QCD Results from e^+e^- Colliders

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Outline

- from 90 to 172 GeV
- results from the Z
- results from the Z

(good and bad news)

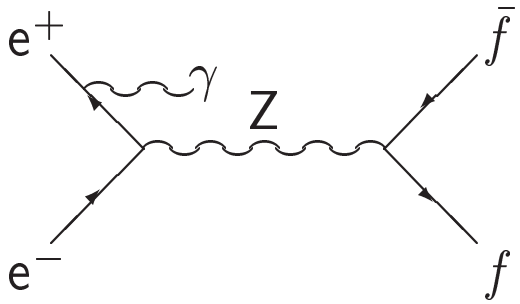
I only cover results which are new since Warsaw.

From 90 to 172 GeV

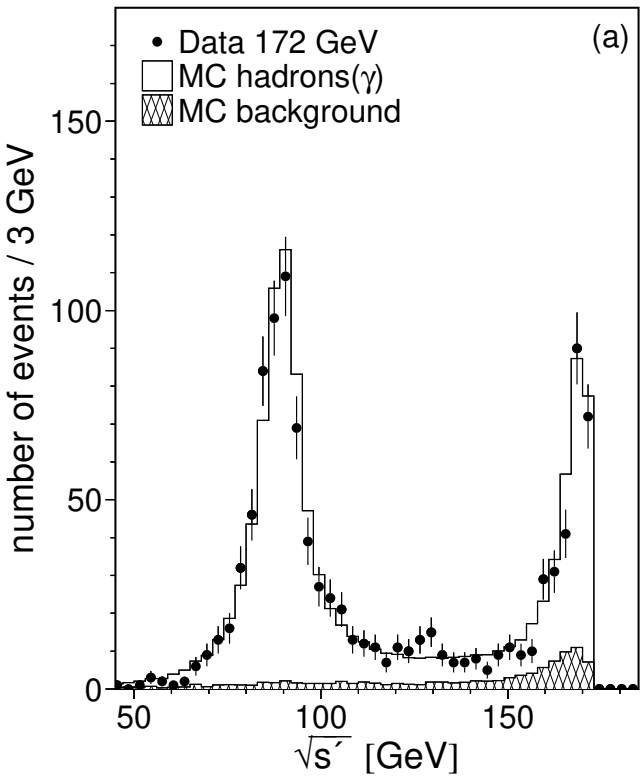
LEP Phase 2		E_{cms} (GeV)	luminosity (pb^{-1}/expt.)
Fall	1995	130–136	5
Summer	1996	161	11
Fall	1996	172	10
Expect	1997	~ 184	$120 \rightarrow 60$ (?)
	1998	~ 192	$200 \rightarrow 260$ (?)
	1999	~ 192	260
	2000	??	??

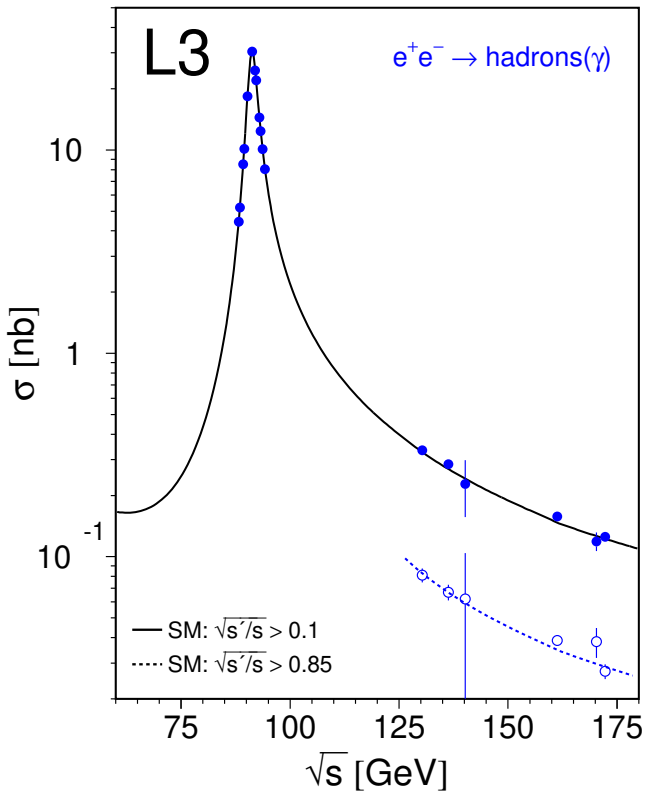
Radiative return to Z

$e^+e^- \to \gamma/Z \to f\bar{f}(\gamma)$, $s = E^2_{cms} \gg m^2_Z$:
Photon radiated from initial e^- or e^+ (ISR)



Large fraction of $e^+e^- \to f\bar{f}(\gamma)$ is radiative return to Z:
Mass $m_{f\bar{f}} = \sqrt{s'}$ of $f\bar{f}$ System: $s' = s - 2E_\gamma\sqrt{s} \approx m^2_Z$





Reject events with high-energy photon
or large $\sum E_{\|}$

Event-Shape Variables

Using MC tuned at Z(LEP-I), compare shape variable X

1. X dist. to MC at high energy
2. evolution of $< X >$ with $\sqrt{s}$

many variables – will not show all

MCs:

PYTHIA JETSET	∼MLLA shower	string frag. (JETSET)
ARIADNE	∼MLLA shower	string frag. (JETSET)
HERWIG	∼MLLA shower	cluster frag.
COJETS	∼LLA shower	independent frag.

Some event-shape variable dists. can be calculated by $\mathcal{O}(\alpha_s^2)$ M.E. + NLLA
Can fit to obtain α_s
— see talk by Phil Burrows (I hope)

Shape Variables – defs.

Thrust T: This observable is defined by the expression [10]

$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right) \quad . \tag{1}$$

The thrust axis $\vec{n}_T$ is the direction $\vec{n}$ which maximises the expression in parentheses. A plane through the origin and perpendicular to $\vec{n}_T$ divides the event into two hemispheres H_1 and H_2.

Thrust major T_{maj}: The maximisation in equation 1 is performed with the condition that $\vec{n}$ must lie in the plane perpendicular to $\vec{n}_T$. The resulting vector is called $\vec{n}_{T_{\mathrm{maj}}}$.

Thrust minor T_{min}: The expression in parentheses is evaluated for the vector $\vec{n}_{T_{\mathrm{min}}}$ which is perpendicular both to $\vec{n}_T$ and to $\vec{n}_{T_{\mathrm{maj}}}$.

Oblateness O: This observable is defined by $O = T_{\mathrm{maj}} - T_{\mathrm{min}}$ [11].

Sphericity S and Aplanarity A: These observables are based on the momentum tensor

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i p_i^2} \quad , \quad \alpha, \beta = 1, 2, 3 \quad .$$

The three eigenvalues Q_j of $S^{\alpha\beta}$ are ordered such that $Q_1 < Q_2 < Q_3$. These then define S [12] and A [13] by

$$S = \frac{3}{2}(Q_1 + Q_2) \quad \text{and} \quad A = \frac{3}{2} Q_1 \quad .$$

C-parameter C: The momentum tensor $S^{\alpha\beta}$ is linearised to become

$$\Theta^{\alpha\beta} = \frac{\sum_i (p_i^\alpha p_i^\beta)/|p_i|}{\sum_i |p_i|} \quad , \quad \alpha, \beta = 1, 2, 3 \quad .$$

The three eigenvalues λ_j of this tensor define C [14] with

$$C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1) \quad .$$

Heavy Jet Mass M_H: The hemisphere invariant masses are calculated using the particles in the two hemispheres H_1 and H_2. We define M_H [15] as the heavier mass, divided by $\sqrt{s}$.

Jet Broadening variables B_T and B_W: These are defined by computing the quantity

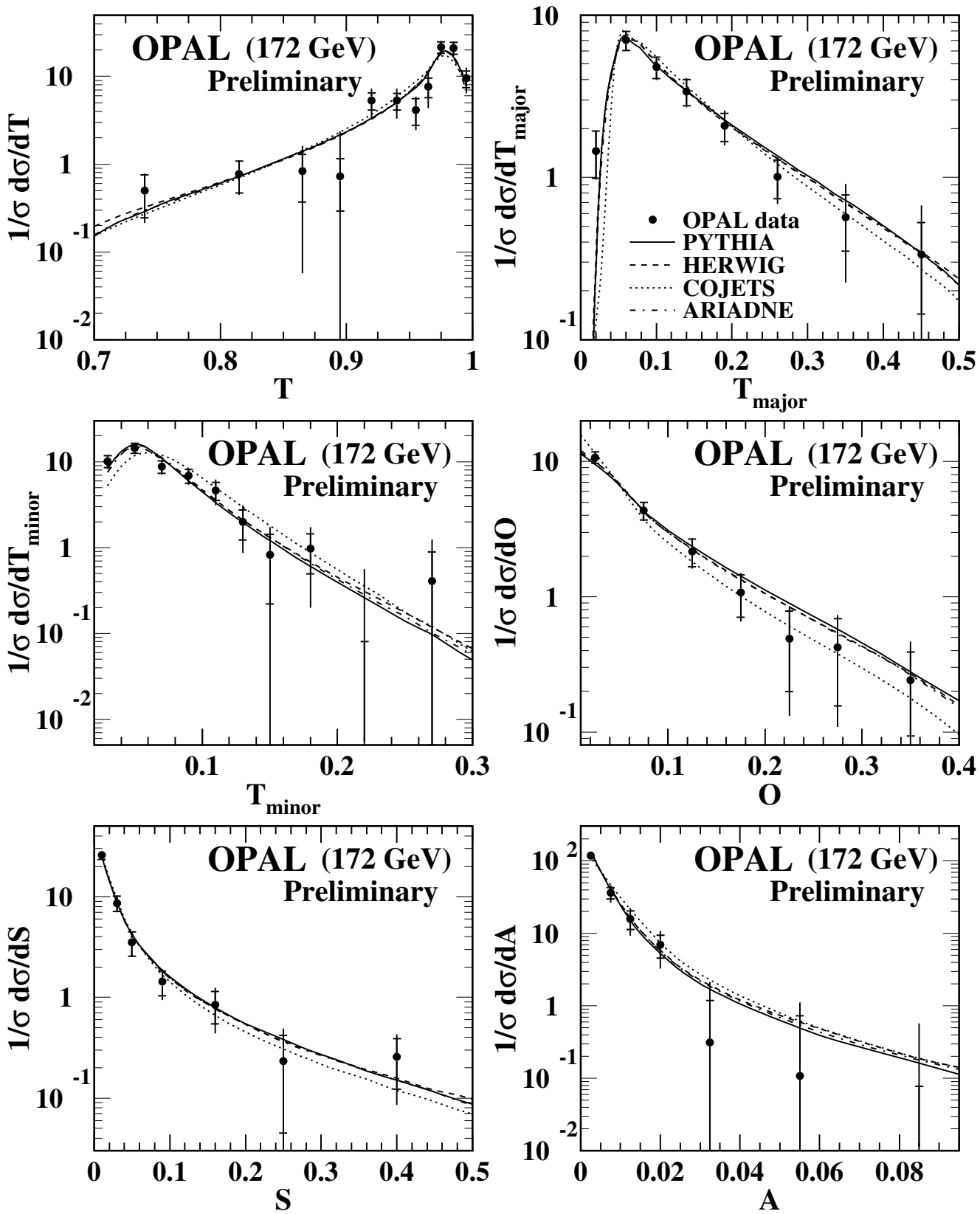
$$B_k = \left(\frac{\sum_{i \in H_k} |p_i \times \vec{n}_T|}{2 \sum_i |p_i|} \right)$$

for each of the two event hemispheres, H_k, defined above. The two observables [16] are defined by

$$B_T = B_1 + B_2 \quad \text{and} \quad B_W = \max(B_1, B_2)$$

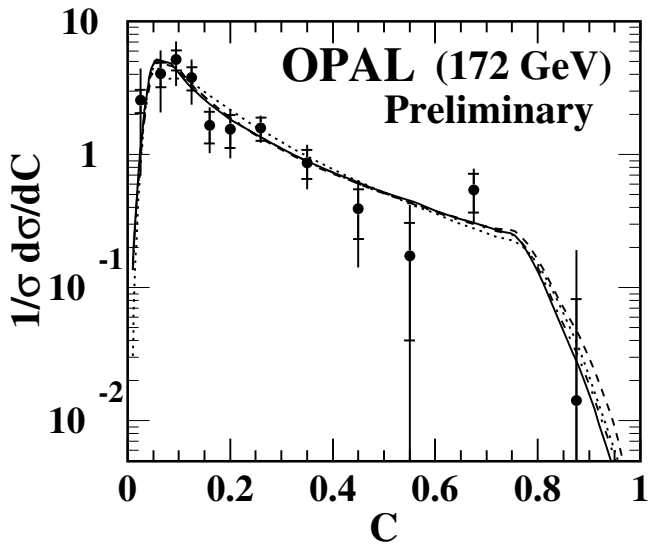
where B_T is the total and B_W is the wide jet broadening.

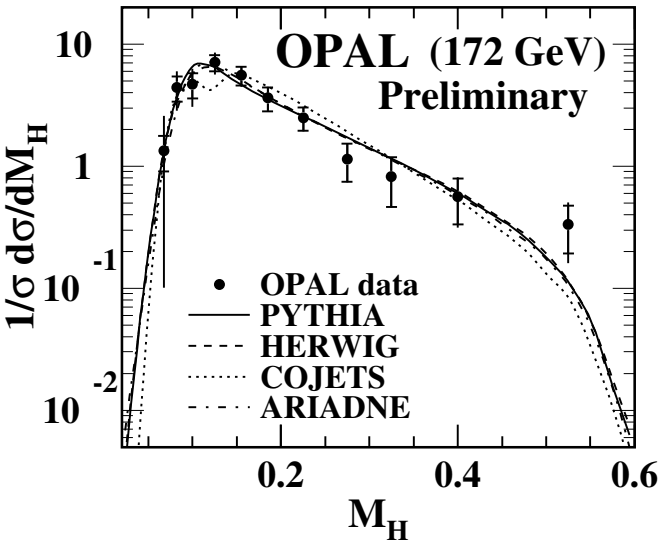
Shape Variables

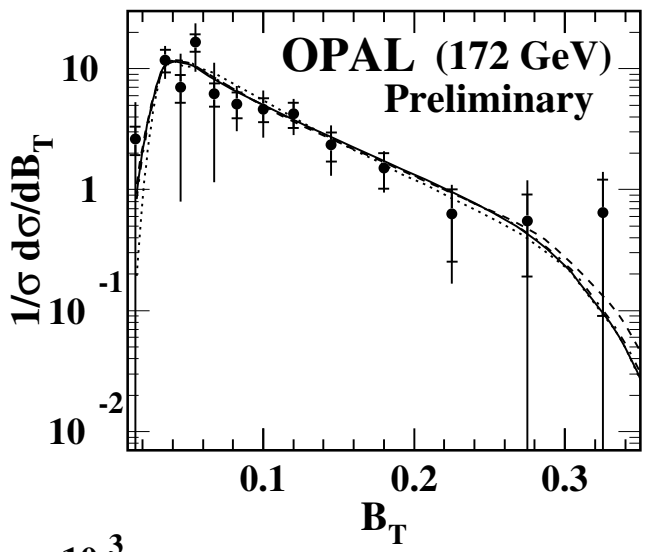


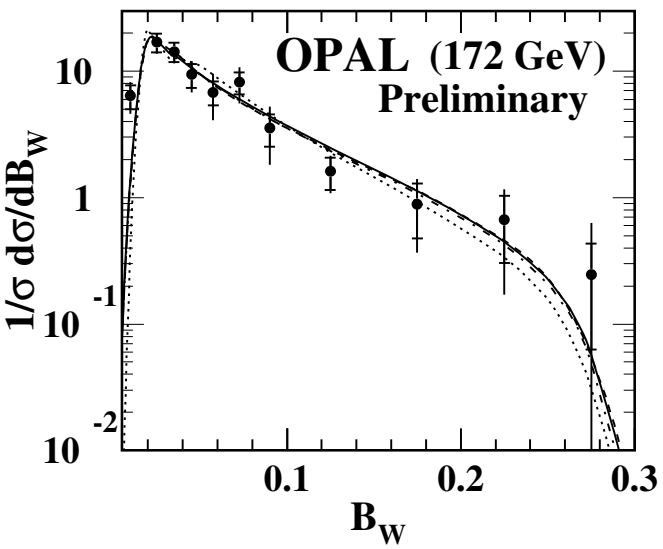
Good agreement

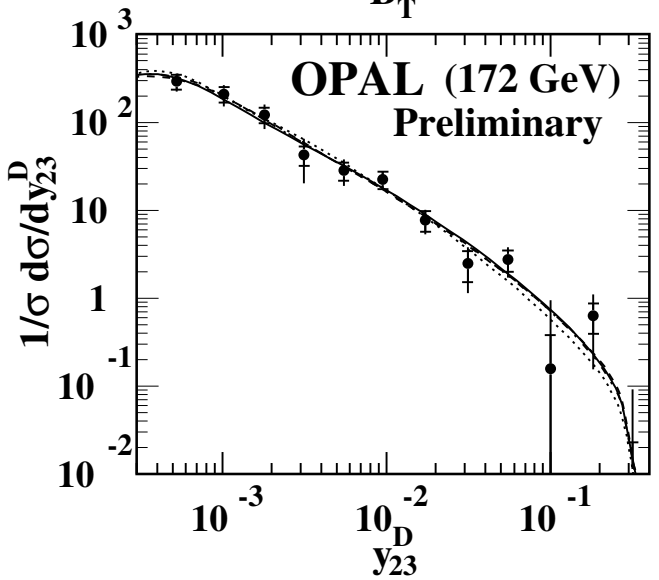
Shape Variables





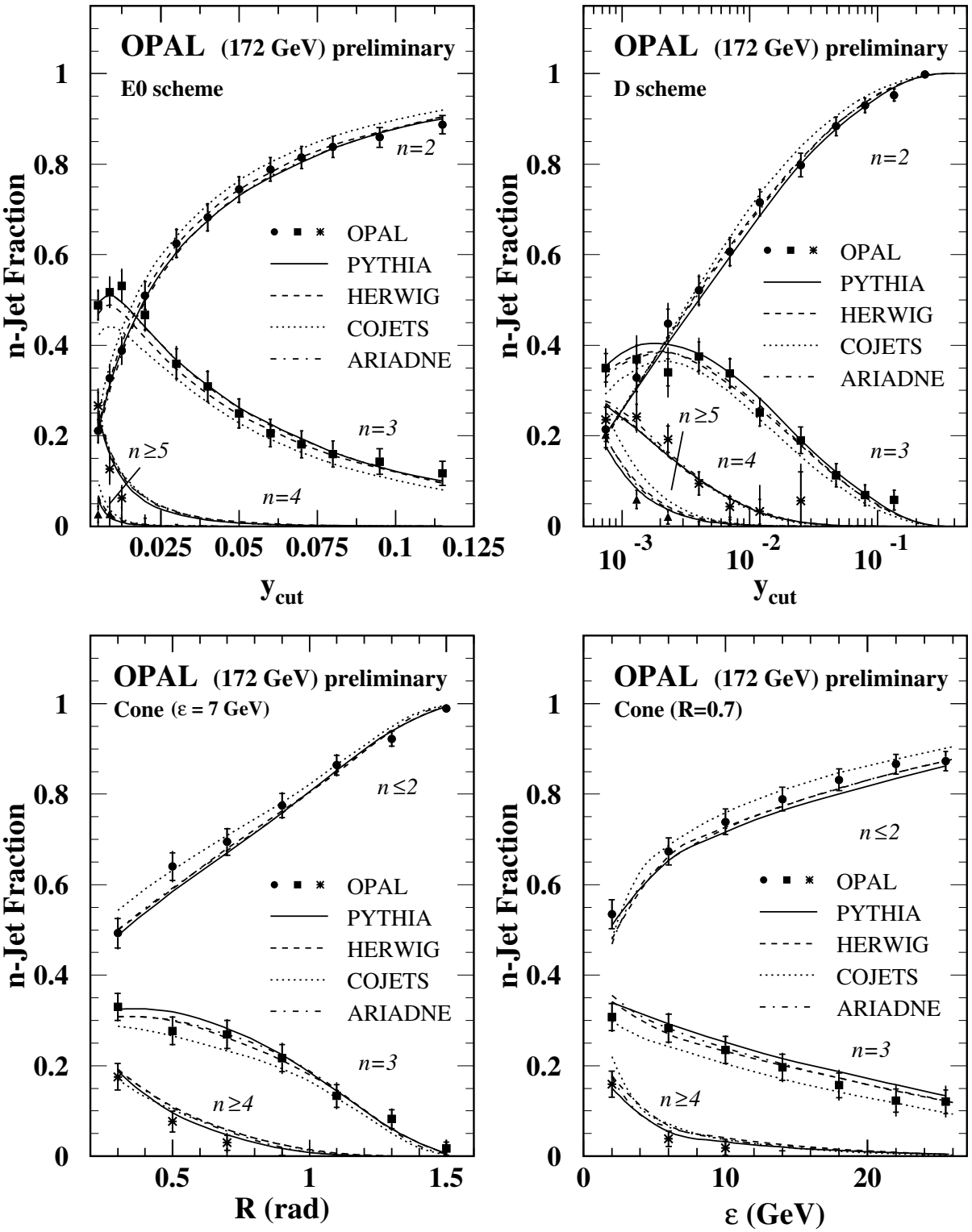






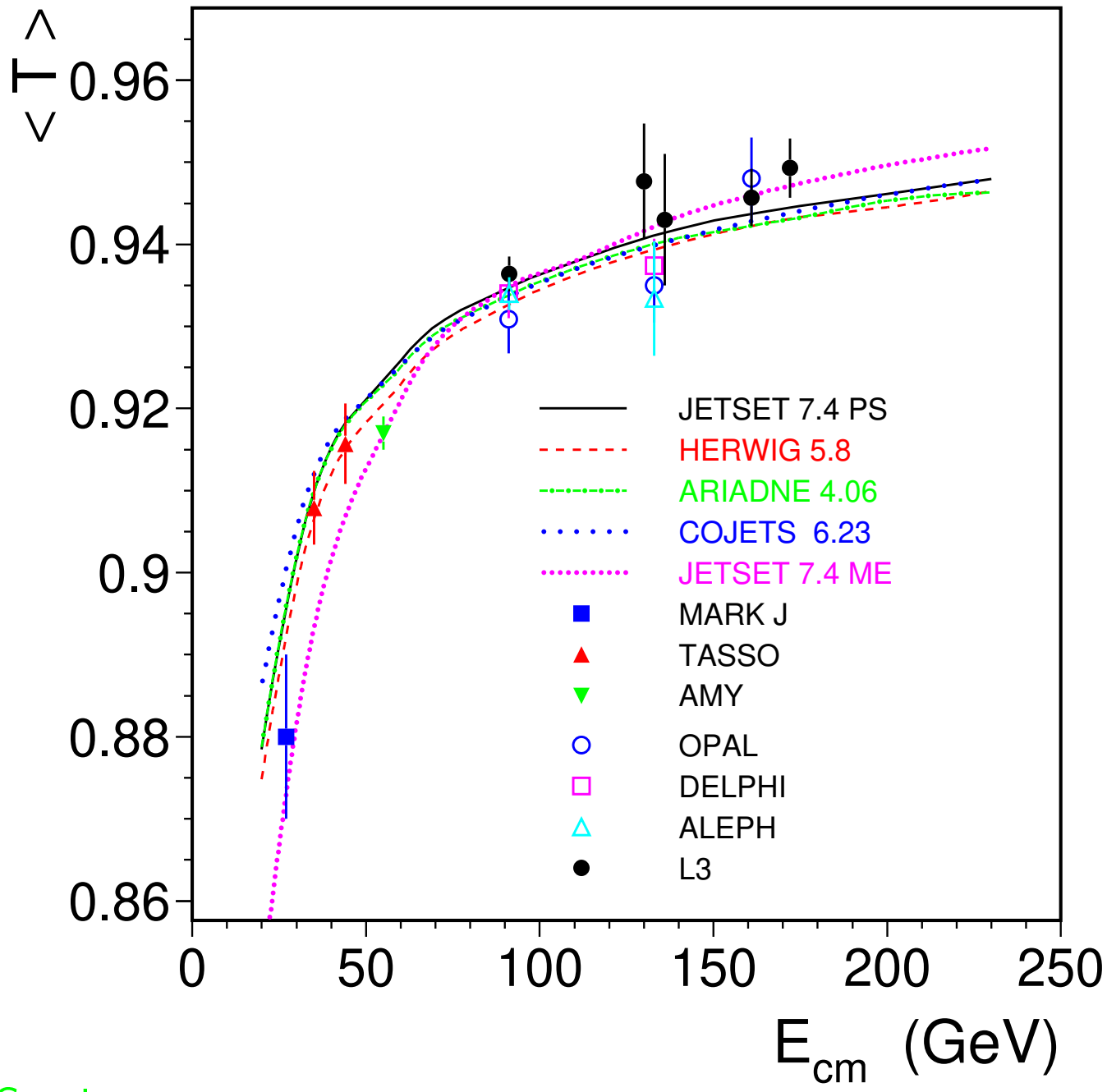
Good agreement

Jet Fractions



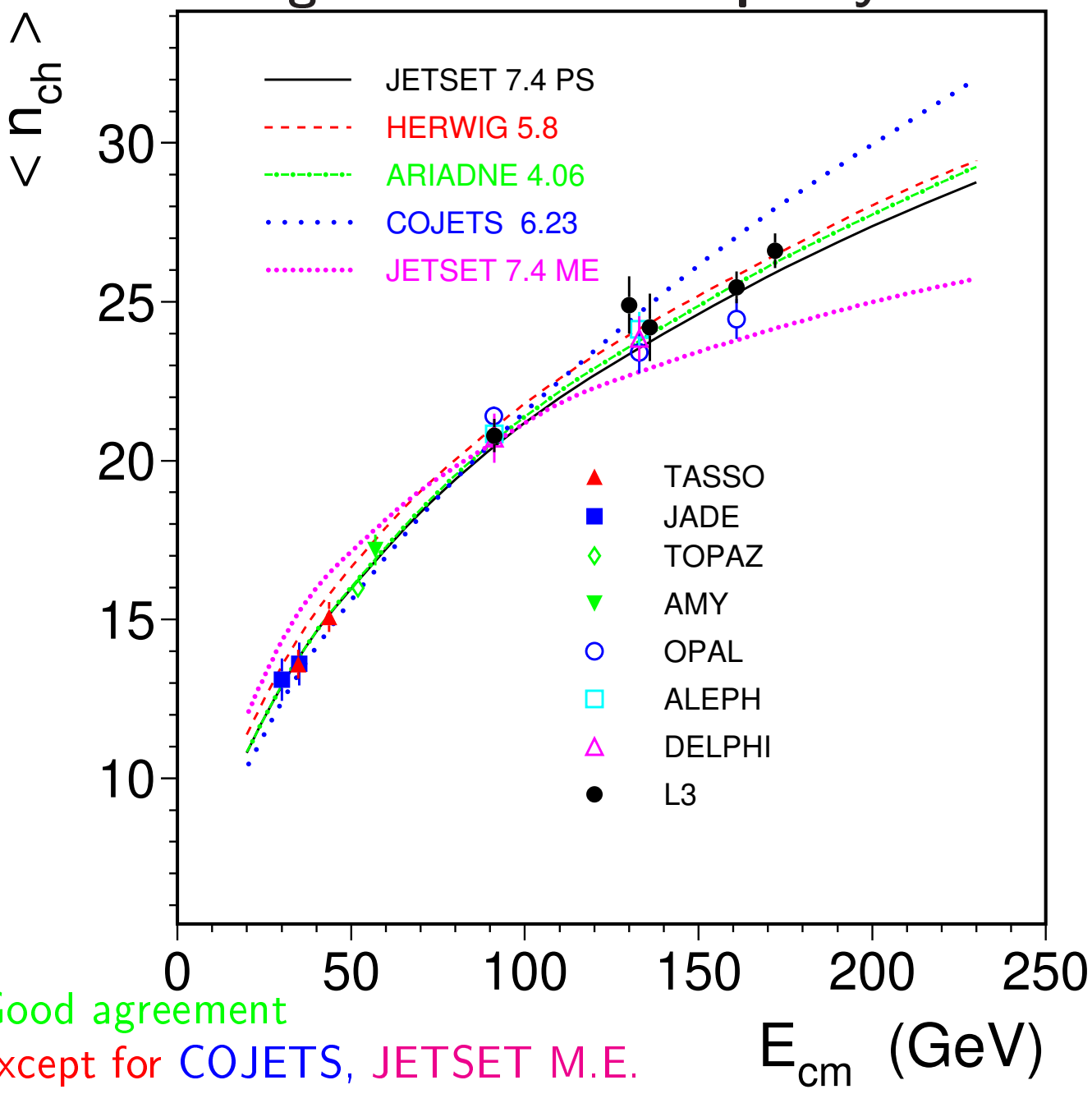
Good agreement

Shape Variables – Evolution



Good agreement

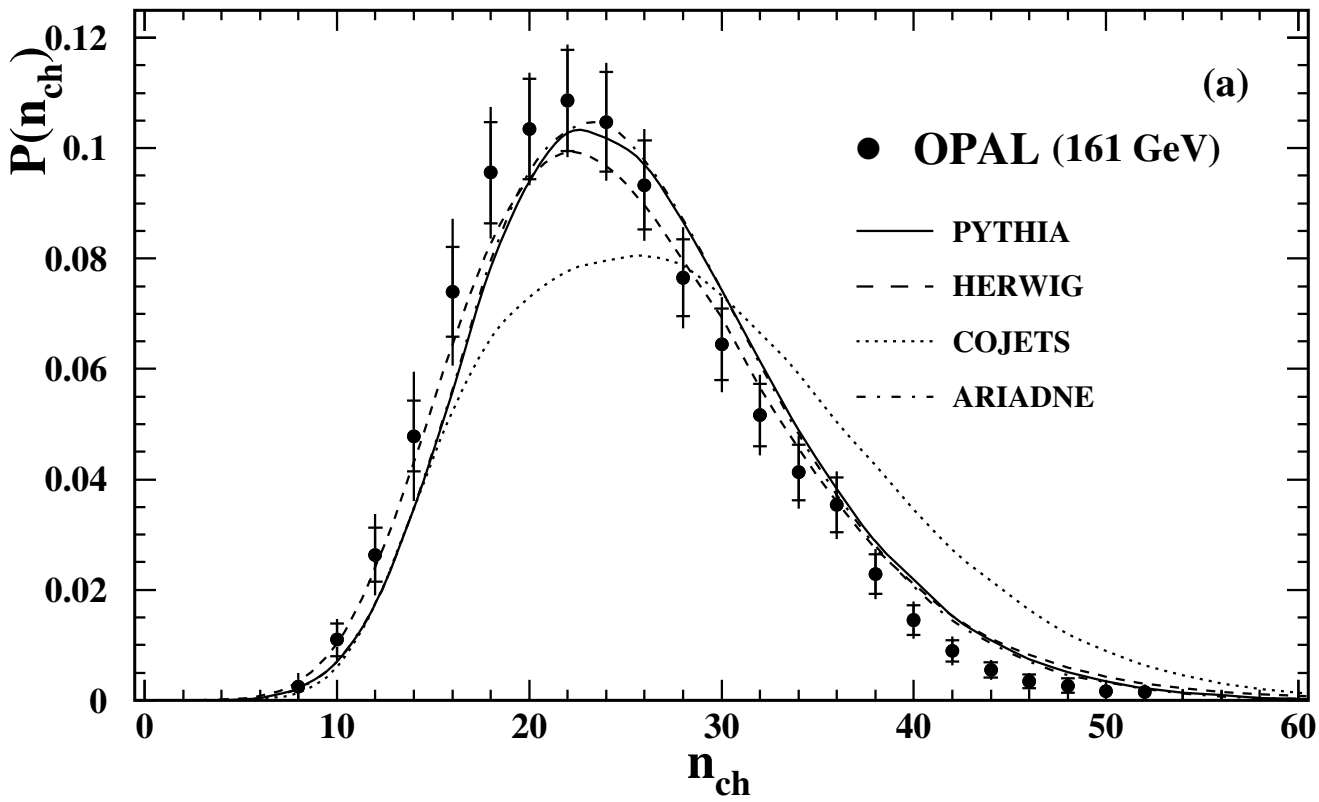
Charged-Particle Multiplicity



Good agreement
except for COJETS, JETSET M.E.

- COJETS disagrees because it has only LLA shower.
  Need MLLA shower, which incorporates
  soft gluon destructive interference.
- JETSET M.E. disagreement not surprising
  String fragmentation must simulate soft gluons.
  Number of soft gluons depends on E_{cm},
  so must be retuned at each E_{cm}.

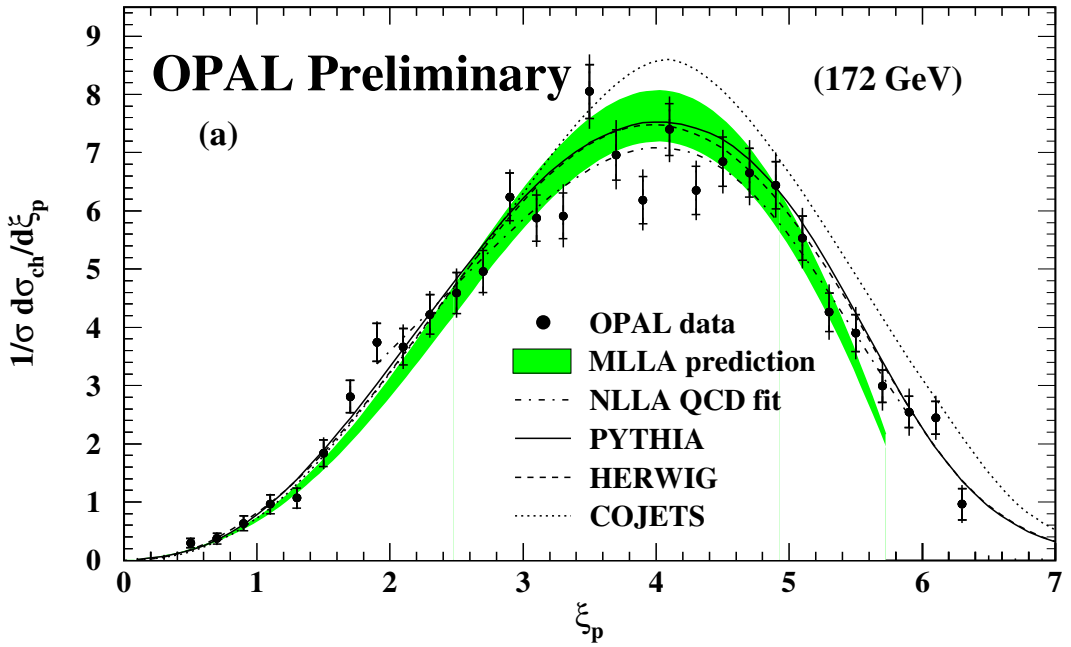
Charged-Particle Multiplicity

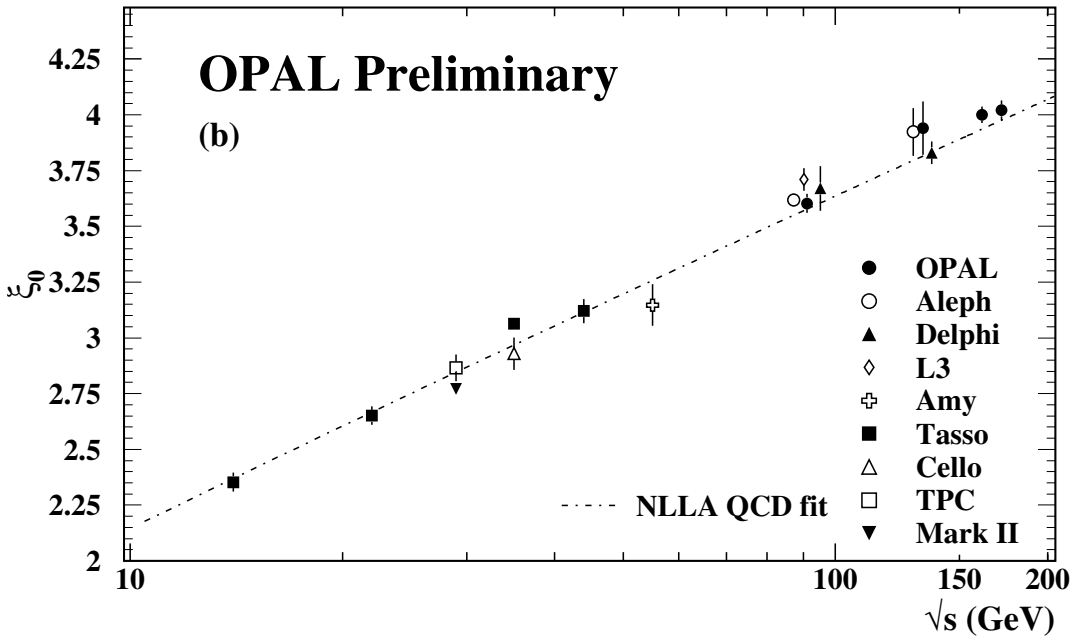


Good agreement

except for COJETS

Single-Particle Spectra





(a) COJETS (LLA) far off
PYTHIA, HERWIG, MLLA a bit too high at max.
MLLA drops a bit too fast at high ξ_p
NLLA Good agreement
So, MLLA begins not to be sufficient.

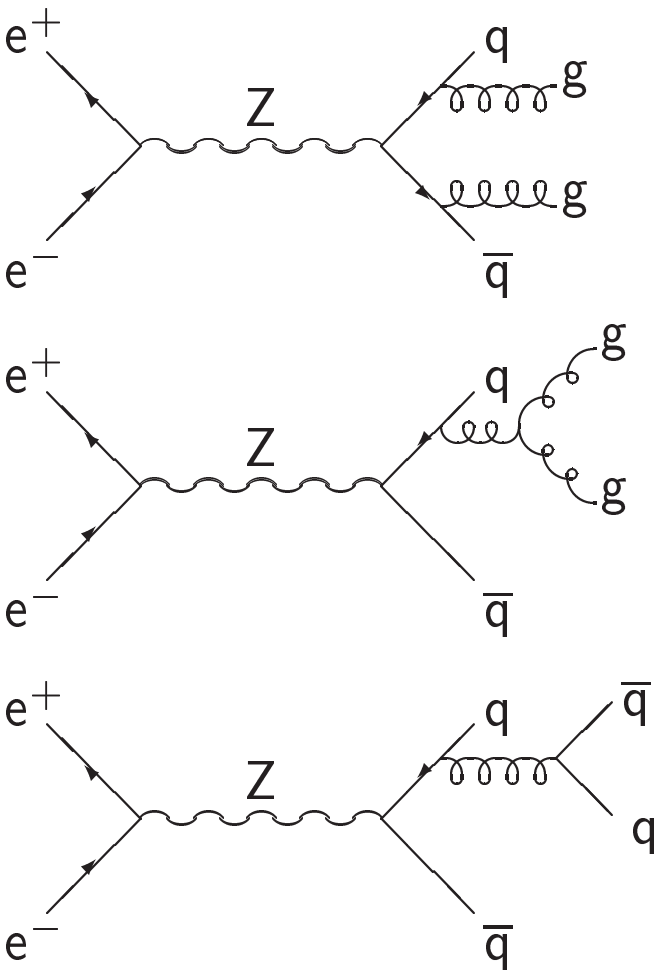
(b) NLLA describes well ξ_p evolution with $\sqrt{s}$.

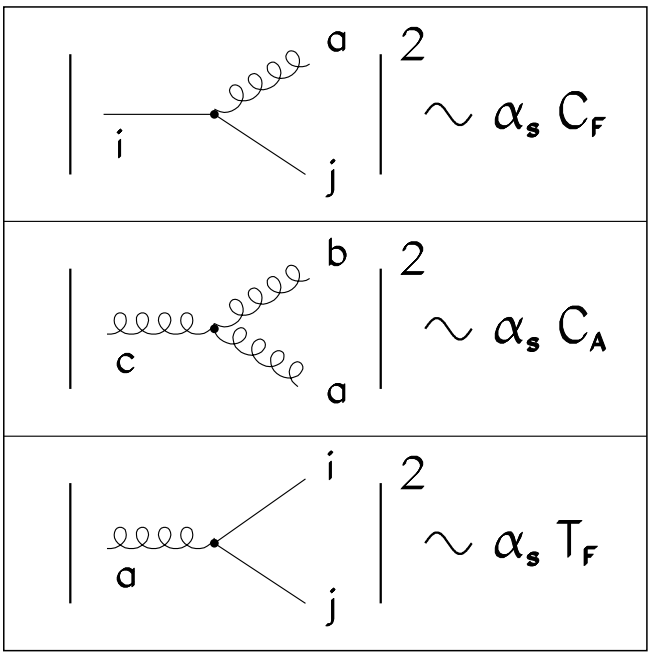
Meanwhile back at the Z

Huge statistics: 4-5 million events per experiment

Color Factors

ALEPH (CERN-PPE/97-002): in 4-jet events,





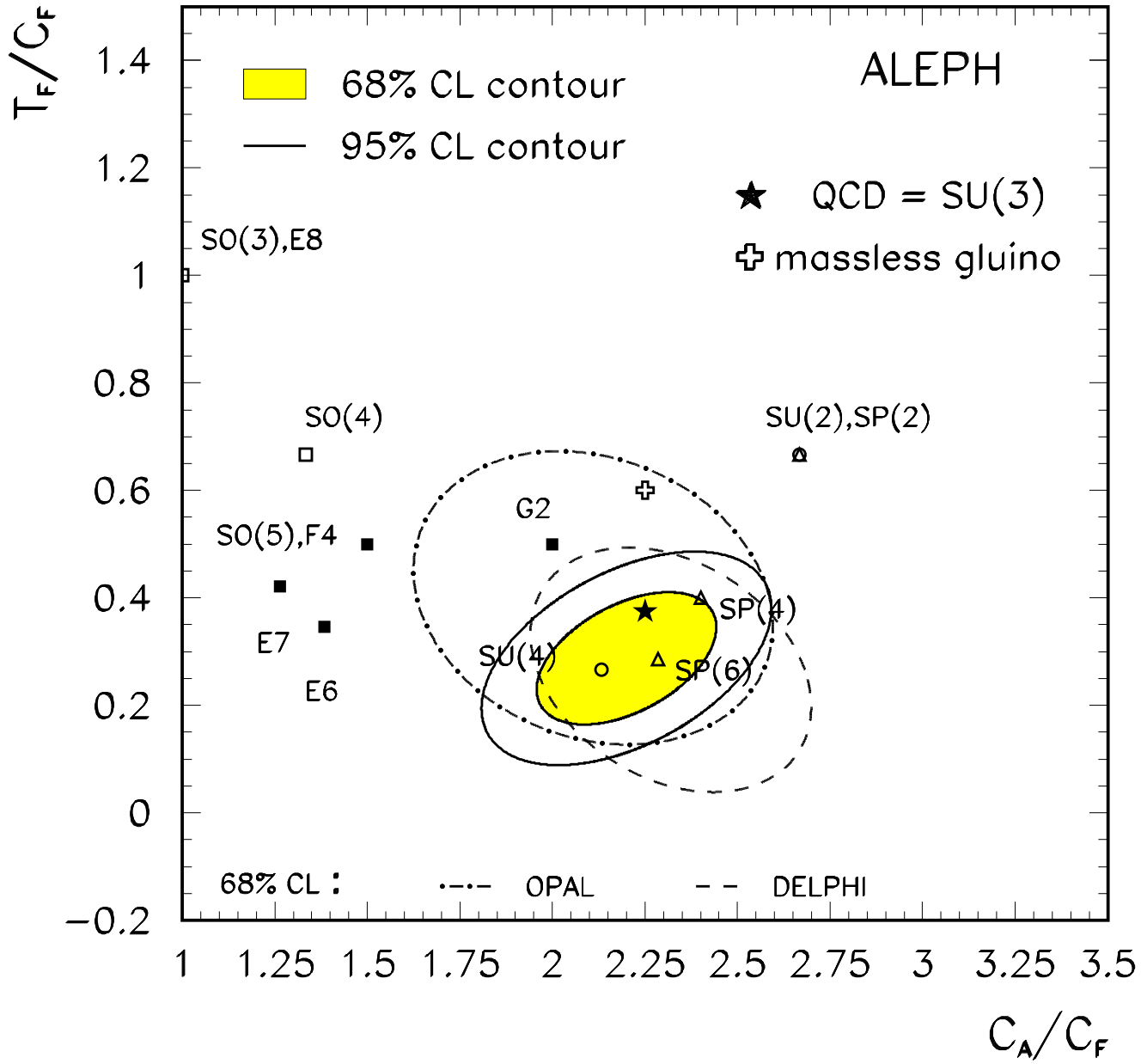
4-jet diagrams are related to Casimir operators (color factors) of color group of QCD: C_F, C_A, T_F

By measuring relative frequencies of 4-jet diagrams, can measure C_F, C_A, T_F

Ang. dists. of diagrams differ

Use complicated angular correlations and jet energies.

Color Factors



Results agree with SU(3)

Gluon Splitting

DELPHI (CERN-PPE/97-039): in 4-jet events, measure

$$g_{b\bar{b}} = \frac{N(Z \to q\bar{q}g,\ g \to b\bar{b})}{N(Z \to \text{hadrons})}$$

Important: uncertainty on $g_{b\bar{b}}$ gives
large syst. error on $R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}}$

Assume 2 jets with smallest angle between them are $g \to q\bar{q}$
(MC: 54% eff.)

Identify jets as b using lifetime tag

Difficult analysis with lots of MC to get efficiencies, purities.

Use OPAL result $g_{c\bar{c}} = 2.27\%$ to estimate contamination from $c\bar{c}$

Result:

DELPHI	$g_{b\bar{b}} = 0.21 \pm 0.11 \pm 0.09\%$
$\mathcal{O}(\alpha_s^2)$+resummed LL, NLL	$g_{b\bar{b}} = 0.18\%$
JETSET PS	$g_{b\bar{b}} = 0.16\%$

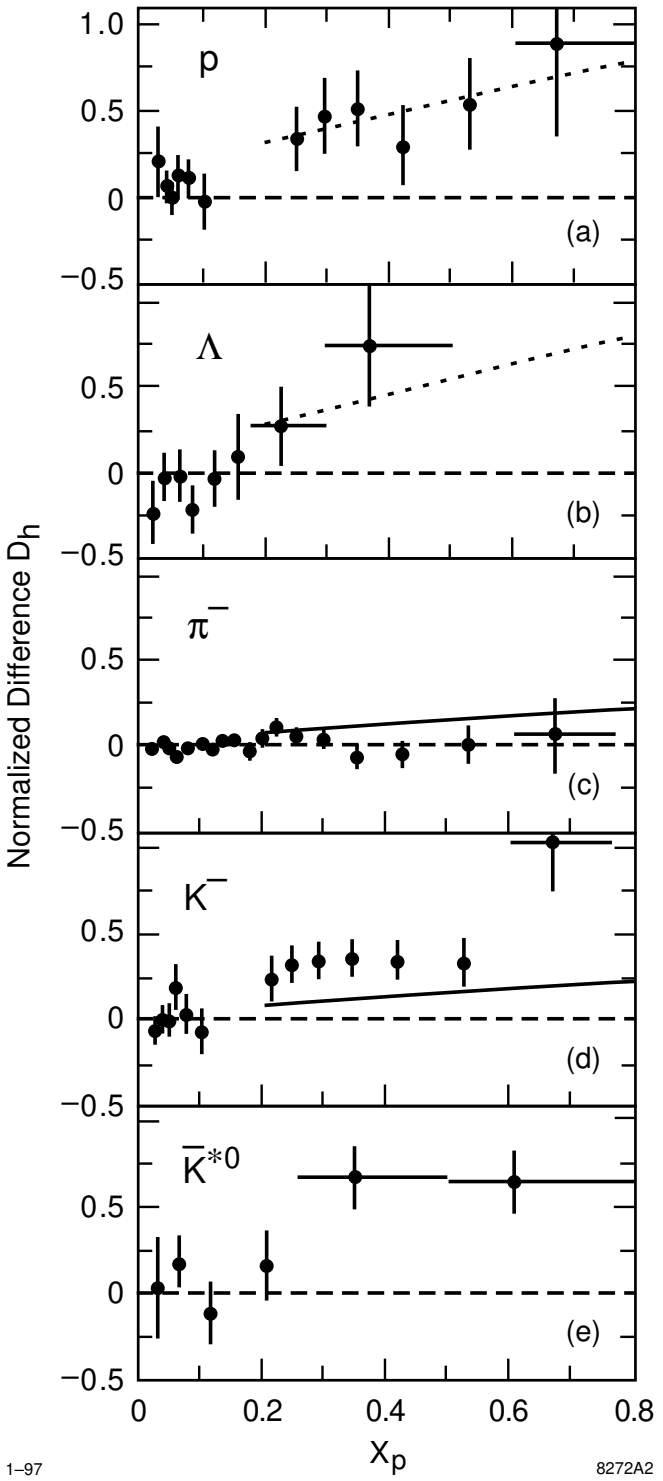
Fragmentation – Leading Particle Effect

SLD (SLAC-PUB-7395): In $e^+e^- \to Z \to q\bar{q}$,
q is preferentially in e^- direction if e^- left-handed.
Thus, polarization tags q hemisphere

Define R_h^q, $R_{\bar{h}}^q$ as rate of production of hadron h, $\bar{h}$ in q hemisphere
Measure

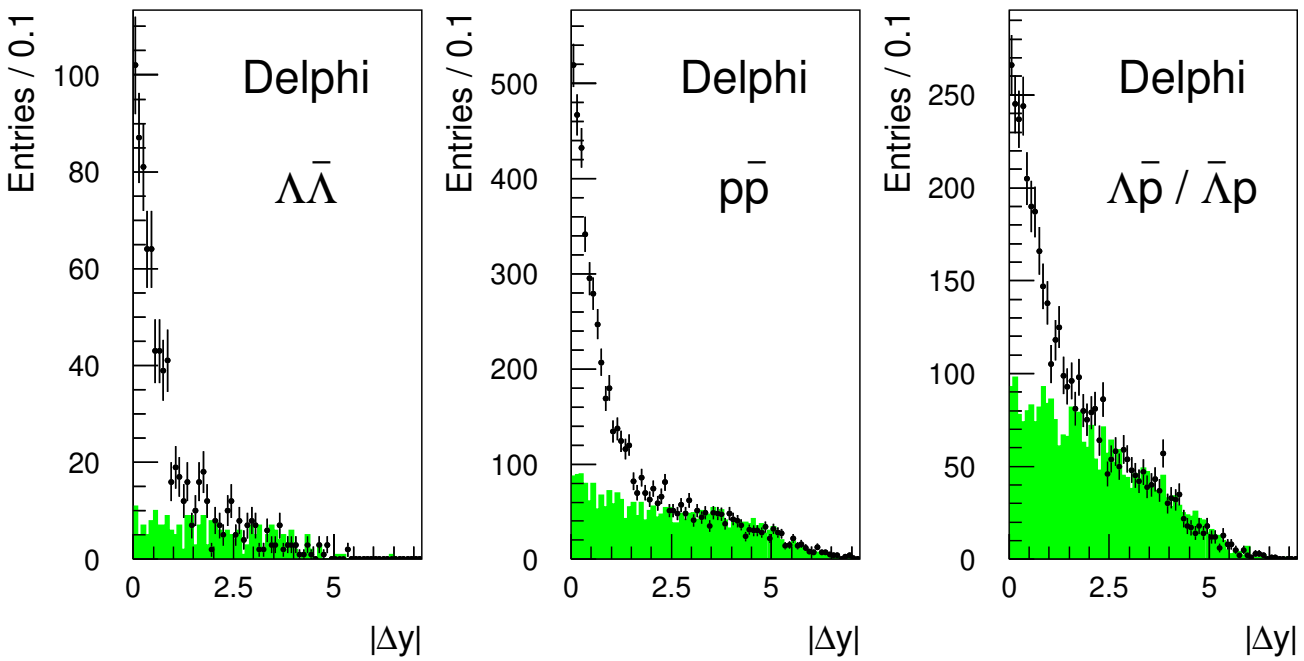
$$D_h = \frac{R_h^q - R_{\bar{h}}^q}{R_h^q + R_{\bar{h}}^q}$$

Results:
$D \approx 0$, all h, $x_p < 0.1$
$D_h > 0$, $x_p > 0.2$,
increasing with x_p,
for all h except π
$\Rightarrow$ leading particle effect
(fast particles tend to include primary quark)
$D_{\pi^-} \approx 0$, all x_p
$\Rightarrow$ no leading particle effect for π^-,
or (more likely) effect washed out by resonances, e.g., ρ



Fragmentation – Baryon Rapidity Correlations

DELPHI (CERN-PPE/97-027):
Measures rapidity difference between $\Lambda\bar{\Lambda}$, $p\bar{p}$, $\Lambda\bar{p}(\bar{\Lambda}p)$

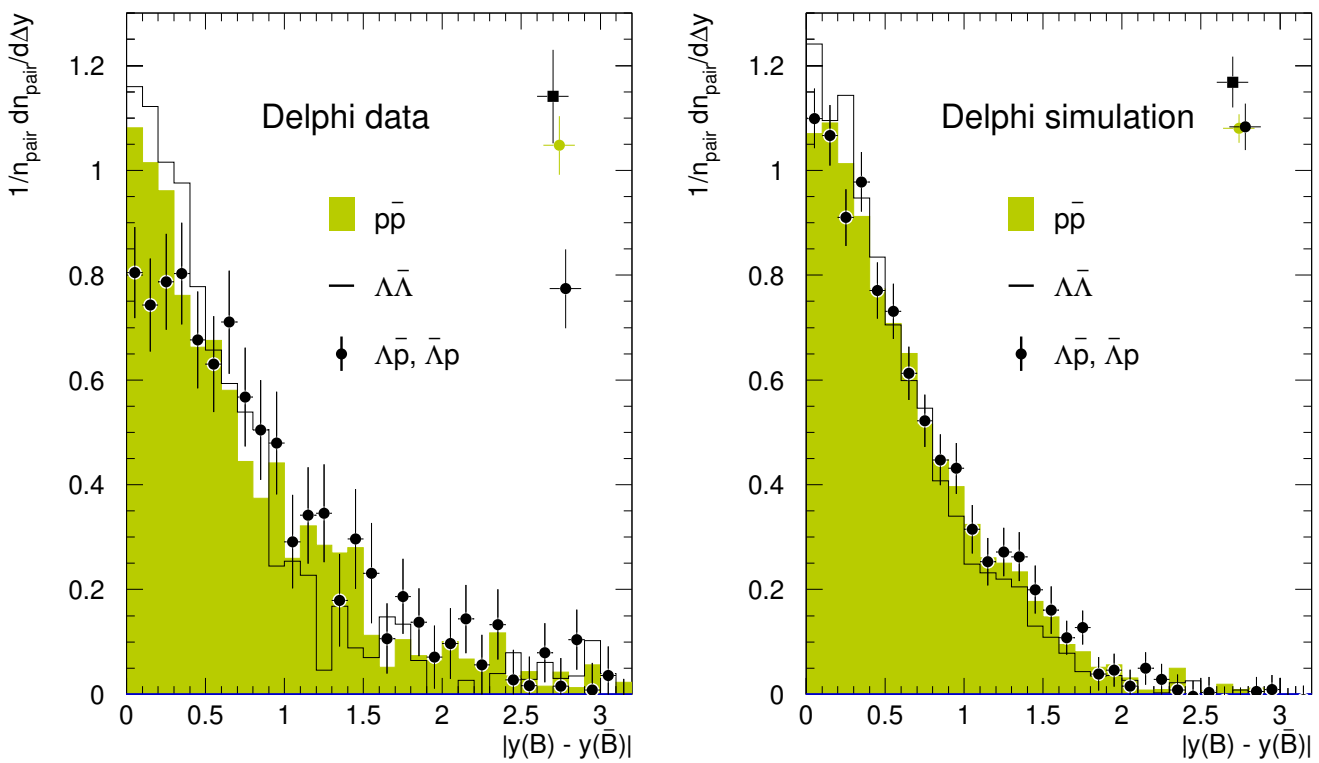


shaded (green) area is $B\bar{B}(\bar{B}\bar{B})$

Subtract $B\bar{B}(\bar{B}\bar{B})$ from $B\bar{B}$:

Fragmentation – Baryon Rapidity Correlations

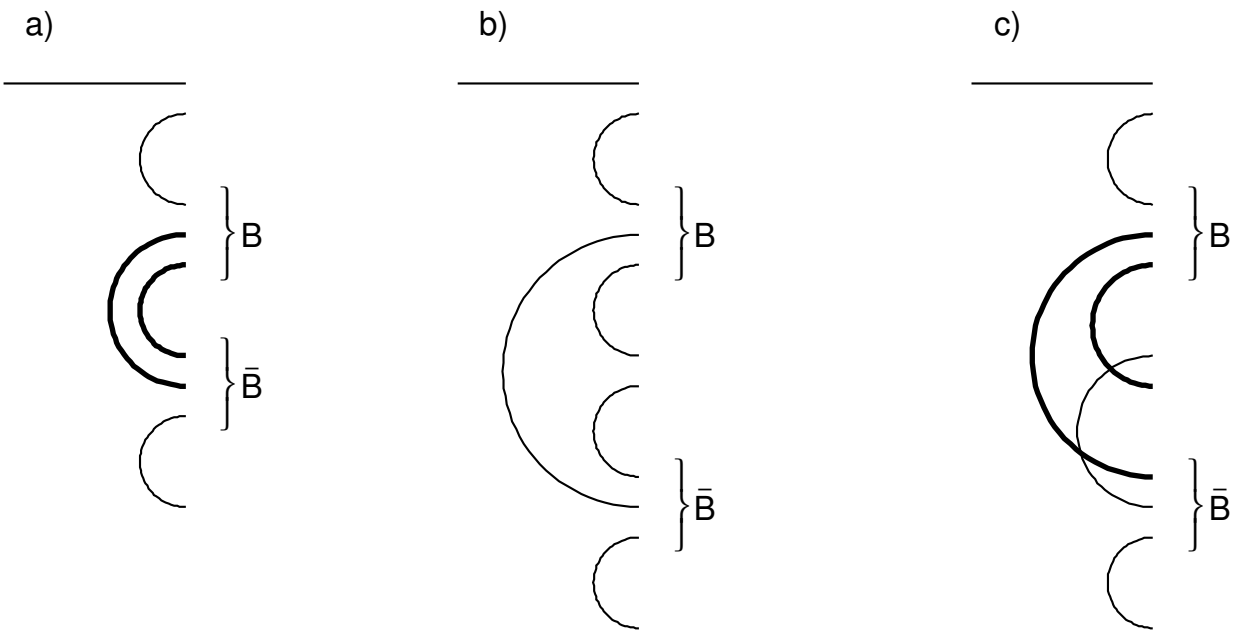
Subtract $B\bar{B}(\bar{B}\bar{B})$ from $B\bar{B}$:



Simulation (JETSET) similar to data
except for $\Lambda\bar{p}(\bar{\Lambda}p)$
Cannot be fixed by tuning JETSET params.
Suggestion: add flavor-dependence to popcorn mechanism

In HERWIG baryons only produced as $B\bar{B}$ in cluster decays.
Therefore highly correlated indep. of $B\bar{B}$ combination
Suggestion: add 3-body cluster decays

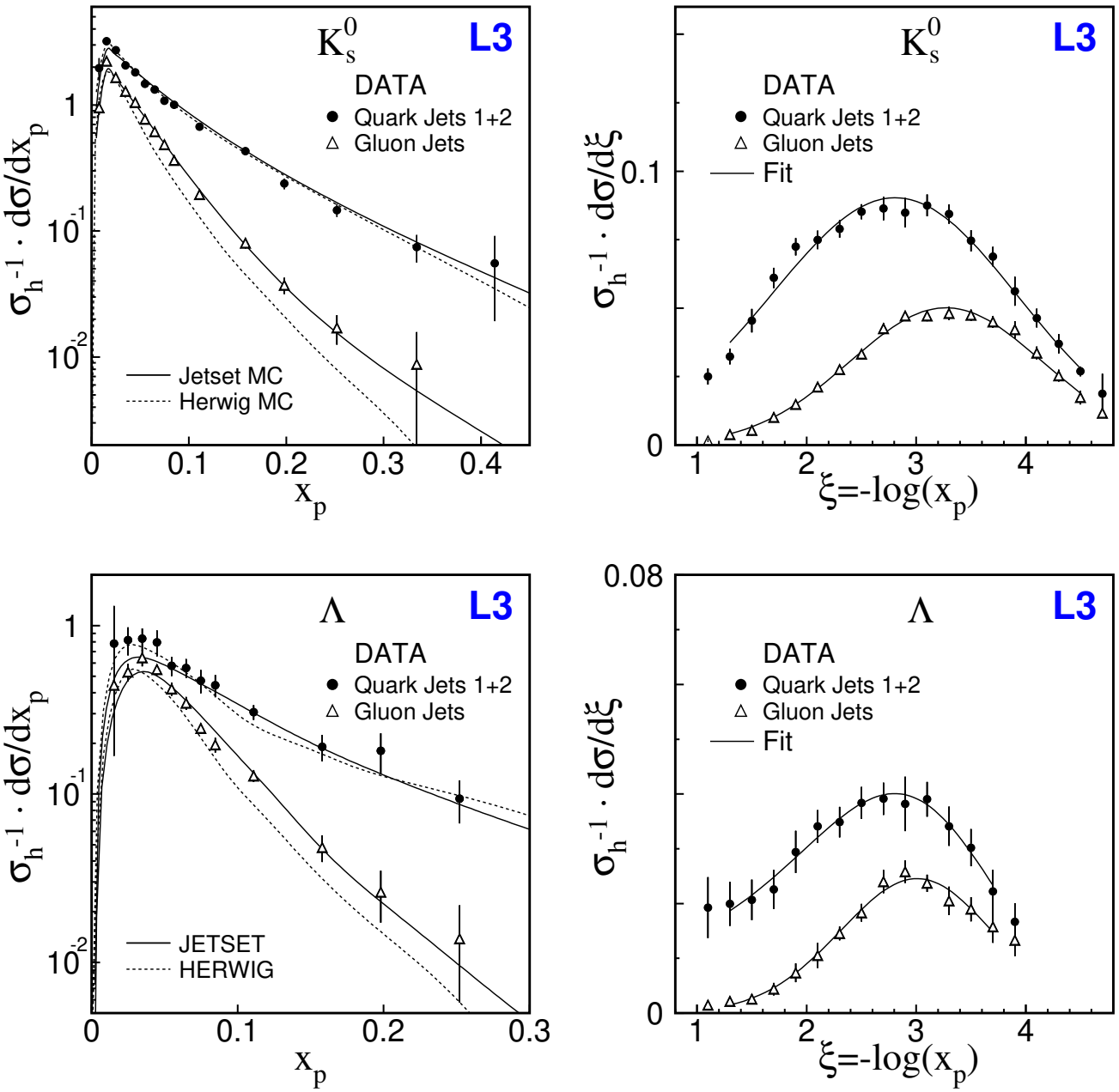
Baryon Production in String Model



diquark popcorn popcorn

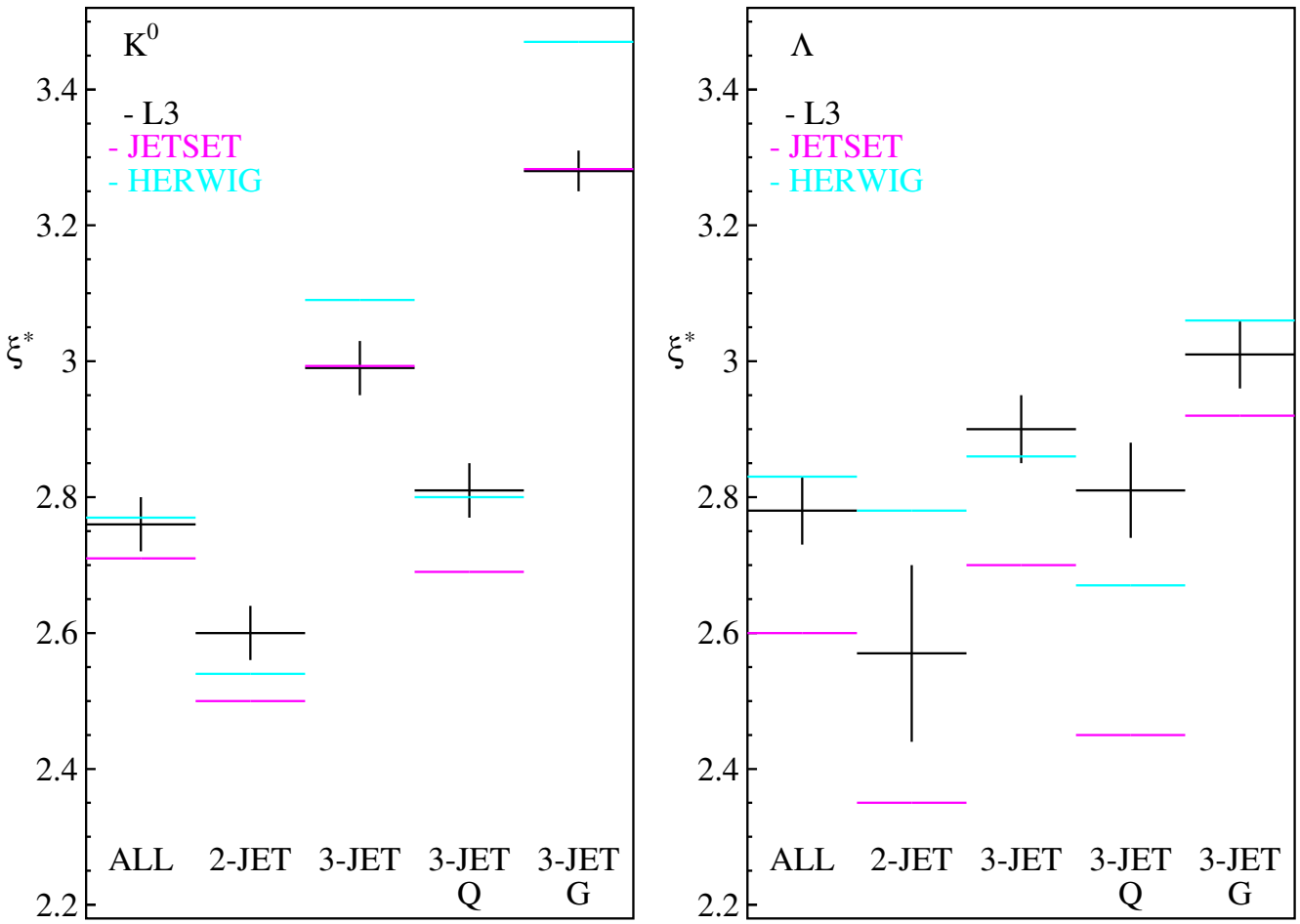
K^0_S, Λ Production

L3 (CERN-PPE/97-50):
In 3-jet events identify lowest E jet as gluon
(JETSET $\mathcal{O}(\alpha_s^2)$ M.E.: 72% of lowest E jets are g)



JETSET agrees
HERWIG - spectra are too soft for g jet

K^0_S, Λ Production



HERWIG agrees better than JETSET.

Here, $\xi = -\log x_p = -\log \frac{p}{E_{\text{beam}}}$

For 3-jet events should correct ξ^* for jet energy:

$$\xi^{*'} = \xi^* - \log \frac{E_{\text{beam}}}{\langle E_{\text{jet}} \rangle}$$

K^0_S, Λ Production

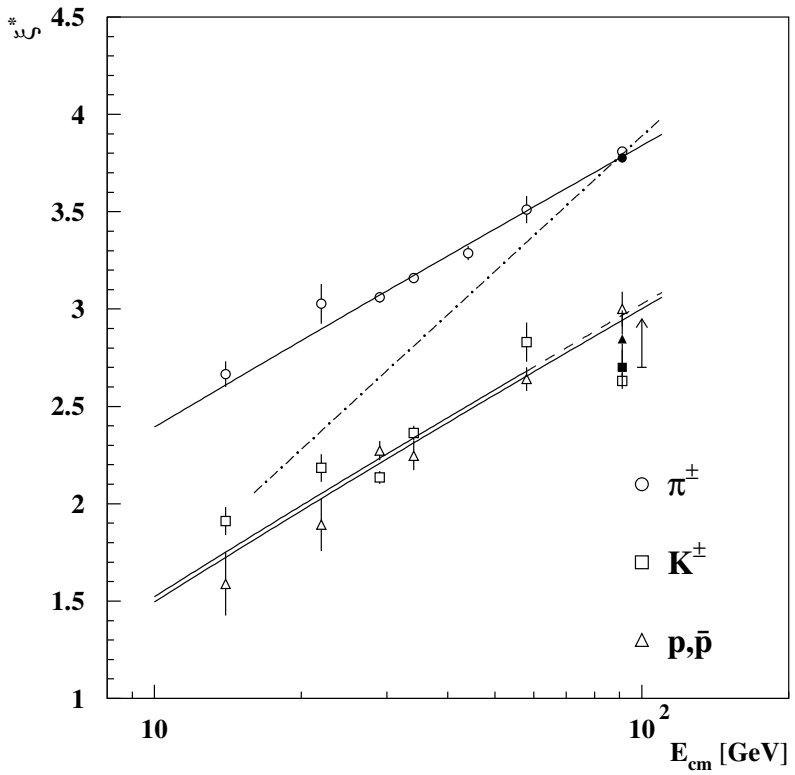
$$\xi^{*\prime} = \xi^* - \log \frac{E_{\text{beam}}}{\langle E_{\text{jet}} \rangle}$$

		K^0_S		Λ	
	$\langle E_{\text{jet}} \rangle$	ξ^*	$\xi^{*\prime}$	ξ^*	$\xi^{*\prime}$
All evts.		2.76±0.04		2.78±0.05	
2-jet ev.	45.5	2.60±0.04	2.60	2.57±0.13	2.57
3-jet ev.	30.6	2.99±0.04	2.59	2.90±0.05	2.50
- Q jets	37.0	2.81±0.04	2.60	2.81±0.07	2.60
- G jets	17.9	3.28±0.03	2.35	3.01±0.05	2.08

Using

$$\sqrt{s} = 2\langle E_{\text{jet}} \rangle$$

Reasonable agreement with MLLA $\sqrt{s}$ dependence.



K^0_S, Λ Production

compared to charged particle (mostly π) using $R(K^0_S)$, $R(\Lambda)$:

$$R(\Lambda) = \frac{\frac{\langle \Lambda \rangle_{\text{per jet}}}{\langle \text{ch} \rangle_{\text{per jet}}}}{\frac{\langle \Lambda \rangle_{\text{per event}}}{\langle \text{ch} \rangle_{\text{per event}}}}$$

K^0 produced similarly to π

Λ produced differently

More Λ in g than in q

JETSET: agrees with data

- frag. fct. softer for diquark than quark
- popcorn

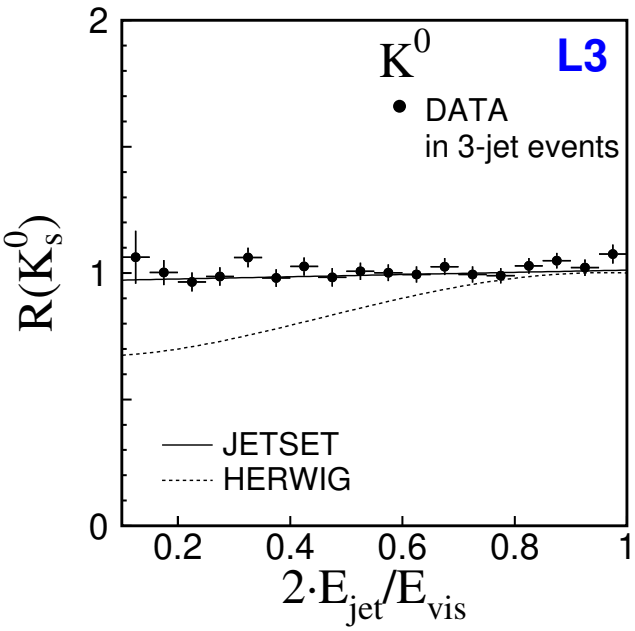
HERWIG: disagrees

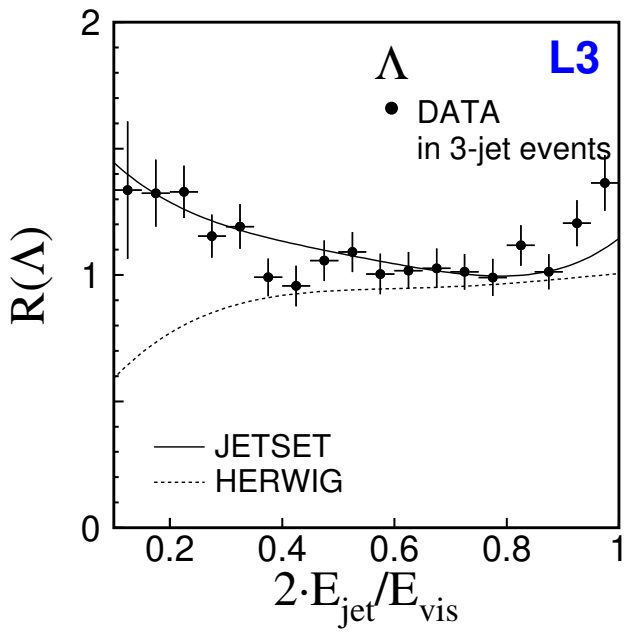
cluster decays depend on M

low-E jet

$\Rightarrow$ low-M clusters

$\Rightarrow$ fewer high-M particles





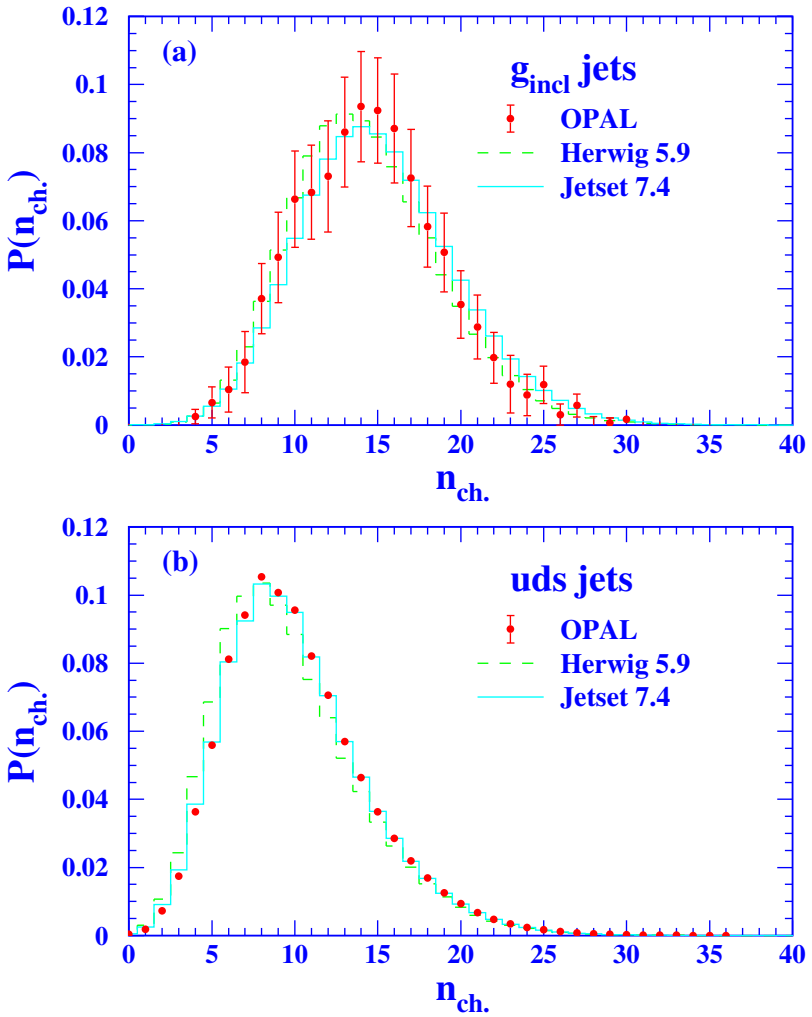
Charged Particle Multiplicity — q/g

OPAL selects g jet in $q\bar{q}g$ events where $q\bar{q}$ close together (10-50°) and both tagged as b (294 events).

Then color field ≈ that in a "gg" event.

They then compare the g with a q from a 2-jet ($q\bar{q}$) event with a light-quark tag (since QCD calculations are for massless quarks)

$\langle E_g \rangle = 41.2$ GeV (from MC) $\approx$ $E_q = E_{beam} = 45.6$ GeV



Good agreement with JETSET, HERWIG

Charged Particle Multiplicity — q/g

Correcting q mult. to 41.2 GeV using QCD $\langle n_{\mathrm{ch}} \rangle$ evolution,

$$r \equiv \frac{\langle n_{\mathrm{ch}} \rangle_{\mathrm{g}}}{\langle n_{\mathrm{ch}} \rangle_{\mathrm{uds}}} = 1.494 \pm 0.025 \pm 0.051$$

Factorial and cumulant moments of the mult. dists. and their ratio:

$$F_q = \frac{\sum_{n=q}^{\infty} \frac{n!}{(n-q)!} P_n}{\left(\sum_{n=1}^{\infty} n\, P_n\right)^q}$$

$$K_q = F_q - \sum_{m=1}^{q-1} \binom{q-1}{m} K_{q-m} F_m$$

$$H_q = \frac{K_q}{F_q}$$

QCD (+ LPHD) analytic calculations (Dremin and Hwa) for H_q

$r_{H_q} = \frac{H_q(\text{gluon})}{H_q(\text{quark})}$	$q = 2$	$q = 3$
OPAL data (prel.)	$0.30 \pm 0.11 \pm 0.10$	$0.01 \pm 0.18 \pm 0.11$
JETSET, hemisph.	0.39 ± 0.01	0.07 ± 0.01
HERWIG, hemisph.	0.33 ± 0.01	0.13 ± 0.01
QCD (event)	0.51	0.23
JETSET, event	0.35 ± 0.01	0.07 ± 0.01
HERWIG, event	0.30 ± 0.01	0.09 ± 0.01

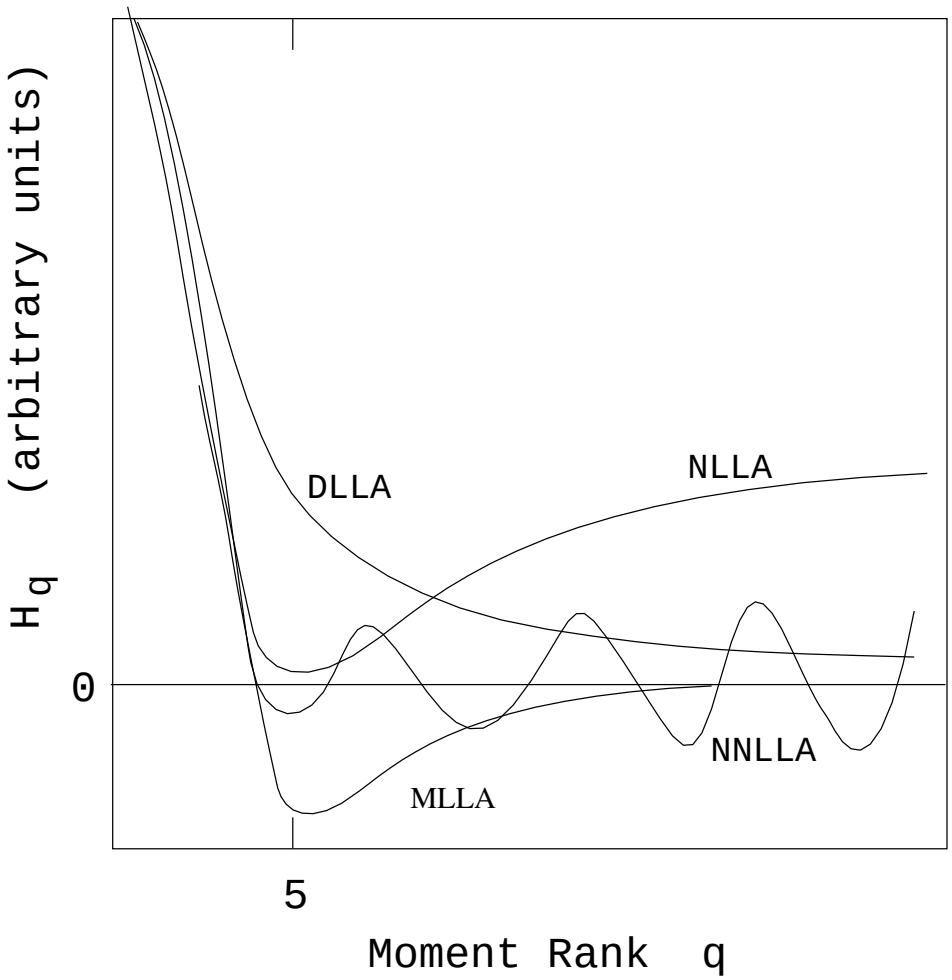
Data agree with analytic QCD within errors.

Charged Particle Multiplicity

Two years ago SLD analysed the mult. dist. in terms of $H_q = \frac{K_q}{F_q}$

QCD predicts behavior of $H_q = \frac{K_q}{F_q}$

Assuming LPHD, same behavior should occur for charged particle mult. dist.



SLD observed the behavior predicted by NNLLA min. + oscillations

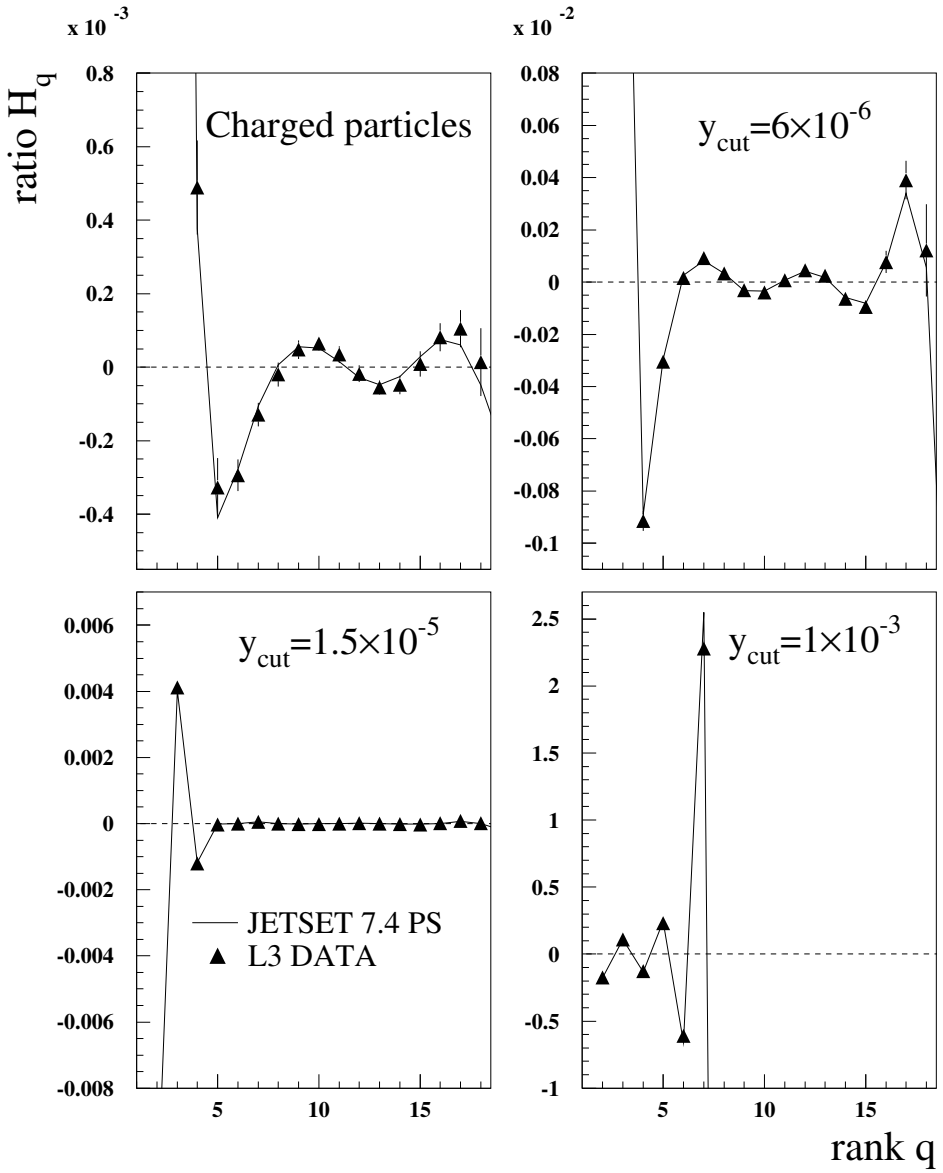
Charged Particle Multiplicity

This behavior confirmed by L3

But also seen in JETSET, which is only MLLA

Could behavior be due to something else?

Look at subjets, jets for small y_{cut} (Durham)



As y_{cut} (E scale) increases, min. + oscillations disappear long before pert. region (where prediction should be best)

Observed min. + oscillations seems merely fortuitous, NOT a confirmation of NNLLA

Local Particle Fluctuations

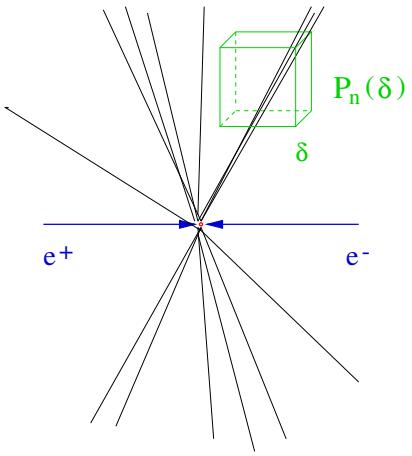
To study dynamical fluctuations in particle density in small regions of phase space,

Usual method:

Normalized Factorial Moments, $F_q(\delta)$

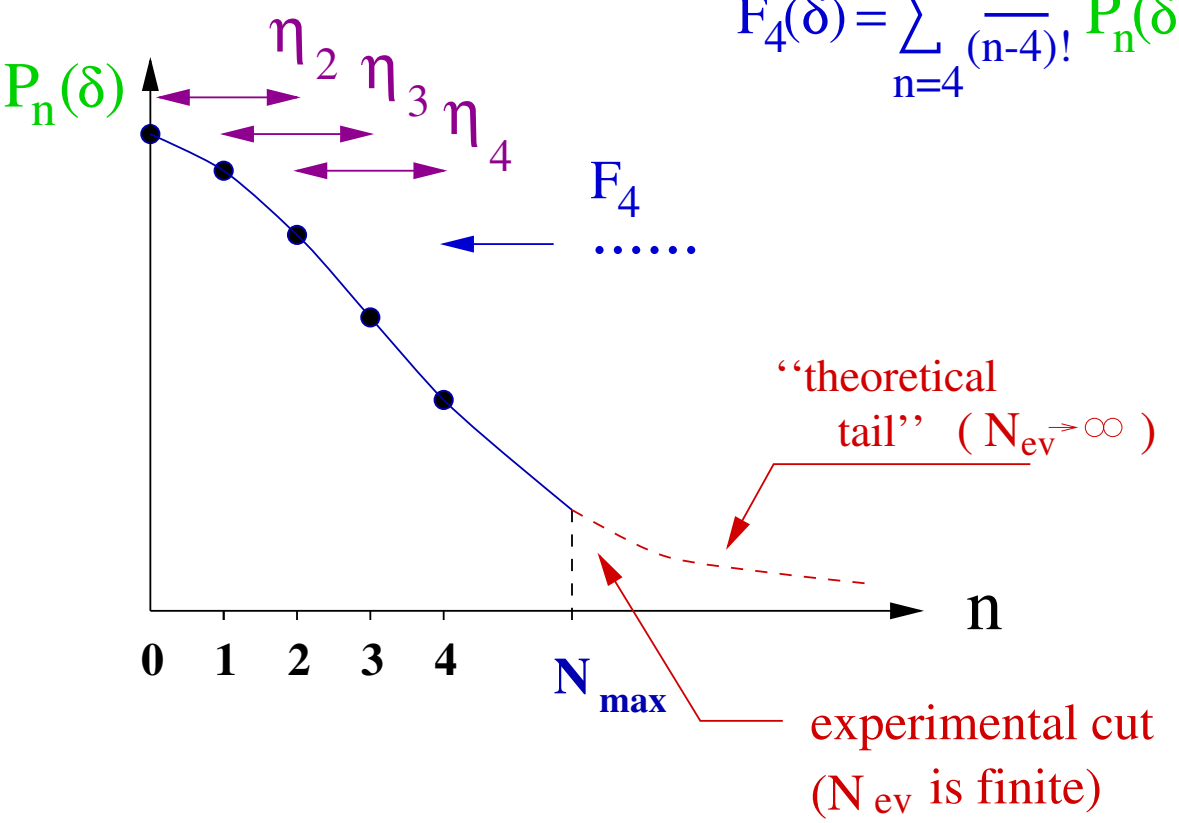
New method: (S. V. Chekanov)

Bunching Parameters, $\eta_q(\delta)$



$$\eta_q(\delta) = \frac{q}{q-1}\,\frac{P_q(\delta)P_{q-2}(\delta)}{P^2_{q-1}(\delta)}$$

NFMs: $F_4(\delta) = \sum_{n=4}^{\infty} \frac{n!}{(n-4)!} P_n(\delta)$



Local Particle Fluctuations

Disadvantages of Normalized Factorial Moments:

- very sensitive to tail of multiplicity dist.
  resulting in a bias to lower values
  Bias decreases with increased statistics

- require resolution of max. number of particles

- "insensitivity" to the underlying physics, $e.g.$, NFM behavior for rapidity w.r.t. thrust axis very similar to rapidity w.r.t. beam

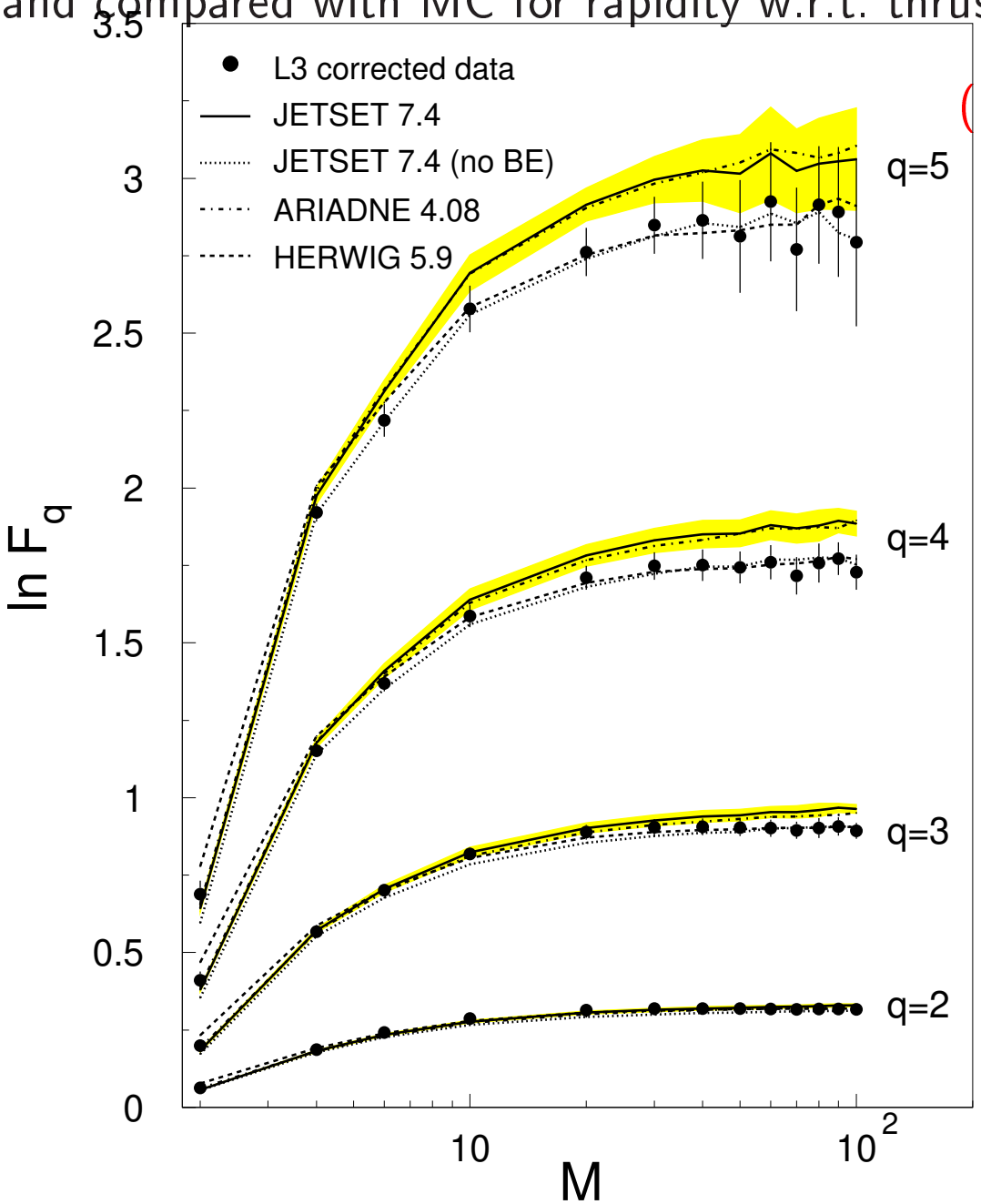
NFMs and BPs

As function of bin size δ:

"Statistical" fluctuations = Indep. production	
P_n is Poisson	$F_q(\delta) = \eta_q(\delta) = 1$
Dynamical fluctuations, scale-inv. correlations	
Intermittency:	$F_q(\delta) \propto \delta^{-\phi_q} \quad , \phi_q > 0$
	$\eta_2(\delta) \propto \delta^{-\phi_2}$
anomalous fractal dimensions, $d_q = \frac{\phi_q}{q-1}$	
monofractal fluctuations	$\eta_2(\delta) \propto \delta^{-d_2}$
	$\eta_{q>2}(\delta) \approx$ const
multifractal fluct. (QCD)	$\eta_2(\delta) \propto \delta^{-d_2}$
	$\eta_{q>2}(\delta) \approx$ not const

Local Particle Fluctuations

L3 (Chekanov, thesis, Nijmegen) measured NFMs and BPs and compared with MC for rapidity w.r.t. thrust axis:

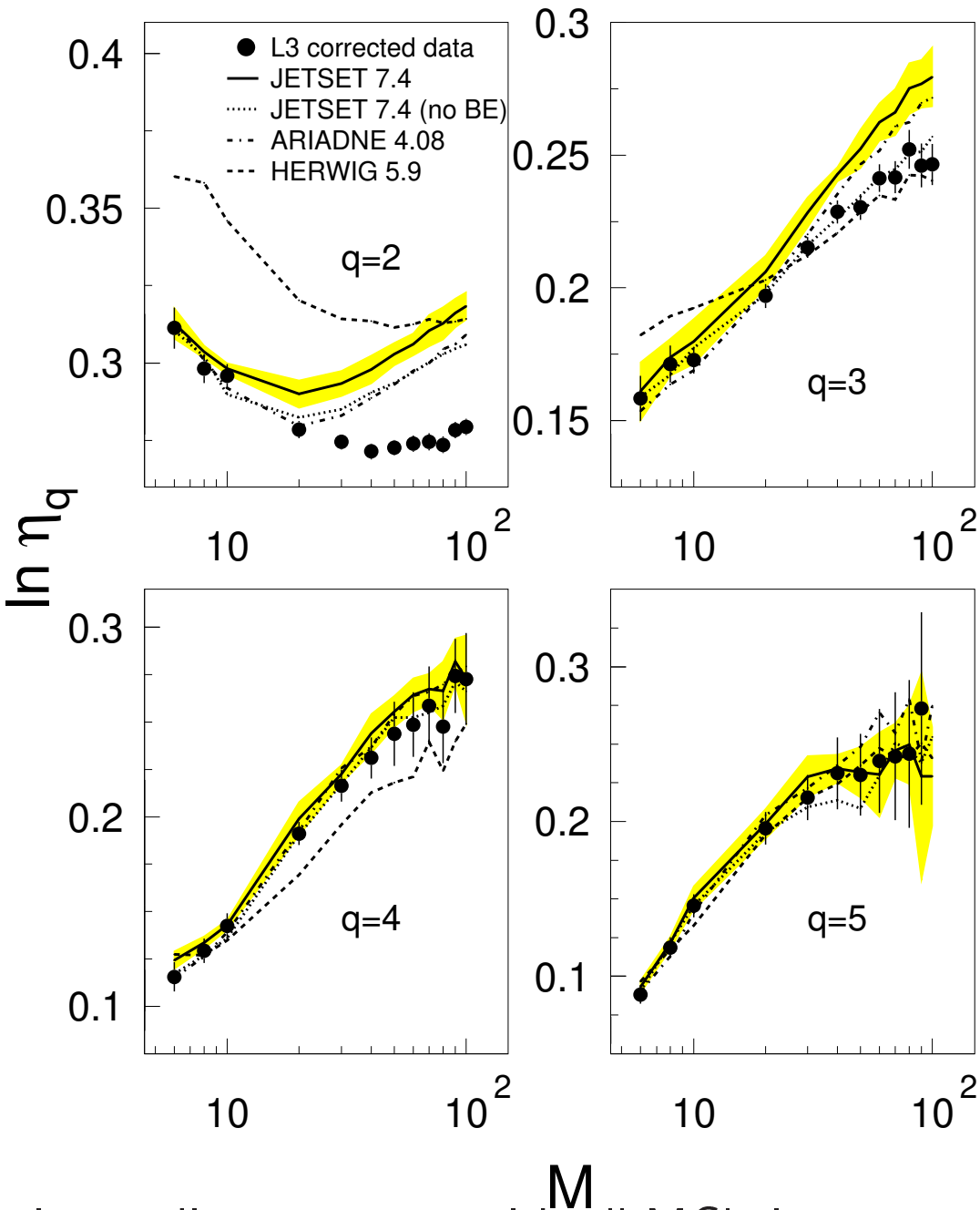


(preliminary)

- JETSET, ARIADNE overestimate F_q
- turning off Bose-Einstein makes agreement better
- HERWIG agrees well

Local Particle Fluctuations

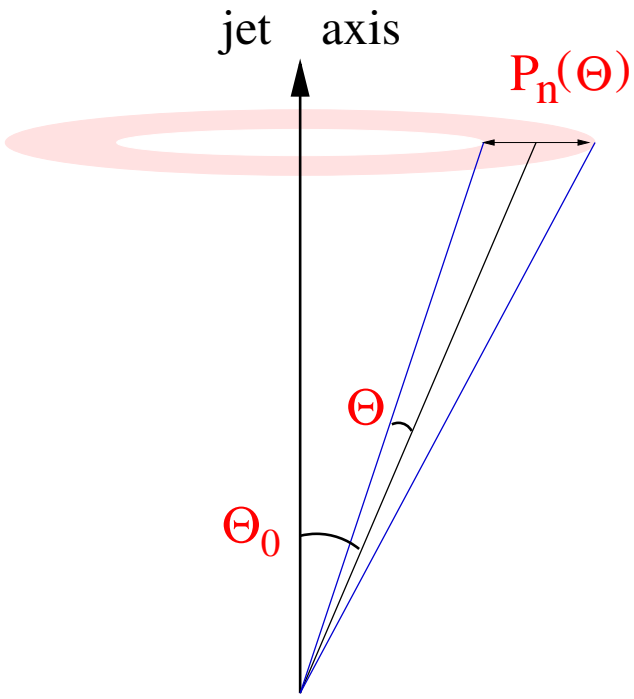
(preliminary)



- Large disagreements with all MC's in η_2
- less disagreement for η_q, $q > 2$
- Largest disagreement for HERWIG
- $\eta_{q\geq 3} \propto \delta^{-d} \Longrightarrow$ local fluctuations are multifractal

Angular Intermittancy

L3 (Chekanov, thesis, Nijmegen) study of Factorial moments in angular bins about thrust axis



$P_n(\Theta)$ - prob. of detecting n hadrons at Θ

- $\Theta \quad \Rightarrow \quad z = \dfrac{\ln(\Theta/\Theta_0)}{\ln(E\Theta/\Lambda)} \qquad E \simeq \dfrac{\sqrt{s}}{2}$

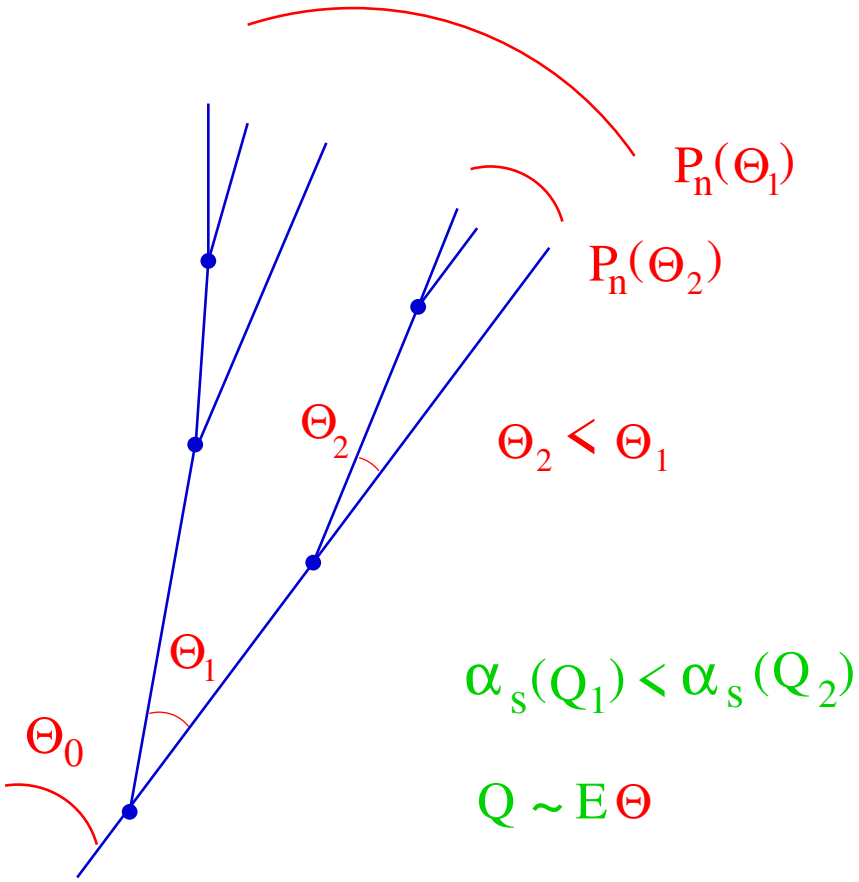
  $0 < \Theta < \Theta_0 \quad \Rightarrow \quad \infty > z > 0$

- $P_n(\Theta) \quad \Rightarrow \quad P_n(z) \quad \rightarrow \quad F_q(z)$

  normalized factorial moments

Angular Intermittancy Test of QCD

(preliminary)



QCD PREDICTIONS:

- Strong correlations of partons

$$F_q(\Theta) \propto \left(\frac{\Theta_0}{\Theta}\right)^{(1-D_q)(q-1)},$$

$$D_q \neq 1$$

- Dependence of D_q on α_s

Angular Intermittancy Test of QCD

- Fixed coupling regime in DLLA:

$$D_q = \gamma_0 \frac{q+1}{q},$$

$\gamma_0 = \sqrt{2\,C_{\rm A}\alpha_s/\pi}$.

- Running coupling regime in DLLA:

Yu.Dokshitzer, I.M.Dremin, Nucl.Phys. B402 (1993) 139

$$D_q \simeq \gamma_0 \frac{q+1}{q}\left(1 + \frac{q^2+1}{4q^2} z\right) \qquad (a)$$

- Another DLLA estimation:

Ph.Brax, J.-L.Meunier, R.Peschanski, Z.Phys. C62 (1994) 649

$$D_q \simeq 2\,\gamma_0 \frac{q+1}{q}\left(\frac{1-\sqrt{1-z}}{z}\right) \qquad (b)$$

- Running coupling regime in MLLA:

Yu.Dokshitzer, I.M.Dremin, Nucl.Phys. B402 (1993) 139

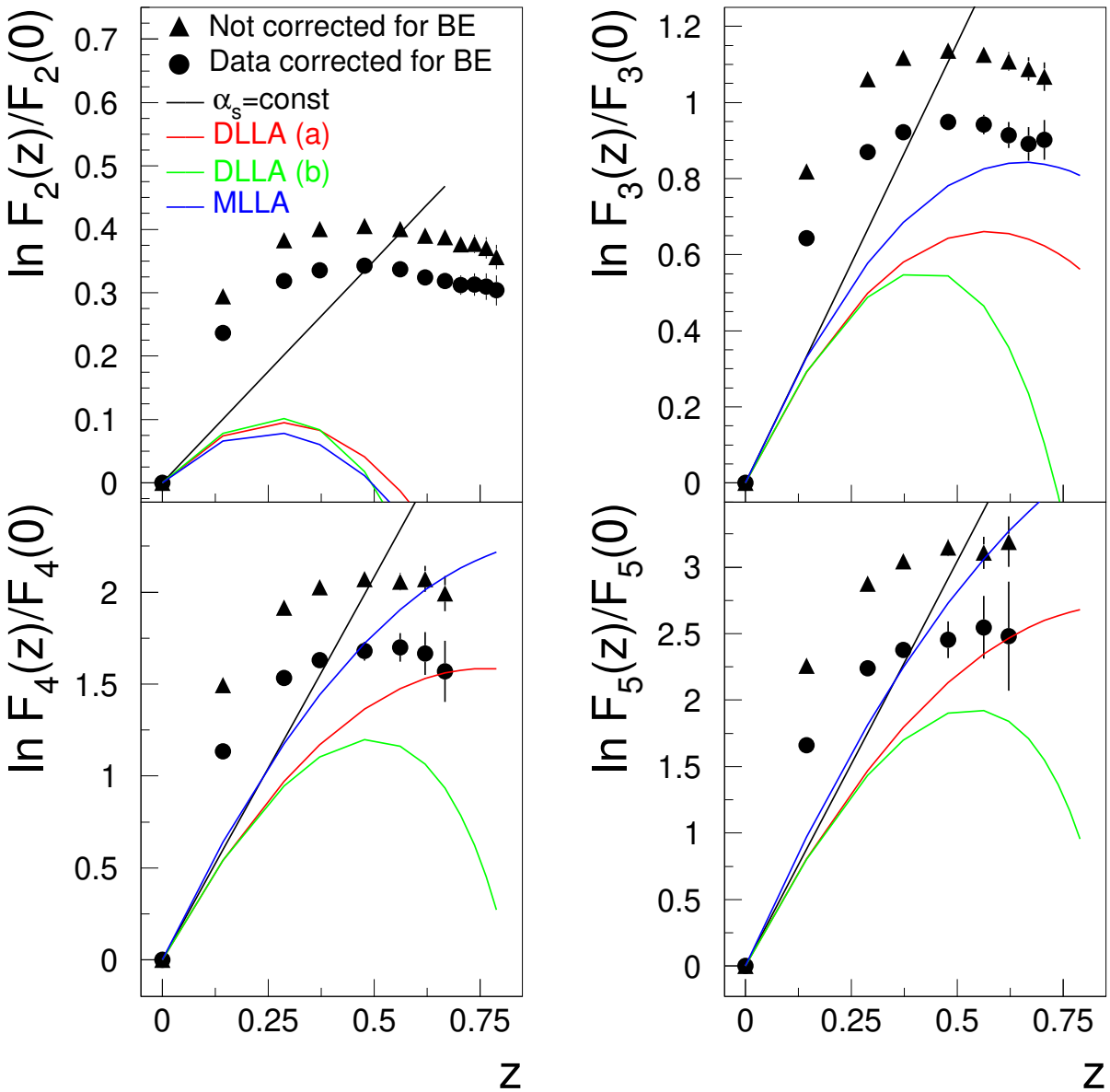
$$\gamma_0 \to \gamma_0^{\rm eff} = \gamma_0 + \gamma_0^2 \frac{b}{4C_{\rm A}}\left[-B\frac{q-1}{2(q+1)} + S_q\right]$$

$$S_q = \frac{q-1}{2(q+1)(q^2+1)} + \frac{1}{4}, \quad b = \frac{11C_{\rm A}}{3} - \frac{2n_f}{3}, \quad B = \frac{1}{b}\left[\frac{11C_{\rm A}}{3} + \frac{2n_f}{3C_{\rm A}^2}\right].$$

Angular Intermittancy Test of QCD

(preliminary)

$\Theta_0 = 25^\circ$ $\Lambda = 0.16$ GeV $n_f = 5$

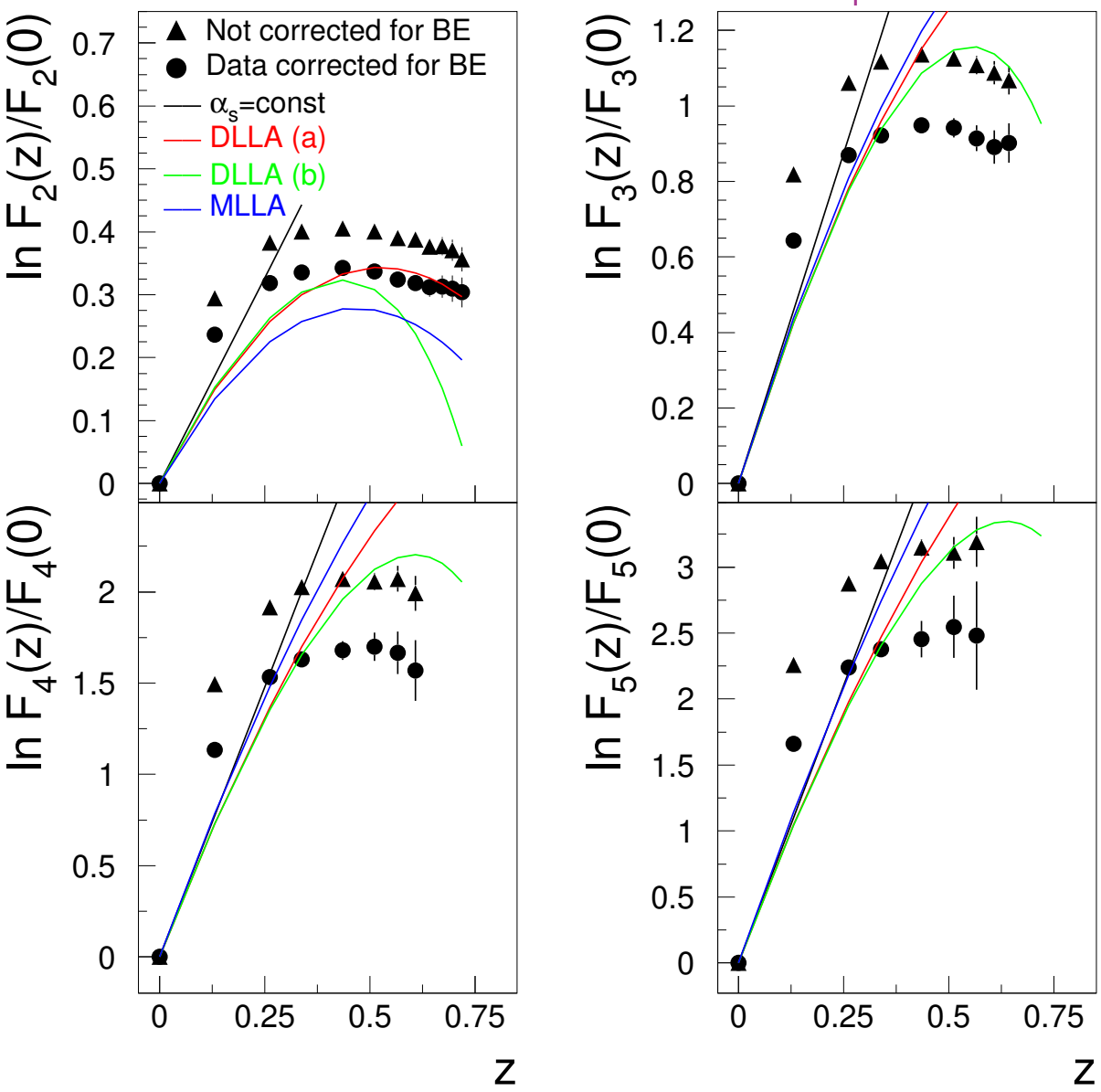


None of predictions agree with data

Angular Intermittancy Test of QCD

(preliminary)

$\Theta_0 = 25°$ $\Lambda = 0.10$ GeV $n_f = 3$



Disagreement is less for smaller Λ, n_f
but still not good

Possible reasons:

- Need higher orders of pert. QCD
- Non-pert. effects

Conclusions

- MLLA MC's (JETSET, ARIADNE, HERWIG) tuned at 91 GeV, perform well through 172 GeV on global quantities, single-particle spectra.

- Analytic QCD calculations in general agree reasonably with data, but in at least one case agreement seems fortuitous.

- MCs, especially HERWIG, need some fixes to describe baryon production.

- New method – Bunching Parameters – to study fluctuations

- At present state of the art, neither MCs nor pert. QCD describe fluctuations