Quark vs Gluon Jet Tagging

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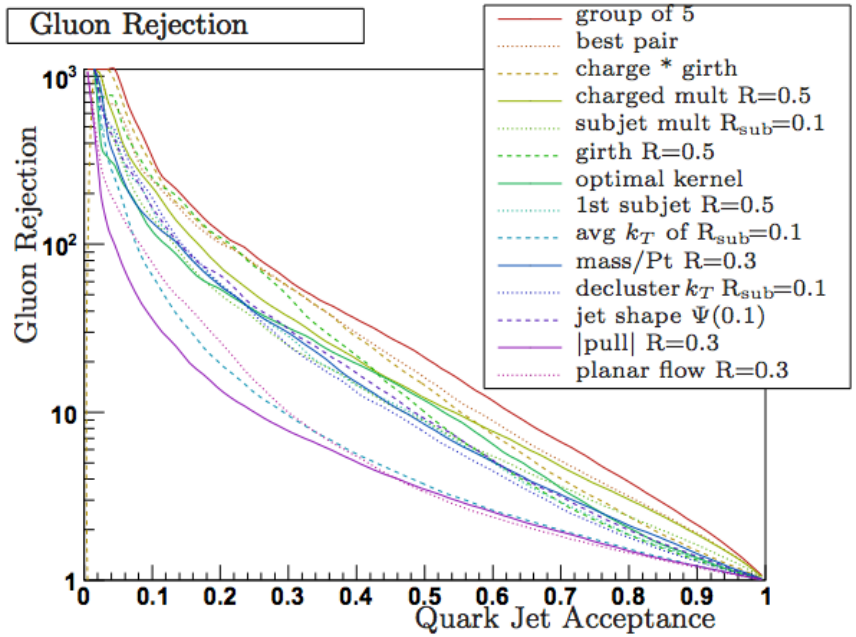
APS DPF 2017

q/g discrimination

- For background (gluon) suppression - e.g. VBF, SUSY, …
- For final state reconstruction - e.g hadronic top or W
- Requires detailed understanding of jet fragmentation properties
- Probes generator PS/tunes

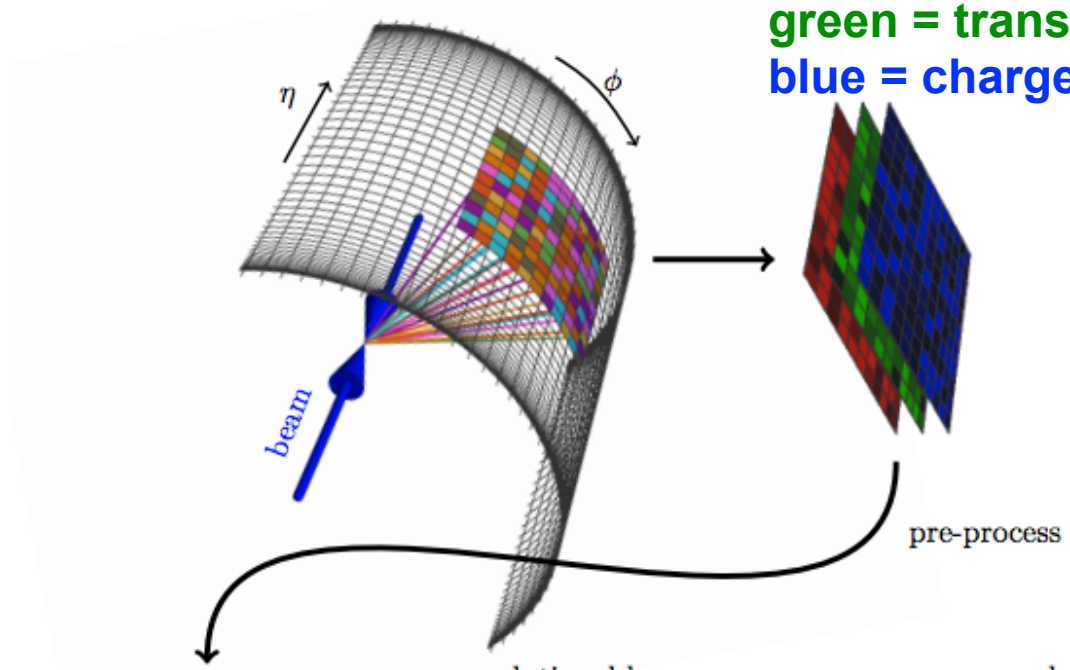
hep-ph/1106.3076



Many observables exploiting different fragmentation properties are useful for q/g discrimination

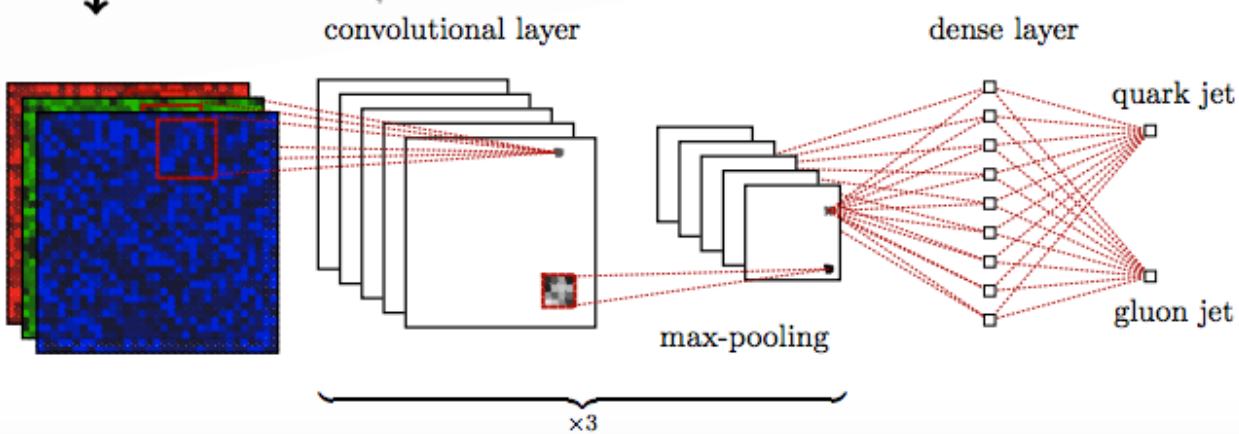
q/g tagging with jet images

red = transverse momenta of charged particles
green = transverse momenta of neutral particles
blue = charged particle multiplicity



RGB jet images: represent the jet with multiple images, exploiting tracking information, in addition to calorimeter images.

hep-ph/1612.01551



Outline

- Performance and uncertainties for quark/gluon tagging with **charged particle multiplicity**

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- First look quark/gluon tagging with **ATLAS jet images**

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n_{track}

- A simple observable: number of tracks ghost-matched to the jet (n_{track})
- Proxy for charged multiplicity ($n_{charged}$) in quark/gluon fragmentation

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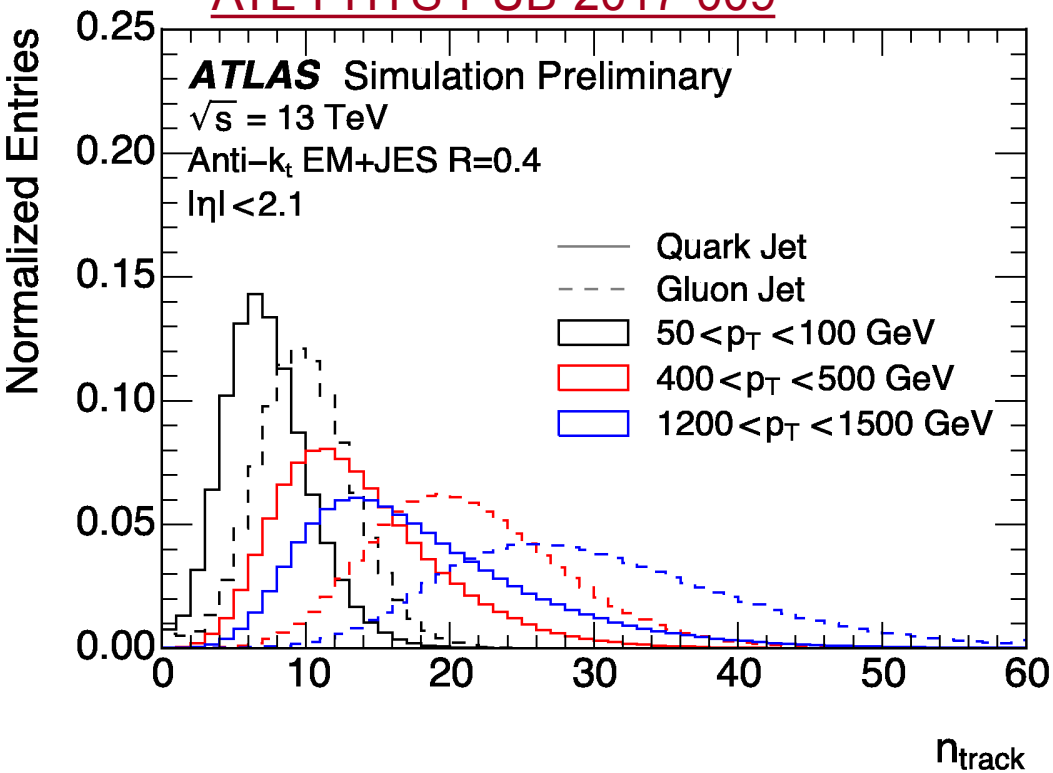

- Particle multiplicity scales with the color charge (C_F/C_A)
- —> powerful q/g discriminant

n_{track}

- A simple observable: number of tracks ghost-matched to the jet (n_{track})
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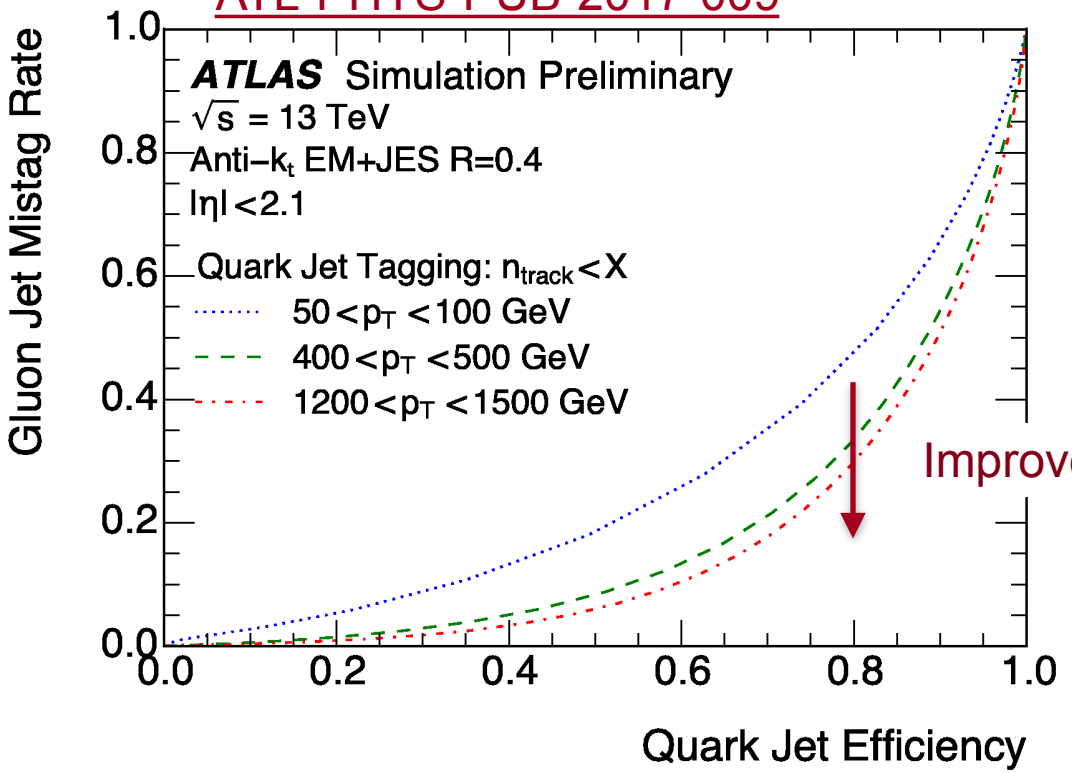


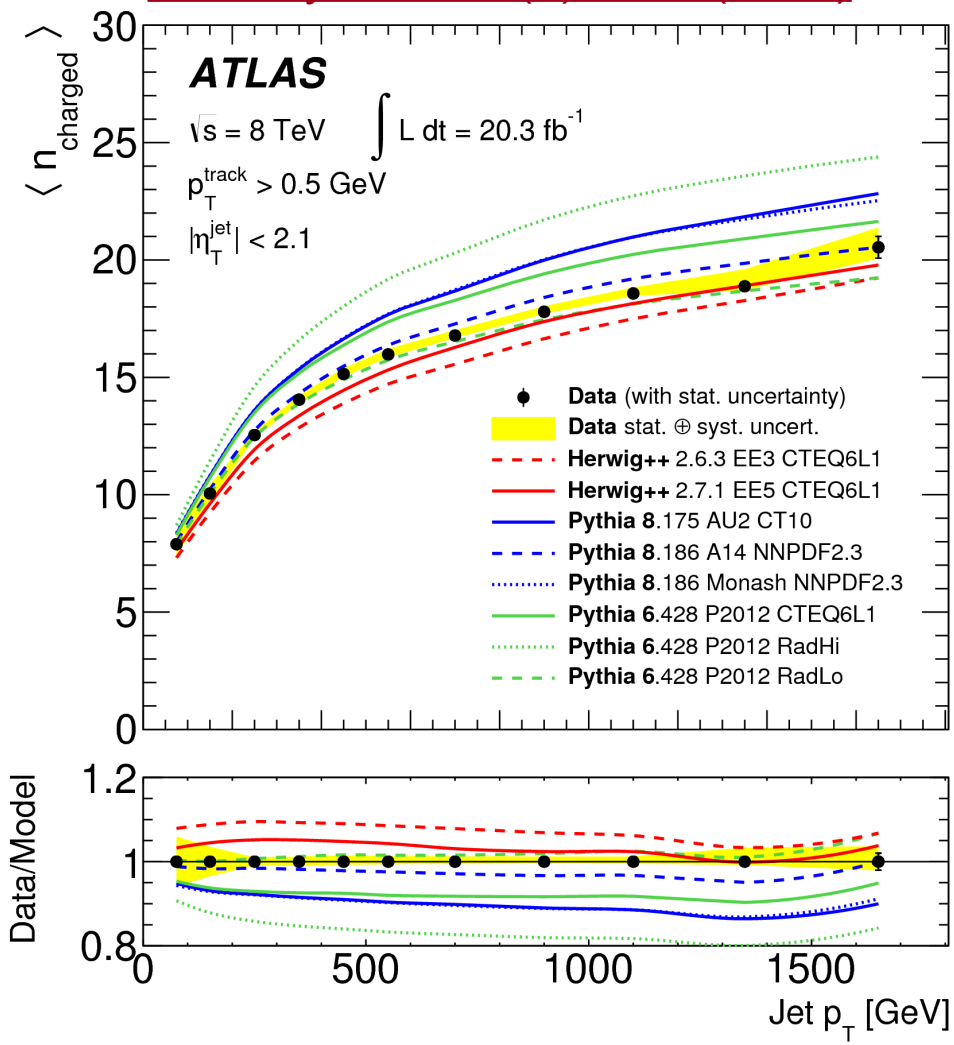
Improved gluon rejection at higher p_T

- Particle multiplicity scales with the color charge (C_F/C_A)
- —> powerful q/g discriminant

$n_{charged}$ modeling

- The challenge is assessing the modeling of the discrimination performance in MC
- Run 1 $n_{charged}$ measurement shows large data/MC discrepancies depending on generator and tuning choices

Eur. Phys. J. C76(6), 1-23 (2016)



Recasting Run 1 measurement for Run 2 tagger

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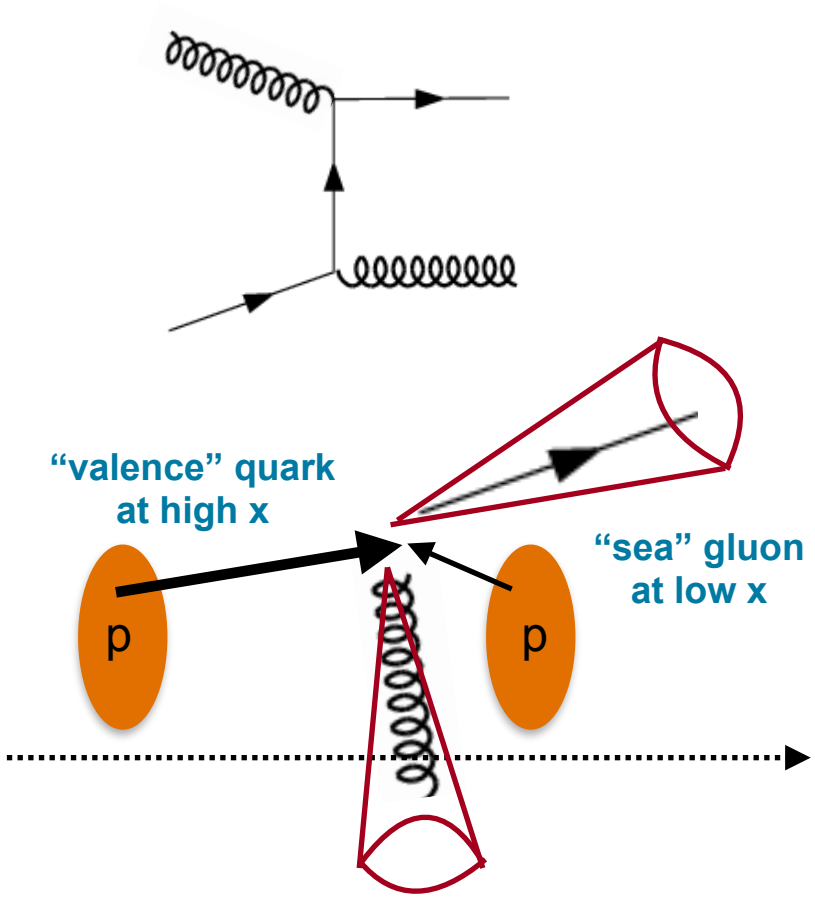
- **Fragmentation modeling uncertainties** from Run 1 charged multiplicity measurement.

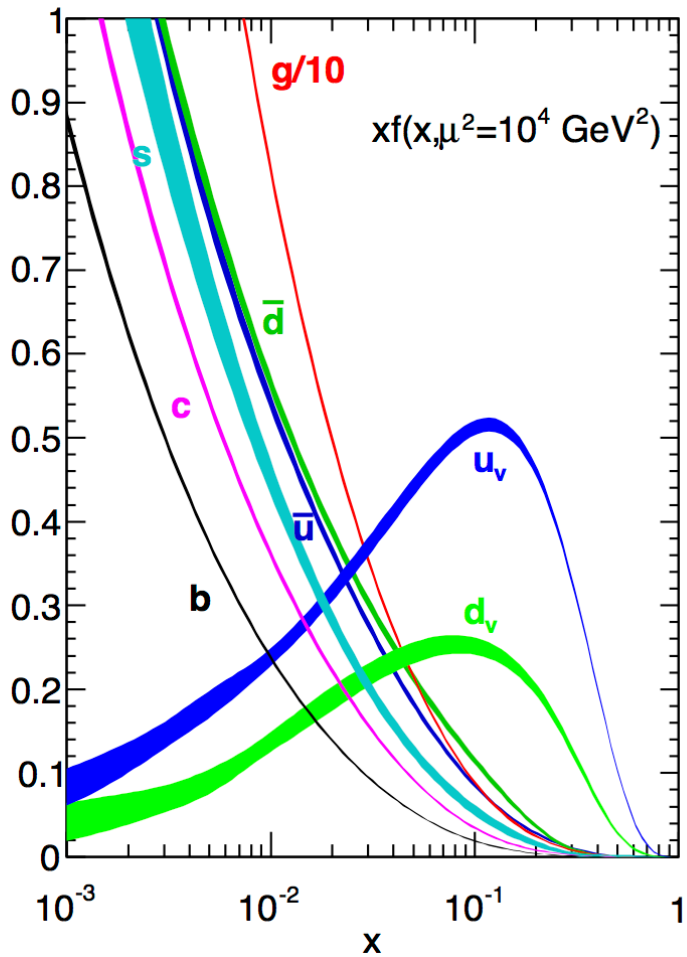
- **Experimental uncertainties** from track reconstruction uncertainties at 13 TeV (Run 2).

$n_{charged}$ for quark and gluon jets

- Extract $n_{charged}$ separately for quarks and gluons by exploiting rapidity difference in dijet events (mostly qg—>qg)



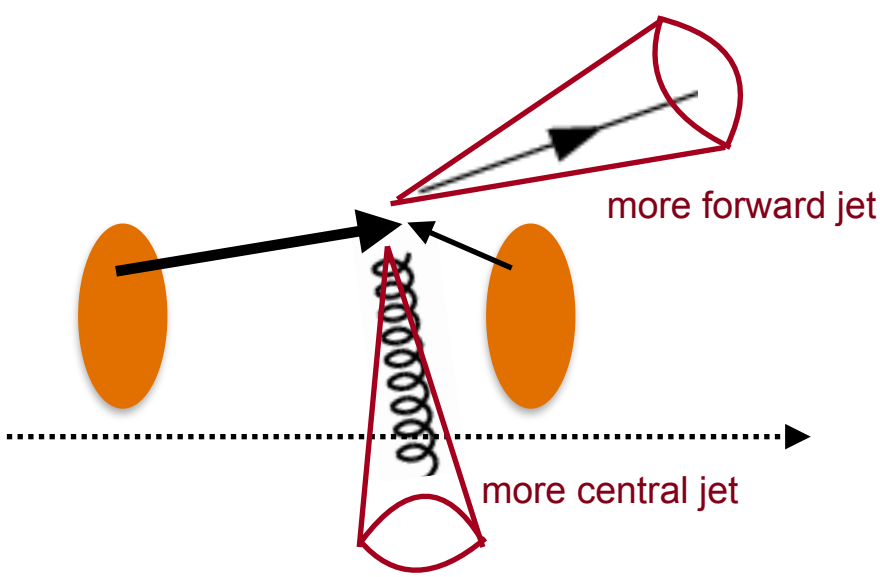
NNPDF Collaboration



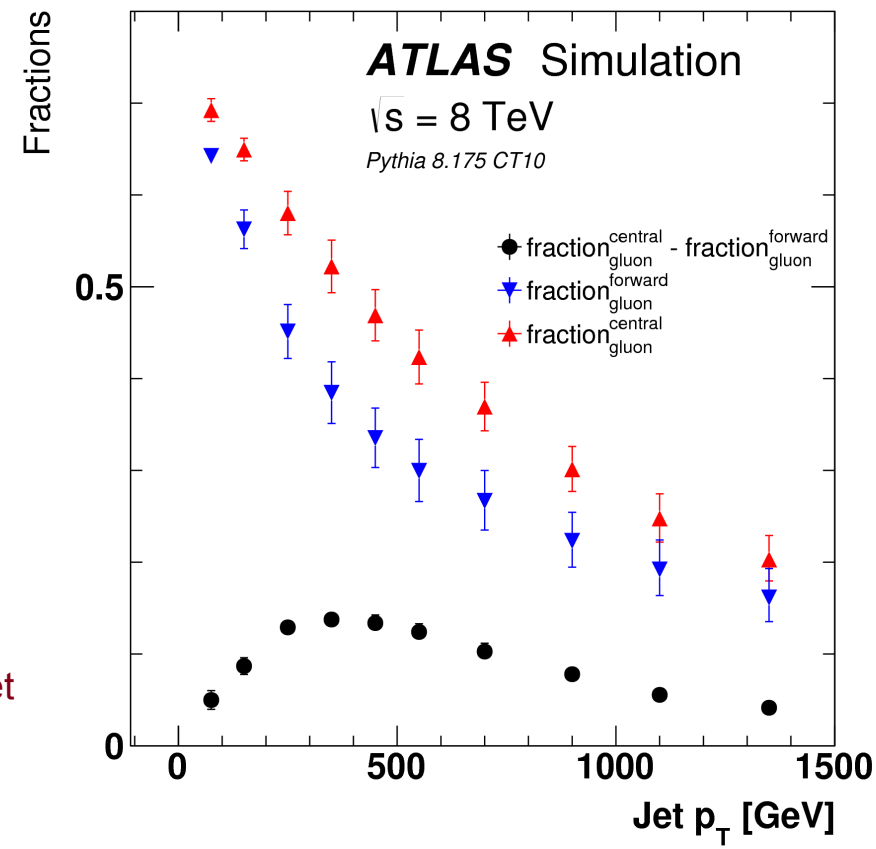
$n_{charged}$ for quark and gluon jets

$$\langle n^f_{\text{charged}} \rangle = f^f_q \langle n^q_{\text{charged}} \rangle + f^f_g \langle n^g_{\text{charged}} \rangle$$
$$\langle n^c_{\text{charged}} \rangle = f^c_q \langle n^q_{\text{charged}} \rangle + f^c_g \langle n^g_{\text{charged}} \rangle$$

Solving for $\langle n^q \rangle$, $\langle n^g \rangle$



Eur. Phys. J. C76(6), 1-23 (2016)



$n_{charged}$ for quark and gluon jets

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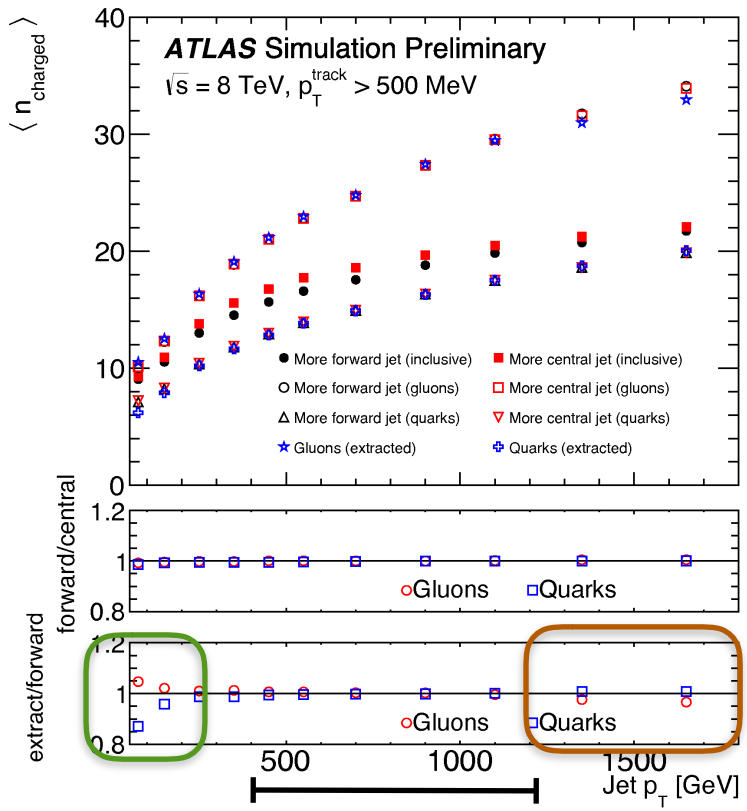
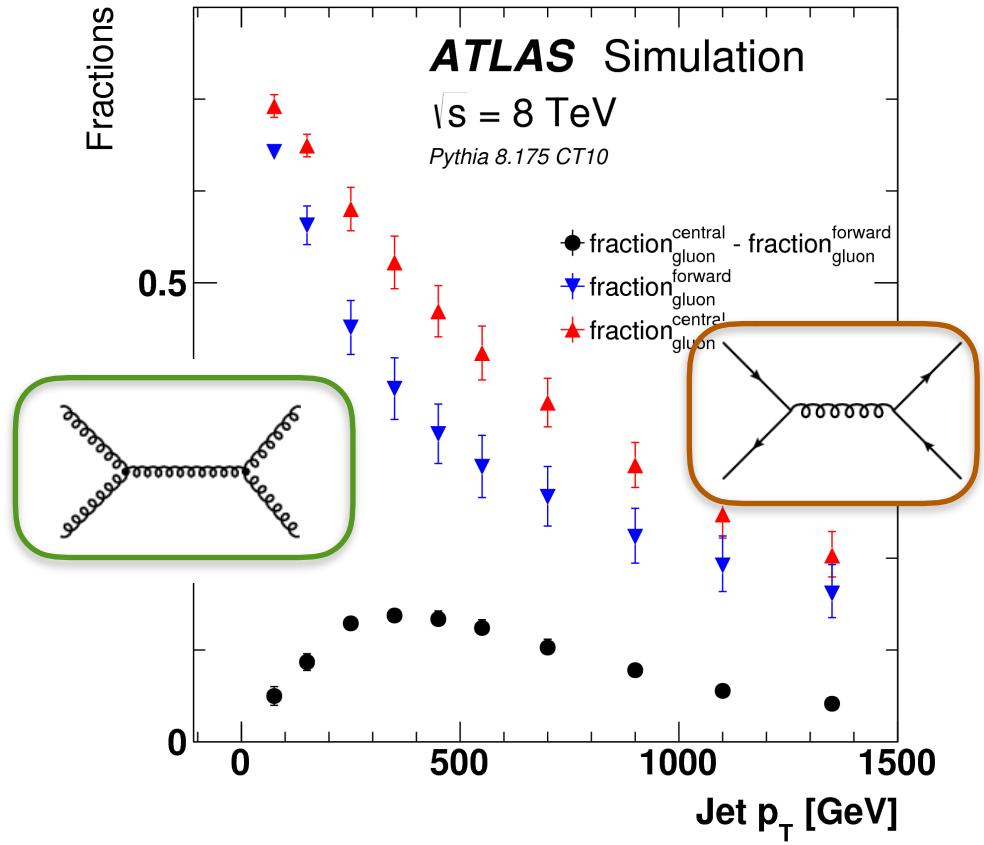


Excellent closure in wide kinematic range

Eur. Phys. J. C76(6), 1-23 (2016)

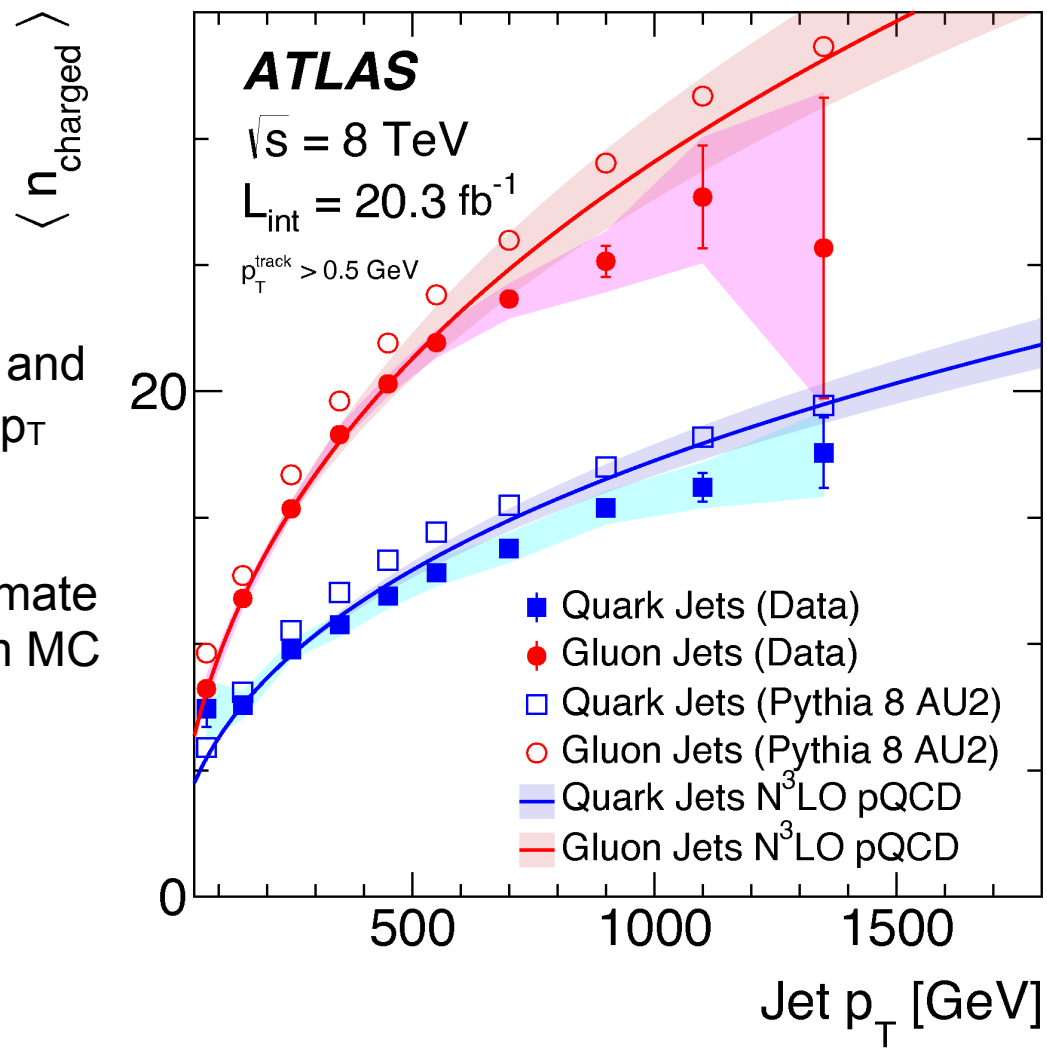


Contamination from **gg** and **qq** events at low and high p_T, respectively

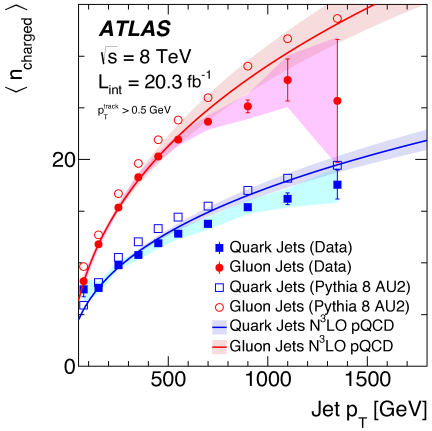
$n_{charged}$ for quark and gluon jets

Eur. Phys. J. C76(6), 1-23 (2016)

- Unfolded measurement of $\langle n_{charged} \rangle$ separately for quark and gluon jets as a function of jet p_T
- Uncertainties from
  - ME and PDF used to estimate quark/gluon fractions from MC
  - detector/physics objects (through unfolding)



From Run 1 measurement to Run 2 tagger



Use Run 1 measurement to assess modeling uncertainty

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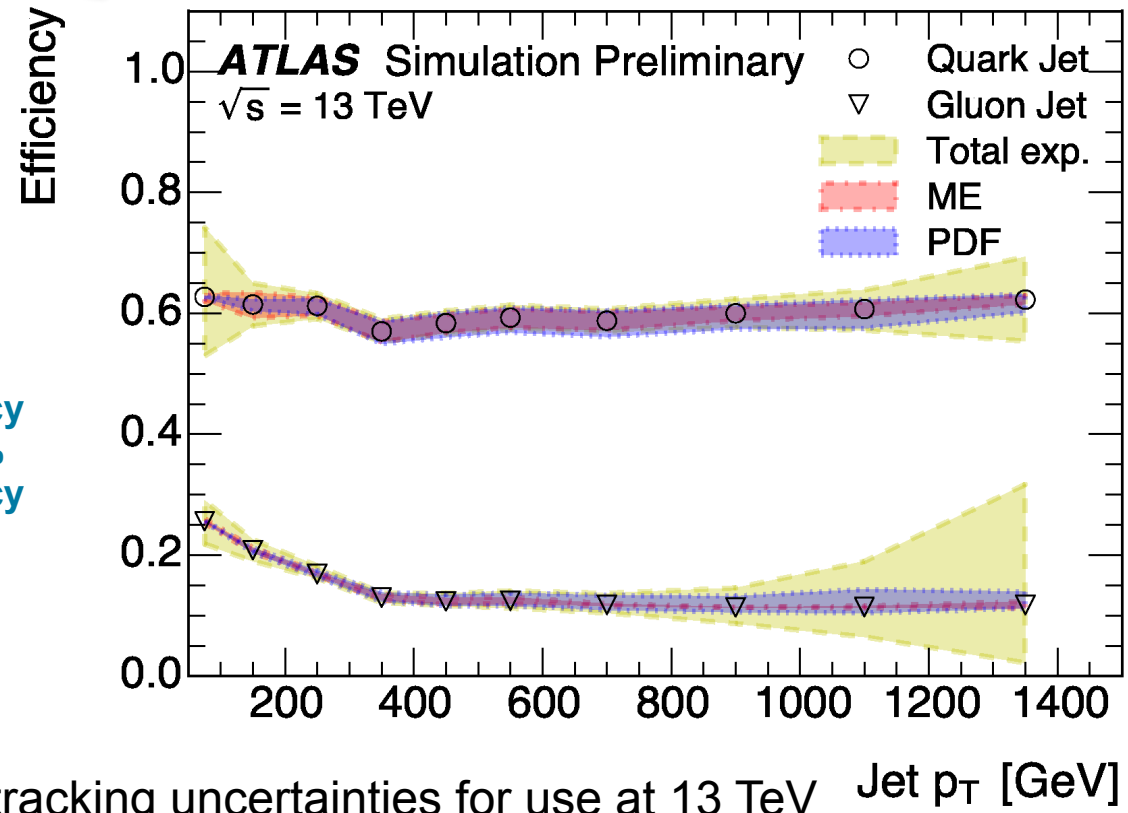

Uncertainties on quark and gluon efficiency @ ~fixed 60% quark efficiency

Add Run 2 experimental tracking uncertainties for use at 13 TeV

Overall uncertainties

- ~5% overall uncertainties across a wide range of p_T
- Precision limited by statistics and gg(qq) contamination at low and high p_T

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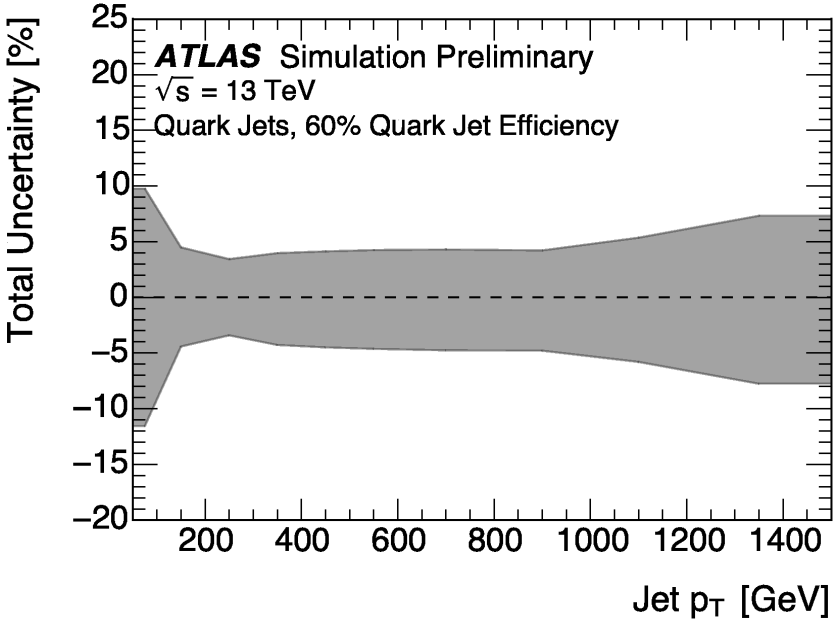
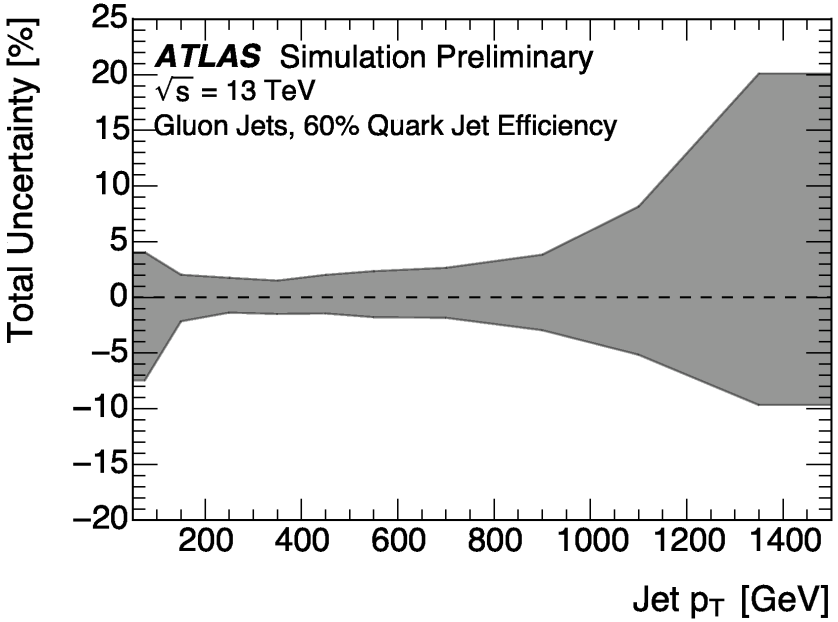




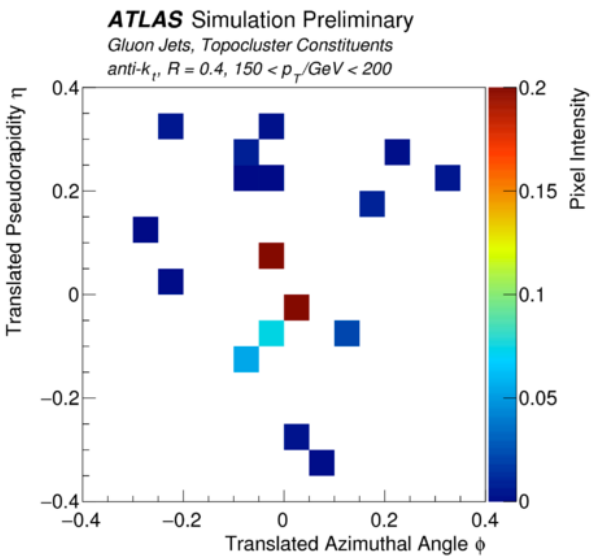
- Caveat: small(*) additional uncertainties for topologies other than dijet

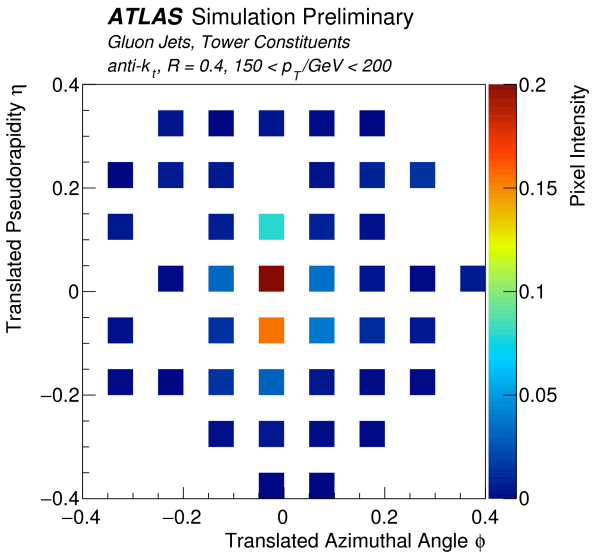
(*) to be assessed case-by-case with MC comparisons

First look quark/gluon tagging with ATLAS jet images

Jet images for q/g tagging

- Boost and rotate jets so that η,ϕ = 0,0
- Different types of constituents:
  - truth-particles
  - charged particle tracks
  - topological calorimeter clusters
  - calorimeter towers
- Build 16x16 pixel image so that the intensity (I) of a pixel is the sum of the p_T of the constituents within the pixel
- Normalize each image so that Σ_{pixels} I = 1





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The CNN tagger

ATLAS Simulation Preliminary

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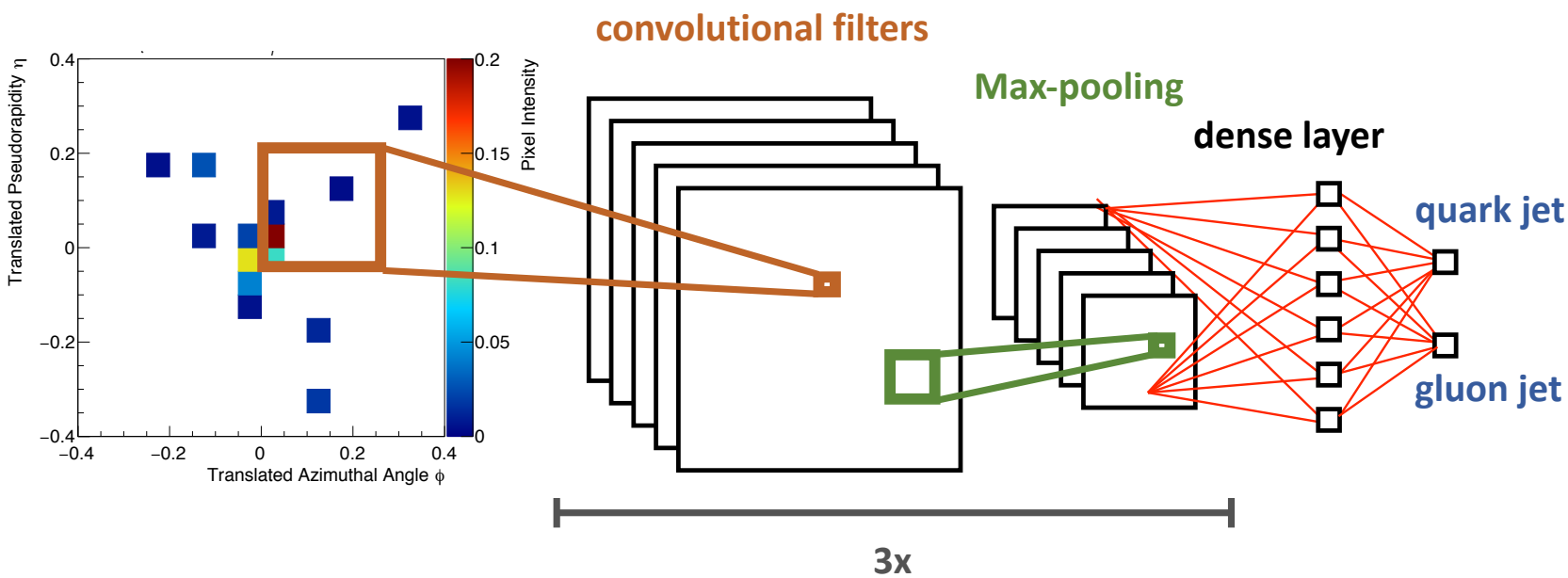

- Convolutional neural network (CNN) learns non-linear representations of the input image with the goal of discriminating between quark and gluon jet images.

- Similar network architecture as in Komiske et al., hep-ph/1612.01551

Input for jet images

- Comparison of CNN tagger performance with different input images (network retrained for each input type)

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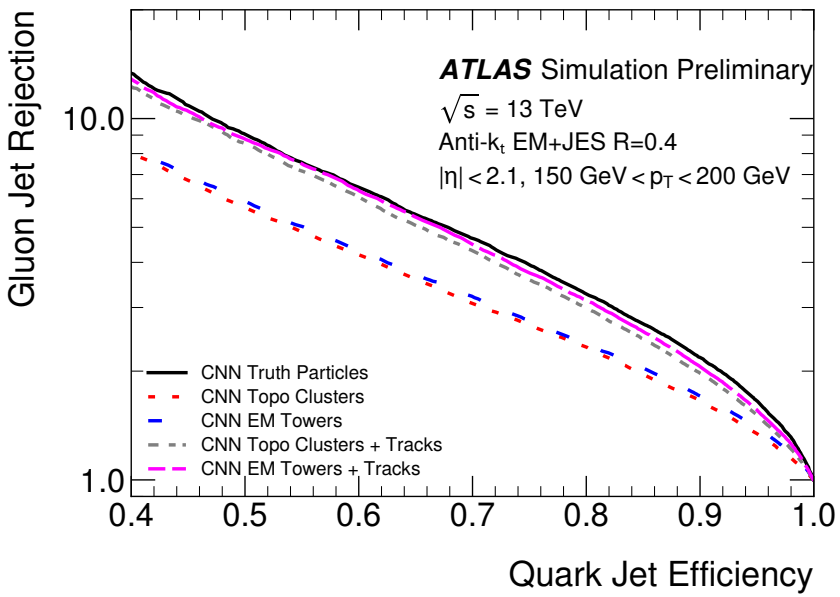

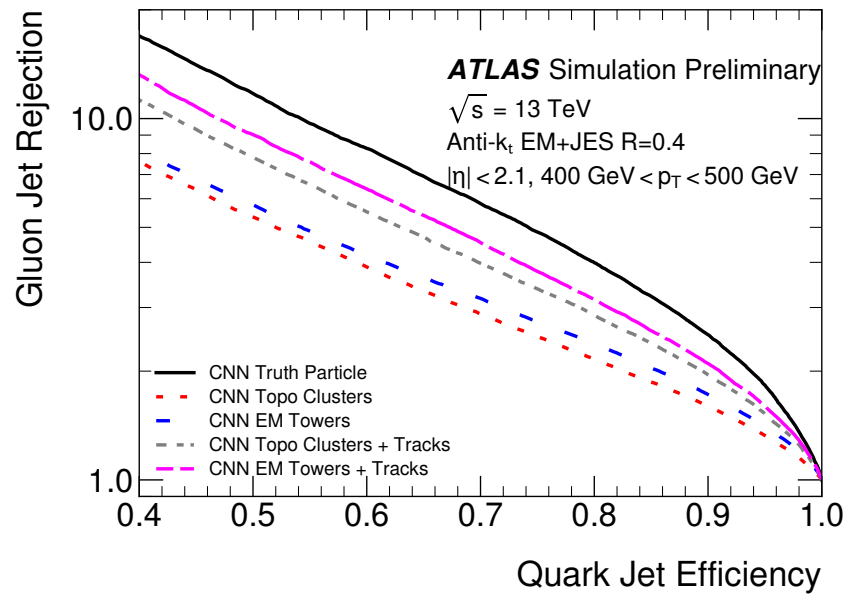

Low p_T:
- Calo+tracks tagger performs as well as truth-particle one.

High p_T:
- Gap wrt truth-particle image.
- Some differences from treatment of calo information (towers vs clusters).

CNN tagger vs high-level observables

- Comparison of CNN tagger performance wrt single observables (n_{track}, jet width) and their combination (likelihood ratio).

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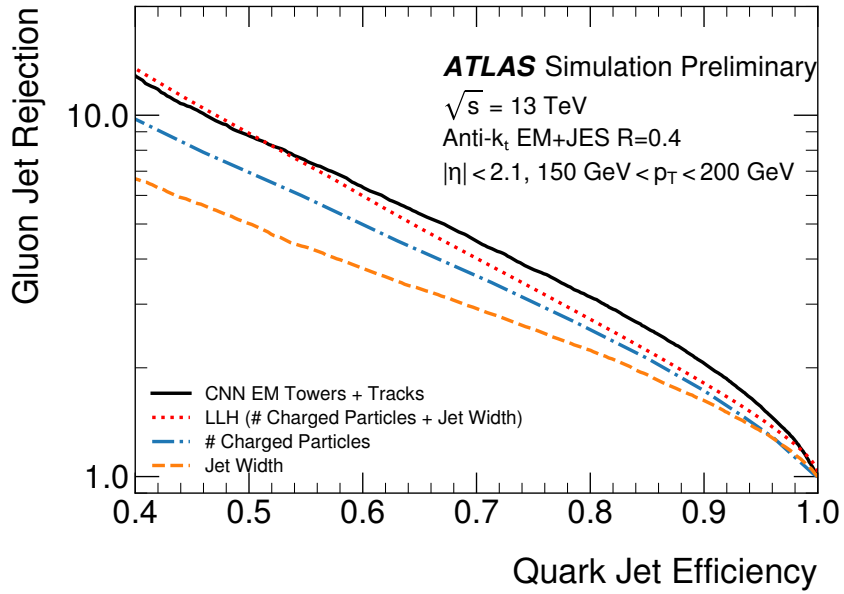

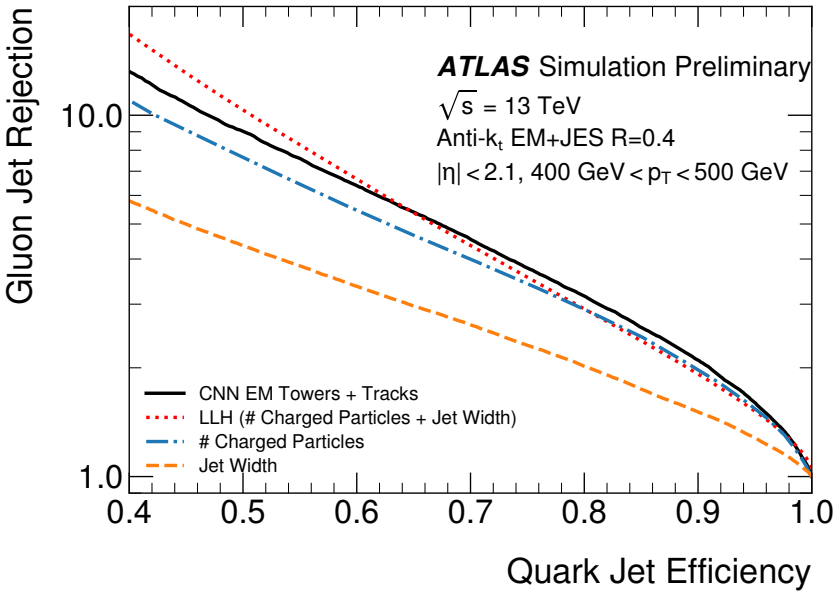

CNN tagger performs at least as well as n_{track}+width

At high p_T, CNN tagger performs better/worse than n_{track}+width depending on quark efficiency working point

MC generators

- Comparison of CNN tagger performance vs fragmentation modeling

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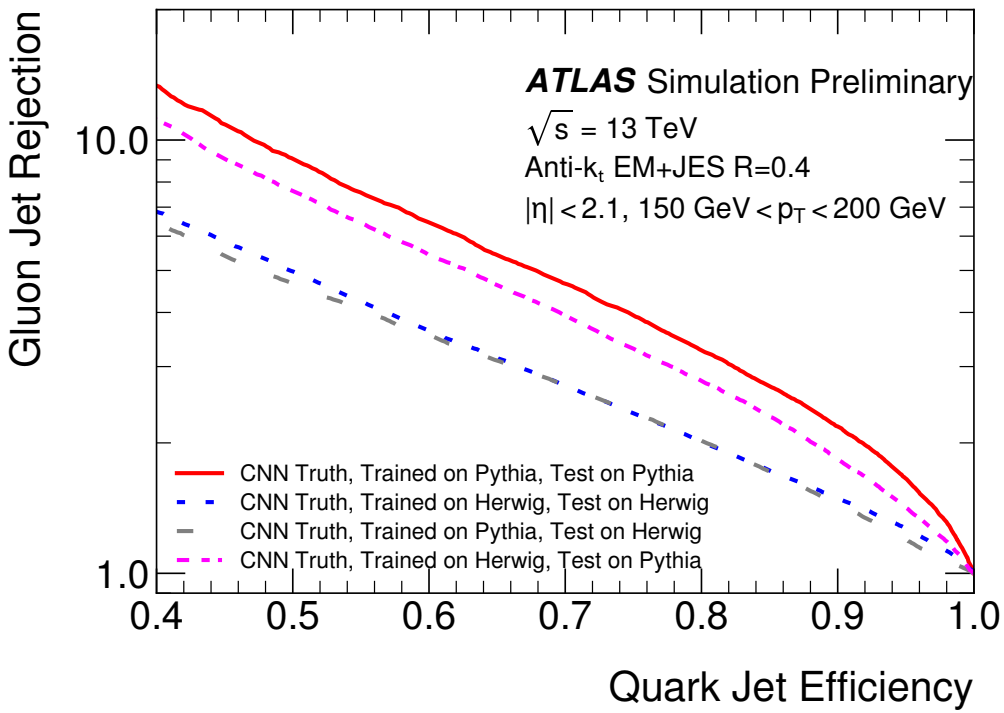
- Similar performance when comparing Sherpa and Pythia (for either training or testing)
- Moderate difference in performance between taggers trained on **Pythia** vs **Herwig** and tested on Pythia
- Large difference in performance when testing on **Pythia** vs **Herwig** (irrespective of training)



- Difference in fragmentation modeling plays a role, but features learned by network only partially sensitive to it.

Summary and outlook

- Established **strategy for calibrating** and deriving uncertainties for **q/g tagging** observables using dijet events
- **~5%** uncertainties for tagger based on **charged particle multiplicity**
- Begun exploration of q/g tagging using **jet images** and **convolutional neural networks**
  - Next steps: understand differences between input objects and what is learnt (e.g. compared with high-level observables).

References

- Measurement of the charged-particle multiplicity inside jets from sqrt(s) = 8 TeV pp collisions with the ATLAS detector
  Eur. Phys. J. C76(6), 1-23 (2016)
- Quark versus Gluon Jet Tagging Using Charged Particle Multiplicity with the ATLAS Detector
  ATL-PHYS-PUB-2017-009
- Quark versus Gluon Jet Tagging Using Jet Images with the ATLAS Detector
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Additional slides

n_{track} - Run 2 tunes

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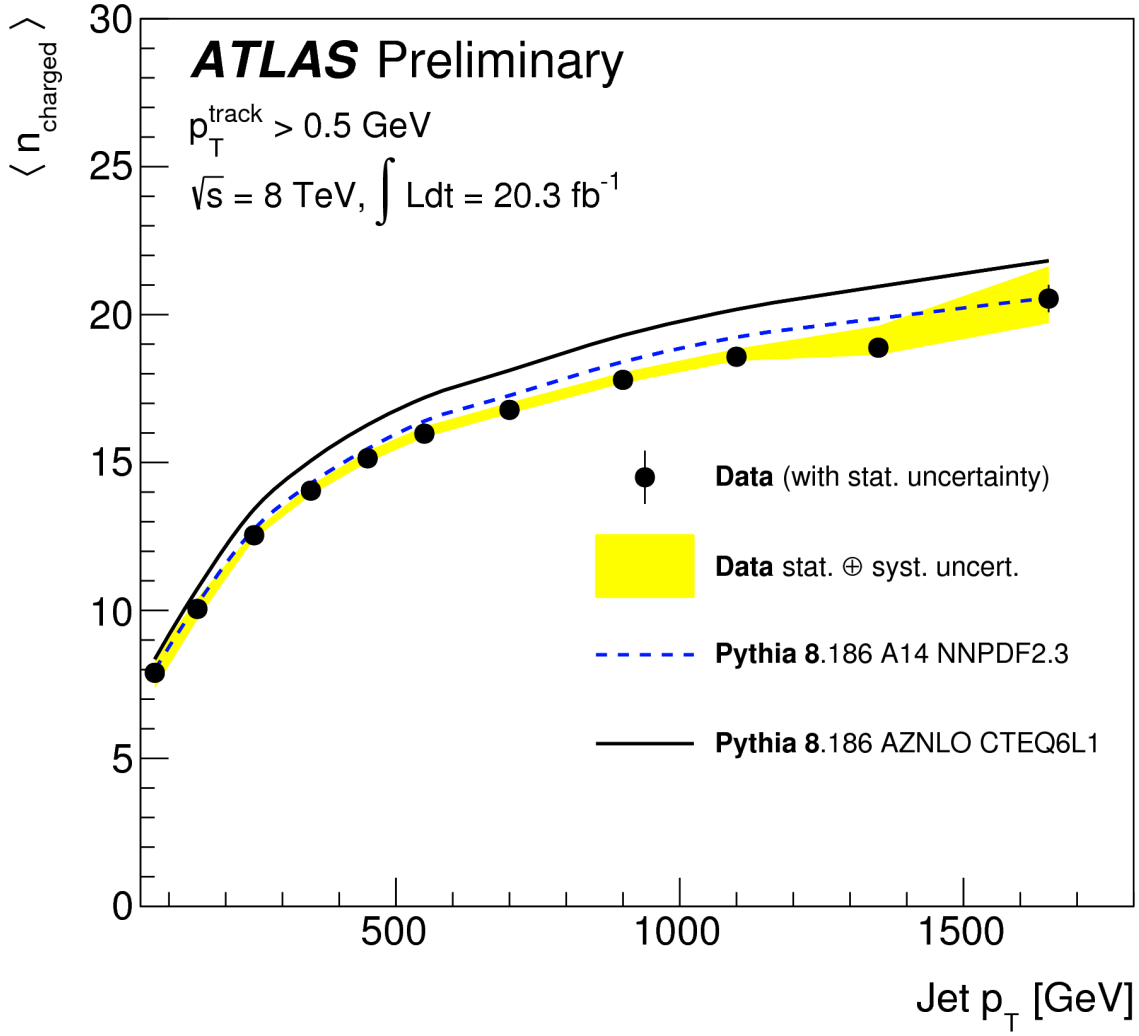

n_{track} - uncertainties

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Gluon $\langle n_{\text{charged}} \rangle$	Jet p_T Range [100 GeV]									
Systematic uncertainty	[0.5,1]	[1,2]	[2,3]	[3,4]	[4,5]	[5,6]	[6,8]	[8,10]	[10,12]	[12,15]
Total exp.	$^{+0.44}_{-0.34}$	$^{+0.29}_{-0.24}$	$^{+0.15}_{-0.24}$	$^{+0.24}_{-0.17}$	$^{+0.21}_{-0.33}$	$^{+0.37}_{-0.43}$	$^{+0.48}_{-0.58}$	$^{+1.01}_{-1.03}$	$^{+2.20}_{-2.39}$	$^{+6.09}_{-6.16}$
ME	0.04	0.06	0.05	0.12	0.14	0.16	0.06	0.01	0.05	0.22
PDF	$^{+0.01}_{-0.01}$	$^{+0.06}_{-0.05}$	$^{+0.11}_{-0.10}$	$^{+0.18}_{-0.19}$	$^{+0.22}_{-0.27}$	$^{+0.25}_{-0.34}$	$^{+0.30}_{-0.48}$	$^{+0.30}_{-0.60}$	$^{+0.41}_{-1.01}$	$^{+0.23}_{-0.81}$
PDF comparison	0.03	0.09	0.00	0.04	0.01	0.10	0.33	0.84	1.76	1.69
Half cone	0.01	0.03	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.01
HS Label	0.06	0.03	0.04	0.05	0.04	0.03	0.01	0.01	0.04	0.05

Quark $\langle n_{\text{charged}} \rangle$	Jet p_T Range [100 GeV]									
Systematic uncertainty	[0.5,1]	[1,2]	[2,3]	[3,4]	[4,5]	[5,6]	[6,8]	[8,10]	[10,12]	[12,15]
Total exp.	$^{+0.82}_{-1.16}$	$^{+0.36}_{-0.41}$	$^{+0.26}_{-0.28}$	$^{+0.22}_{-0.30}$	$^{+0.25}_{-0.32}$	$^{+0.30}_{-0.35}$	$^{+0.32}_{-0.36}$	$^{+0.41}_{-0.47}$	$^{+0.69}_{-0.67}$	$^{+1.42}_{-1.70}$
ME	0.06	0.23	0.19	0.23	0.22	0.25	0.26	0.22	0.23	0.16
PDF	$^{+0.02}_{-0.02}$	$^{+0.11}_{-0.10}$	$^{+0.17}_{-0.16}$	$^{+0.27}_{-0.24}$	$^{+0.33}_{-0.27}$	$^{+0.38}_{-0.28}$	$^{+0.44}_{-0.30}$	$^{+0.47}_{-0.28}$	$^{+0.62}_{-0.33}$	$^{+0.45}_{-0.21}$
PDF comparison	0.04	0.01	0.17	0.23	0.17	0.10	0.01	0.21	0.44	0.39
Half cone	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00
HS Label	0.07	0.03	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02

n_{track} - uncertainties

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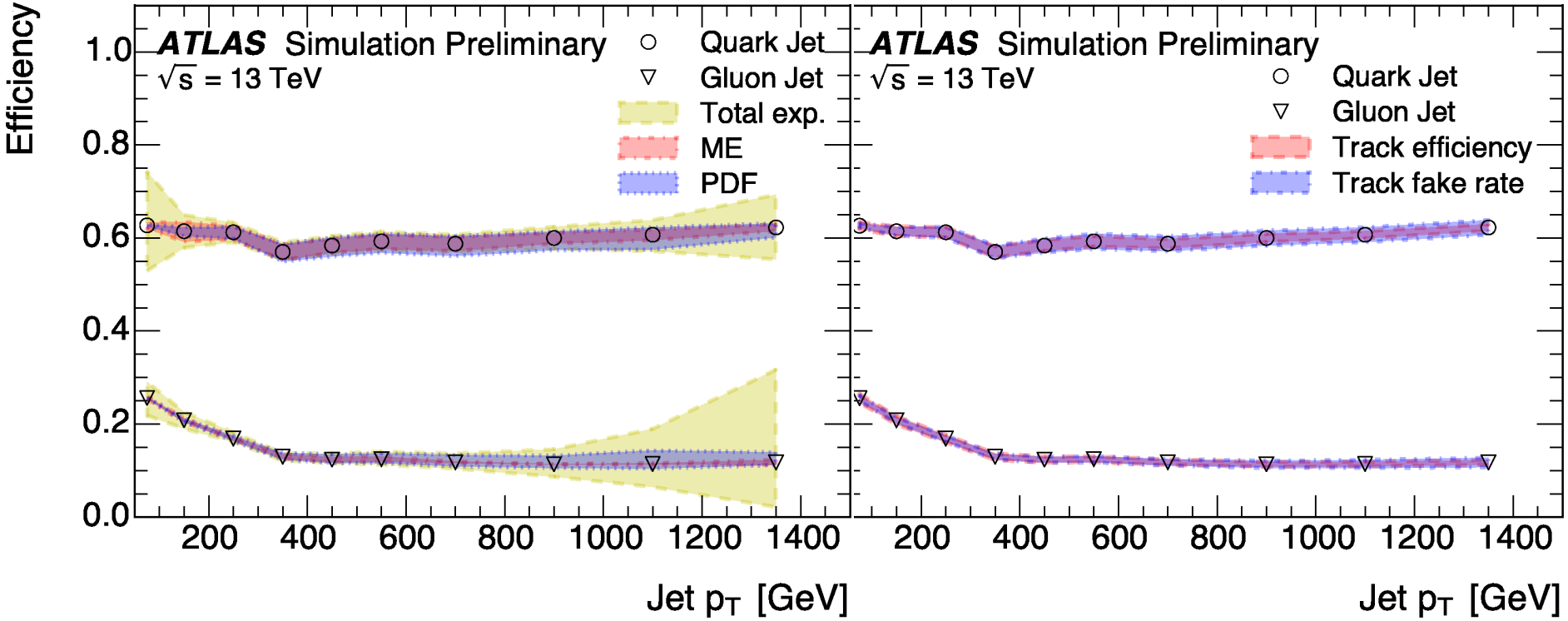

CNN - track-truth and η range

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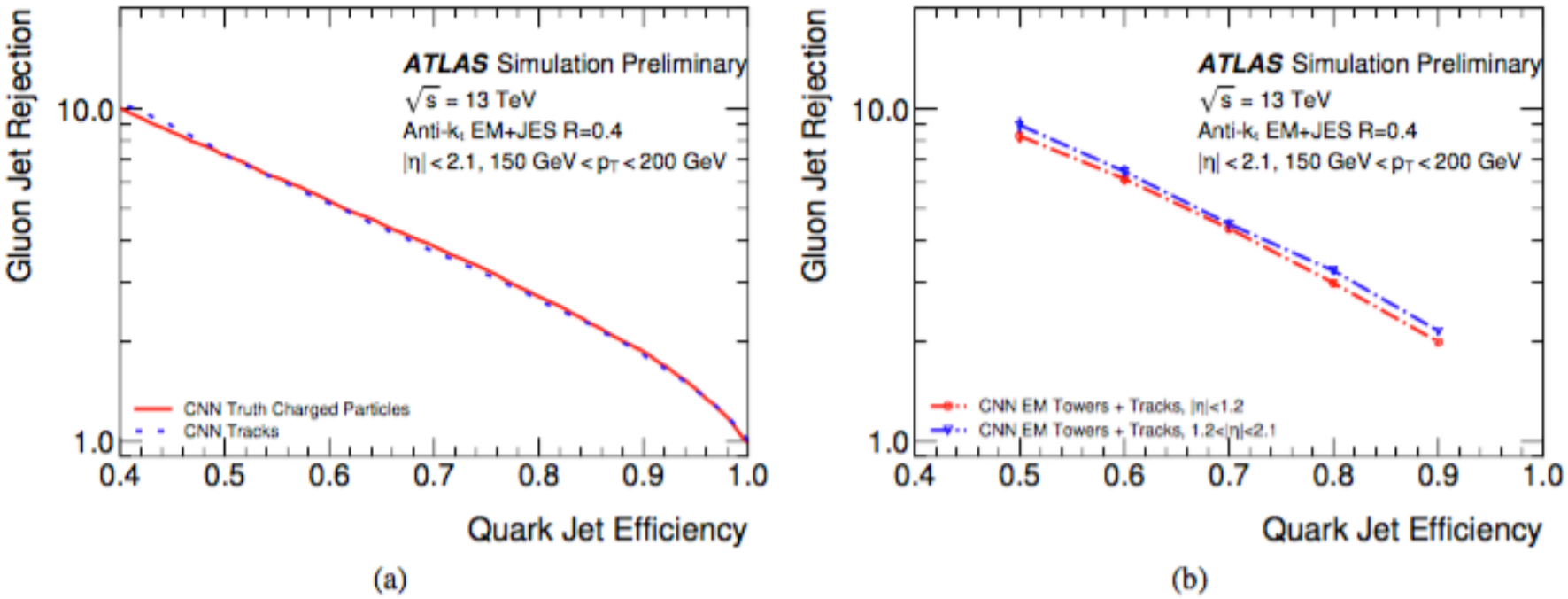

Figure 7: Gluon jet rejection as a function of the quark jet efficiency using the CNN tagger for jets with $150 < p_T < 200$ GeV. (a) Comparison between using track images and truth charge particle images as input. (b) Comparison between different $|\eta|$ ranges. The full $|\eta|$ range ($|\eta| < 2.1$) is used for training.

CNN - pileup

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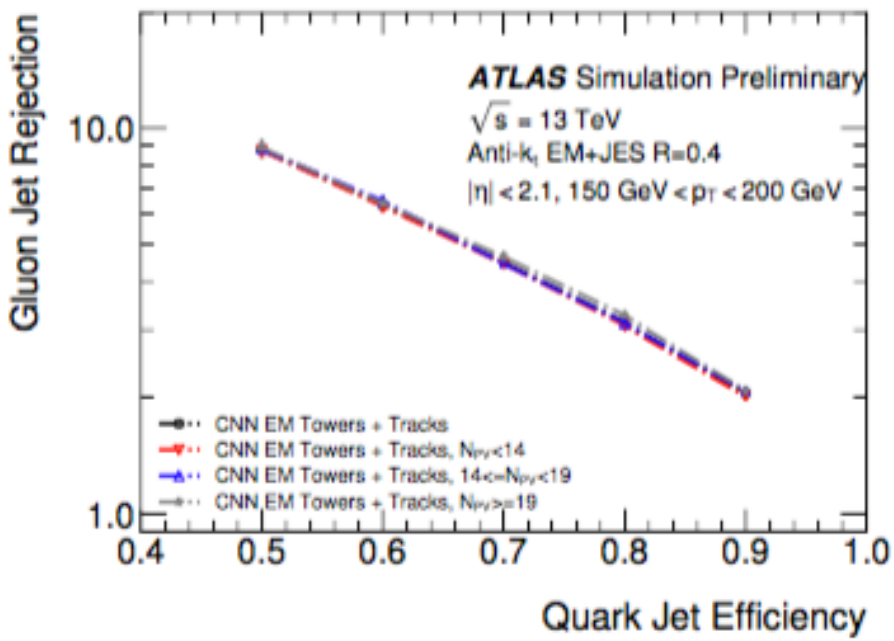

Figure 8: Gluon jet rejection as a function of the quark jet efficiency evaluated at different pileup conditions, quantified by the number of reconstructed primary vertices (N_{PV}).

CNN - fragmentation modeling

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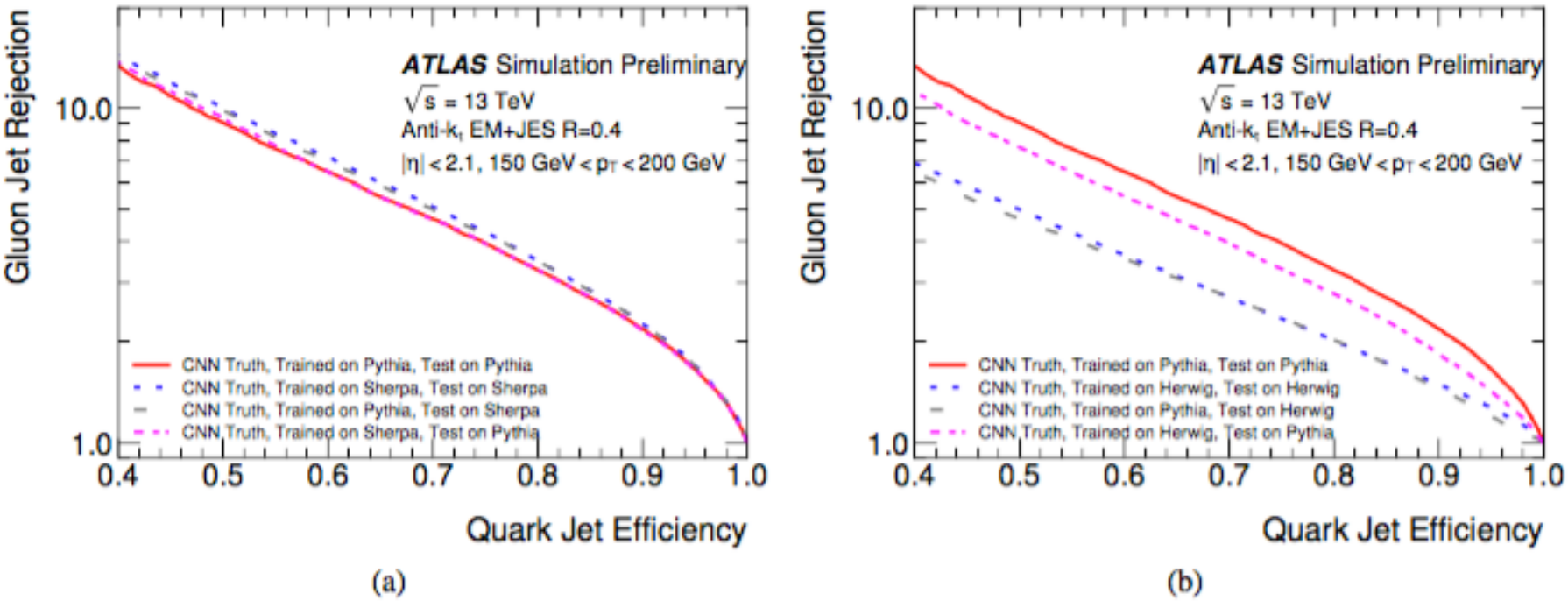
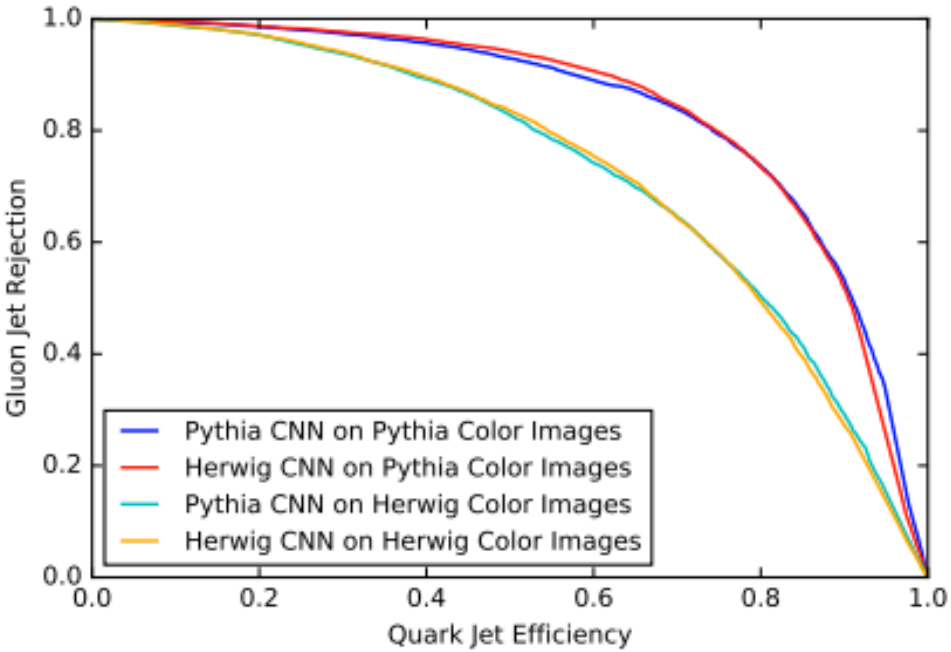


Figure 11: Gluon jet rejection as a function of the quark jet efficiency comparing PYTHIA to (a) SHERPA and (b) HERWIG for jets with $150 < p_T < 200$ GeV.

CNN - fragmentation modeling

Komiske, Metodiev, Schwartz - JHEP 01 (2017) 110



Pythia with Monash tune

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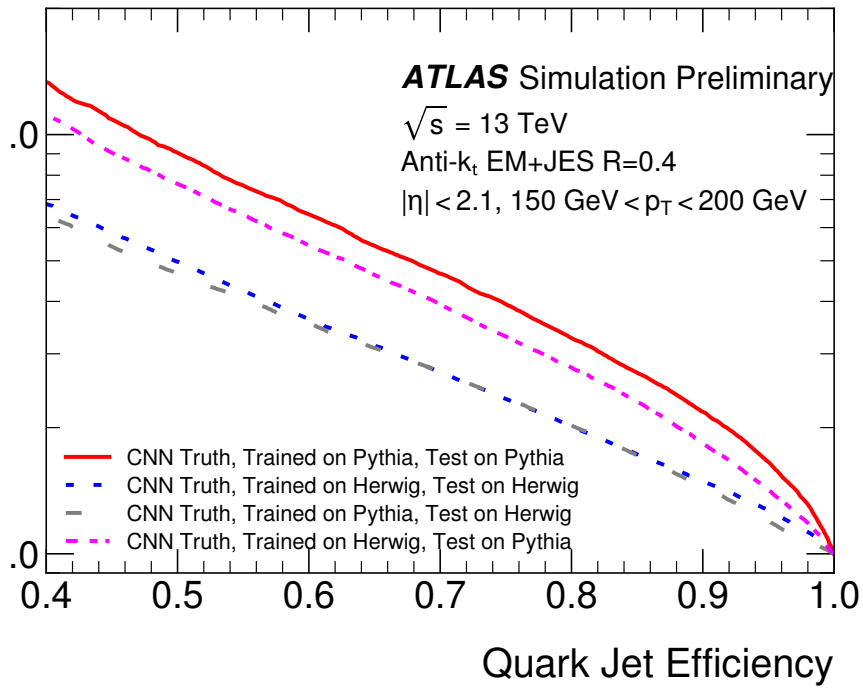

Pythia with A14 tune

CNN - average convolution differences

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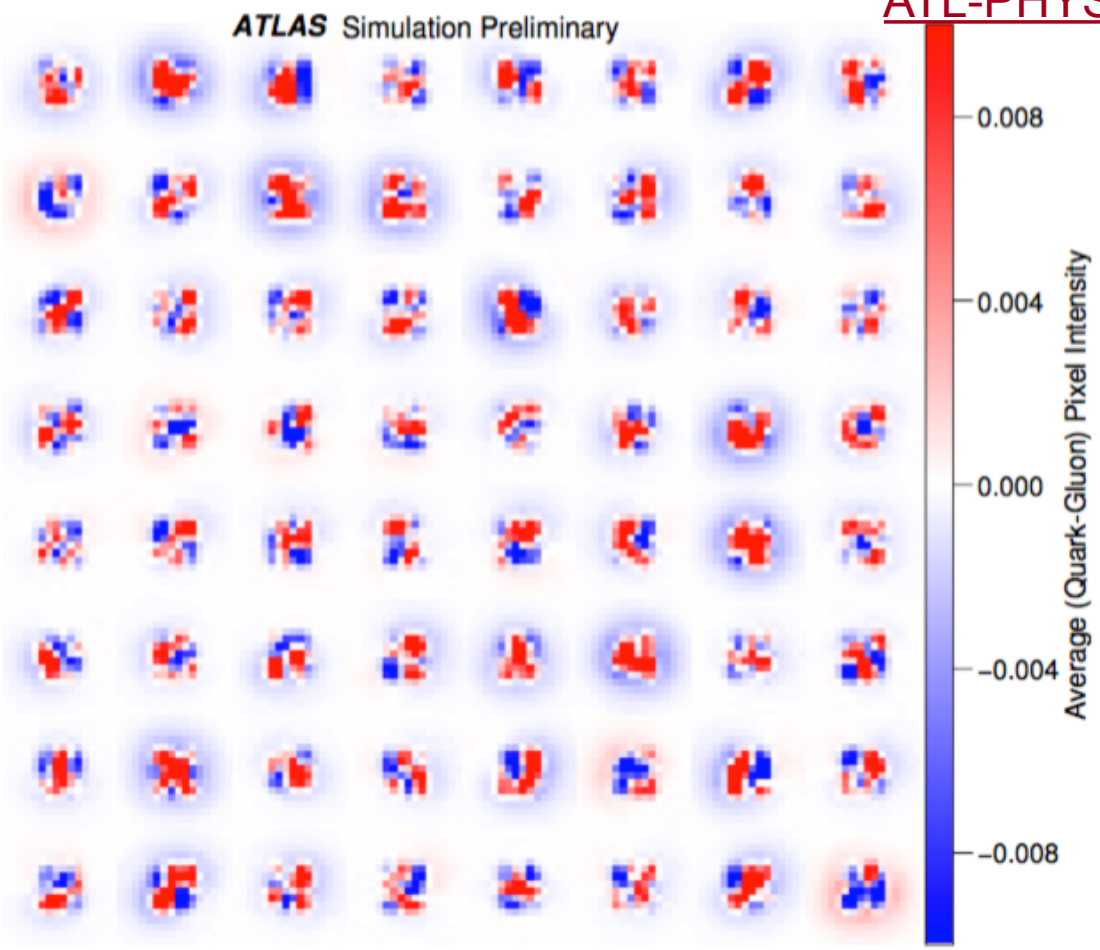

(a)

Figure 13: Average convolved filter differences for jet images (same color scheme as left plot; red is more quark-like). The filters of the first convolutional layer are considered.

CNN - correlation

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