Novel approach to measure quark/gluon jets at the LHC

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MCnet

Outline

I. Part I (A. Siódmok)

a) Introduction and Motivation

b) How well the Monte Carlo Generators can describe the q/g jets [JHEP 1707 (2017) 091], [Eur.Phys.J. C77 (2017) no.12, 876]

c) How changing of energy of collision can help us to get more precise measurements? [Eur.Phys.J. C51 (2007) 607-617]

II. Part II (P. Baroň)

a) Novel approach to measure quark/gluon jets at the LHC

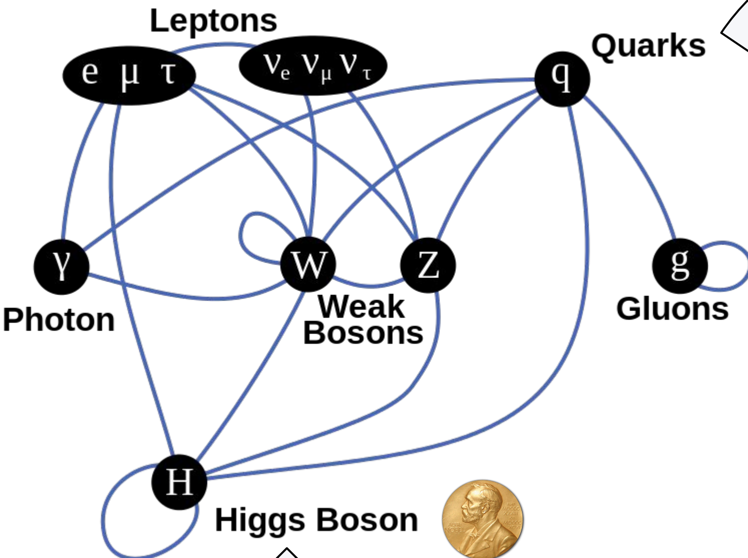
b) Preliminary results

c) Summary and outlook

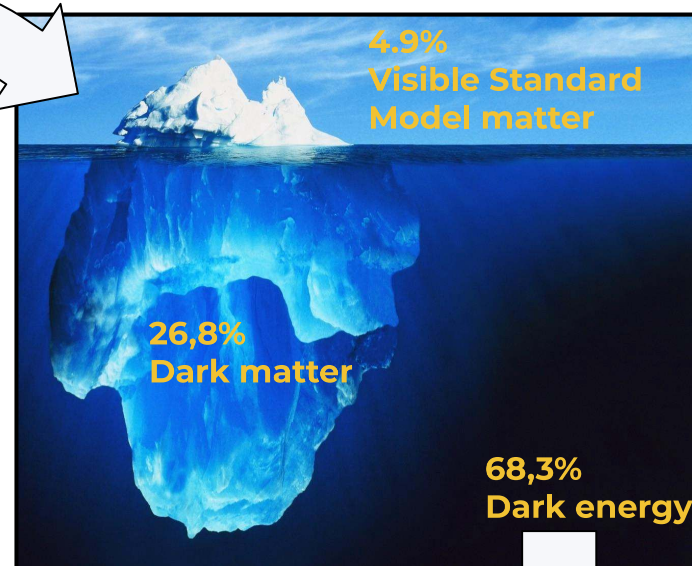
Motivation

Standard Model

very successful theory



Physics beyond SM must exist



LHC

European Strategy for Particle Physics

“Europe's top priority should be the exploitation of the full potential of the LHC”

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:

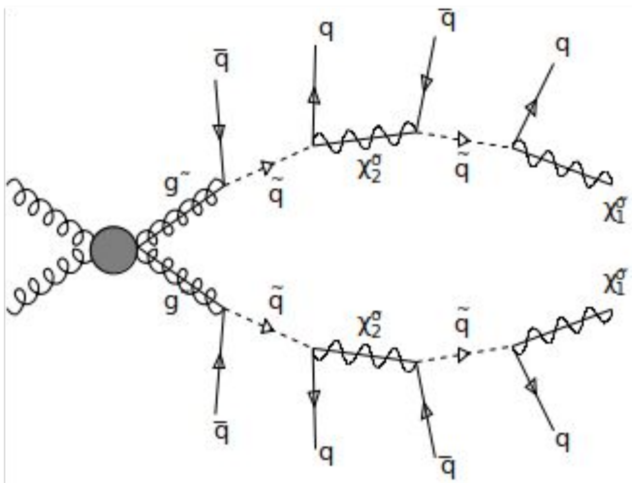


Fig. From J. Gallicchio and M. D. Schwartz, Phys. Rev. Lett.107 (2011)

- 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')

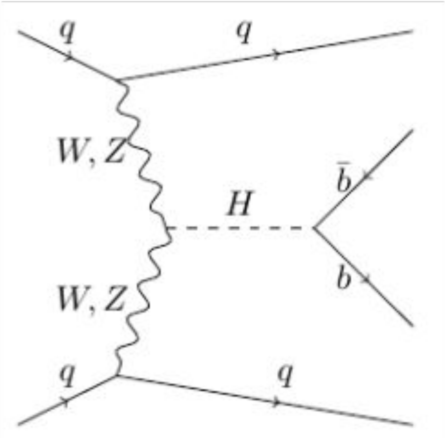
Why we would like to distinguish Q/G jets?

Interesting standard model physics also tends to be quark-heavy

Examples:

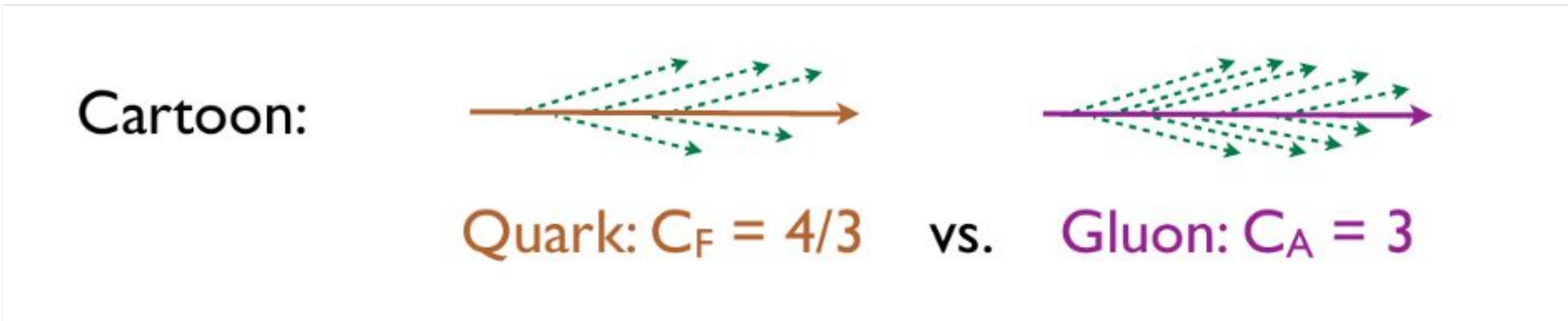
- W's decaying hadronically (no b's!): $W^+ \to u\bar{d}$ or $c\bar{s}$
- Tops ($t\bar{t} \to b\bar{b} \;\; + \;\; 0$, 2, or 4 light quarks)
- Vector Boson Scattering/Fusion (forward 'tag' jets are quarks)

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



Introduction – q/g jets perturbative component

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



Expectation:

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

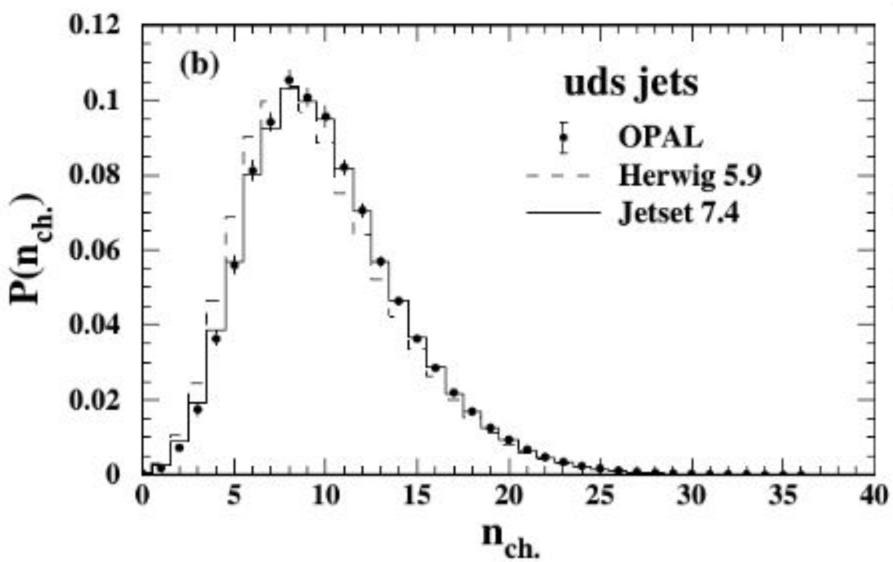
Introduction – q/g jets perturbative component

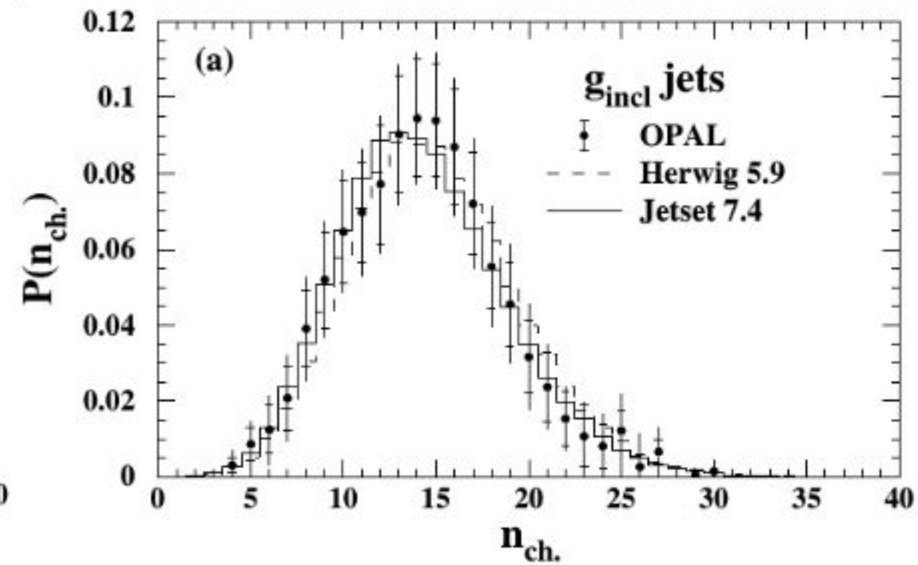
Cartoon:

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]

Introduction – q/g jets perturbative component

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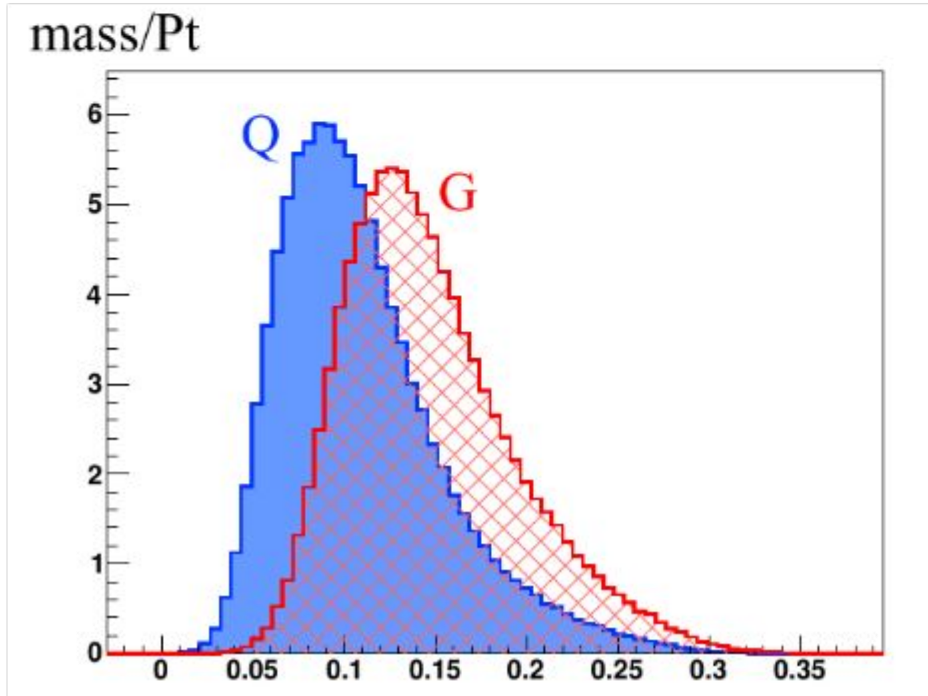
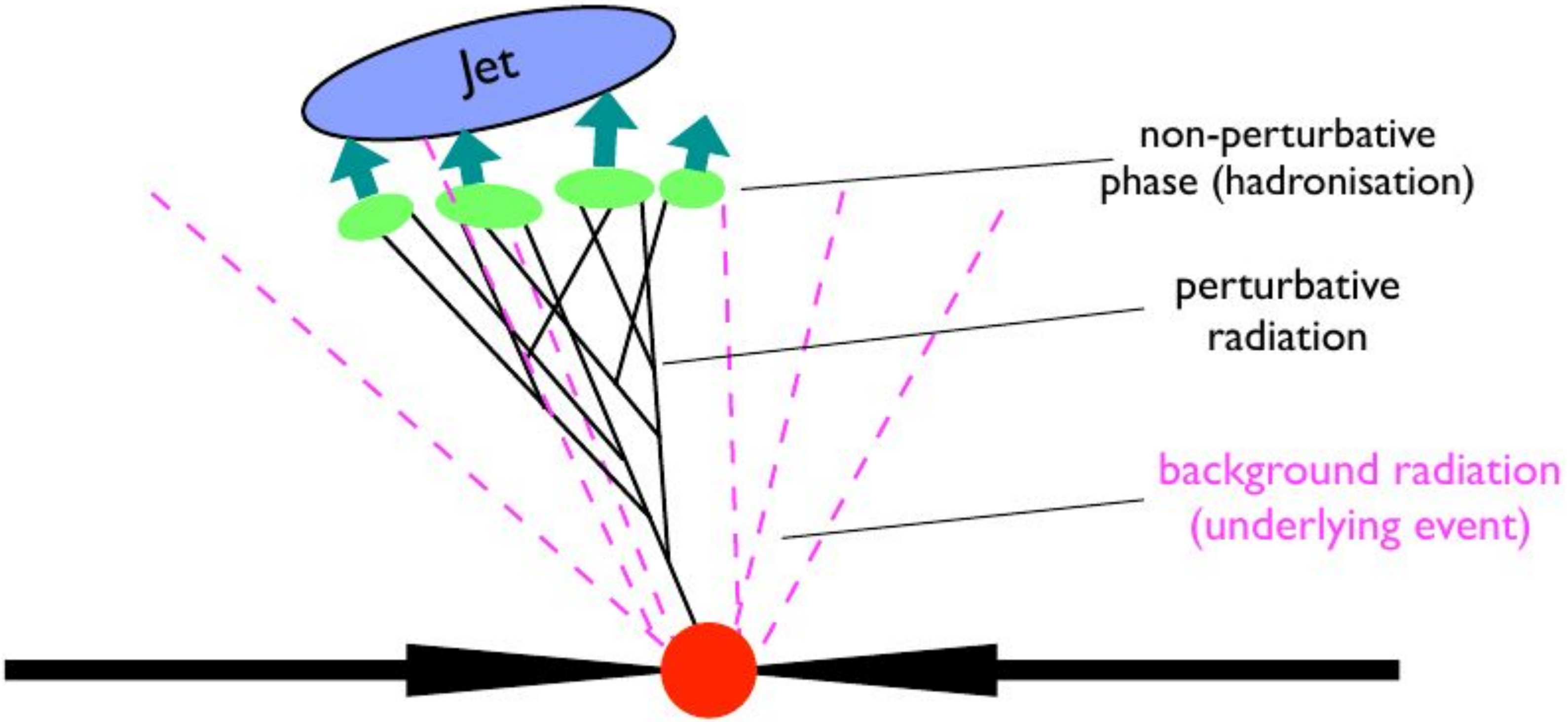
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Average Jet Mass in the small angle limit:

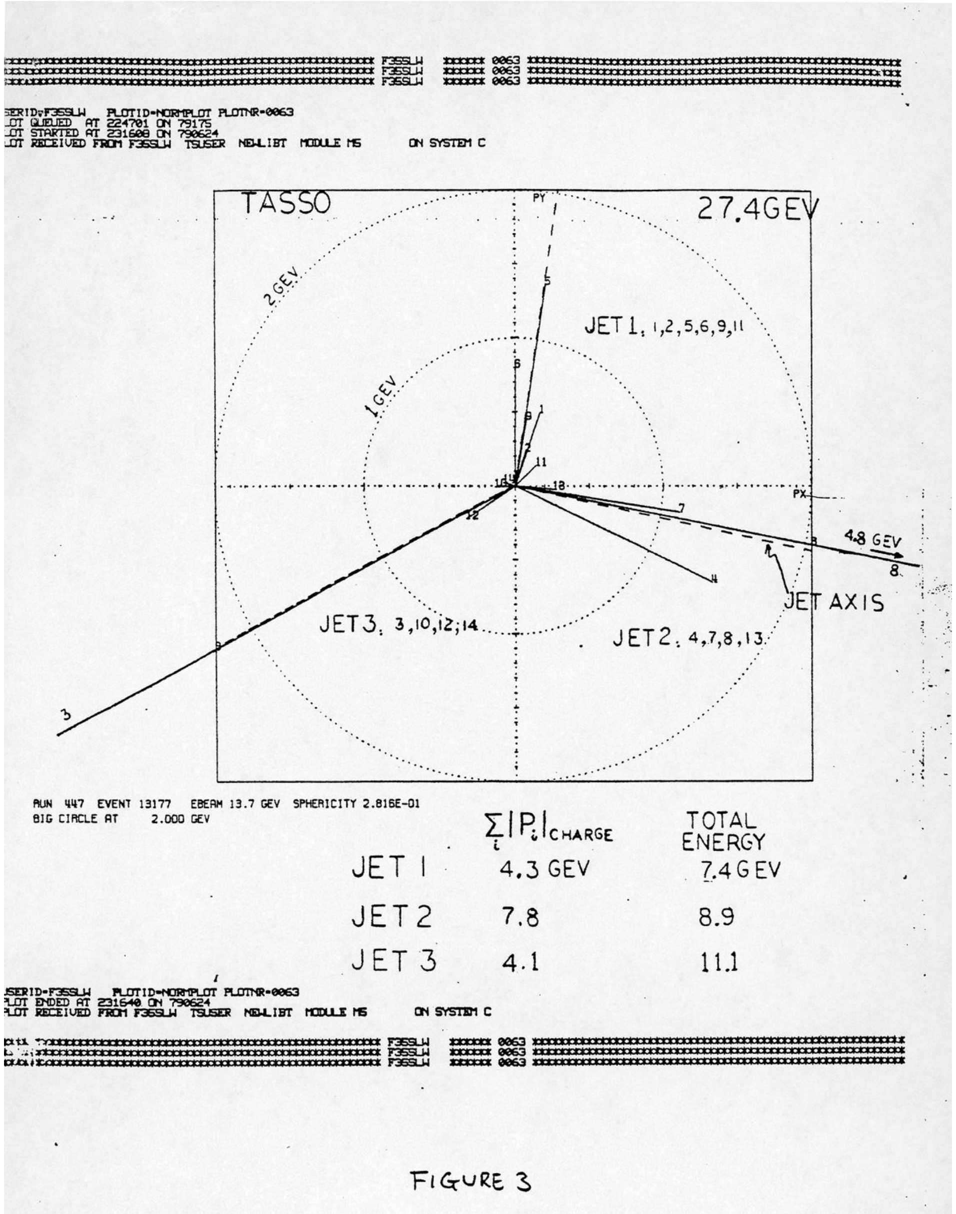
$$\langle M^2 \rangle = C \frac{\alpha_s}{\pi} p_T^2 R^2$$



Introduction – jet structure

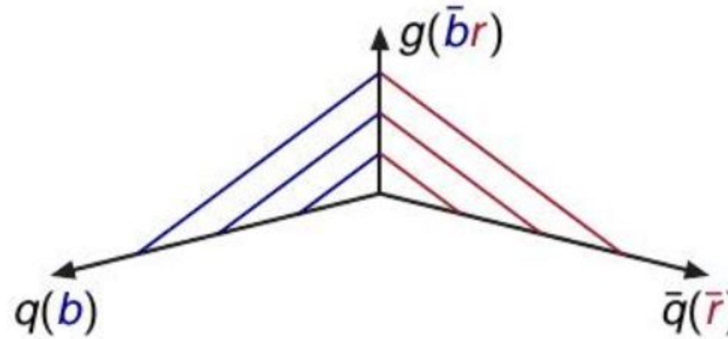


History: Discovery of the gluon



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)

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A Direct observation of quark - gluon jet differences at LEP #4

OPAL Collaboration • G. Alexander (Tel Aviv U.) et al. (Jun, 1991)

Published in: *Phys.Lett.B* 265 (1991) 462-474

Quark / gluon jet discrimination at HERA #5

Jon Pumplin (Michigan State U. and DESY) (Jul 21, 1992)

Published in: *Nucl.Phys.B* 390 (1993) 379-398

Why we would like to distinguish Q/G jets?

Jet structure and quark/gluon separation in CDF #3

CDF Collaboration • M. Ninomiya (Tsukuba U.) for the collaboration. (1993)

Published in: In *Tsukuba 1993, Proton antiproton collider physics* 248-256 • Contribution to: 9th Topical Workshop on Proton - Antiproton Collider Physics, 248-256

A Measurement of quark and gluon jet differences at the Z0 resonance #3

SLD Collaboration • Yoshihito Iwasaki (Tohoku U.) for the collaboration. (Aug, 1994)

Published in: DPF Conf.1994:1606-1608 • Contribution to: 1994 Meeting of the American Physical Society, Division of Particles and Fields (DPF 94), 1606-1608

Quark Gluon Jet Discrimination with Weakly Supervised Learning #2

Jason Sang Hun Lee (Seoul U.), Sang Man Lee (Seoul U.), Yunjae Lee (Seoul U.), Inkyu Park (Seoul U.), Ian James Watson (Seoul U.) et al. (Nov 12, 2019)

Published in: *J.Korean Phys.Soc.* 75 (2019) 9, 652-659

Data-driven quark and gluon jet modification in heavy-ion collisions #2

Jasmine Brewer (MIT, Cambridge, CTP), Jesse Thaler (MIT, Cambridge, CTP), Andrew P. Turner (MIT, Cambridge, CTP) (Aug 19, 2020)

e-Print: 2008.08596 [hep-ph]

Measurement of quark- and gluon-like jet fractions using jet charge in PbPb and pp collisions at 5.02 TeV #6

CMS Collaboration • Albert M Sirunyan (Yerevan Phys. Inst.) et al. (Apr 1, 2020)

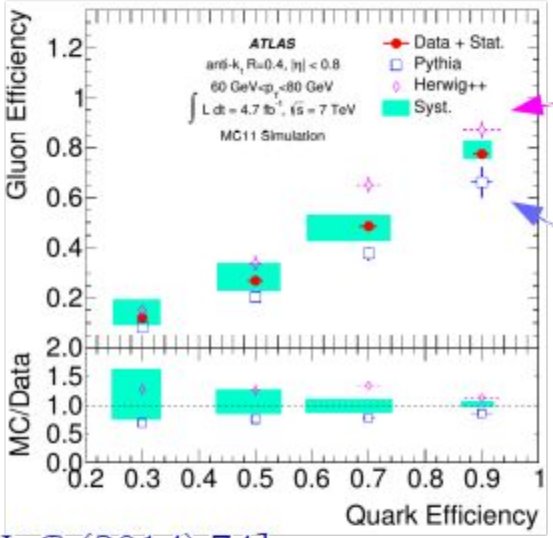
Published in: *JHEP* 07 (2020) 115 • e-Print: 2004.00602 [hep-ex]

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

ATLAS Collaboration (Apr 11, 2017)

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

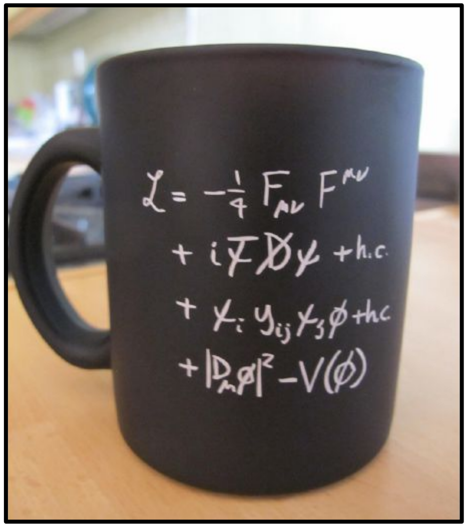
Motivation - Monte Carlo Event Generators (MCEG)

Standard Model

There is a **huge gap** between a one-line formula of a fundamental theory, like the Lagrangian of the SM, and the experimental reality that it implies

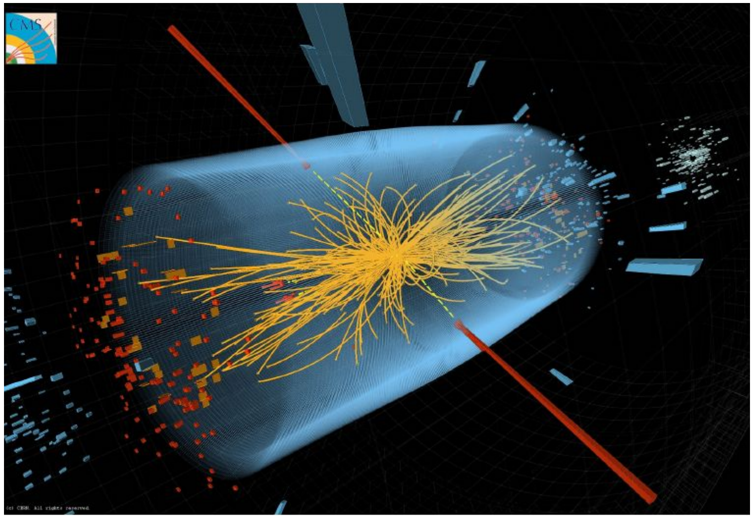
Theory

Standard Model Lagrangian



Experiment

LHC event



- MC event generators are designed to bridge the that **gap**
- "Virtual collider" ⇒ Direct comparison with data

⇩

Almost all **HEP measurements and discoveries** in the modern era have **relied on MCEG**, most notably the discovery of the Higgs boson.

Published papers by ATLAS, CMS, LHCb: **2252**
Citing at least 1 of 3 existing MCEG: **1888** (**84%**)

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

Cartoon:

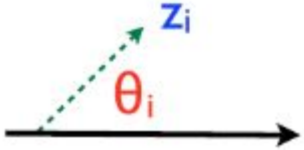
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Probe radiation pattern with e.g. Generalized Angularities

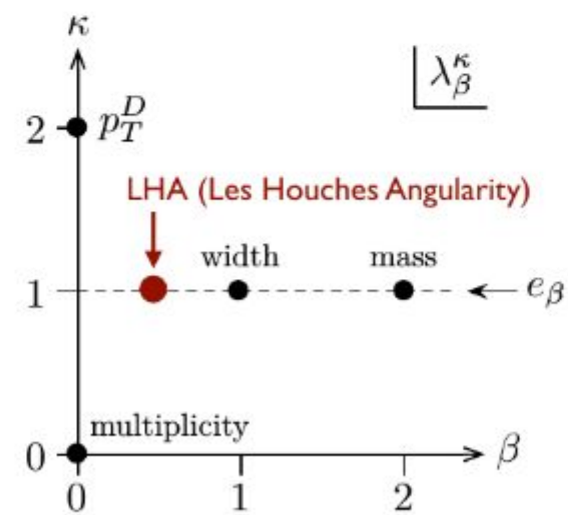
$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} z_i^\kappa \theta_i^\beta$$

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)

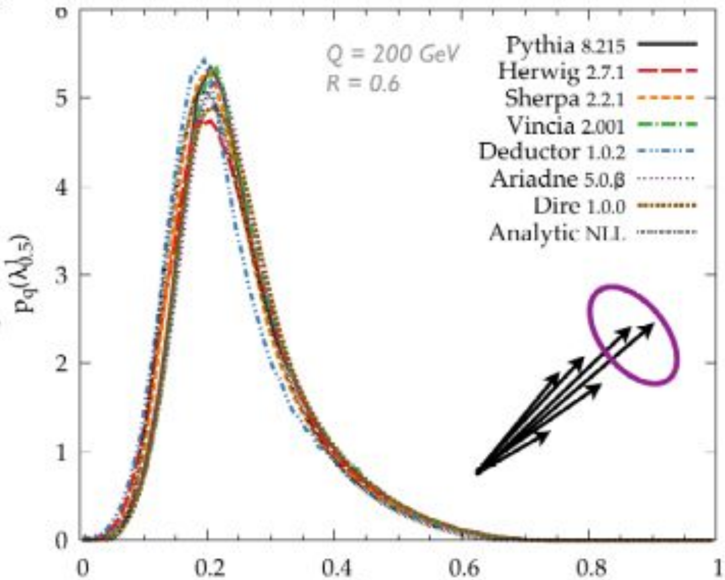
Additionally different Parton Shower algorithms

- 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]

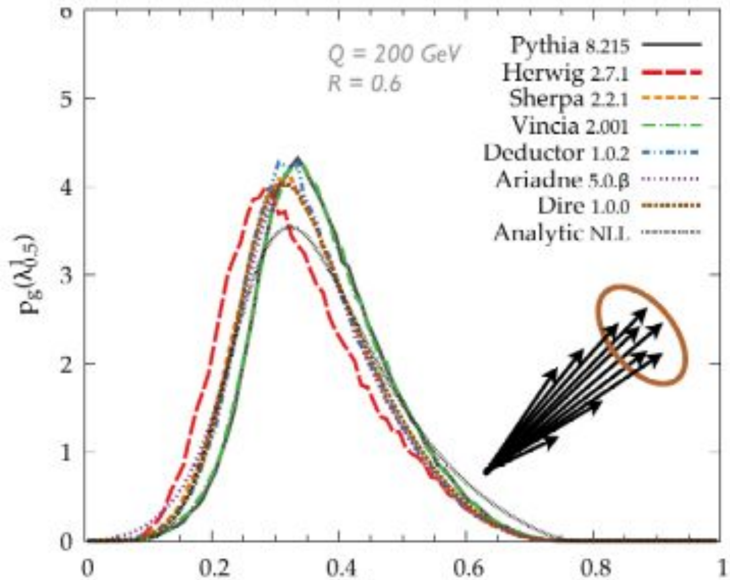
$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)



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

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.

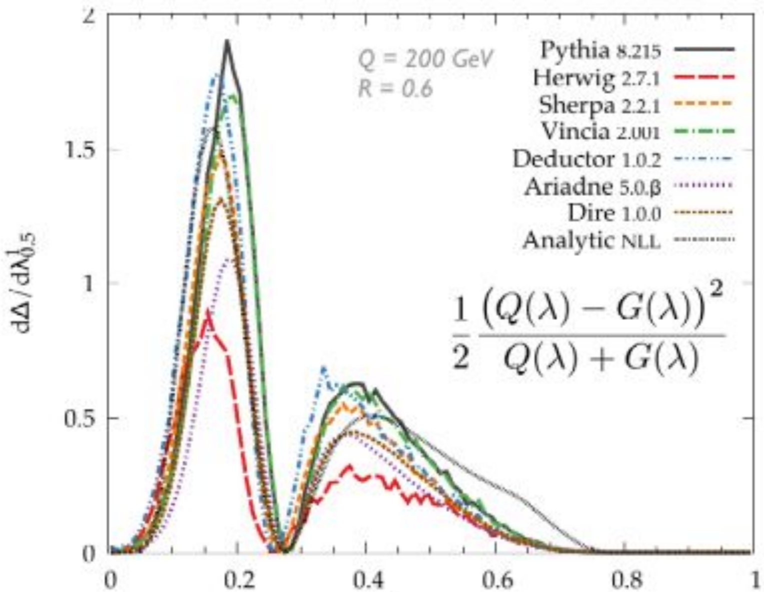
Q/G jet Les Houches study

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

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

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

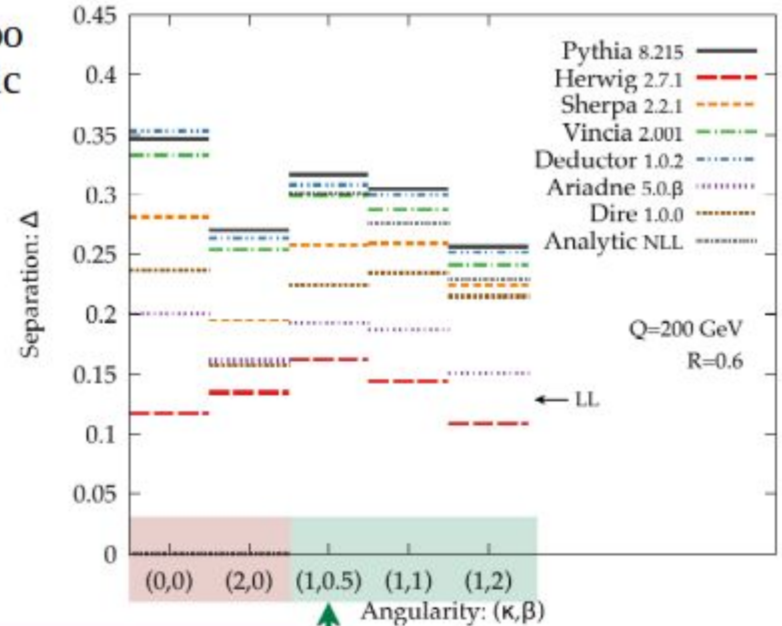
Differential



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

Pythia too optimistic

Integrated Values



Affects both IRC unsafe and IRC safe observables

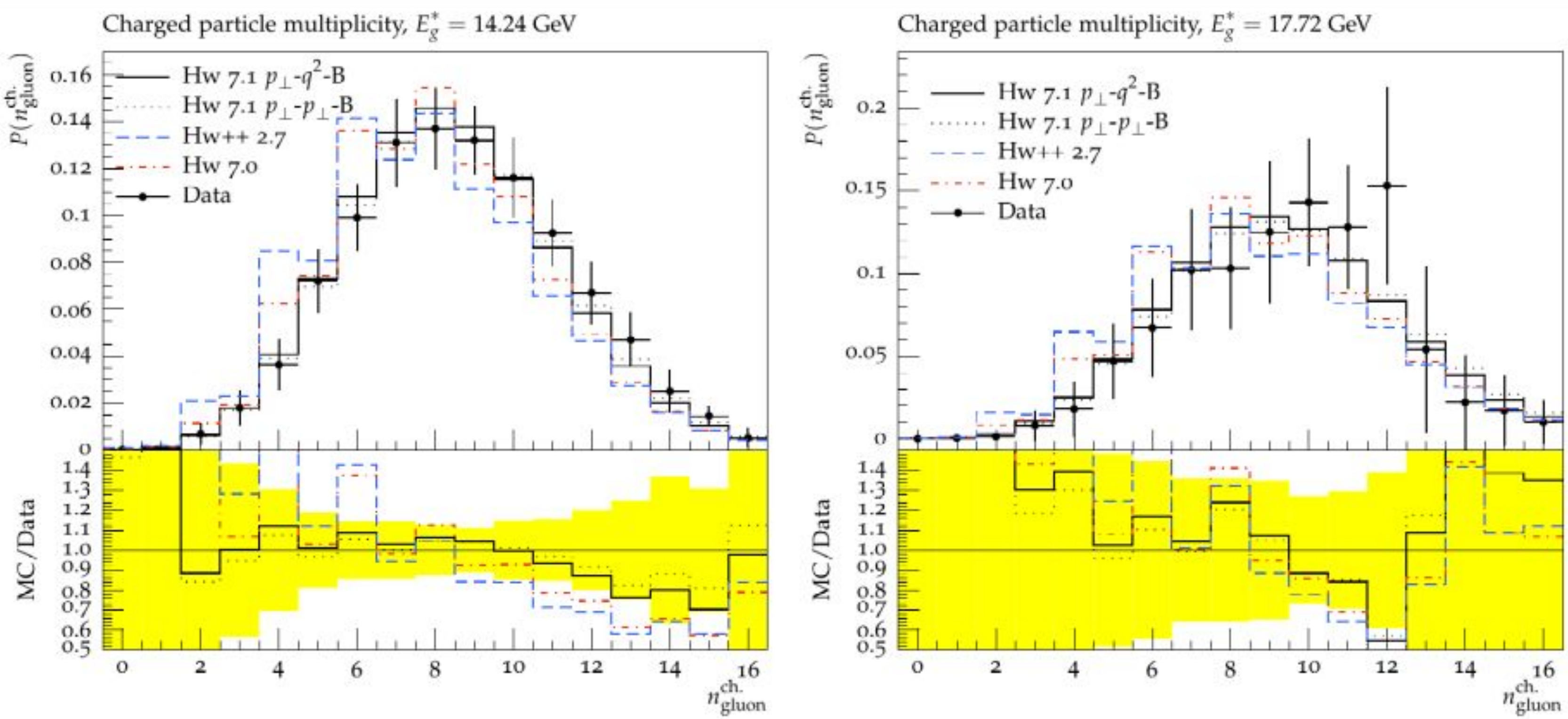
How we improved simulation of Q/G jets in Herwig

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)

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.

What is a Quark Jet?

From lunch/dinner discussions

[slide by Jesse Thaler]

Ill-Defined ↓ **Well-Defined**

What people sometimes think we mean ↑ **What we mean**

Quark as noun

Quark as adjective

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

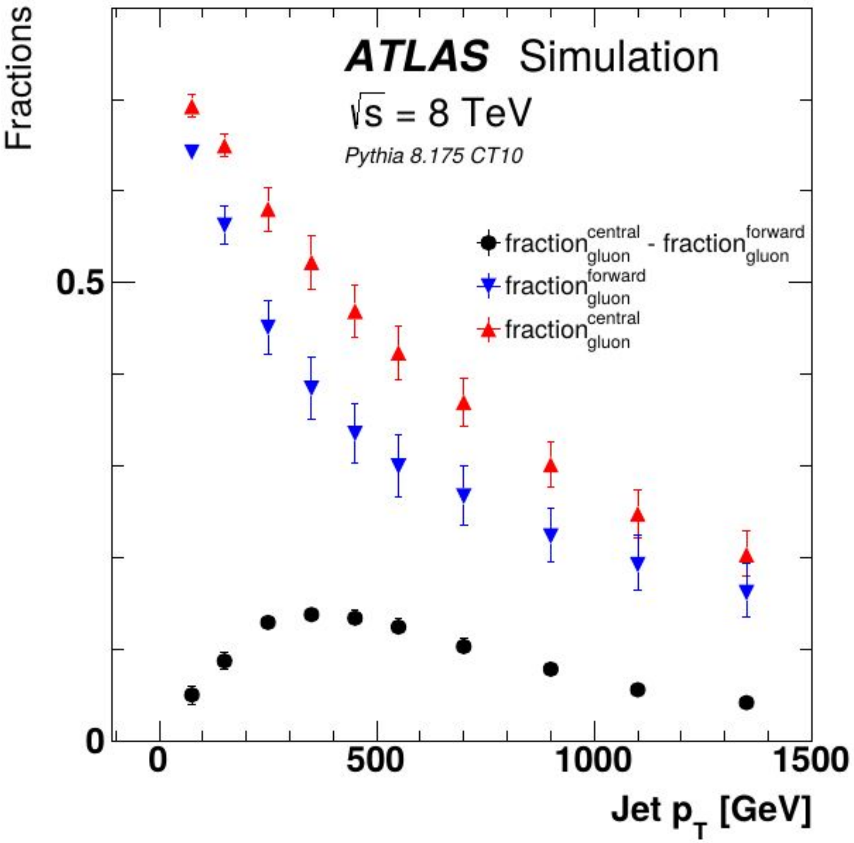
A parton-level jet object that has been quark-tagged
using a soft-safe flavored jet algorithm (automatically
collinear safe if you sum constituent flavors)

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)

LHC how to define G enhanced sample

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

ATLAS Collaboration (Apr 11, 2017)



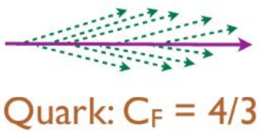
Using phase space cuts, for example:

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

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

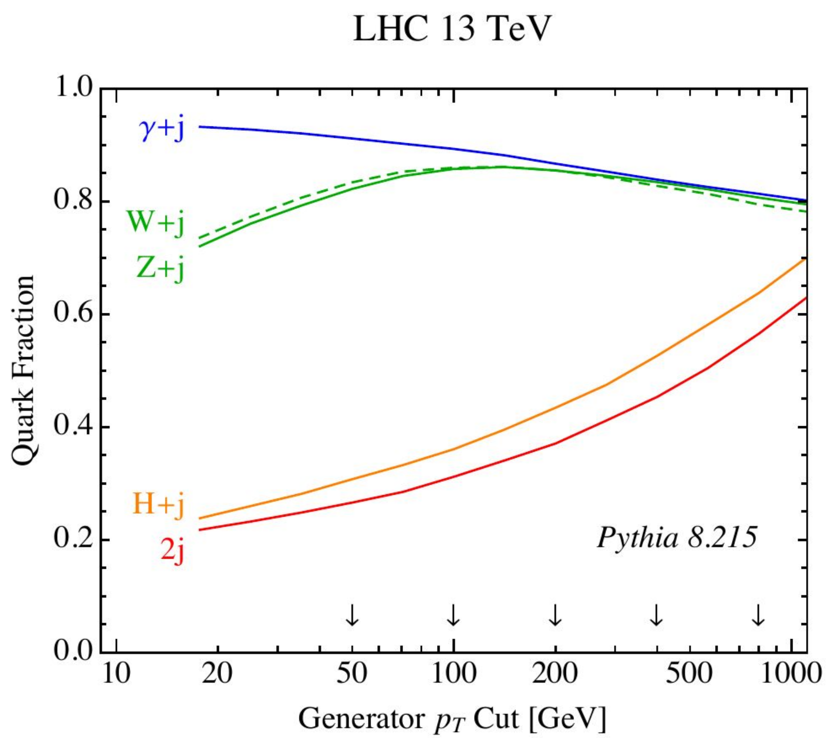
Same Pt Quark and Gluon

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?

LHC Q/G jet measurement

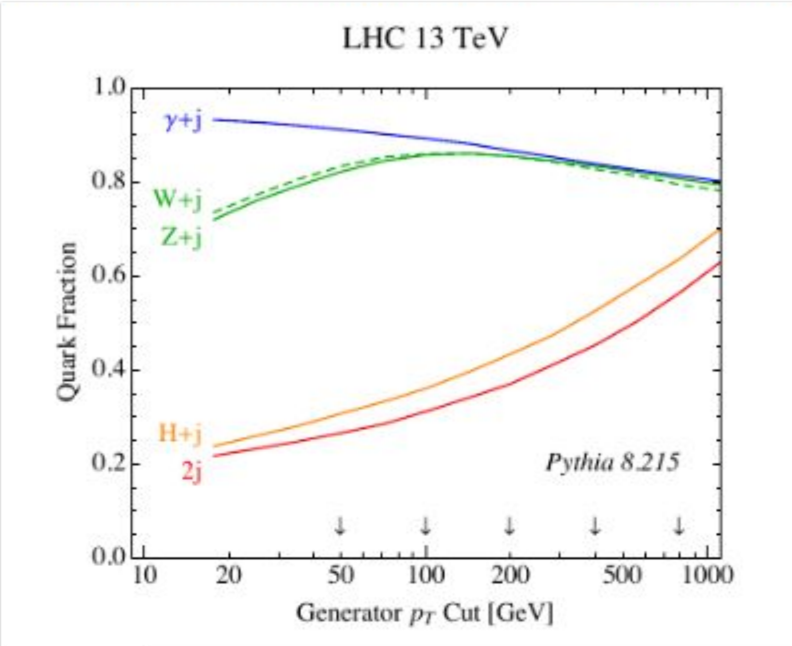


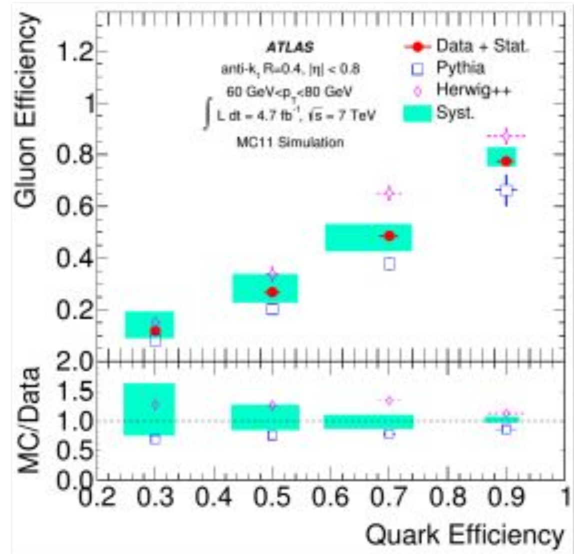
$$pp \to Z + j \ (\text{“quark-enriched”}) : \quad p_T^Z > p_T^{\min}, \quad \frac{p_T^{\text{jet}}}{p_T^Z} > 0.8, \quad |y_{\text{jet}} - y_Z| < 1.0.$$

$$pp \to 2j \ (\text{“gluon-enriched”}) : \quad \frac{p_{T,1} + p_{T,2}}{2} > p_T^{\min}, \quad \frac{p_{T,2}}{p_{T,1}} > 0.8, \quad |y_1 - y_2| < 1.0.$$

LHC Q/G jet measurement

This technique exploits significant, pT dependent differences in the q and g-jet content between dijet and γ+jet samples





- Goal: to measure the quark/gluon shapes from data, dijet (*DJ*) and photon+jet (*γ J*) events.
- Ideally, solve for q/g (for each bin i) from:

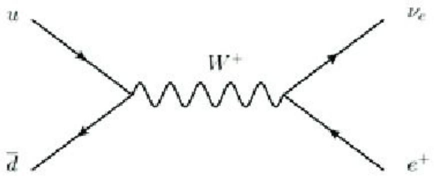
$$h_i(DJ) = P_Q(DJ)q_i + P_G(DJ)g_i$$
$$h_i(\gamma J) = P_Q(\gamma J)q_i + P_G(\gamma J)g_i$$

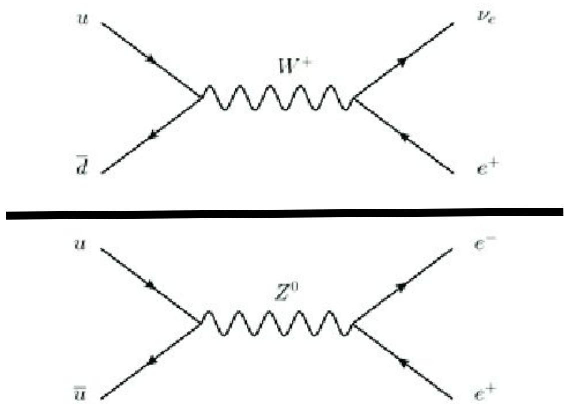
P_Q = quark percentage, from MC
h = histogram value, from data
q/g = pure q/g jet distributions (solving for these)

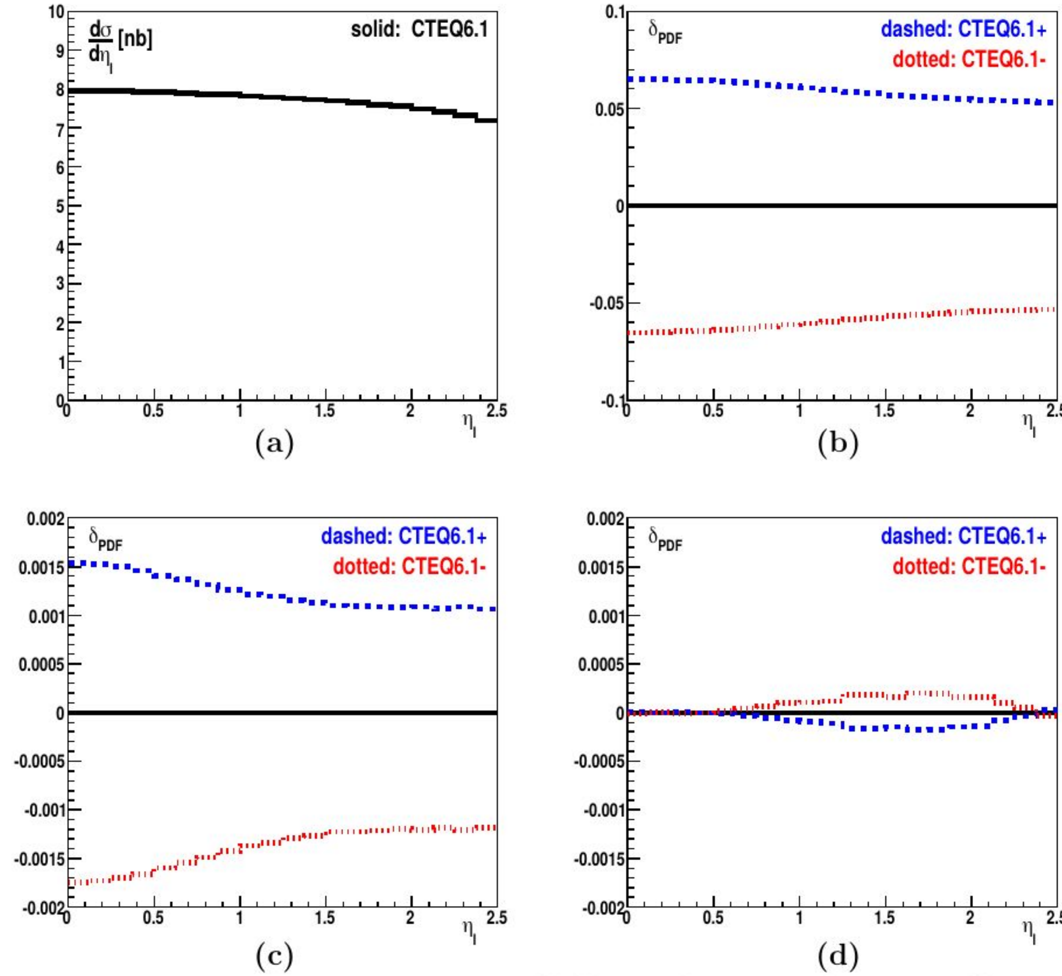
Can changing the energy of collision help us?

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]







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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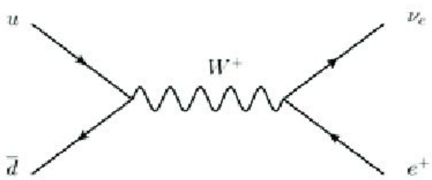

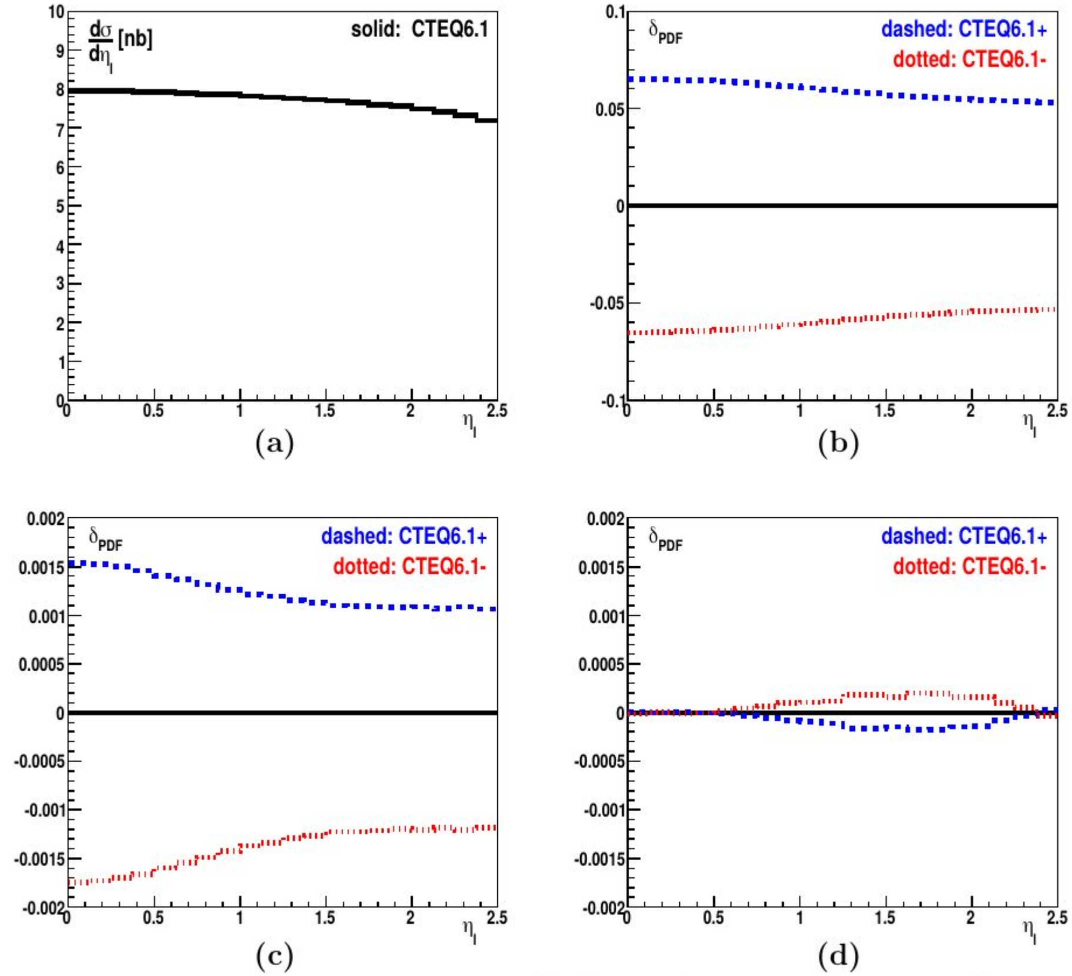

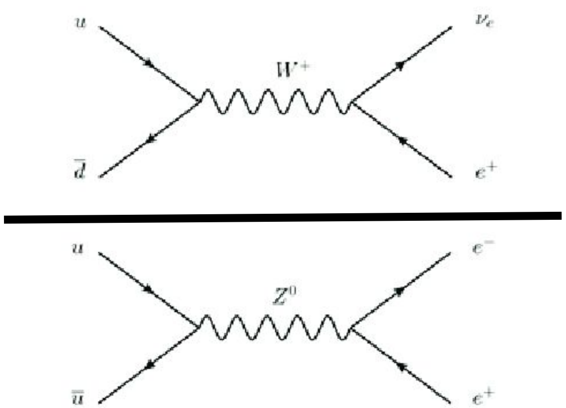

Yes it can!
Sadly not very used up to now at the LHC

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

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

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Probe radiation pattern with e.g. Generalized Angularities

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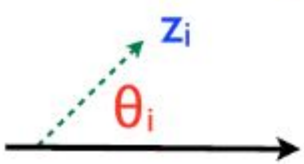
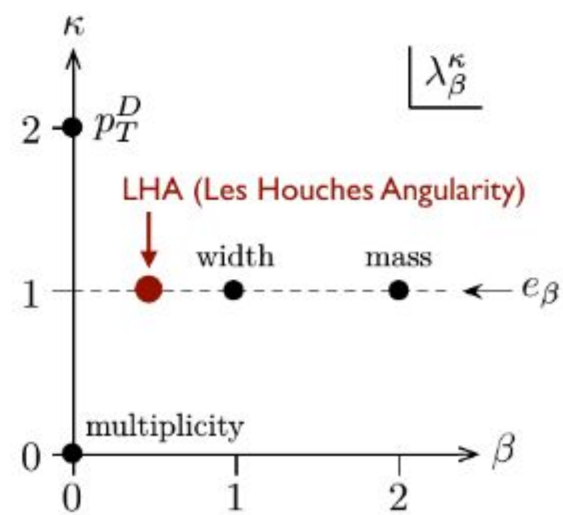


$$(\lambda_\beta^\kappa)_{\mathrm{quark}} < (\lambda_\beta^\kappa)_{\mathrm{gluon}}$$



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

Part II - a) Novel approach

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

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

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

Part II - a) Novel approach

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

$$\lambda_g = ?$$

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 :

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

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.

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

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

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

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

Part II - a) Novel approach

Lets 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:

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

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

Part II - a) Novel approach

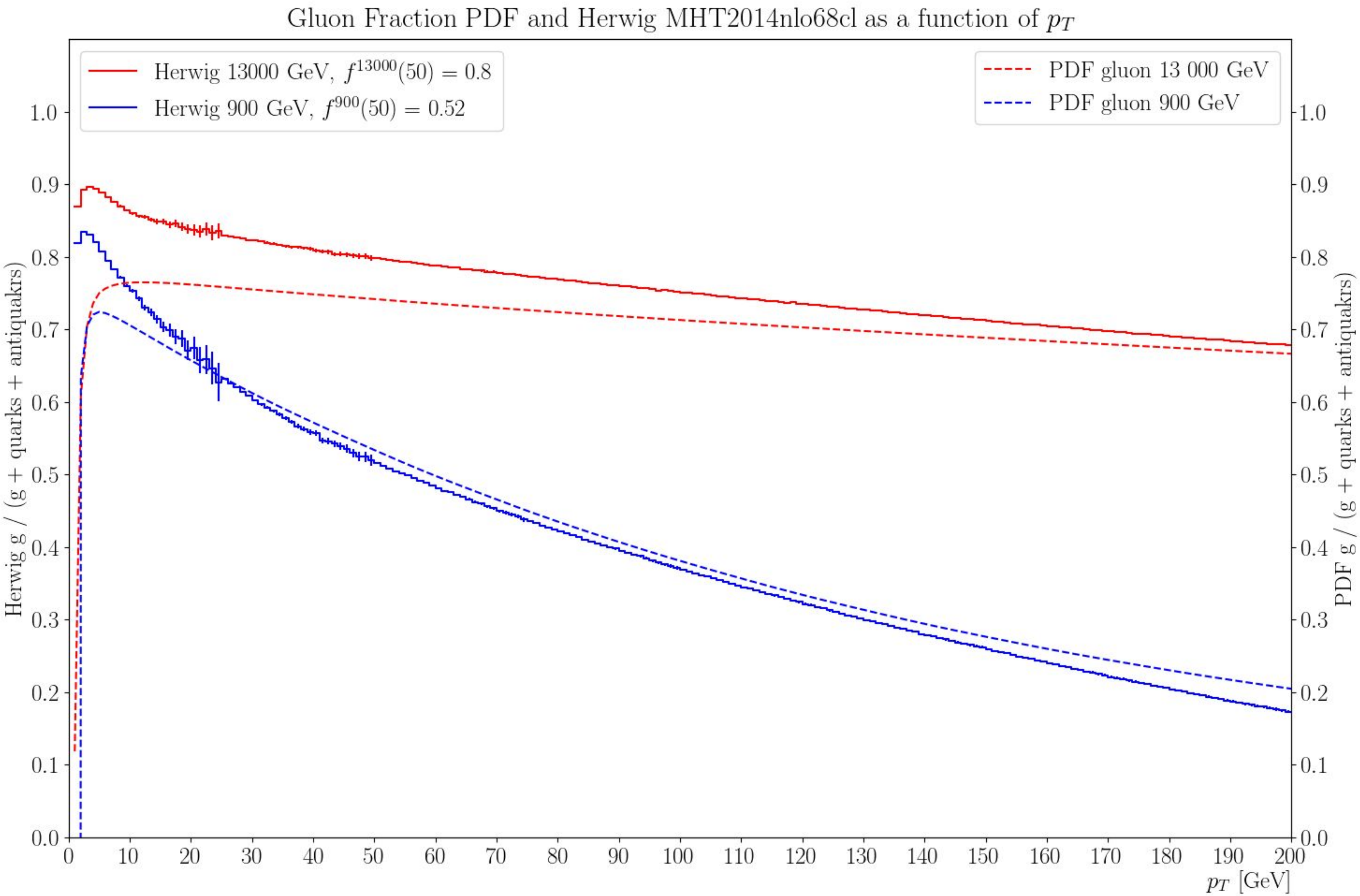
$$\lambda_g = \frac{(1-f^{13000})\lambda^{900} - (1-f^{900})\lambda^{13000}}{f^{900} - f^{13000}}$$

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

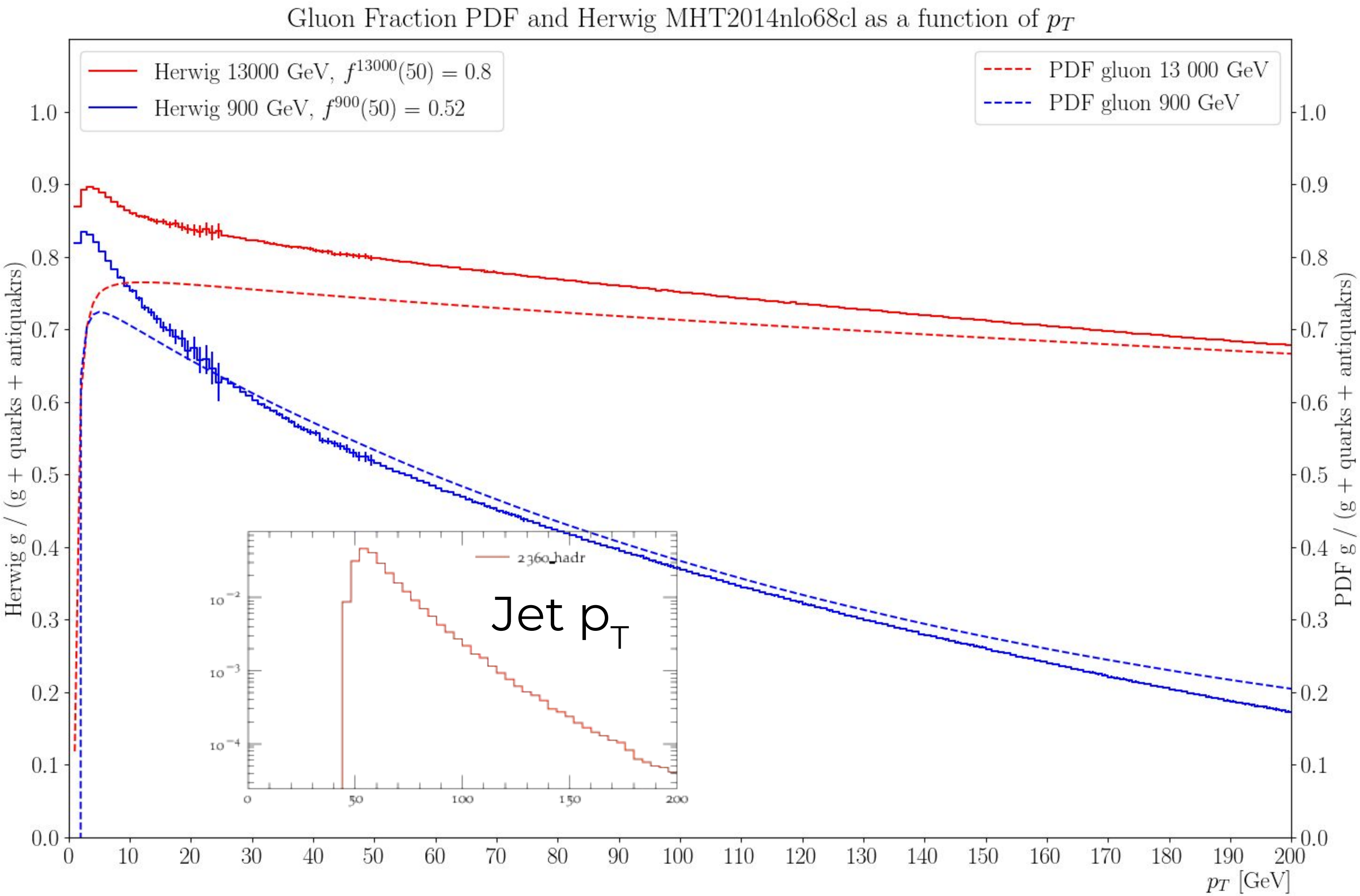
λ^{900}, λ^{13000} ... measurement (same cuts, average $p_T > 50$ GeV)

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

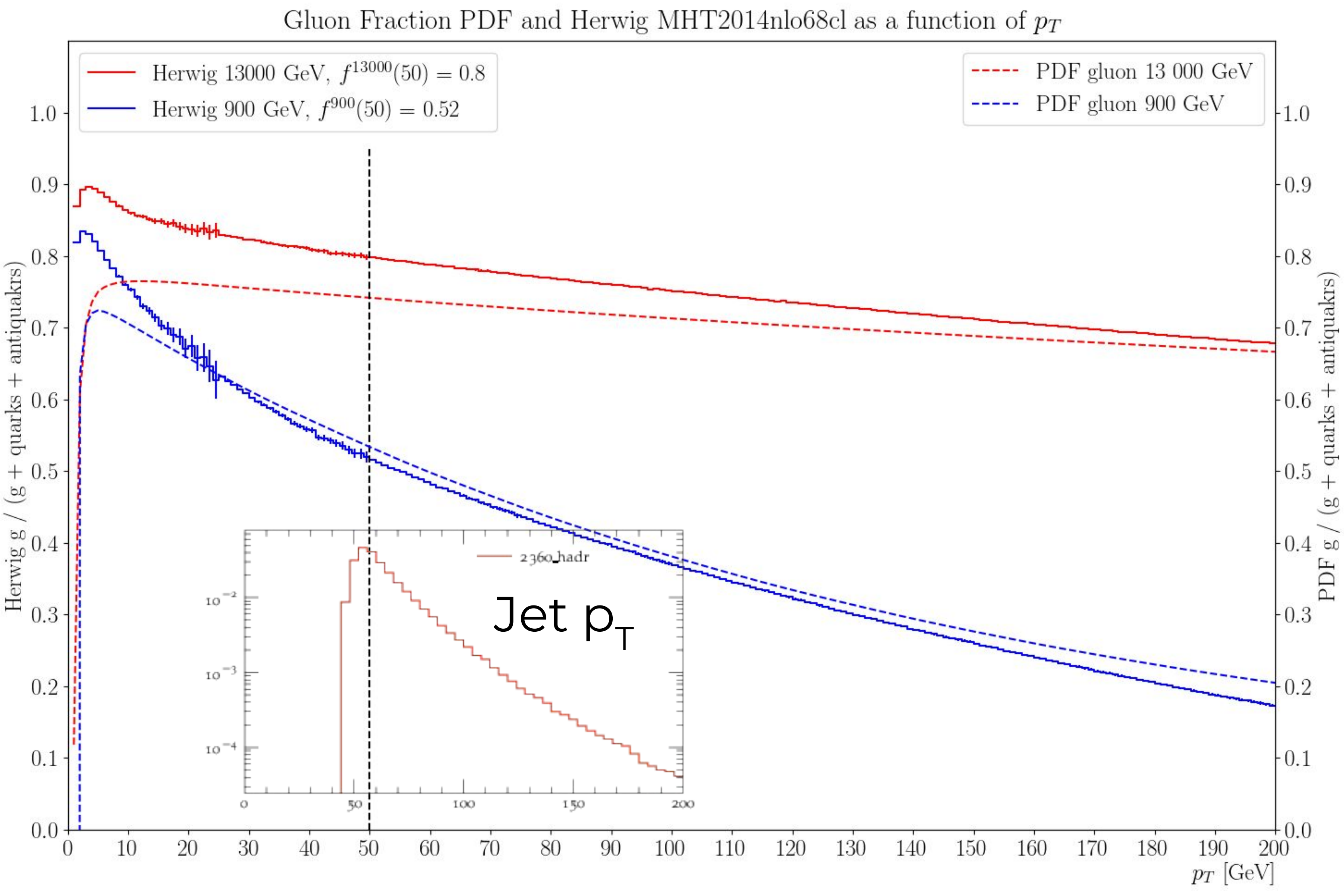
Part II - b) Preliminary results



Part II - b) Preliminary results



Part II - b) Preliminary results



Q/G jet Les Houches study

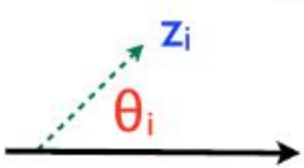
[Gras, Hoeche, Kar, Larkoski, Lönnblad, Plätzer, AS, Skands, Soyez, Thaler, JHEP 1707 (2017) 091]

Cartoon:

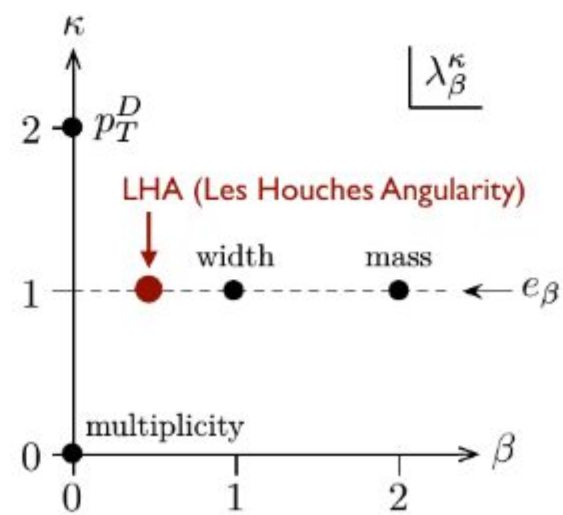
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Probe radiation pattern with
e.g. Generalized Angularities

$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} \underbrace{z_i^\kappa}_{\text{momentum fraction}} \underbrace{\theta_i^\beta}_{\text{angle to recoil-free axis}}$$



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



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

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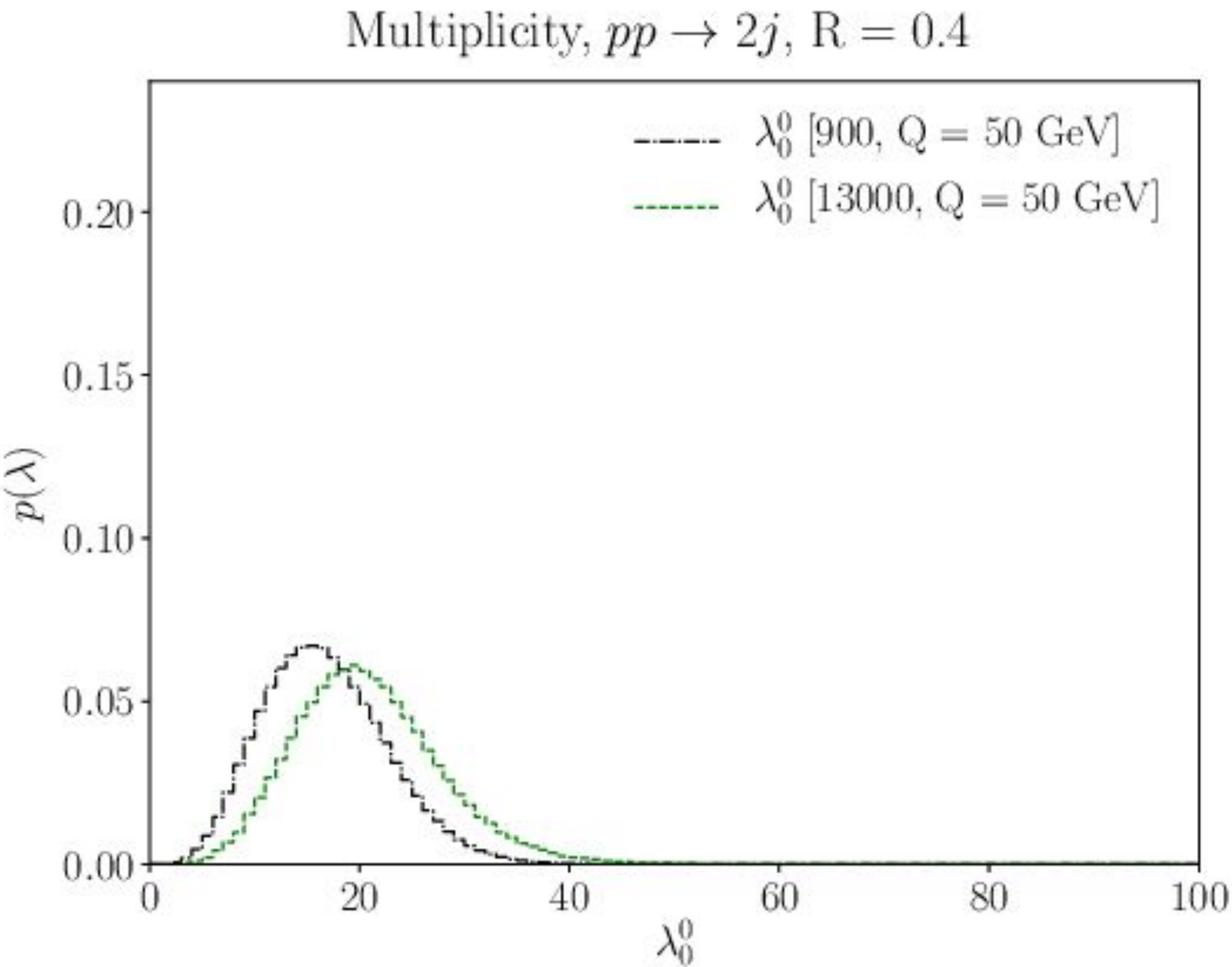

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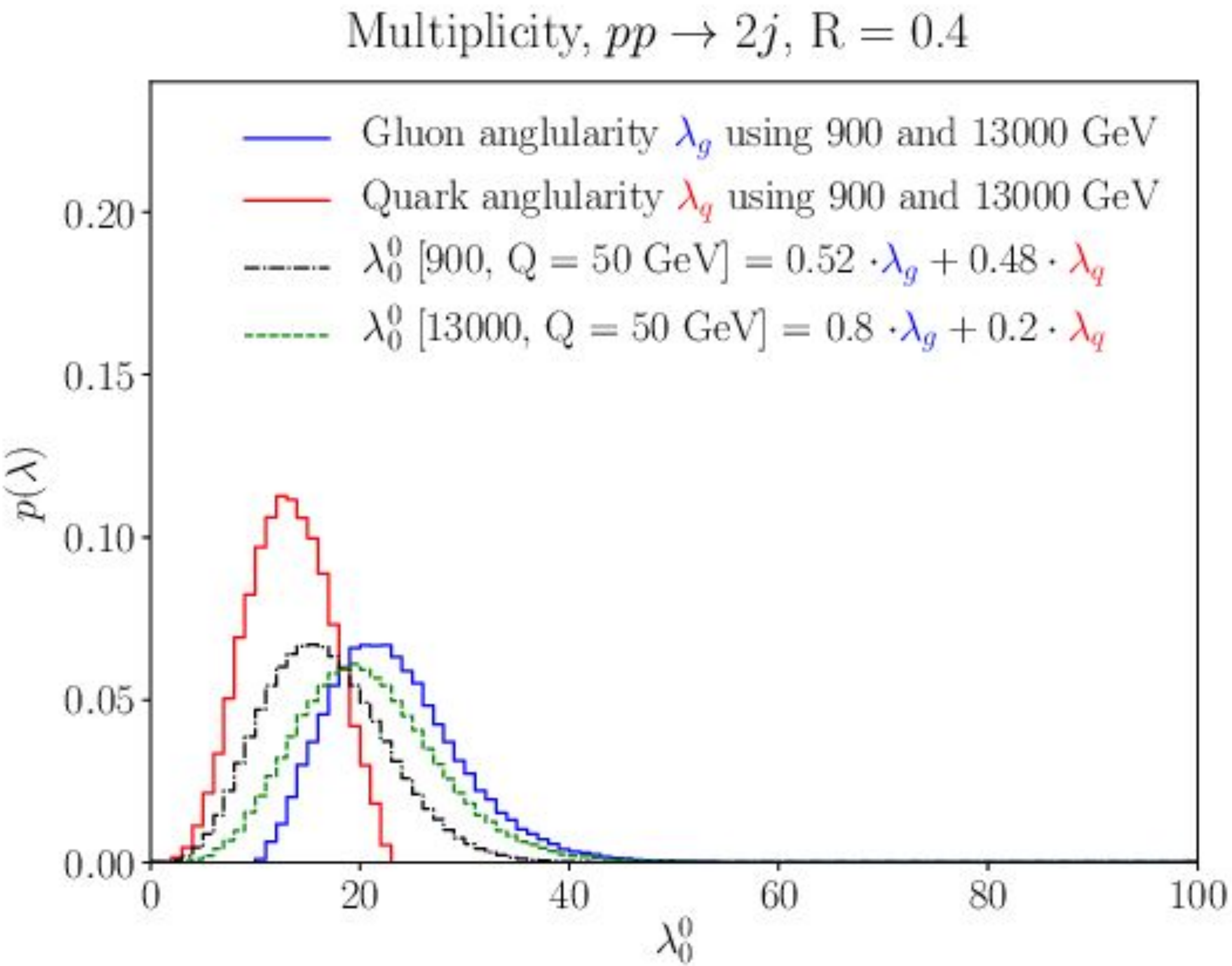
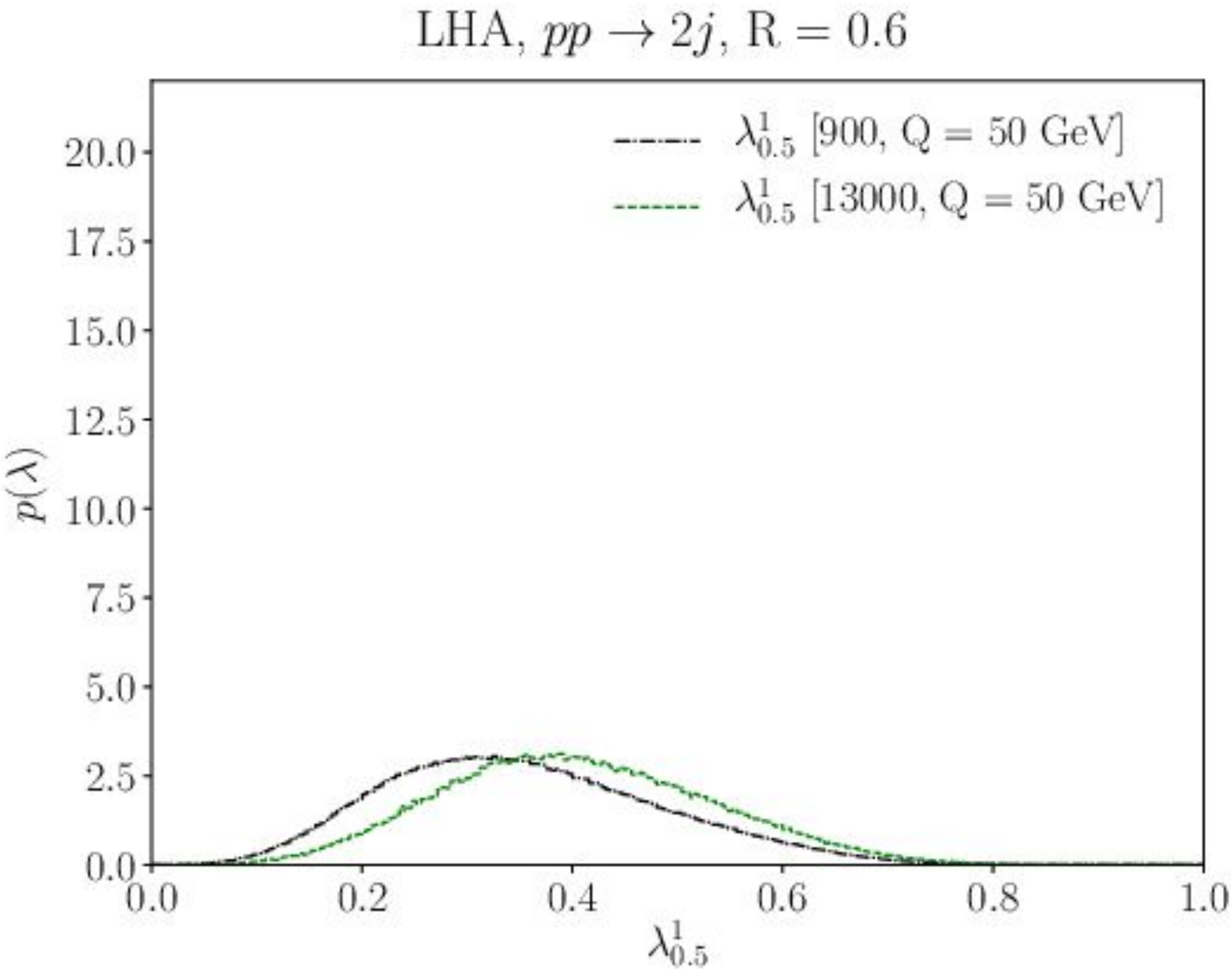
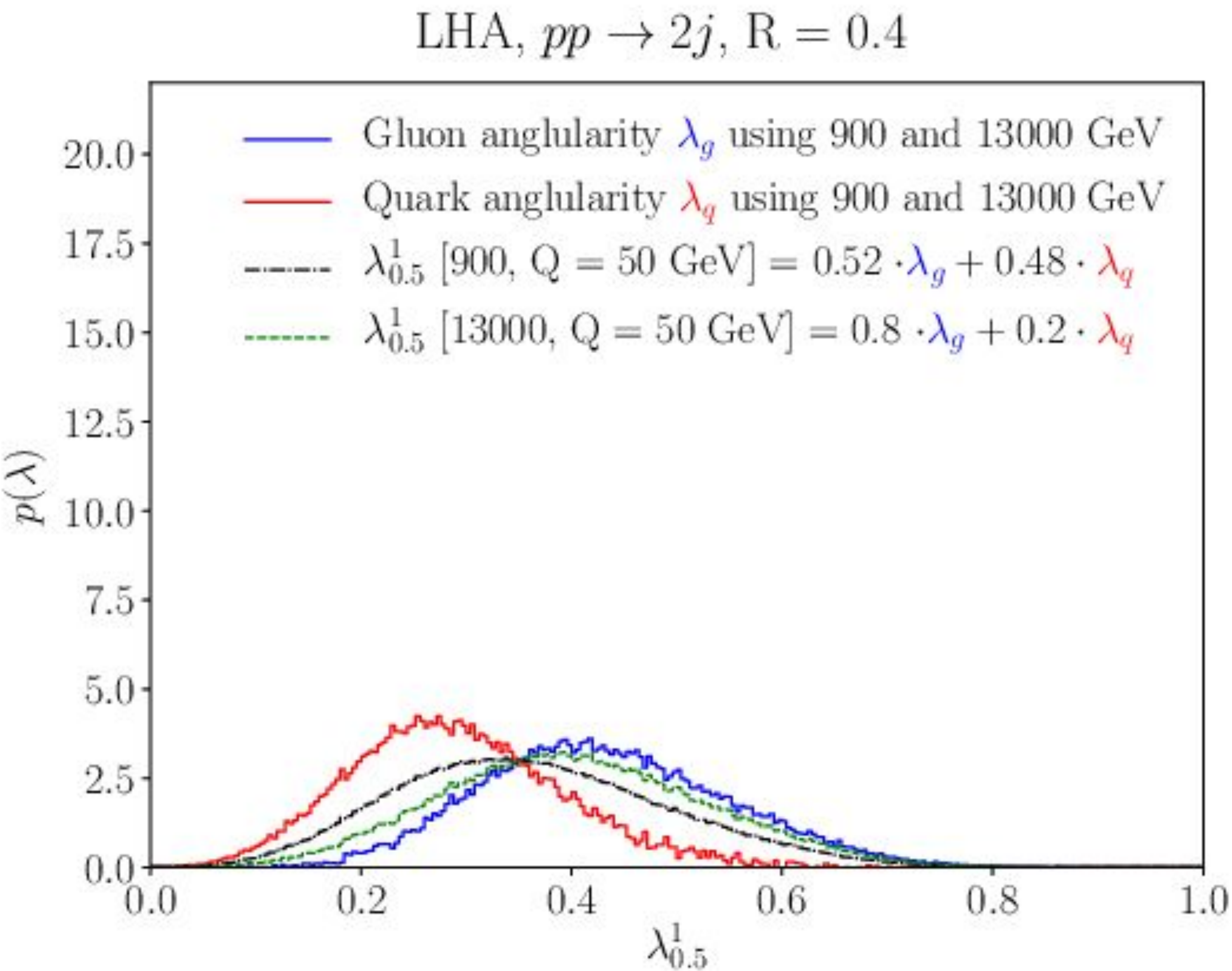


Part II - b) Preliminary results



Part II - b) Preliminary results



Part II - a) Novel approach

Lets 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:

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

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

Part II - a) Novel approach

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

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

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

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

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

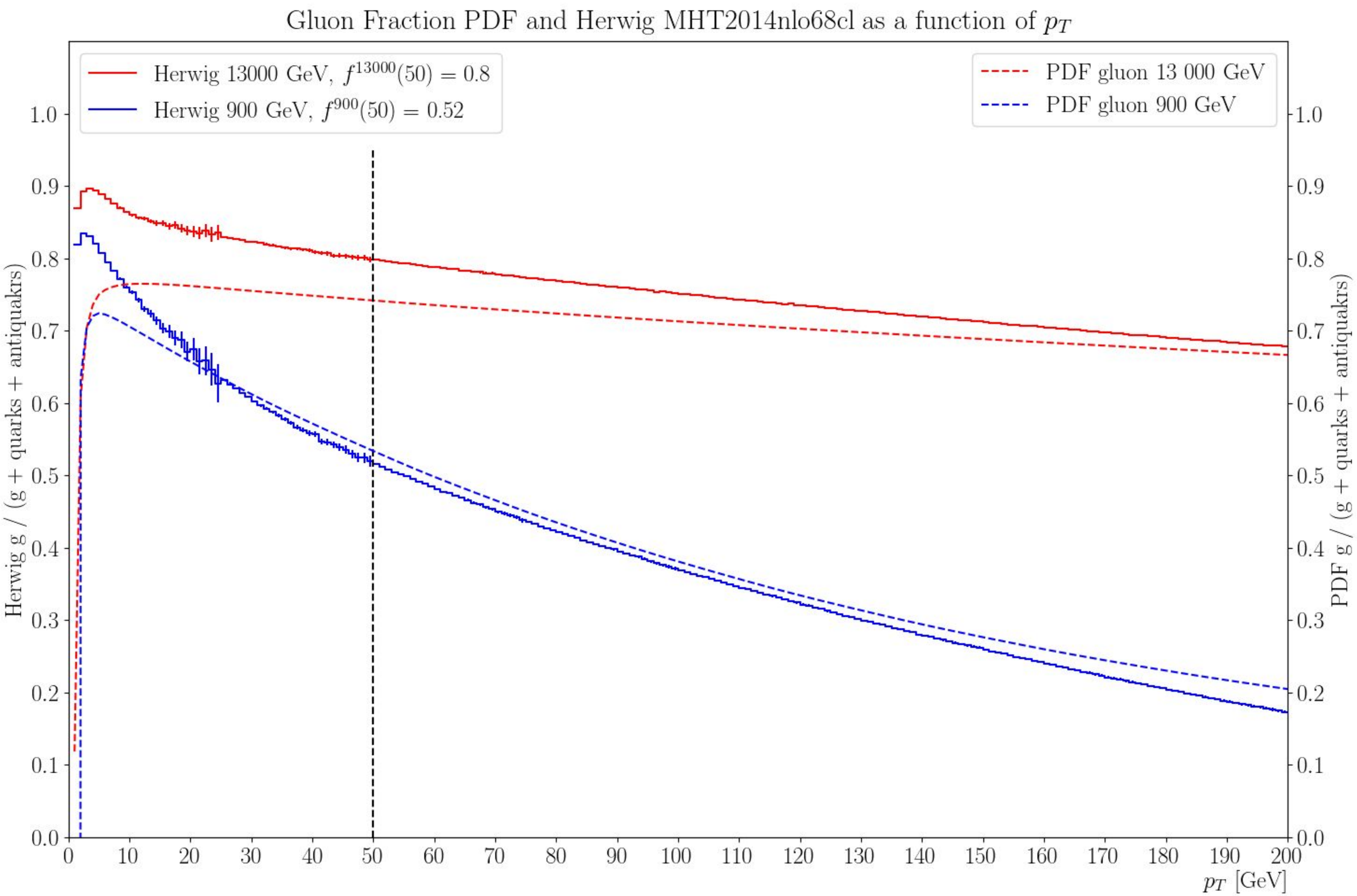
$$\lambda_g = \frac{(1 - f^{13000})\lambda^{900} - (1 -}{f^{900} - f^{1300}}$$

and

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

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

Part II - b) Preliminary results



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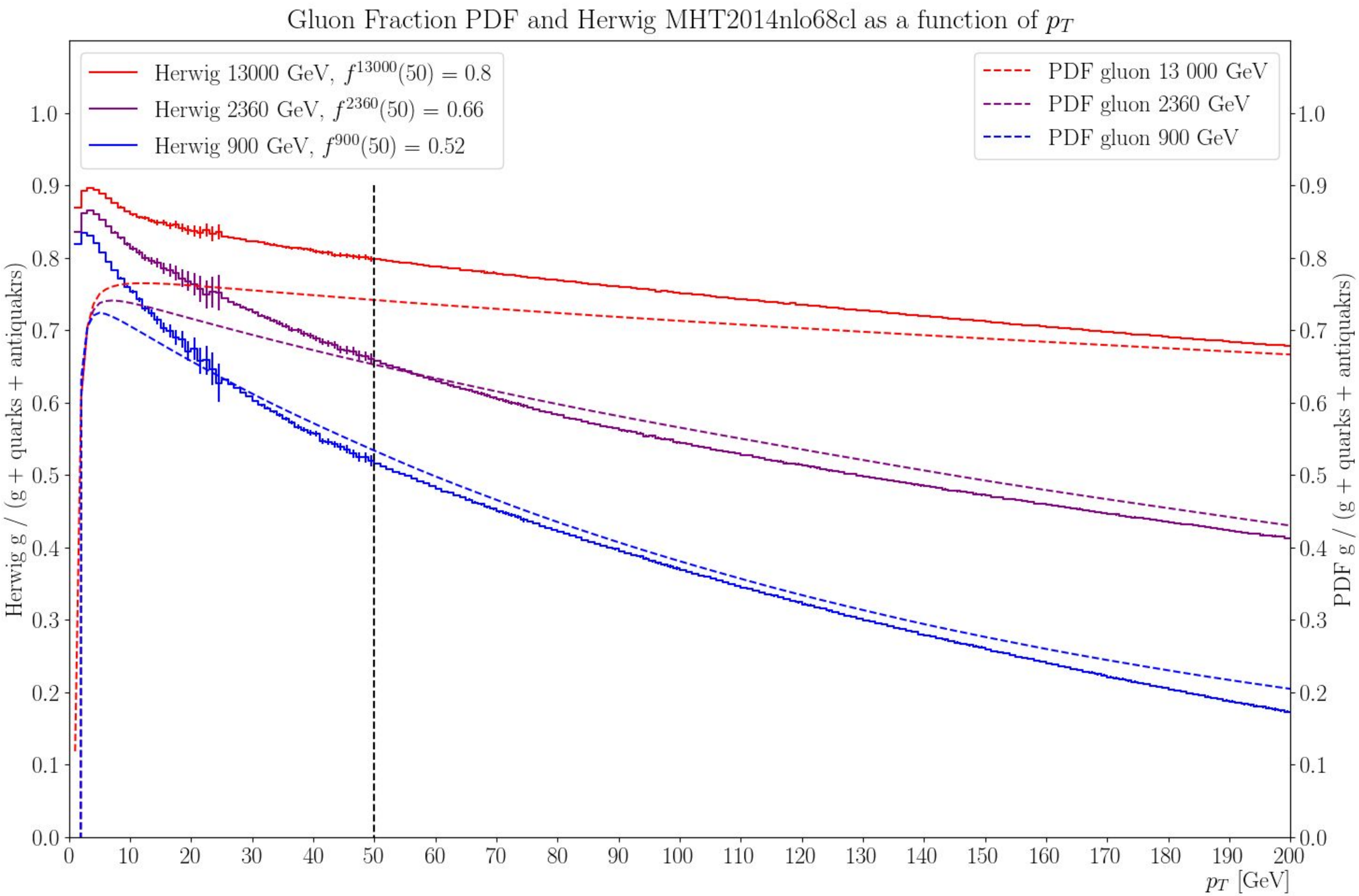

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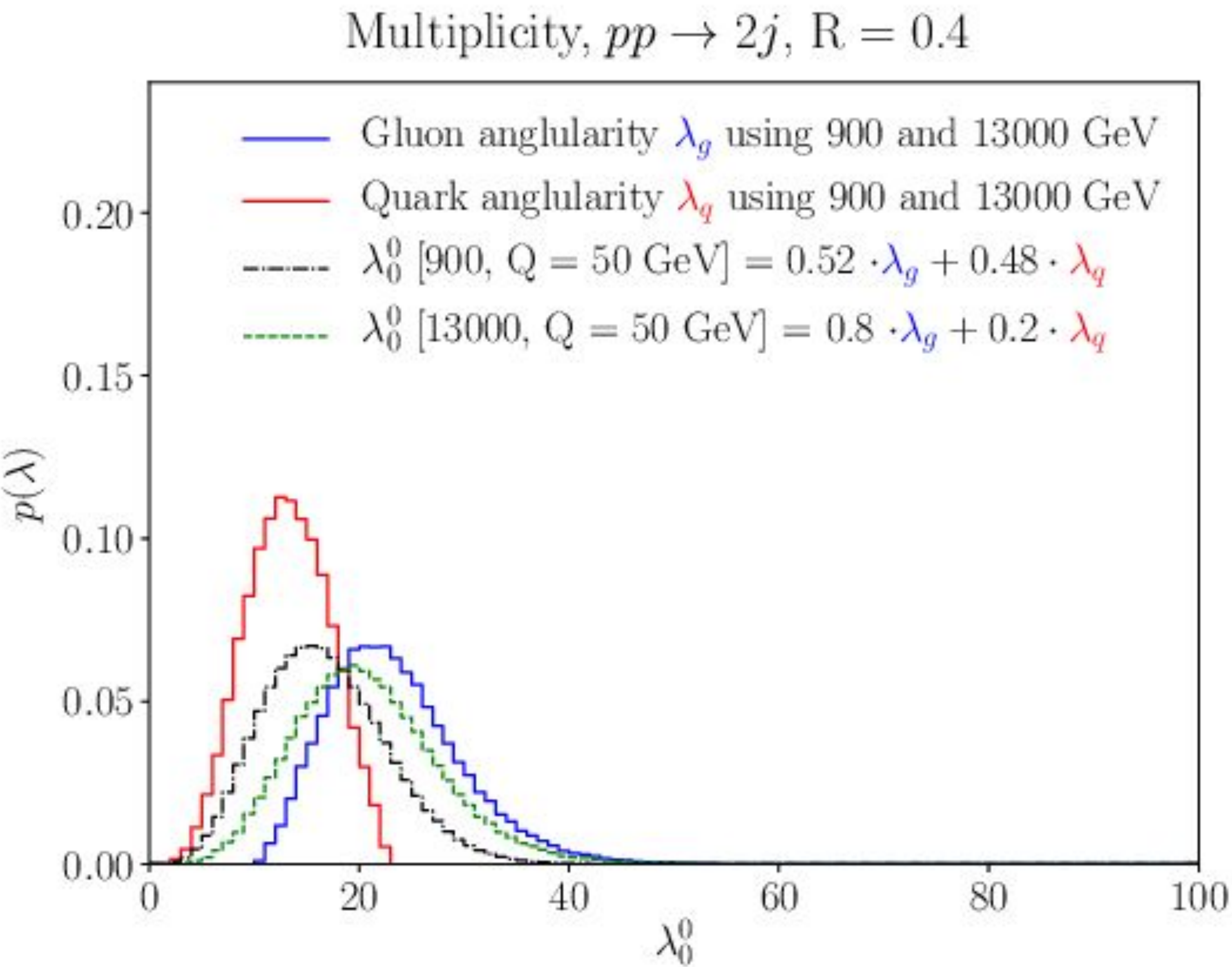

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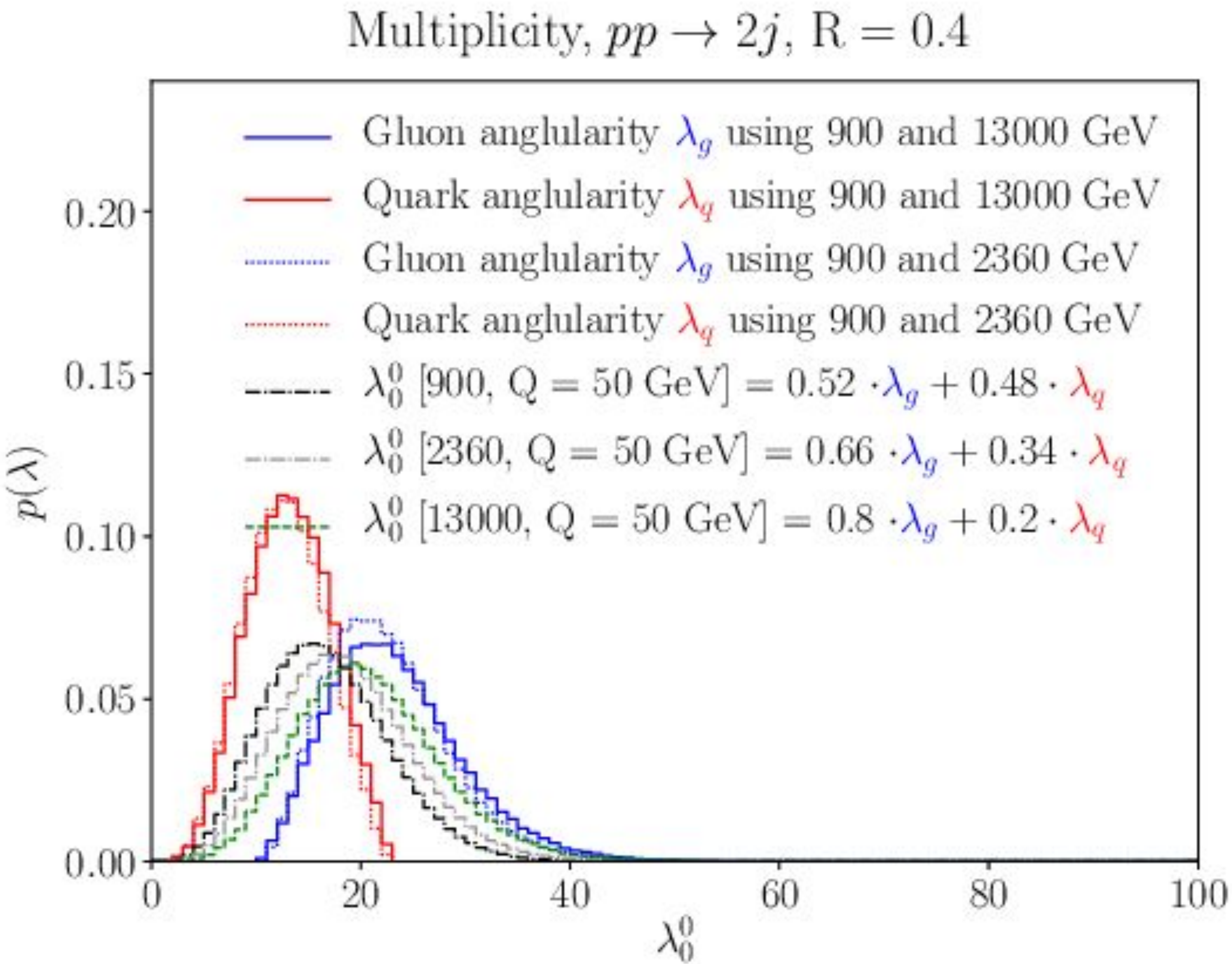

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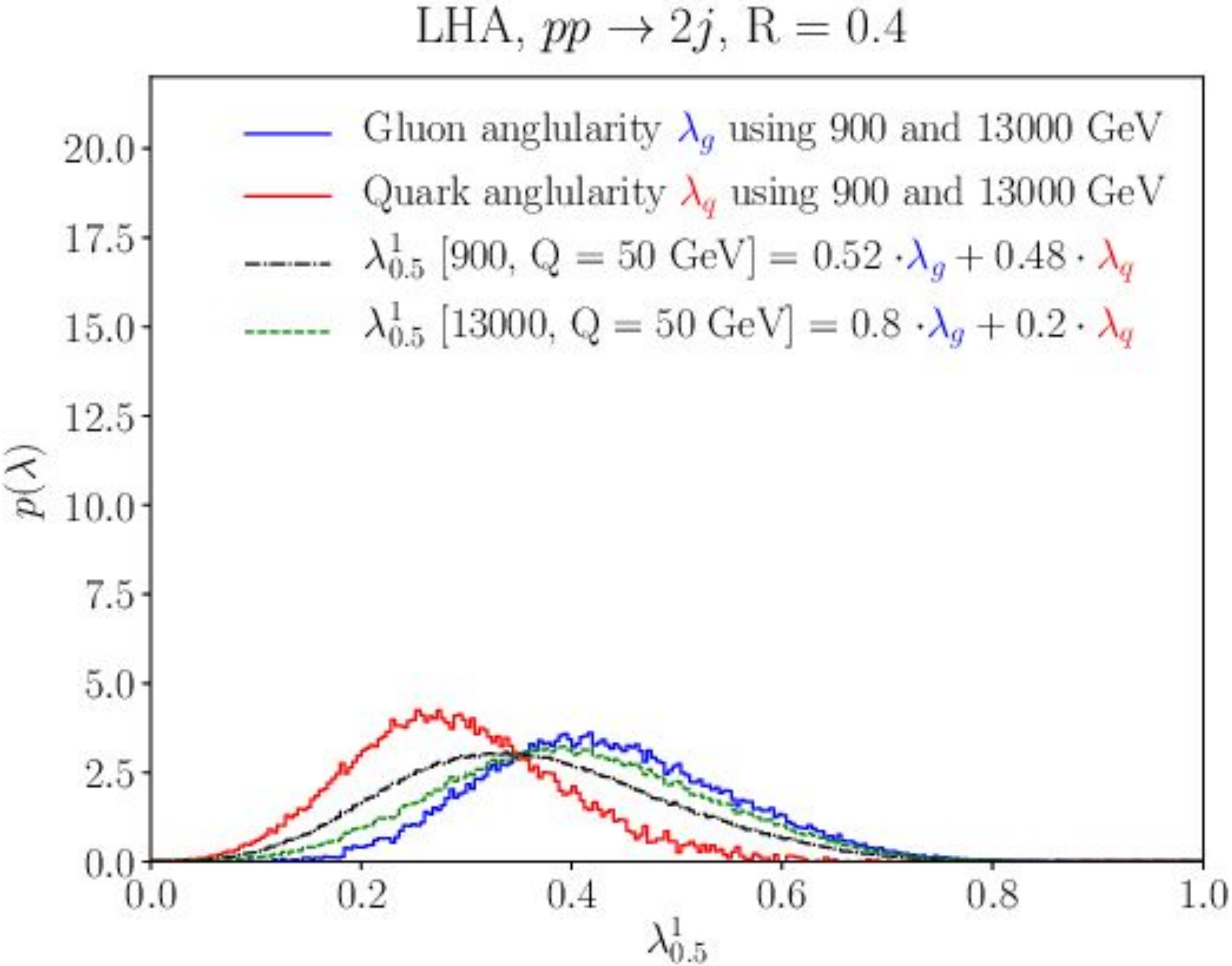

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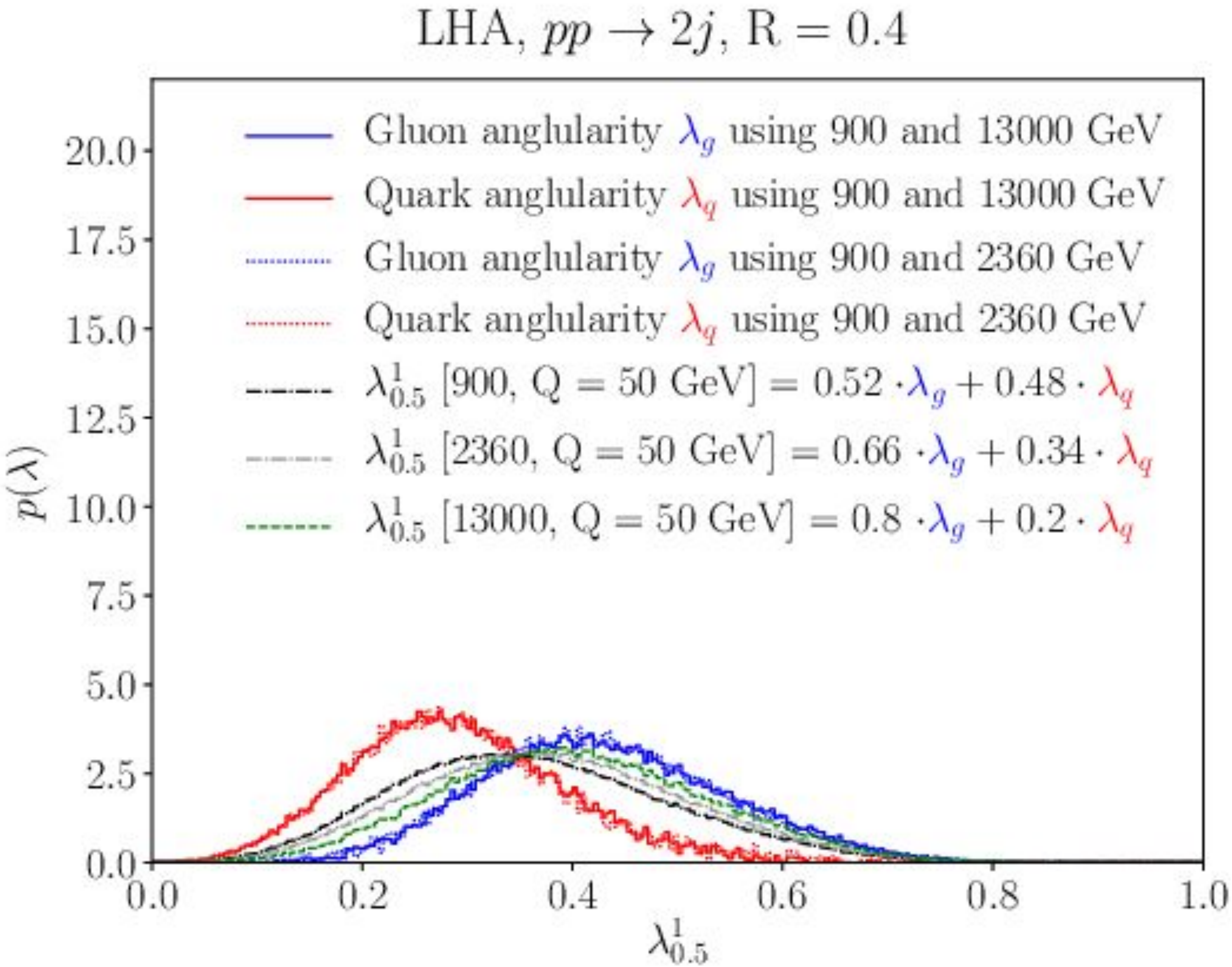
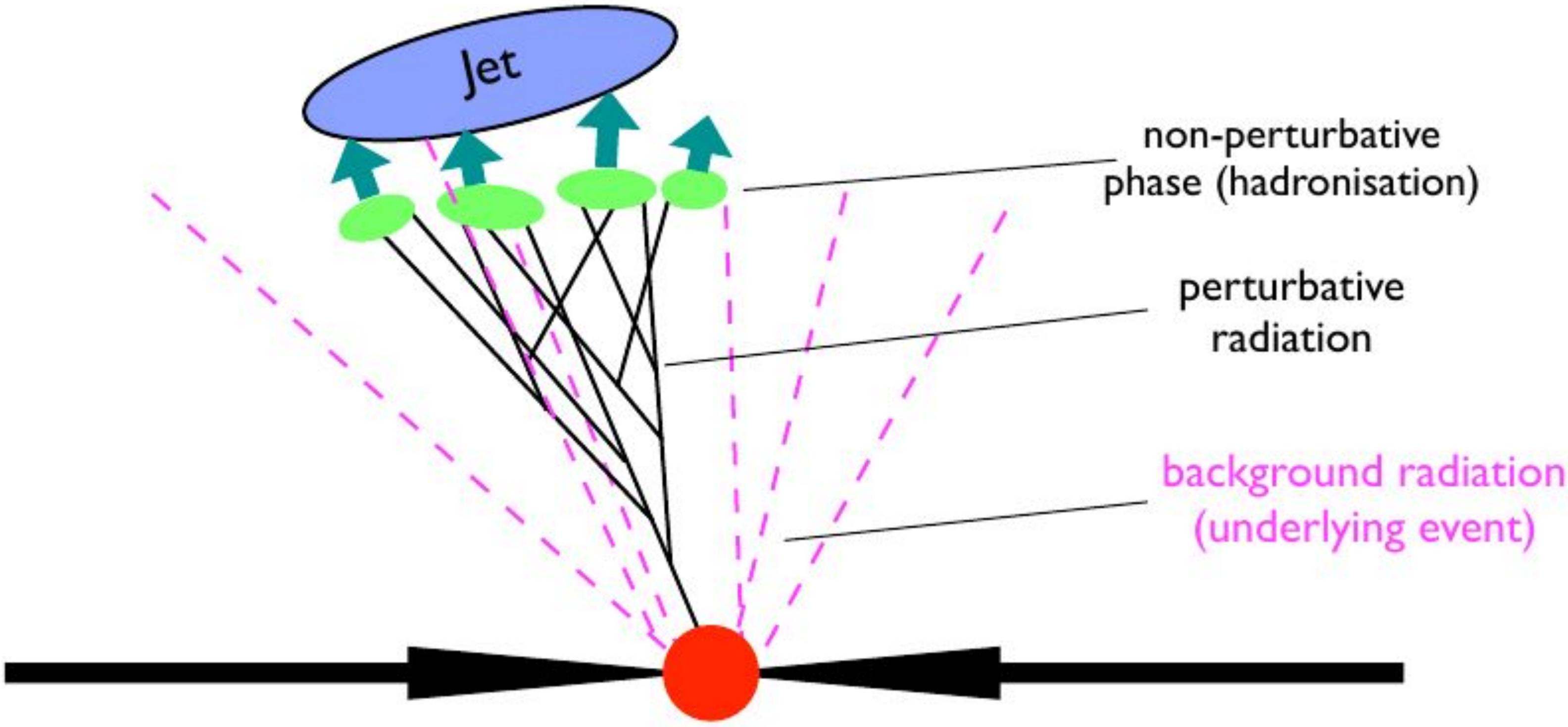


Introduction – jet structure



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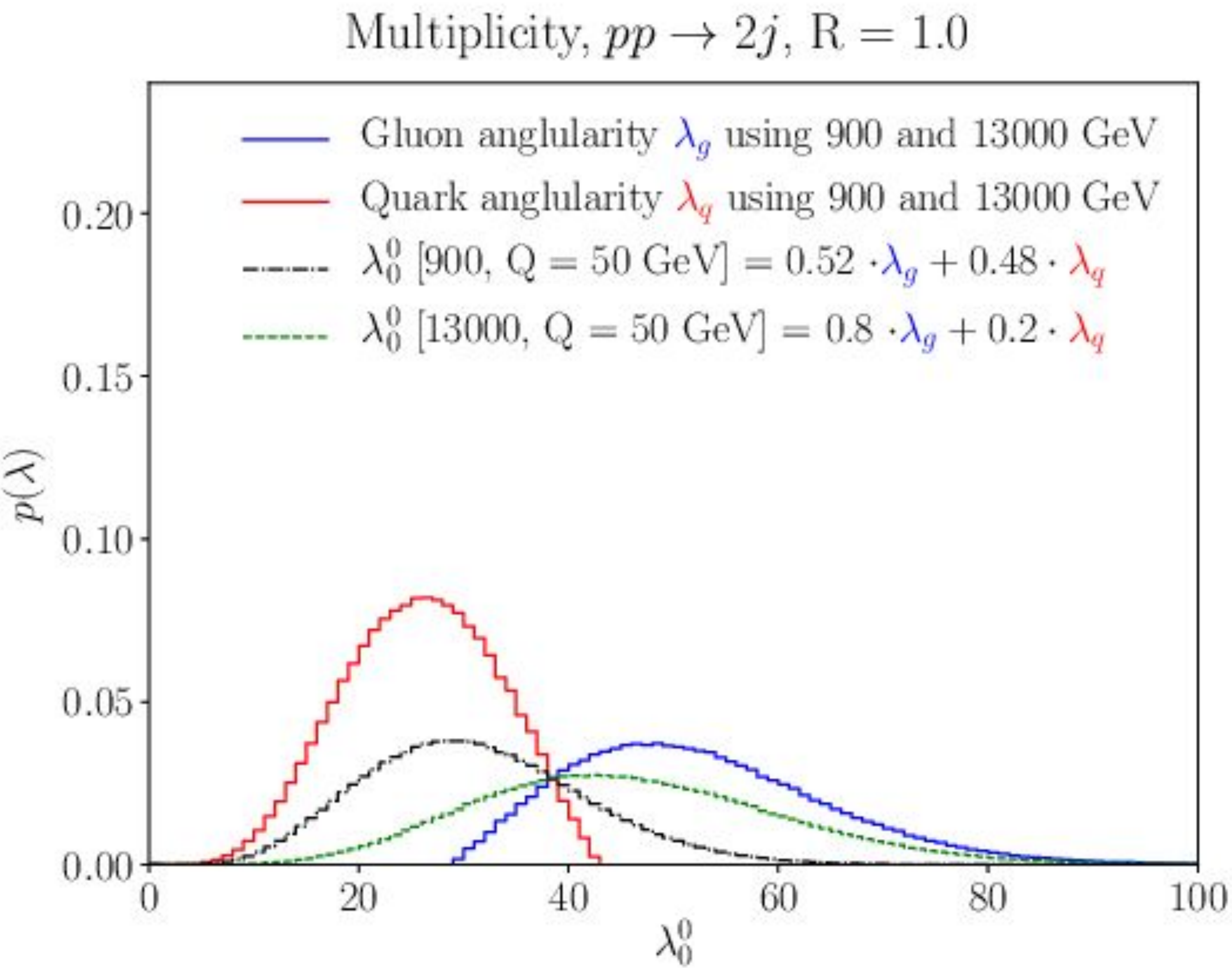

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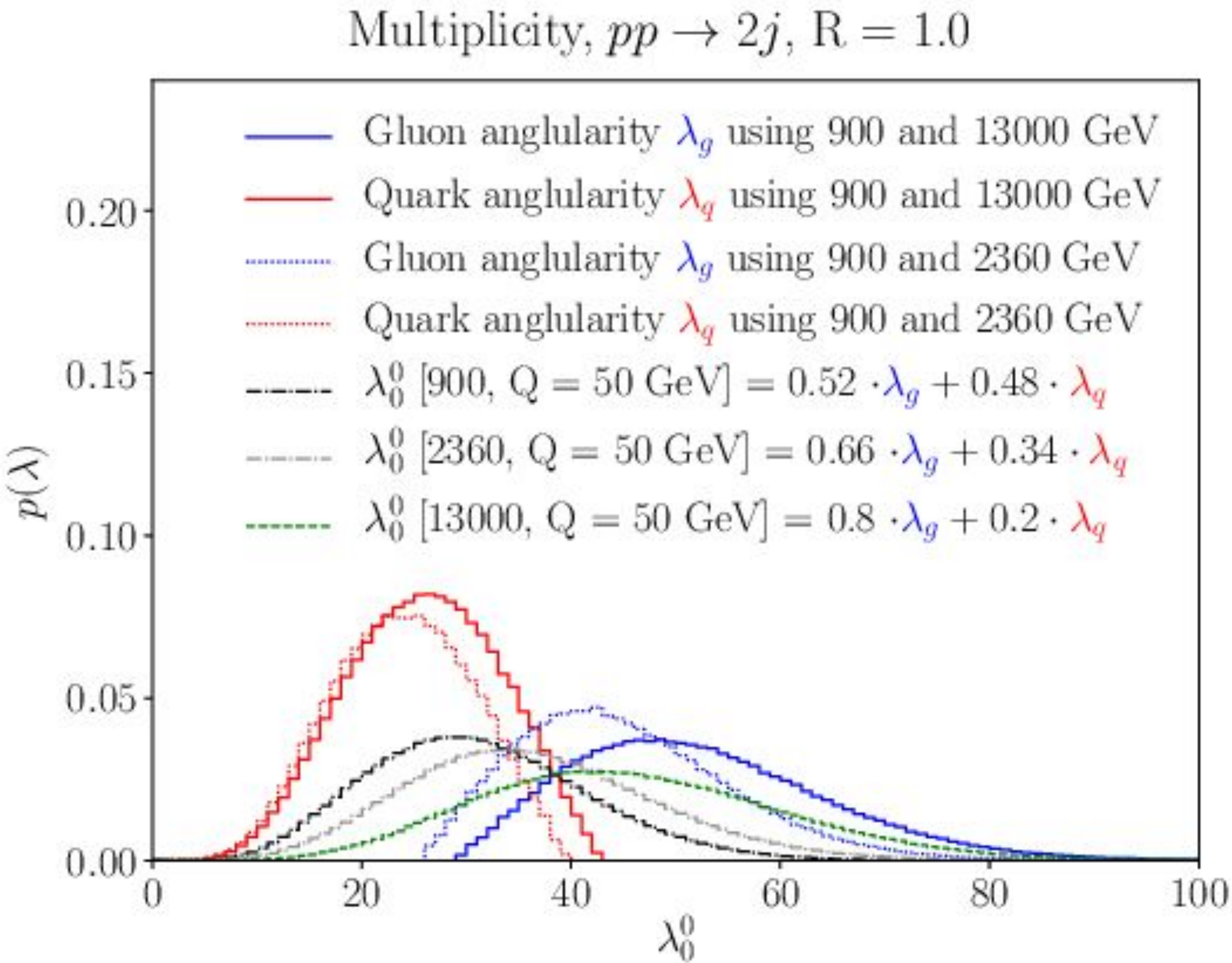

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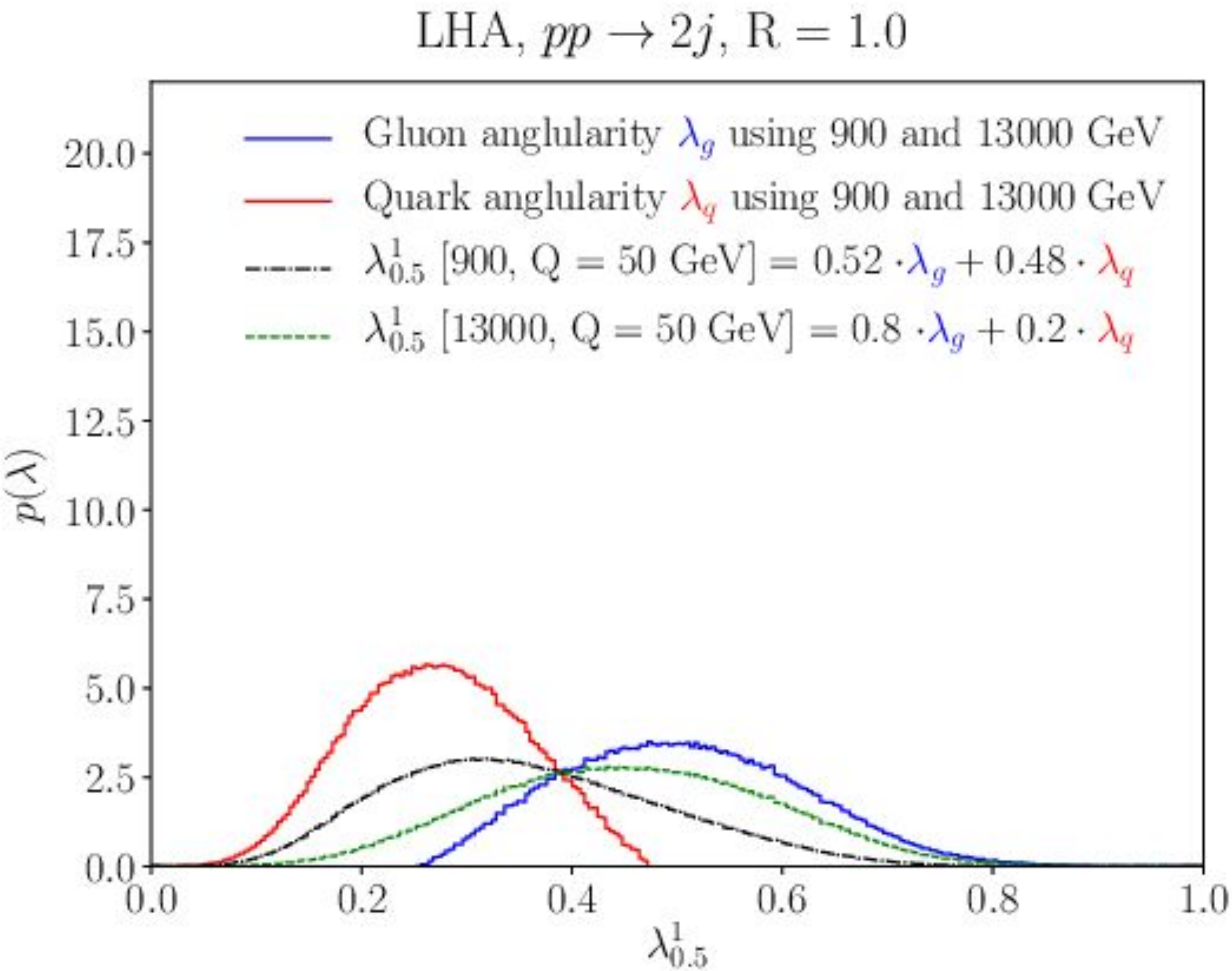

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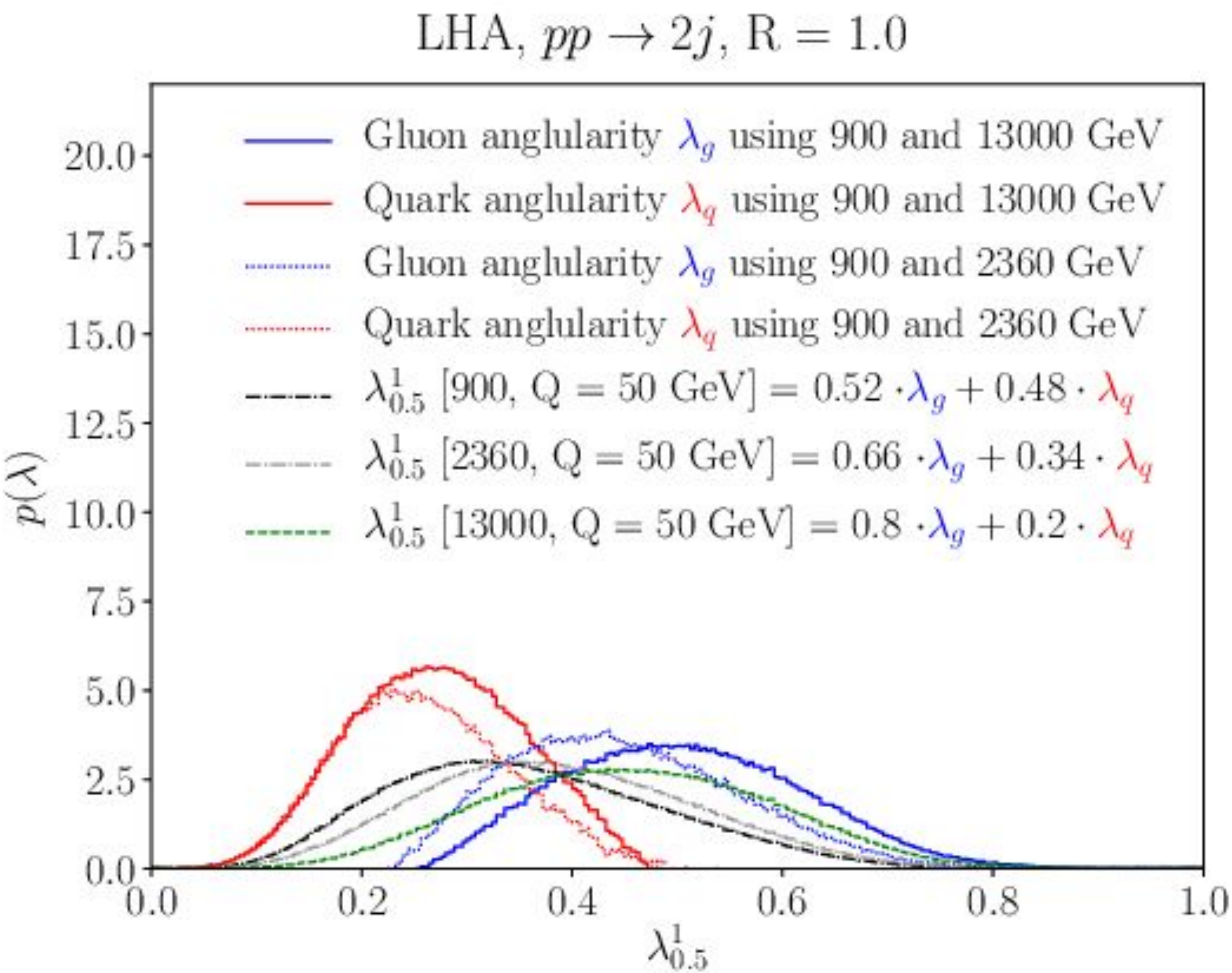
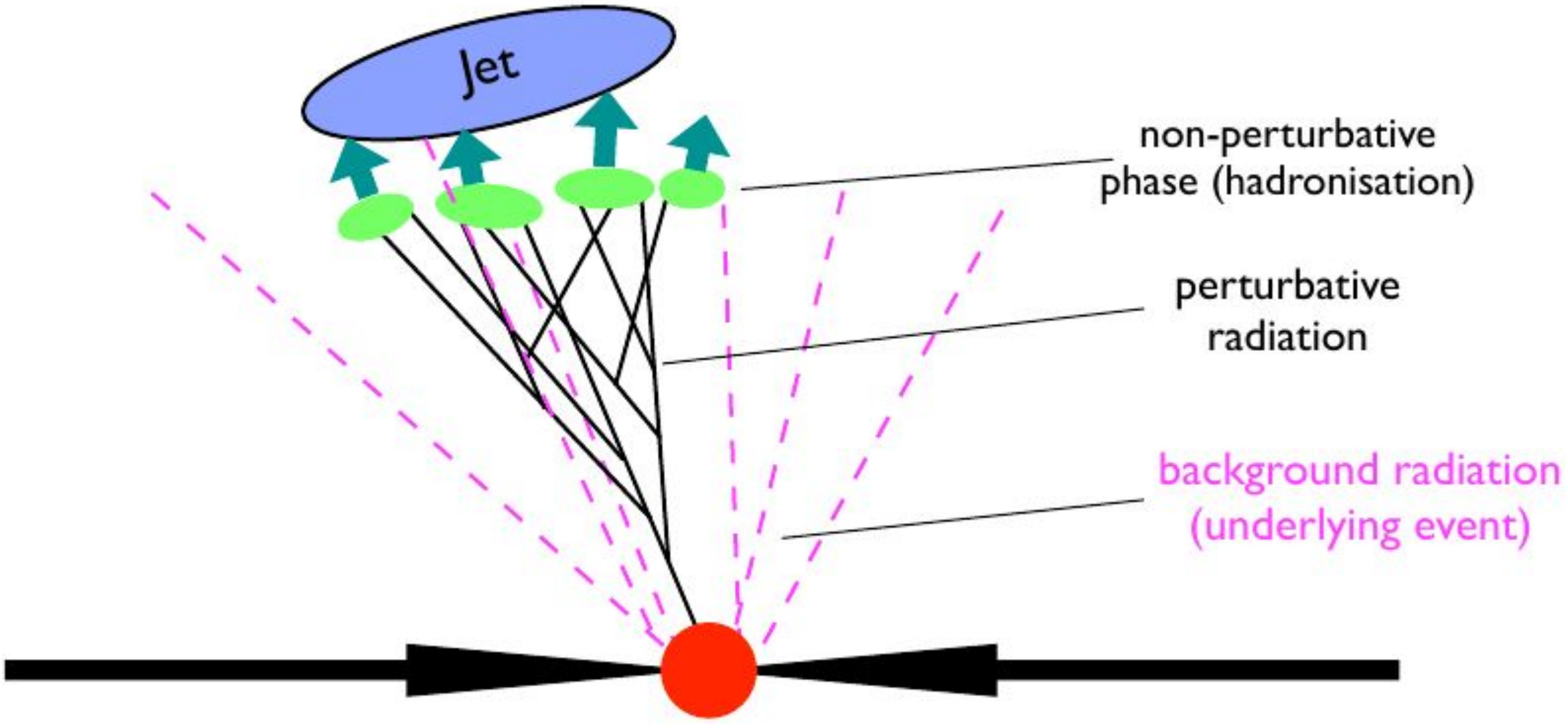


Introduction – jet structure



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 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

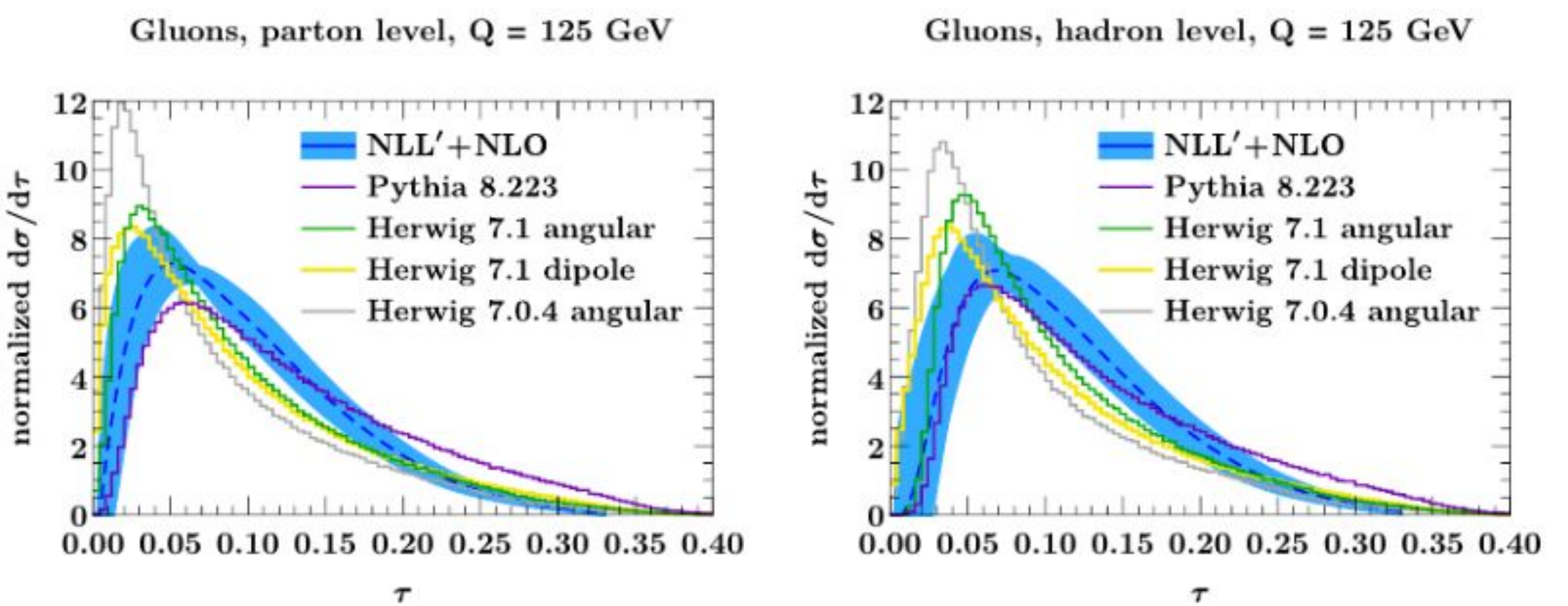
Daniel Reichelt (Dresden, Tech. U.), Peter Richardson (CERN and Durham U., IPPP), Andrzej Siodmok (Cracow, INP) (Aug 4, 2017)

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

"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"

How we improved simulation of Q/G jets in Herwig

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