Novel approach to measure quark/gluon jets at the LHC

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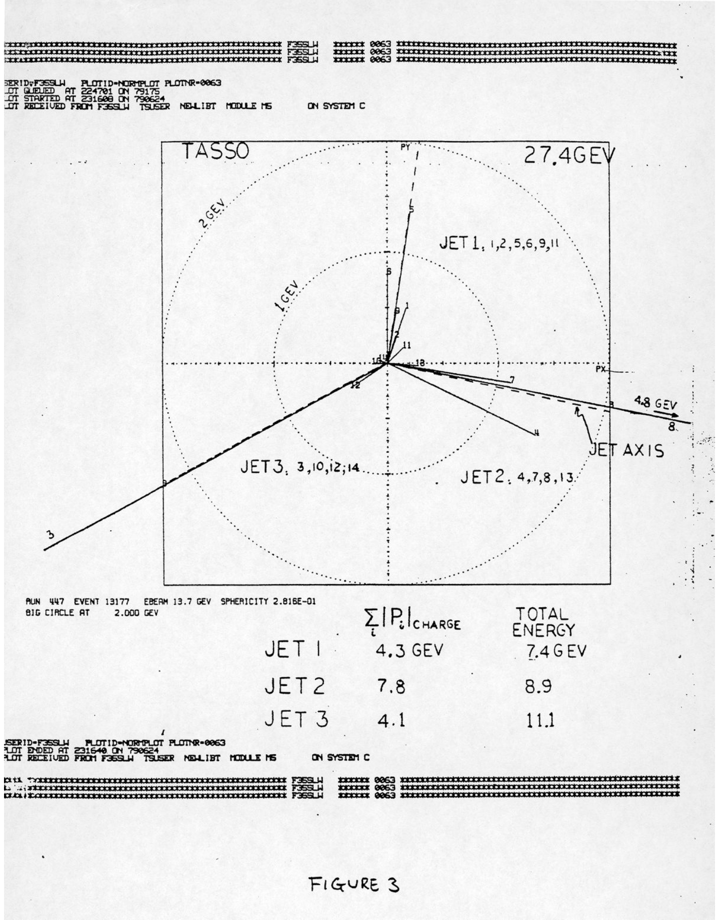
4.9.2023

Outline:

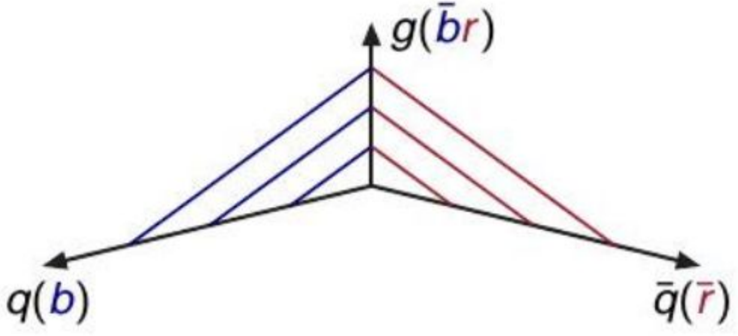
1. Introduction and Motivation
2. Theory
3. Results
4. Conclusion

Back-up



This collision event recorded in **1979**, provided the first evidence of the gluon.

Recorded as event 13177 of run 447 of the TASSO experiment at the Deutsches Elektronen-Synchrotron (DESY), the graphic shows three jets of particles produced in an electron-positron collision.



Introduction and Motivation:

Quark - Gluon Separation in Three Jet Events #1

Hans Peter Nilles (SLAC), K.H. Streng (SLAC) (Aug 1, 1980)

Published in: *Phys.Rev.D* 23 (1981) 1944

pdf links DOI cite 32 citations

A Monte Carlo Program for Quark and Gluon Jet Generation #2

Torbjorn Sjostrand (Lund U., Dept. Theor. Phys.) (Apr 1, 1980)

pdf cite 1 citation

Quark and gluon jet separation: Conventional and neural network methods #2

Z. Fodor (Eotvos U.) (Jul, 1991)

Published in: *Conf.Proc.C* 910725V1 (1991) 438 • Contribution to: Joint International Lepton Photon Symposium at High Energies (15th) and European Physical Society Conference on High-energy Physics, 438

⋮

Quark versus Gluon Jet Tagging Using Charged Particle Multiplicity with the ATLAS Detector #7

ATLAS Collaboration (Apr 11, 2017)

BSM searches: often signature for a BSM signals: many quark, backgrounds: QCD gluons

- 8-jet Gluino event: $pp \to \tilde{g}\tilde{g}$ and each $\tilde{g}$ decays to 4 quarks:

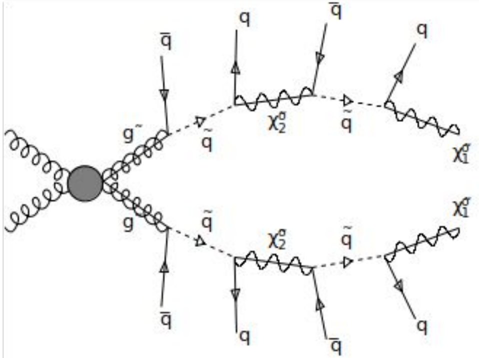


Fig. From J. Gallicchio and M. D. Schwartz, Phys. Rev. Lett.107 (2011)

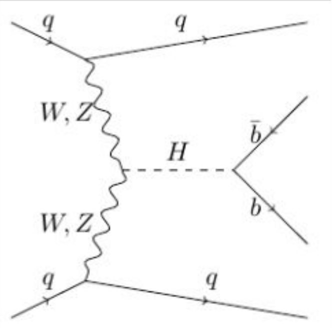
- Higgs $H^+ \to c\bar{s}$ (for charged Higgs mass between τ and t mass)
- Measure Z' coupling to hadrons (or find a leptophobic Z'/W')

Interesting standard model physics also tends to be quark-heavy

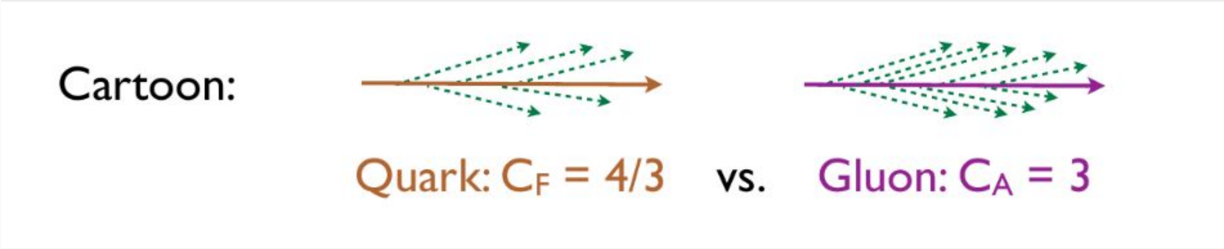
Examples:

- W's decaying hadronically (no b's!): $W^+ \to u\bar{d}$ or $c\bar{s}$
- Tops ($t\bar{t} \to b\bar{b} \quad + \quad 0$, 2, or 4 light quarks)
- Vector Boson Scattering/Fusion (forward 'tag' jets are quarks)

QCD background: mainly composed by gluons
Signal: mainly composed by quarks



Gluon has a greater effective color charge (squared) than quark:



Expectation:

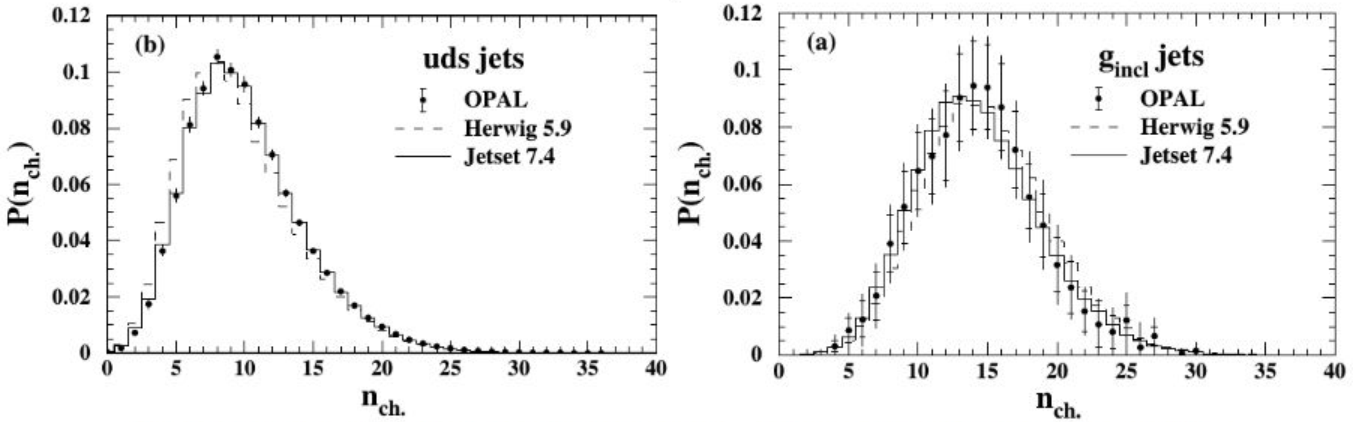
- Gluon will radiate more
- Gluon will radiate wider
- Multiple radiation → effect will exponentiate

Introduction and Motivation:

Cartoon:

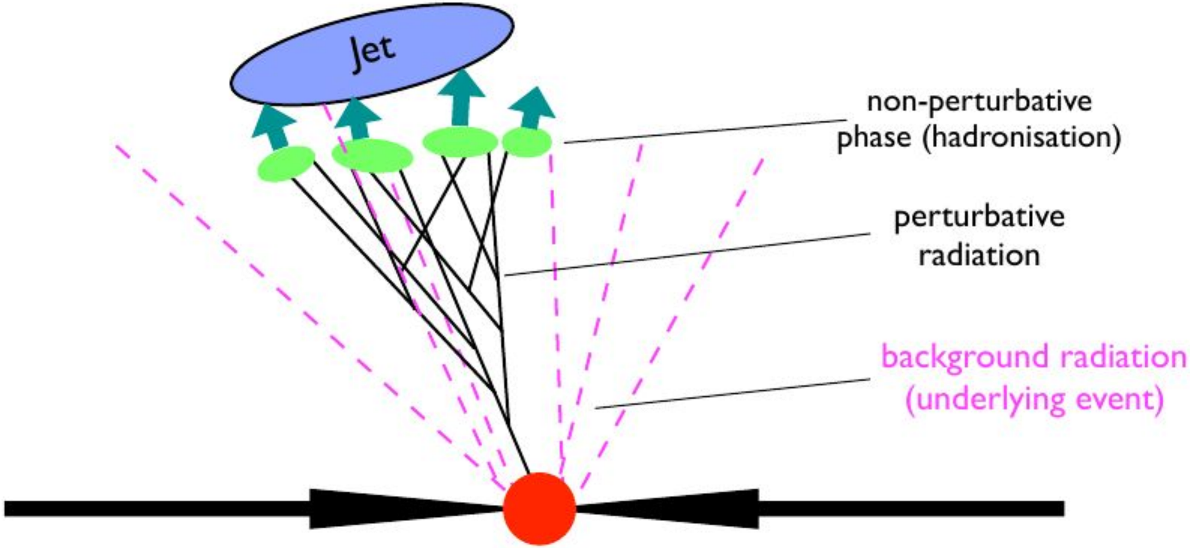
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Gluon will radiate more, gluon will radiate wider $\dfrac{\langle N_g \rangle}{\langle N_q \rangle} = \dfrac{C_A}{C_F}$



"Multiplicity distributions of gluon and quark jets and tests of QCD analytic predictions"
[hep-ex/9708029]

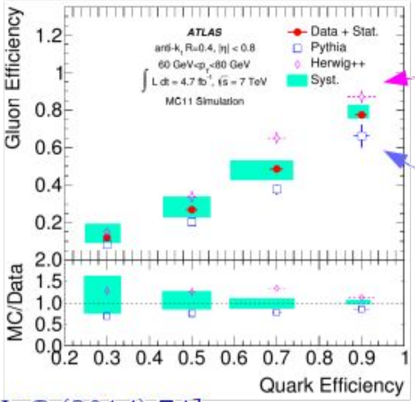
Introduction and Motivation:



- hadronisation: $-\Lambda / R$
- MPI: $+\Lambda * R^2$

Introduction and Motivation:

Efficiency is simply the ratio of the number of jets selected by a discriminant over the total number in the sample.



[ATLAS, Eur. Phys. J. C (2014) 74]

Herwig++ is too pessimistic, Quark and gluon jets looks more the same than in the data.

Pythia is too optimistic, Quark and Gluon jets are too different compared to data.

Conclusion:

"A detailed study of the jet properties reveals that quark-and gluon-jets look more similar to each other in the data than in the Pythia 6 simulation and less similar than in the Herwig++ simulation."

Problem: Q/G jets LHC data show discrepancy with the predictions from MC generators

[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, AS, Skands, Soyez, Thaler, JHEP 1707 (2017) 091]

Cartoon:

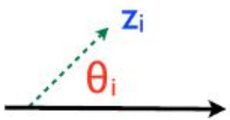
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Probe radiation pattern with e.g. Generalized Angularities

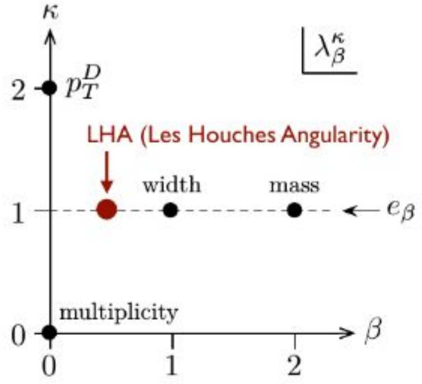
$$\lambda_\beta^\kappa = \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction

angle to recoil-free axis



$(\lambda_\beta^\kappa)_{\text{quark}} < (\lambda_\beta^\kappa)_{\text{gluon}}$



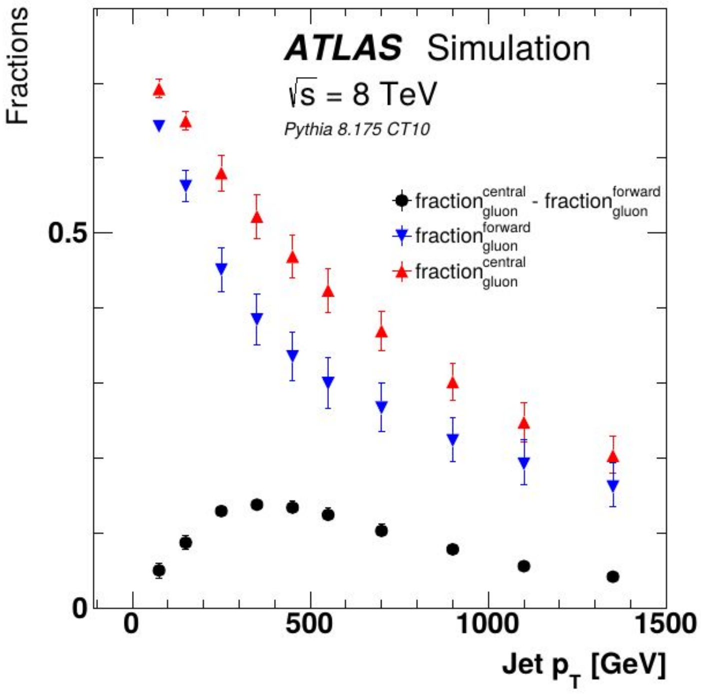
[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

Introduction and Motivation:

Quark versus Gluon Jet Tagging Using Charged Particle Multiplicity with the ATLAS Detector

ATLAS Collaboration (Apr 11, 2017)

#7

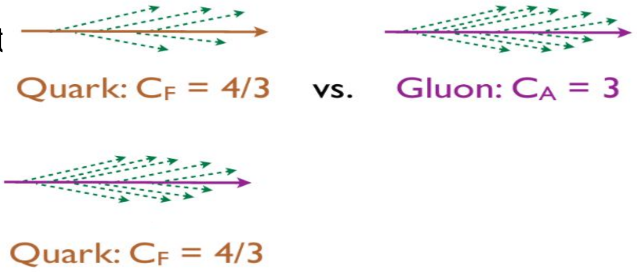


Using phase space cuts, for example:

- Pt - jet transverse momentum
- η - jet rapidity (central/forward)

But then we will have quark and gluon sample jets with different (Pt, η).

Same Pt



But hight Pt Q will radiate more and look like a G

Can we find a way to get enhanced Q/G with the same Pt, η?

2. Theory

Can we find a way to get enhanced Q/G with the same Pt, η?

[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, AS, Skands, Soyez, Thaler, JHEP 1707 (2017) 091]

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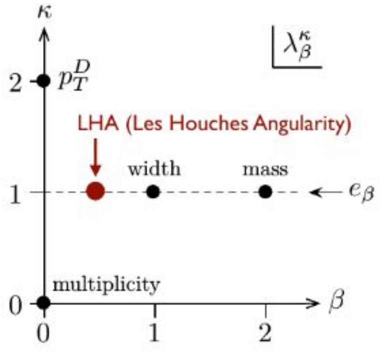
$$(\lambda^\kappa_\beta)_{\text{quark}} < (\lambda^\kappa_\beta)_{\text{gluon}}$$



[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

Can we find a way to get enhanced Q/G with the same Pt, η?

Theory:

Each angularitity λ is composed of gluon λ_g and quark λ_q angularities

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$$\lambda = f\,\lambda_g + (1-f)\lambda_q$$

Each angularitity λ is composed of gluon λ_g and quark λ_q angularities

$$\lambda = f\,\lambda_g + (1-f)\lambda_q$$

f ... gluon fraction
$(1-f)$ ... quark fraction

Can we reverse the equation

$$\lambda = f\,\lambda_g + (1-f)\lambda_q$$

and obtain

$$\lambda_g = ?$$

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$$\lambda = f\,\lambda_g + (1\text{-}f)\lambda_q$$

and obtain

$$\lambda_g = ?$$

No, it is still function of unknown λ_q :

$$\lambda_g = \lambda_g\,(\lambda_q\,)$$

Can we reverse the equation

$$\lambda = f\,\lambda_g + (1-f)\lambda_q$$

and obtain

$$\lambda_g = ?$$

No, it is still function of unknown λ_q :

$$\lambda_g = \lambda_g\,(\lambda_q\,)$$

But, here comes the idea of measurement at different energies.

Can we find a way to get enhanced Q/G with the same Pt, η?

Let's write equations for measurement at energy 900 GeV and 13 000 GeV

Yes, we can:-)

Can we find a way to get enhanced Q/G with the same Pt, η?

Yes, we can:-)

Let's write equations for measurement at energy 900 GeV and 13 000 GeV

$$\lambda^{900} = f^{900}\lambda_g + (1 - f^{900})\lambda_q$$

$$\lambda^{13000} = f^{13000}\lambda_g + (1 - f^{13000})\lambda_q$$

Theory:

Can we find a way to get enhanced Q/G with the same Pt, η?

Yes, we can:-)

Let's write equations for measurement at energy 900 GeV and 13 000 GeV

$$\lambda^{900} = f^{900}\lambda_g + (1 - f^{900})\lambda_q$$
$$\lambda^{13000} = f^{13000}\lambda_g + (1 - f^{13000})\lambda_q$$

One can reverse:

$$\lambda_g = \frac{(1 - f^{13000})\lambda^{900} - (1 - f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$$

$$\lambda_q = \frac{f^{900}\lambda^{13000} - f^{13000}\lambda^{900}}{f^{900} - f^{13000}}$$

Assuming λ_g and λ_q are energy independent.

Theory:

Can we find a way to get enhanced Q/G with the same Pt, η?

Yes, we can:-)

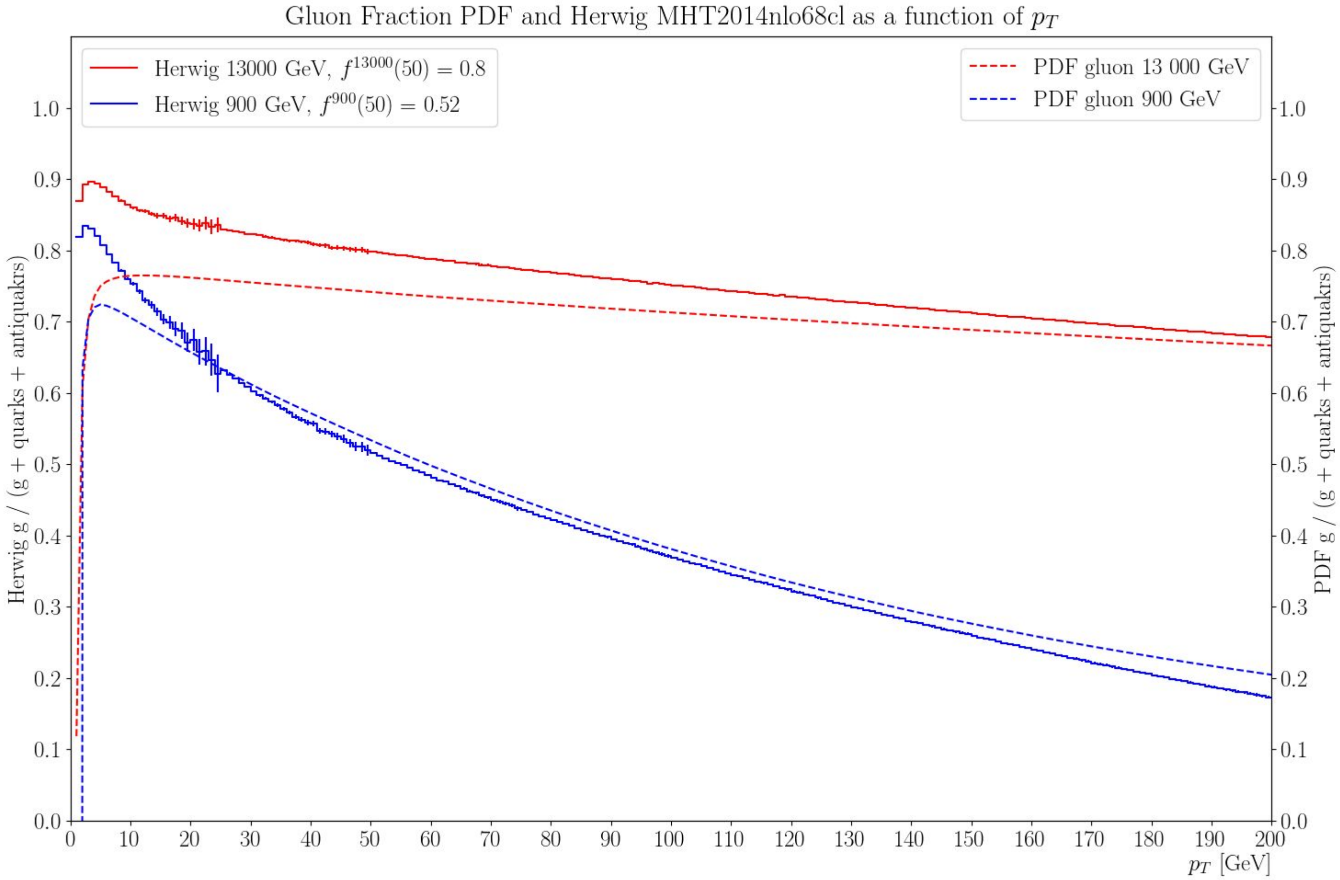
$$\lambda_g = \frac{(1 - f^{13000})\lambda^{900} - (1 - f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$$

$$\lambda_q = \frac{f^{900}\lambda^{13000} - f^{13000}\lambda^{900}}{f^{900} - f^{13000}}$$

λ^{900}, λ^{13000} ... measurement (same cuts, average p_T > 50 GeV)

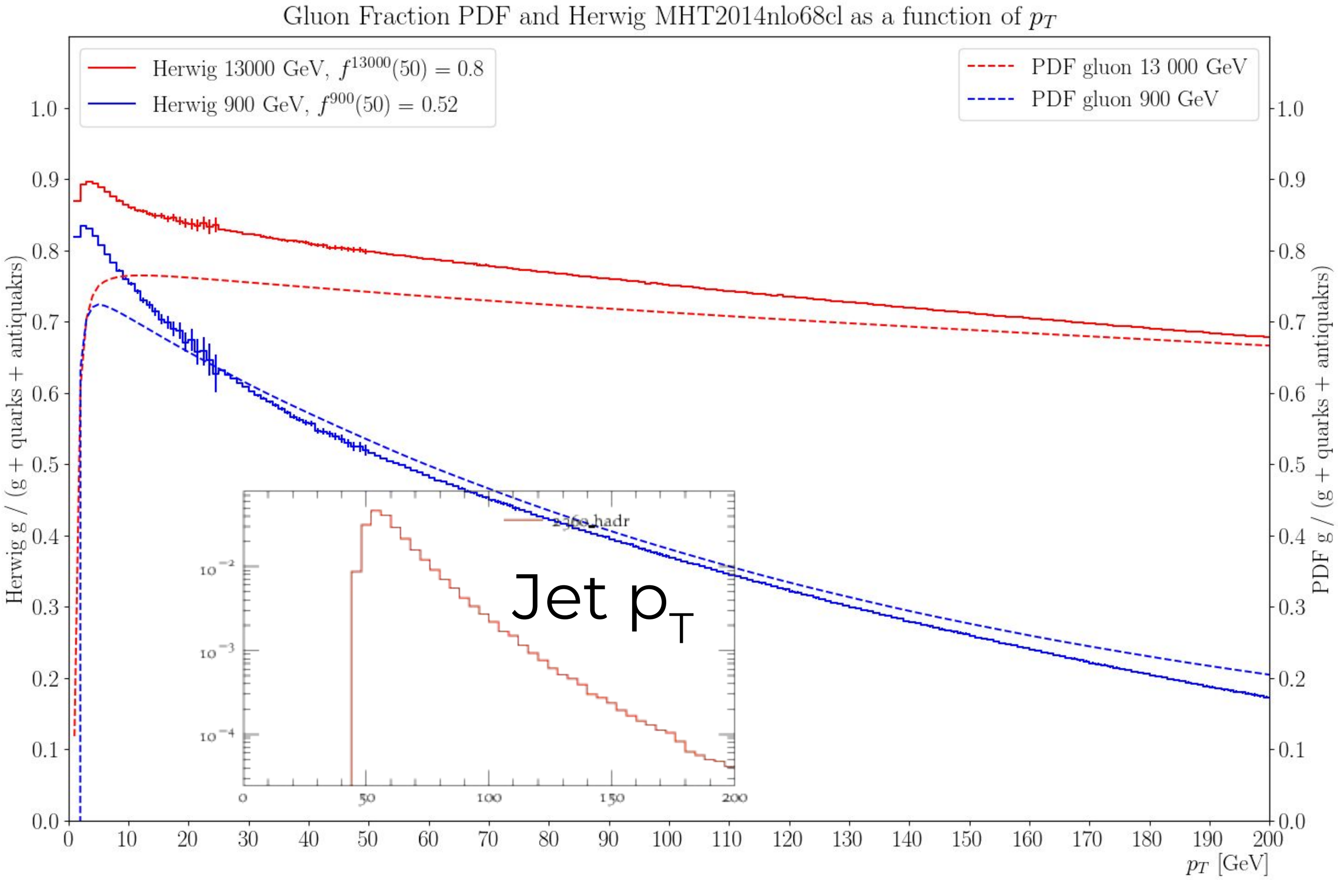
f^{900}, f^{13000} ... simulation

Theory:



Gluon Fraction PDF and Herwig MHT2014nlo68cl as a function of p_T
Herwig 13000 GeV, $f^{13000}(50) = 0.8$
Herwig 900 GeV, $f^{900}(50) = 0.52$
PDF gluon 13 000 GeV
PDF gluon 900 GeV
Herwig g / (g + quarks + antiquakrs)
PDF g / (g + quarks + antiquakrs)
p_T [GeV]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Theory:



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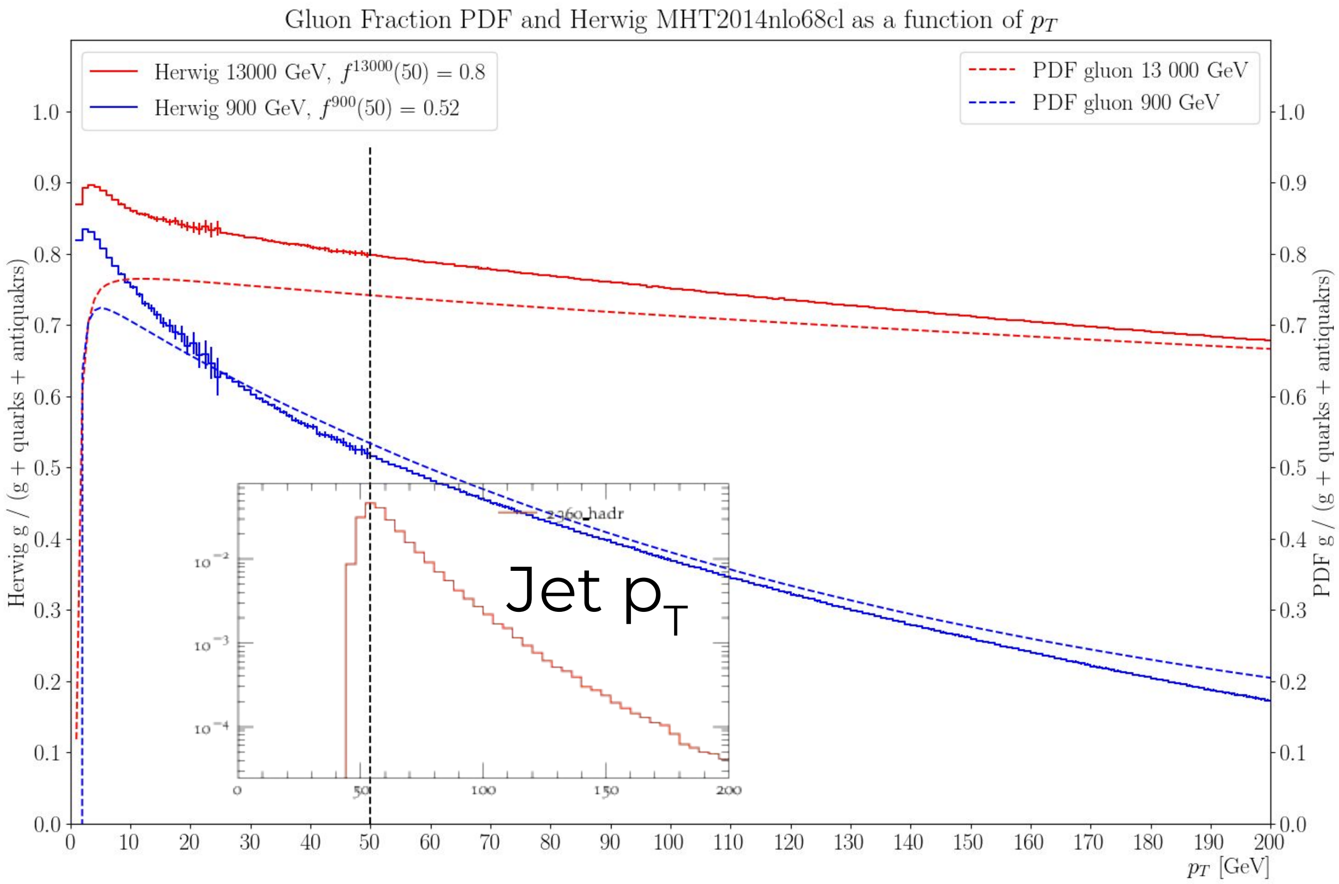
Herwig g / (g + quarks + antiquakrs)
PDF g / (g + quarks + antiquakrs)
p_T [GeV]
Jet p_T

Theory:



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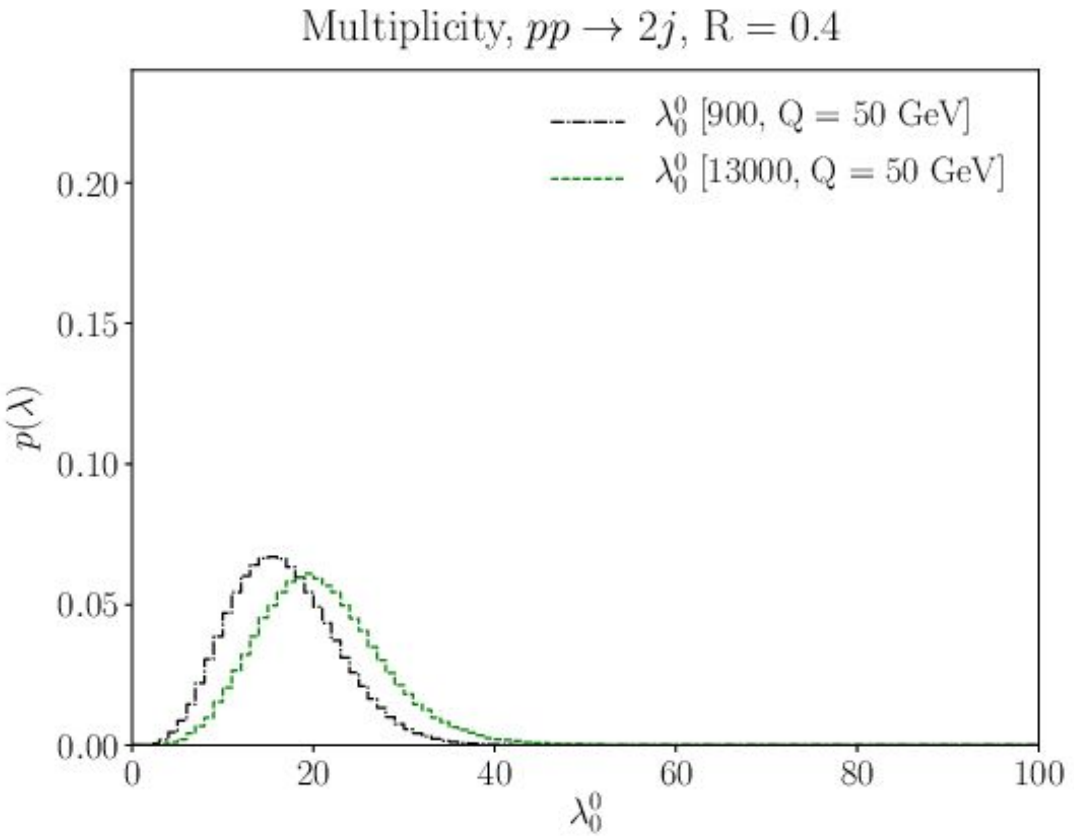
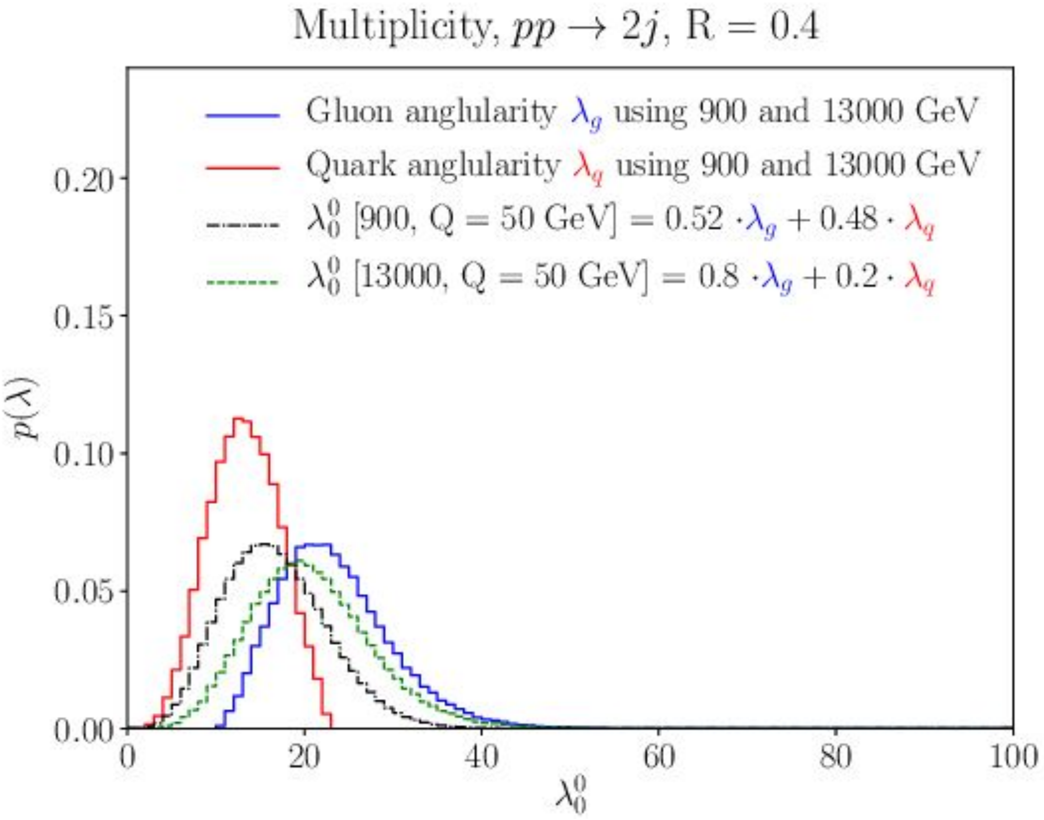
PDF g / (g + quarks + antiquakrs)
p_T [GeV]
Jet p_T

Theory:


Multiplicity, $pp \to 2j$, R = 0.4
λ_0^0 [900, Q = 50 GeV]
λ_0^0 [13000, Q = 50 GeV]
$p(\lambda)$
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
λ_0^0

Theory:



Multiplicity, $pp \to 2j$, R = 0.4
Gluon anglularity λ_g using 900 and 13000 GeV
Quark anglularity λ_q using 900 and 13000 GeV
λ_0^0 [900, Q = 50 GeV] = $0.52 \cdot \lambda_g + 0.48 \cdot \lambda_q$
λ_0^0 [13000, Q = 50 GeV] = $0.8 \cdot \lambda_g + 0.2 \cdot \lambda_q$
$p(\lambda)$
0.00
0.05
0.10
0.15
0.20
0
20
40
60
80
100
λ_0^0

Let's add another energy:

$$\lambda^{900} = f^{900}\,\lambda_g + (1 - f^{900})\lambda_q$$

$$\lambda^{2360} = f^{2360}\,\lambda_g + (1 - f^{2360})\lambda_q$$

$$\lambda^{13000} = f^{13000}\,\lambda_g + (1 - f^{13000})\lambda_q$$

$$\lambda_q = \frac{f^{900}\lambda^{13000} - f^{13000}\lambda^{900}}{f^{900} - f^{13000}}$$

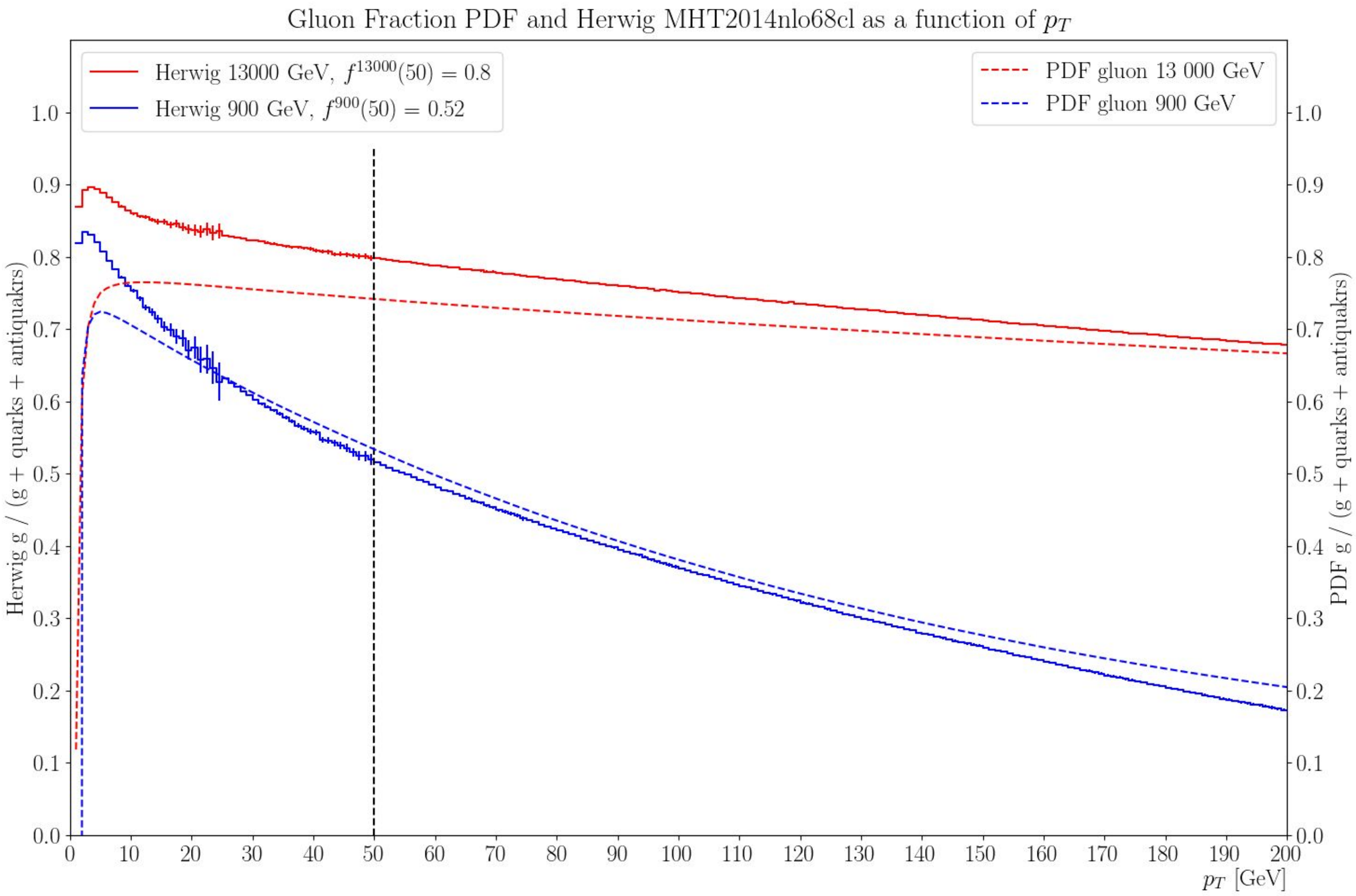
$$\lambda_q = \frac{f^{900}\lambda^{2360} - f^{2360}\lambda^{900}}{f^{900} - f^{2360}}$$

and

$$\lambda_g = \frac{(1 - f^{13000})\lambda^{900} - (1 - f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$$

$$\lambda_g = \frac{(1 - f^{2360})\lambda^{900} - (1 - f^{900})\lambda^{2360}}{f^{900} - f^{2360}}$$

Theory: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p_T [GeV]
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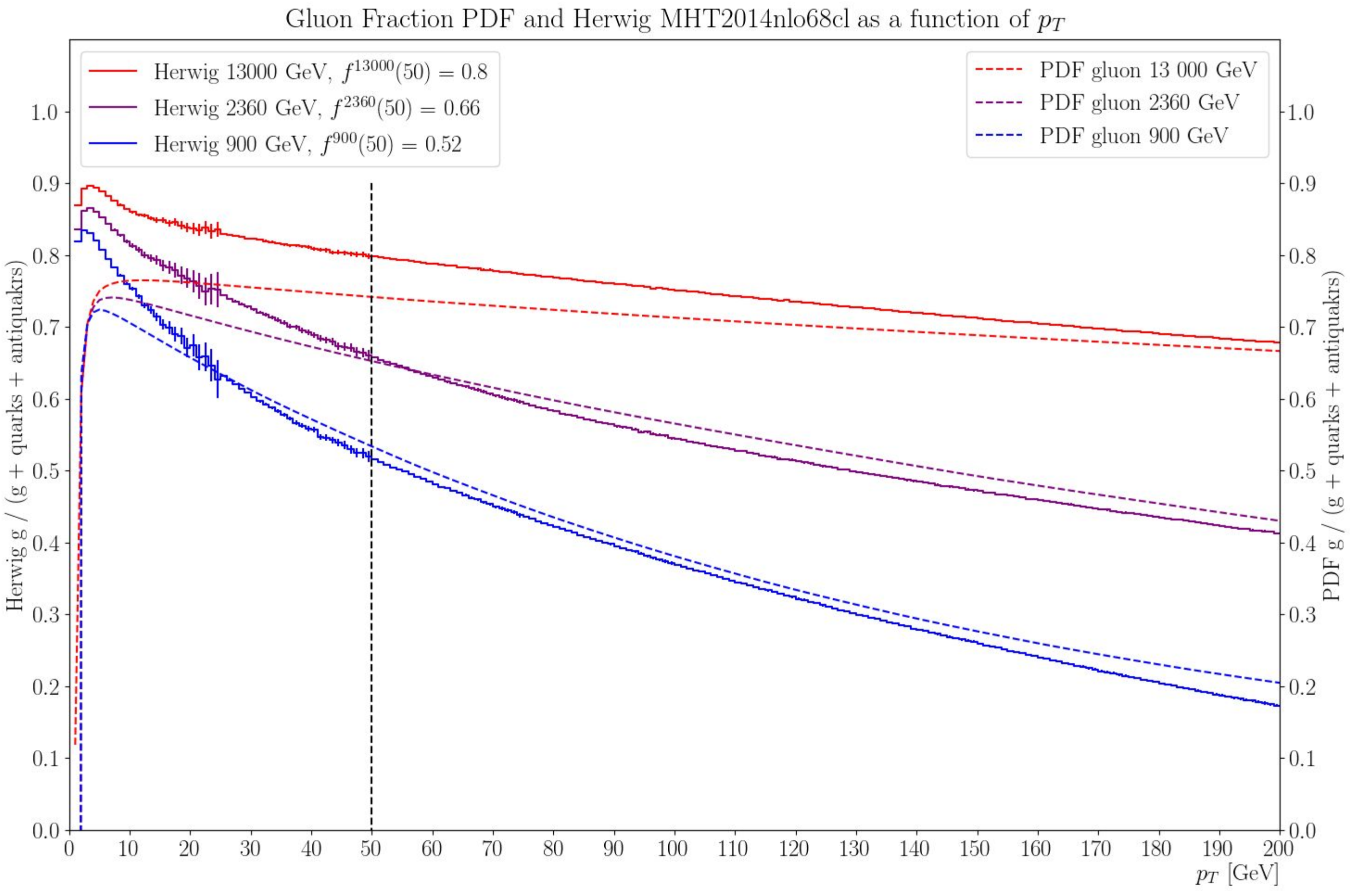
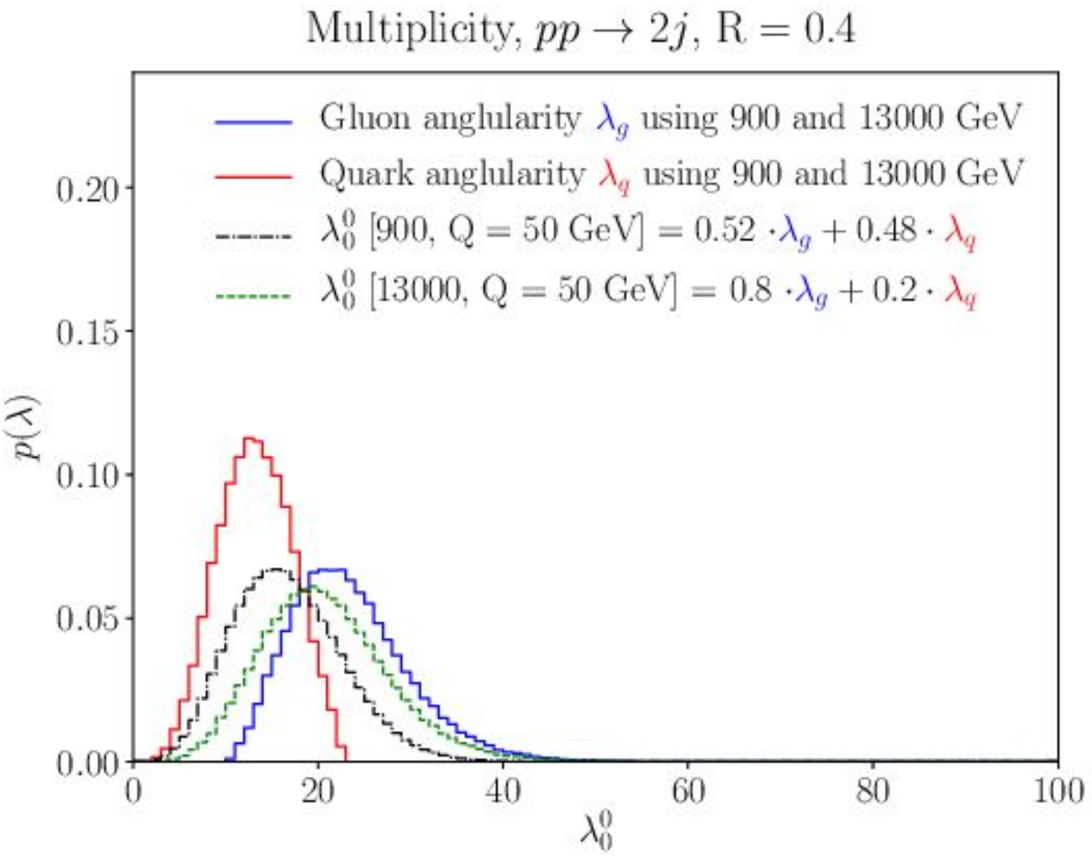
200

Theory:



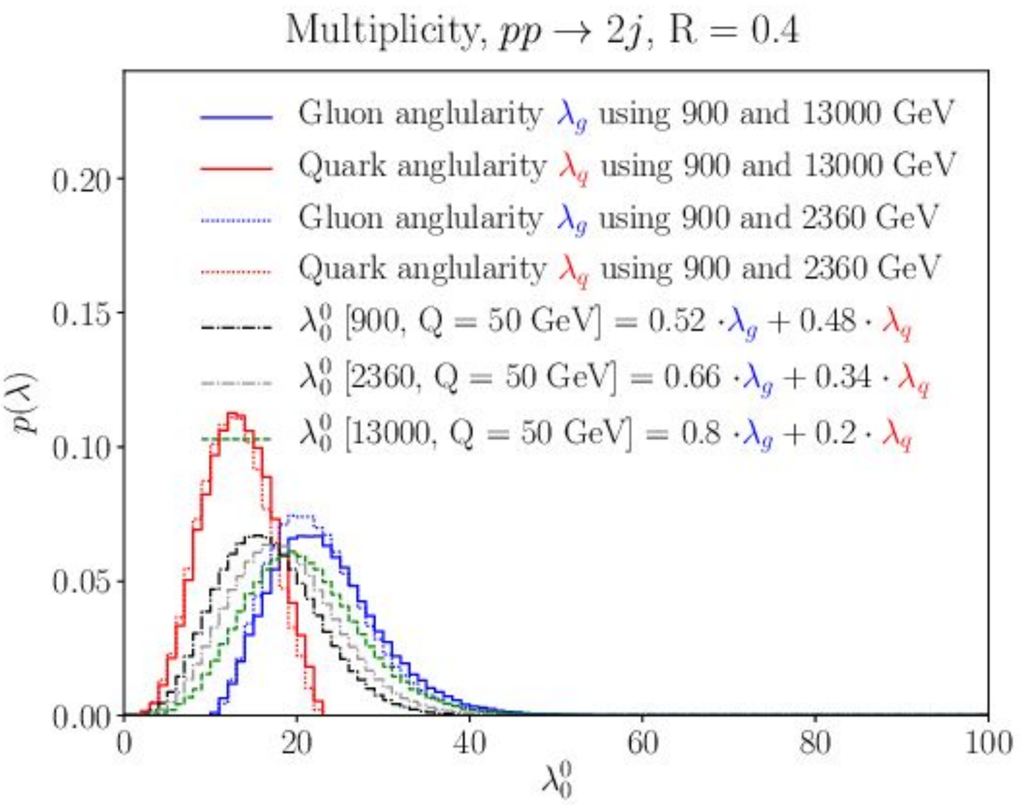
Gluon Fraction PDF and Herwig MHT2014nlo68cl as a function of p_T
Herwig 13000 GeV, $f^{13000}(50) = 0.8$
Herwig 2360 GeV, $f^{2360}(50) = 0.66$
Herwig 900 GeV, $f^{900}(50) = 0.52$
PDF gluon 13 000 GeV
PDF gluon 2360 GeV
PDF gluon 900 GeV
Herwig g / (g + quarks + antiquakrs)
PDF g / (g + quarks + antiquakrs)
p_T [GeV]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

Theory:



Multiplicity, $pp \to 2j$, R = 0.4
Gluon anglularity λ_g using 900 and 13000 GeV
Quark anglularity λ_q using 900 and 13000 GeV
λ_0^0 [900, Q = 50 GeV] = 0.52 $\cdot \lambda_g$ + 0.48 $\cdot$ λ_q
λ_0^0 [13000, Q = 50 GeV] = 0.8 $\cdot \lambda_g$ + 0.2 $\cdot$ λ_q
$p(\lambda)$
0.00
0.05
0.10
0.15
0.20
0
20
40
60
80
100
λ_0^0

Theory:



Multiplicity, $pp \to 2j$, R = 0.4
Gluon anglularity λ_g using 900 and 13000 GeV
Quark anglularity λ_q using 900 and 13000 GeV
Gluon anglularity λ_g using 900 and 2360 GeV
Quark anglularity λ_q using 900 and 2360 GeV
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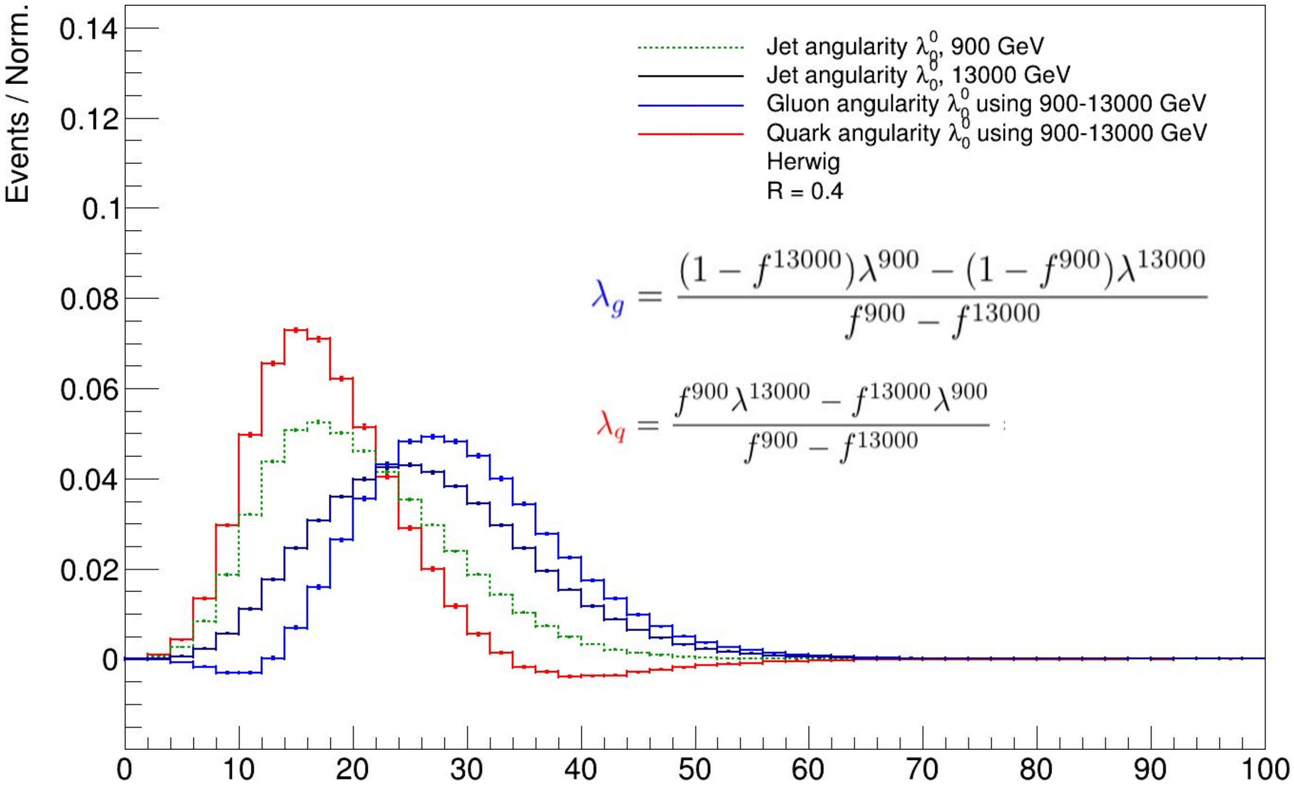
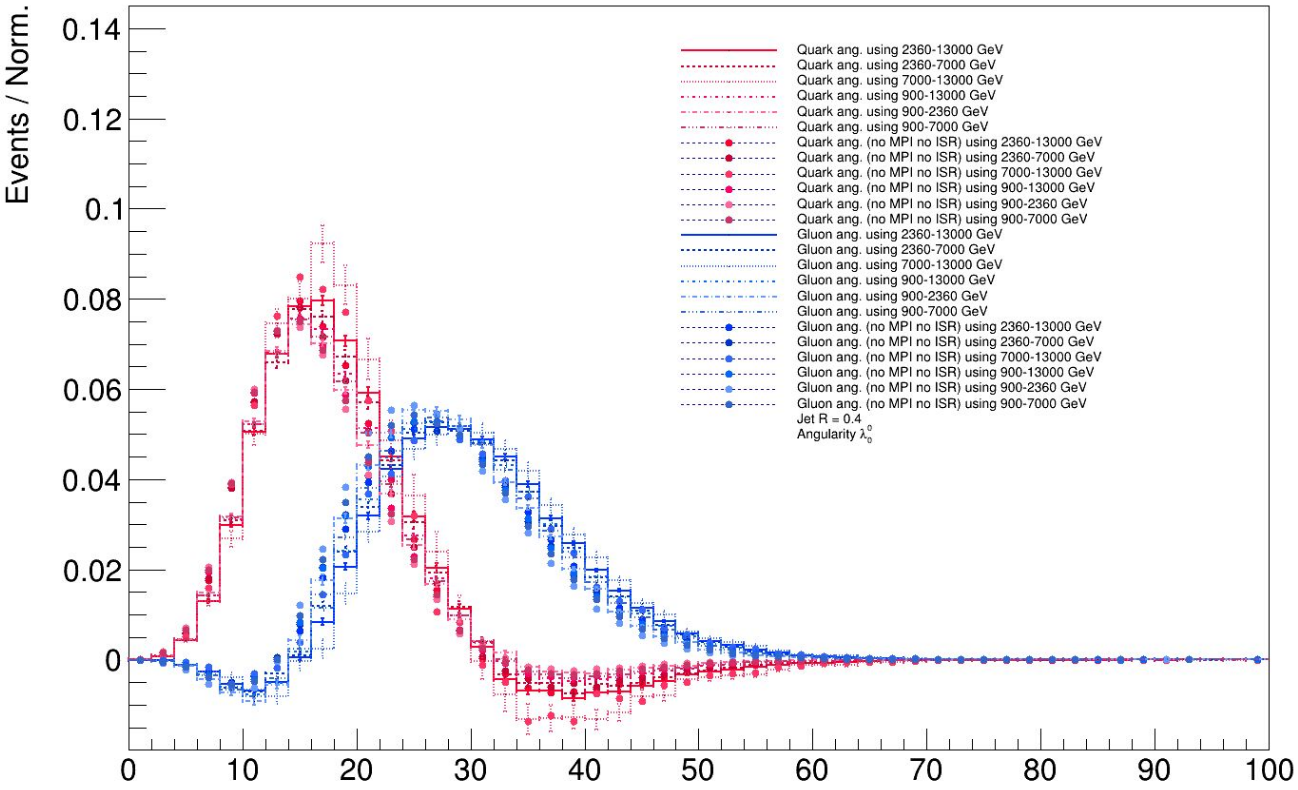
λ_0^0 [2360, Q = 50 GeV] = 0.66 $\cdot\lambda_g$ + 0.34 $\cdot$ λ_q
λ_0^0 [13000, Q = 50 GeV] = 0.8 $\cdot\lambda_g$ + 0.2 $\cdot$ λ_q
$p(\lambda)$
λ_0^0
0.00
0.05
0.10
0.15
0.20
0
20
40
60
80
100

Theory:



Events / Norm.
Jet angularity λ_0^0, 900 GeV
Jet angularity λ_0^0, 13000 GeV
Gluon angularity λ_0^0 using 900-13000 GeV
Quark angularity λ_0^0 using 900-13000 GeV
Herwig
R = 0.4
$\lambda_g = \frac{(1-f^{13000})\lambda^{900} - (1-f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$
$\lambda_q = \frac{f^{900}\lambda^{13000} - f^{13000}\lambda^{900}}{f^{900} - f^{13000}}$

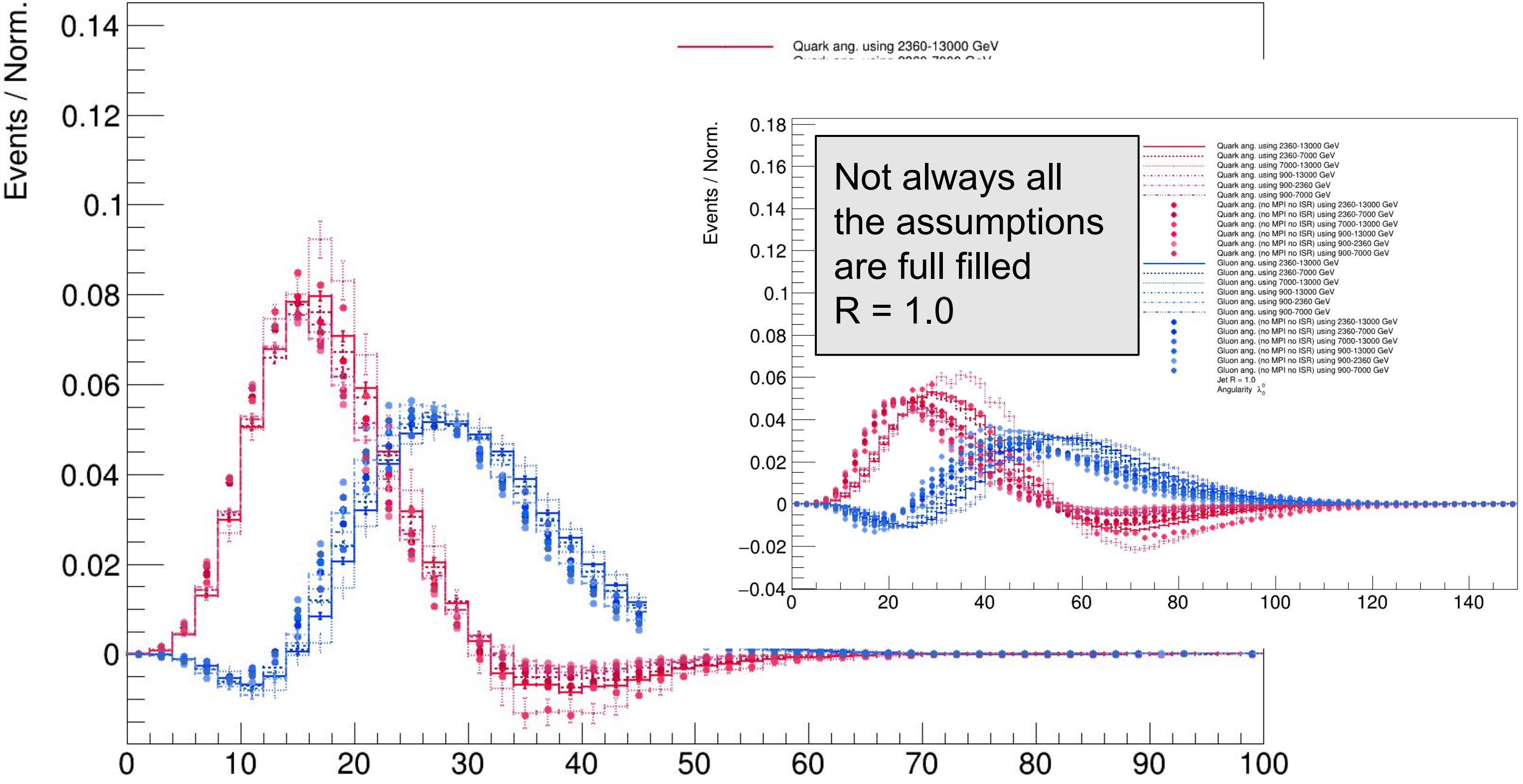
Let's use more 6 energy combinations:
900-2360, 900-7000, 900-13000, 2360-7000, 2360-13000, 7000-13000 GeV



Dotted lines test the robustness to Multi Parton Interactions MPI and Initial State Radiation ISR

Theory:

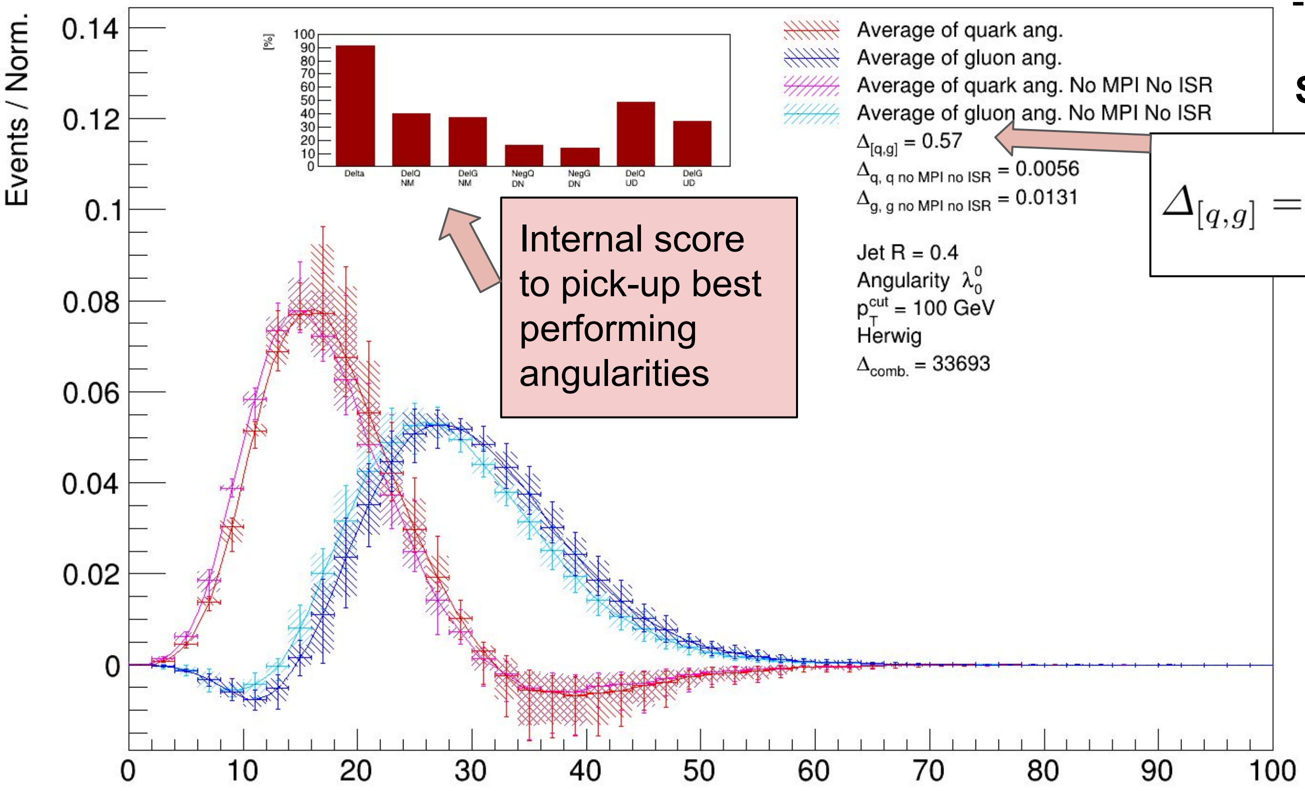
Let's use more 6 energy combinations:
900-2360, 900-7000, 900-13000, 2360-7000, 2360-13000, 7000-13000 GeV



Dotted lines test the robustness to Multi Parton Interactions MPI and Initial State Radiation ISR

Theory:

Simplified averaged plot over 6 energy combinations: - filled area (energy comb. variation),
- ticks - stat. Unc.



Internal score to pick-up best performing angularities

Separation power:

$$\Delta_{[q,g]} = \frac{1}{2}\sum_{i=1}^{N}\frac{(\lambda_{q_i} - \lambda_{g_i})^2}{\lambda_{q_i} + \lambda_{g_i}}$$

3. Results

Results:

Selection of dijet events:

$N^{jets} = 2$
veto neutrinos

$p_{T\ \mathrm{sublead}}/p_{T\ \mathrm{lead}} > 0.8$

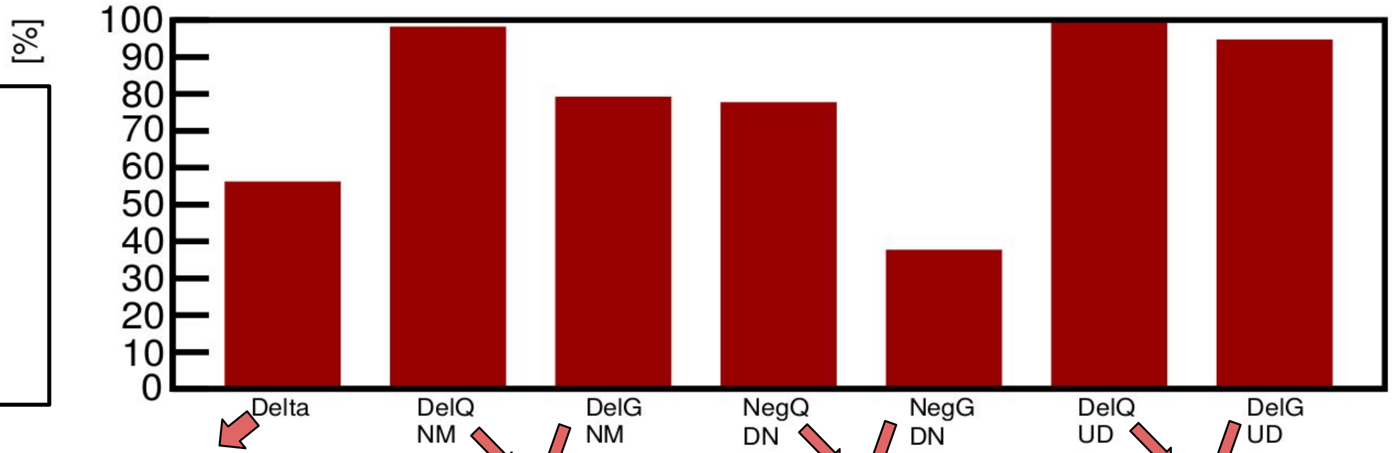
We considered all combinations of:

- 5 – angularities λ_0^0, $\lambda_{0.5}^1$, λ_1^1, λ_0^2, λ_2^1
- 2 – using groomed (MMDT) / not groomed jets
- 5 – jet radii $R = 0.2, 0.4, 0.6, 0.8, 1.0$
- 4 – regions - dijet average $p_T^{\mathrm{cut}} = 50$ GeV, 100, 200, and 400 GeV

  $(p_{T\ \mathrm{lead}} + p_{T\ \mathrm{sublead}})/2 > p_T^{\mathrm{cut}}$
- 2 – quark/gluon
- 2 – MPI and ISR switched on/off
- 6 – energy combinations: 900–2360, 900–7000, 900–13000, 2360–7000, 2360–13000, 7000–13000 GeV
- 2 – event generators Herwig and Pythia

Results:

Each column represents percentile of given feature of all our studied plots.



In **separation between Q/G jets** about 55 % of variations have lower performance

Separation power between noMPI variations - **robustness to noMPI no ISF**

Negativity (percentage of negative area to whole area) **negative bins**

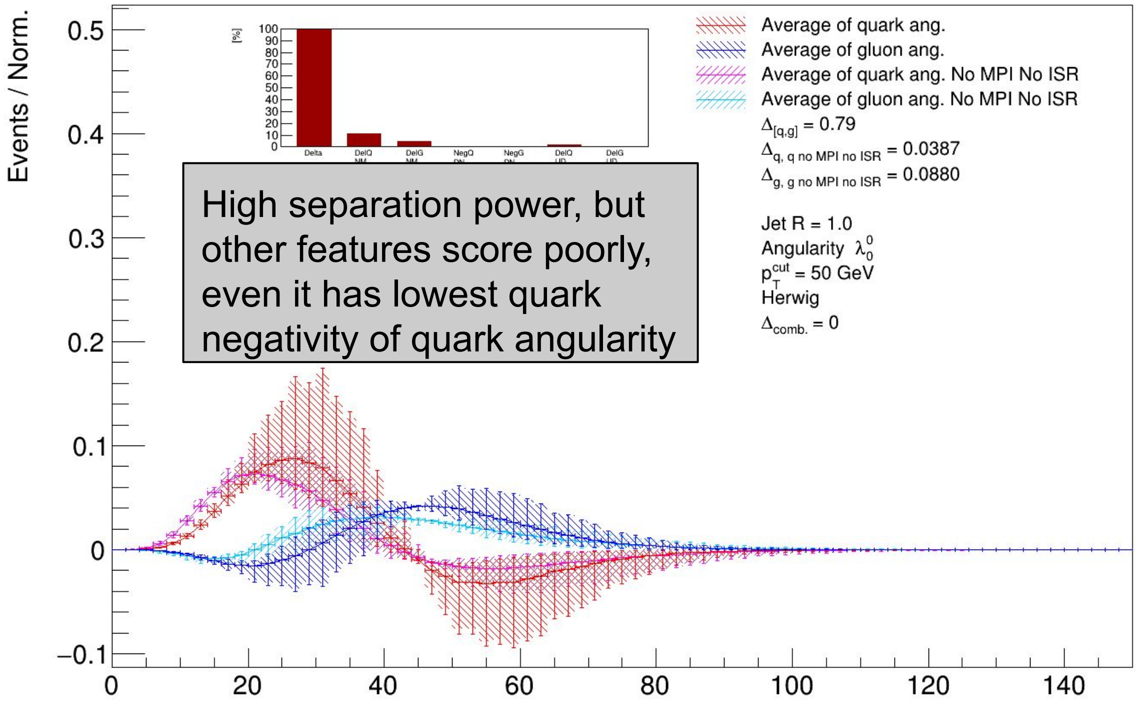
Separation power to UP and DOWN energy combination variations **robustness to different energy combination used**

Combining all columns gives us our internal score :

$$\Delta_{\mathrm{comb}} = 1000 \cdot \ln \Big[1 + (\mathrm{Delta})^3 \cdot (\mathrm{DelQ\ NM}) \cdot (\mathrm{DelG\ NM}) \cdot (\mathrm{NegQ\ DN}) \cdot (\mathrm{NegG\ DN}) \cdot (\mathrm{DelQ\ UD}) \cdot (\mathrm{DelG\ UD}) \Big]$$

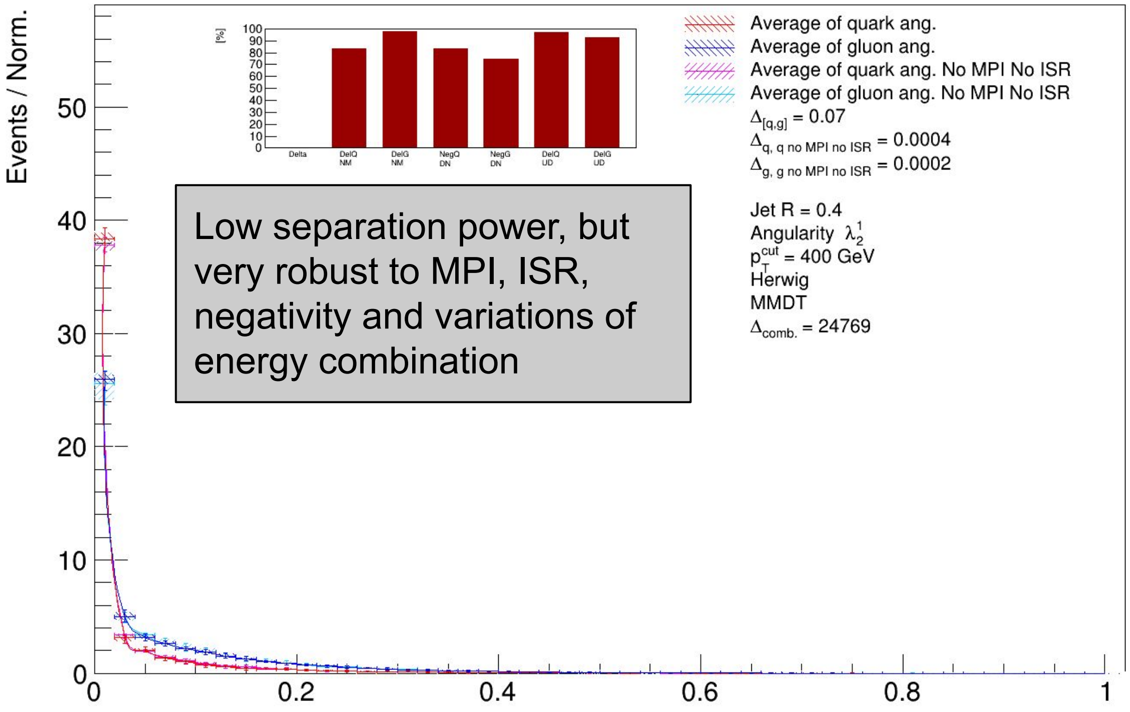
min-max
0-41447

Why we looking into other features then separation power (bad examples):

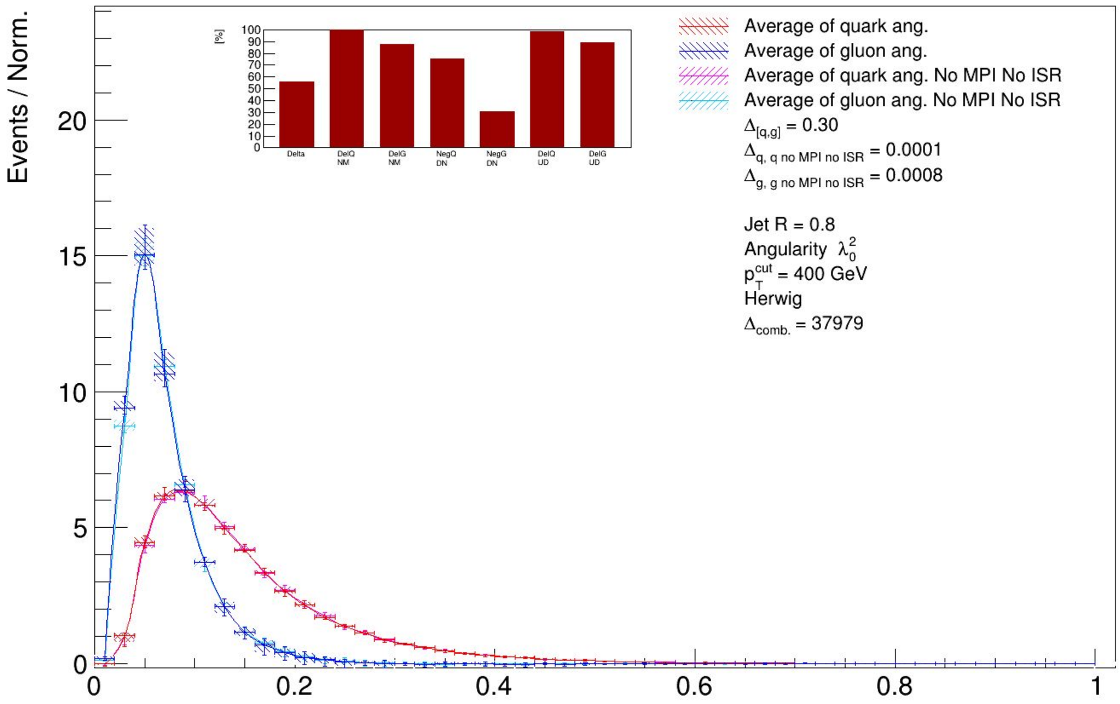


Results:

Why we looking into other features then separation power (bad examples):

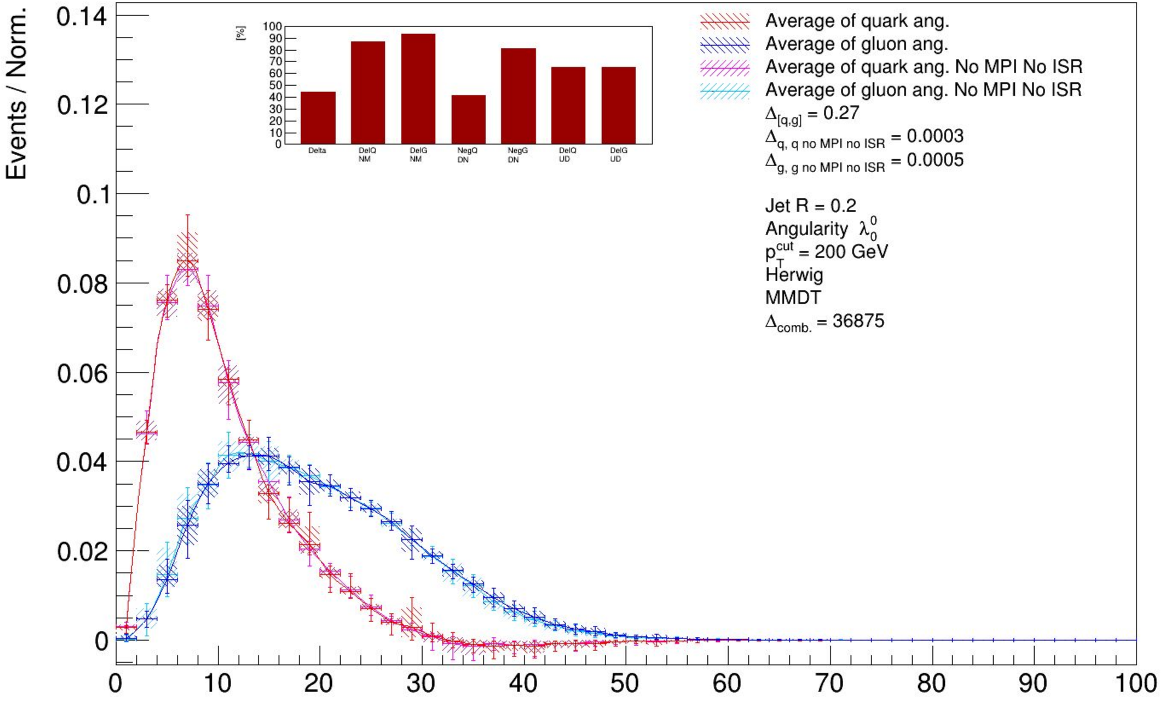


Best performing angularities: p_T^D

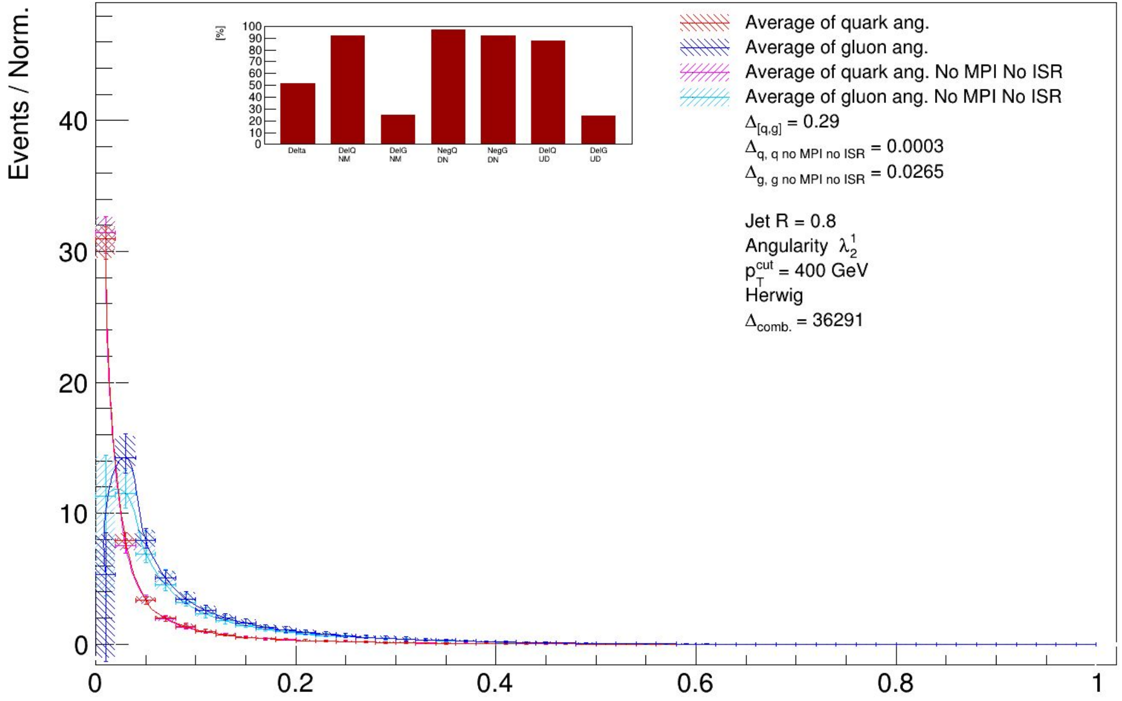


Results:

Best performing angularities: Multiplicity

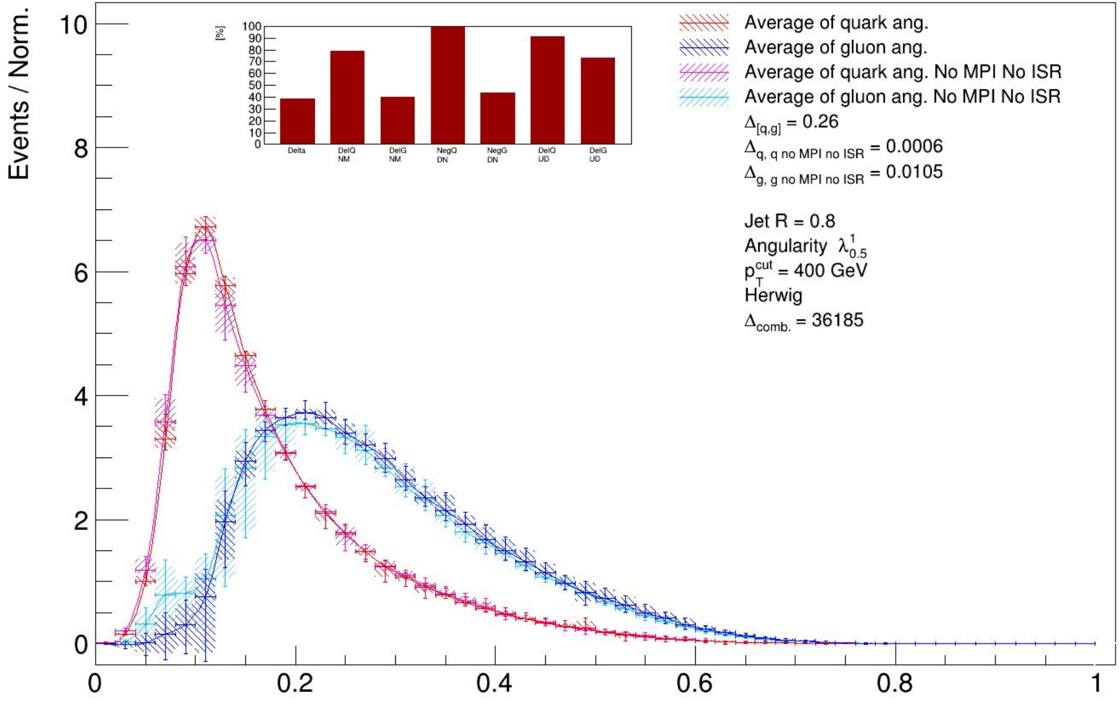


Best performing angularities: Mass

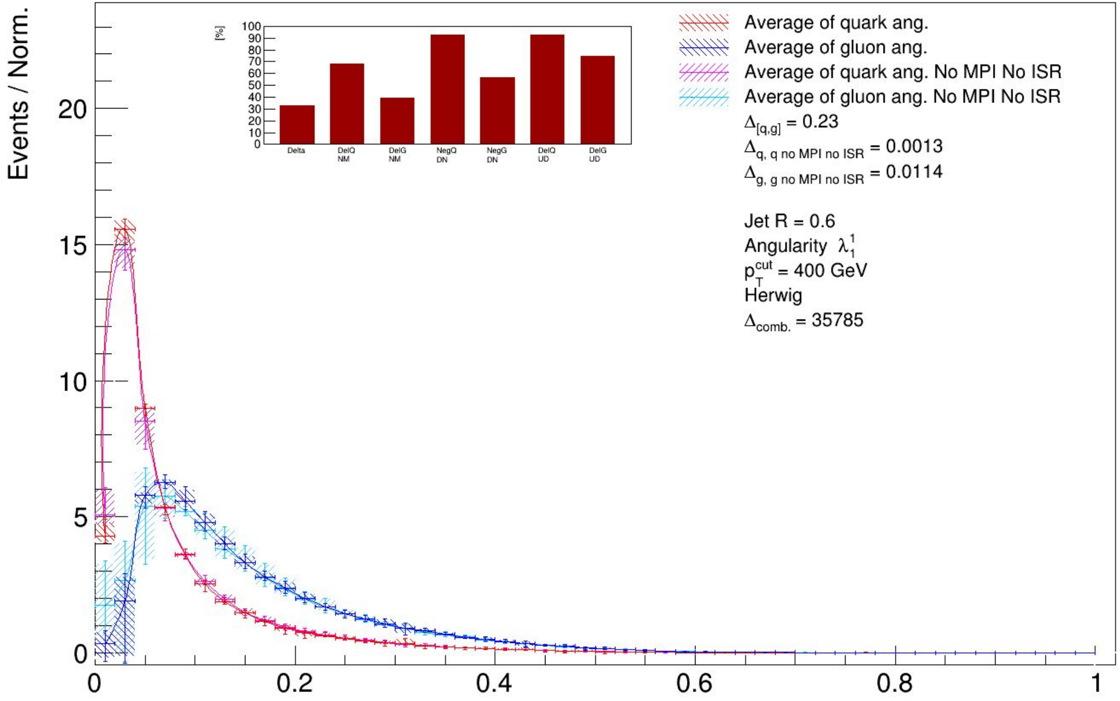


Results:

Best performing angularities: LHA



Best performing angularities: Width

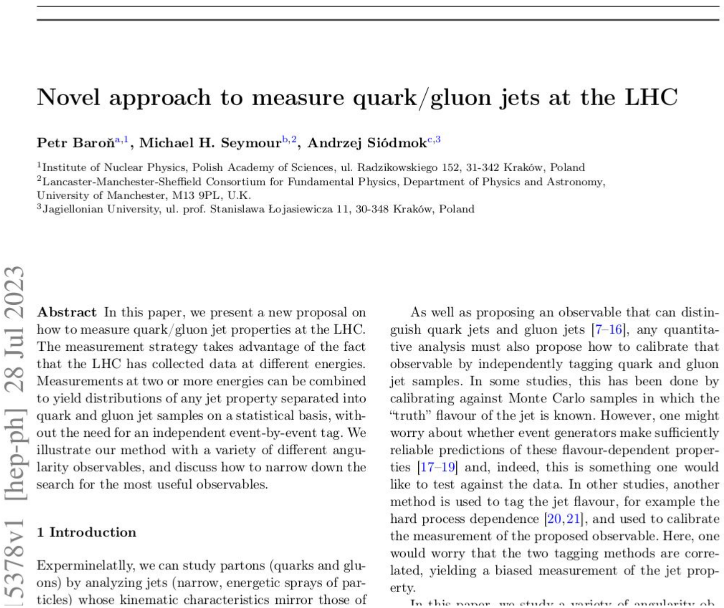


4. Conclusion

Conslution:

- Main idea it that properties of jets of a given flavour and transverse momentum, are almost entirely independent of the jet's production mechanism.
  Thus, the energy-dependence can be used to extract the flavour-dependent properties on a statistical basis.
- We proposed selection of best performing angularities
- More details: https://arxiv.org/abs/2307.15378

- Plans:
  - Multidim angularities (2D, 3D) with machine learning approach to enhance separation power
  - Derive jet topics: https://arxiv.org/abs/1802.00008 since all ingredients should be in place
  - Perform measurement - we will be happy to contribute:-)



5378v1 [hep-ph] 28 Jul 2023

Novel approach to measure quark/gluon jets at the LHC

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[2]Lancaster-Manchester-Sheffield Consortium for Fundamental Physics, Department of Physics and Astronomy, University of Manchester, M13 9PL, U.K.
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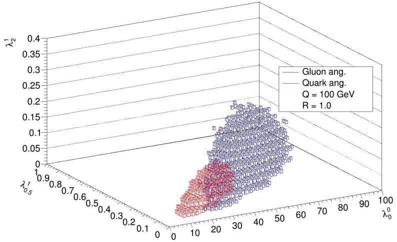
Abstract In this paper, we present a new proposal on how to measure quark/gluon jet properties at the LHC. The measurement strategy takes advantage of the fact that the LHC has collected data at different energies. Measurements at two or more energies can be combined to yield distributions of any jet property separated into quark and gluon jet samples on a statistical basis, without the need for an independent event-by-event tag. We illustrate our method with a variety of different angularity observables, and discuss how to narrow down the search for the most useful observables.

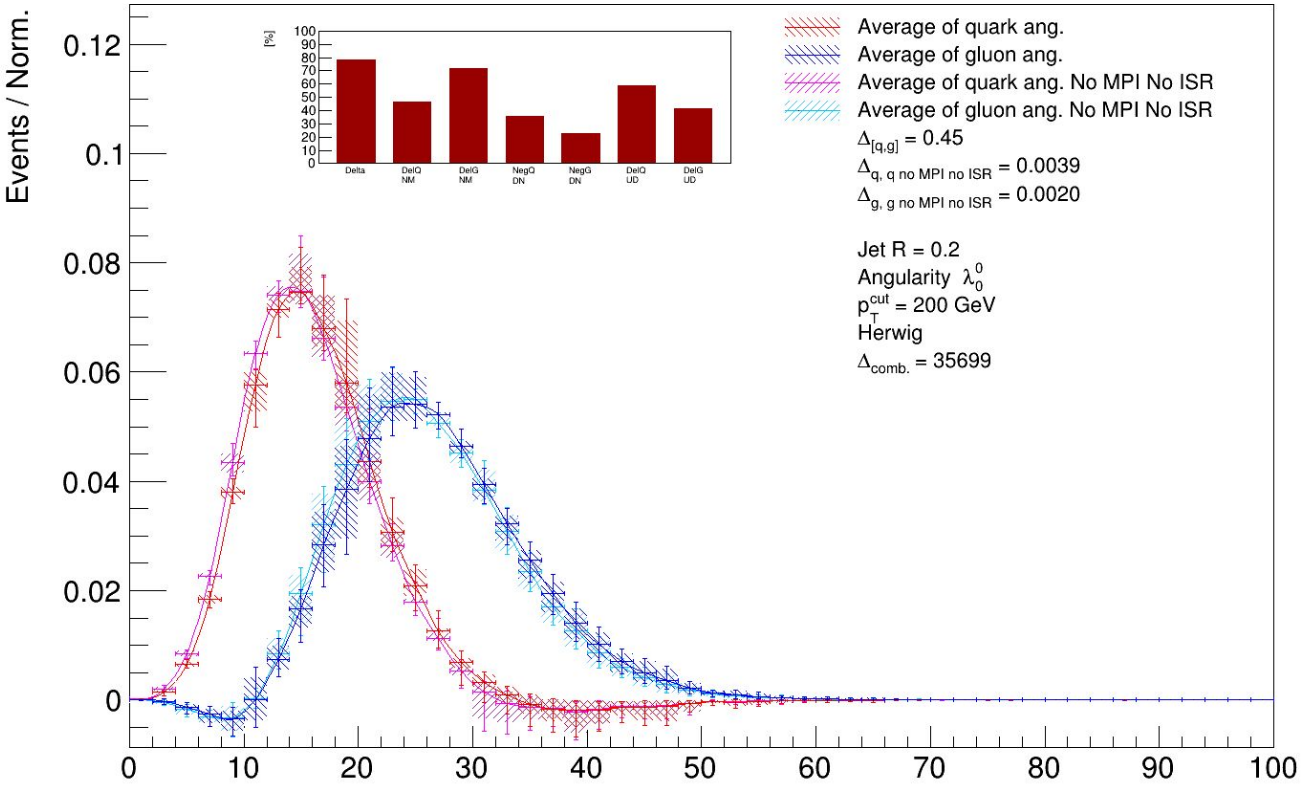
1 Introduction

Experminelatlly, we can study partons (quarks and gluons) by analyzing jets (narrow, energetic sprays of particles) whose kinematic characteristics mirror those of

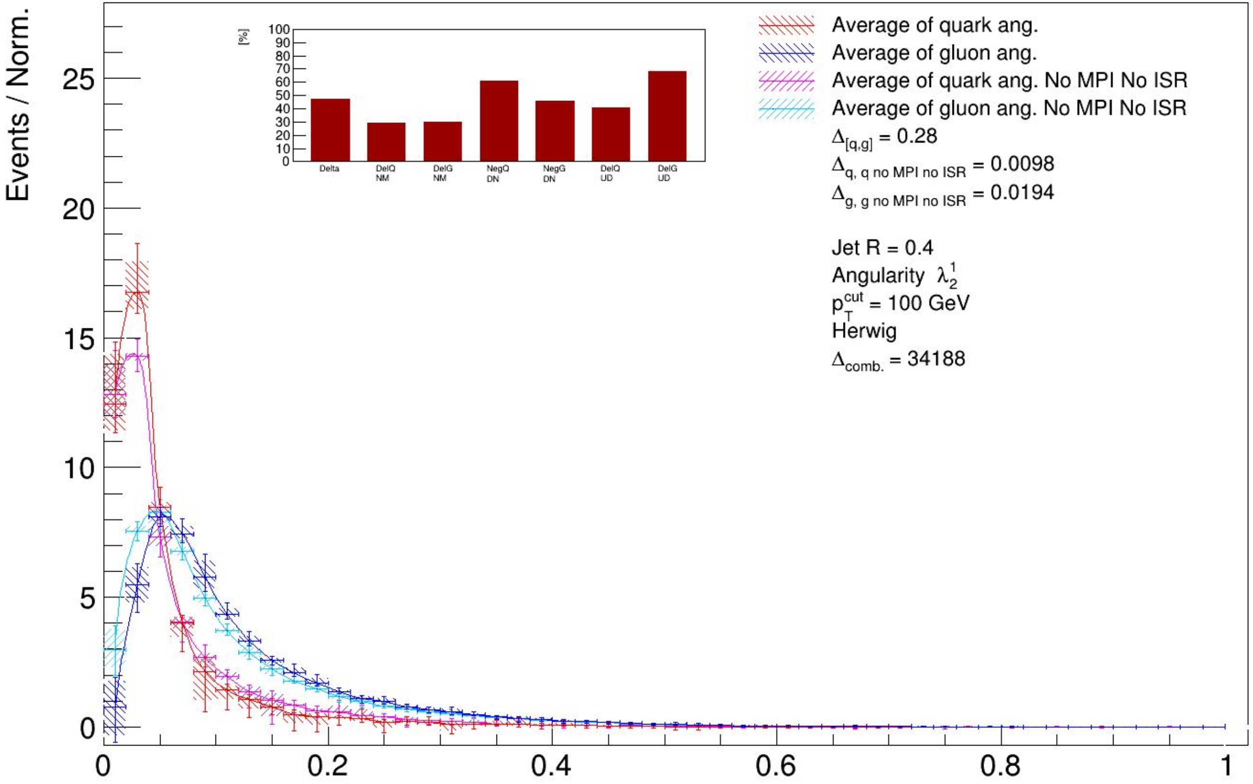
As well as proposing an observable that can distinguish quark jets and gluon jets [7–16], any quantitative analysis must also propose how to calibrate that observable by independently tagging quark and gluon jet samples. In some studies, this has been done by calibrating against Monte Carlo samples in which the "truth" flavour of the jet is known. However, one might worry about whether event generators make sufficiently reliable predictions of these flavour-dependent properties [17–19] and, indeed, this is something one would like to test against the data. In other studies, another method is used to tag the jet flavour, for example the hard process dependence [20,21], and used to calibrate the measurement of the proposed observable. Here, one would worry that the two tagging methods are correlated, yielding a biased measurement of the jet property.



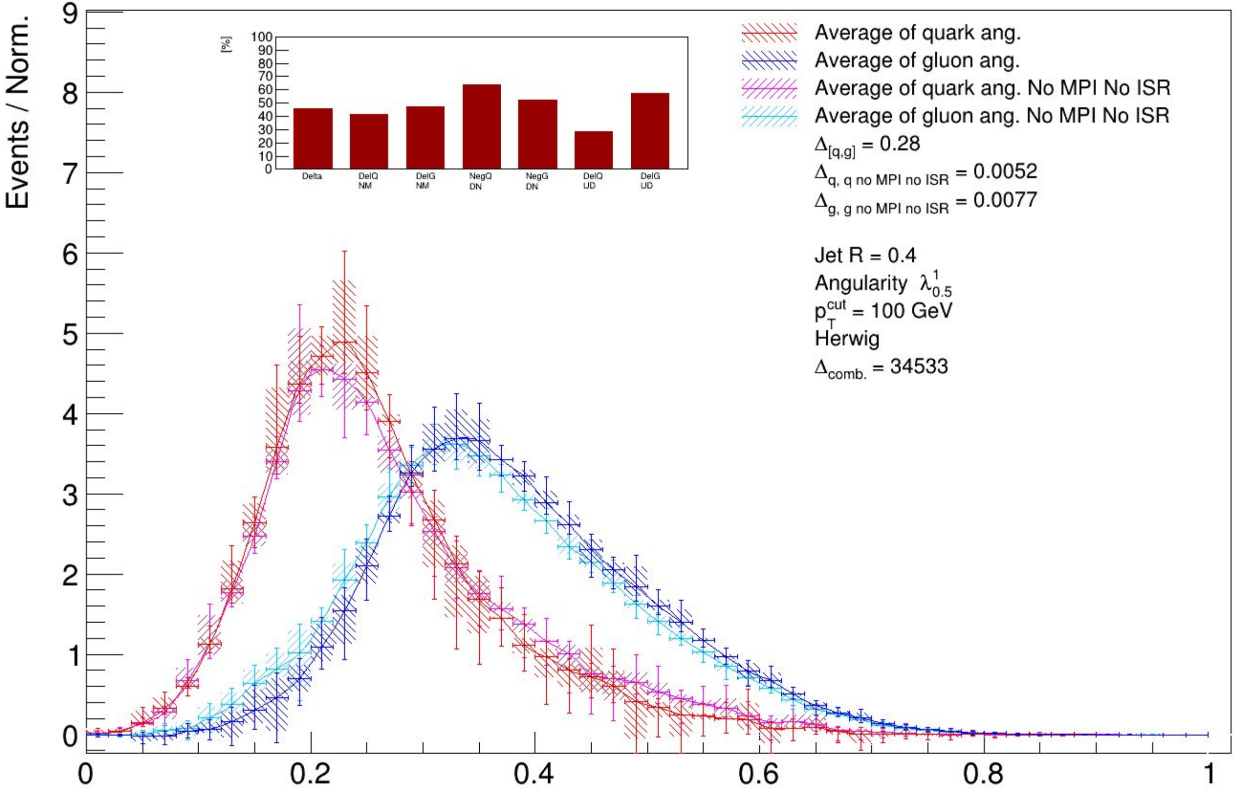
Wild cards (chosen by "eye"): multiplicity



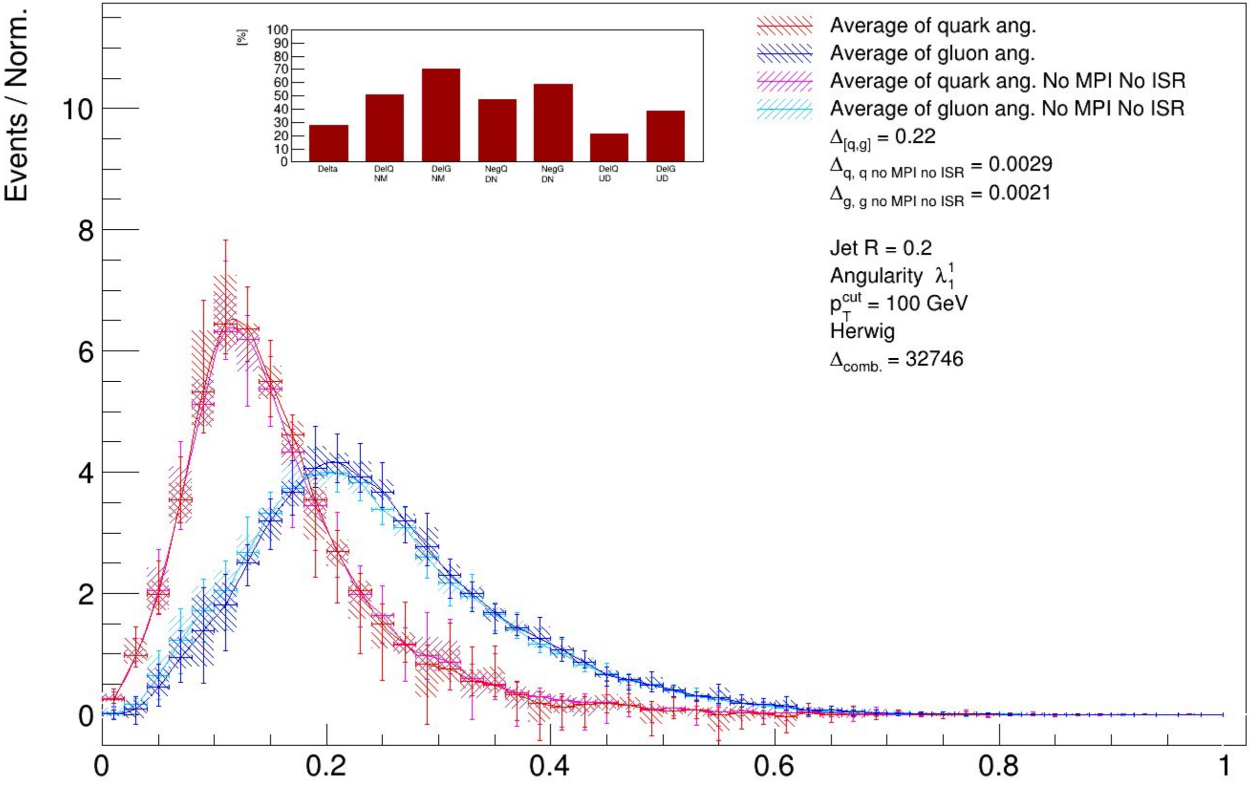
Wild cards (chosen by “eye”): mass



Wild cards (chosen by “eye”): LHA



Wild cards (chosen by “eye”): width



Herwig vs Pythia

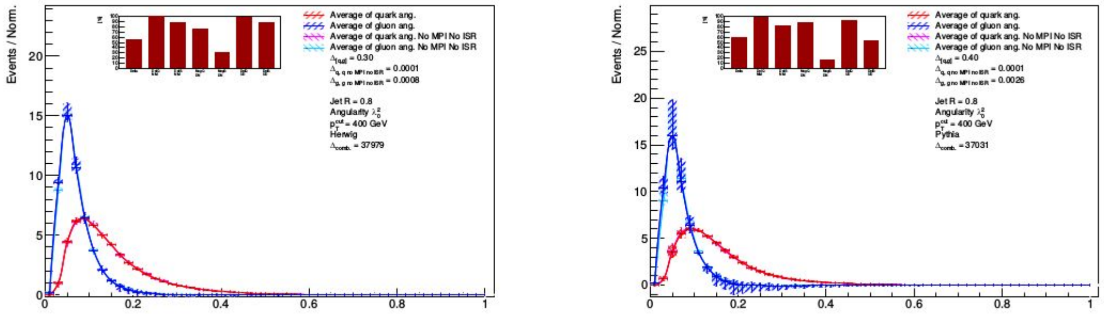


Fig. 17 Quark and gluon averaged angularities λ_0^2, $R = 0.8$ with highest score $\Delta_{\text{comb}} = 37979$ using HERWIG event generator (left) and $\Delta_{\text{comb}} = 37031$ using PYTHIA event generator (right), with $p_T^{\text{cut}} = 400$ GeV, using the average of 6 energy combinations 900–2360, 900–7000, 900–13000, 2360–7000, 2360–13000, 7000–13000 GeV.

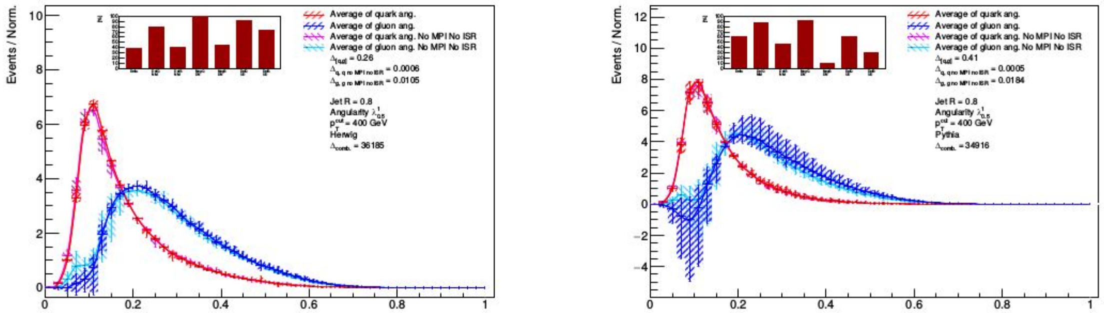
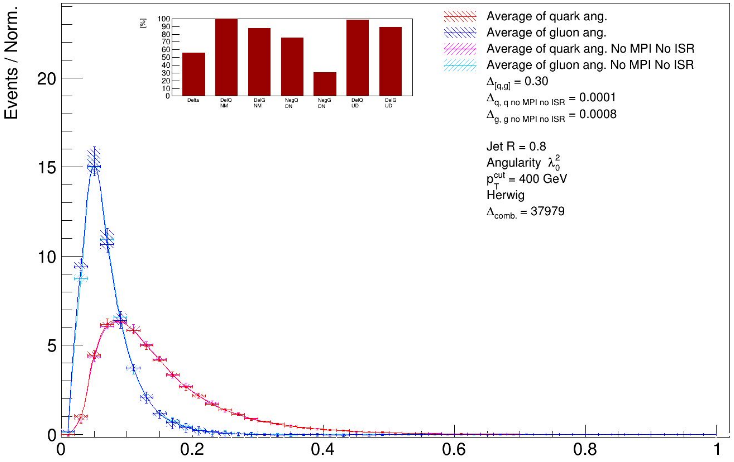
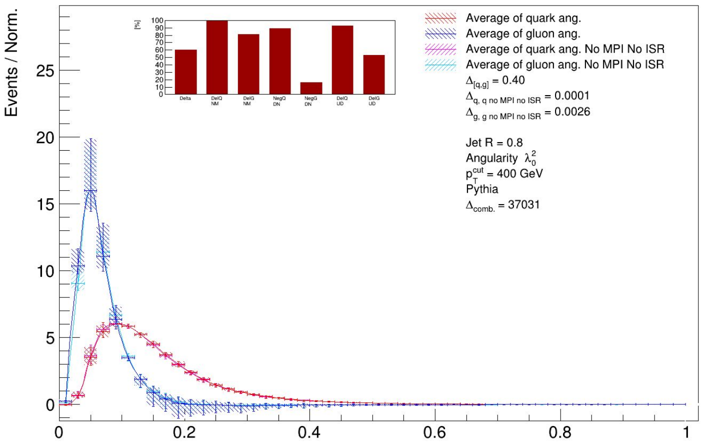


Fig. 18 Quark and gluon averaged angularities MMDT $\lambda_{0.5}^1$, $R = 0.8$ with score $\Delta_{\text{comb}} = 36185$ using HERWIG event generator (left) and $\Delta_{\text{comb}} = 34916$ using PYTHIA event generator (right), with $p_T^{\text{cut}} = 400$ GeV, using the average of 6 energy combinations 900–2360, 900–7000, 900–13000, 2360–7000, 2360–13000, 7000–13000 GeV.

Results:

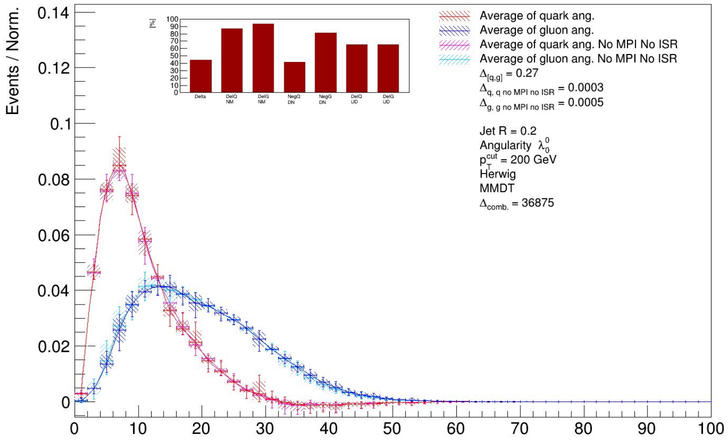
Best performing angularities: p_T^D

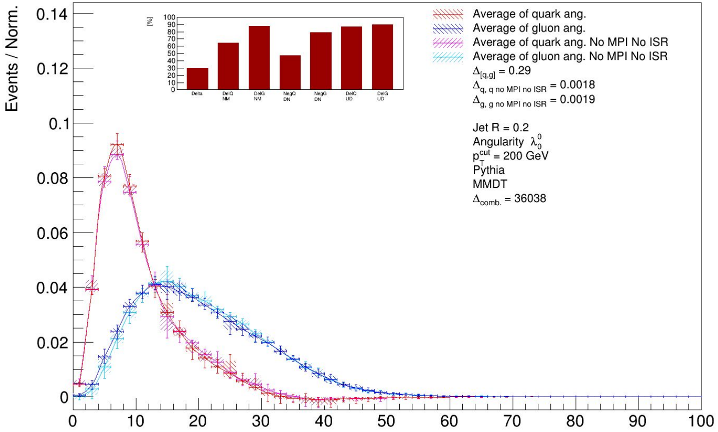




Results:

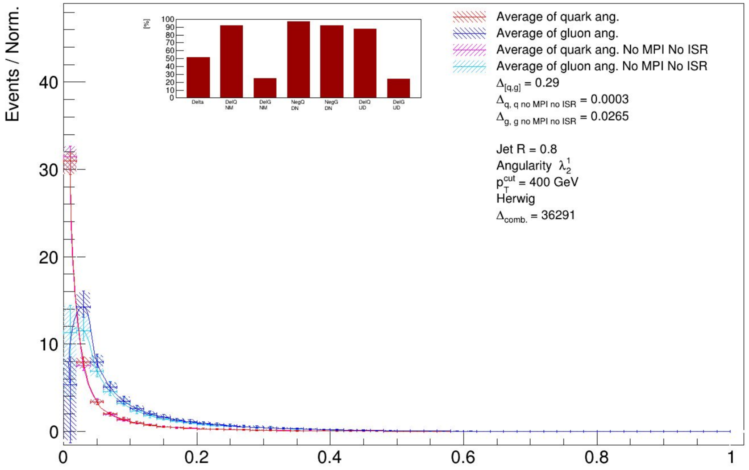
Best performing angularities: Multiplicity

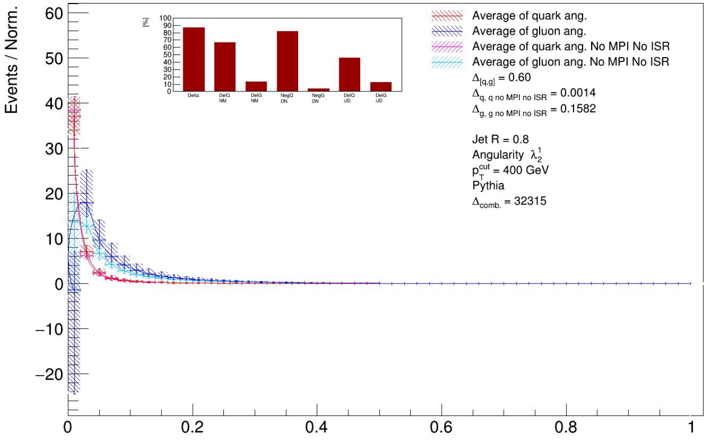




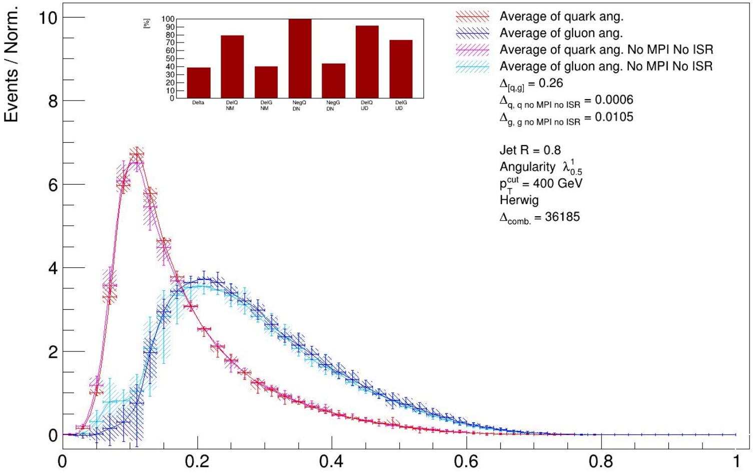
Results:

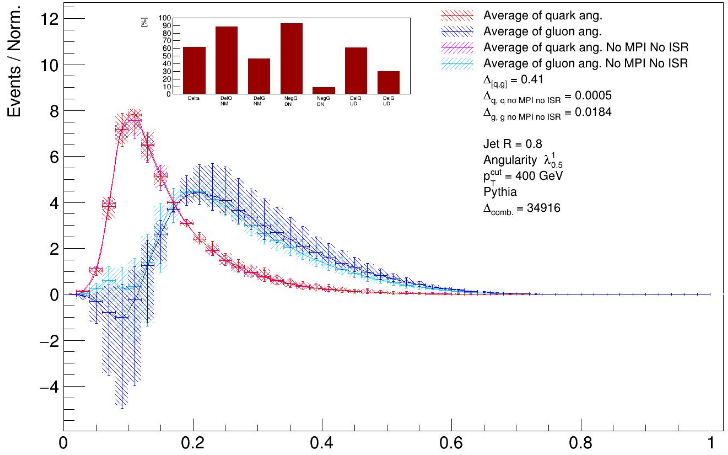
Best performing angularities: Mass





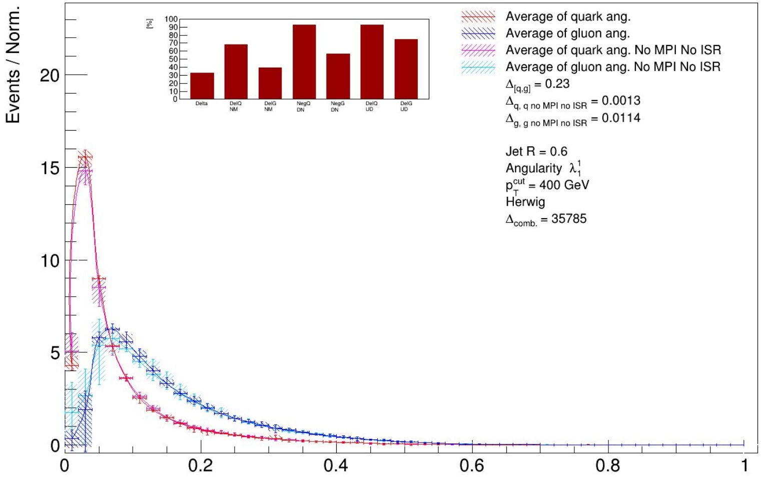
Best performing angularities: LHA

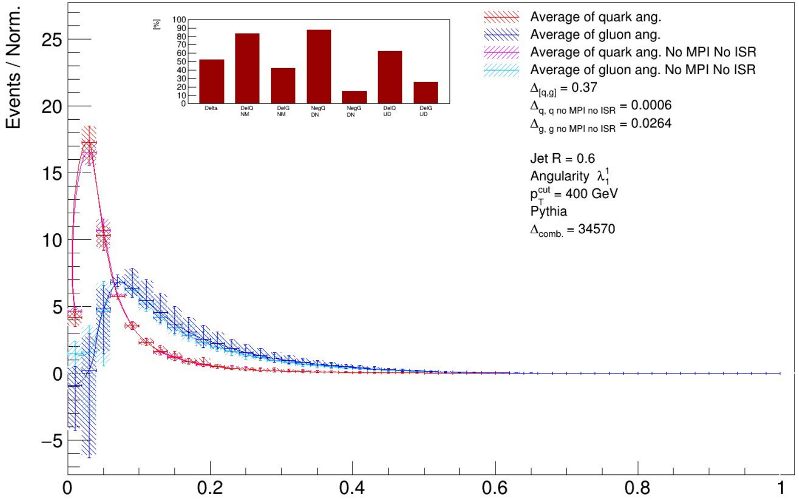




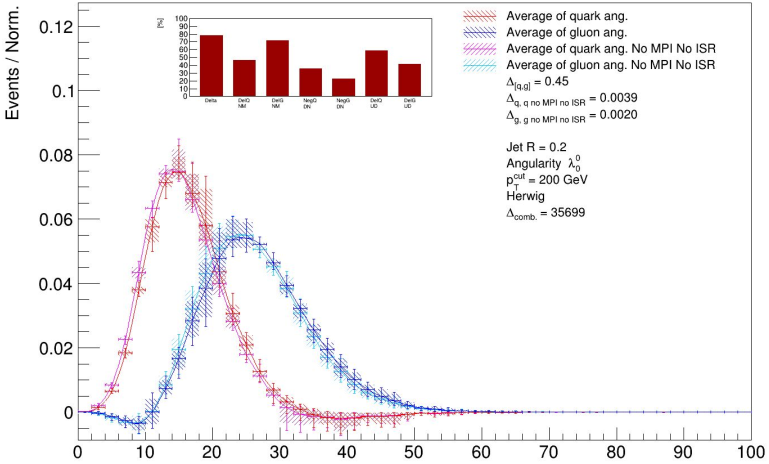
Results:

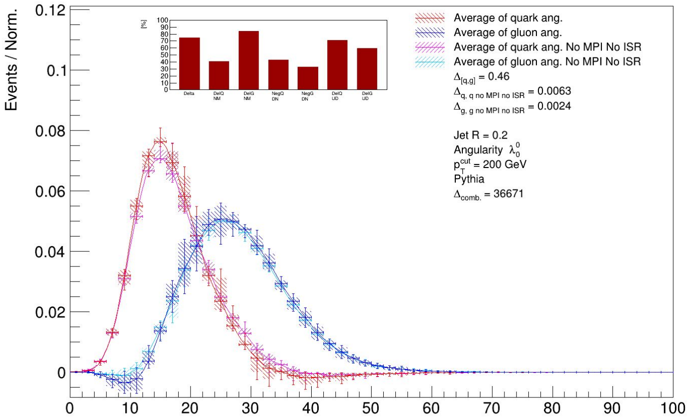
Best performing angularities: Width



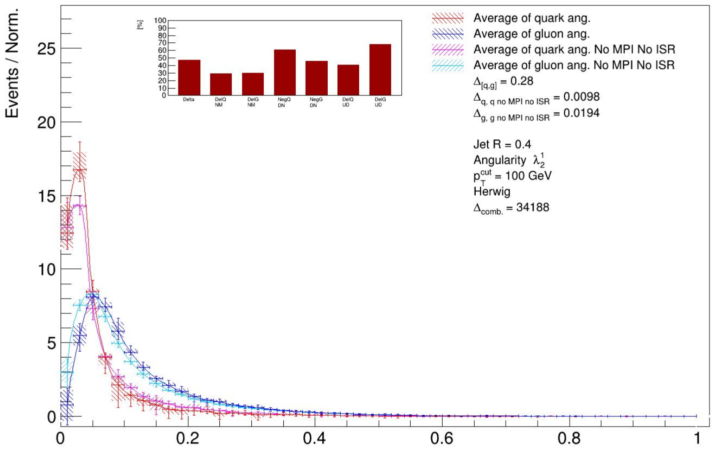


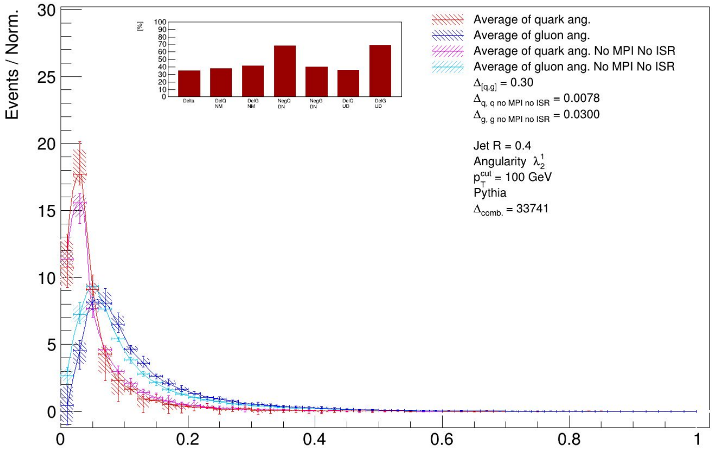
Wild cards (chosen by “eye”): multiplicity



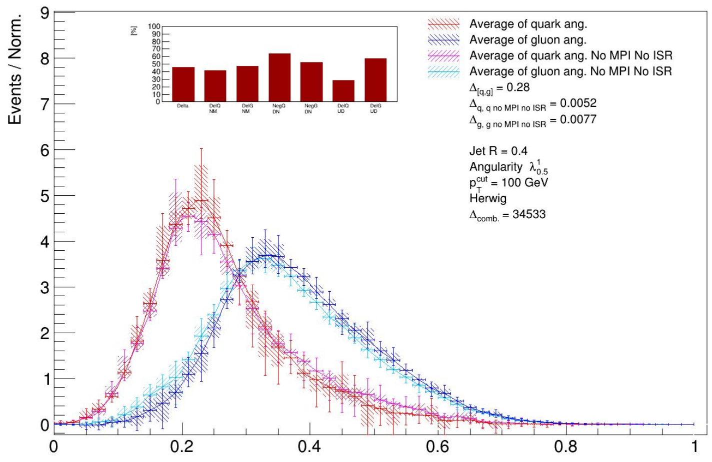


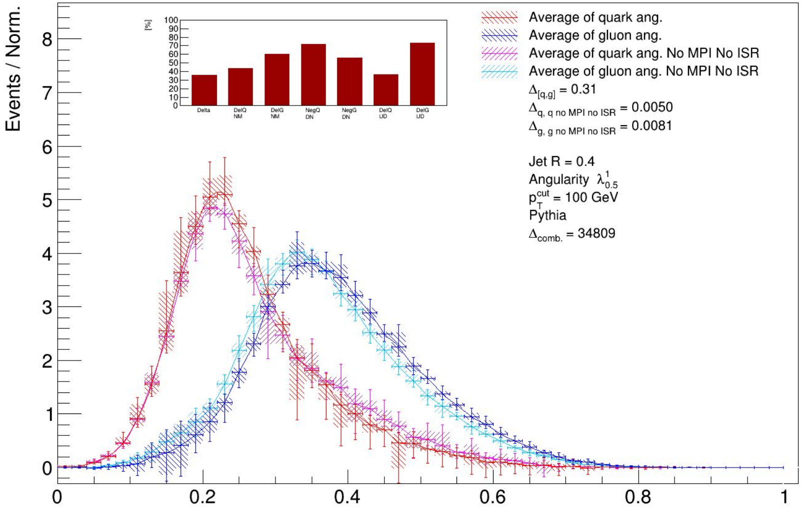
Wild cards (chosen by “eye”): mass



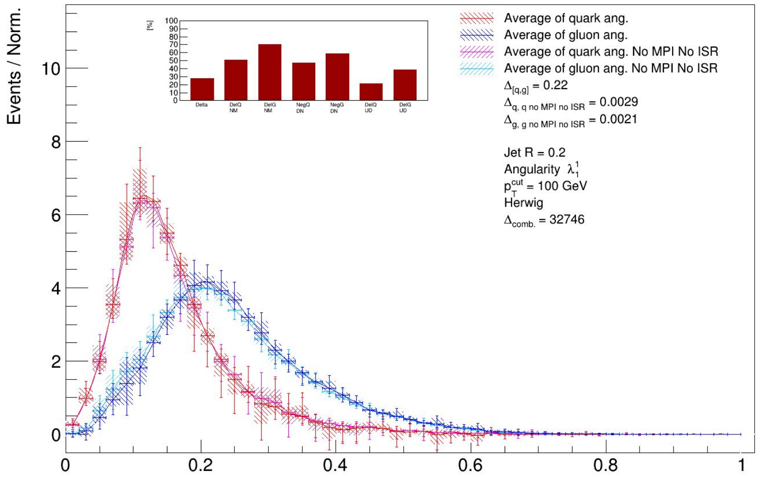


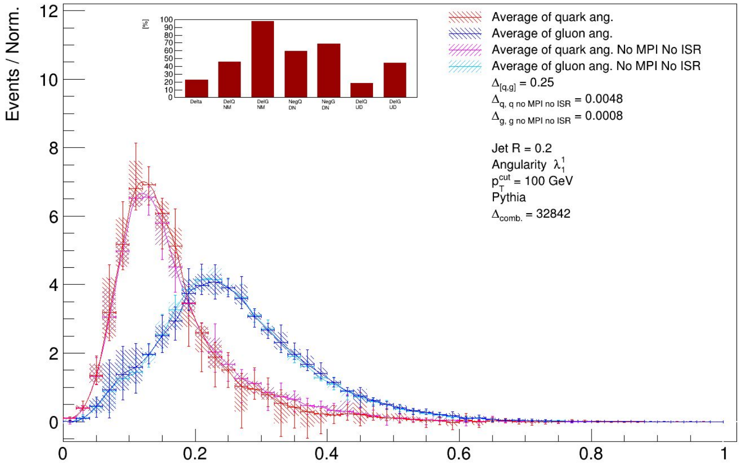
Wild cards (chosen by “eye”): LHA



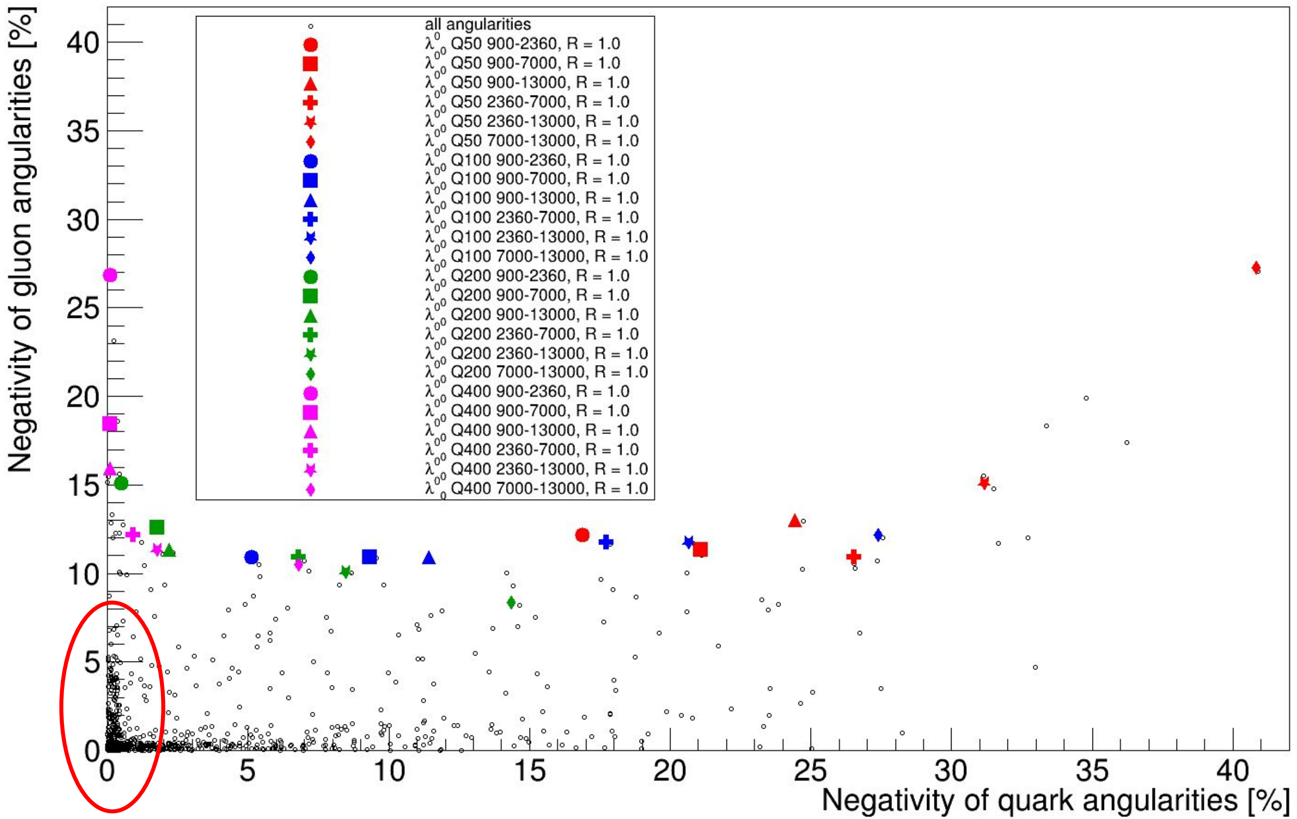


Wild cards (chosen by “eye”): width

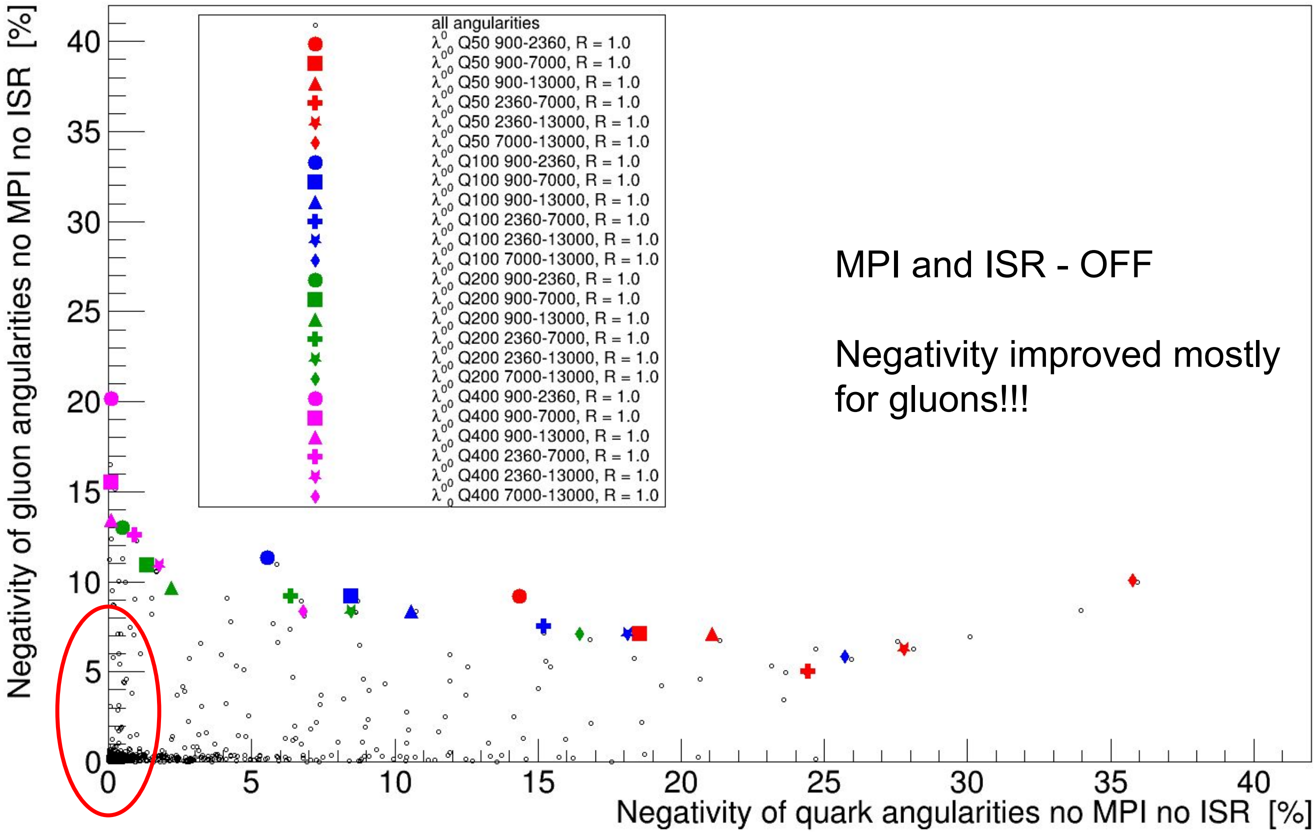




Back-up

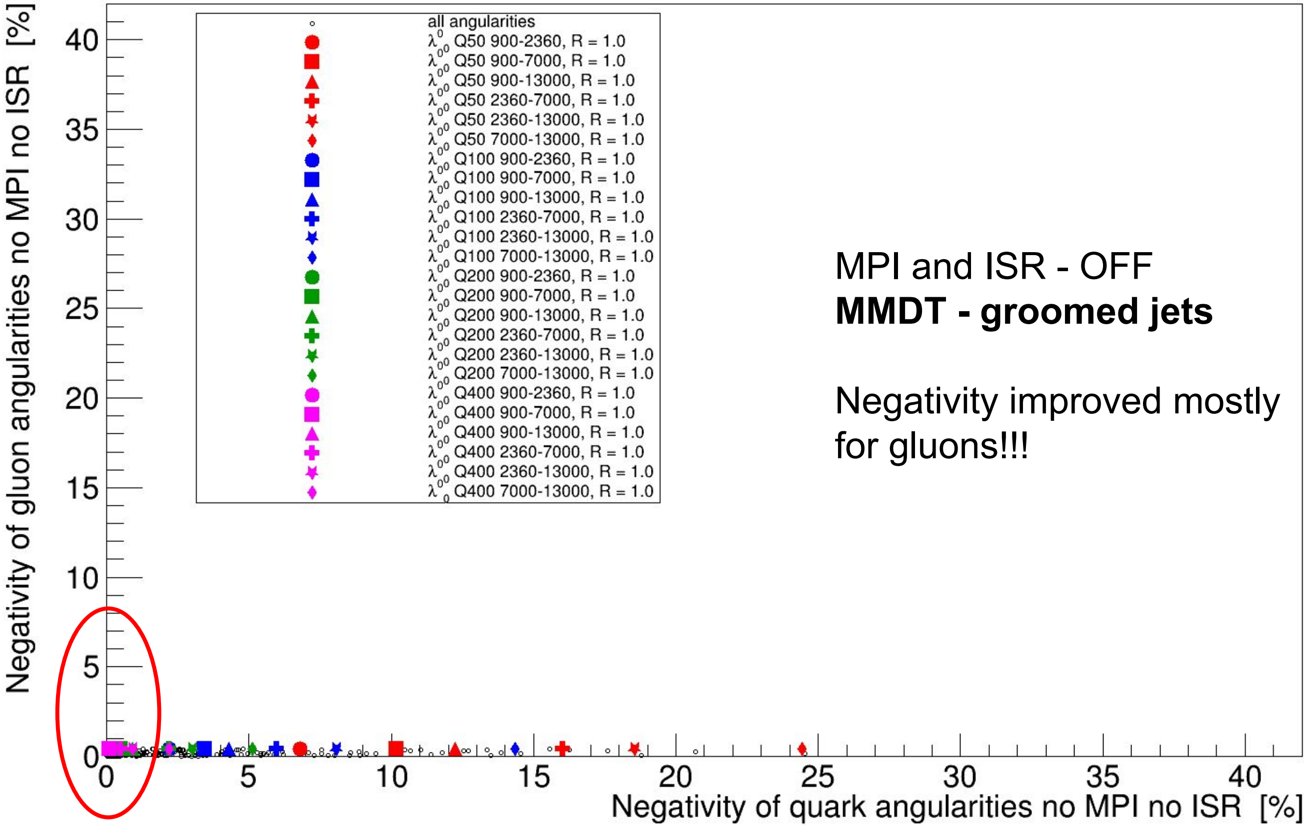


Negativity of gluon angularities [%]
Negativity of quark angularities [%]
all angularities
λ^0_0 Q50 900-2360, R = 1.0
λ^0_0 Q50 900-7000, R = 1.0
λ^0_0 Q50 900-13000, R = 1.0
λ^0_0 Q50 2360-7000, R = 1.0
λ^0_0 Q50 2360-13000, R = 1.0
λ^0_0 Q50 7000-13000, R = 1.0
λ^0_0 Q100 900-2360, R = 1.0
λ^0_0 Q100 900-7000, R = 1.0
λ^0_0 Q100 900-13000, R = 1.0
λ^0_0 Q100 2360-7000, R = 1.0
λ^0_0 Q100 2360-13000, R = 1.0
λ^0_0 Q100 7000-13000, R = 1.0
λ^0_0 Q200 900-2360, R = 1.0
λ^0_0 Q200 900-7000, R = 1.0
λ^0_0 Q200 900-13000, R = 1.0
λ^0_0 Q200 2360-7000, R = 1.0
λ^0_0 Q200 2360-13000, R = 1.0
λ^0_0 Q200 7000-13000, R = 1.0
λ^0_0 Q400 900-2360, R = 1.0
λ^0_0 Q400 900-7000, R = 1.0
λ^0_0 Q400 900-13000, R = 1.0
λ^0_0 Q400 2360-7000, R = 1.0
λ^0_0 Q400 2360-13000, R = 1.0
λ^0_0 Q400 7000-13000, R = 1.0



MPI and ISR - OFF

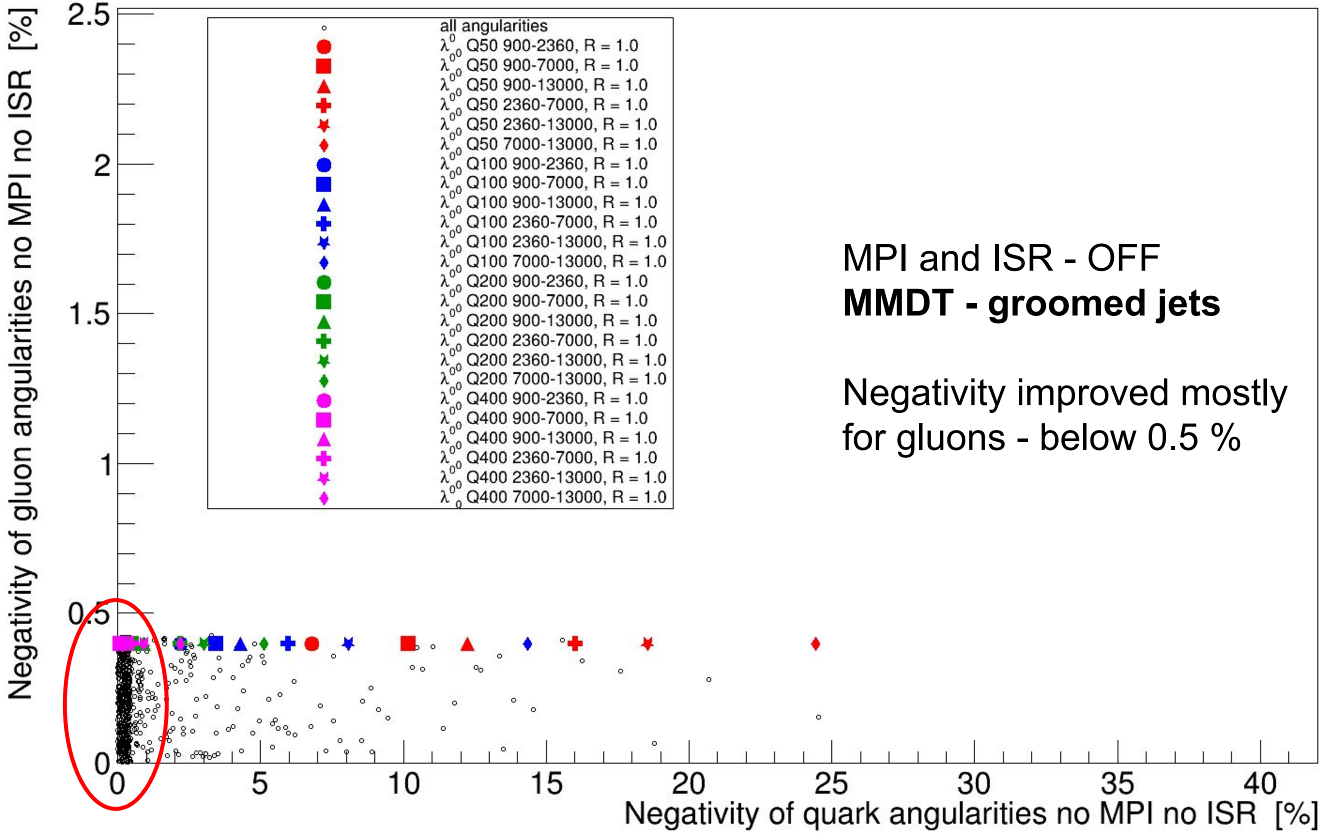
Negativity improved mostly for gluons!!!



MPI and ISR - OFF
MMDT - groomed jets

Negativity improved mostly for gluons!!!

ZOOMED



MPI and ISR - OFF
MMDT - groomed jets

Negativity improved mostly for gluons - below 0.5 %

Back-up

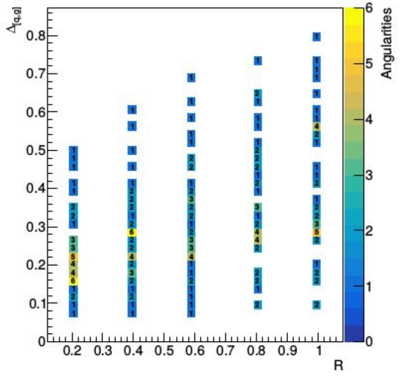


Fig. 19 First column scatter plot of $\Delta_{[q,g]}$ as a function of jet radius.

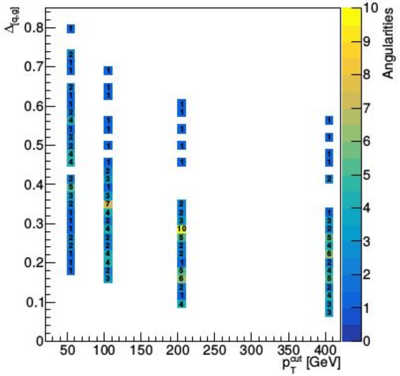


Fig. 21 First column scatter plot of $\Delta_{[q,g]}$ as a function of p_T^{cut}.

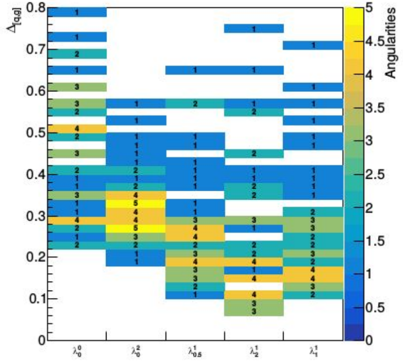


Fig. 20 First column scatter plot of $\Delta_{[q,g]}$ as a function of jet angularity.

Back-up

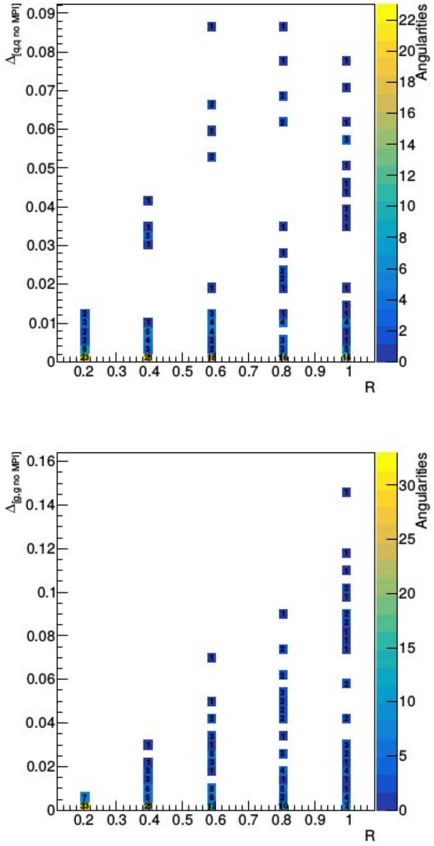


Fig. 22 Second/third column quark $\Delta_{[q,q\ \mathrm{noMPI}]}$ (top) and gluon $\Delta_{[g,g\ \mathrm{noMPI}]}$ (bottom) as a function of jet radius.

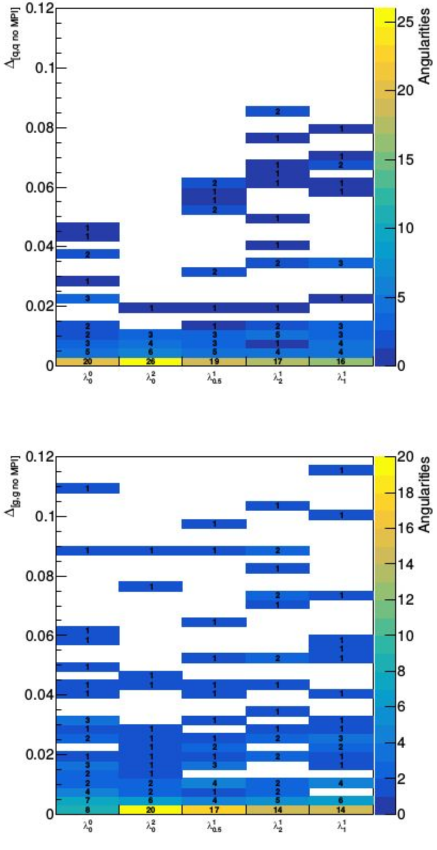


Fig. 23 Second/third column quark $\Delta_{[q,q\ \mathrm{noMPI}]}$ (top) and gluon $\Delta_{[g,g\ \mathrm{noMPI}]}$ (bottom) as a function of angularities.

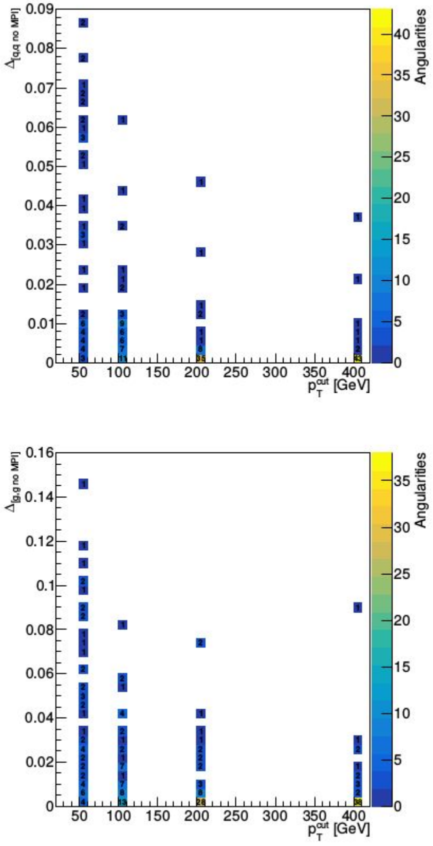


Fig. 24 Second/third column quark $\Delta_{[q,q\ \mathrm{noMPI}]}$ (top) and gluon $\Delta_{[g,g\ \mathrm{noMPI}]}$ (bottom) as a function of p_T^{cut}.

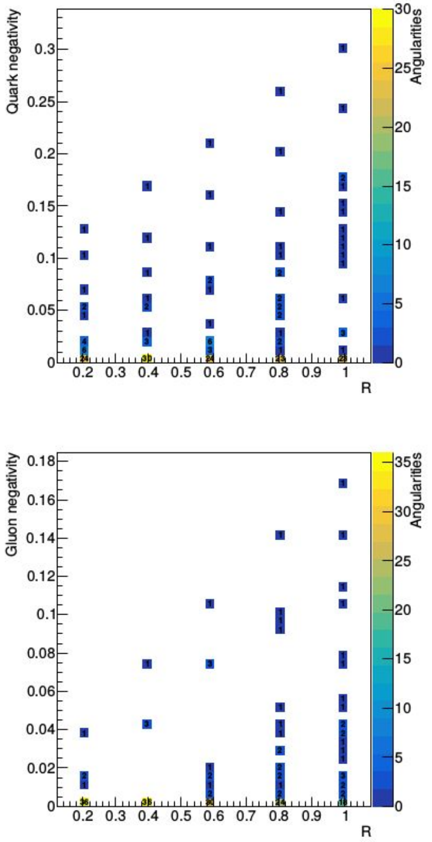


Fig. 25 Fourth/fifth column quark (top) and gluon negativity (bottom) as a function of jet radius.

Back-up

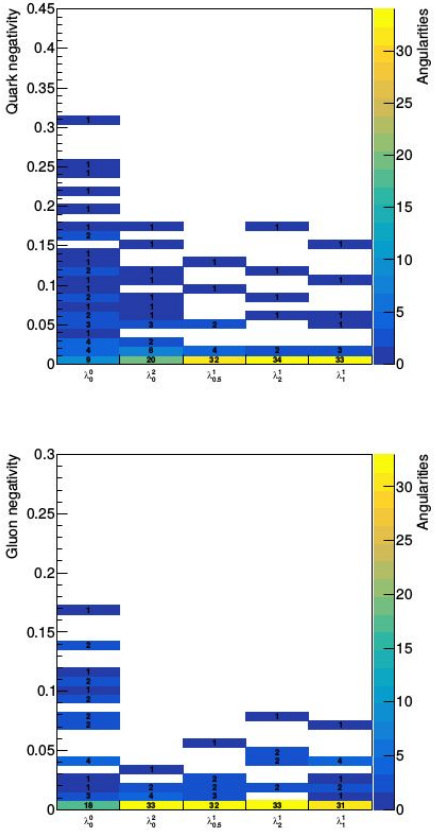


Fig. 26 Fourth/fifth column quark (top) and gluon negativity (bottom) as a function of angularities.

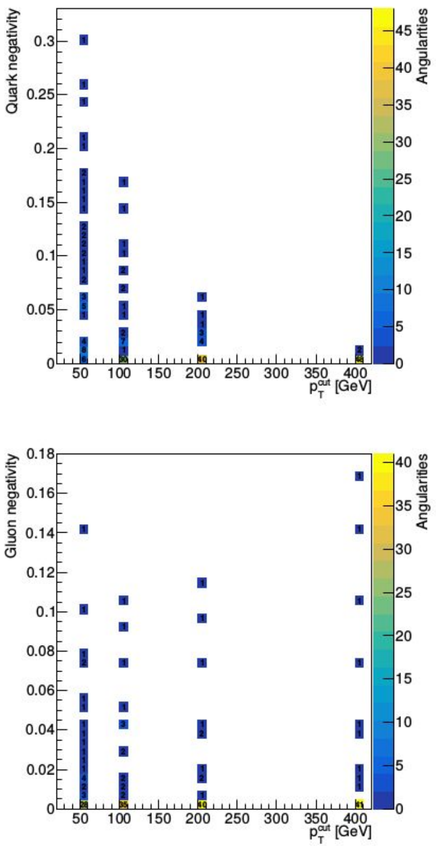


Fig. 27 Fourth/fifth column quark (top) and gluon negativity (bottom) as a function of p_T^{cut}.

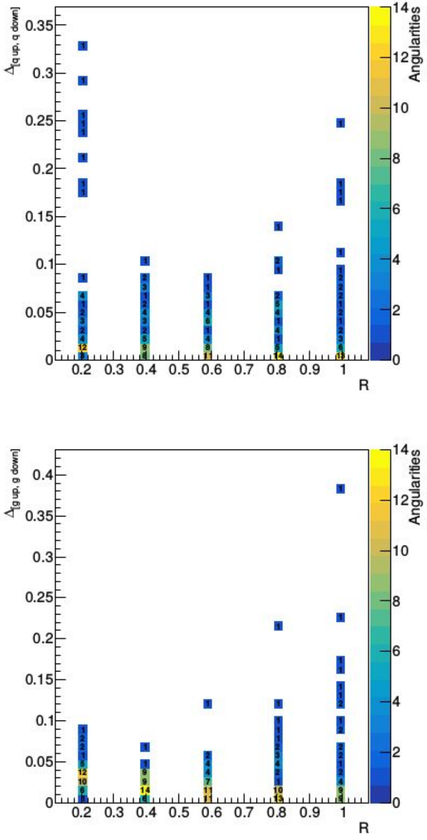


Fig. 28 Sixth/Seventh column quark $\Delta_{[q\ down, q\ up]}$ (top) and gluon $\Delta_{[g\ down, g\ up]}$ (bottom) as a function of jet radius.

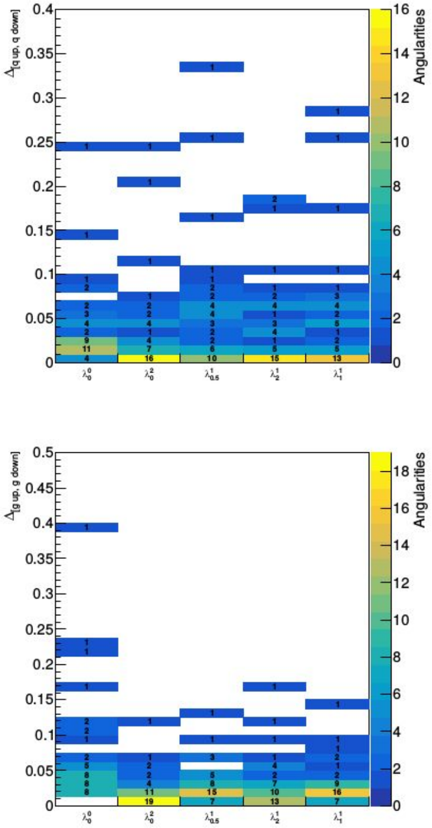
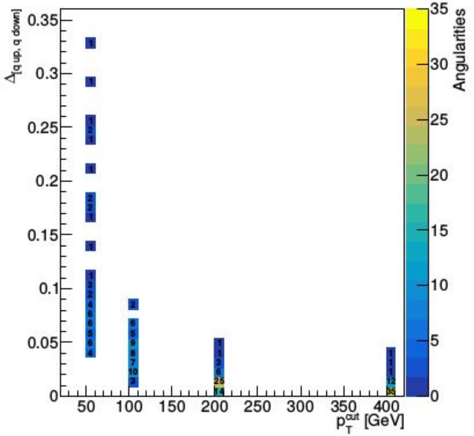


Fig. 29 Sixth/Seventh column quark $\Delta_{[q\ down, q\ up]}$ (top) and gluon $\Delta_{[g\ down, g\ up]}$ (bottom) as a function of angularities.



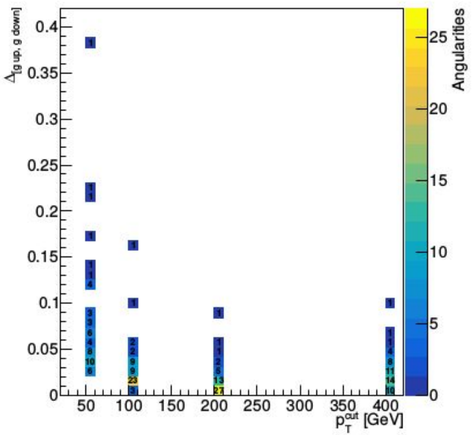
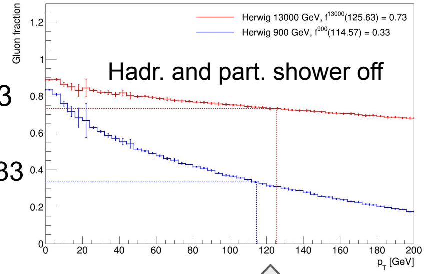


Fig. 30 Sixth/Seventh column quark $\Delta_{[q\ \mathrm{down}, q\ \mathrm{up}]}$ (top) and gluon $\Delta_{[g\ \mathrm{down}, g\ \mathrm{up}]}$ (bottom) as a function of p_T^{cut}.

Theory:



$f^{13000} = 0.73$

$f^{900} = 0.33$

Each angularitity λ is composed of gluon λ_g and quark λ_q angularities

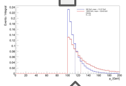
$$\boxed{\lambda = f\,\lambda_g + (1 - f)\,\lambda_q}$$

where

f ... gluon fraction

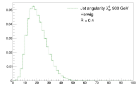
$(1 - f)$ ... quark fraction

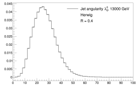
taken from simulation



$p_T^{cut} = 100$ GeV

Let's write equations for measurement at energy 900 GeV and 13 000 GeV (with the same event selection)





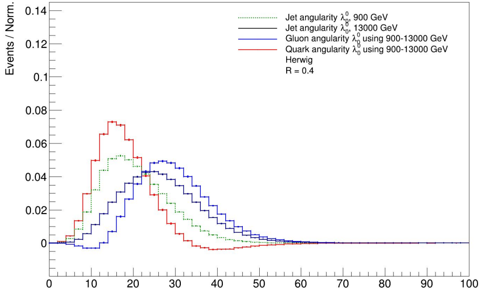
$$\lambda^{900} = f^{900}\,\lambda_g + (1 - f^{900})\lambda_q$$

$$\lambda^{13000} = f^{13000}\,\lambda_g + (1 - f^{13000})\lambda_q$$

Assuming λ_g and λ_q are energy independent.

$$\lambda_g = \frac{(1 - f^{13000})\lambda^{900} - (1 - f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$$

$$\lambda_q = \frac{f^{900}\lambda^{13000} - f^{13000}\lambda^{900}}{f^{900} - f^{13000}}$$



What is a Quark Jet?

From lunch/dinner discussions

[slide by Jesse Thaler]

Ill-Defined	What people sometimes think we mean	
		A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
	Quark as noun	An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard matrix element in the context of a factorization theorem
		A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)
	Quark as adjective	A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)
Well-Defined	What we mean	