Quark/Gluon discrimination

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Q: What does quark/gluon discrimination mean?

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Q: What does quark/gluon discrimination mean?

A: Tagging a jet as quark or gluon jet

Q: Is that even well-defined?

(Or are you becoming senile already?)

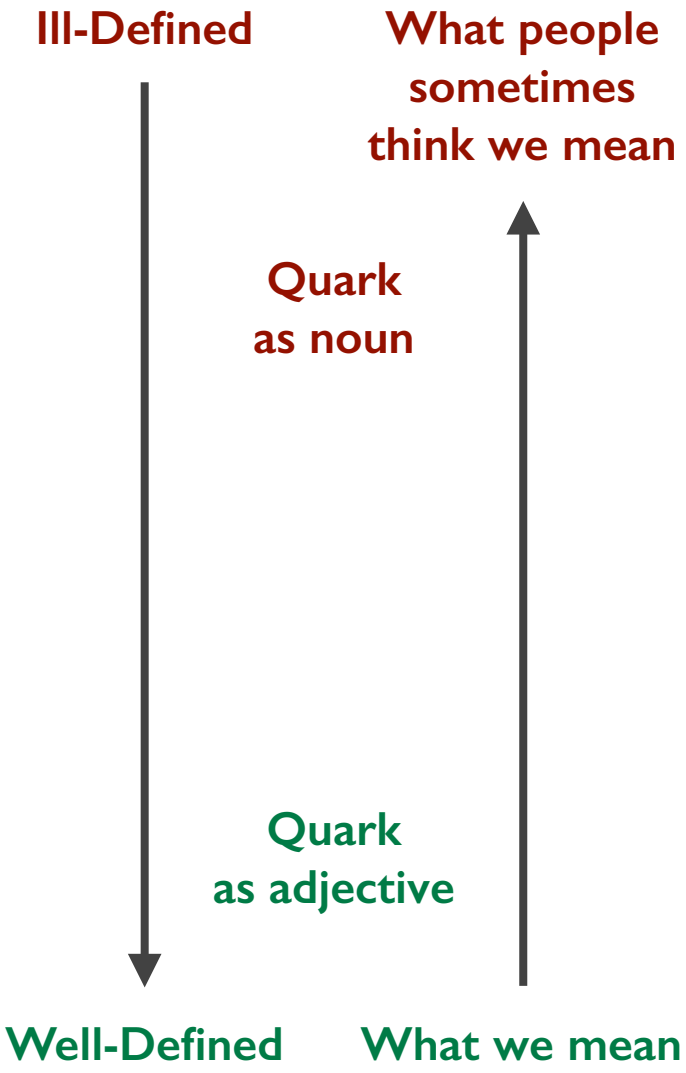
A: One needs to be careful...

(I'll (hopefully) try to convince you of the opposite)

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)

The main idea

- Study q/g separation using jet shapes
  - What jet shape?
  - What separation criterion?

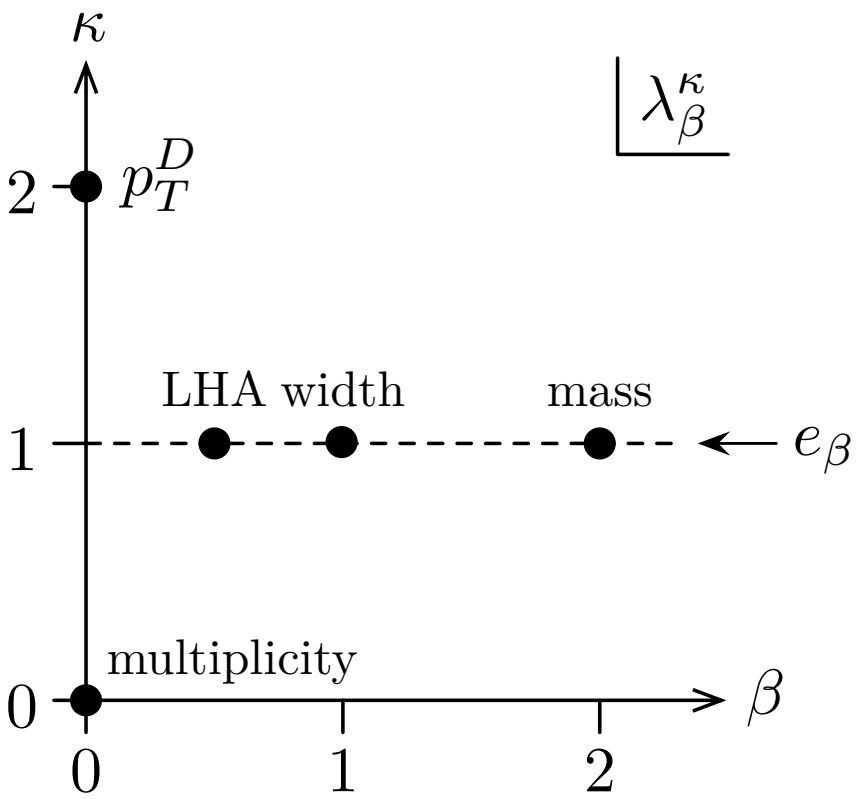
- Several studies:
  - Idealised e^+e^- Monte-Carlo study [Les-Houches, 2015]
  - How could we learn something from the LHC? [in progress]
  - How could we learn something from FCC-ee? [some ideas]

Discriminants: generalised angularities

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

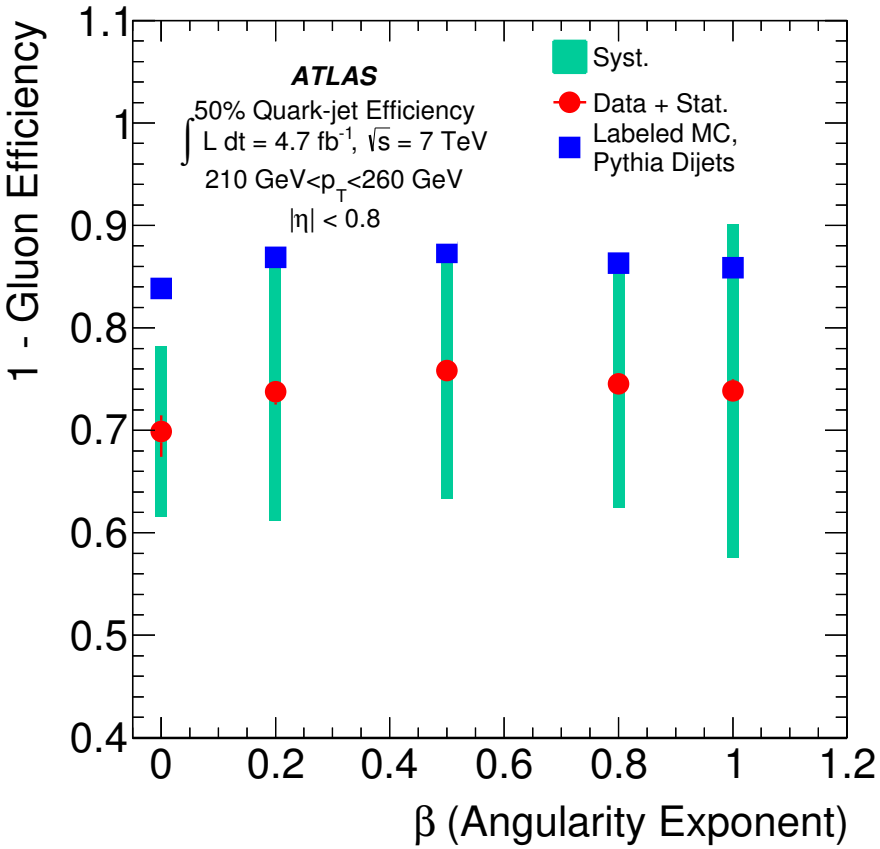
[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

- quark radiation $\propto C_F$
  gluon radiation $\propto C_A$
  $\Rightarrow (\lambda_\beta^\kappa)_{\text{quark}} < (\lambda_\beta^\kappa)_{\text{gluon}}$
- 5 working points
- will focus on $\lambda_{\text{LHA}} \equiv \lambda_{1/2}^1$
- $\kappa = 1$, $\beta > 0$ are IRC-safe
- larger β sensitive to larger angles



A puzzle

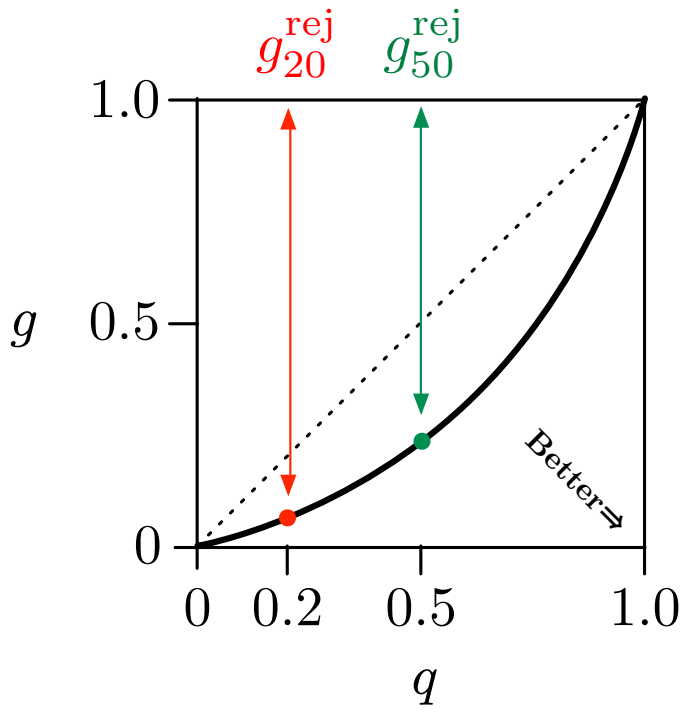
[ATLAS, 1405.6583]



- Casimir scaling: $\epsilon_g = (\epsilon_q)^{C_A/C_F}$.
  $\epsilon_q = 0.5 \Rightarrow 1 - \epsilon_g = 0.79$
- NLL predicts
  - a larger discrimination
  - an increase with β
- agrees qualitatively with Pythia
- data quite different

Calls for further investigations

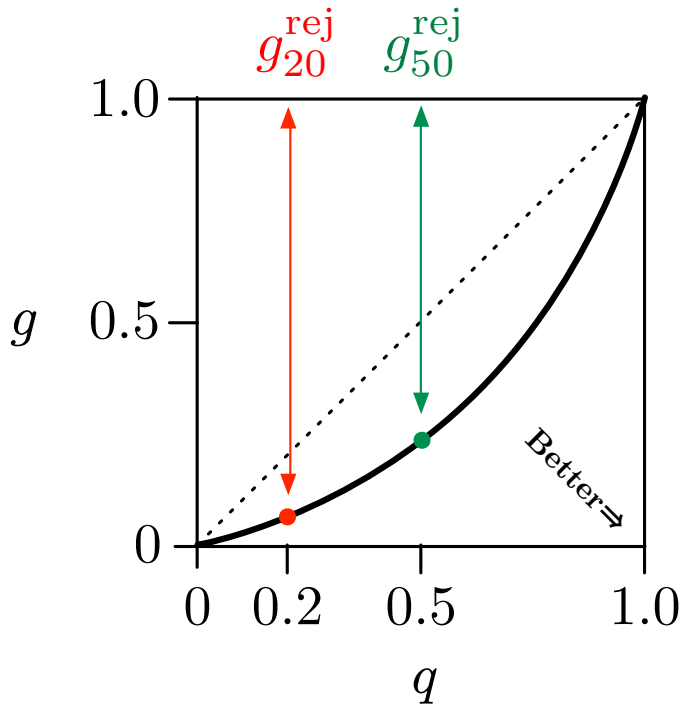
Quantifying q/g separation



Examples:

- g_{rej}^{α}: gluon rejection for a given quark efficiency α
- q_{rej}^{α}: quark rejection for a given gluon efficiency α
- Mutual information
  (from information theory)

Quantifying q/g separation



Examples:

- g_{rej}^{α}: gluon rejection for a given quark efficiency α
- q_{rej}^{α}: quark rejection for a given gluon efficiency α
- Mutual information
  (from information theory)

Our separation measure:

$$\Delta = \int d\lambda \frac{d\Delta}{d\lambda}$$

$$\frac{d\Delta}{d\lambda} = \frac{1}{2}\frac{[p_q(\lambda) - p_g(\lambda)]^2}{p_q(\lambda) + p_g(\lambda)}$$

- something like S^2/B
- symmetric in q↔g
- information as a function of λ

Idealised tests in e^+e^- collisions

Framework

Truth-level: parton-shower event generator

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

Explore different configurations:

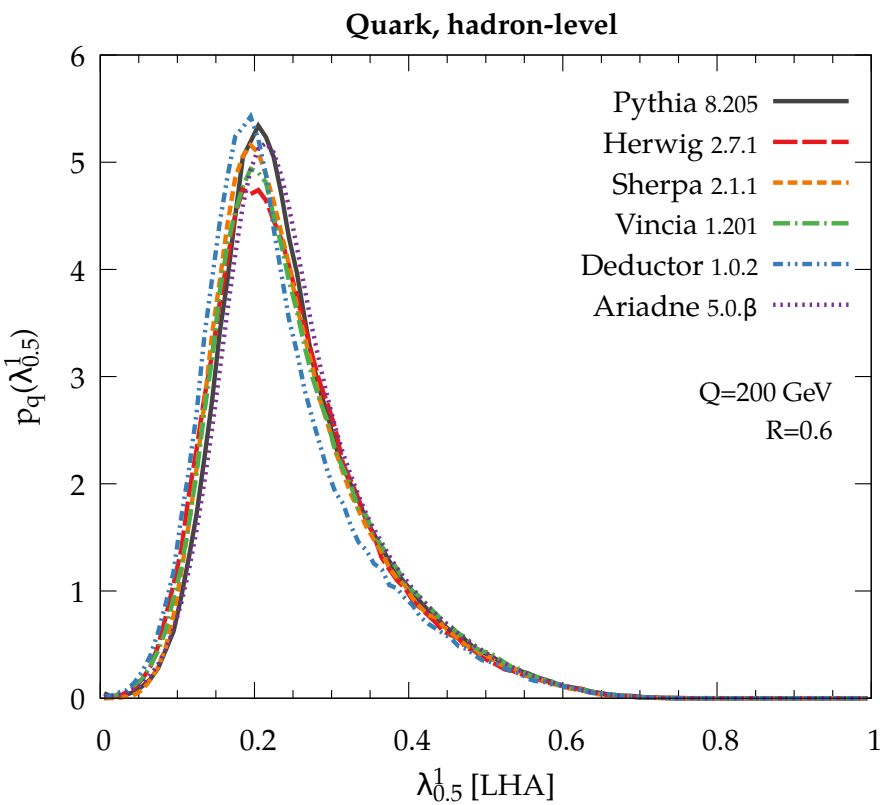
- Vary the collision energy Q (we impose $E_{\text{jet}} > 0.8Q/2$)
- Vary the jet radius R

Several Monte-Carlo generators at parton and hadron level:

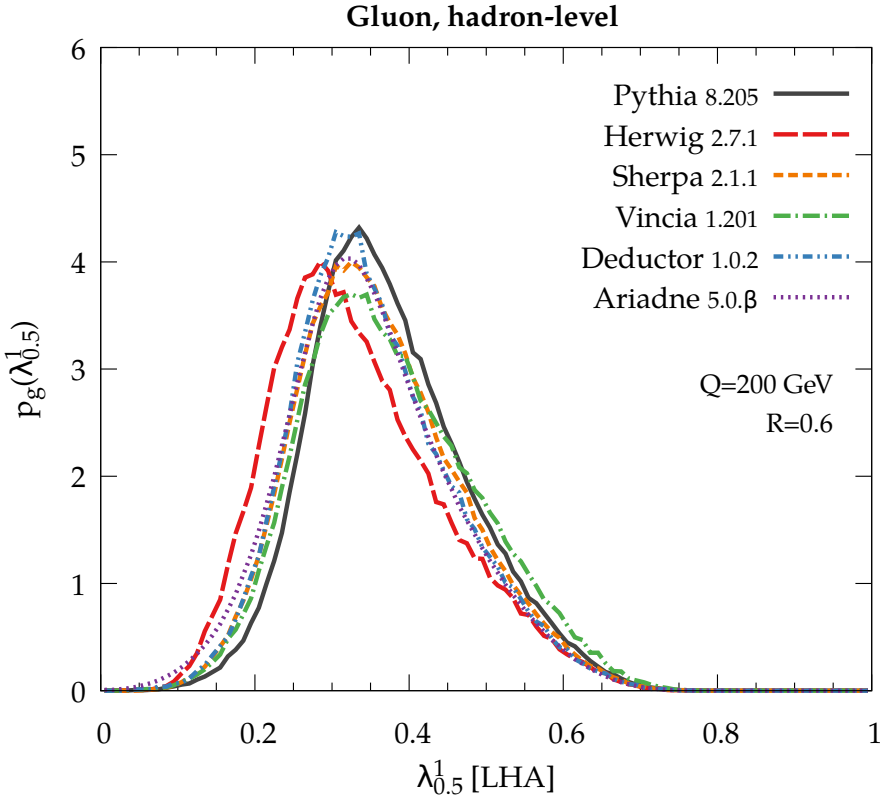
- Pythia (v8.205)
- Herwig++ (v2.7.1)
- Sherpa (v2.1.1)
- Vincia (v1.201)
- Deductor (v1.0.2) (+Pythia)
- Ariadne (v5.0.β)

Distributions for λ_{LHA} (hadron level)

Quarks



Gluons



Distributions for λ_{LHA} (hadron level)

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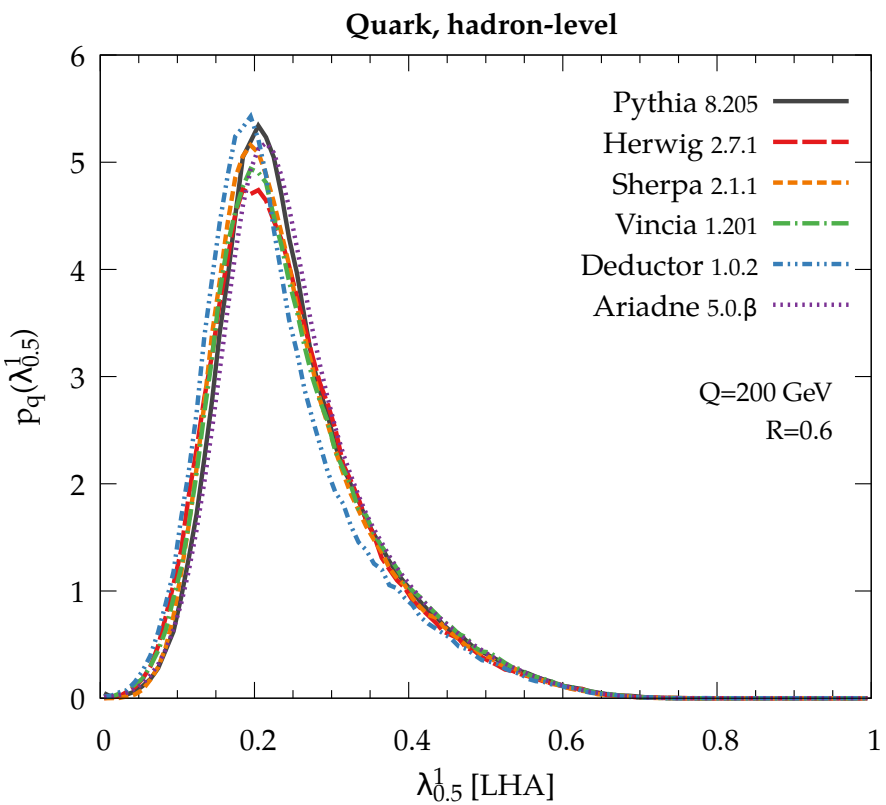
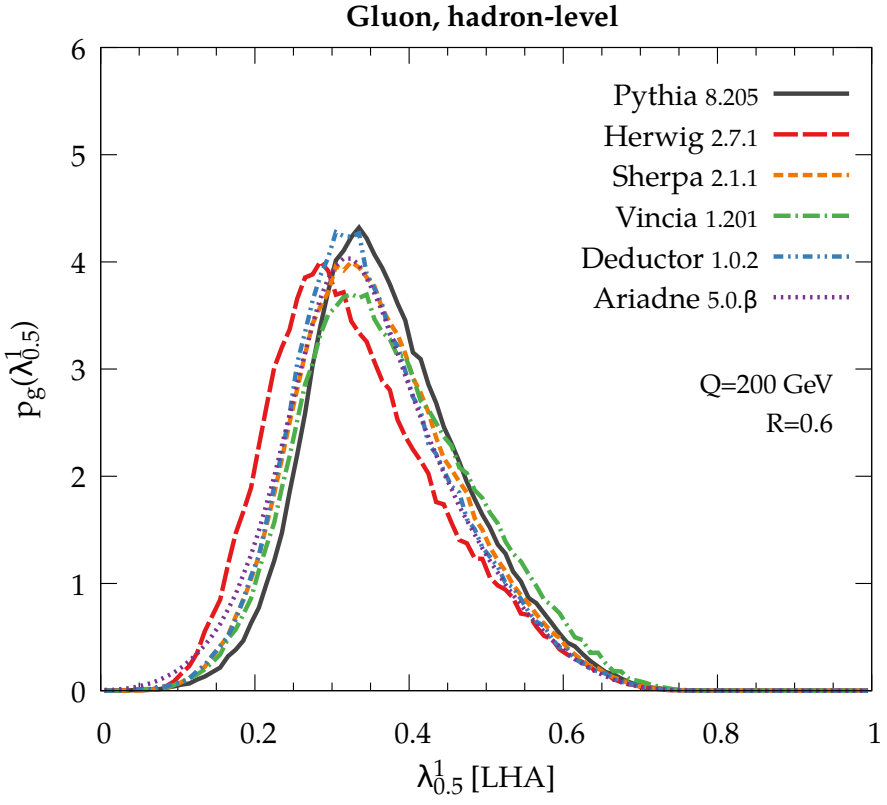


- Good agreement

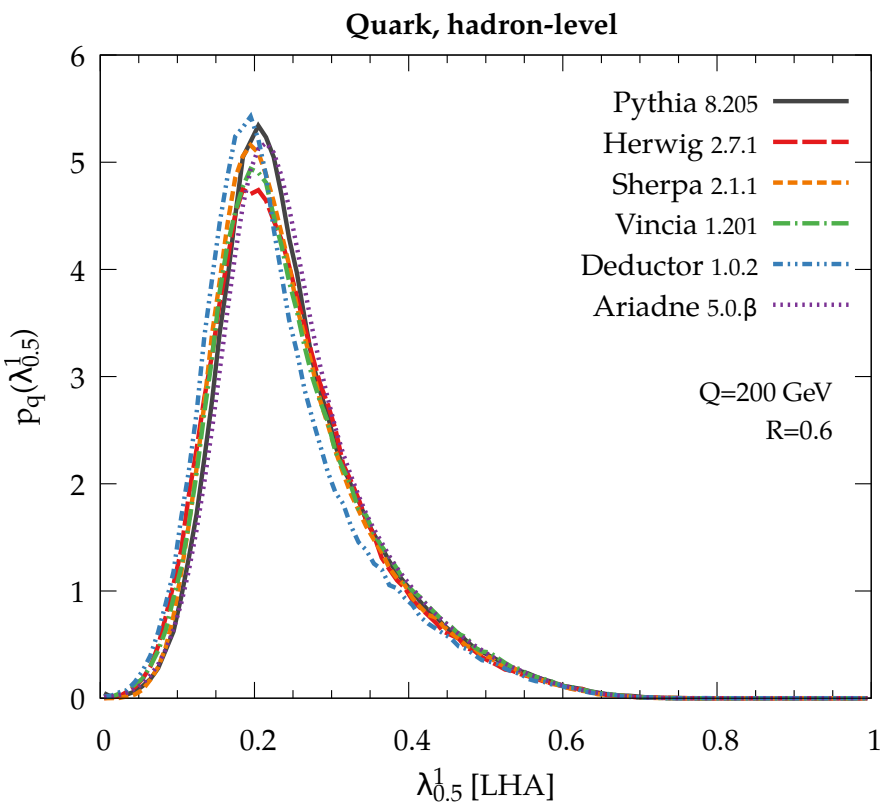
Gluons



- Larger spread

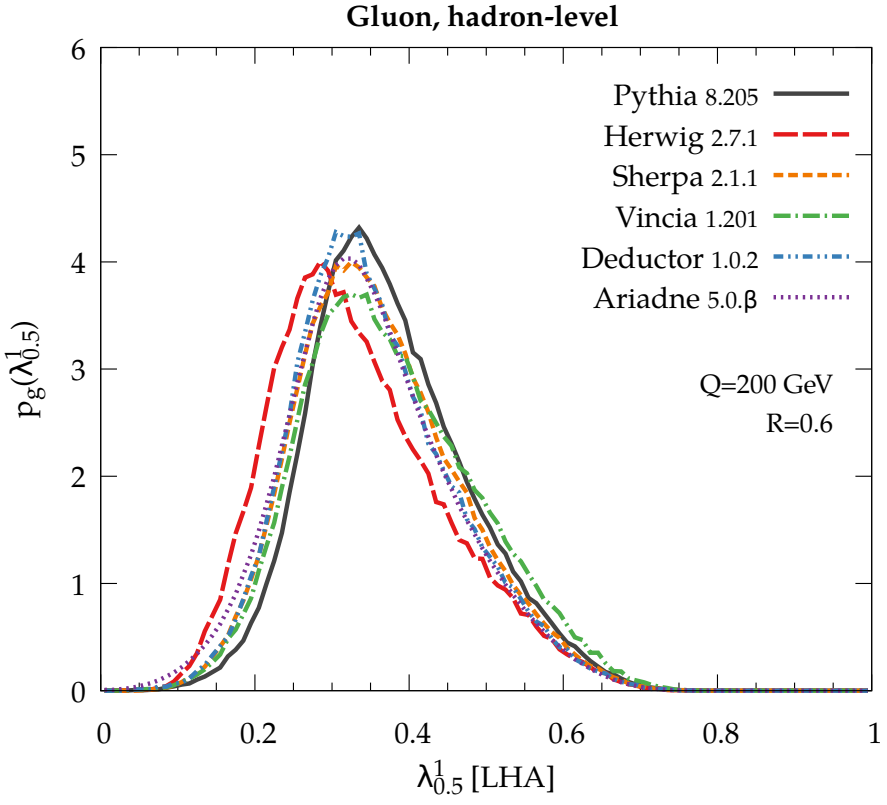
Distributions for λ_{LHA} (hadron level)

Quarks



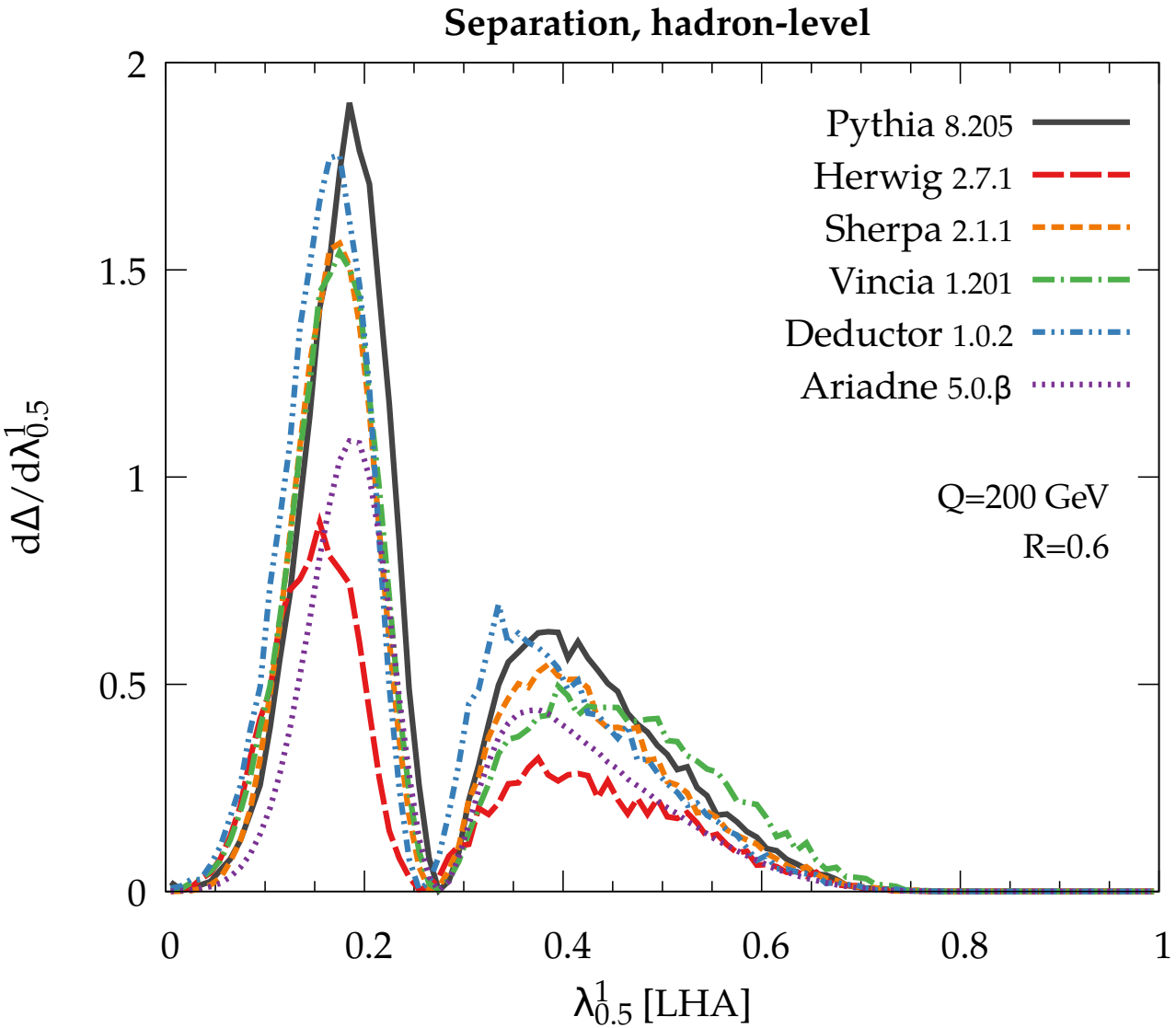
- Good agreement
- LEP constraints

Gluons



- Larger spread
- No data

Separation (hadron level)

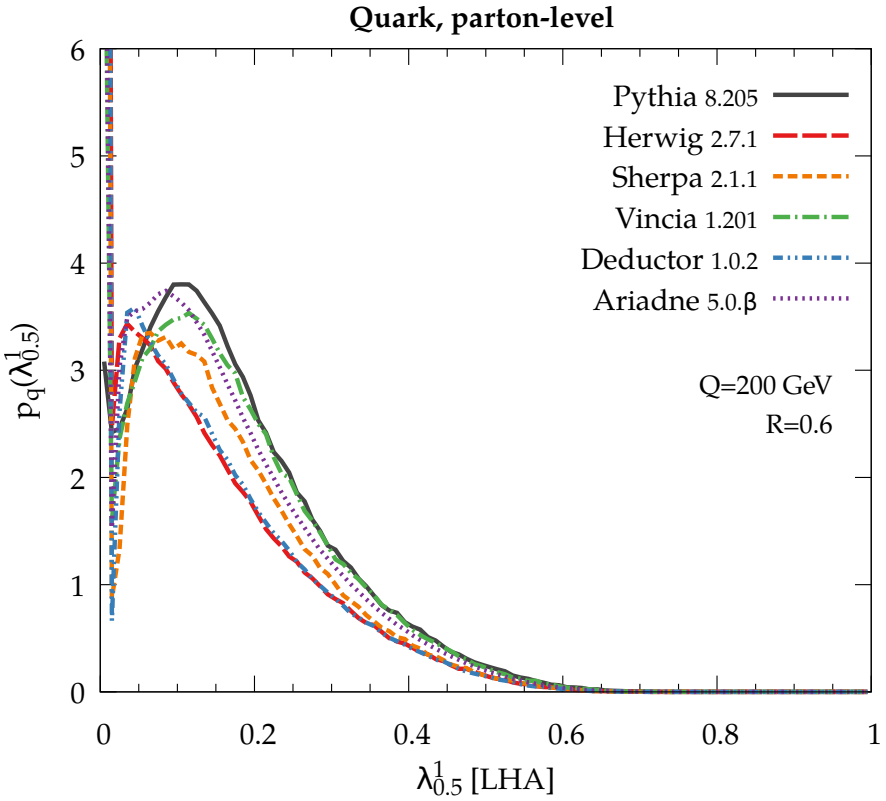


Indicates where discriminative power lies

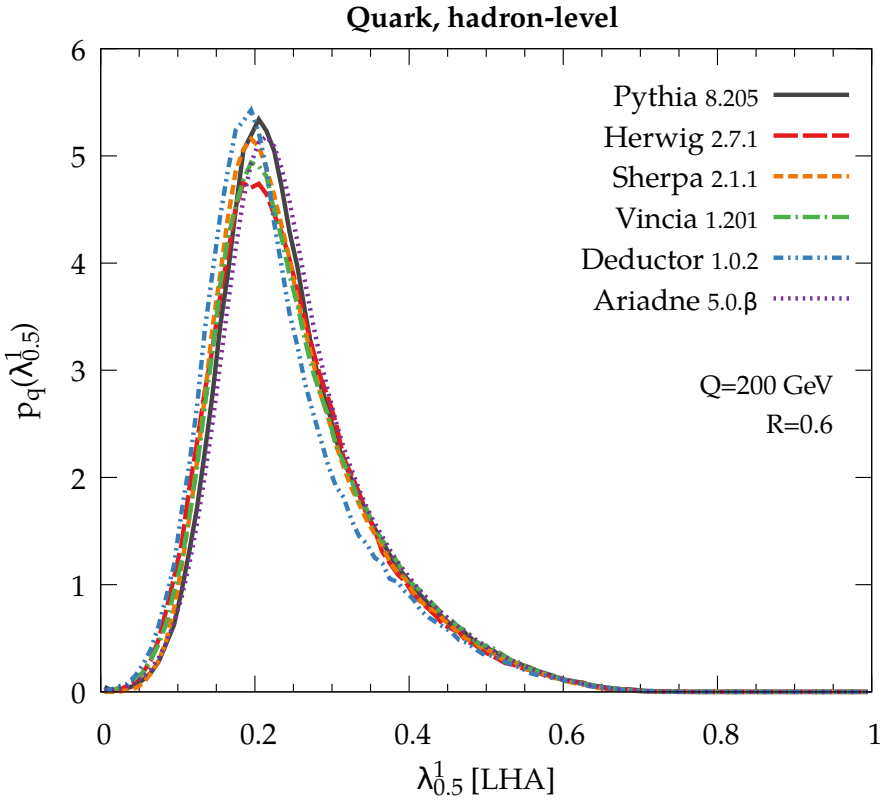
- Significant spread
- Pythia more optimistic, Herwig more pessimistic

Non-perturbative effects (take carefully)

Parton level



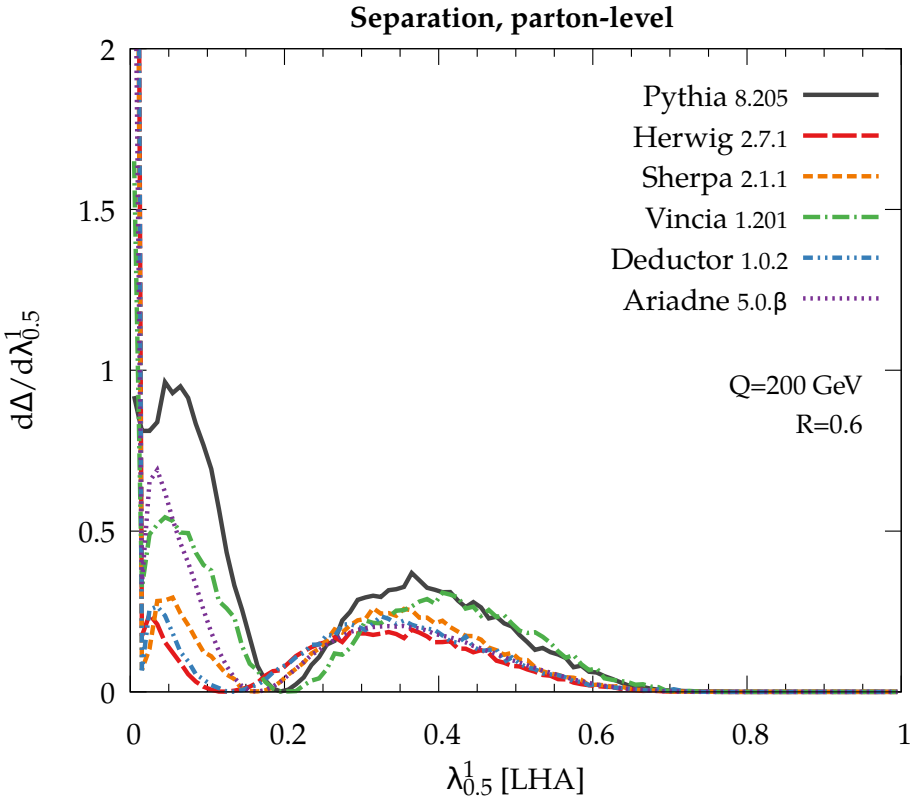
Hadron level



Large hadronisation effects (here for quarks)

Non-perturbative effects (take carefully)

Parton level



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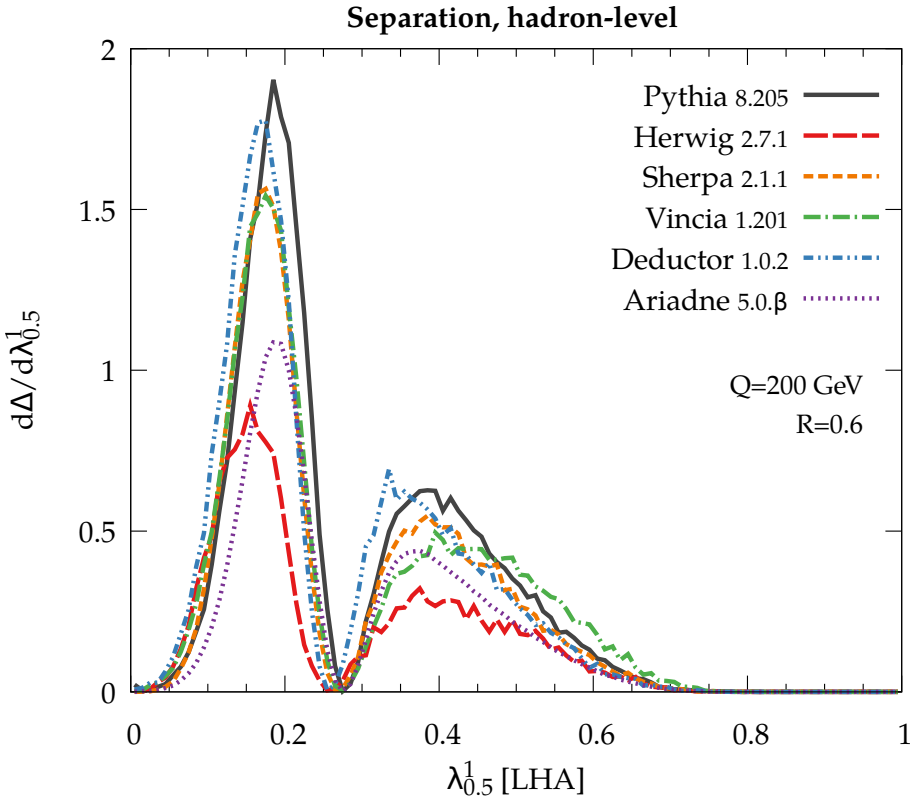
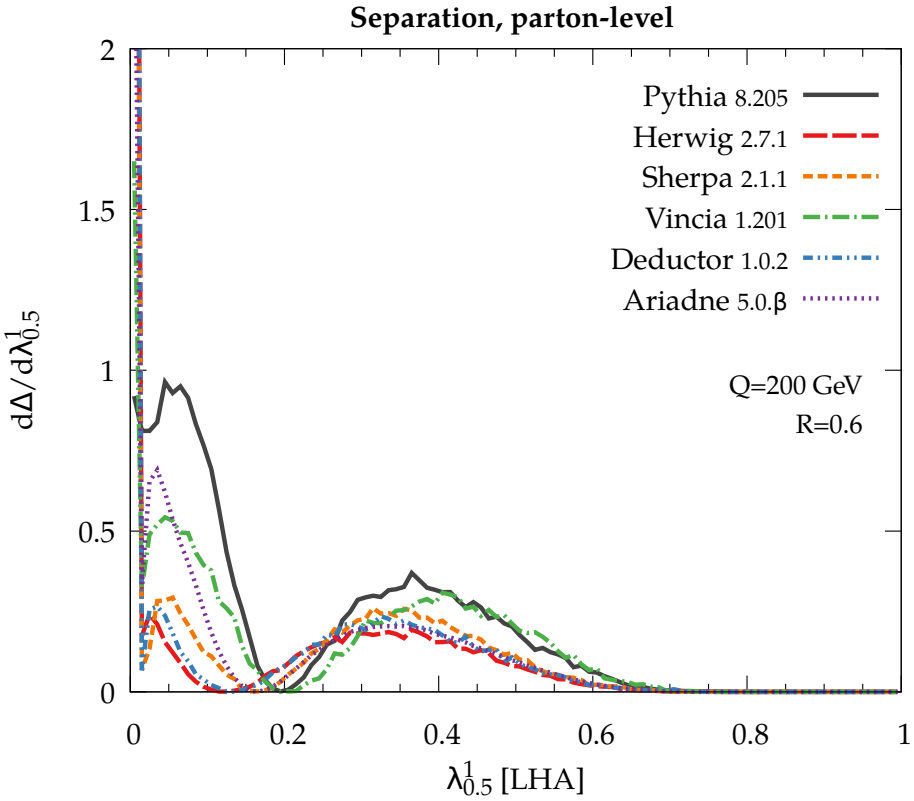


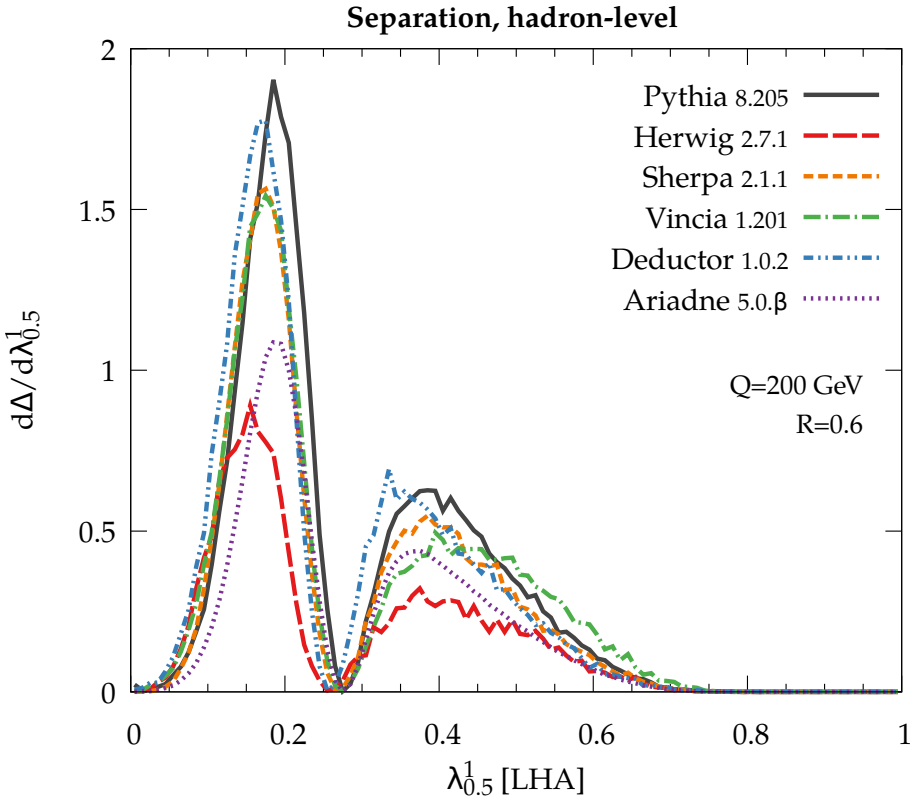
Large hadronisation effects (here for quarks and for separations)

Non-perturbative effects (take carefully)

Parton level



Hadron level

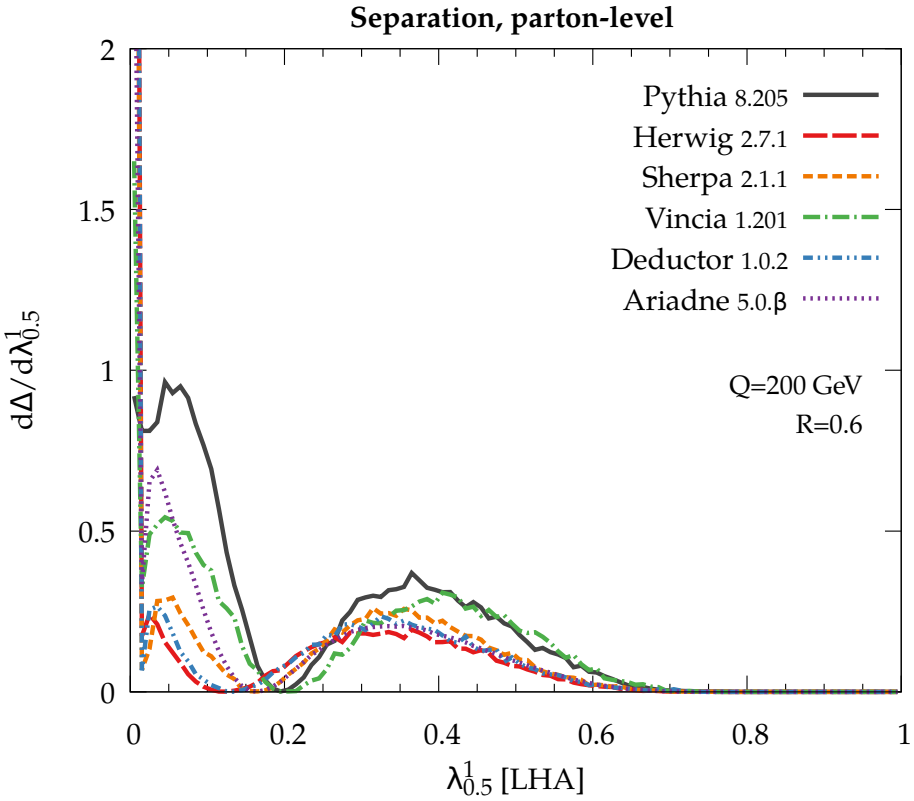


Large hadronisation effects (here for quarks and for separations)

Large differences between MCs also seen at parton level

Non-perturbative effects (take carefully)

Parton level



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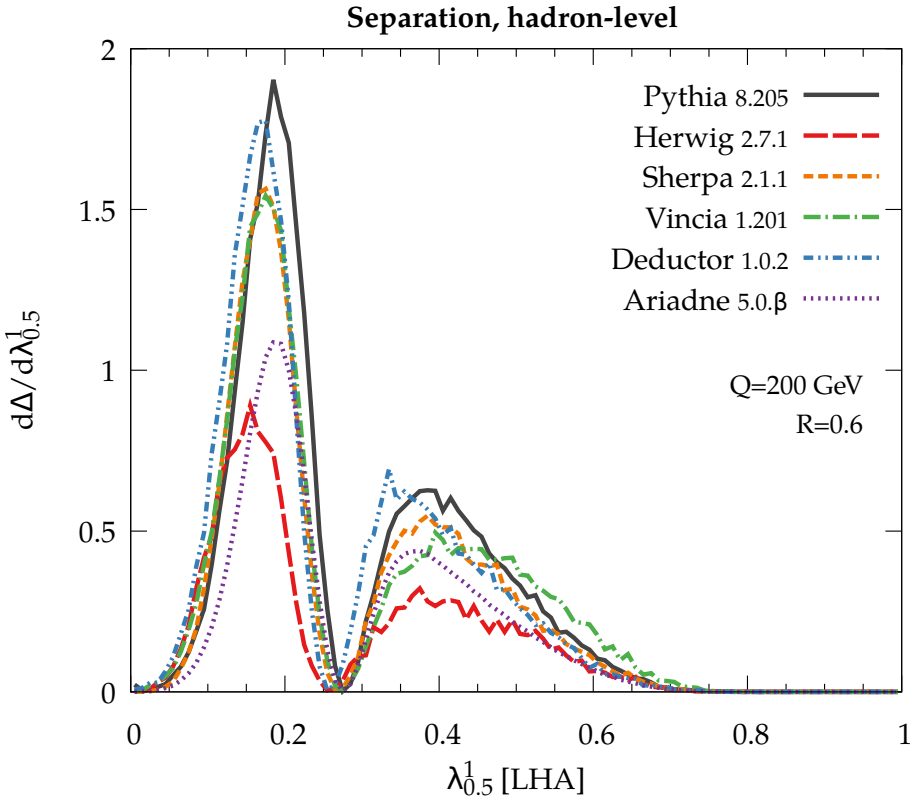


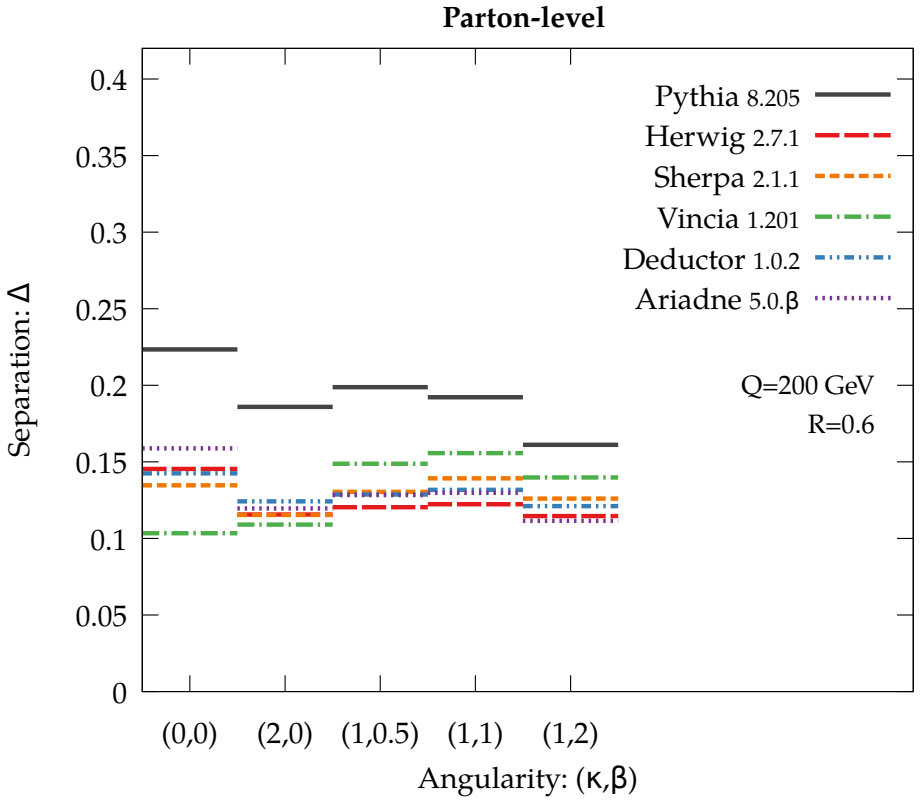
Large hadronisation effects (here for quarks and for separations)

Large differences between MCs also seen at parton level

$\Rightarrow$ challenge for both pQCD and NP models

Overall separation — observable dependence

Parton level



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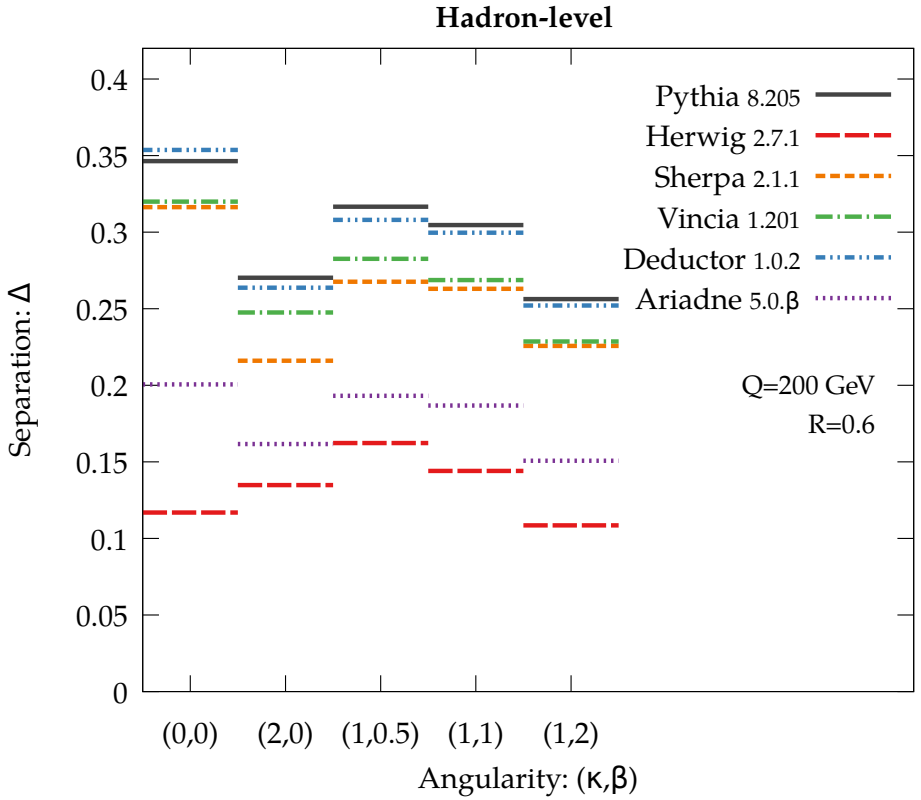
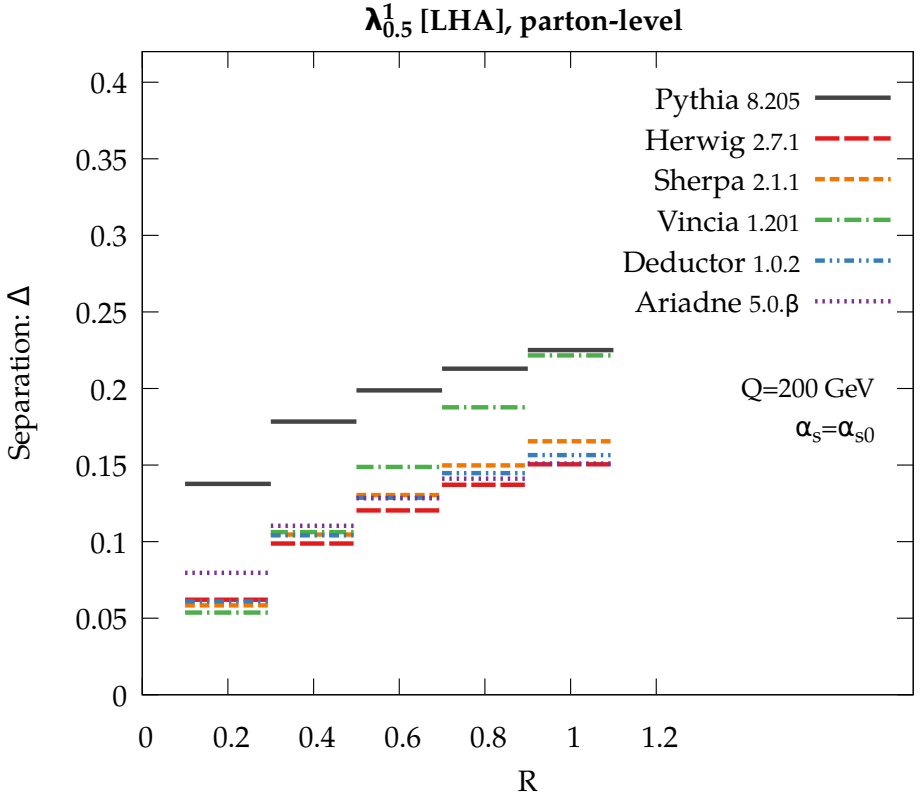


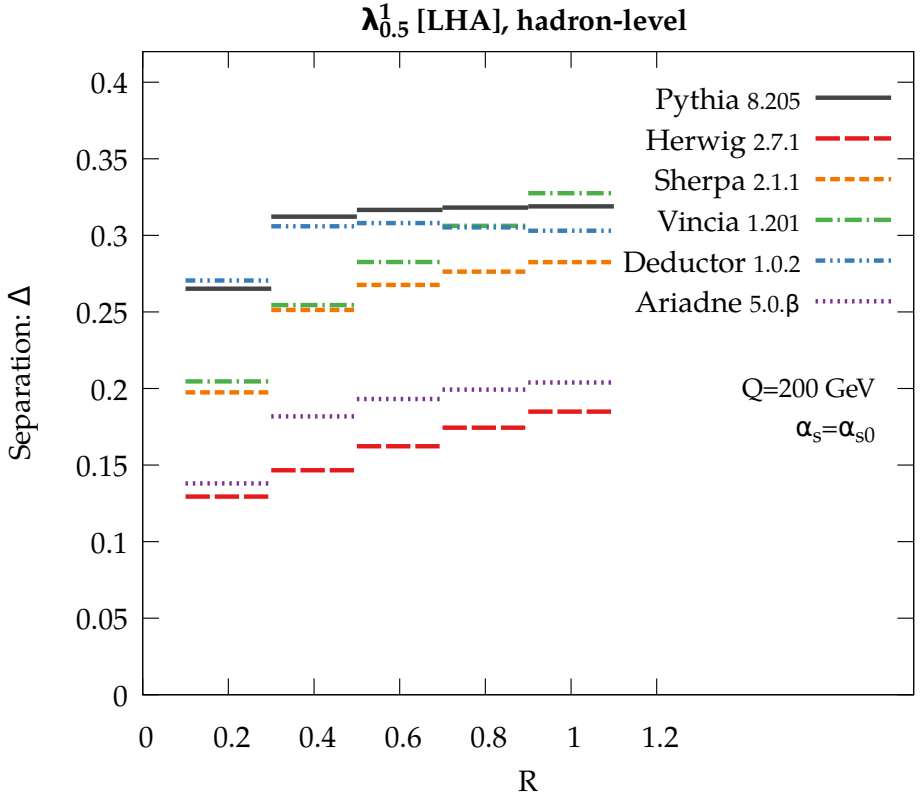
- Large spread in discrimination power (even more at hadron level)
- Seen for both IRC-unsafe and IRC-safe (less expected) observable
- For $\kappa = 1$ (IRC-safe), all MC see that lower β is better

Overall separation — parametric dependence

Parton level



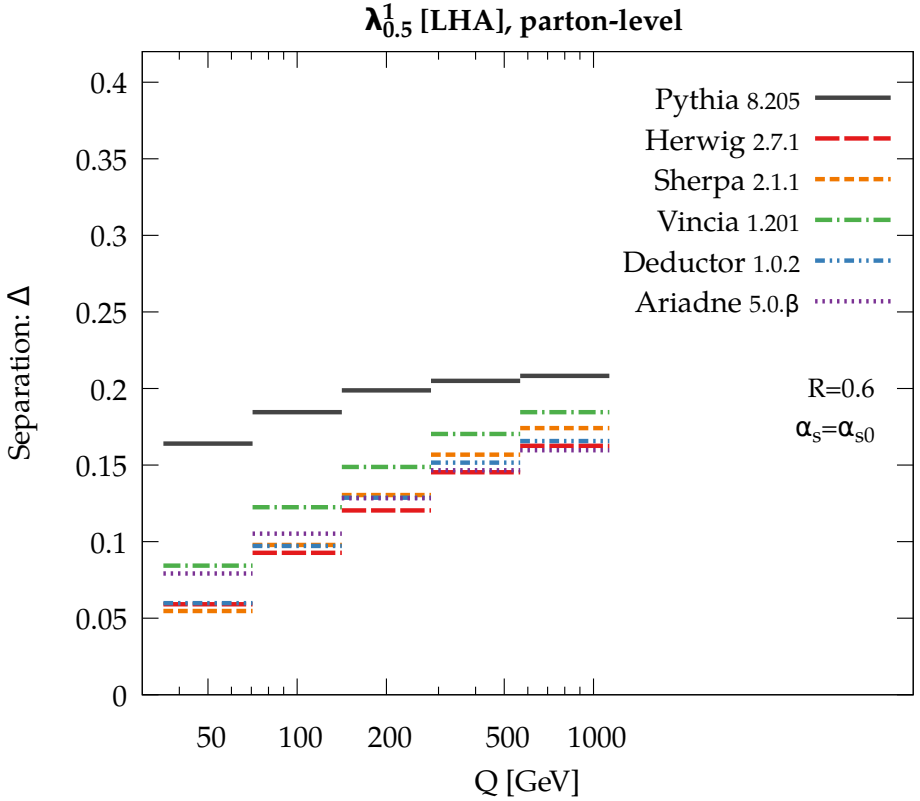
Hadron level



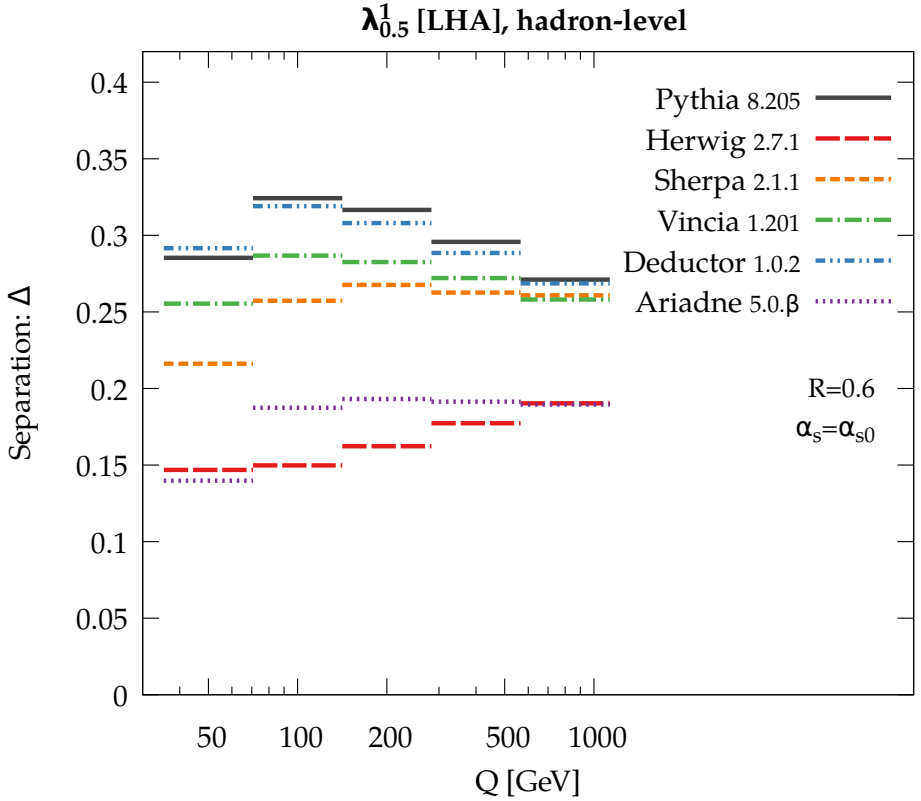
- R increases $\Rightarrow$ Δ increases

Overall separation — parametric dependence

Parton level



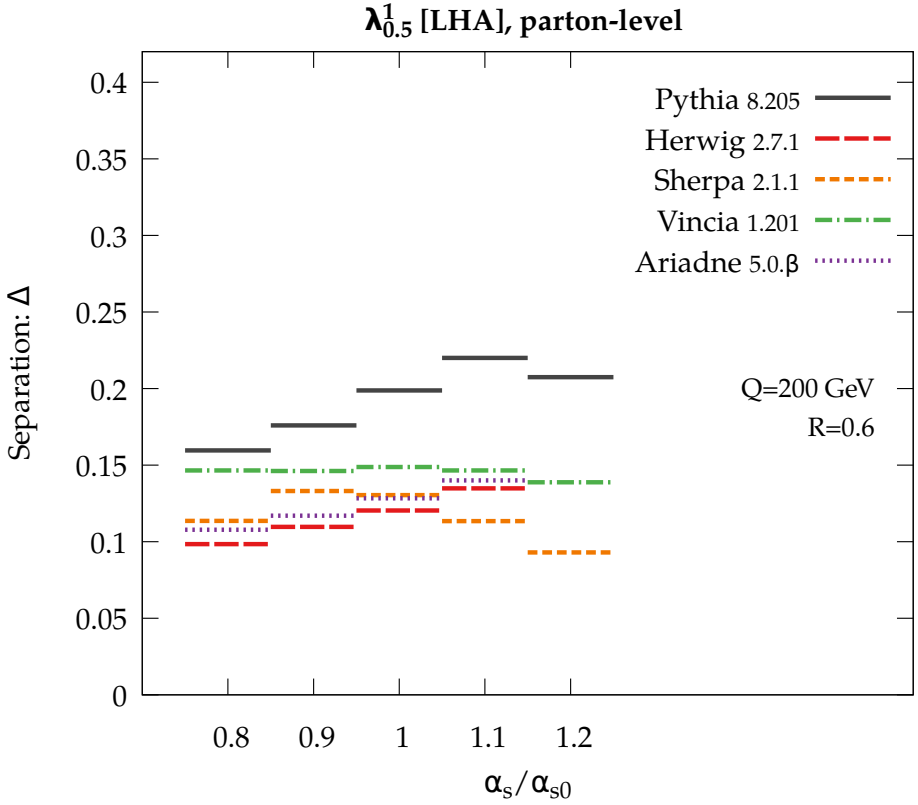
Hadron level



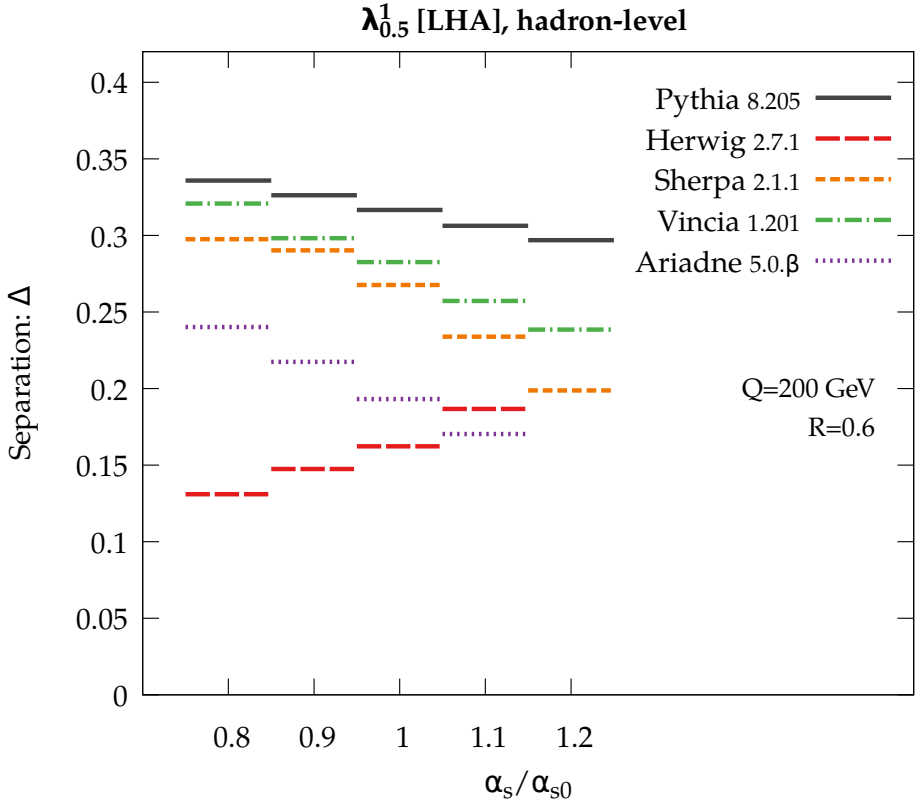
- R increases $\Rightarrow$ Δ increases
- Q increases $\Rightarrow$ Δ increases (not clear at hadron level)

Overall separation — parametric dependence

Parton level



Hadron level



- R increases $\Rightarrow$ Δ increases
- Q increases $\Rightarrow$ Δ increases (not clear at hadron level)
- α_s increases $\Rightarrow$ Δ not clear at parton level
  All decrease except Herwig++

Overall separation — parametric dependence

- R increases $\Rightarrow$ Δ increases
- Q increases $\Rightarrow$ Δ increases (not clear at hadron level)
- α_s increases $\Rightarrow$ Δ not clear at parton level
  All decrease except Herwig++

Analytic expectations

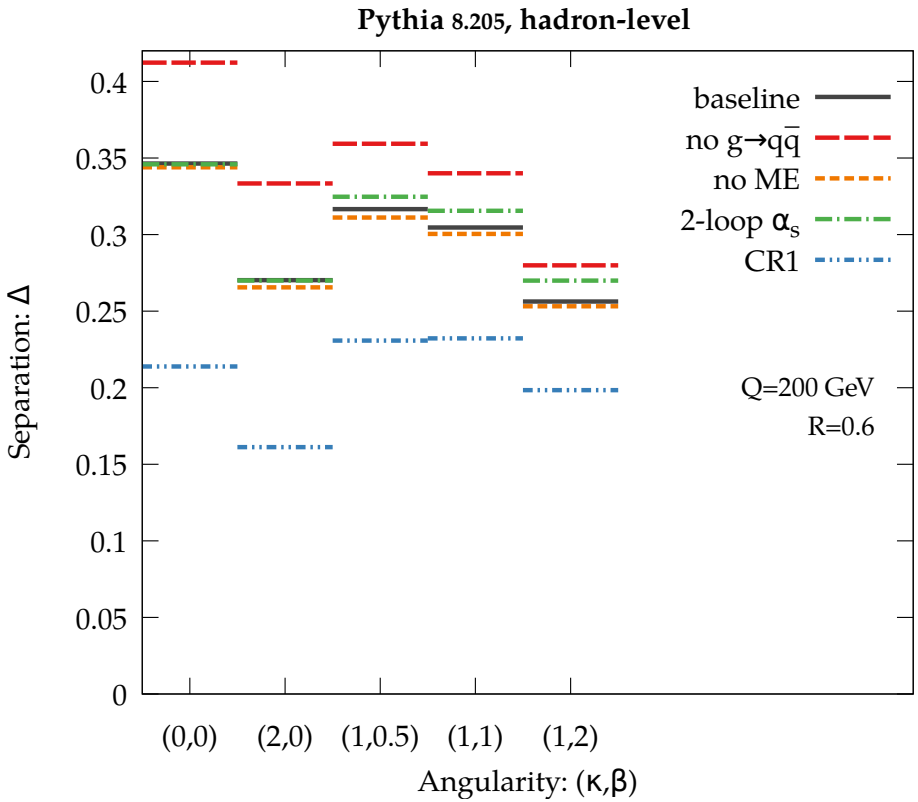
- Argument 1: Q, R increases $\Rightarrow$ more phase-space $\Rightarrow$ larger Δ
- Argument 2 (NLL): smaller α_s $\Rightarrow$ smaller Δ
- $\alpha_s(QR)$: correlated dependences
  not obviously seen in MC results

$\Rightarrow$ need for deeper understanding (at least in pQCD)

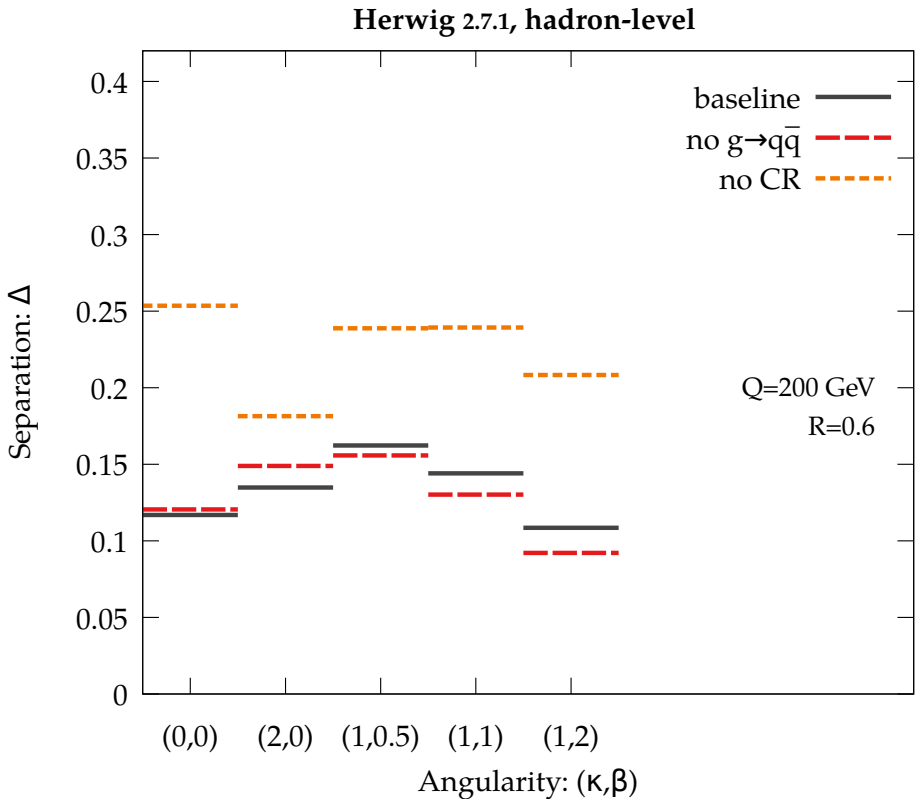
A deeper look into generators

Try to understand this by playing with switches in the generators

Pythia8 – hadron level



Herwig++ – hadron level



- NOT an uncertainty but an indication of what drives Δ
- Some large effects (e.g. colour reconnection, $g \to q\bar{q}$) some small

Recap so far

Main observations

- Better agreement for quarks than for gluons (LEP data)
- Sizeable non-perturbative effects
- Q, R, α_s dependence not obviously understood
- Some generator settings have large effects

LEP data does NOT constrain all relevant aspects of parton shower

What next?

We want stronger constraints on MC tuning.

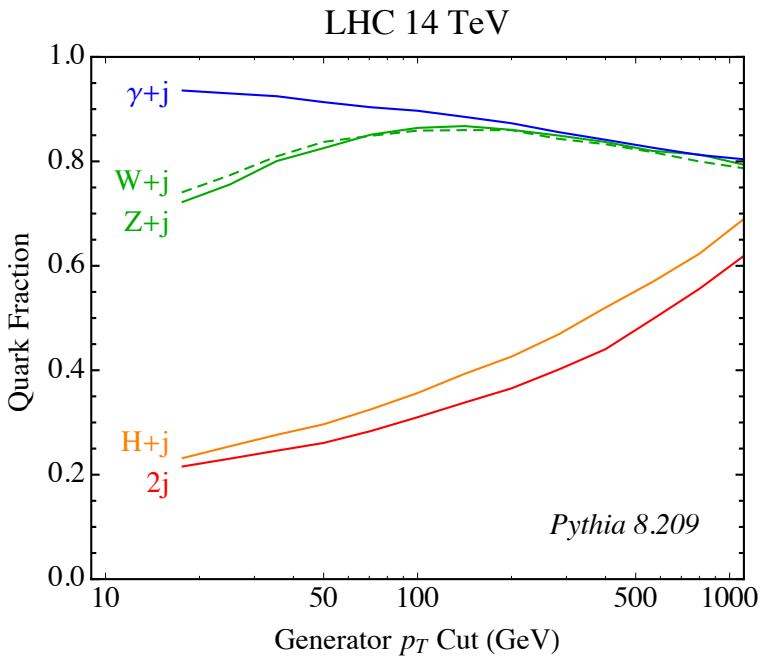
- Study the β dependence (already at LEP)
- Can we get more constraints from the LHC?
- Can we get more constraints from the future e^+e^- colliders?

Also, we want improved analytic calculations

Prospects at the LHC

MC tuning and q/g separation at the LHC

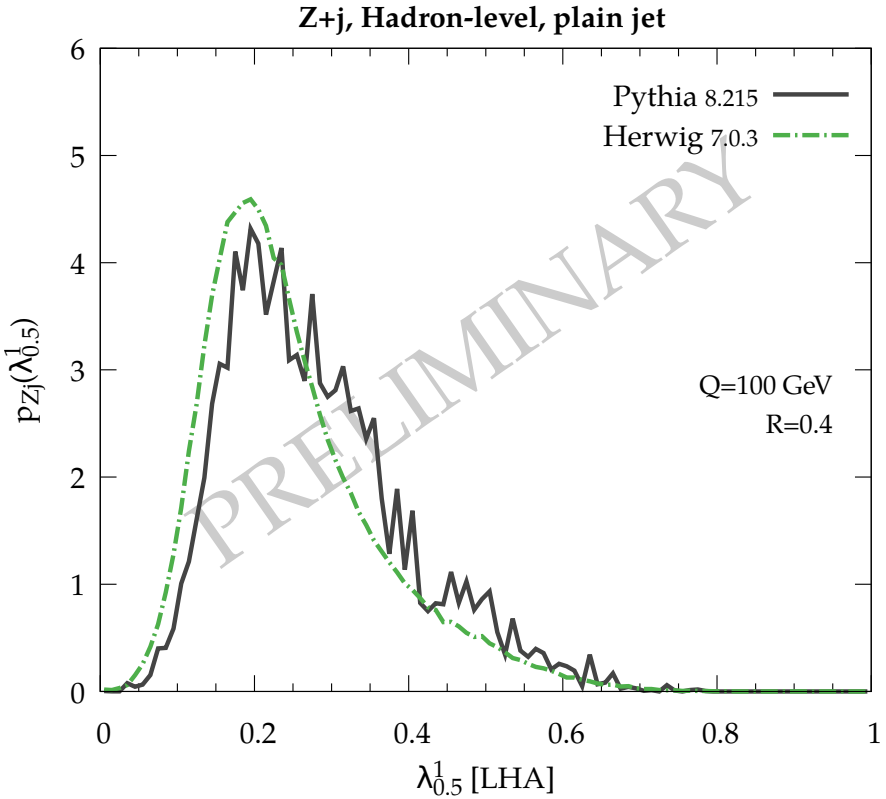
- Genuine "physical" cross-section measurements
- No inversion back to q/g
- Selected
  - Z+jet (quark-enriched)
  - dijets (gluon-enriched)
- Wishlist
  - $p_{t,jet}$ and R dependence
  - β dependence
  - grooming (mMDT/SoftDrop)



(Very) preliminary results

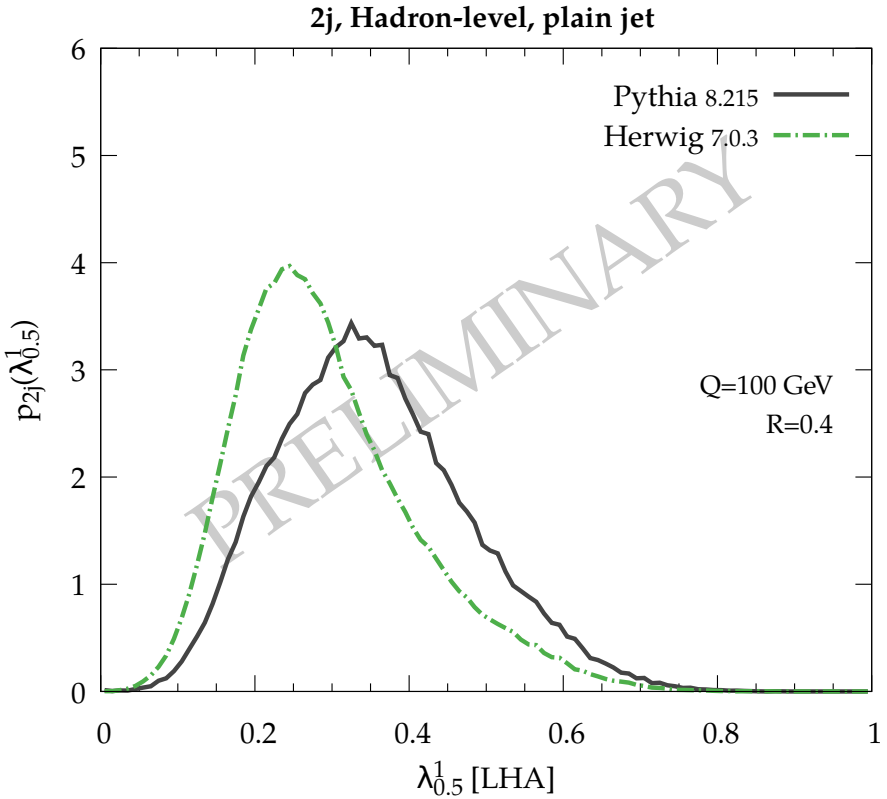
Distributions:

$pp \to Z$+jet



decent agreement

$pp \to$dijets

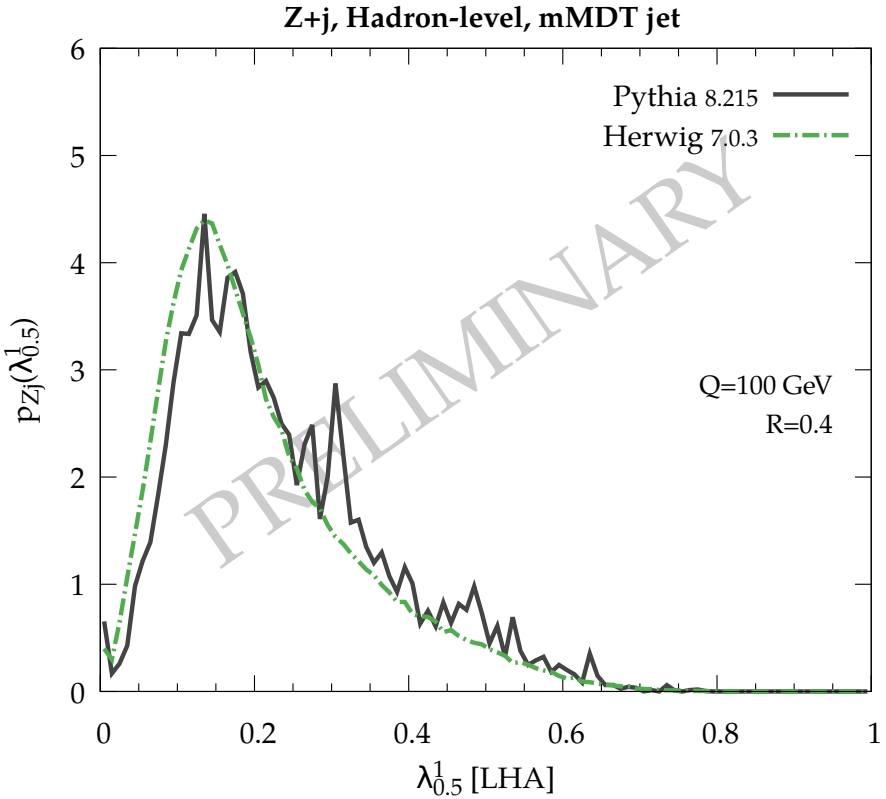


larger differences

(Very) preliminary results

Distributions with mMDT:

$pp \to Z$+jet



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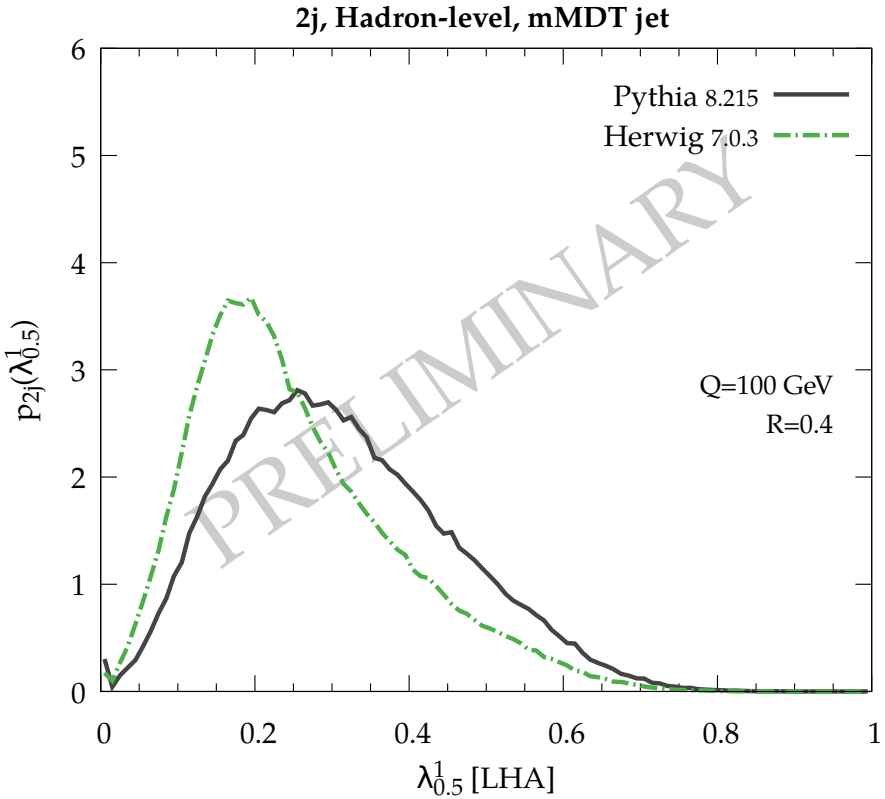
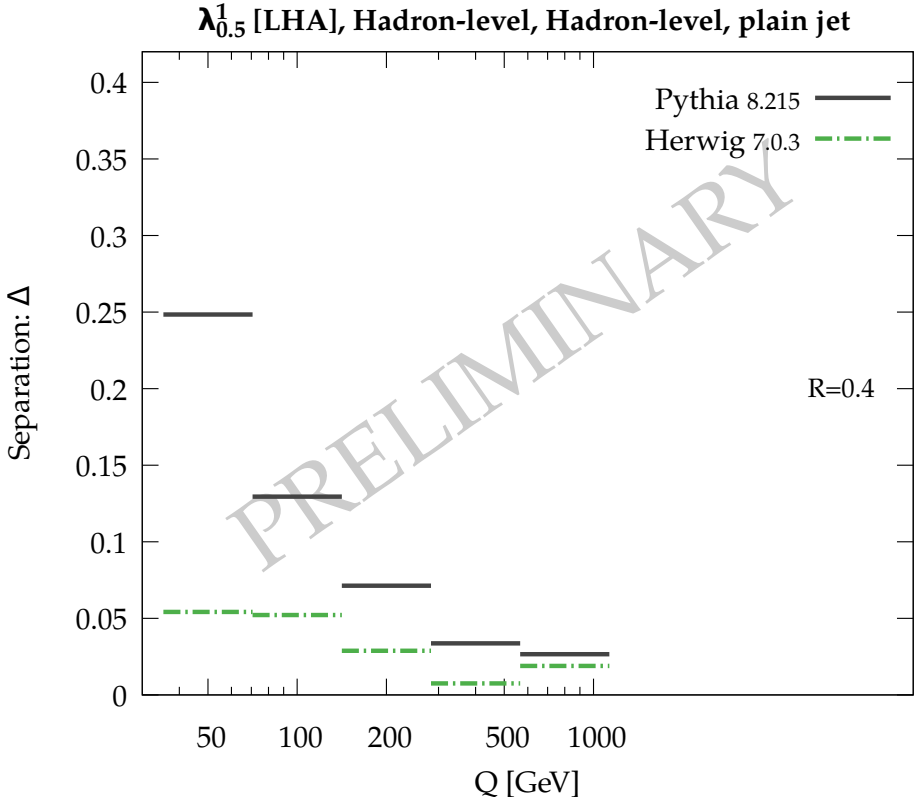


larger differences

(Very) preliminary results

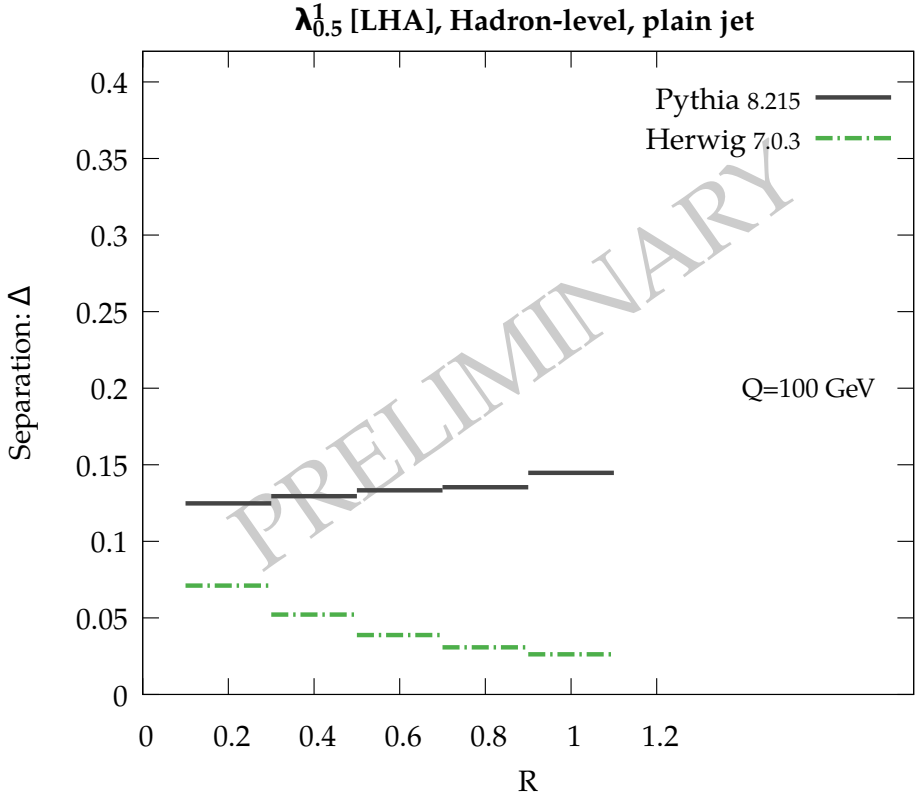
Distributions with mMDT:

separation vs. p_t



Pythia more optimistic

separation vs. R



Opposite trends

Looking forwards to a FCC-ee

A few generic ideas

WANTED: a clean sample of "gluon-enriched" jets

Possible processes of interest:

- bbg (i.e. b-jet, b-jet, jet)
- HZ with $Z \to \ell^+\ell^-$ and $H \to gg$

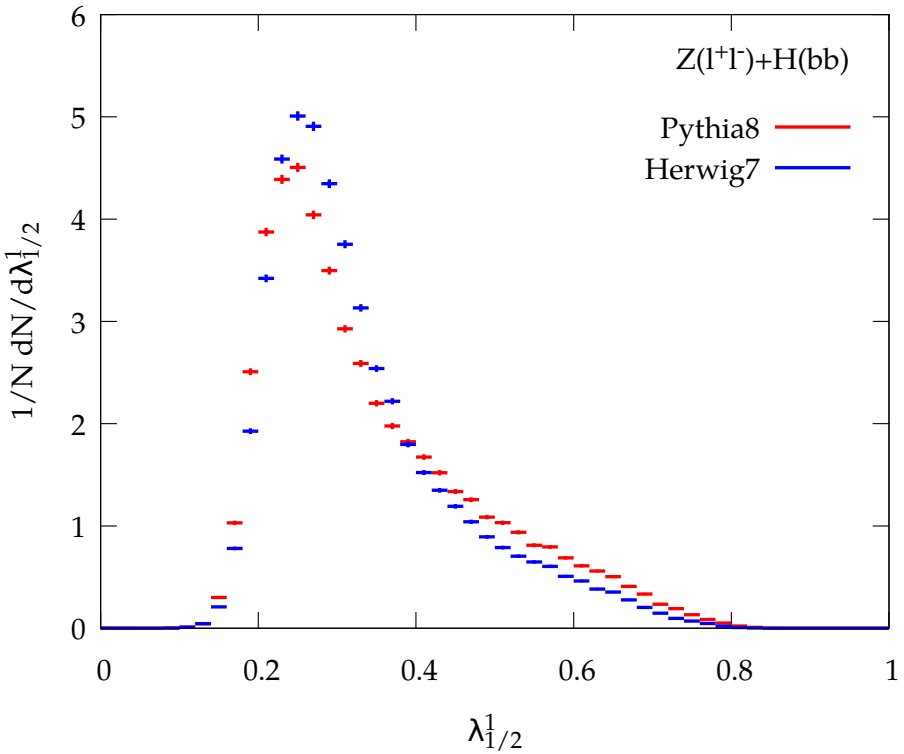
Notes:

- also increased precision compared to LEP
- still room for studies using LEP data

Example: HZ events at $\sqrt{s} = 240$ GeV

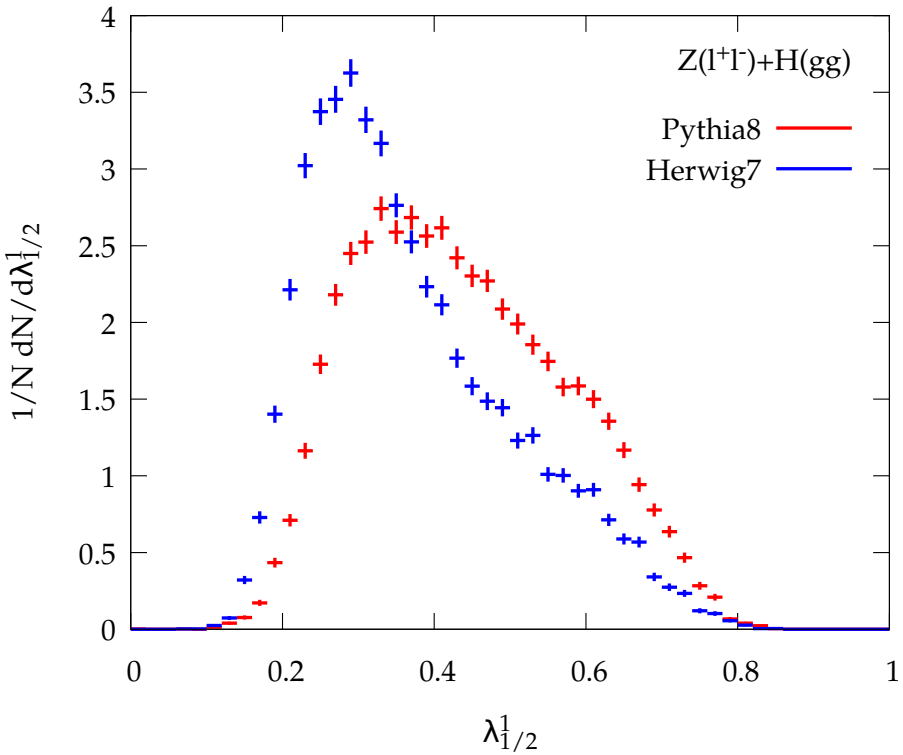
$Z \to e^+e^-/\mu^+\mu^-$, $|m_{\ell\ell} - M_Z| < 20$ GeV, $|m_{jj} - M_H| < 15$ GeV.

$H \to b\bar{b}$



decent agreement

$H \to gg$

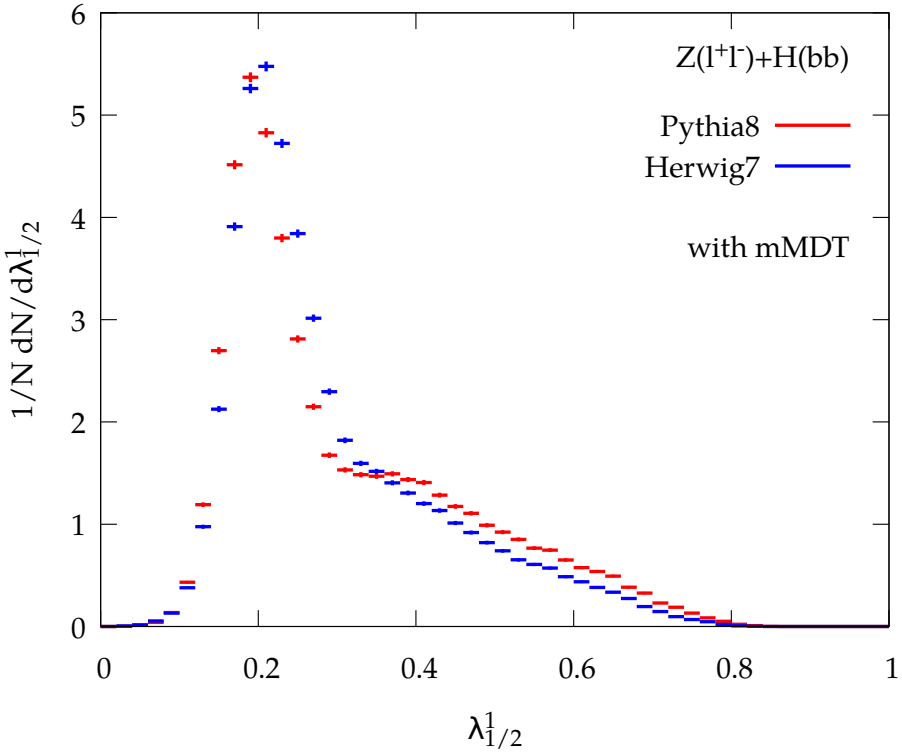


larger differences

Example: HZ events at $\sqrt{s} = 240$ GeV

Works also after applying the (modified) MassDrop (small angle)

$H \to b\bar{b}$



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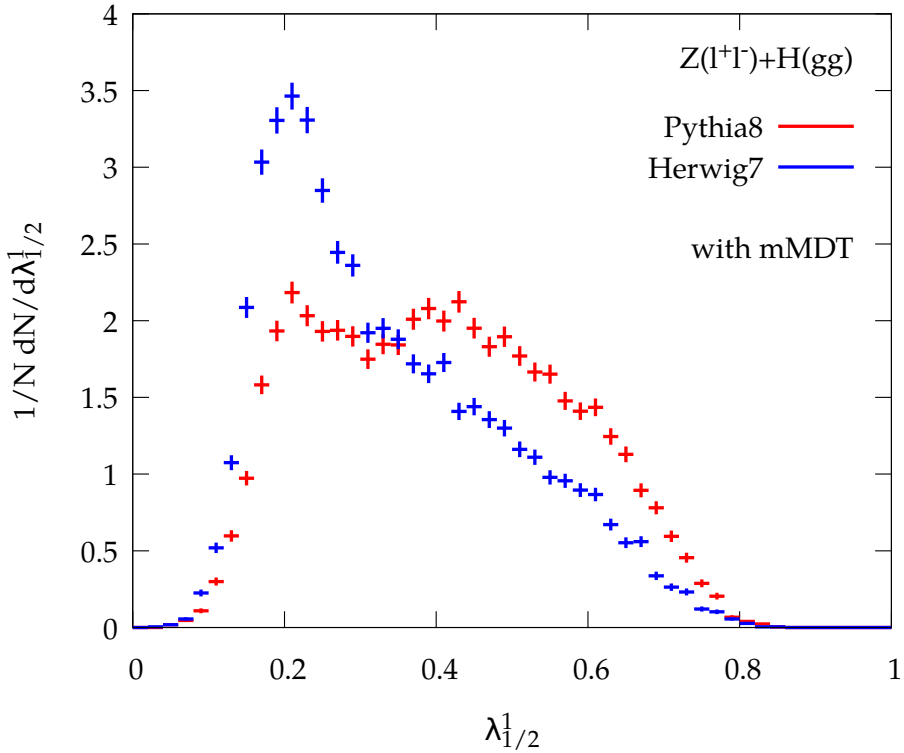

larger differences

Conclusions

- q/g discrimination has exciting physics applications
- How well this can be done is still not fully clear
- Three studies:
  - Simple ee tests: compare different generators
    - more spread for gluons than for quarks
    - Strong sensitivity to NP effects
    - details unclear in the shower
  - Prospects for LHC: constraints from measured cross-sections
  - Prospects for FCC-ee: potential to get cleaner constraints