Rapidity Gaps

and

Colour (Re-)Connection

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(L3 Collaboration)

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most work by

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All results are PRELIMINARY

IPP Workshop on
Multiparticle Production in QCD Jets

Durham

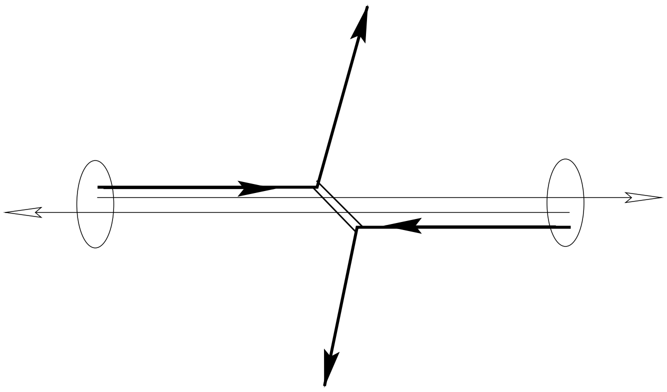
14 December 2001

Rapidity gaps in Z decays

- 10% of di-jet events from ep collision have large rapidity gap (HERA)
- 1% of events with 2 High E_T jets have large rapidity gap in $p\bar{p}$ collisions (TEVATRON)

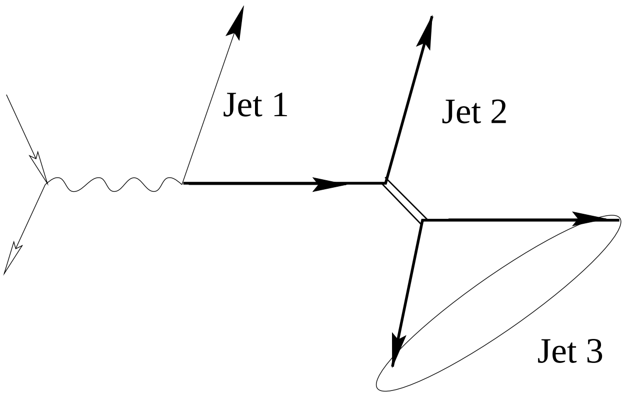
Possible Explanation: *Colour singlet exchange*

$p\bar{p}$:



Colour singlet exchange in hadronic Z decays?

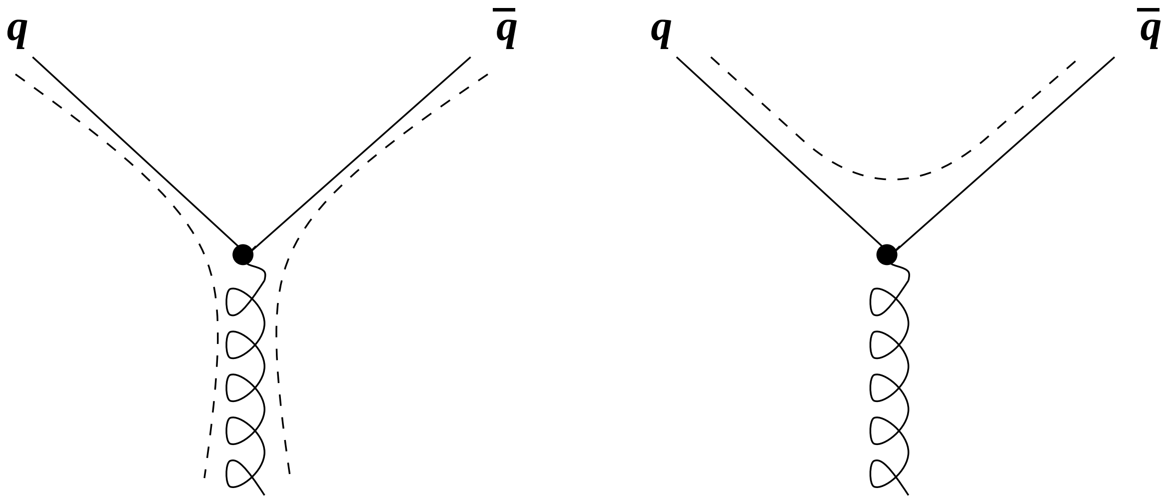
$e^- e^+$:



Study Gaps in 3 jet events in $e^- e^+$ annihilation

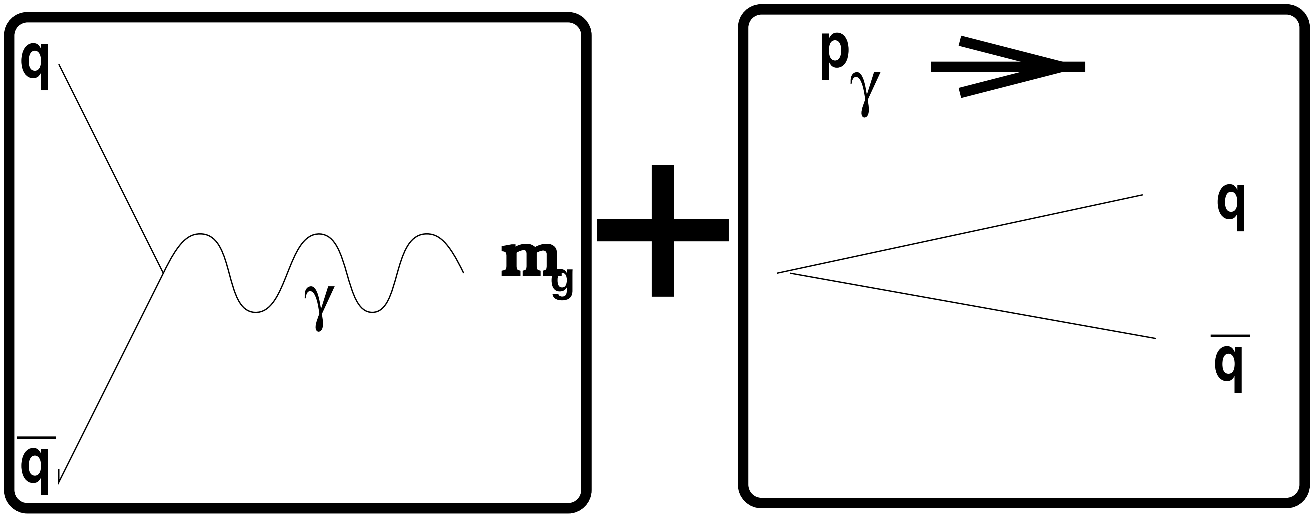
- Clean environment ⇒ No underlying *minimum bias* event
- Not plagued by "gap survival probability" ($\sim$ 50% in $p\bar{p}$)

Rapidity gaps in Z decays



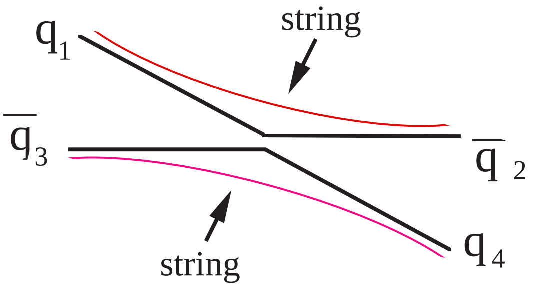
Colour Octet *Colour Singlet*

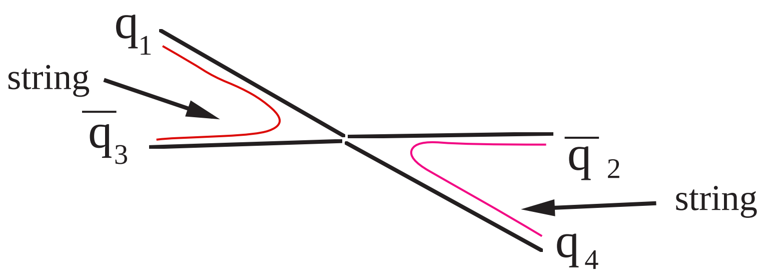
- Colour octet simulated using JETSET Parton Shower program
- Model colour singlet exchange as:



OPTION	Nature of Fragmentation
CS0	$q\bar{q}$ generated in gluon rest frame, boosted back to the overall CMS, then usual parton shower.
CS2	The gluon is fragmented as a single jet.

Colour Reconnection

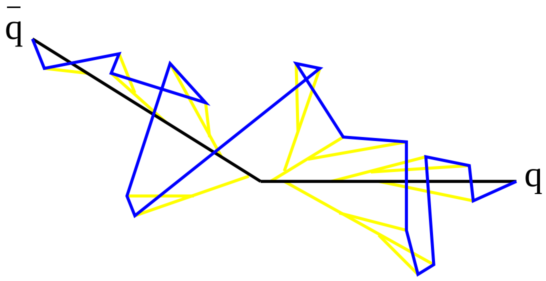


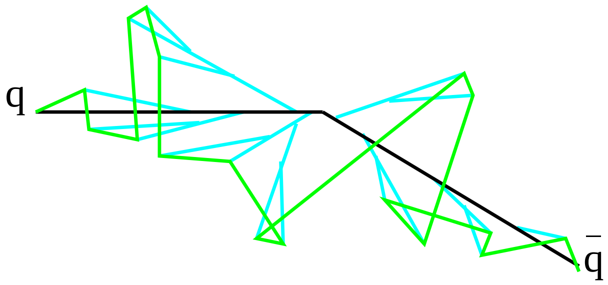


$\mathrm{WW} \to q\bar{q}q\bar{q}$

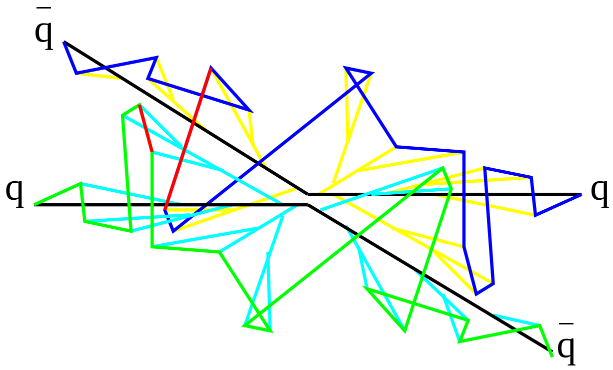
Immediate reconnection
Very unlikely

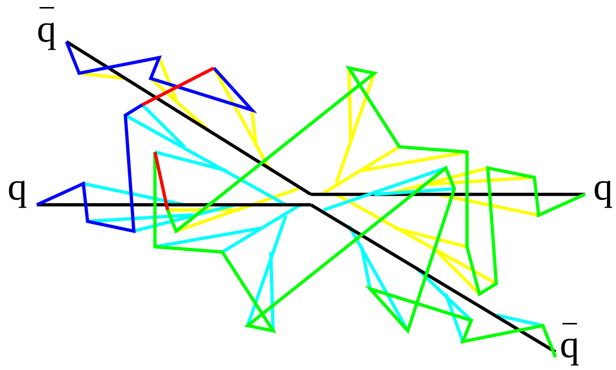
As parton shower progresses, we get more (soft) gluons.





And reconnection is more likely.





Reconnection is most likely near end of parton shower or in non-perturbative hadronization

A Colour Reconnection Model

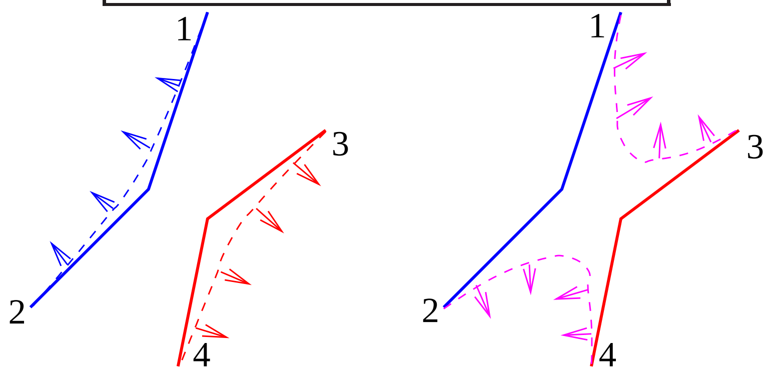
Rathsman Model: based on Generalised Area Law

"Area" of string between partons i, j $A_{ij} = 2\,(p_i p_j - m_i m_j)$

➪ reduces to $(E + |p_z|)^2$ in CM system (along z-axis)

String-reinteractions probability: $P = R_0\,[1 - \exp(-b \cdot dA)]$

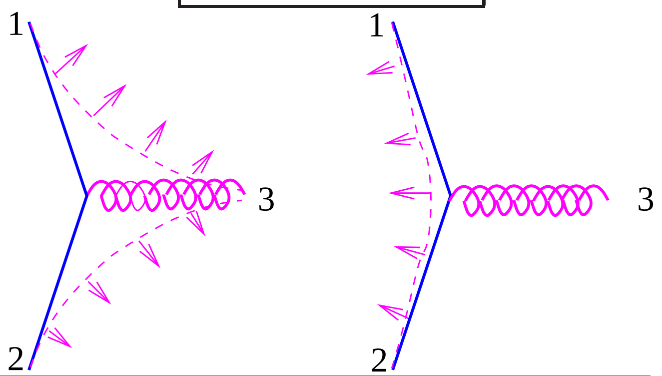
$\boxed{e^- e^+ \to W^- W^+ \to q\bar{q}q\bar{q}}$



$\Delta A = (A_{13} + A_{24}) - (A_{12} + A_{34})$

$\Rightarrow$ shift in W-mass $\sim \mathcal{O}$ (65 MeV)

$\boxed{e^- e^+ \to q\bar{q}g}$



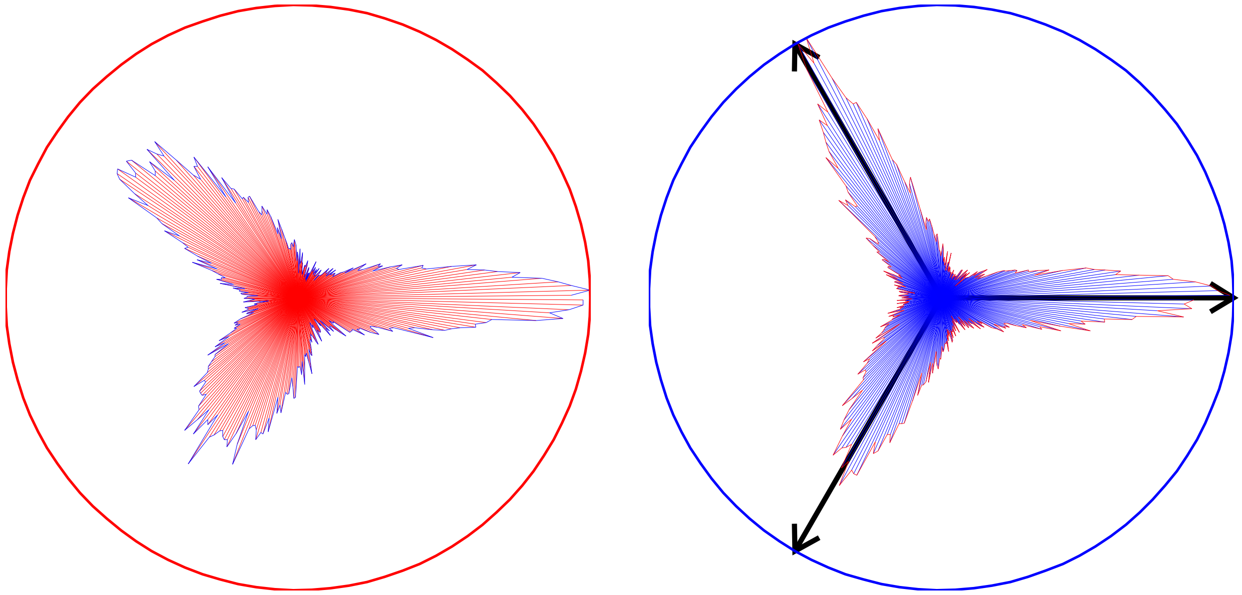
$\Delta A = A_{12} - (A_{13} + A_{23})$

$\Rightarrow$ Colour singlet exchange

☞ Fragmentation Parameters *tuned* for $R_0 = 0.1$

Rapidity gaps in Z decays

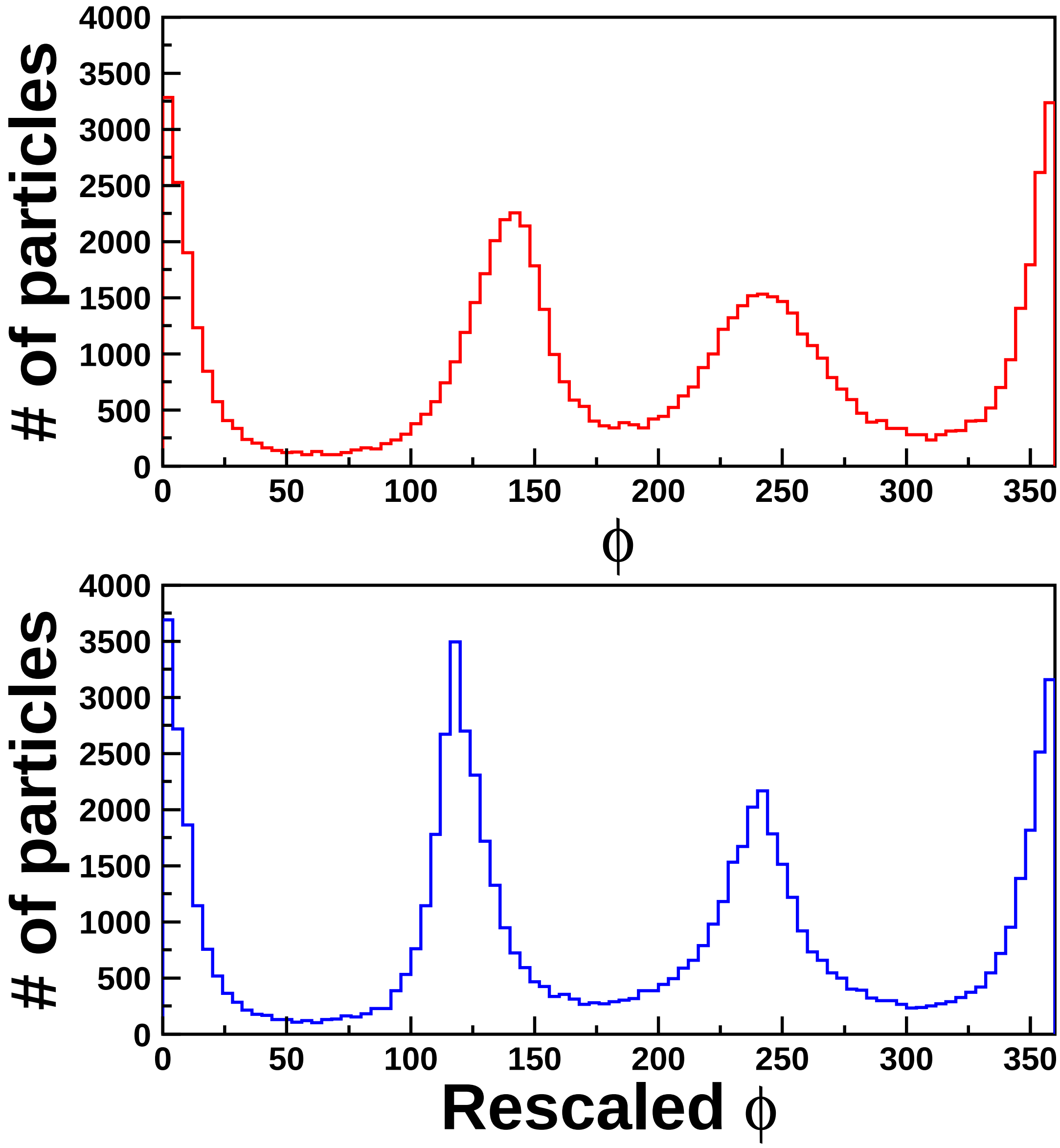
- ❑ Apply a jet algorithm (Use JADE as default and DURHAM for systematics) at fixed y_{cut} value(s)
- ❑ Select 3-jet event and demand symmetric configuration by imposing cuts on jet separation angles
- ❑ Define *event plane* by the 2 most energetic jets with the most energetic jet along x-axis
- ❑ Project the particle momenta in the event plane
  $\Rightarrow$ *Flower Plot*



- ❑ For event-by-event comparison, *rescale angles* so as to align the 3-jet axes along 0°, 120°, 240°

Rapidity gaps in Z decays

More conventionally:



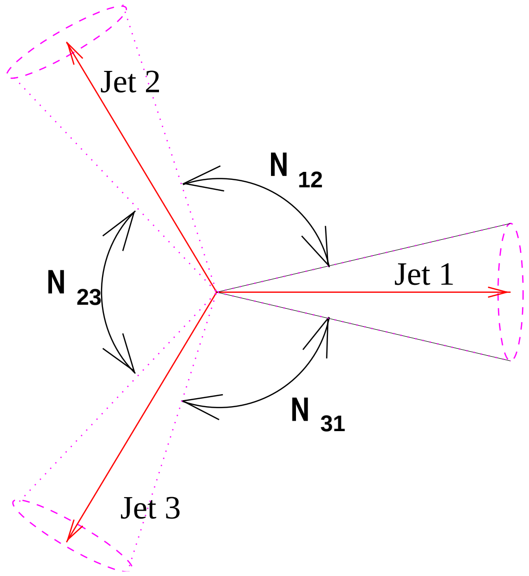
➠ Study particle flow in the "Gaps" (inter-jet regions)

➥ To reduce effects from fragmentation fluctuation, ignore core of the jet defined by a cone around the 3 jet directions

➥ Two cone definitions are used: Half angle of 15°, 20°

Sensitive Variables

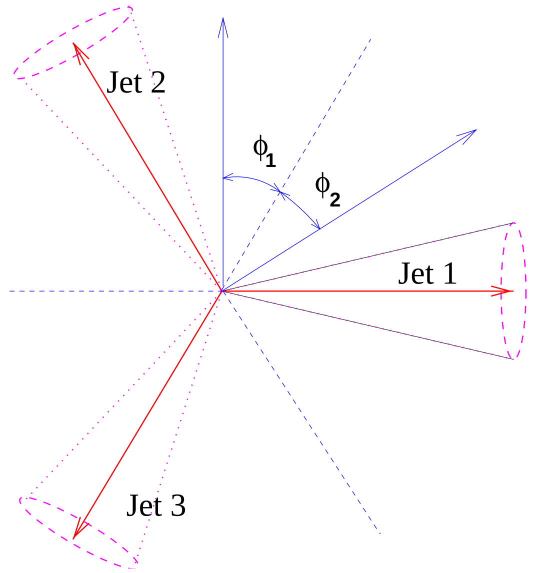
Number of particles in GAP ij, N_{ij}
Particle Asymmetry in GAP 12:



$$A^{\mathsf{N}}_{12} = \frac{-N_{12} + N_{23} + N_{31}}{N_{12} + N_{23} + N_{31}}$$

Similarly, A^{N}_{23}, A^{N}_{13},

Angle from bisector in GAP ij,
$B_{ij} = \min(\phi_1, \phi_2, \phi_3, \ldots)$
Angular Asymmetry in GAP 12:



$$A^{\mathsf{B}}_{12} = \frac{-B_{12} + B_{23} + B_{31}}{B_{12} + B_{23} + B_{31}}$$

Similarly, A^{B}_{23}, A^{B}_{13},

Alternative Angle definition for GAP ij,
Max. angular separation between adjacent particles, S_{ij}
with asymmetries A^{S}_{12}, A^{S}_{23}, A^{S}_{13}

Assuming jet 3 is g,

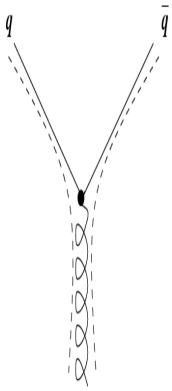
$$A_{\mathsf{q\bar{q}}} = A_{12} \qquad A_{\mathsf{qg}} = \frac{1}{2}(A_{13} + A_{23})$$

Sensitive Variables

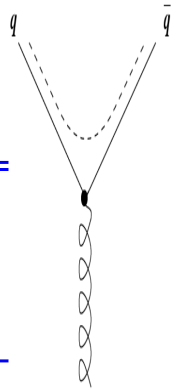
Colour Flow ⇒

- ➢ More particles (N)
- ➢ Smaller angular separation (Gap angle B & S)

Jets Ordered: Primary quarks in first 2 jets



OCTET	SINGLET
$N_{23} \approx N_{31} > N_{q\bar{q}}$ $A^{N}_{23} \approx A^{N}_{31} < A^{N}_{q\bar{q}}$	$N_{23} \approx N_{31} < N_{q\bar{q}}$ $A^{N}_{23} \approx A^{N}_{31} > A^{N}_{q\bar{q}}$
$B_{23} \approx B_{31} < B_{q\bar{q}}$ $A^{B}_{23} \approx A^{B}_{31} > A^{B}_{q\bar{q}}$	$B_{23} \approx B_{31} > B_{q\bar{q}}$ $A^{B}_{23} \approx A^{B}_{31} < A^{B}_{q\bar{q}}$
$S_{23} \approx S_{31} < S_{q\bar{q}}$ $A^{S}_{23} \approx A^{S}_{31} > A^{S}_{q\bar{q}}$	$S_{23} \approx S_{31} > S_{q\bar{q}}$ $A^{S}_{23} \approx A^{S}_{31} < A^{S}_{q\bar{q}}$

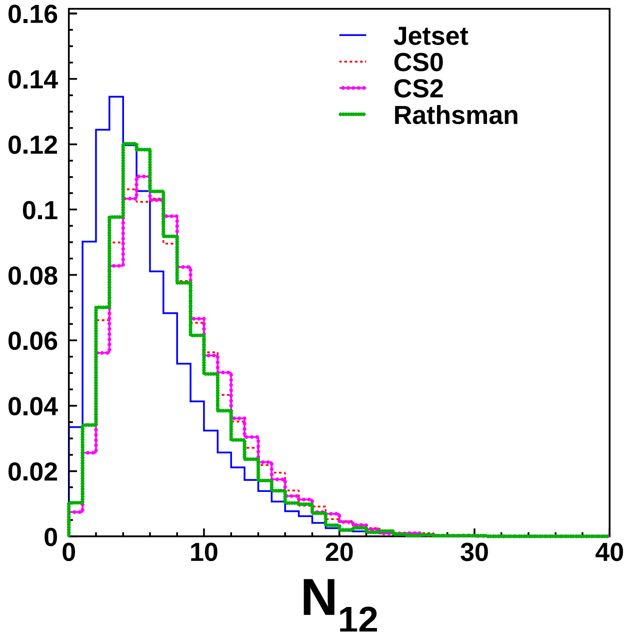


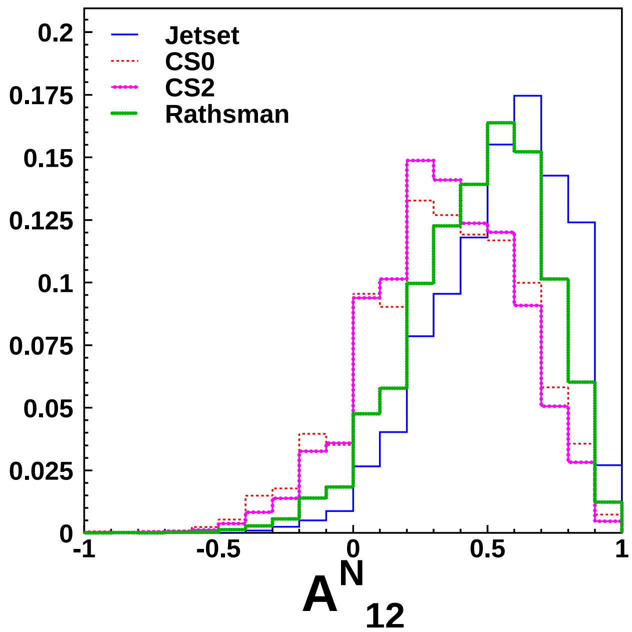
$<$No. of particles$>$

	Jetset	CS 0	CS 2	Rathsman
Total	56.5	54.2	54.8	58.0
$q\bar{q}$ Gap (15° cone)	5.5	7.3	7.4	6.8
Other Gap (15° cone)	9.1	7.3	7.2	9.2
$q\bar{q}$ Gap (20° cone)	4.1	5.7	5.8	5.3
Other Gap (20° cone)	7.3	5.7	5.8	7.4

Sensitive Variables

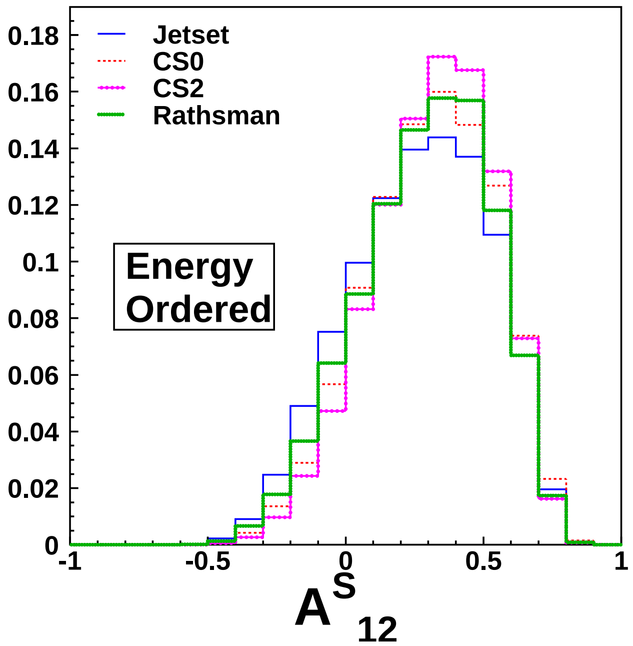
Particle Flow Asymmetry:

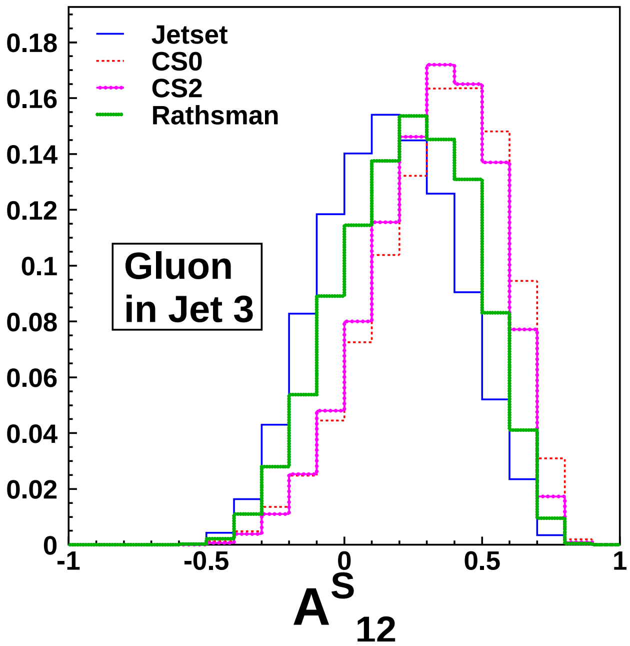




Asymmetries are sensitive to colour singlet exchange

Separation-angle Asymmetry:





Gluon purity in the third jet improves sensitivity

Data

❑ *Integrated luminosity*: $\boxed{\text{Lum} = 75.1\text{pb}^{-1}\ (1994{+}1995)}$

❑ *Hadronic Event Selection using*:

- Clusters in Calorimeters
- Charged-tracks

Selected Events	Clusters	Tracks
DATA	1,948K	1,744K
JETSET	5,637K	5,034K

❑ *Jets and selection of 3 Jet events*:

➡ JADE algorithm with $y_{cut} = 0.05$;
DURHAM ($k_\perp$) algorithm with $y_{cut} = 0.01, 0.02$

➡ Jet separation angle: $\theta_{12},\ \theta_{23},\ \theta_{31} \in [90^\circ,\ 150^\circ]$

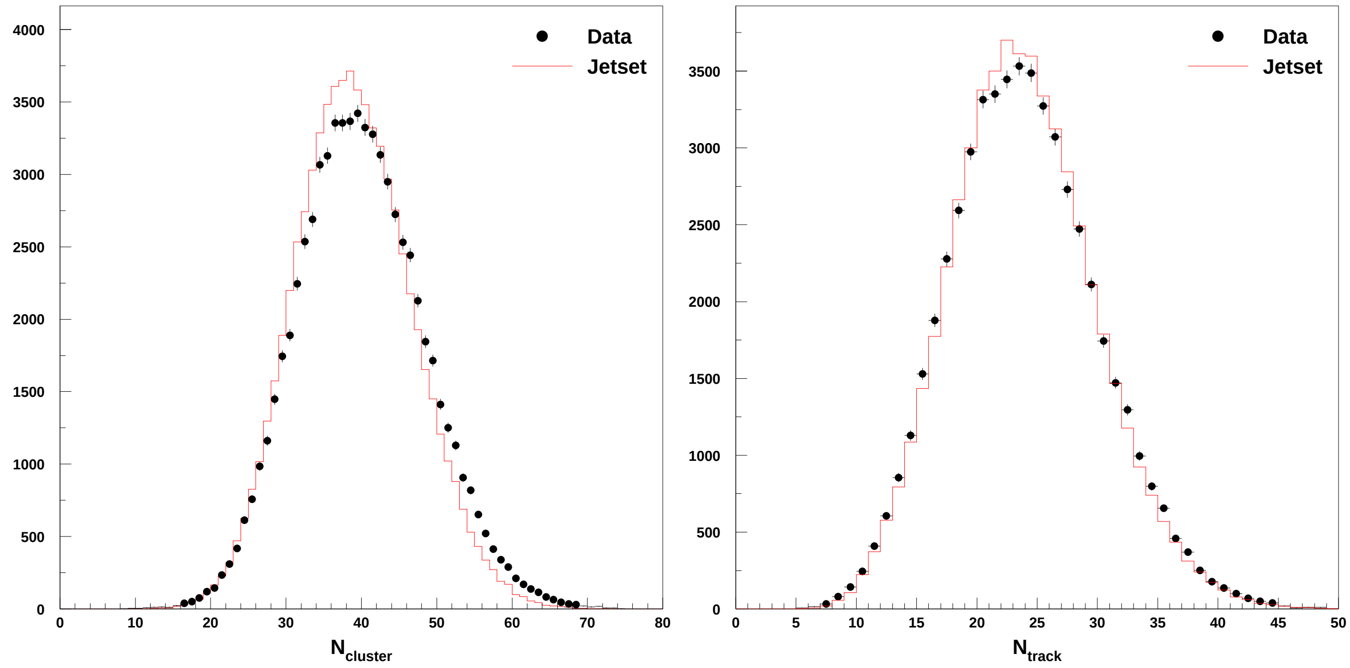
	Fraction of 3jet Mercedes events					
	Clusters			Tracks		
	JADE	$k_\perp$	$k_\perp$	JADE	$k_\perp$	$k_\perp$
y_{cut}	.05	.02	.01	.05	.02	.01
DATA	.036	.033	.028	.031	.026	.021
JETSET	.038	.035	.031	.032	.027	.023

Data

$\langle N_{\text{objects}} \rangle$:

	Data	Jetset
Clusters	39.51	38.53
Charged tracks	23.41	23.39

Multiplicity for Mercedes 3 jet events:



⇒ Clusters/tracks used as "objects" in the detector for cluster/track based selection

Data

Energy Ordering ($E_1 > E_2 > E_3$)

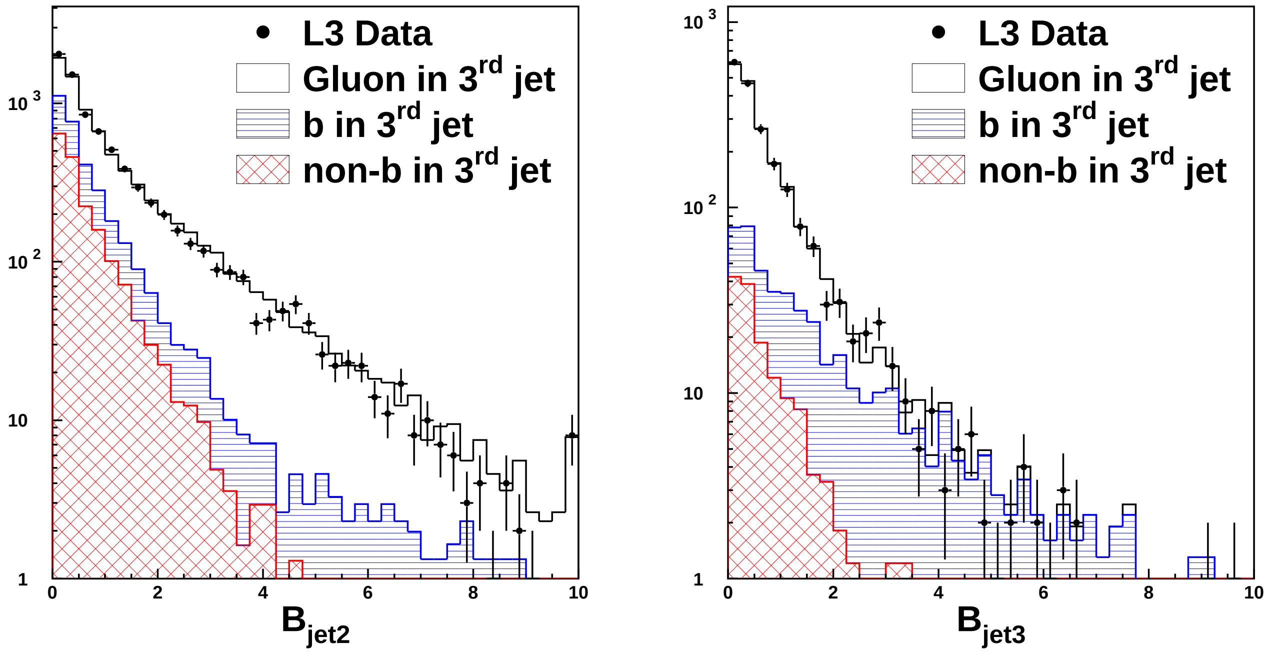
Probability (%) of gluon in third jet	Clusters	Tracks
All 3 jet Events	69	59
Mercedes Events	48	40

Anti-*B-tagging*

➩ Probability (P_i): track$_i$ consistent with zero lifetime

➥ flat for zero lifetime, peaks at 0 for lifetime > 0

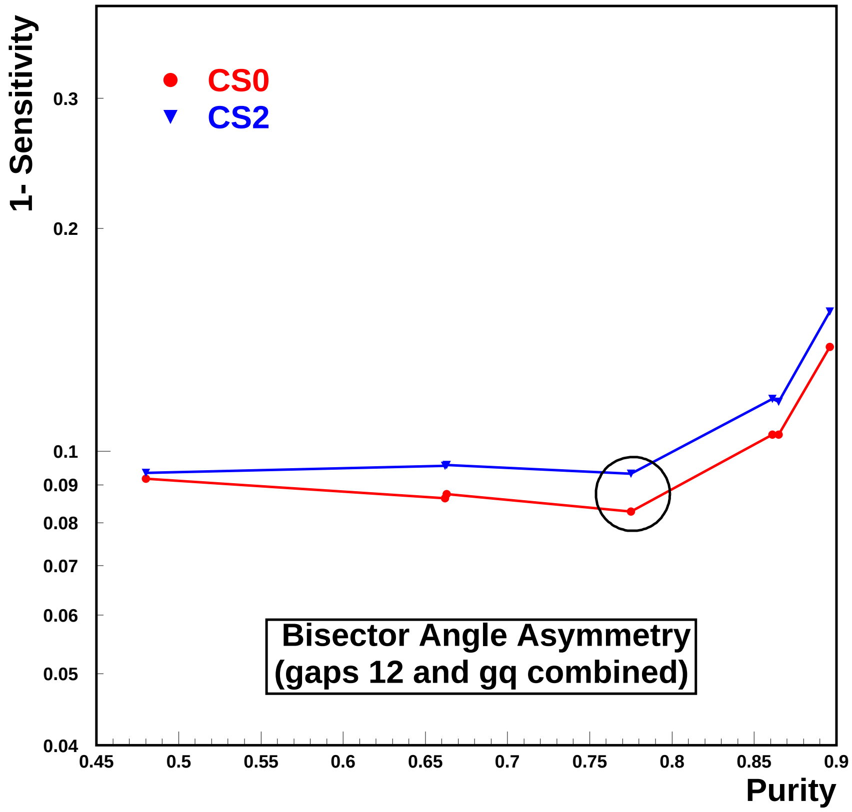
➠ *For each jet* weighted discriminant: $B_{jet} = -\log(\underbrace{\prod}_{i\in jet} P_i)$



Gluon Tag: B_{Jet1}, B_{Jet2} > CUT1, B_{JET3} < CUT2

Data

☞ CUTi *tuned* to get best sensitivity of measurement

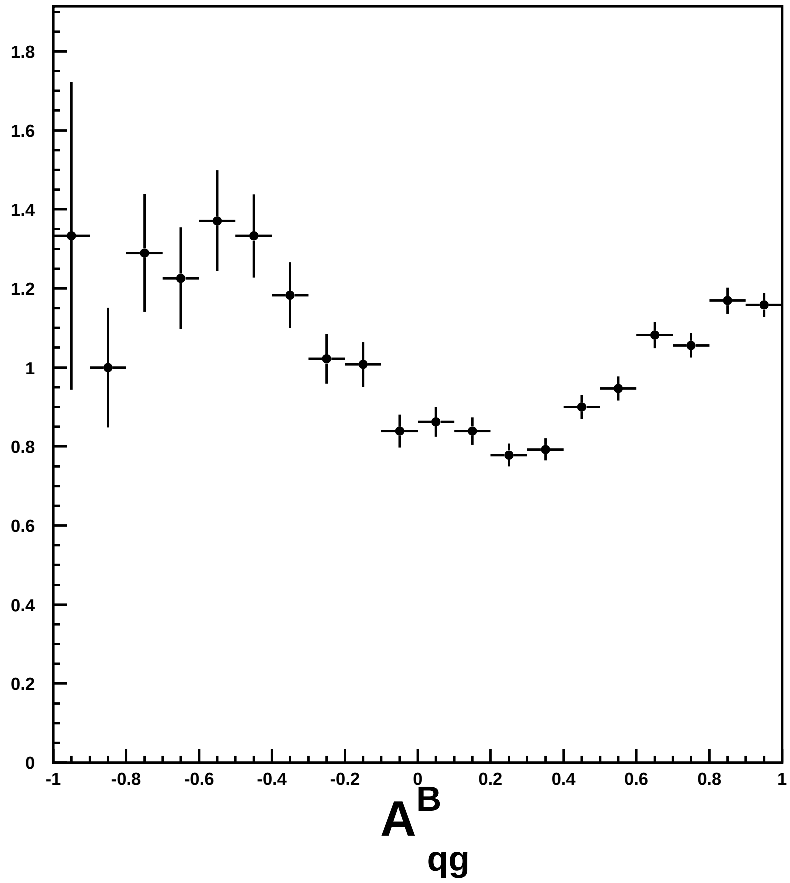


Optimized "Gluon" Tagged Event Statistics

	Clusters			Tracks		
B_{Jet2}	$\geq$ 1.25			$\geq$ 1.75		
B_{Jet3}	$\leq$ 1.50			$\leq$ 1.25		
y_{cut}	JADE .05	$k_\perp$ .02	$k_\perp$ .01	JADE .05	$k_\perp$ .02	$k_\perp$ .01
Π (%)	78	79	78	82	84	83
DATA	2668	2116	2516	2048	1507	1856

Data

Correct detector level distributions *bin-by-bin*

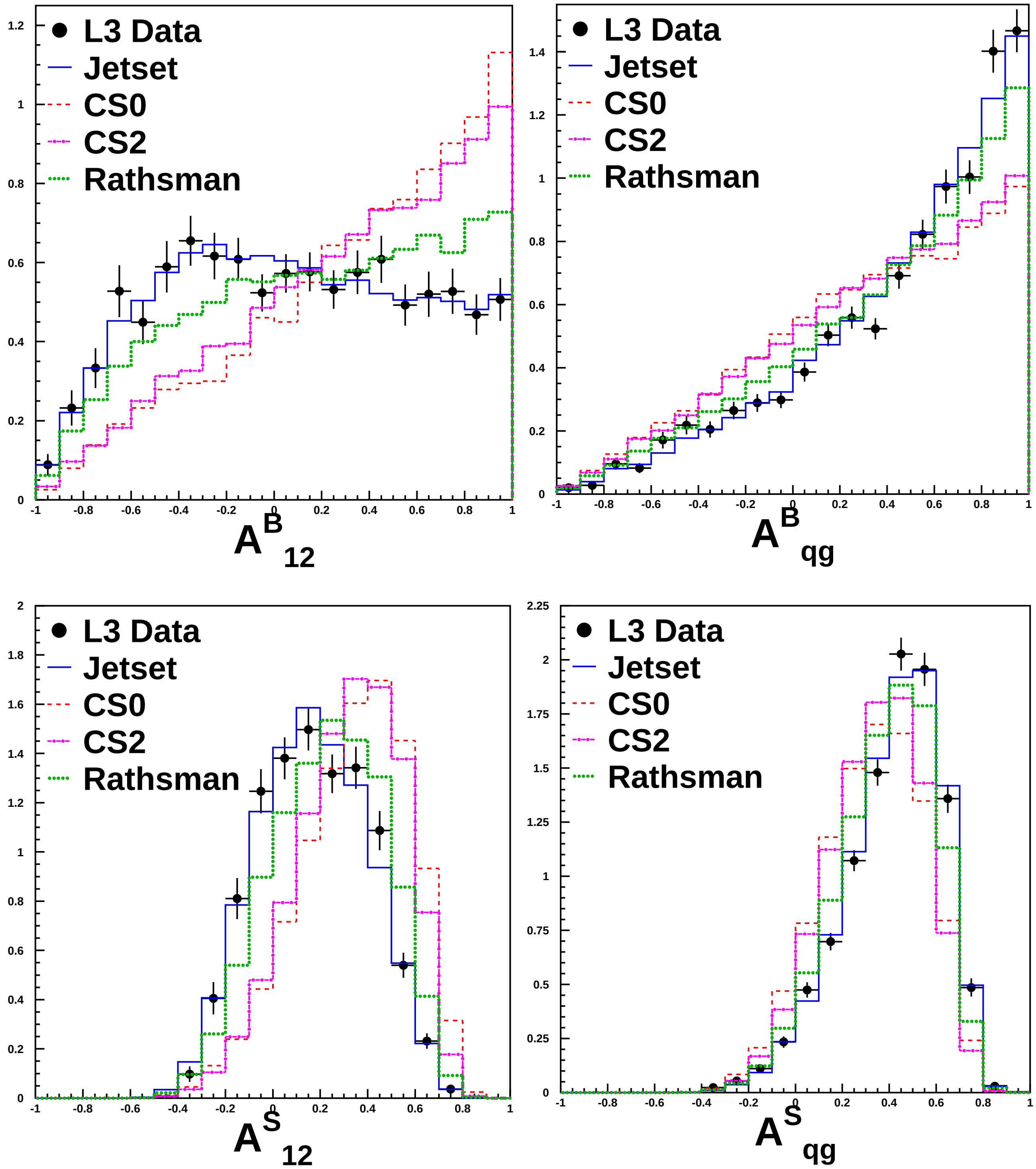


$\Rightarrow$ typical correction factor $\leq$ 20%

Systematic uncertainties (%)

Asymmetry	Jet	Gtag	Total
A^B_{12}	6.2	4.8	7.9
A^B_{qg}	5.8	3.2	6.6
A^S_{12}	7.2	8.1	10.9
A^S_{qg}	4.1	4.0	5.8

Results



Pure Colour Singlet Exchange disfavoured by Data

Results

Comparison of Models

Variable	Bins	χ^2 (Probability) Data Vs.	
		Jetset	Rathsman
A^B_{12}	20	6.2 (99%)	59.3 (5×10^{-6})
A^B_{qg}	19	16.9 (53%)	60.5 (2×10^{-6})
A^S_{12}	12	4.7 (94%)	77.8 (4×10^{-12})
A^S_{qg}	13	6.5 (89%)	47.2 (4×10^{-6})

JETSET explains trends in DATA

Determine CS fraction r by minimising χ^2

$$\chi^2(r) = \sum_i \frac{[f^i_{data} - r f^i_{CS0} - (1-r) f^i_{Jetset}]^2}{(\sigma^i_{stat})^2 + (\sigma_{syst} * f^i_{data})^2}$$

Fit to A^B_{12}: r $= 0.017 \pm 0.053$ (χ^2/d.o.f. $= 6.1/19$)

All estimates of r are compatible to 0

☞ Obtain 95% CL upper bound

Best limit obtained by a combined fit to (A^S_{12} and A^S_{qg}):

$R^{95\%} = 6.7$ (9.0) % for CS0 (CS2)

Conclusions - Rapidity Gaps

3-jet events from 2 million hadronic Z decays,
have been analyzed using
several asymmetry variables sensitive to colour flow.

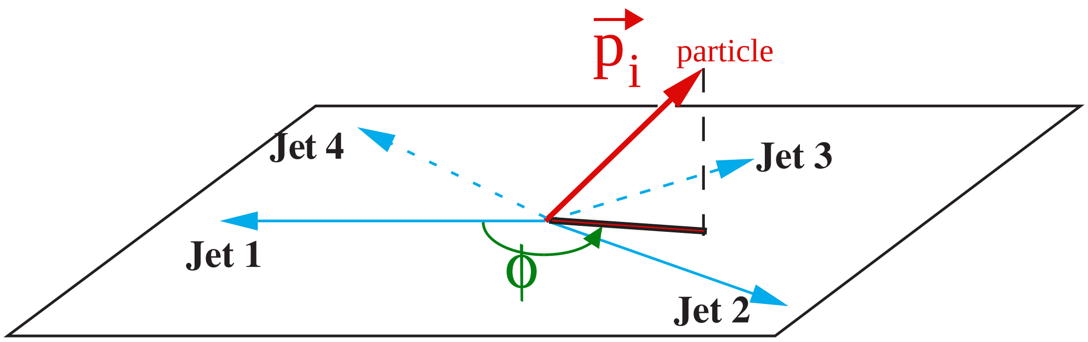
- Data are well explained by colour octet gluons alone.
- Colour singlet gluon contributes $\lesssim 8\%$, 95% CL.
- Rathsman model (with $R_0 = 0.1$) differs significantly from the data

Colour Reconnection in $W^+W^- \longrightarrow q\bar{q}q\bar{q}$

Particle/Energy Flow Method:

- Require 4 jets – Durham $y_{\text{cut}} = 0.01$
- Jet 1 $\equiv$ most energetic jet
- Jet 2 $\equiv$ jet from same W as jet 1
- Jet 3 $\equiv$ remaining jet closest to jet 2
- Angles between adjacent jets, θ_{ij}:
  - two angles $\theta_{ij} < 100°$
  - two angles $100° < \theta_{ij} < 140°$

  Ensures 4 jets approximately in a plane.



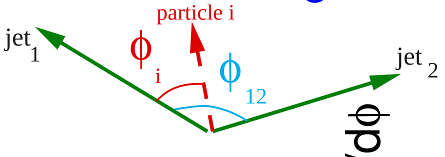
- Project particles onto plane defined by adjacent jets (4 planes)

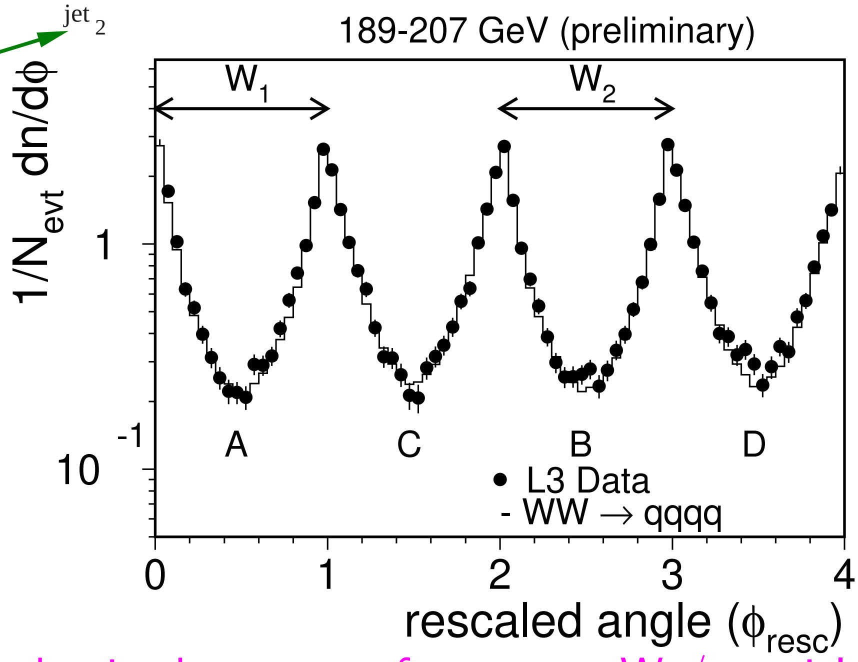
L3 Data

selected $W^+W^- \rightarrow q\bar{q}q\bar{q}$ events

$\langle\sqrt{s}\rangle$ GeV	$\mathcal{L}$ pb^{-1}	N_{event}	N_{MC}	ϵ %	correct pairing %
189	176.4	208	226.0	14.2	88
192	29.7	38	37.9	14.3	90
196	83.7	104	101.0	13.4	92
200	84.3	97	91.9	12.2	93
202	35.5	36	37.2	11.3	93
205	77.8	75	74.8	10.3	93
207	138.9	108	120.8	8.9	91
combined					
198.2	626.6	666	689.6	12.0	91

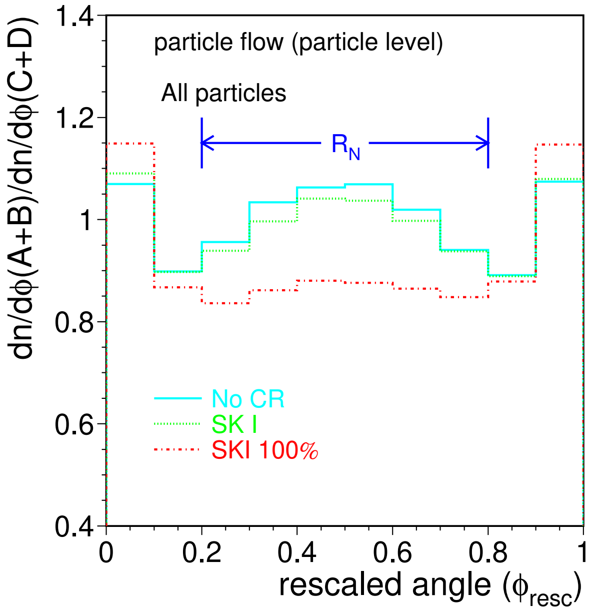
- Rescale angles and subtract background bin-by-bin



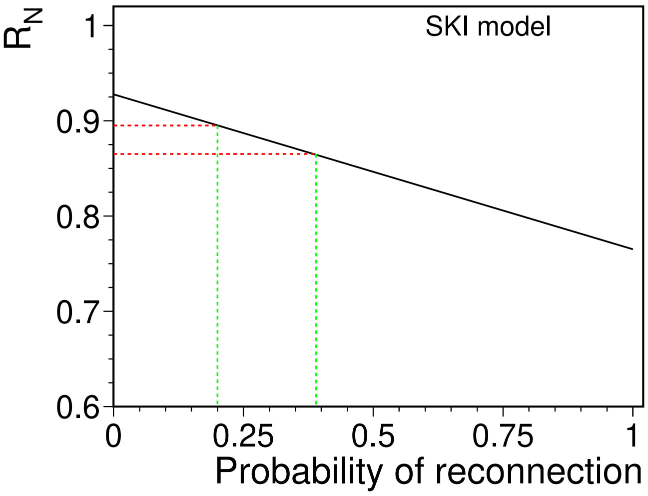


Interjet regions are sensitive to CR effects

Variable: particle density between q from same W / particle density between q from different W

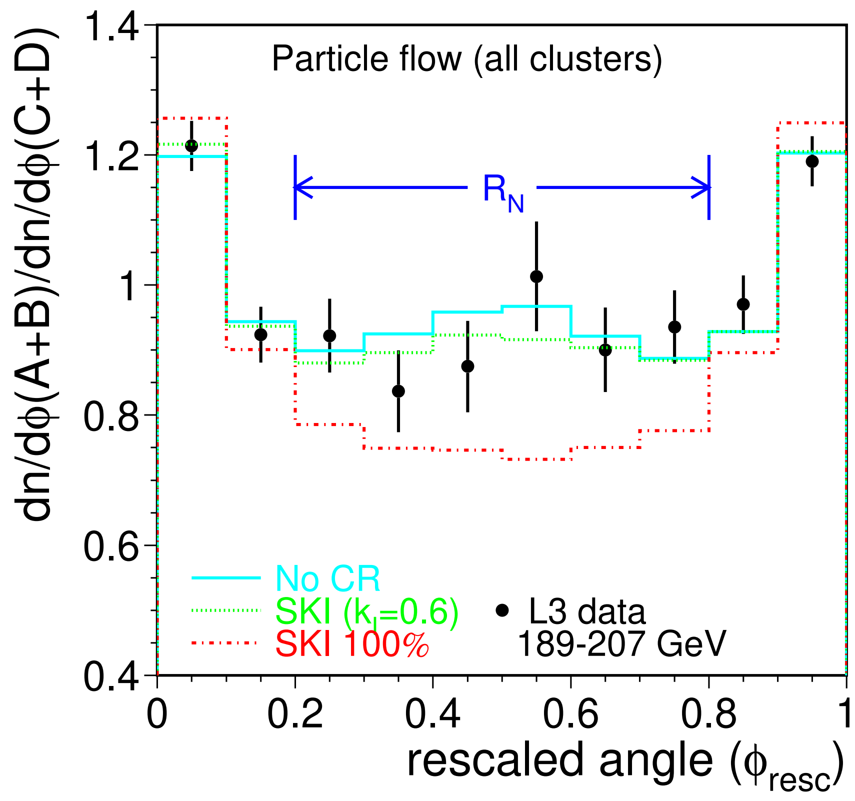


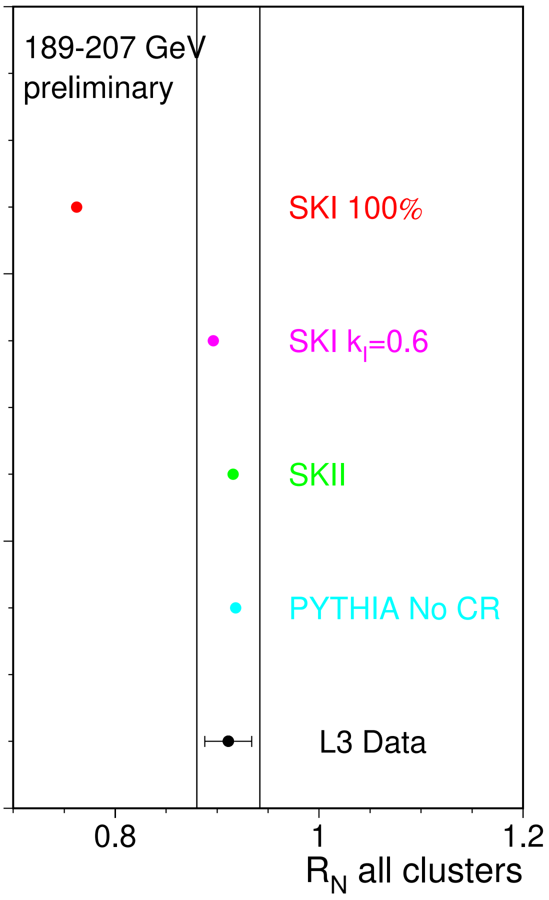
$$R_N = \frac{\int_{0.2}^{0.8} \frac{1}{N_{evt}} \cdot \frac{dn}{d\phi}(regions A+B)}{\int_{0.2}^{0.8} \frac{1}{N_{evt}} \cdot \frac{dn}{d\phi}(regions C+D)}$$



Comparison with Colour Reconnections Models

$\sqrt{s} = 189$ -207 GeV





$$R_N = 0.911 \pm 0.023(stat.) \pm 0.021(syst.)$$
$$R_E = 0.719 \pm 0.035(stat.) \pm 0.018(syst.)$$

Model	R_N detector	R_E detector
No CR	0.918 ± 0.003	0.672 ± 0.003
SkII	0.916 ± 0.003	0.667 ± 0.003
SKI	0.896 ± 0.003	0.659 ± 0.003
SKI 100%	0.762 ± 0.003	0.581 ± 0.003

$\Rightarrow$ Data compatible with PYTHIA NoCR or small CR effects.

How to define the boundary?

Asymmetry variables

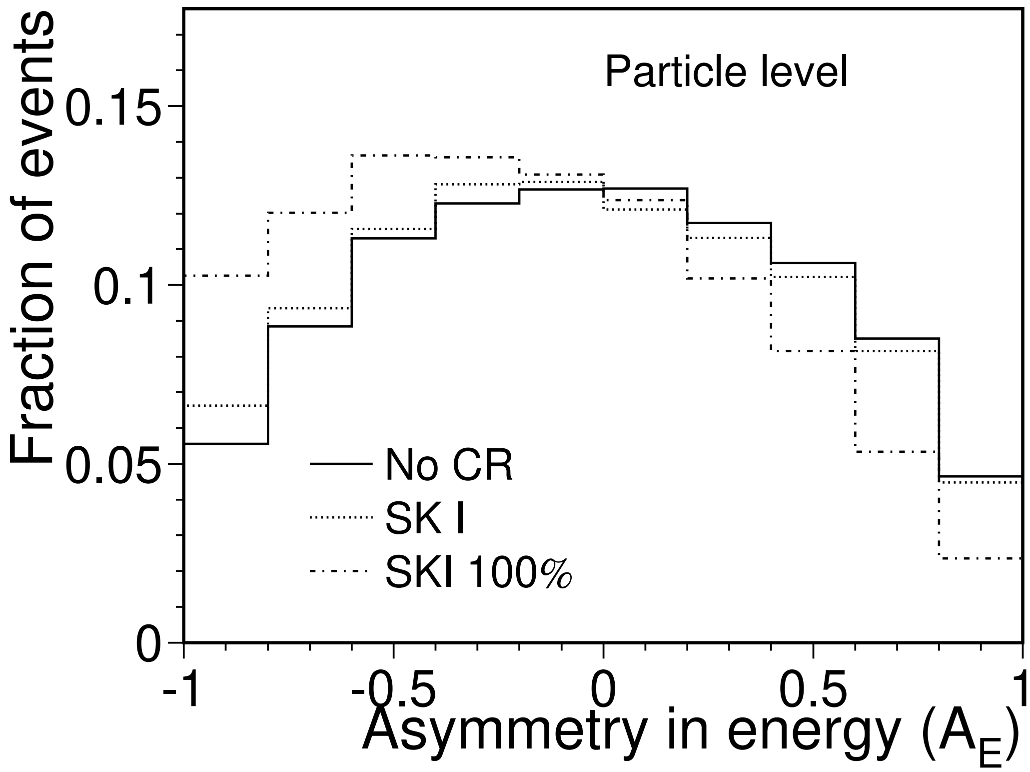
On an event by event basis compute the following quantities:

$$A_E = \frac{E_A+E_B-E_C-E_D}{E_A+E_B+E_C+E_D} \text{ and } A_N = \frac{N_A+N_B-N_C-N_D}{N_A+N_B+N_C+N_D}$$

where A, B, C and D are the interjet regions and:

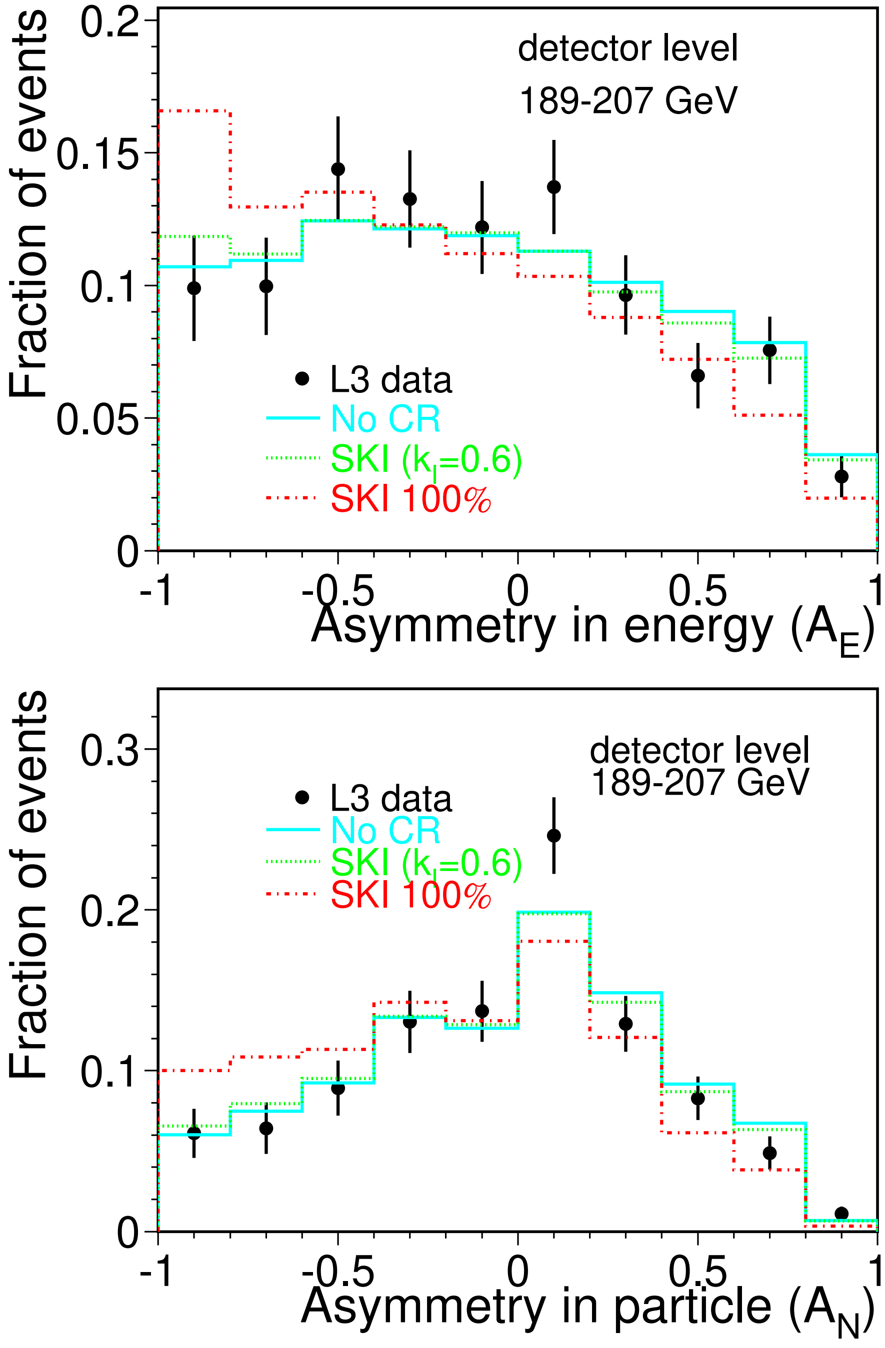
$$N_{region} = \int_{0.3}^{0.7} \frac{dN}{d\phi} d\phi \; ; \qquad E_{region} = \int_{0.3}^{0.7} \frac{dE}{d\phi} d\phi$$

At particle level:



Asymmetry variables

At detector level



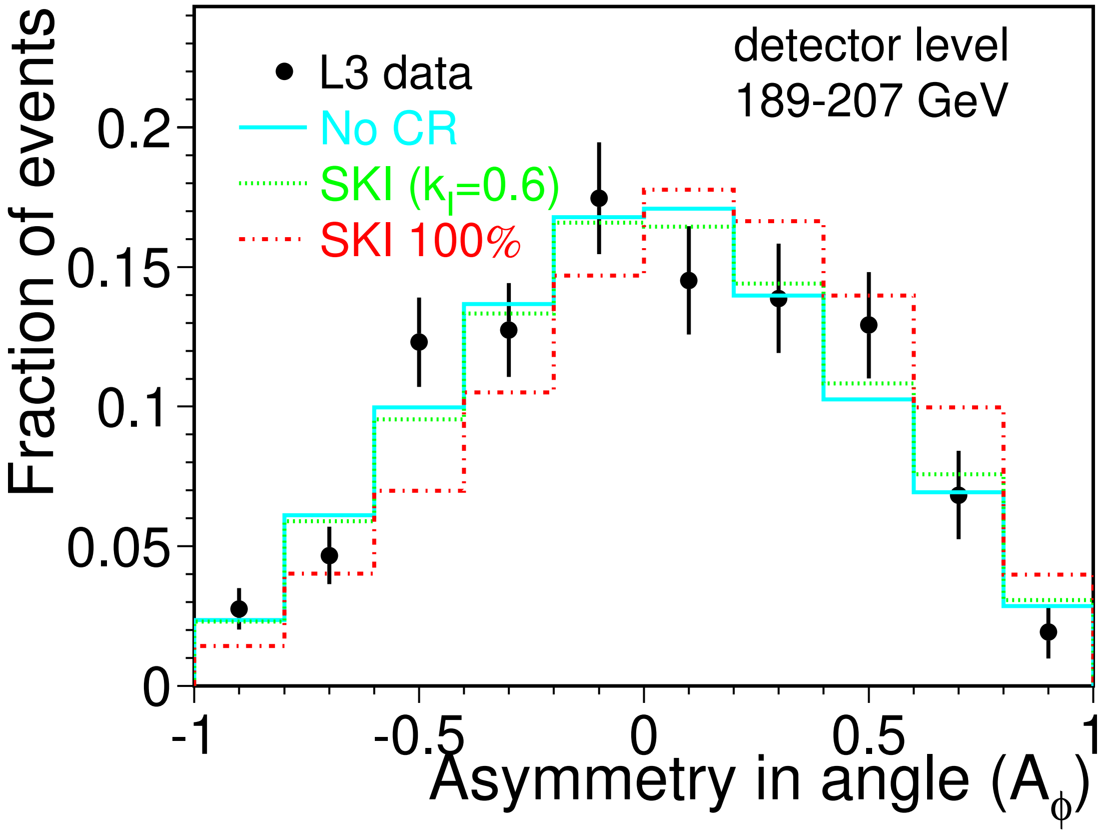
Model	$< A_E >$	$< A_N >$
No CR	-0.109 $\pm$ 0.003	-0.042 $\pm$ 0.003
SKI (k_I=0.6)	-0.131 $\pm$ 0.003	-0.059 $\pm$ 0.003
SKI 100%	-0.229 $\pm$ 0.003	-0.164 $\pm$ 0.003
L3 data	-0.129 $\pm$ 0.019	-0.049 $\pm$ 0.017

On an event by event basis compute the following quantities:

$$A_\phi = \frac{\psi_A+\psi_B-\psi_C-\psi_D}{\psi_A+\psi_B+\psi_C+\psi_D}$$

where ψ_{region} is the minimum angle between the region bisector and any particle.

$\psi_{region} = min(\phi^i_{rec} - 0.5)$



Model	$< A_\phi >$ particle	$< A_\phi >$ detector
No CR	-0.041 $\pm$ 0.003	0.013 $\pm$ 0.003
SKI	-0.027 $\pm$ 0.003	0.028 $\pm$ 0.004
SKI 100%	+0.058 $\pm$ 0.003	0.121 $\pm$ 0.004

L3 data: $< A_\phi > = 0.011 \pm 0.017(stat.)$

Conclusions - Colour Reconnection

- Particle or Energy flow is used to compare the inter-jet region between jets from same W with that between jets from different W's
- Data consistent with no or small CR
- Use of asymmetry variables, as in rapidity gap study, will improve limits on CR