Simulation of quark/gluon jets

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MCnet

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Outline

1. Motivation and definitions
2. LH Quark/gluon jets discrimination [Les Houches arXiv:1605.04692]
3. What we have learnt [JHEP 1707 (2017) 091]
4. How we improved the q/g jets simulation in Herwig [arXiv:1708.01491]
5. Outlook

Motivation

BSM searches: often signature for a BSM signals: many quark, backgrounds: QCD gluons

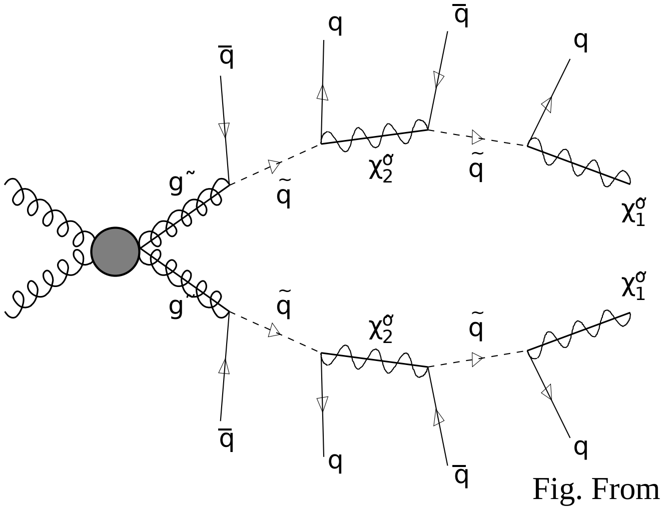
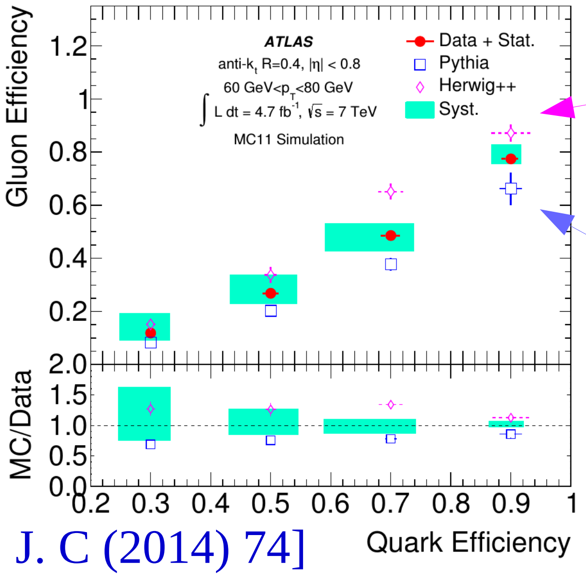


Fig. From J. Gallicchio and M. D. Schwartz, Phys. Rev. Lett.107 (2011)

Problem: Q/G jets LHC data show discrepancy with the predictions from MC generators



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

Pythia too optimistic, Quark and Gluon jets are too similar compared to data.

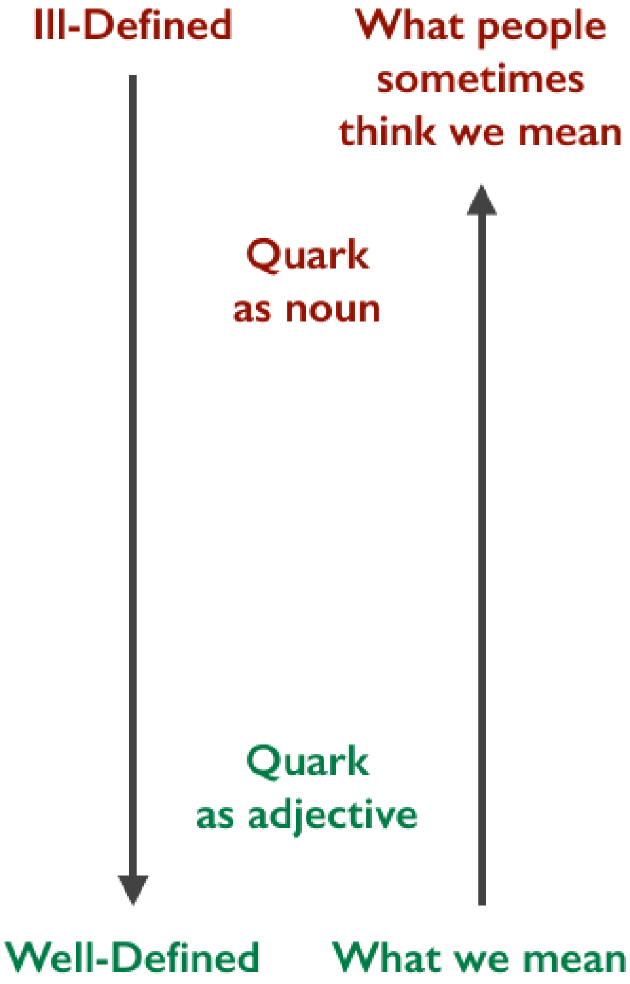
[ATLAS, Eur. Phys. J. C (2014) 74]

Definition

What is a Quark Jet?

From lunch/dinner discussions

[slide by Jesse Thaler]



Ill-Defined

What people sometimes think we mean

Quark as noun

Quark as adjective

Well-Defined

What we mean

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)

Definition

Cartoon:

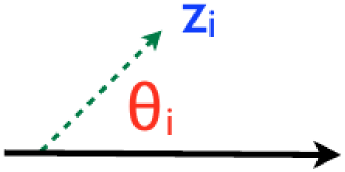
Quark: $C_F = 4/3$ vs. Gluon: $C_A = 3$

Probe radiation pattern with
e.g. Generalized Angularities

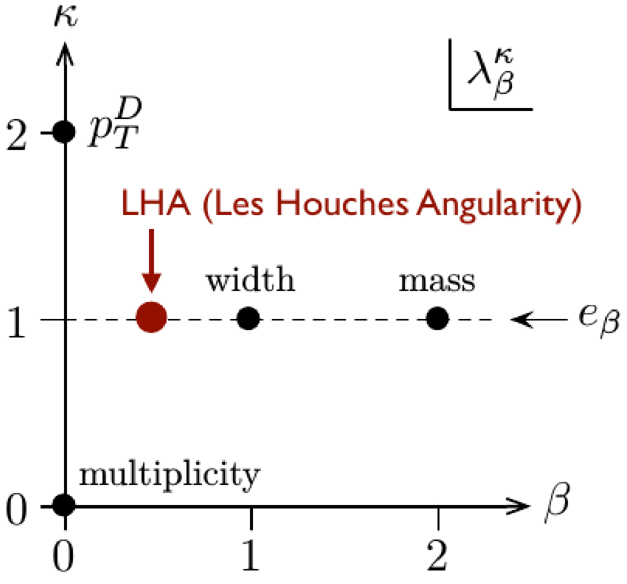
$$\lambda_\beta^\kappa = \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\beta$$

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]

2. Idealized case of e+e- [Les Houches arXiv:1605.04692]

Framework

Processes:

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

Different settings:

- Changing the collision energy Q
- Changing the jet radius R

Different Monte-Carlo generators at parton and hadron level:

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

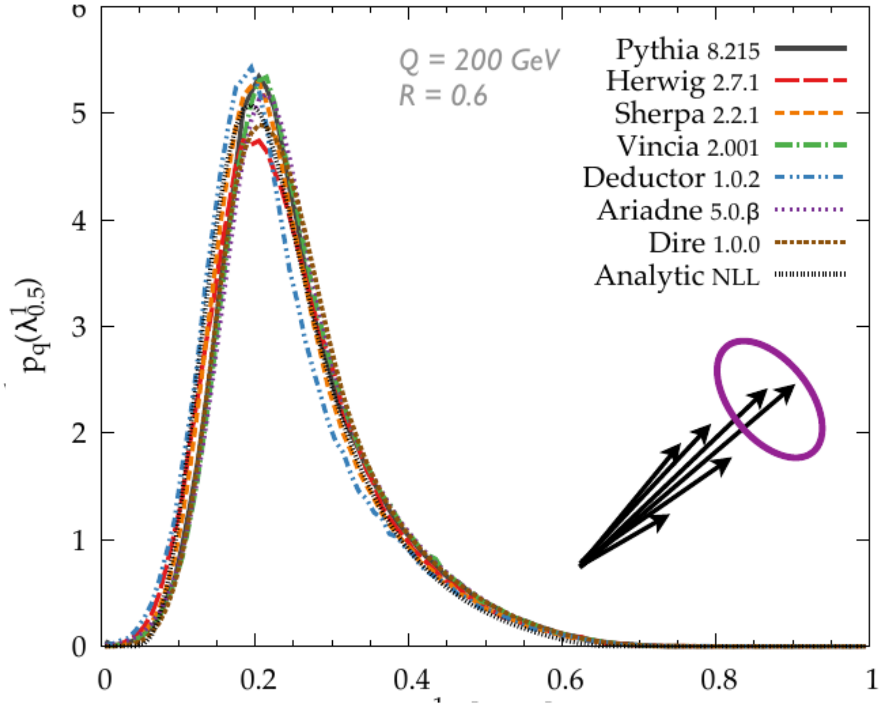
Additionally different Parton Shower algorithms

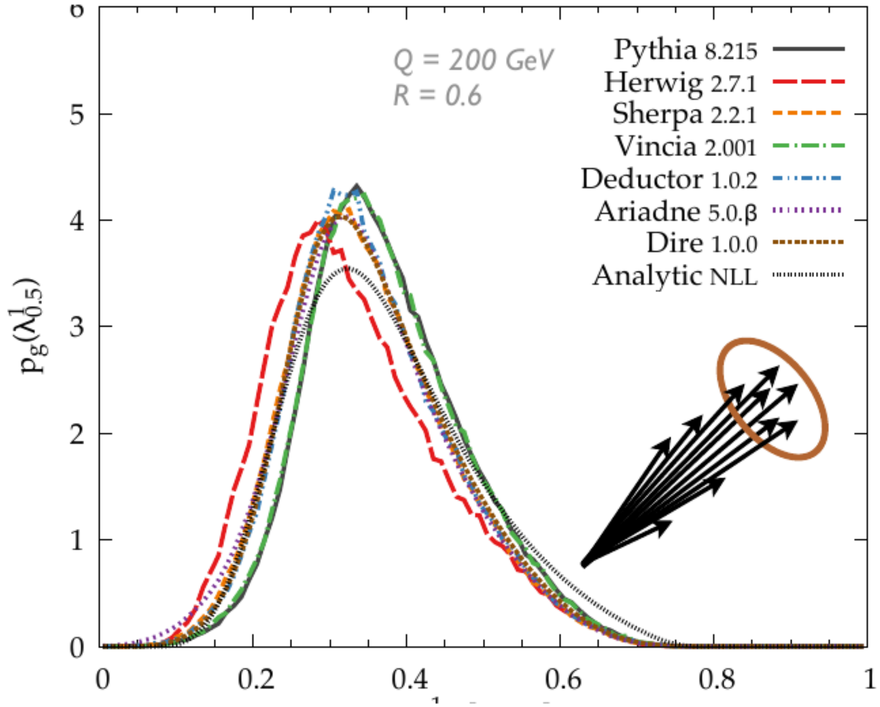
- Vincia (v1.201 - plugin to Pythia)
- Deductor (v1.0.2 + hadronization from Pythia)
- Ariadne (v5.0.β + hadronization from Pythia)

LHA – Idealized Quark/Gluon distributions

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

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

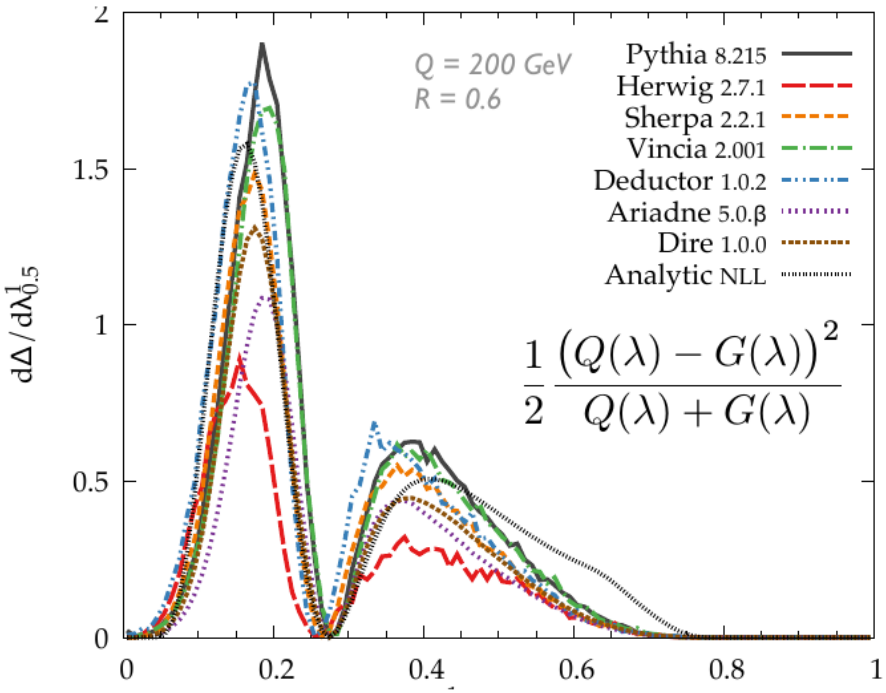
LHA – Separation power

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

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

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

Differential

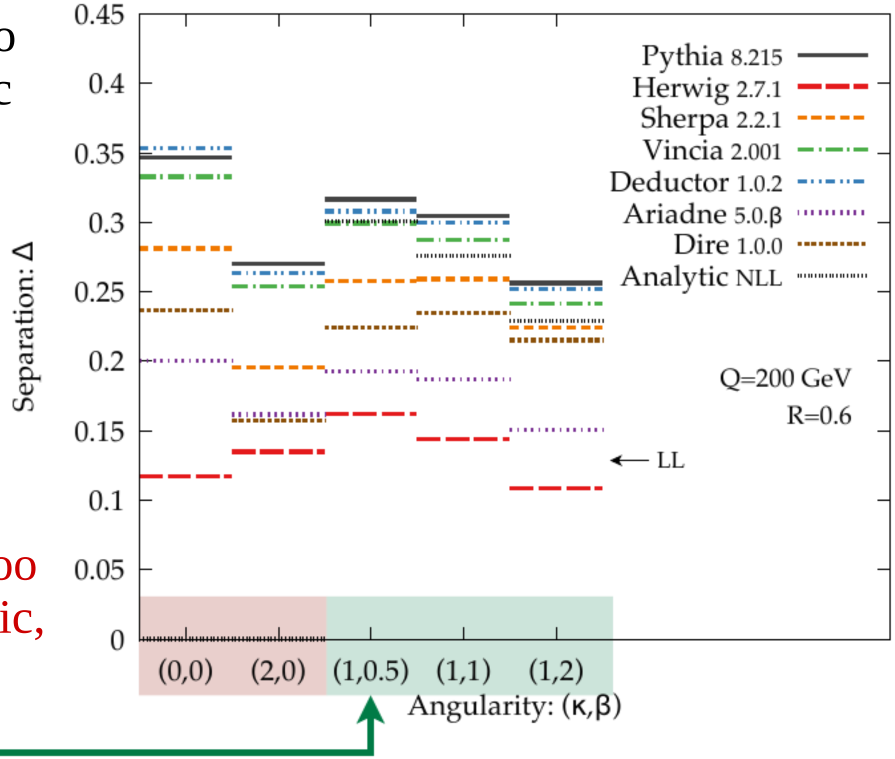


$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

Pythia too optimistic

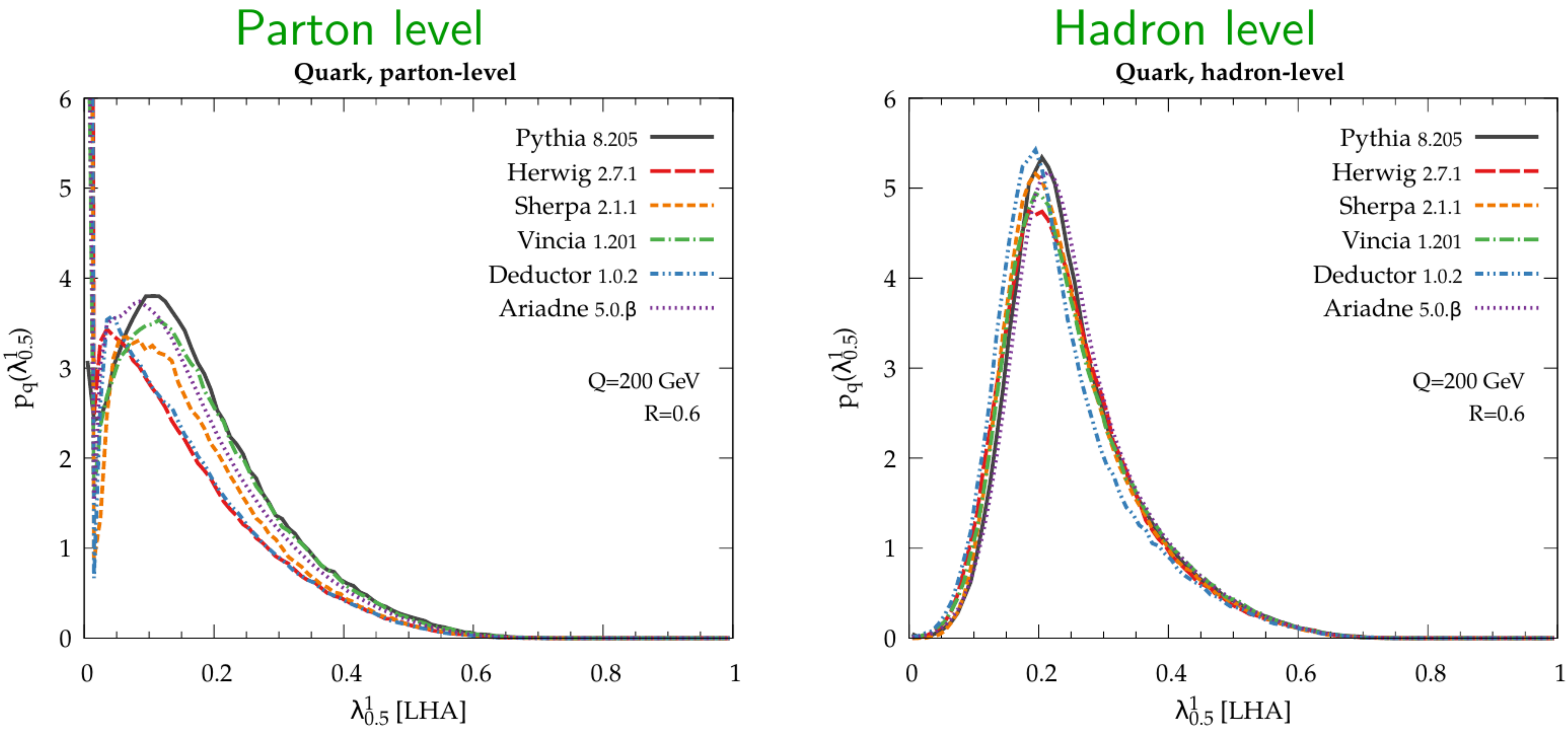
Herwig too pessimistic,

Integrated Values



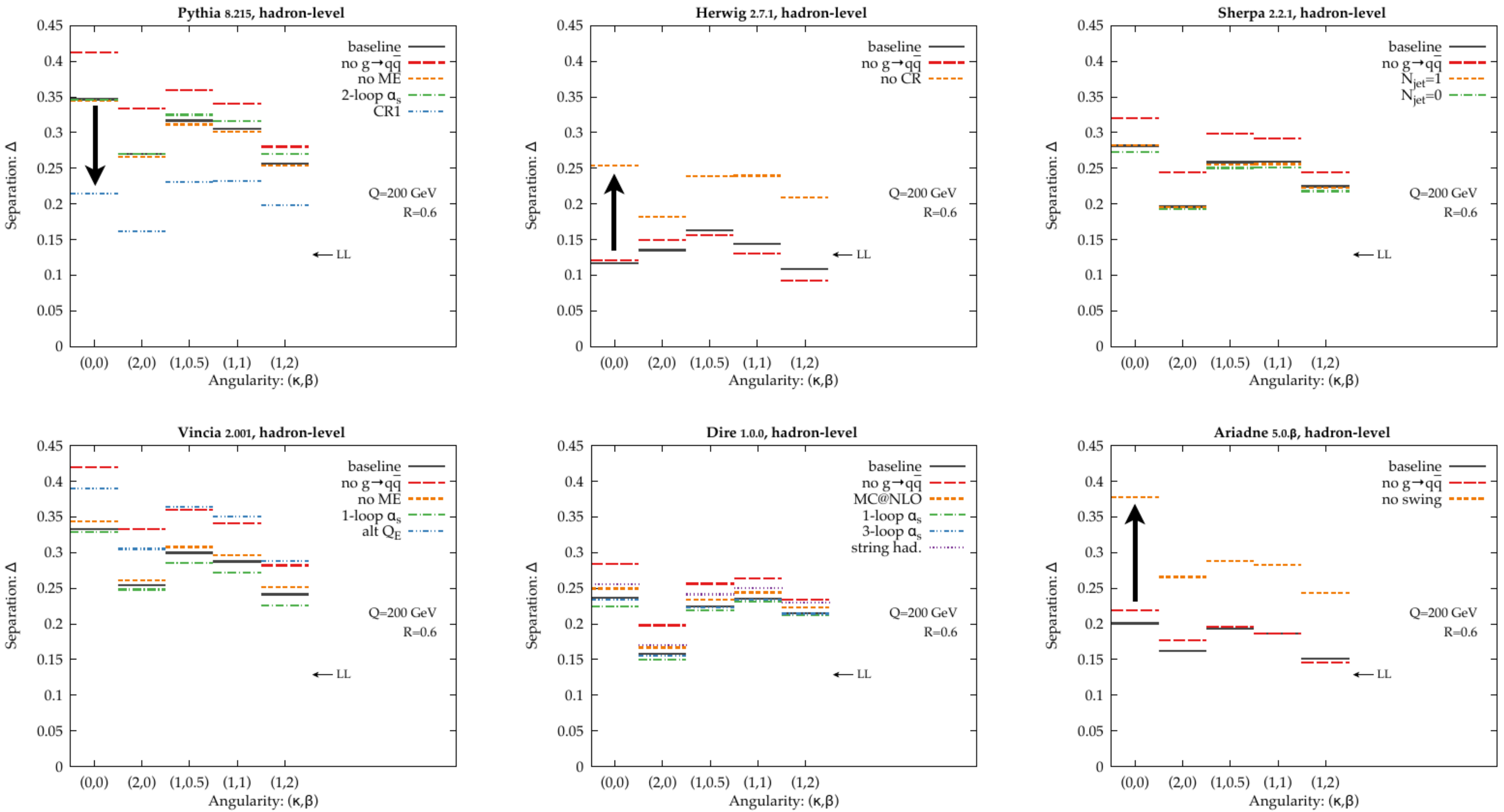
Affects both IRC unsafe and IRC safe observables

Separation power – non-perturbative effects



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

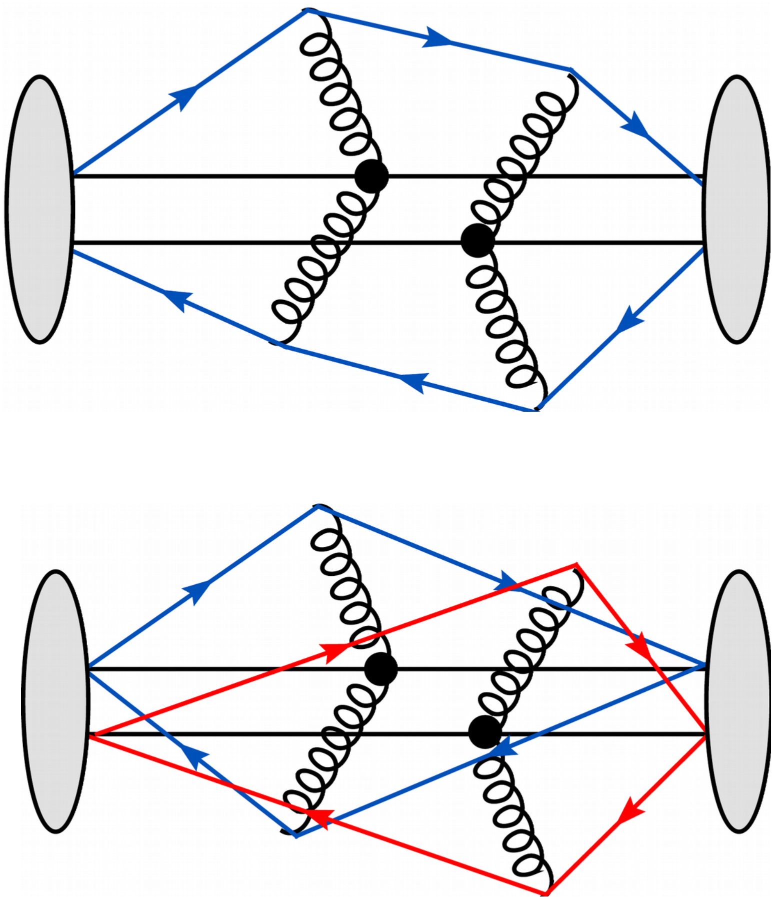
Separation power – sensitivity to MC options

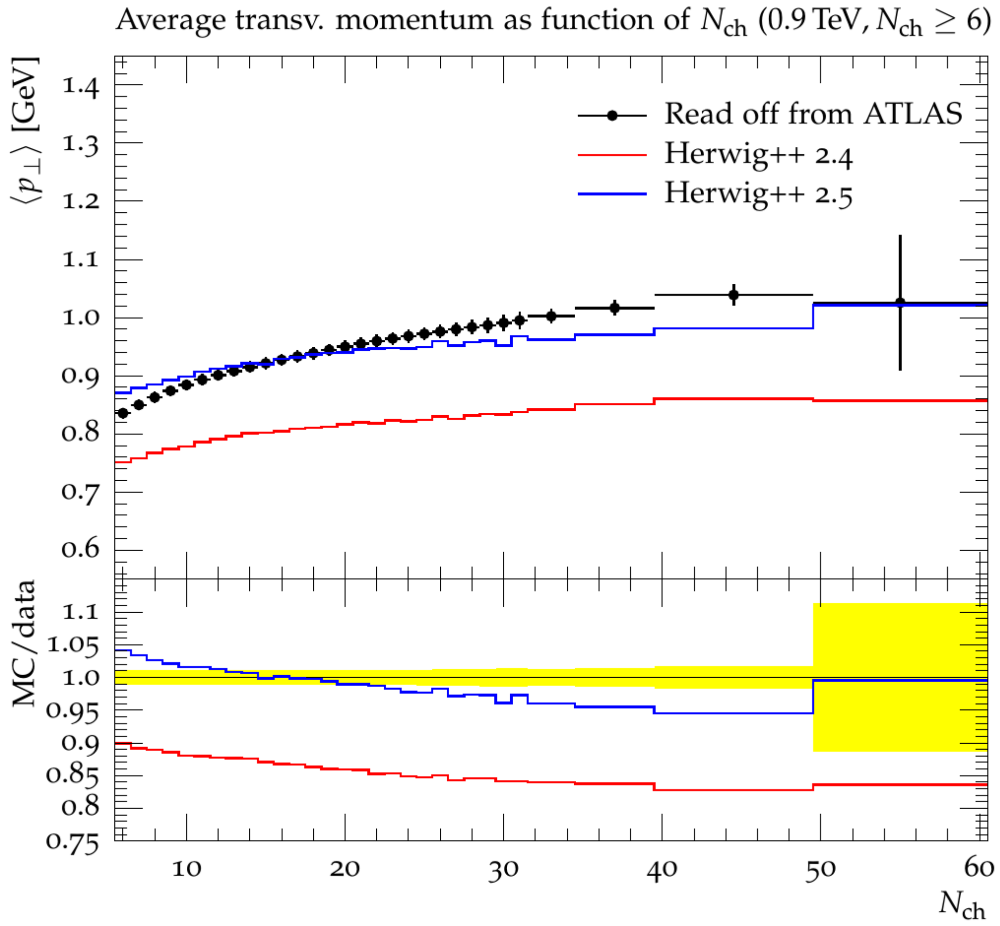


Huge effect of color reconection – very unexpected!

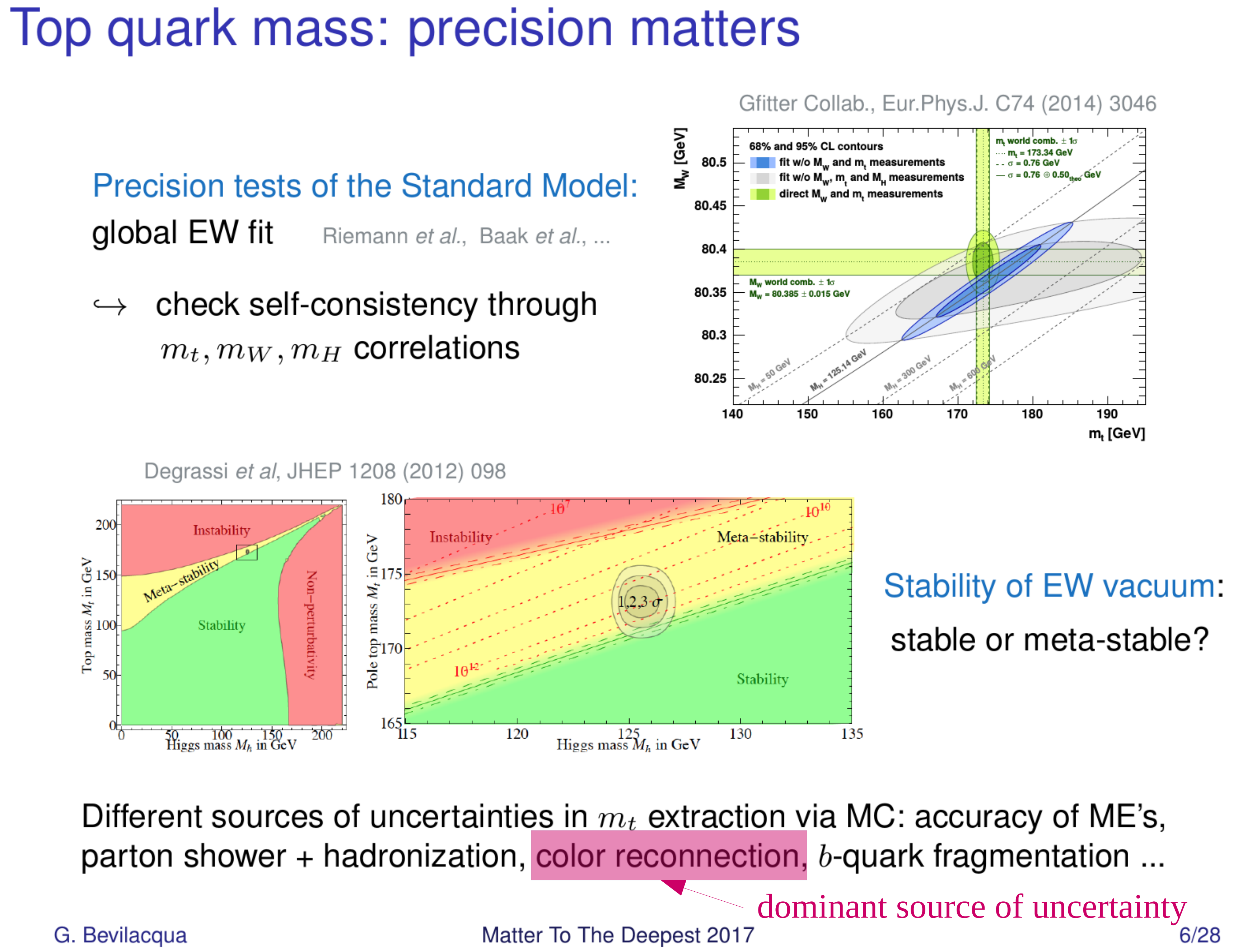
Herwig – Colour reconection

- 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, ...





Herwig – Colour reconection



Top quark mass: precision matters

Gfitter Collab., Eur.Phys.J. C74 (2014) 3046

Precision tests of the Standard Model:

global EW fit   Riemann *et al.*, Baak *et al.*, ...

↪ check self-consistency through m_t, m_W, m_H correlations

Degrassi *et al*, JHEP 1208 (2012) 098

Stability of EW vacuum:

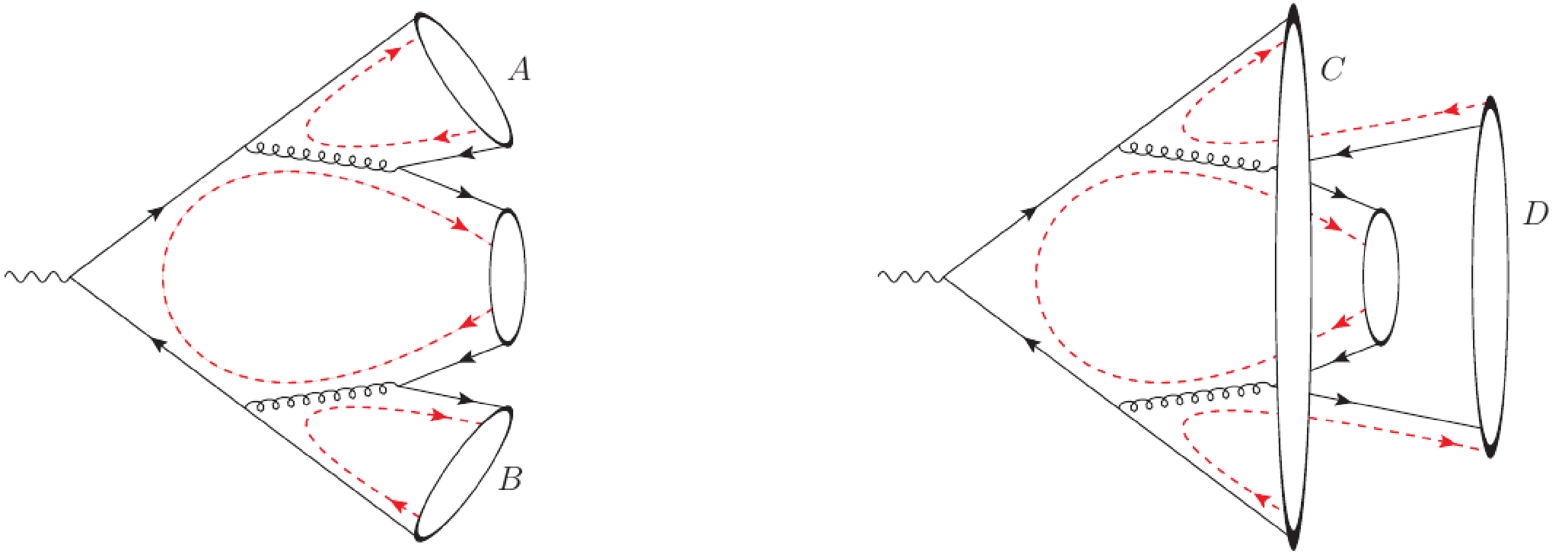
stable or meta-stable?

Different sources of uncertainties in m_t extraction via MC: accuracy of ME's, parton shower + hadronization, color reconnection, b-quark fragmentation ...

dominant source of uncertainty

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]

Improving the Simulation of Quark and Gluon Jets with Herwig 7

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

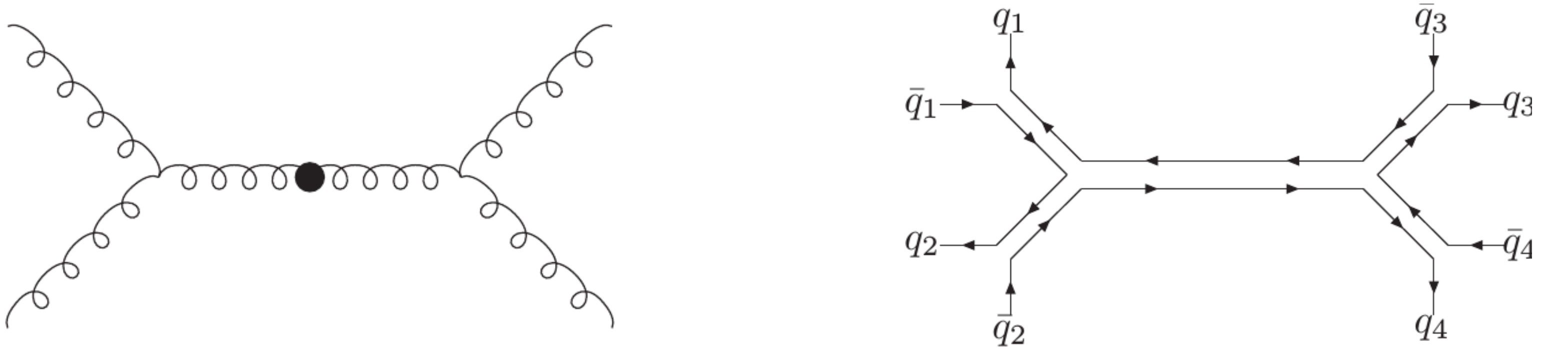
Strategy:

Data which has not previously been used.

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 – Improvements of Color reconection

- 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)



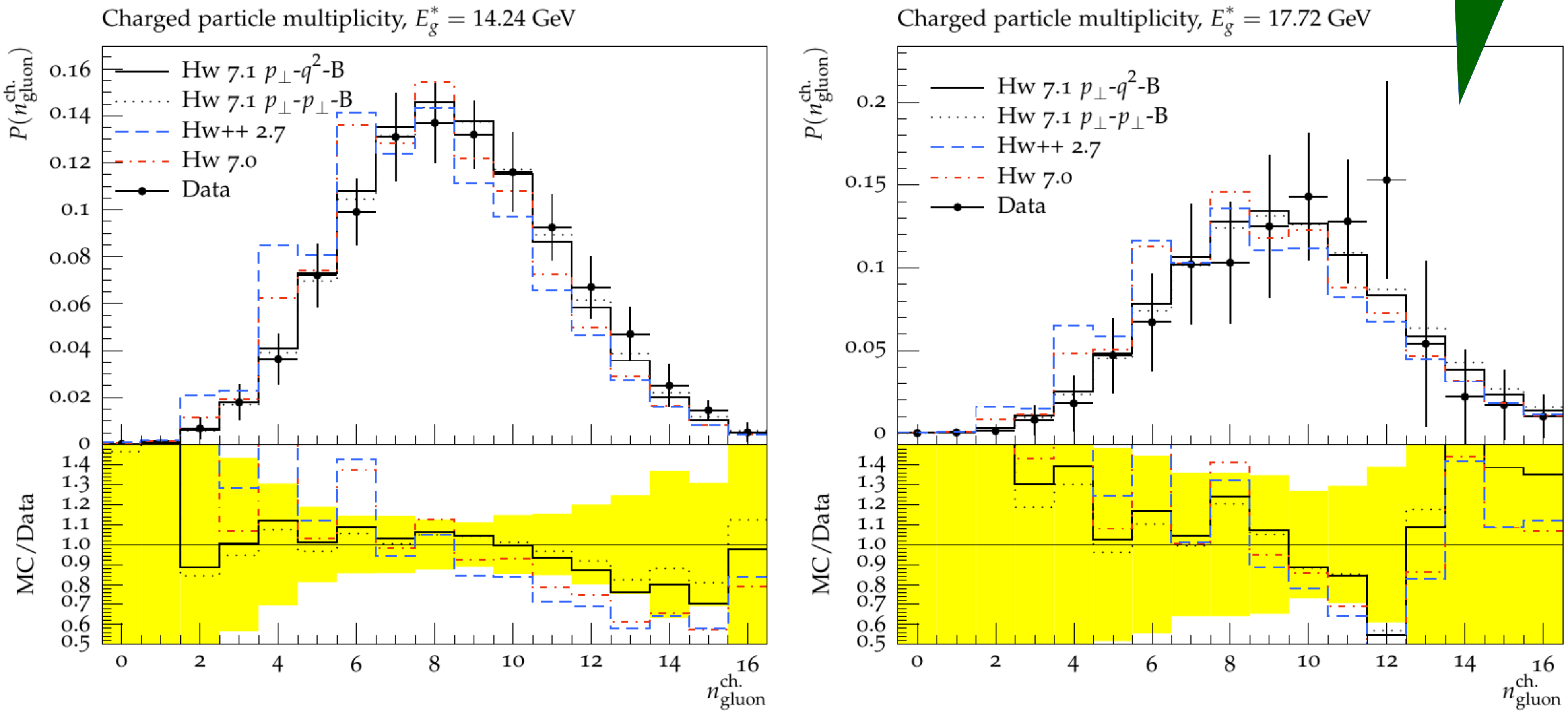
- Clusters containing partons from the parton shower of each of the original gluons, i.e. $q_1,\bar{q}_3$ and $q_4,\bar{q}_2$, will have large masses and the rearrangement to give the clusters $q_1,\bar{q}_2$ and $q_4,\bar{q}_3$ will be kinematically favoured, although it means the original gluons will effectively become colour singlets rather than octets.
- this is physically possible we would expect that it occurs at a rate which is suppressed in the number of colours, N_C, as $1/N_C^2=1/9$, not the much higher reconnection rate 2/3 which is current default value.
- We forbid the reconnection which would lead to a gluon produced in any stage of the parton-shower evolution becoming a colour-singlet after hadronization.

Herwig – Colour reconection

Data which has not previously been used for tuning.

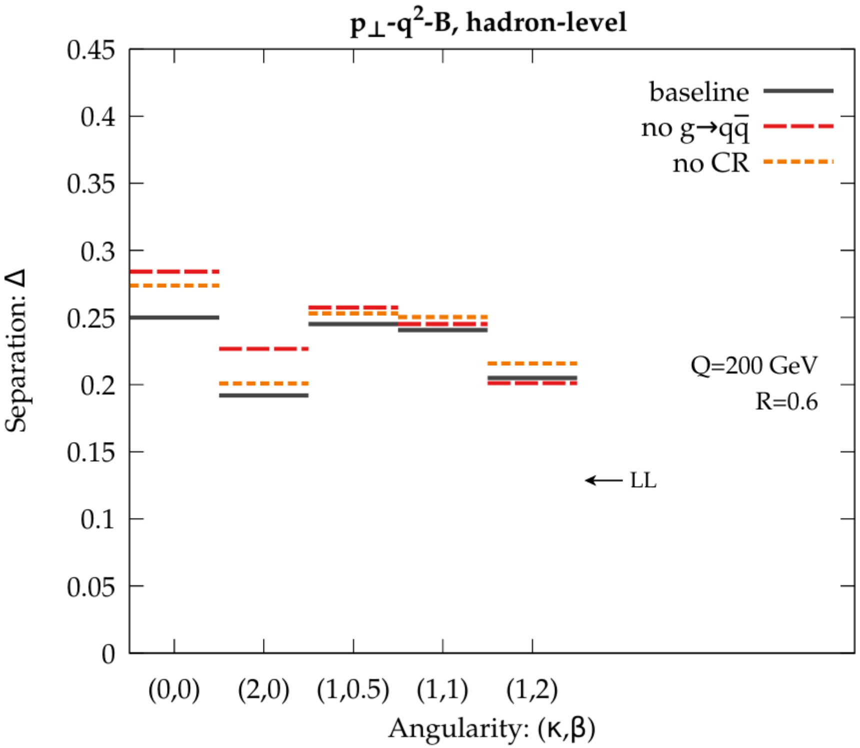
OPAL

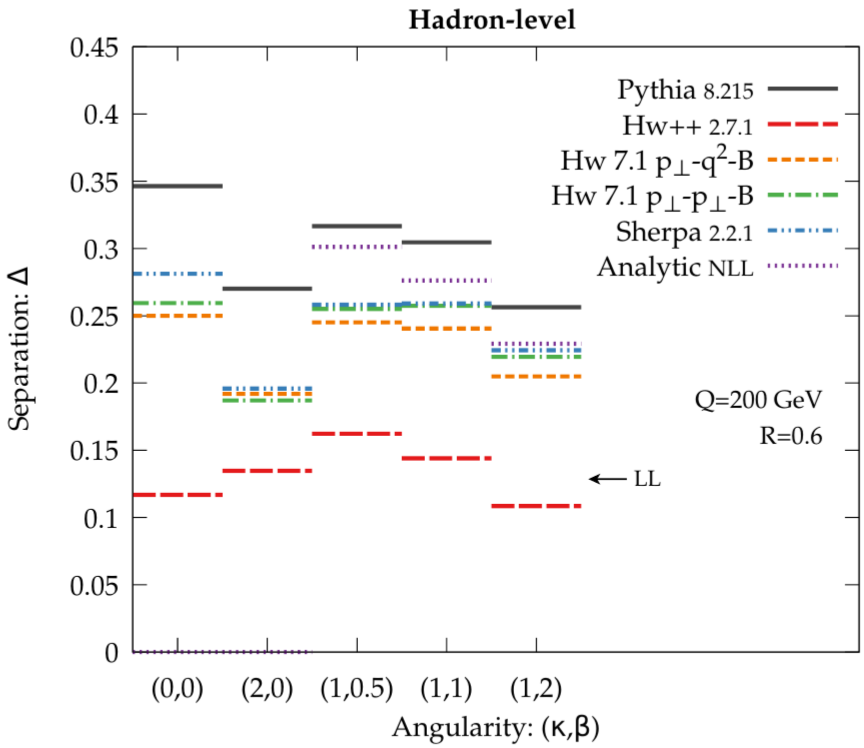
Multiplicity distribution of charged particles in gluons jets for two different gluon energies.



Herwig – Colour reconection

Idealized Quark/Gluon distributions





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

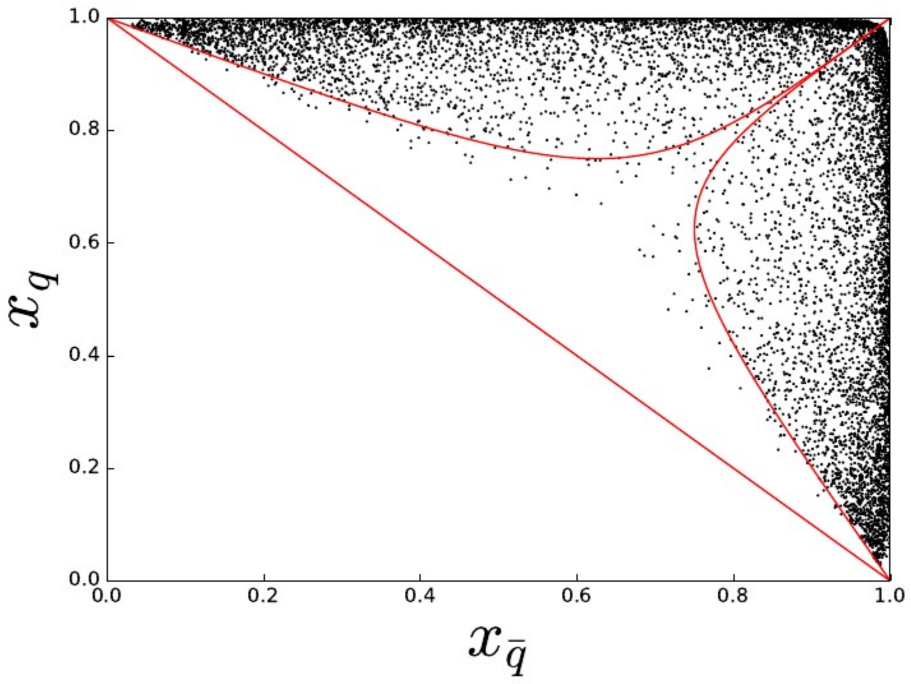
- Herwig is now more optimistic when it comes to distinguishing q/g jets.
- Spread of predictions is reduced.

Herwig – Parton Shower kinematics

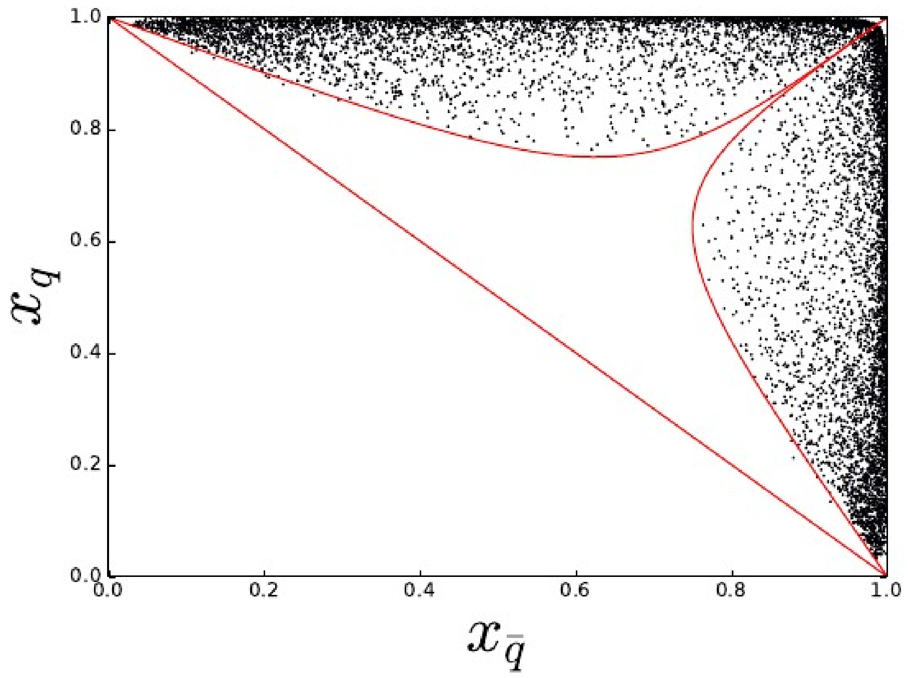
Choices that are formally subleading but can have a large effect on physical observables.

- Choice of minimal scale not fixed: we investigated pt and q cut-off.
- Kinematics: choice of whether to preserve pT or virtuality q^2 during the subsequent evolution.

Preserve pT



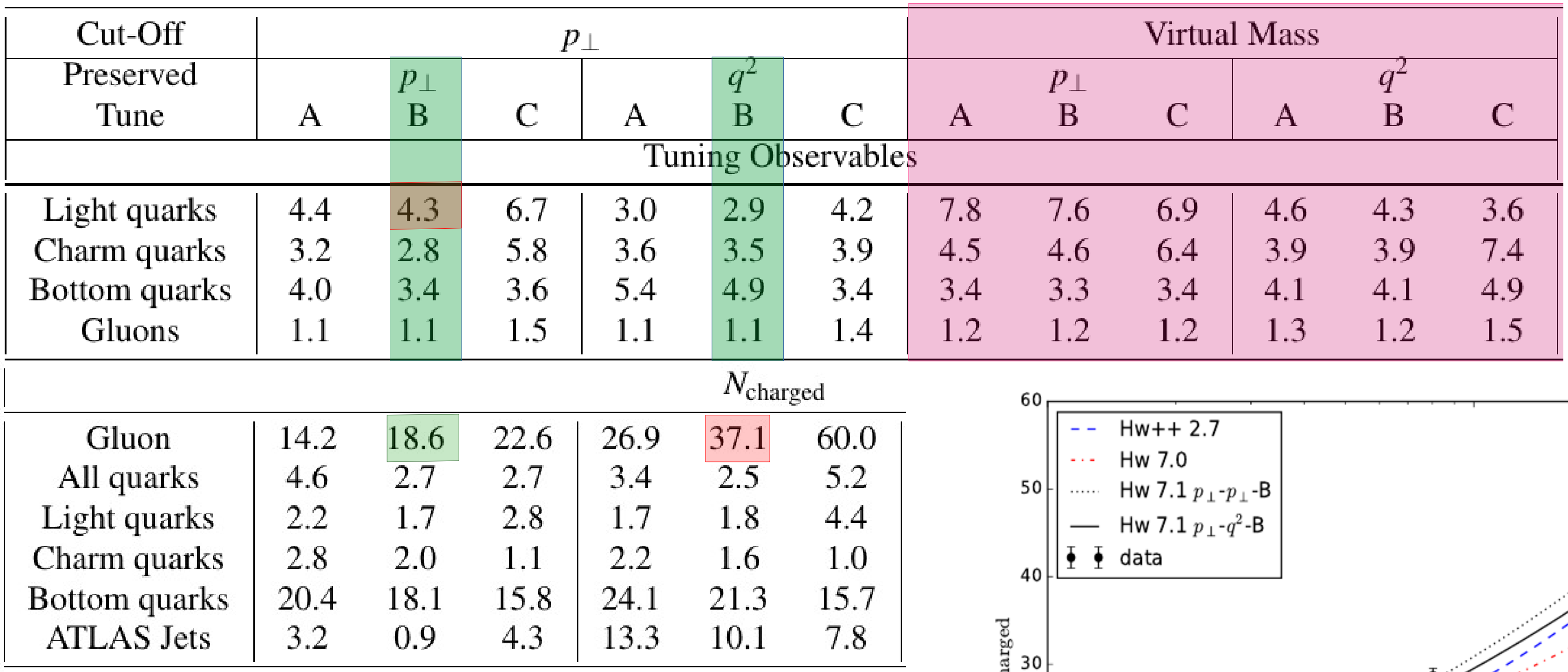
Preserve virtuality q^2



Tuning

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

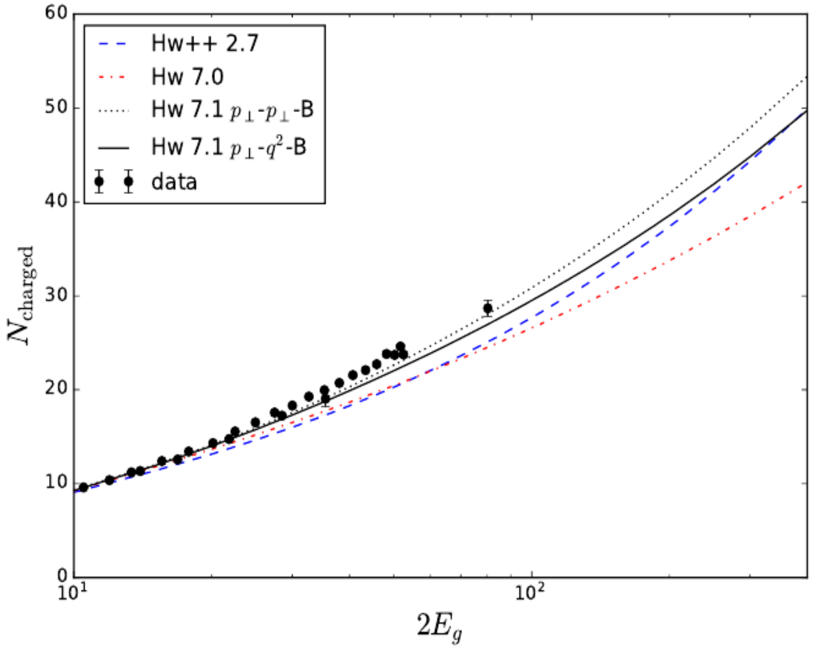
12 tunes for different PS options and weights w on low-energy charged multiplicity data A(w=0),B(w=100),C(w=1000)



Cut-Off	$p_\perp$						Virtual Mass					
Preserved		$p_\perp$			q^2			$p_\perp$			q^2	
Tune	A	B	C	A	B	C	A	B	C	A	B	C
				Tuning Observables								
Light quarks	4.4	4.3	6.7	3.0	2.9	4.2	7.8	7.6	6.9	4.6	4.3	3.6
Charm quarks	3.2	2.8	5.8	3.6	3.5	3.9	4.5	4.6	6.4	3.9	3.9	7.4
Bottom quarks	4.0	3.4	3.6	5.4	4.9	3.4	3.4	3.3	3.4	4.1	4.1	4.9
Gluons	1.1	1.1	1.5	1.1	1.1	1.4	1.2	1.2	1.2	1.3	1.2	1.5
					N_{charged}							
Gluon	14.2	18.6	22.6	26.9	37.1	60.0						
All quarks	4.6	2.7	2.7	3.4	2.5	5.2						
Light quarks	2.2	1.7	2.8	1.7	1.8	4.4						
Charm quarks	2.8	2.0	1.1	2.2	1.6	1.0						
Bottom quarks	20.4	18.1	15.8	24.1	21.3	15.7						
ATLAS Jets	3.2	0.9	4.3	13.3	10.1	7.8						

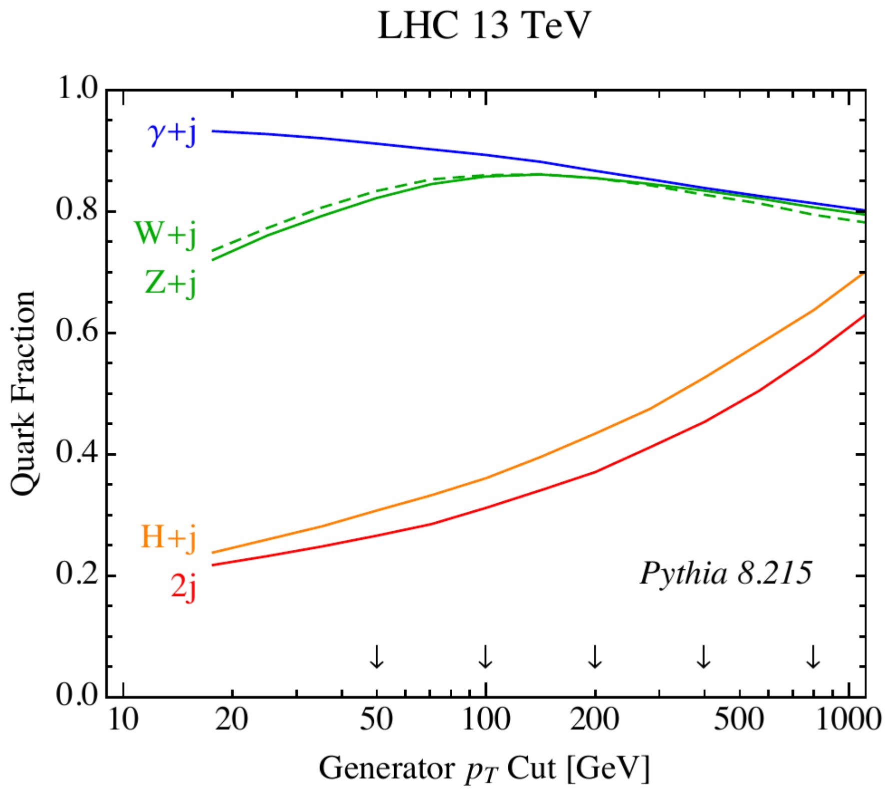
χ'^2

- 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.

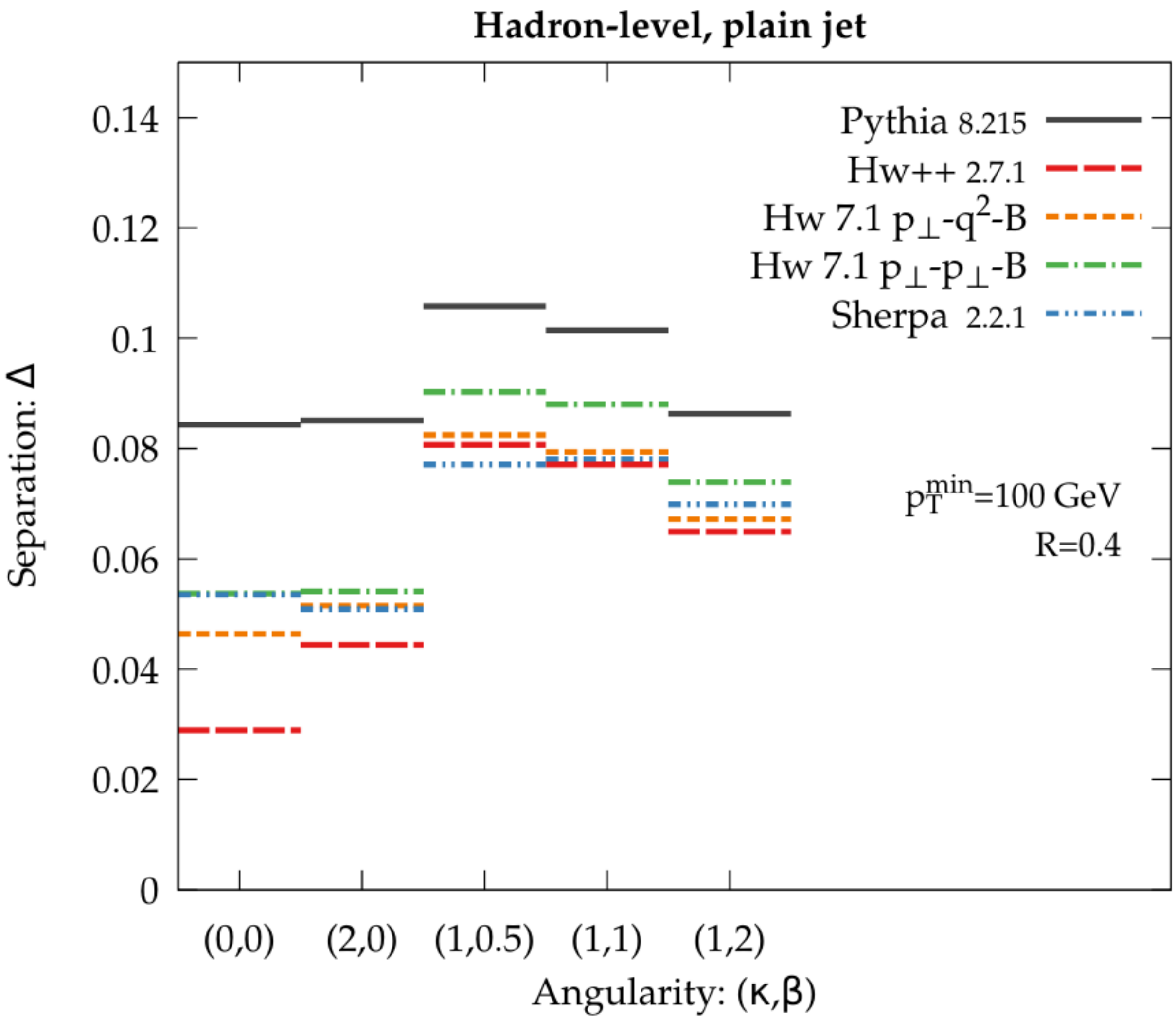
LHC



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

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

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

Summary and outlook

1. The properties of quark and gluon jets, and the differences between them, are increasingly important at the LHC.

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

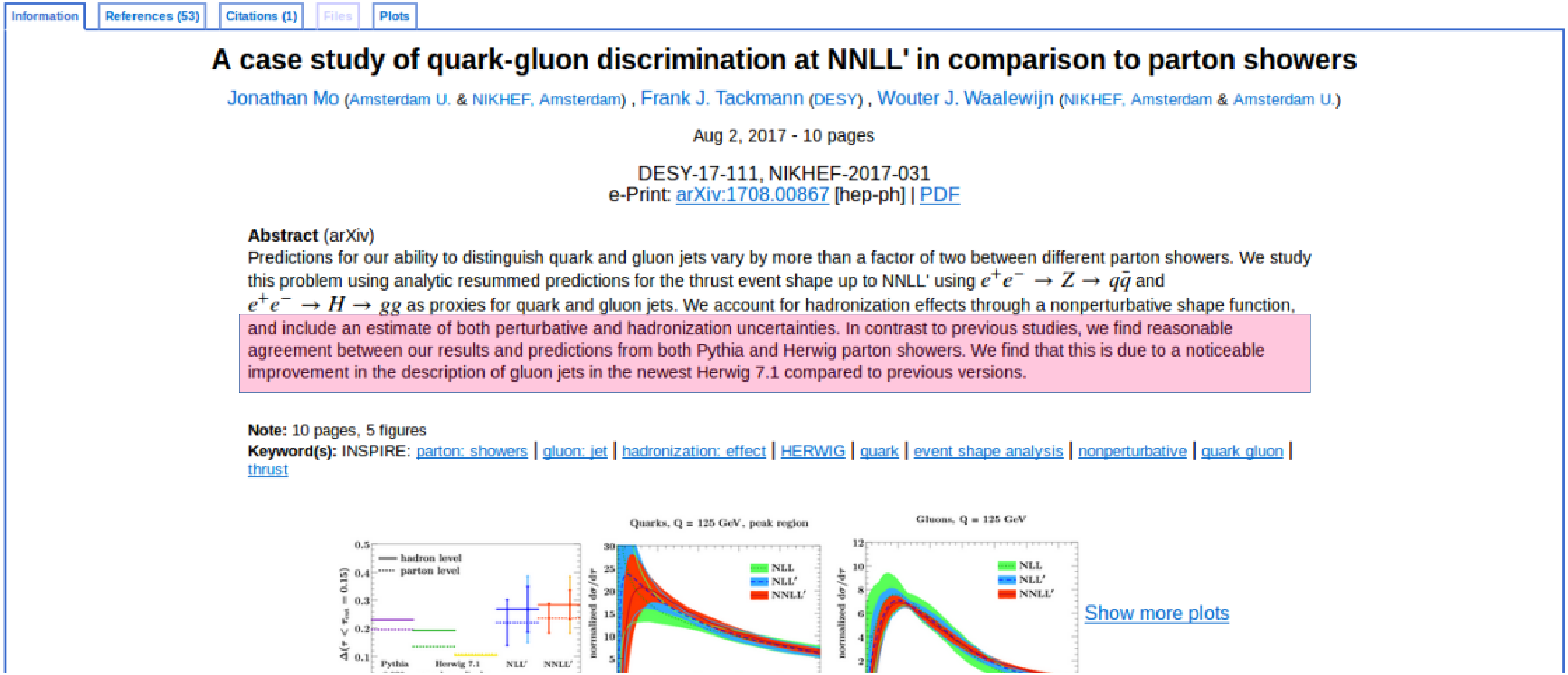
3. We have performed a tuning the Herwig 7 event generator using data on gluon jets from LEP for the first time.

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.

Causality violation



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

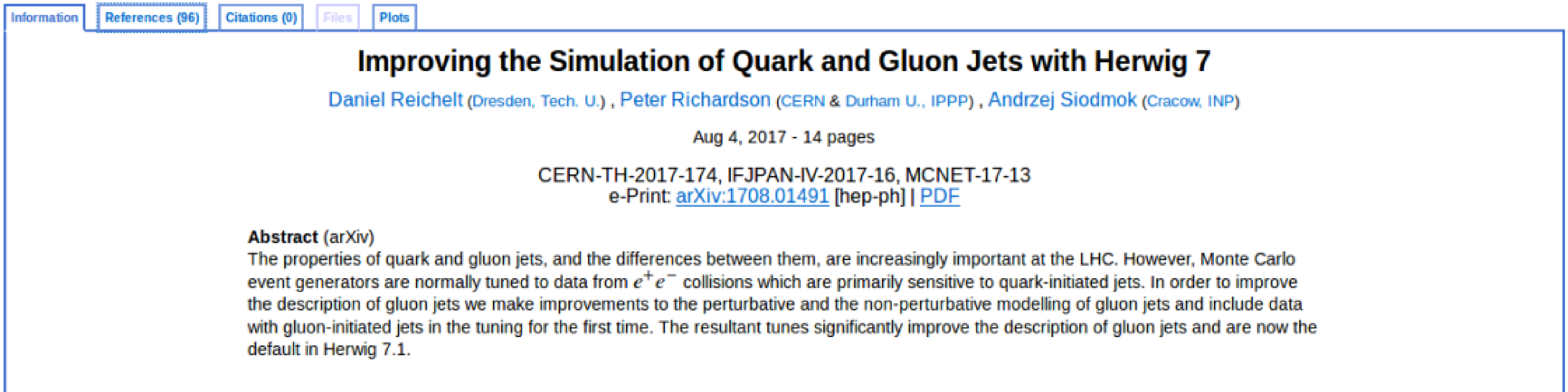
Jonathan Mo (Amsterdam U. & NIKHEF, Amsterdam) , Frank J. Tackmann (DESY) , Wouter J. Waalewijn (NIKHEF, Amsterdam & Amsterdam U.)

Aug 2, 2017 - 10 pages

DESY-17-111, NIKHEF-2017-031
e-Print: arXiv:1708.00867 [hep-ph] | PDF

Abstract (arXiv)
Predictions for our ability to distinguish quark and gluon jets vary by more than a factor of two between different parton showers. We study this problem using analytic resummed predictions for the thrust event shape up to NNLL' using $e^+e^- \to Z \to q\bar{q}$ and $e^+e^- \to H \to gg$ as proxies for quark and gluon jets. We account for hadronization effects through a nonperturbative shape function, and include an estimate of both perturbative and hadronization uncertainties. In contrast to previous studies, we find reasonable agreement between our results and predictions from both Pythia and Herwig parton showers. We find that this is due to a noticeable improvement in the description of gluon jets in the newest Herwig 7.1 compared to previous versions.

Note: 10 pages, 5 figures
Keyword(s): INSPIRE: parton: showers | gluon: jet | hadronization: effect | HERWIG | quark | event shape analysis | nonperturbative | quark gluon | thrust



Improving the Simulation of Quark and Gluon Jets with Herwig 7

Daniel Reichelt (Dresden, Tech. U.) , Peter Richardson (CERN & Durham U., IPPP) , Andrzej Siodmok (Cracow, INP)

Aug 4, 2017 - 14 pages

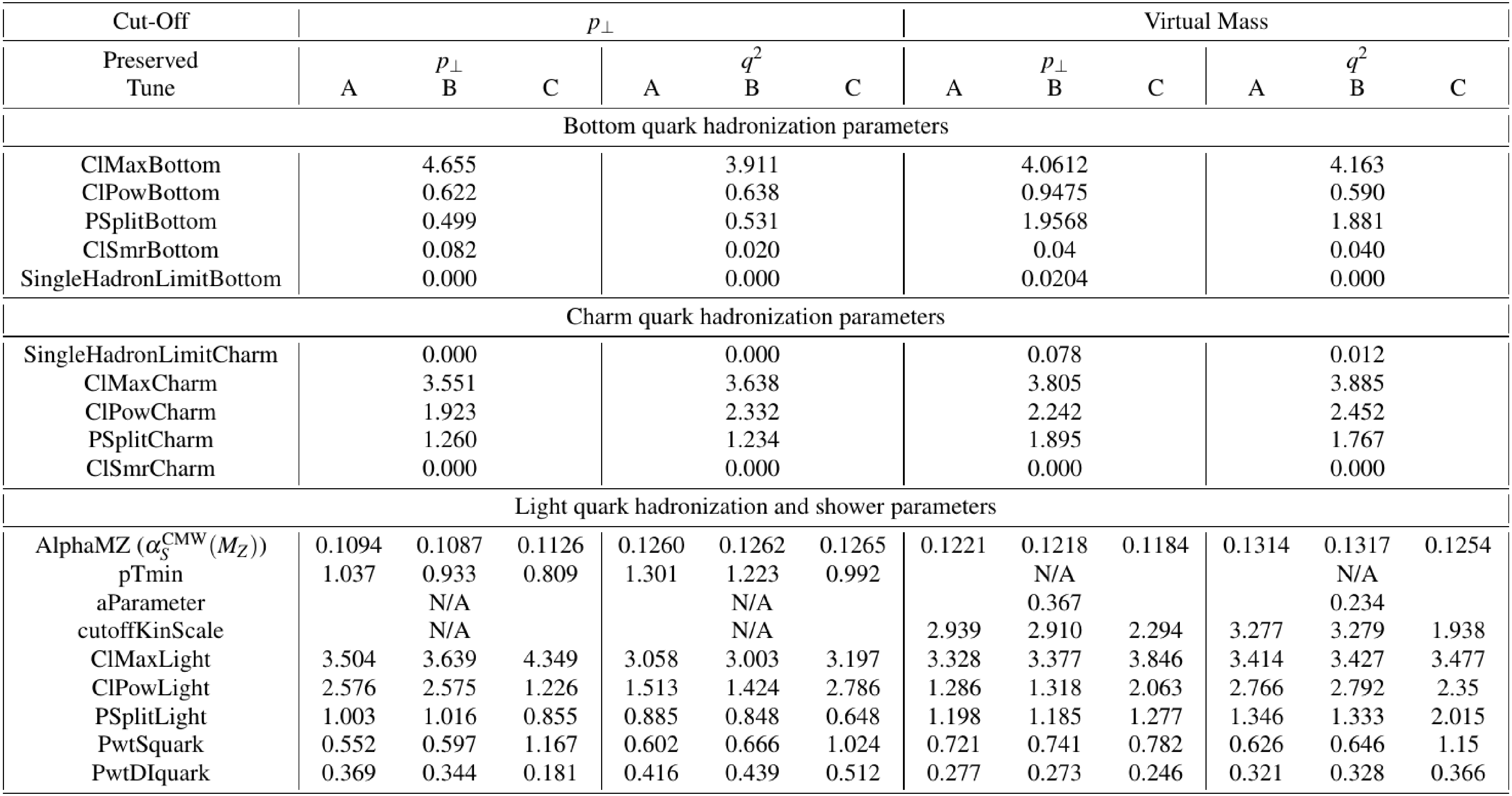
CERN-TH-2017-174, IFJPAN-IV-2017-16, MCNET-17-13
e-Print: arXiv:1708.01491 [hep-ph] | PDF

Abstract (arXiv)
The properties of quark and gluon jets, and the differences between them, are increasingly important at the LHC. However, Monte Carlo event generators are normally tuned to data from e^+e^- collisions which are primarily sensitive to quark-initiated jets. In order to improve the description of gluon jets we make improvements to the perturbative and the non-perturbative modelling of gluon jets and include data with gluon-initiated jets in the tuning for the first time. The resultant tunes significantly improve the description of gluon jets and are now the default in Herwig 7.1.

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	$p_\perp$			q^2			$p_\perp$			q^2		
Tune	A	B	C	A	B	C	A	B	C	A	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 ($\alpha_S^{\text{CMW}}(M_Z)$)	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