LHC signatures of QCD and EW instantons

Topological effects in the SM

Dec. 18th, 2020

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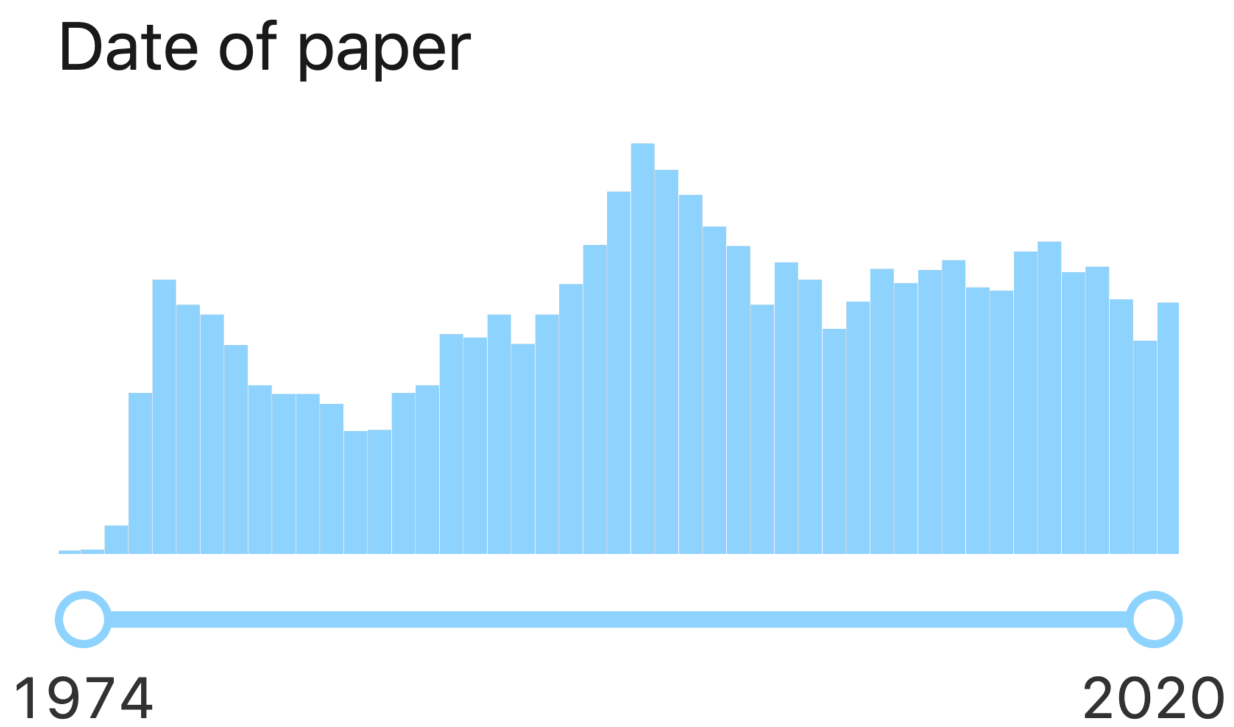
Introduction

- Topological phenomena, and Instantons in the SM are a well established (and rich) field since the 70s

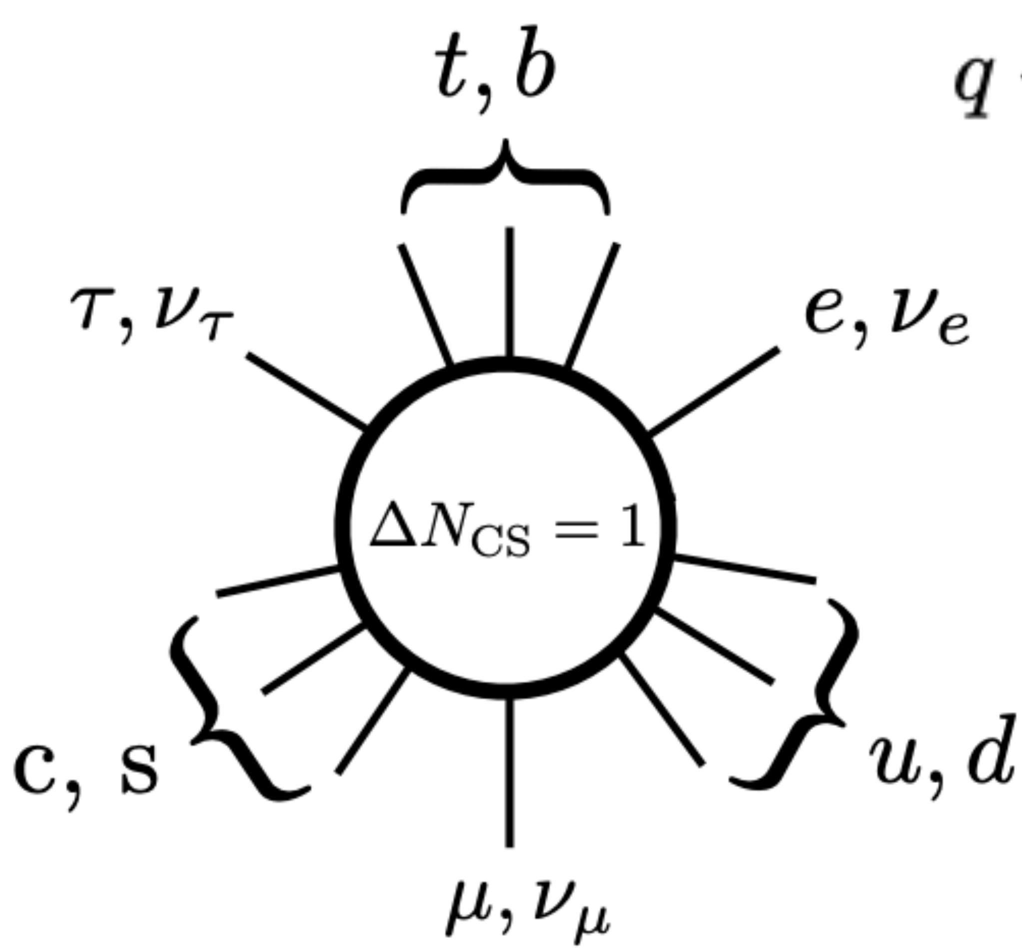


- Quite some activity in the 90s in studying possible manifestation of these processes at high-energy colliders
- Besides the HERA QCD Instanton searches, very little happened since then
- What can the LHC tell us about SM Instantons?

EW Sphalerons signature

- A $\Delta N_{CS} = 1$ Sphaleron transition should give rise to 12 fermions (7 quarks, 3 leptons), violating
- Additionally, expect to be produced in association with a large number ($1/\alpha$) of γ, Z, W, H bosons
- The process of interest at colliders is then:

$$q + q \to 7\bar{q} + 3\bar{\ell} + n_B W/Z/\gamma/H$$

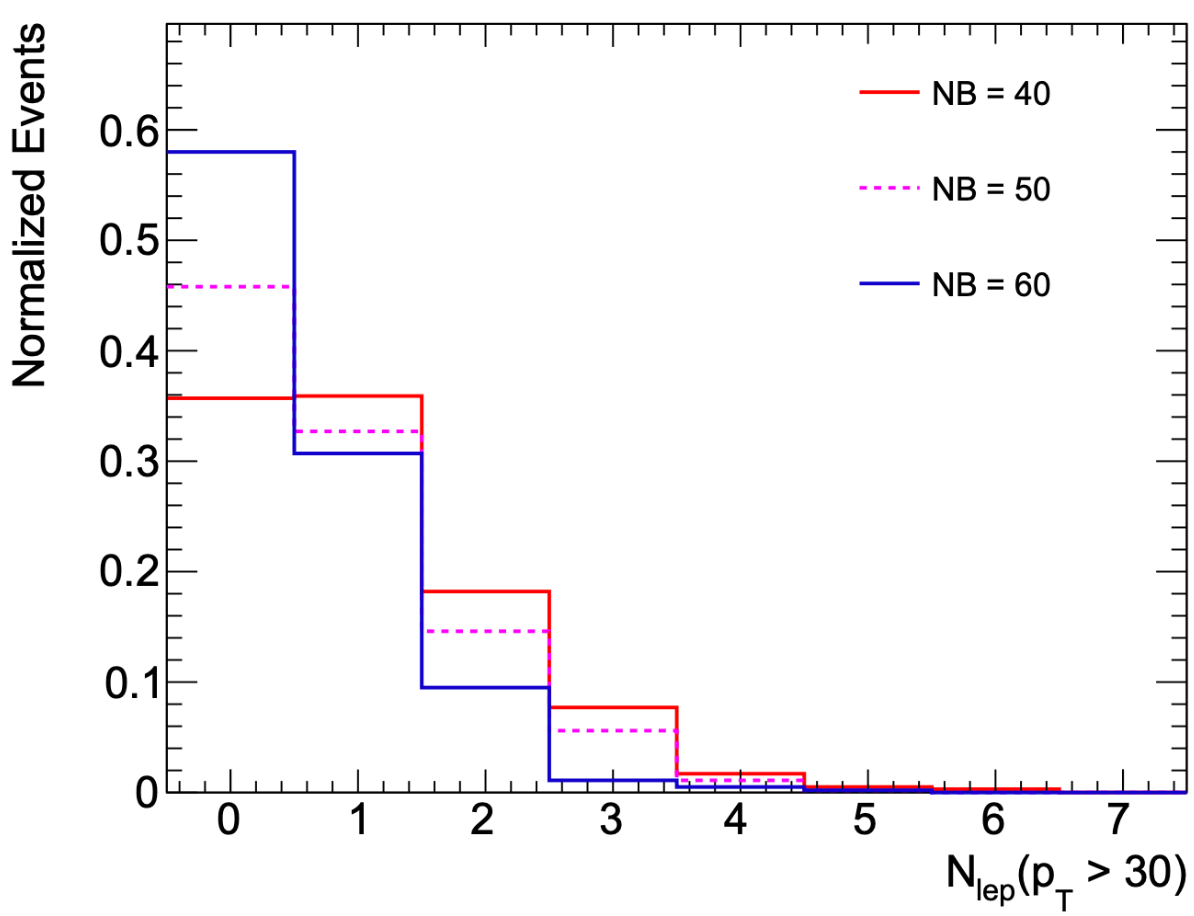


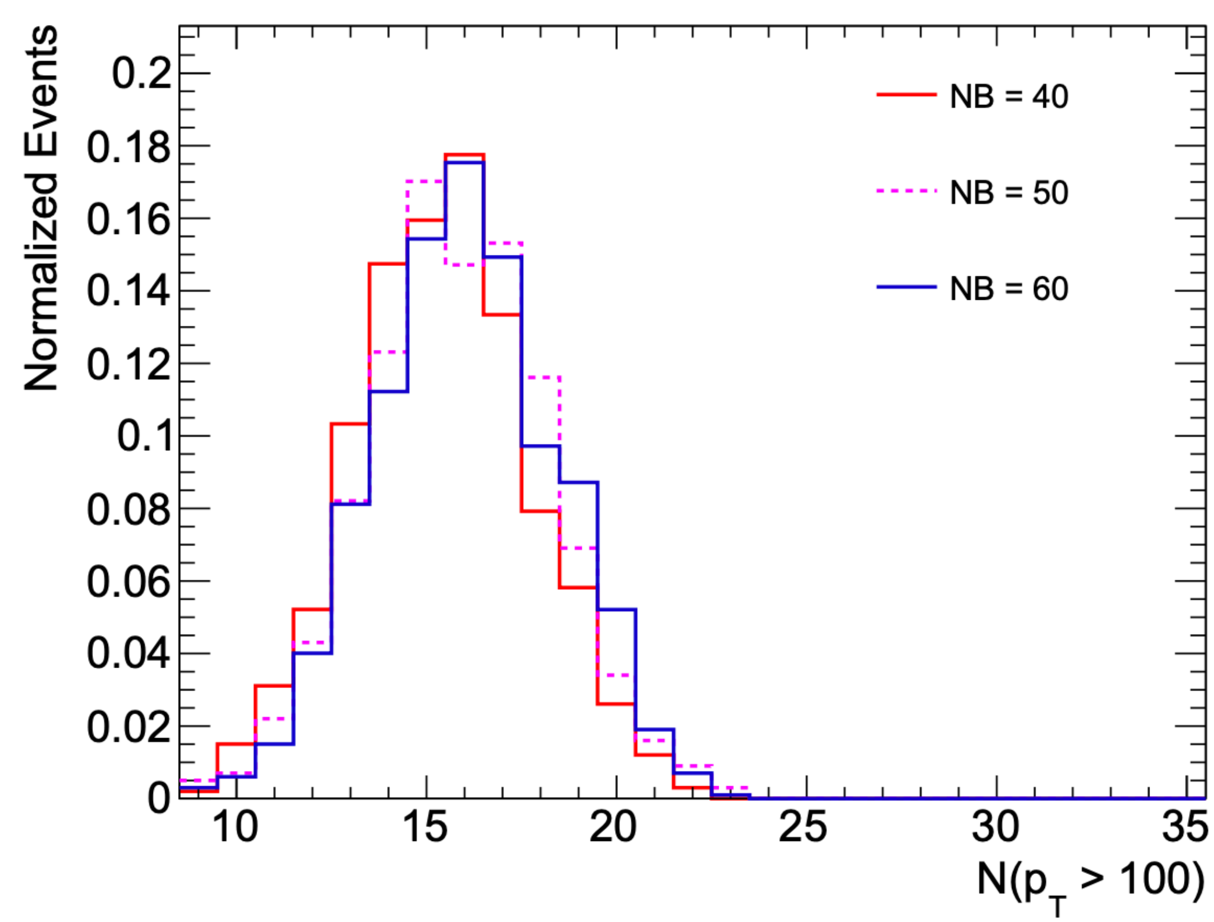
- Recently revamped interest due to claims [1710.07223] of cross-section being unsuppressed at ~LHC energies

Signatures

- Simulation of Sphaleron processes at colliders first implemented in HERWIG with the HERBVI plugin [9504232]
- Recently re-implemented in Herwig7 [1910.04761]
- CMS using "own" generator, BaryoGen [1805.02786], which ignores the associated boson production
- Expect a very high multiplicity final state with many high-p_T objects (leptons, γ, jets, b-jets)

[1910.04761]

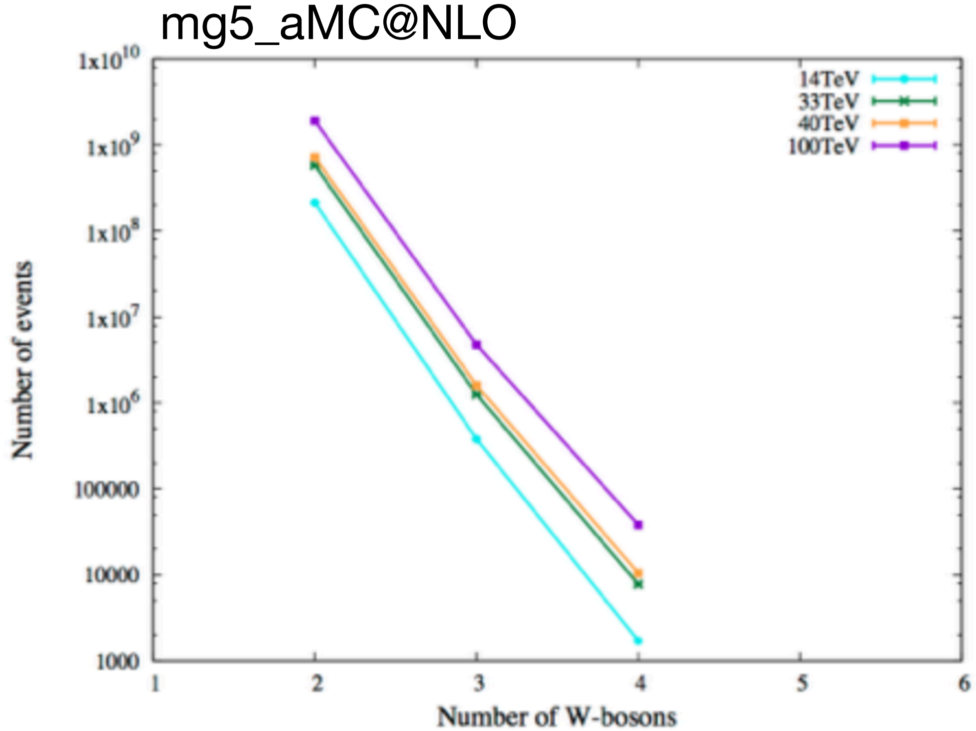


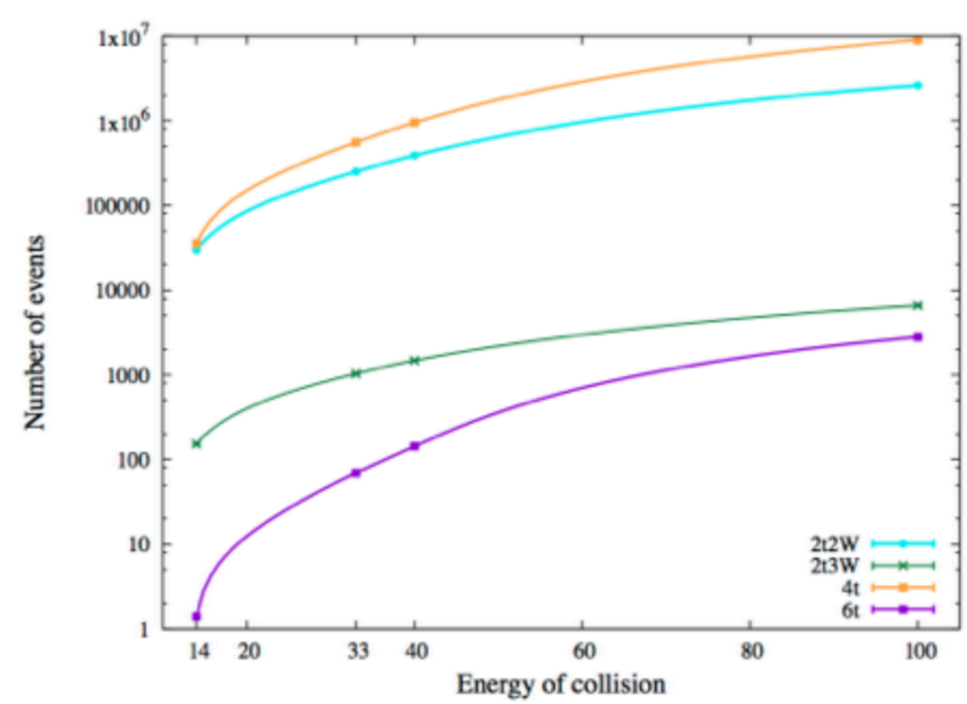


Experimental considerations

- No problems with trigger, any high-p_T trigger would fire
- Reconstruction efficiency would be high for ~all of the Sphaleron decay products
- No need for any complicated analysis strategy,
just count the leptons and jets (b-jets if you want)
- Nothing even remotely similar to this in the SM, can define background free signal regions: *single event == discovery*
- No way this could have escaped detection in experiments, plenty of searches for multi-V/H production, tt+X, …

mg5_aMC@NLO





EW Sphalerons at colliders

- Despite recent claims, production of SM EW sphalerons at (present and future) high-energy colliders is ~impossible
- Does this hold for generic SM extensions? Could anyone think of ways to make Sphaleron transitions “easier” at colliders?
  - Likely excluded by cosmological/astrophysical evidence?
  - Shall/can we look for Gia’s saturon model? It seemed to be not substantially different from the QBH we already search for

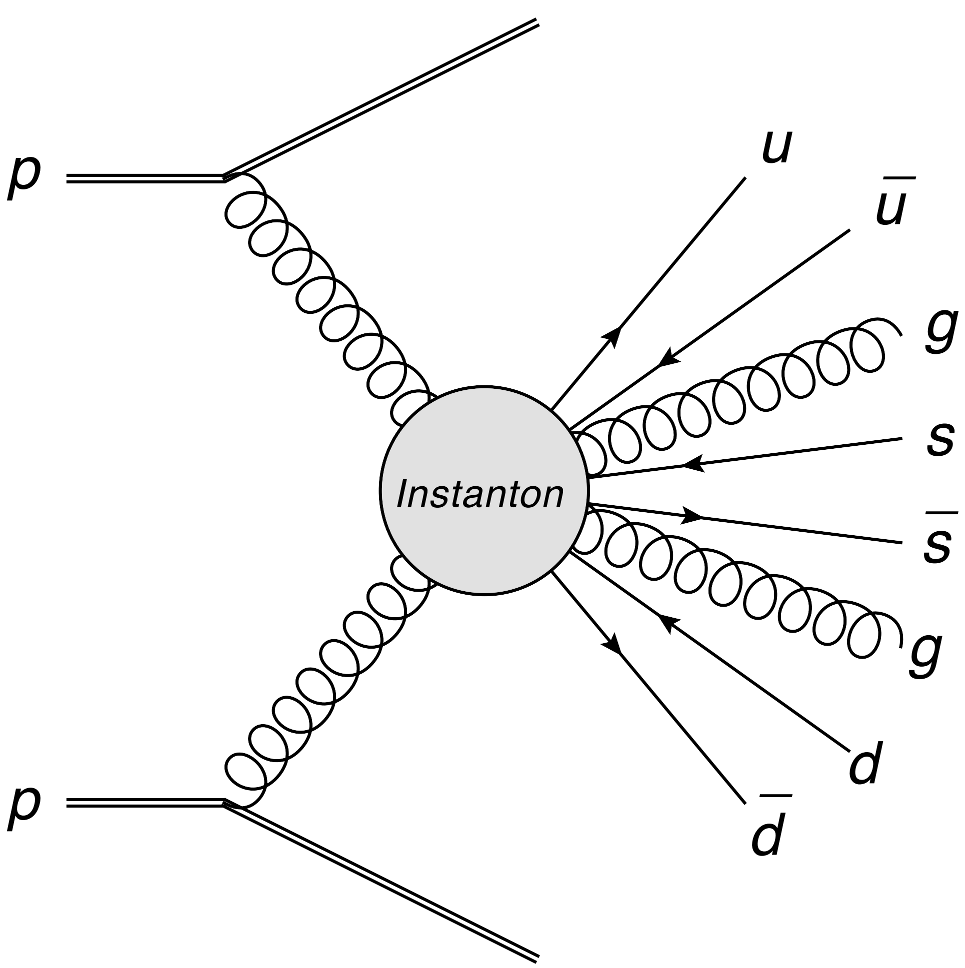
- Sphaleron signature is distinct and unlike anything we typically search for at hadron colliders
- Even if impossible in the SM it could probably still be considered as a useful BSM benchmark

QCD instanton signature

- A $\Delta N_{CS} = 1$ transition should give rise to $2N_f$ fermions pairs of different chiralities, and an additional large number of gluons

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

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



- Cross-sections so far calculated for gluon initiated processes
  - Dominant contribution due to PDFs
- Need to cut-off contribution of large-size instants (initial state/virtuality)

Cross-Sections

- Instanton cross-section as a function of the partonic com energy, and the number of associated gluons expected, from 2010.02287

$\sqrt{\hat{s}}$ [GeV]	50	100	150	200	300	400	500
$\langle n_g \rangle$	9.43	11.2	12.22	12.94	13.96	14.68	15.23
$\hat{\sigma}_{\text{tot}}^{\text{inst}}$ [pb]	207.33×10^{3}	1.29×10^{3}	53.1	5.21	165.73×10^{-3}	13.65×10^{-3}	1.89×10^{-3}

- Also computed for an additional jet with p_T > 150 GeV

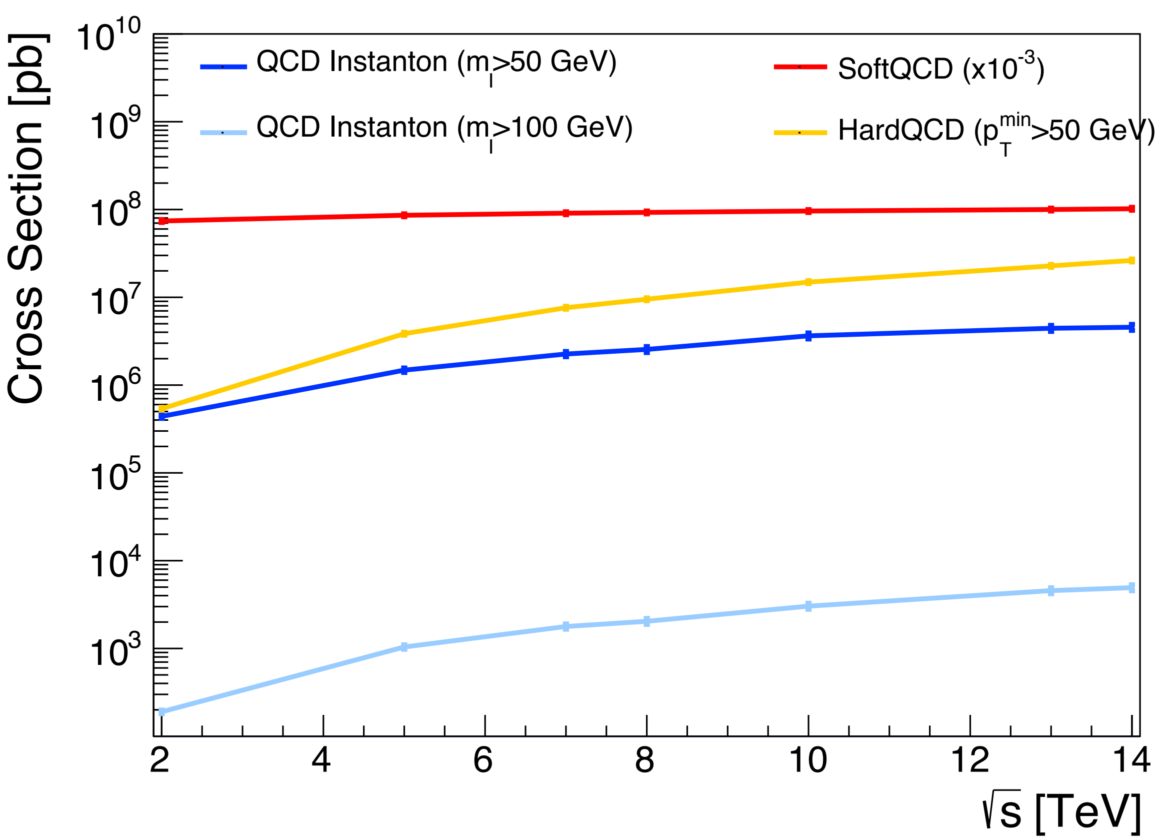
$\sqrt{\hat{s}}$ [GeV]	310	350	375	400	450	500
$\hat{\sigma}_{\text{tot}}^{\text{inst}}$ [pb]	3.42×10^{-23}	1.35×10^{-18}	1.06×10^{-17}	1.13×10^{-16}	9.23×10^{-16}	3.10×10^{-15}

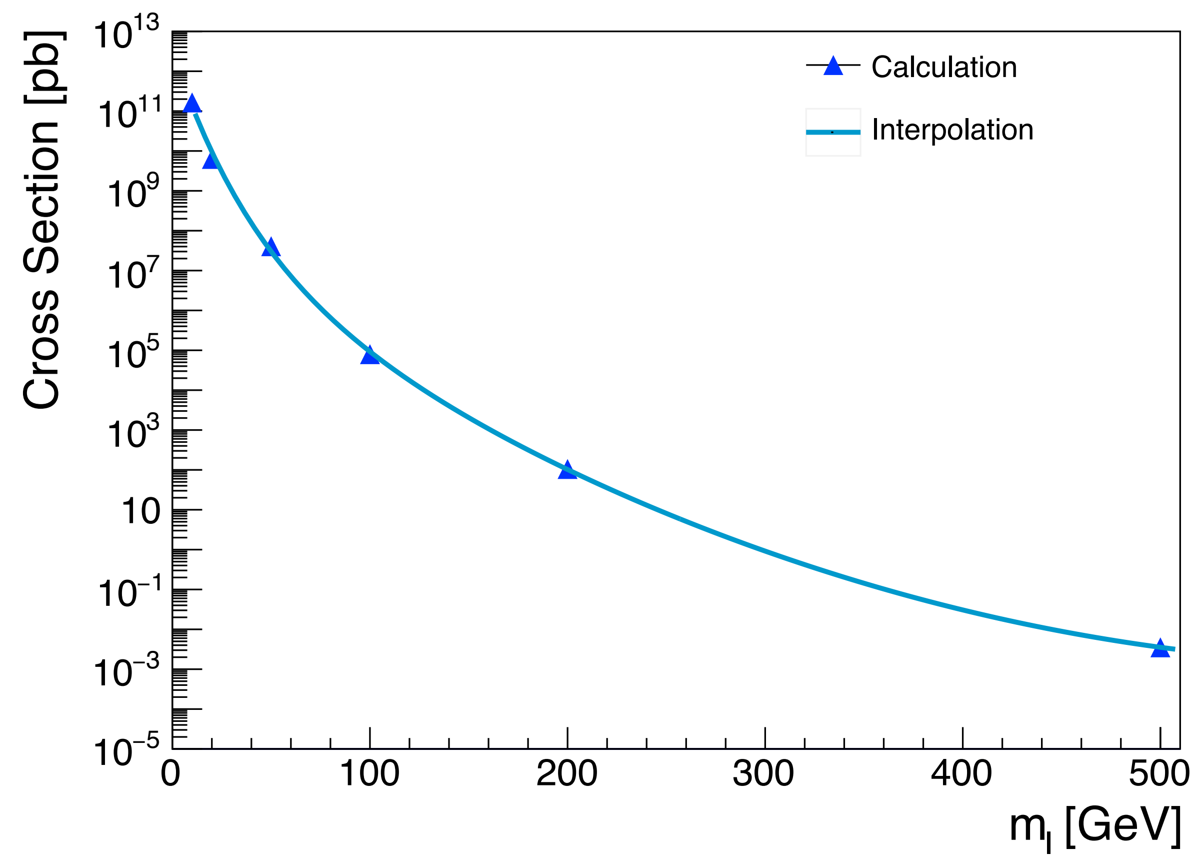
- And resulting cross-sections in pp/ppbar at various energies

E_{min} [GeV]	50	100	150	200	300	400	500
$\sigma_{p\bar{p}\to I}$ $\sqrt{s_{p\bar{p}}}$=1.96 TeV	2.62 μb	2.61 nb	29.6 pb	1.59 pb	6.94 fb	105 ab	3.06 ab
$\sigma_{pp\to I}$ $\sqrt{s_{pp}}$=14 TeV	58.19 μb	129.70 nb	2.769 nb	270.61 pb	3.04 pb	114.04 fb	8.293 fb
$\sigma_{pp\to I}$ $\sqrt{s_{pp}}$=30 TeV	211.0 μb	400.9 nb	9.51 nb	1.02 nb	13.3 pb	559.3 fb	46.3 fb
$\sigma_{pp\to I}$ $\sqrt{s_{pp}}$=100 TeV	771.0 μb	2.12 μb	48.3 nb	5.65 nb	88.3 pb	4.42 pb	395.0 fb

Cross-Sections

- Cross-section quickly dropping with the instanton mass
  - Need to find balance between a decently large cross-section and sufficiently high mass (to get high-pT decay products)
- The dependence on the pp centre-of-mass energy is somewhat different between the Instanton and SM pQCD jet production or soft QCD models
  - But models of the total cross-section are usually “tuned” to data





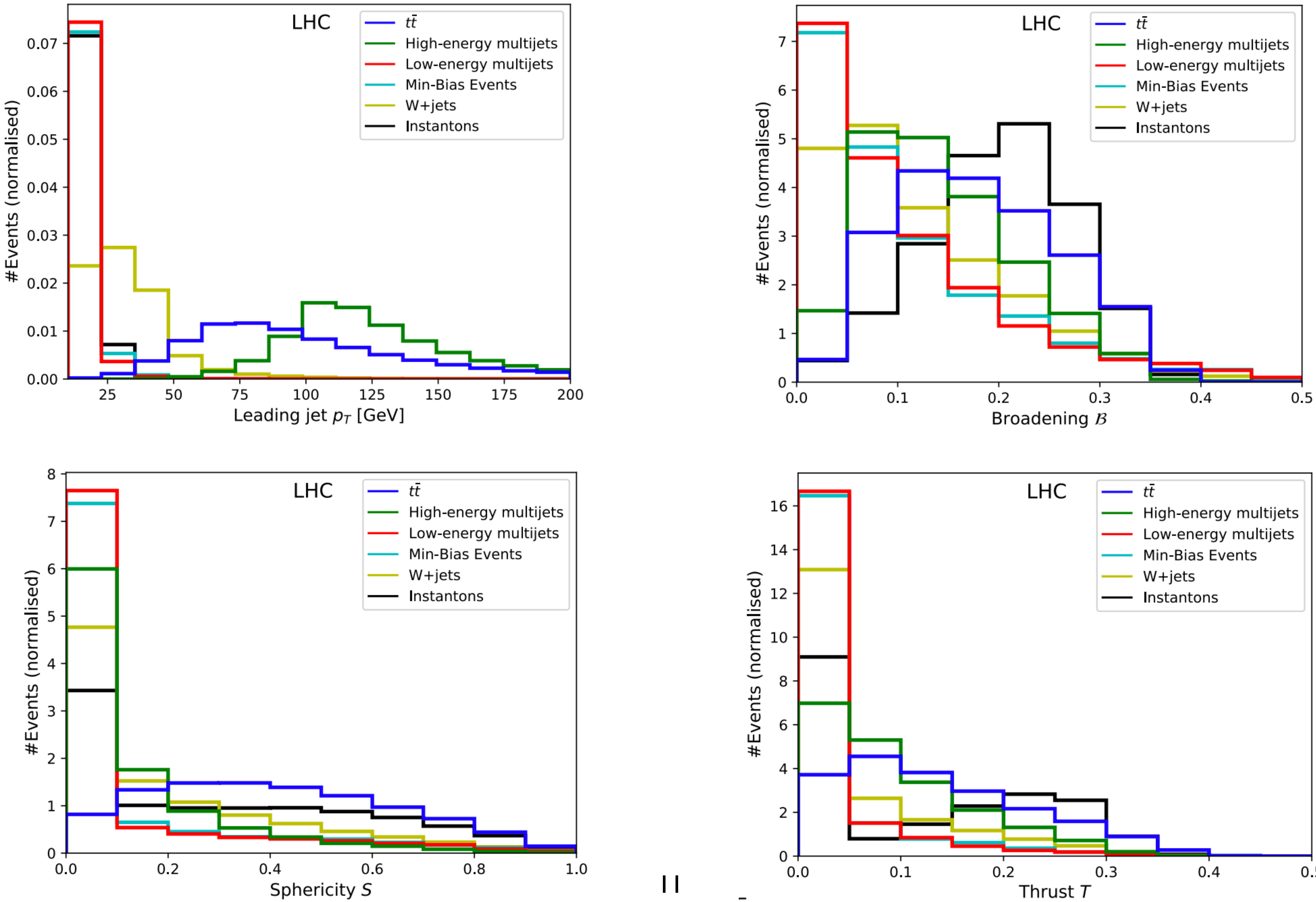
Signal simulation

- 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]

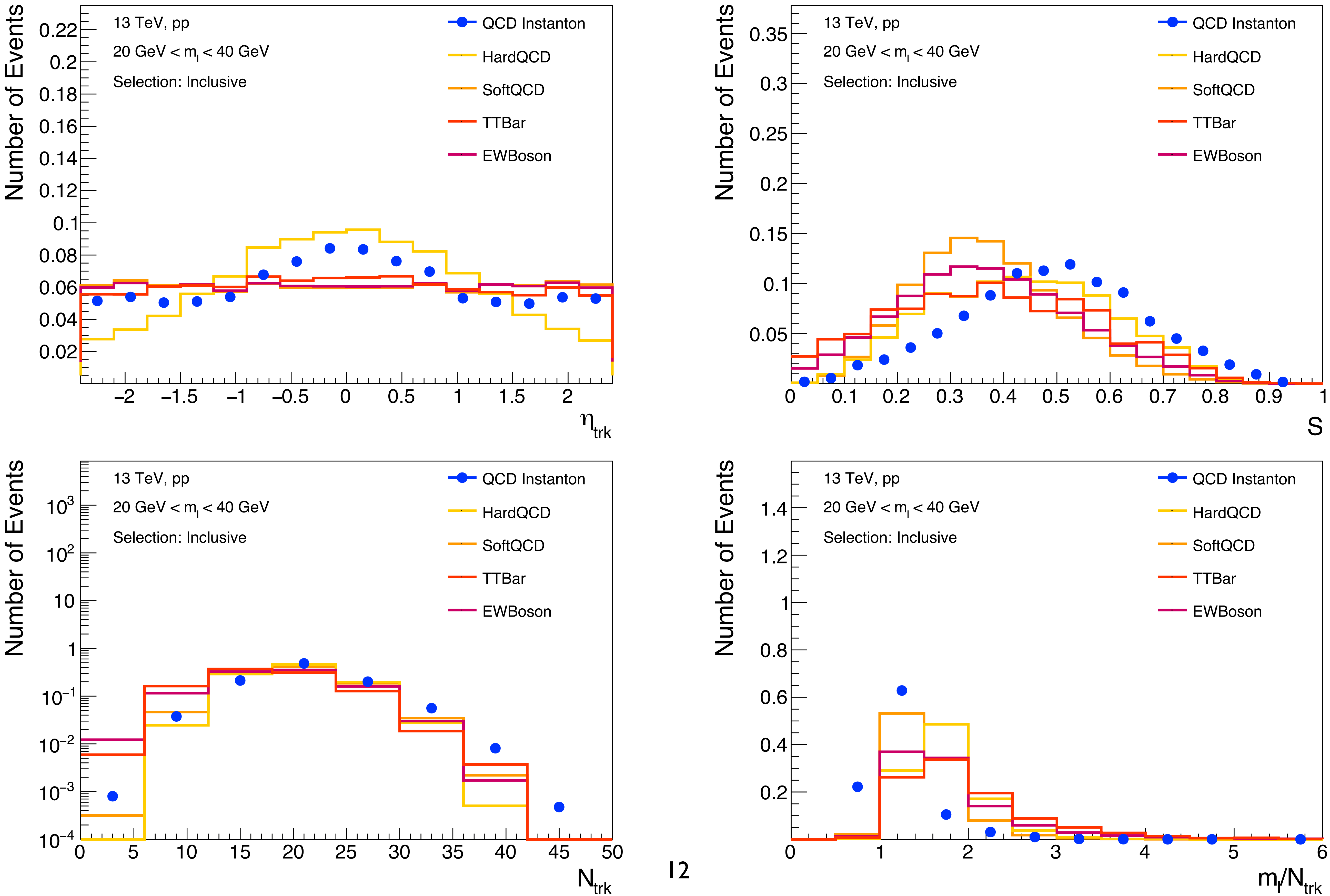
anti-k_T jets, R=0.4, p_T>10 GeV



Track observables

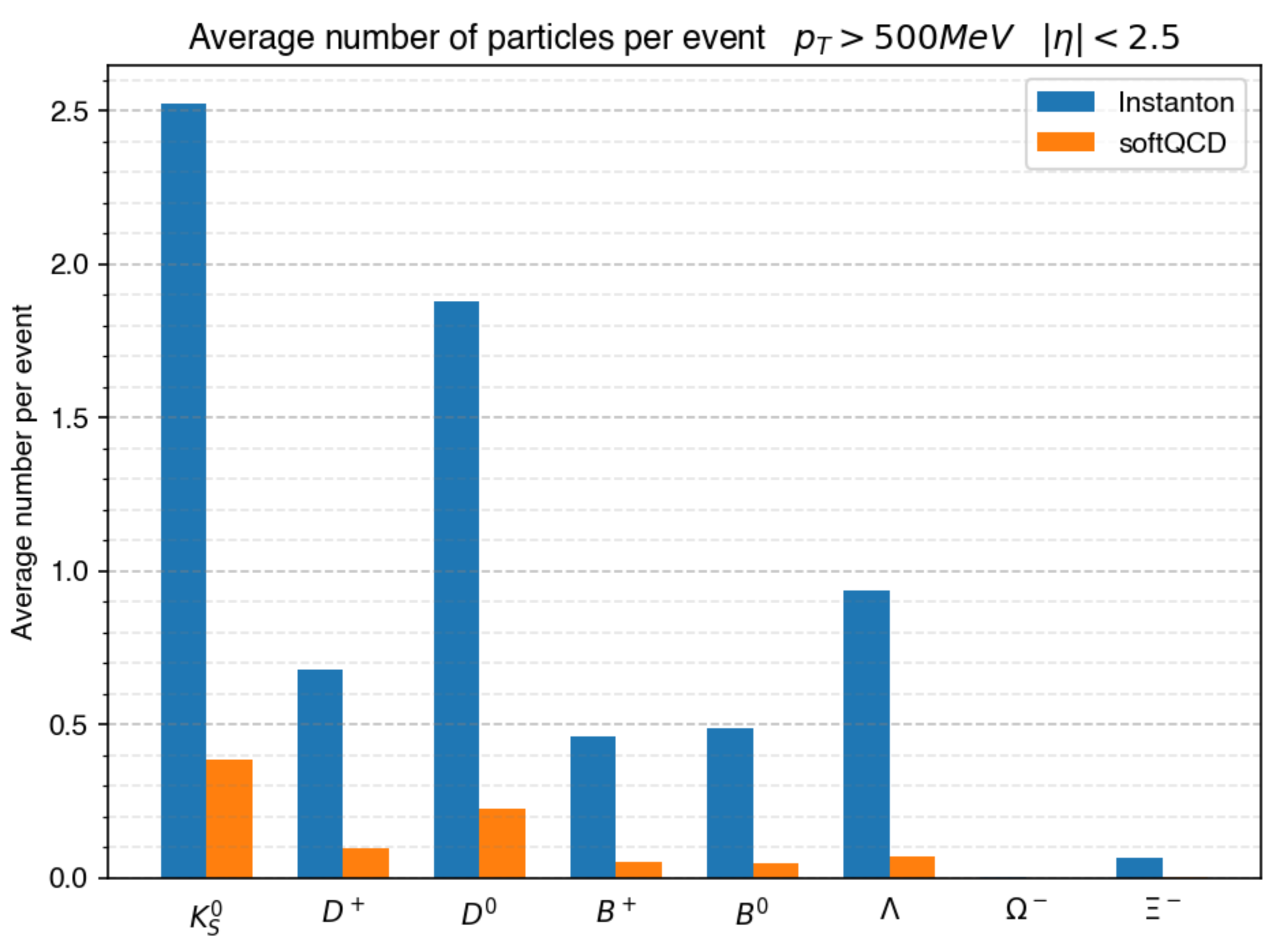
[2012.09120]

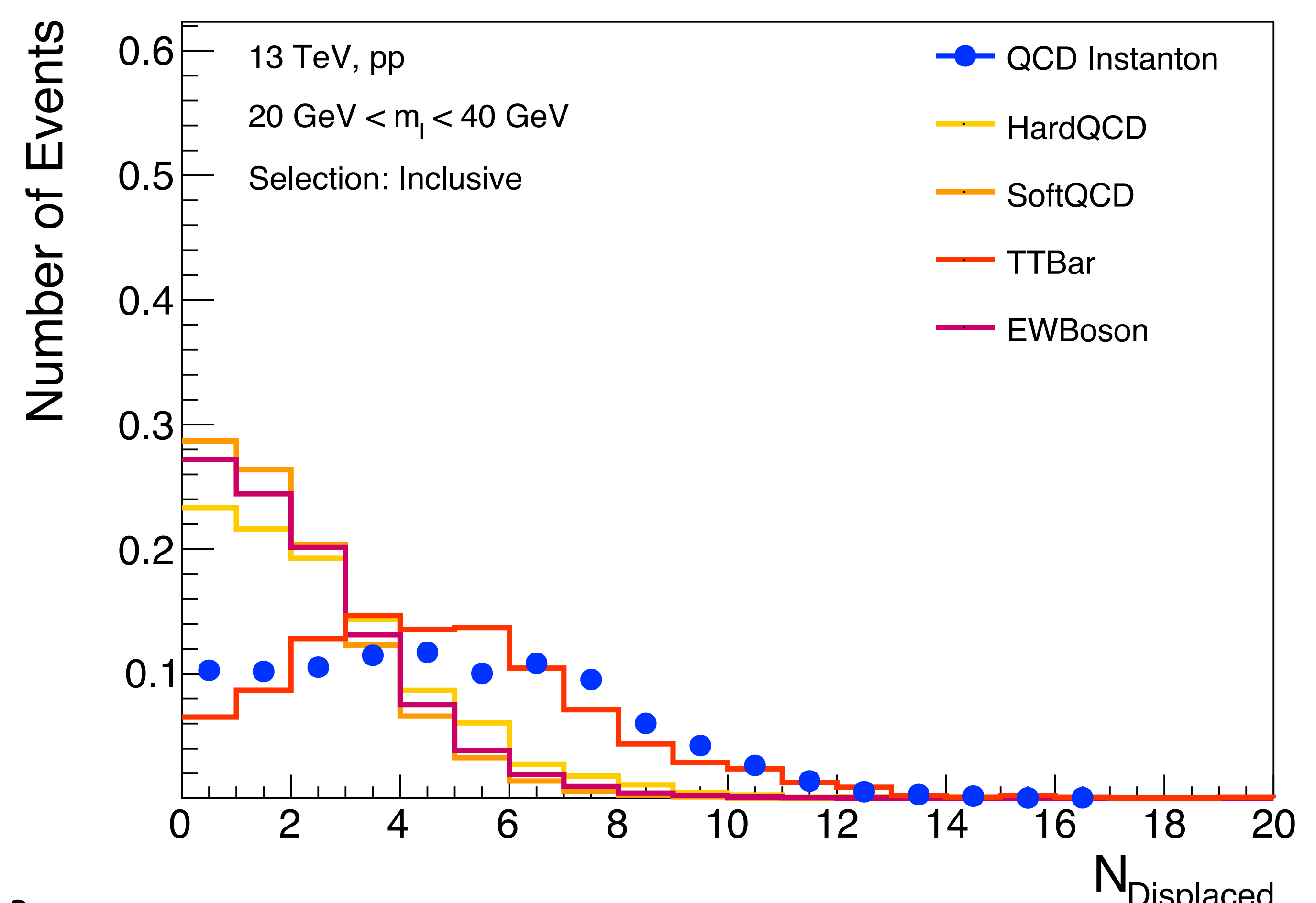
tracks p_T>500 MeV, $|\eta|$<2.5



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?)

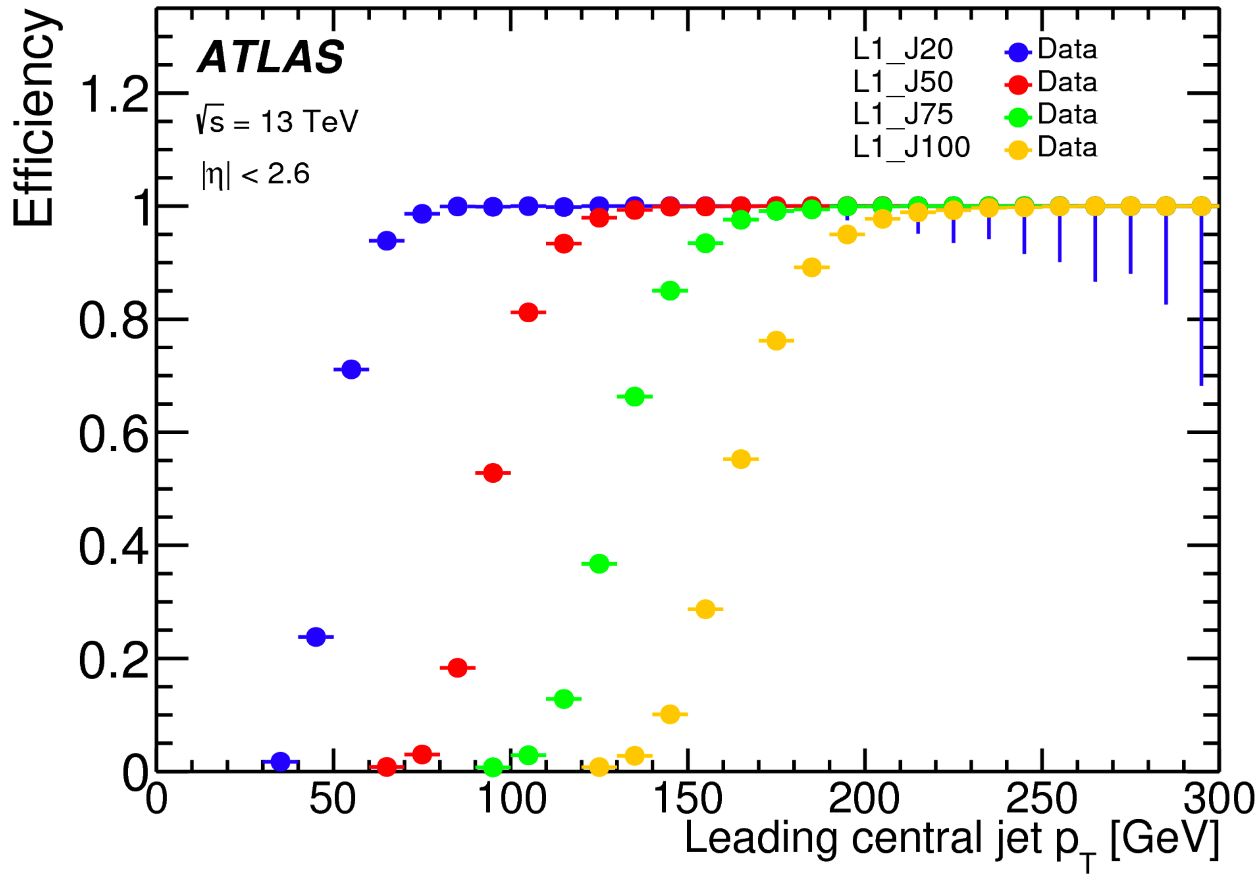


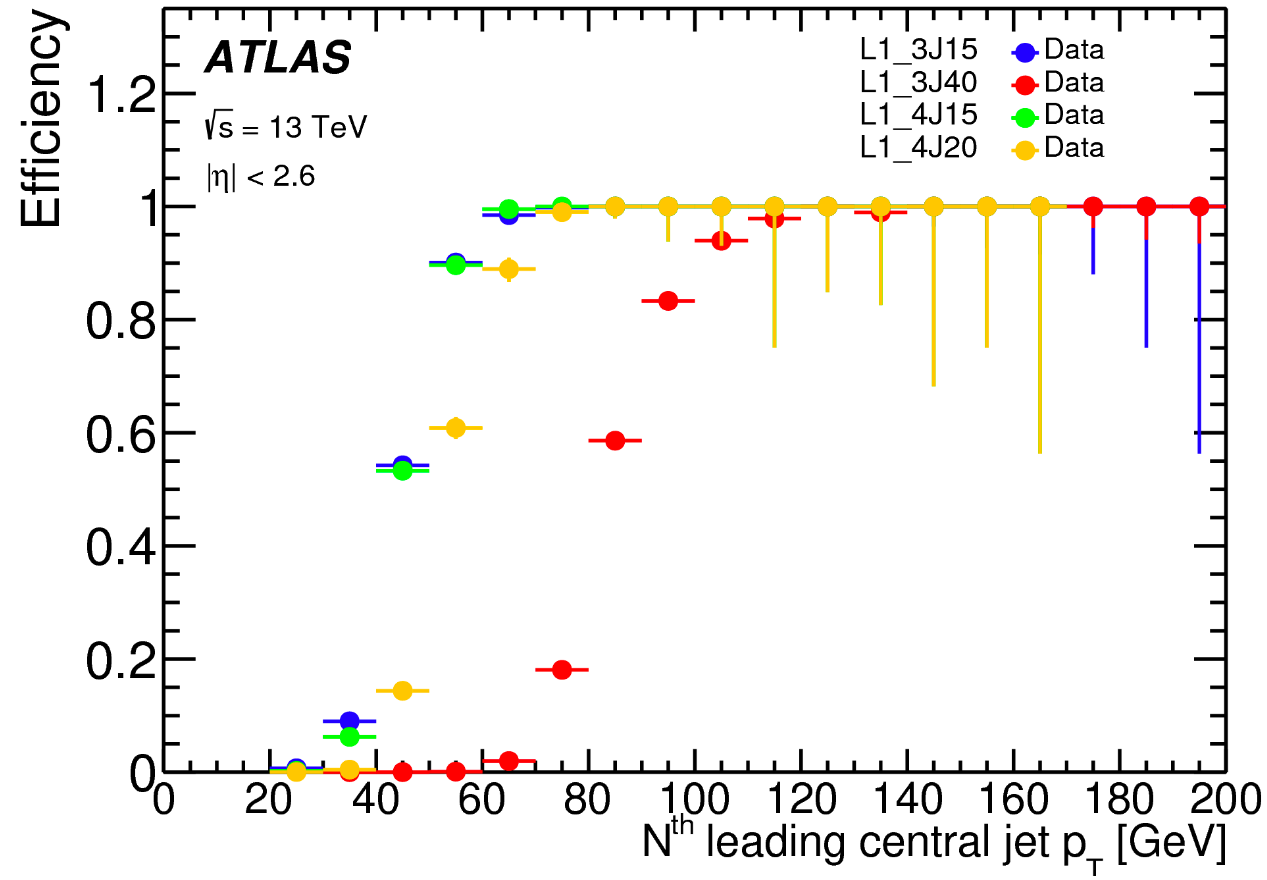


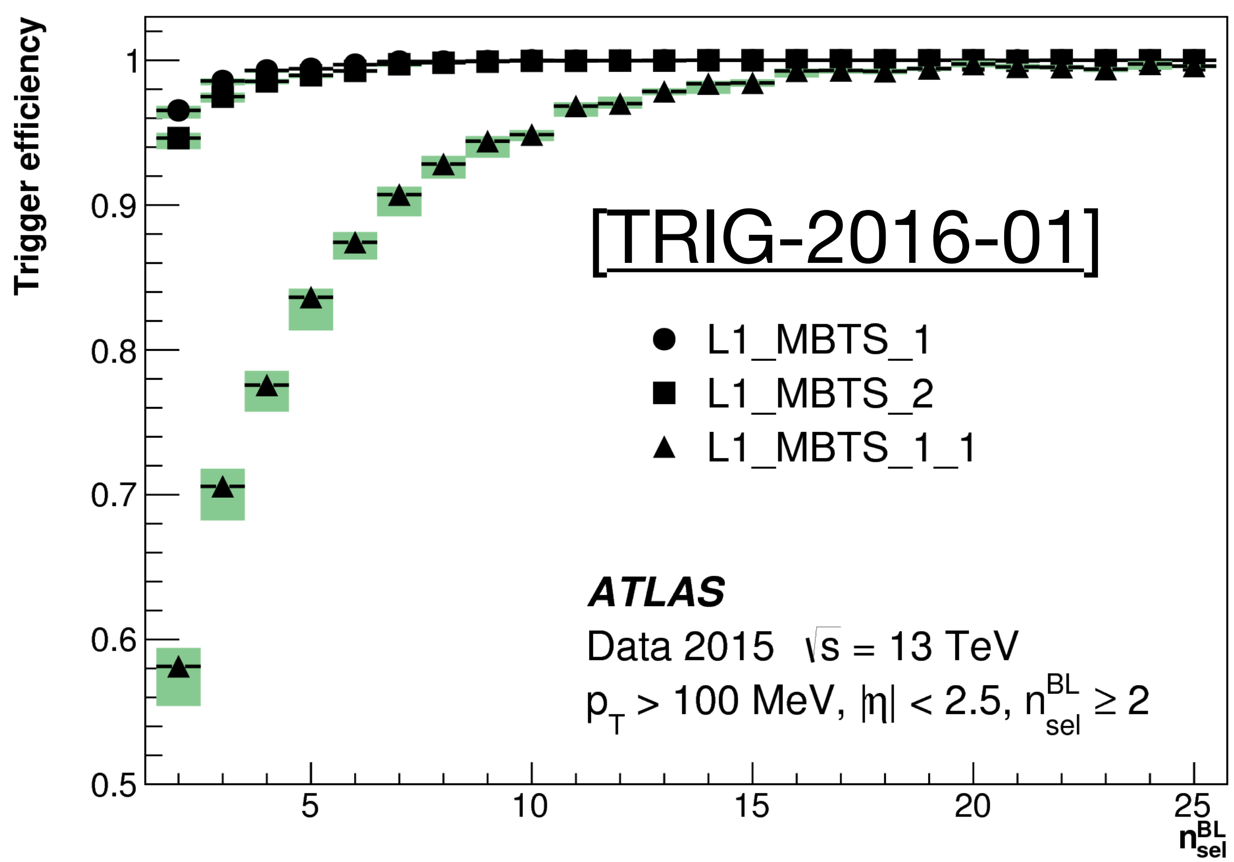
Triggers

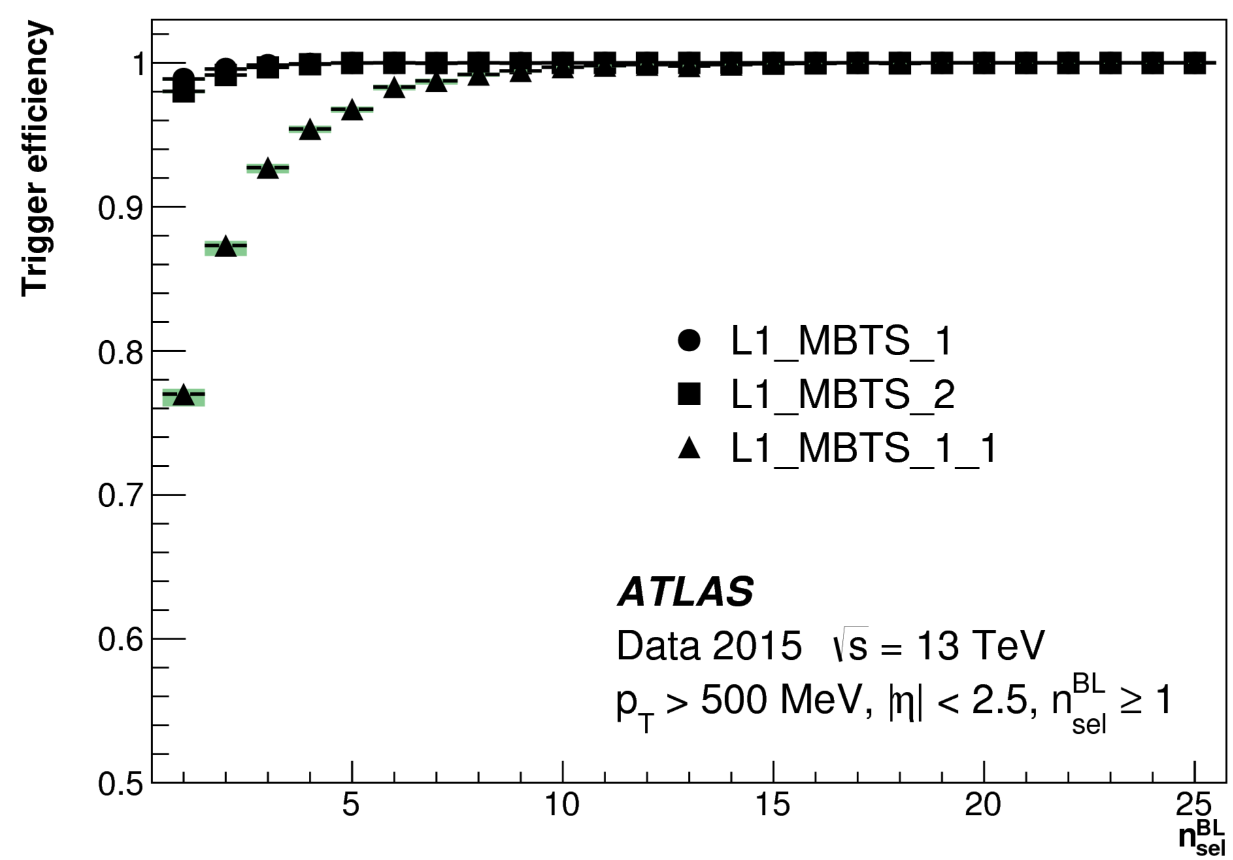
- Instanton cross-section is large, but events not easy to trigger
- Jet triggers
  - Single jet trigger: p_T>500 GeV -> no way
  - Multijet triggers: p_T >100 GeV -> still too high thresholds topological selections could help (i.e. event shapes)?
  - Can lower the rate by prescaling, but significantly 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









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

Analysis optimisation

- Tried to optimise possible Instanton signal regions
  - SM backgrounds generated with Pythia8
  - Detector simulation with Delphes

- Three signal regions defined for each regime
  - **Standard:** applies selections on Ntrk, Njets and ml/Ntrk
  - **Event-shape:** applies in addition requirements on the Broadening and Thrust observables
  - **Tight:** Applies a further requirement on displaced tracks

- In addition define two regions which are signal depleted and could be used to validate the background
  - Or to directly estimate it with an “ABCD” like approach
  - Obtained relaxing or reverting some of the signal requirements

The soft QCD regime

	Signal Region			Control Region	
	Standard	Event-Shape	Tight	A	B
Invariant mass of rec. tracks (Instanton Mass), m_I	$20\ \text{GeV} < m_I < 40\ \text{GeV}$				
Selection Requirements					
Number of rec. tracks, N_{Trk}	>20	>20	>20	>15	>20
Number of rec. tracks/Instanton mass, m_I/N_{Trk}	<1.5	<1.5	<1.5	>2.0	<1.5
Number of Jets, N_{Jets}	$=0$	$=0$	$=0$	$=0$	$=0$
Broadening, $\mathcal{B}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Thrust, $\mathcal{T}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Number of displaced vertices, $N_{\text{Displaced}}$			>6		<4
Expected Events for $\int L dt = 1\,\text{pb}^{-1}$ in the Signal Region ($\mathcal{S} > 0.85$)					
N_{Signal}	$1.1 \cdot 10^7$	$8.9 \cdot 10^6$	$5.9 \cdot 10^6$	<1	$6.8 \cdot 10^5$
$N_{Background}$	$6.2 \cdot 10^6$	$4.3 \cdot 10^6$	$1.8 \cdot 10^5$	$3 \cdot 10^5.$	$3.3 \cdot 10^6$

- Huge number of signal events expected even in just 1 pb^{-1}
  - Would allow for clear observation of this process
  - Yet unclear how well we can describe soft QCD backgrounds
  - Assumed an uncertainty of 20-40% from comparisons of different models (H7/Sherpa/Pythia8)

The hard QCD regime

	Signal Region			Control Region	
	Standard	Event-Shape	Tight	A	B
Invariant mass of rec. tracks (Instanton Mass), m_I	200 GeV $< m_I <$ 300 GeV				
Selection Requirements					
Number of rec. tracks, N_{Trk}	>80	>80	>80	>80	>80
Number of rec. tracks/Instanton mass, m_I/N_{Trk}	<3.0	<3.0	<3.0	>3.0	<3.0
Number of Jets, N_{Jets}	3-6	3-6	3-6	3-6	3-6
Broadening, $\mathcal{B}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Thrust, $\mathcal{T}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3
Number of displaced vertices, $N_{\text{Displaced}}$			>15		<10
Results					
Expected Events for $\int L dt = 1\,\text{pb}^{-1}$ in the Signal Region ($\mathcal{S}$ >0.85)					
N_{Signal}	5.6	1.0	0.54	0.04	0.21
$N_{Background}$	1900	9.6	0.64	200	1100

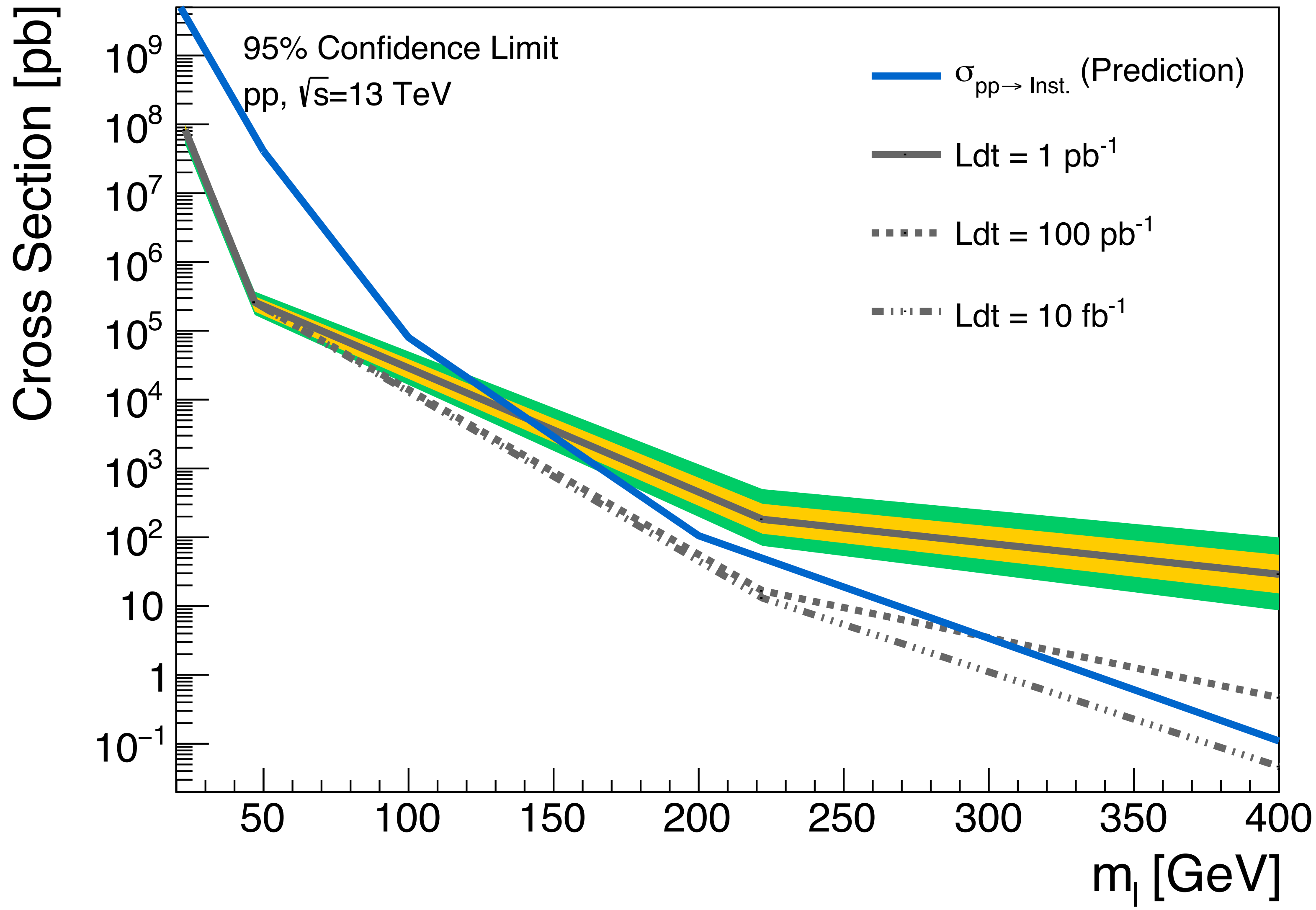
- Tight selection would allow a S/B ~ 1
- But an observation would only be possible with 10 pb^{-1}

The top regime

	Signal Region			Control Region		
	Standard	Event-Shape	Tight	A	B	C
Invariant mass of rec. tracks m_I	$300\text{ GeV} < m_I < 500\text{ GeV}$					
Selection Requirements						
Number of rec. tracks, N_{Trk}	-	-	-			
Number of rec. tracks/inst. mass, m_I/N_{Trk}	<3.0	<3.0	<3.0	>3.0	<3.0	<3.0
Number of Jets, N_{Jets}	>7	>7	>7	>7	>7	>5
Broadening, $\mathcal{B}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3	>0.3
Thrust, $\mathcal{T}_{\text{Tracks}}$		>0.3	>0.3	>0.3	>0.3	>0.3
Number of displaced vertices, $N_{\text{Displaced}}$			>20		<15	>20
Identified Leptons	-	-	-	-	-	1
Expected Events for $\int L dt = 1\,\text{pb}^{-1}$ in the Signal Region ($\mathcal{S}$ >0.85)						
N_{Signal}	0.007	0.004	0.0021	0.002	0.0003	-
$N_{Background}$	0.204	0.015	0.0074	33	0.0022	0.002

- For the tight region S/B of only ~0.3
- In 10 fb^{-1} we would only get 2 events
  - Likely hopeless, consistent with [2010.02287]

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]

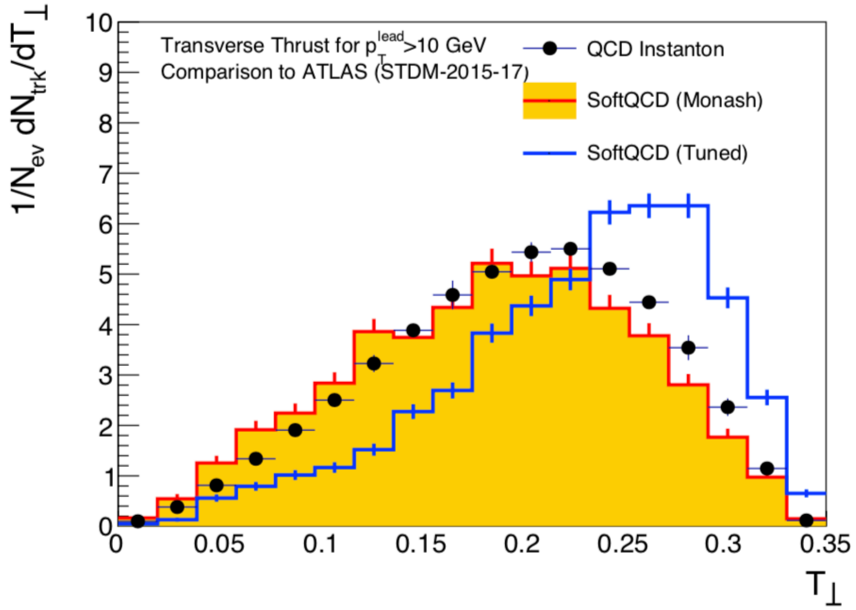


Figure 19. Predicted distribution of the event thrust of the MONASH *softQCD* tune of PYTHIA8 as well as a modified version with significantly enhanced multiple parton interaction probability (MPI:ALPHASVALUE = 0.150) in comparison to the measurement at 13 TeV of the ATLAS Collaboration [50]

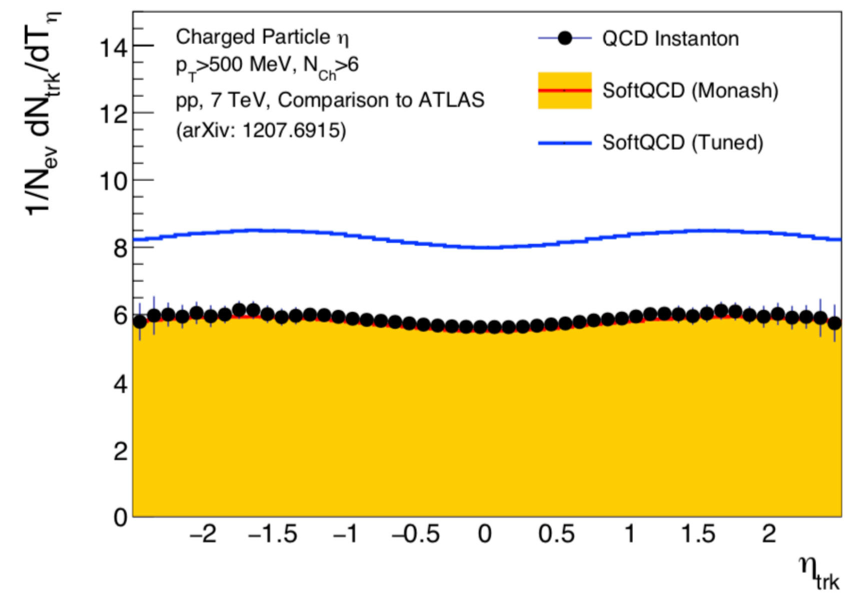
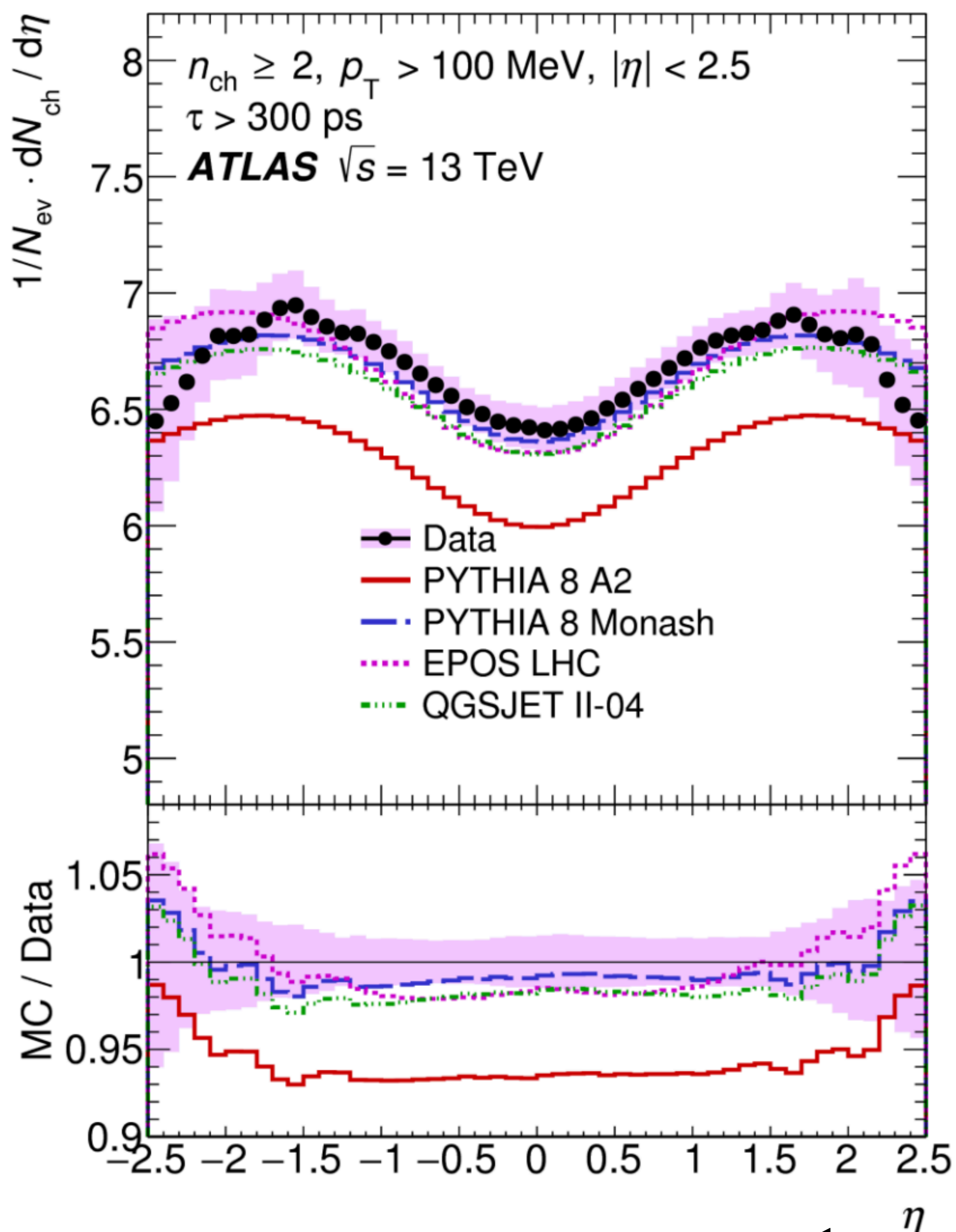


Figure 20. Predicted distribution of the charged particle spectrum vs. η of the MONASH *softQCD* tune of PYTHIA8 as well as a modified version with significantly enhanced multiple parton interaction probability (MPI:ALPHASVALUE = 0.150) in comparison to the measurement at 7 TeV of the ATLAS Collaboration [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}

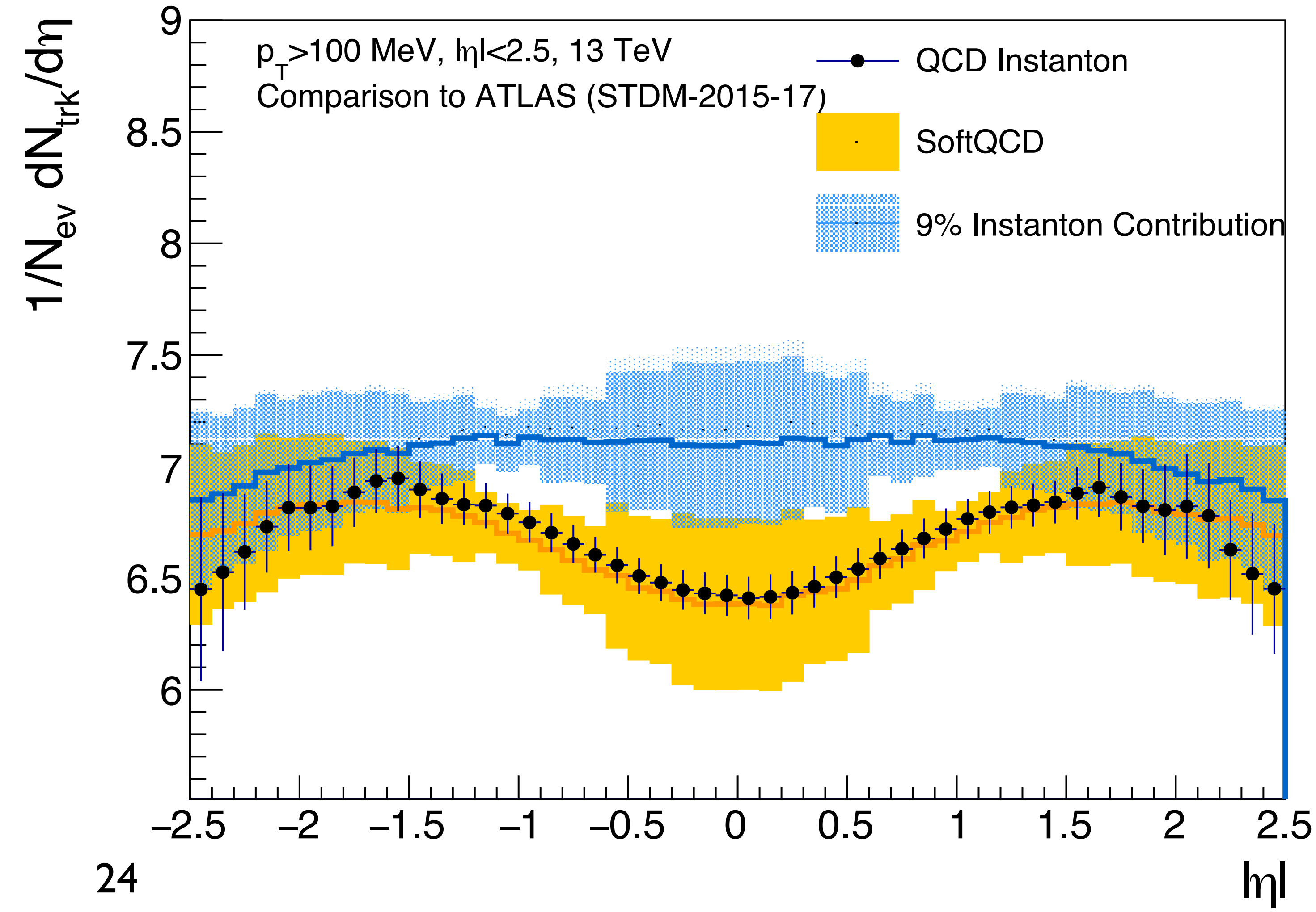
- ATLAS 13 TeV measurement of charged particles in Minimum Bias events
  - Track pT requirement of 100 MeV
- Nch/Nevt prediction depends on the total cross-section models
- But the η dependence is consistently well described
- We have seen the Instanton would predict a much more central distribution 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
  - Different correlation assumed for the bkg
- For a $\sigma = 71\mu b^{-1}$ and a signal efficiency of ~90%, exclude cross-sections:

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

[2012.09120]



Instantons in Drell-Yan

$$u_L + \bar{u}_L \quad \to \quad \gamma^* + \bar{d}_R + d_R + \bar{s}_R + s_R + n_g\, g$$
$$\hookrightarrow \ell^+ + \ell^-$$

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- Instanton contributions distort the angular distribution in DY
  - Contributions large at small q_T and high virtuality
  - High virtualities to cut-off large-size instantons

- Large violation of the Lam-Tung relation A_0-A_2=0 expected
  - Consequence of the helicity flip of the initial-state quarks
- Obviously a regime where other effects are important
  - Soft-gluon resummation, TMDs, Boer-Mulders, …
- Could we get a full calculation of the effect?
- Maybe more relevant for low-energy/fixed-target experiments

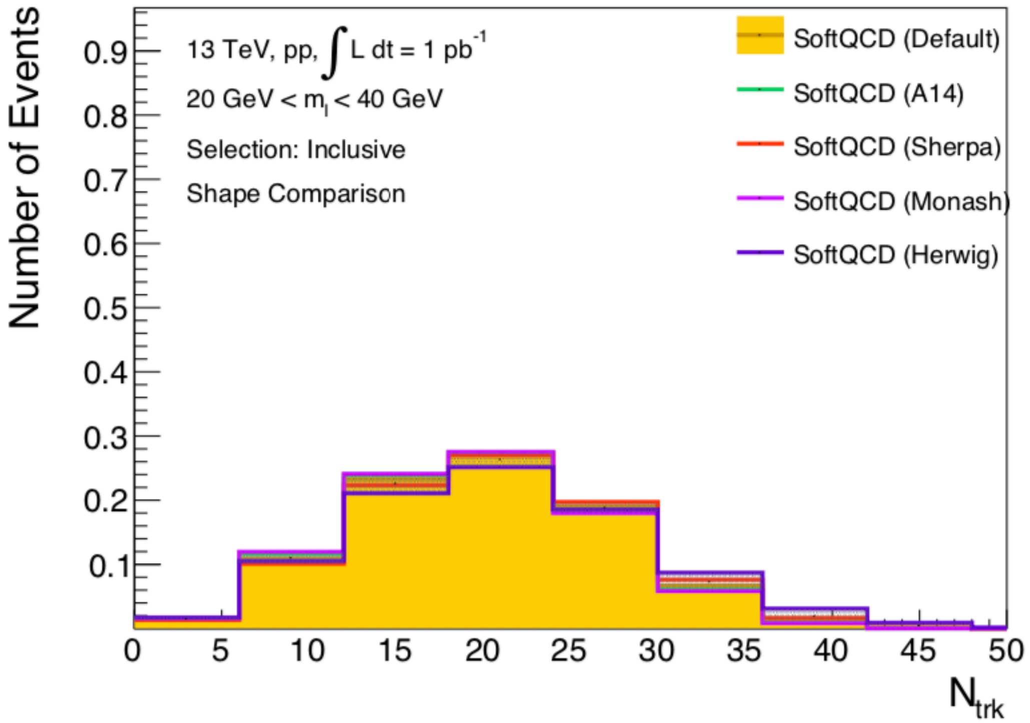
Summary

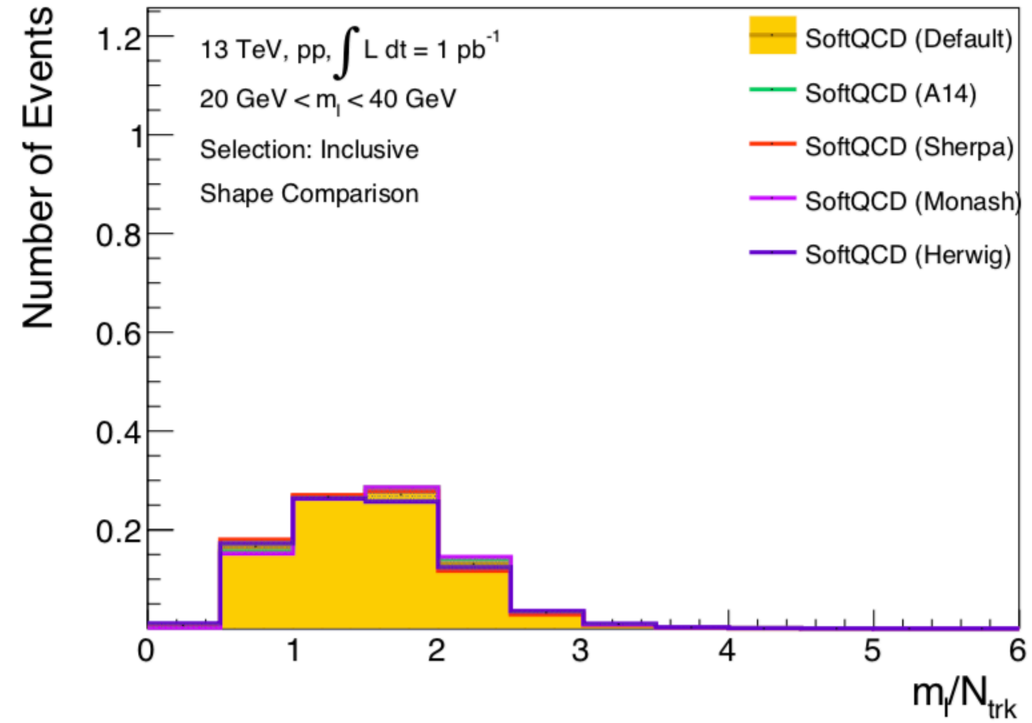
* EW sphaleron transitions are an experimentalist's dream
  * Spectacular signature, no chance of missing it
  * Unfortunately not possible in the SM
* Can we expect similar signatures in BSM extensions?

* QCD Instanton production more promising
  * At high masses difficult to collect enough events
  * Analysis of small/dedicated datasets at low-mass should be possible and would be very sensitive
  * Even inclusive Minimum Bias measurements would have sensitivity
* How dependent are these conclusions on the assumed models?

Backup

$\sqrt{s'}$ [GeV]	$1/\rho$ [GeV]	$\alpha_S(1/\rho)$	$\langle n_g \rangle$	$\hat{\sigma}$ [pb]
10.7	0.99	0.416	4.59	$4.922 \cdot 10^9$
11.4	1.04	0.405	4.68	$3.652 \cdot 10^9$
13.4	1.16	0.382	4.90	$1.671 \cdot 10^9$
15.7	1.31	0.360	5.13	$728.9 \cdot 10^6$
22.9	1.76	0.315	5.44	$85.94 \cdot 10^6$
29.7	2.12	0.293	6.02	$17.25 \cdot 10^6$
40.8	2.72	0.267	6.47	$2.121 \cdot 10^6$
56.1	3.50	0.245	6.92	$229.0 \cdot 10^3$
61.8	3.64	0.223	7.28	$72.97 \cdot 10^3$
89.6	4.98	0.206	7.67	$2.733 \cdot 10^3$
118.0	6.21	0.195	8.25	235.4
174.4	8.72	0.180	8.60	6.720
246.9	11.76	0.169	9.04	0.284
349.9	15.90	0.159	9.49	0.012
496.3	21.58	0.150	9.93	$5.112 \cdot 10^{-4}$
704.8	29.37	0.142	10.37	$21.65 \cdot 10^{-6}$
1001.8	40.07	0.135	10.81	$0.9017 \cdot 10^{-6}$
1425.6	54.83	0.128	11.26	$36.45 \cdot 10^{-9}$
2030.6	75.21	0.122	11.70	$1.419 \cdot 10^{-9}$
2895.5	103.4	0.117	12.14	$52.07 \cdot 10^{-12}$


13 TeV, pp, ∫ L dt = 1 pb^-1
20 GeV < m_l < 40 GeV
Selection: Inclusive
Shape Comparison
SoftQCD (Default)
SoftQCD (A14)
SoftQCD (Sherpa)
SoftQCD (Monash)
SoftQCD (Herwig)
Number of Events
N_trk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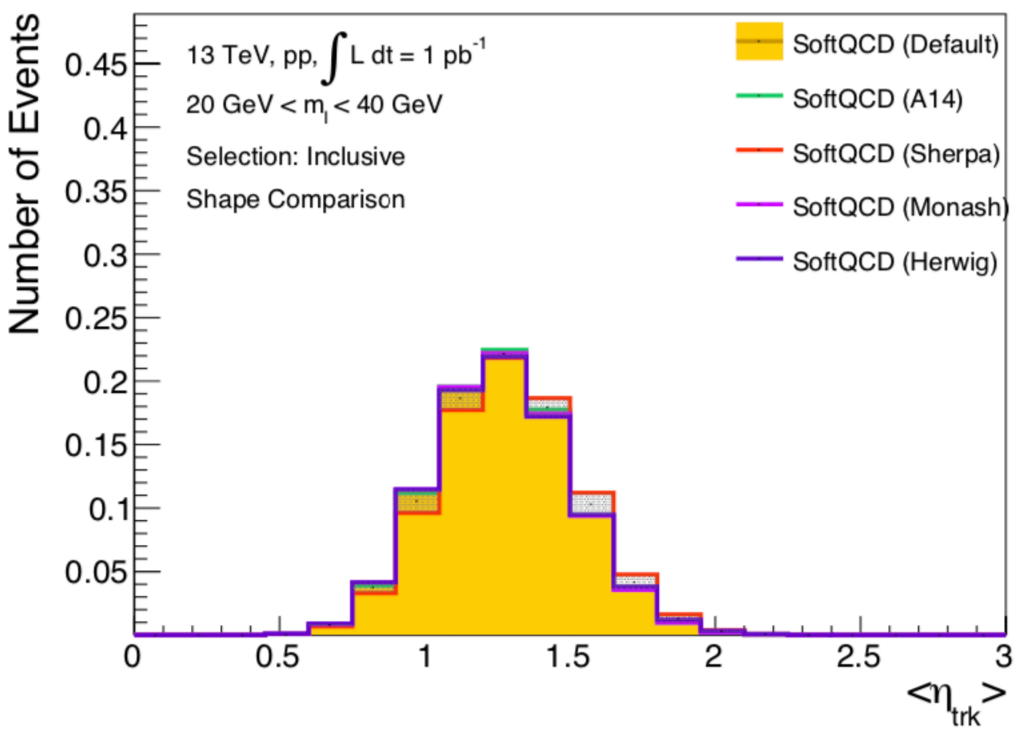
SoftQCD (Herwig)
Number of Events
m_l/N_trk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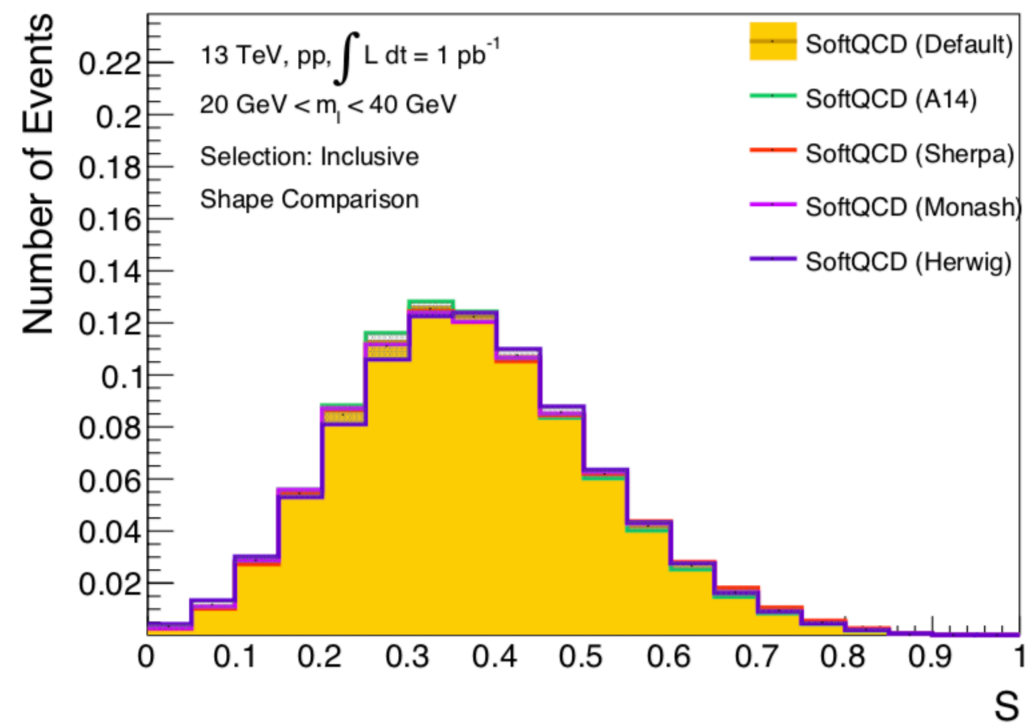
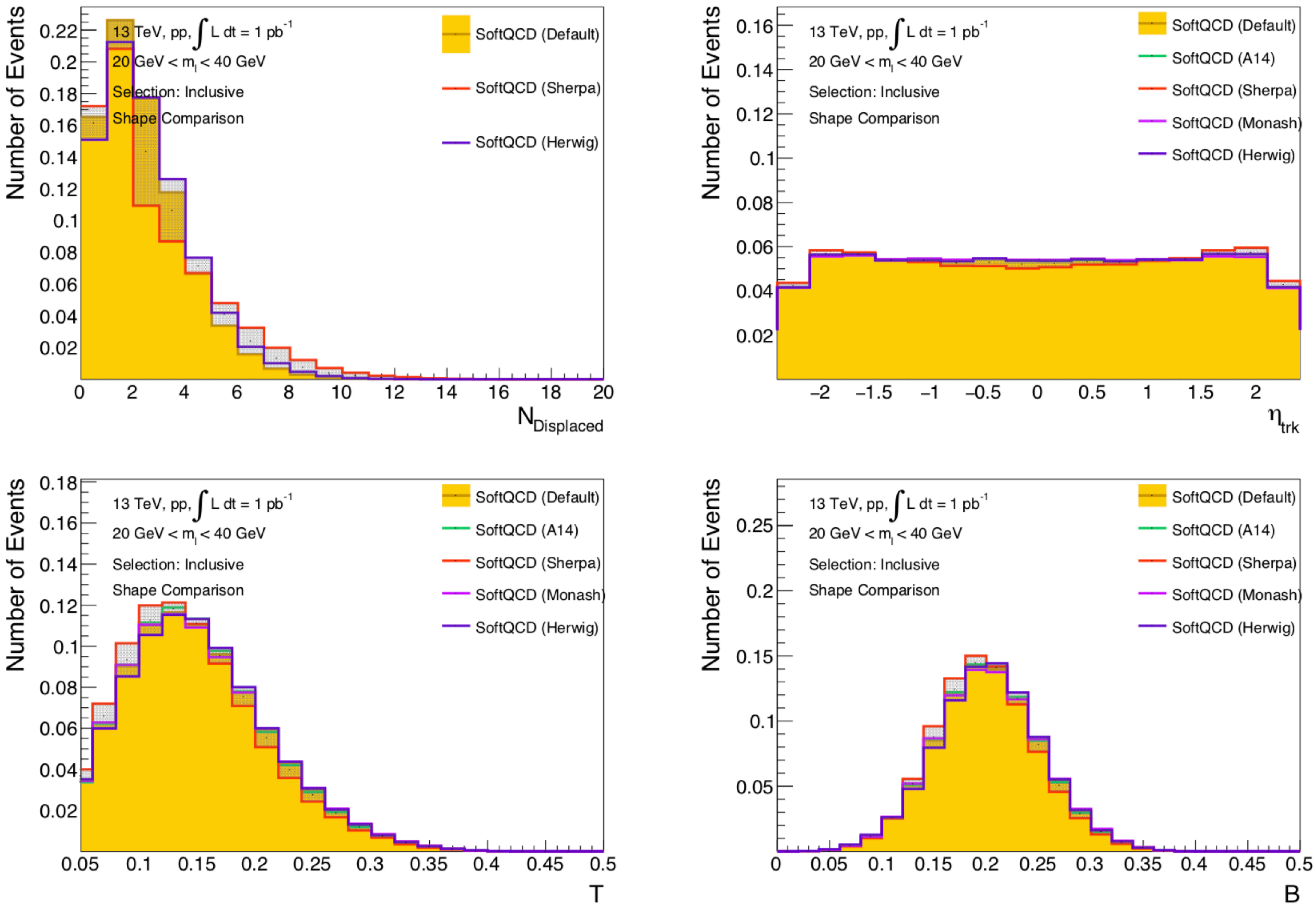
SoftQCD (A14)
SoftQCD (Sherpa)
SoftQCD (Monash)
SoftQCD (Herwig)
Number of Events
<η_trk>


13 TeV, pp, ∫ L dt = 1 pb^-1
20 GeV < m_l < 40 GeV
Selection: Inclusive
Shape Comparison
SoftQCD (Default)
SoftQCD (A14)
SoftQCD (Sherpa)
SoftQCD (Monash)
SoftQCD (Herwig)
Number of Events
S


13 TeV, pp, ∫ L dt = 1 pb-1
20 GeV < m_l < 40 GeV
Selection: Inclusive
Shape Comparison
SoftQCD (Default)
SoftQCD (Sherpa)
SoftQCD (Herwig)
Number of Events
N_Displaced
13 TeV, pp, ∫ L dt = 1 pb-1
20 GeV < m_l < 40 GeV
Selection: Inclusive
Shape Comparison
SoftQCD (Default)
SoftQCD (A14)
SoftQCD (Sherpa)
SoftQCD (Monash)
SoftQCD (Herwig)
Number of Events
η_trk
13 TeV, pp, ∫ L dt = 1 pb-1
20 GeV < m_l < 40 GeV
Selection: Inclusive
Shape Comparison
SoftQCD (Default)
SoftQCD (A14)
SoftQCD (Sherpa)
SoftQCD (Monash)
SoftQCD (Herwig)
Number of Events
T
13 TeV, pp, ∫ L dt = 1 pb-1
20 GeV < m_l < 40 GeV
Selection: Inclusive
Shape Comparison
SoftQCD (Default)
SoftQCD (A14)
SoftQCD (Sherpa)
SoftQCD (Monash)
SoftQCD (Herwig)
Number of Events
B