Recent QCD results from OPAL

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Outline

- ✓ Color reconnection (CR) & glueballs in gluon jets
  (accepted by Eur. Phys. J. C, hep-ex/0306021)
- ✓ Unbiased gluon jet studies using the jet boost algorithm
  (Phys. Rev. D69 (2004) 032002)
- ✓ Measurement of α_s from radiative events
  (OPAL Preliminary Note OPAL-PN519, April 2003)

Analyses based on $e^+e^- \rightarrow q\bar{q}$ events collected with OPAL detector at Z^0 mass

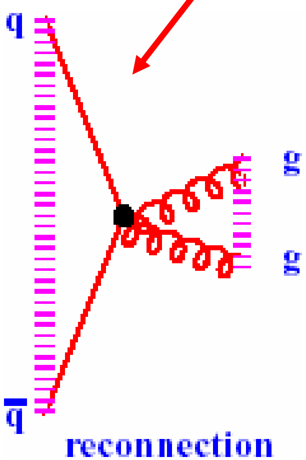
Rapidity gaps & CR

Rapidity: $y = \frac{1}{2}\ln\left(\frac{E + p_{||}}{E - p_{||}}\right)$

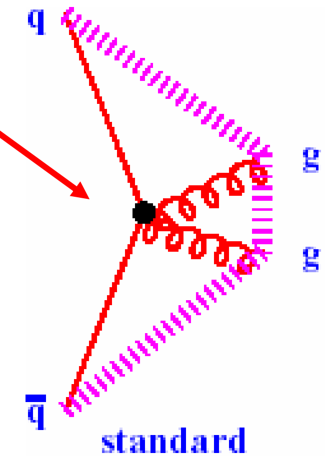
where: E= energy of the particle
$p_{||}$ = 3-momentum component w.r.t. jet axis

Rapidity gap event: event in which two populated regions in rapidity are separated by an empty region

Color reconnection (CR): rearrangement of the color structure of an event from its simplest configuration



- ✓ string segments can either cross or appear as disconnected entities whose endpoints are gluons (suppression $1/N_C^2$; N_C= 3, number of colors)
- ✓ in events with an isolated gluonic system a rapidity gap can form between the particles coming from the isolated segment (often highest rap. part of a gluon jet) and the rest of the event



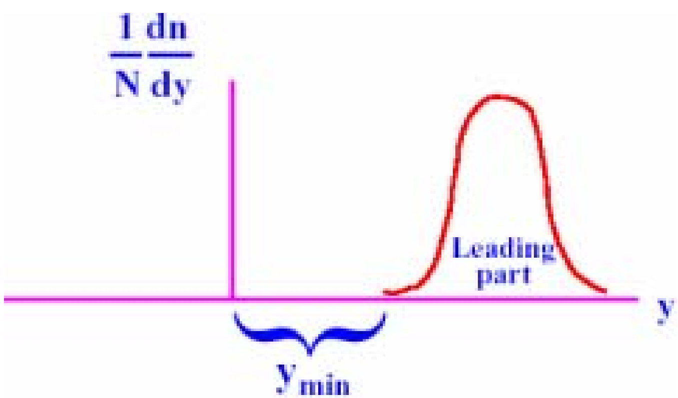
⇨ **Rapidity gaps in gluon jets provide a sensitive means to search for color reconnection effects**

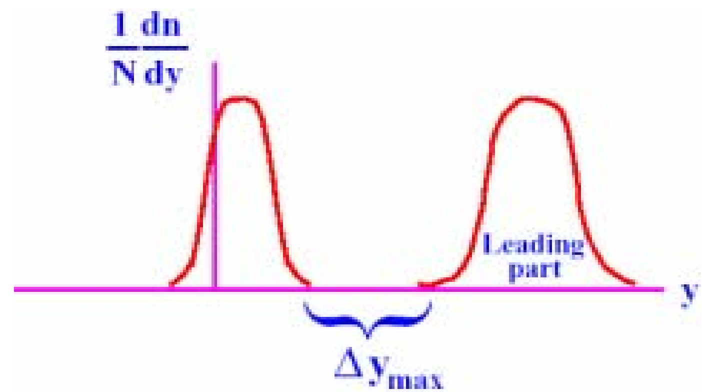
Models & Analysis strategy

CR models: Rathsman-CR (Jetset 7.4+CR), Herwig-CR, Ariadne-CR

1. verify that all the models (with and without CR) give a good description of the global features of hadronic events at the Z^0 peak

2. select gluon jets with a rapidity gap (purity ~ 86 %):
   - ✓cut on the smallest particle rapidity: $y_{min} \geq 1.4$
   - ✓cut on the largest rapidity difference: $\Delta y_{max} \geq 1.3$ (not used to test Herwig-CR)





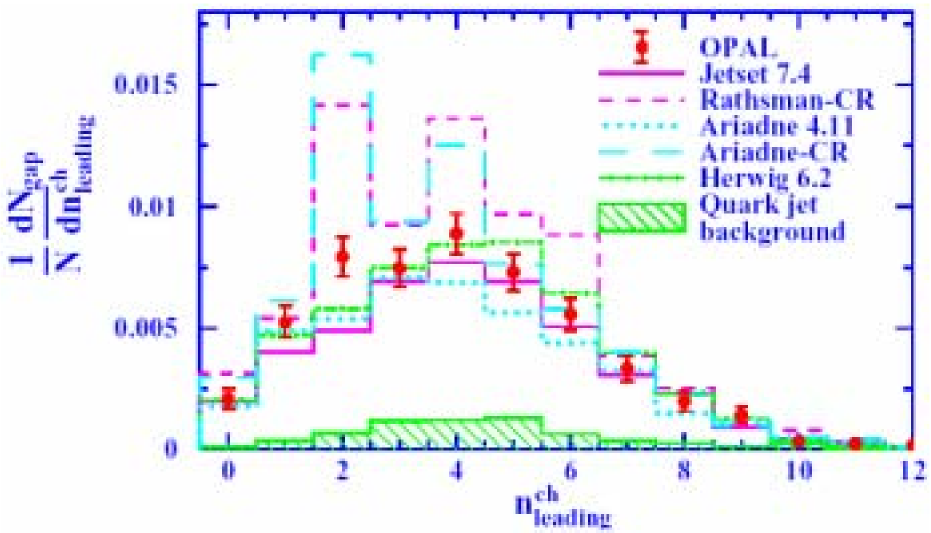
3. study the distribution of the charged particle multiplicity $n^{ch}_{leading}$ and the total electric charge $Q_{leading}$[a] of the leading part of the gluon jet

[a] proposed for gluball searches by P. Minkowski, W. Ochs, Phys. Lett. B485 (2000) 139

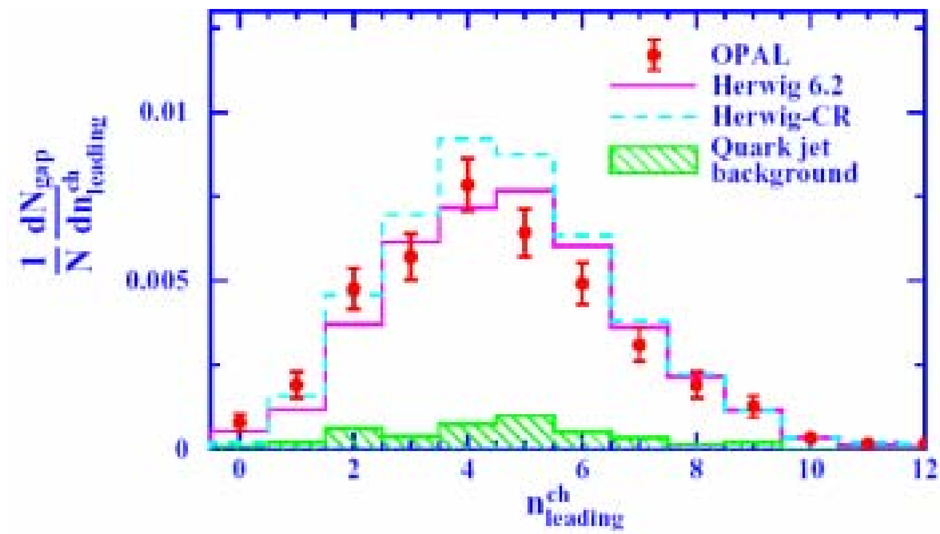
$n^{ch}_{leading}$ distributions

✦ distributions normalized to the total number of selected gluon jets before the rapidity gap requirement

✓using both y_{min} and Δy_{max} selections



✓using y_{min} selection only

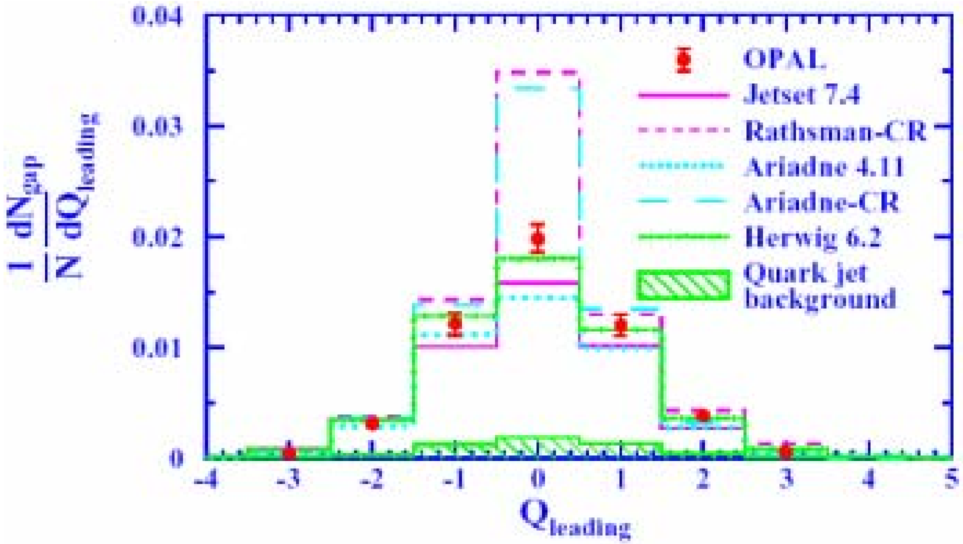


⇨ Rathsman-CR, Ariadne-CR: large excess of entries at $n^{ch}_{leading}$ = 2,4

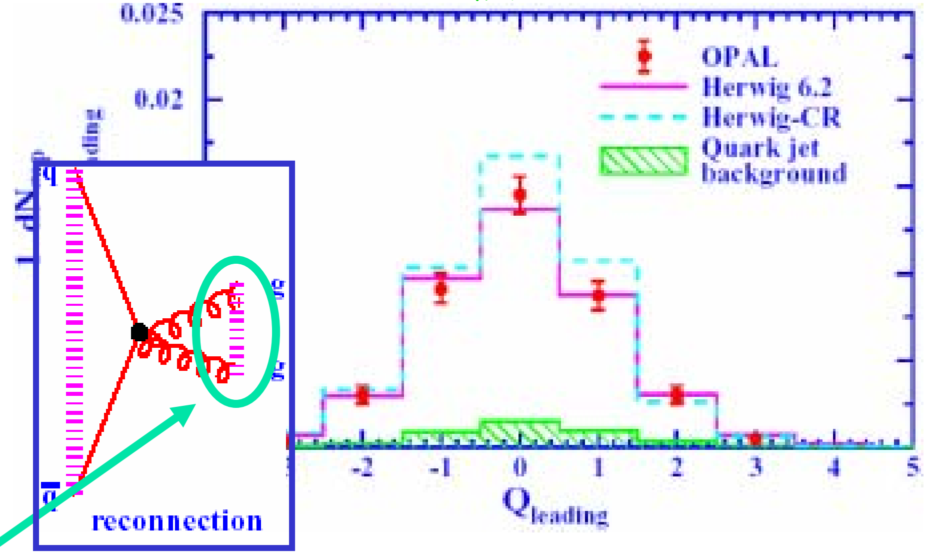
⇨ Herwig-CR: less striking effect for $3 \leq n^{ch}_{leading} \leq 5$

$Q_{leading}$ distributions

✓using both y_{min} and Δy_{max} selections



✓using y_{min} selection only



⇨Rathsman-CR, Ariadne-CR: large excess of entries at $Q_{leading} = 0$

the excess of entries in the distributions is a consequence of events with an isolated gluonic system in the leading part of the gluon jets

⇨Jetset and Ariadne: predictions 15-20% low for the $Q_{leading} = 0$ bin

BUT no spiking behavior in the data for the $n^{ch}_{leading}$ distributions ⇨ cannot conclude this is due to color reconnection (? some other problems ?)

Re-tuning of CR models

Question: tune Rathsman-CR or Ariadne-CR to describe these distributions while continuing to provide a good description of inclusive Z^0 decays?

Rathsman-CR	Ariadne-CR
$Q_0 = 5.5\ \mathrm{GeV}/c^2$ $b = 0.27$	$p_{T,min} = 4.7\ \mathrm{GeV}/c$ $b = 0.17$

(Q_0 , $p_{T,min}$ = cut-offs of the parton cascade in the two models;

b = parameter controlling the longitudinal momentum spectrum of hadrons)

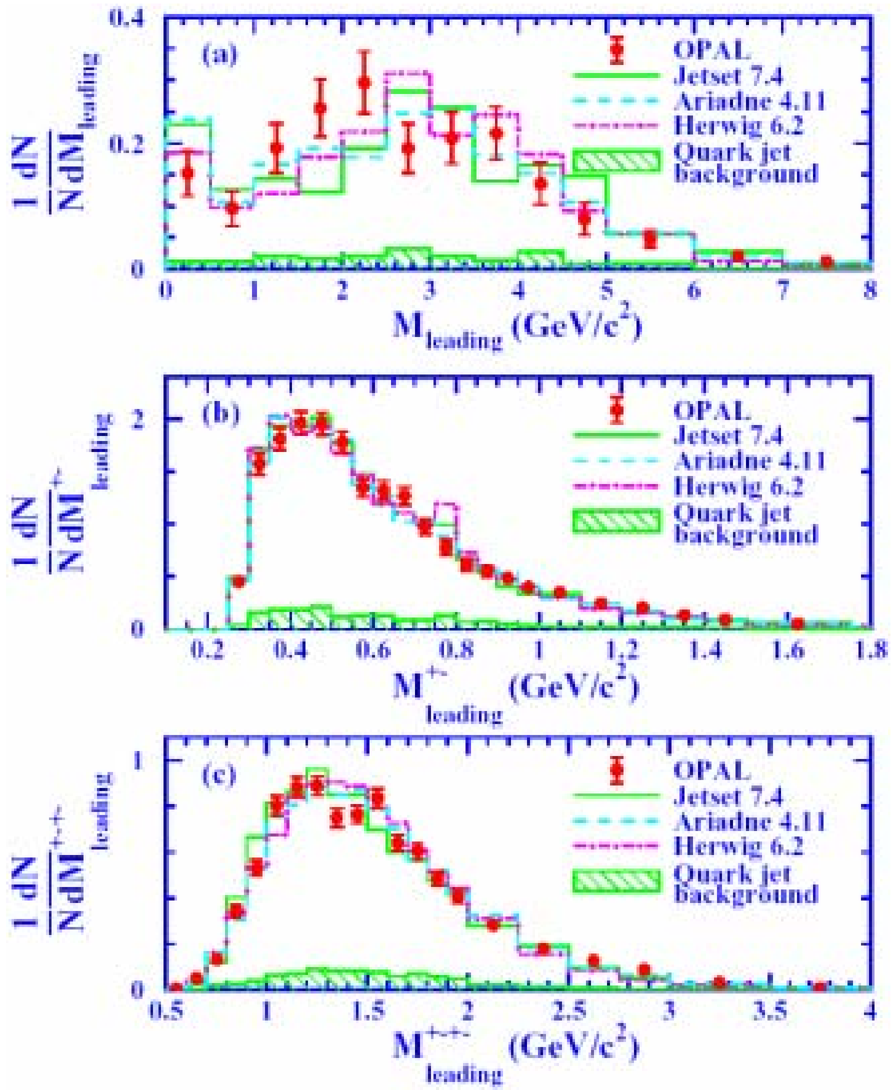
BUT

in both cases the description of the global features of inclusive Z^0 decays is severly degraded

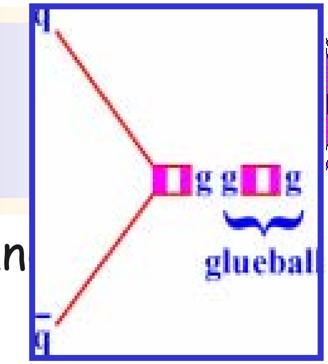
⇨**Rathsman-CR and Ariadne-CR models are both DISFAVORED**

⇨**No definite conclusion concerning Herwig-CR**

Search for glueballs



rapidity gap between gluon jet an
the event



⇨ enhanced probability for a color octet field to be created between the gluon and residual $q\bar{q}$ system

⇨ creation of glueballs through gg pair production from the vacuum

Examine invariant masses in the leading part of the gluon jets:

$M_{leading}$ = total

$M^{+-}_{leading}$ =of two oppositely charged particles

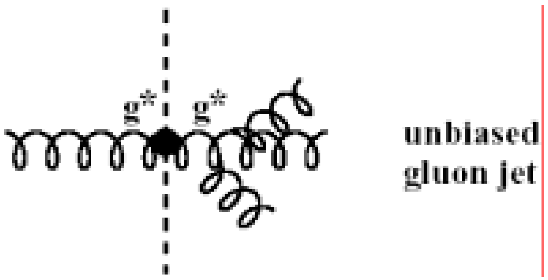
$M^{+-+-}_{leading}$ = of four charged particles

⇨ **No evidence for anomalous production of scalar particles is observed**

Unbiased gluon jets studies

✓ **Theoretical calculations:**

define gluon jet multiplicity INCLUSIVELY



→ N_g: particles in hemisphere of *gg* color singlet: UNBIASED gluon jet

✓ **Experimental analyses:**

gluon jet often defined using a jet reconstruction algorithm (jet finder)

→ N_g: particles associated to the jet by the algorithm: BIASED gluon jet

→ multiplicity strongly dependent from jet finder used

→ comparison to theory ambiguous

NO natural source of unbiased gluon jets except radiative Υ decay

Only two direct measurement :

✓ using $\Upsilon \rightarrow \gamma g g$ events: E_{jet} ~ 5 GeV (CLEO)

✓ using $e^+e^- \rightarrow q_{tag}\bar{q}_{tag}g_{incl}$: E_{jet} ~ 40 GeV (OPAL)

and one indirect:

✓ $N^{ch.}_{q\bar{q}g} - N^{ch.}_{q\bar{q}}$: 10 GeV < E_{jet} < 30 GeV (OPAL) only mean multiplicity!!

Purpose of this study

I. test if the BOOST algorithm proposed by the Lund theory group[b] to reconstruct unbiased gluon jets provides a good description of unbiased jets

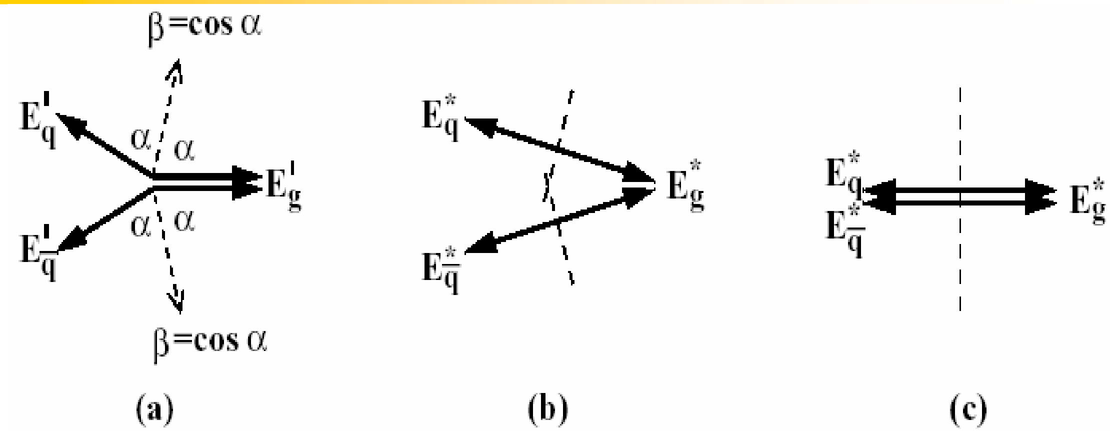
II. measure unbiased gluon jet properties at different energies using this method

III. compare the results with theoretical predictions

b P.Eden. G. Gustafson, JHEP 9809 (1998) 015

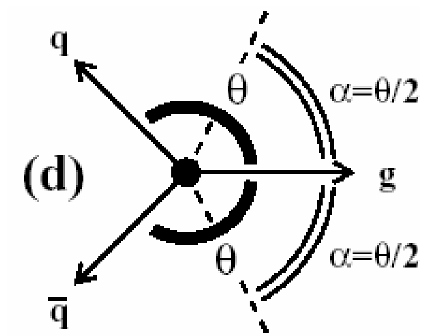
Boost Algorithm (BA)

✓ BA based on **Color Dipole Model**:
in events symmetric w.r.t gluon direction (**a**) we can boost (**b**) and combine the two independent dipoles to yield the dipole structure of *gg* event (**c**)



✓ Reconstruct a 3-jet event configuration in a multihadronic event and identify the gluon jet (25000 events, purity ~ 85 %)

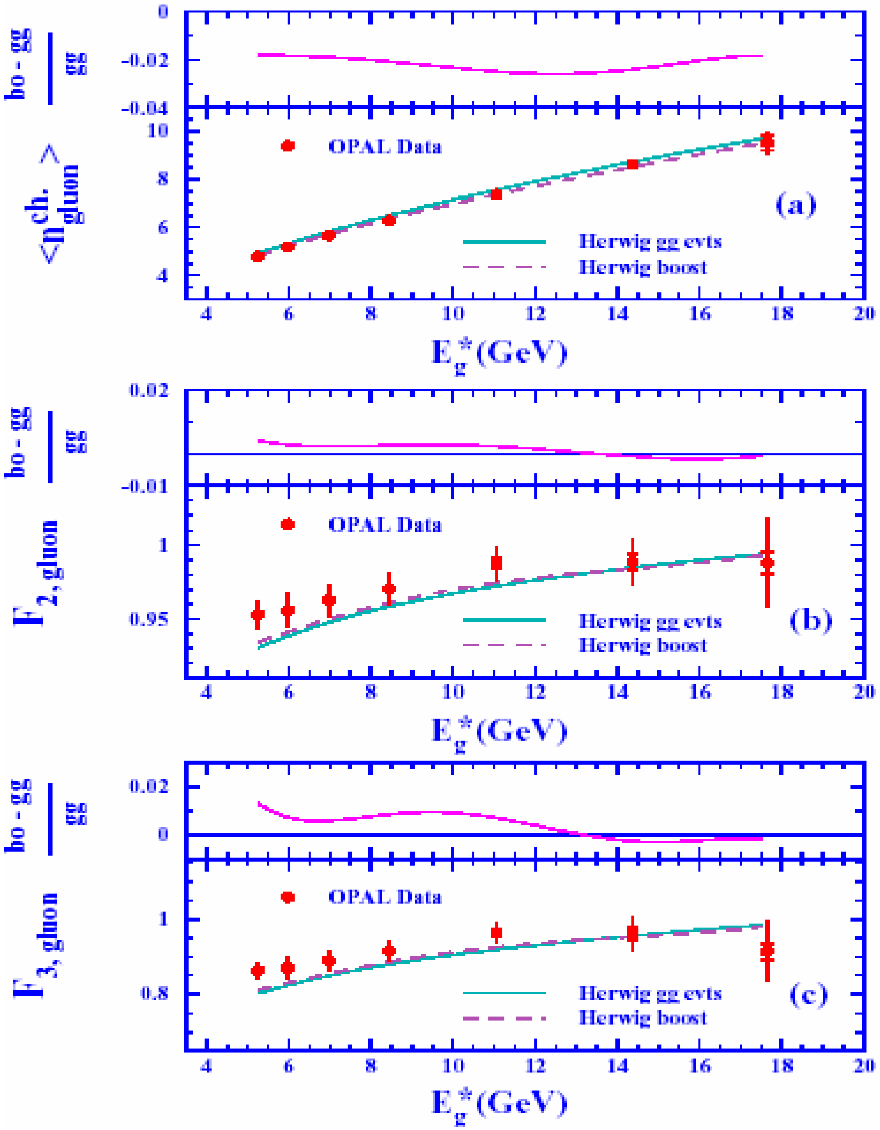
✓ Apply Lorentz BOOST to the event.
In the new frame (d): $\theta_{qg} = \theta_{\bar{q}g} = \theta$



Multiplicity of gluon jet: number of particles lying inside the cone-like region defined by the bisectors of θ_{qg} and $\theta_{\bar{q}g}$

Energy scale of gluon jet: $E_g^* = p_{\perp,gluon} = \frac{1}{2}\sqrt{\frac{s_{qg}s_{\bar{q}g}}{s}}$ (range divided in 7 bins)

MC test of BA (multiplicity)



✓ test the BA using Herwig Monte Carlo

✓ compare results of BOOST method with unbiased gluon jets from color singlet *gg events*

MULTIPLICITY DISTRIBUTIONS

⇨ good agreement for $E_g^* > 5$ GeV

⇨ measurement of multiplicity distributions in seven energy intervals between 5.25 and 17.72 GeV

⇨ extract mean multiplicity $< n_{gluon}^{ch.} >$ and factorial moments F_2 and F_3

Other MC tests of BA

FRAGMENTATION FUNCTION

⇨ good agreement for $E_g^* > 14\,\text{GeV}$ (at smaller energies the jet mass becomes important)

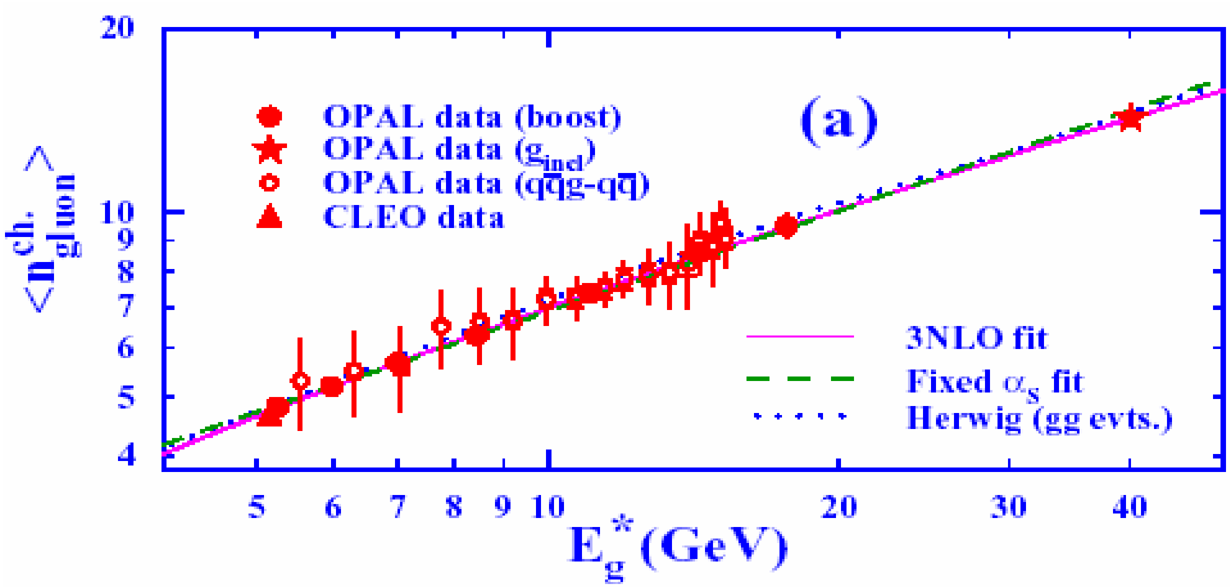
⇨ measurement of fragmentation functions in two intervals at 14.24 and 17.72 GeV

other tests:

✓ no jet finder dependence observed

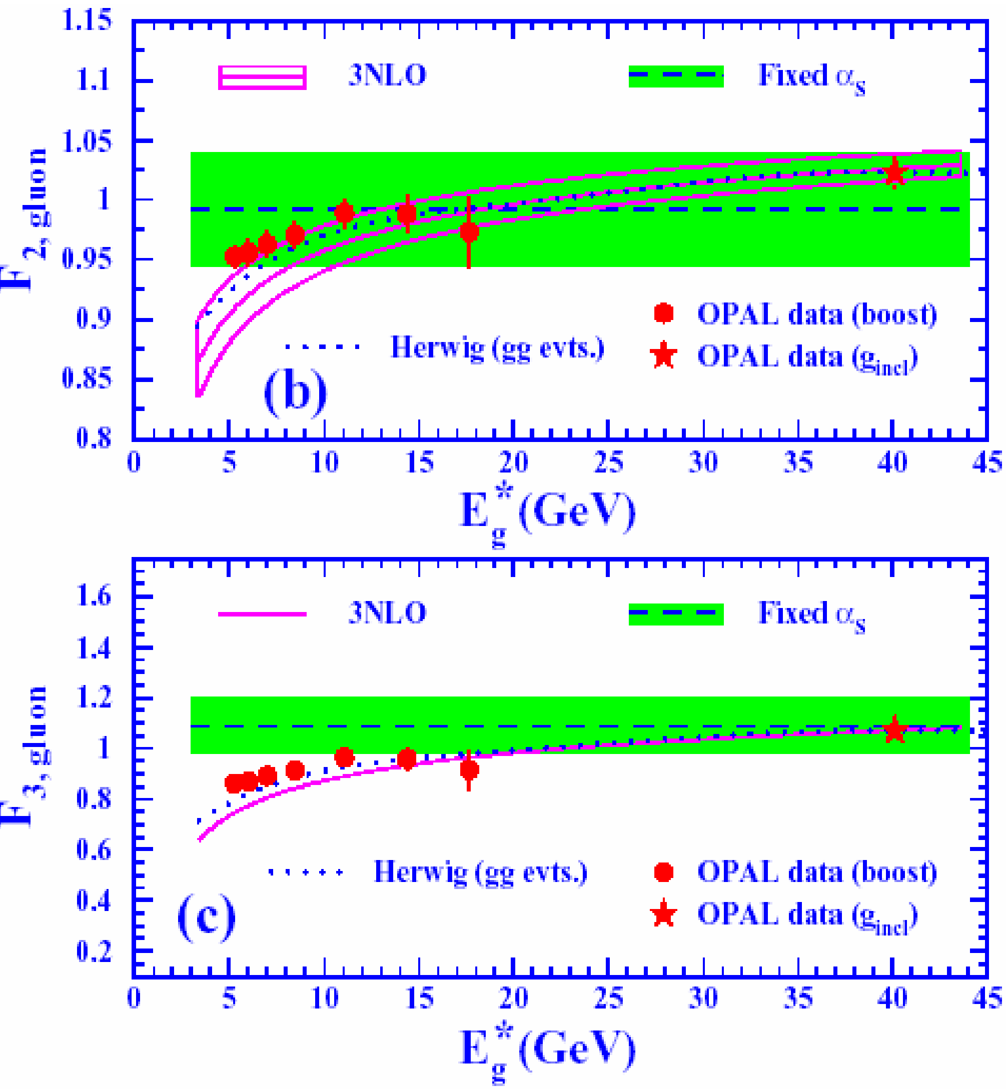
✓ checked massless jets (partons) assumption (as 80% of the examined gluon jets arise from $b\bar{b}$ initiated events)

Results: mean multiplicity



- ✓ Results consistent with previous measurements of unbiased gluon jets
- ✓ Most precise results for $5.25 < E_g^* < 20\,GeV$
- ✓ Theoretical expressions successfully fitted to experimental data:
  - o 3NLO: takes into account the running nature of α_s
  - o Fixed α_s : incorporates more accurately higher order effects

Results: factorial moments



✓ First measurement of F_2 and F_3 for unbiased gluon jets over an energy range

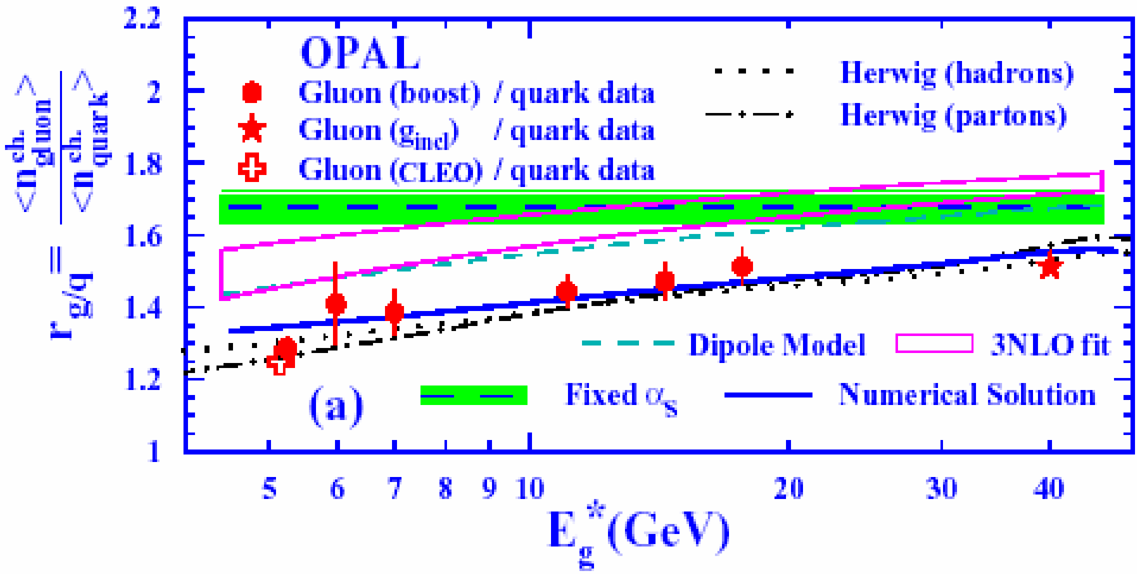
✓ 3NLO expression fitted to three highest energy data points:

- o reasonable description of $F_{2,gluon}$ and $F_{3,gluon}$ energy evolution above 14 GeV
- o lower energies: predictions below data (probably hadronization effects)

✓ Fixed α_s prediction:

- o general agreement with the data for $F_{2,gluon}$
- o lies above the data for $F_{3,gluon}$ except for $E_g^* \approx 40$ GeV

Results: multiplicity ratio



Quark term: inclusive $e^+e^- \to q\bar{q}$ data at the same gluon energy scale E_g^*, corrected (Herwig) for small energy difference and heavy quark contribution

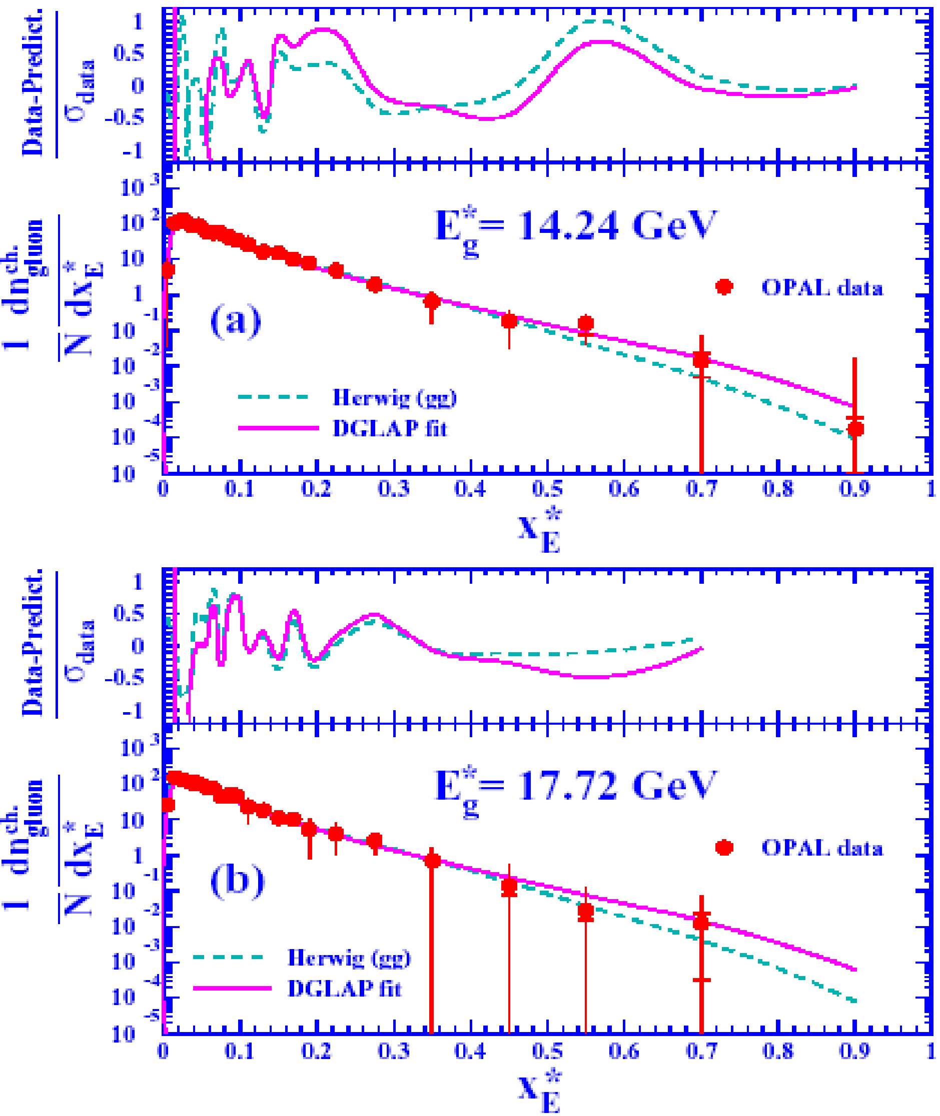
✓ 3NLO and fixed α_s are 15-20% above the data

✓ Dipole Model is about 10-15% above the data

✓ Numerical solution of QCD evolution equation (better treatment of energy conservation and phase space limits) well describes the data

⇨ Energy conservation and phase space limits are important issues

Results: fragmentation function



✓ data fitted using the DGLAP evolution equation (valid at NLO in the $\overline{MS}$ scheme)

✓ the fit provides a good description of the measurements and yields a result for the strong coupling constant:

$\alpha_s(m_Z) = 0.128 \pm 0.008(stat) \pm 0.015(syst)$

consistent with the world average and provides a unique consistency check of QCD

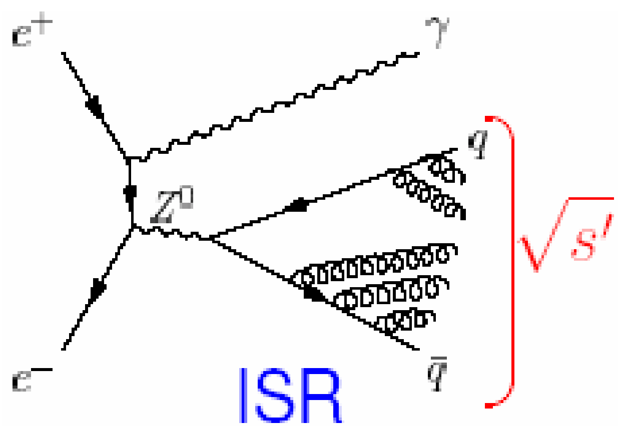
α_s from radiative events

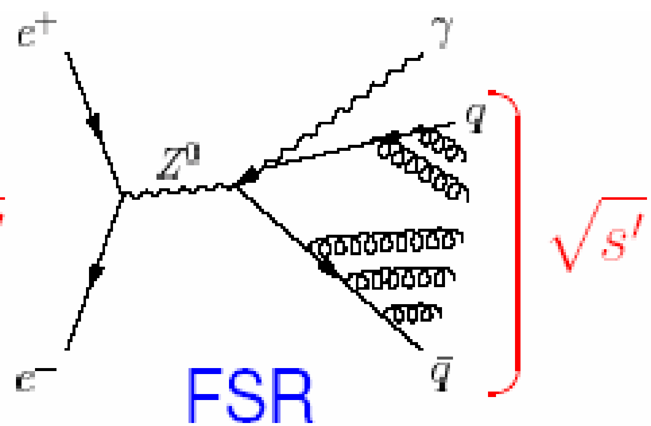
✓ hadronic events with a hard isolated photon ($e^+e^- \rightarrow q\bar{q}\gamma$), collected at the Z^0, are used to measure α_s

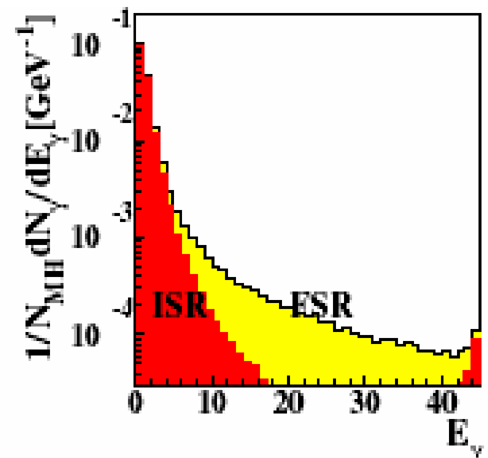
✓ fit event shape variables for the reduced centre-of-mass energies ($\sqrt{s'}$) ranging from 20 to 80 GeV

✓ assume that photons emitted before or immediately after the Z^0/γ production don't interfere with QCD processes

✓ at the Z^0, detected isolated high energy photons come mainly from FSR



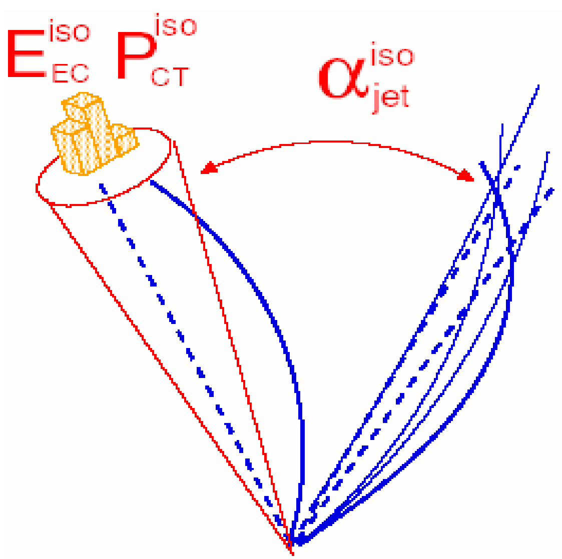




Isolated EM Cluster Selection

Signal → MH events with ISR/FSR photon (E_γ > 10 GeV)

Backgrounds
- ✓ non-radiative MH events
- ✓ two photon processes
- ✓ τ pair production



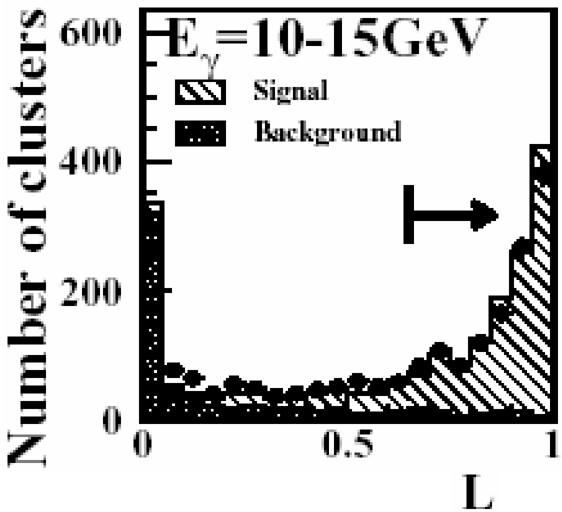
Isolation conditions on EM clusters

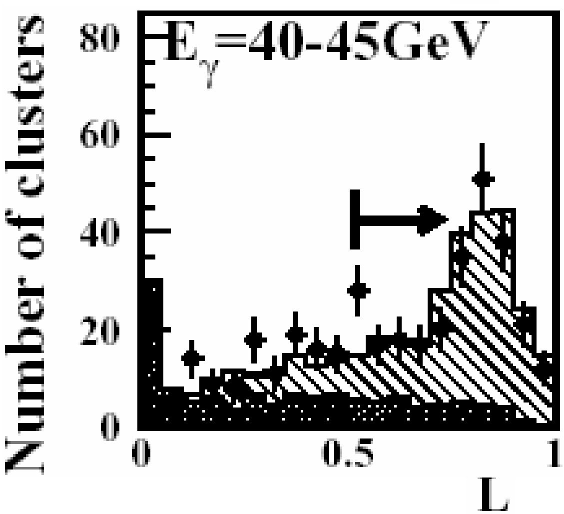
- ✓ unassociated with tracks
- ✓ $E_{cluster} \geq 10$ GeV
- ✓ polar angle w.r.t. beam axis $|\cos\theta_{EC}| < 0.72$
- ✓ angle w.r.t. axis of any jet $\alpha^{iso}_{jet} > 25^o$
- ✓ $P^{iso}_{CT} < 0.5$ GeV/c, $\alpha = 0.2$ rad
- ✓ $E^{iso}_{EC} < 0.5$ GeV , $\alpha = 0.2$ rad

11625 clusters after isolation cuts (53% non-rad MH, 0.6% $\tau\tau$, 0.01% 2γs)

Likelihood photon selection

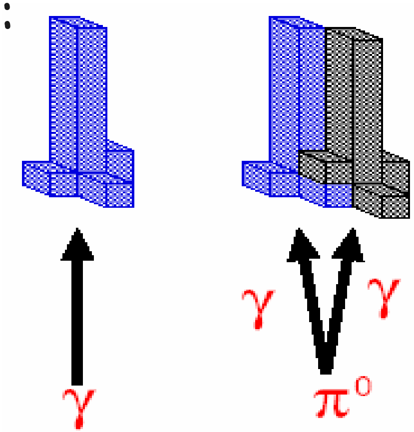
Preliminary





reduce bkg from clusters arising from π^0 decay

- ✓ LH ratio method with 4 input variables:
  - o $|\cos\theta_{EC}|$;
  - o α^{iso}_{jet};
  - o cluster shape fit variable;
  - o distance between EM cluster and associated presampler cluster



- ✓ events divided in 7 subsamples according to $E_{cluster}$
- ✓ cut on likelihood chosen to keep 80% of signal events

Background estimation

✓ Background fraction estimated from data by two independent methods:

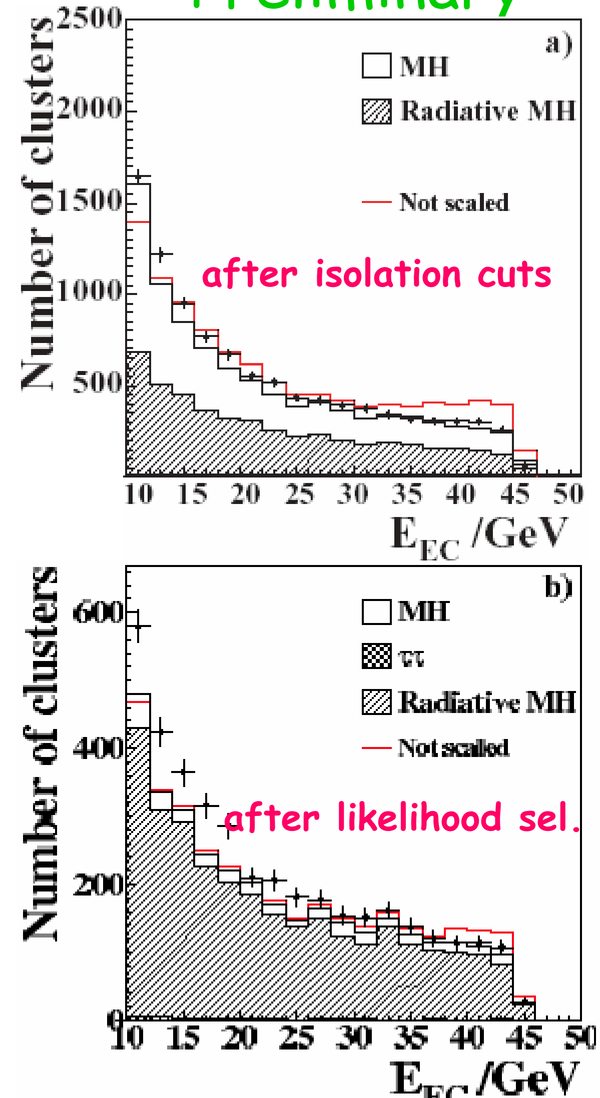
- o fit likelihood distributions in the data with a linear combination of MC distributions for signal and bkg events : $C_i = f_{bkg}\, C_i^{bkg} + (1- f_{bkg})C_i^{sig}$
- o assuming isospin symmetry (systematic check)

$$N_{\pi^0} = \frac{1}{2} N_{\pi^\pm} \qquad N_{K^0} = \frac{1}{2} N_{K^\pm} \qquad N_n = N_p$$

select charged hadrons satisfying isolation cut criteria

⇨ obtain rate of isolated neutral hadrons from rate of isolated charged hadrons

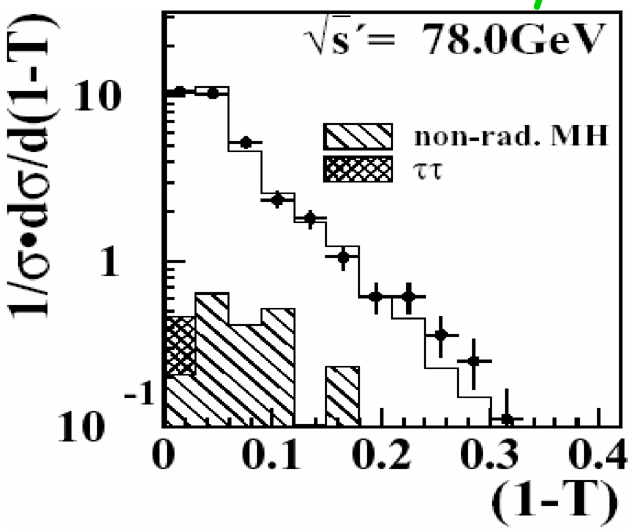
Preliminary

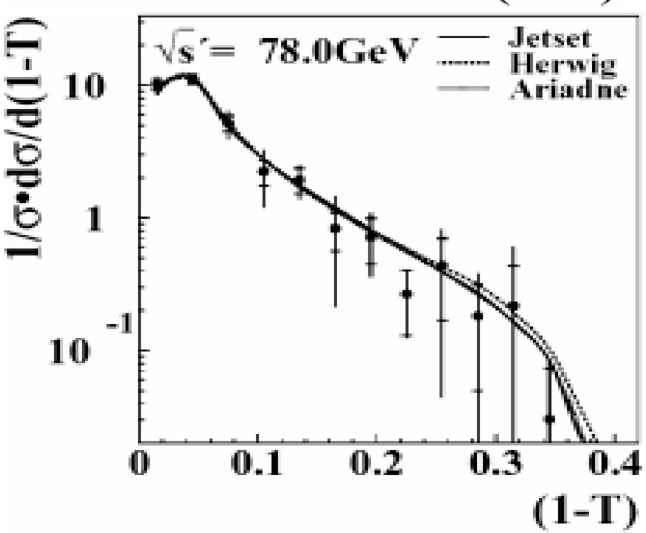


Final BKG:
- o non-rad MH < 10% for $E_{cluster}$ = 10-35 GeV
  10-15% for $E_{cluster}$ = 35-45 GeV
- o 2 photons processes < 0.01%
- o $\tau\tau$ events 0.5-1.0%

Event Shape variables

Preliminary

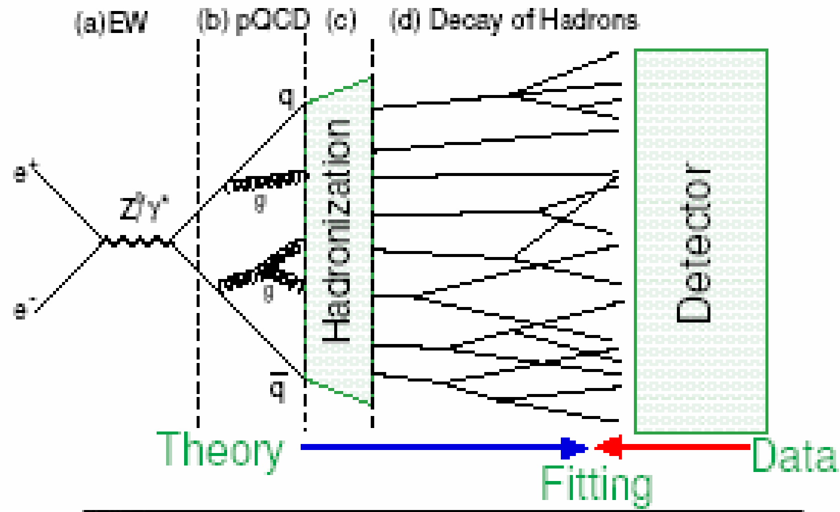




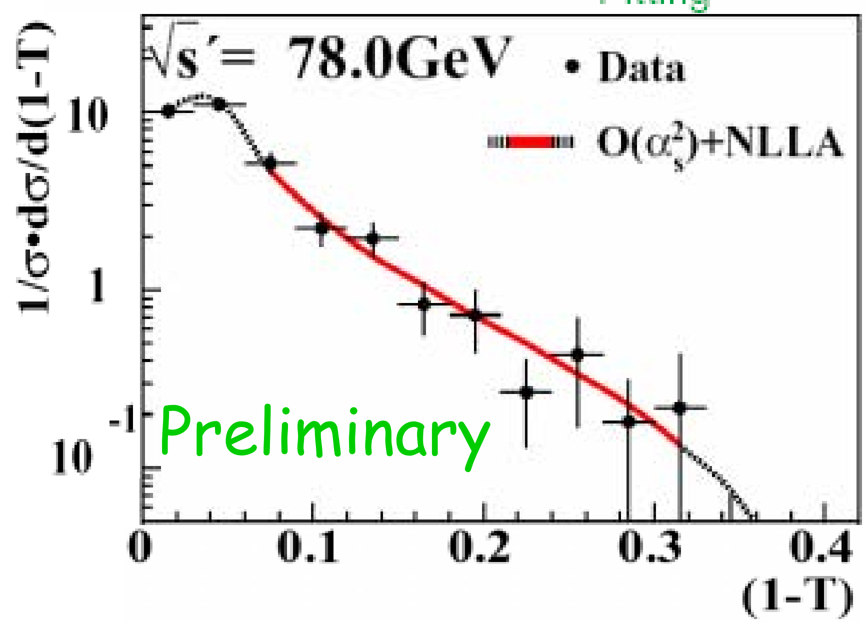
- ✓ α_s determined from:
  - o Thrust T,
  - o heavy jet mass M_H,
  - o jet broadening variables B_T and B_W
- ✓ boost into the CMS of hadrons (Lorentz boost determined from energy and angle of the γ candidate)
- ✓ calculate event shape variables
- ✓ subtract normalized background distribution from data distribution at detector level
- ✓ bin-by-bin correction for detector effects (acceptance, resolution) → distributions at hadron level

Measurement of α_s

α_s measured by fitting pQCD predictions to the event shape distributions corrected at hadron level



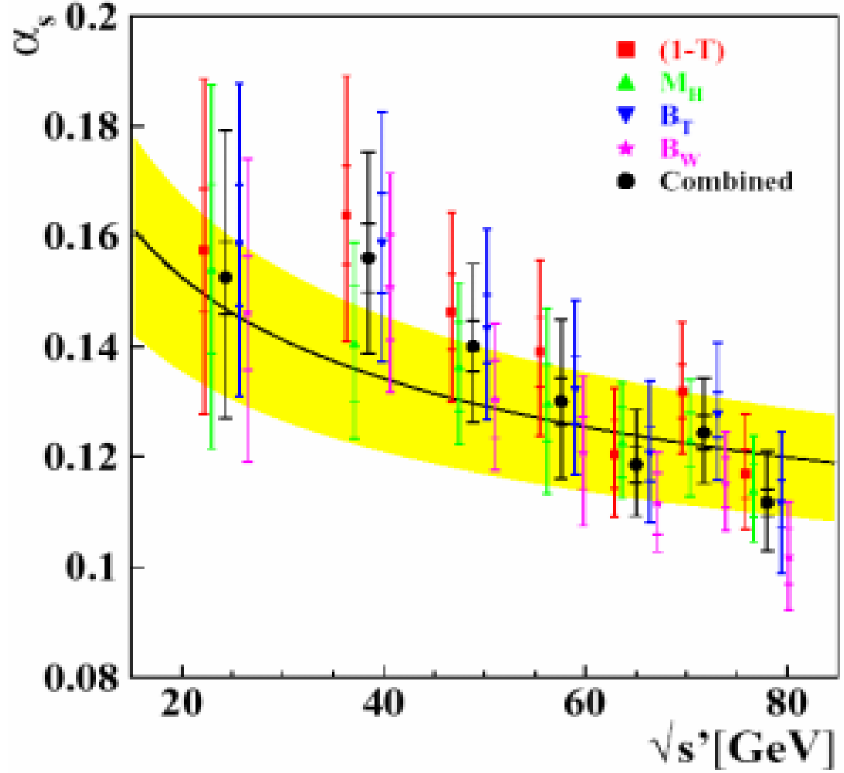
- ✓ correct theoretical calculation to hadron level multiplying by a correction factor $R^{had} = H_i/P_i$
- ✓ least χ^2 method with $\alpha_s(Q)$ free parameter
- ✓ fitting range: regions with small and uniform corrections



Combination of α_s results

Preliminary

values of α_s combined to obtain energy dependence of α_s and an overall combined result for $\alpha_s(M_Z)$



✓ solution of the RGE at NNLO fitted to the values of α_s, treating $\Lambda^{(5)}_{\overline{MS}}$ as a free parameter:

$$\Lambda^{(5)}_{\overline{MS}} = 0.2027 \pm 0.0141(stat)^{+0.1130}_{-0.0939}(syst)GeV$$

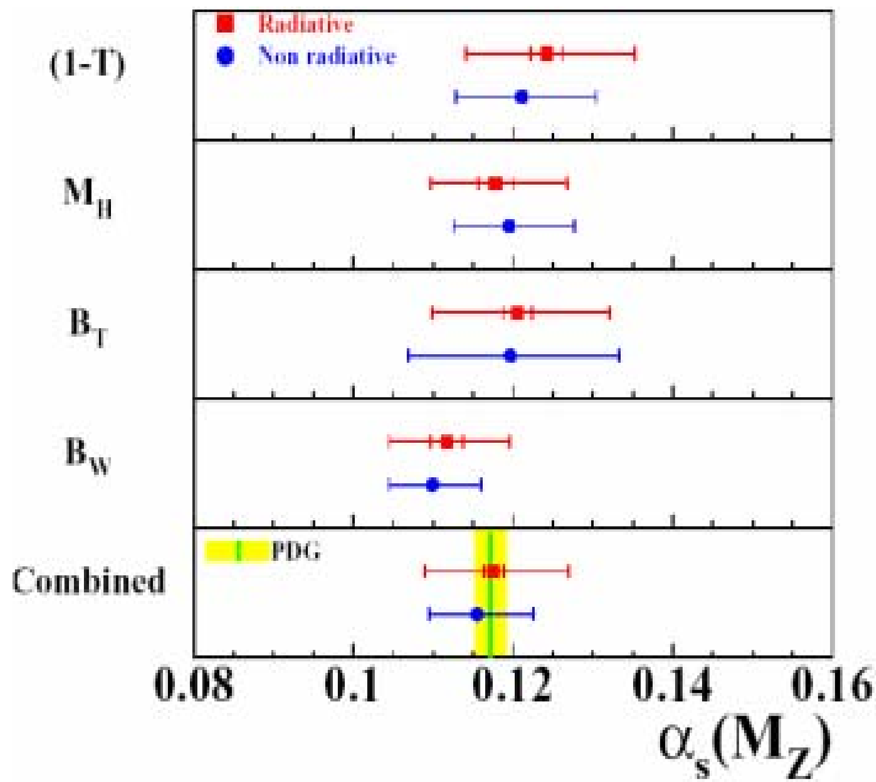
Comparison of α_s results

Preliminary

✓ evolve values of α_s at each energy to M_Z and combine them:

$$\alpha_s(M_Z) = 0.1176 \pm 0.0012(stat)^{+0.0093}_{-0.0085}(syst)$$

agrees with previous OPAL analysis using non-rad. MH events, world average PDG value and similar analyses using radiative MH events by DELPHI and L3



Summary

- ✓ Color reconnection models Rathsman-CR and Ariadne-CR DISFAVORED
- ✓ No evidence for glueball-like objects
- ✓ Boost Algorithm to study unbiased gluon jets: data found in overall good agreement with theory
- ✓ α_s measured over an energy range from 20 to 80 GeV. Combining the results we obtain:

$$\alpha_s(M_Z) = 0.1176 \pm 0.0012(stat)^{+0.0093}_{-0.0085}(syst)$$

Gluon jet scales