QCD @ high energy e^+e^- colliders: experiment

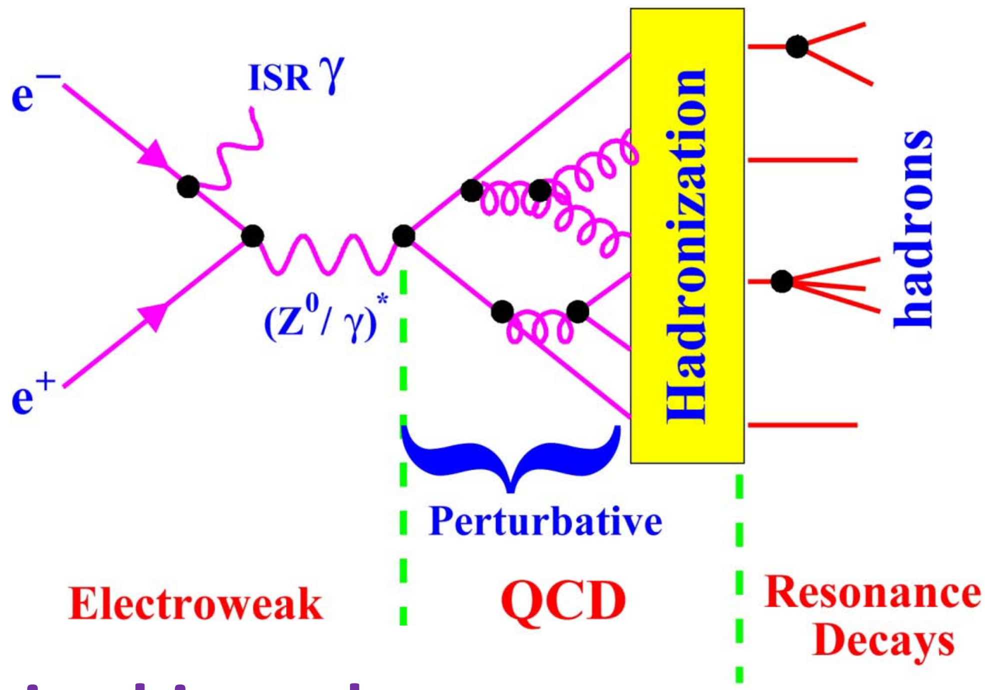
Bill Gary

U. California, Riverside

bill.gary@ucr.edu

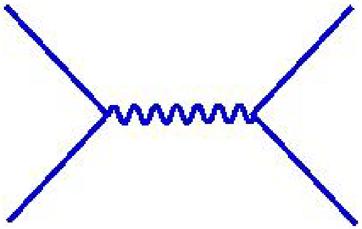
OPAL, Babar, CMS, & CTEQ Collaborations

QCD events in e^+e^- annihilations

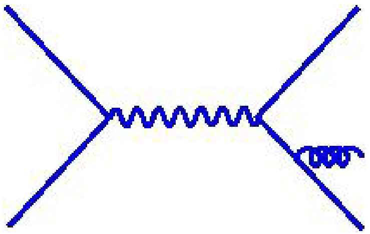


Perturbative hierarchy:

2-jets (tree): α_S^0
→ no QCD

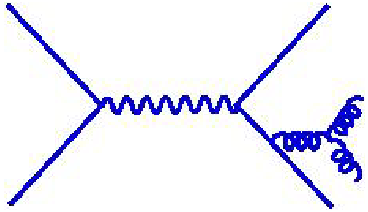


3-jets (tree): α_S^1
→ Leading order
(LO) one loop



Perturbative calculations

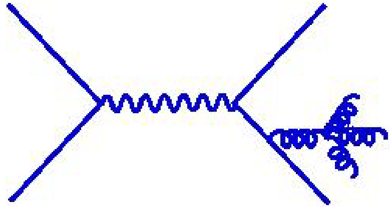
- **NLO**: α_S^2 [1980's and 1990's]
  → 2-loop corrections to $e^+e^- \rightarrow$ 2 jets
  → all variables (MC integration programs)



- **NLLA**: [1990's] Next-to-leading-log-approximation
  → summation of colinear terms to all orders in α_S

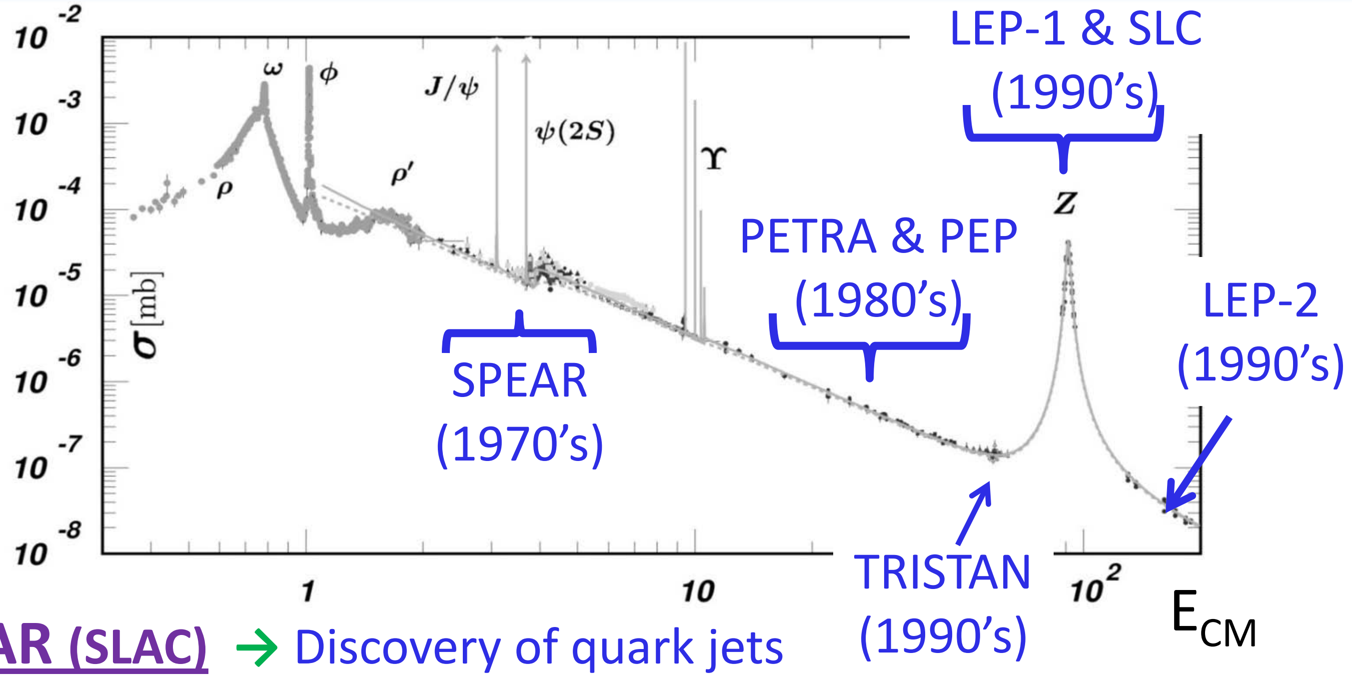
- **NLO+NLLA**: the standard at end of LEP data-taking (2000)

- **NNLO**: α_S^3 → 3-loop corrections
  → total $e^+e^- \rightarrow$ hadron cross section [1990's]
  → Event shapes (Thrust, etc.) [2007]



- Current state-of-the-art : **NNLO + matched NLLA** [2008,…]

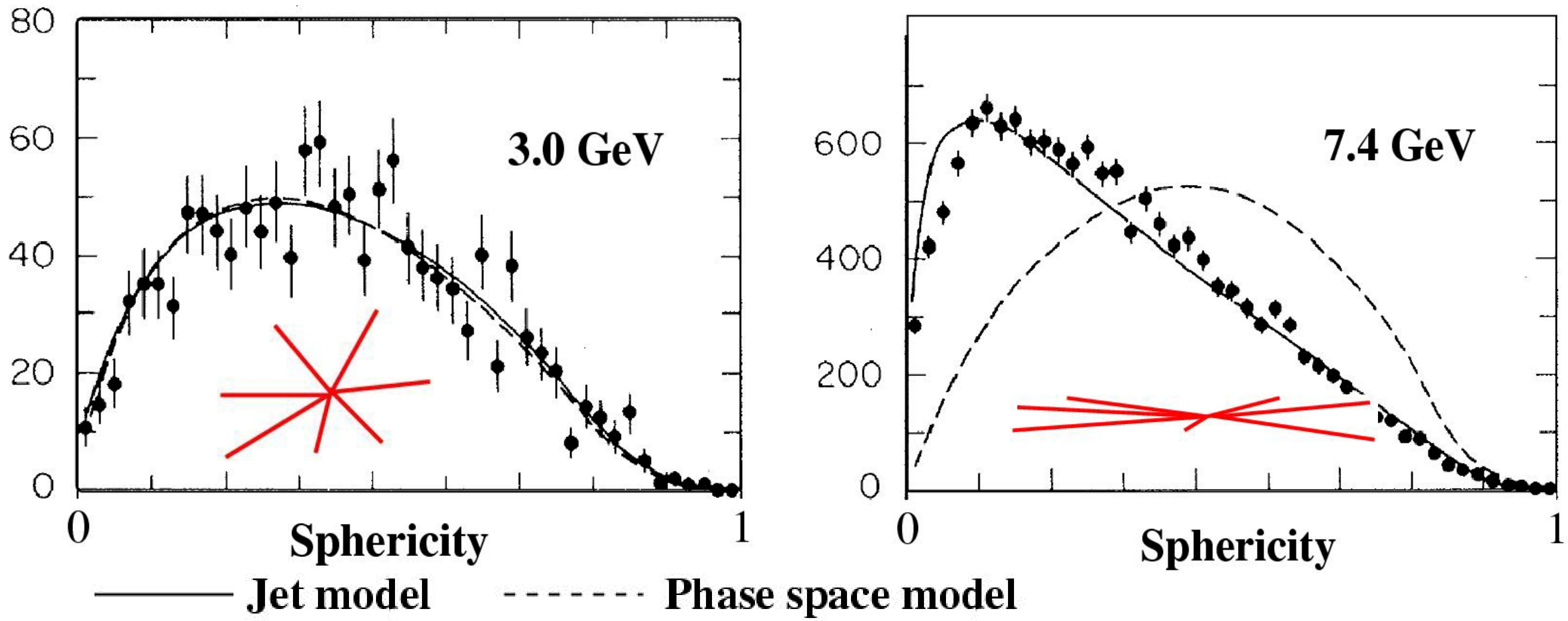
e^+e^- accelerators & experiments



- **SPEAR (SLAC)** → Discovery of quark jets
- **PETRA (DESY) & PEP (SLAC)**: first high energy (> 10 GeV) jets
  - → Discovery of gluon jets, many pioneering QCD studies
- **LEP (CERN) and SLC (SLAC)**:
  - → Large energies [small α_S → more reliable calculations, smaller had. uncertainties] ; large data samples (~3×10^6 hadronic Z decays)
  - → Precision tests of QCD

Discovery of jets: SPEAR @ SLAC

SLAC-LBL Collaboration, G. Hanson et al., PRL 35 (1975) 1609



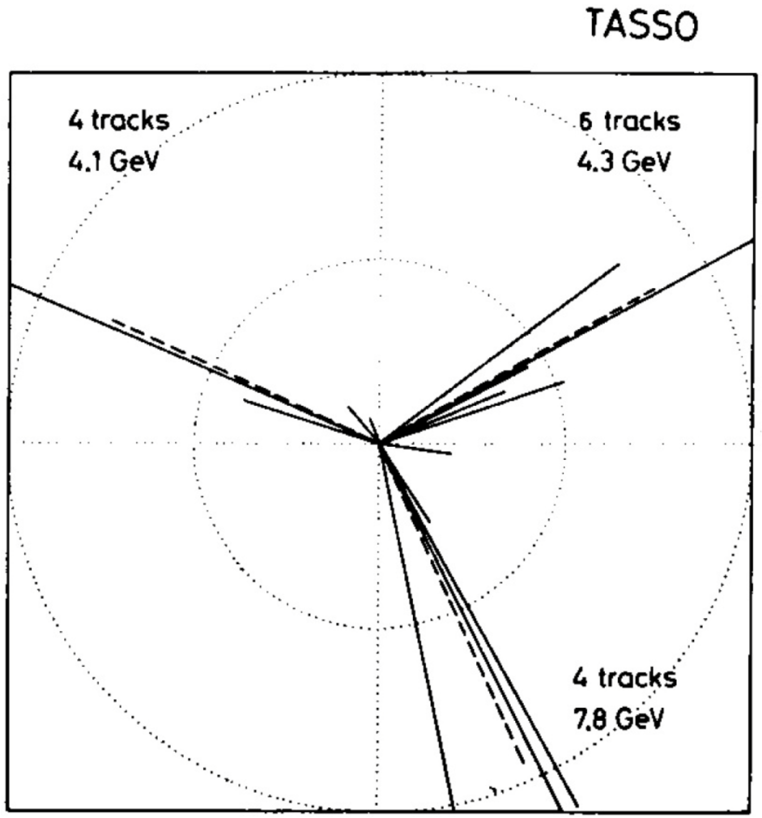
Sphericity: $S = 3(\sum_i p_{\perp,i}^2)_{\min.} / (2\sum_i p_i^2)$

higher energies → particles cluster around an axis

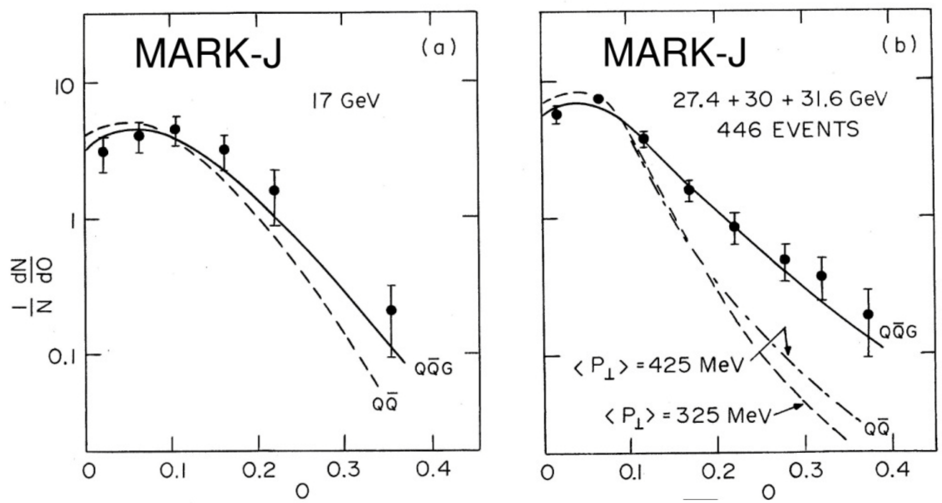
→ first observation of jet structure

Discovery of gluon jets: PETRA @ DESY

TASSO, PLB86(1979)243; MARK-J PRL43(1979)830; PLUTO PLB86(1979)418; JADE PLB91(1980)142



1st three-jet event seen by TASSO



Oblateness O = $T_{major} - T_{minor}$:

→ Events at E_{CM} ~30 GeV exhibit larger Oblateness (planar structure) than models without hard gluon radiation

Monte Carlo event generators

Essential :

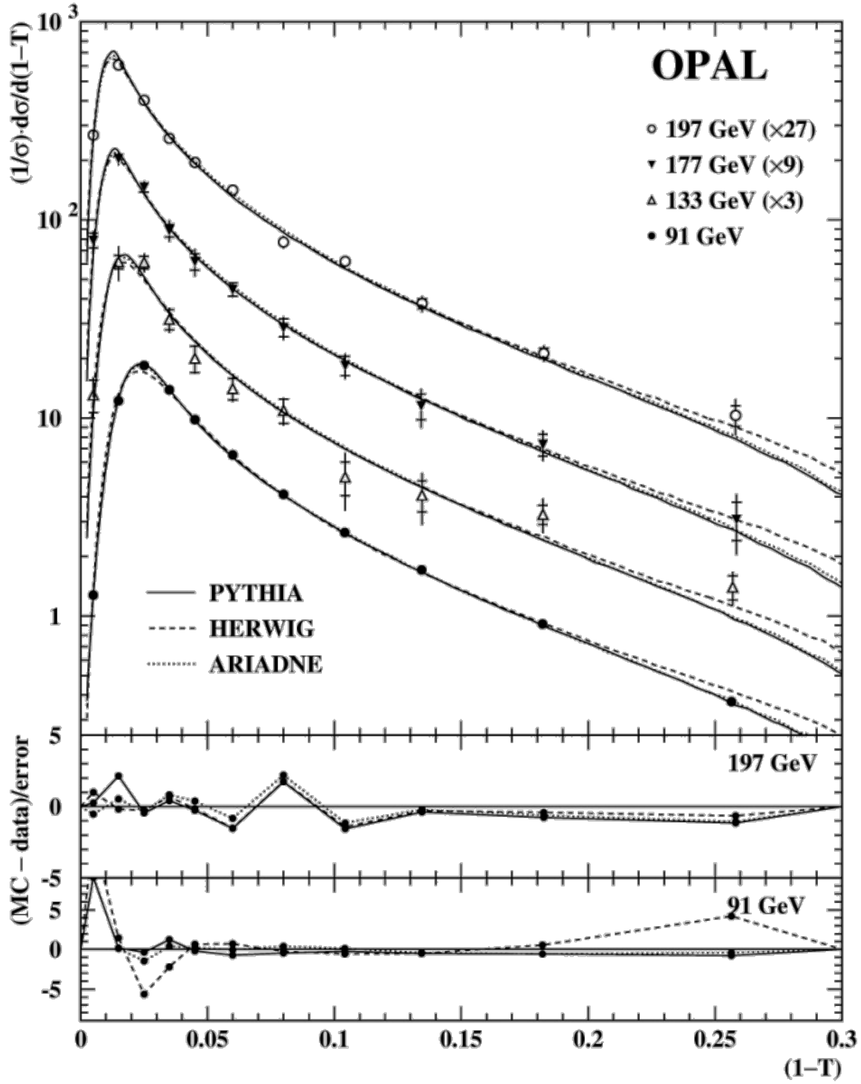
- detector response
- hadronization effects
- sensitivity to physics

Principal programs:

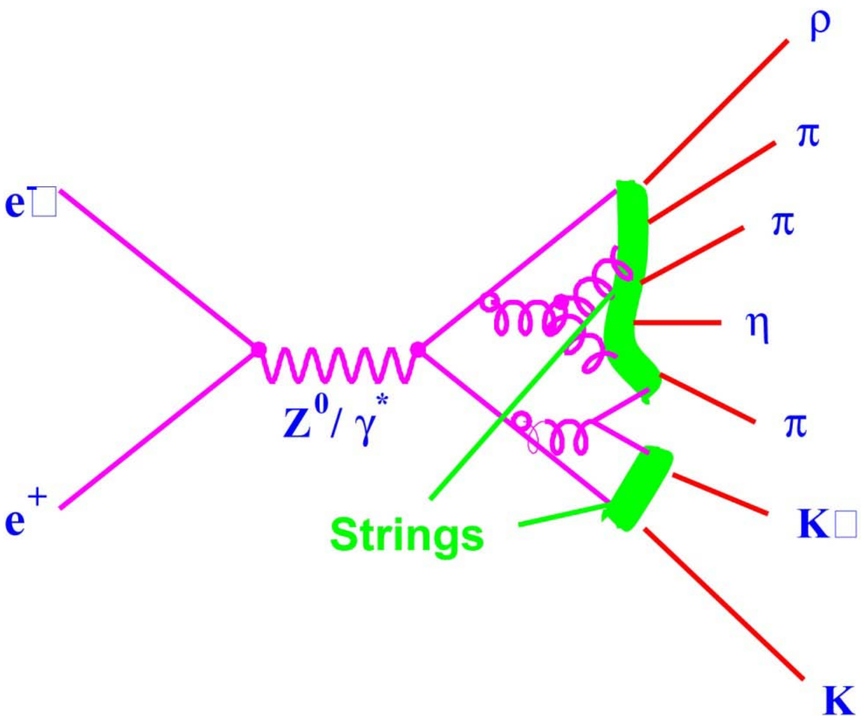
- Pythia (aka Jetset)
- Herwig
- Ariadne

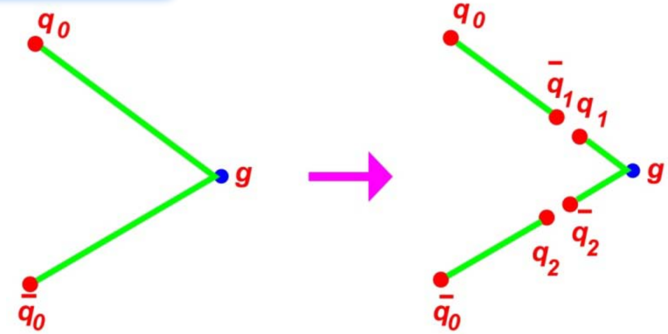
Tuned: LEP-1 data

- global properties: Thrust distr., $\langle n_{ch} \rangle$
- identified particle rates & spectra



Jetset/Pythia

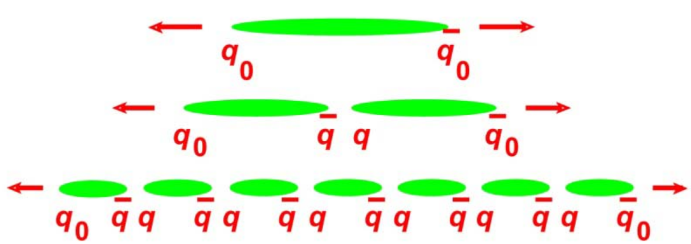




<u>hadronization</u>:

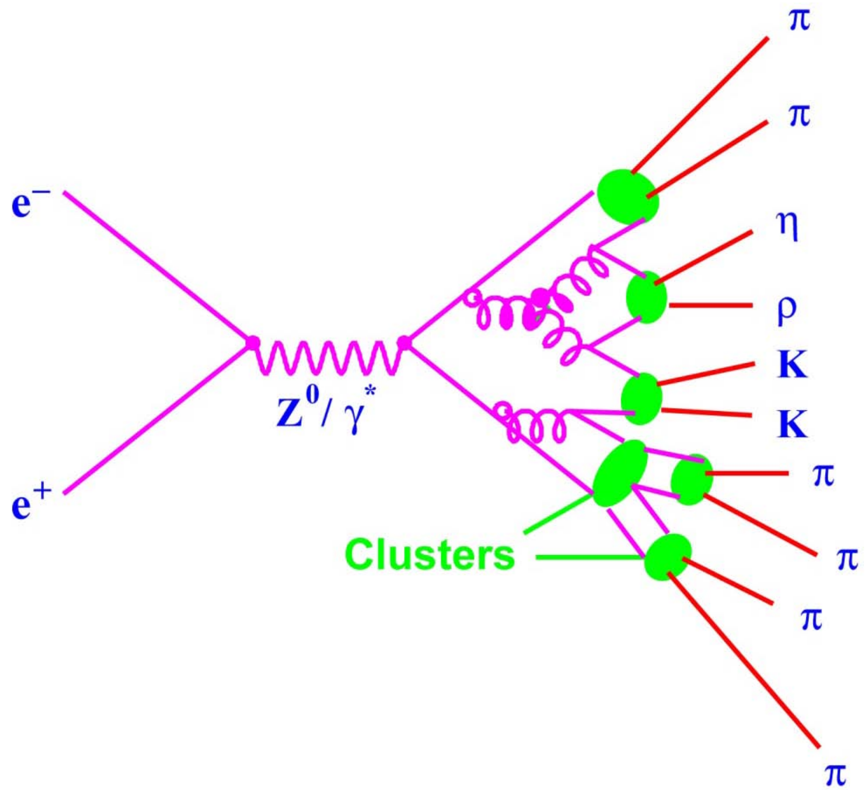
- → the Lund String model
- → q-$\bar{q}$ terminate each segment
- → color triplet fields

Each segment hadronizes in its rest frame:



- → Longitudinal phase space model
- → Analytic parametrizations for momenta & particle species

Herwig



hadronization:

→ the cluster model

→ use leading order color flow of pQCD to evolve partonic system to low mass colorless clusters

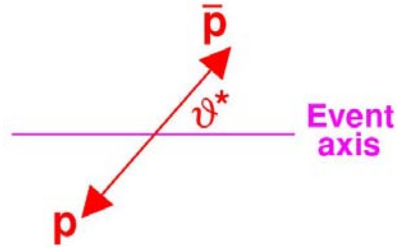
→ **2-body isotropic phase space** decay of clusters

→ No analytic parametrizations

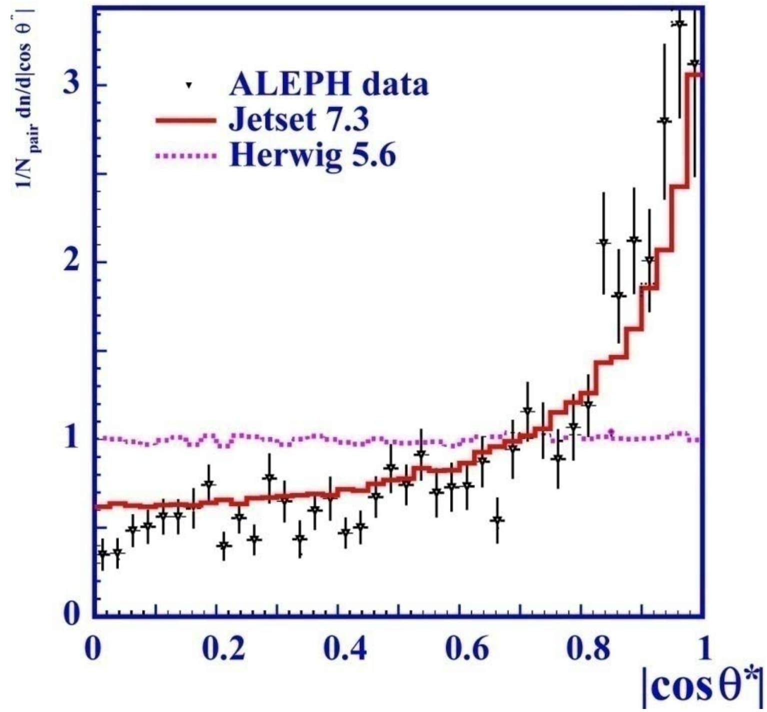
→ Simpler and more intuitive than string fragmentation

String vs. cluster hadronization

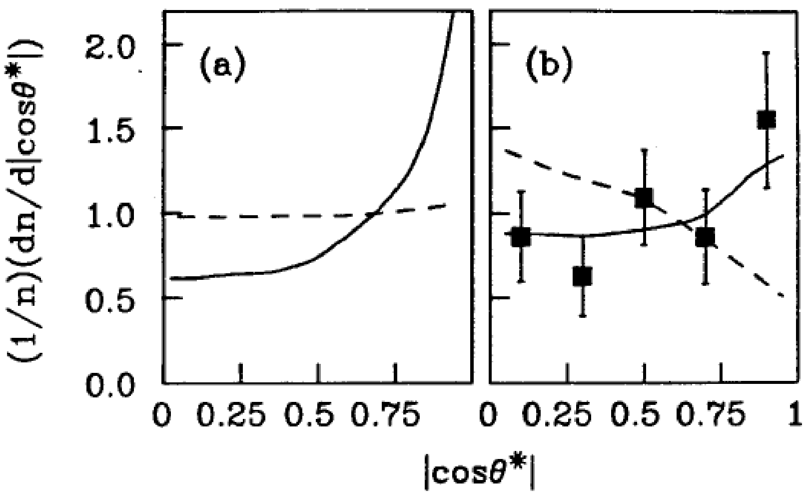
cos θ^* distribution of $\bar{p}p$ pairs:



ALEPH (LEP), Phys. Rep. 294 (1998) 1



TPC (PEP), PRL 55 (1985) 1047



→ rules out simplest (purest) form of isotropic cluster decay

→ Herwig: introduce angular correlations between perturbatively produced partons and the clusters that contain them → "string-like"

Jet algorithms

Many QCD tests: group particles into

Recombination ``cluster'' algorithms

→ the most common choice for e^+e^- events

- Metric: $y_{ij} = M_{ij}^2 / s$; $s = E_{CM}^2$
- combine particle pair ij with smallest y_{ij}
- E-scheme: add 4-momenta → $p_k = p_i + p_j$
- E0-scheme: require jets to be massless → $\begin{cases} E_k = E_i + E_j \\ \vec{p}_k = \dfrac{\vec{p}_i + \vec{p}_j}{|\vec{p}_i + \vec{p}_j|} E_k \end{cases}$
- iterate until all pairs satisfy $y_{ij} > y_{cut}$

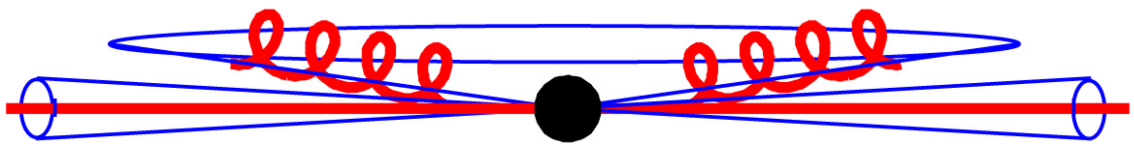
The JADE jet finder

JADE Collaboration (PETRA), Z. Phys. C33 (1986) 23

→ The original recombination jet algorithm

- Metric: $M_{ij}^2 = 2E_iE_j(1-\cos\theta_{ij}) \approx$ (invariant mass)^2
- Original version: E0-scheme combination of particles

Can lead to "**junk jets**":



→ a 2-jet event with soft, colinear radiation can be classified, unnaturally, as a 3-jet event

→ Inhibits NLLA re-summation techniques (what is 2-jets @ one order becomes >2-jets at higher order)

The k_T ("Durham") jet finder

S. Catani et al., Phys. Lett. B269 (1991) 432

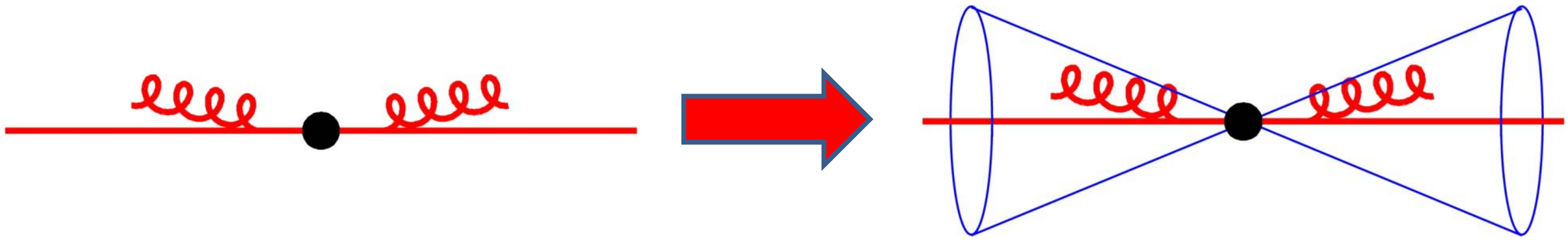
- Metric: $M_{ij}^2 = 2\ \min\ (E_i^2, E_j^2)\ (1-\cos\theta_{ij})$
- E-scheme combination of particles

For small emission angles θ_{ij} ,

$$M_{ij}^2 \approx 2\min\ (E_i^2, E_j^2)\ [1-(1-\theta_{ij}^2/2+\cdots)] \approx \min\ (E_i^2, E_j^2)\,\theta_{ij}^2 \approx K_\perp^2$$

→ smaller of the transverse momentum of i wrt j vs. j wrt i

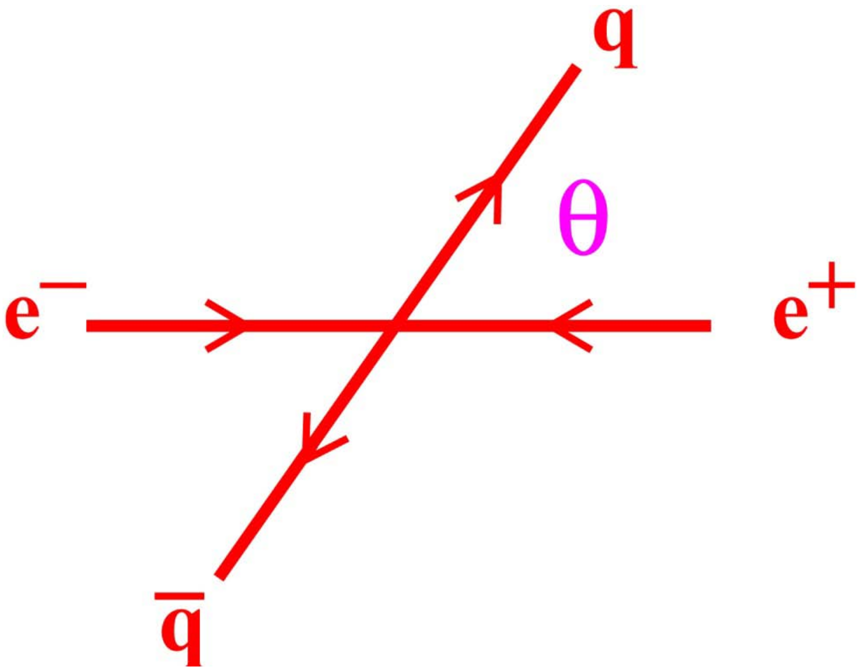
→ soft colinear radiation is attached to the correct jet



→ Largely inhibits junk jets, allows resummation

2-jet matrix element: Spin of the quark

Matrix elements → Predictions for the energy & angular distributions of jets



$d\sigma/d\Omega \sim \underline{1 + \cos^2\theta}$
(spin ½)

$\sim \underline{\sin^2\theta}$
(spin 0)

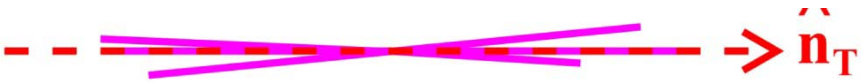
(integrating over FB asymmetry)

Angle θ_{thrust} between thrust & beam axes

Thrust axis:

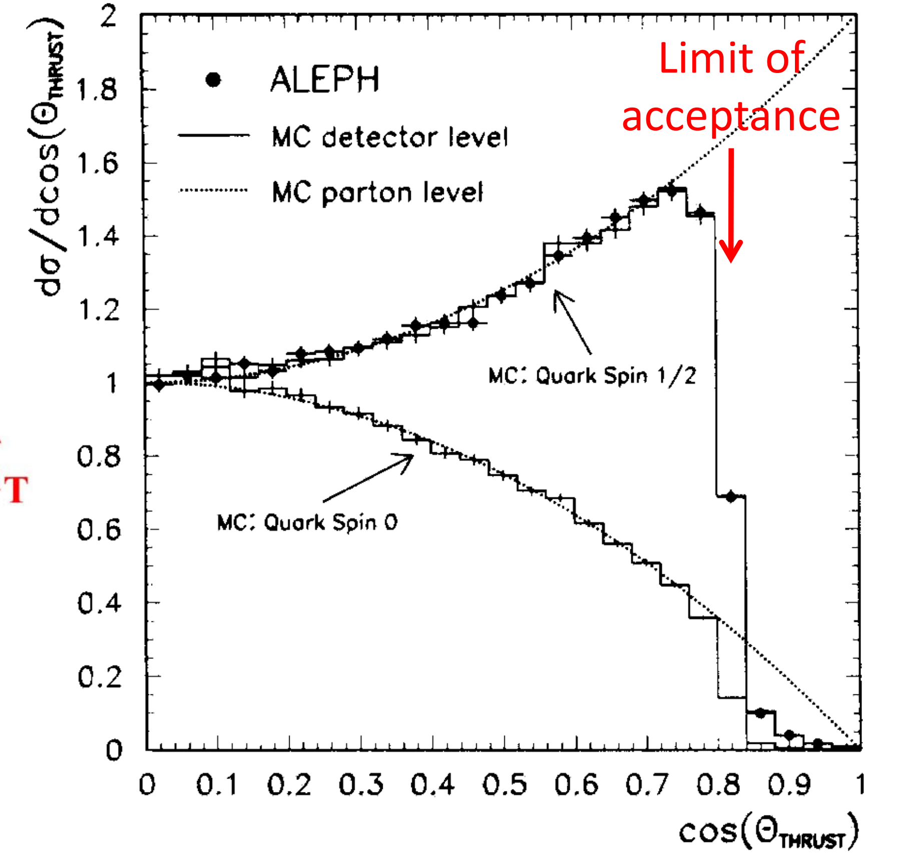
direction $\hat{n}_T$ that maximizes longitudinal momentum sum

$$T = \max \frac{\sum |\vec{p}_i \cdot \hat{n}_T|}{\sum |\vec{p}_i|}$$

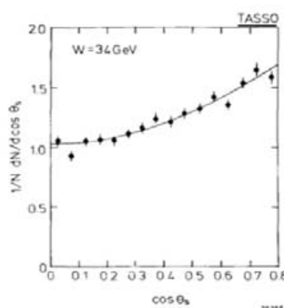


$T \sim 1$

ALEPH Collab. (LEP), Phys. Rep. 294 (1998) 1



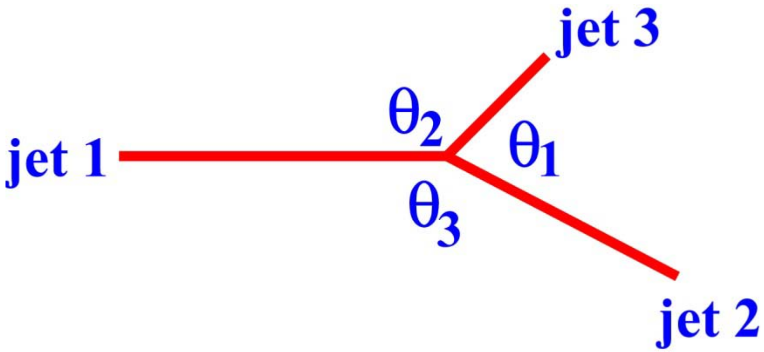
TASSO (PETRA)
1984: Sphericity axis



3-jet matrix element: Spin of the gluon

Example: SLD Collaboration (SLC), PR D55 (1997) 2533

- **Select 3-jet events**: JADE jet finder with $y_{cut} = 0.02$
  → 25% of events classified as 3-jet events



$$E_i = E_{CM} \sin\theta_i / \sum_{i=1,3} \sin\theta_i$$

- **Calculate jet energies**: assume massless jets & E, p cons.

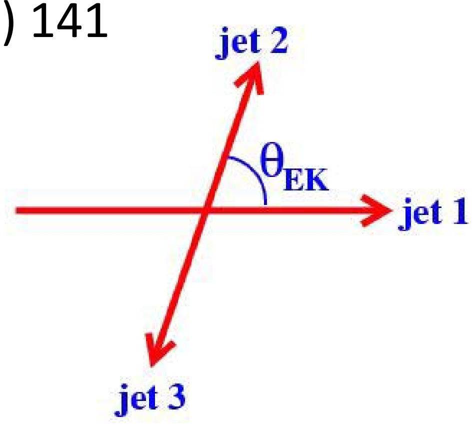
- **Order by energy**: $E_1 > E_2 > E_3$
  → jet 3 is the gluon jet in 75% of the events (energy tagging)

- **Scaled jet energies**: $x_i = 2E_i / E_{CM}$

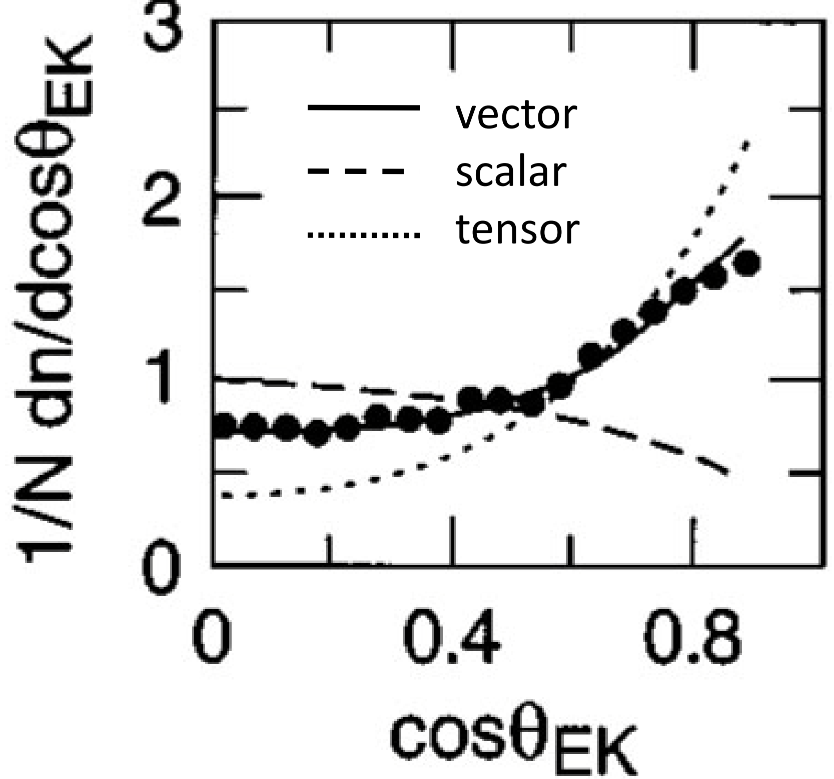
Ellis-Karliner angle $\cos\theta_{EK} = (x_2 - x_3) / x_1$

J.Ellis & I. Karliner, Nucl. Phys. B148 (1979) 141

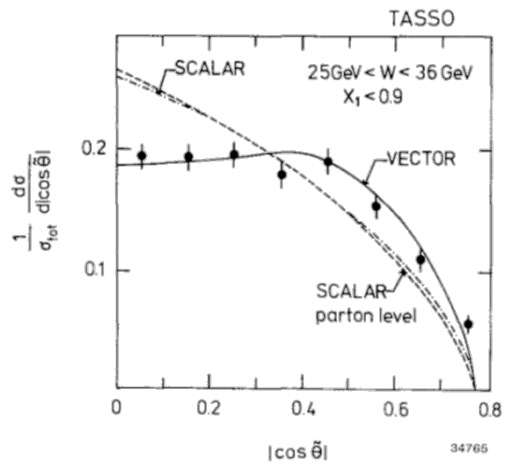
Scaled jet energies $x_i = 2E_i / E_{CM}$



SLD (SLC), PR D55 (1997) 2533



TASSO Collaboration (PETRA)
PL B97 (1980) 453

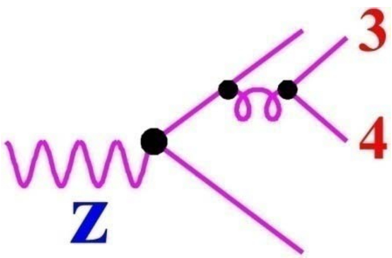


4-jet matrix element: triple-gluon vertex

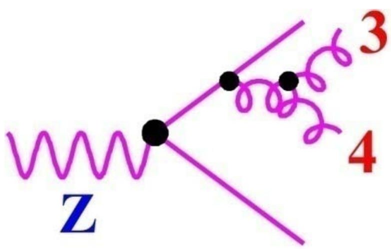
Example: L3 Collaboration (LEP), PL B248 (1990) 227

- **Select 4-jet events**: JADE jet finder with $y_{cut} = 0.02$
  → 9% of events classified as 4-jet events

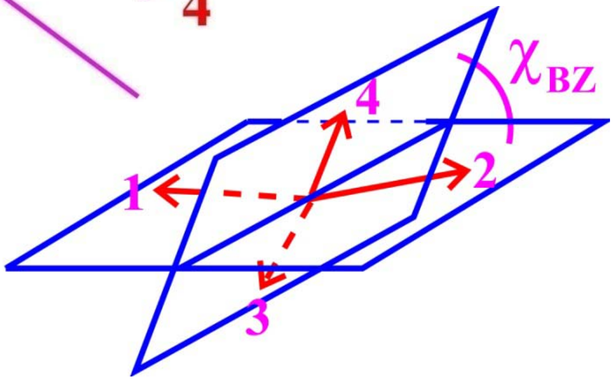
- **Order jets by energy**: $E_1 > E_2 > E_3 > E_4$
  → jets 3 & 4 more likely to be the radiated particles



versus

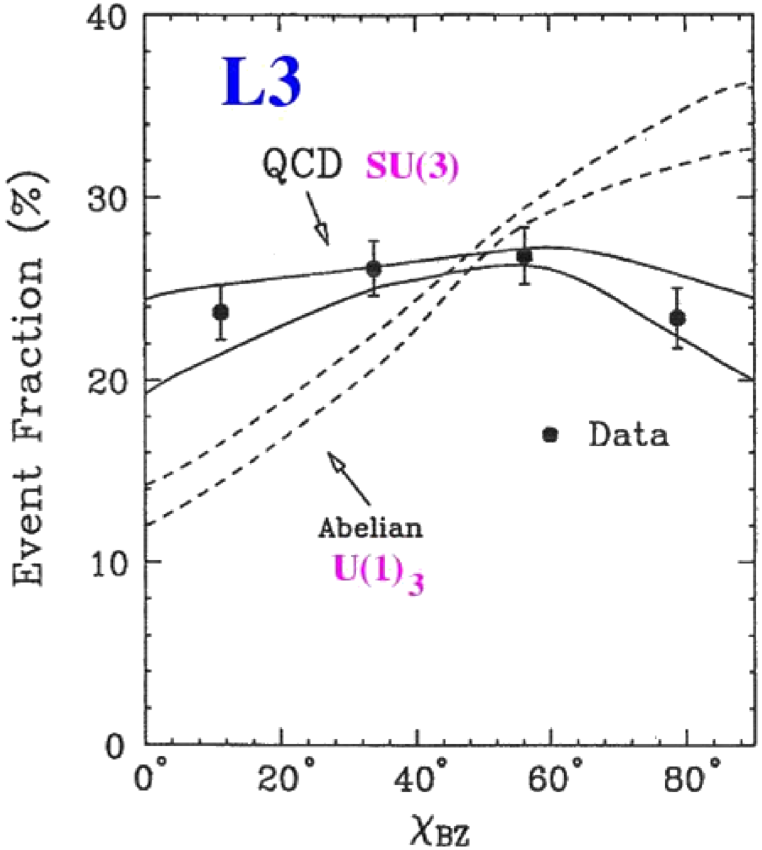


- **Bengtsson-Zerwas angle**: χ_{BZ}



Bengtsson-Zerwas angle χ_{BZ}

L3 (LEP), PL B248 (1990) 227



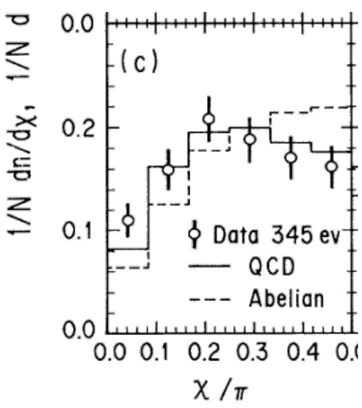
Abelian model $U(1)_3$:

→ 3 quark colors

→ No 3-gluon coupling

4-jet angular structure sensitive to the **gauge group structure** of strong interactions

VENUS (Tristan), PRL 66 (1991) 280



α_S: (1) Inclusive measurements

Inclusive: independent of event shape (topology)

- $R_\ell = \Gamma\,[Z \rightarrow \text{hadrons}] \,/\, \Gamma\,(Z \rightarrow \ell^+\ell^-)$
- σ^0_{had} (Born-level peak hadronic cross section @ the Z)
- $\sigma^0_{lep} = \sigma^0_{had} \,/\, R_\ell$ (peak leptonic cross section @ the Z)
- $R_\tau = \Gamma[\tau \rightarrow \text{hadrons}] \,/\, \Gamma(\tau \rightarrow \ell^+\ell^-)$

→ based on event counting

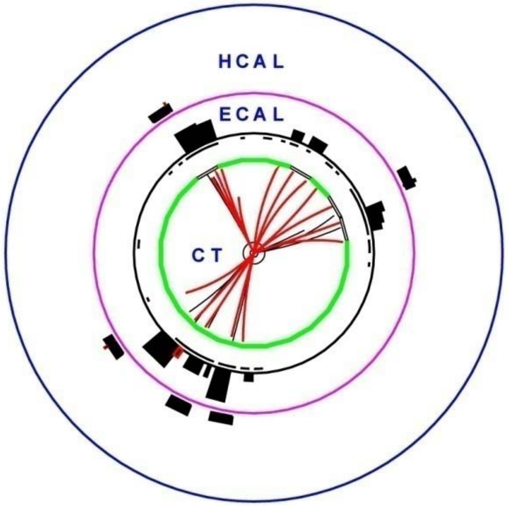
→ known to α_S^3 [1990's]

→ small theoretical & experimental uncertainties

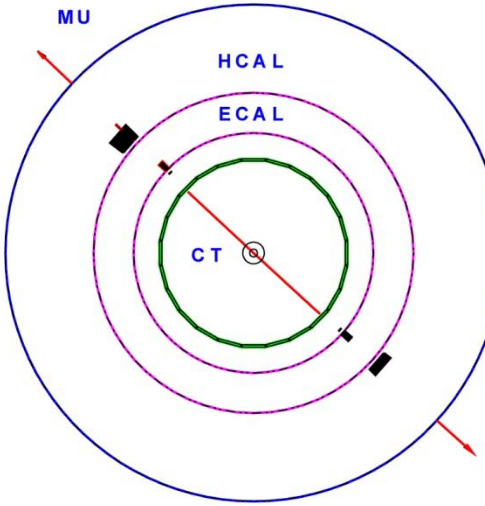
→ no hadronization corrections, etc.

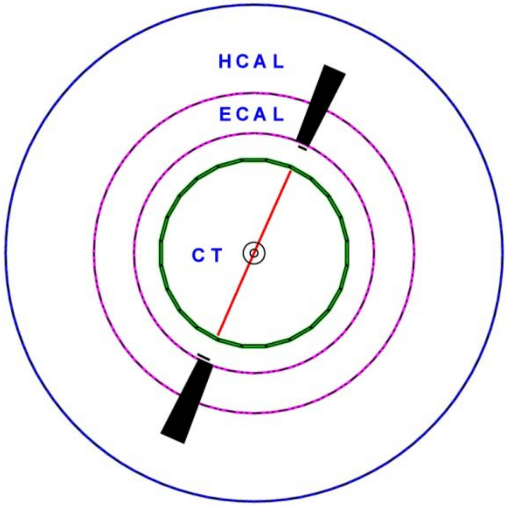
→ reliable determination of α_S

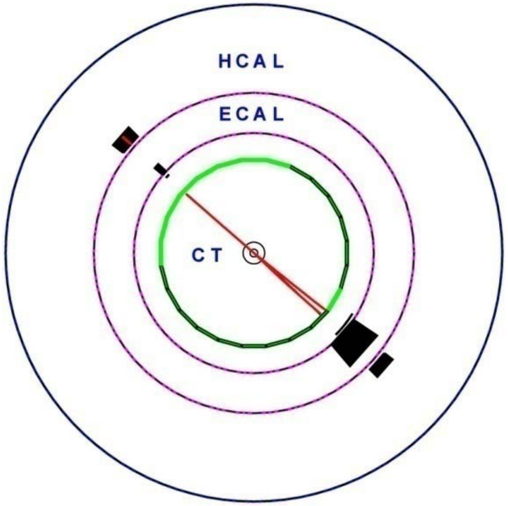
$R_\ell = \Gamma$ [Z → hadrons] / Γ (Z → $\ell^+\ell^-$)



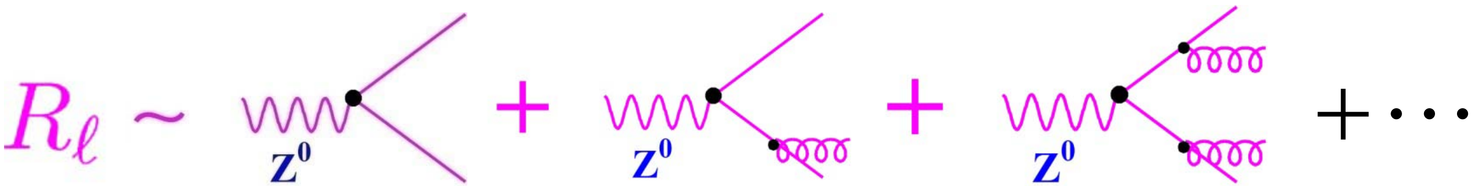
versus







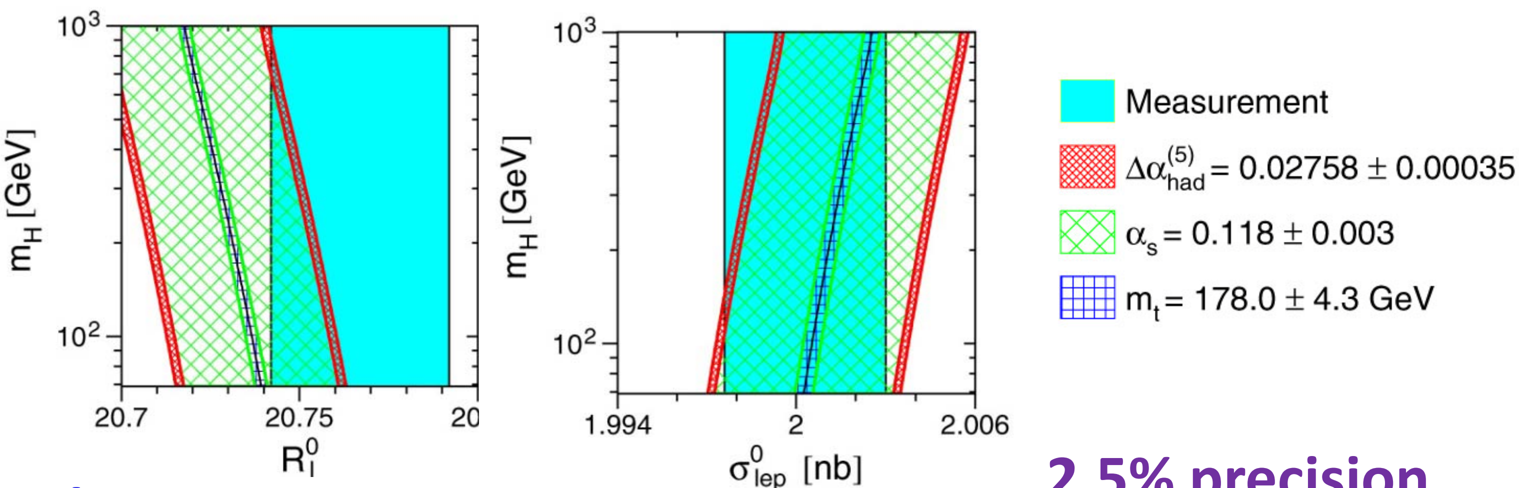
α_s from R_ℓ and $\sigma^0_{lep} = \sigma^0_{had} / R_\ell$



$$= R^0_\ell \, (1 + \delta_{QCD})$$

$$\delta_{QCD} = 0.333\alpha_S + 0.0952\alpha_s^2 + 0.484\alpha_s^3 \approx \underline{0.042}$$

LEP & SLC Collabs., Phys. Rep. 427 (2006)257



LEP combined:

(~ $12\text{x}10^6$ Z events)

$$\alpha_S(M_Z) = 0.1189 \pm 0.0030$$

→ **2.5% precision**

Experimental uncertainties dominant

α_S: (2) Event shapes

Event shapes: the momentum structure of an event

→ 3-jet dominated; one entry "y" per event;
leading terms ~ α_S

- **Thrust**
- Jet broadening **B_W & B_T** ; y_{23} ; Heavy jet mass **M_H**, **C parameter**; differ in higher order corrections

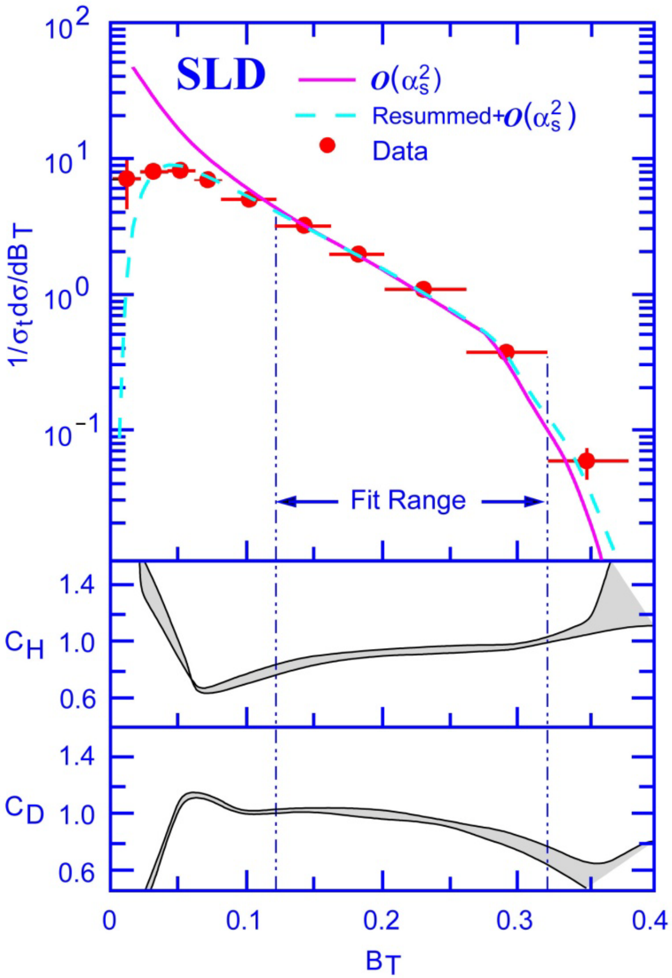
→ known to **α_S^2 +NLLA** [1990's; "final" LEP & SLC studies]

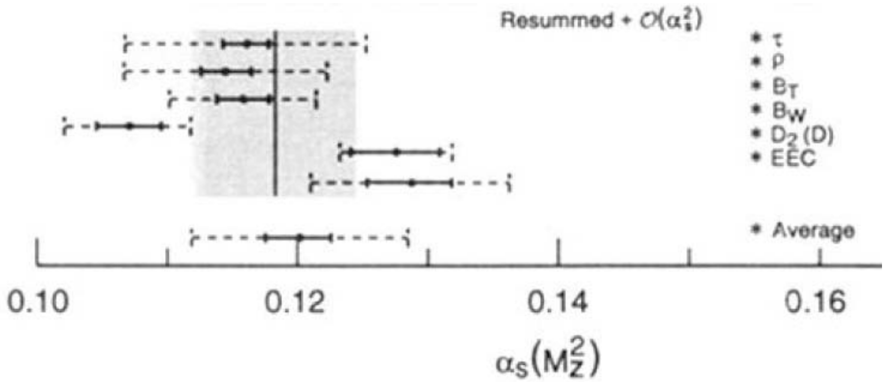
→ now known to **α_S^3 +NLLA** : recent & onging re-analyses

→ require hadronization corrections: MC hadron/parton ratios

α_s^2 + NLLA studies

Example: SLD Collaboration (SLC), PRD51 (1995) 962





Solid: experimental uncertainties

Dashed: experimental + theory uncertainties

Shaded: average α_s and total uncertainty

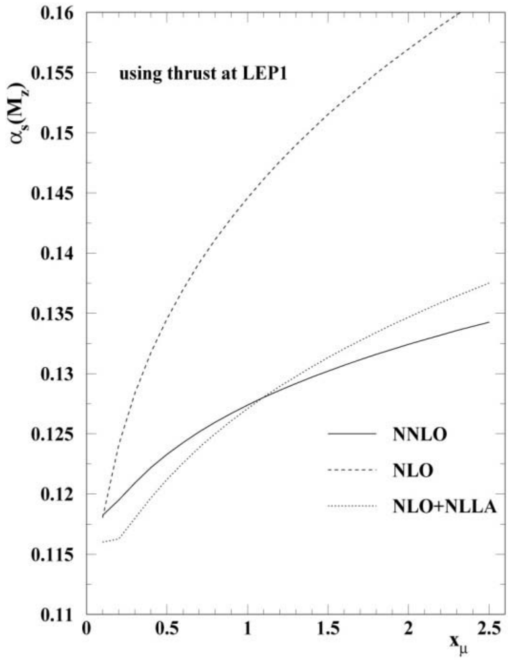
$$\alpha_S(M_Z) = 0.1192 \pm 0.0025\,(\text{expt.}) + 0.0070\,(\text{theor.})$$

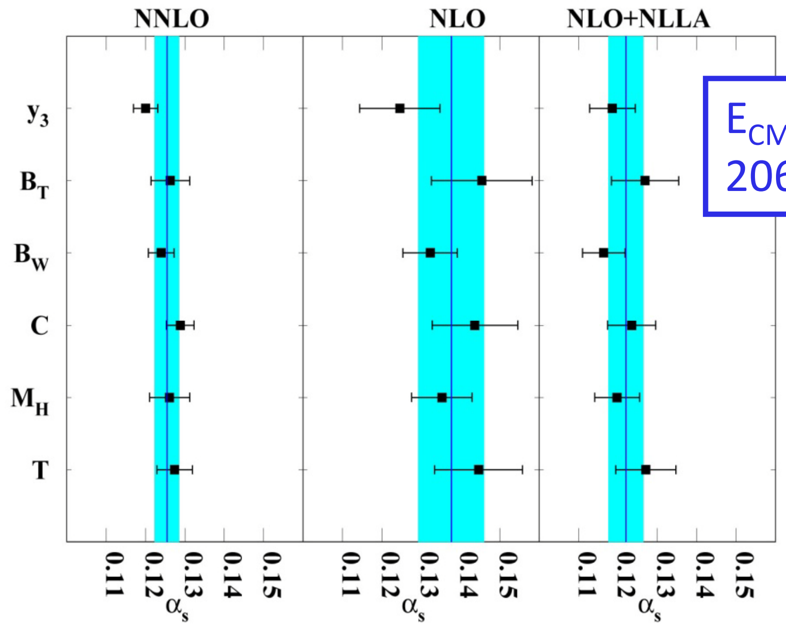
- → **6% precision**
- → uncertainty dominated by **unknown higher order terms** (dependence on assumption for renormalization scale)

New: α_S^3 calculations of event shapes

[Gehrmann-De Ridder et al., JHEP 12(2007)094]

→ Re-analysis of ALEPH data [G.Dissertori et al., JHEP 02(2008)040]





E_{CM}=91-206 GeV)

Renormalization scale uncertainty **reduced 30%** wrt α_S^2+NLLA

$$\alpha_S(M_Z) = 0.1240 \pm 0.0013\,(\text{expt.}) + 0.0031\,(\text{theor.})$$

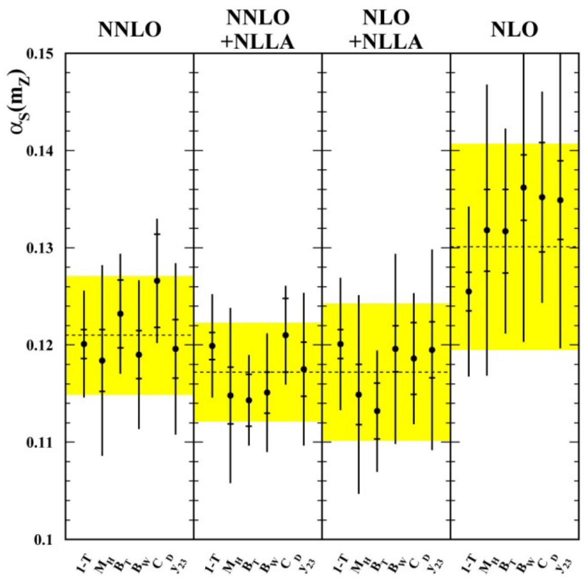
→ **2.7% precision**

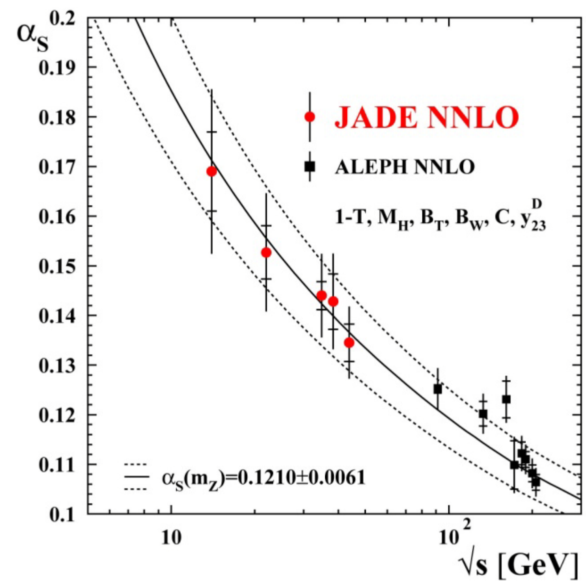
α_S^3 + NLLA studies

→ **α_S^3 + NLLA matching** [Gehrmann et al., PL B664 (2008) 265]

→ Reanalysis of JADE data [JADE Collab., arXiv:0810.1389]

E_{CM}=14-44 GeV)





Renormalization scale uncertainty **reduced 60%** wrt α_S^2+NLLA

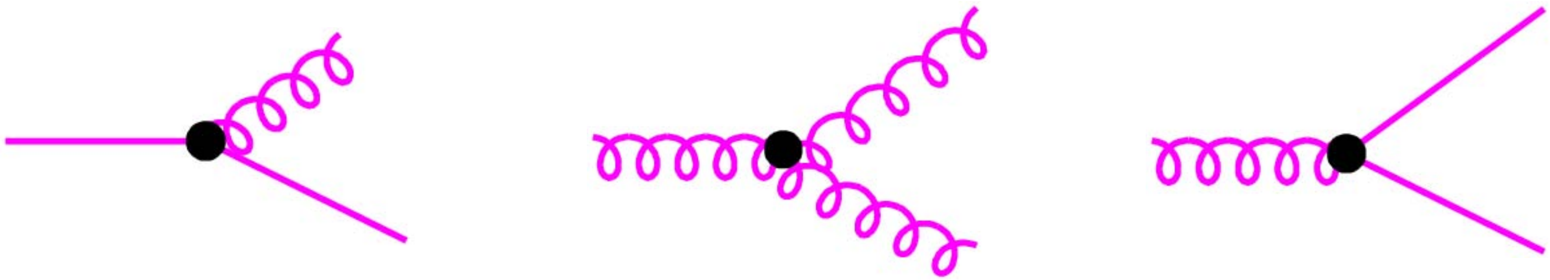
$$\alpha_S(M_Z) = 0.1172 \pm 0.0021\,(\text{expt.}) + 0.0046\,(\text{theor.})$$

→ **4.3% precision**

α_S^3 + NLLA: OPAL and ALEPH, in preparation

Color factors C_F, C_A, T_F

C_F, C_A, T_F measure the relative probabilities of



gluon radiation:	triple gluon vertex:	gluon splitting:
$q \rightarrow qg$	$g \rightarrow gg$	$g \rightarrow qq$
$C_F = 4/3$	$C_A = 3$	$T_F = T_R\, n_f = \frac{1}{2} n_f = 2.5$

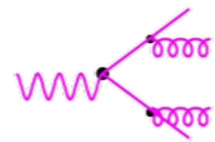
→ The **gauge structure** of strong interactions

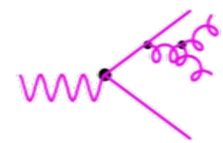
→ The most important numbers in QCD besides α_S !

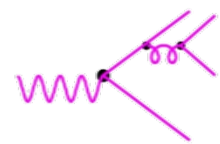
Angular correlations in 4-jet events

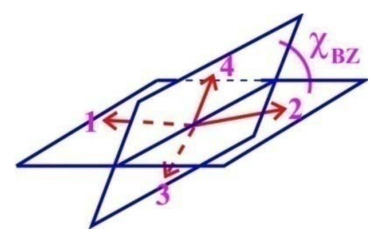
$e^+e^- \rightarrow$ 4-jets @ α_s^2 (tree level): [K.Ellis, Ross & Terrano, NP B178 (1978) 421]

$$\frac{1}{\sigma_0}\frac{d\sigma}{dy} = \left(\frac{\alpha_S C_F}{\pi}\right)^2 \times \Big[\sigma_A(y) + \left(1 - \frac{1}{2}\frac{C_A}{C_F}\right)\sigma_B(y) + \left(\frac{C_A}{C_F}\right)\sigma_C(y) + \left(\frac{T_F}{C_F} n_f\right)\sigma_D(y) + \left(1 - \frac{1}{2}\frac{C_A}{C_F}\right)\sigma_E(y) \Big]$$







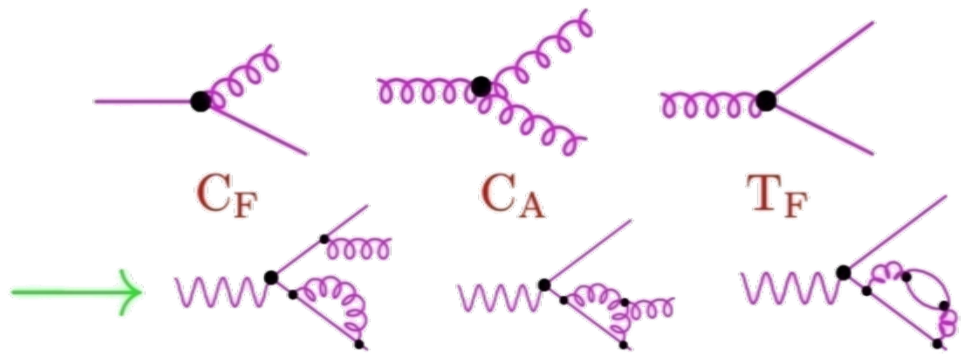


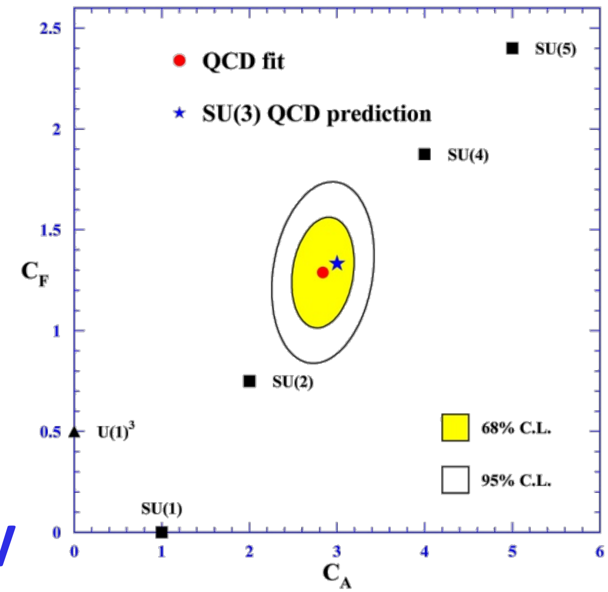
- $\sigma_A \cdots \sigma_E$: kinematic factors, independent of gauge group
- Angular observables "y" differ for the three diagrams: χ_{BZ}
- α_s^3 expressions [Nagy & Trocsanyi, PRD57 (1998) 5793]

Color factors from event shapes

Example: S. Kluth et al. (JADE+LEP), EPJ C21 (2001) 199

Virtual terms in $\geq \mathcal{O}(\alpha_S^2)$ 2- and 3-jet cross sections $\sim C_A, C_F, T_F$





→ **Thrust** and **C parameter** to $\mathcal{O}(\alpha_S^2)$+NLLA

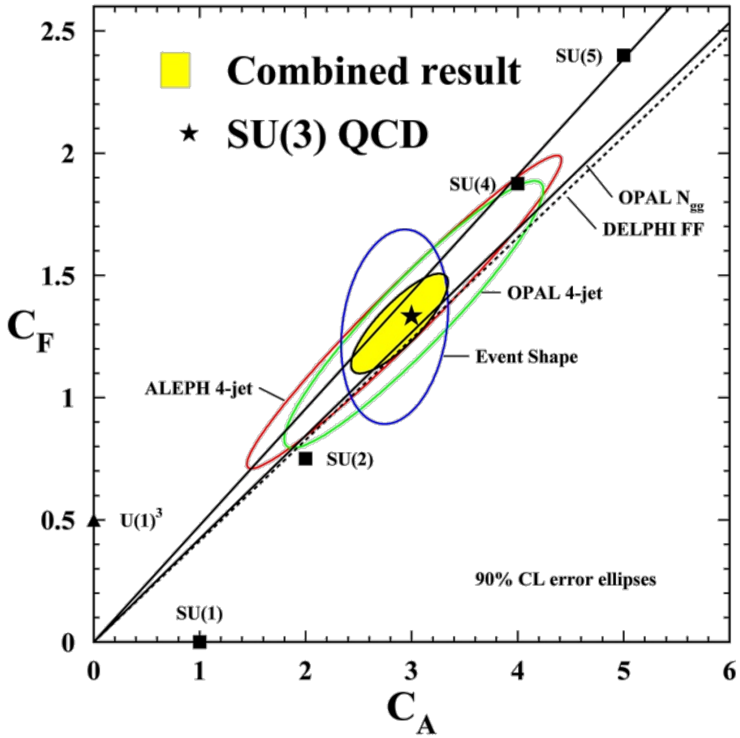
→ Simultaneously fit data from **14-189 GeV** (PETRA, PEP, TRISTAN, LEP), use constraint on C_A, C_F from **running α_S**

	QCD	
$C_A = 2.84 \pm 0.24$	3	→ 8% precision
$C_F = 1.29 \pm 0.18$	1.33	→ 14% precision

Color factors from a combination of 4-jet events & event shapes

S. Kluth, Rept. Prog. Phys. 69 (2006) 1771

- → Combine 4-jet and event shape results, accounting for correlations between measurements
- → Include constraints on C_A/C_F from differences between gluon & quark jets

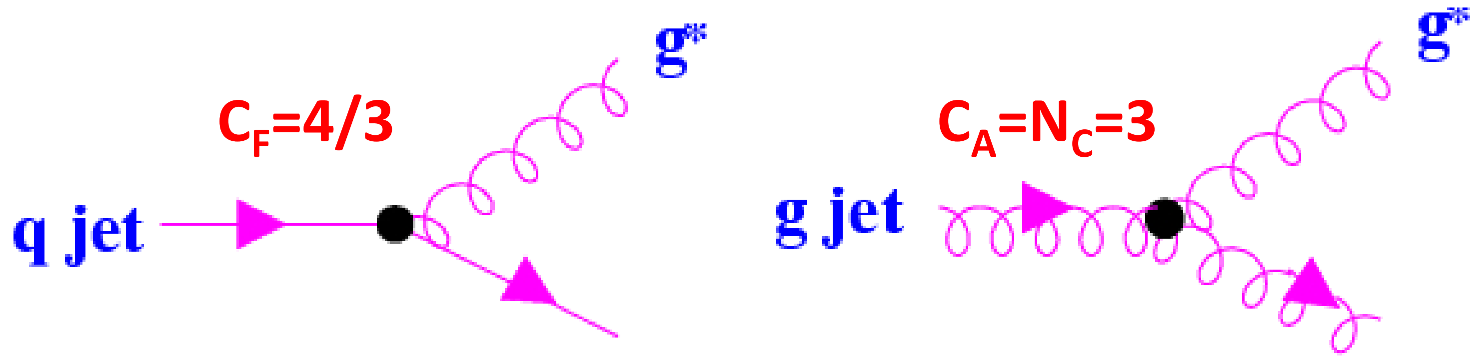


	QCD
$C_A = 2.89 \pm 0.21$	3
$C_F = 1.30 \pm 0.09$	1.33

→ 7% precision for <u>both</u> C_A & C_F

Differences between quark & gluon jets

Quark and gluon jets have **different coupling strengths** to emit gluons → expressed by the **color factors**



→ Naïve "asymptotic" expectation: $r_{g/q} = \frac{\langle n_g \rangle}{\langle n_q \rangle} = \frac{C_A}{C_F} = 2.25$

[Brodsky & Gunion, PRL37(1976)402; Veneziano et al., PLB78(1978)243]

→ Gluon jets have a **larger** multiplicity, **softer** fragmentation function, and are **broader**, than quark jets

→ Expect large differences, on order **~ 2**

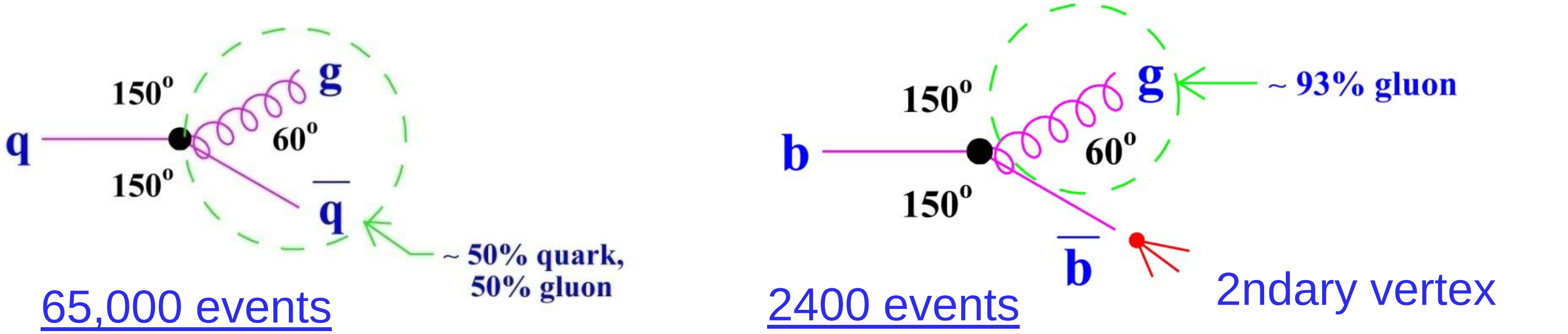
Particle multiplicity difference: $r_{G/Q}$

OPAL (LEP), ZPC58(1993)387

→ Select 1-fold symmetric events (increase event statistics, highest energy jet = q jet) : "**Y events**"

→ K_T jet finder, y_{cut}=0.02

→ Anti-tag the gluon jet from $b\bar{b}g$ events

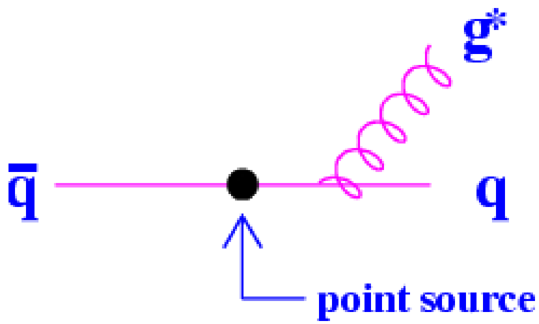


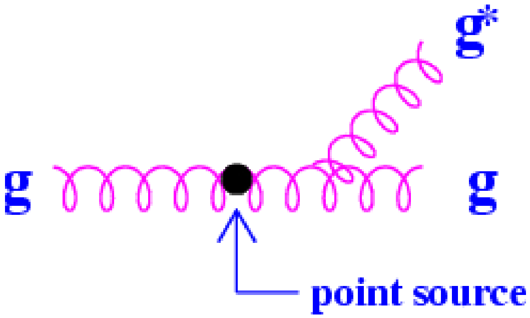
→ Algebraically solve for G and Q results: $r_{G/Q}$ **= 1.25±0.04**

Note: $r_{G/Q}$ **≠ 2.25**: the jets are **biased** (depend on a jet definition) **non-asymptotic**, and the quarks not **massless** (20% b jets)

Unbiased G & Q jets: quantitative tests of QCD

QCD calculations → G & Q jets defined through pair production from a color singlet (point) source





Quark jets: inclusive e^+e^- annihilations

Gluon jets: e.g., $\Upsilon \rightarrow \gamma gg$ decays

→ Jet properties given by **inclusive sum** over hemispheres

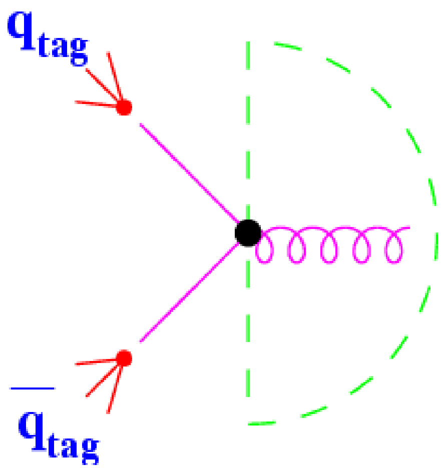
→ No jet algorithm dependence or ambiguity about which (soft) particles to assign to the G and Q jets

→ **Unbiased jets**

Unbiased high energy G jet

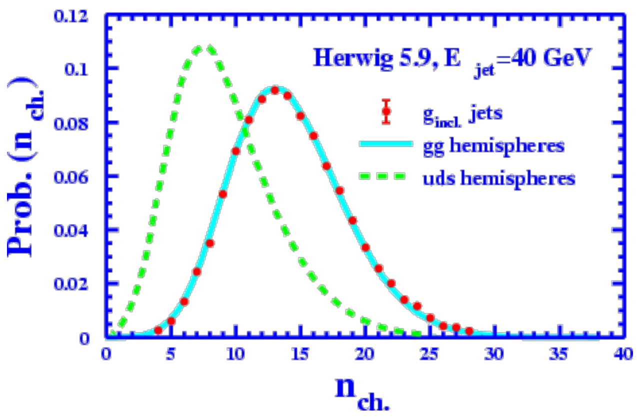
J.W. Gary, PRD 49 (1994) 4503

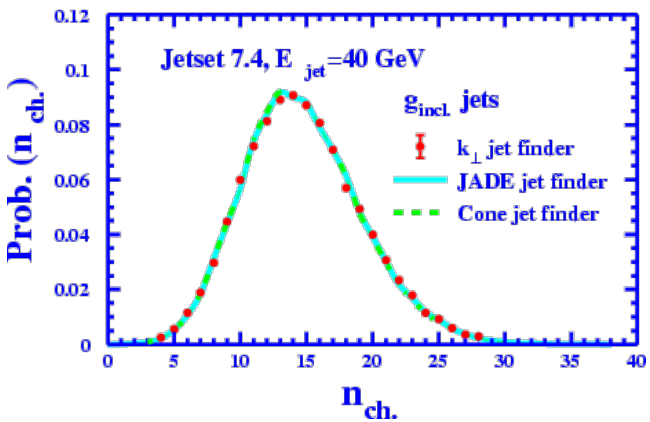
→ Gluon jet hemispheres in $e^+e^- \to Z \to q_{tag}\bar{q}_{tag}g_{gincl}$ events

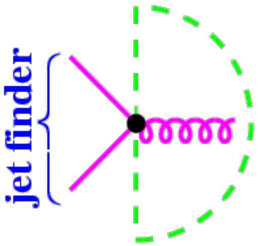


Gluon jet hemisphere "g_{incl}" defined by all particles in hemisphere opposite to two tagged b (quark) jets

g_{incl} properties same as a gg hemisphere, independent of jet finder → truly unbiased !

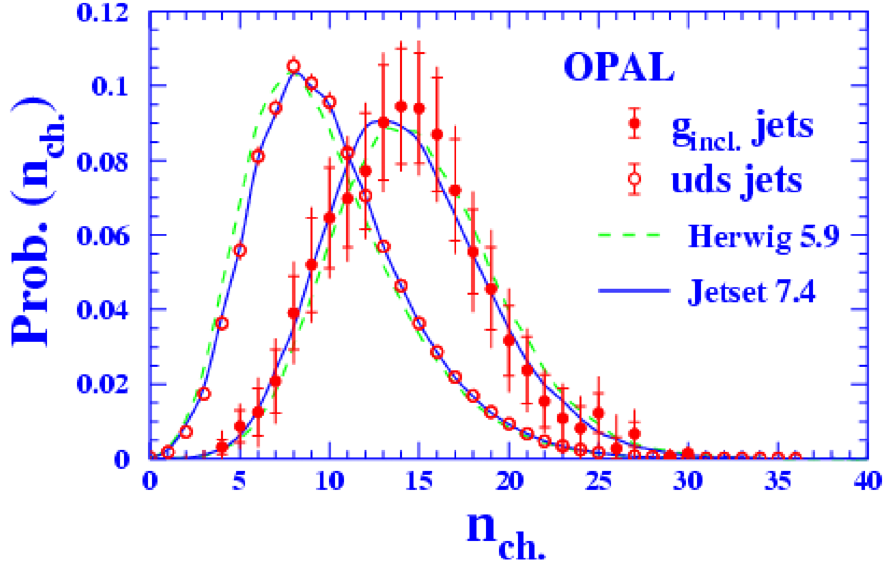


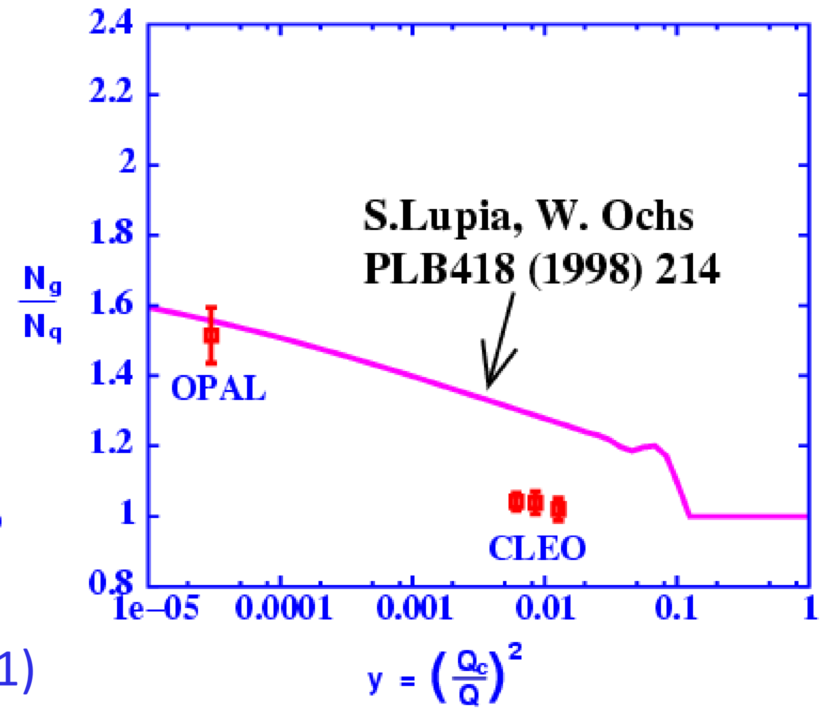




High energy G & Q jets: theory versus data

OPAL (LEP), EPJC11(1999)217



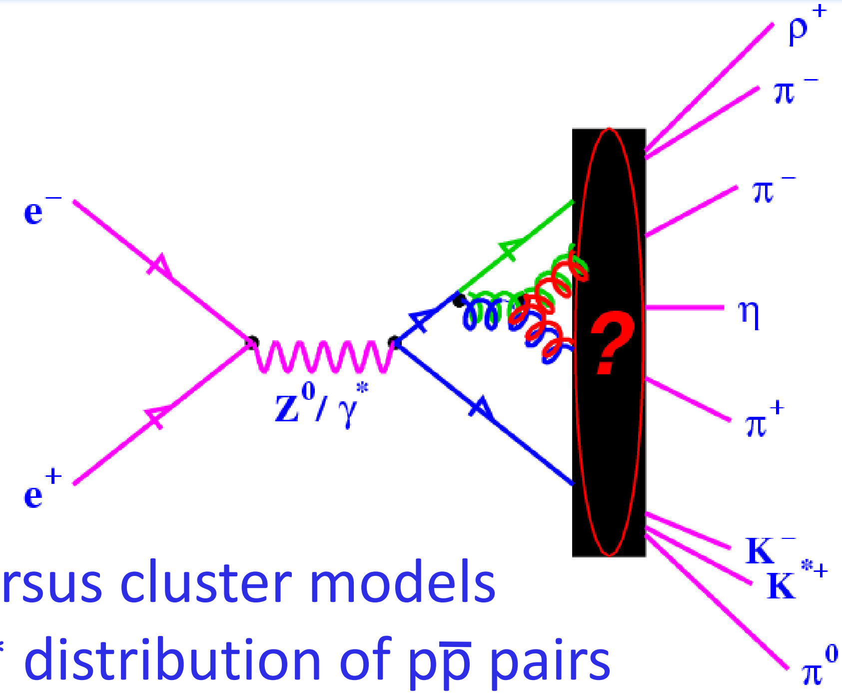


$r_{G/Q}$ = 1.51±0.04 (hadr. corr. ≈1)

→ Perfect agreement between theory & data
[also for higher moments, OPAL, EPCJ1(1998)479]

→ CLEO $\Upsilon \to \gamma gg$ data too low in energy: non-perturbative effects dominate

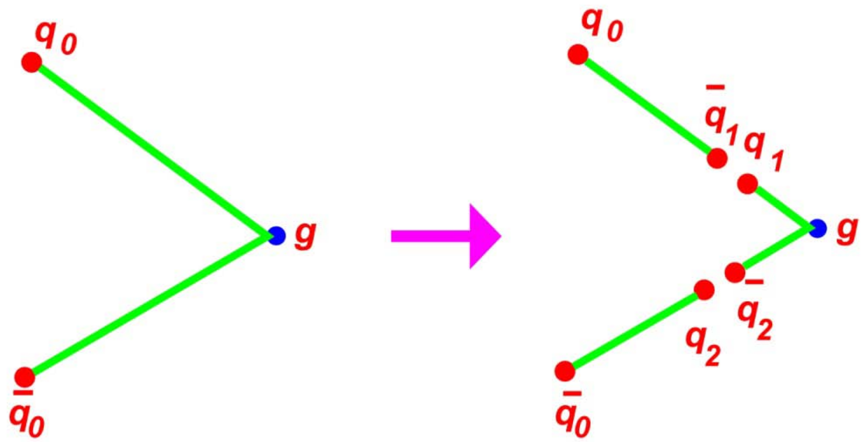
Studies of the hadronization process



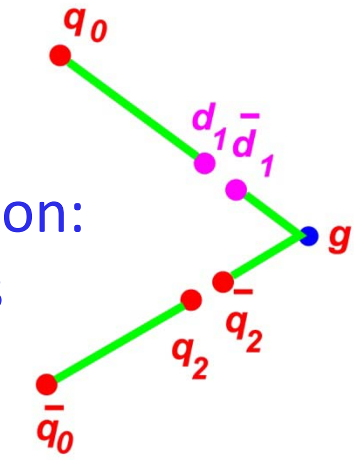
- String versus cluster models
  - → $\cos\theta^*$ distribution of $p\bar{p}$ pairs
    [already discussed]
  - → Baryon production in gluon jets
- The baryon production mechanism: diquarks or popcorn
- Color reconnection
- Octet neutralization of gluon jets

Baryon production in gluon jets

Gluon jets in the Lund model → **kinks on the string**



Baryon production: diquarks



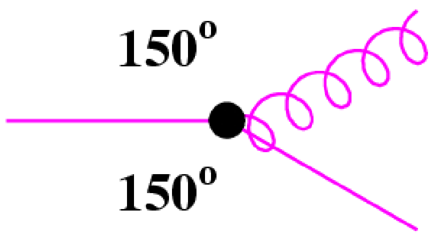
→ A gluon jet has **2 chances** to acquire a leading baryon, compared to only 1 chance for a quark jet

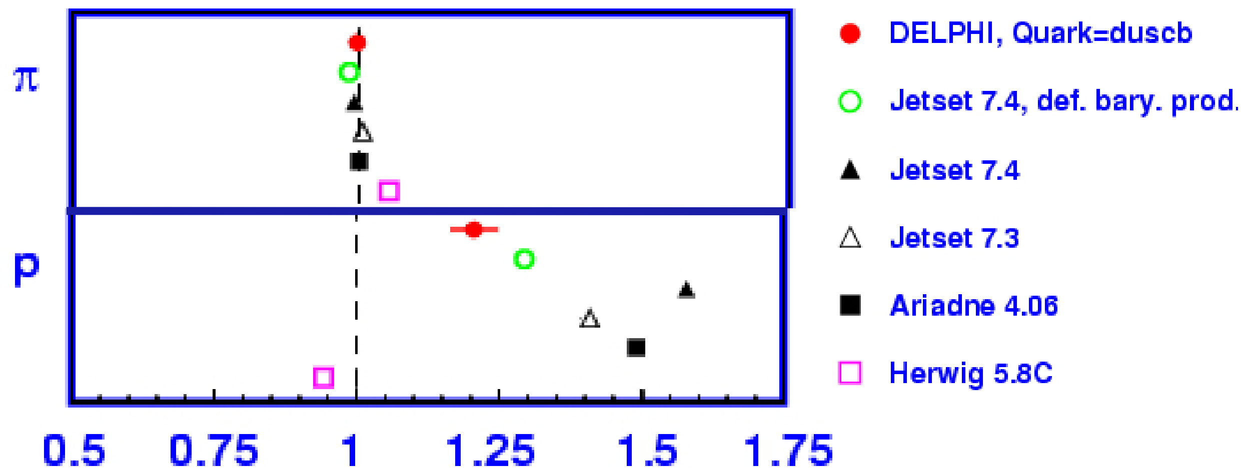
→ An enhancement of baryon production in gluon jets, beyond the enhancement common to all particle species due to the color factors

Baryon production in gluon jets

DELPHI (LEP), EPJC17(2000)207

$$R_h = [\langle n_h \rangle_{gluon} / \langle n_h \rangle_{quark}] \,/\, [\langle n_{ch} \rangle_{gluon} / \langle n_{ch} \rangle_{quark}]$$





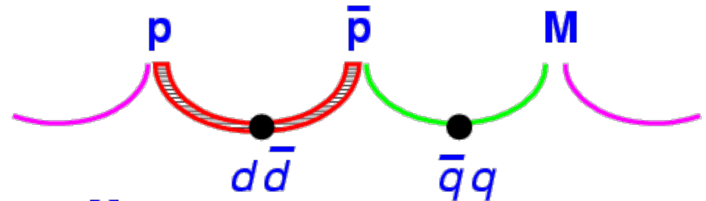
→ **~20% enhancement of protons** in gluon jets **beyond** the ~25% enhancement for all charged particles

→ No mechanism for this enhancement in the cluster model

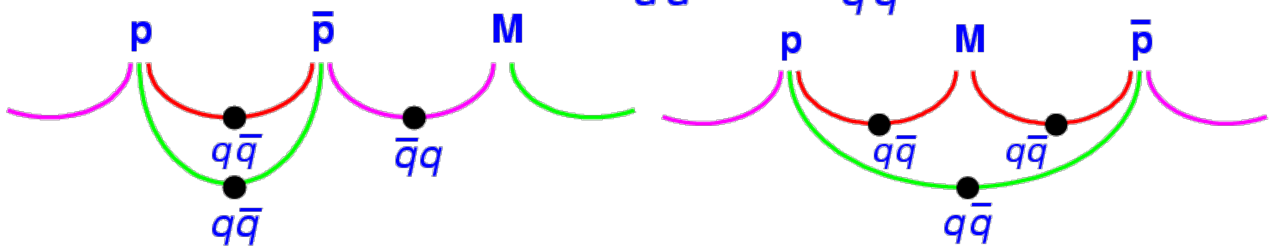
→ Additional evidence against the simple cluster model

Baryon production mechanism

Lund string model: **diquarks**:

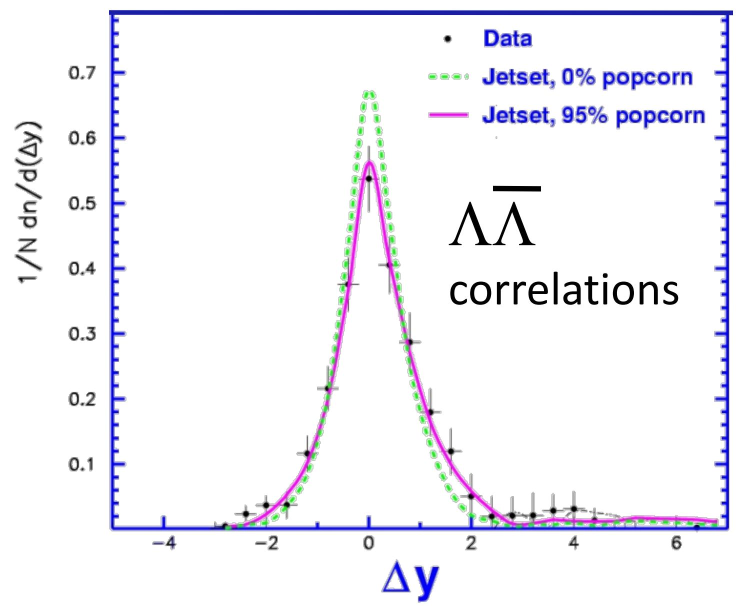


or "**popcorn**":



Popcorn model → looser correlations in phase space (rapidity) than for diquarks

OPAL (LEP), PLB305(1993)415



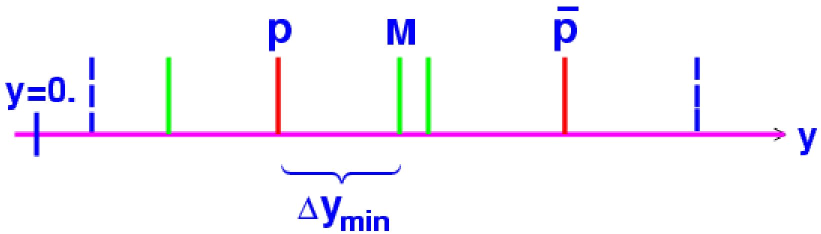
TPC, OPAL, ALEPH, DELPHI (1985-2000):

→ $\Lambda\bar{\Lambda}$ & $p\bar{p}$ rapidity correlations

→ need popcorn at **> 50% level** but sensitivity not strong

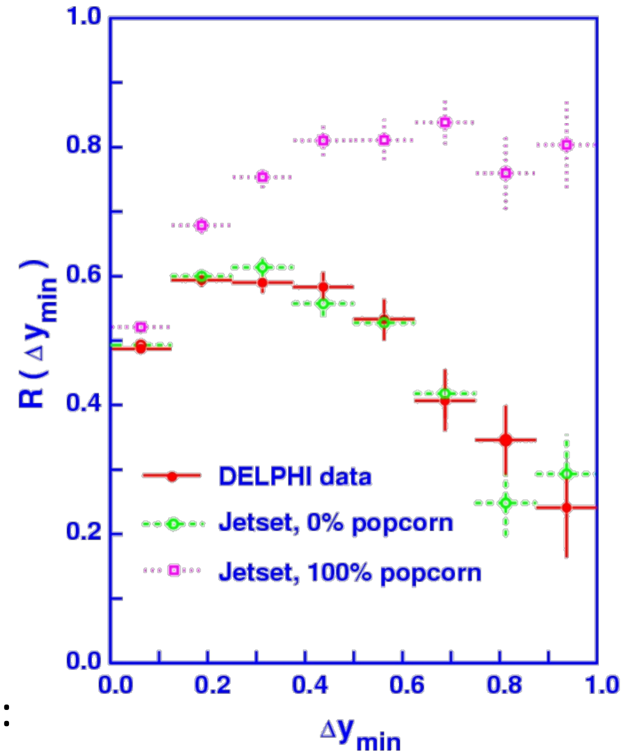
Baryon production mechanism

DELPHI (LEP) PLB480(2000)61:



→ $R = N_{pMp} / [N_{pp} + N_{pMp}]$ vs. Δy_{min}

→ Previous studies insensitive;
diquark model strongly **favored**



OPAL (2009) [awaiting CERN-PH-EP preprint number]:

→ Delphi study of R versus Δy_{min} also insensitive;
[popcorn model also describes data to within ~ 2σ if the diquark fragmentation function parameter PARJ(45) is varied]

→ Rapidity differences too model dependent

Baryon production mechanism

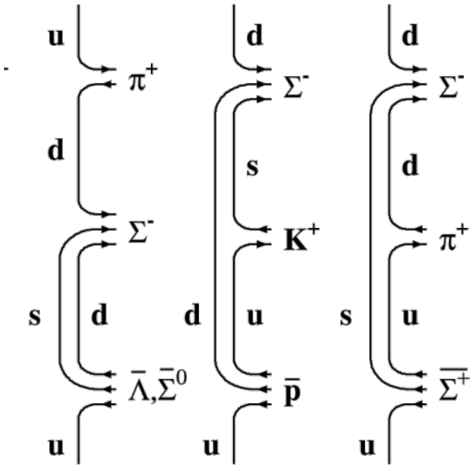
OPAL (2009), CERN-PH-EP XXX

→ use **pure quantum number correlations**

→ Σ^- more likely to be compensated by $\overline{\Lambda}$, $\overline{\Sigma^-}$, $\overline{\Xi^-}$ in diquark model

→ measure $F = F_{\Sigma^-,\overline{\Lambda}} + F_{\Sigma^-,\overline{\Sigma^-}} + F_{\Sigma^-,\overline{\Xi^-}}$

popcorn fraction



d,s → $\overline{\Sigma^-}$, $\overline{\Xi^-}$

	Data	MC (0.0)	MC (0.5)	MC (0.67)	MC (0.91)
F	0.48±0.10	0.87	0.79	0.73	0.55
$\langle \Delta y \rangle$ for $\Lambda\overline{\Lambda}$	0.71±0.04	0.66	0.69	0.67	0.75

- MC's: search parameter space, choose set with best χ^2
- Pure diquark model disfavored with **3.8 σ** significance

Summary

- e^+e^- unrivaled in simplicity
  → clear, unique & varied results
- Discovery of quark jets
- Discovery of gluon jets
- First precise measurements of α_S and the color factors
- First observations of gluon & quark jet differences
- Uniquely sensitive probes of the hadronization process
- Provides tuning for the MCs