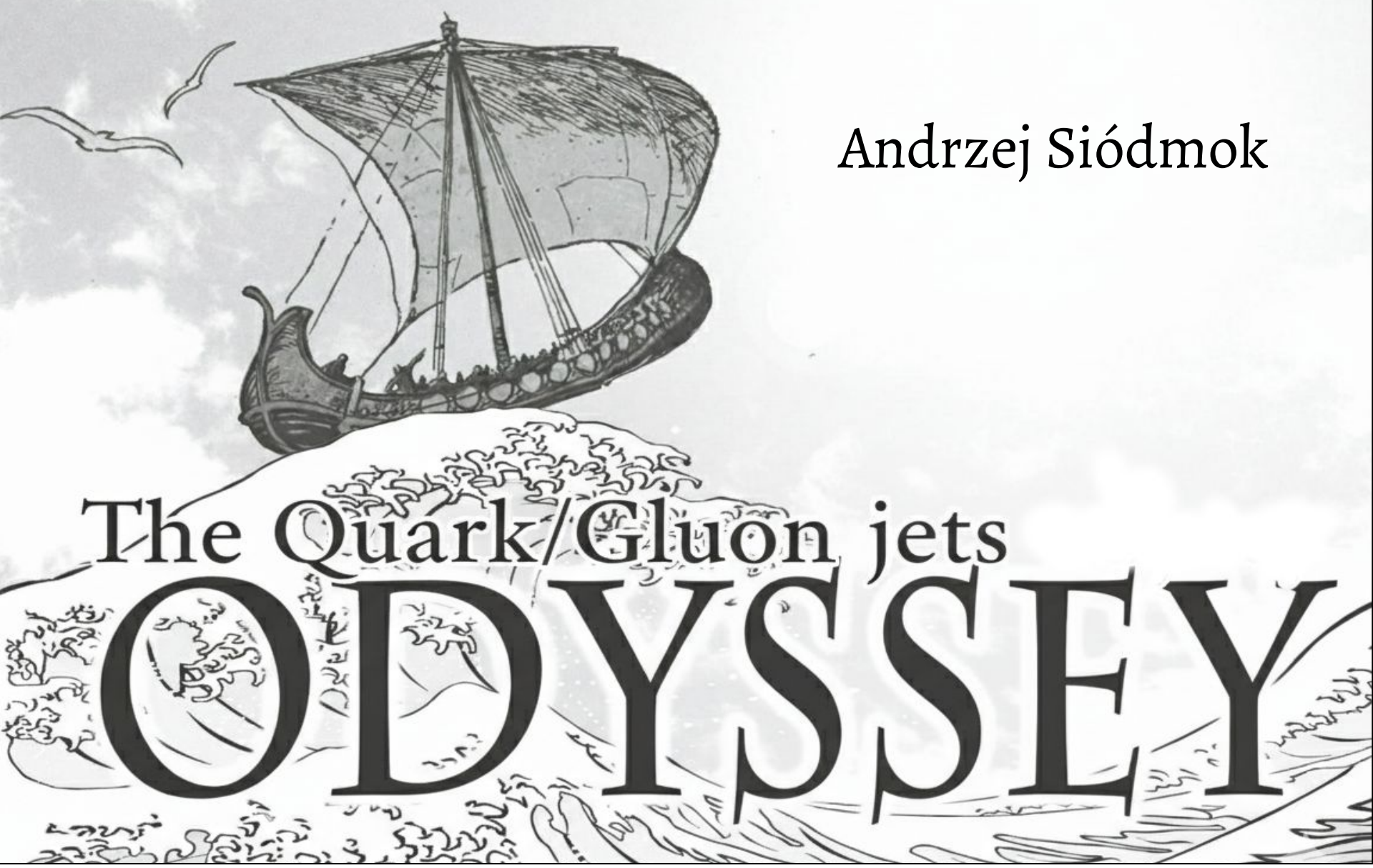

The Quark/Gluon jets ODYSSEY

Andrzej Siódmok

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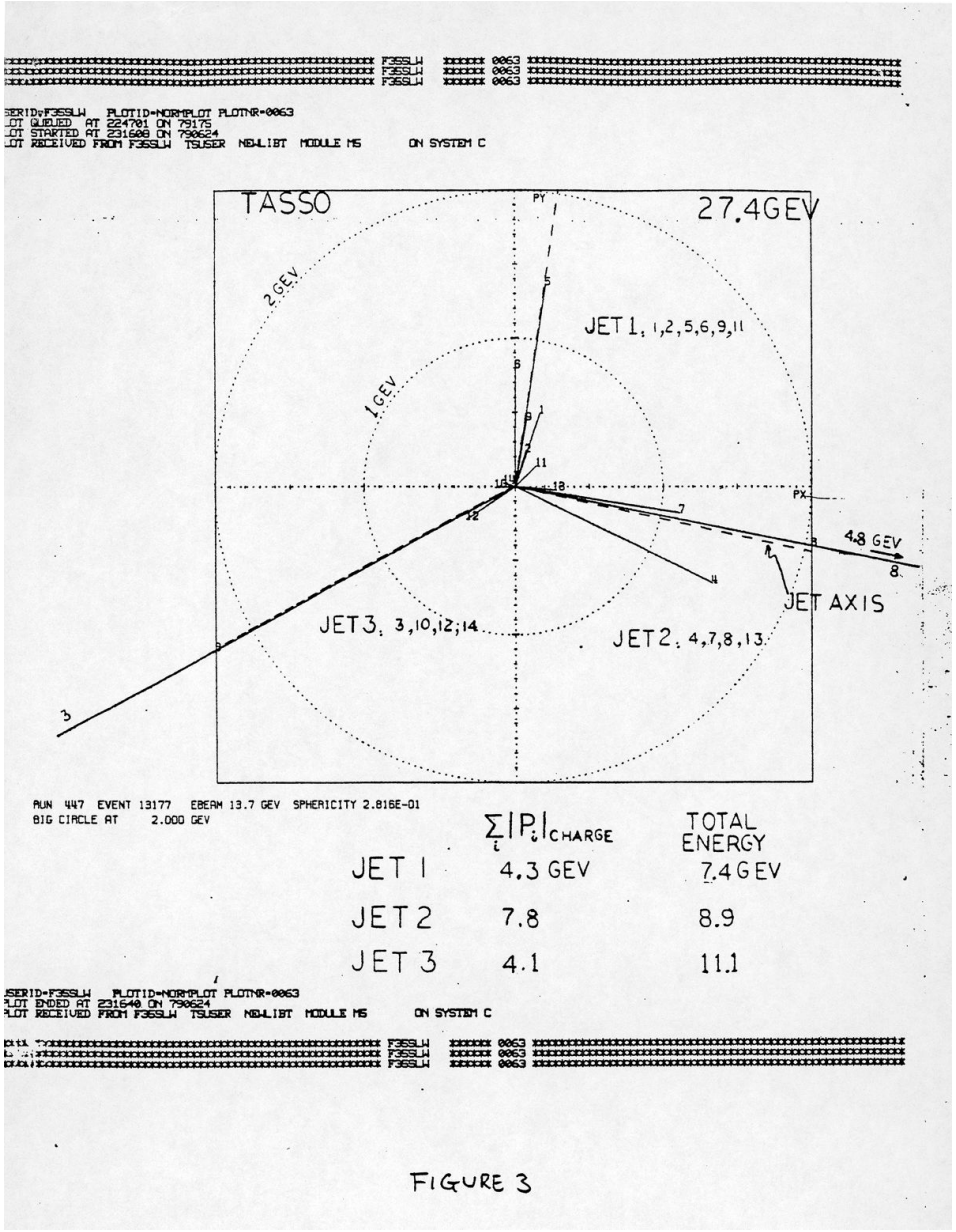
UCZELNIA BADAWCZA INICJATYWA DOSKONAŁOŚCI
NARODOWE CENTRUM NAUKI
NCN: 2019/34/E/ST2/00457
H7
MCnet
OpenMAPP

The Quark/Gluon jets Odyssey

Chapters:

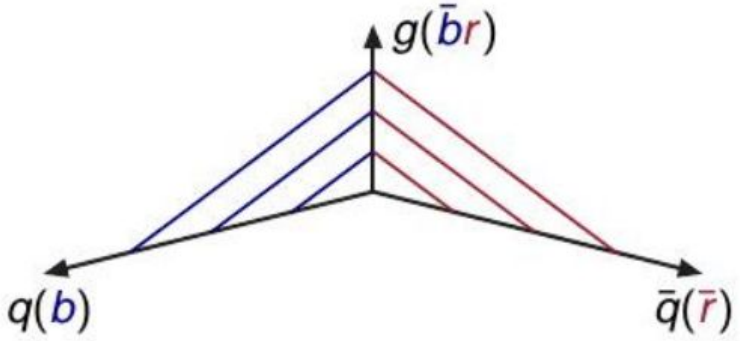
1. The beginning of the journey
2. Les Houches Mountain
3. Lost in colors but reconnected
4. Energy is our hope!
5. 100 meters underground

1. The beginning of the journey



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 DESY, the graphic shows three jets of particles produced in an electron-positron collision.



Distinguish Q/G jets as is old as gluon's discovery

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)

Why we would like to distinguish Q/G jets?

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:

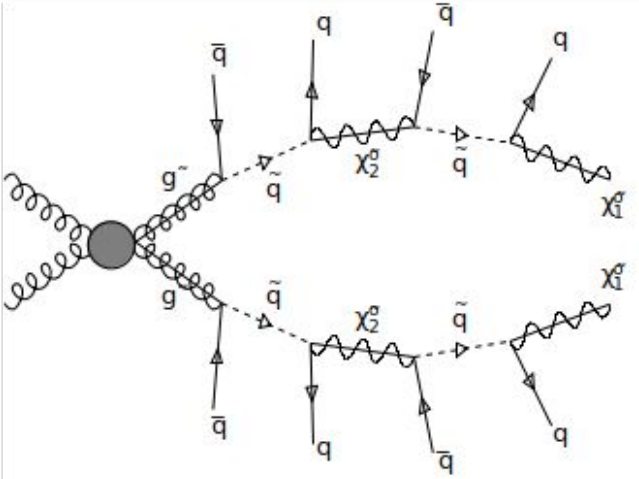
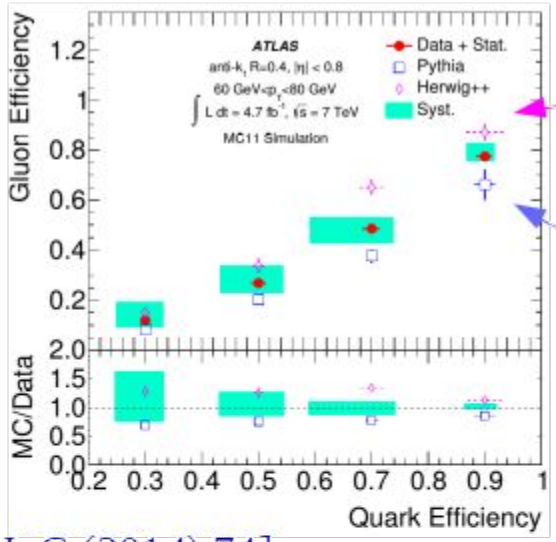


Fig. From J. Gallicchio and M. D. Schwartz, Phys. Rev. Lett.107 (2011)

- 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')

LHC Q/G jet measurement

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



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.

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

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

Chapter 2. Les Houches Mountain

JHEP

Published for SISSA by Springer

Received: *May 2, 2017*
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Published: *July 18, 2017*

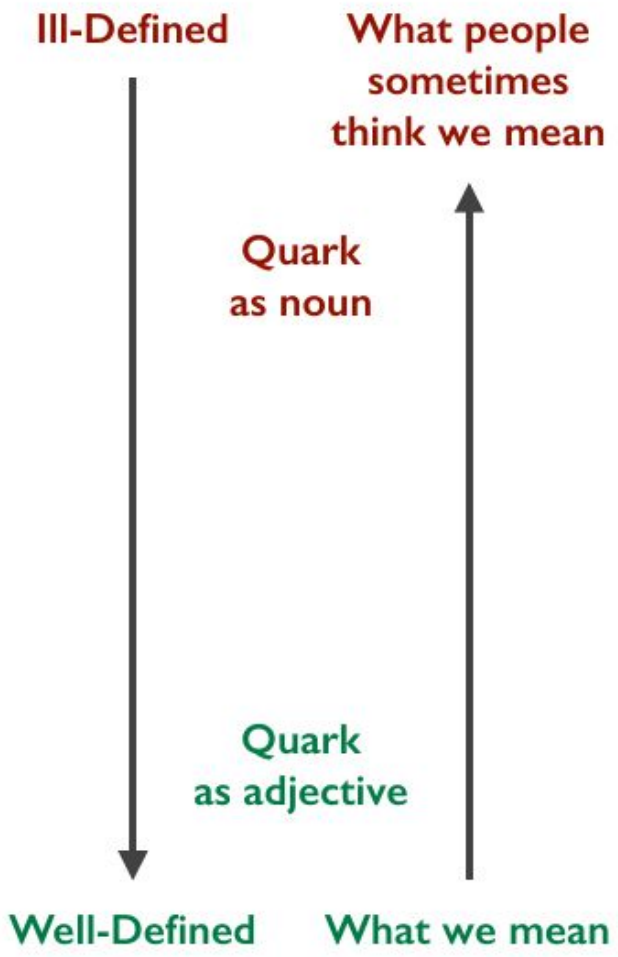
Systematics of quark/gluon tagging

Philippe Gras,[a] **Stefan Höche,**[b] **Deepak Kar,**[c] **Andrew Larkoski,**[d] **Leif Lönnblad,**[e] **Simon Plätzer,**[f,g] **Andrzej Siódmok,**[h,i] **Peter Skands,**[j] **Gregory Soyez**[k,1] **and Jesse Thaler**[l,1]

What is a Quark Jet?

From lunch/dinner discussions

[slide by Jesse Thaler]



A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

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)

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)

Chapter 2. Les Houches Mountain

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

Cartoon:

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

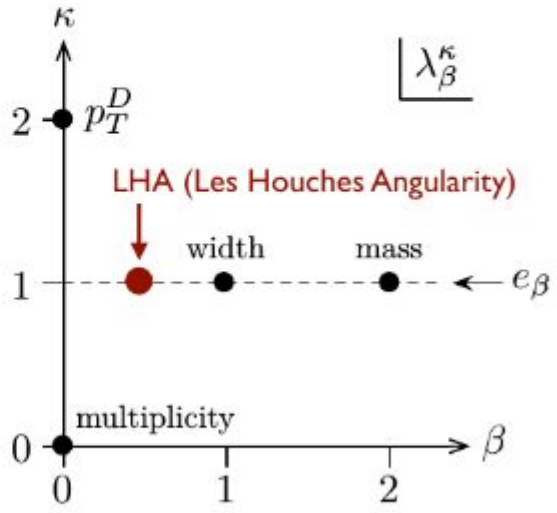
Probe radiation pattern with
e.g. Generalized Angularities

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

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]

Chapter 2. Les Houches Mountain

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

Framework

Processes:

- Quark: $e^+e^- \to (\gamma/Z)^* \to u\bar{u}$
- Gluons: $e^+e^- \to H^* \to gg$

Different Monte-Carlo generators at parton and hadron level:

- Pythia 8 (v8.205)
- Herwig++ (v2.7.1)
- Sherpa (v2.1.1)

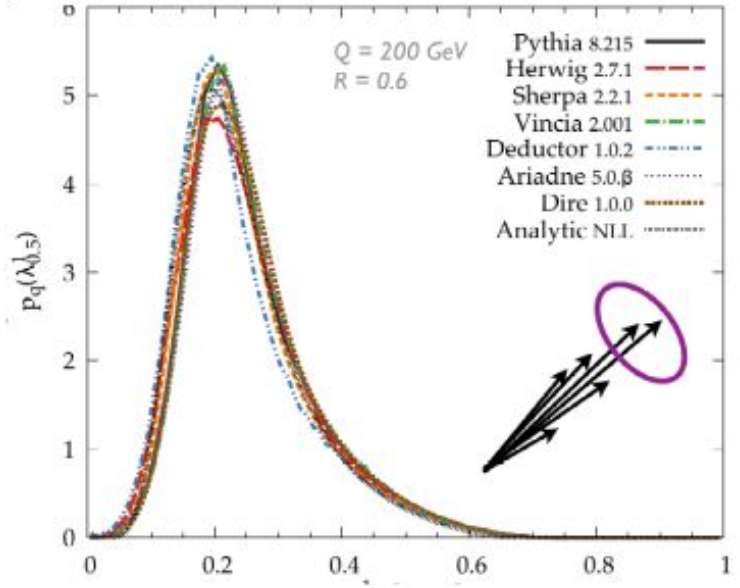
Additionally different Parton Shower algorithms

- Vincia (v1.201 - plugin to Pythia)
- Deductor (v1.0.2 + hadronization from Pythia)
- Ariadne (v5.0.β + hadronization from Pythia)

Q/G jets Les Houches study

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

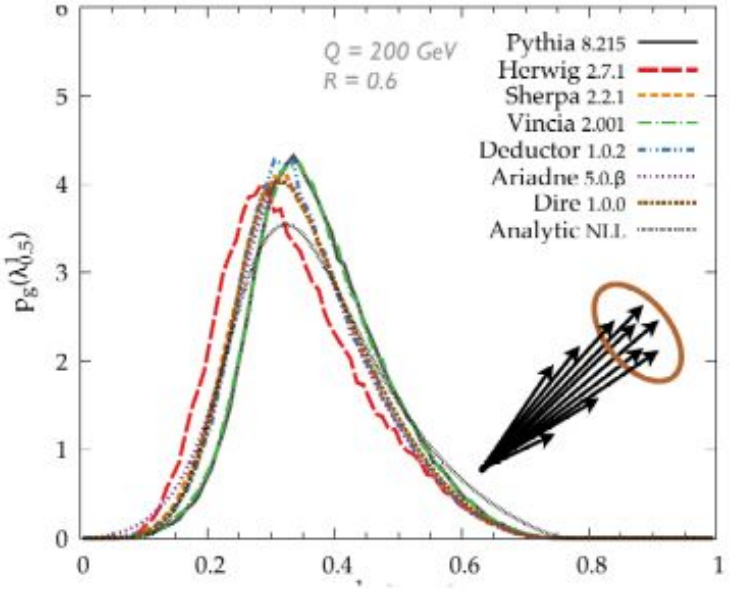
$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)



$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Small spread

Constrained by LEP



$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Large spread

Up to now no e+e- data has been used to constrain it.

Direction: Colour reconnections effects surprisingly very important!

Chapter 3. Lost in colors but reconnected

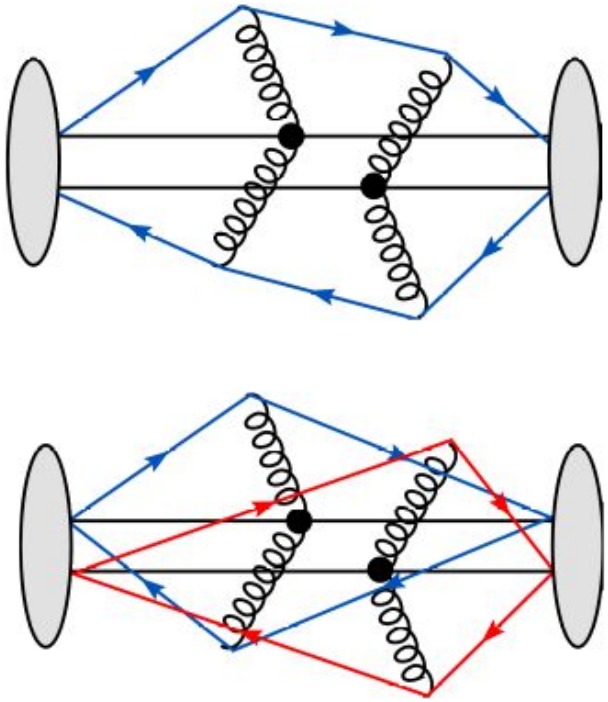
Improving the Simulation of Quark and Gluon Jets with Herwig 7

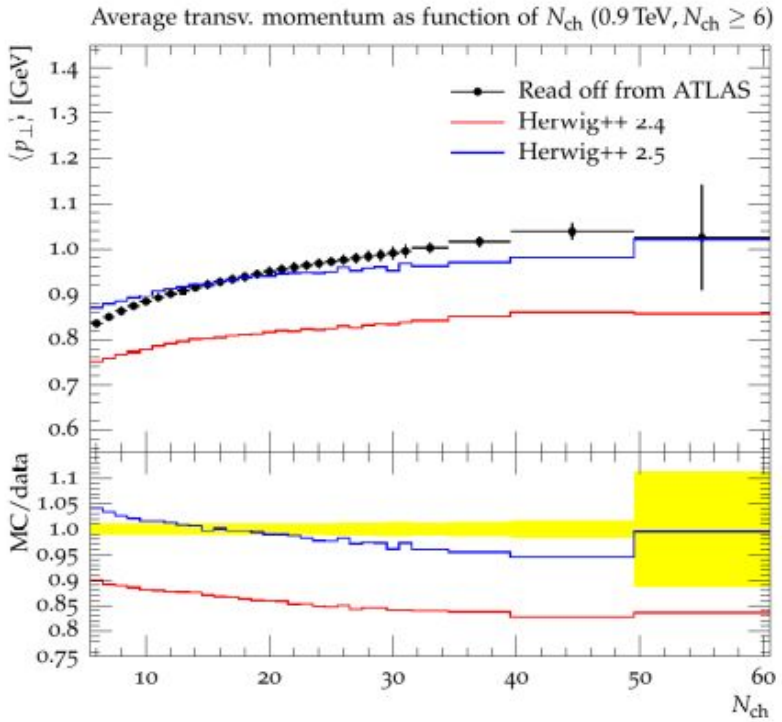
Daniel Reichelt (Dresden, Tech. U.), Peter Richardson (CERN and Durham U., IPPP), Andrzej Siodmok (Cracow, INP) (Aug 4, 2017)

Published in: *Eur.Phys.J.C* 77 (2017) 12, 876 • e-Print: 1708.01491 [hep-ph]

Colour reconnection

- The least understood part of the Multiple Particle Interaction models.
- Needed to describe the Underlying Event and Min Bias data (sensitive to MPI phenomena)
- Crucial to constrain it, important for top mass, g/q gluon, ...





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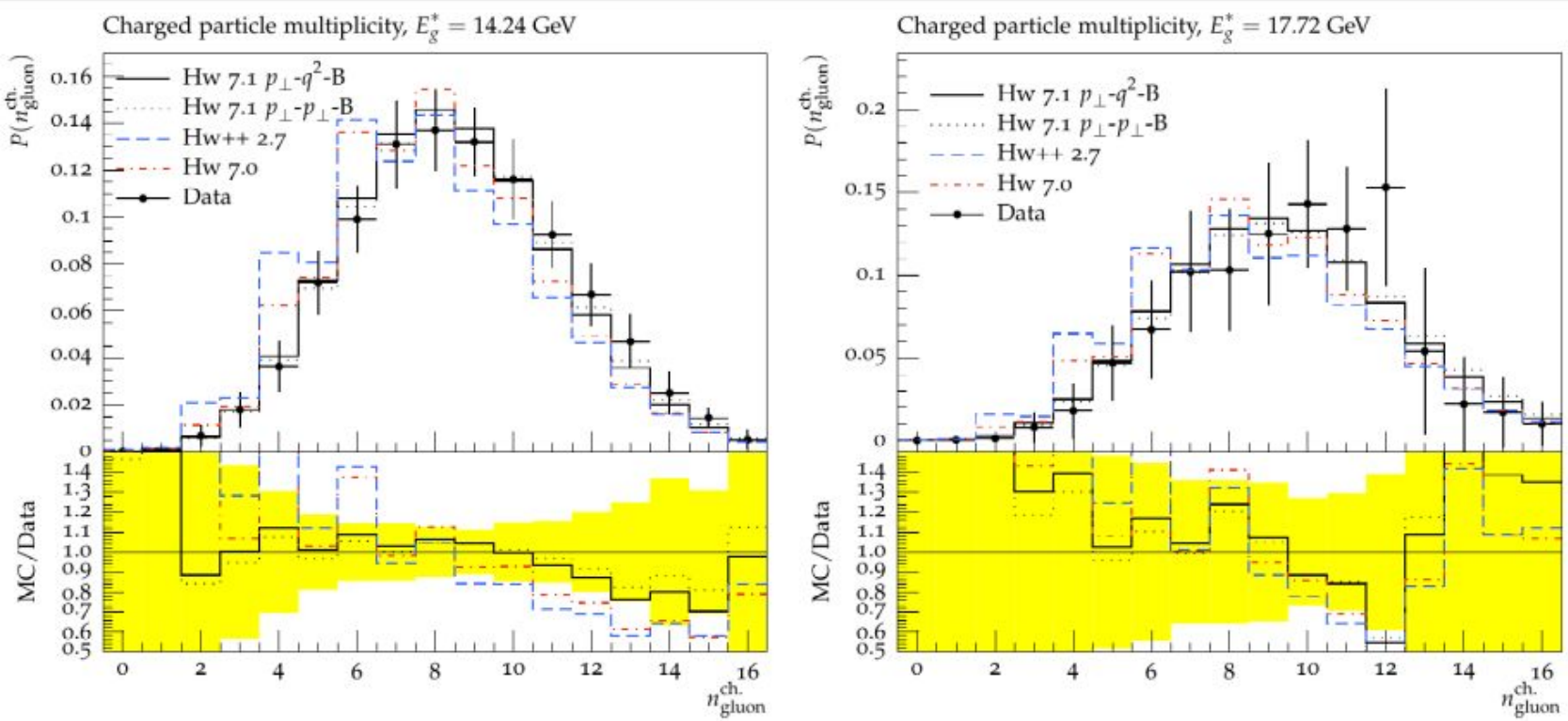
Published in: *Eur.Phys.J.C* 77 (2017) 12, 876 • e-Print: 1708.01491 [hep-ph]

Preservation of the data/analyses is crucial!

Multiplicity distribution of charged particles in gluons jets for two different gluon energies.



Data was one of the **key for the improvement** and it is still needed for the progress. However it is hard to measure "clear" q/g samples at the LHC.

How we improved simulation of Q/G jets in Herwig?

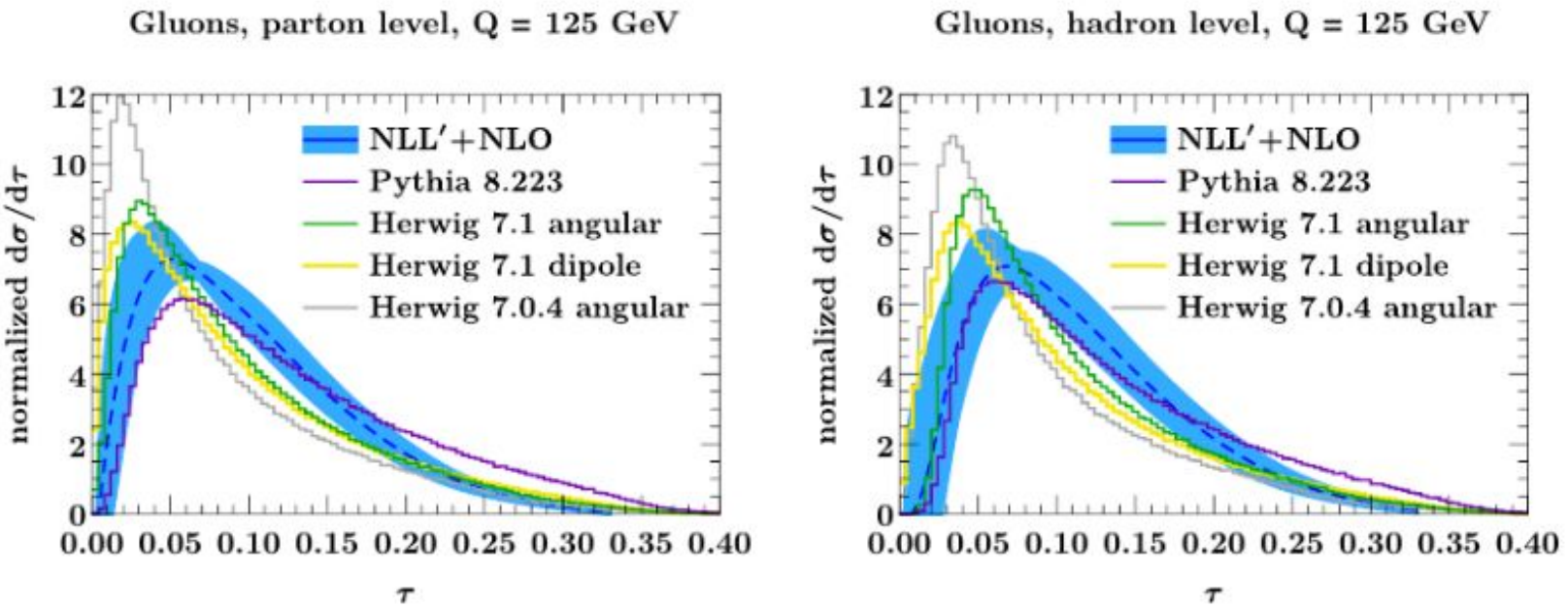
A case study of quark-gluon discrimination at NNLL' in comparison to parton showers #3

Jonathan Mo (Amsterdam U. and NIKHEF, Amsterdam), Frank J. Tackmann (DESY), Wouter J. Waalewijn (NIKHEF, Amsterdam and Amsterdam U.)
(Aug 2, 2017)

Published in: *Eur.Phys.J.C* 77 (2017) 11, 770 • e-Print: 1708.00867 [hep-ph]

Thrust - similar to general angularity (1,2) but not restricted to particles in a jet.

$$T = \max_{\hat{t}} \frac{\sum_i |\hat{t}\cdot\vec{p}_i|}{\sum_i |\vec{p}_i|}, \quad \tau = 1 - T$$

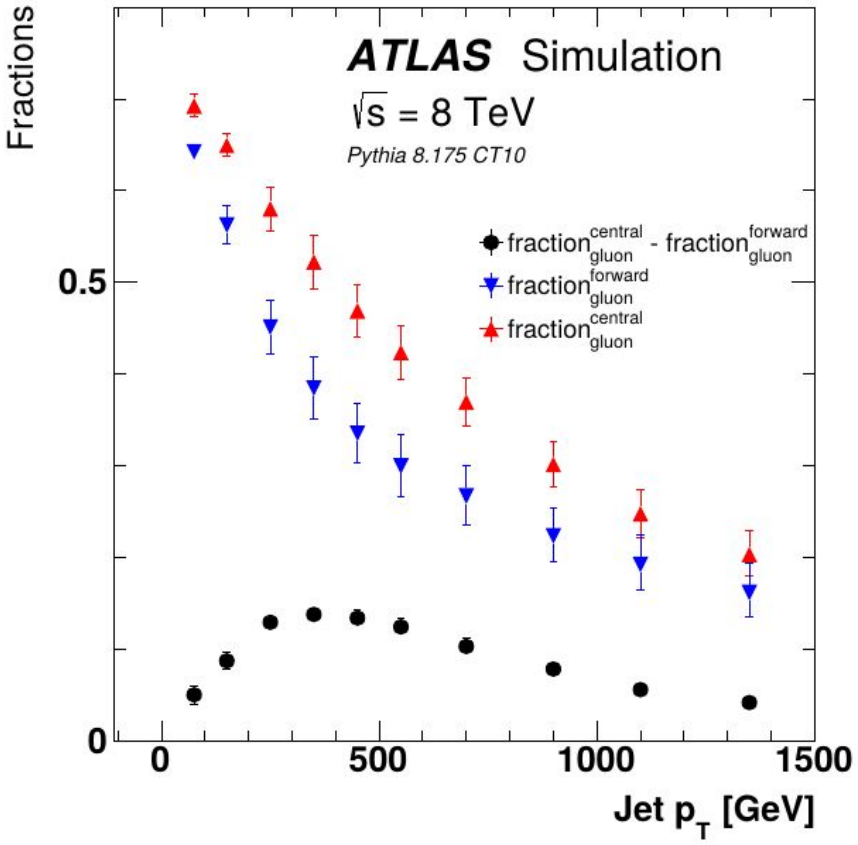


"This highlights the substantial improvement in the description of gluon jets in the latest version of Herwig"

LHC how to define gluon enhanced sample

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

ATLAS Collaboration (Apr 11, 2017)



Using phase space cuts, for example:

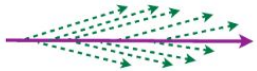
- Pt - jet transverse momentum
- η - jet rapidity (central/forward)

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

Same Pt Quark and Gluon

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

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



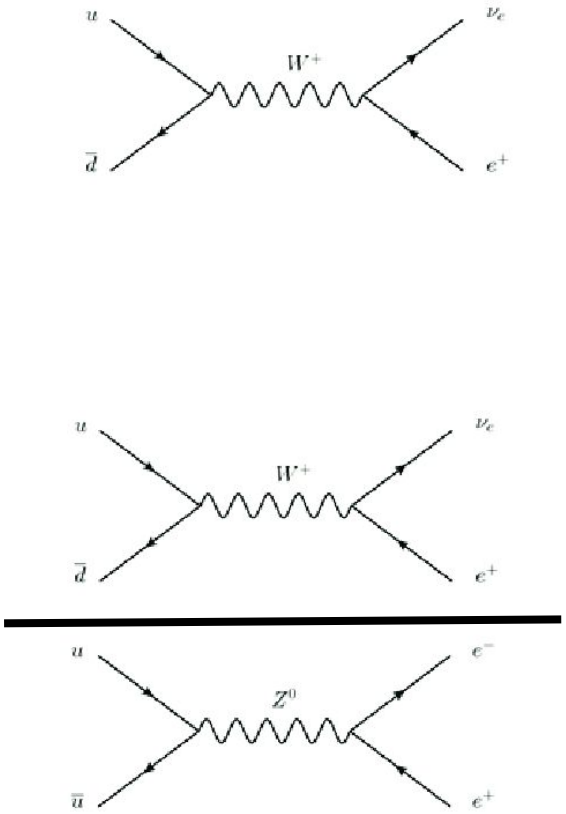
Quark: $C_F = 4/3$

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

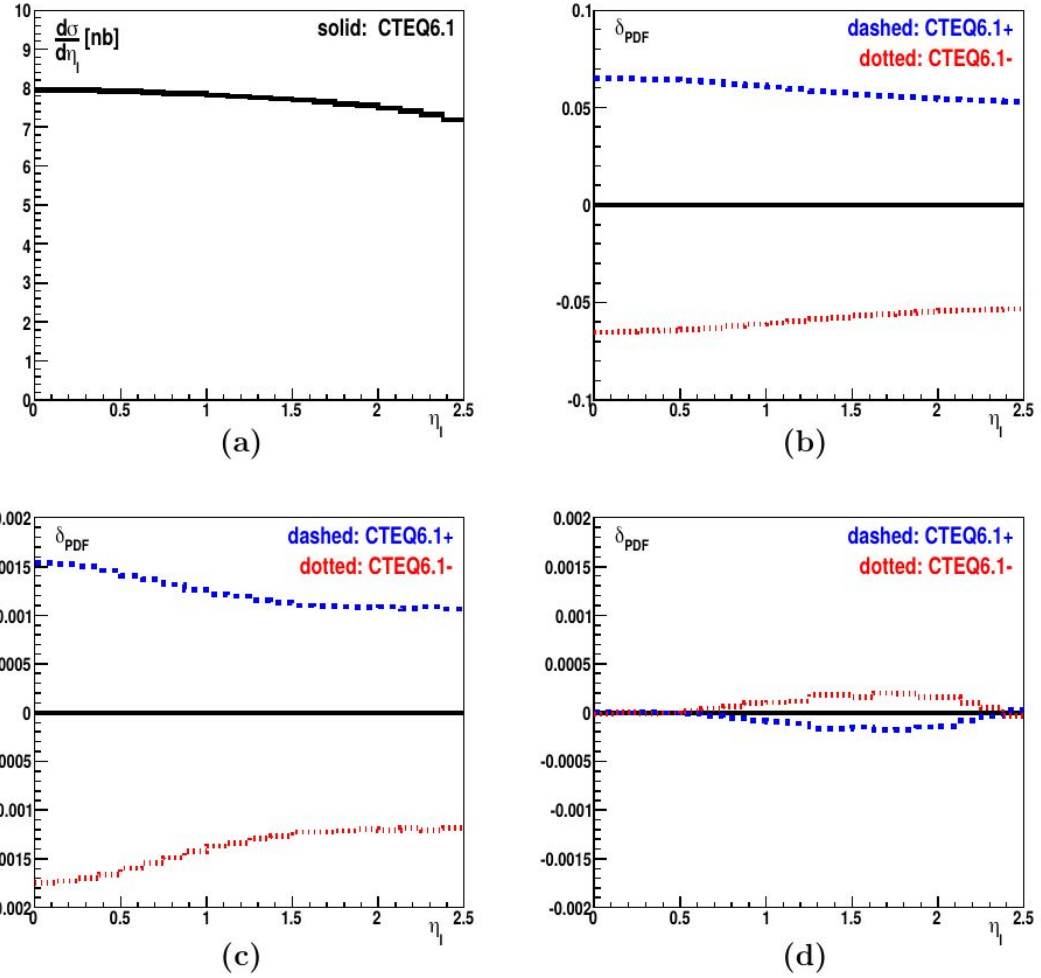
Chapter 4. Energy is our hope!

Z boson as "the standard candle" for high-precision W-boson physics at LHC

[Krasny, Fayette, Płaczek, AS, Eur.Phys.J. C51 (2007) 607-617]



Collect data at the two CM-energies:
$\sqrt{s_1}$ and $\sqrt{s_2} = (M_Z/M_W) \times \sqrt{s_1}$.
Run light isoscalar beams at LHC



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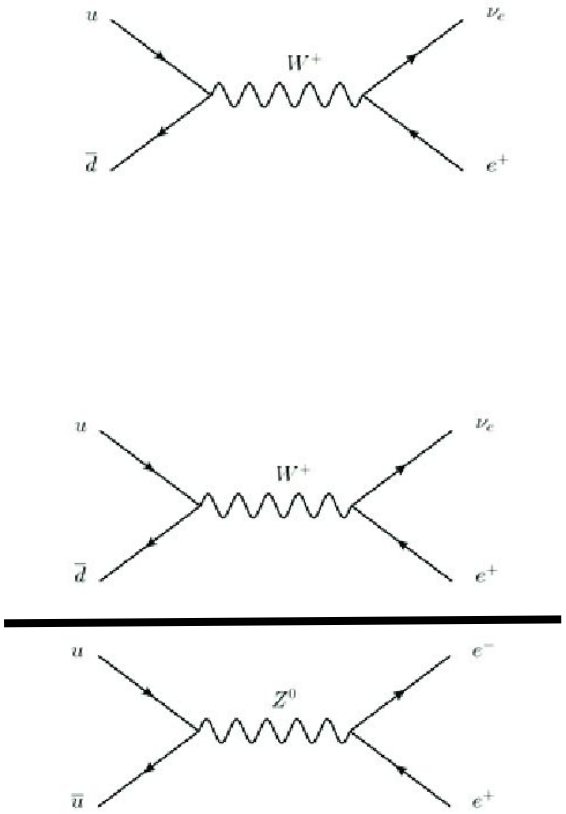

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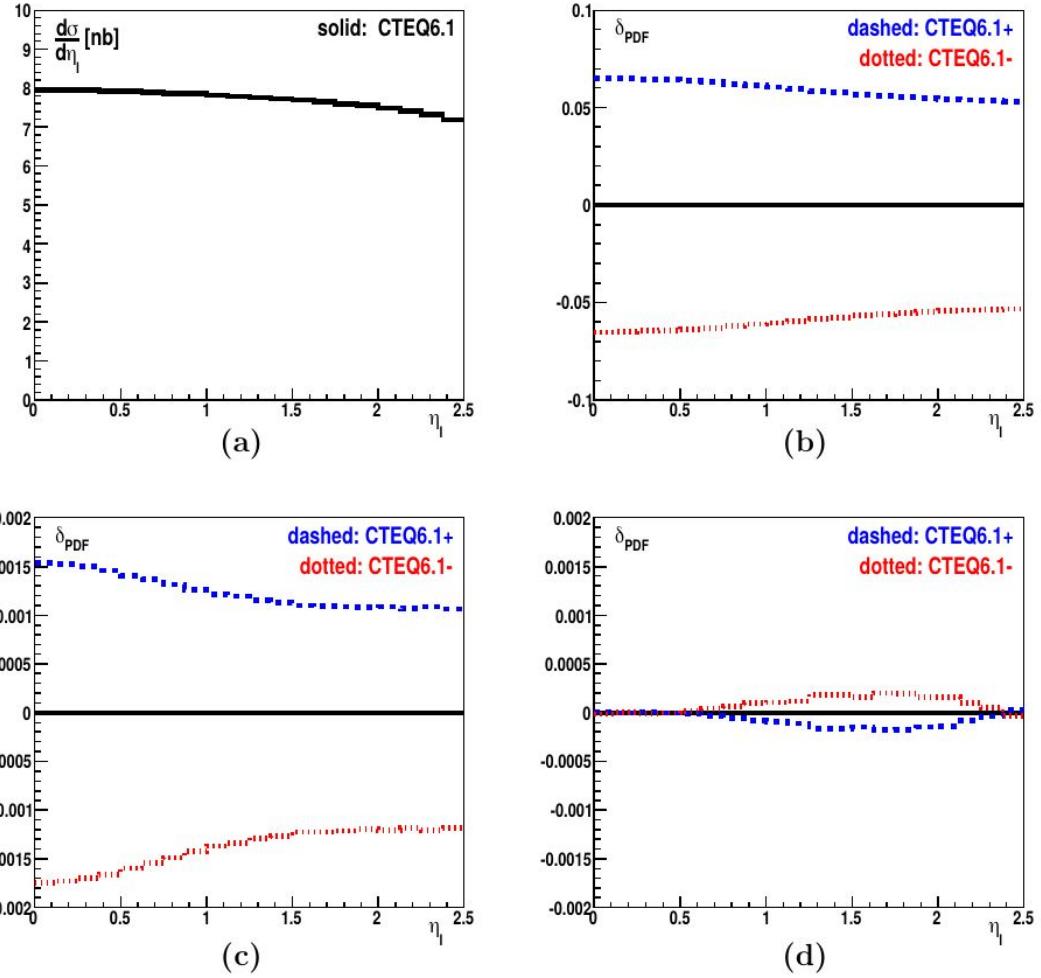
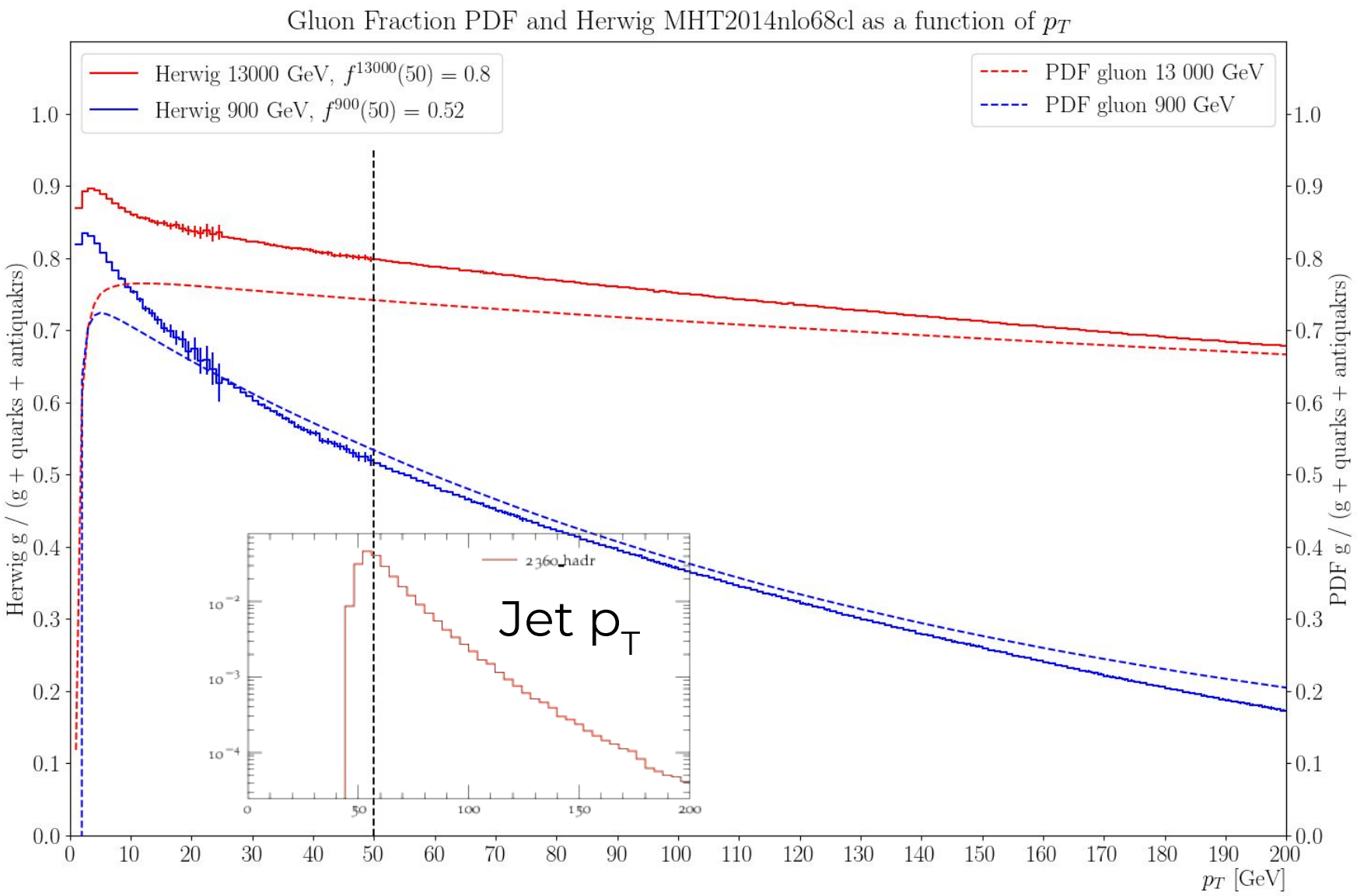
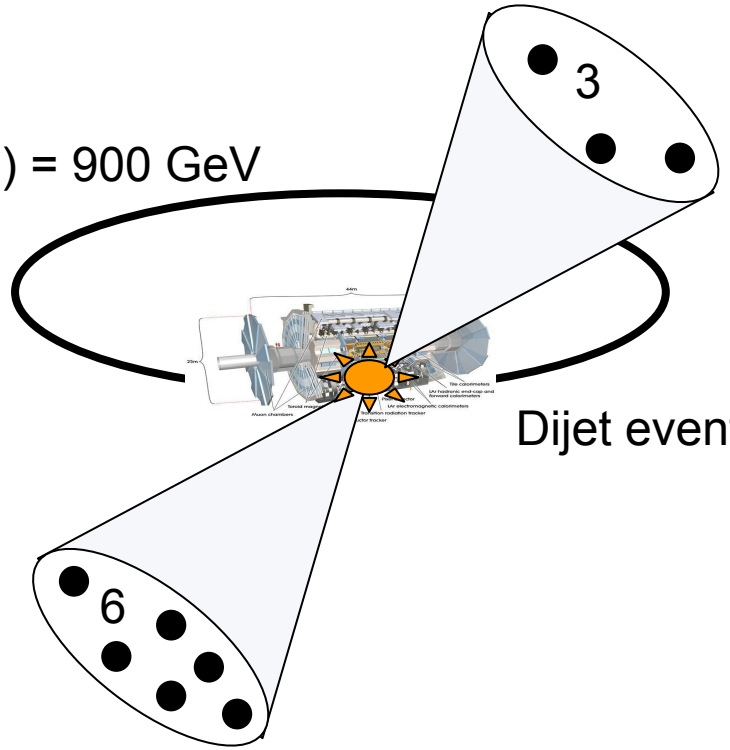


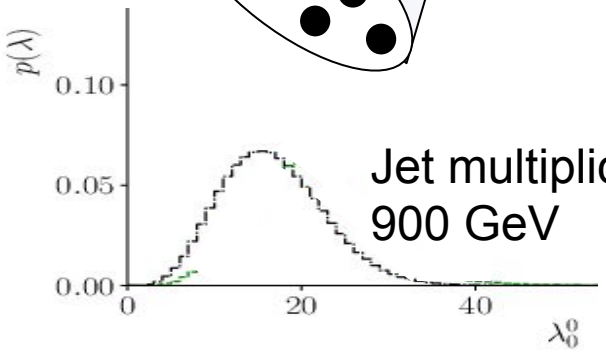
Yes it can!
Sadly not very used up to now at the LHC

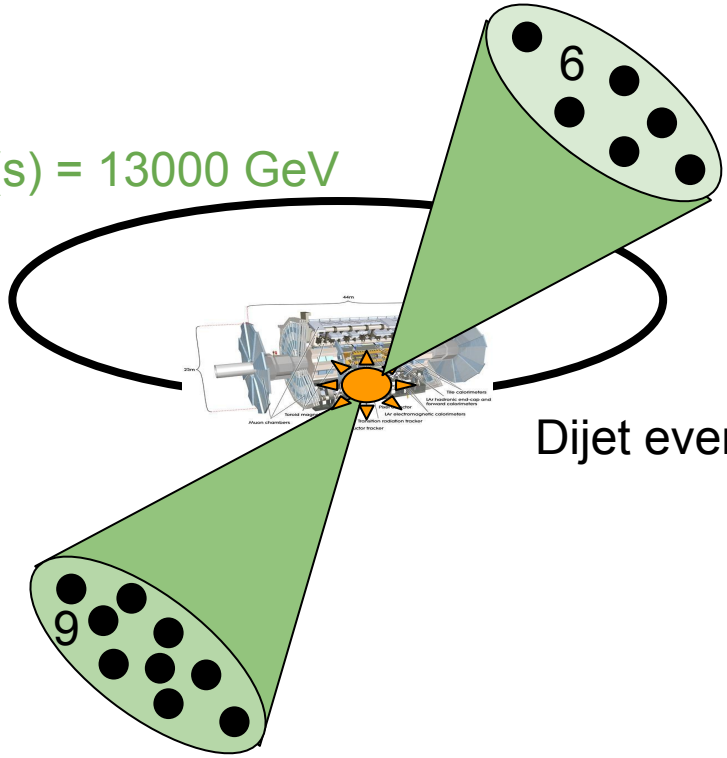
Measurement at different energy

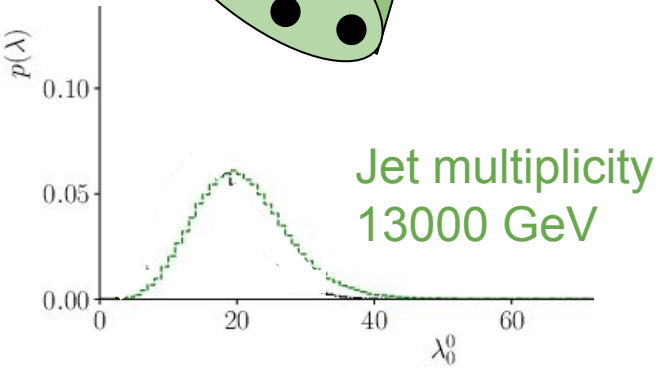


Novel approach to measure quark/gluon jets at the LHC





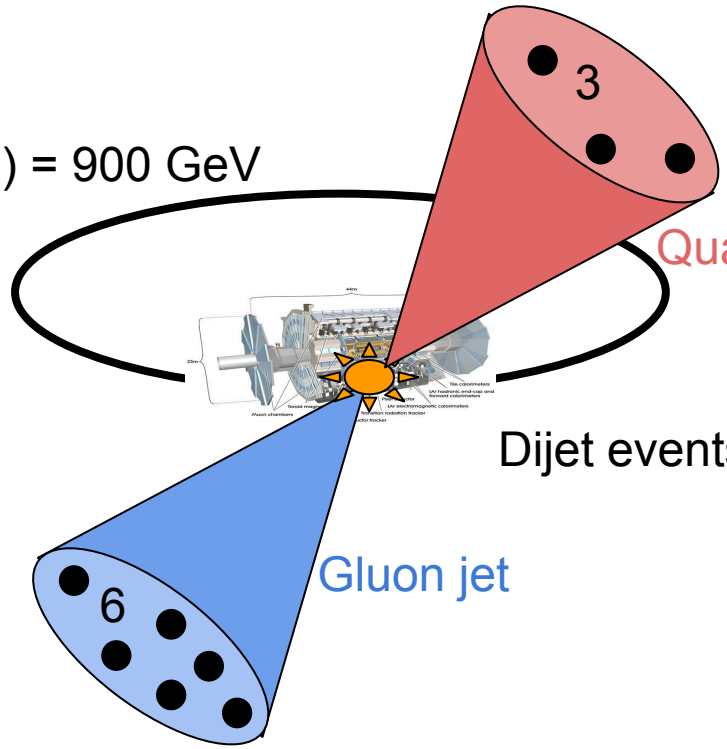


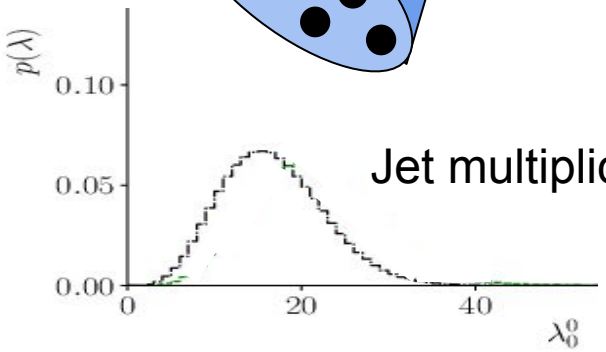


Petr Baroň (Cracow, INP), Michael H. Seymour (Manchester U.), Andrzej Siódmok (Jagiellonian U.) (Jul 28, 2023)

Published in: *Eur.Phys.J.C* 84 (2024) 1, 28 • e-Print: 2307.15378 [hep-ph]

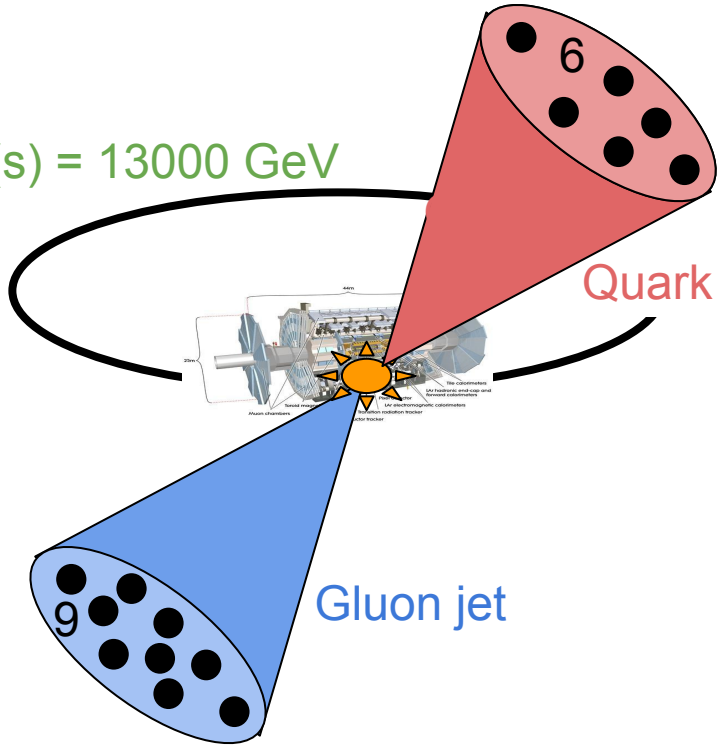
sqrt(s) = 900 GeV

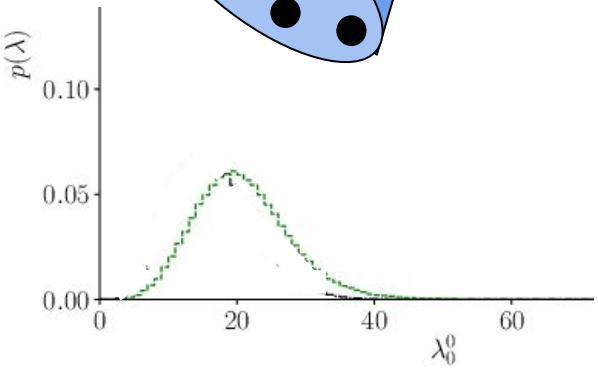




Jet multiplicity

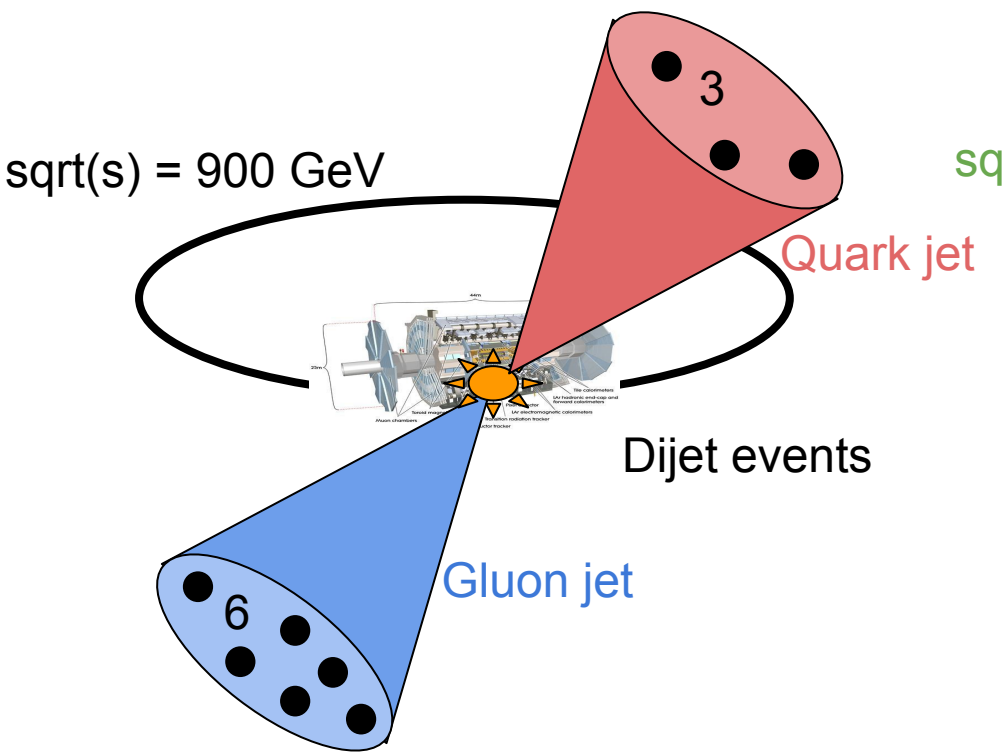
sqrt(s) = 13000 GeV

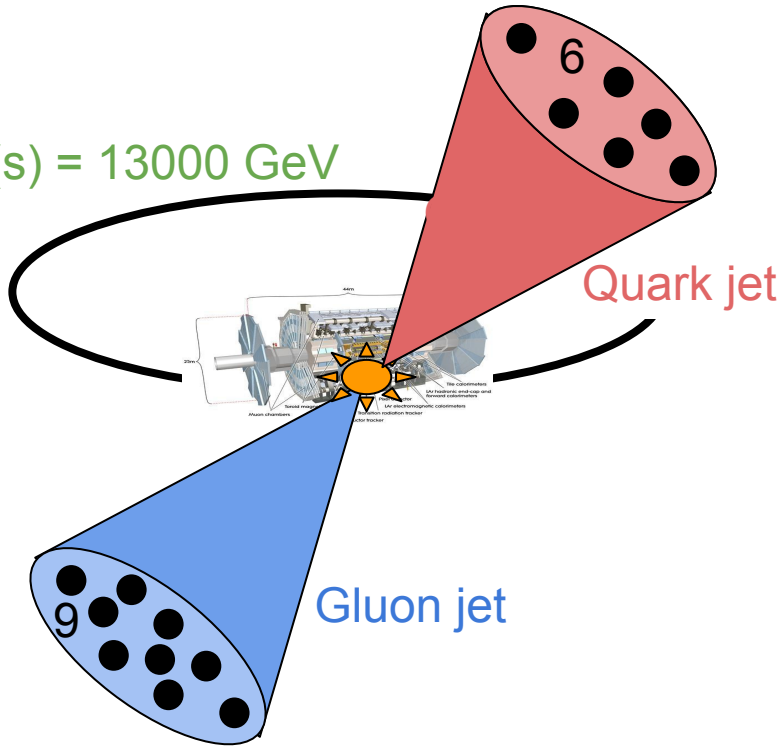




$\lambda^{900} = f^{900}\lambda_g + (1 - f^{900})\lambda_q$

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



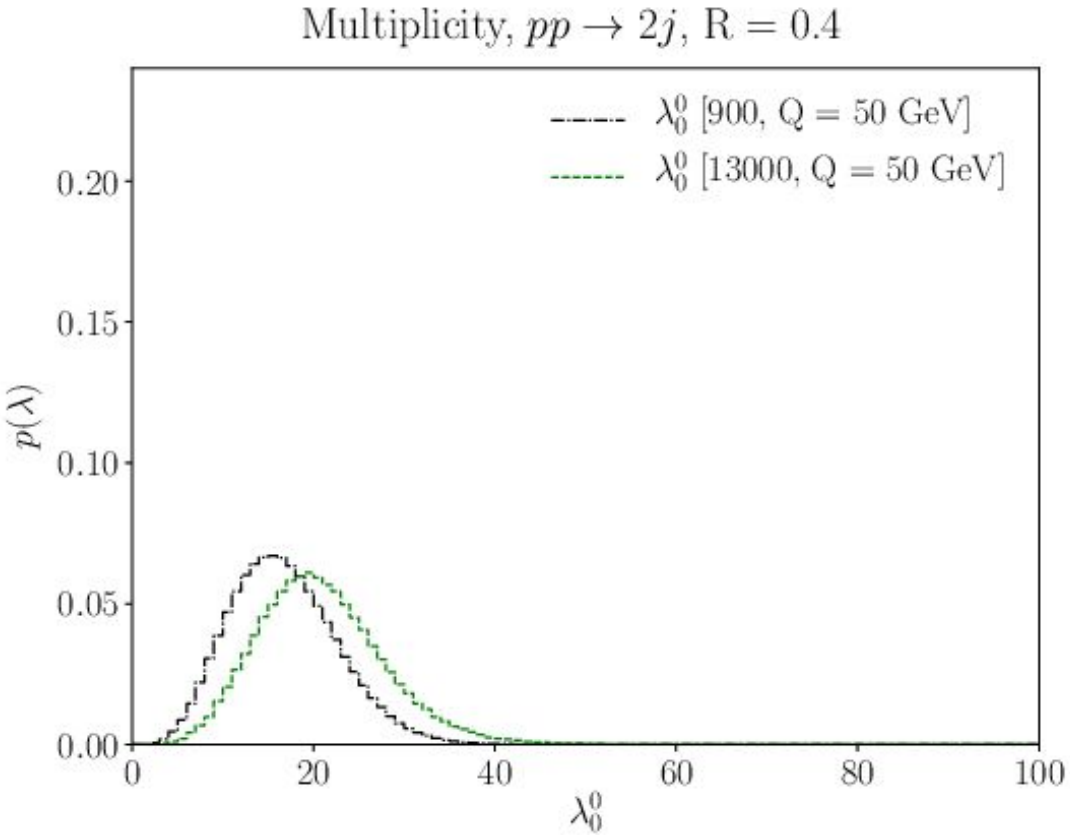


$$\lambda^{900} = f^{900}\lambda_g + (1 - f^{900})\lambda_q$$

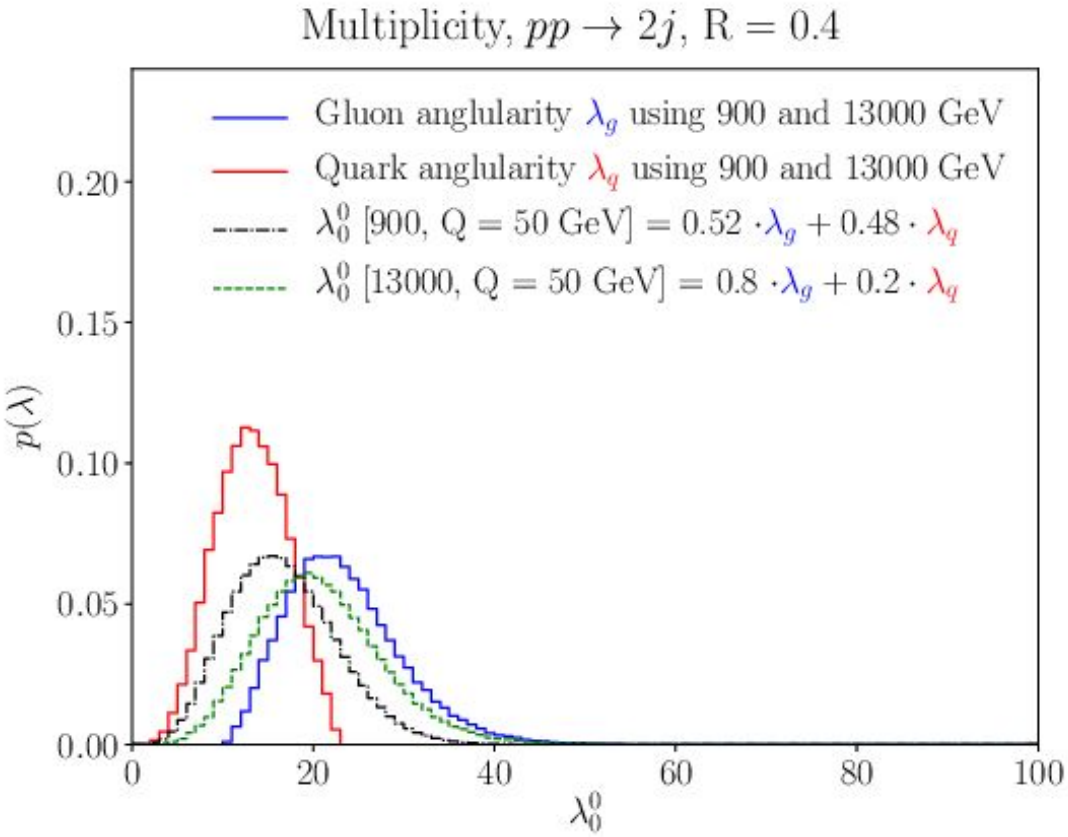
$$\lambda^{13000} = f^{13000}\lambda_g + (1 - f^{13000})\lambda_q$$

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

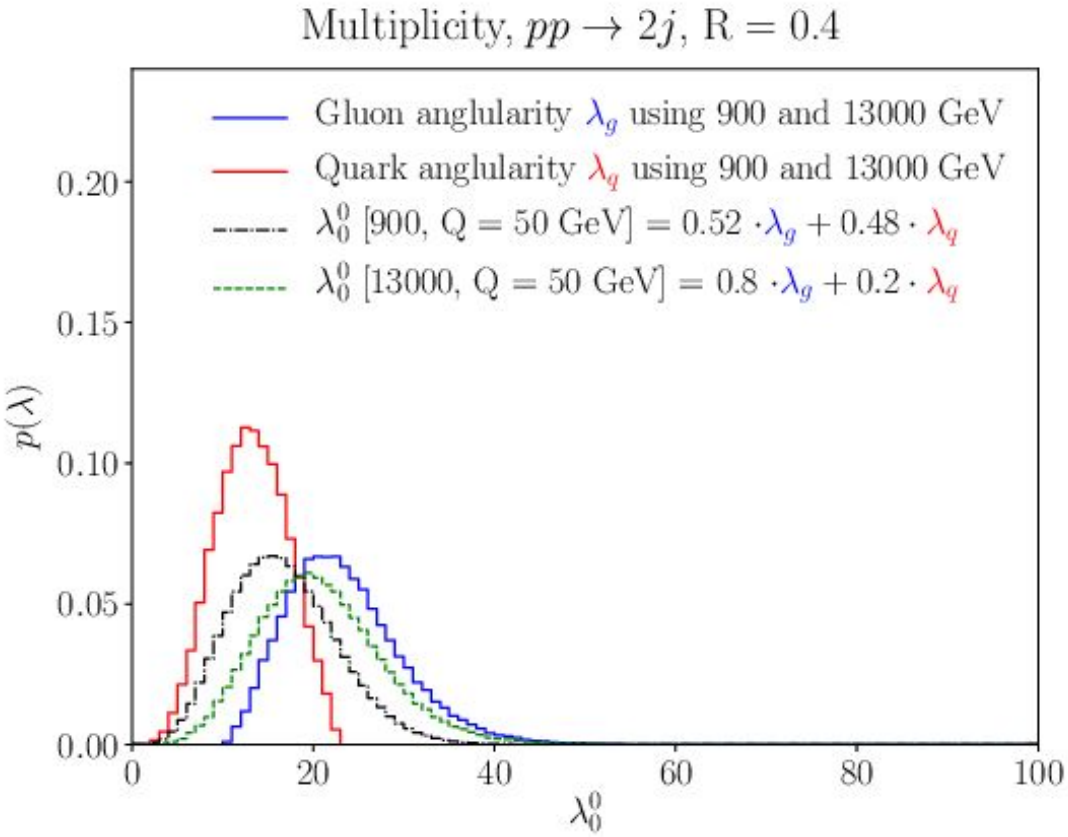
The method in practice: measurement



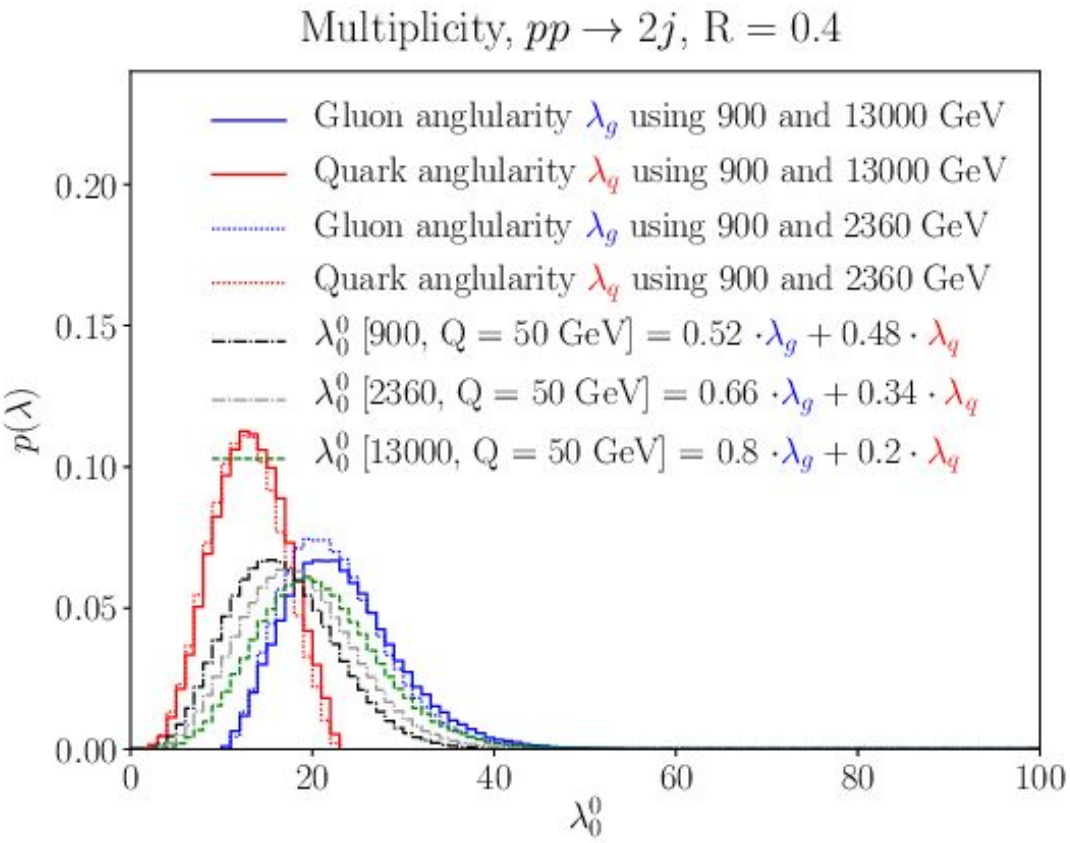
The method in practice: q/g distributions



The method in practice: q/g distributions



The method in practice: energy dependence



Results

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 $p_T^{\text{cut}} = 50$ GeV, 100, 200, and 400 GeV

  $(p_{T\ \text{lead}} + p_{T\ \text{sublead}})/2 > p_T^{\text{cut}}$ $\qquad$ $p_{T\ \text{sublead}}/p_{T\ \text{lead}} > 0.8$

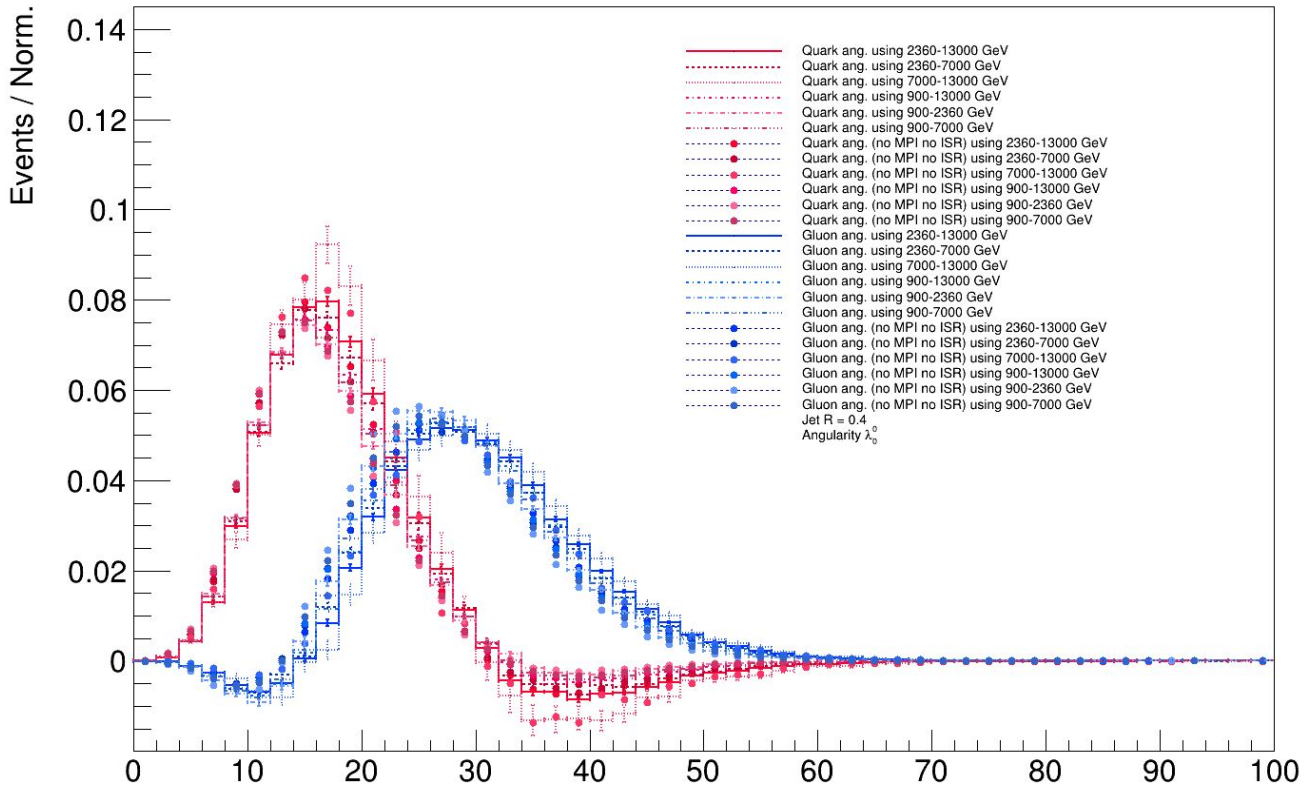
- 2 – quark/gluon
- 2 – MPI and ISR switched on/off
- 6 – energy combinations: 900–2360, 900–7000, 900–13000, 2360–7000, 2360–13000, 7000–13000 GeV
- 2 – event generators HERWIG and PYTHIA

[in total 9600 distributions]

The method in practice: energy dependence

Let's use more 6 energy combinations:

900-2360, 900-7000, 900-13000, 2360-7000, 2360-13000, 7000-13000 GeV

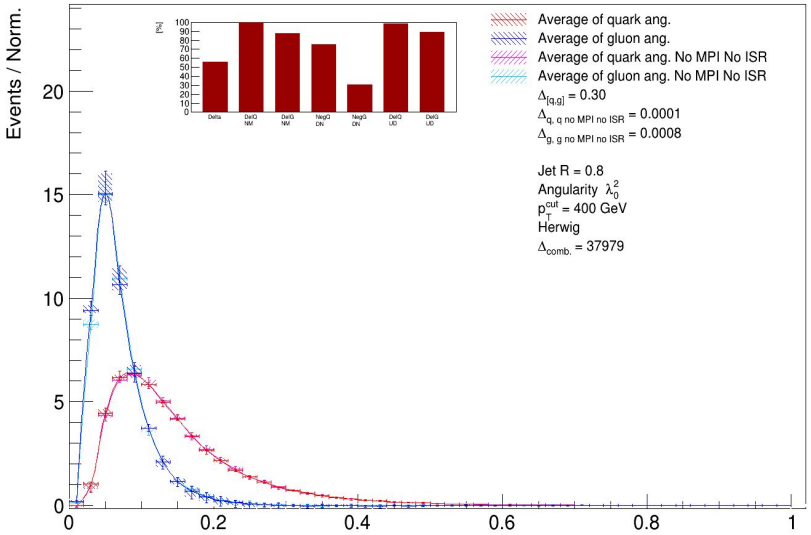


Dotted lines test the robustness to Multi Parton Interactions MPI and Initial State Radiation ISR

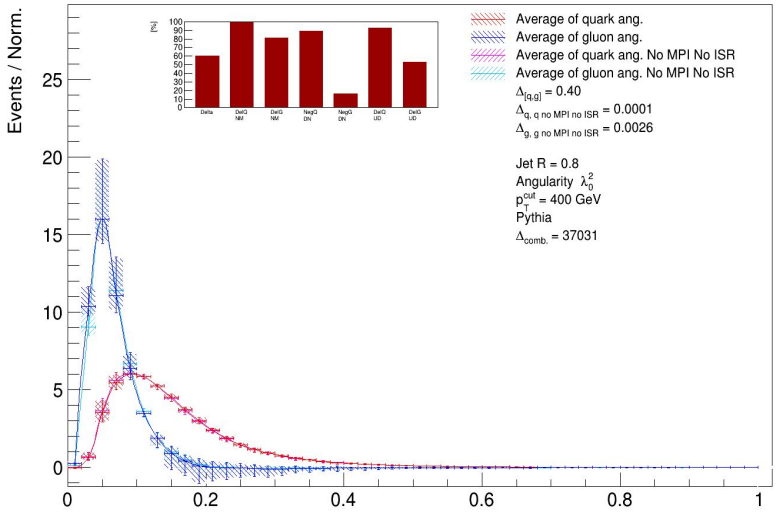
Results - best results

Best performing angularities: p_T^D

Herwig 7



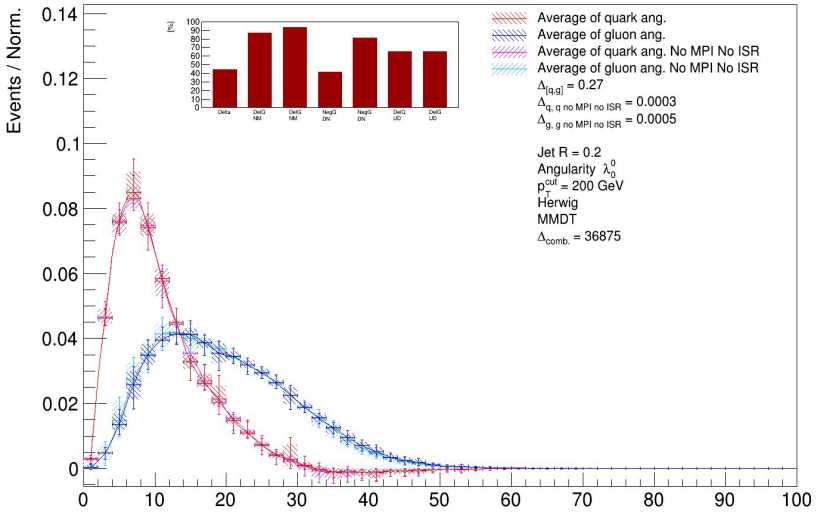
Pythia 8



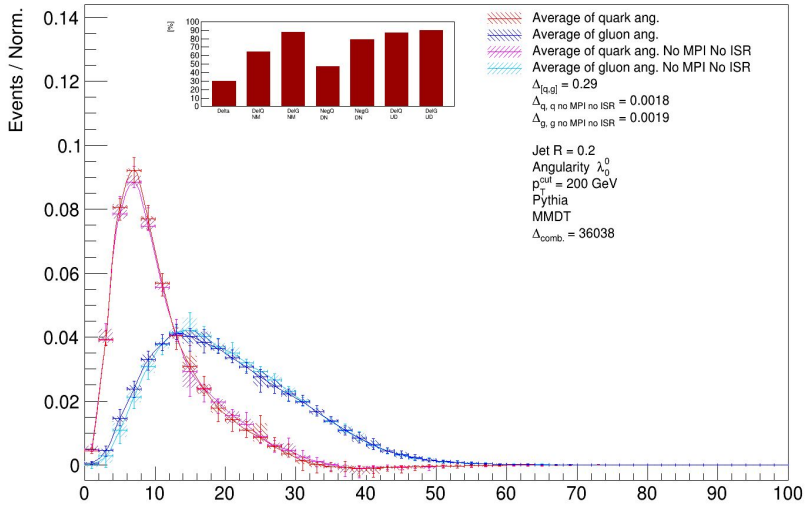
Results - best results

Best performing angularities: Multiplicity

Herwig 7



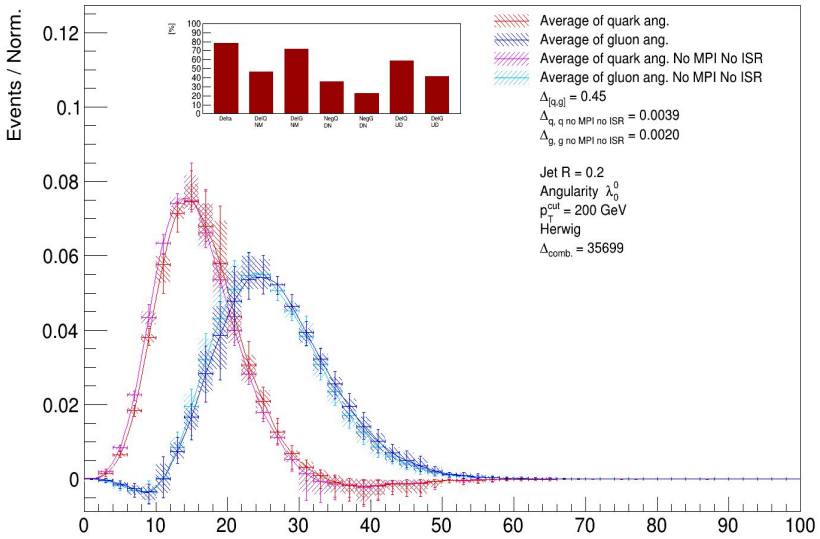
Pythia 8



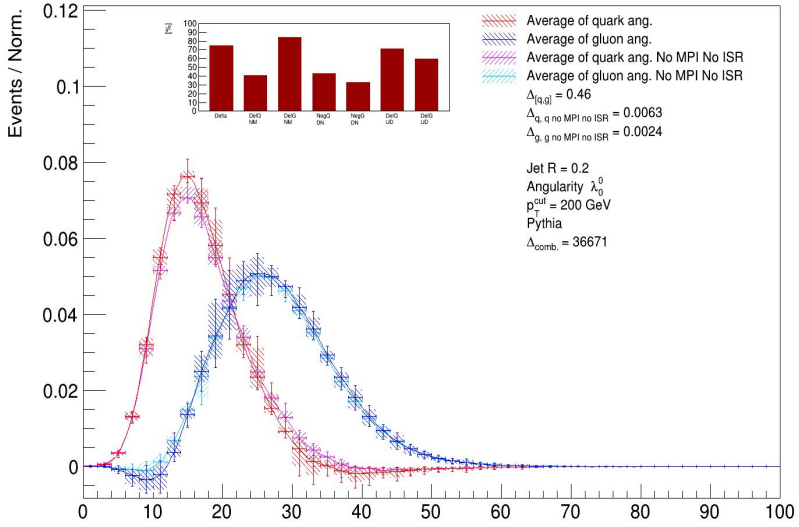
Results - best results

Wild cards (chosen by “eye”): multiplicity

Herwig 7



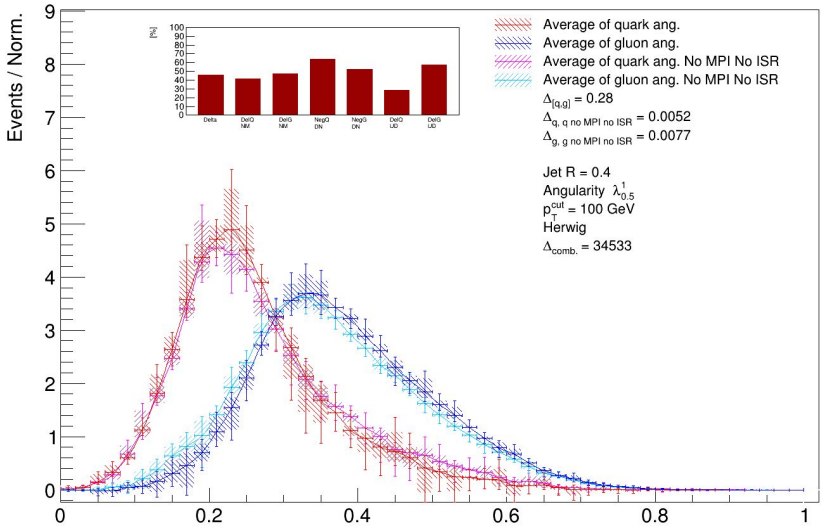
Pythia 8



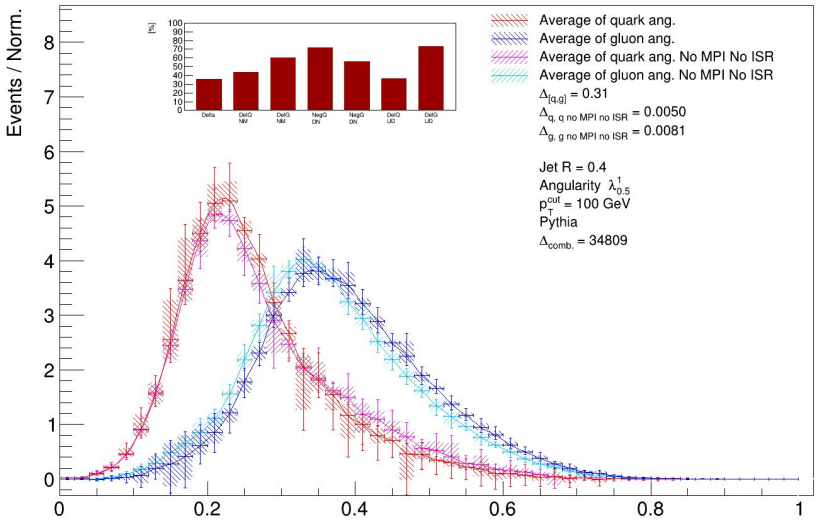
Results - best results

Wild cards (chosen by “eye”): LHA

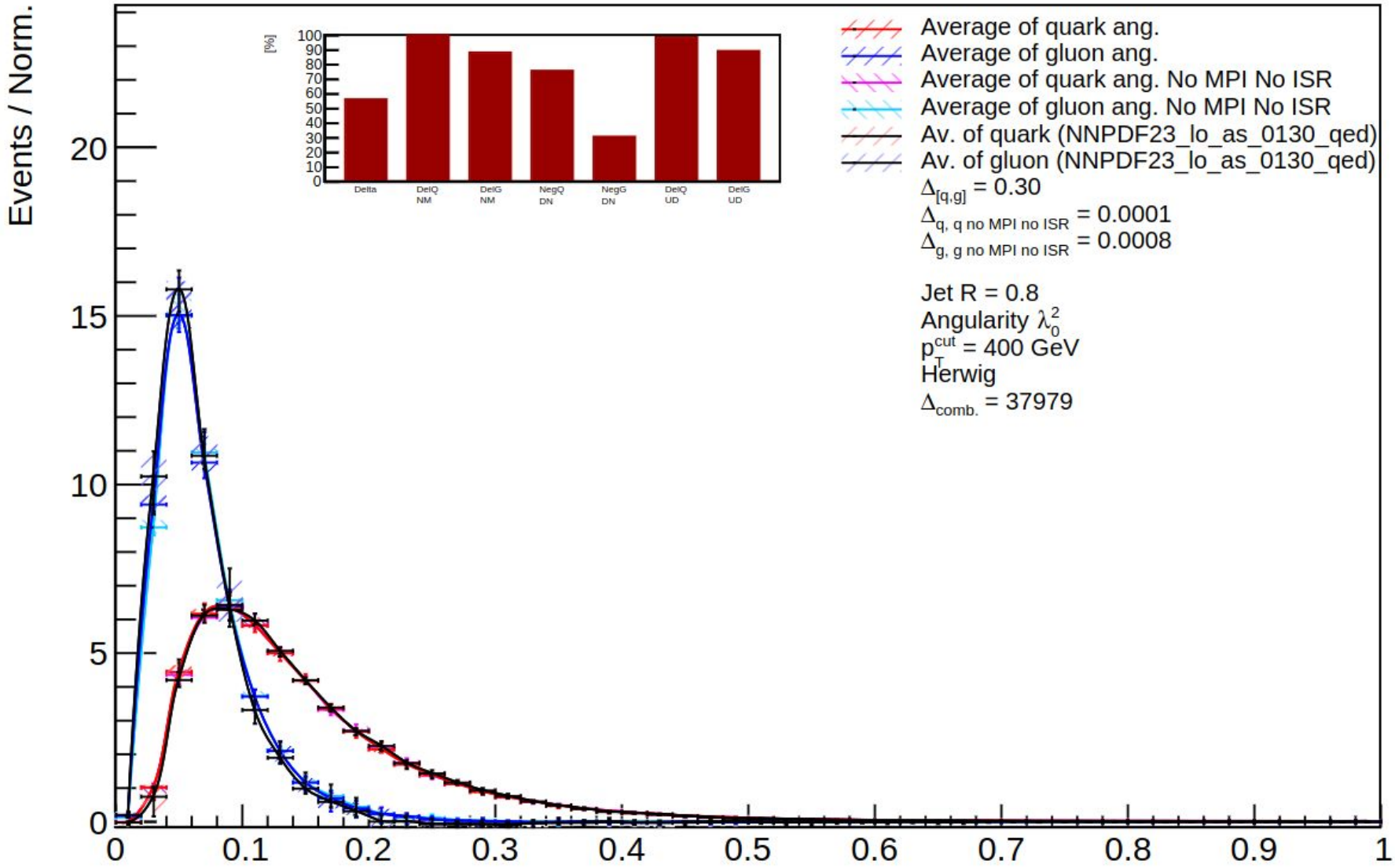
Herwig 7



Pythia 8



Results - PDF dependence



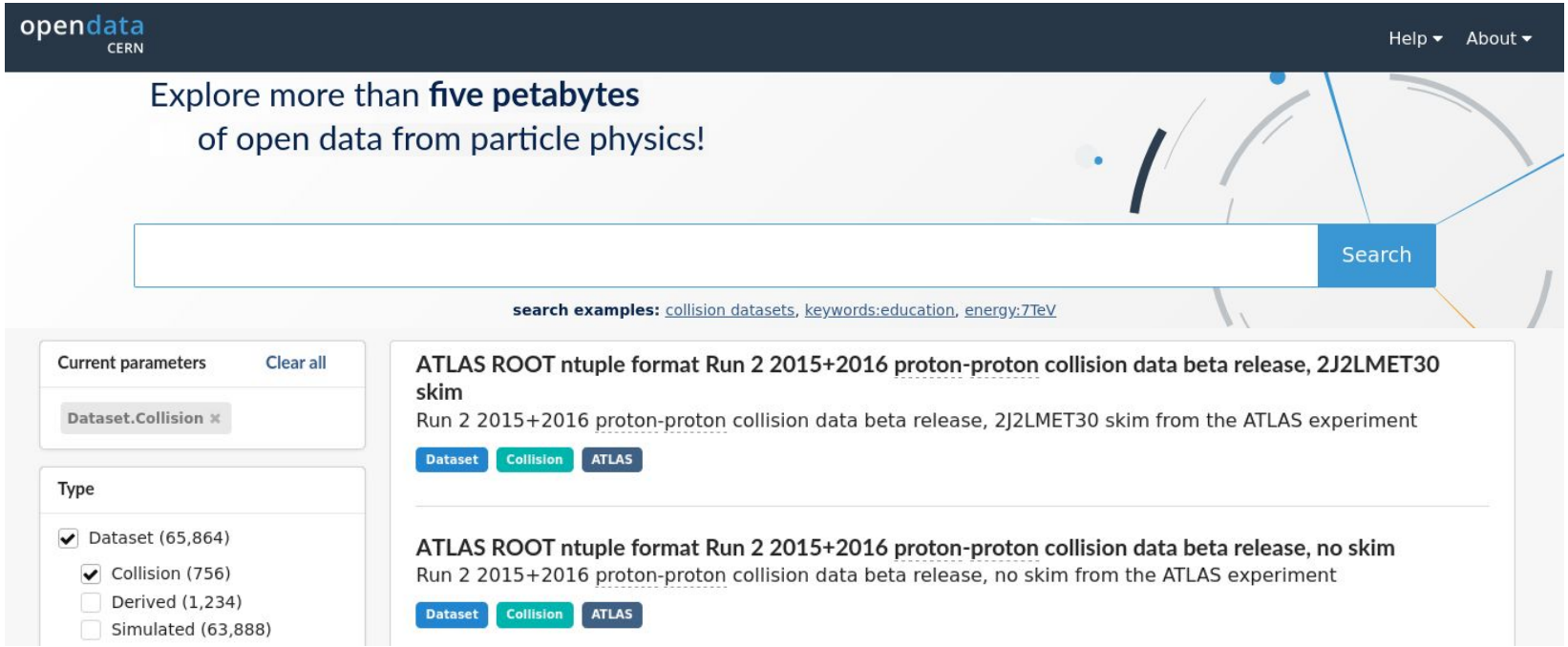
Chapter 4. 100 meters underground

The **main aim** is to perform the **measurement** at LHC
Two paths:

- Go to experiments: but it looks like experiments are not ready to reanalyse even 7 TeV data!
  (We saw how important is legacy data from LEP data!)

OpenMAPP

- Go to OpenData



Chapter 4. 100 meters underground

The team:

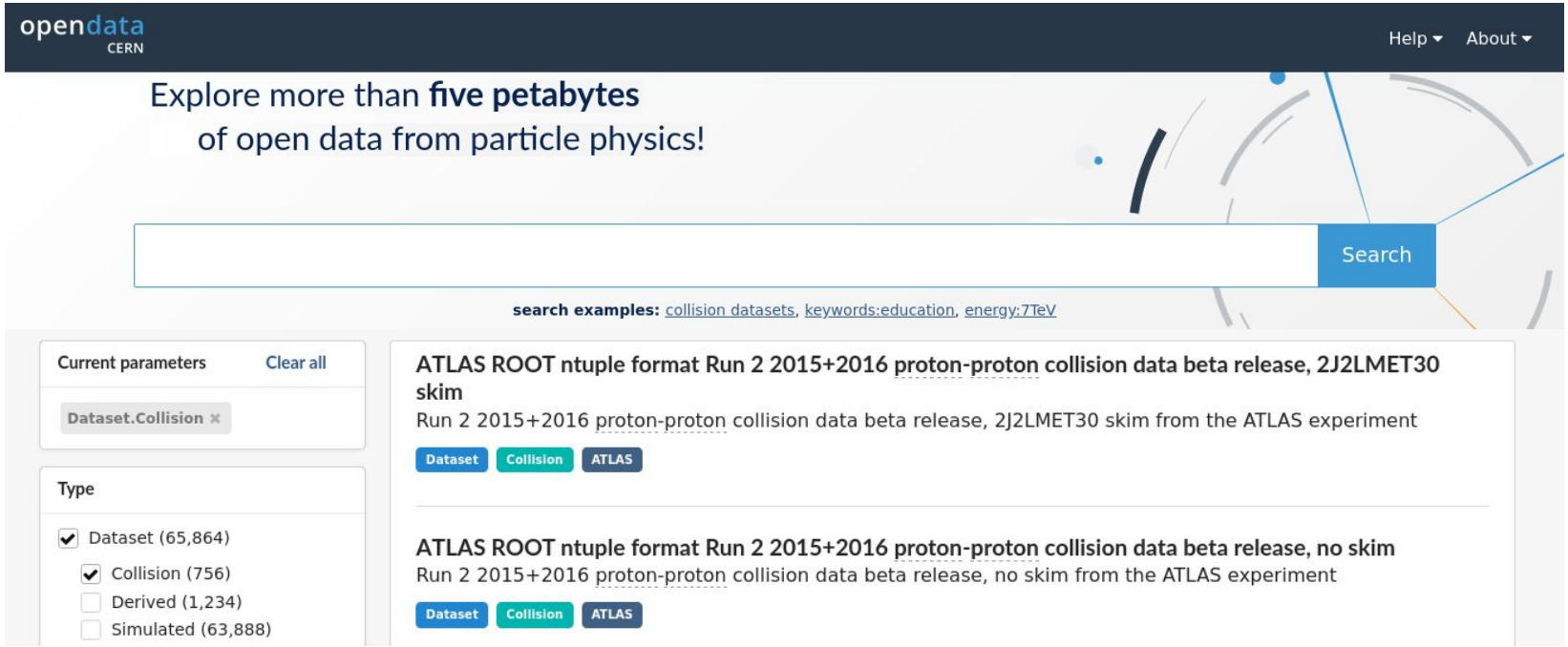

Van Dung Le


Julie Hogan


Petr Baron


Mike Seymour


AS



4.1 Data selection

	7TeV	8TeV	13TeV
data original content	Jet[6] raw ak5 jet raw ak5 jet constituents corrected ak5 jet	Jet[7] raw ak5 jet raw ak5 jet constituents corrected ak5 jet	JetHT[8] raw ak4CHS jet raw ak4CHS jet constituents corrected ak4CHS jet
derived content	raw ak4CHS jet ak4CHS jet charged angularities	raw ak4CHS jet ak4CHS jet charged angularities	ak4CHS jet charged angularities

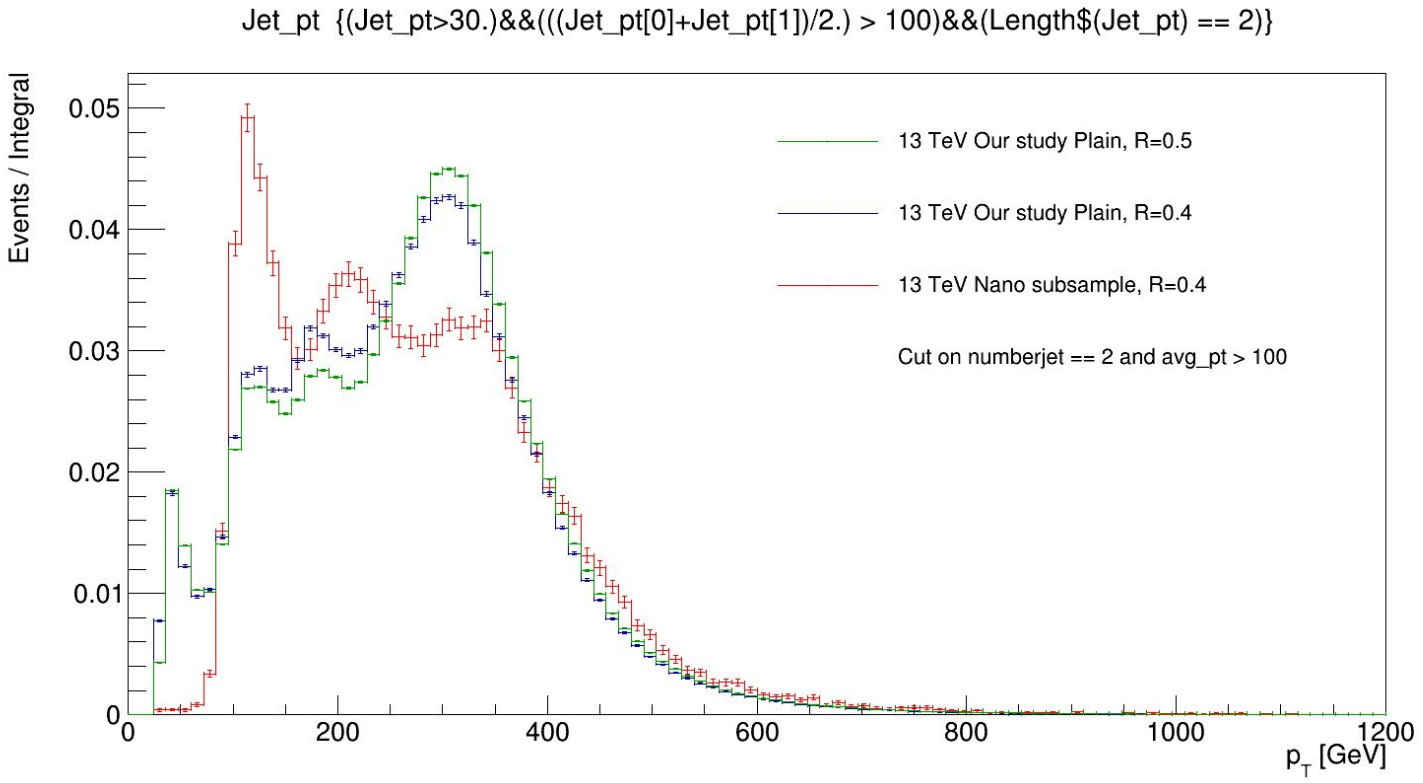
[6] CMS collaboration (2020). *Jet primary dataset in AOD format from RunB of 2011 (/Jet/Run2011B-12Oct2013-v1/AOD)*. 2022. DOI: 10.7483/OPENDATA.CMS.5JYA.HKSG. URL: http://opendata.cern.ch/record/275.

[7] CMS Collaboration (2022). *Jet primary dataset in AOD format from Run of 2012 (/Jet/Run2012A-22Jan2013-v1/AOD)*. 2017. DOI: 10.7483/OPENDATA.CMS.WVJ9.YVN2. URL: https://opendata.cern.ch/record/24406.

[8] CMS Collaboration (2024). *JetHT primary dataset in MINIAOD format from RunH of 2016 (/JetHT/Run2016H-UL2016_MiniAODv2-v2/MINIAOD)*. 2024. DOI: 10.7483/OPENDATA.CMS.LT9E.T7RQ. URL: https://opendata.cern.ch/record/30541.

Different jet redii at 7 TeV (R=0.5) and 13 TeV (R=0.4) we need to re-analyzed data at 7 and 8 TeV...

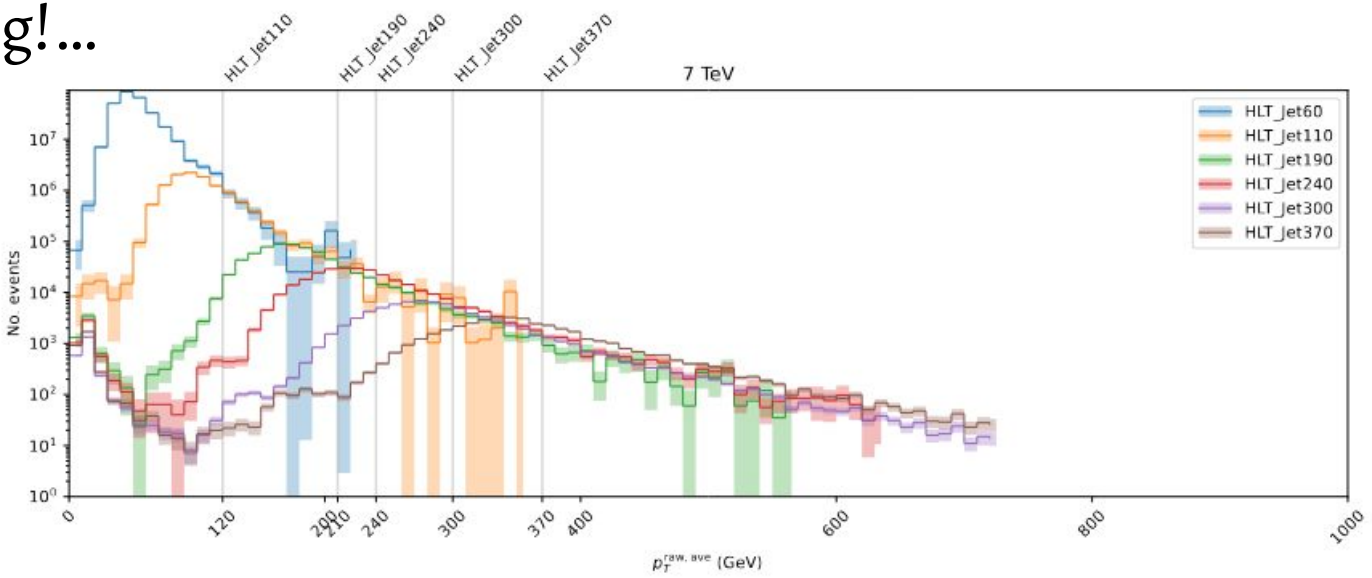
First try... many surprises

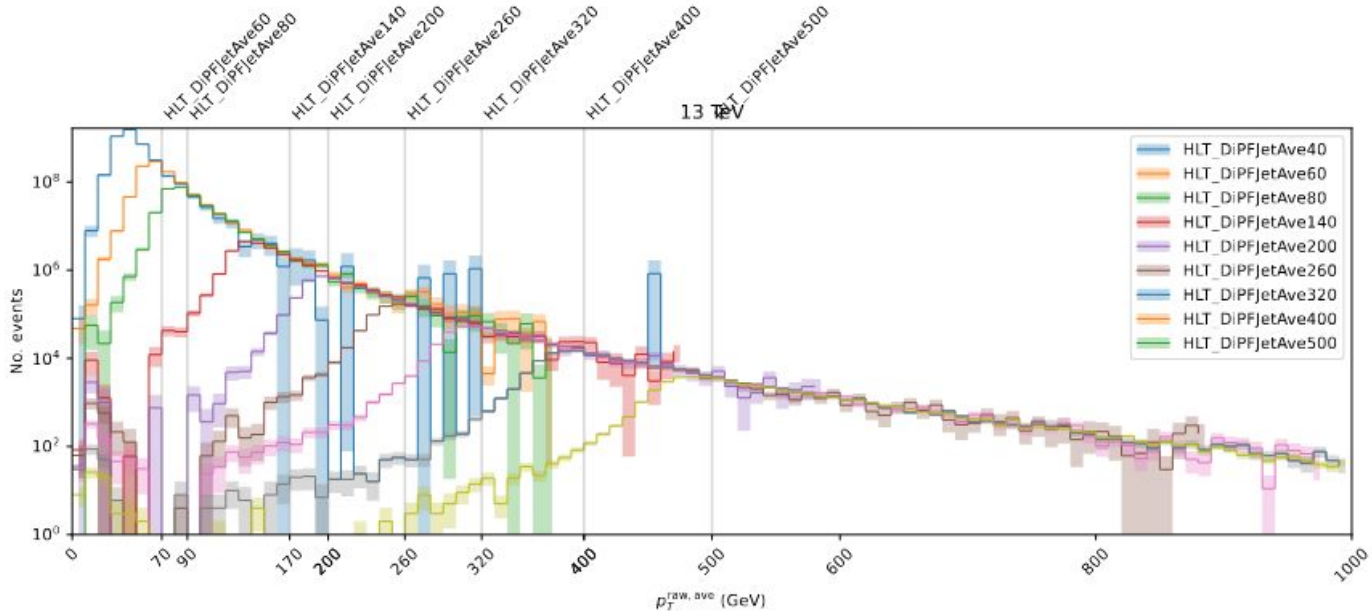


Chapter 4. 100 meters underground

Trigger scaling!...

PRELIMINARY





Chapter 4. 100 meters underground

Many things to understand, difficult and long journey …

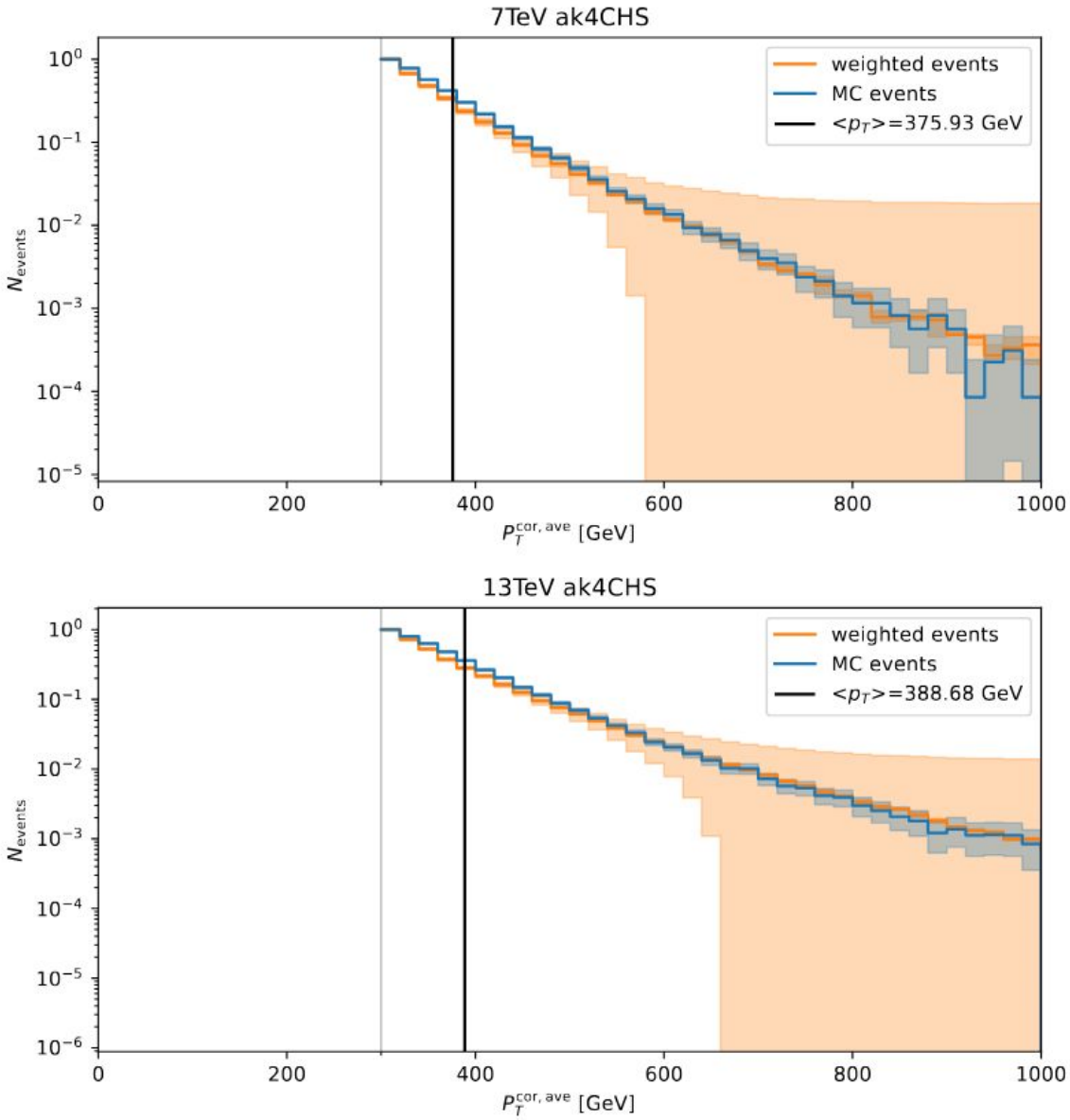
- Pileup offset corrections (L1Offset)
- Relative Jet Energy Scale (L2Relative)
- Absolute Jet Energy Scale (L3Absolute)
- Residual corrections to account for the small differences between data and simulation (L23Residual)
- Clustered using the anti-kt algorithm with radius parameter of 0.4 with pileup contributions mitigated using the Charged Hadron Subtraction (CHS).
- Each data set has to be analysed with different version of CMS software (different classes, functions, parameters, naming convention - new interdisciplinary research discipline: **“software archeology”**)

Chapter 4. 100 meters underground

We go the jets defined in the same way at two different energies!

MC events - Herwig in a good agreement with data!

PRELIMINARY

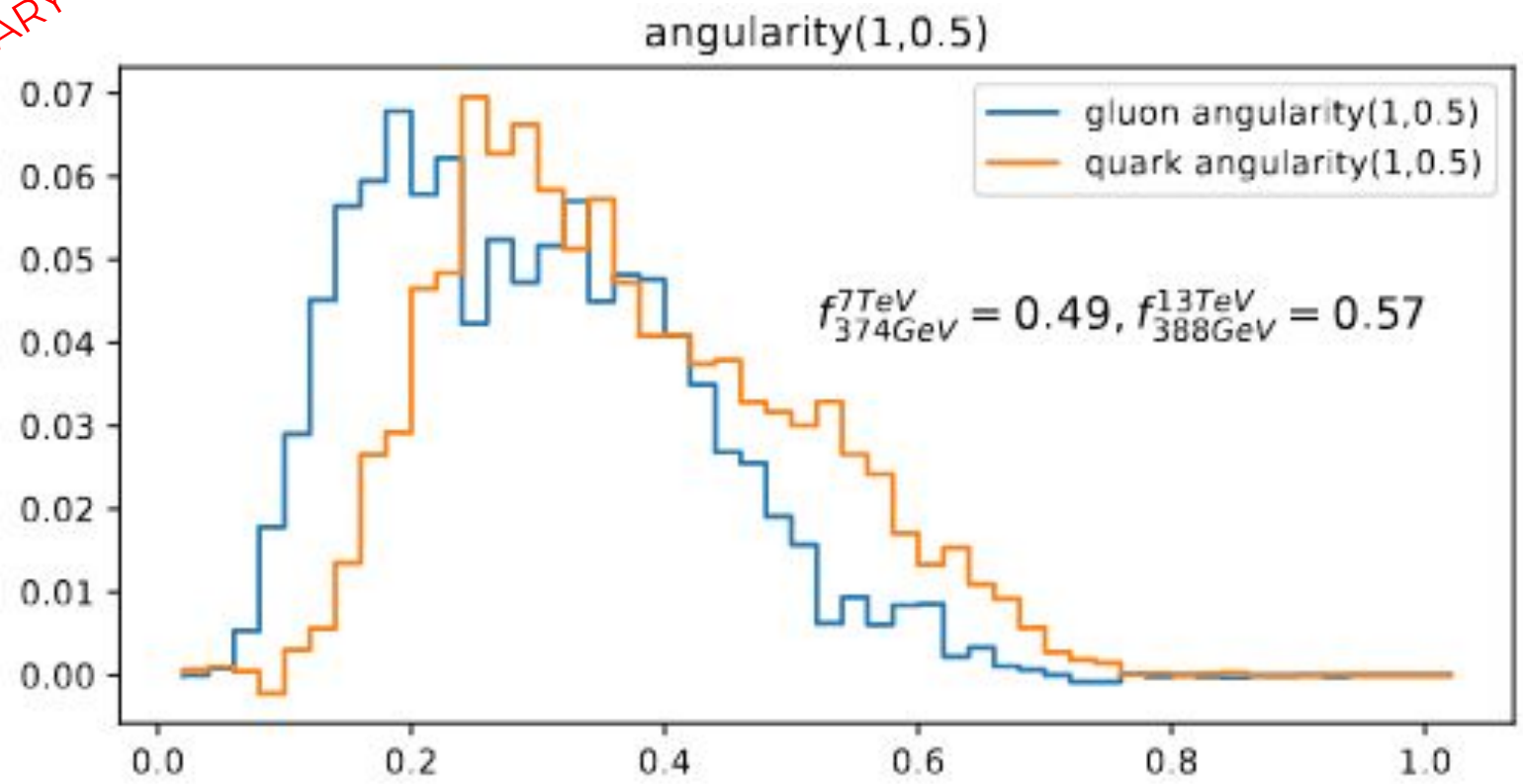


Chapter 4. 100 meters underground

We go the jets defined in the same way at two different energies!

First measurement of q/g angularity using the new method!

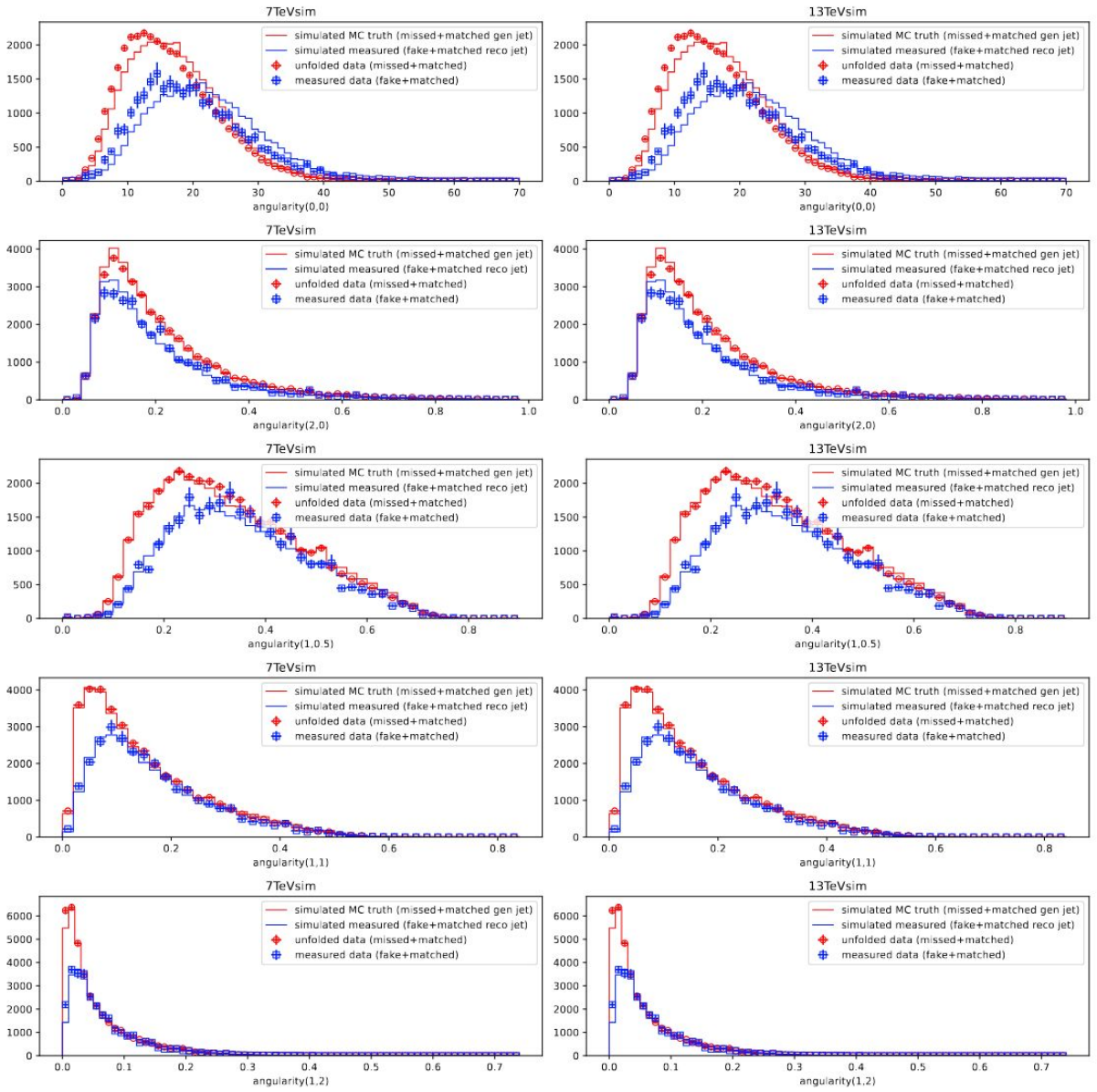
PRELIMINARY



Comparison with theoretical predictions we need to take into account detector effects, two ways: 1) detector semaring of MC predictions or 2) data unfolding... we decided to go both ways :)

The last step: Unfolding!

PRELIMINARY

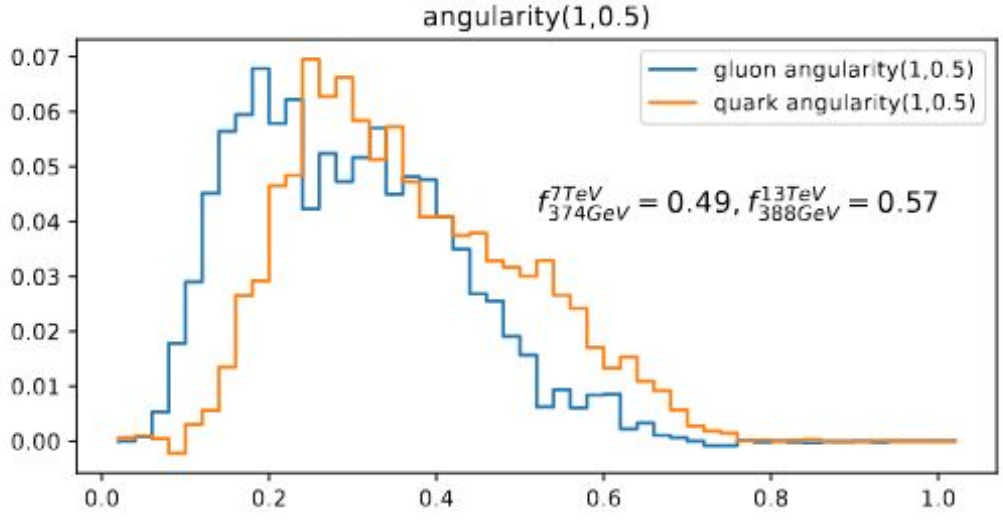


Summary

Conclusion:

- We propose a **novel way** to **measure Q/G jets**
- It is **free of the kinematic biases** - problematic in other methods
- Uses **unique** opportunity that LHC ran at **different energies**
- **Best results** are **robust** to Initial State Radiation and MPI

- The **main aim** is to perform the **measurement** at LHC but it looks like experiments are not ready to reanalyse even 7 TeV data!
- We see how important is legacy data from LEP data (next slides)!
- So we decided to use OpenData to measure it by ourselves
- Very challenging but we are getting to our “Ithaca”



Thank you for your attention!

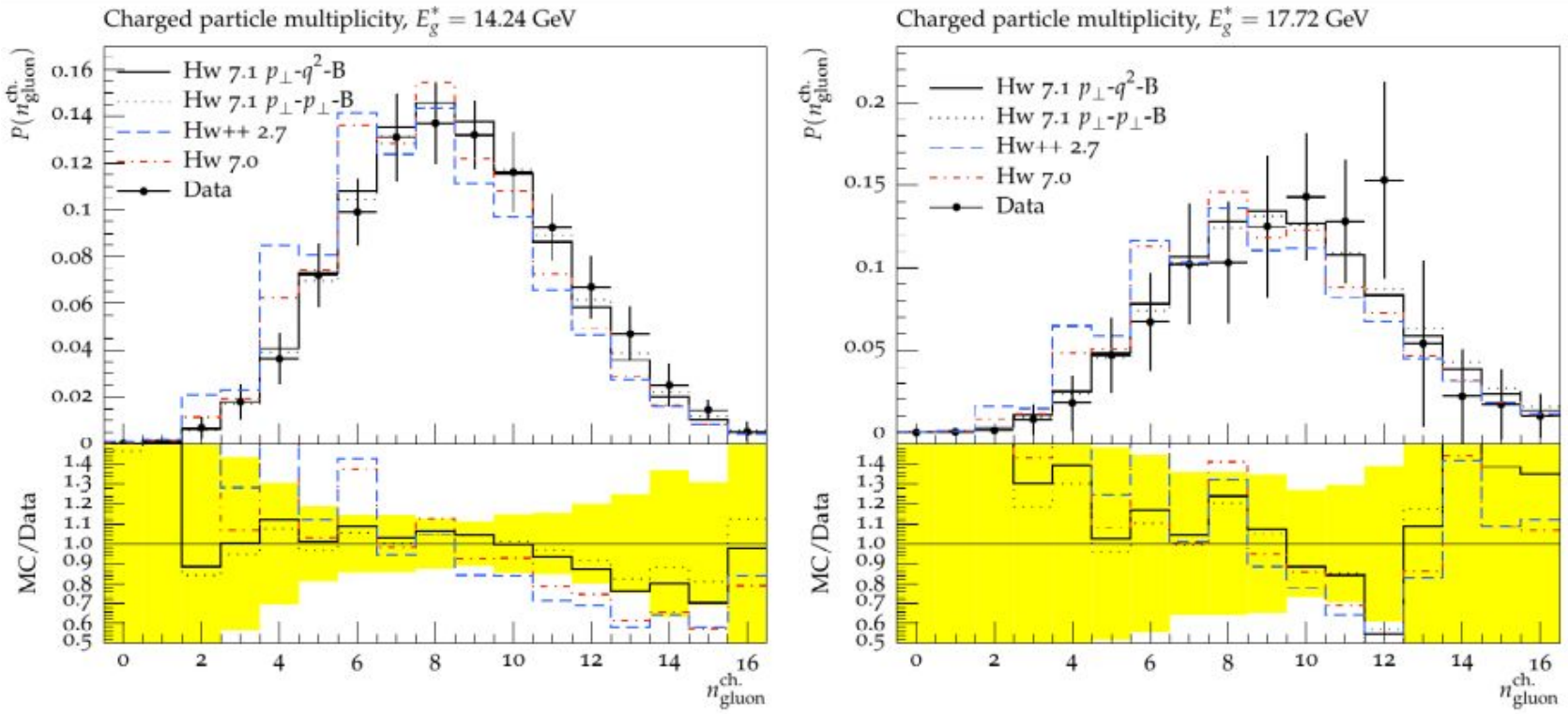
How we improved simulation of Q/G jets in Herwig

Improving the Simulation of Quark and Gluon Jets with Herwig 7 #17

Daniel Reichelt (Dresden, Tech. U.), Peter Richardson (CERN and Durham U., IPPP), Andrzej Siodmok (Cracow, INP) (Aug 4, 2017)

Published in: *Eur.Phys.J.C* 77 (2017) 12, 876 • e-Print: 1708.01491 [hep-ph]

Multiplicity distribution of charged particles in gluons jets for two different gluon energies.



Data was one of the **key for the improvement** and it is still needed for the progress.
However it is hard to measure “clear” q/g samples at the LHC.

ALICE - angularites at 5.02 TeV

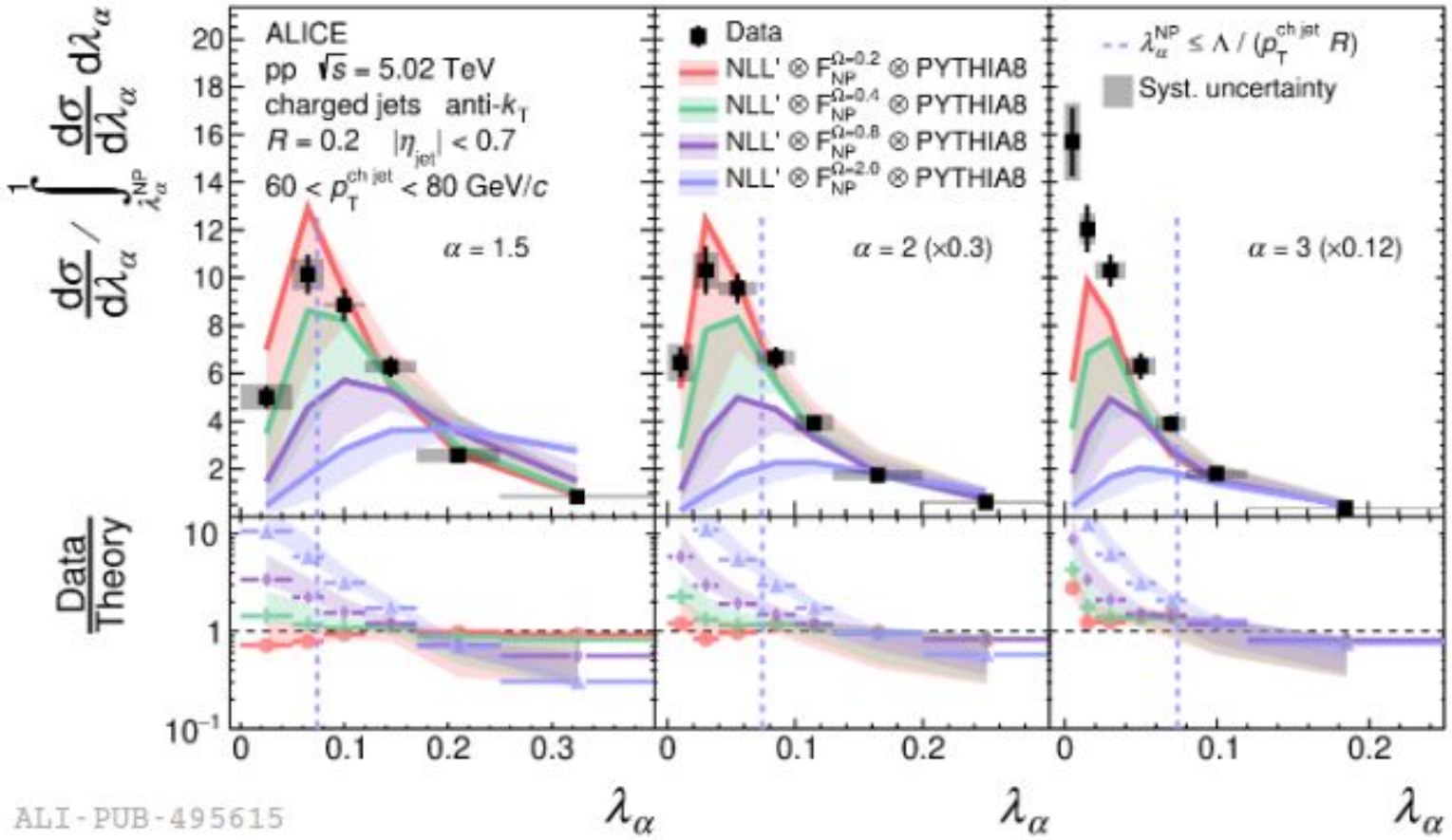


Figure 1 – Example comparison of the ungroomed jet angularities with different values of $\alpha \in \{1.5, 2, 3\}$ to NLL′ SCET calculations convolved with different amounts of smearing with a nonperturbative shape function [4]. Distributions are normalized to the perturbative region, right of the vertical dashed line, which uses $\Lambda = 1$ GeV.

Backup

How we improved simulation of Q/G jets in Herwig

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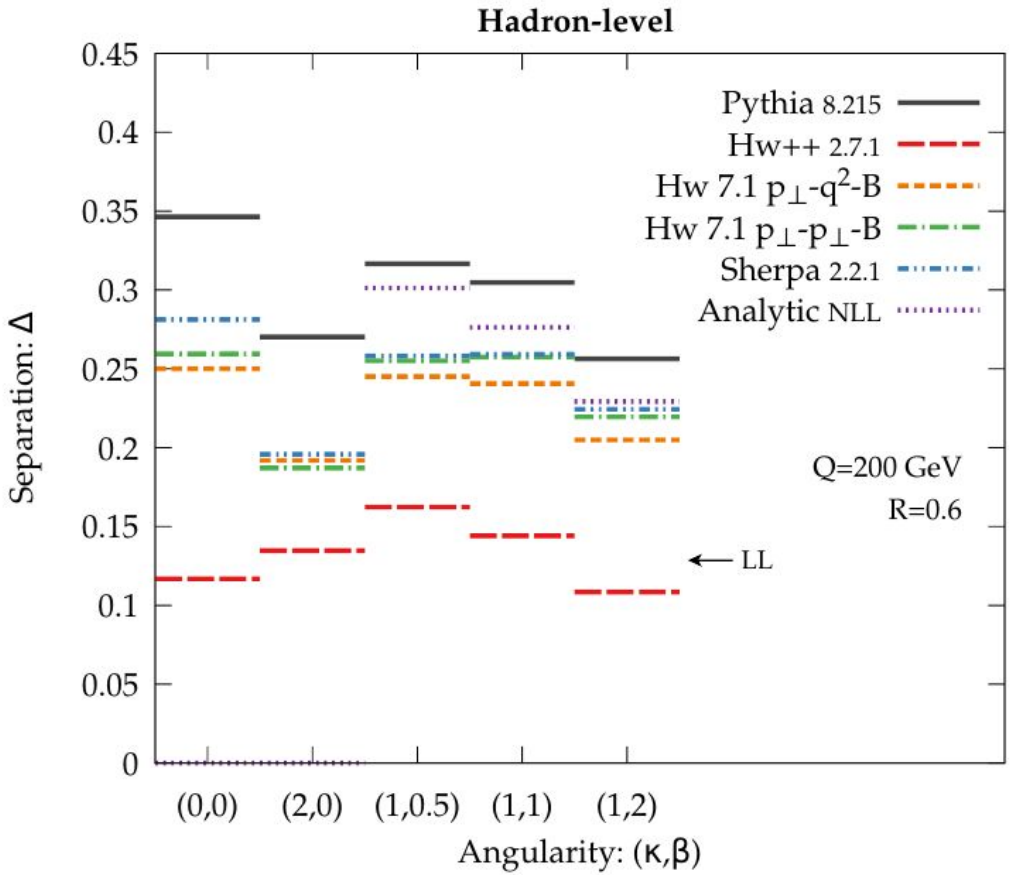
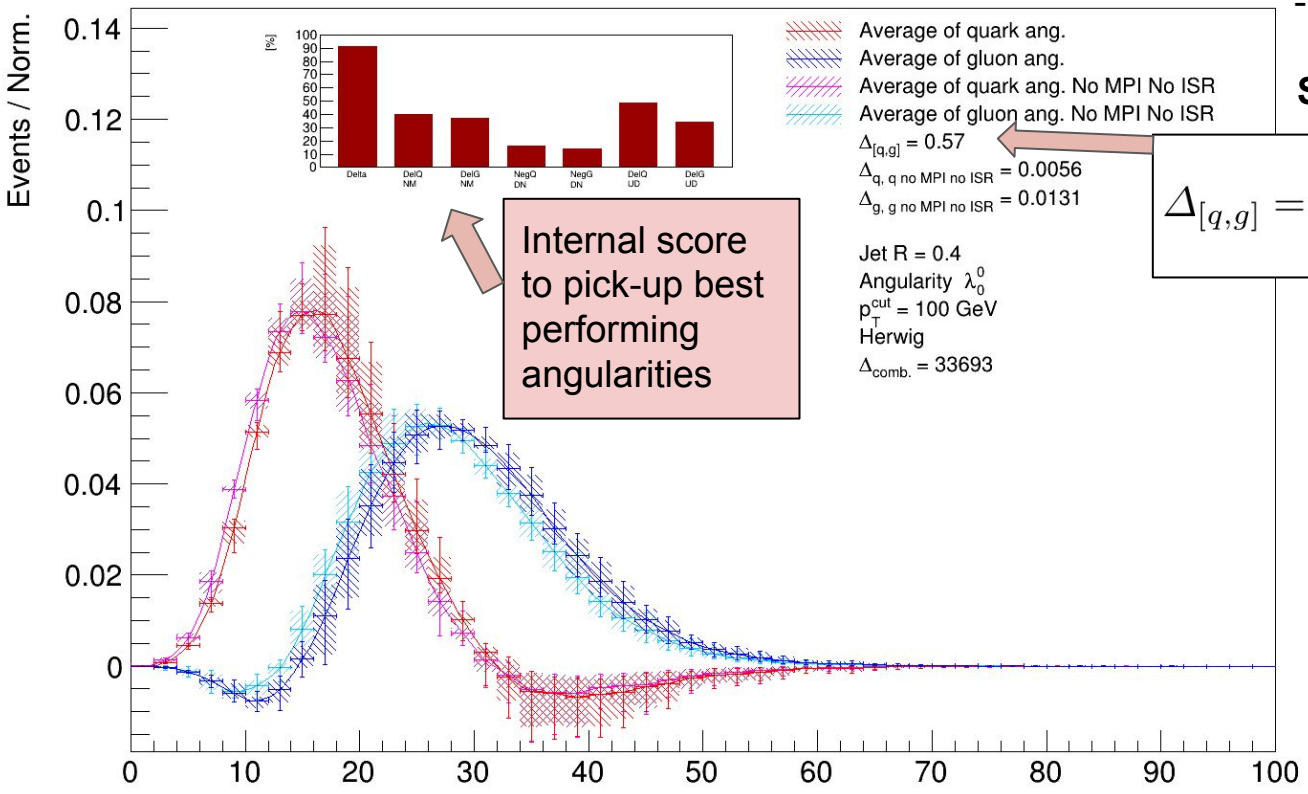


The method in practice: robustness

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



Internal score to pick-up best performing angularities

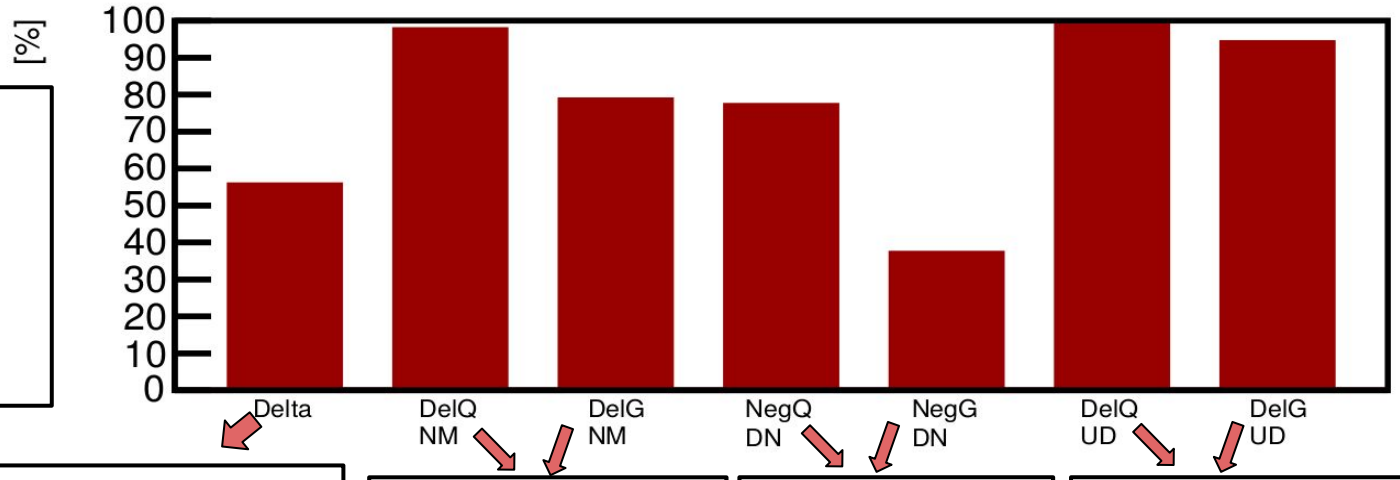
Separation power:

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

[in total 9600 distributions]

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**

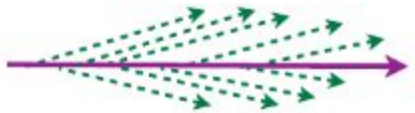
Combining all columns gives us our internal score :

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

min-max 0-41447

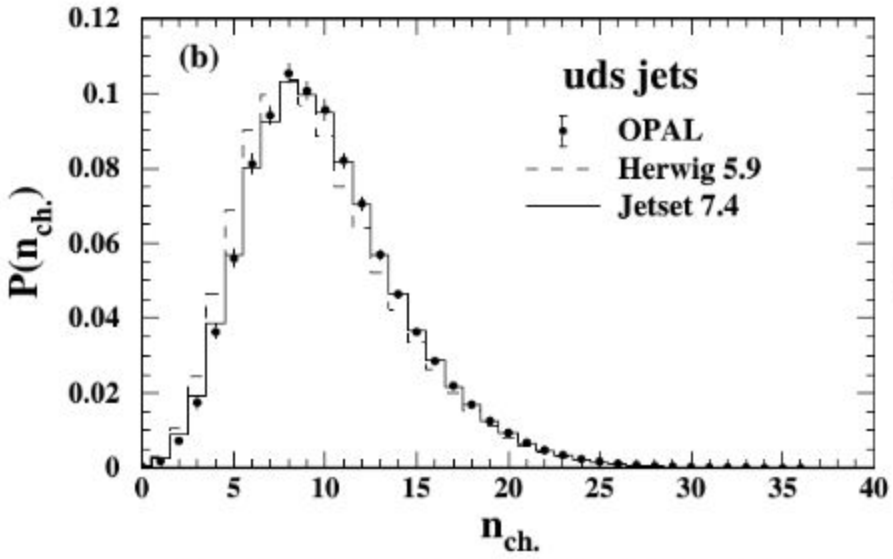
Q/G jets properties

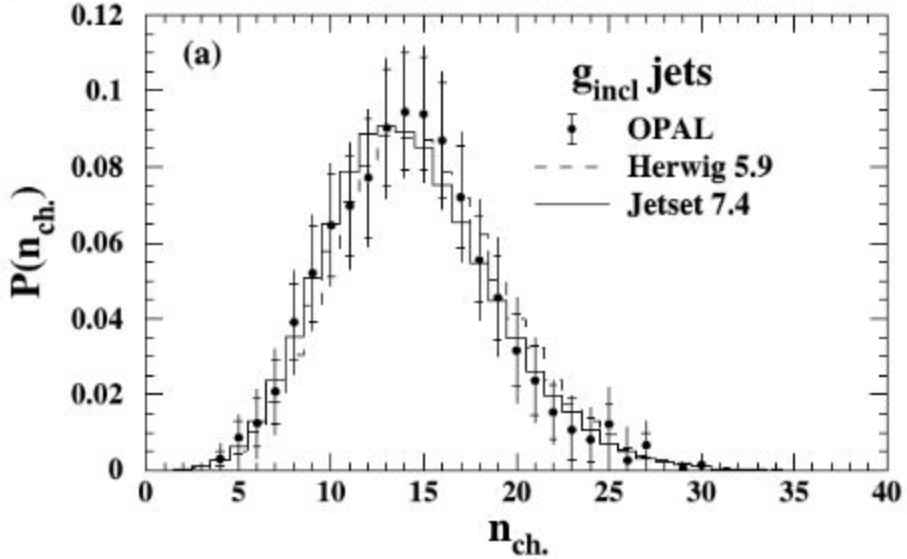
Cartoon:



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

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



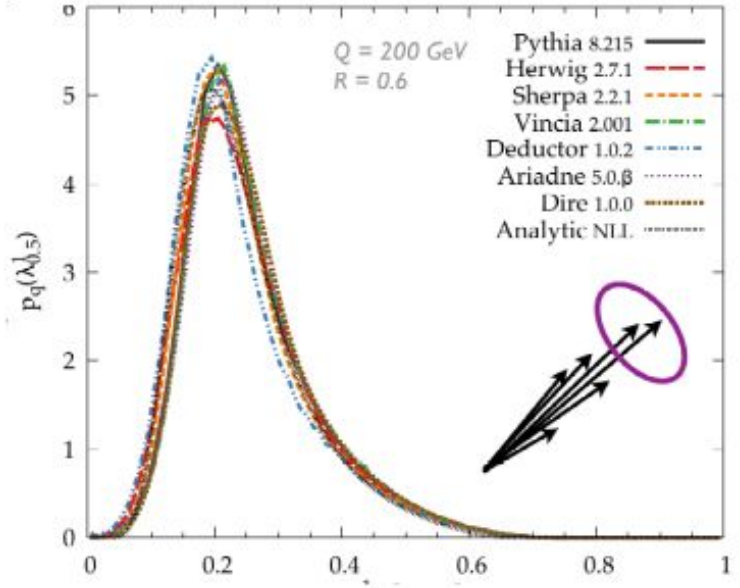


"Multiplicity distributions of gluon and quark jets and tests of QCD analytic predictions" [hep-ex/9708029]

Q/G jet Les Houches study

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

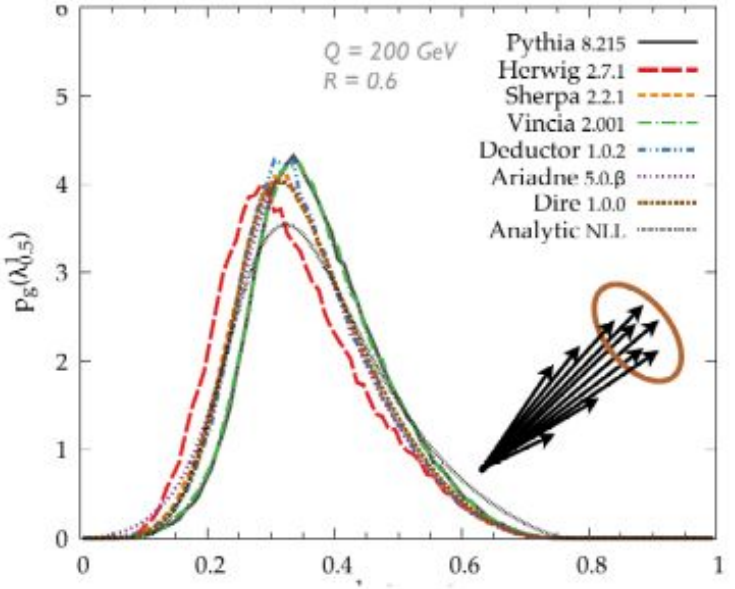
$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)



$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Small spread

Constrained by LEP



$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Large spread

Up to now no e+e- data has been used to constrain it.

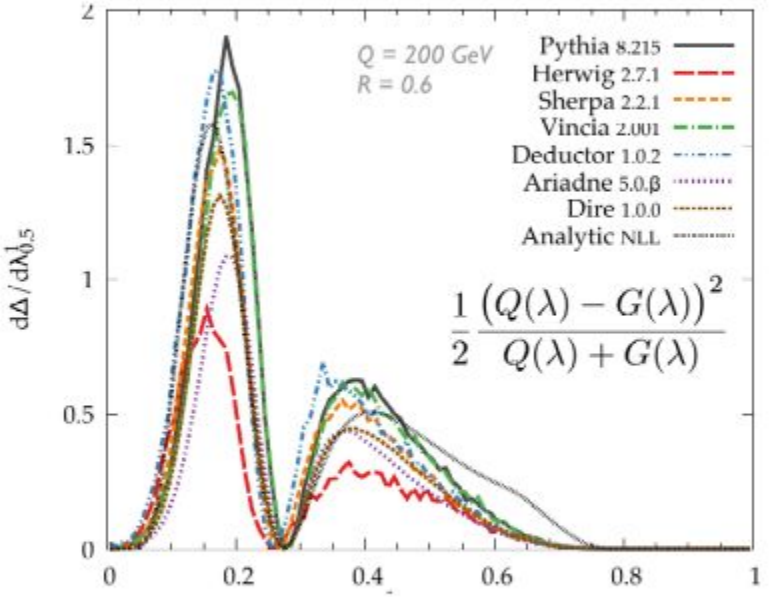
Q/G jet Les Houches study

$$\Delta = \frac{1}{2}\int d\lambda \frac{\left(p_q(\lambda) - p_g(\lambda)\right)^2}{p_q(\lambda) + p_g(\lambda)}$$

$\Delta = 0$ - corresponds to no discrimination power.

$\Delta = 1$ - corresponds to perfect discrimination power.

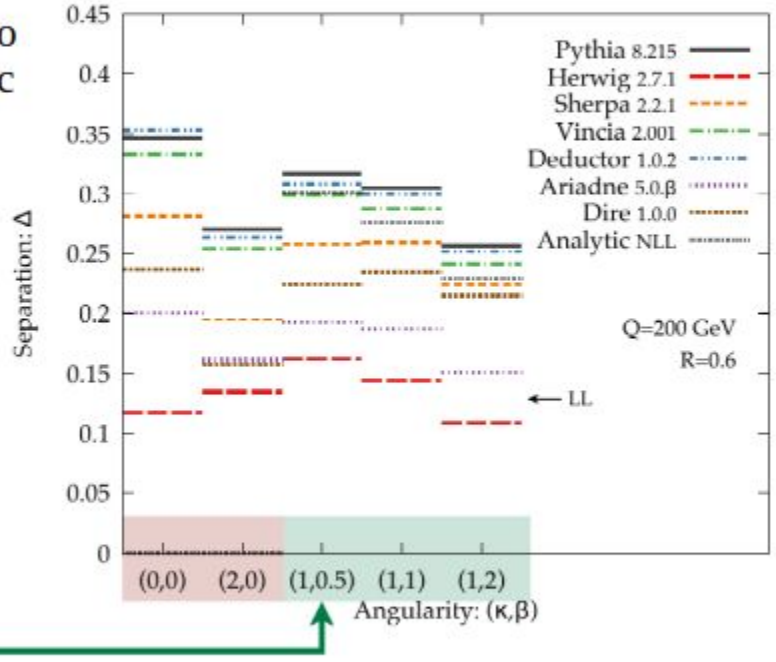
Differential



$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Pythia too optimistic

Integrated Values



Affects both IRC unsafe and IRC safe observables

Chapter 3. Lost in colors but reconnected

Improving the Simulation of Quark and Gluon Jets with Herwig 7

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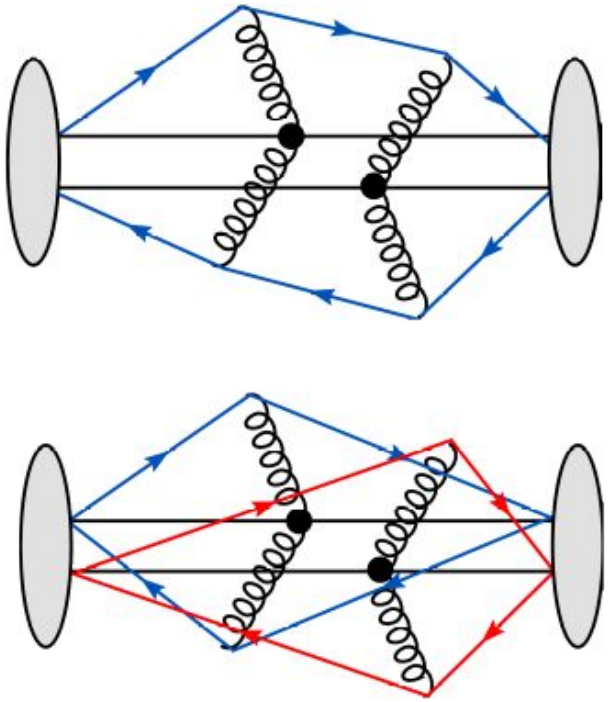
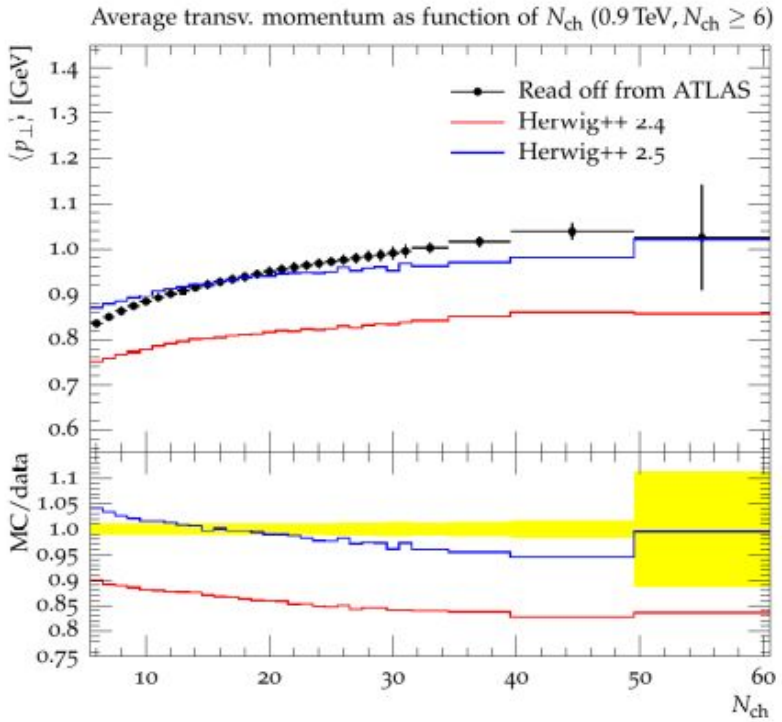
Colour reconnection

- The least understood part of the Multiple Particle Interaction models.
- Needed to describe the Underlying Event and Min Bias data (sensitive to MPI phenomena)
- Crucial to constrain it, important for top mass, g/q gluon, ...





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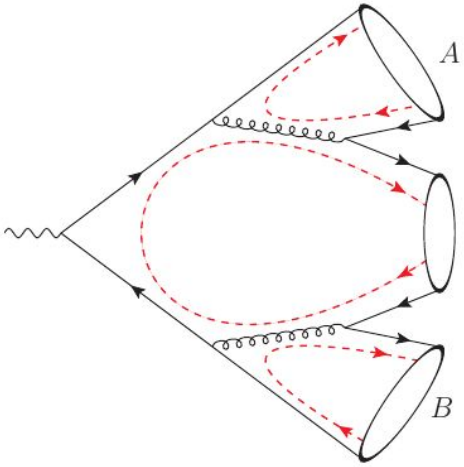
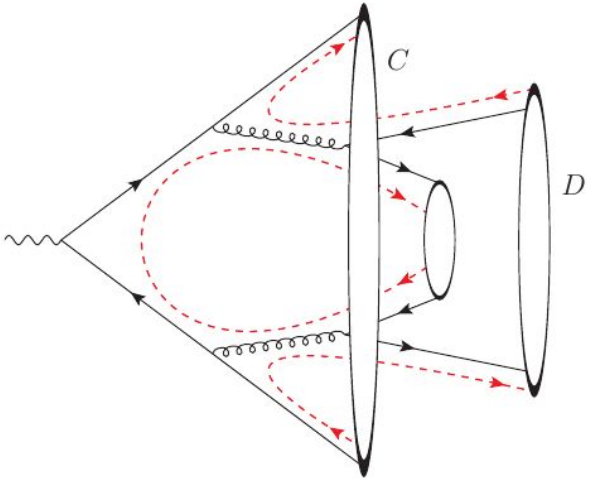
Cluster hadronization [Webber, Nucl. Phys. B238 (1984) 492]





- perturbative QCD provides *preconfinement* [Amati, Veneziano, Phys. Lett. B83 (1979) 87]
- i.e. small cluster masses $M_{\text{cl}} \gtrsim M_{\text{parton 1}} + M_{\text{parton 2}}$

- improved description of soft events/UE at hadron colliders: manually reduce cluster masses
- if $M_C + M_D < M_A + M_B$ accept alternative clustering with probability p_{reco} (model parameter)

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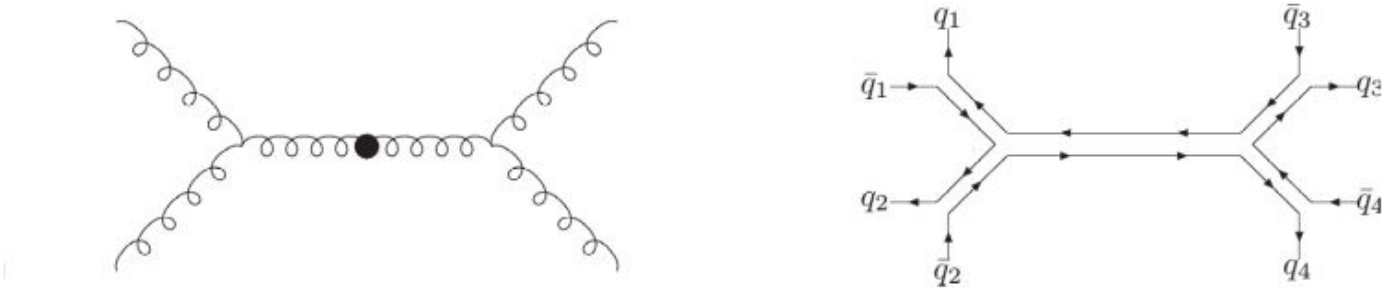
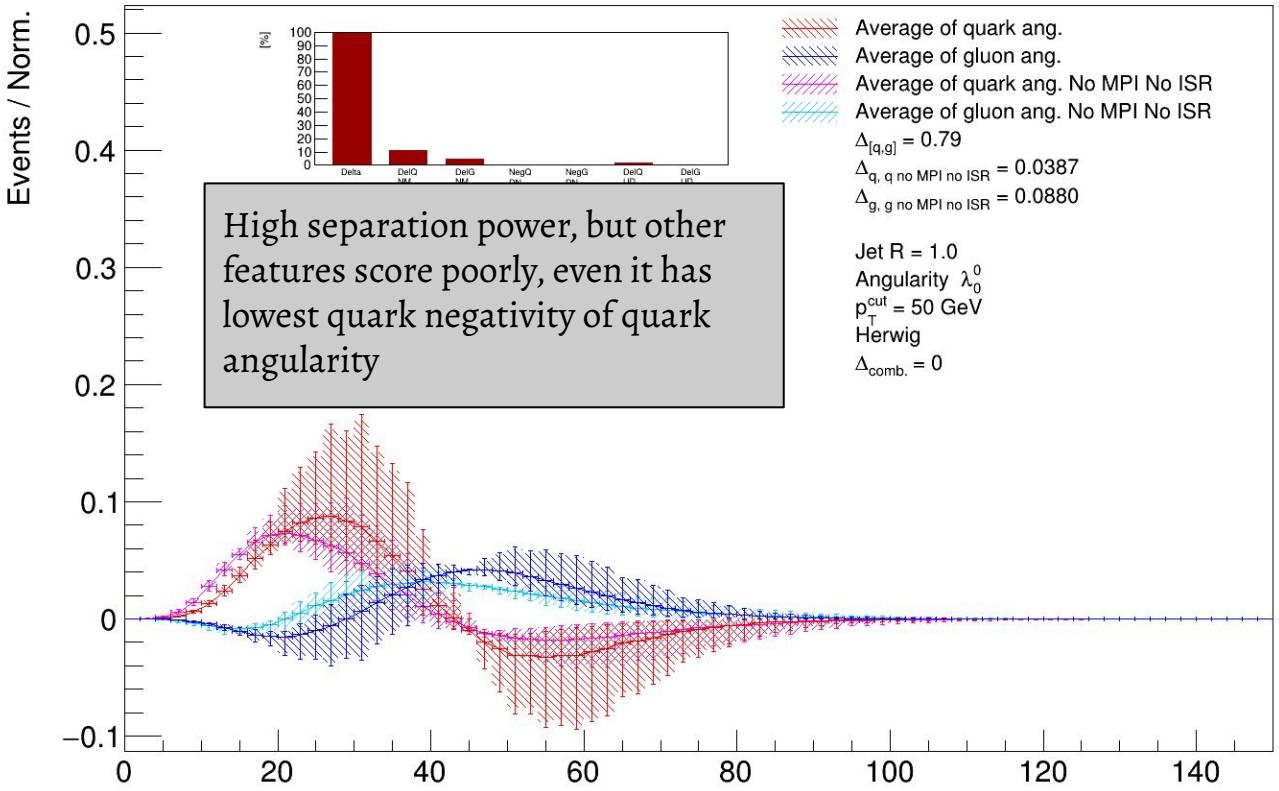
- Possible that the color lines of a gluon produced at any stage of the shower can be reconnected leading to the production of a color-singlet object (see example below)



- Clusters containing partons from the parton shower of each of the original gluons, i.e. $q_1,\bar{q}_3$ and $q_4,\bar{q}_2$, will have large masses and the rearrangement to give the clusters $q_1,\bar{q}_2$ and $q_4,\bar{q}_3$ will be kinematically favoured, although it means the original gluons will effectively become colour singlets rather than octets.
- It occurs at a rate which is suppressed as $1/N_C^2=1/9$, and rate 2/3 which is current default.
- Fix: we forbid the reconnection which would lead to a gluon produced in any stage of the PS evolution becoming a colour-singlet after hadronization.

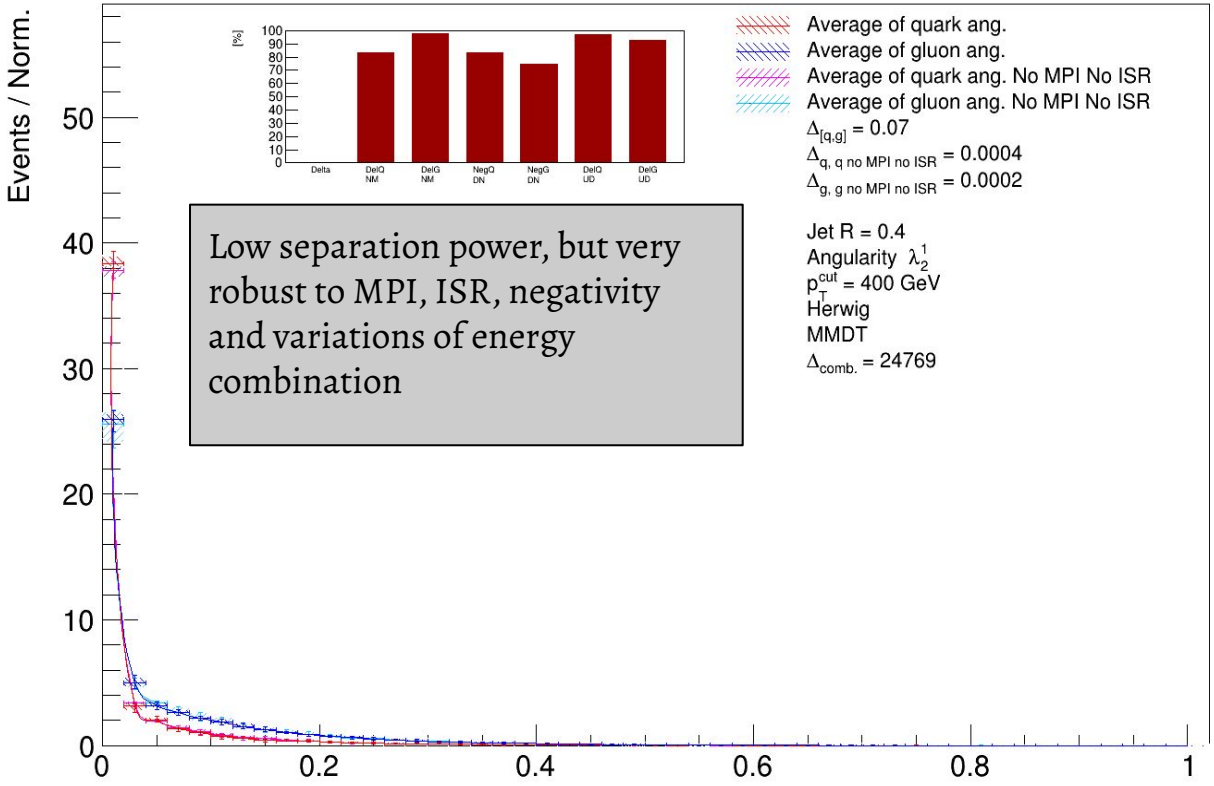
Results

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



Results

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



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