MANCHESTER 1824

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Europhysics
HEP 2007
Manchester

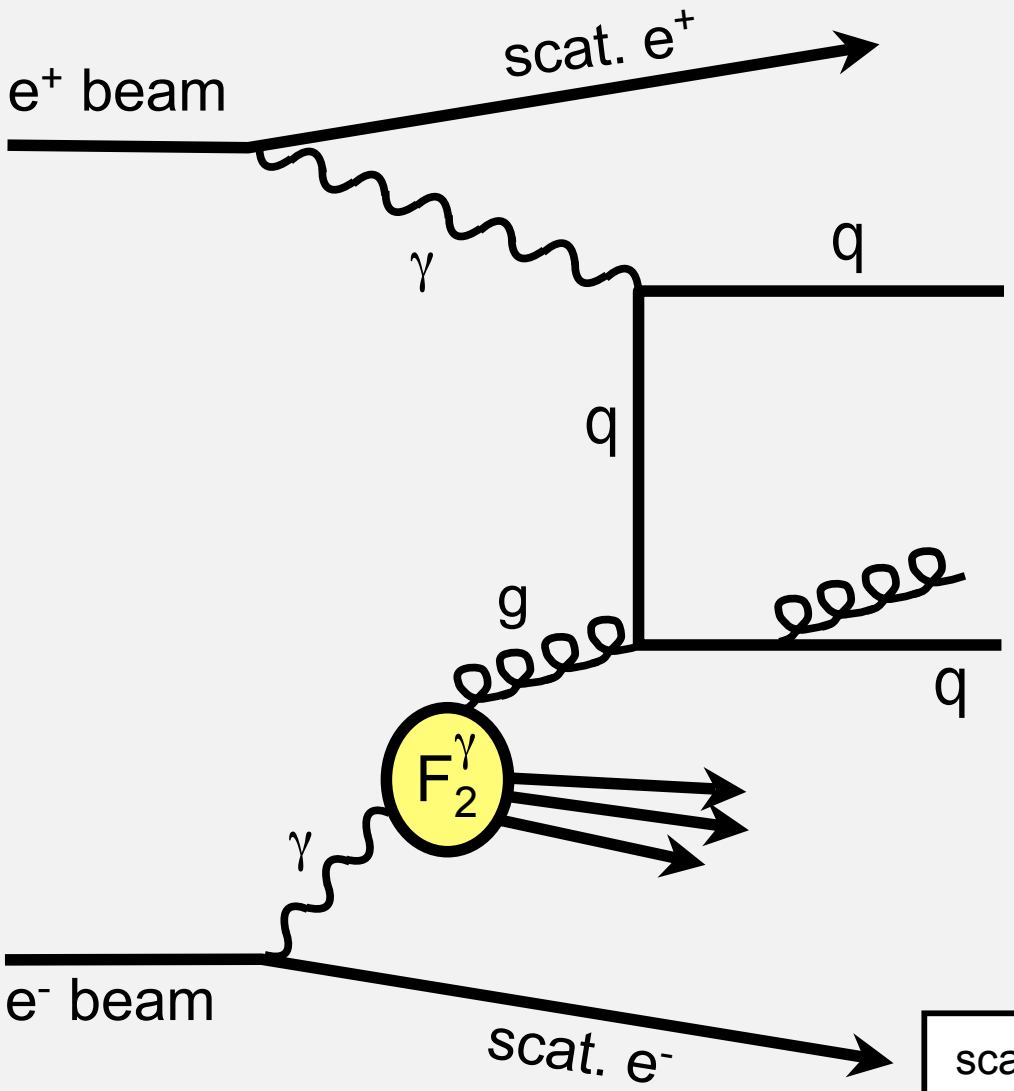
Hadronic Photon-Photon Scattering at LEP

…and their description by NLO QCD

Concentrate on new results for 3 measurements with problematic relationships with NLO QCD

- *b-quark production cross section (ALEPH)*
- *Inclusive jet production (OPAL)*
- *Inclusive hadron production (OPAL)*

(Hadronic) Things you can do with two photons



Hadronisation

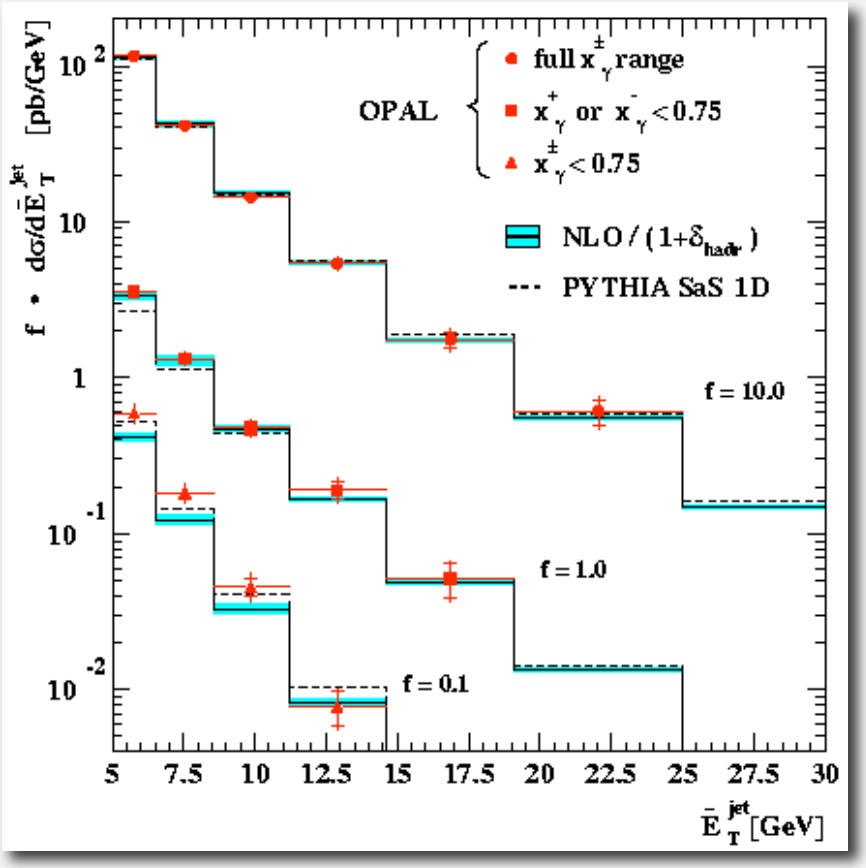
Measurements

- Total hadr. x-section
- Jet x-sections
- Hadron spectra
- Heavy quarks
- Resonances
- …

scattered electrons untagged
→ quasi real photons

Examples of a working relationship

Di-jet production



NLO: Klasen et al.

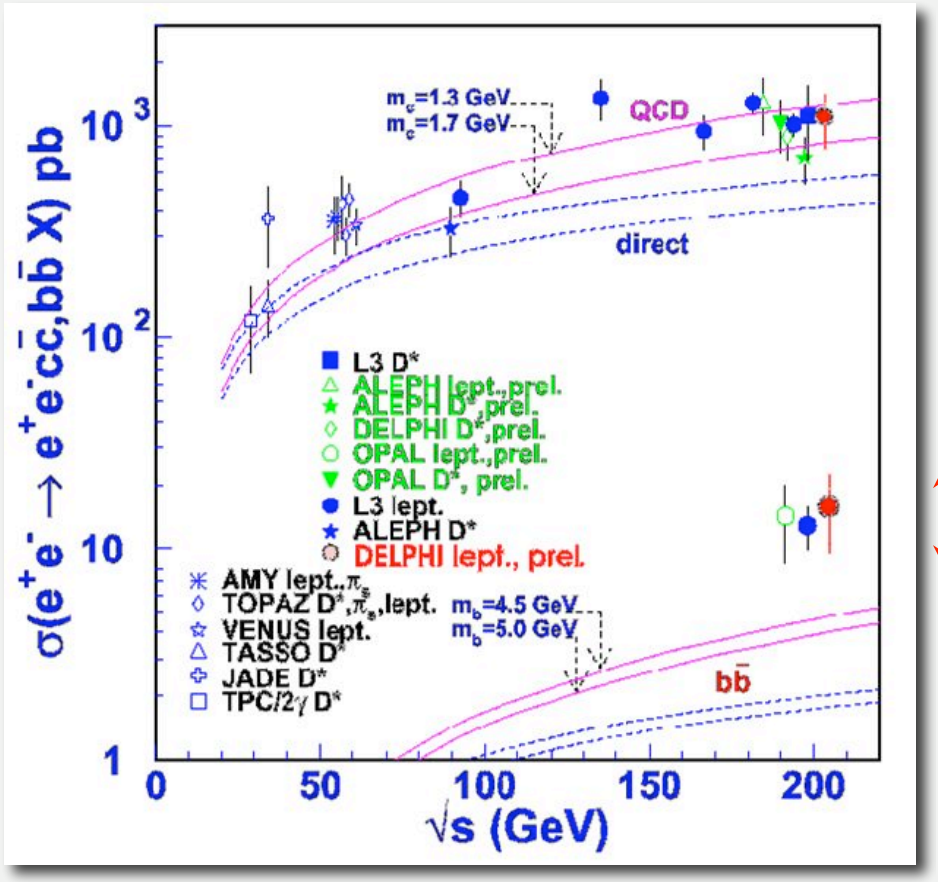
Ingredients:

- Photon radiation
  - QED process
  - Well understood
- Photon structure function
  - Reasonably well determined
  - Suppressed at large momenta
- Partonic processes
  - Same matrix elements as in jet production at e^+e^-, Hera …
- Hadronisation
  - Models tested in other processes

Should work … and does

Total cross-section of $c\bar{c}$ and $b\bar{b}$ production

QCD to NLO: M.Drees et al.



$c\bar{c}$: Good agreement theory - experiment

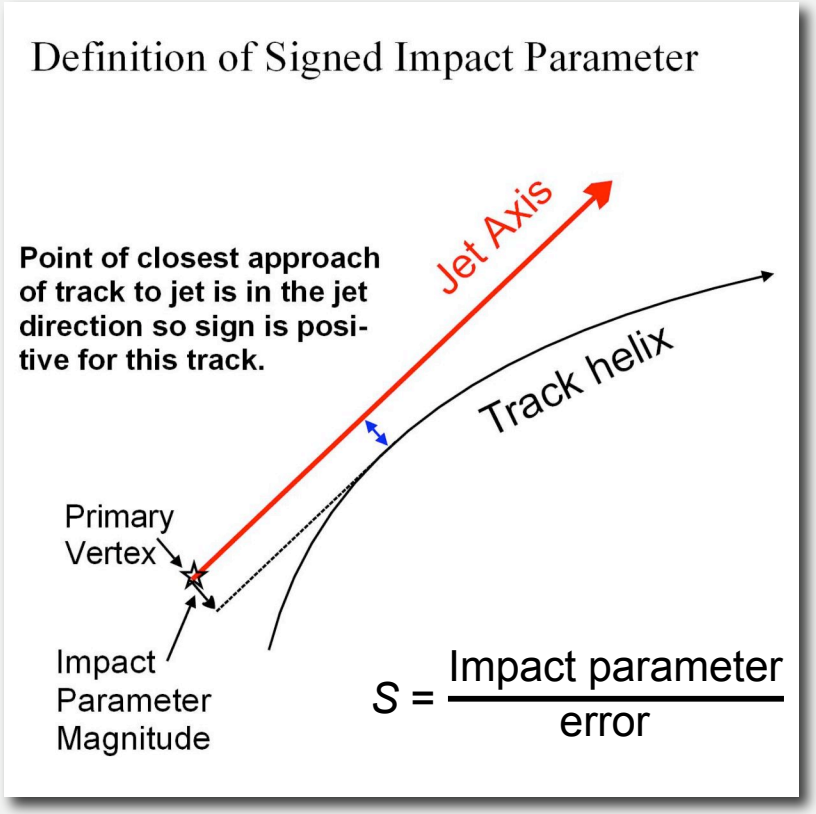
$b\bar{b}$: Here the trouble starts

All measurements so far (DLO) above NLO QCD

But all use the same method…
(fit rel. lepton p_T distribution)

ALEPH: New measurement of $b\bar{b}$ cross section

First measurement to use life-time tag in $\gamma\gamma \rightarrow$ heavy flavour



Function from fit to negative *S* distribution applied to tracks

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Probability *P* that track is from primary vertex

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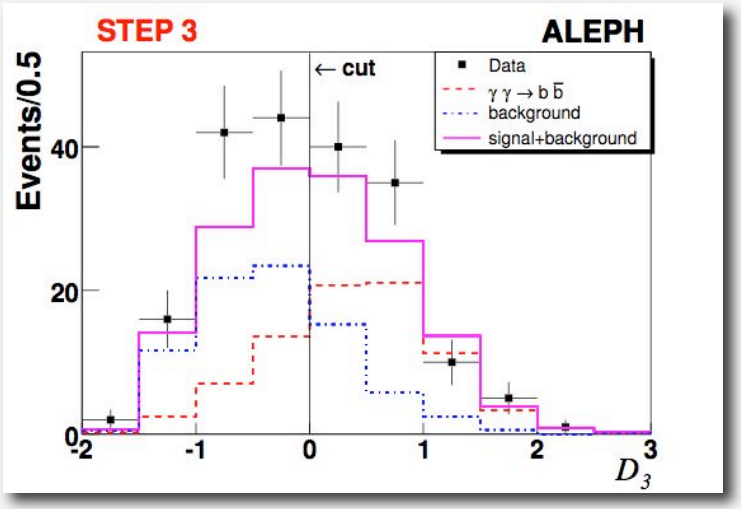
Combine to form:

P_{jet} Probability for all tracks in a jet

P_{event} Probability for all tracks in the event

ALEPH: $b\bar{b}$ cross section cont.

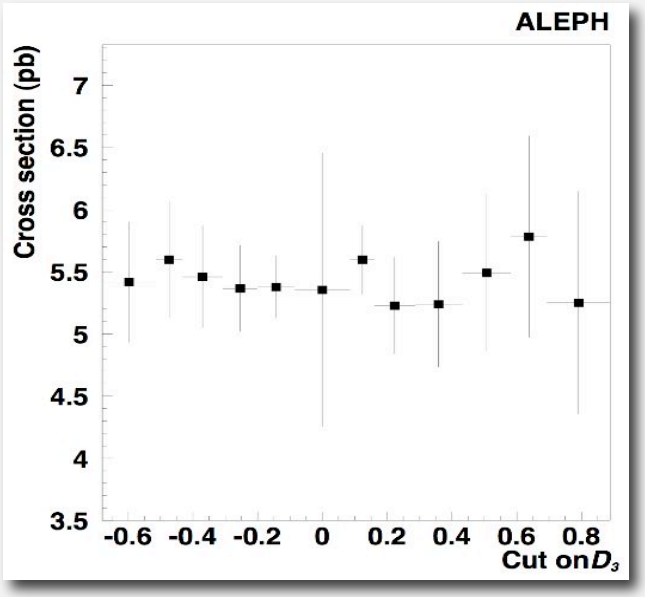
Iterative Discriminant Analysis (3 steps)



- 93 events in 698 pb^{-1}
- background 24.2 events
- Selection efficiency 0.0184 ± 0.0009

Input to IDA

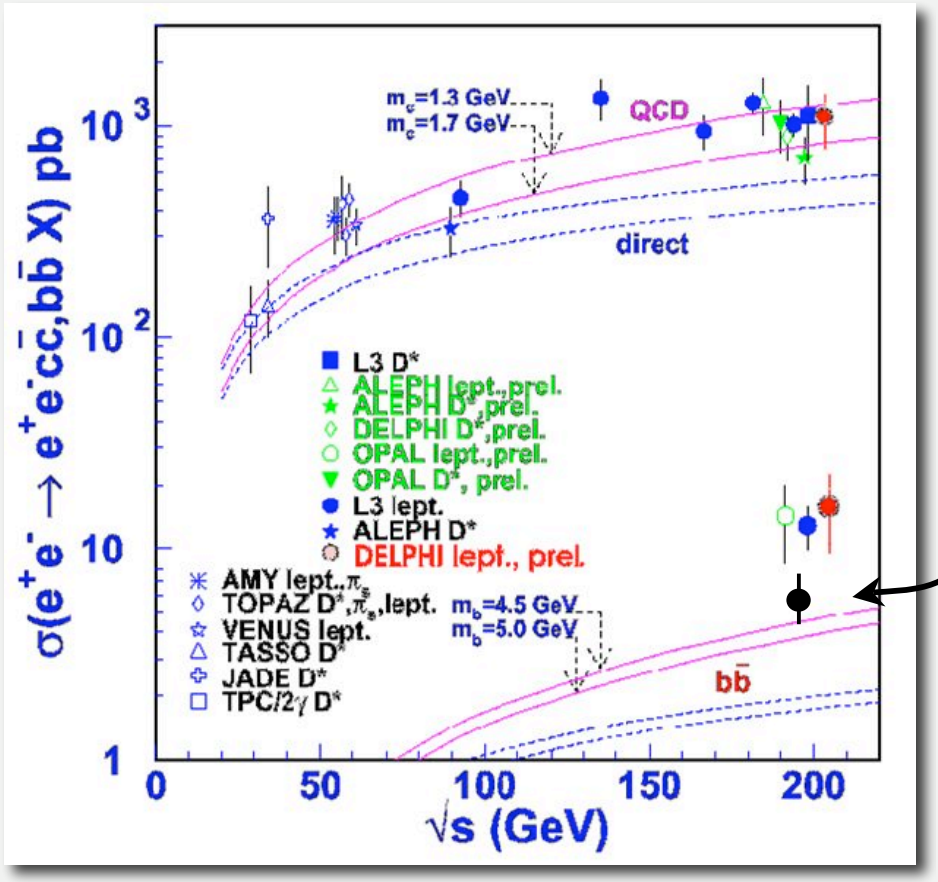
- P_{event}, P_{jet1}, P_{jet2}
- mass and p_T of jet 1
- 5 largest *S*
- thrust of the event



Stability w.r.t. cut on D_3

ALEPH: $b\bar{b}$ cross section cont.

QCD to NLO: M.Drees et al.



$\sigma(e^+e^- \to e^+e^-\ b\bar{b}\ X)$

$(5.4 \pm 0.8_{stat} \pm 0.8_{syst})$ pb

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Consistent with NLO QCD!

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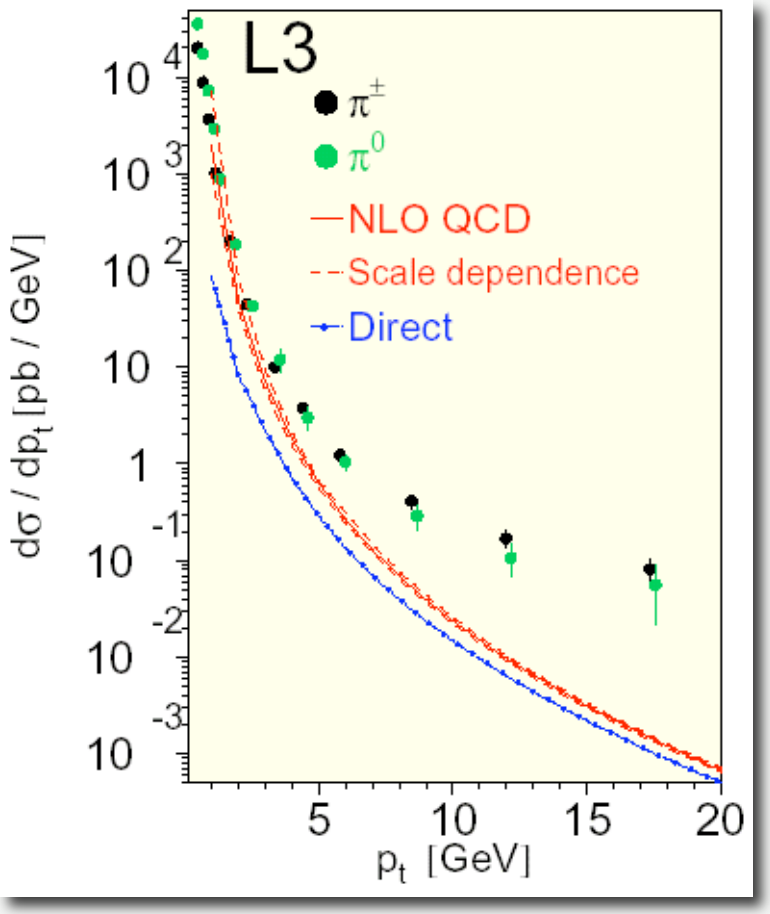
Barely consistent with previous measurements

Hadron spectra and NLO QCD

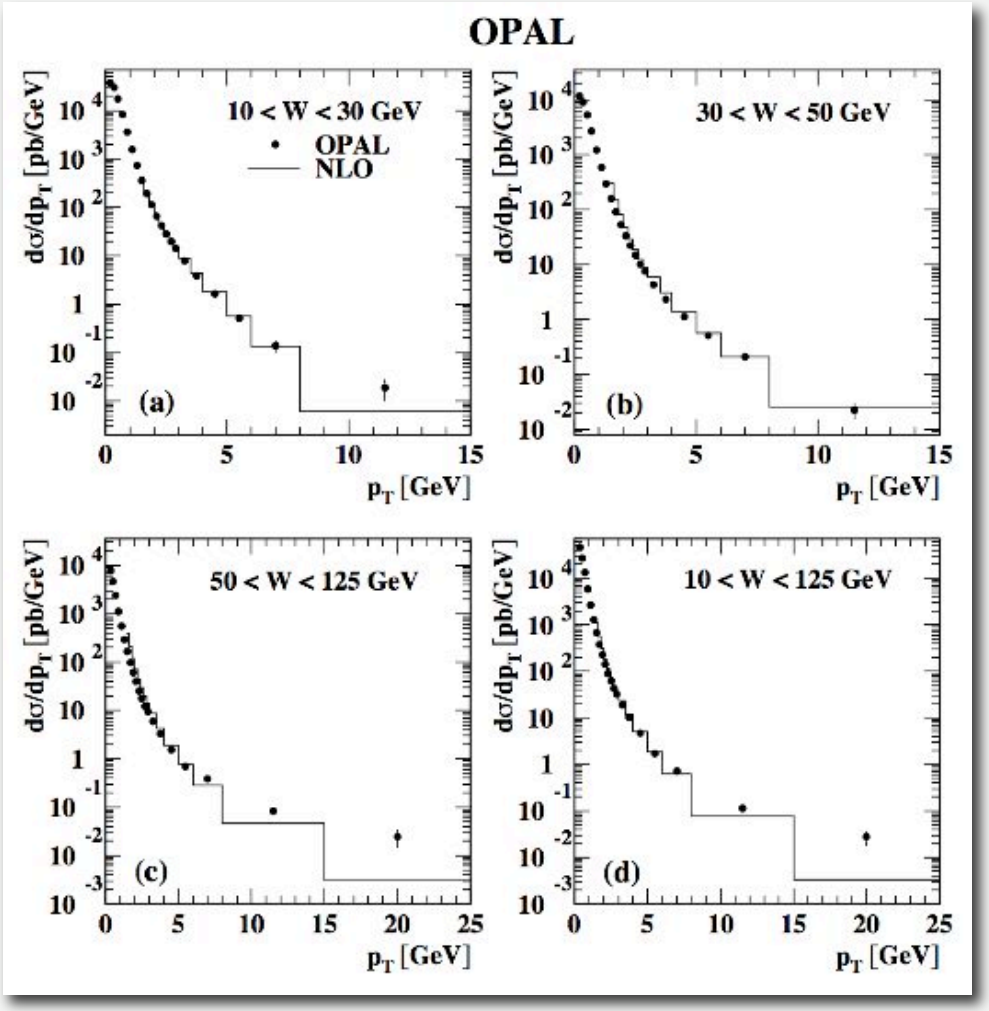
Problem with pQCD?



NLO: B. Kniehl

Problem with fragmentation functions?

OPAL: Inclusive hadron production



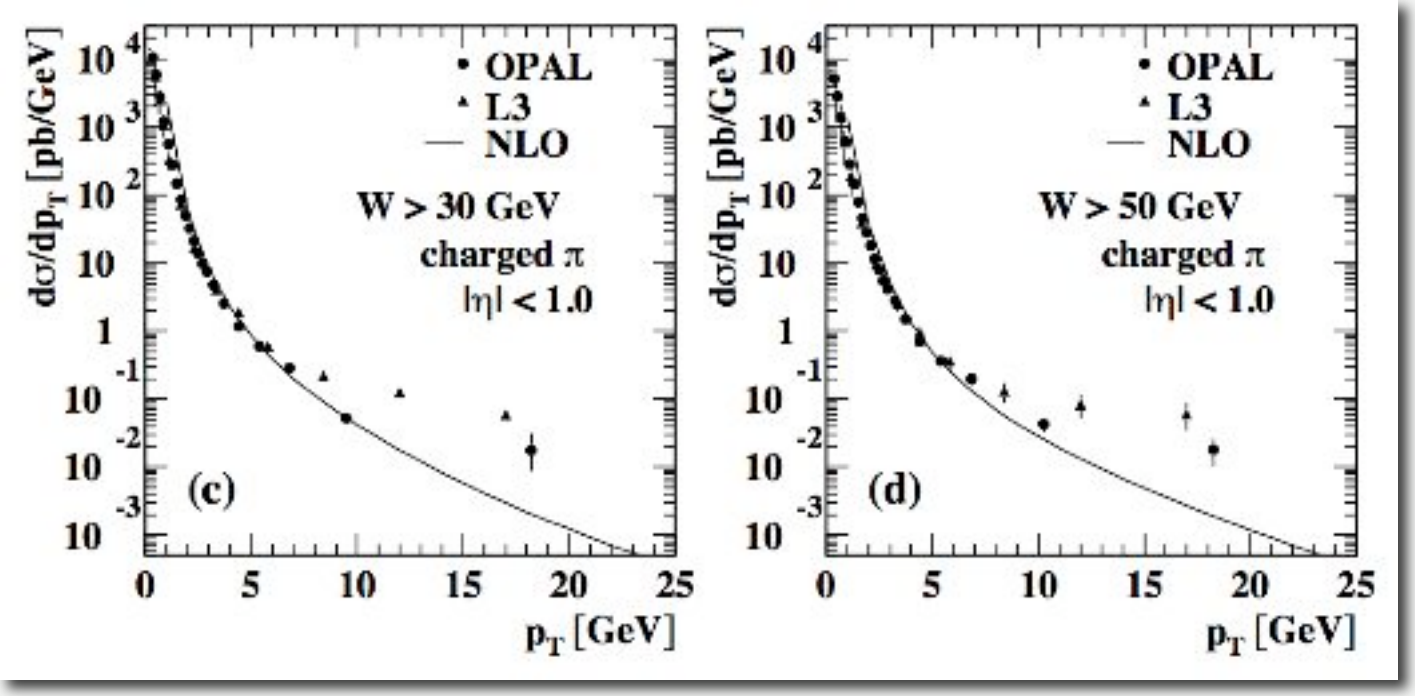
NLO: B. Kniehl

- 613 pb^{-1} at a mean e^+e^- cme of 196 GeV
- Main selection criteria
  - > 6 well measured tracks
  - Calorimeter E < 50 GeV
  - Missing momentum < 8 GeV
  - Reject events with scattered electron
- Bin-by-bin background subtraction and acceptance correction

Consistent with NLO QCD except at highest p_T

OPAL: Inclusive hadron production cont.

Comparison to L3 results

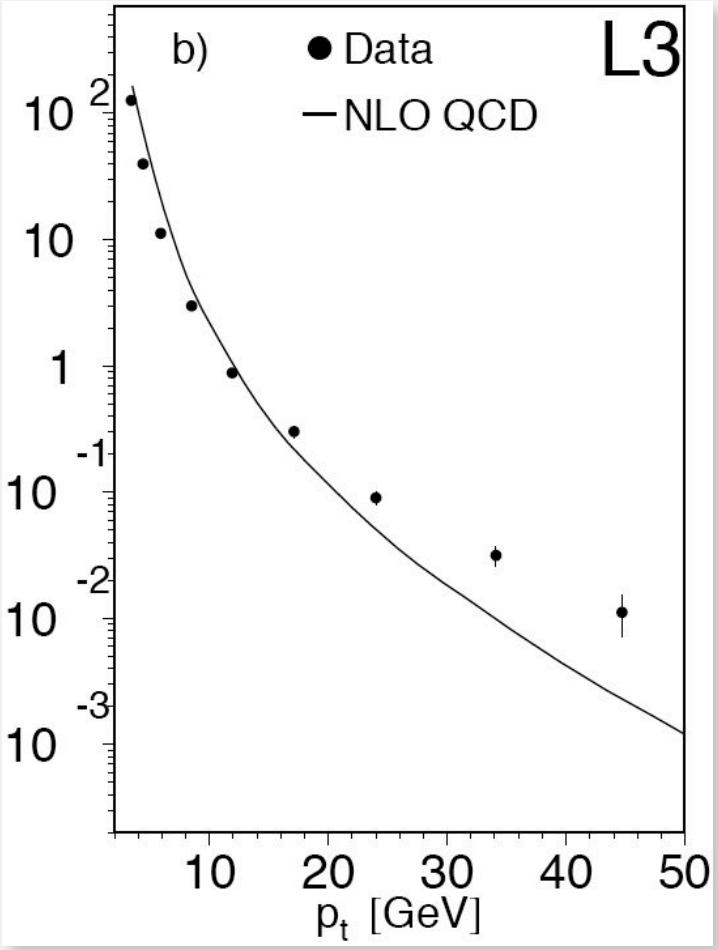


OPAL results measured for hadrons in given W range and $|\eta|<1.5$, then scaled for fraction of charged pions and reduced $|\eta|$ range

OPAL sees a steeper slope, leading to less disagreement with NLO QCD at high p_T

Single jet inclusive cross-section

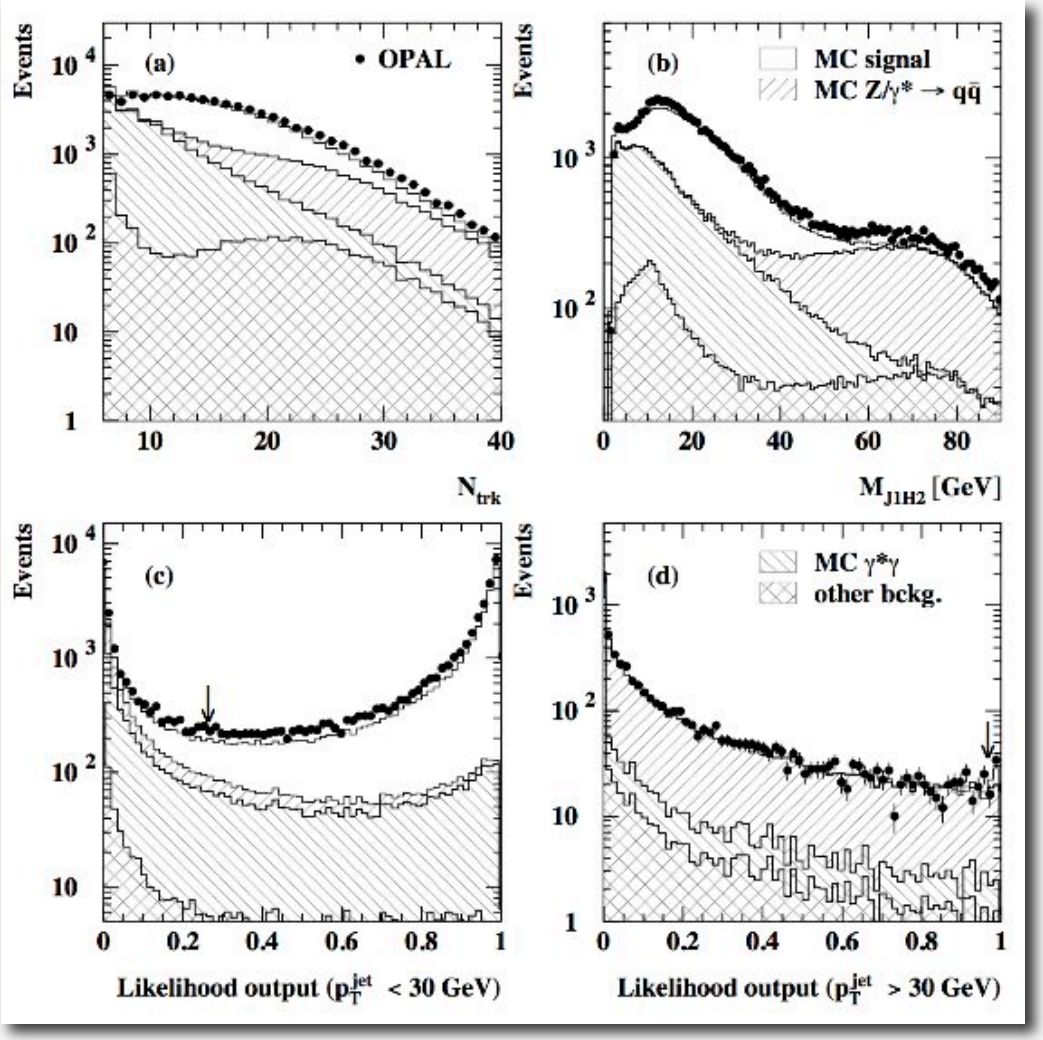
Problem with pQCD?



NLO: L. Bertora, S. Frixione

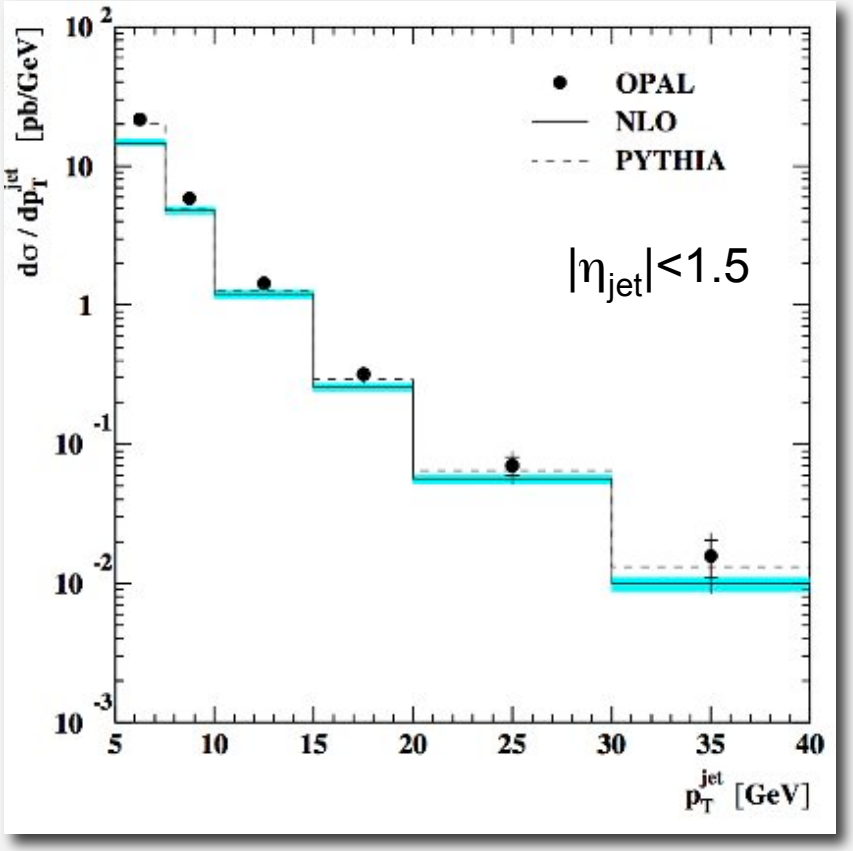
Problem with hadronisation models?

OPAL: Single jet inclusive cross-section



- 593 pb^{-1} at a mean e^+e^- cme of 198.5 GeV
- Cut-based pre-selection followed by max. likelihood build from 7 inputs
  - optimised separately for $p_{T,jet}$< 30 GeV and $p_{T,jet}$< 30 GeV due to very different BKGS situation
- Jets found using the k_T jet algorithm
- Bin-by-bin background subtraction and acceptance correction

OPAL: Single jet inclusive cross-section cont.



NLO: M. Klasen et al. (shown)
L. Bertora, S. Frixione (consistent)

Good agreement with NLO QCD

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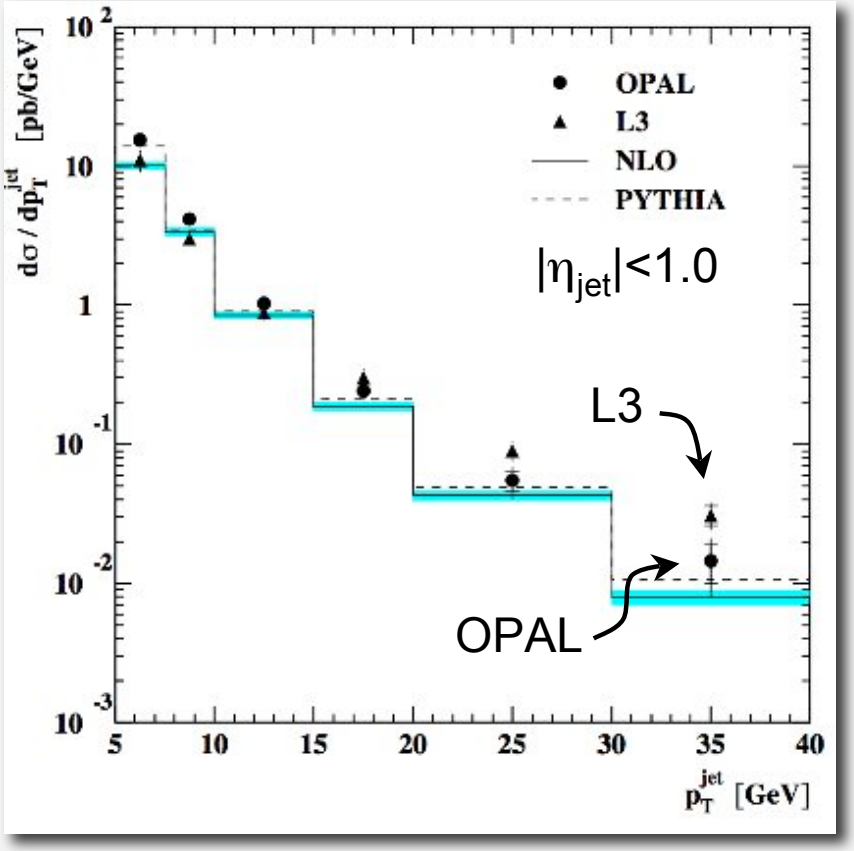
(also at low $p_{T,jet}$ when considering underlying event and hadronisation effects of about 20% below $p_{T,jet}$ = 15 GeV)

OPAL: Single jet inclusive cross-section cont.

Comparison to L3 results



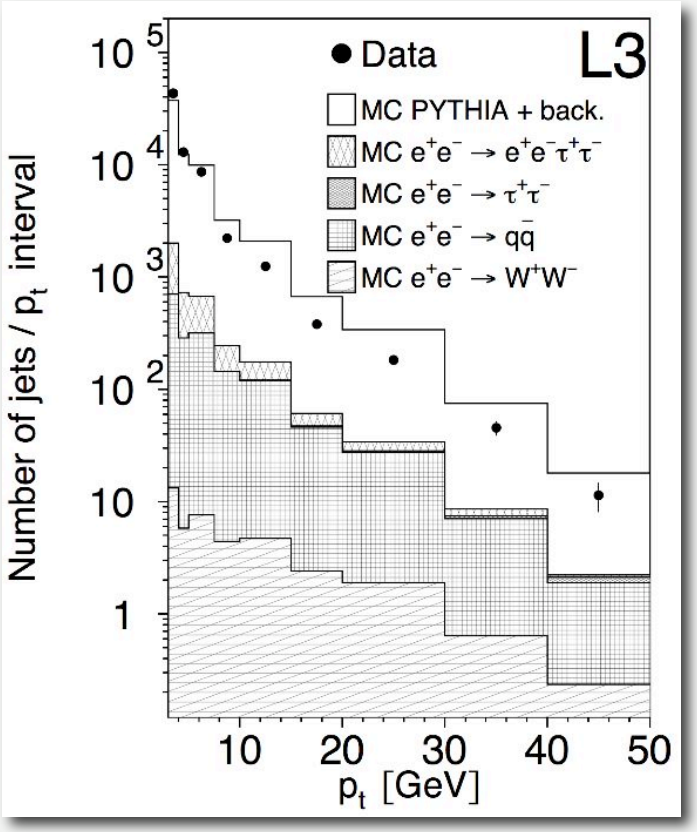
NLO: M. Klasen et al. (shown)
L. Bertora, S. Frixione (consistent)

L3 measurement has different shape

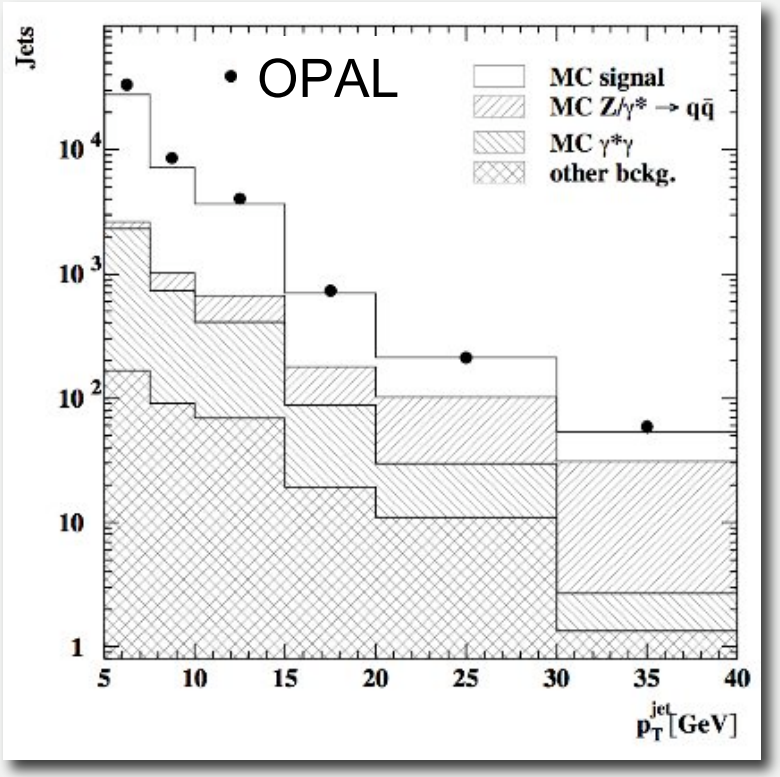
Note OPAL measurement does not extend to highest p_T measured by L3

Background

Background to inclusive jet p_T spectra



Background ~20% above $p_{T,jet}$ > 20 GeV



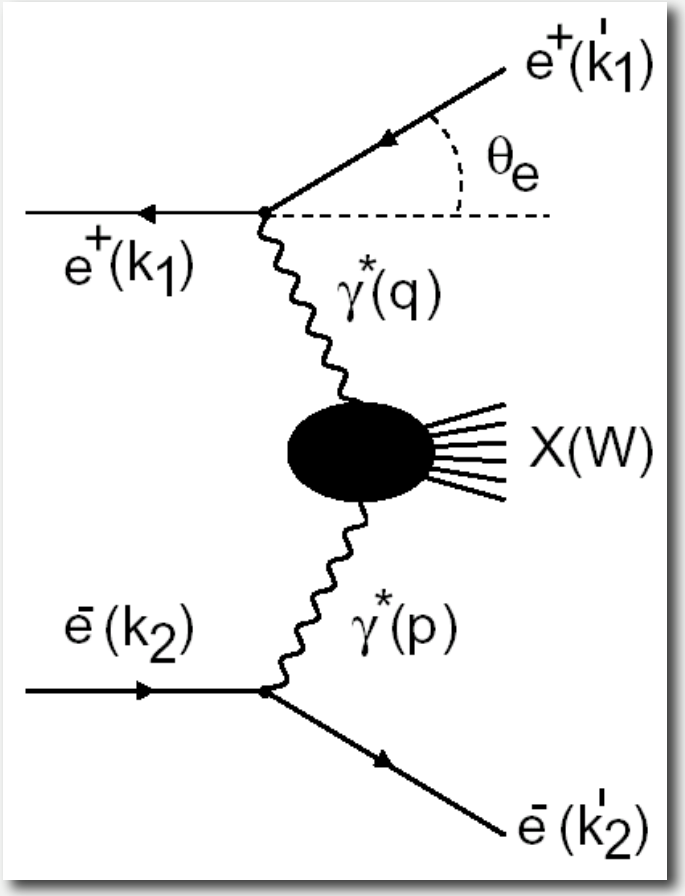
Background rising from 30% at $p_{T,jet}$ = 20 GeV to 60% at $p_{T,jet}$ = 40 GeV

Conclusions

- Three new measurements of quantities that showed problems in description by NLO QCD
- bb cross section and single jet production found to be consistent with theory in new results
- Excess still seen for highest p_T hadrons (> 15 GeV), but less severe.

Additional slides

Kinematics of photon-photon collisions



Forward Detectors — tagged ..... untagged

$$Q^2 \equiv -q^2 = -(k_1 - k_1')^2 \quad , \quad P^2 \equiv \ldots$$

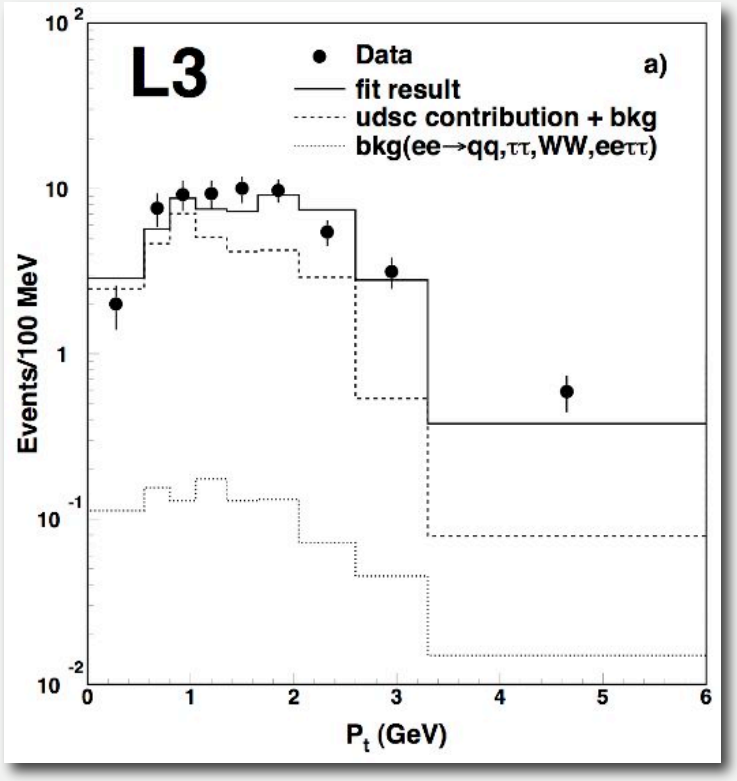
$$Q^2 \approx 2 E_b E_{tag1} (1 - \cos\theta_{e1})$$

$$W^2 = (q + p)^2$$

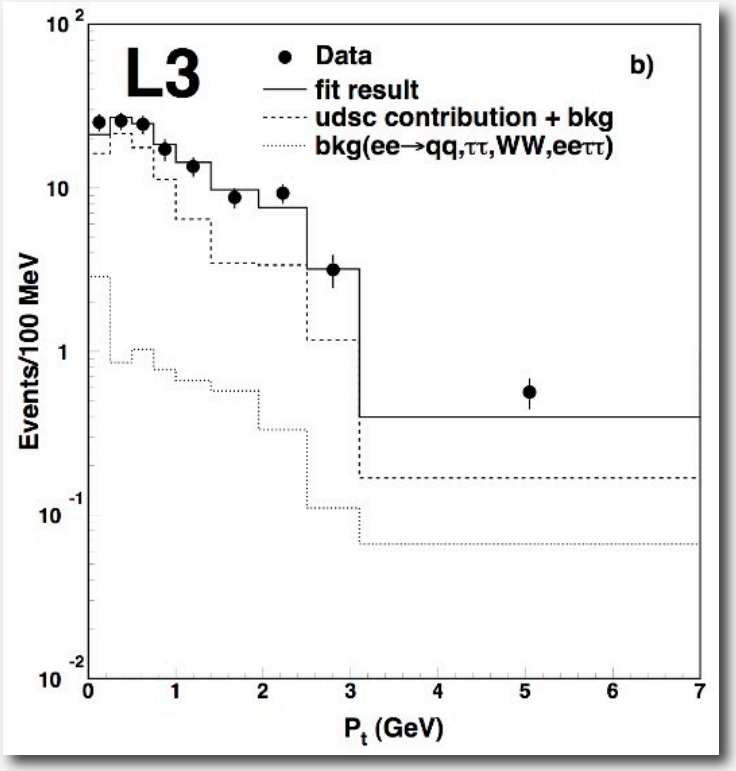
untagged ..... tagged — Forward Detectors

All results discussed are for two untagged electrons [Q^2 & $P^2 \approx 0$]

L3: $b\bar{b}$ cross section from lepton p_T



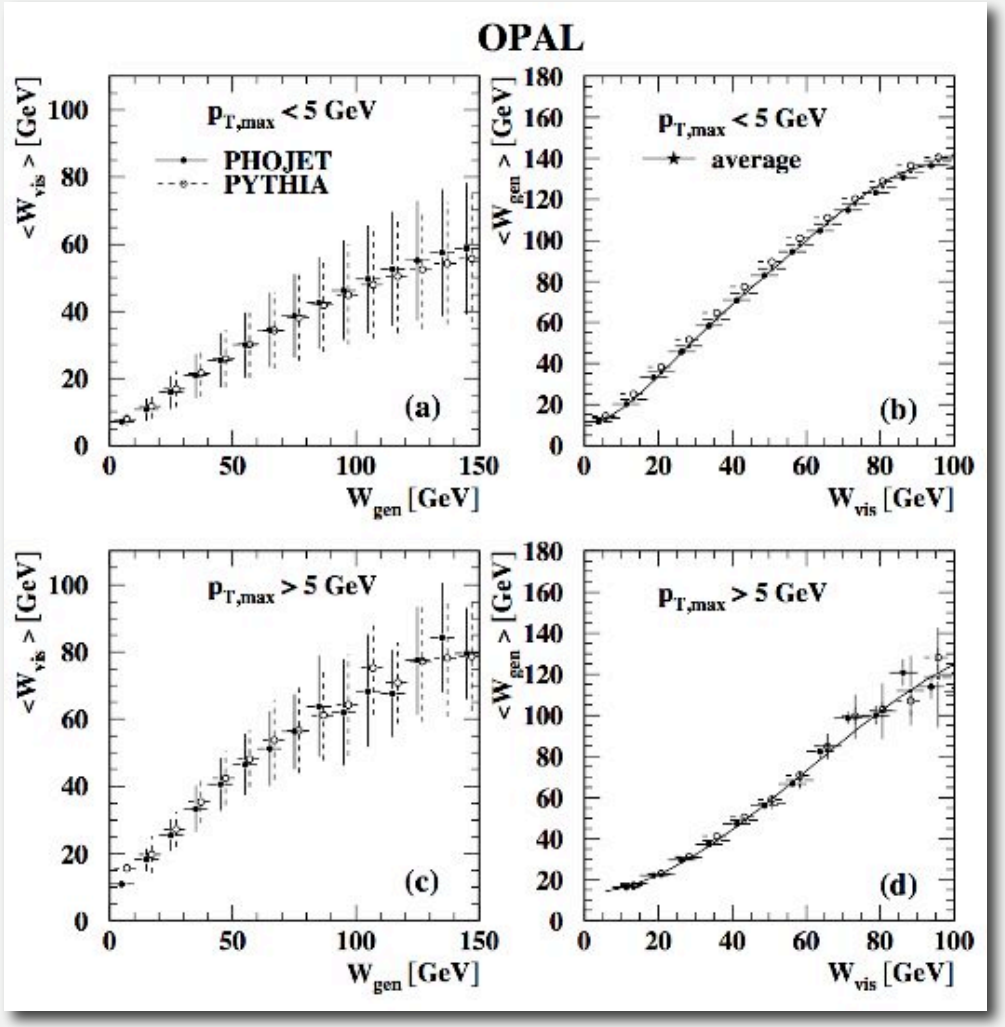
Electron candidate p_T



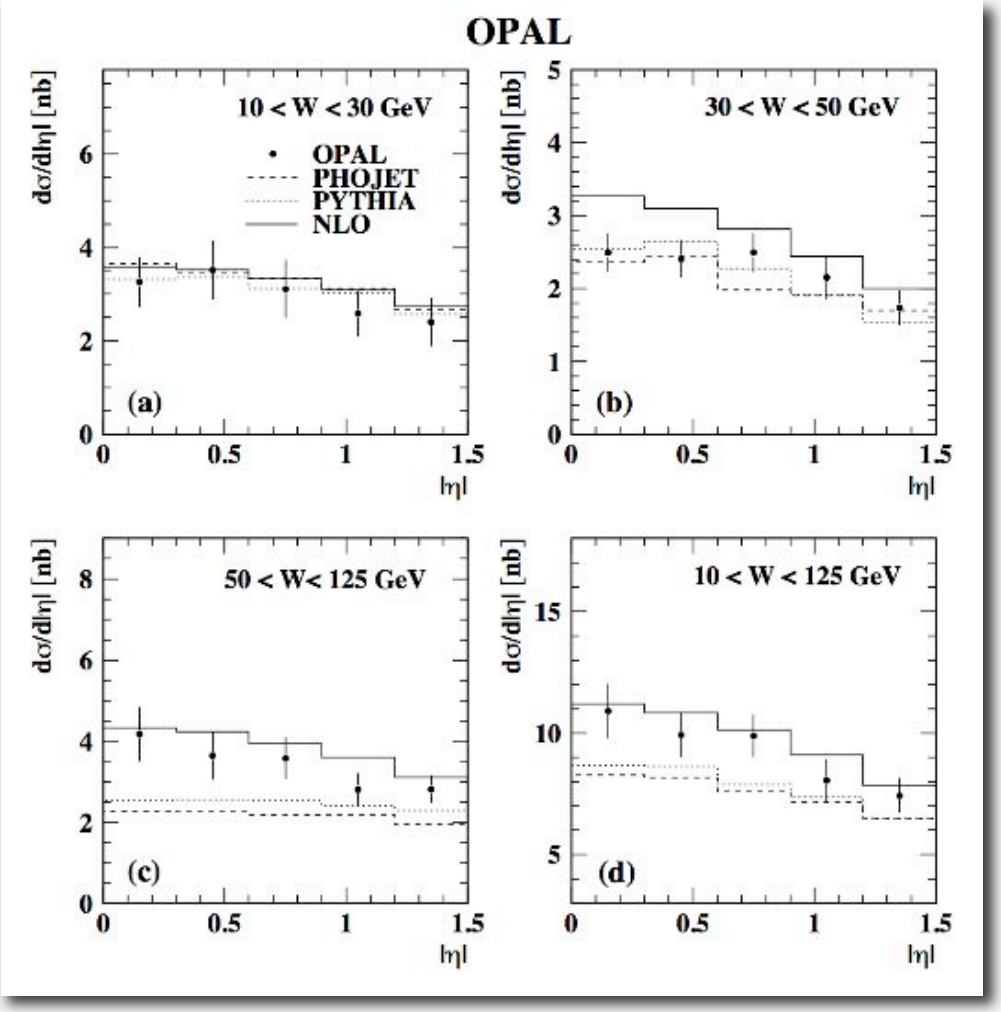
Muon candidate p_T

…relative to the closest jet

OPAL: Inclusive hadron production cont.



OPAL: Inclusive hadron production cont.



OPAL: Single jet inclusive cross-section cont

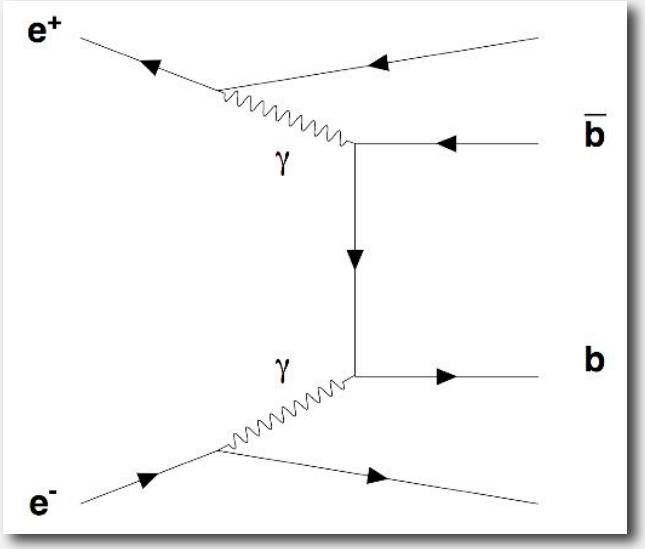
List of input variables for max. likelihood selection

The final event selection uses seven input variables for the likelihood function:

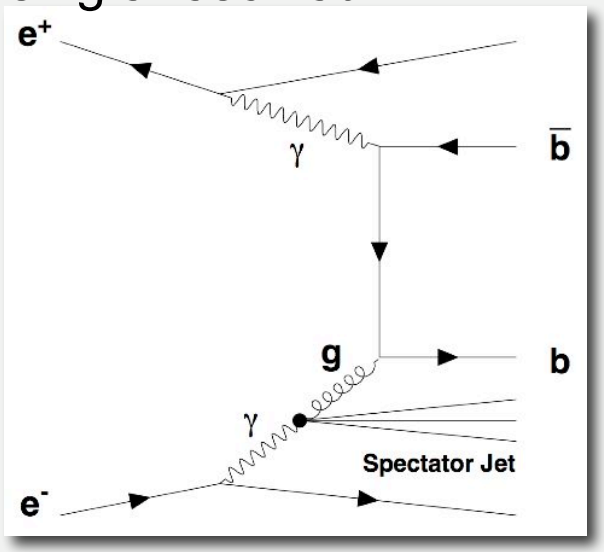
1. The visible invariant mass measured in the ECAL only, W_{ECAL} (in the range [0-80] GeV);
2. The visible invariant mass calculated from the entire hadronic final state, W_{rec} (in the range [0-120] GeV);
3. The number of tracks (in the range [6-70]);
4. The sum of all energy deposits in the ECAL (in the range [0-80] GeV);
5. The sum of all energy deposits in the HCAL (in the range [0.1-55] GeV);
6. The missing transverse momentum of the event calculated from the measured hadronic final state (in the range from zero to $\sqrt{s_{\mathrm{ee}}}/2$);
7. To improve the rejection of background coming from hadronic Z decays, an invariant mass, M_{J1H2}, is calculated from the jet with highest $p_{\mathrm{T}}^{\mathrm{jet}}$ in the event and the four-vector sum of all hadronic final state objects in the hemisphere opposite to the direction defined by this jet (considered in the range [0.1-100] GeV).

ALEPH: $b\bar{b}$ cross section cont.

direct



single resolved



Diagrams contributing to b-quark production in $\gamma\gamma$ collisions

ALEPH: $b\bar{b}$ cross section cont.

Jet finding using the PTCLUS algorithm:

The direction of partons in an event was estimated using jets found with a dedicated jet finder (PTCLUS) that optimises the reconstruction of resolved events. The PTCLUS algorithm consists of three steps.

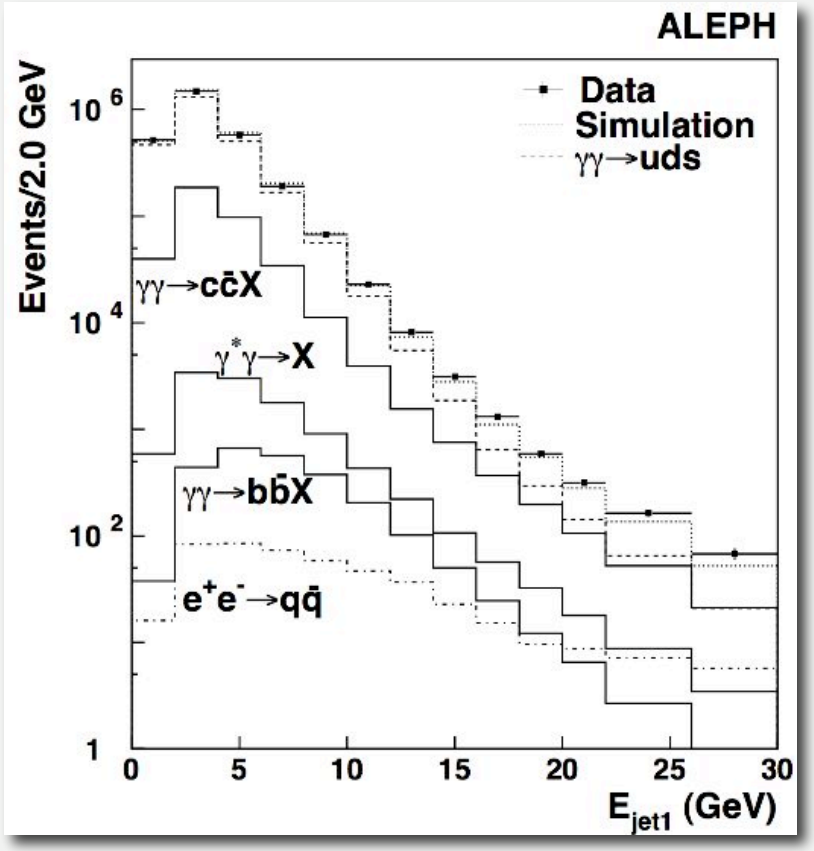
- The most energetic energy flow object is taken as the first jet initiator. The algorithm then loops through all the remaining objects in order of decreasing energy. If the angle between an object's momentum vector $\boldsymbol{p}$ and the jet momentum $\boldsymbol{p}_{\text{jet}}$ is less than 90° and the transverse momentum of the object with respect to $\boldsymbol{p}+\boldsymbol{p}_{\text{jet}}$ is smaller than 0.5 GeV/c then, the object is added to the jet. Otherwise the object is used as a new jet initiator. The procedure is repeated until all objects have been assigned to a jet.

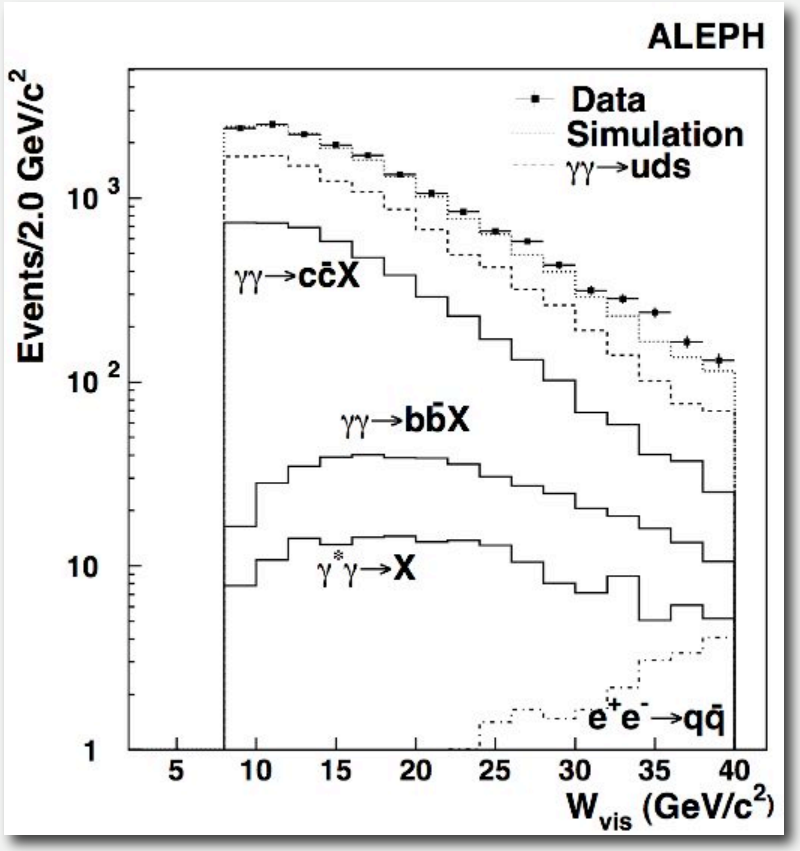
- The distance between two jets is defined as $Y = M^2/E_{\text{vis}}^2$ where M is the invariant mass of the pair of jets, assumed to be massless, and E_{vis} is the visible energy. The pair of jets with the smallest value of Y is merged provided $Y < 0.1$ and they are within 90° of each other.

- The process of merging jets may result in objects having a larger transverse momentum with respect to the jet to which they have been assigned than to another jet. If this is the case the object is reassigned to the other jet. A maximum of five reassignments may occur after each merger.

The last two steps are repeated until no pair of jets has $Y < 0.1$.

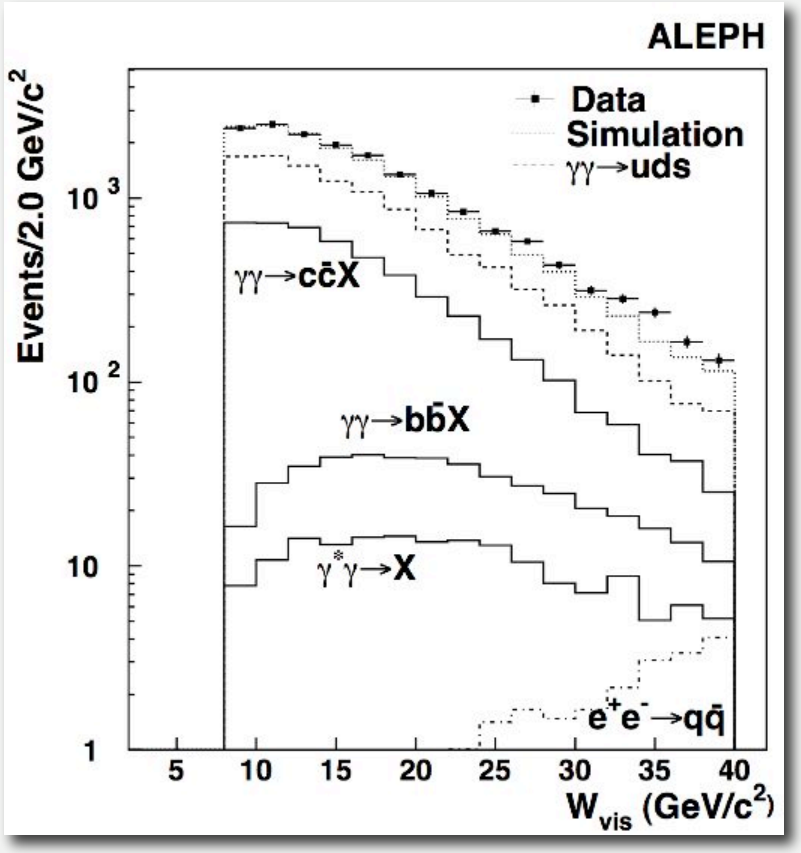
ALEPH: $b\bar{b}$ cross section cont.

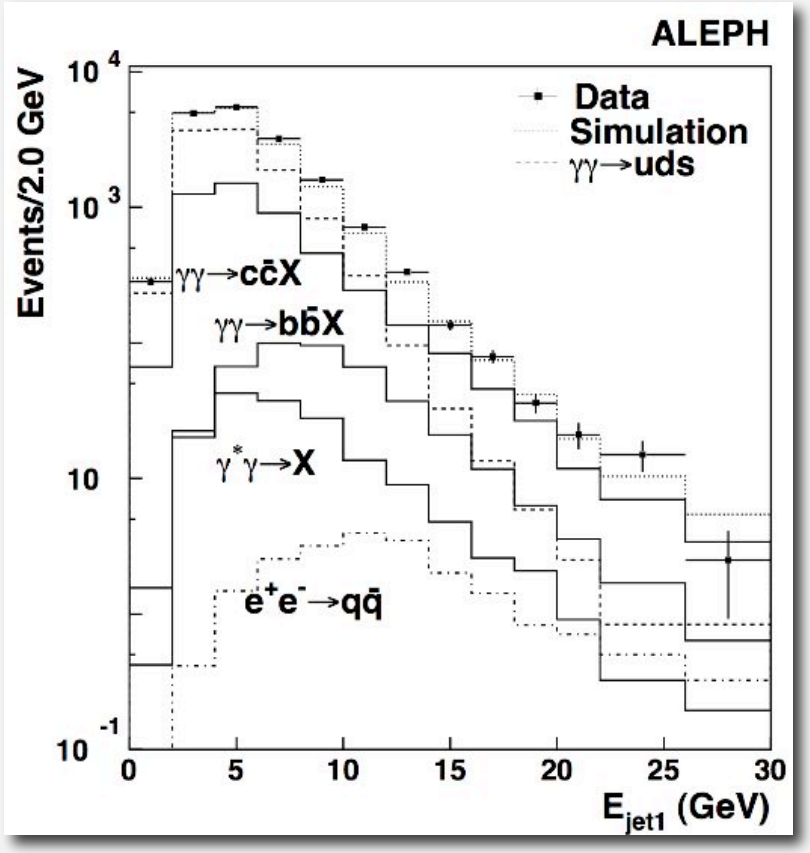




Contribution of signal / bkgs processes to data sample after pre-selection:
→ > 4 tracks, W_{vis} [4…40] GeV, E_{fwd} < 30 GeV, $E_{T,miss}$ < 6 GeV, T< 0.97

ALEPH: $b\bar{b}$ cross section cont.



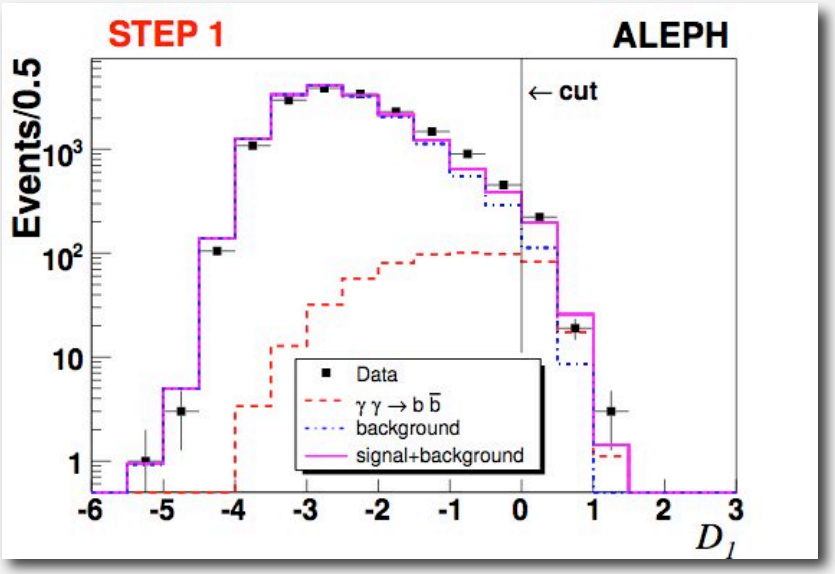


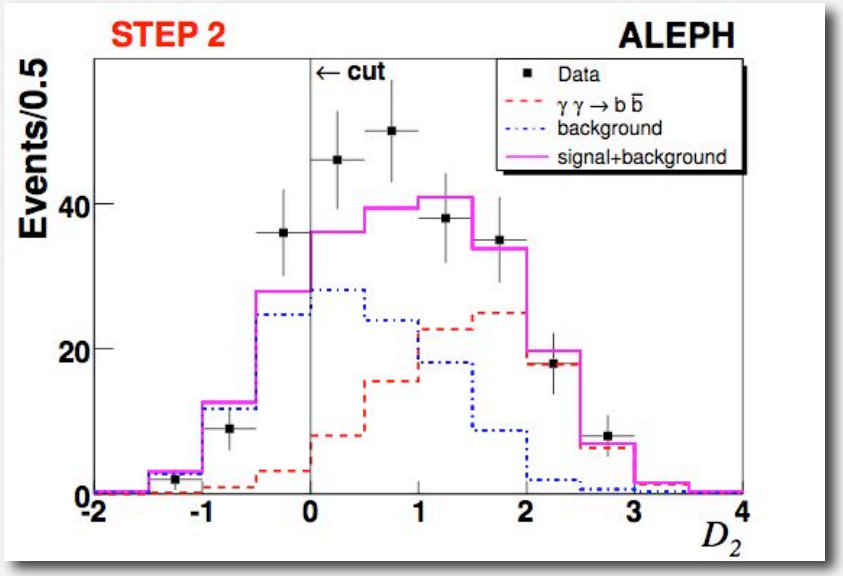
Signal / bkgs processes after b-enhancement selection:

→ > 7 tracks, W_{vis} [8…40] GeV, $N_{jet} > 1$, $P_{event} < 0.05$

→ 3rd (4th) largest *S* greater than 0.0 (-10.0)

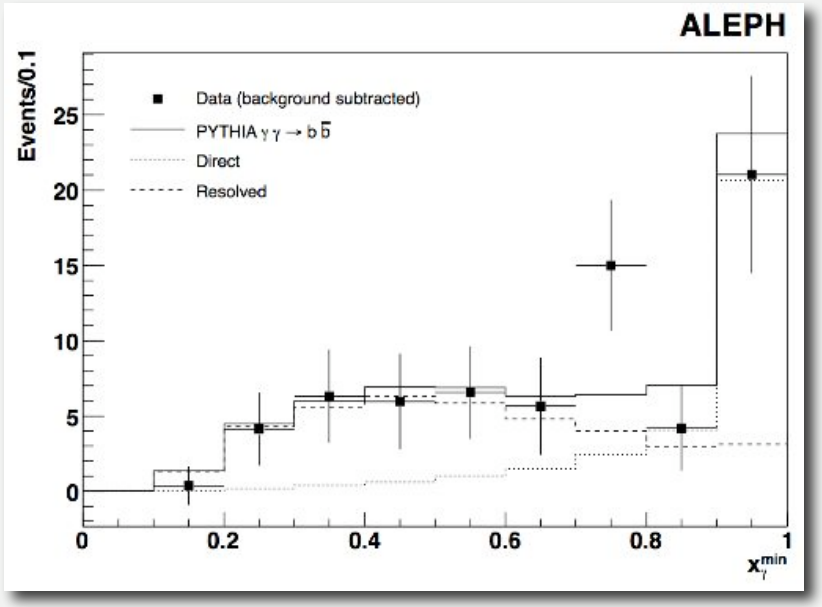
ALEPH: $b\bar{b}$ cross section cont.



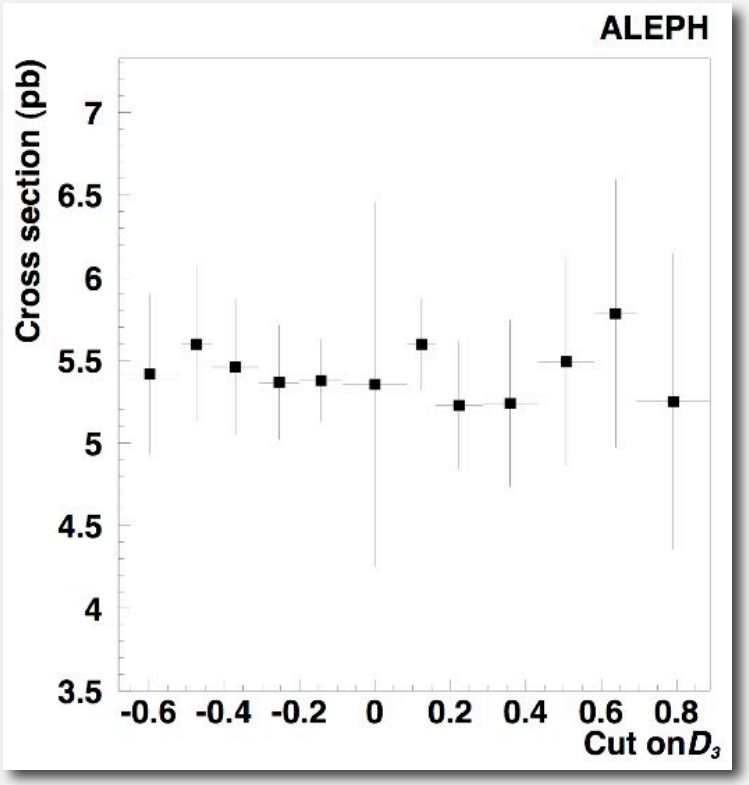


Iterative Discriminant Analysis
Steps 1 and 2

ALEPH: $b\bar{b}$ cross section cont.

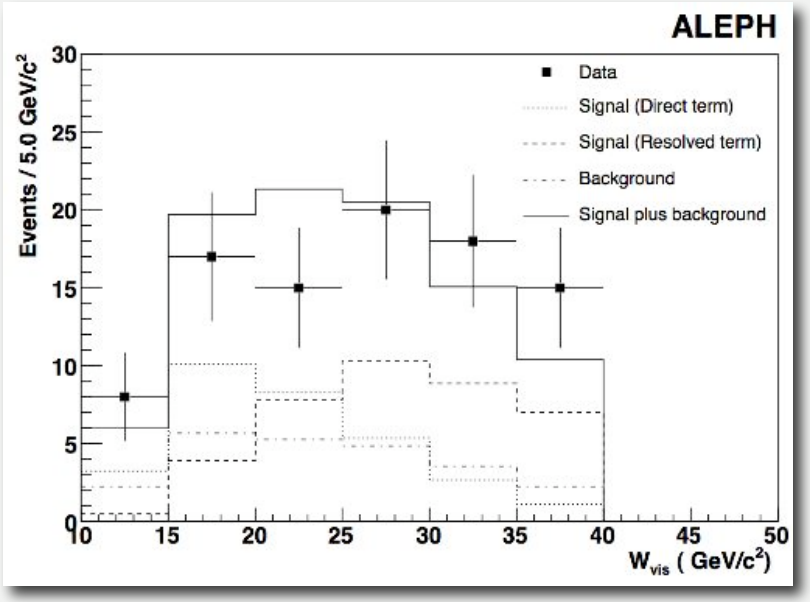


Fitting the direct and single resolved contributions on the $x_{\gamma,min}$ distribution



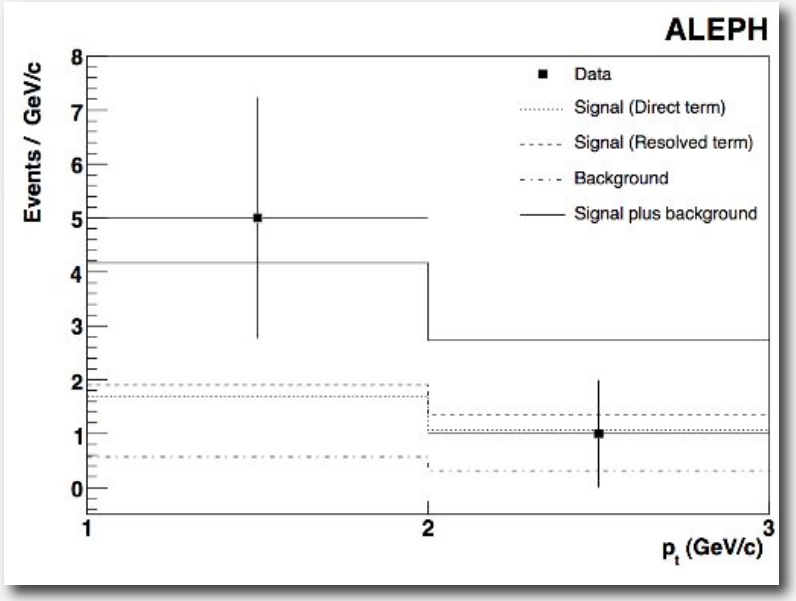
Systematic study on the stability of the result on the choice of the cut on D_3

ALEPH: $b\bar{b}$ cross section cont.



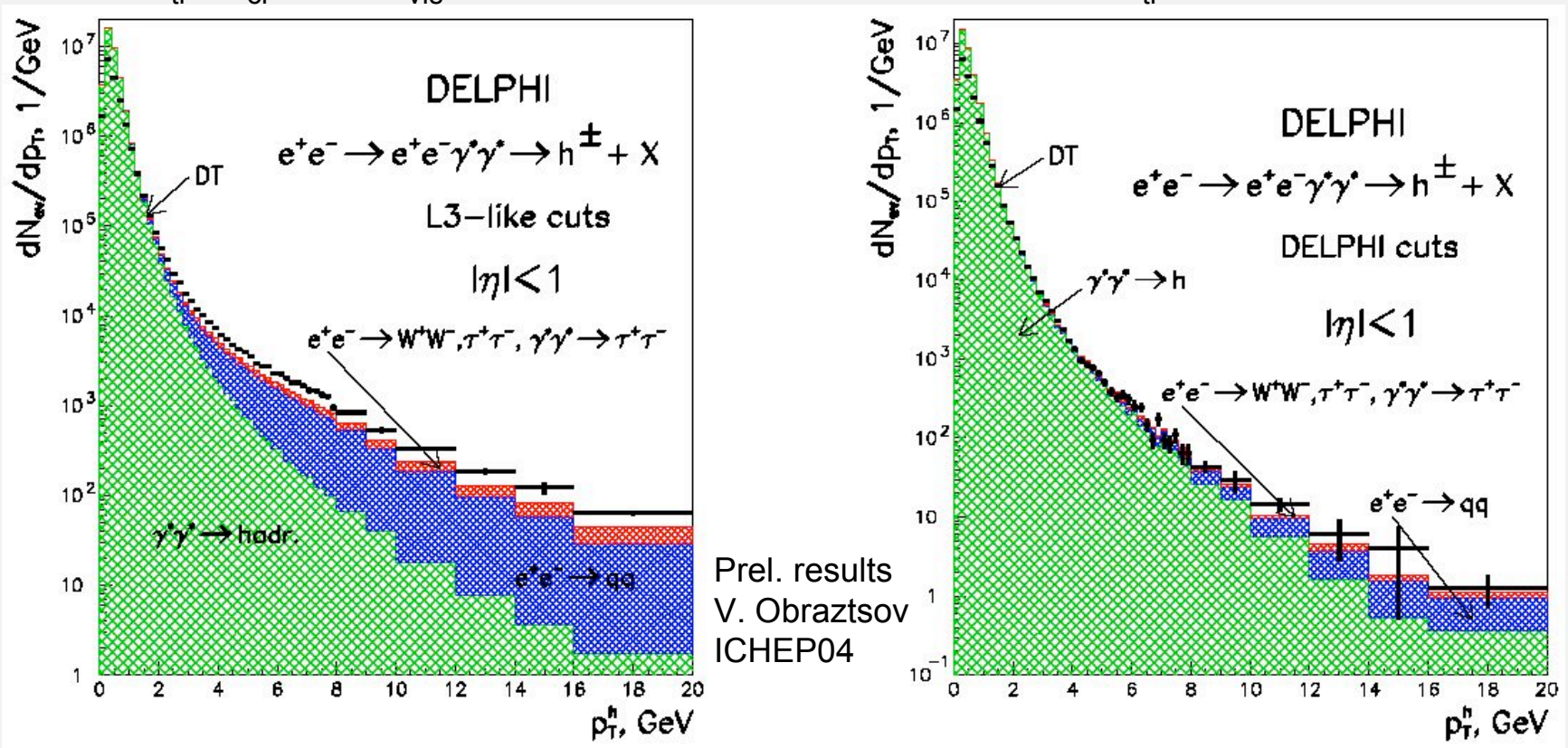
W_{vis} Distribution of selected events

Transverse energy w.r.t. to nearest jet of e,μ in selected events



Hadron transverse momentum spectra : DELPHI

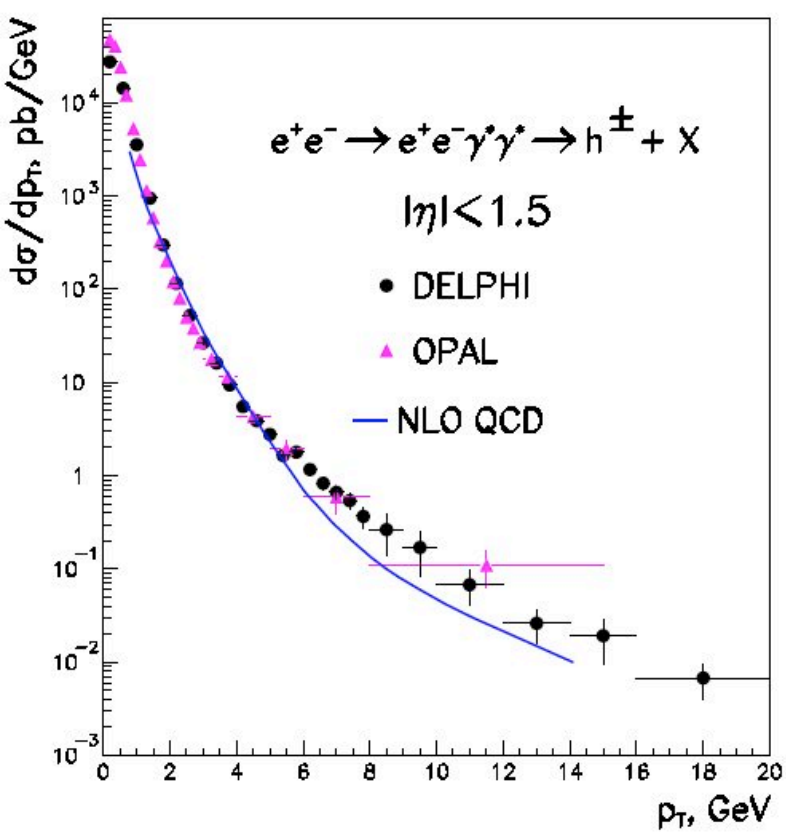
- E-cut: $E_{cal} < 0.4 \sqrt{s}$ (~78 GeV)
- $N_{tr}+N_{cl} > 6$, $W_{vis} > 5$ GeV
- 5 GeV < W_{vis} < 35 GeV
- 5 < N_{tr} < 30

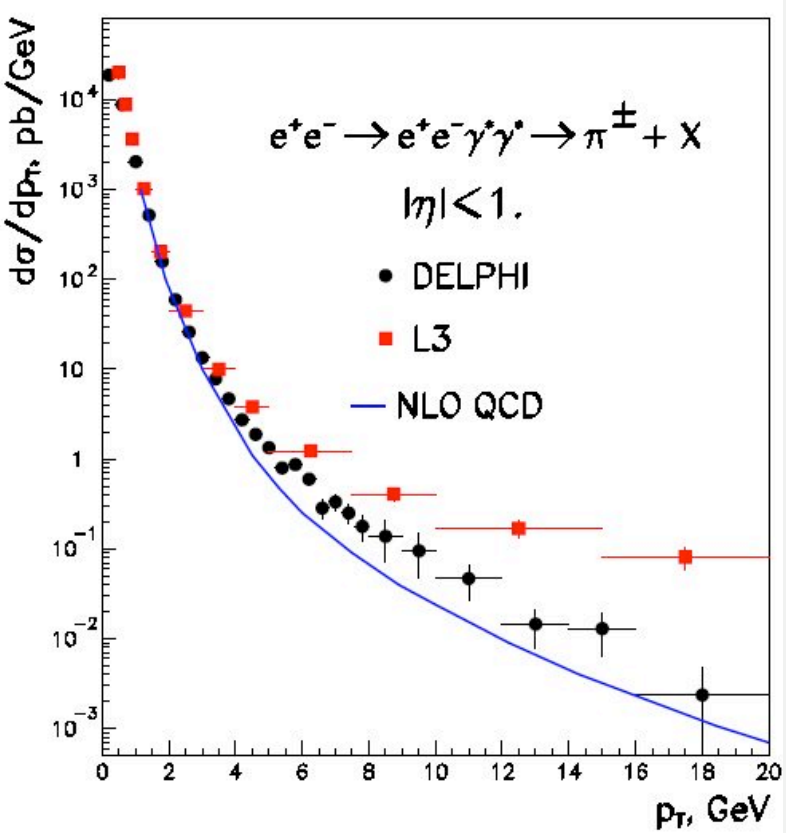


Prel. results
V. Obraztsov
ICHEP04

For L3 cuts DELPHI finds high p_T region dominated by Z→qq BKGS (this is not the case in the L3 analysis)

Hadron transverse momentum spectra : DELPHI





Preliminary results
V.Obraztsov
ICHEP04

DELPHI finds only a slight access w.r.t. NLO QCD