Search for new phenomena in dijet events with quark/gluon tagger using the ATLAS detector

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Outline

Introduction

- Over the past seventy years, the theory of the Standard Model (SM)[1] of particle physics has accurately described the phenomena related to fundamental particles and the interactions among them.
- However, theoretical & experimental flaws exist in the SM.
    - Parameters in the model are experimentally determined, not derived from calculations.
    - Neutrinos having non-zero rest mass contradicted the SM predictions.
    - The SM doesn't account for gravity and dark matter.
- Beyond the SM (BSM) theories that correctify such issues, predict new particles coupling to quarks/gluons.
    - eg, in some supersymmetry scenarios, light quarks can be produced via gluinos and squarks.

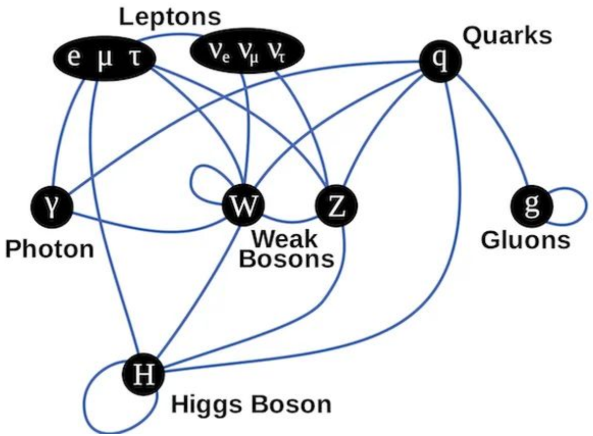
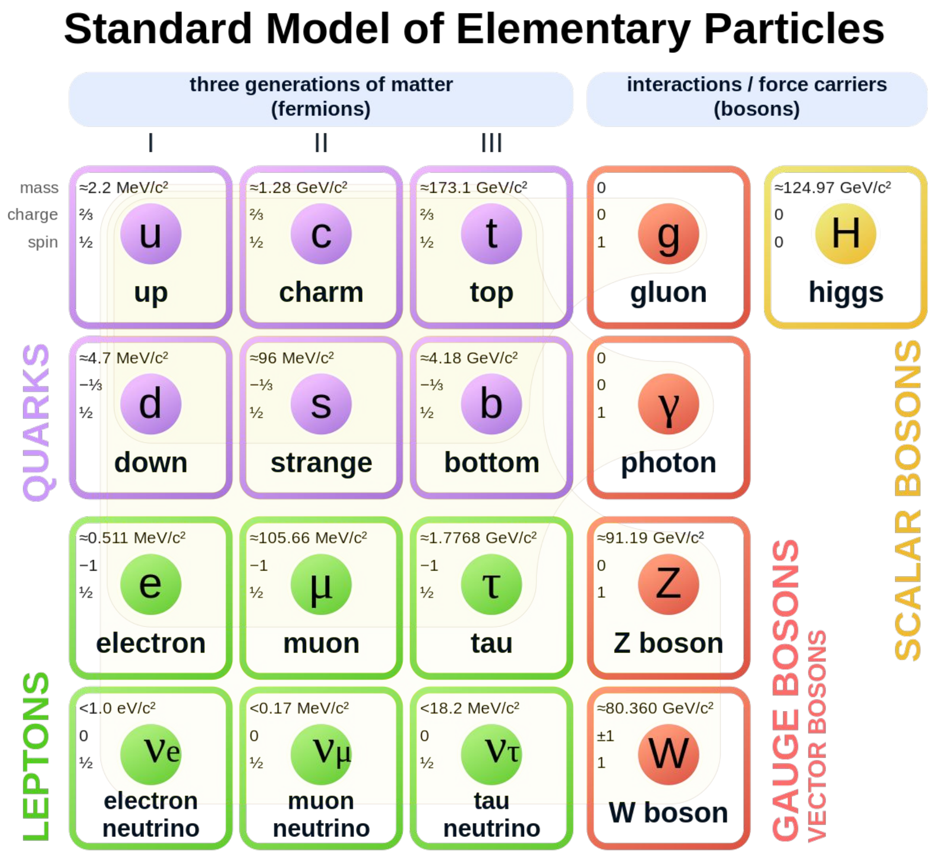


Diagram of elementary particle interactions

The theoretical framework

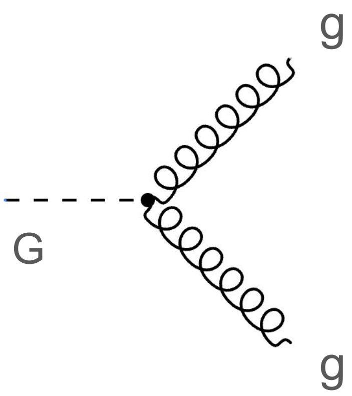
- The SM is a theoretical framework in particle physics.
- It describes how fundamental particles interact through the fundamental forces.
  - Fermions:
    - Quarks
    - Leptons
  - Bosons:
    - Photon: Electromagnetic
    - W and Z Bosons: Weak Force
    - Gluons: Strong Force
    - Higgs Boson: Gives other particles mass through the Higgs field.



The theoretical framework

This thesis searches for new resonances predicted by several BSM:

- Kaluza-Klein (KK) Graviton
  - A unified field of gravity and electromagnetism.
  - Propose that our universe has a fifth spatial dimension.
  - Quantize the gravitational field results in KK gravitons.
  - Dominantly decay to a pair of gluons.
- Quantum Black Hole (QBH)
  - Black holes with sizes comparable to the Planck length (10^{-35}m).
  - Quantum mechanical effects are expected to be significant.
  - Primarily results in particle-like jets (mainly quarks) close to its energy scale.



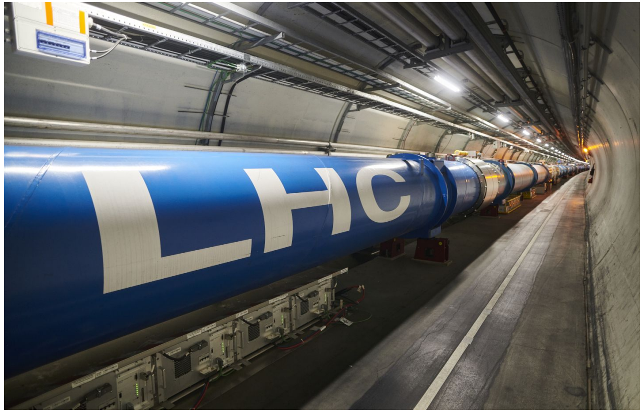
Graviton decay

The ATLAS (A Toroidal LHC ApparatuS) Experiment

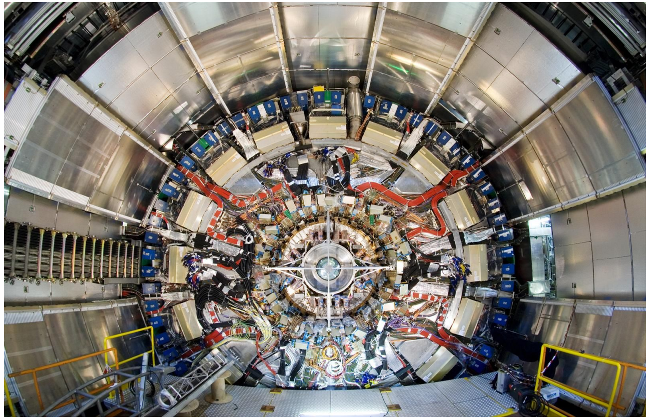
Conseil **E**uropéen pour la **R**echerche **N**ucléaire (CERN)

- The Large Hadron Collider (LHC) built by CERN is the world's largest and most powerful particle accelerator.
  - It consists of a 27-kilometre ring of superconducting magnets.
  - With a number of accelerating structures to boost the energy of the particles.

- The ATLAS experiment is a general-purpose particle detector at the LHC.
  - It is the largest detector in the world.

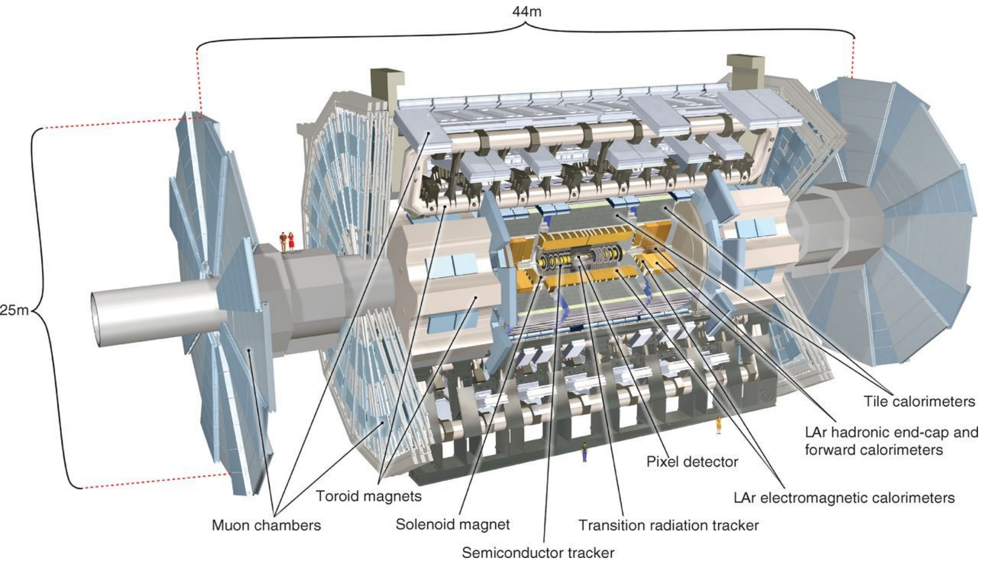


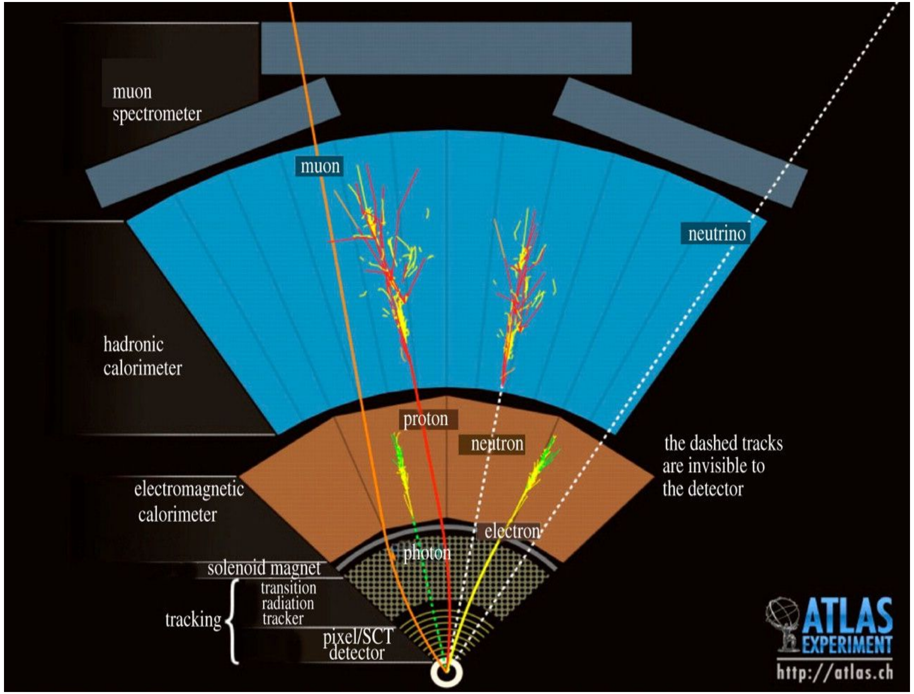
The LHC



ATLAS detector

The ATLAS Experiment





ATLAS detector slice

Jets in ATLAS

What Are Jets:

- In high-energy collisions, quarks and gluons (partons) are scattered. Due to quantum chromodynamics (QCD) , they hadronise to colourless hadrons, creating jets of particles.
- Jets are collimated streams of particles, clustered using dedicated algorithms.

Why Jets Are Crucial:

- Many interesting processes in the LHC produce quarks and gluons.
  - Including the production of the Higgs boson, top quarks, and potential new BSM particles.
- By studying jets, researchers gain insights into these processes and can test the predictions of QCD.

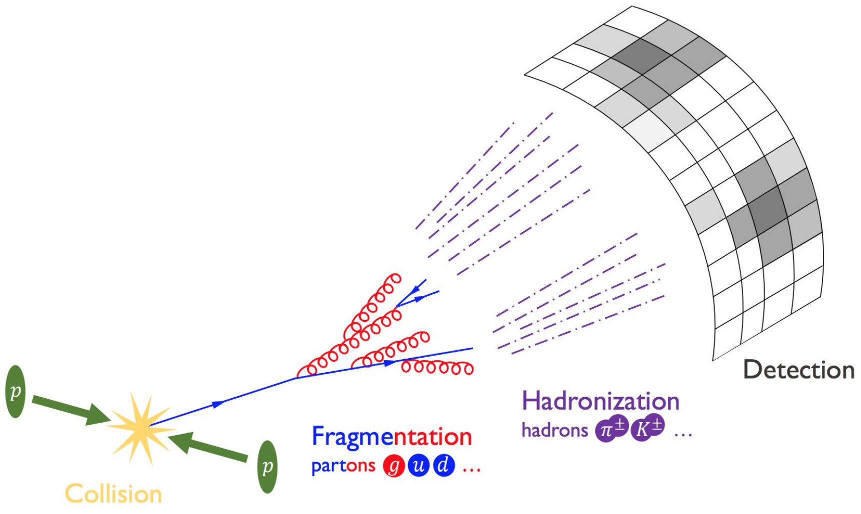


Diagram of jets

Jets in ATLAS

How to reconstruct jets:

- anti-kT Algorithm:
  - Sequential recombination based on the distance between two particles *i* and *j* (*R*=0.4, *p*=-1 in our analysis).
  - Process:
    - Compute $d_{i,j}$ and d_{iB} for the set of particles.
    - If the minimum $d_{i,j}$ is smaller than the smallest d_{iB}, combine particles *i* and *j*. Back to the first step.
    - If the smallest d_{iB} is the minimum, remove particles *i* .
    - Repeat until no particles are left.

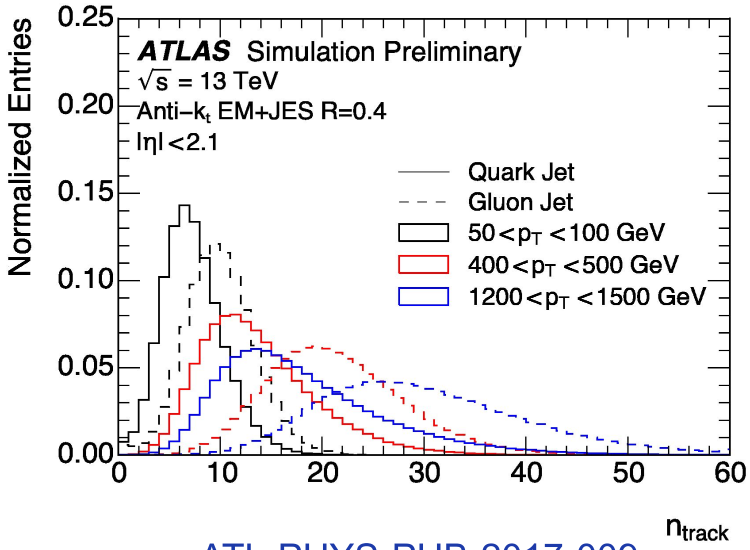
$$d_{ij} = \min\left(k_{ti}^{2p}, k_{tj}^{2p}\right) \frac{\Delta_{ij}^2}{R^2}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = k_{ti}^{2p}$$

The construction and calibration of q/g jets taggers

- Dijet events generated by QCD processes in SM.
  - Quark and gluon jets are difficult to distinguish due to QCD colour confinement.
  - Gluon jets have more charged constituents than quark jets on average due to more colour charges.
    - Gluons tend to be wider and have larger track multiplicity (N_{trk}).



ATL-PHYS-PUB-2017-009

The construction and calibration of q/g jets taggers - motivation

- Light-quark and gluon jet discrimination in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector CERN-PH-EP-2014-058
  - Jet pT 40 GeV - 360 GeV

Wider and higher pT range

- Quark versus Gluon Jet Tagging Using Charged Particle Multiplicity with the ATLAS Detector ATL-PHYS-PUB-2017-009
  - Based on N_{trk} (Number of tracks)

A new tagger built

- Calibration of the quark/gluon tagging variables with Rel20.7 samples link
  - Only calibrate the N_{trk} tagger
  - Matrix method is used
  - Only full 2016 data is used

More data, systematics

The construction and calibration of q/g jets taggers - definition & selections

- Object definition:
  - PFlow jet (Antik$_T$ R=0.4)
  - Gluon: partonLabelID = 21 (truth-labelling)
  - Light Quark: partonLabelID =1,2,3
- Event Selection
  - j1: leading jet
  - j2: subleading jet
  - forward/central jet:
    - For each jet pair, the jet with the smaller (larger) |η| is classified as the more central (forward) jet.
    - Forward region = quark-enrich subsample
    - Central region = gluon-enrich subsample

Selection	Multi-jet sample
Trigger	HLT_j420
Number of jets	≥ 2
$p_T(j_1)$	> 500
$p_T(j_2)$	> 500
$p_T(j_1)/p_T(j_2)$	< 1.5
$\lvert\eta(j_1)\rvert$	< 2.1
$\lvert\eta(j_2)\rvert$	< 2.1
Target parton	Quark(forward $\lvert \eta \rvert$) or Gluon (central $\lvert \eta \rvert$)

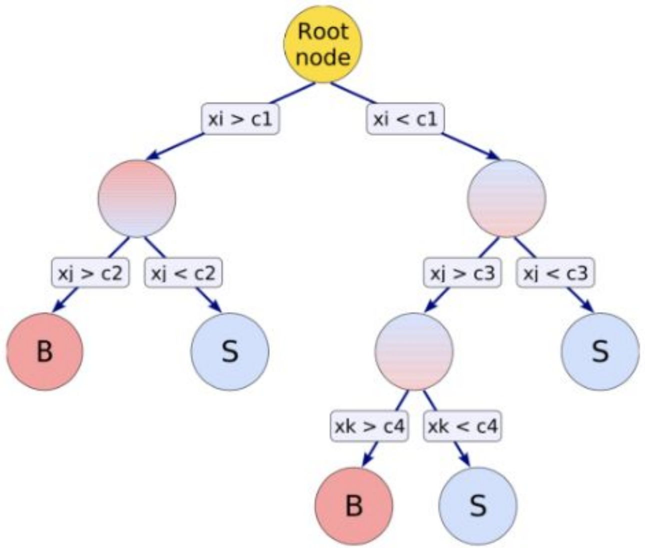
The construction and calibration of q/g jets taggers - Tagger definitions

- Previous calibration was performed on N_{trk} -only tagger.
- In addition to the N_{trk}, a new Boosted Decision Tree (BDT) tagger is constructed:
  - Make use of more jet variables as input : N_{trk} , W_{trk}, C^1_{trk} , p_T
  - W_{trk}, and Energy Correlation function C^1_{trk} is defined as

$$w_{\text{track}} = \frac{\sum_{i \in \text{Jet}} p_{\text{T},i} \Delta R_{i,\text{Jet}}}{\sum_{i \in \text{Jet}} p_{\text{T},i}}, \text{ tracks } i$$

$$C_{1,\text{ track}}^{\beta=0.2} = \frac{\sum_{i,j \in \text{Jet}} p_{\text{T},i} p_{\text{T,j}} (\Delta R_{i,j})^{\beta}}{\left(\sum_{i \in \text{Jet}} p_{\text{T},i}\right)^2}, \text{ tracks } i, j$$

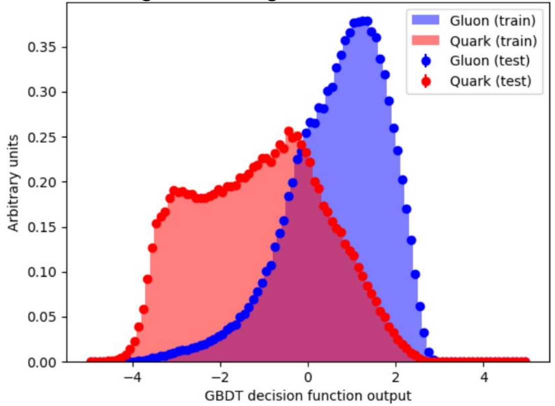
  - Output a BDT score.



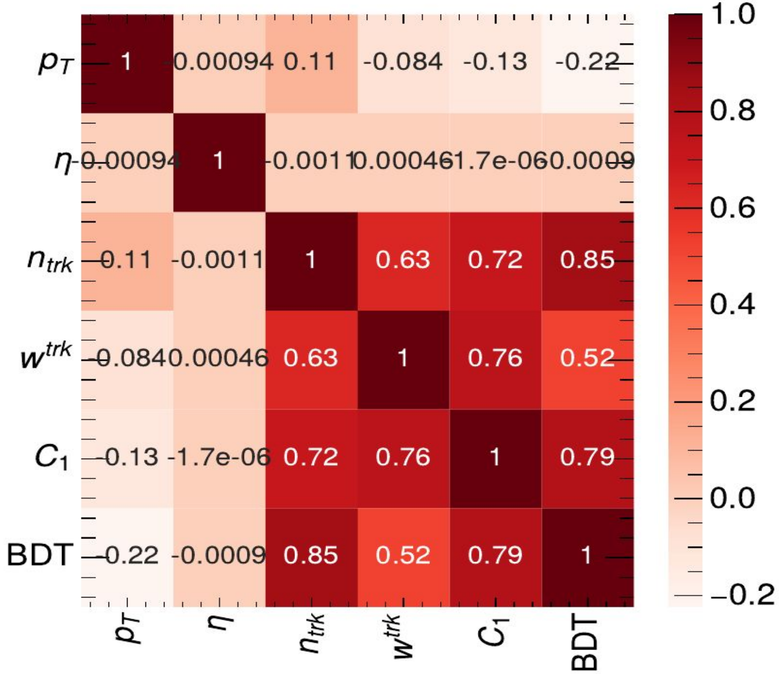
Schematic of decision tree: leaf nodes at bottom are labeled "signal" and "background" after binary splits are made; these labels depend on the majority of events that end up in nodes

- Frame: LightGBM.
- training:validation:testing = 0.8:0.1:0.1
- Training weights: Flat dijet pT weights to emphasize on high pT jets
- Testing and evaluation: event weights
- Output BDT scores show consistency - no overtraining.

Training vs Testing - BDT score distribution



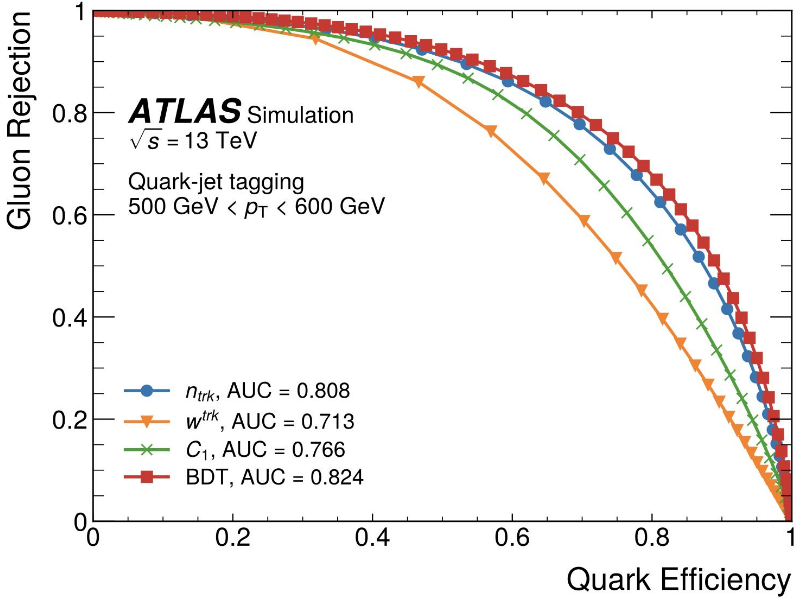
Correlation matrix of jet variables

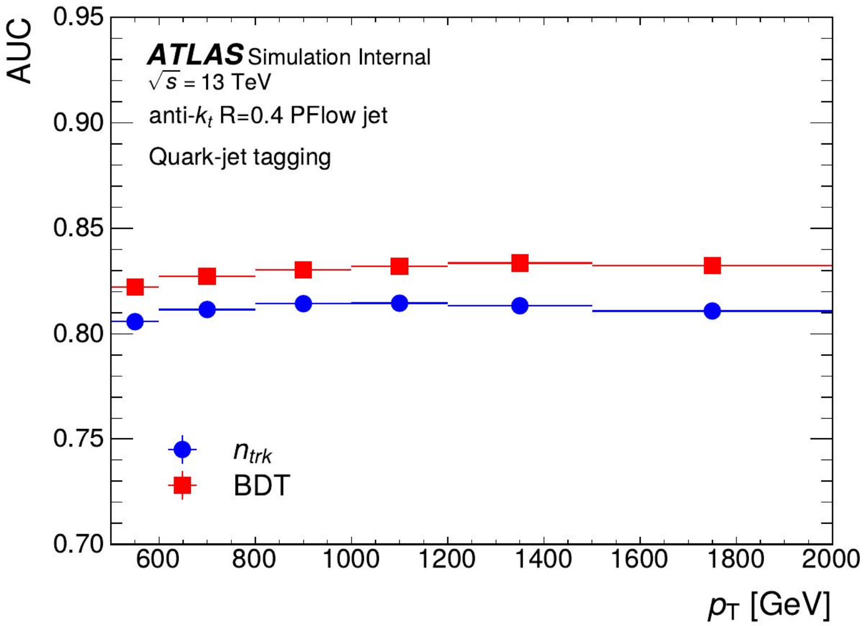


N_{trk} and BDT show relatively strong correlation

The construction and calibration of q/g jets taggers - Tagger definitions

- N_{trk}, W_{trk}, C_1 show discrimination power.
- BDT performs better than N_{trk} across pT range.





The construction and calibration of q/g jets taggers - Matrix Method

- To calibrate:
  - Extract pure quark or gluon jets.
- Step:
  - Calculate q/g fraction matrix (*F*) from the monte carlo (MC).
  - Apply the inverse matrix to the data.
    - *P(x)* is the distribution of jet tagging variables *x*

$$\begin{pmatrix} p_F(x) \\ p_C(x) \end{pmatrix} = \underbrace{\begin{pmatrix} f_{F,Q} & f_{F,G} \\ f_{C,Q} & f_{C,G} \end{pmatrix}}_{\equiv F} \begin{pmatrix} p_Q(x) \\ p_G(x) \end{pmatrix}$$

  - *Assumption: $P_Q(x)$ and $P_G(x)$ have the same shapes in quark-enriched (forward region) and gluon-enriched (central region) subsamples*

The tagging variables depend on the jet's pT, thus the matrix method is performed in each pT bin:

p_T bin boundary [GeV]					
500-600	600-800	800-1000	1000-1200	1200-1500	1500-2000

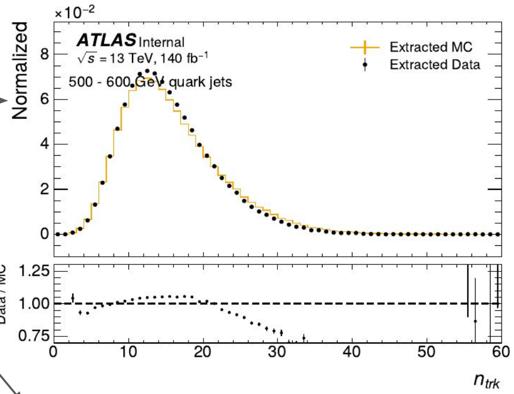
The construction and calibration of q/g jets taggers - Matrix Method

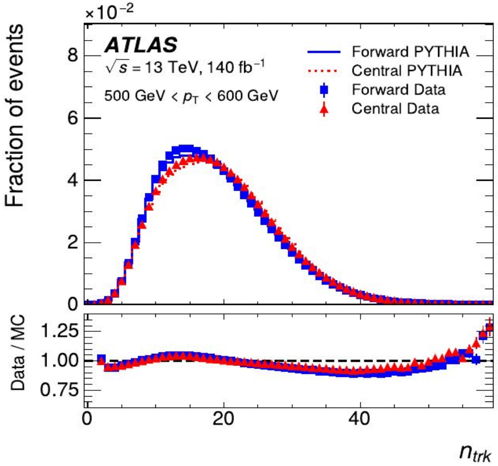
$$\begin{pmatrix} p_F(x) \\ p_C(x) \end{pmatrix} = \underbrace{\begin{pmatrix} f_{F,Q} & f_{F,G} \\ f_{C,Q} & f_{C,G} \end{pmatrix}}_{\equiv F} \begin{pmatrix} p_Q(x) \\ p_G(x) \end{pmatrix}$$

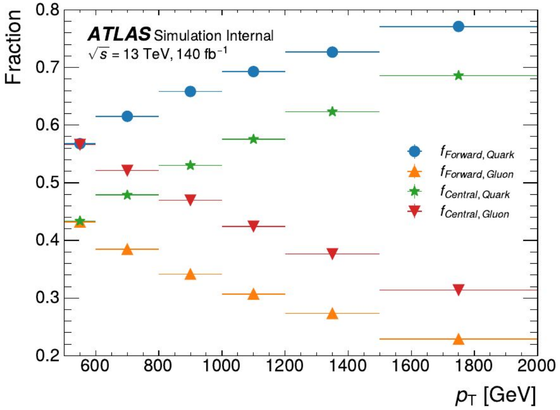
input

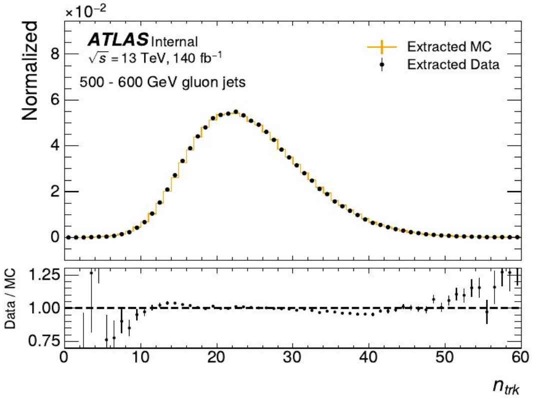
input

output (extraction)







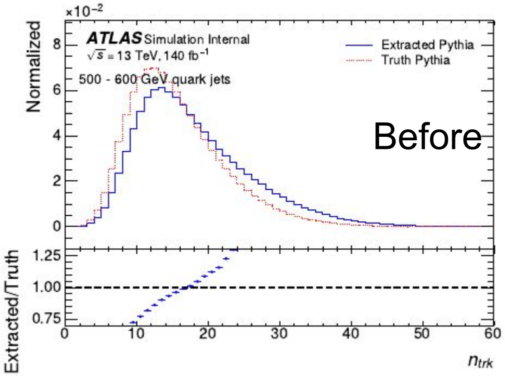


- The difference between the forward and the central region shows a systematic shift for both parton types because of the η-dependence of reconstruction.
- Re-weight more central jets with re-weighting factor:

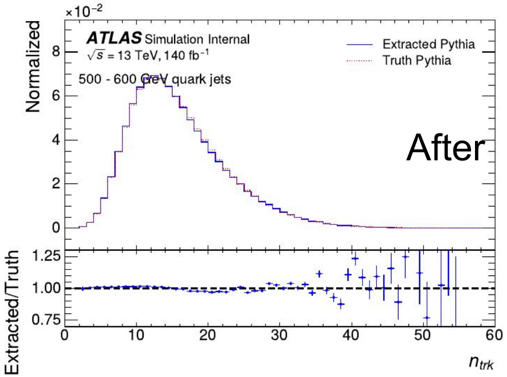
$$w(x) = \frac{p_{\mathrm{F}}(x)}{p_{\mathrm{C}}(x)}.$$

to match forward quark shape in order to account for the tracking efficiency.

- Re-weighting factor from quark jets will be used as nominal.
- Re-weighting factor from gluon jets will be studied as a systematic uncertainty.



Before re-weighting



After re-weighting

The construction and calibration of q/g jets taggers - Scale factor

To study the **performance** of N_{trk}- and BDT-taggers :

1. Defined quark tagging efficiencies (**ϵ**) as working points (WP).

$$\varepsilon_{Q/G}(x^{WP}) = \int_{x<x^{WP}} p_{Q/G}(x)dx.$$

2. Rejection as :

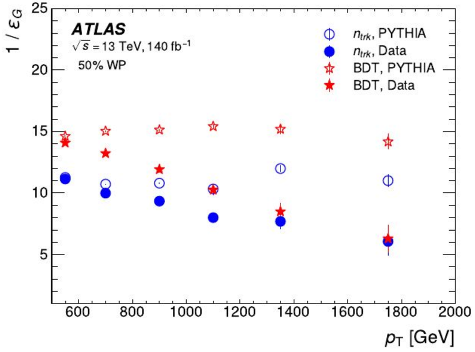
$$\xi_{Q/G}(x^{WP}) = 1/\int_{x>x^{WP}} p_{Q/G}(x)dx = 1/(1-\varepsilon_{Q/G}(x^{WP})).$$

3. **Data-to-MC Scale Factors (SF)** is given to match the shape of the jet tagging variables (*x*) of the simulation to that of the data.

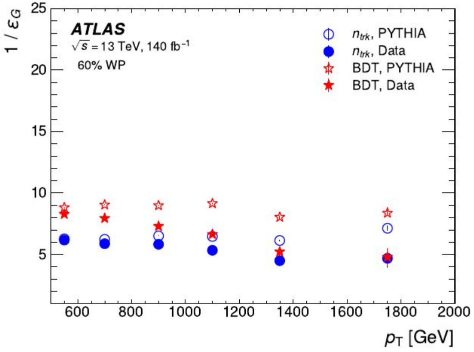
$$\mathrm{SF}_Q(x^{WP}) = \frac{\varepsilon_Q^{\mathrm{Data}}(x^{WP})}{\varepsilon_Q^{\mathrm{MC}}(x^{WP})}.$$

$$\mathrm{SF}_G(x^{WP}) = \frac{\xi_G^{\mathrm{Data}}(x^{WP})}{\xi_G^{\mathrm{MC}}(x^{WP})}.$$

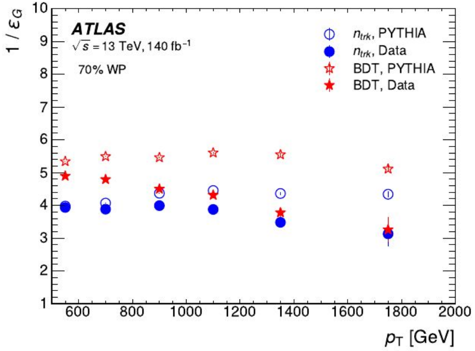
- The BDT-tagger is found to have better performance that the N_{trk}-tagger.
    - Eg. at 50% WP:
        - N_{trk}-tagger can reject ~ 90% of gluon-jets
        - BDT-tagger can reject ~ 93% of gluon-jets.



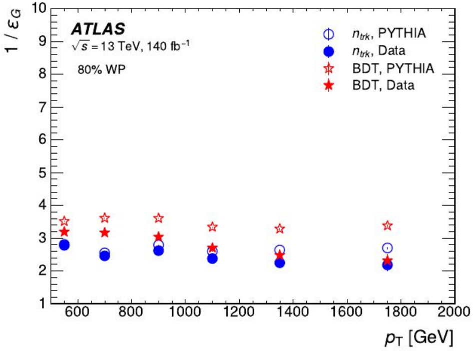
(a) Working Point:50%



(b) Working Point:60%



(c) Working Point:70%



(d) Working Point:80%

The construction and calibration of q/g jets taggers - Systematics

- Hadronisation uncertainty
  - Sherpa cluster-based vs Sherpa string-based hadronisation
- Parton shower modeling uncertainty
  - Herwig dipole-based vs Heriwig angule-ordered parton shower
- Matrix element
  - Pythia8 vs Powheg+Pythia8
- Scale Variation
  - variations of the renormalisation and factorisation are used to estimate the uncertainty due to missing higher order corrections.
  - the envelope of the variations is taken among 7 variations
    - $\mu_R, \mu_F \in (2,2),(2,1),(1,0.5),(1,2),(0.5,2),(0.5,1),(0.5,0.5)$
- Splitting Kernel
  - variations of the non singular part of the splitting functions
  - Envelope is taken
- PDF uncertainty
  - NNPDF23LO with 100 variations

The construction and calibration of q/g jets taggers - Systematics

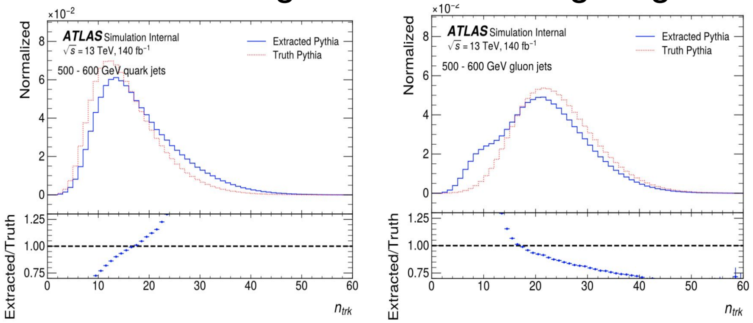
- JES/JER
  - AntiKt R=0.4 PFlow jet
  - max(σ_{up}, σ_{down}), σ_i = quadratic sum of variations, i=up, down

- Tracking
  - Number of tracks is the important input for both taggers
  - 2 schemes, efficiency and fake
  - Quadratic sum of 2 variations

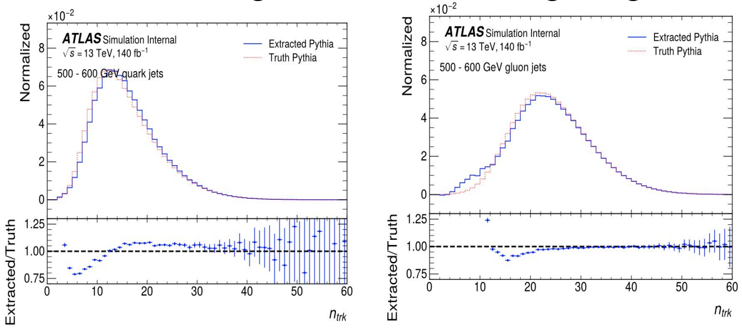
The construction and calibration of q/g jets taggers - Systematics

- MC non-closure
  - Difference in SFs between Truth MC vs Extracted MC
- Re-weighting
  - Difference in SFs using Quark reweighting factor vs Gluon reweighting factor.
- Statistical Uncertainty
  - 5000 trails
  - In one trail:
    - MC - Gaussian
    - Data - Poisson
    - Same workflow as nominal
  - Take RMS of SFs from 5000 trails

Before gluon factor reweighting

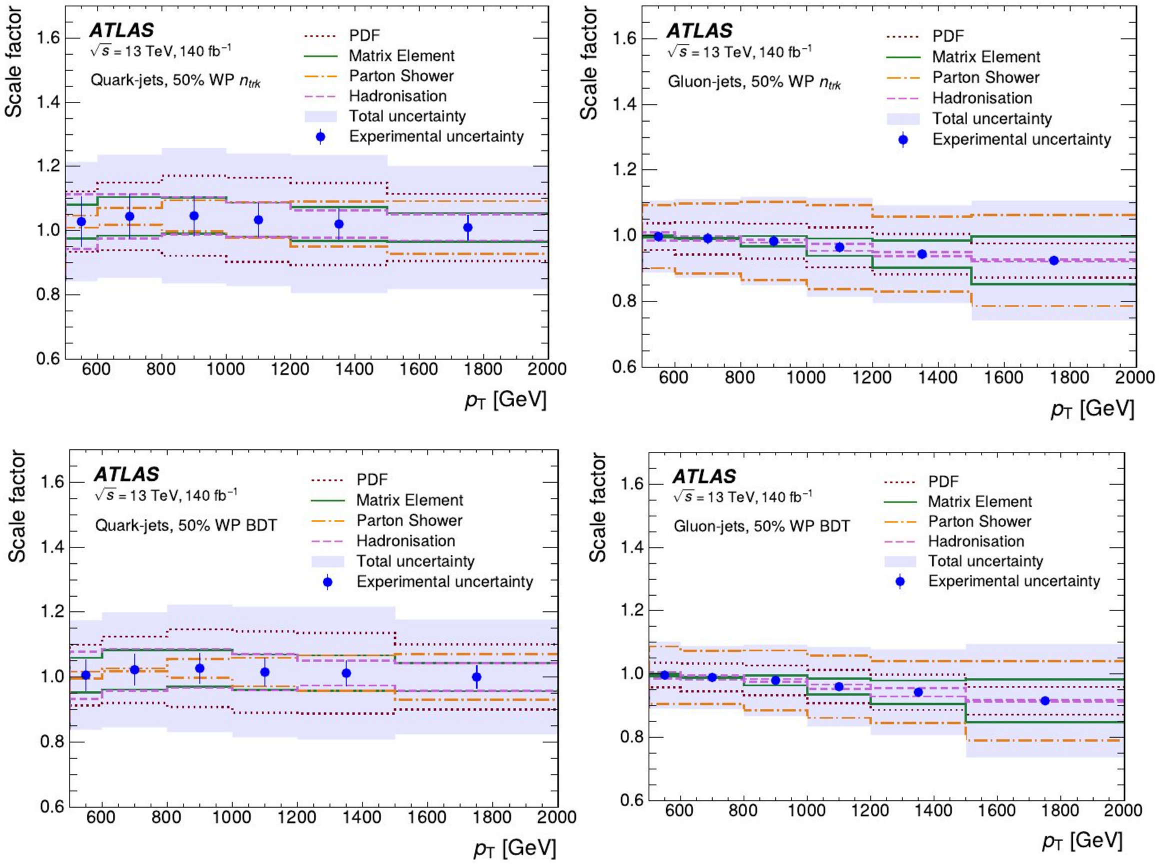


After gluon factor reweighting



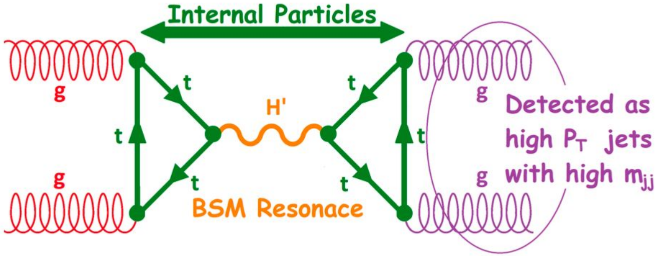
The construction and calibration of q/g jets taggers - Results

- SFs from 0.92 - 1.02 for both N_{trk}- and BDT-taggers
- Total uncertainty ~20%
- Dominated by theoretical uncertainty (~18%)

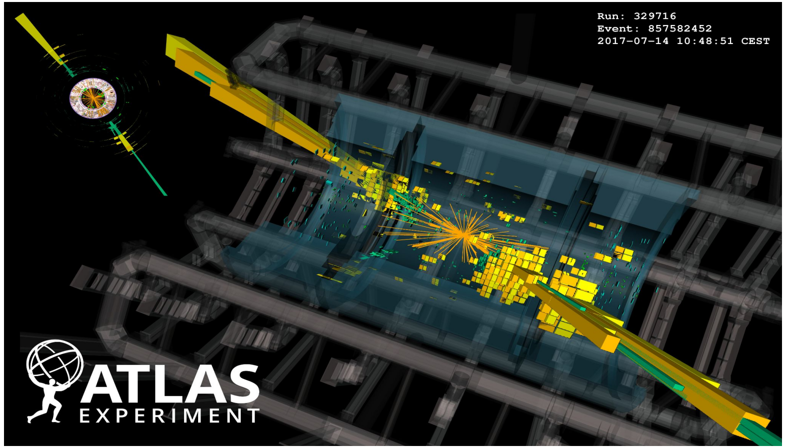


Search for new phenomena in dijet events - Introduction

- Searching for the evidence of the BSM resonances that decay into two jets (dijet).
  - Performed in invariant mass (mjj) spectrum.
  - Classifying jets as quark or gluon-initiated enhances sensitivity (quark/gluon tagging).
  - Effective for improving BSM searches.



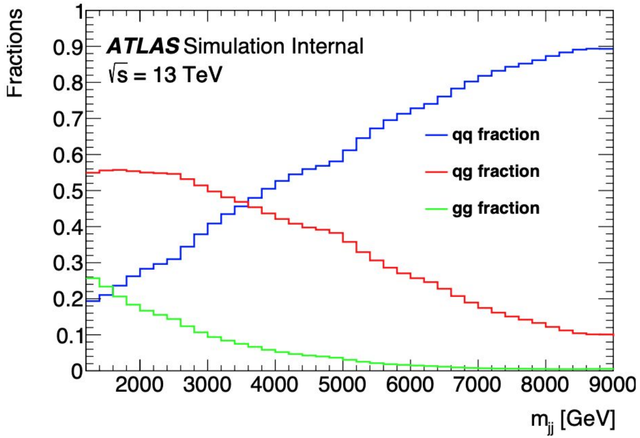
- Compared to previous analysis, this analysis has:
  - higher luminosity
  - optimised event selection
  - novel gluon tagging implementation!



An ATLAS high mass dijet event

Search for new phenomena in dijet events - Strategy

- Search for BSM high-mass resonances
    - Dijet events from QCD processes have a falling distribution of mjj.
    - A resonance appears as a peak in the mjj spectrum.
    - Three categories for mjj spectrum:
        - inclusive (untagged)
        - >= single-gluon (1-g tagged)
        - double-gluon (2-g tagged).
    - Tagging primarily based upon number of charged particles in jets.



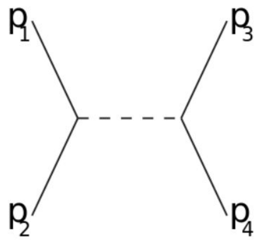
Search for new phenomena in dijet events - Event selections

- HLT_j420
- $n_j \geq 2$
- Leading jet pT > 380 GeV
- Subleading jet pT > 150 GeV
- $|\Delta\varphi| > 1$
- mjj > 1.1 TeV
- $|\eta| < 2.1$
- $|y*| < 0.8$

- We define y* is the rapidity of outgoing jet in the parton-parton centre-of-mass frame :

$$y^* = (y_1 - y_2)/2$$

  - $y_{1,2}$ represent the rapidity of the leading two jets in the laboratory frame.
  - y* of signal will peak at 0, as s-channel indicates.
  - It improves the sensitivity to higher energies where new phenomena are expected.



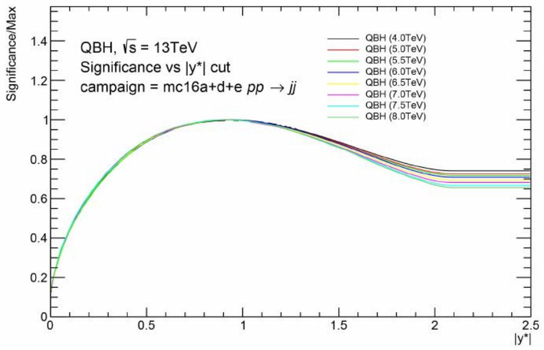
s-channel

Search for new phenomena in dijet events - Signal Optimisation

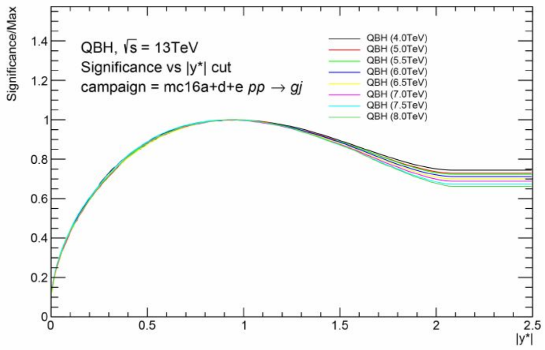
- The significance is defined as:

$$S = \sqrt{\sum_i 2\left[(S_i + B_i) \cdot \ln\left(1 + \frac{S_i}{B_i}\right) - S_i\right]}$$

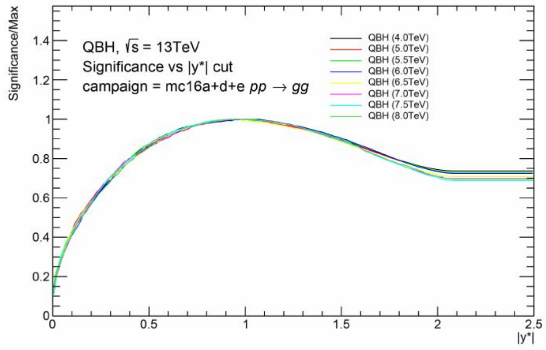
where S_i (B_i) is the number of signal (background) events in the i^{th} bin.



(a) Inclusive



(b) ≥ 1 g-tag



(c) 2 g-tag

Peak at ~ 0.8

Search for new phenomena in dijet events - q/g selections

- Define a threshold where *c* and *m* are constants obtained from the MC:

$$n_{\mathrm{q(g)}} = c_{\mathrm{q(g)}} + m_{\mathrm{q(g)}} \ln(p_{\mathrm{T}})$$

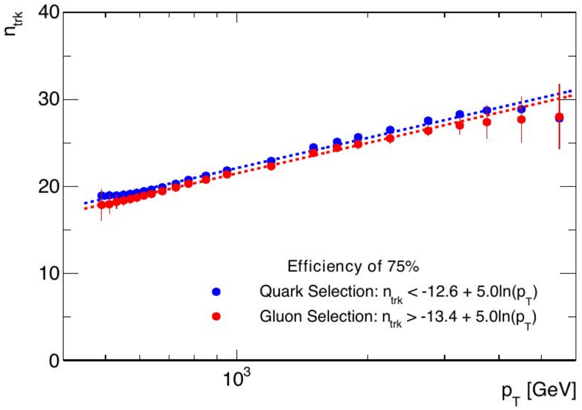
- A jet is tagged as being more likely to be quark-initiated if Ntrk is less than the threshold n_q, and more likely to be gluon-initiated if Ntrk is greater than the threshold n_g:

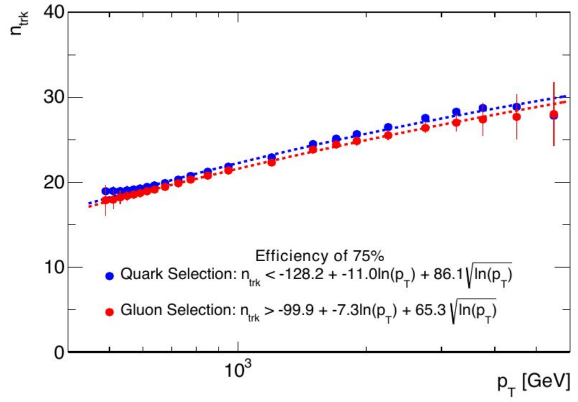
$$N_{\mathrm{trk}} \leq n_{\mathrm{q}} \text{ quark-initiated sample}$$

$$N_{\mathrm{trk}} \geq n_{\mathrm{g}} \text{ gluon-initiated sample}$$

- An alternative fit function is derived as a cross check:

$$n_{\mathrm{q(g)}} = c + m\ln(p_{\mathrm{T}}) + n\sqrt{\ln(p_{\mathrm{T}})}.$$





75% gluon efficiency WP is chosen for tagging.

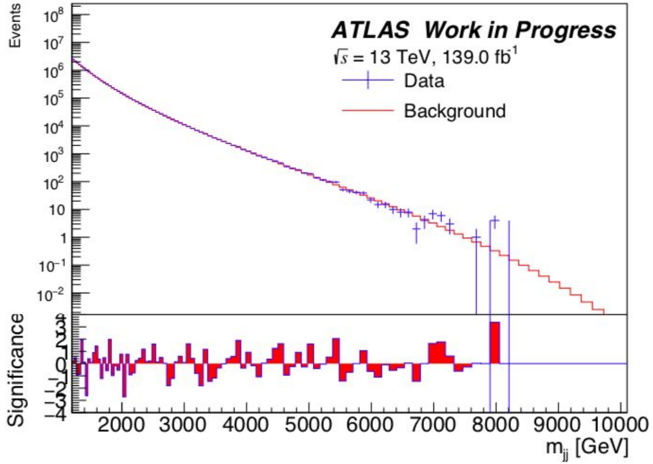
Search for new phenomena in dijet events - Background fit

The SM background of the mjj spectrum is established through a functional fitting procedure applied to the data:

$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x + p_5 (\ln x)^2}$$

$$x \equiv m_{jj} / \sqrt{s},$$

No significant deviation is observed



p-value ~ 0.89

Search for new phenomena in dijet events - Fit function test

- The fit stability tests are employed to assess the behaviour of the background fit function under different scenarios:
  - signal + background template (B_1)
  - background-only template (B_2)
- Ideally, B_1 and B_2 should be consistent
- Test with model-independent Gaussian signals

Mass (TeV)	Width (percentage)	Signal Strength	B_1 from S+B fit Mean ± Rms	B_2 from B-only fit Mean ± Rms	Ratio B_1/B_2
2	5	1	20 062 716.45 ± 4370.57	20 064 025.61 ± 4003.07	1.00007
2	5	3	20 063 730.27 ± 4882.09	20 067 248.18 ± 4003.14	1.00017
2	5	5	20 062 961.53 ± 4521.62	20 070 470.90 ± 4003.36	1.00037
5	5	1	20 062 414.49 ± 4005.80	20 062 458.64 ± 4003.05	1.00000
5	5	3	20 062 420.85 ± 4002.94	20 062 547.11 ± 4003.09	1.00001
5	5	5	20 062 420.96 ± 4002.82	20 062 635.82 ± 4003.25	1.00001
5	10	1	20 062 435.18 ± 4010.37	20 062 483.50 ± 4002.87	1.00000
5	10	3	20 062 448.75 ± 4007.22	20 062 622.26 ± 4002.95	1.00001
5	10	5	20 061 413.12 ± 3682.05	20 062 761.08 ± 4003.12	1.00007
7	5	1	20 062 420.38 ± 4002.68	20 062 420.29 ± 4002.98	1.00000
7	5	3	20 062 422.56 ± 4002.86	20 062 432.08 ± 4003.08	1.00000
7	5	5	20 062 422.86 ± 4002.98	20 062 444.09 ± 4003.20	1.00000

Results show consistency!

Search for new phenomena in dijet events - Results

- Upper limits set on signal cross-section x acceptance x gluon-tagging efficiency x branching ratio for BSM resonances.
- Three categories are investigated.

untagged Limits [TeV]						
	Obs	Exp $^{+2\sigma}$	Exp $^{+1\sigma}$	Exp	Exp $^{-1\sigma}$	Exp $^{-2\sigma}$
Graviton	3.78	3.15	3.35	3.60	3.80	4.11
QBH	9.57	9.19	9.56	9.76	9.98	10.01

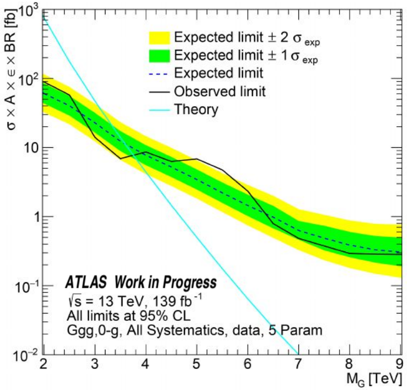
Table 6.33 Limits in the untagged region for signal models.

1-g tagged Limits [TeV]						
	Obs	Exp $^{+2\sigma}$	Exp $^{+1\sigma}$	Exp	Exp $^{-1\sigma}$	Exp $^{-2\sigma}$
Graviton	4.01	3.36	3.51	3.85	4.00	4.31
QBH	9.88	9.47	9.68	9.88	9.99	10.04

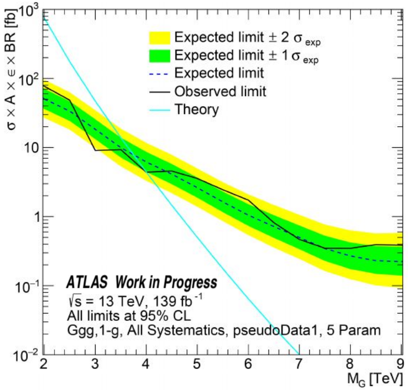
Table 6.34 Limits in the 1-g tagged region for signal models.

2-g tagged Limits [TeV]						
	Obs	Exp $^{+2\sigma}$	Exp $^{+1\sigma}$	Exp	Exp $^{-1\sigma}$	Exp $^{-2\sigma}$
Graviton	4.26	3.93	4.15	4.41	4.66	4.93
QBH	10.00	9.73	9.90	10.00	10.05	10.07

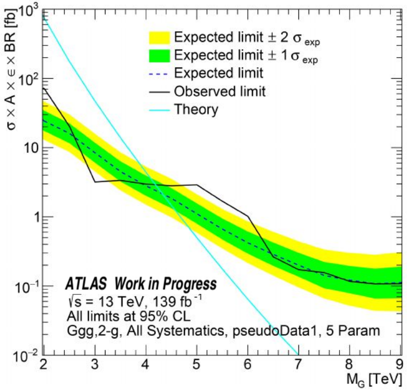
Table 6.35 Limits in the 2-g tagged region for signal models.



(a)



(b)



(c)

Incorporating gluon-tagging improves search limits on the mjj spectrum

Conclusion

- From 2015-2018, the LHC achieved a center-of-mass energy of $\sqrt{s}$ = 13 TeV. ATLAS experiment recorded a total integrated luminosity of 140 fb^{-1}, this enabled the efficient search for new BSM particles.
- A **new** quark/gluon jet tagger 'BDT-tagger' is constructed.
  - The performance of both N_{trk}- and BDT-taggers are studied.
    - The BDT-tagger is found to have better performance than the N_{trk}-tagger across the whole pT range.
    - Scale factors accounting for data/MC differences are provided with a total systematic uncertainty of ~20%.
  - Will benefit various analyses such as SM measurements, or new physics searches.
- **First** search for new resonances decaying into two jets with q/g-tagging conducted.
  - Three categories for mjj spectrum defined, with optimised event selections.
  - Upper limits are set for benchmark models, search sensitivity is enhanced by employing q/g-tagging.
- Outlook
  - More jet variables such as jet mass, can be incorporated as inputs to the construction of q/g taggers.
  - Several algorithms such as neural network, can be utilized to develop q/g tagger.
  - Event selection method can be improved through machine learning techniques.

Publications

1. ATLAS Collaboration, *Performance and calibration of quark/gluon-jet taggers using 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.* , Chin. Phys. C, 2023, **Cover page article, ATLAS Physics Briefing**

2. ATLAS Collaboration, *Search for new phenomena in dijet events using quark/gluon tagging based on track multiplicity.* (Work in Progress)

3. ATLAS Collaboration, *Search for heavy resonances decaying into a pair of Z bosons in the $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\nu$ final states using 139 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.* , Eur. Phys. J. C, 81 (2021) 332 (other work led to publication)

Many thanks to :

Defense committee; Prof. Shu Li; Prof. Shih-Chieh Hsu; Prof. Iain Bertram; Ke Li; Ben Nachman; Haoran Zhao; Nishu Nishu; Rongqian Qian; Jack Lindon; Jyoti Prakash Biswal…

Detailed lists of my contributions are given in backup slides

Many thanks ！

Backup & Contributions

Contributions

Performance and calibration of quark/gluon-jet taggers:

a. Served as a contact editor for the publication, and also as editor for the internal documentation.
b. Served as an analysis contact for the analysis team, communicating and presenting analysis results regularly in the group and subgroup meetings.
c. Multi-jet samples trimming and production. Upgrade framework to the latest AnalysisBase release.
d. Code development for the analysis framework in charge of: matrix method implementation and scale factor calculation and the MC-to-MC scale factors.
e. Alternative MC samples study aiming to estimate modelling uncertainties.
f. Estimation of theoretical and experimental systematic uncertainties for the analysis.
g. Measurement of the efficiencies of quark/gluon taggers in all working points provided.
h. Quark/gluon tagger construction, including the BDT model training, validation and testing.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Chin. Phys. C

CERN-EP-2023-151
18th August 2023

Performance and calibration of quark/gluon-jet taggers using 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

The identification of jets originating from quarks and gluons, often referred to as quark/gluon tagging, plays an important role in various analyses performed at the Large Hadron Collider, as Standard Model measurements and searches for new particles decaying to quarks often rely on suppressing a large gluon-induced background. This paper describes the measurement of the efficiencies of quark/gluon taggers developed within the ATLAS Collaboration, using $\sqrt{s}$ = 13 TeV proton–proton collision data with an integrated luminosity of 140 fb^{-1} collected by the ATLAS experiment. Two taggers with high performances in rejecting jets from gluon over jets from quarks are studied: one tagger is based on requirements on the number of inner-detector tracks associated with the jet, and the other combines several jet substructure observables using a boosted decision tree. A method is established to determine the quark/gluon fraction in data, by using quark/gluon-enriched subsamples defined by the jet pseudorapidity. Differences in tagging efficiency between data and simulation are provided for jets with transverse momentum between 500 GeV and 2 TeV and for multiple tagger working points.

ATLAS Note
ANA-JETM-2020-02-INT1
21st July 2023
Draft version 0.9

Performance and calibration of quark/gluon jet taggers using 140 fb^{-1}of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Wanyun Su[a,b,c], Ke Li[c], Ben Nachman[d], Evan Saraivanov[c], Htet A. Myin[c], Rongqian Qian[b], Haoran Zhao[c], Shih-Chieh Hsu[c], Shu Li[a,b]

[a]*Tsung-Dao Lee Institute,* [b]*Shanghai Jiao Tong University,* [c]*University of Washington,* [d]*Lawrence Berkeley National Laboratory*

The identification of jets originated from quarks or gluons in ATLAS is defined from the number of charged tracks in the jets and from a more advanced boosted decision tree algorithm. This note describes the measurement of the tagging efficiencies of the aforementioned taggers, using 140 fb^{-1} of data collected by ATLAS produced by $\sqrt{s}$ = 13 TeV proton–proton collisions produced by the Large Hadron Collider. A matrix method is established to determine the data quark/gluon fraction, using quark/gluon enriched sub-samples defined from the jets pseudo-rapidity. Data-to-simulation scale factors for quark and gluon categories are given for jets with transverse momentum between 500 GeV - 2 TeV, for tagger working points corresponding to 50%, 60%, 70% and 80% fixed efficiencies.

List of contributions

Wanyun Su	Ntuple production, framework development, systematics study, BDT training, scale factor study, eta dependency study, alternative sample study, analysis contact, paper editor.
Ke Li	Contact, note editor, framework maintainer, supervising students.
Ben Nachman	Analysis advisor.
Evan Saraivanov	analysis checking.
Htet A. Myin	analysis checking.
Rongqian Qian	scale factor study, eta dependency study, alternative sample study
Haoran Zhao	framework development, BDT training, systematics study, scale factor study, eta dependency study, alternative sample study
Shih-Chieh Hsu	Supervising students.
Shu Li	Supervising students.

Contributions

Search for new phenomena in dijet events:

a. Analysis cutflow cross check with standalone codes.
b. Signal injection test in all categories, with 4 & 5 parameters functions.
c. Background fit stability test in all categories with String and Gaussian signals.
d. y* cut optimisation.
e. Code development for the analysis framework (dijetntuplemaker), including workspace generation and QCD background fit function tests.
f. string signal samples generations(see git commit).
g. regularly presented analysis twice at the JDM meeting.
h. Tracking systematics implementation.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

11th September 2023

Search for new phenomena in dijet events using quark/gluon tagging based on track multiplicty

Iain Bertram[a], Jyoti Prakash Biswal[b], Doug Gingrich[b,c], Shih-Chieh Hsu[d], Shu Li[e], Jack Lindon[b], Fairhurst Lyons[b], Ben Nachman[f], Nishu Nishu[b], Katherine Rybacki[a], Wanyun Su[e], Dengfeng Zhang[b], Yan Zhou[g]

[a]*Lancaster University, United Kingdom*
[b]*University of Alberta, Canada*
[c]*TRIUMF, Canada*
[d]*University of Washington, United States of America*
[e]*Tsung-Dao Lee Institute, China*
[f]*Lawrence Berkeley National Laboratory, United States of America*
[g]*Tsinghua University, China*

A search for new resonance decays producing a pair of jets is performed using 139 fb^{-1} of ATLAS pp collision data recorded from the Large Hadron Collider operating at $\sqrt{s} = 13$ TeV. To increase the sensitivity to observe new resonances preferentially decaying to one or more gluons, a gluon-tag method based on the number of associated particle tracks is employed.

Contributions

Search for heavy resonances decaying into a pair of Z bosons :

a. Analysis workspace generation and optimisation, especially combined the 4l and llvv final states, and combined ggF and VBF cross section, improved overall sensitivity.
b. Statistical uncertainties study, mainly luminosity uncertainty calculation by scaling data from $36fb^{-1}$ to $80fb^{-1}$.
c. p-value, upper limit and exclusion contours extraction for 2HDM.
d. Comparison between ATLAS and CMS high mass results on 4l final state.
e. Served as combination contact.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Eur. Phys. J. C 81 (2021) 332
DOI: 10.1140/epjc/s10052-021-09013-y

CERN-EP-2020-153
11th February 2022

Search for heavy resonances decaying into a pair of Z bosons in the $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A search for heavy resonances decaying into a pair of Z bosons leading to $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states, where ℓ stands for either an electron or a muon, is presented. The search uses proton–proton collision data at a centre-of-mass energy of 13 TeV collected from 2015 to 2018 that corresponds to the integrated luminosity of 139 fb^{-1} recorded by the ATLAS detector during Run 2 of the Large Hadron Collider. Different mass ranges spanning 200 GeV to 2000 GeV for the hypothetical resonances are considered, depending on the final state and model. In the absence of a significant observed excess, the results are interpreted as upper limits on the production cross section of a spin-0 or spin-2 resonance. The upper limits for the spin-0 resonance are translated to exclusion contours in the context of Type-I and Type-II two-Higgs-doublet models, and the limits for the spin-2 resonance are used to constrain the Randall–Sundrum model with an extra dimension giving rise to spin-2 graviton excitations.

Data and MC samples

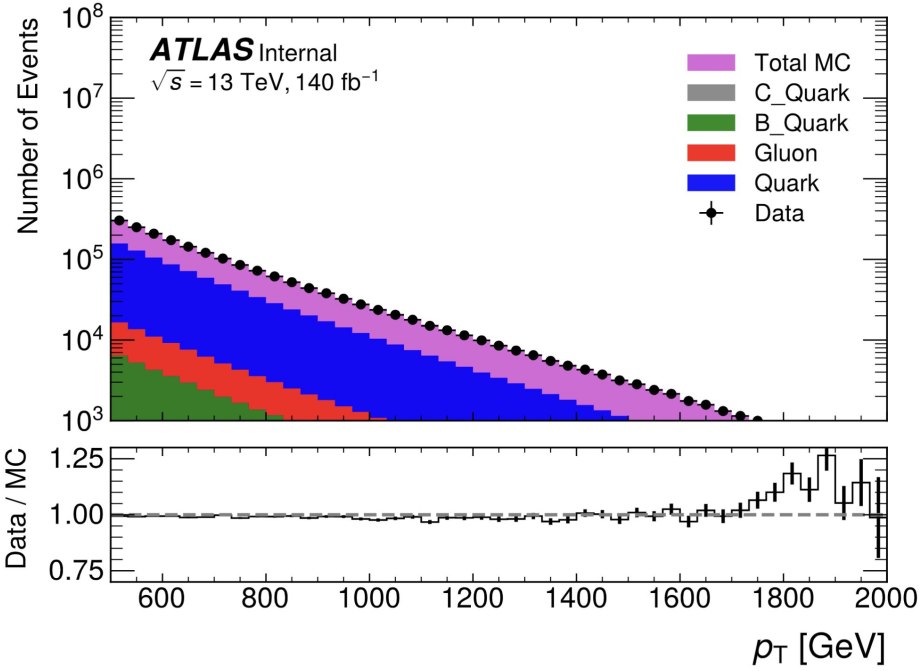
- Data 15-18 (140 fb^{-1}) DAOD JETM1
- Simulation (dijet events)
  - See the table
- Analysis Release
  - AnalysisBase,21.2.135

Table 1: The MC simulation used for the multi-jet processes in this calibration. The PDF sets, generators for a hard process, simulator of parton showers, and the order in α_s of cross-section calculations to obtain yield normalization are shown.

nominal ->

Sample ID	PDF set	Generator (Hard process)	Cross-section normalization	Parton shower	Hadronization	Slice
364701–364712	NNPDF2.3LO	PYTHIA8(v.235)	LO	p_T-ordered	String-based	JZW
364677–364685	CT10	SHERPA2.2.5	LO	p_T-ordered	Cluster-based	JZ/JZW
364686–364684	CT10	SHERPA2.2.5	LO	p_T-ordered	String-based	JZ/JZW
364902-364909	MMHTNLO	HERWIG7	NLO	Dipole	Cluster-based	JZW
364922-364929	MMHTNLO	HERWIG7	NLO	Angular-ordered	Cluster-based	JZW
600624 - 600631	NNPDF2.3LO	Powheg+PYTHIA8	NLO	p_T-ordered	String-based	JZ

Leading jet pT spectrum

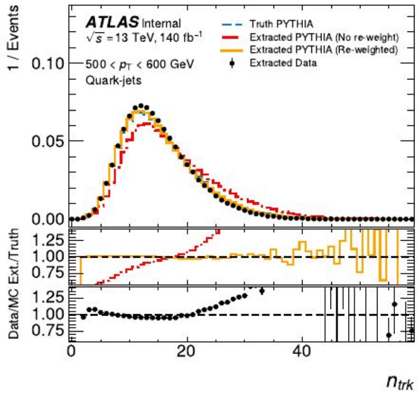


The calibration of quark/gluon jets taggers - Matrix Method

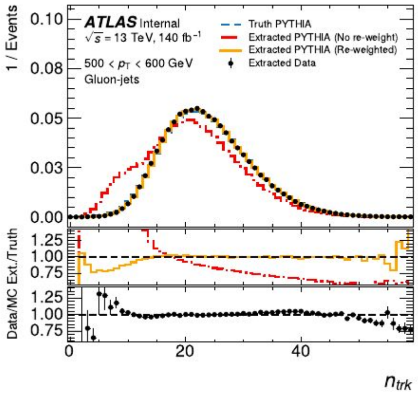
500 - 600 GeV

The distribution of Ntrk/BDT of truth MC match to that of extracted MC after re-weighting

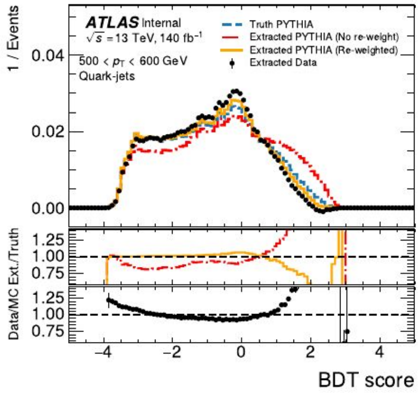
⟶ matrix method works!

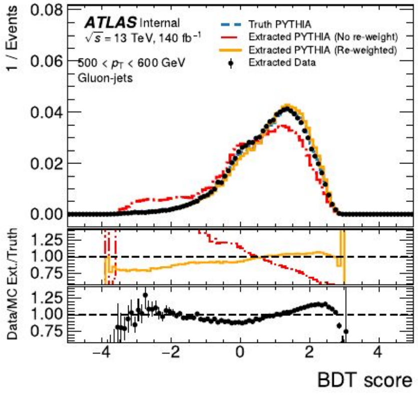


(a)

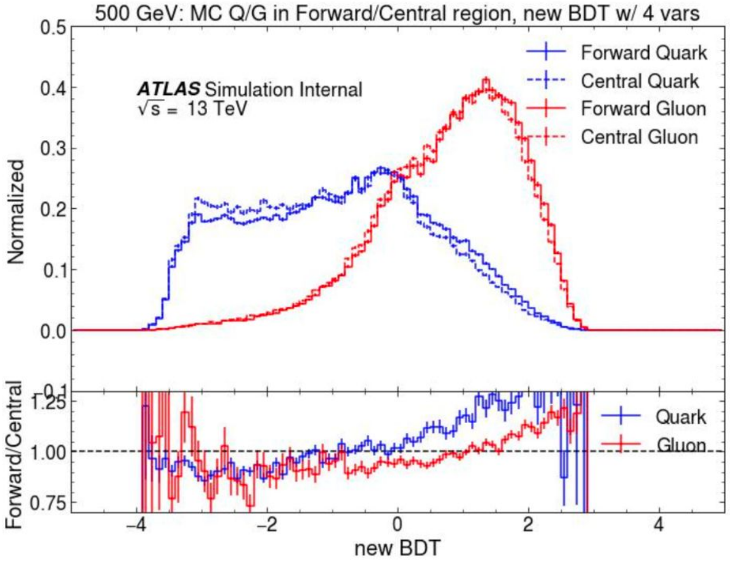


(b)

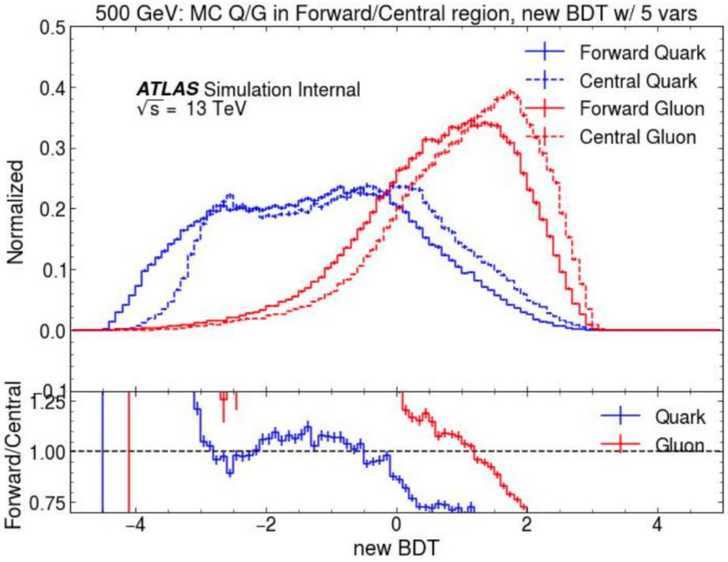




BDT score comparison using different inputs



(a) Training without $|\eta|$, scenario 1



(b) Training with $|\eta|$, scenario 2

The result shows a strong discrepancy if including $|\eta|$ in the training. This violates the assumptions that the partons show same distribution in forward and central regions, Besides, the BDT tagger with $|\eta|$ included would lead to poor performance for jets in the central region when analyses use such tagger on a pure sample of quark-jets (eg. Z+jet samples).

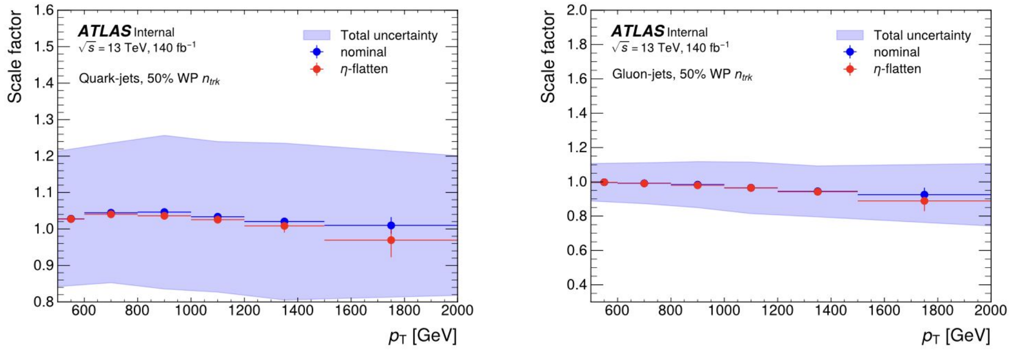
η dependency test

Approach:

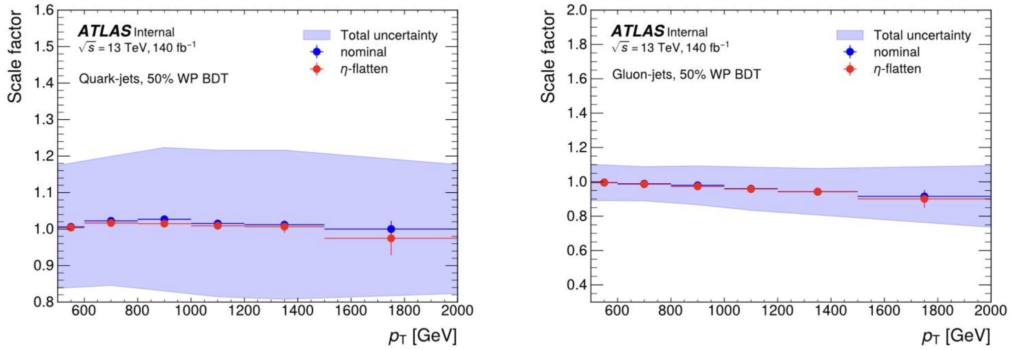
1. For each pT bin, reweight the η to flat distribution.
2. Evaluate N_{trk} and BDT tagger efficiency, and calculate scale factors

Difference in SFs <4%

and are within total systematic unc.

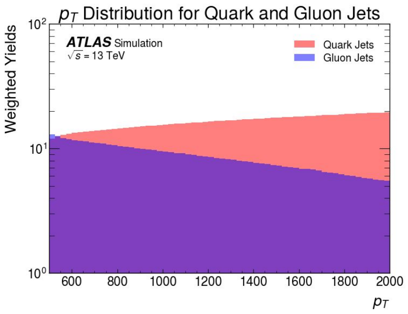


(a) (b)



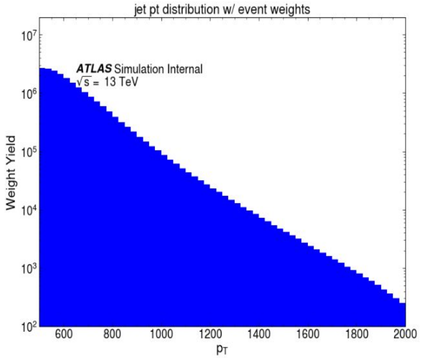
BDT flatten pT study

-The BDT was trained in the full dataset (q+g) rather than doing it separately, the BDT will learn that a jet with an higher pT is more q-like and maybe it might be underperforming w.r.t. the other variables



q/g fraction is pT-dependent

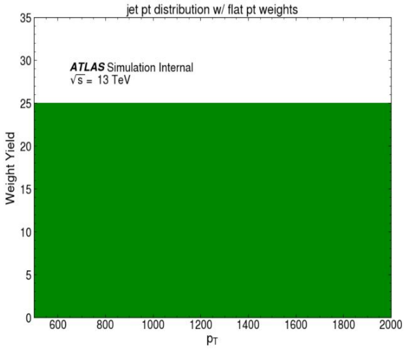
Two approaches:



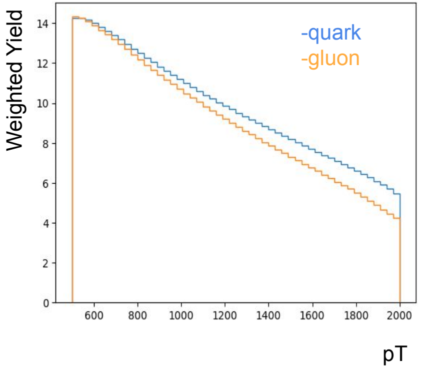
(a) Event Weight

Dijet flatten

The pT spectrum was flattened in the inclusive dijet events.



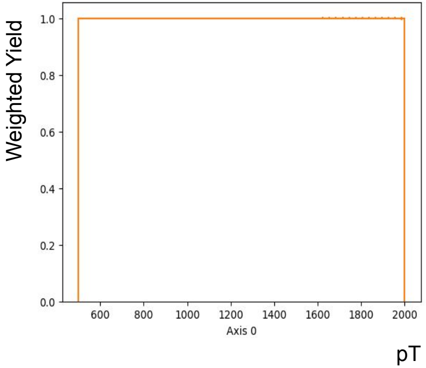
(b) Flatpt Weight



q

/g flatten

The pT spectrum was flattened in each of q/g jet



BDT flatten pT study - 50% WP

	500-600	600-800	800-1000	1000-1200	1200-1500	1500-2000

Dijet flatten

```
Quark GBDT_newScore SF:  [1.00683911 1.02296756 1.0272528  1.02021184 1.01054741 0.99162948]

Gluon GBDT_newScore SF:  [0.99717565 0.99023186 0.98091868 0.96516437 0.94431819 0.90485574]
```

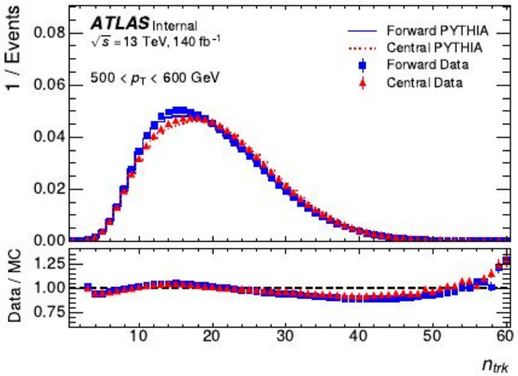
Difference in SFs < 1%

q/
g flatten

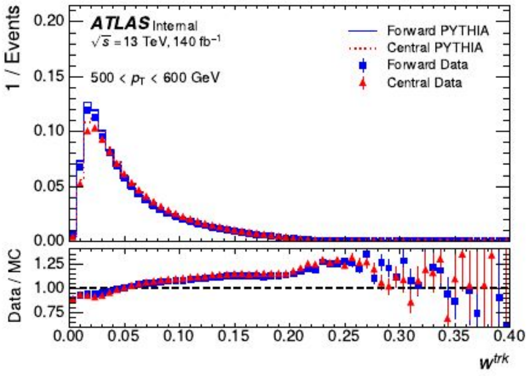
```
Quark GBDT_newScore SF:  [1.01227623 1.02786604 1.02750741 1.01991293 1.00838897 0.99449926]

Gluon GBDT_newScore SF:  [0.99970836 0.99129879 0.98266503 0.96787263 0.94621082 0.90473793]
```

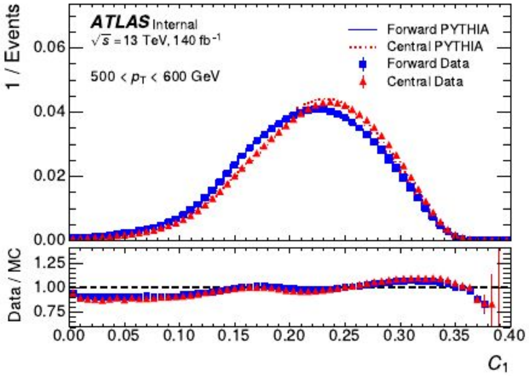
Quark/gluon tagging variables in forward/central region

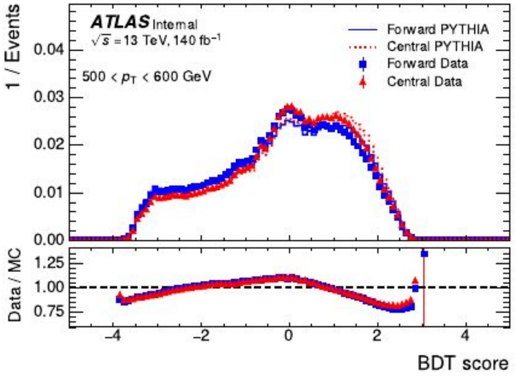


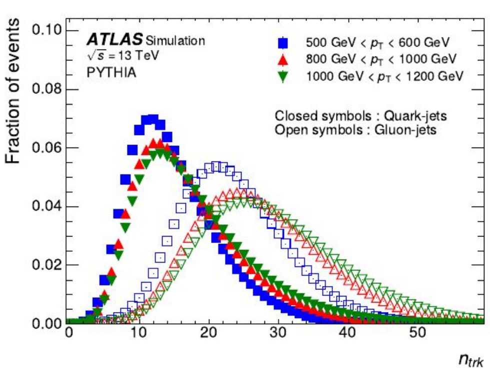
(a)



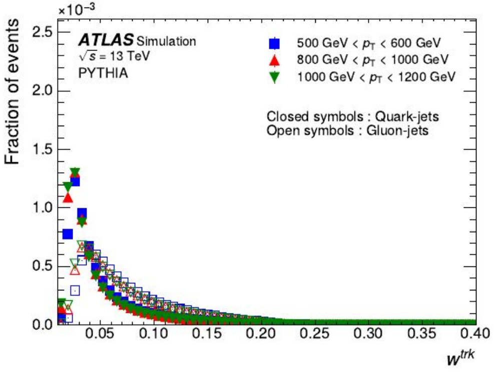
(b)



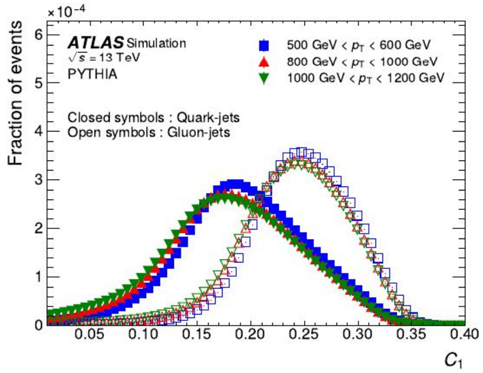


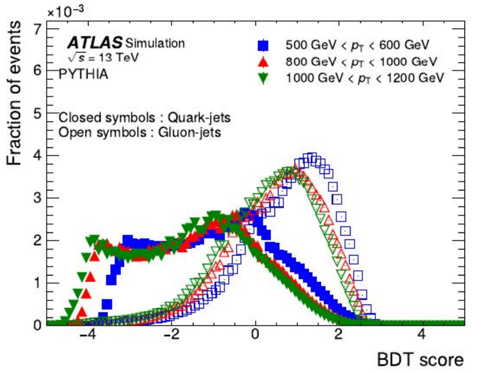

ATLAS Simulation
√s = 13 TeV
PYTHIA
500 GeV < p_T < 600 GeV
800 GeV < p_T < 1000 GeV
1000 GeV < p_T < 1200 GeV
Closed symbols : Quark-jets
Open symbols : Gluon-jets
Fraction of events
n_{trk}

(a)

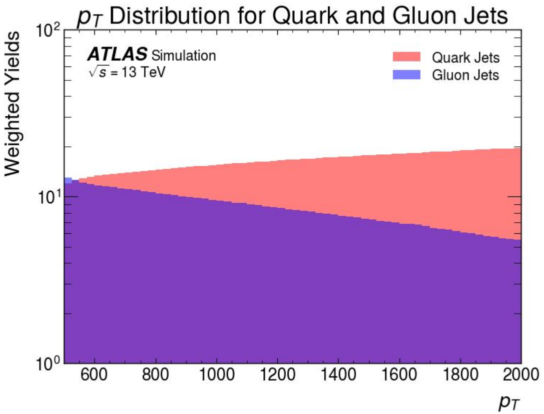

×10⁻³
ATLAS Simulation
√s = 13 TeV
PYTHIA
500 GeV < p_T < 600 GeV
800 GeV < p_T < 1000 GeV
1000 GeV < p_T < 1200 GeV
Closed symbols : Quark-jets
Open symbols : Gluon-jets
Fraction of events
w^{trk}

(b)

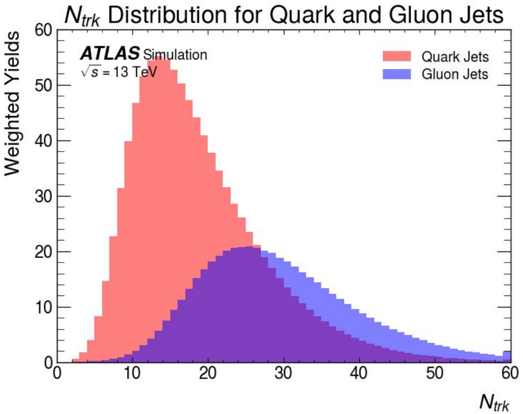

×10⁻⁴
ATLAS Simulation
√s = 13 TeV
PYTHIA
500 GeV < p_T < 600 GeV
800 GeV < p_T < 1000 GeV
1000 GeV < p_T < 1200 GeV
Closed symbols : Quark-jets
Open symbols : Gluon-jets
Fraction of events
C_1


×10⁻³
ATLAS Simulation
√s = 13 TeV
PYTHIA
500 GeV < p_T < 600 GeV
800 GeV < p_T < 1000 GeV
1000 GeV < p_T < 1200 GeV
Closed symbols : Quark-jets
Open symbols : Gluon-jets
Fraction of events
BDT score

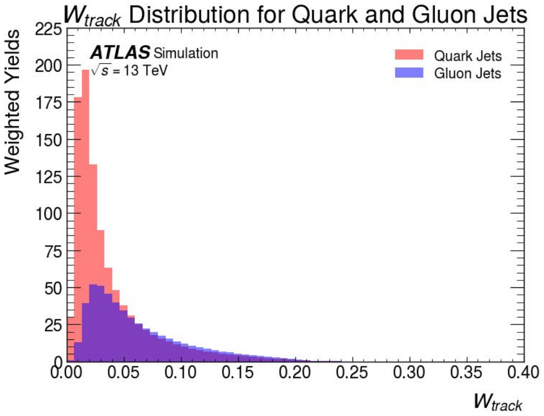
Quark/gluon tagging variables - Truth q/g features in flat pT weight



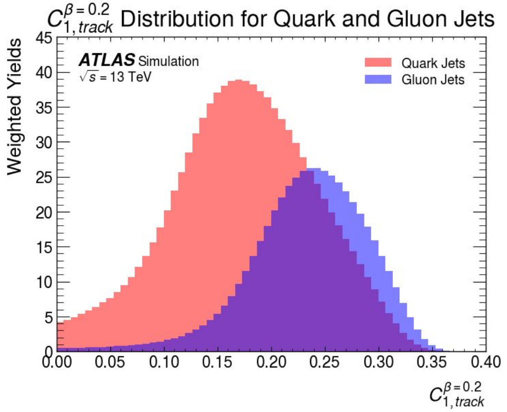
p_T with flat weight



N_{trk} :
Most important feature



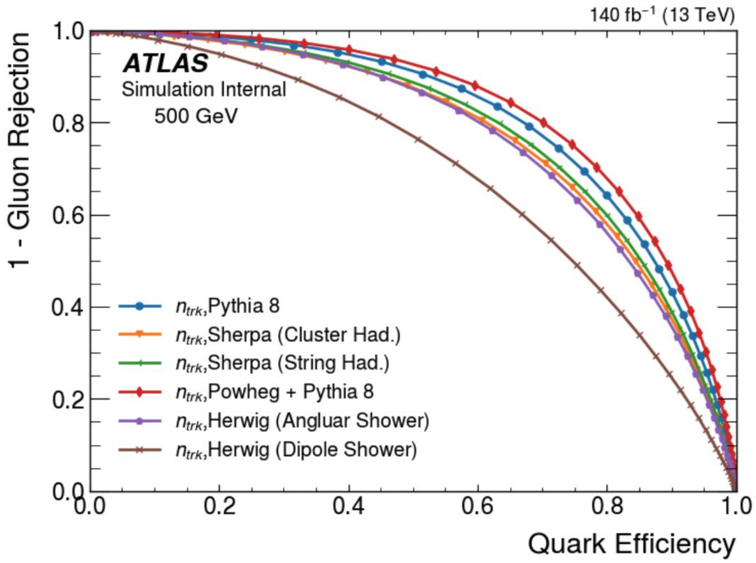
$$w_{\text{track}}$$

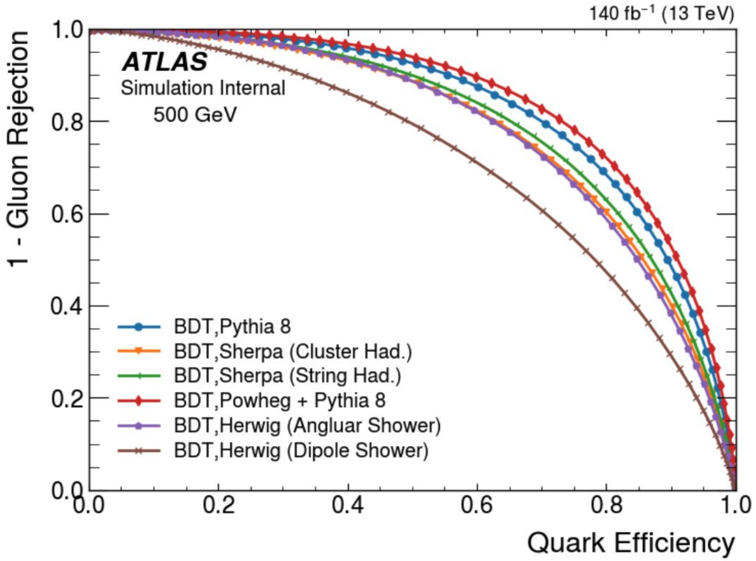


$$C_{1,\text{ track}}^{\beta=0.2}$$

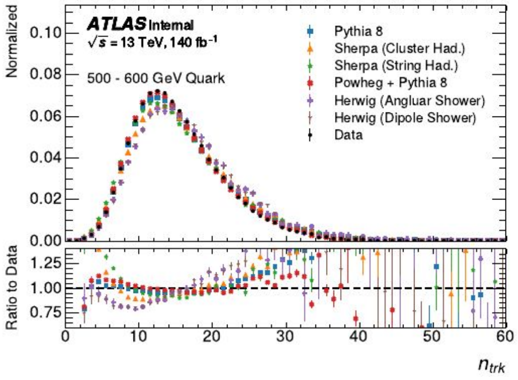
Comparison of different generators - ROC

Since this modelling difference is so critical for this analysis, some more illustration of the differences between the different MC samples would be great to see.

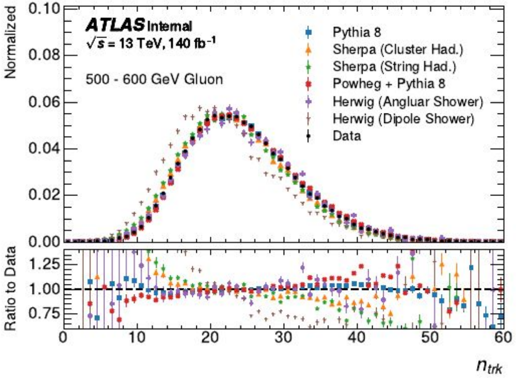




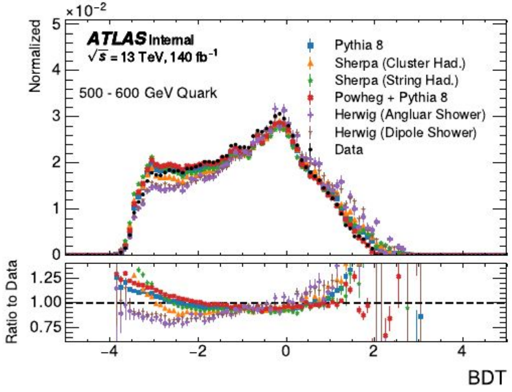
Comparison of different generators - Ratio to data

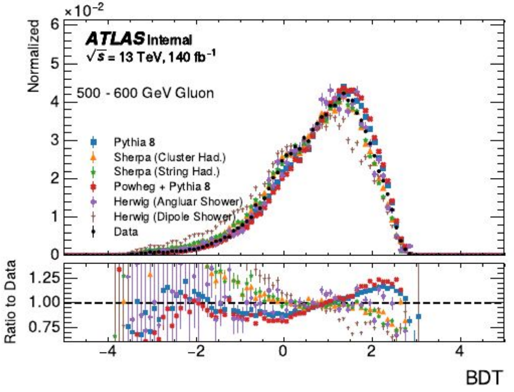


(a)



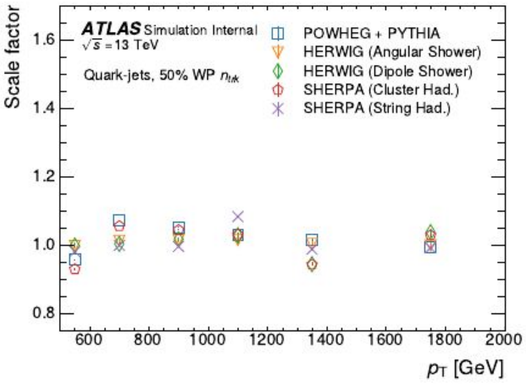
(b)



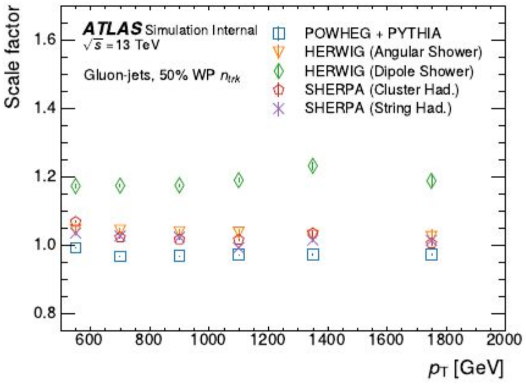


The calibration of quark/gluon jets taggers - Results

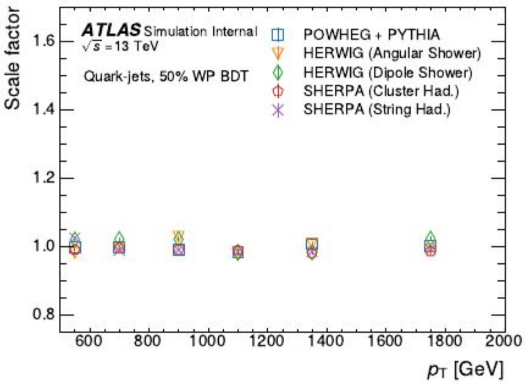
- To account for modelling differences between the PYTHIA and alternative MC samples
- MC-to-MC SFs from 0.9 - 1.1 for most MCs
- Relatively large SFs (~1.3) for HERWIG dipole MC in gluon-jets

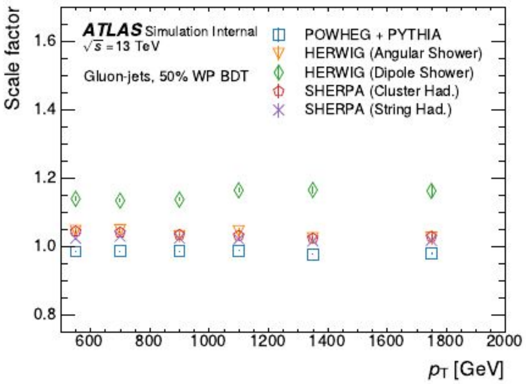


(a)



(b)





Dijet search - Flowchart

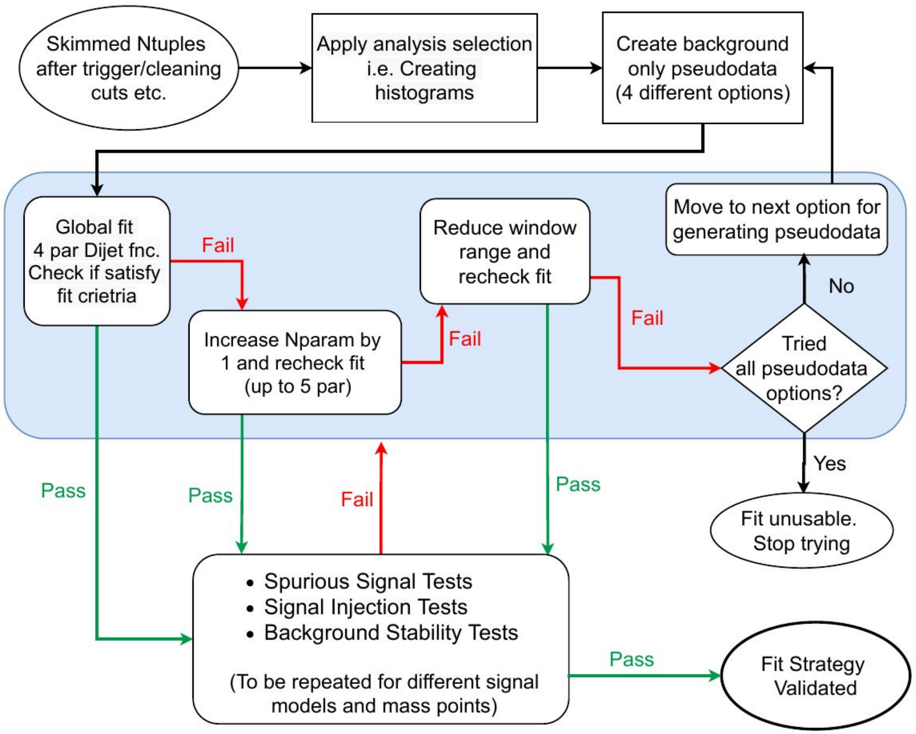


Figure 6.66 Analysis top-level flowchart.

Dijet search - Systematics

Currently considered systematics:

- Uncertainty on background model.
- Uncertainty on integrated luminosity on the data.
- Uncertainty on gluon-tag efficiency.
- JES and JER.
- Tracking systematics