# Study of Rapidity Gap Events in Hadronic Z Decays with L3 detector

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(L3 collaboration)


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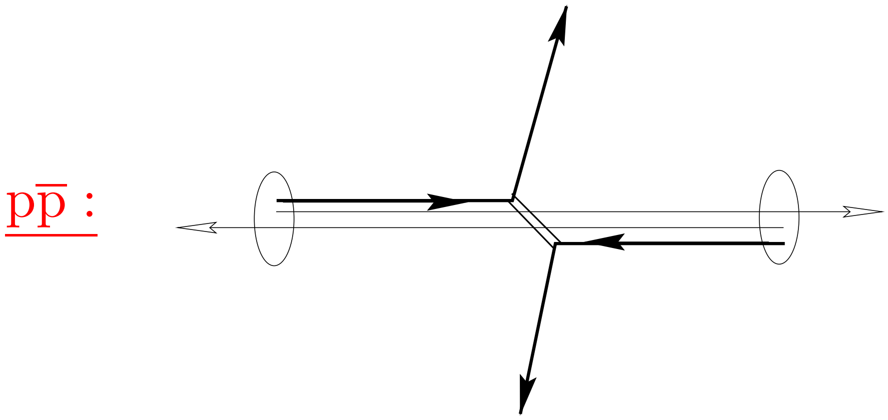
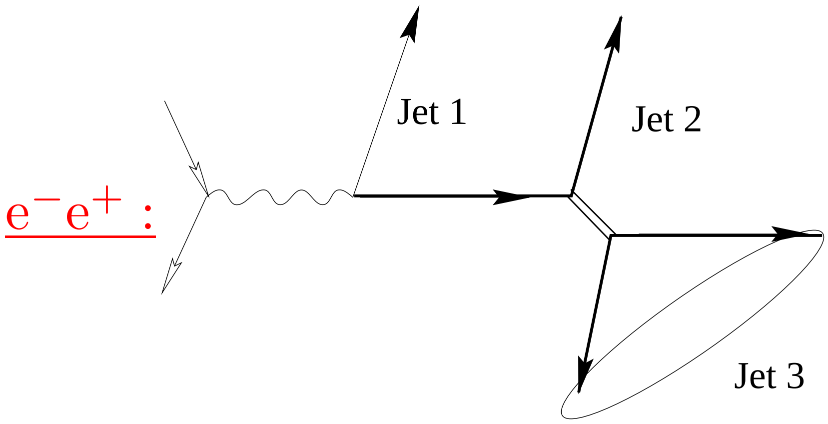
# Introduction

- 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*



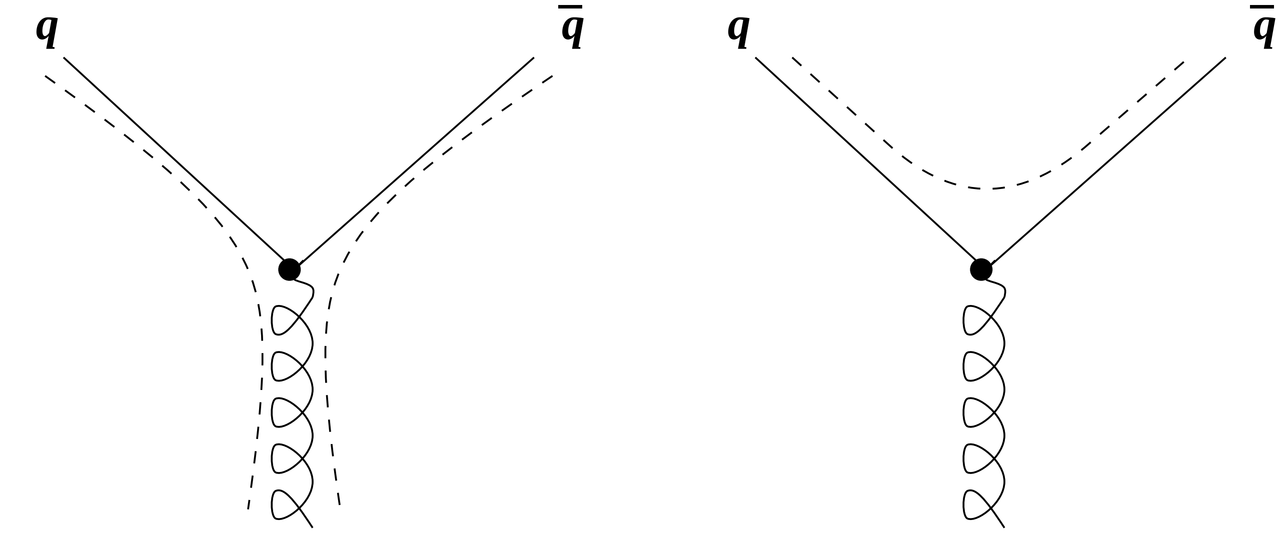

**Colour singlet exchange in hadronic Z decays?**




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

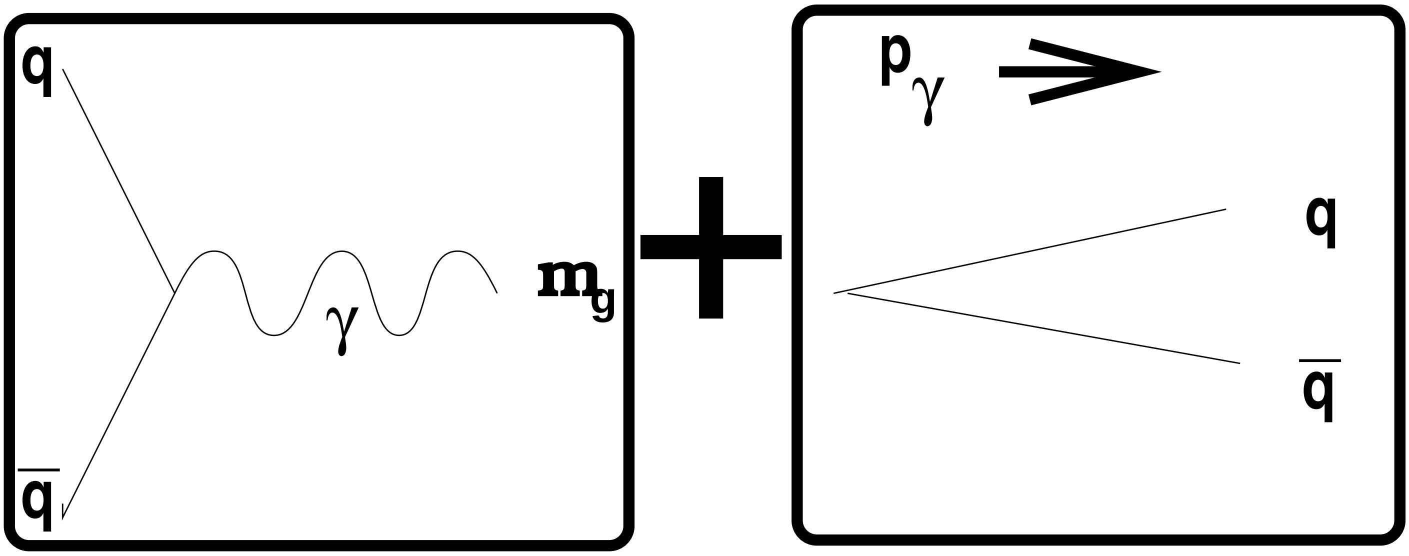
- Clean environment ⇒ No underlying *minimum bias* event
- Not plagued by "gap survival probability" ($\sim$ 50% in $p\bar{p}$)

# QCD Models




***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. |

# QCD Models

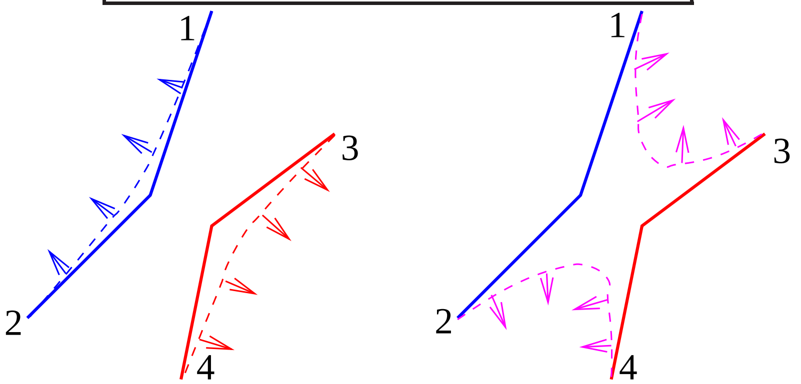
Rathsman Model: based on Generalised Area Law

"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)

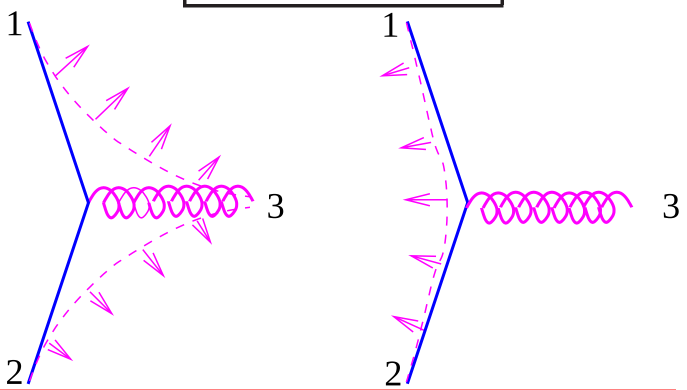
String-reinteractions probability: $P = R_0\,[1 - \exp(-b \cdot dA)]$

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




$\Delta A = (A_{13} + A_{24}) - (A_{12} + A_{34})$
$\Rightarrow$ shift in W-mass $\sim \mathcal{O}$ (65 MeV)

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

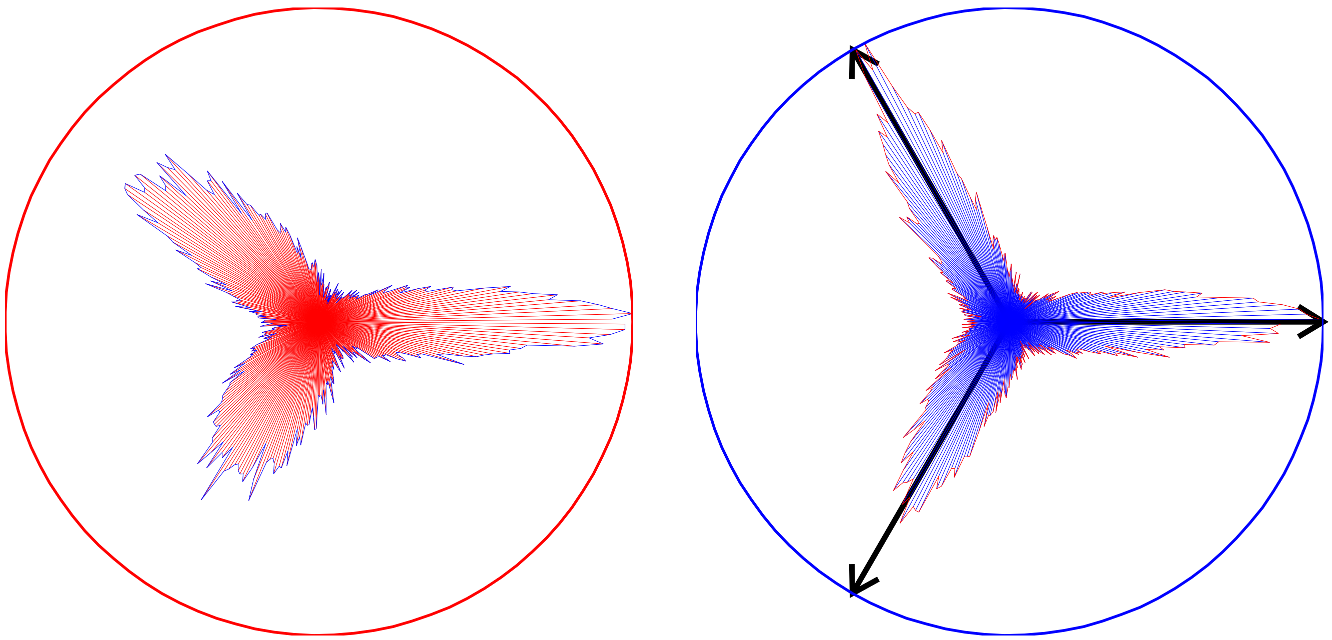



$\Delta A = A_{12} - (A_{13} + A_{23})$
$\Rightarrow$ Colour singlet exchange

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

# Methodology

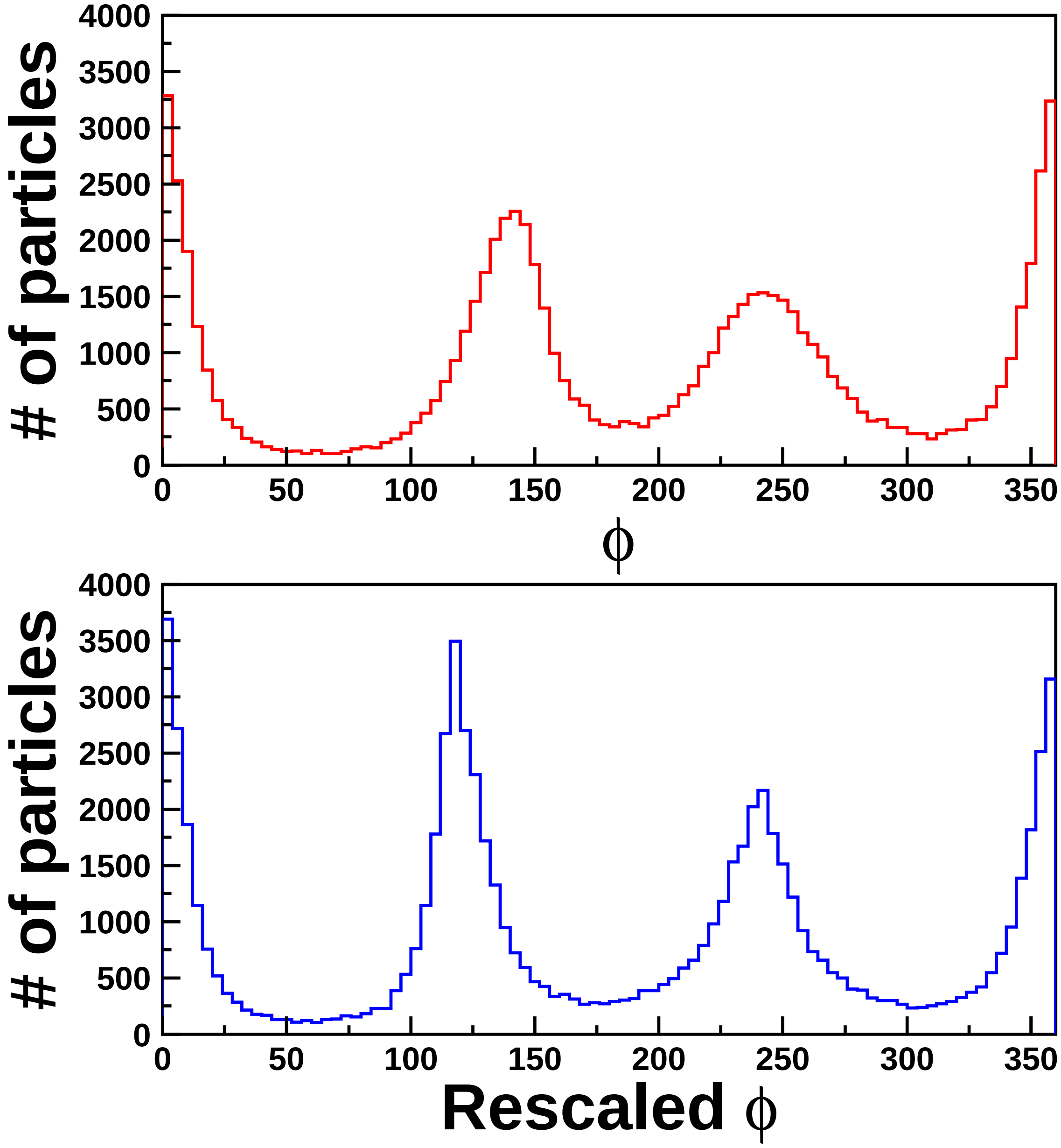
- Apply a jet algorithm (Use JADE as default and DURHAM for systematics) at fixed $\mathrm{y_{cut}}$ value(s)
- Select 3-jet event and demand symmetric configuration by imposing cuts on jet separation angles
- Define *event plane* by the 2 most energetic jets with the most energetic jet along $x$-axis
- 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 $0°$, $120°$, $240°$

# Methodology

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°

# Methodology

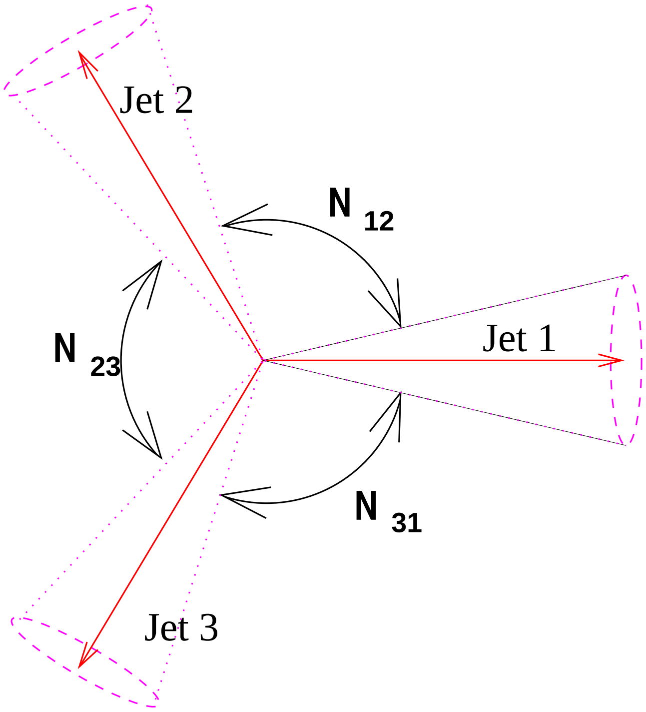
☛ For remaining particles in the gaps:

Number of particles in GAP:
$N_{ij} \quad (i,j = 1,3)$

Particle Asymmetry in GAP 12:

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

Similarly, define $A^{N}_{23}$ and $A^{N}_{31}$

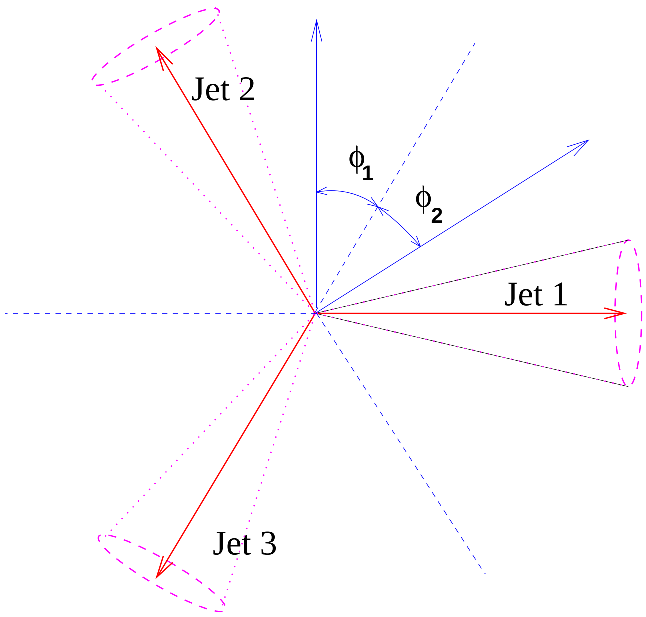



Angle from the bisector in GAP between jets 1 and 2:
$B_{12} = \mathrm{Min}(\phi_1,\phi_2)$

Angular Asymmetry for bisector-angle in GAP 12:

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

Similarly, define $A^{B}_{23}$ and $A^{B}_{31}$




Alternative Gap Angle definition:

Maximum separation angle between adjacent particles $S_{ij}$

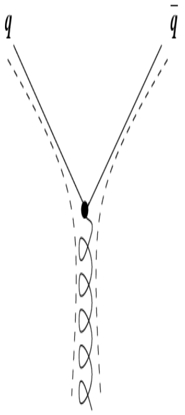
☞ Similarly, define $A^{S}_{12}$, $A^{S}_{23}$ and $A^{S}_{31}$

# Methodology

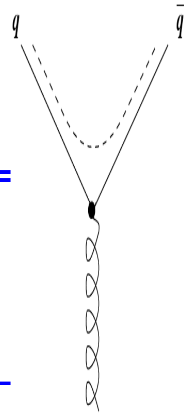
Colour Flow $\Rightarrow$

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

**Jets Ordered: Primary quarks in first 2 jets**



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

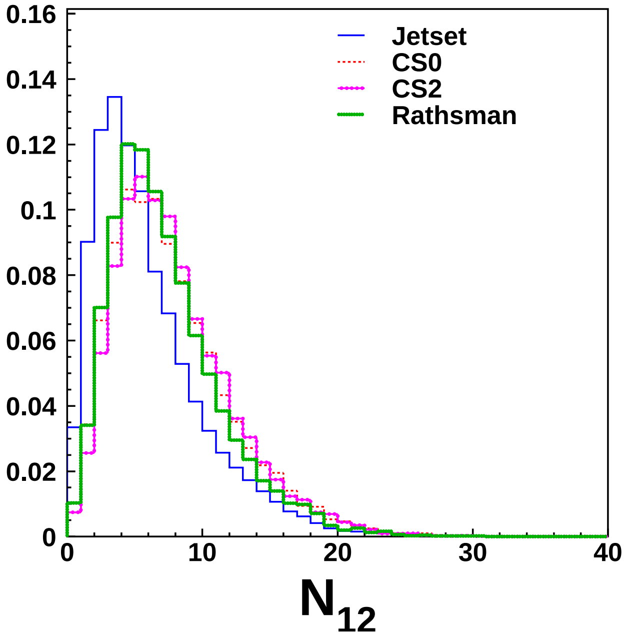


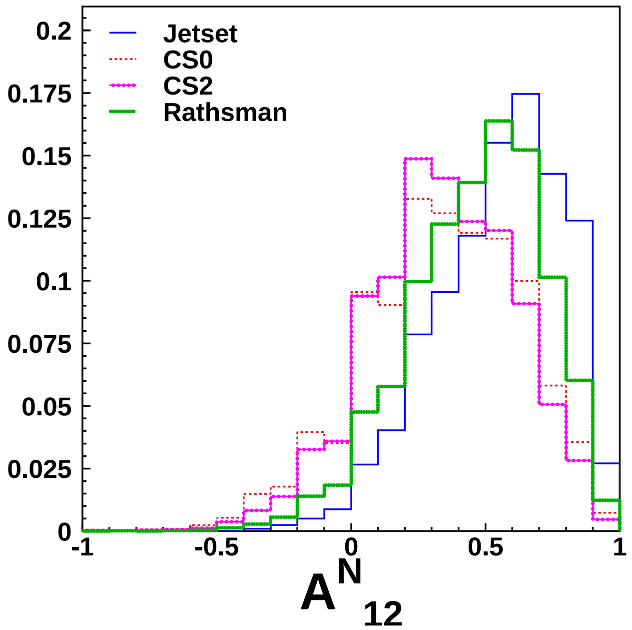
<No. of particles>

| | 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 |

# Methodology

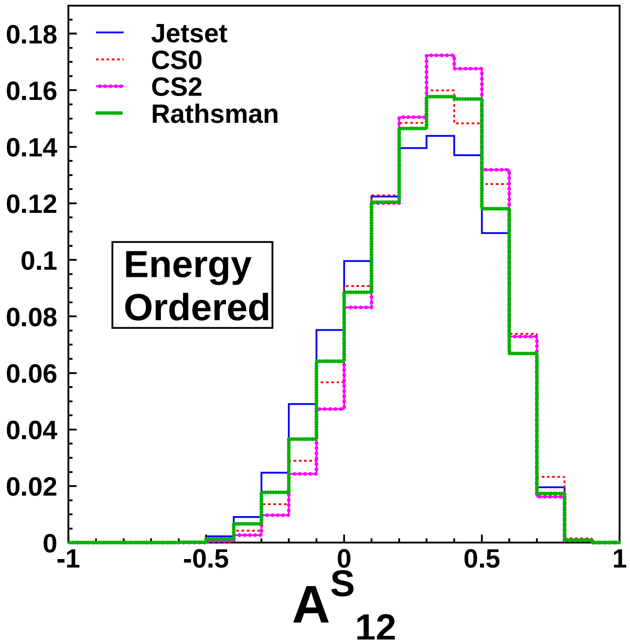
## Particle Flow Asymmetry:

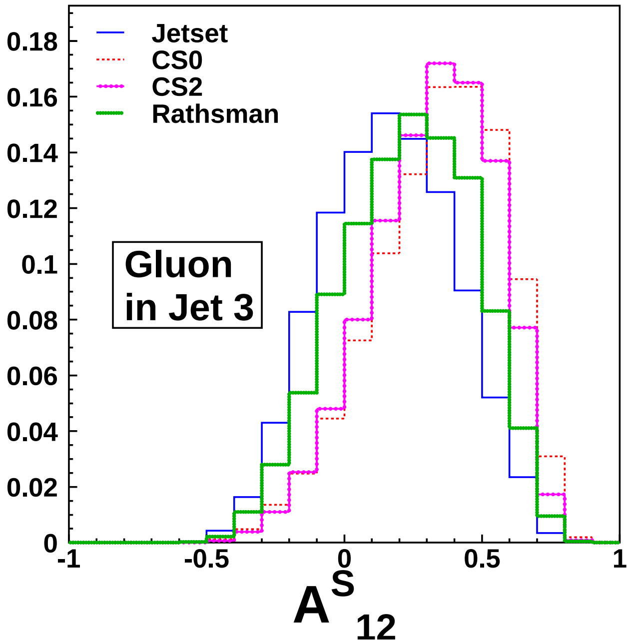



Asymmetries are sensitive to colour singlet exchange

## Separation-angle Asymmetry:




Gluon purity in the third jet improves sensitivity

# Data

- *Integrated luminosity*: $\boxed{\text{Lum} = 75.1\mathrm{pb}^{-1}\ (1994{+}1995)}$
- *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 $\mathrm{y_{cut}} = 0.05$;
    DURHAM ($\mathrm{k}_\perp$) algorithm with $\mathrm{y_{cut}} = 0.01, 0.02$
  - ➡ Jet separation angle: $\theta_{12},\ \theta_{23},\ \theta_{31} \in [90°,\ 150°]$

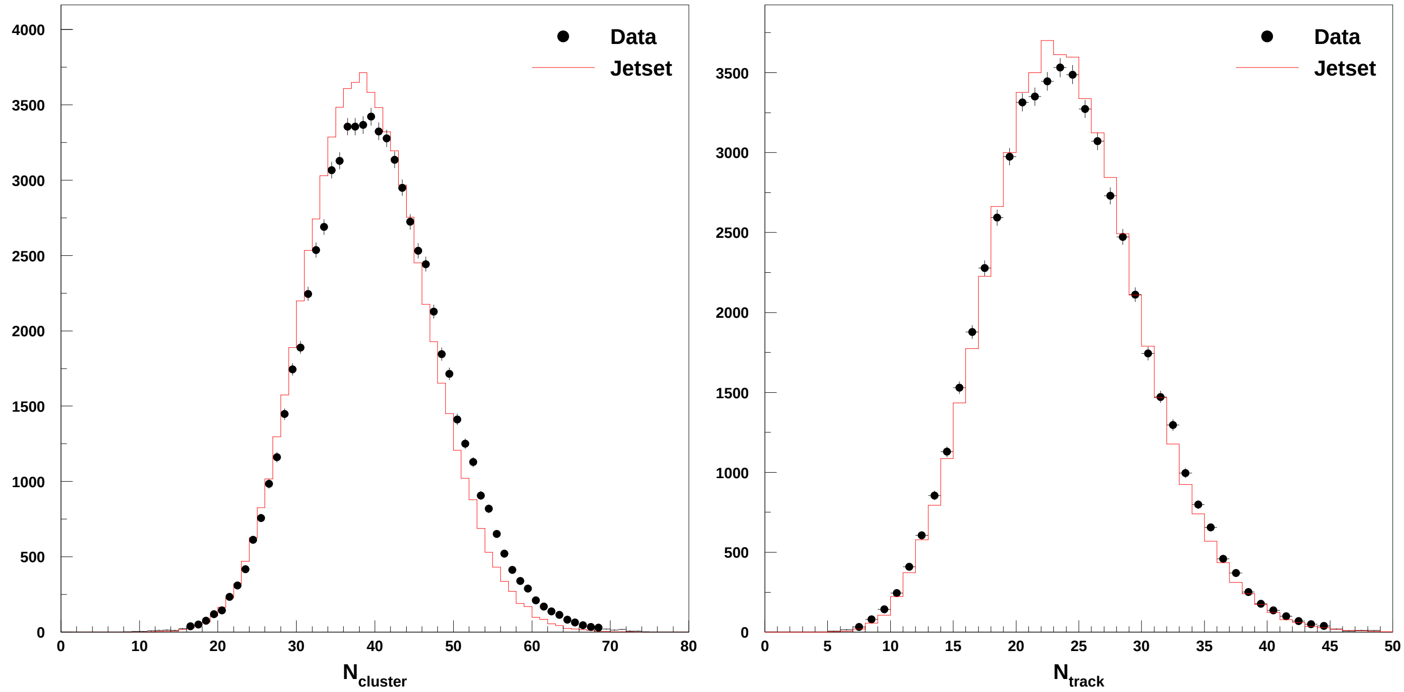
| | Fraction of 3jet Mercedes events | | | | | |
|---|---|---|---|---|---|---|
| | Clusters | | | Tracks | | |
| $\mathrm{y_{cut}}$ | JADE .05 | $\mathrm{k}_\perp$ .02 | $\mathrm{k}_\perp$ .01 | JADE .05 | $\mathrm{k}_\perp$ .02 | $\mathrm{k}_\perp$ .01 |
| DATA | .036 | .033 | .028 | .031 | .026 | .021 |
| 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

# Gluon Jet Identification

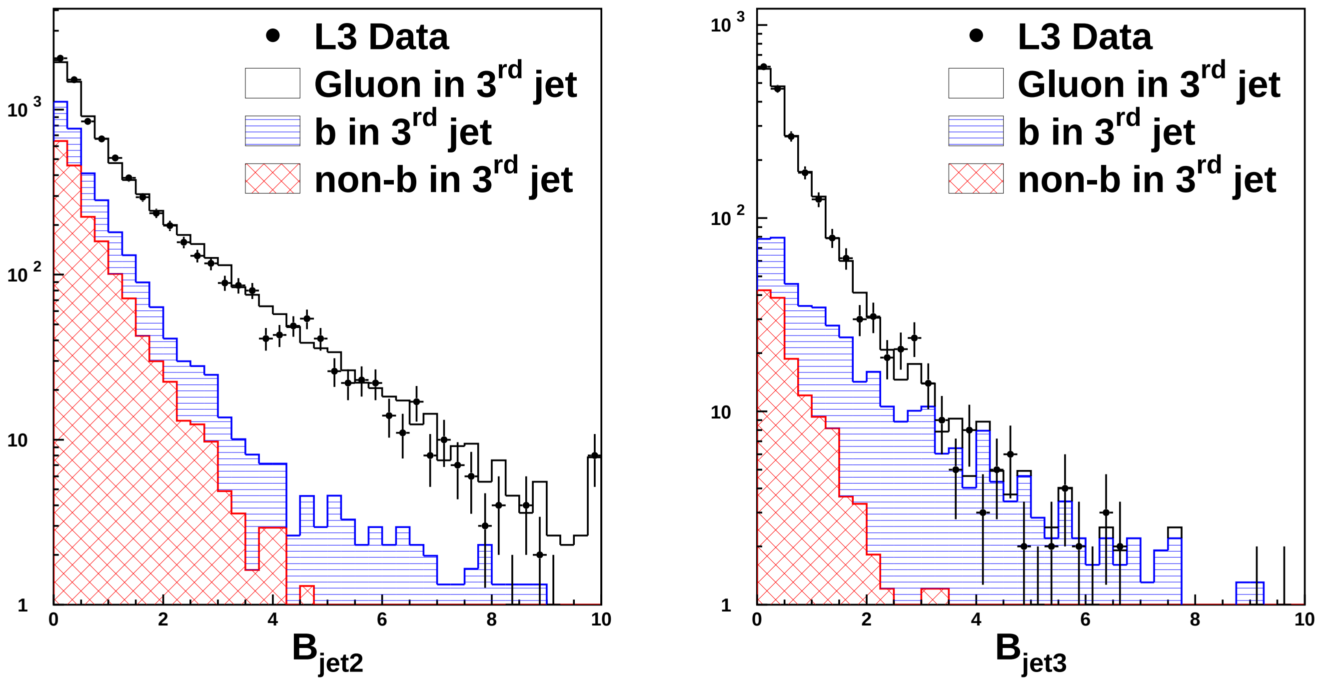
**Energy Ordering ($E_1 > E_2 > E_3$)**

| 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

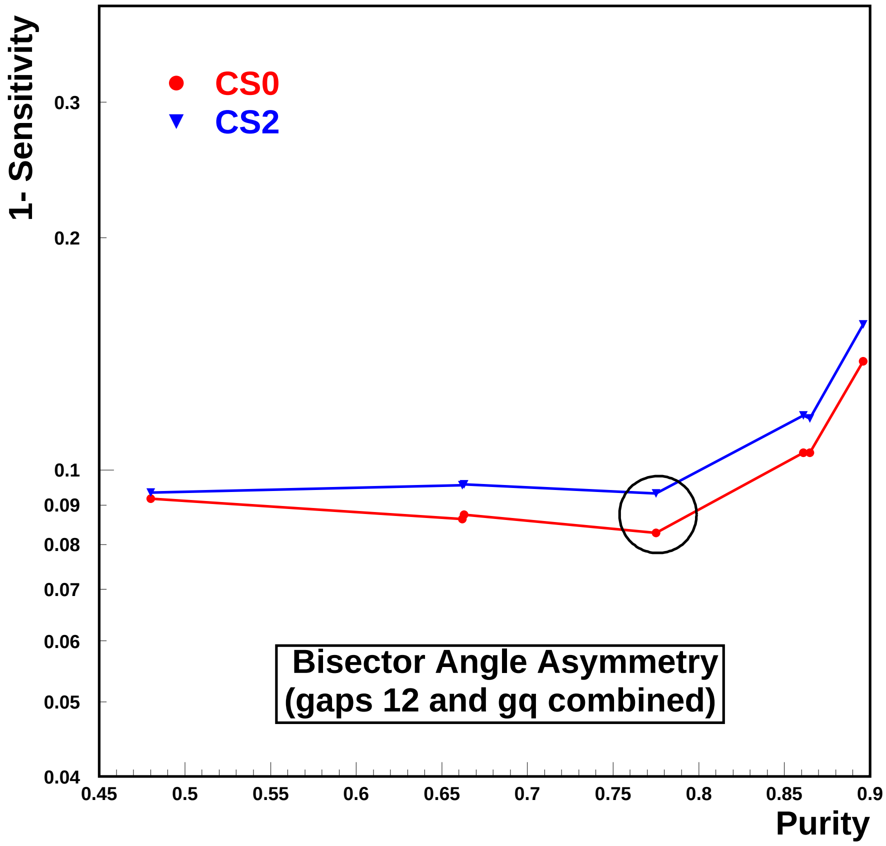
*For each jet* weighted discriminant: $B_{jet} = -\log(\underbrace{\prod}_{i \in jet} P_i)$




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

# Gluon Jet Identification

☞ CUT$i$ *tuned* to get best sensitivity of measurement

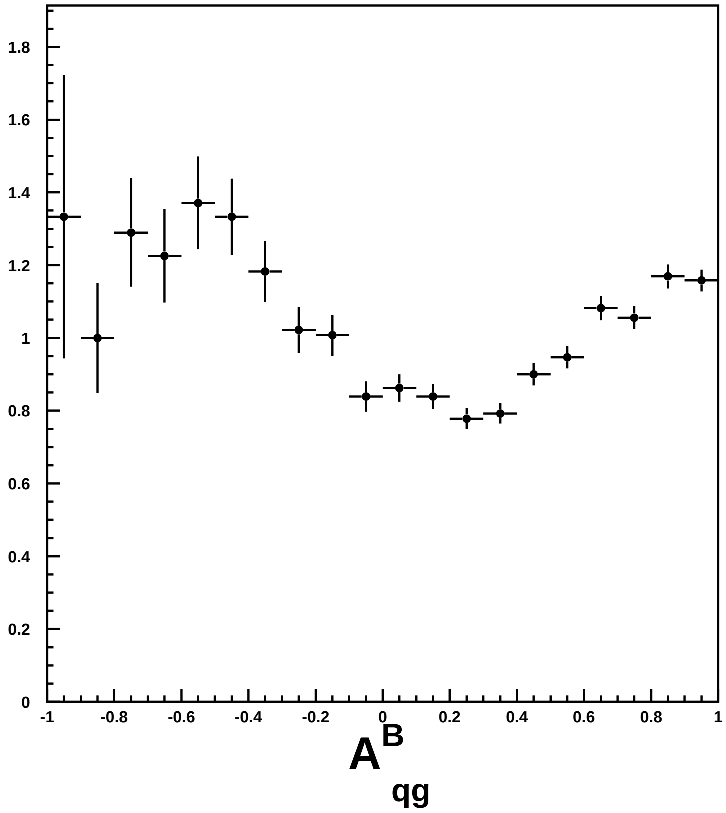



Optimized "Gluon" Tagged Event Statistics

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

# Results

Correct detector level distributions *bin-by-bin*

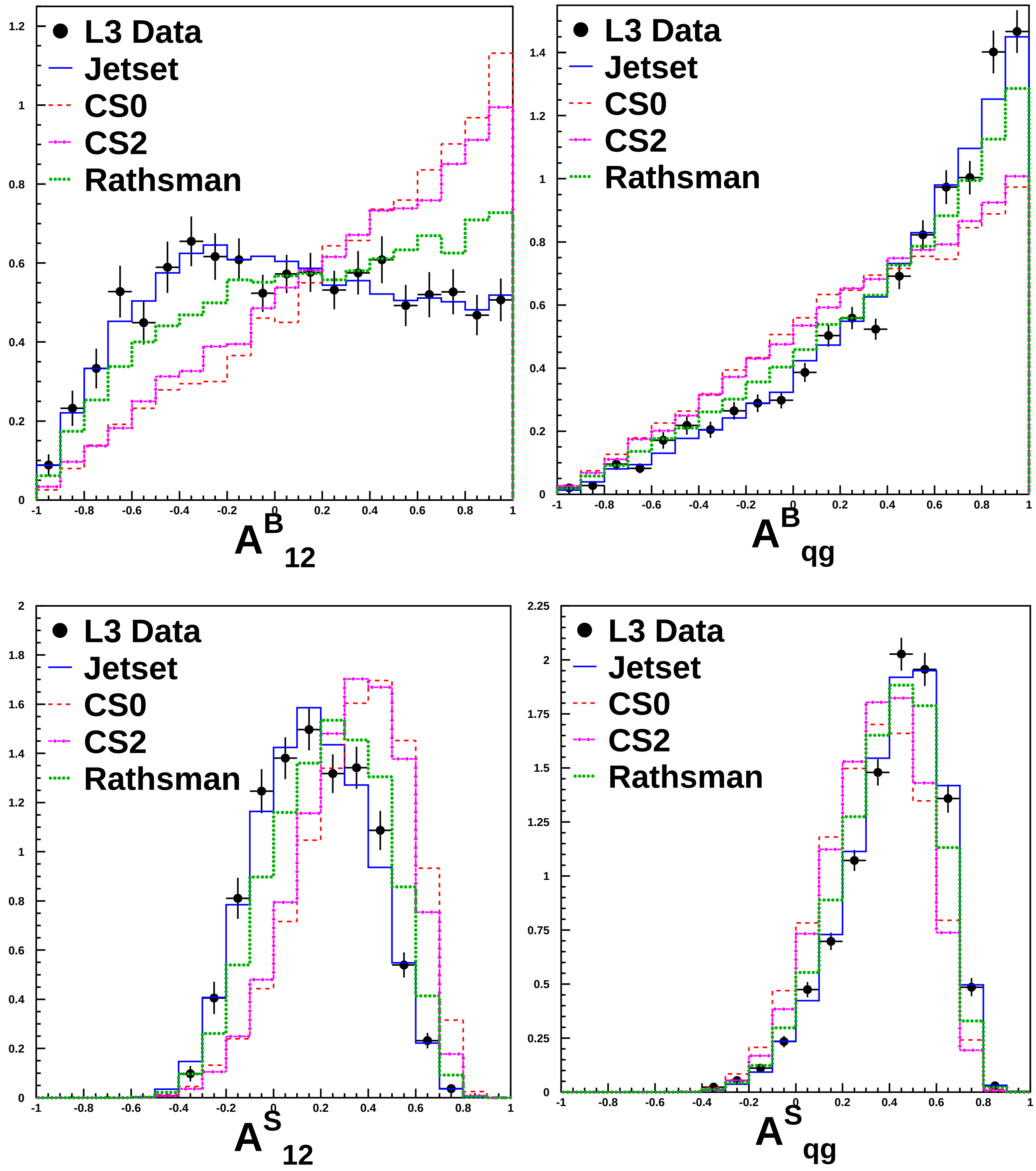



$\Rightarrow$ typical correction factor $\leq$ 20%

**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 | $\chi^2$ (Probability) Data Vs. Jetset | Rathsman |
|---|---|---|---|
| $A^B_{12}$ | 20 | 6.2 (99%) | 59.3 ($5 \times 10^{-6}$) |
| $A^B_{qg}$ | 19 | 16.9 (53%) | 60.5 ($2 \times 10^{-6}$) |
| $A^S_{12}$ | 12 | 4.7 (94%) | 77.8 ($4 \times 10^{-12}$) |
| $A^S_{qg}$ | 13 | 6.5 (89%) | 47.2 ($4 \times 10^{-6}$) |

JETSET explains trends in DATA

Determine CS fraction $r$ by minimising $\chi^2$

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

Fit to $A^B_{12}$: r $= 0.017 \pm 0.053$ ( $\chi^2$/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)

# Summary

- Several asymmetry variables sensitive to colour flow between jets are identified.
- Colour singlet exchange is looked in 2 million hadronic Z decays.
- An analysis is performed using calorimetric clusters and is cross-checked with charged tracks.
- Data are well explained by colour octet exchange alone.
- Rathsman model which suggests a different colour flow picture is investigated. For string reinteraction probability $R_0 = 0.1$, the model differs significantly from data.
- 95% CL upper bounds of colour singlet exchange are obtained at the level of 7-9%.