Measurement of Angular Correlations and Soft Jets

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Jet @ Geneva Airport

Outline

1. Motivation
2. Event Selection and Observables
3. Tuning
4. Analysis of OPAL Data (results not yet reviewed)
5. Results

Motivation

Why QCD?

- Dominant in collisions
- Control of QCD effects as background processes
- Interesting by itself!

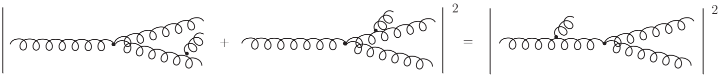
⇒ Modelling of QCD jets is very important for MCs

⇒ Shower properties:
Coherence, emission of soft jets, angular correlations of jets

Shower Properties

Coherence, emission of soft jets, angular correlations of jets

- Showers: Correct in soft and collinear limit
- QCD colour coherence:
  Destructive interference between colour partners



⇒ Angular ordering or
Angular vetos or
Coherent dipoles / antennae

⇒ Comparing different shower models

Monte Carlo Showers

HERWIG++ [M Bähr et al, 0803.0883]

- Angular ordered parton shower:

  Quasi-collinear splitting functions + angular ordering
- $p^2_{\perp\text{dip}}$-ordered dipole shower with partitioned dipoles (similar to SHERPA)

  [S Plätzer, S Gieseke, 0909.5593]
- Option to switch to q^2-ordering as non-coherent example

PYTHIA8 [T Sjöstrand, S Mrenna, P Skands, 0710.3820]

- Angular vetos to obtain coherence
- Ordering variable: $p^2_{\perp\text{evol}}$

VINCIA [W Giele, D Kosower, P Skands, 0707.3652] as a plugin to PYTHIA8

- Reproduction of soft and collinear limits with antenna functions
- Ordering variable: Antenna $p^2_{\perp\text{A}}$ or antenna mass

Event Selection and Observables

- ME: $e^+e^- \to q\bar{q}$ for 5 flavours $(u,\ d,\ c,\ s,\ b)$ @ 91.2 GeV
- Higher jets produced by shower (no higher-order matching)
- $e^+e^-\ k_t$ algorithm: $d_{ij} = 2 \cdot \text{min}(E_i^2, E_j^2)(1 - \cos\theta_{ij})$
  $y_{ij} = d_{ij}/Q^2$
- Jets ordered in energy (1st jet refers to hardest)
- $3 \to 4$ clustering scale $y_{3\to 4} > 0.0045$ (~ 6 GeV)
  as compromise between
  - statistics and
  - minimizing influence of hadronization and B decays

Event Selection and Observables

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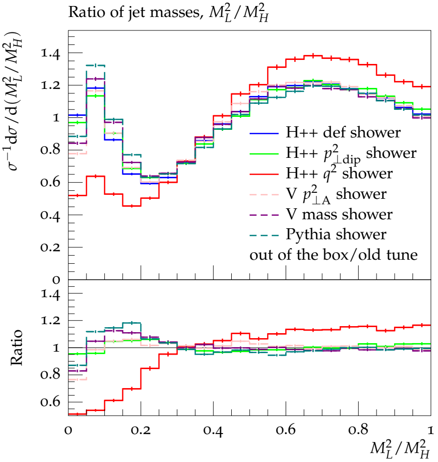
- $y_{3\to4} > 0.0045$ to minimize influence of hadronization and B decays
- All events clustered into 2 jets
- $y_{3\to4} > y_{2\to3}/2$
  ("compressed" scale hierarchy)
- Ratio of jet masses M_L^2/M_H^2

  [J Alcaraz Maestre et al, 1203.6803]



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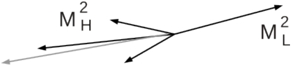
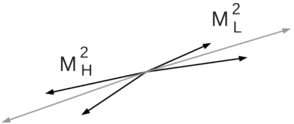
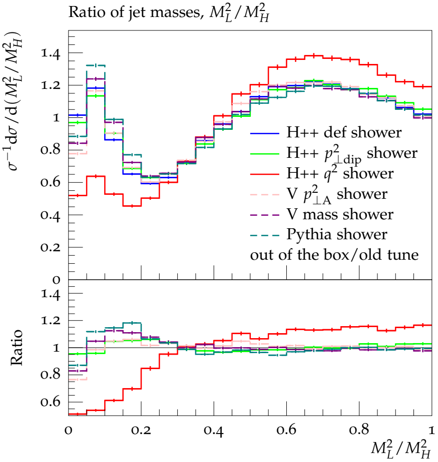


M_L^2/M_H^2 small



M_L^2/M_H^2 large



Event Selection and Observables

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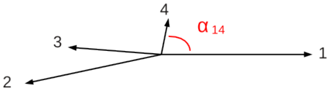
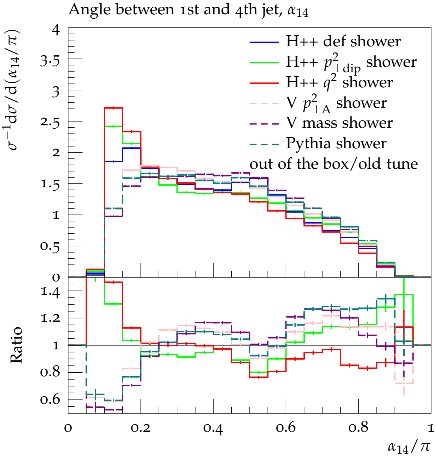
- $y_{3\to4} > 0.0045$ to minimize influence of hadronization and B decays
- All events clustered into 4 jets
- $\alpha_{12/13} > 2\pi/3$
  (1st and 2nd / 1st and 3rd
  jet back-to-back)
  $\alpha_{23} < \pi/6$
  (2nd and 3rd jet collinear)
- Angle between 1st and 4th jet: α_{14}

[J Alcaraz Maestre et al, 1203.6803]





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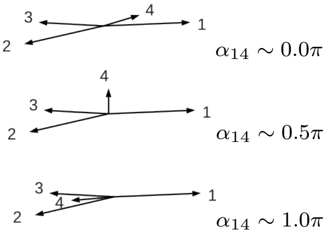

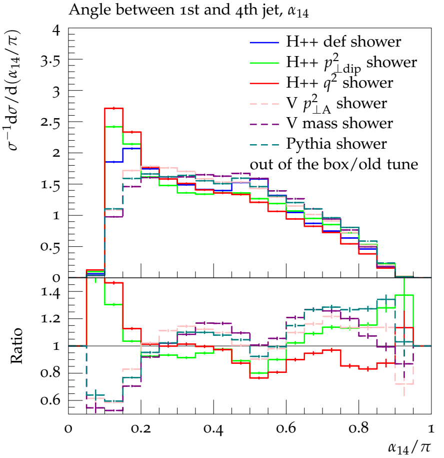

Tuning: Observables and χ^2/N_{dof}

- Aim: Similarly well description of the same LEP data by all showers
- Professor framework [A Buckley et al, 0907.2973]
- Observables:
  - \- Event shapes (ALEPH, DELPHI) [ALEPH Coll., PRPLC,294,1], [DELPHI Coll., ZEPYA,C73,11]
  - \- Jet rates (OPAL) [JADE Coll., OPAL Coll., HEP-EX/0001055]
  - \- Identified particle spectra (ALEPH) [DELPHI Coll., ZEPYA,C73,11]
  - \- b quark fragmentation functions (ALEPH) [ALEPH Coll., HEP-EX/0106051]
  - \- Mean particle multiplicities (PDG) [Particle Data Group, PHLTA,B667,1]

χ^2/N_{dof}	Default	Tune
HERWIG++ Angular Ordered Default Shower	20.2	16.9
HERWIG++ $p^2_{\perp\text{dip}}$-Ordered Dipole Shower	348.5	23.0
HERWIG++ q^2-Ordered Dipole Shower	358.2	25.3
VINCIA $p^2_{\perp\text{A}}$-Ordered Shower	9.1	7.0
VINCIA Mass-Ordered Shower	14.6	9.3
PYTHIA8 Shower	8.0	7.4

Tuning, Effect of Hadronization

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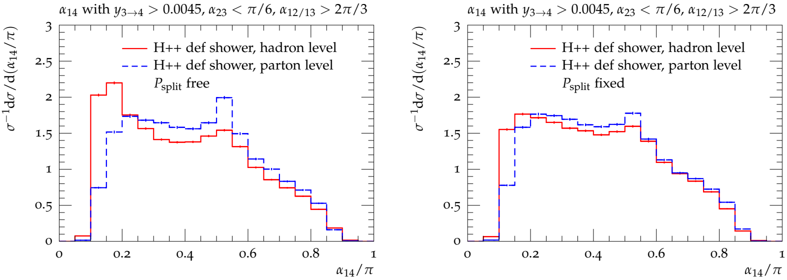
← due to keeping P_{split} fixed ↓



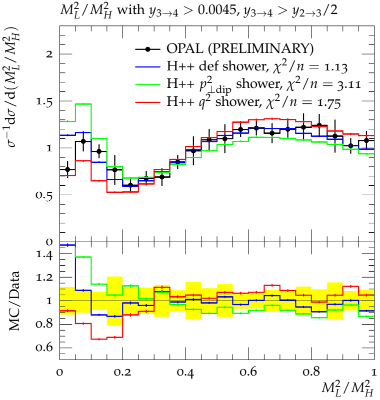
Data Analysis

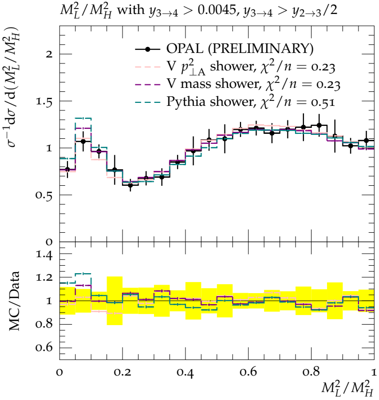
- Framework for reconstructing, analysing and correcting OPAL data

  [OPAL Coll., HEP-EX/0503051]
- Data set covers LEP2 run $\Rightarrow$ $\sim 400\,000$ event samples @ 91.2 GeV
- Selection of Events
  - Various criteria for tracks and clusters to select hadronic Z^0 decays
  - Containment cut $|\cos\theta_T| < 0.9$
- Reconstruction and Correction
  - Events reconstructed with energy flow algorithm
  - Detector correction: PYTHIA6 events with detector simulation

    $\Rightarrow$ Ratio (hadron level / detector level) for each bin for each observable
- Systematic Uncertainties (ordered in decreasing effect)
  1. Detector correction with HERWIG
  2. Variation of the reconstruction procedure
  3. Variation of the containment cut $|\cos\theta_T| < 0.7$

Data Plots: M_L^2/M_H^2 with tuned parameters





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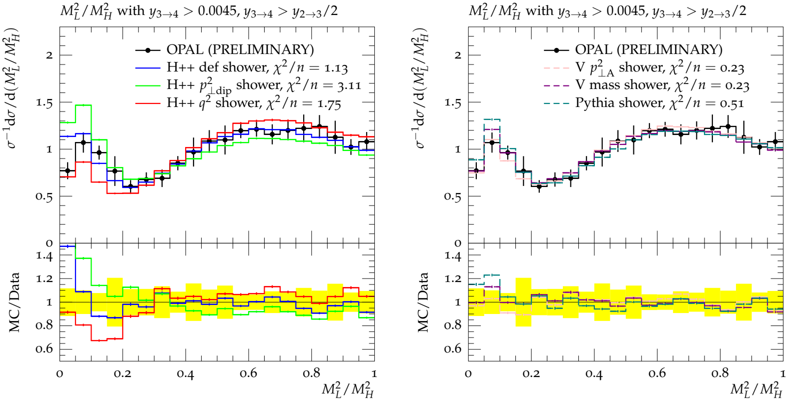

$\Rightarrow$ Reduce to easier Observable = Asymmetry:

$$AS(x) = \frac{N_{\text{left}}}{N_{\text{right}}} = \frac{\sum\limits_{x<x_0} y(x)}{\sum\limits_{x>x_0} y(x)}$$ for different asymmetry axis x_0

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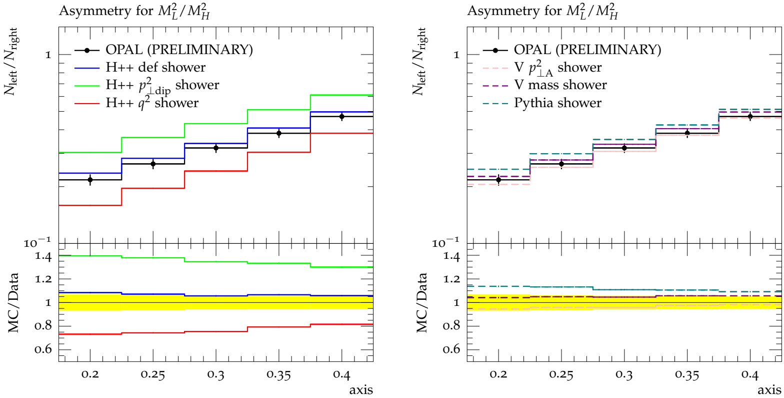

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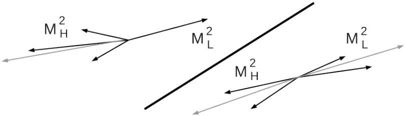
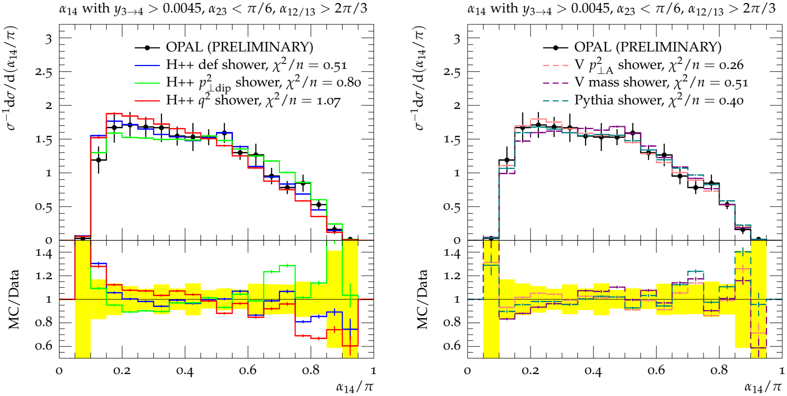
$$AS(x) = \frac{N_{\text{left}}}{N_{\text{right}}} = \frac{\sum\limits_{x<x_0} y(x)}{\sum\limits_{x>x_0} y(x)} \approx$$



Data Plots: α_{14} with tuned parameters



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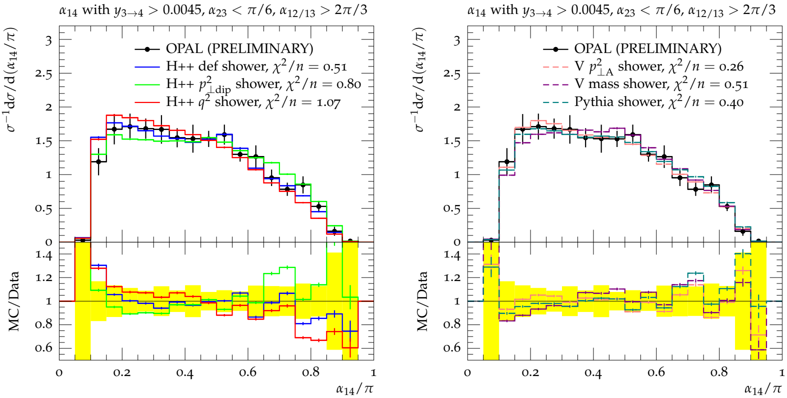


⇒ Reduce to easier Observable = Division of different regions:

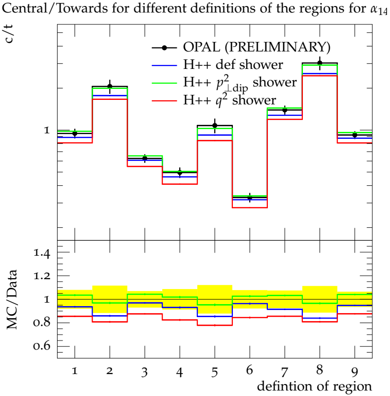
$$AS(x) = \frac{\sum\limits_{x_1<x<x_2} y(x)}{\sum\limits_{x_3<x<x_4} y(x)}$$

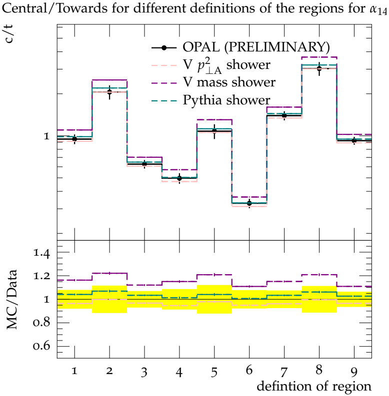
Towards region (t): 1st and 4th jet collinear

Away region (a): 1st and 4th jet back-to-back

Central region (c): 1st jet approx. ⊥ 4th jet

Data Plots: α_{14} with tuned parameters


Central/Towards for different definitions of the regions for α_{14}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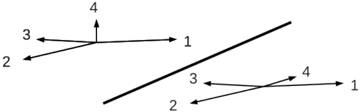

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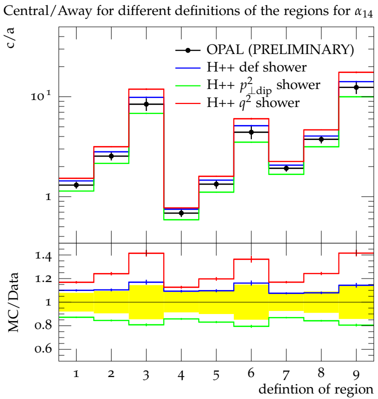
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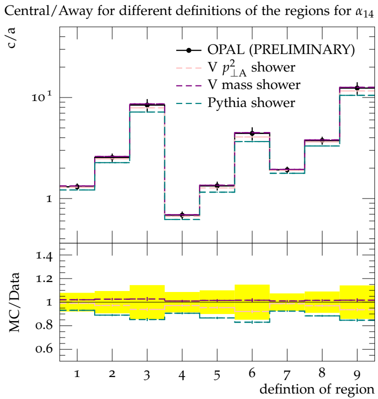
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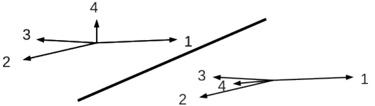


Conclusion

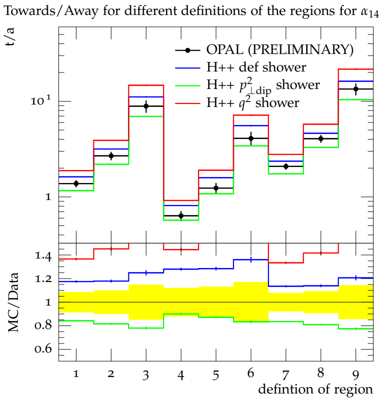
- Proposed new observables for measurement of soft shower properties
- Measurement of the new observables (OPAL data)
- MCs provide (mostly) consistent and good description of the data
- Hadronization effects showing up in new observables for HERWIG++
- Possibility to discriminate between the showers on hadron level
  ⇒ complete error analysis in the data?!

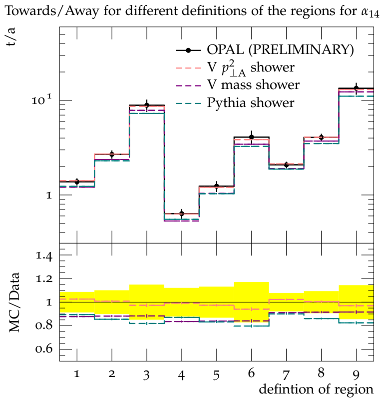
Additional Slides

α_{14}: Definitions of the Regions

		Central/Towards	Central/Away	Towards/Away
#	Central Region	Towards Region	Away Region	Towards region
1	$0.4 < \alpha_{14}/\pi < 0.6$	$\alpha_{14}/\pi < 0.3$	$\alpha_{14}/\pi > 0.6$	$\alpha_{14}/\pi < 0.3$
2	$0.4 < \alpha_{14}/\pi < 0.6$	$\alpha_{14}/\pi < 0.2$	$\alpha_{14}/\pi > 0.7$	$\alpha_{14}/\pi < 0.3$
3	$0.4 < \alpha_{14}/\pi < 0.6$	$\alpha_{14}/\pi < 0.4$	$\alpha_{14}/\pi > 0.8$	$\alpha_{14}/\pi < 0.3$
4	$0.45 < \alpha_{14}/\pi < 0.55$	$\alpha_{14}/\pi < 0.3$	$\alpha_{14}/\pi > 0.6$	$\alpha_{14}/\pi < 0.2$
5	$0.45 < \alpha_{14}/\pi < 0.55$	$\alpha_{14}/\pi < 0.2$	$\alpha_{14}/\pi > 0.7$	$\alpha_{14}/\pi < 0.2$
6	$0.45 < \alpha_{14}/\pi < 0.55$	$\alpha_{14}/\pi < 0.4$	$\alpha_{14}/\pi > 0.8$	$\alpha_{14}/\pi < 0.2$
7	$0.35 < \alpha_{14}/\pi < 0.65$	$\alpha_{14}/\pi < 0.3$	$\alpha_{14}/\pi > 0.6$	$\alpha_{14}/\pi < 0.4$
8	$0.35 < \alpha_{14}/\pi < 0.65$	$\alpha_{14}/\pi < 0.2$	$\alpha_{14}/\pi > 0.7$	$\alpha_{14}/\pi < 0.4$
9	$0.35 < \alpha_{14}/\pi < 0.65$	$\alpha_{14}/\pi < 0.4$	$\alpha_{14}/\pi > 0.8$	$\alpha_{14}/\pi < 0.4$

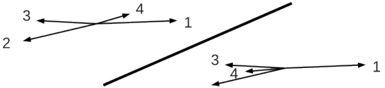
Data Plots: α_{14} with tuned parameters





⇒ Reduce to easier Observable = Devision of different regions:

$$AS(x) = \frac{\sum\limits_{x_1<x<x_2} y(x)}{\sum\limits_{x_3<x<x_4} y(x)} \approx$$



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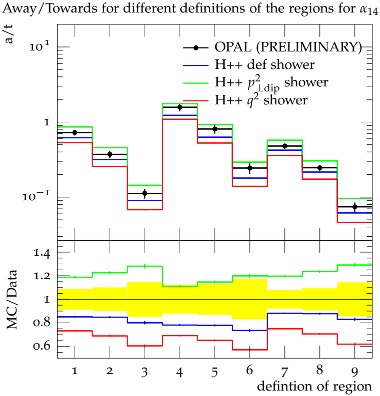

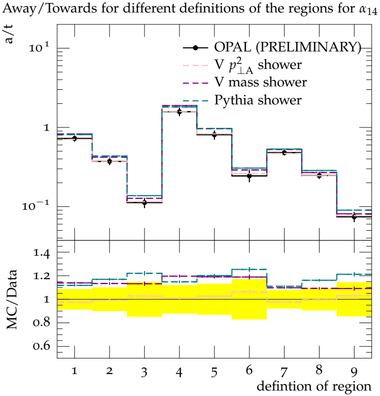

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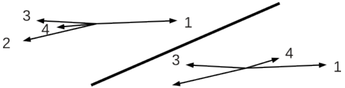
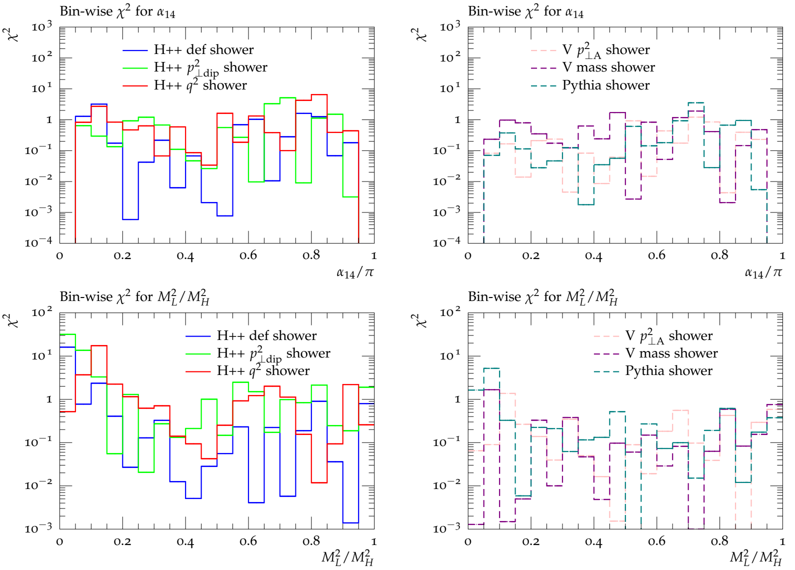
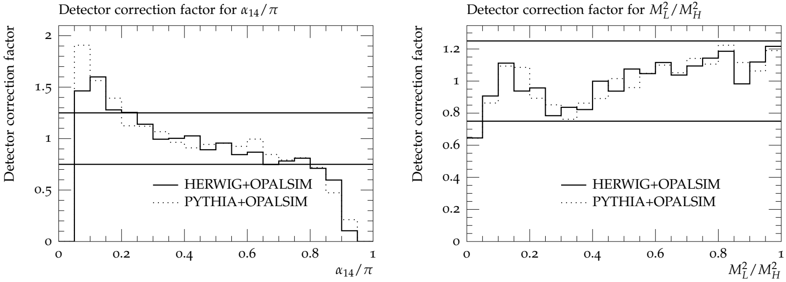


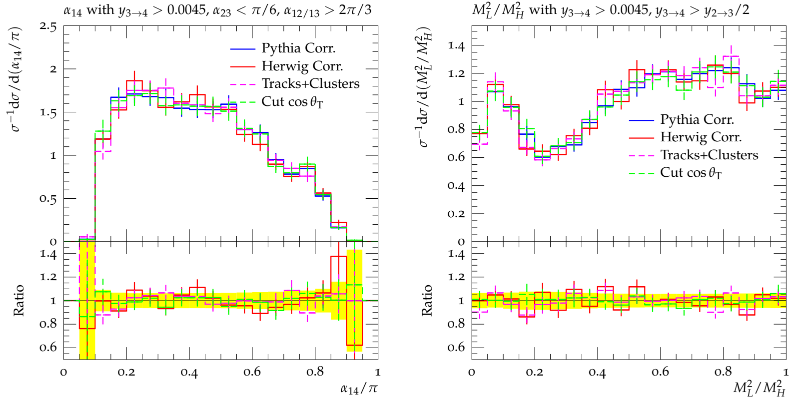
Bin-wise χ^2



Detector correction factor



Systematic Uncertainties



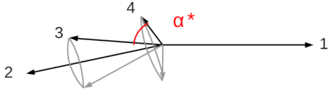
Systematic Uncertainties (ordered in decreasing contribution)

1. Detector correction with HERWIG
2. Variation of the reconstruction procedure
3. Variation of the containment cut $|\cos\theta_T| < 0.7$

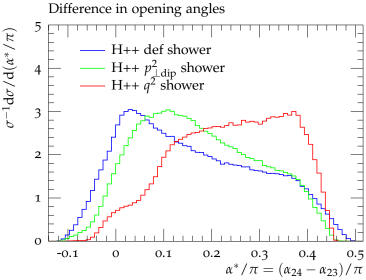
Parton Level Observable

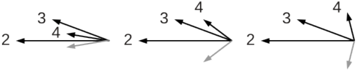
[S Plätzer, S Gieseke, 0909.5593]

- ME: $e^+e^- \to q\bar{q}$ for 5 flavours $(u,\ d,\ c,\ s,\ b)$ @ 91.2 GeV
- All higher jets produced by shower (no matching)
- 4 parton events, ordered in energy (1st parton is hardest)
- $E_4 < E_{\text{tot}}/10$ (4th jet soft),
  $\alpha_{23} < \pi/8$ (2nd and 3rd jet collinear),
  $\alpha_{24} < \pi/2$ (4th jet emitted by dipole 2-3)



- Difference in opening angles:
  $\alpha^* = \alpha_{24} - \alpha_{23}$





⇒ Similar observable on hadron level?

Tuning Observables: Event Shapes

Observable	Weight
In-plane $p_\perp$ in GeV w.r.t. sphericity axes	1.0
In-plane $p_\perp$ in GeV w.r.t. thrust axes	1.0
Out-of-plane $p_\perp$ in GeV w.r.t. sphericity axes	1.0
Out-of-plane $p_\perp$ in GeV w.r.t. thrust axes	1.0
Mean out-of-plane $p_\perp$ in GeV w.r.t. thrust axis vs. x_p	1.0
Mean $p_\perp$ in GeV vs. x_p	1.0
Scaled momentum $x_p = \|p\|/\|p_{\text{beam}}\|$	1.0
Log of scaled momentum, $\log(1/x_p)$	1.0
Energy-energy correlation, EEC	1.0
Sphericity, S	1.0
Aplanarity, A	2.0
Planarity, P	1.0
D parameter	1.0
C parameter	1.0
1-Thrust	1.0
Thrust major, M	1.0
Thrust minor, m	2.0
Oblatness, $O = M - m$	1.0
Charged multiplicity distribution	2.0
Mean charged multiplicity	150.0

Tuning Observables: Particle Spectra, Jet Rates and B Observables

Observable	Weight
$K^{*\pm}(892)$ spectrum	1.0
ρ spectrum	1.0
$\omega(782)$ spectrum	1.0
Ξ^- spectrum	1.0
K^{*0} spectrum	1.0
ϕ spectrum	1.0
$\Sigma^\pm$ spectrum	1.0
γ spectrum	1.0
$K^\pm$ spectrum	1.0

Observable	Weight
Λ^0 spectrum	1.0
π^0 spectrum	1.0
p spectrum	1.0
η' spectrum	1.0
$\Xi^0(1530)$ spectrum	1.0
$\pi^\pm$ spectrum	1.0
η spectrum	1.0
K^0 spectrum	1.0

Observable	Weight
Differential 2-jet rate	2.0
Differential 3-jet rate	2.0

Observable	Weight
Differential 4-jet rate	2.0
Differential 5-jet rate	2.0

Observable	Weight
b quark fragmentation function $f(x_B^{\text{weak}})$	7.0
Mean of b quark fragmentation function $f(x_B^{\text{weak}})$	3.0

Tuning Observables: Mean multiplicities

Observable	Weight
$\rho^0(770)$	10.0
$\Delta^{++}(1232)$	10.0
$K^{*+}(892)$	10.0
Σ^0	10.0
Λ_b^0	10.0
K^+	10.0
$\Xi^0(1530)$	10.0
$\Lambda(1520)$	10.0
$D_s^{*+}(2112)$	10.0
$\Sigma^-(1385)$	10.0
$f_1(1420)$	10.0
$\phi(1020)$	10.0
K_2^{*0}	10.0
Ω^-	10.0
$\Sigma^\pm(1385)$	10.0
$\psi(2S)$	10.0
D^{*+}	10.0

Observable	Weight
$\chi_{c1}(3510)$	10.0
D^+	10.0
Σ^+	10.0
$f_1(1285)$	10.0
$f_2(1270)$	10.0
$J/\psi(1S)$	10.0
B_u^+	10.0
$B^*{*}$	10.0
Λ_c^+	10.0
D^0	10.0
$f_2'(1525)$	10.0
$\Sigma^\pm$	10.0
D_{s2}^+	10.0
$K^{*0}(892)$	10.0
Σ^-	10.0
π^+	10.0
$f_0(980)$	10.0

Observable	Weight
B^*	10.0
π^0	10.0
η	10.0
$a_0^+(980)$	10.0
D_{s1}^+	10.0
$\rho^+(770)$	10.0
Ξ^-	10.0
$\omega(782)$	10.0
$\Upsilon(1S)$	10.0
$\Sigma^+(1385)$	10.0
D_s^+	10.0
p	10.0
B_s^0	10.0
K^0	10.0
B^+, B_d^0	10.0
Λ	10.0
$\eta'(958)$	10.0

Tuning Parameters HERWIG++

	Default	Range	Angular Ordering Tune
α_{M_Z}	0.120	$0.100 - 0.125$	0.123
$p_{\mathrm{T}}^{\mathrm{min}}$	1.00 GeV	$(0.50 - 1.50)$ GeV	1.39 GeV
$m_{g,c}$	0.95 GeV	$(0.67 - 3.00)$ GeV	0.70 GeV
$\mathrm{Cl}_{\mathrm{max}}$	3.25 GeV	$(2.00 - 4.50)$ GeV	3.59 GeV
$\mathrm{Cl}_{\mathrm{pow}}$	1.28	$2.00 - 10.00$	2.59
P_{split}	1.14	fixed	0.60

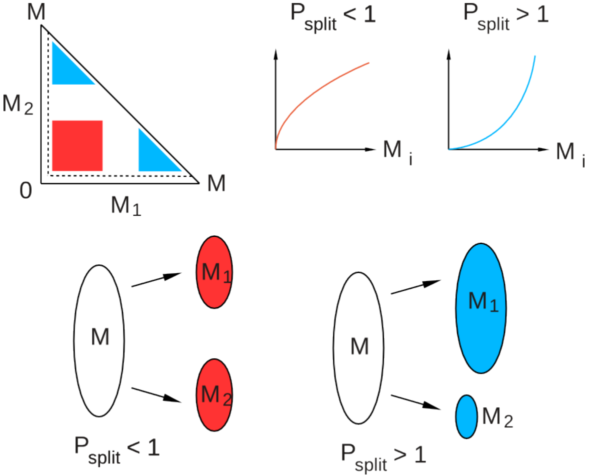
	Default	Range	$p^2_{\perp \mathrm{dip}}$-Ordering Tune	q^2-Ordering Tune
α_{M_Z}	0.113	$0.100 - 0.138$	0.128	0.138
$\mu_{\mathrm{IR},FF}$	1.41 GeV	$(0.50 - 2.00)$ GeV	0.78 GeV	0.72 GeV
$m_{g,c}$	1.08 GeV	$(0.67 - 3.00)$ GeV	0.70 GeV	0.96 GeV
$\mathrm{Cl}_{\mathrm{max}}$	4.17 GeV	$(2.00 - 4.50)$ GeV	3.12 GeV	2.73 GeV
$\mathrm{Cl}_{\mathrm{pow}}$	5.73	$2.00 - 10.00$	5.72	2.00
P_{split}	0.77	$0.00 - 1.40$	0.74	1.33

Tuning Parameters PYTHIA8 and VINCIA

	Default	Range	PYTHIA8 Tune
α_S	0.138	$0.120 - 0.139$	0.139
$p_{\mathrm{T}}^{2\,\mathrm{min}}$	0.40	$0.40 - 1.00$	0.41
a_{L}	0.30	$0.20 - 0.70$	0.35
b_{L}	0.80	$0.50 - 1.50$	0.94
a_{ED}	0.50	$0.50 - 0.10$	0.95
σ	0.304	$0.200 - 0.400$	0.284

			VINCIA	
	Default	Range	$p^2_{\perp \mathrm{A}}$-Ordering Tune	Mass-Ordering Tune
α_S	0.129	$0.120 - 0.132$	0.132	0.132
$p_{\mathrm{T}}^{2\,\mathrm{min}}$	0.60	$0.46 - 1.00$	0.65	0.84
a_{L}	0.38	$0.20 - 0.70$	0.26	0.47
b_{L}	0.90	$0.50 - 1.50$	0.74	0.82
a_{ED}	1.00	$0.50 - 0.10$	0.93	0.50
σ	0.275	$0.200 - 0.400$	0.270	0.294

Tuning Parameter: P_{split}



$M_1 = m_1 + (M - m_1 - m_q)\mathcal{R}_1^{1/\text{P}_{\text{split}}}$ and $M_2 = m_2 + (M - m_2 - m_q)\mathcal{R}_2^{1/\text{P}_{\text{split}}}$