Measurement of observables sensitive to coherence effects in hadronic Z decays with the OPAL detector at LEP

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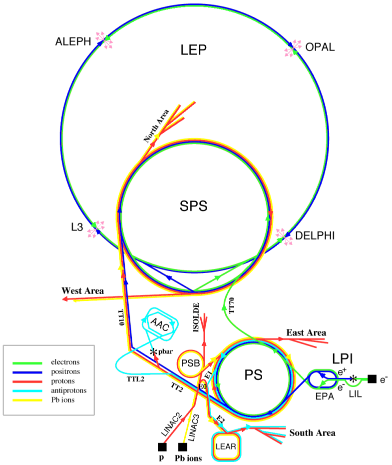
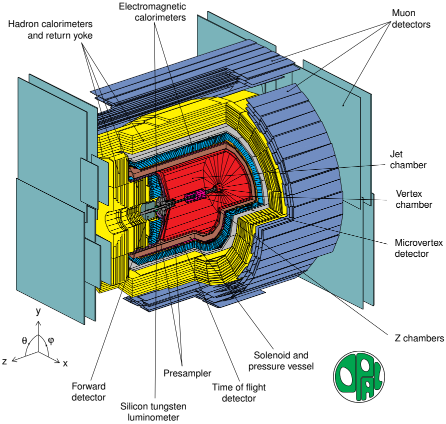
The LEP Accelerator



- The world most famous e^+e^- collider running 1989-1995(LEP-I), 1996-2000(LEP-II).
- Energy ranges $\approx$ 91 GeV(LEP-I) and 91-208 GeV(LEP-II).
- Host of four big experiments: **OPAL**, ALEPH, DELPHI, L3.

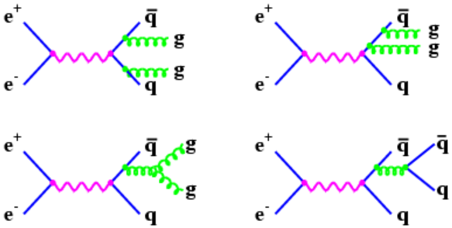
The OPAL Collaboration and Detector



Omni-**P**urpose **A**pparatus at **L**EP

- Collaboration of more than 300 people.
- Advanced multipurpose detector with almost 4π solid angle coverage.
- Collected more than 400k e^+e^- hadronic annihilation events at $\sqrt{s} = 91.2$ GeV at LEP-II.

QCD at OPAL: motivation



- $e^+e^- \rightarrow Z^0 \rightarrow$ *hadrons* is perfect to study QCD effects
- Particular interest: QCD colour coherence can be studied with 4-jet events.
  - Provides better understanding of QCD.
  - Validates well established and new Monte Carlo models.

Theory Models to Validate

Existing models are based on parton showers $1 \to 2$ ($p_I \to p_i p_j$), dipole showers $2 \to 3$ ($p_I p_K \to p_i p_j p_k$) and QCD antenna $2 \to 3$ ($p_I p_K \to p_i p_j p_k$). In combination with ordering variables it gives:

Model	Ordering variable	Meaning
HERWIG++ $\tilde{q}^2$	$\frac{Q_I^2 M_{IK}^4}{Q_K^2 (M_{IK}^2 - Q_I^2 - Q_K^2)}$	parton shower
HERWIG++ $p^2_{\perp \mathrm{dip}}$	$\frac{Q_I^2 Q_K^2 (M_{IK}^2 - Q_I^2 - Q_K^2)}{(M_{IK}^2 - Q_I^2)^2}$	dipole shower
HERWIG++ q^2_{dip}	Q_I^2	dipole shower, no angular ordering, our "straw man"
VINCIA $p^2_{\perp \mathrm{ant}}$	$\frac{Q_I^2 Q_K^2}{M_{IK}^2}$	QCD antenna
VINCIA m^2_{ant}	$\min(Q_I^2, Q_K^2)$	QCD antenna
PYTHIA 8 $p^2_{\perp \mathrm{evol}}$	$\frac{Q_I^2 (M_{IK}^2 - Q_K^2)(Q_I^2 + Q_K^2)}{(M_{IK}^2 + Q_I^2)^2}$	parton shower

Here the notation $Q_I^2 = (p_i + p_j)^2$, $Q_K^2 = (p_j + p_k)^2$, and $M_{IK}^2 = (p_I + p_K)^2 = (p_i + p_j + p_k)^2$ is used.

Measurements and Predictions

Measurements:

- LEP-II data sample with $\sqrt{s} = 91.2$ GeV, calibration samples from LEP-II/LEP-II.
- Pythia6 and Herwig MC samples passed through detector simulation to unfold the data to particle level.
- 4-jet events are reconstructed with Durham algorithm ($y^{4\to3} > 0.045$) from tracks and calorimeter clusters. For details of selection see backup and Ref. [2].

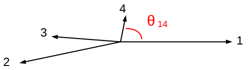
Predictions:

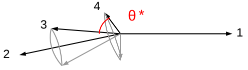
- Several MC samples of 5×10^6 events to extract model predictions. Parameters of every model were tuned to describe the same (independent) LEP data in the best way.
- 4-jet events are reconstructed in the same way as in data.

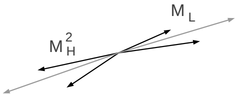
The event topologies resulting from four-jet events

Observables:

- θ_{14} the emission angle of the soft fourth jet with respect to the first jet
- $\theta^* = \theta_{24} - \theta_{23}$, the difference in opening angles
- $\rho = M_L^2/M_H^2$, the ratio of the invariant masses-squared of the jets at the end of the clustering process, ordered such that $M_L^2 \leq M_H^2$.

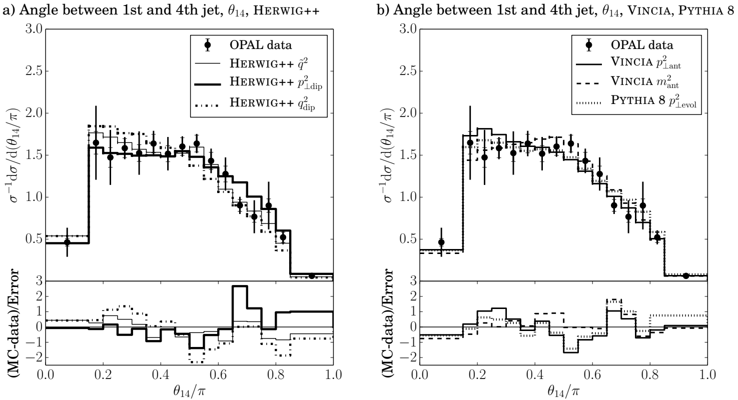






- $C_2^{(1/5)} \approx E_4 \theta_{14}^{1/5} \theta_{23\,4}^{1/5} E_{\mathrm{vis}}/(E_1 E_{23} \theta_{1\,23}^{1/5})$, the 2-point double ratio with the total visible energy E_{vis} in the event. $\theta_{23\,4}$ denotes the angle between the softest jet and the (23) jet pair and analogously for $\theta_{1\,23}$.

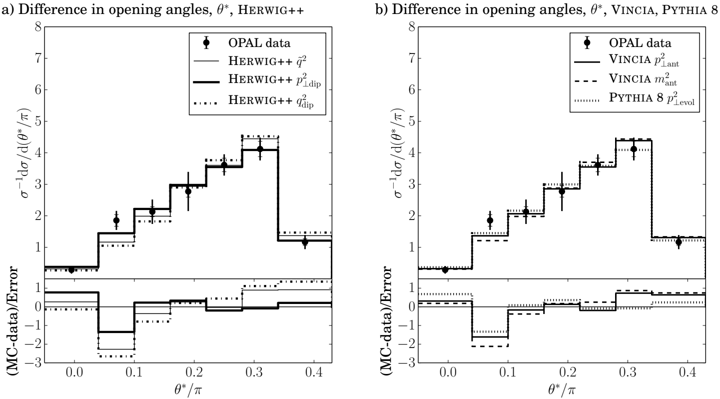
Angle between first and fourth jet, θ_{14}



	$\chi^2/ndof(p - value)$		$\chi^2/ndof(p - value)$[1]
HERWIG++ $\tilde{q}^2$	4.8/15 (99.4%)	VINCIA $p^2_{\perp \mathrm{ant}}$	8.3/15 (91.1%)
HERWIG++ $p^2_{\perp \mathrm{dip}}$	12.8/15 (61.8%)	VINCIA m^2_{ant}	8.1/15 (92.0%)
HERWIG++ q^2_{dip}	16.4/15 (35.6%)	PYTHIA 8 $p^2_{\perp \mathrm{evol}}$	7.1/15 (95.5%)

[1] Upcoming revision of Ref. [2]

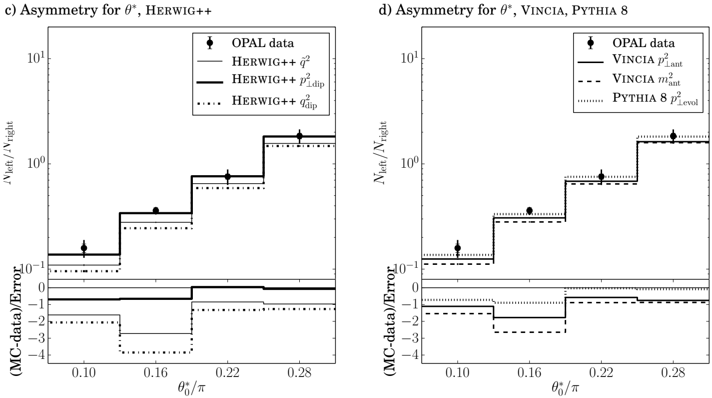
The difference in opening angles, θ^*



	$\chi^2/ndof(p-value)$
HERWIG++ $\tilde{q}^2$	6.1/6 (41.2%)
HERWIG++ $p^2_{\perp\mathrm{dip}}$	2.8/6 (83.3%)
HERWIG++ q^2_{dip}	8.8/6 (18.5%)

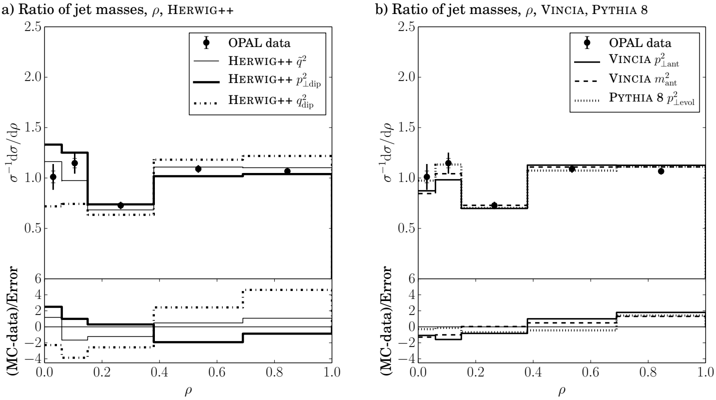
	$\chi^2/ndof(p-value)$
VINCIA $p^2_{\perp\mathrm{ant}}$	2.5/6 (86.8%)
VINCIA m^2_{ant}	3.3/6 (77.0%)
PYTHIA 8 $p^2_{\perp\mathrm{evol}}$	5.1/6 (53.1%)

The asymmetry of difference in opening angles, θ^*



$$N_{left}/N_{right} = Asymmetry = \sum_{\theta^* < \theta^*_0} n(\theta^*) / \sum_{\theta^* > \theta^*_0} n(\theta^*).$$

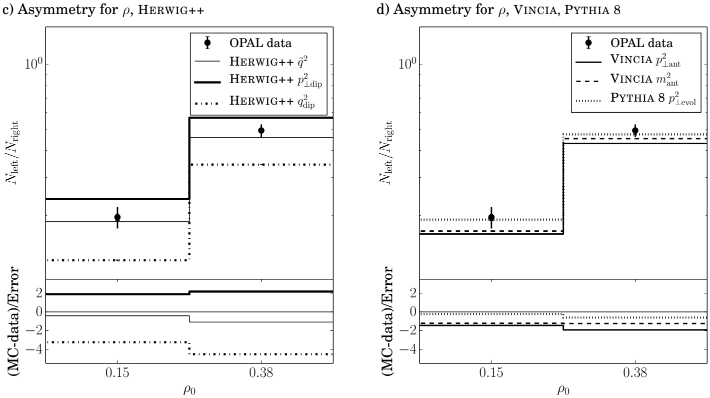
The ratio of jet masses



	$\chi^2/ndof(p-value)$
HERWIG++ $\tilde{q}^2$	6.6/4 (15.9%)
HERWIG++ $p^2_{\perp\mathrm{dip}}$	10.1/4 (3.9%)
HERWIG++ q^2_{dip}	42.8/4 (0.0%)

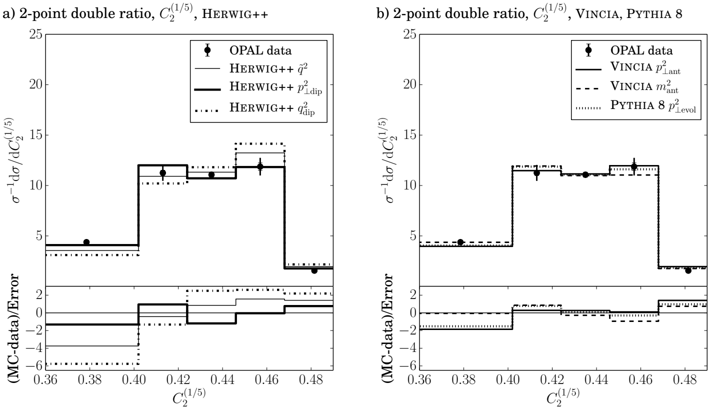
	$\chi^2/ndof(p-value)$
VINCIA $p^2_{\perp\mathrm{ant}}$	2.6/4 (62.7%)
VINCIA m^2_{ant}	6.8/4 (14.7%)
PYTHIA 8 $p^2_{\perp\mathrm{evol}}$	3.9/4 (42.0%)

The asymmetry of the ratio of jet masses



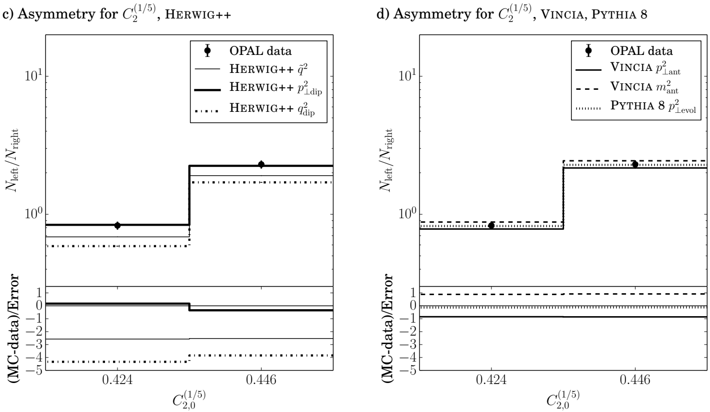
$$N_{left}/N_{right} = Asymmetry = \sum_{\rho<\rho_0} n(\rho) / \sum_{\rho>\rho_0} n(\rho).$$

The 2-point double ratio, $C_2^{(1/5)}$



	$\chi^2/ndof(p-value)$		$\chi^2/ndof(p-value)$
HERWIG++ $\tilde{q}^2$	16.2/4 (0.0%)	VINCIA $p^2_{\perp\mathrm{ant}}$	4.3/4 (36.7%)
HERWIG++ $p^2_{\perp\mathrm{dip}}$	6.0/4 (19.9%)	VINCIA m^2_{ant}	5.3/4 (25.8%)
HERWIG++ q^2_{dip}	41.2/4 (0.0%)	PYTHIA 8 $p^2_{\perp\mathrm{evol}}$	2.3/4 (68.1%)

The asymmetry of the 2-point double ratio



$$N_{left}/N_{right} = Asymmetry = \sum_{C_2^{(1/5)} < C_{2,0}^{(1/5)}} n(C_2^{(1/5)}) / \sum_{C_2^{(1/5)} > C_{2,0}^{(1/5)}} n(C_2^{(1/5)}).$$

Conclusions

- Presented measurements of distributions $e^+e^- \to Z^0 \to 4 - jets$ sensitive to QCD colour coherence, the radiation model and the ordering parameter. The study has validated the most widely used Monte Carlo models for the QCD 4-jet final states.
- It was found that:
  - The HERWIG++ with a $q^2_{\rm dip}$ model provides the least satisfactory description of the data.
  - The PYTHIA 8 and both variants of VINCIA provide the best description of the data.

Backup slides

Event selection

Charged tracks are required to have transverse momentum relative to the beam axis larger than 0.15 GeV, and photons to have energies larger than 0.10 GeV (0.25 GeV) in the barrel (endcap) region of the electromagnetic calorimeter. The selection of hadronic annihilation events is the same as described in Ref. [5]. Briefly, a minimum of five charged tracks is required, and a containment condition $|\cos\theta_{\mathrm{T}}| < 0.90$ is applied, where θ_{T} is the polar angle of the thrust axis [6, 7] with respect to the beam axis, calculated using all accepted charged tracks and electromagnetic clusters.

Event reconstruction

Jets were reconstructed with Durham algorithm. For this algorithm the measure of distance between objects is

$$y_{ij} = 2\mathrm{min}(E_i^2, E_j^2)(1 - \cos\theta_{ij})/s.$$

Here E_i and E_j are the energies and θ_{ij} is the angle between reconstruction objects i and j and the center-of-mass energy-squared is denoted by s. In the event the with minimal distance are sequentially merged.
To remove clusters matched to tracks. the energy-flow algorithm [3, 4] was applied.

Access policy

The OPAL data is analysed in “Data Preservation“ mode. It implies some specific features:

- Absence of regular collaboration structure: groups, spokesperson, administration.
- Absence of dedicated manpower, support and infrastructure.
- Permanent Editorial Board, that should be contacted before making an analysis.

Extra sources

The used figures originate from the Refs. [2, 8, 9, 10].

Bibliography

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