Improving the Simulation of Quark and Gluon Jets with Herwig 7

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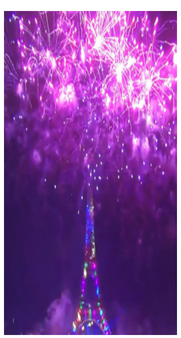
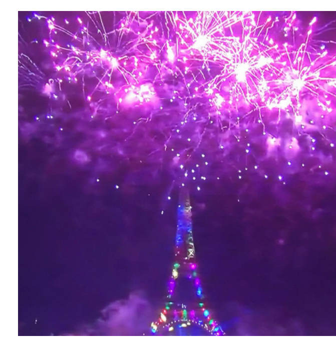
MCnet





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Outline

1. Motivation and definitions

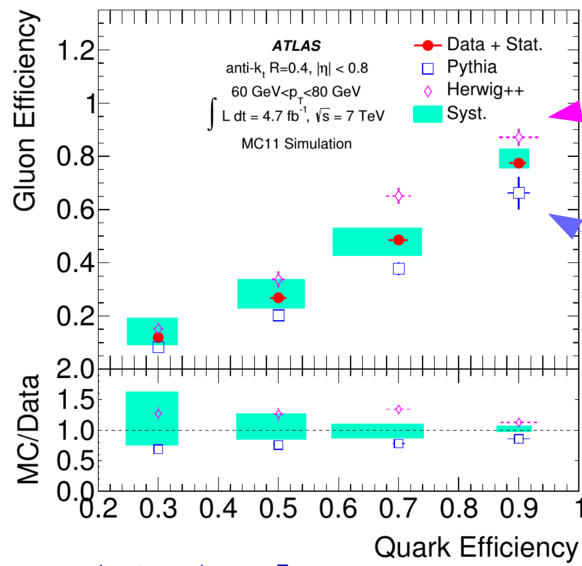
2. How we improved the q/g jets simulation in Herwig 7

   [D. Reichelt, P. Richardson, AS, Eur.Phys.J. C77 (2017) no.12, 876]

3. Outlook

Motivation - LHC Q/G jet measurements

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



Herwig++ Quark and gluon jets looks more the same than in the data.

In Pythia 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

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

Cartoon:

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

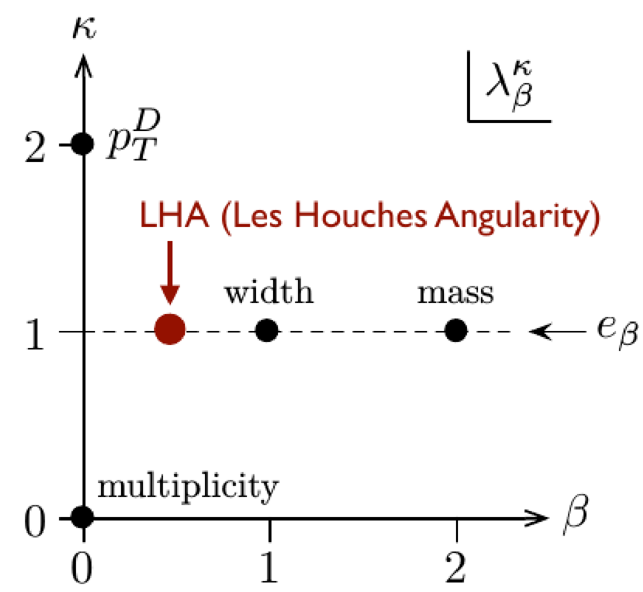
Probe radiation pattern with
e.g. Generalized Angularities

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

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]

Motivation - Idealized case of e+e- [Les Houches]

[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)

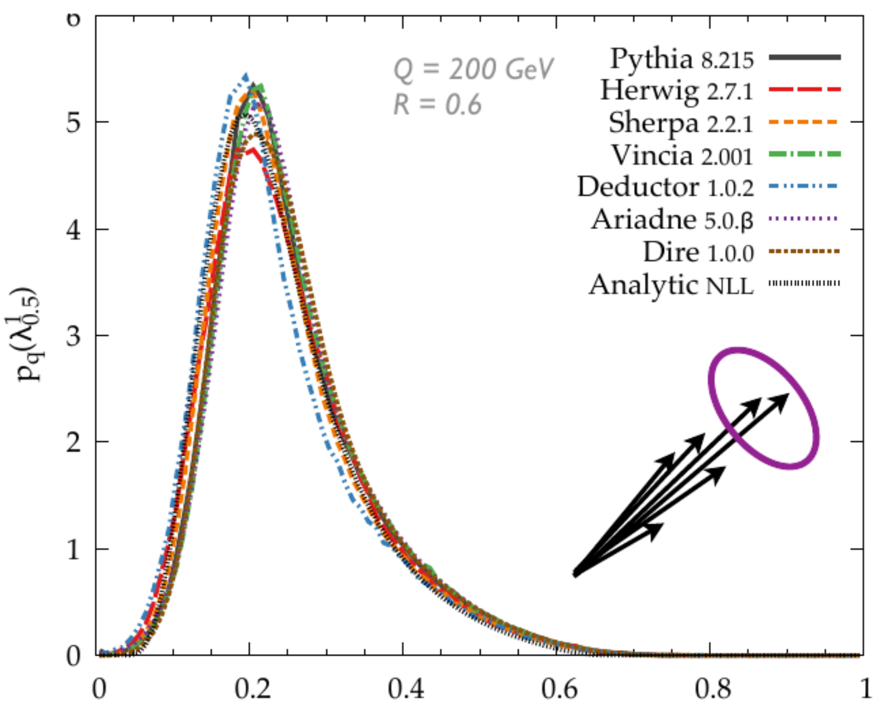
Additionally different Parton Shower algorithms

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

LHA – Idealized Quark/Gluon distributions

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

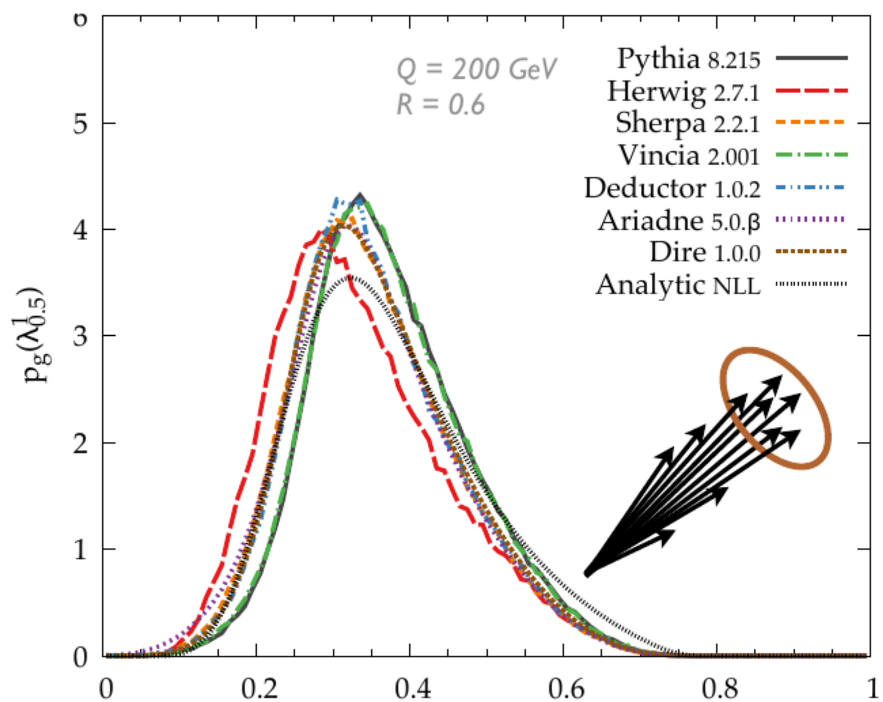
$e^+e^- \to$ quarks ($C_F = 4/3$) vs. $e^+e^- \to$ gluons ($C_A = 3$)



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

Small spread

Constrained by LEP



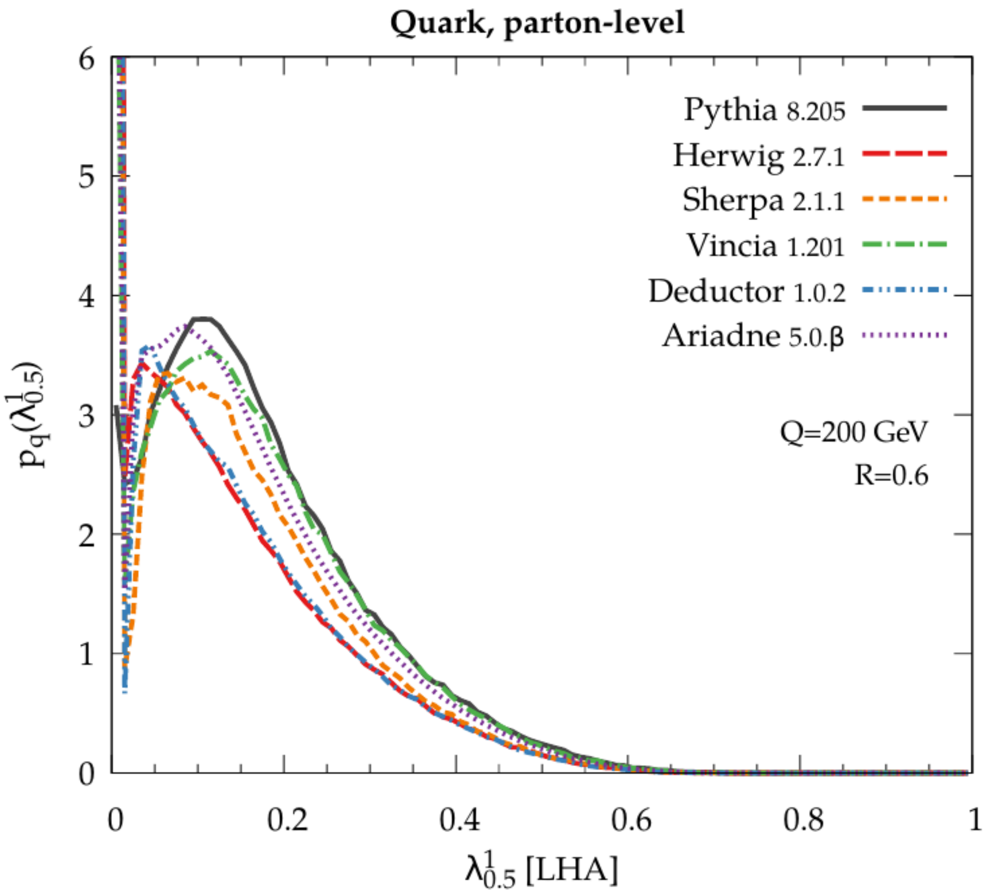
$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Large spread

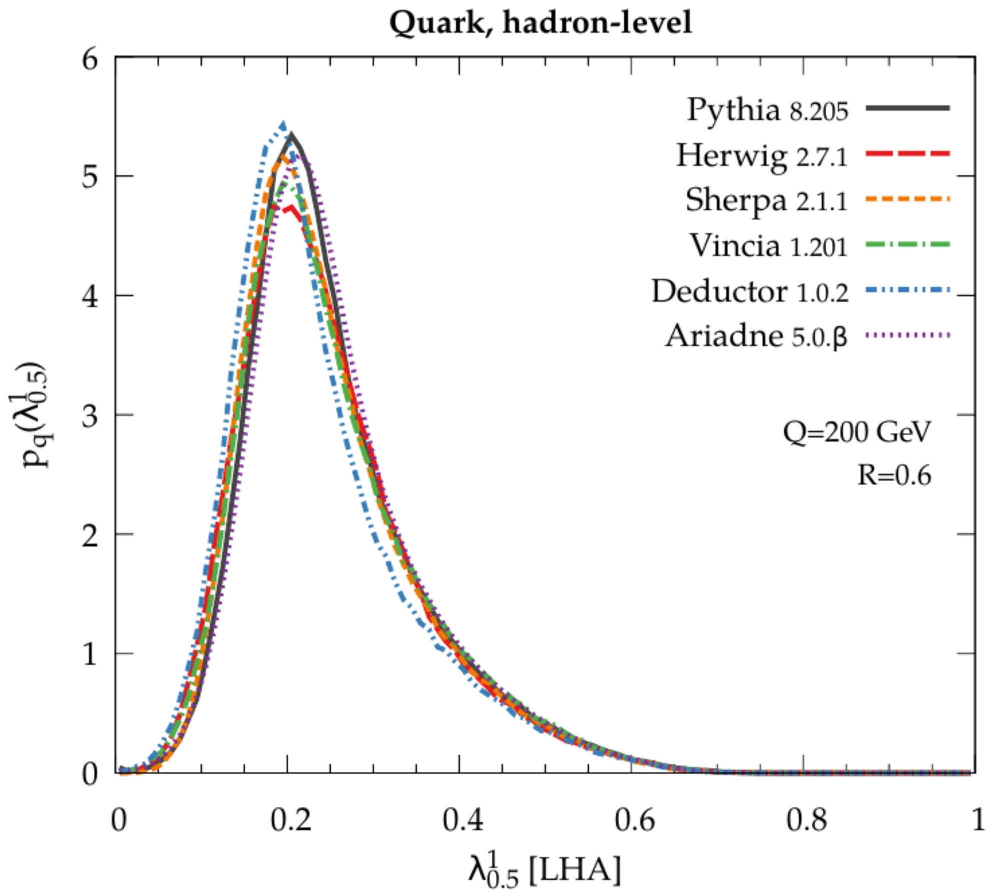
Up to now no e+e- data has been used to constrain it.

Separation power – non-perturbative effects

Parton level



Hadron level



Large hadronisation effects (here for quarks)
Large differences between MCs also seen at parton level.
Interplay of perturbative and non-perturbative (NP) effects => challenge for both pQCD and NP models

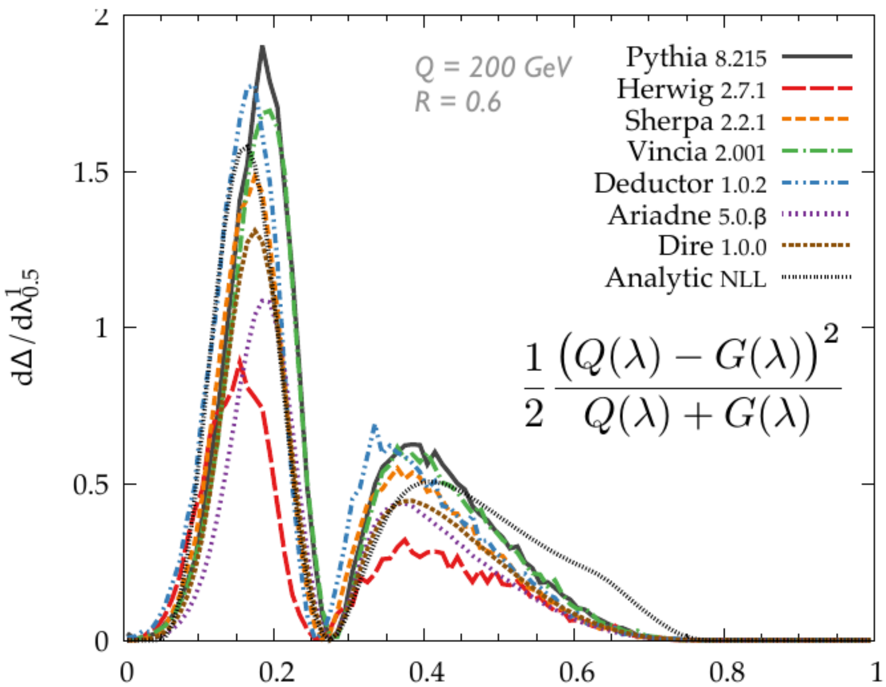
LHA – Separation power

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

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

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

Differential

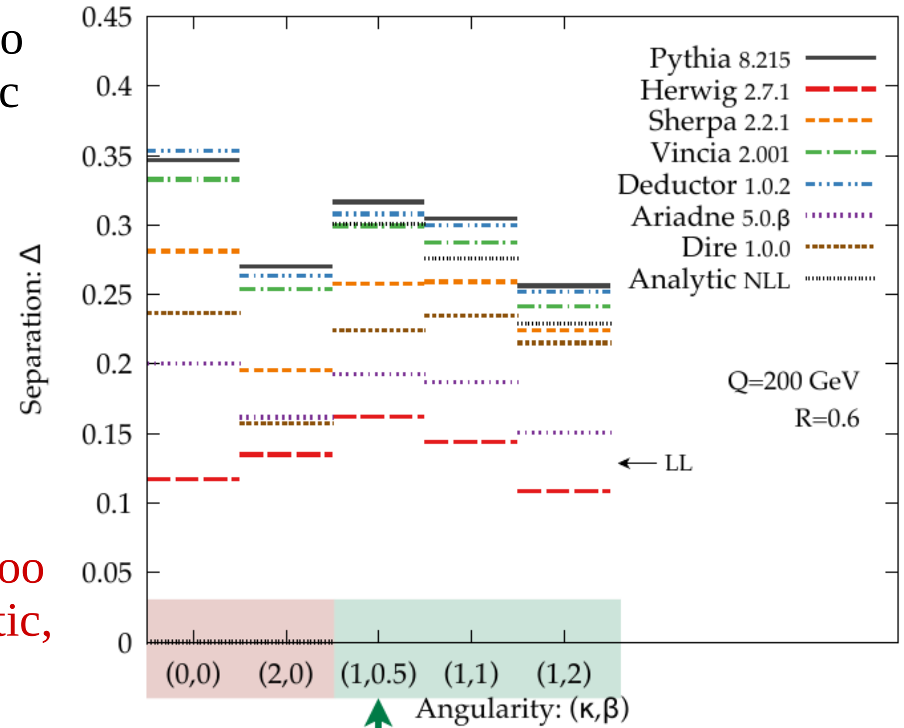


$$\text{LHA} = \sum_i z_i\sqrt{\theta_i}$$

Integrated Values

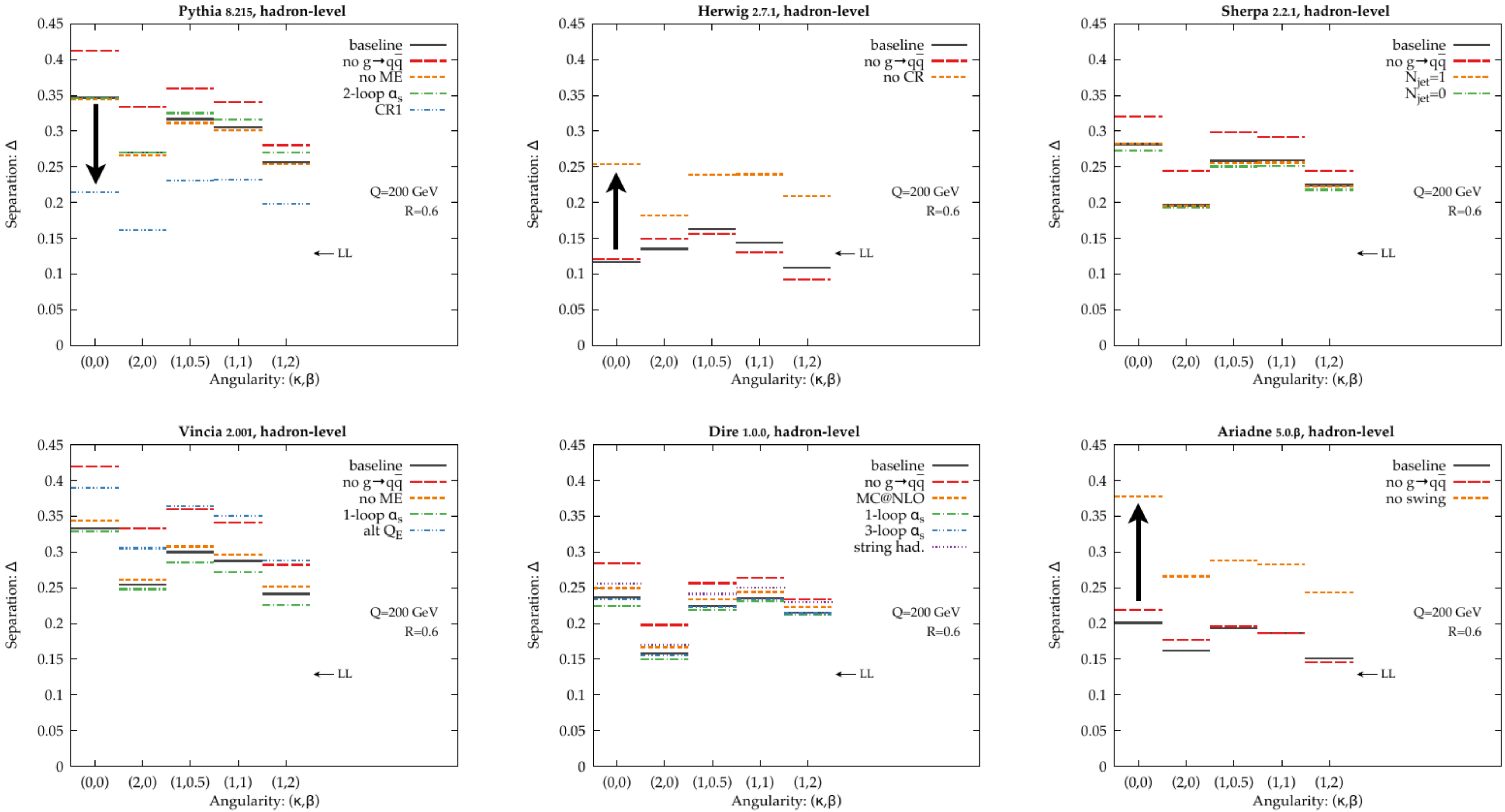
Pythia too optimistic

Herwig too pessimistic,



Affects both IRC unsafe and IRC safe observables

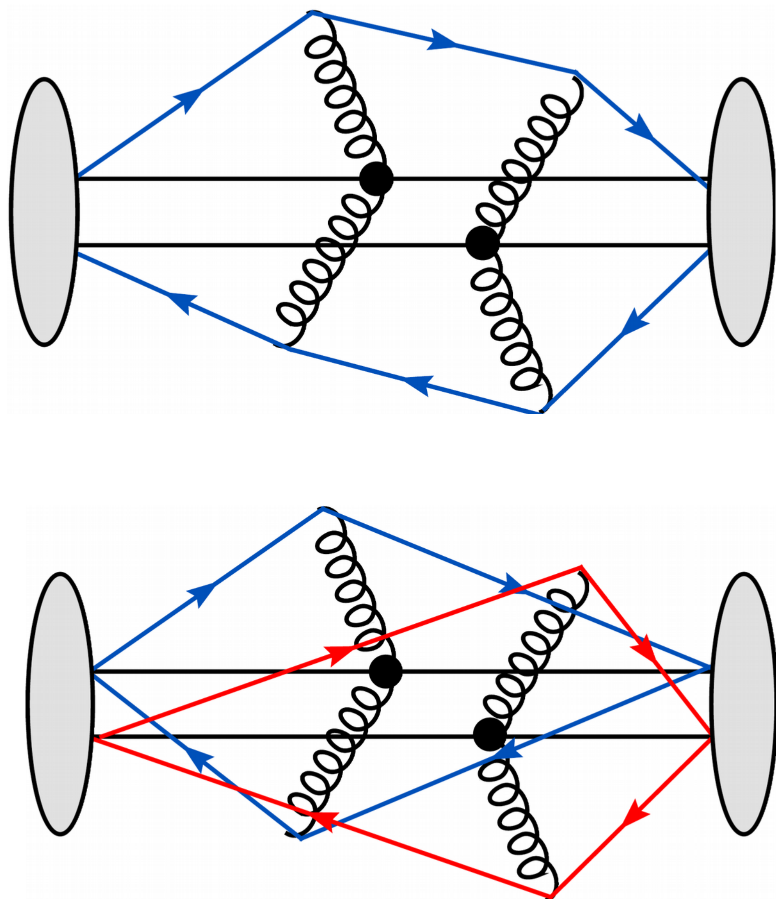
Separation power – sensitivity to MC options

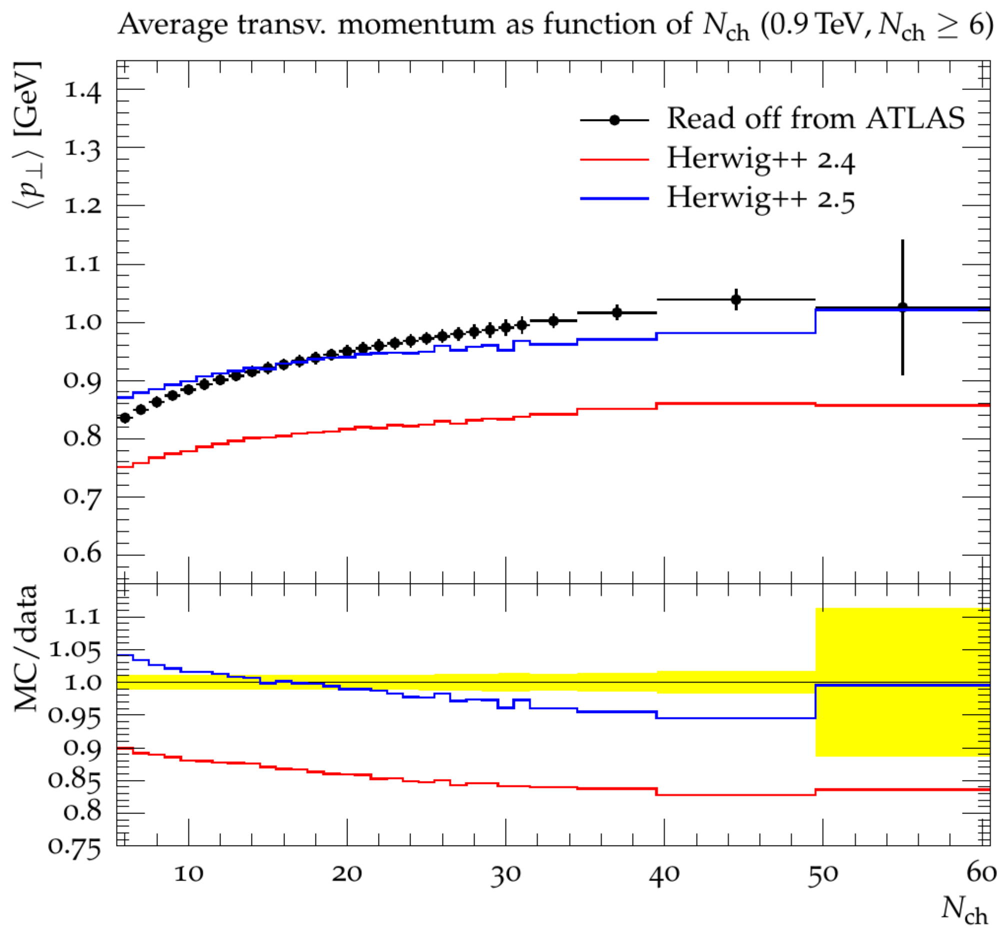


Huge effect of color reconnection – very unexpected!

Colour reconection

- 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, ...





In fact it was tasted against LEP data and had small effect on all observables which we tested.

[D. Reichelt, P. Richardson, AS, arXiv:1708.01491]

Strategy:

Data has not previously been used for tuning. Now available in Rivet!

1. Search for the LEP and LHC data sensitive to gluon jets.
   - Data on gluon jets in e+e−collisions from the OPAL experiment [G. Abbiendi, et al.,: Phys.Rev.D69, 032002 and Eur. Phys. J. C37 (1), 25 (2004)]
   - In pp collisions from ATLAS [G. Aad, et al., Eur. Phys. J. C76 (6), 322 (2016)]
2. Improve the non-perturbative color reconnection model.
3. Improve the perturbative Parton Shower kinematics.

Herwig – Jets

Perturbative (soft-collinear app.) - Parton shower

Some (more or less clever) choices still to be made:

1) Evolution variable: angle (soft limit).

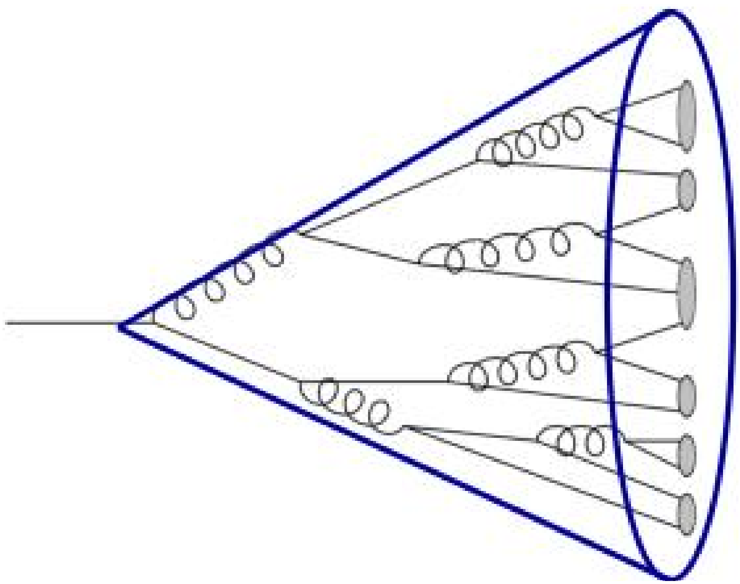
2) Choice of minimal scale.

3) Kinematics reconstruction.

Non-perturbative – Cluster hadr.

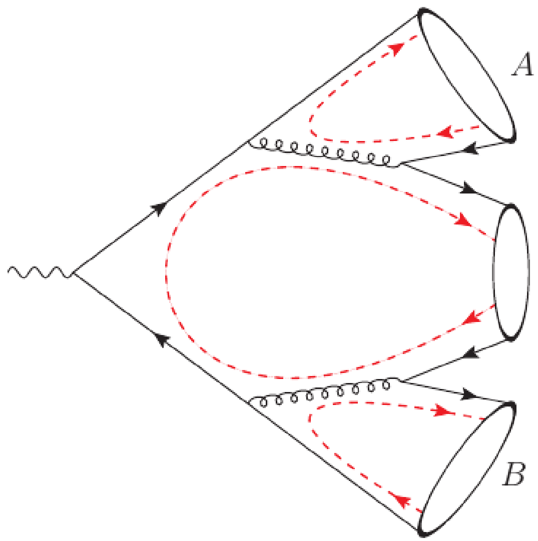
- PS provides colour pre-confinement

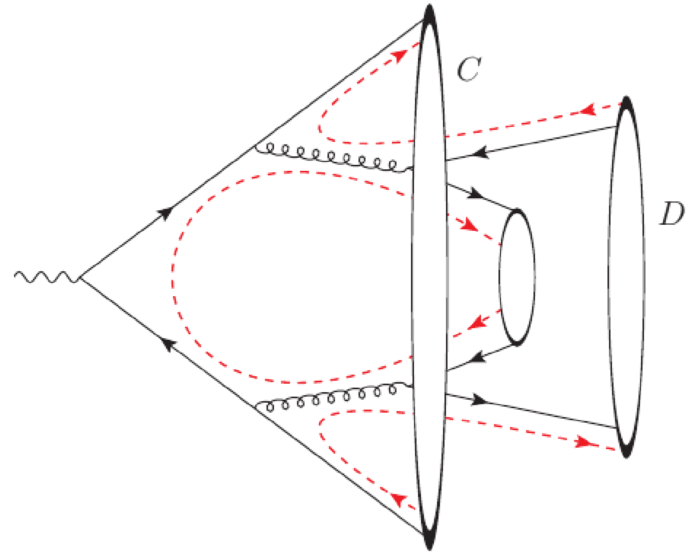
- colour-singlet pairs end up close in phase space



Herwig – Colour reconection

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





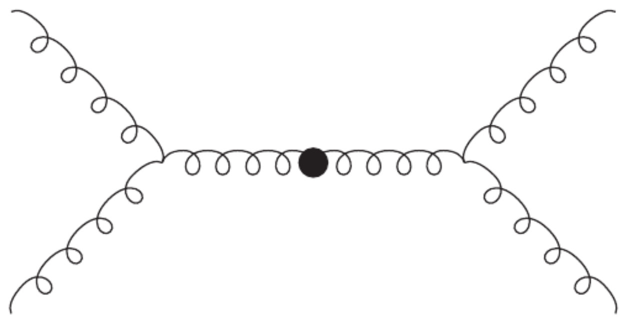
- perturbative QCD provides *preconfinement* [Amati, Veneziano, Phys. Lett. B83 (1979) 87]
- i.e. small cluster masses $M_{\text{cl}} \gtrsim M_{\text{parton 1}} + M_{\text{parton 2}}$

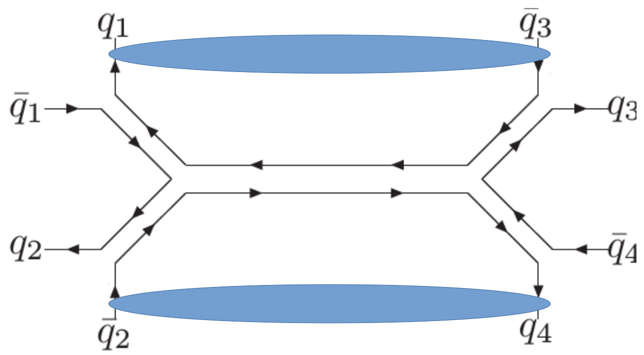
- improved description of soft events/UE at hadron colliders: manually reduce cluster masses
- if $M_C + M_D < M_A + M_B$ accept alternative clustering with probability p_{reco} (model parameter)

[Gieseke, Rohr,AS Eur.Phys.J. C72 (2012) 2225]

Herwig – Improvements of Color reconection

- However, it's 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 of the original gluons, i.e. $q_1,\bar{q}_3$ and $q_4,\bar{q}_2$, will have large masses, clusters $q_1,\bar{q}_2$ and $q_4,\bar{q}_3$ will be kinematically favoured $\Rightarrow$ original gluons will effectively become colour singlets rather than octets.

Herwig – Improvements of Color reconection

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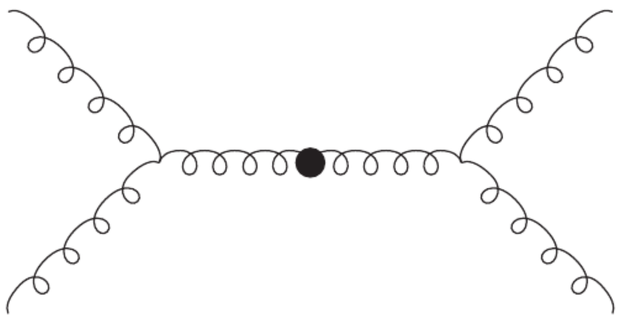
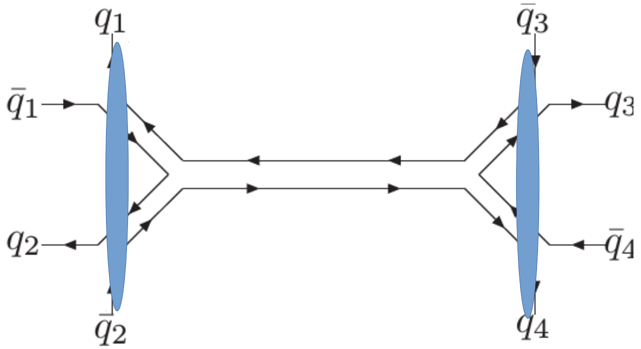


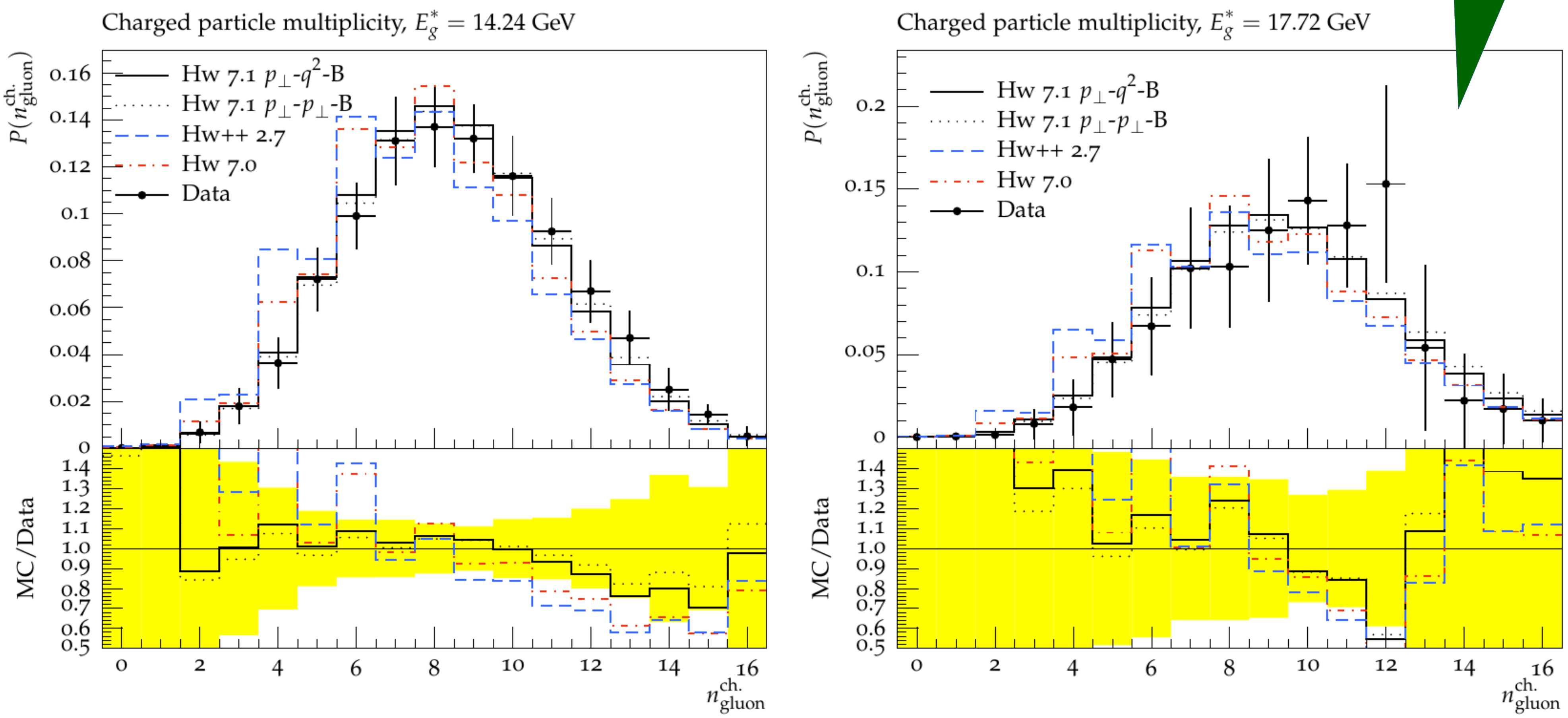


- Clusters of the original gluons, i.e. $q_1,\bar{q}_3$ and $q_4,\bar{q}_2$, will have large masses, clusters $q_1,\bar{q}_2$ and $q_4,\bar{q}_3$ will be kinematically favoured ⇒ original gluons will effectively become colour singlets rather than octets.
- It occurs at a rate which is suppressed as $1/N_C^2=1/9$, 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.

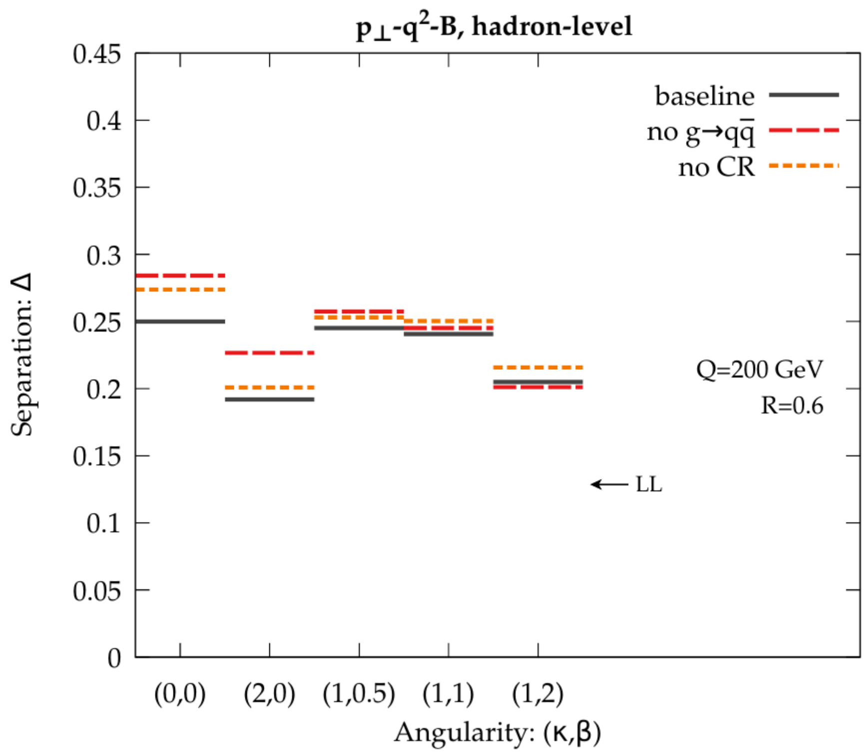
OPAL

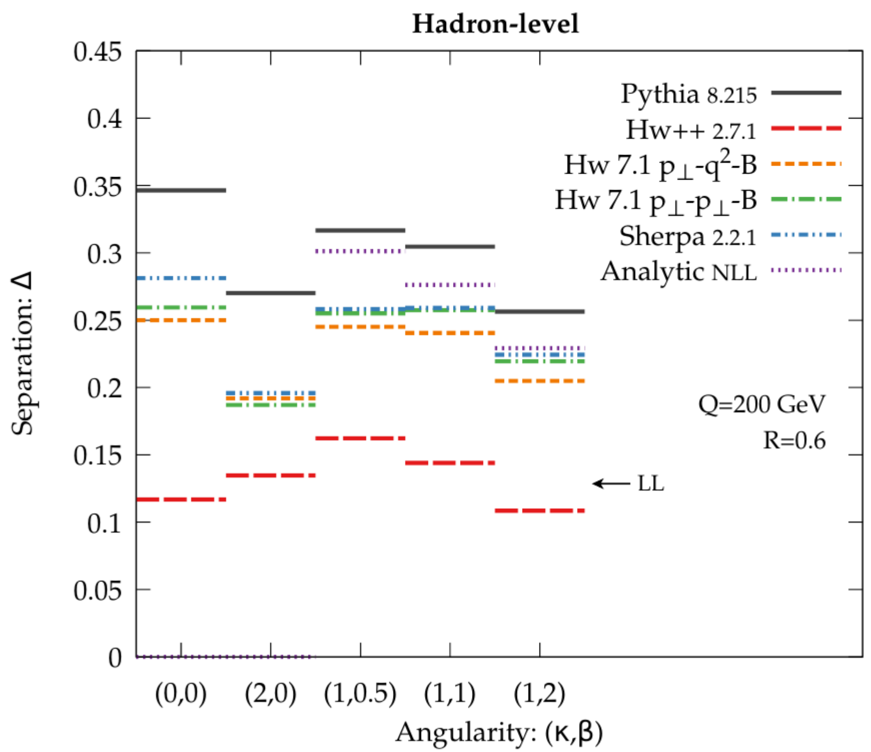
Data which has not previously been used for tuning.

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



Idealized Quark/Gluon distributions





- Sensitivity to CR is gone especially for IRC safe observables – as expected.

- Herwig is now more optimistic when it comes to distinguishing q/g jets.
- Spread of predictions is reduced.

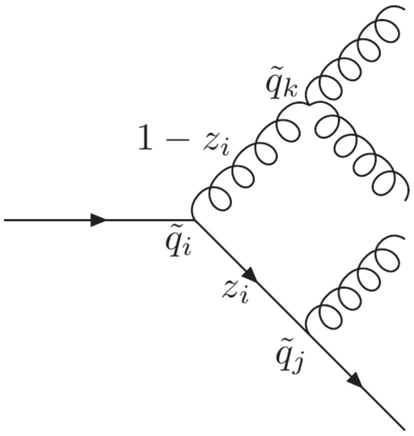
Kinematics reconstruction:

- Formally subleading but can have a large effect on physical observables, see for example
  "Momentum conservation and unitarity in parton showers and NLL resummation"
  [S. Höche, D. Reichelt, F. Siegert JHEP 1801 (2018) 118]

One emission:

the virtuality of the parton i:

$$q_i^2 = \frac{p_{Ti}^2}{z(1-z)} + \frac{m_j^2}{z} + \frac{m_k^2}{1-z}$$



Multiple emissions:

When there is more than one emission, different variants are available to reconstruct the kinematics. We must decide which properties of the originally generated kinematics to preserve once the masses of j and/or k in are no longer on-shell but the virtualities generated by any subsequent emissions.

Note:
Study of two emissions in the dipole shower – recoil problem?
[M. Dasgupta, F. Dreyer, K. Hamilton, P. Monni, G. Salam 1805.09327]

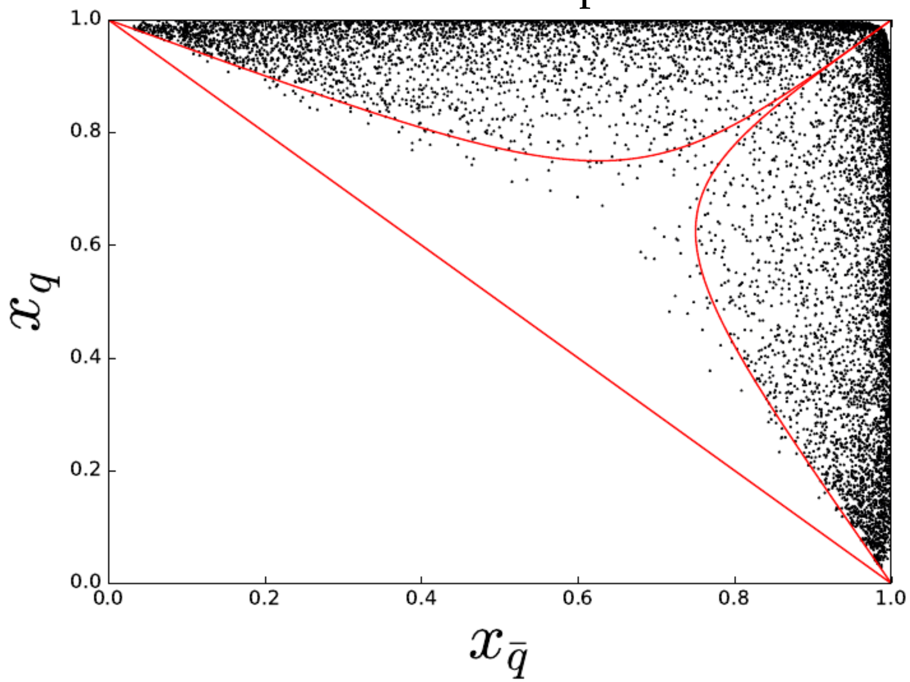
Herwig – Parton Shower kinematics

We investigated:

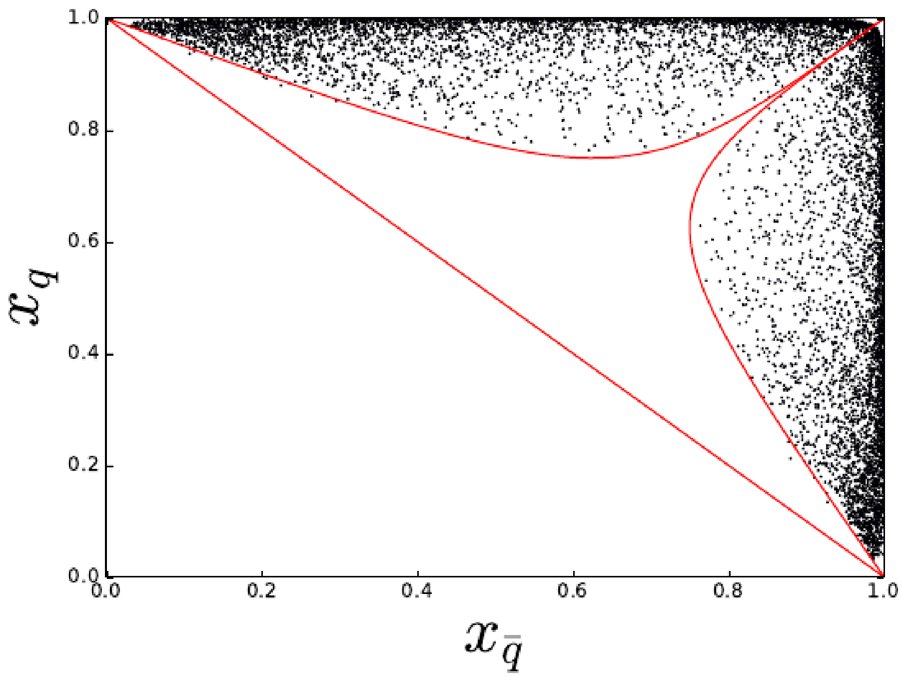
- **Minimal scale**: **pt** and **q cut-off**.
- **Kinematics reconstruction**:
  - **pt preserving**, requires the pt of each splitting to have the same value as was calculated when the children were on shell.
  - **q2 preserving**, in which the virtuality of an intermediate state is preserved by reducing pt, or set it equal to zero if not possible.

Dalitz plot for $e^+e^- \to q\bar{q}$ after multiple emission from the quark and antiquark.

Preserve pT



Preserve virtuality q^2



$x_i = 2E_i/Q$ where E_i is the energy of parton i and Q is the centre-of-mass energy

Tuning

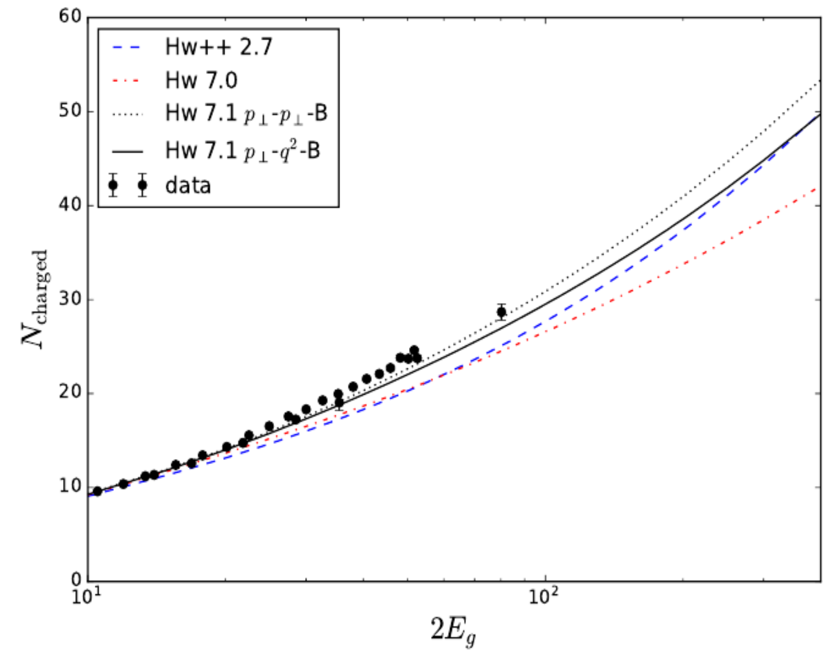
Unfortunately, when the PS is changed we need to retune the hadronization model:

Summary of tunes for different PS options.

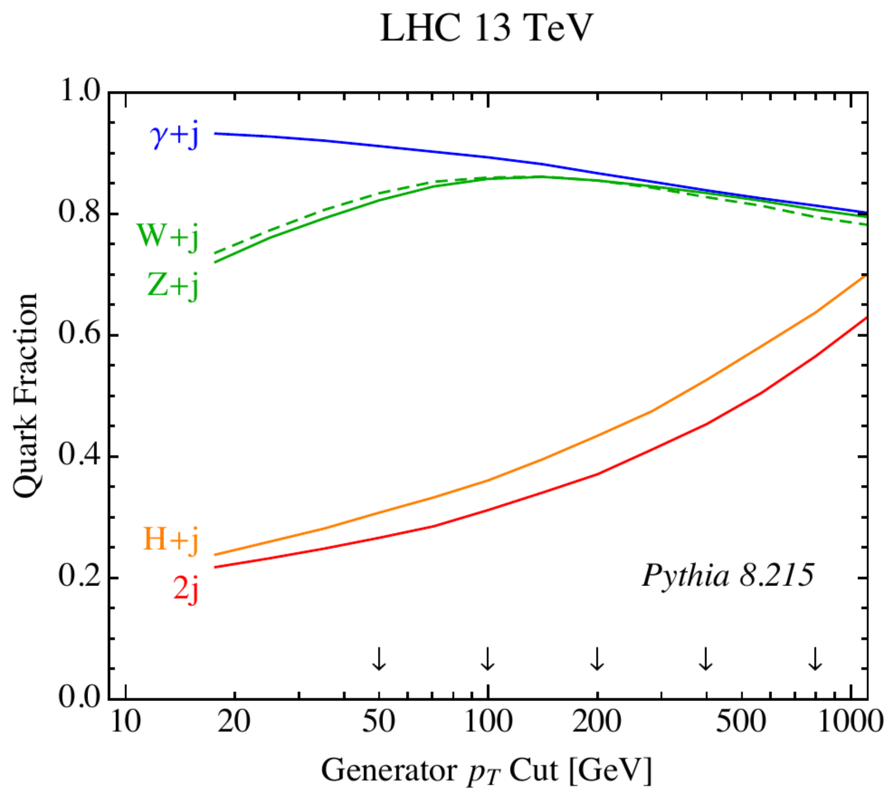
Cut-Off	$p_\perp$		Virtual Mass	
Preserved Tune	$p_\perp$ B	q^2 B	$p_\perp$ B	q^2 B
Tuning Observables				
Light quarks	4.3	2.9	7.6	4.3
Charm quarks	2.8	3.5	4.6	3.9
Bottom quarks	3.4	4.9	3.3	4.1
Gluons	1.1	1.1	1.2	1.2
N_{charged}				
Gluon	18.6	37.1		
All quarks	2.7	2.5		
Light quarks	1.7	1.8		
Charm quarks	2.0	1.6		
Bottom quarks	18.1	21.3		
ATLAS Jets	0.9	10.1		

χ'^2

- the data on light quark jets, in particular event shapes measured at LEP favour preserving q^2 the data on the charged particle multiplicity in gluon jets favours preserving the pT of the branching.



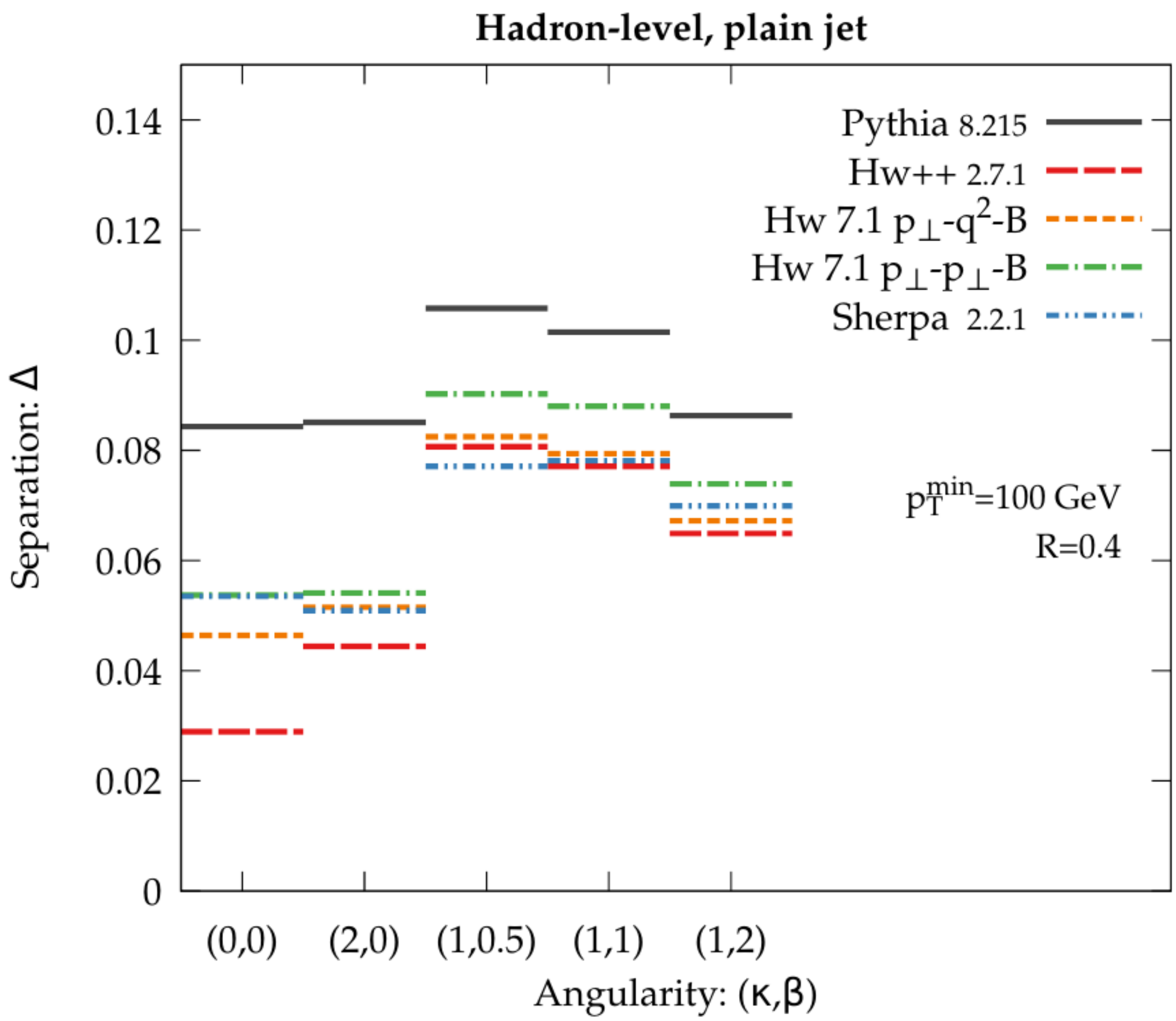
Evolution of # charged particles in gluon jets vs twice the energy of the gluon jet.



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

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

LHC



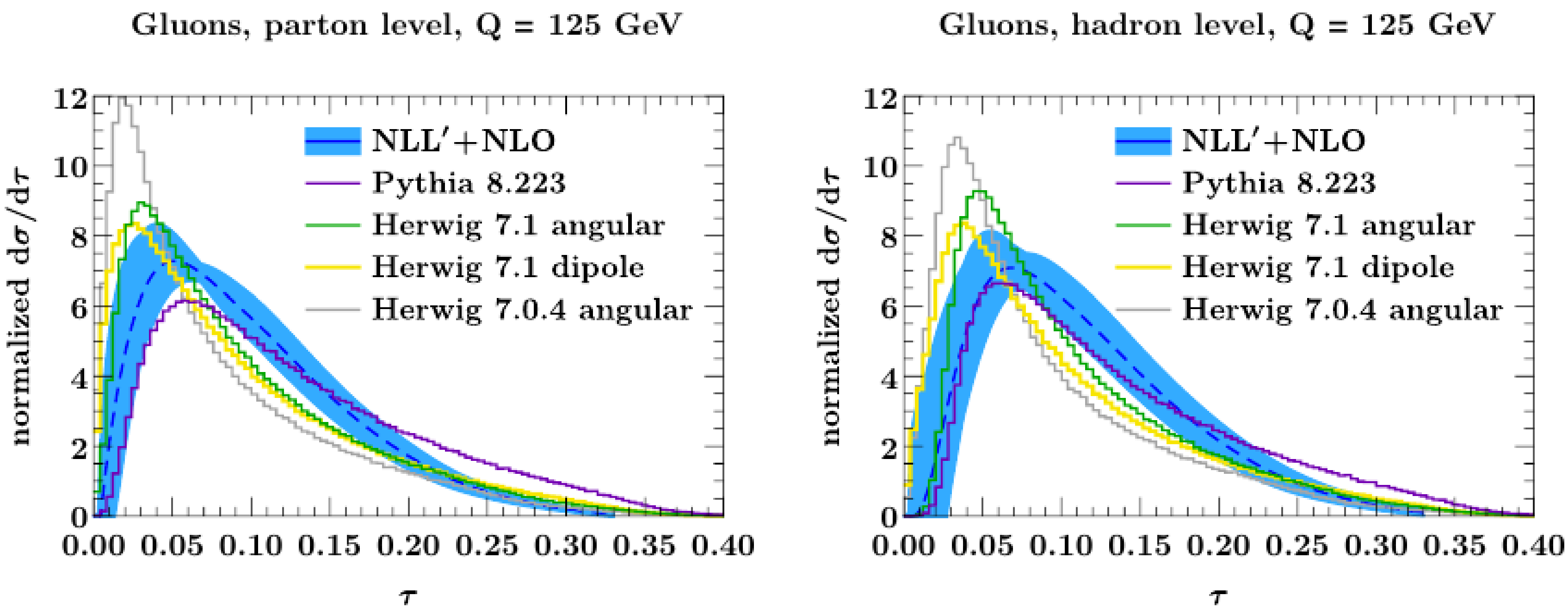
- Improvements of Herwig led to better discrimination power at the LHC (interesting would be to check against more q/g data, however most of them are not available to us ...).
- Spread of prediction reduced especially for IRC unsafe observables
- Parton Shower Uncertainties? [Bellm, Nail, Plätzer, Schichtel, AS Eur.Phys.J. C76 (2016)]

Comparison with a recent resummation results

"A case study of quark-gluon discrimination at NNLL in comparison to parton showers"
[J. Mo, F.Tackmann, W. Waalewijn, 1708.00867]

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"

Summary and outlook

1. The properties of quark and gluon jets, and the differences between them, are increasingly important at the LHC, see Ben's talk on alpha_s.

2. Quark jets well constrained by the LEP data, this was not the case for gluon jets.

3. We have performed a tuning the Herwig 7 event generator using data on gluon jets from LEP for the first time.

4. Improvements of perturbative and non-perturbative aspects of the simulation led to significantly better description of gluon jets, in particular their charge particle multiplicity.

5. However still there is a tension between the data on charged particle multiplicities, for both quark and gluon initiated jets, and the data on event shapes and particle spectra from LEP.

6. The tension might be resolved by improvements of the non-perturbative hadronization modelling and more detailed studies on the recoil in PS.

7. New ideas on how to measure observables sensitive to Q/G jets

MCnet Short-term studentships

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training studentships

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Application rounds every 3 months.

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MC*net* projects
Pythia
Herwig
Sherpa
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Ariadne
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Thank you for your attention!

Tuning

Unfortunately, when the PS is change we need to retune the hadronization model which is a big effort.

Cut-Off	$p_\perp$						Virtual Mass					
Preserved Tune	A	$p_\perp$ B	C	A	q^2 B	C	A	$p_\perp$ B	C	A	q^2 B	C
Bottom quark hadronization parameters												
ClMaxBottom		4.655			3.911			4.0612			4.163	
ClPowBottom		0.622			0.638			0.9475			0.590	
PSplitBottom		0.499			0.531			1.9568			1.881	
ClSmrBottom		0.082			0.020			0.04			0.040	
SingleHadronLimitBottom		0.000			0.000			0.0204			0.000	
Charm quark hadronization parameters												
SingleHadronLimitCharm		0.000			0.000			0.078			0.012	
ClMaxCharm		3.551			3.638			3.805			3.885	
ClPowCharm		1.923			2.332			2.242			2.452	
PSplitCharm		1.260			1.234			1.895			1.767	
ClSmrCharm		0.000			0.000			0.000			0.000	
Light quark hadronization and shower parameters												
AlphaMZ ($\alpha_S^{\mathrm{CMW}}(M_Z)$)	0.1094	0.1087	0.1126	0.1260	0.1262	0.1265	0.1221	0.1218	0.1184	0.1314	0.1317	0.1254
pTmin	1.037	0.933	0.809	1.301	1.223	0.992		N/A			N/A	
aParameter		N/A			N/A			0.367			0.234	
cutoffKinScale		N/A			N/A		2.939	2.910	2.294	3.277	3.279	1.938
ClMaxLight	3.504	3.639	4.349	3.058	3.003	3.197	3.328	3.377	3.846	3.414	3.427	3.477
ClPowLight	2.576	2.575	1.226	1.513	1.424	2.786	1.286	1.318	2.063	2.766	2.792	2.35
PSplitLight	1.003	1.016	0.855	0.885	0.848	0.648	1.198	1.185	1.277	1.346	1.333	2.015
PwtSquark	0.552	0.597	1.167	0.602	0.666	1.024	0.721	0.741	0.782	0.626	0.646	1.15
PwtDIquark	0.369	0.344	0.181	0.416	0.439	0.512	0.277	0.273	0.246	0.321	0.328	0.366