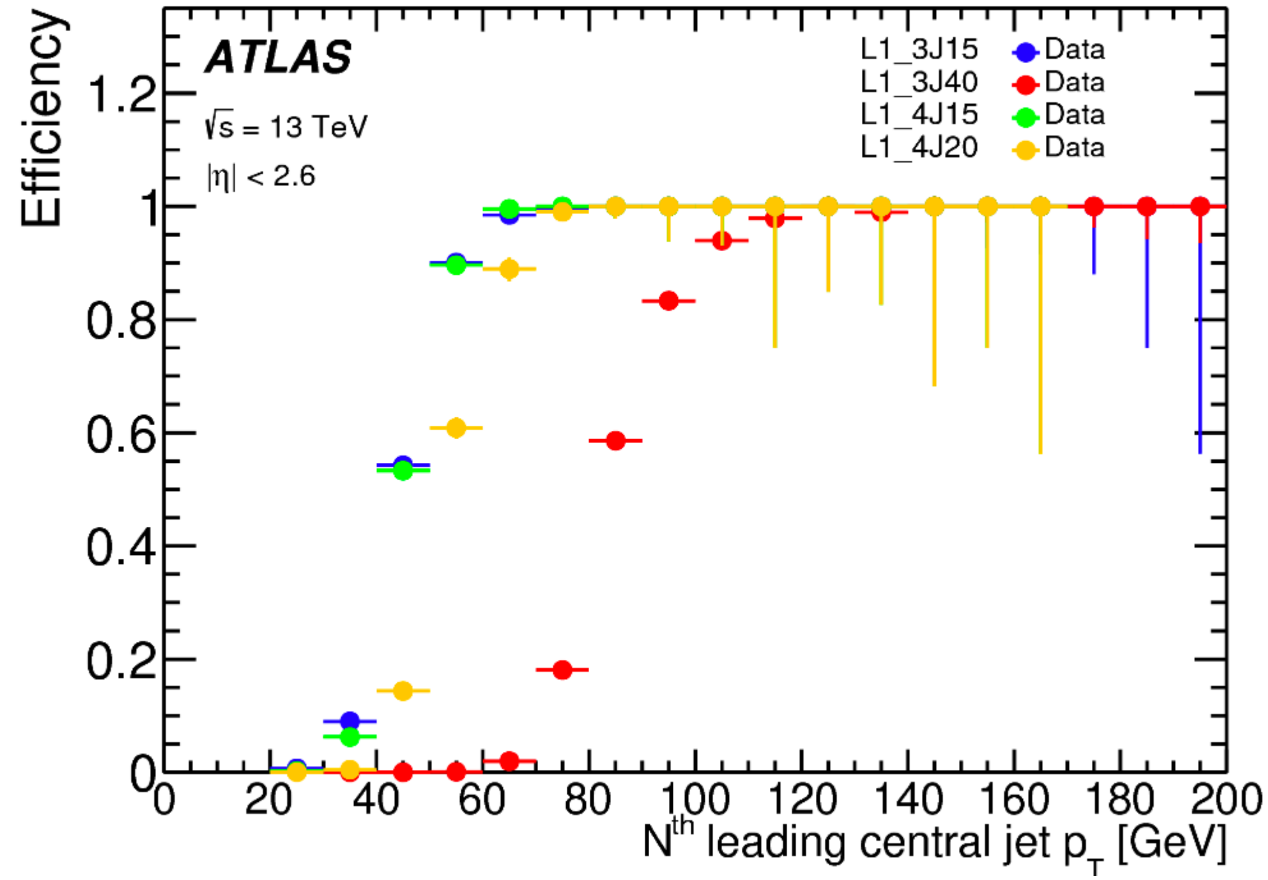


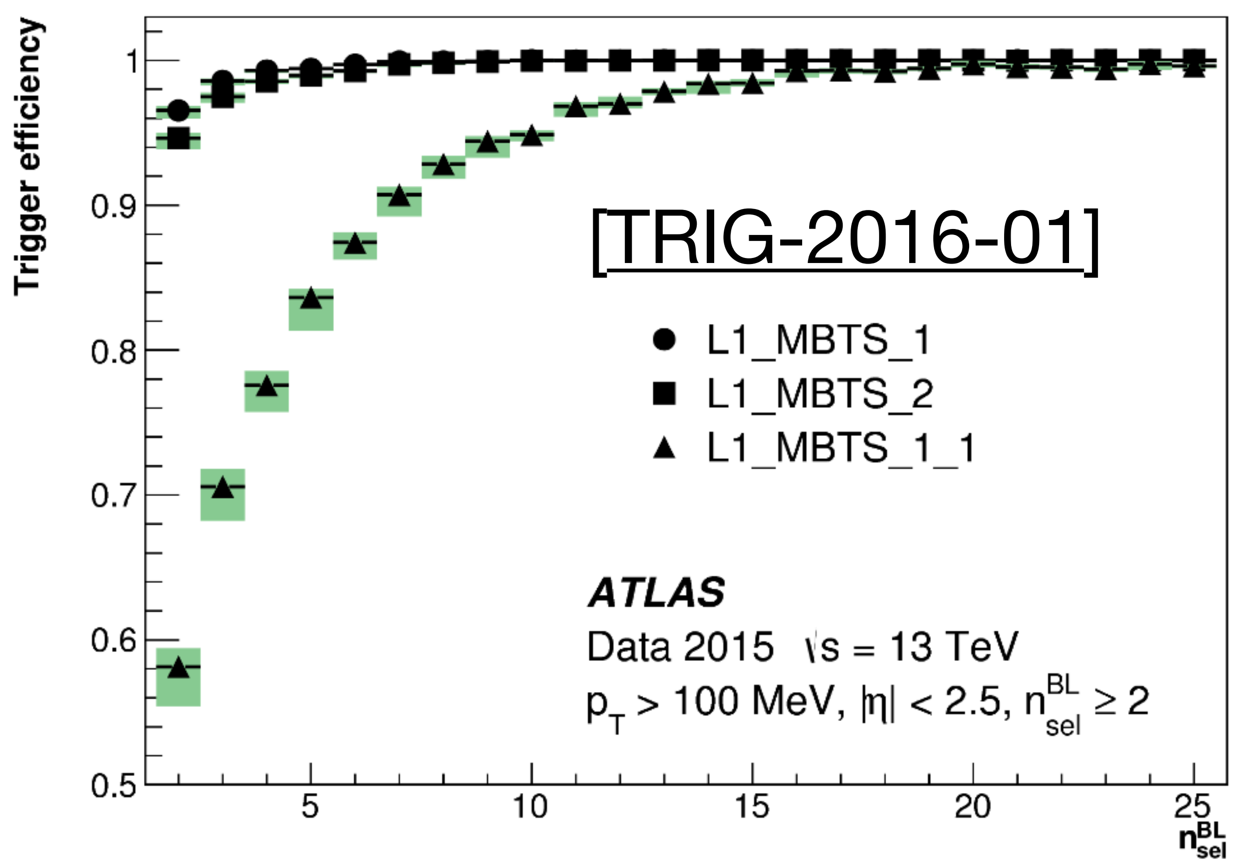
Triggers

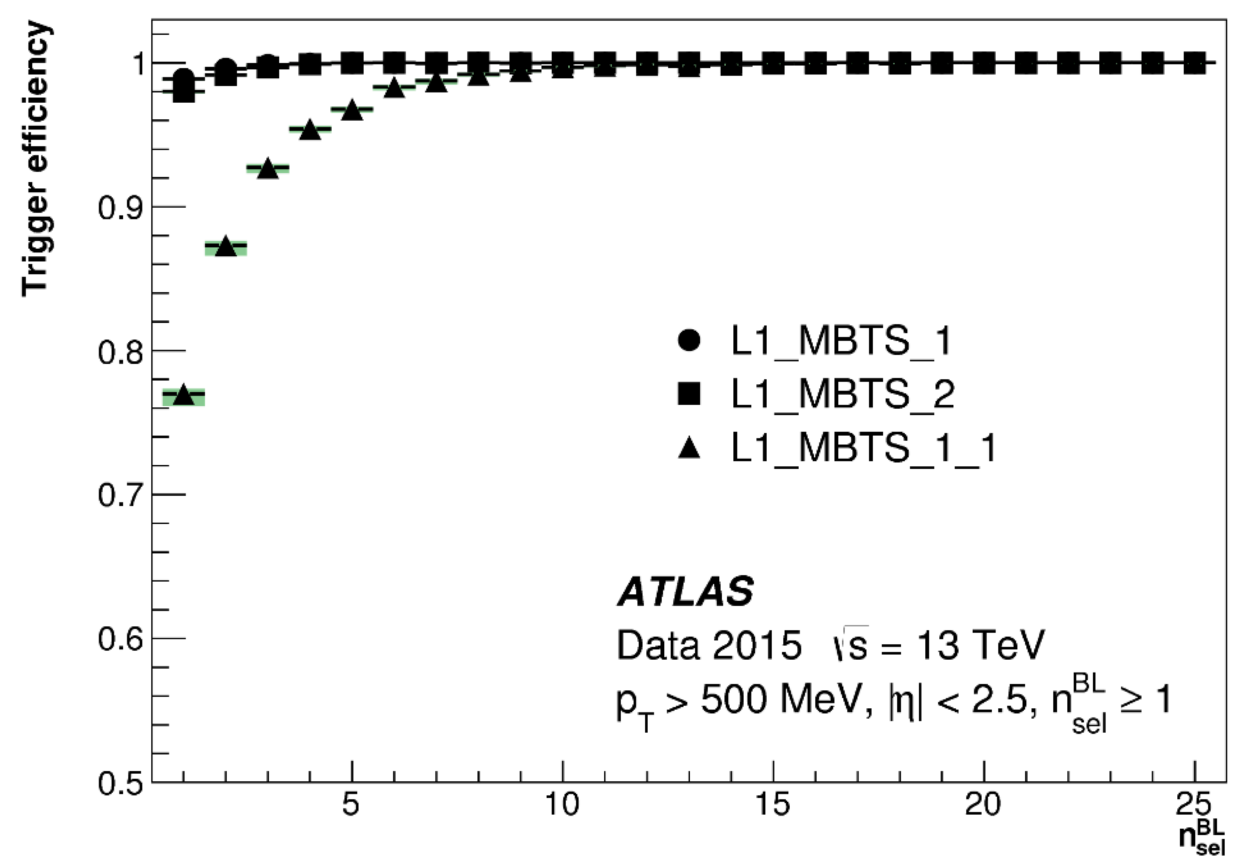
- Instanton cross-section is large, but events not easy to trigger
- Jet triggers
  - Single jet trigger: p_T>500 GeV -> no way
  - Multijet triggers: p_T >100 GeV -> still too high thresholds
    topological selections could help (i.e. event shapes)?
  - Can lower the rate by prescaling, but significantly reduces the collected statistics (factors 10 - 1000)
- Leptons
  - Leptons from semileptonic B/C-hadrons? -> too soft
- Minimum Bias triggers
  - Only require a few high-p_T tracks -> high acceptance
  - Typically used for monitoring and luminosity measurements
  - Very high prescales, will only get small fraction of total lumi

ATLAS TRIGGERS









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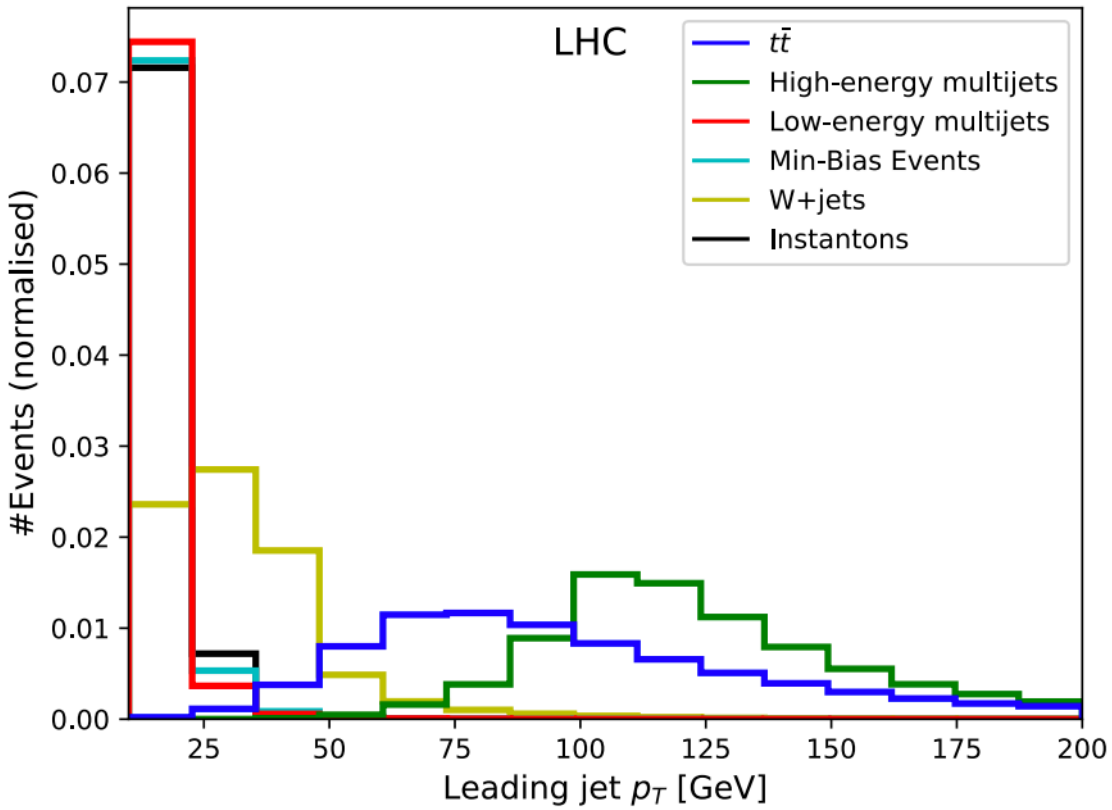

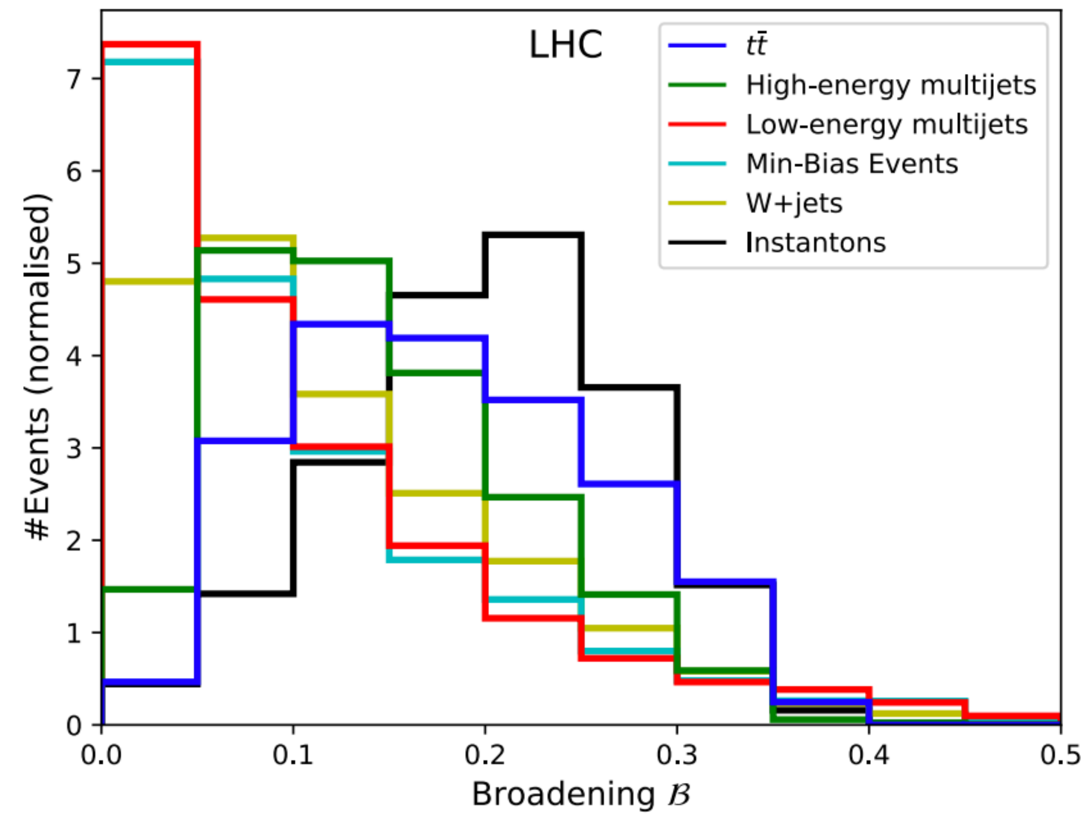

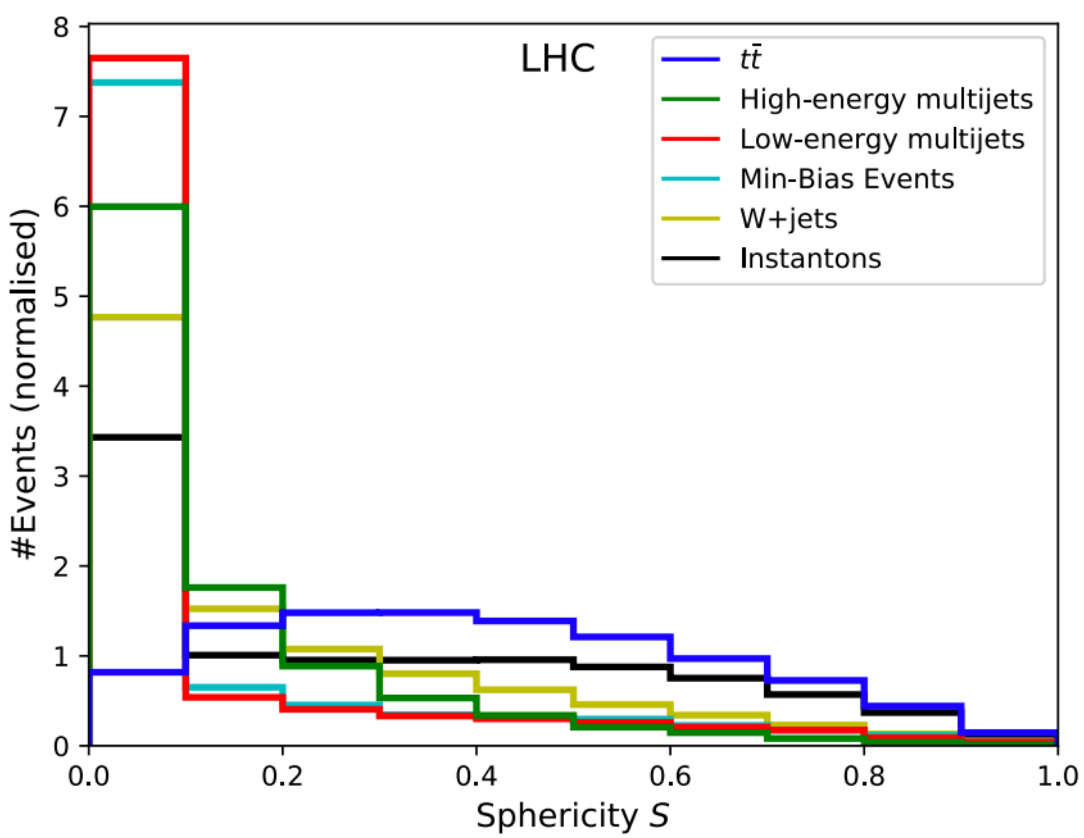

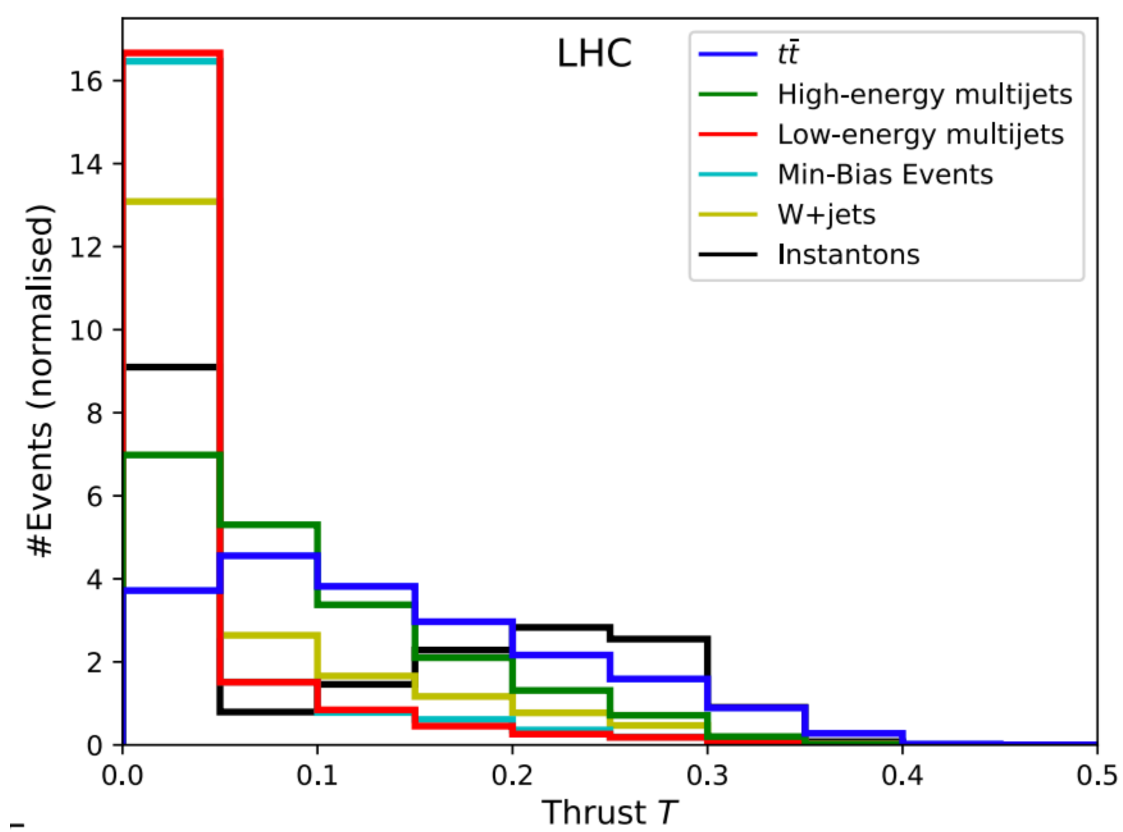

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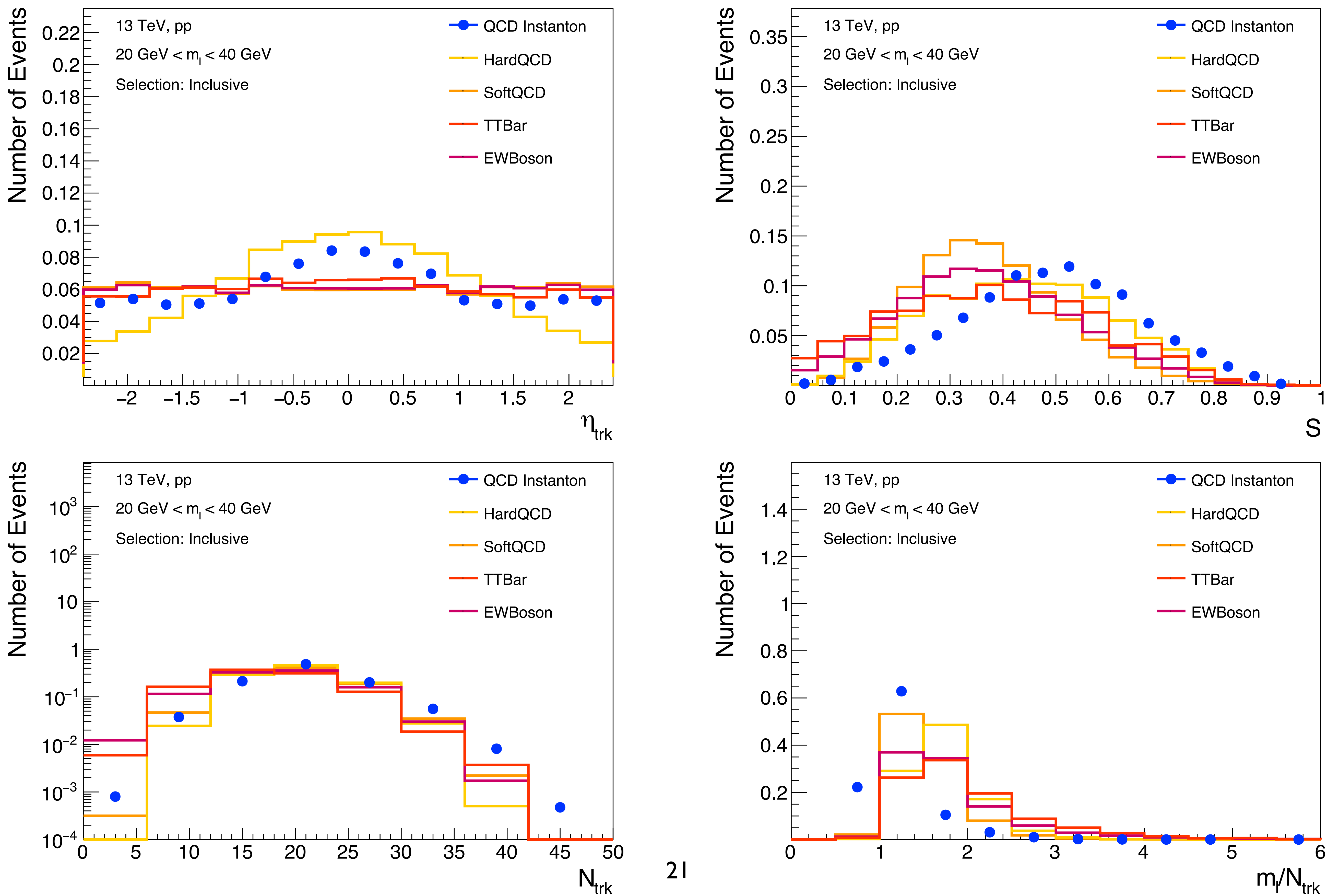

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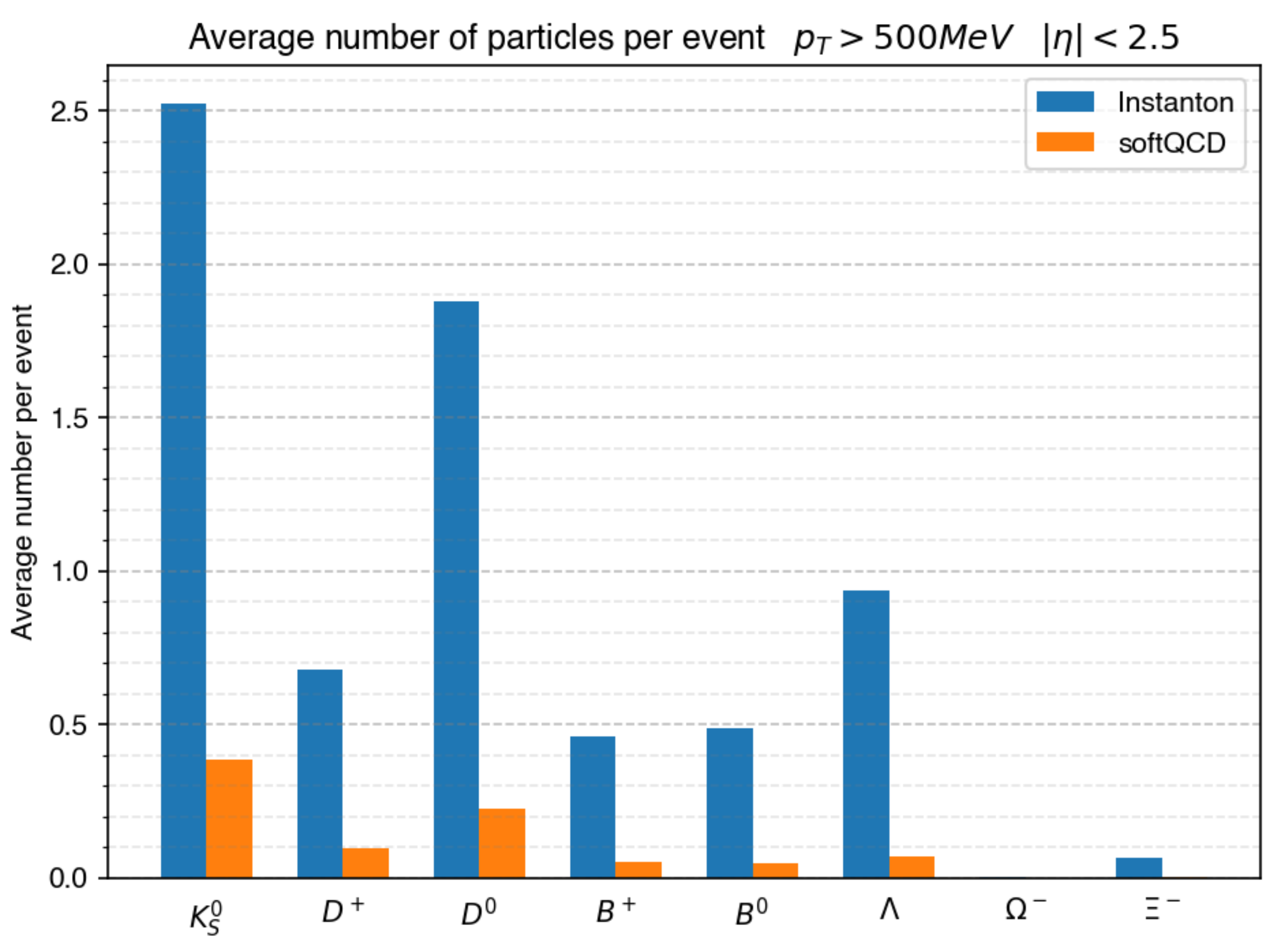

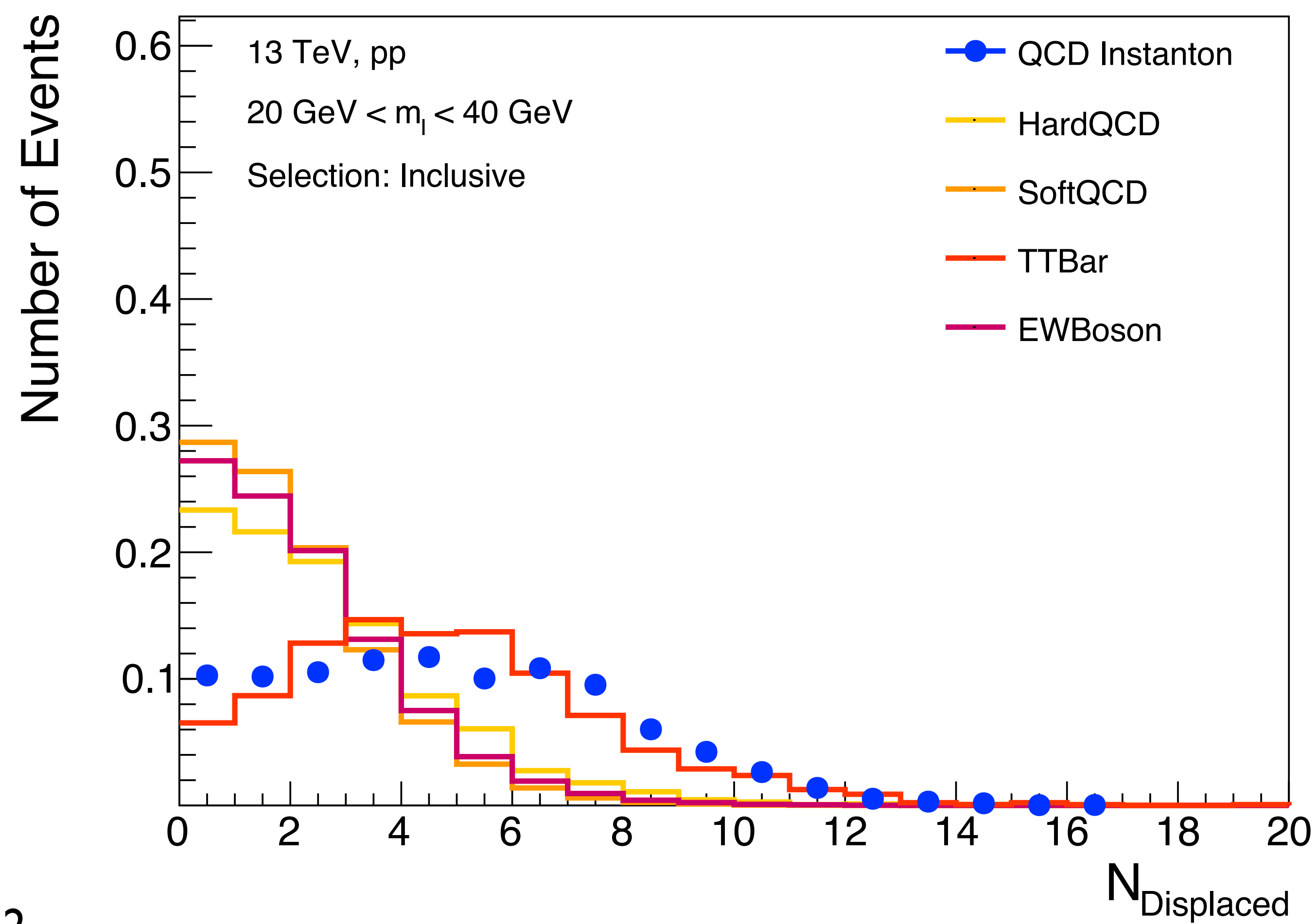

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