Novel approach to measure quark/gluon jets at the LHC

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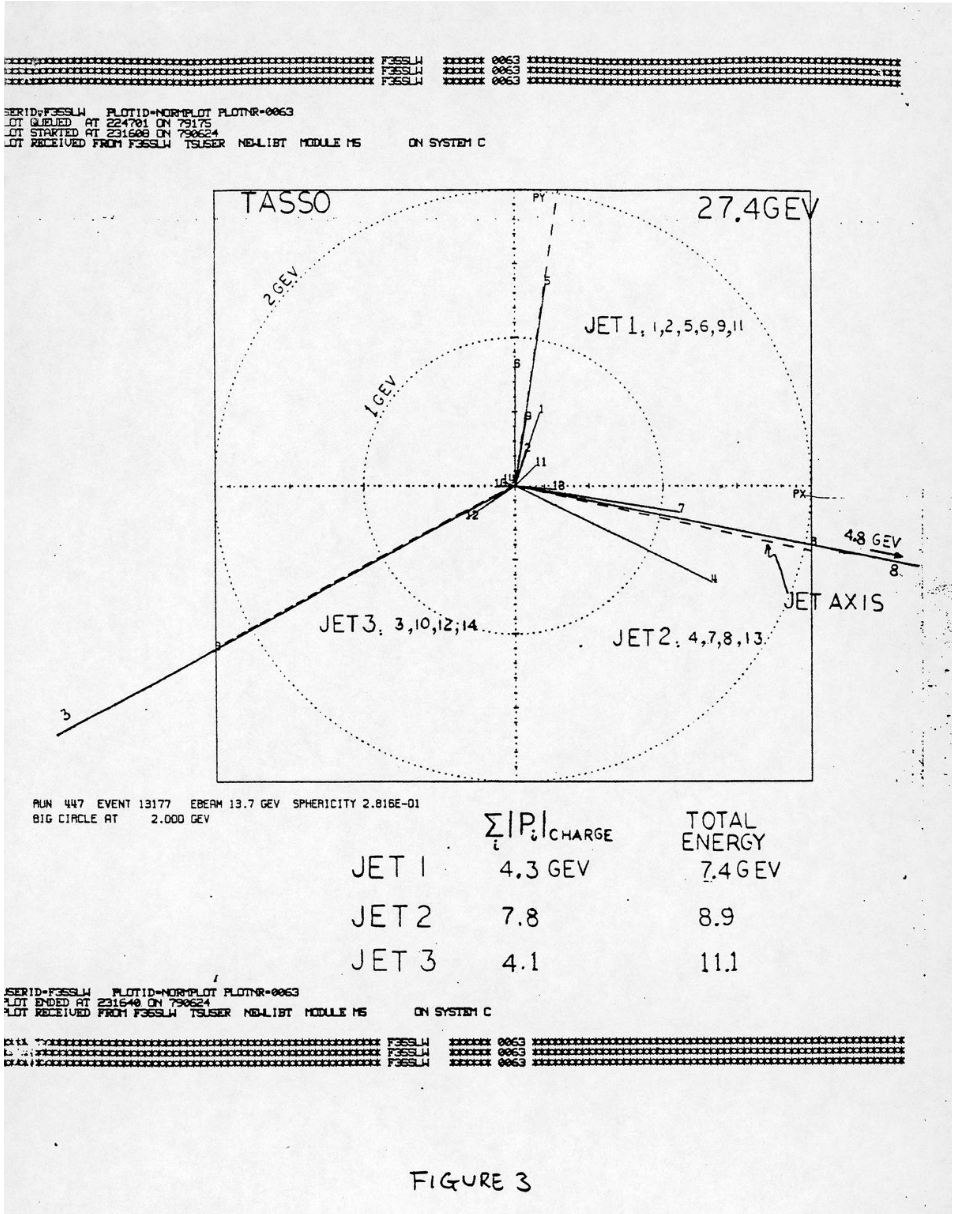
Outline

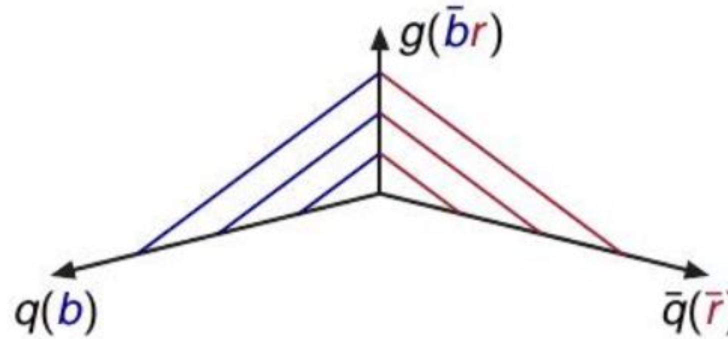
1. Introduction and Motivation
2. Novel approach to measure quark/gluon jets at the LHC
3. Preliminary results
4. Summary and outlook

History: Discovery of the gluon



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.



Distinguish Q/G jets as is as 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

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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:

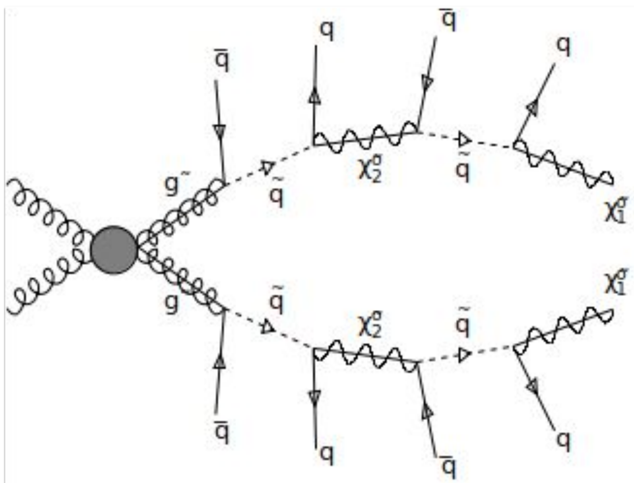


Fig. From J. Gallicchio and M. D. Schwartz, Phys. Rev. Lett.107 (2011)

- 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')

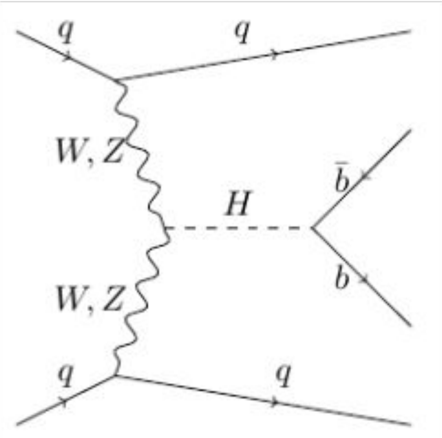
Why we would like to distinguish Q/G jets?

Interesting standard model physics also tends to be quark-heavy

Examples:

- W's decaying hadronically (no b's!): $W^+ \rightarrow u\bar{d}$ or $c\bar{s}$
- Tops ($t\bar{t} \rightarrow b\bar{b} \quad + \quad 0$, 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:

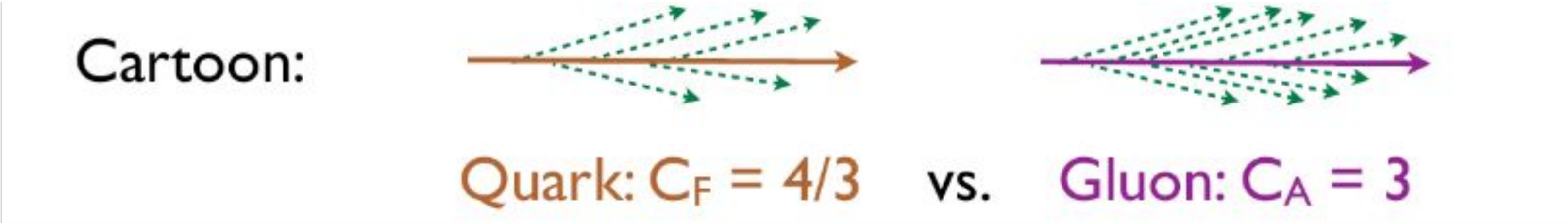
Cartoon:

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

Expectation:

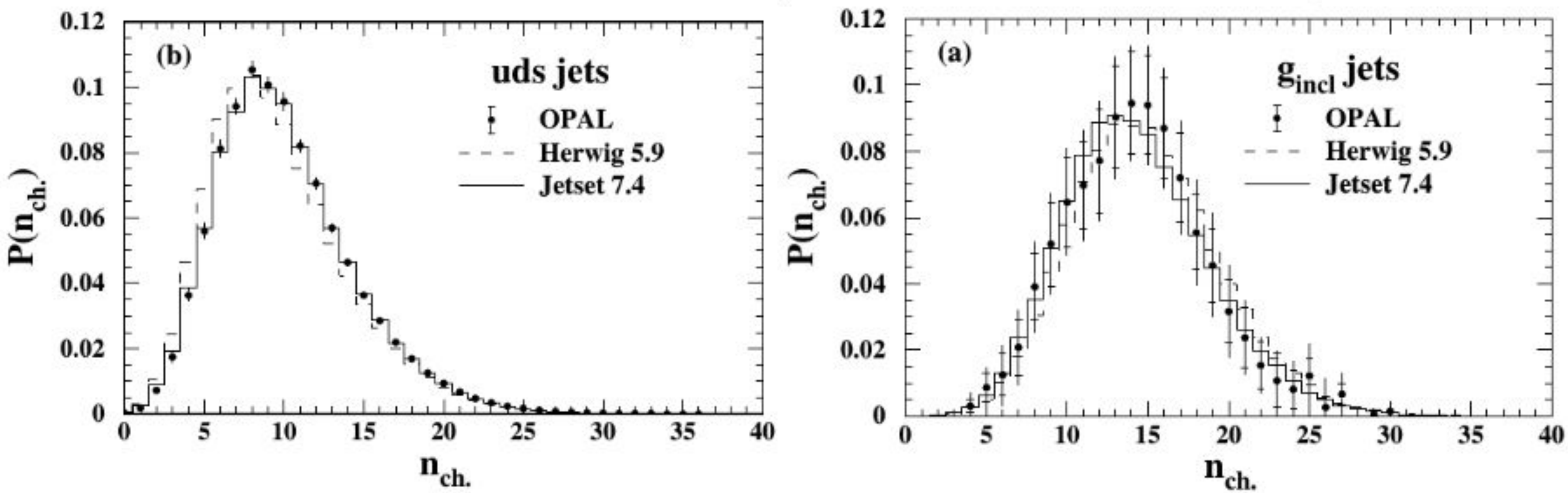
- Gluon will radiate more
- Gluon will radiate wider
- Multiple radiation → effect will exponentiate

Introduction – q/g jets perturbative component



Gluon will radiate more, gluon will radiate wider

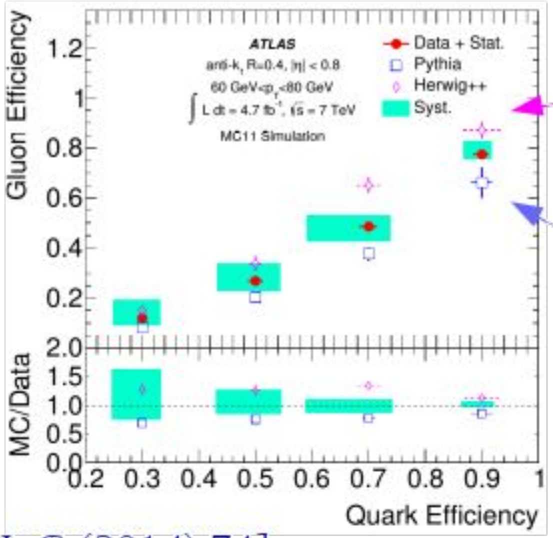
$$\frac{\langle N_g \rangle}{\langle N_q \rangle} = \frac{C_A}{C_F}$$



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

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.



[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

Q/G jet Les Houches study

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

Cartoon:

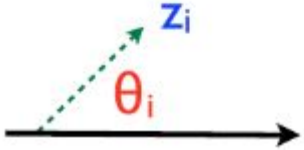
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Probe radiation pattern with
e.g. Generalized Angularities

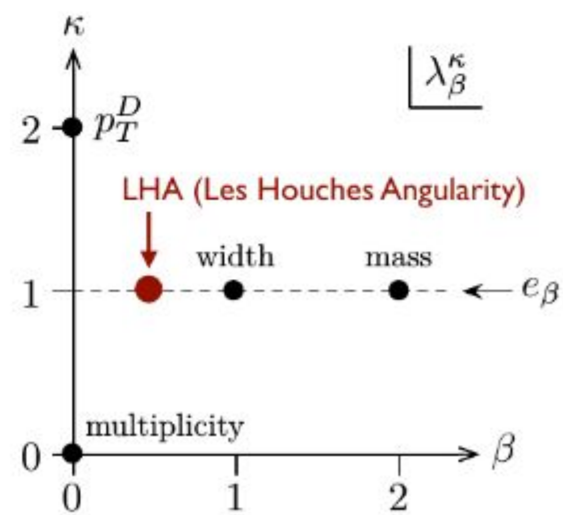
$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction

angle to recoil-free axis



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



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

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)

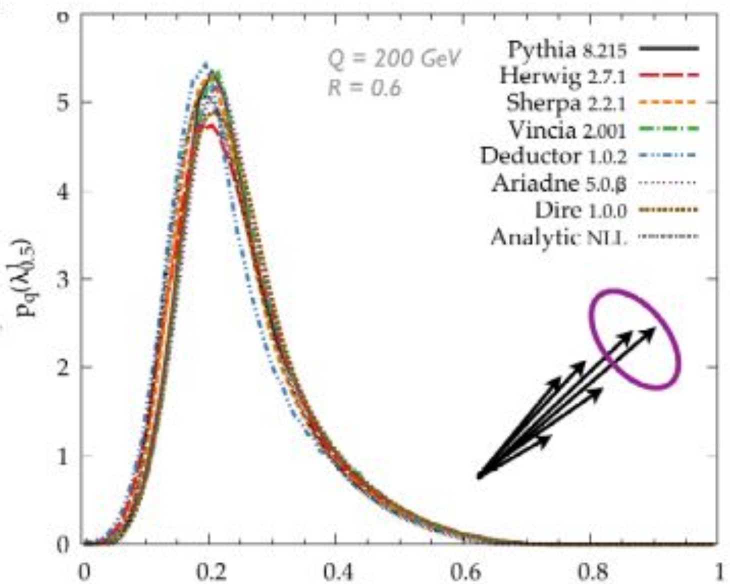
Additionally different Parton Shower algorithms

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

Q/G jet Les Houches study

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

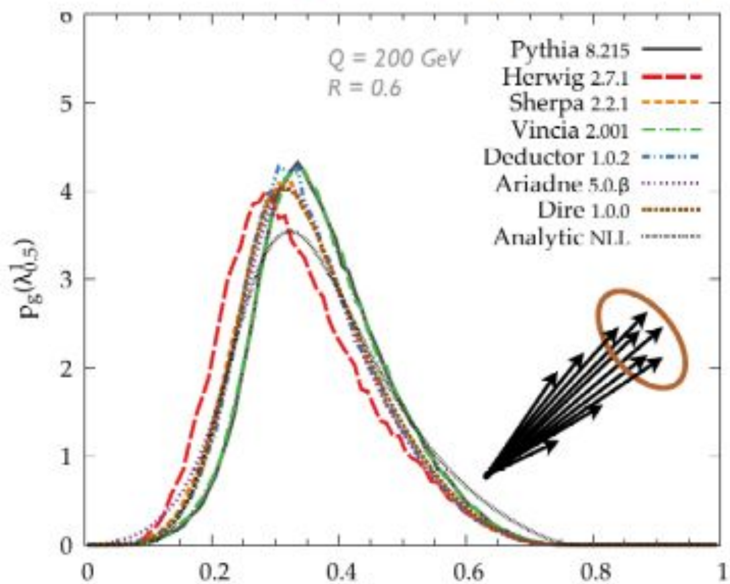
$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)



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

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.

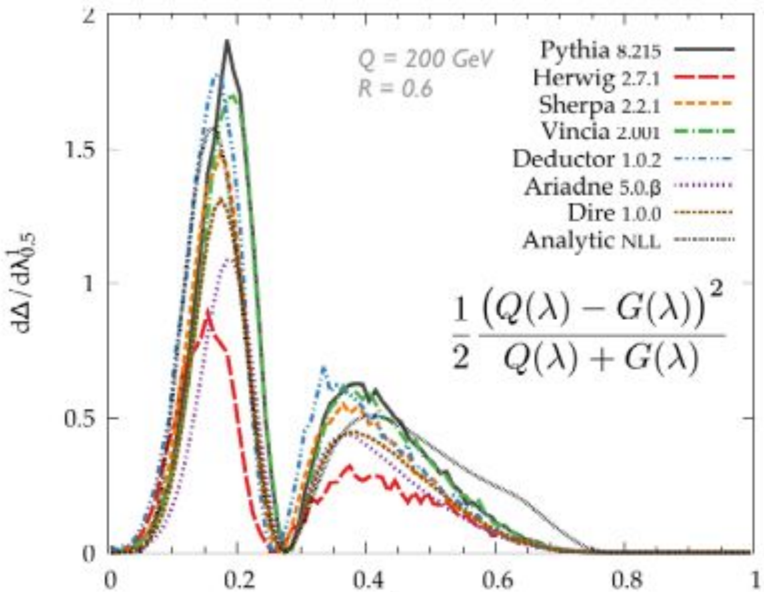
Q/G jet Les Houches study

$$\Delta = \frac{1}{2}\int \mathrm{d}\lambda \, \frac{\big(p_q(\lambda)-p_g(\lambda)\big)^2}{p_q(\lambda)+p_g(\lambda)}$$

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

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

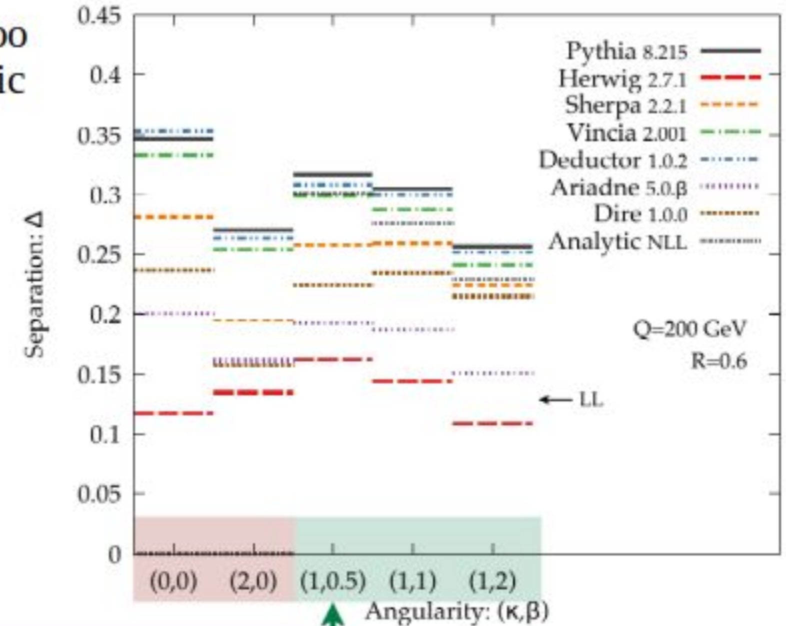
Differential



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

Pythia too optimistic

Integrated Values



Affects both IRC unsafe and IRC safe observables

How we improved simulation of Q/G jets in Herwig

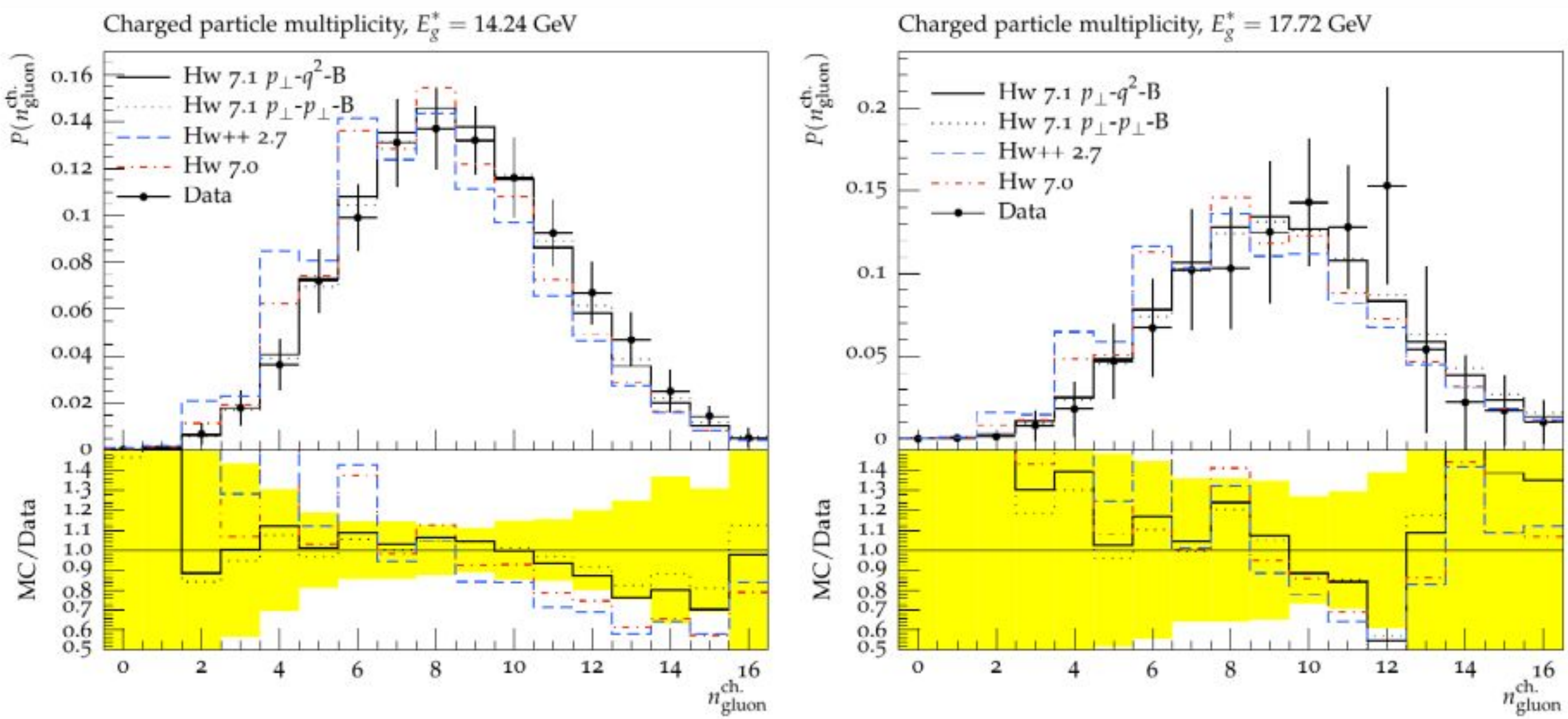
Improving the Simulation of Quark and Gluon Jets with Herwig 7

#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.

LHC how to define G enhanced sample

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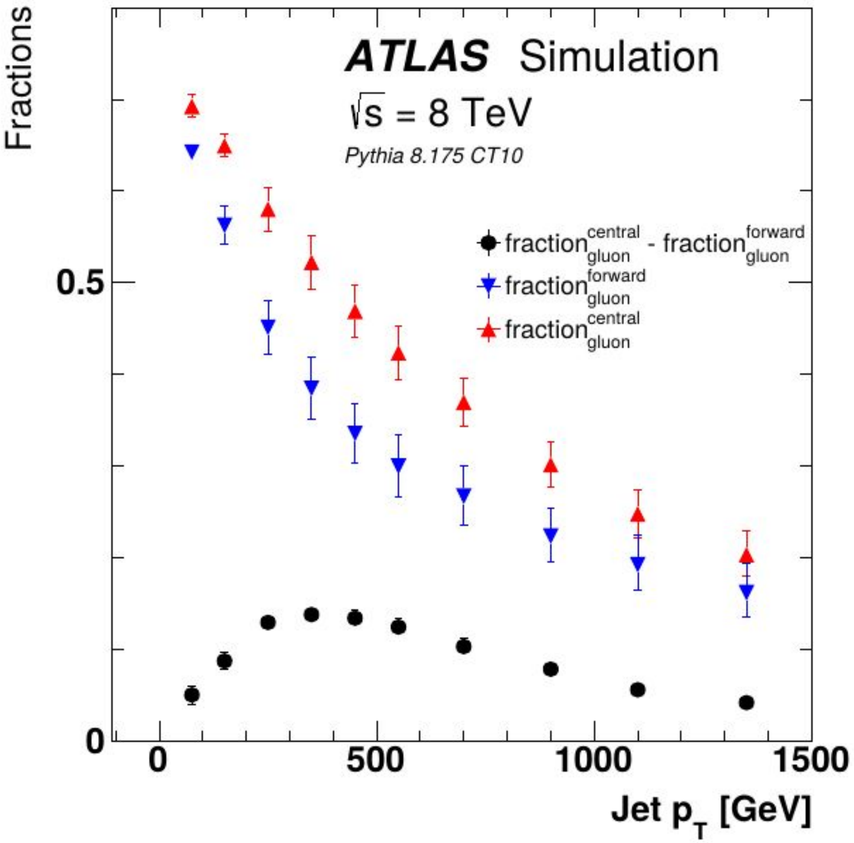


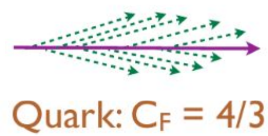
Using phase space cuts, for example:

- 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

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

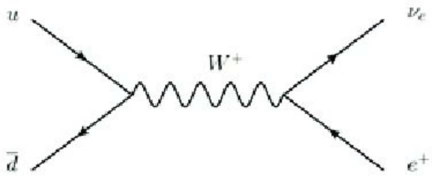


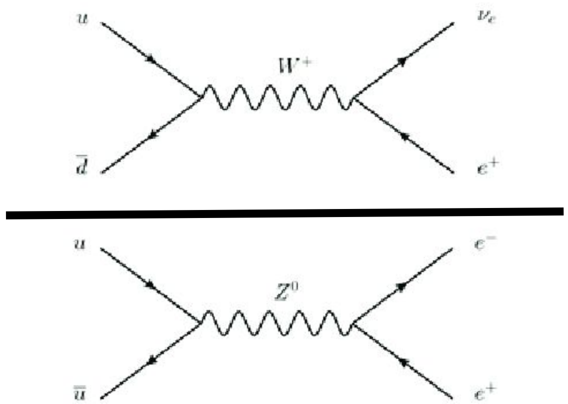
Can we find a way to get enhanced Q/G with the same Pt, η?

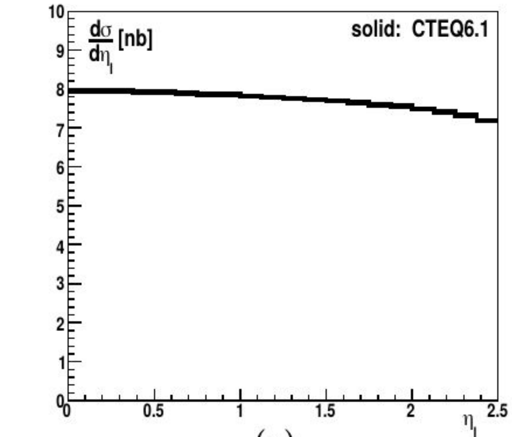
Can changing the energy of collision help us?

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

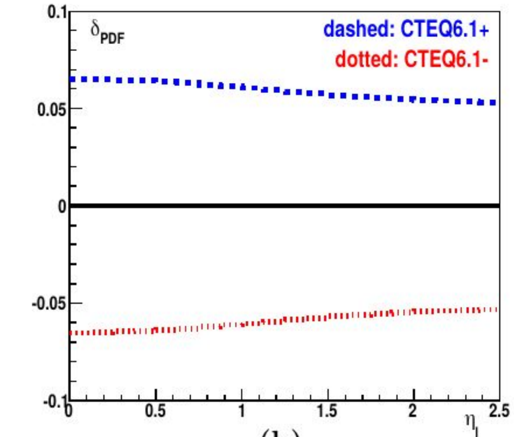
[Krasny, Fayette, Płaczek, AS, Eur.Phys.J. C51 (2007) 607-617]







(a)



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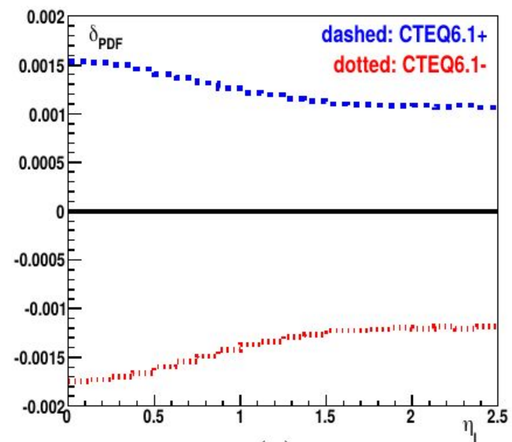
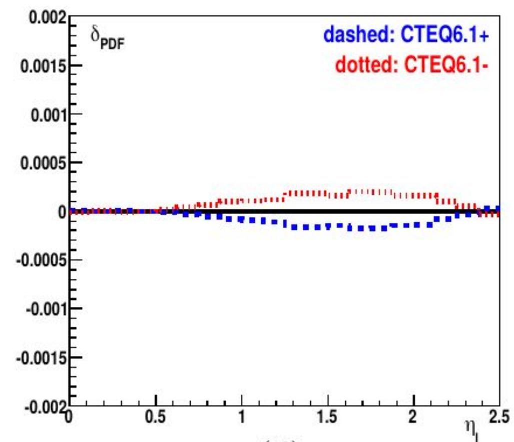


(c)



(d)

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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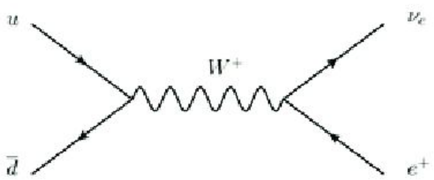

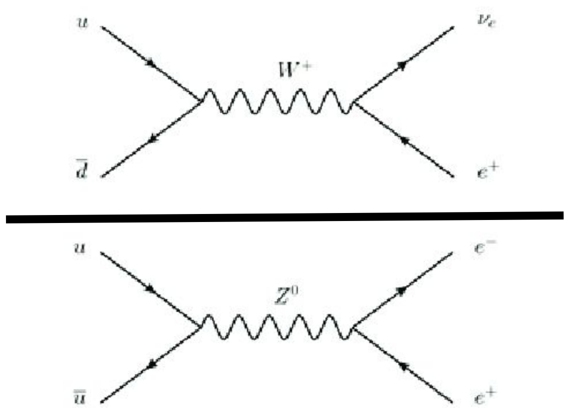

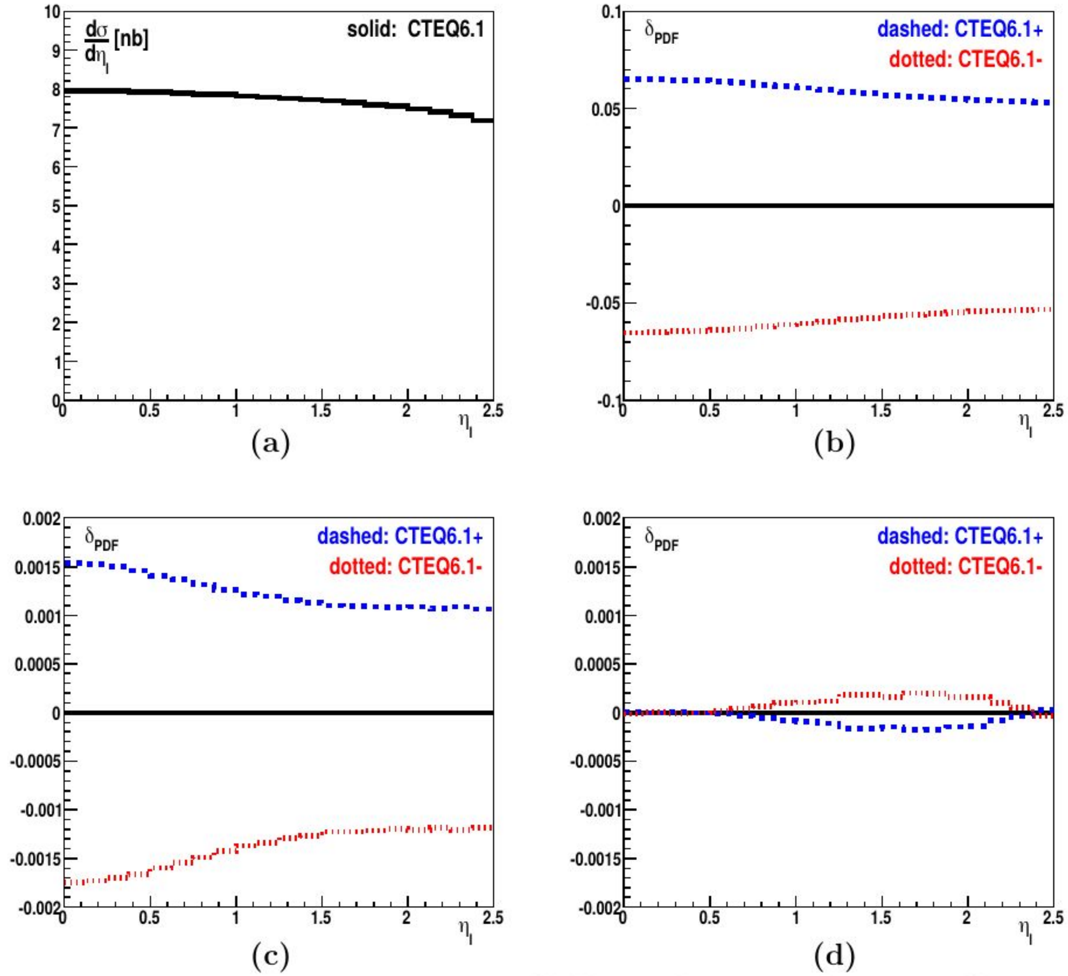

Yes it can!
Sadly not very used up to now at the LHC

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

Novel approach

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

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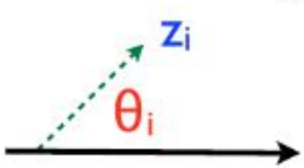

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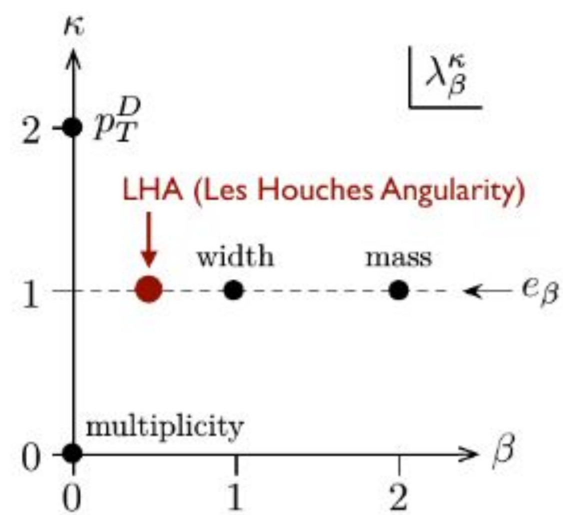

[Larkoski,Salam,Thaler,13]
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Novel approach

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

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

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

Novel approach

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

Can we reverse the equation

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

and obtain

$$\lambda_g = ?$$

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

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

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

Novel approach

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

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

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One can reverse:

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

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

Part II - a) Novel approach

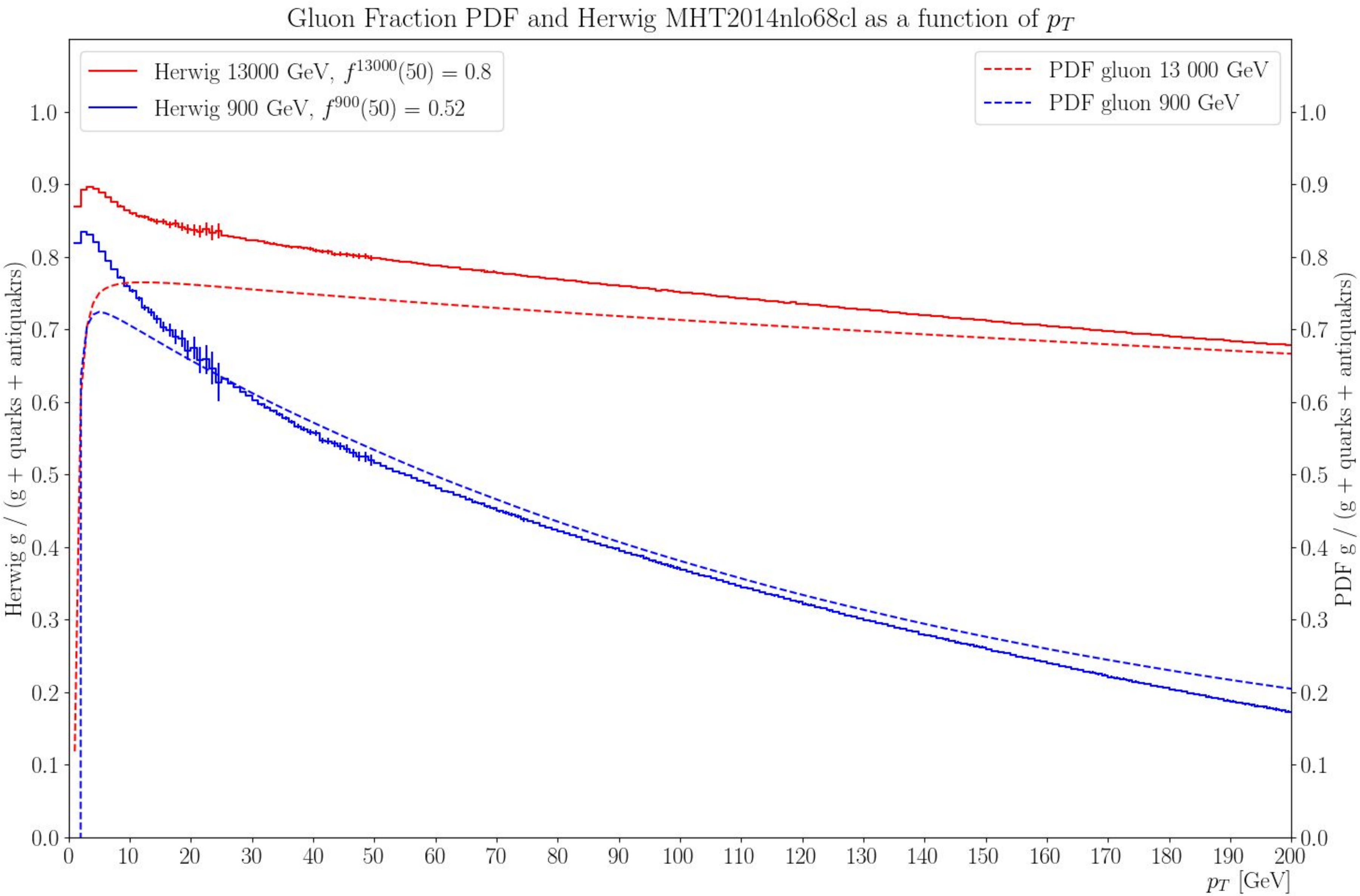
$$\lambda_g = \frac{(1-f^{13000})\lambda^{900} - (1-f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$$

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

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

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

Preliminary results



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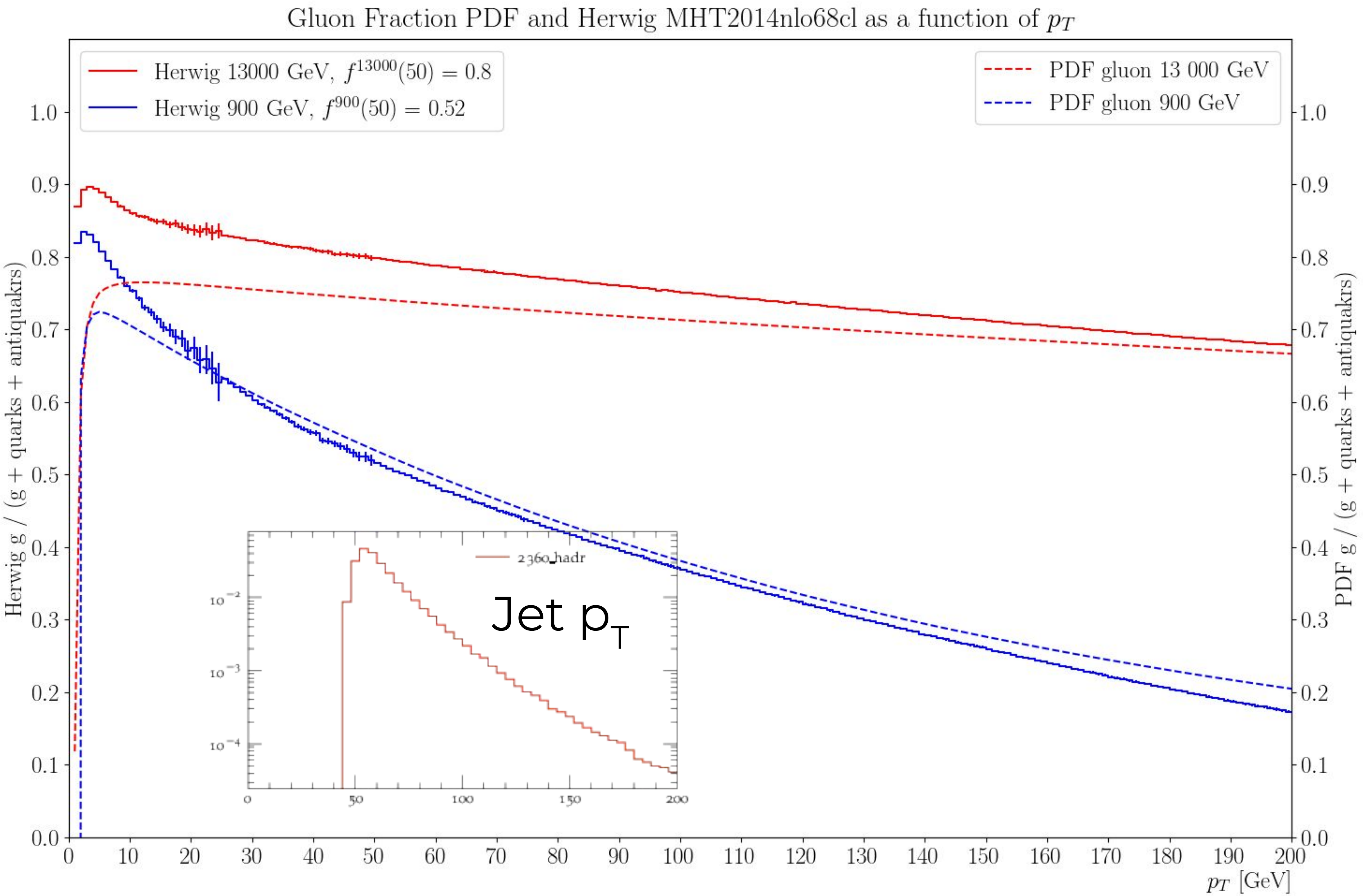

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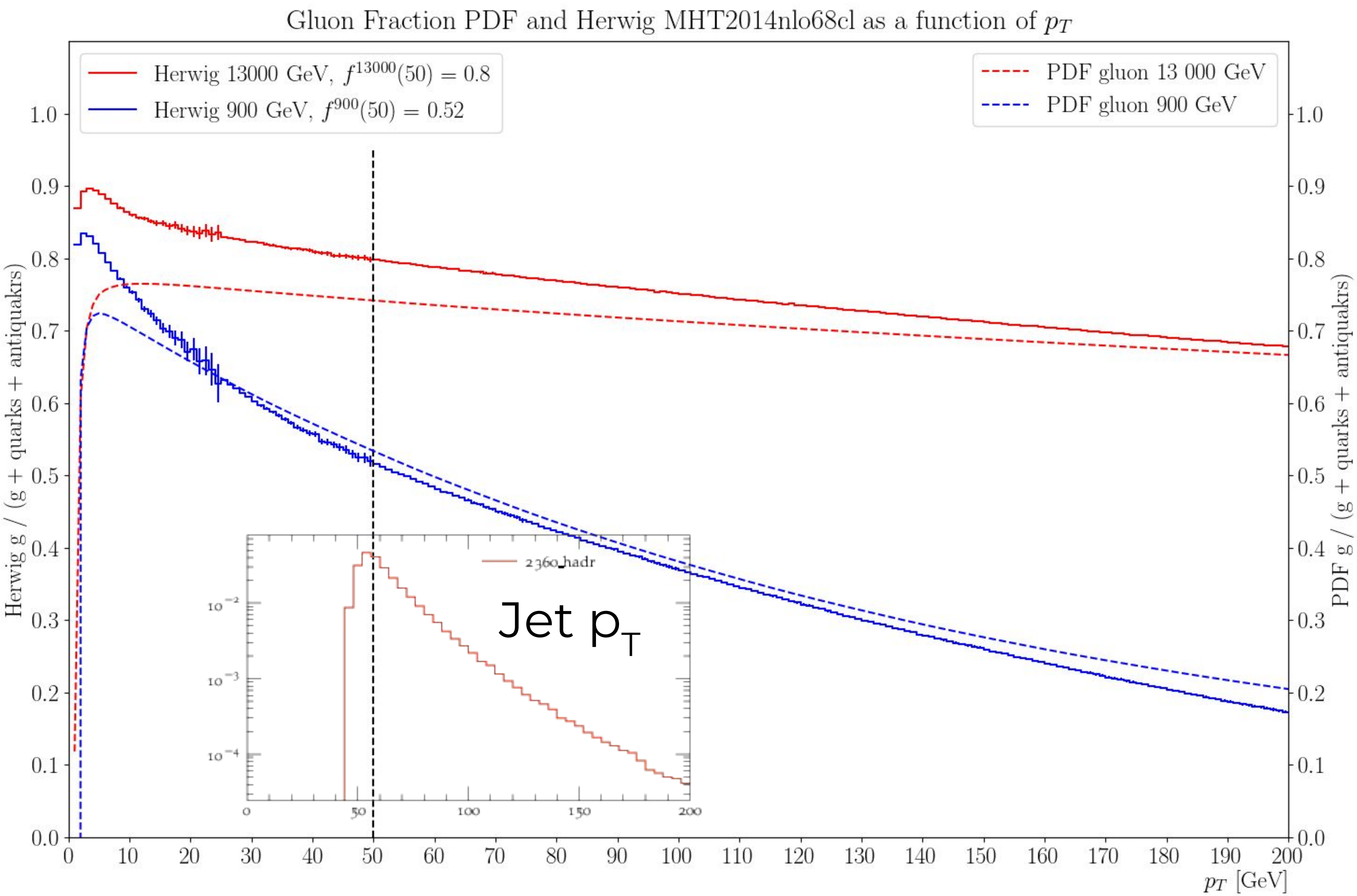

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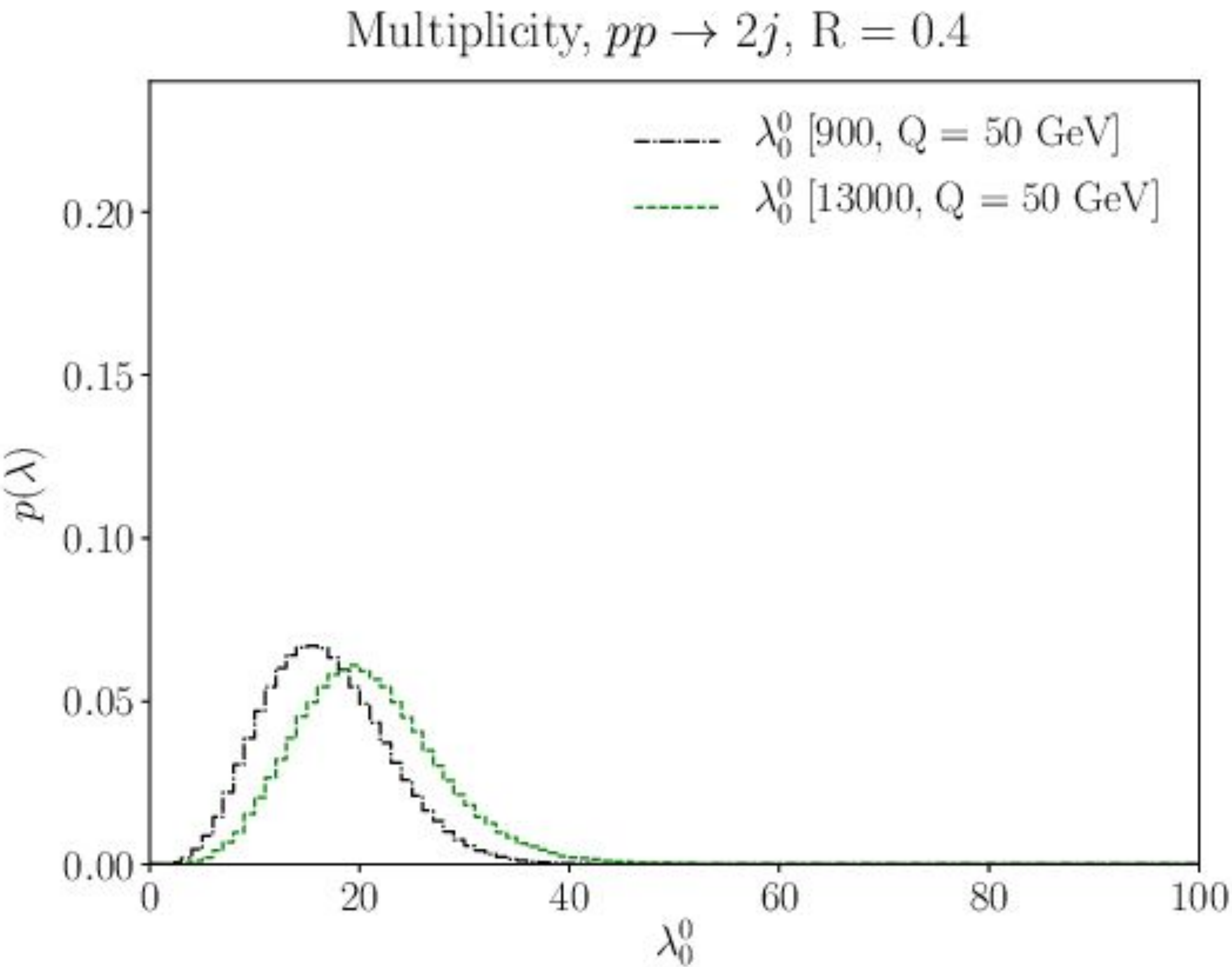

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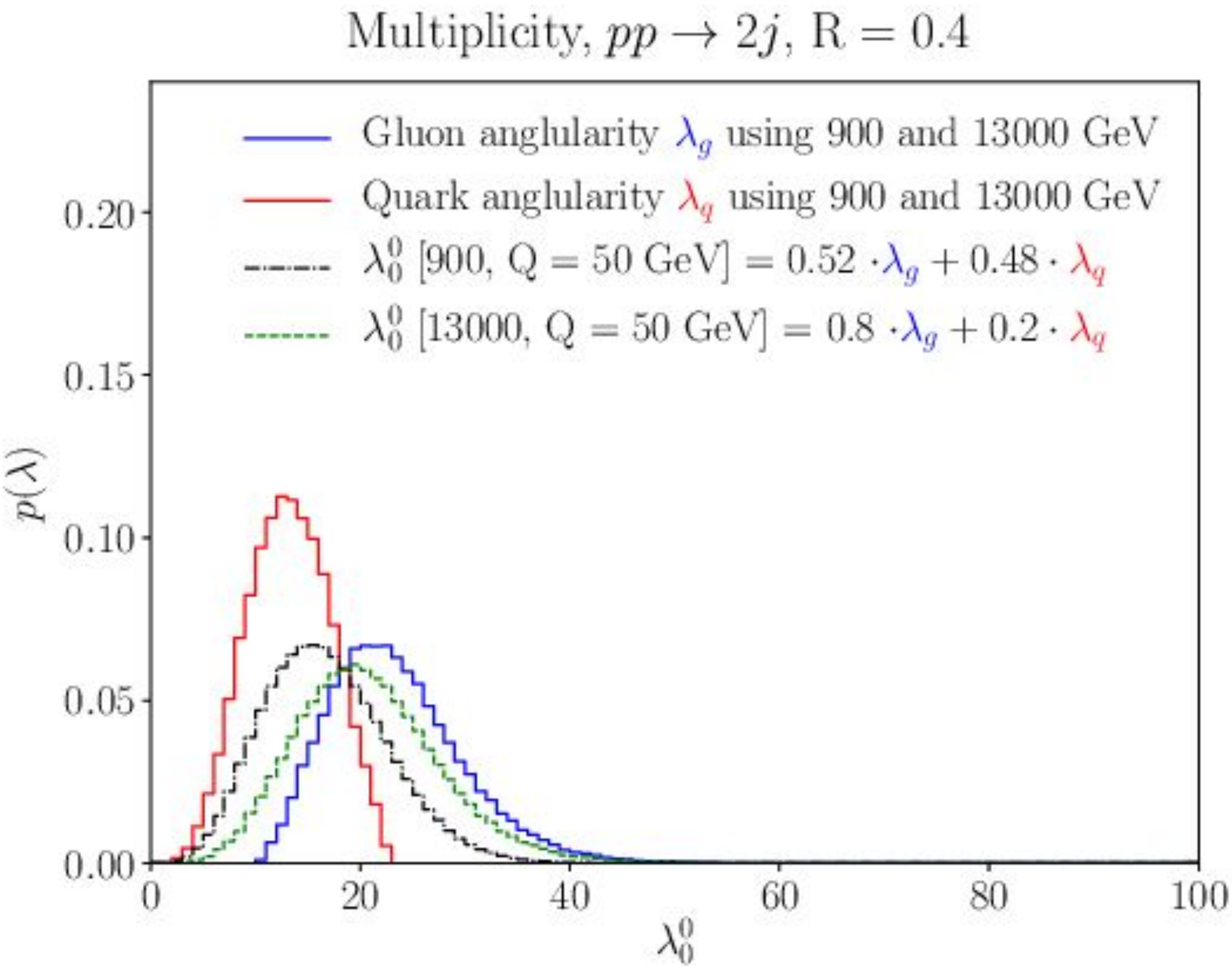

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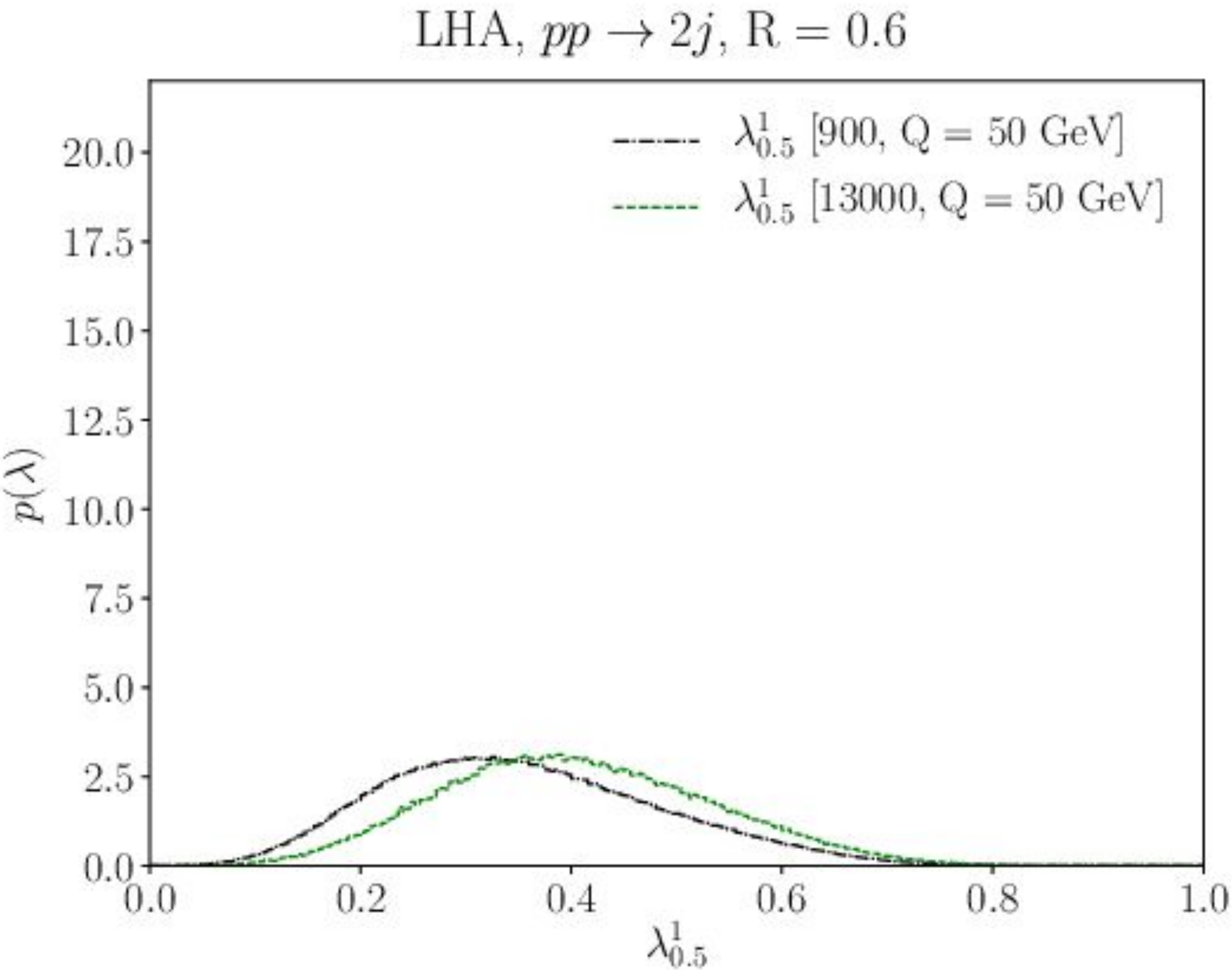

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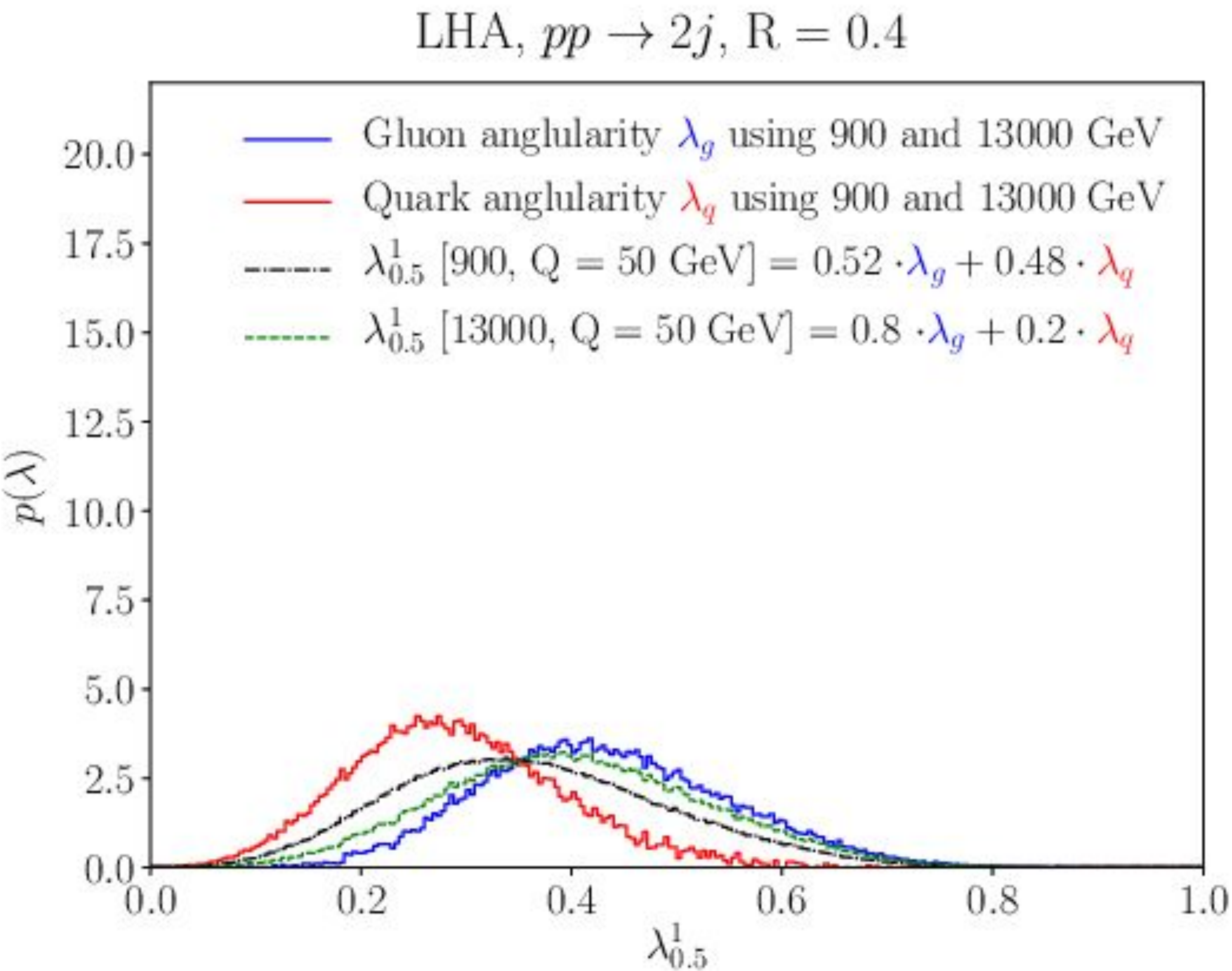

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Lets write equations for measurement at energy 900 GeV and 13 000 GeV

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

One can reverse:

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

Preliminary results

Lets write equations for measurement at energy 900 GeV and 13 000 GeV

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

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

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

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

$$\lambda_g = \frac{(1 - f^{13000})\lambda^{900} - (1 -}{f^{900} - f^{1300(}}$$ and

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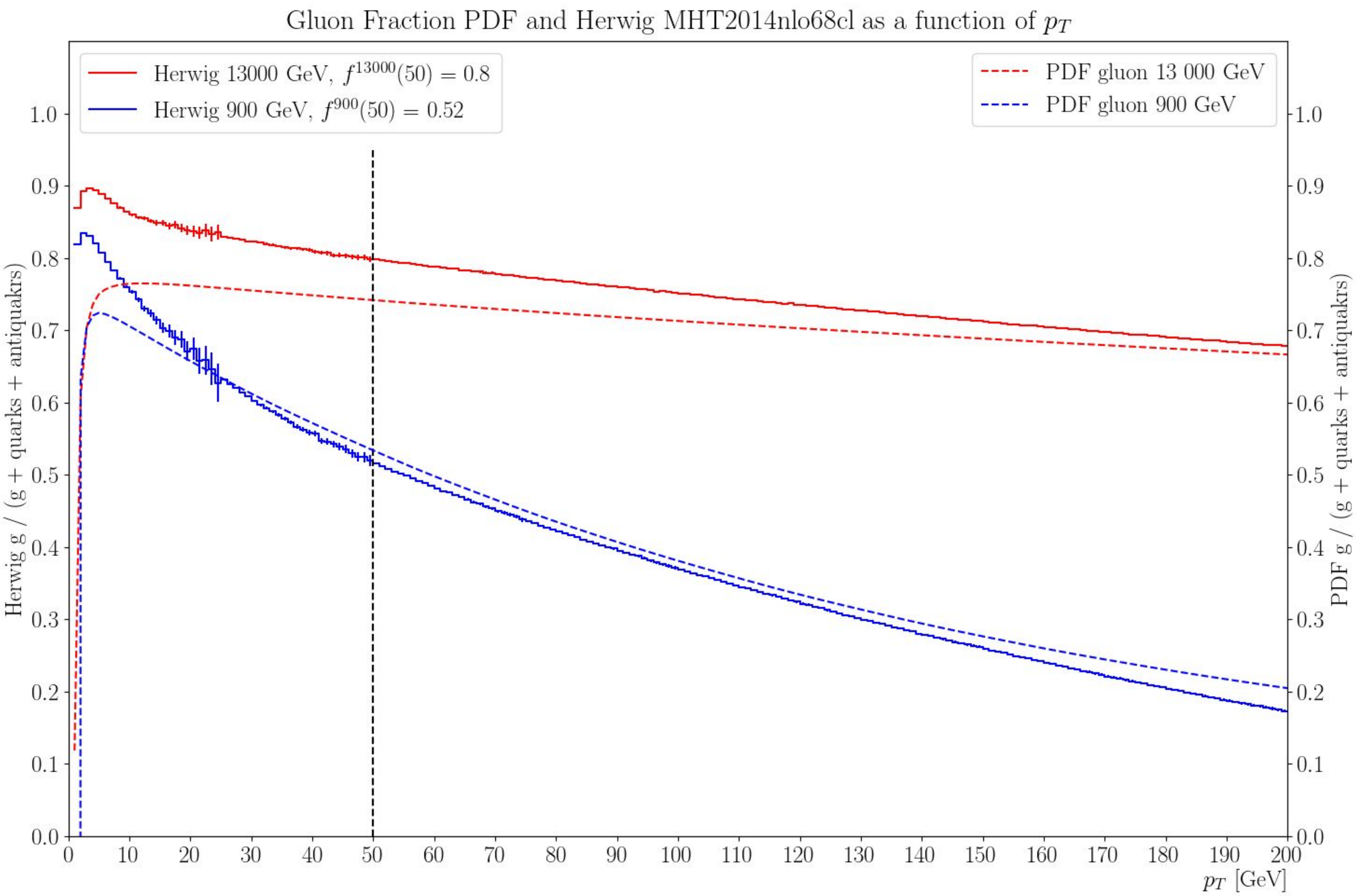

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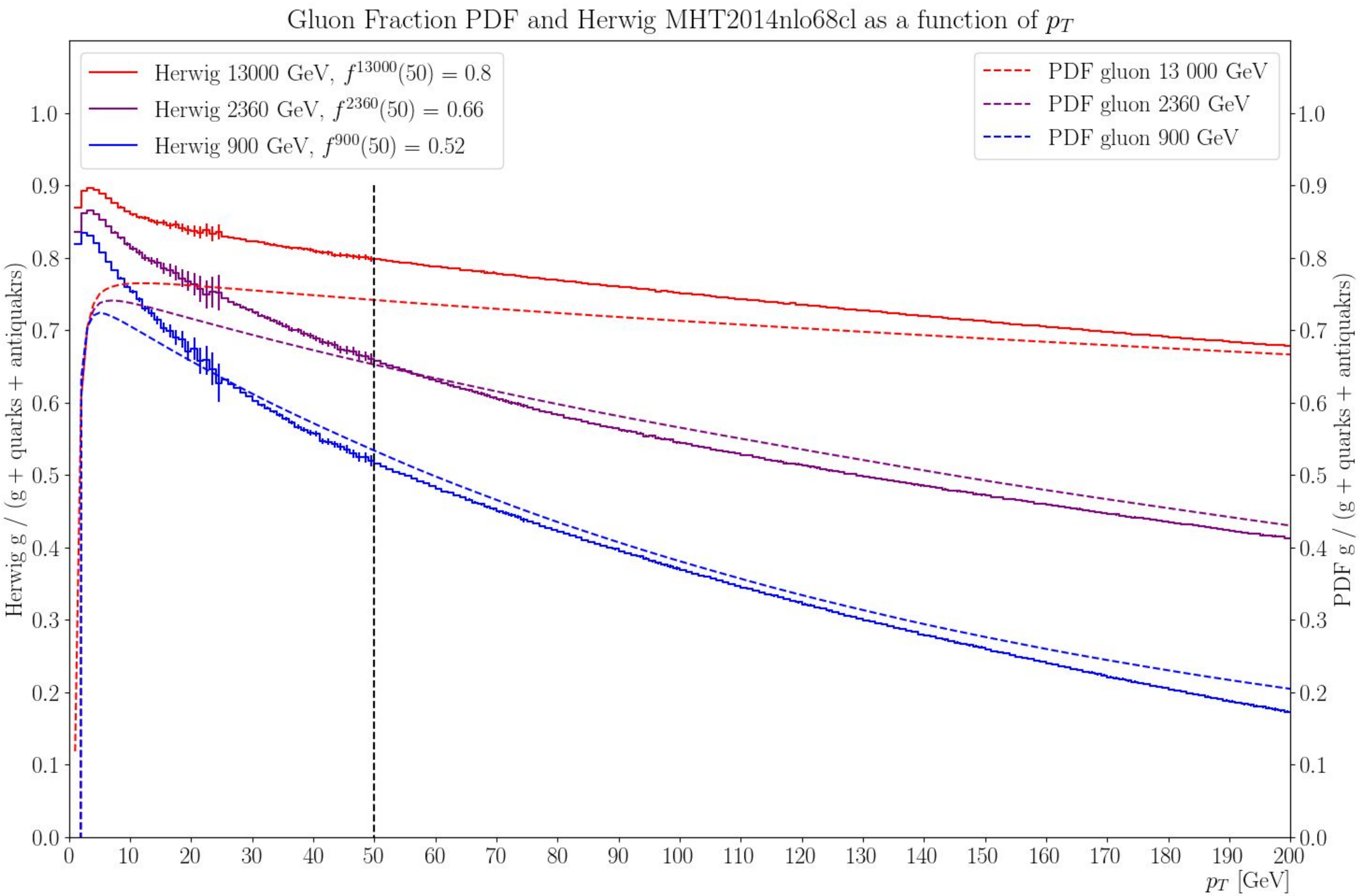

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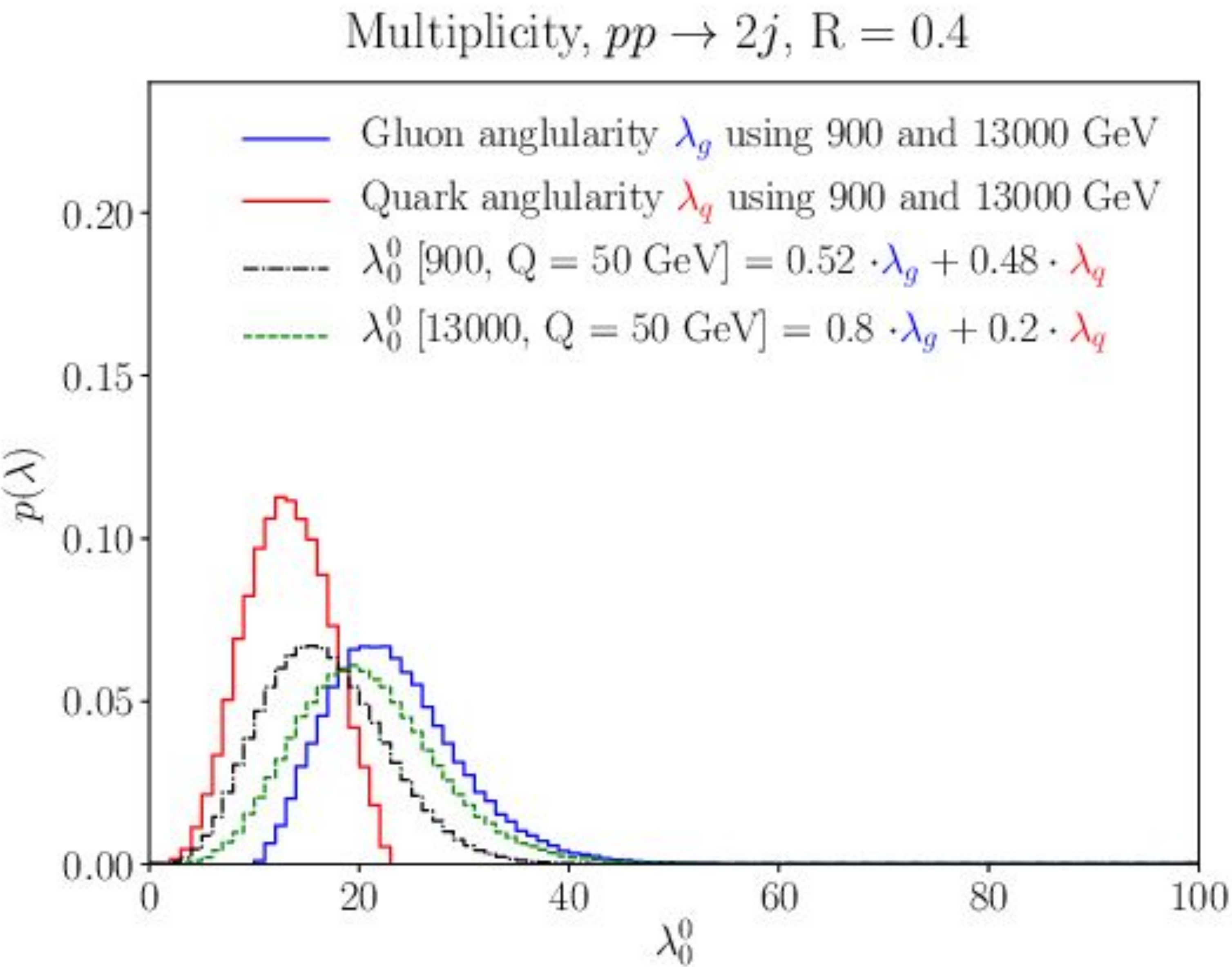

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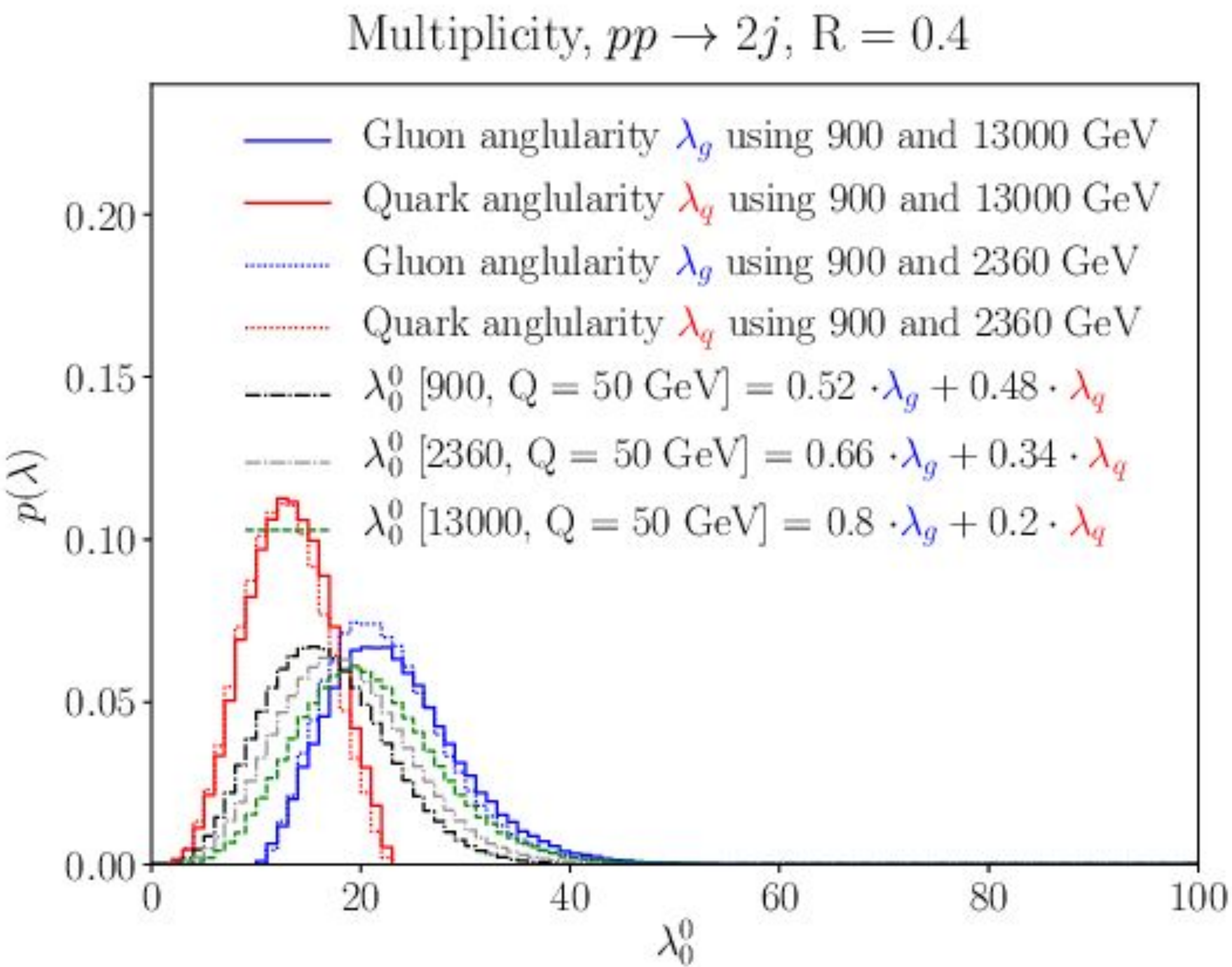

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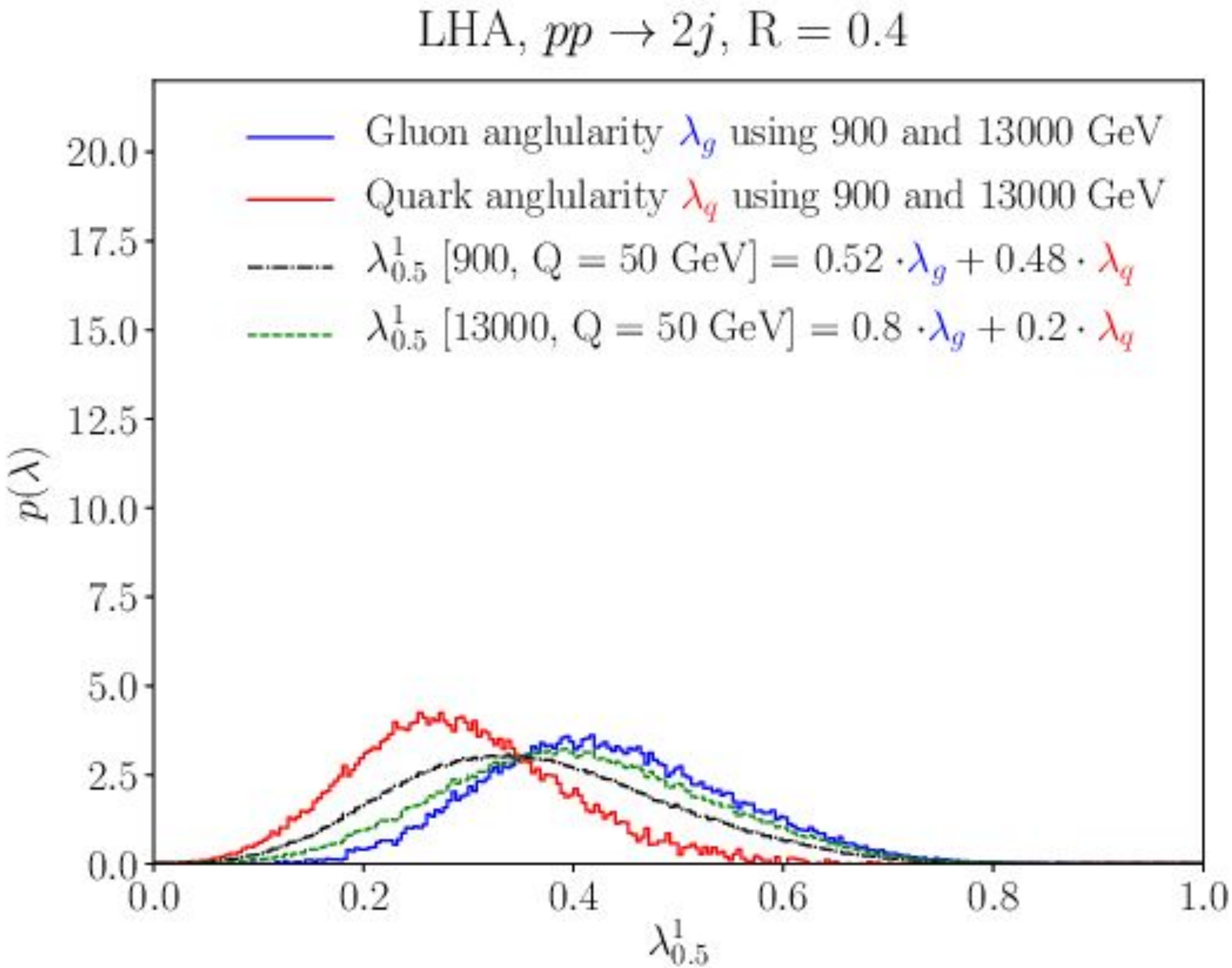

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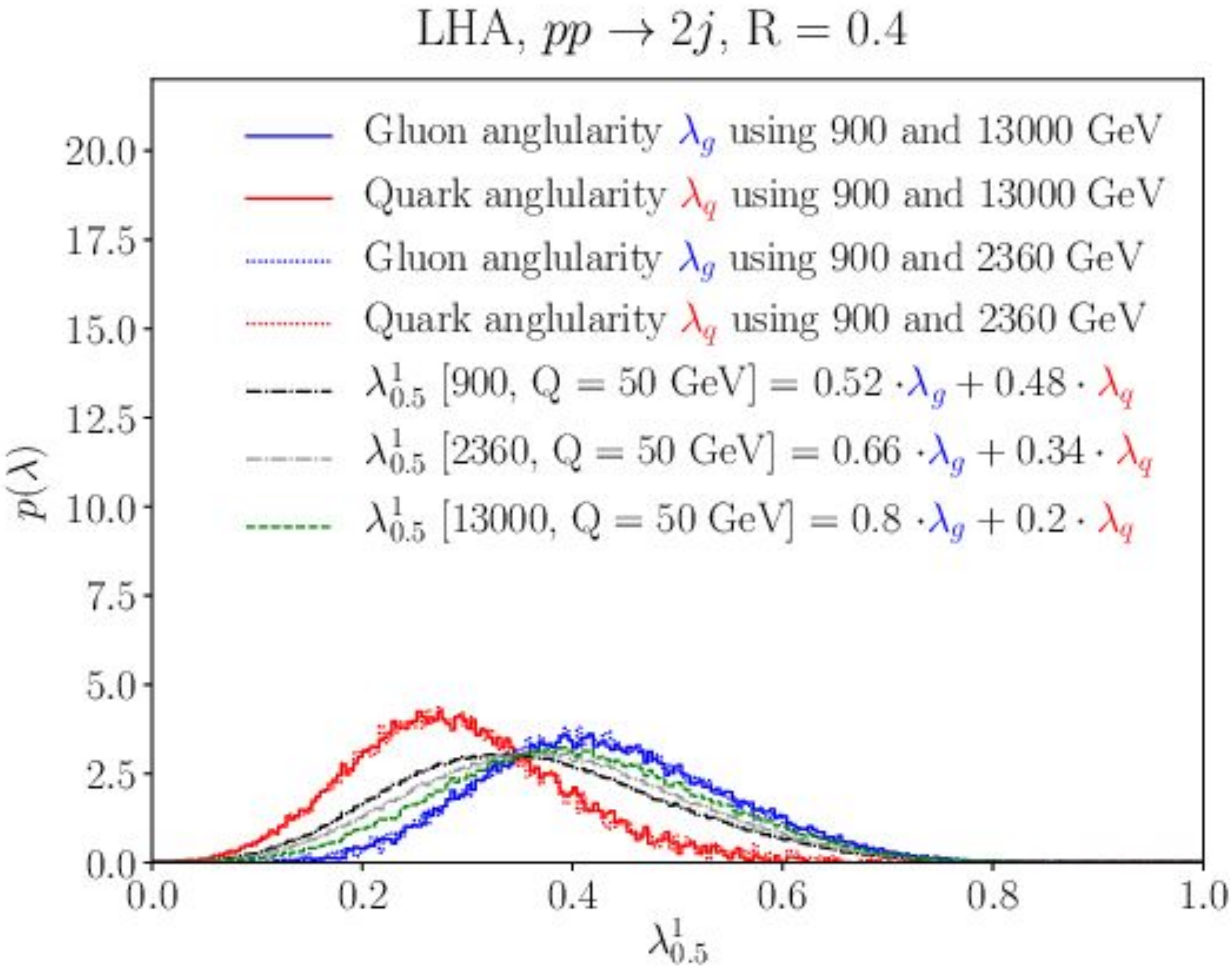
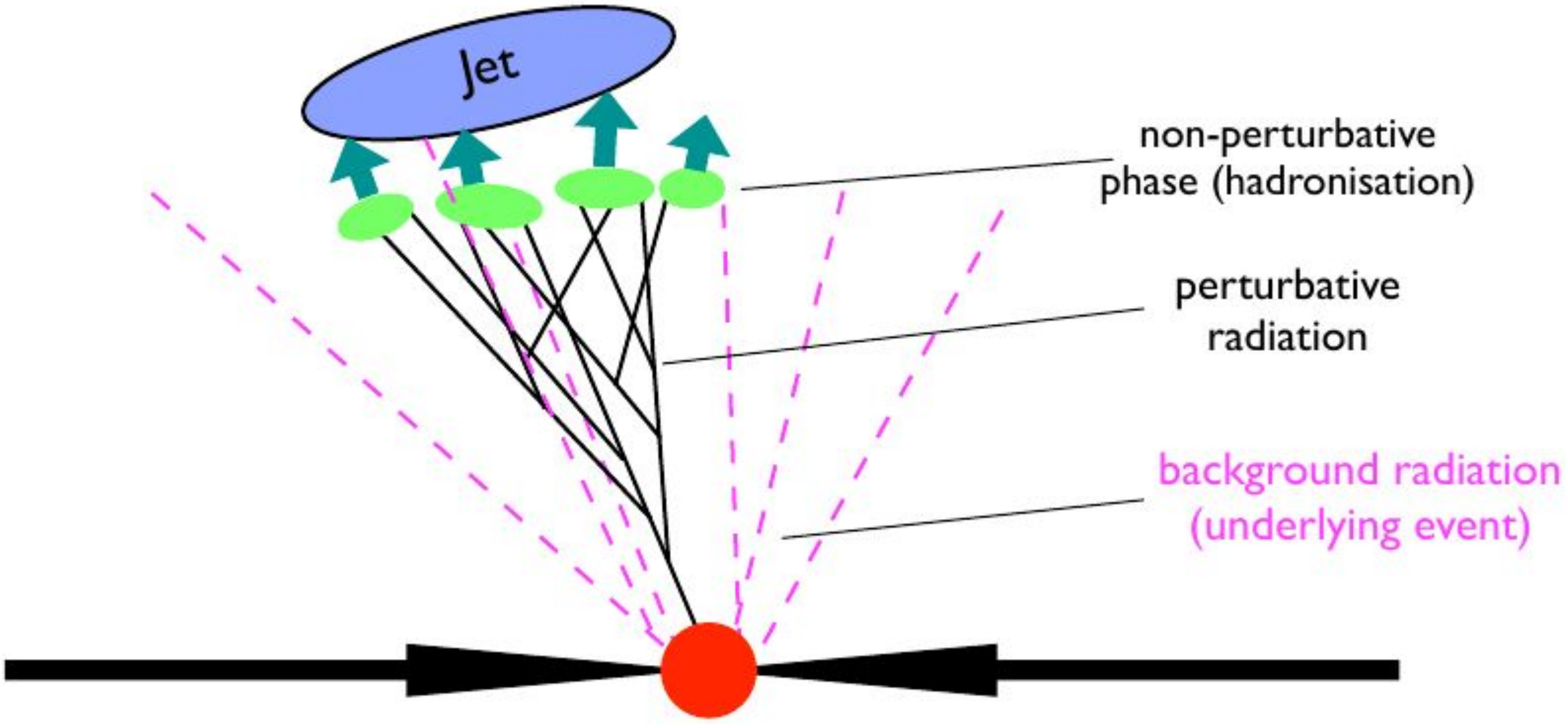
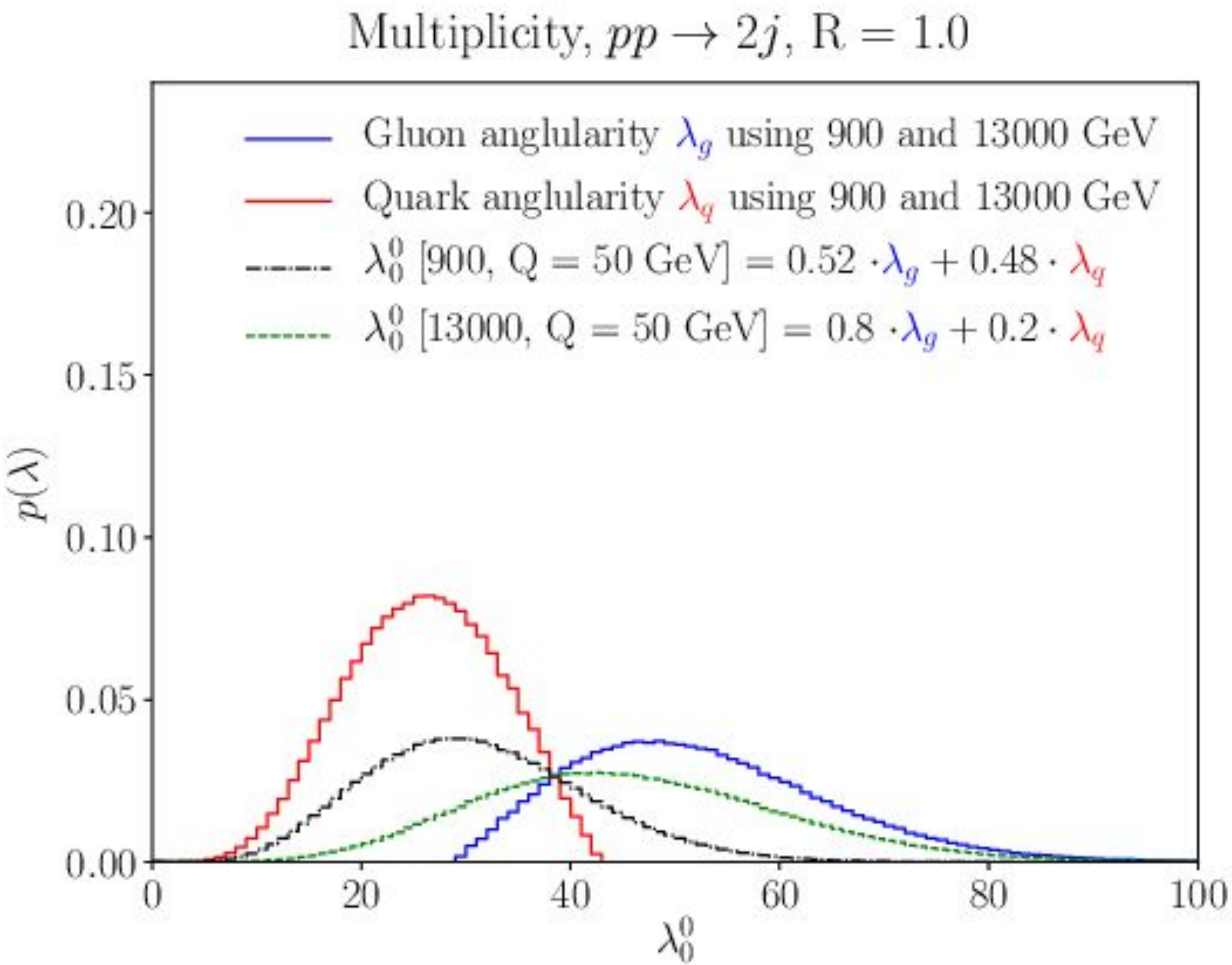


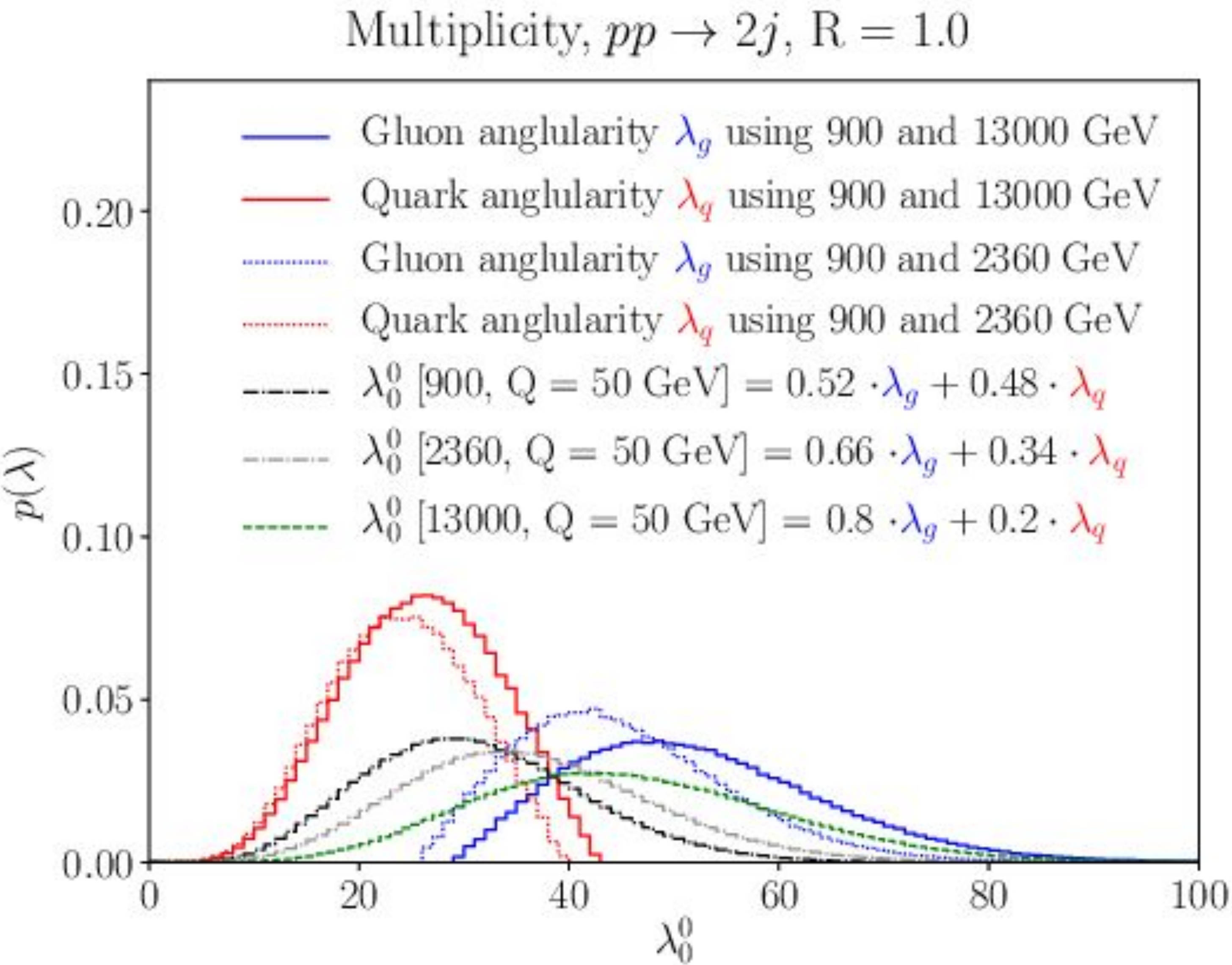
Jet contamination (ISR + MPI)



Jet contamination (ISR + MPI)



Jet contamination (ISR + MPI)



Part II - c) Summary and Outlooks

Summary

1. Preliminary results look very promising.
2. As expected we see that with increasing jet radius we get contamination, most likely due to ISR + UE event background.

Outlooks

1. Optimize, cuts (Pt, rapidity, R)
2. Investigate results with grooming techniques
3. Estimate uncertainties:
   - 3 MC generators (Pythia, Herwig, Sherpa)
   - 3 PDF (MRST, CTEQ, NNPDF)
   - more energies
4. Publish the results.
5. Measure it at the LHC.
6. Use the measurement to improve MC generators.

How we improved simulation of Q/G jets in Herwig

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)

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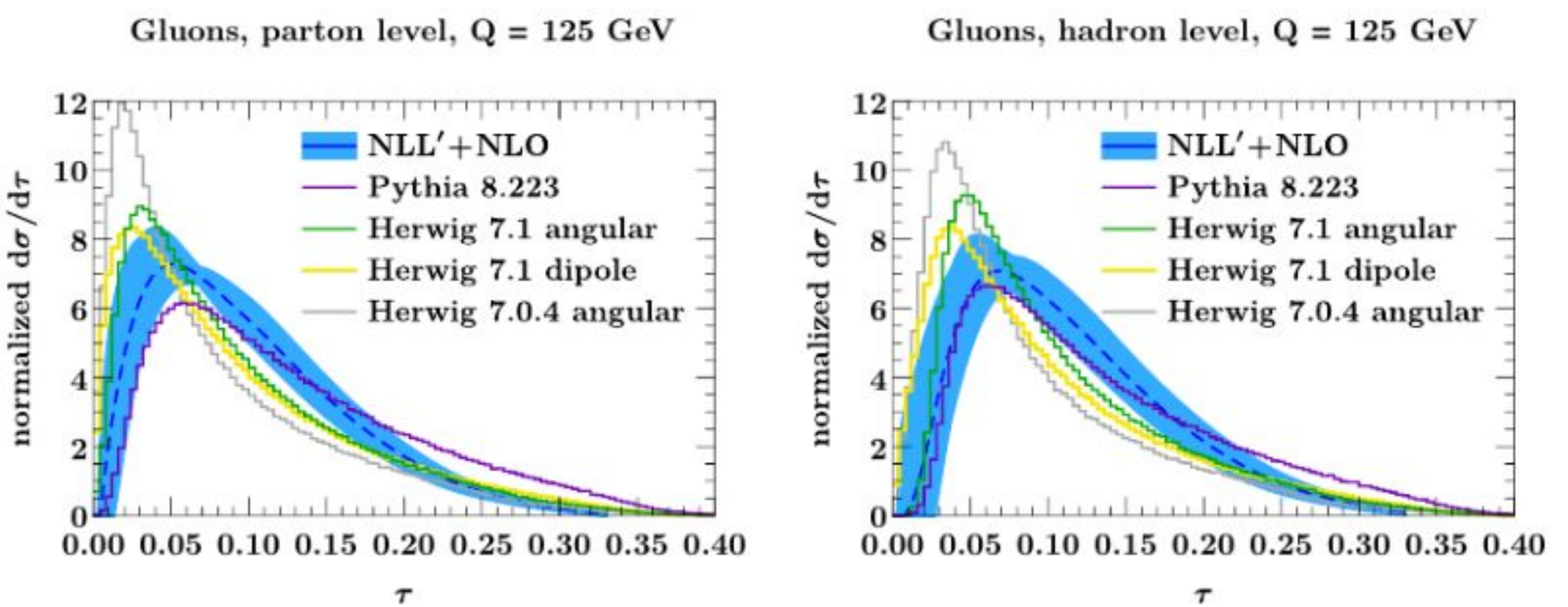
"A case study of quark-gluon discrimination at NNLL0 in comparison to parton showers"

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"