Heavy quark production in $\gamma\gamma$ collisions

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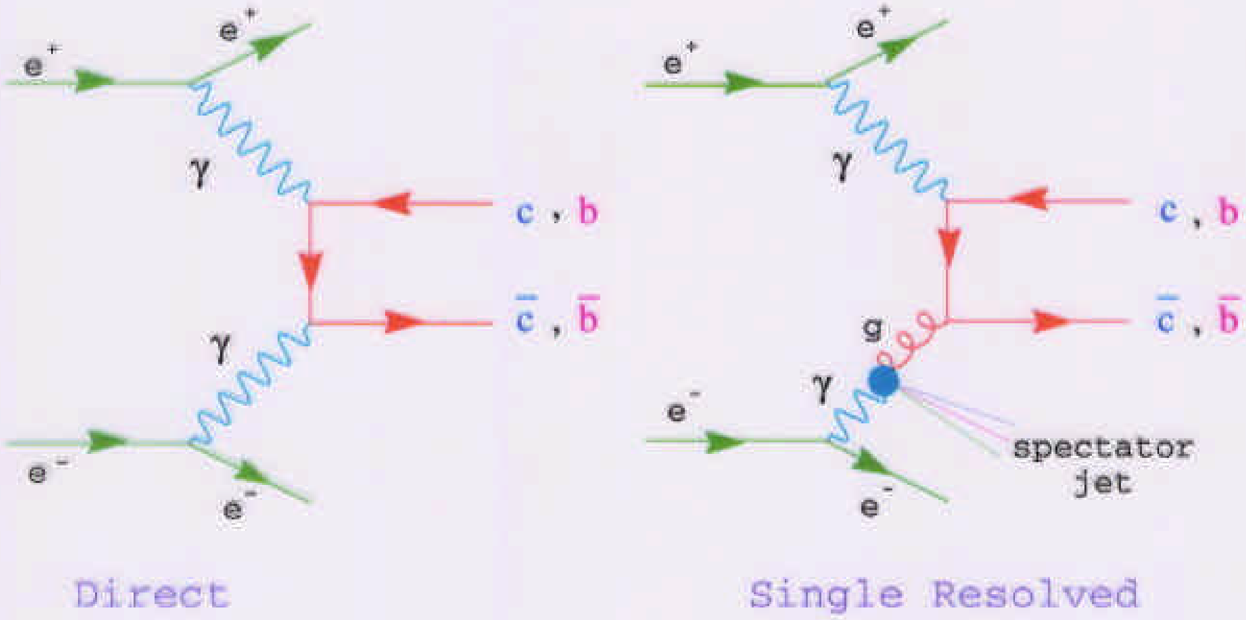
XXXth International Conference on
High Energy Physics
July 27 - August 2, Osaka, Japan

Motivation



Test of perturbative QCD:

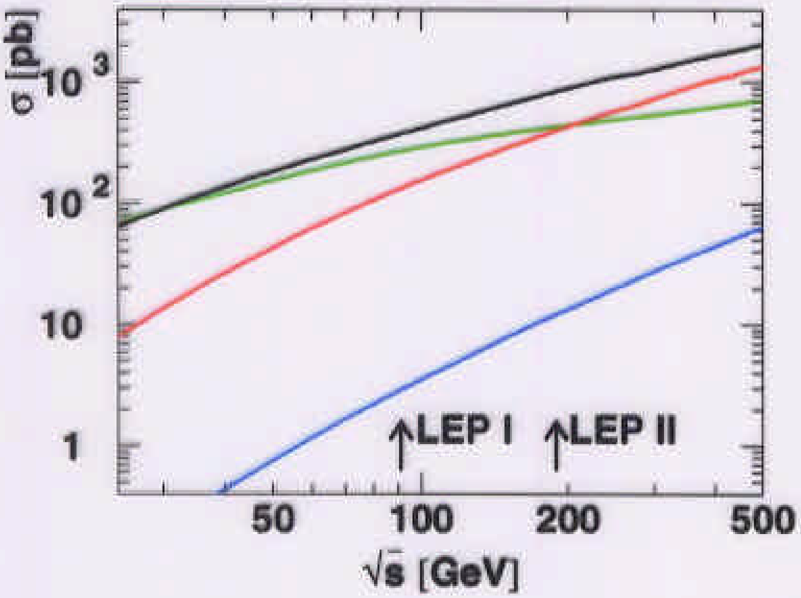
LEP II energies:

VMD : direct : resolved $\approx$ 0 : 1 : 1

- direct process depends on quark mass (m_c, m_b) and α_s
- resolved process depends on gluon content of photon
- heavy quark production primarily charm $\sigma(\gamma\gamma \rightarrow c\bar{c}X) >> \sigma(\gamma\gamma \rightarrow b\bar{b}X)$

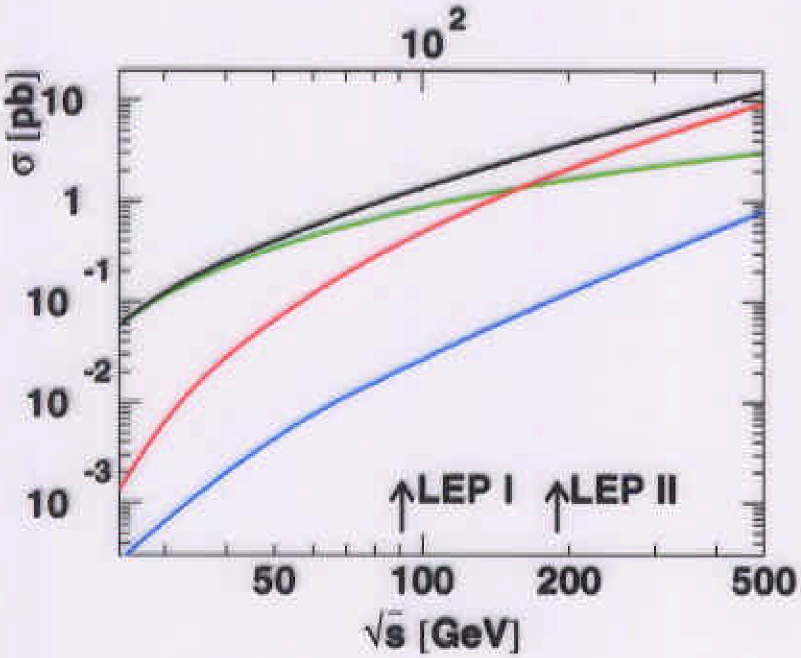
Total Cross Sections
Theoretical Prediction
(Drees, Krämer, Zunft, Zerwas)

$\sigma(e^+e^- \rightarrow e^+e^-c\bar{c})$



- direct
- single resolved
- double resolved

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



- direct
- single resolved
- double resolved

Identification of Heavy Flavour

Charm identification:

ALEPH	$D^{*\pm}$	$\mu^{\pm}$	
DELPHI	$D^{*\pm}$		$D^{\pm}$, D^{0}, Λ_c
L3	$D^{*\pm}$	$e^{\pm}$, $\mu^{\pm}$	
OPAL	$D^{*\pm}$		

Bottom identification:

L3 $e^{\pm}$, $\mu^{\pm}$

Data analysed:

ALEPH	$\mu^{\pm}$	183 GeV	53 pb^{-1}
	$D^{*\pm}$	183 - 189 GeV	236 pb^{-1}
DELPHI	$D^{*\pm},\ldots,\Lambda_c$	161 - 204 GeV	458 pb^{-1}
L3	$D^{*\pm}$	189 GeV	176 pb^{-1}
	$e^{\pm}$	189 - 202 GeV	410 pb^{-1}
	$e^{\pm}$, $\mu^{\pm}$	189 - 202 GeV	410 pb^{-1}
OPAL	$D^{*\pm}$	183 - 189 GeV	220 pb^{-1}

In total 8 contributions !!!

(# 109, 110, 268, 270, 582, 584, 586, 756)

Measurements / Observables

Charm:

- $\sigma(e^+e^- \to e^+e^- c\bar{c}X)$
  ALEPH, DELPHI, L3, OPAL
- $d\sigma/dp_T^{D*}$, $d\sigma/d\eta^{D*}$
  ALEPH, L3, OPAL
- fraction of direct and resolved contribution
  ALEPH, OPAL
- $\sigma(\gamma\gamma \to c\bar{c}X)$ vs. $W_{\gamma\gamma}$
  L3
- $F^2_{\gamma,c}$
  OPAL

Bottom:

- $\sigma(e^+e^- \to e^+e^- b\bar{b}X)$
  L3

$D^{*\pm}$: Goldplated Method

Identify charm events with decay:
$D^{*\pm} \rightarrow D^0 \pi_s^+$

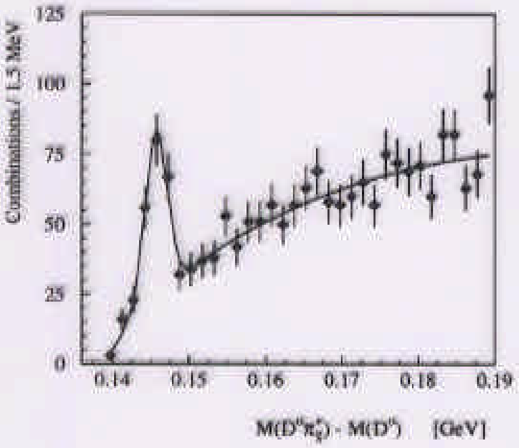
$\Delta m = m(D^{*\pm}) - m(D^0) = 145\,\text{MeV}$
$\Rightarrow$ 6 MeV kinetic energy only
$\Rightarrow$ clear signature

All 4 LEP experiments use it:

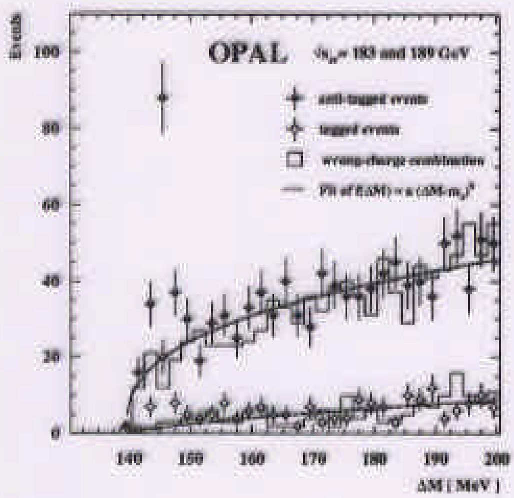
$D^0 \rightarrow K^- \pi^+$	ADLO
$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	ADO
$D^0 \rightarrow K^- \pi^+ \pi^0$	AL
$D^0 \rightarrow K_s \pi^+ \pi^-$	D

3 experiments give differential distributions
2 experiments quantify fraction of direct/resolved contributions

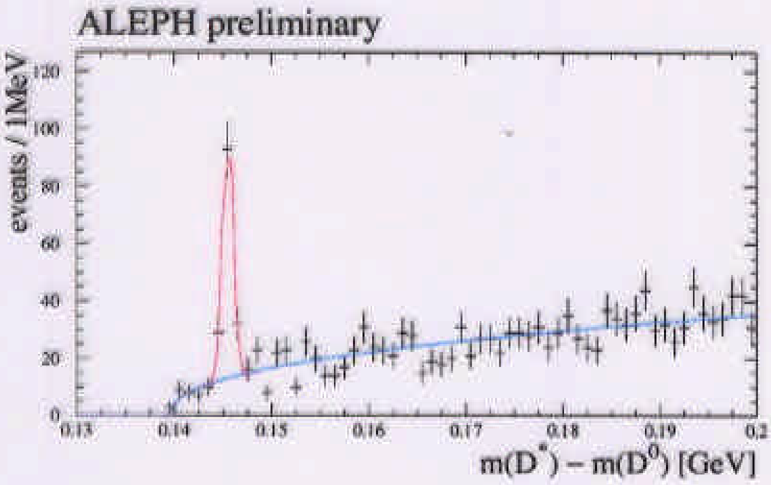
$D^{*\pm}$, signals



L3: 144 events

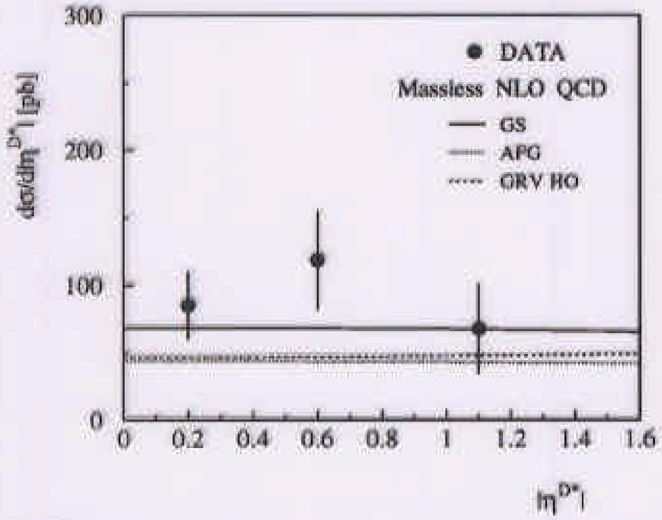


OPAL: 100 events



ALEPH: 113 events

$D^{*\pm}$, pseudorapidity

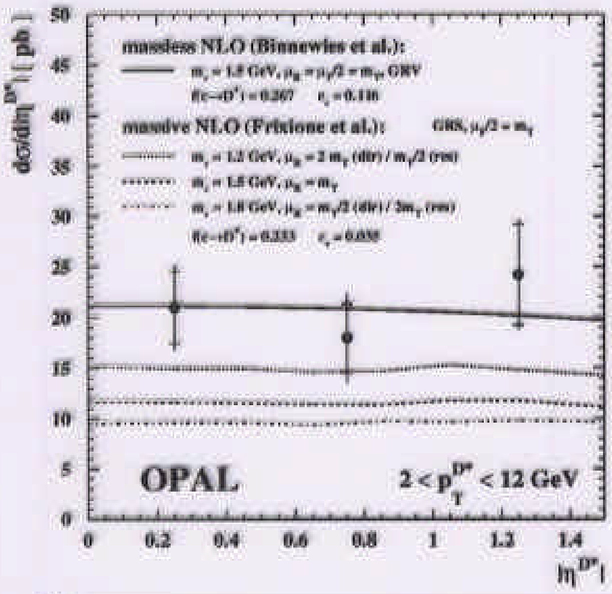


L3:

1 GeV $< p_t(D^{*\pm}) <$ 5 GeV

$|\eta| < 1.4$

reasonable agreement with NLO QCD (massless)

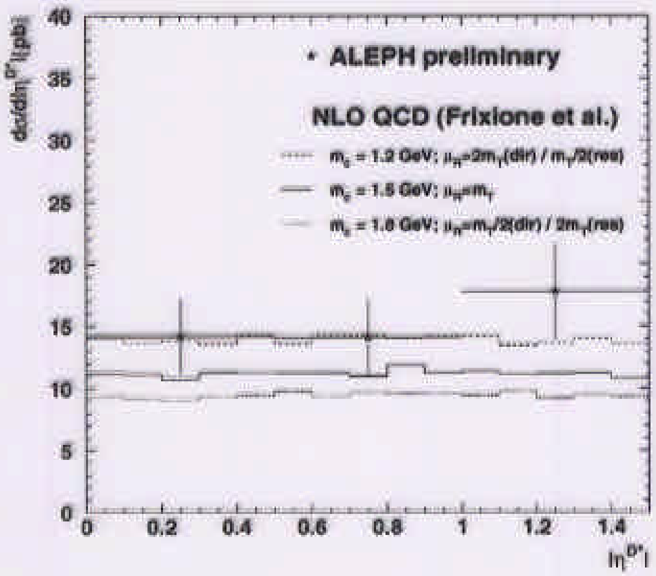


OPAL:

2 GeV $< p_t(D^{*\pm}) <$ 12 GeV

$|\eta| < 1.5$

good agreement with NLO QCD (massless)



ALEPH

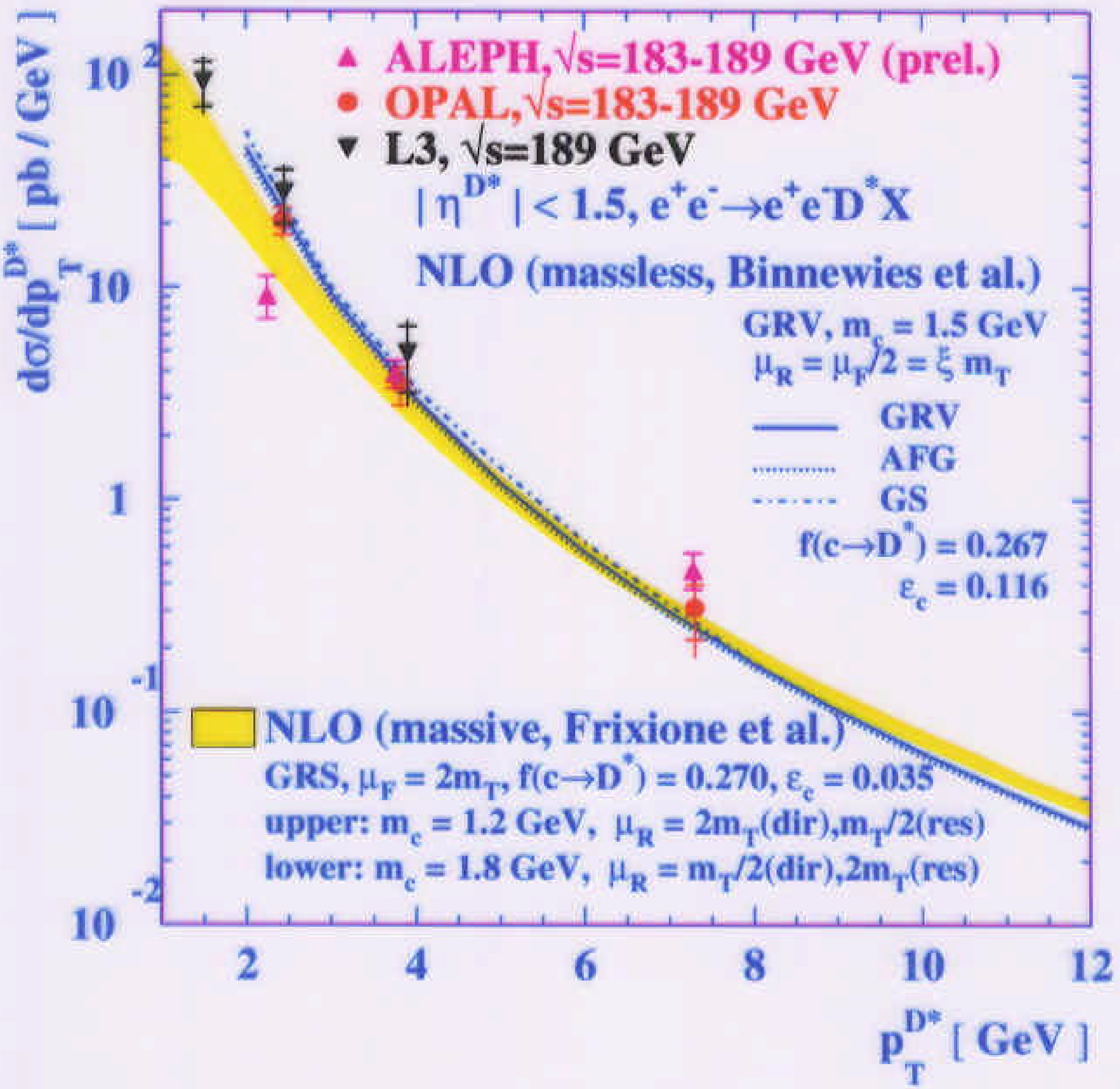
2 GeV $< p_t(D^{*\pm}) <$ 12 GeV

$|\eta| < 1.5$

good agreement with NLO QCD (massive)

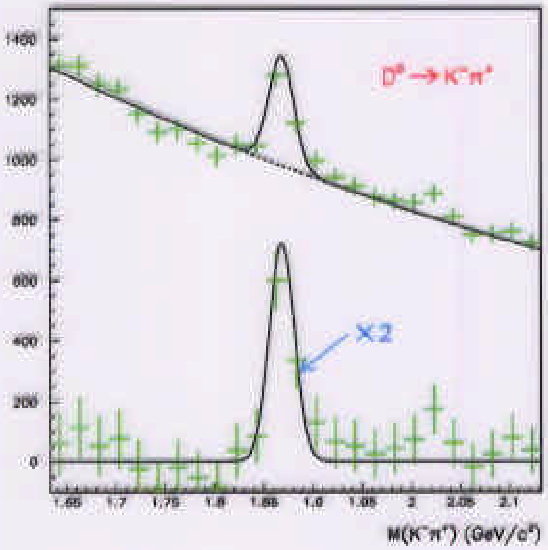
$D^{*\pm}$, $d\sigma/dp_t^{D*}$

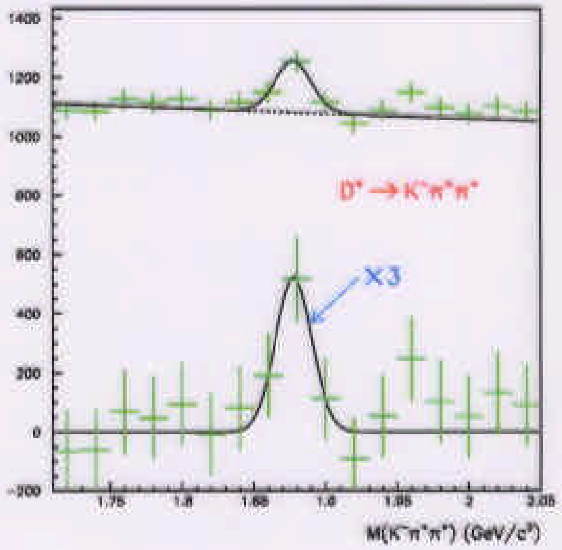
Differential distribution $d\sigma/dp_t^{D*}$ by ALEPH, OPAL, L3:

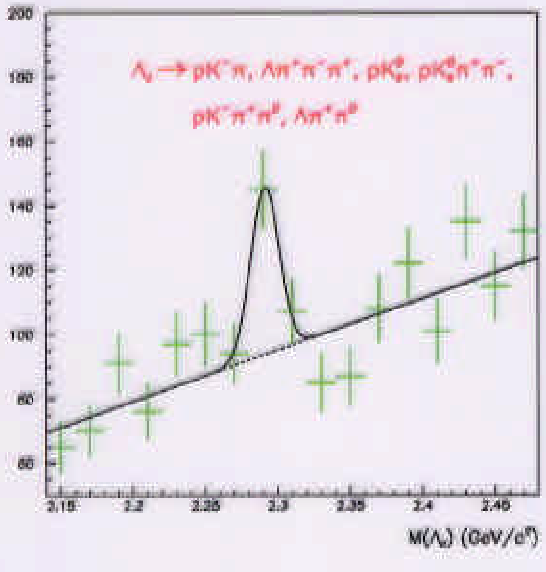


$(D^{*\pm})$, $D^{\pm}$, D^0, Λ_c: DELPHI

D^0: 498 ± 74 events
D^+: 277 ± 66 events
Λ_c: 62 ± 26 events







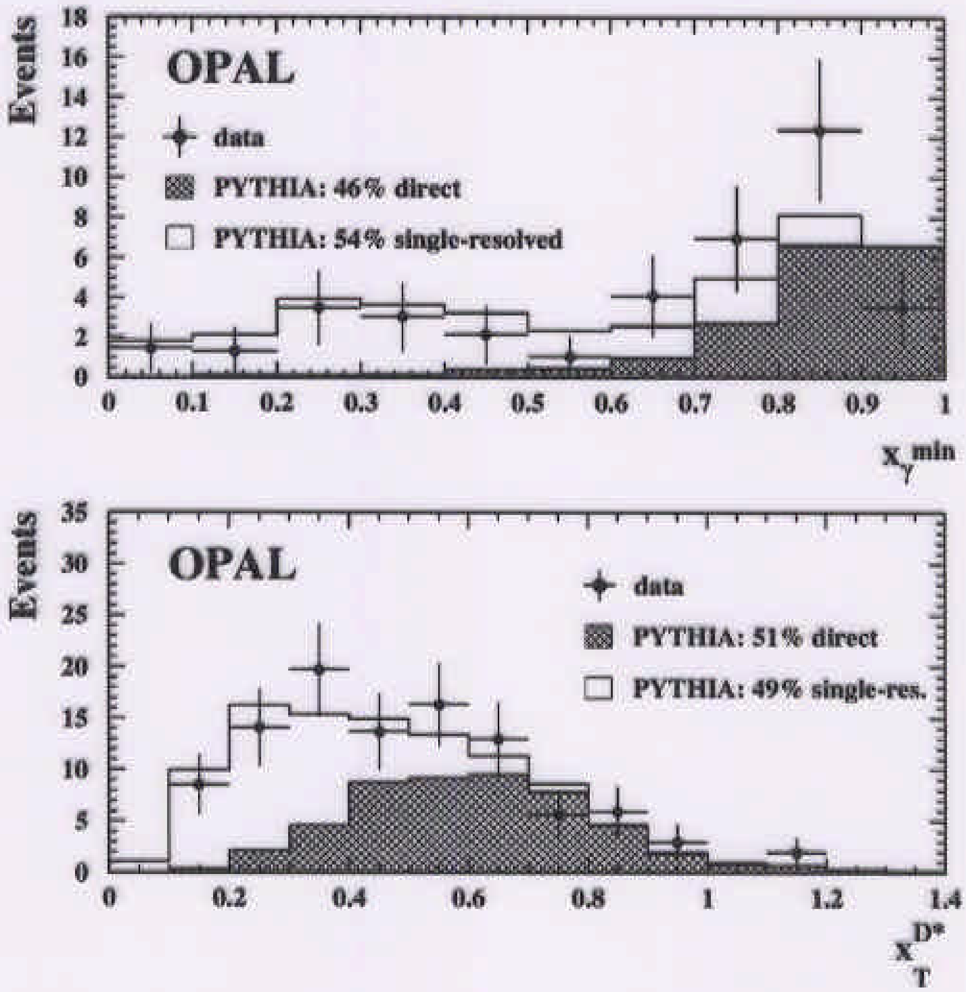
Within errors:
$\sigma_{D0}^{\text{direct}} \approx \sigma_{D+}^{\text{direct}}$
$\sigma_{D*+}/\sigma_{D+}^{\text{direct}} = 2.1^{+2.4}_{-0.9}$
(2J+1) relation:
$\sigma_{D*+} = 3\sigma_{D0} = 3\sigma_{D+}$

Cross sections agree with theory (large errors);
$D^{*\pm}$ sample (155 events) used for $\sigma(e^+e^- \to c\bar{c}X)$
direct and single resolved contributions needed

Direct and Resolved Contribution: OPAL

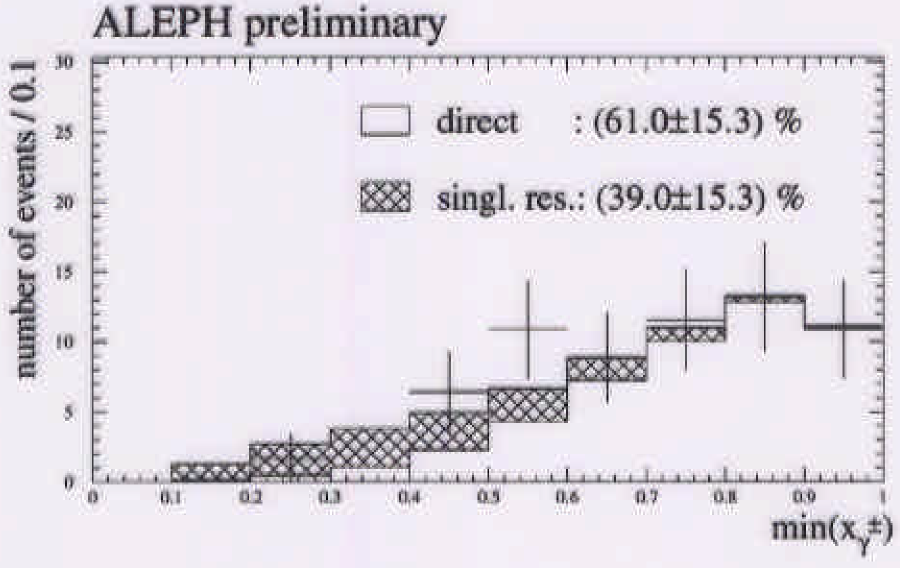
$$x_\gamma^{\mathrm{min}} = \mathrm{min}\,(x_\gamma^{\pm}); \quad x_\gamma^{\pm} = \frac{\sum_{\mathrm{jets}}(E \pm p_z)}{\sum_{\mathrm{particles}}(E \pm p_z)}$$

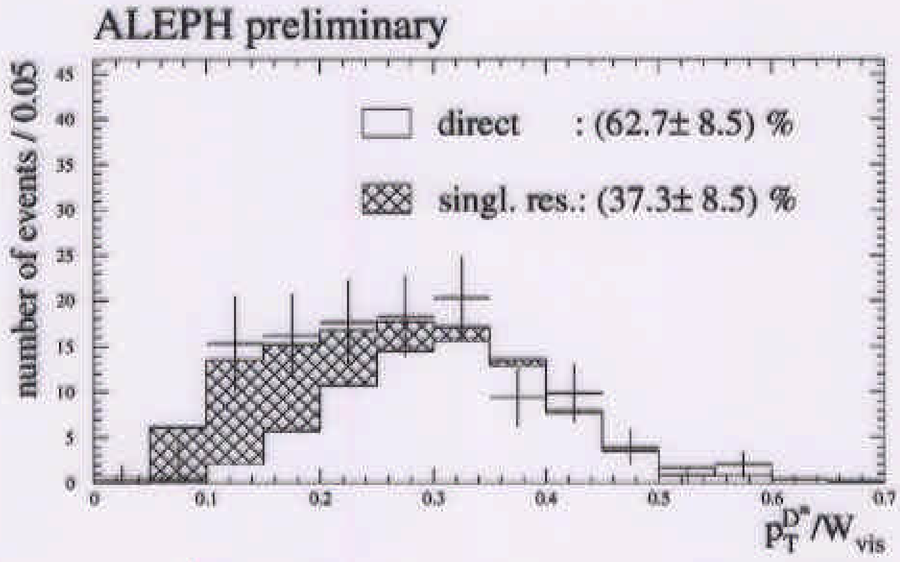
$$x_T^{D*} = (2)p_t^D * / W_{\mathrm{vis}}$$



$\sigma_{\mathrm{dir}}(e^+e^- \to e^+e^- c\bar{c}X) = 401 \pm 46 \pm 87 \pm 75(\mathrm{extr.})$ pb
$\sigma_{\mathrm{res}}(e^+e^- \to e^+e^- c\bar{c}X) = 562 \pm 64 \pm 121 \pm 149(\mathrm{extr.})$ pb

Direct and Resolved Contribution: ALEPH





$\sigma_{\rm dir}(e^+e^- \to e^+e^- c\bar{c}X) = 345 \pm 28 \pm 72\,{\rm pb}$

$\sigma_{\rm res}(e^+e^- \to e^+e^- c\bar{c}X) = 307 \pm 25 \pm 150\,{\rm pb}$

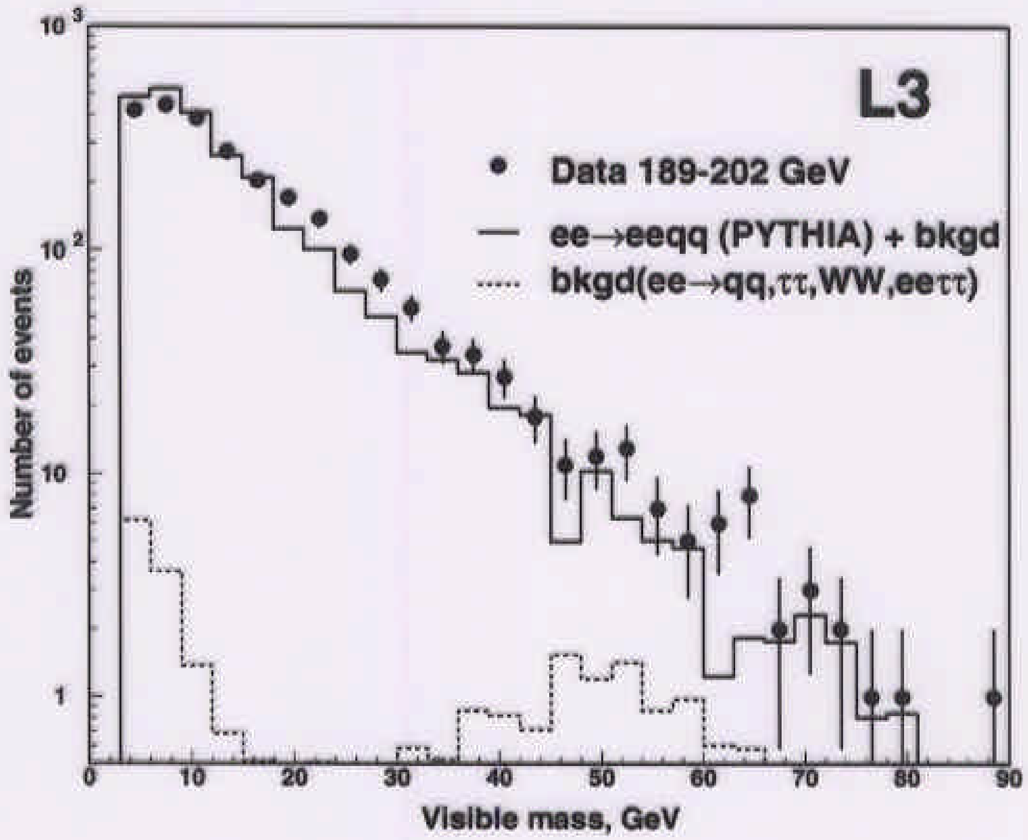
Extrapolation R to full p, η range is large:

$R_{\rm dir} = 11.9 \pm 1.5$

$R_{\rm res} = 17.5 \pm 7.2$

$\sigma(\gamma\gamma \to c\bar{c}X)$ vs. $W_{\gamma\gamma}$: $W_{\rm vis}$

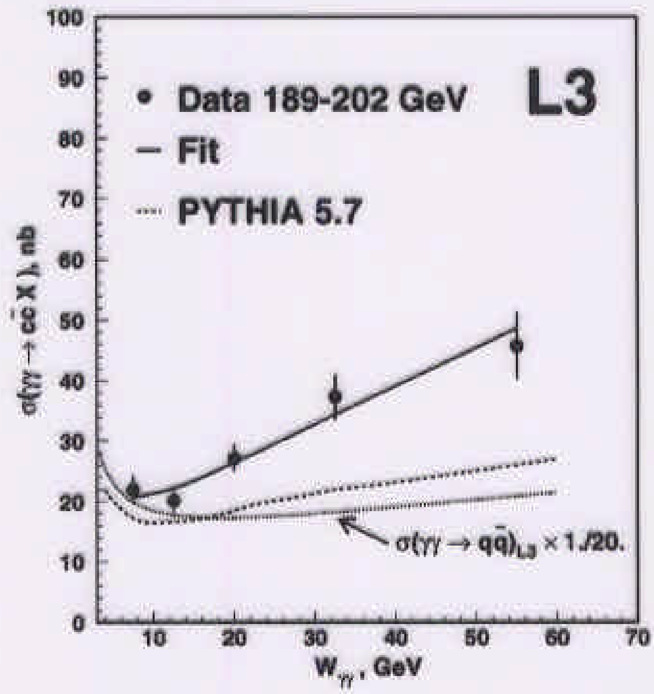
Semileptonic events: 2455 events with $e^{\pm}$



Monte Carlo are lower than data
at intermediate and high visible mass

$\sigma(\gamma\gamma \to c\bar{c}X)$ vs. $W_{\gamma\gamma}$: Pomeron

$\sigma_{tot} = As^{\varepsilon} + Bs^{-\eta}$
(Pomeron + Reggeon;
by Donnachie and Landshoff)



Fit	$\varepsilon = 0.400 \pm 0.062 \pm 0.096$	$(\eta = 0.34)$ fix
PDG	$\varepsilon = 0.095 \pm 0.02$	$(\eta = 0.34 \pm 0.02)$

$\Rightarrow$ hard pomeron contribution
PYTHIA is only 66% of charm cross section
$\Rightarrow$ NLO corrections needed

Charm Structure Function $F_{2,c}^{\gamma}$

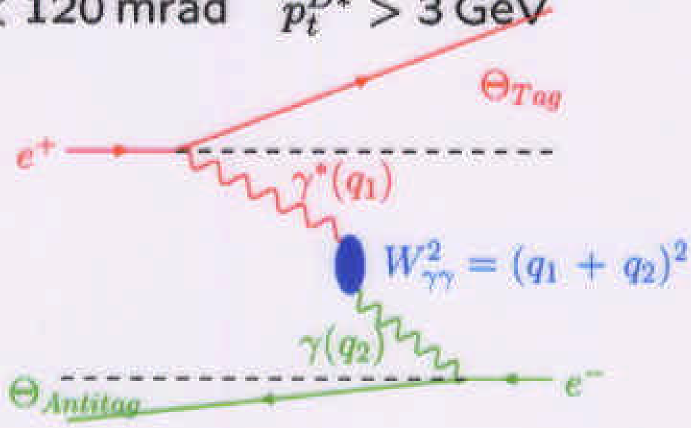
Measurement of $F_{2,c}^{\gamma}$ in single-tag events:

1) identify charm events OPAL: 29.8±5.9 D*events

2) single tag = one electron (or positron) detected

33 mrad $< \vartheta <$ 55 mrad $\quad p_t^{D*} > 1$ GeV

60 mrad $< \vartheta <$ 120 mrad $\quad p_t^{D*} > 3$ GeV



$$\frac{d^2\sigma_{e\gamma\to eX}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^2}\left[\left(1+(1-y)^2\right)F_2^{\gamma}(x,Q^2) - y^2 F_L^{\gamma}(x,Q^2)\right]$$

with

$$Q^2 = 2EE_{\text{tag}}(1-\cos\theta_{\text{tag}})$$
$$x \approx \frac{Q^2}{Q^2+W^2}$$
$$y \approx 1 - \frac{E_{\text{tag}}}{E}\cos^2(\theta_{\text{tag}})$$

y small $\Rightarrow$ contribution from F_L^{γ} small

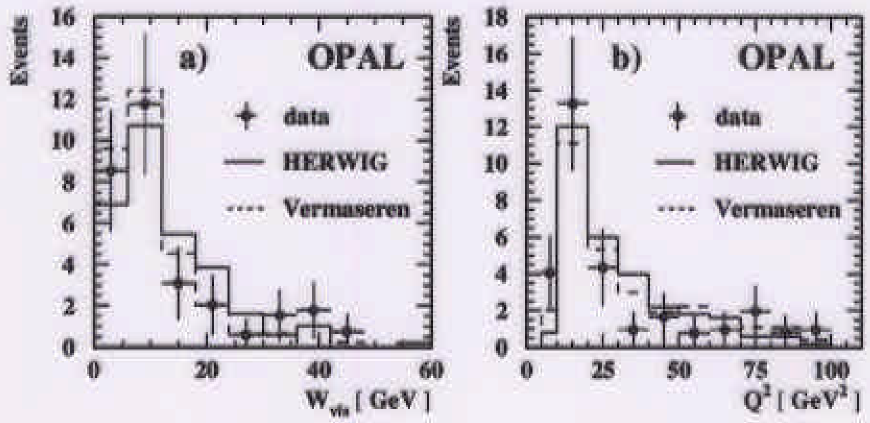
studied in two x-ranges:

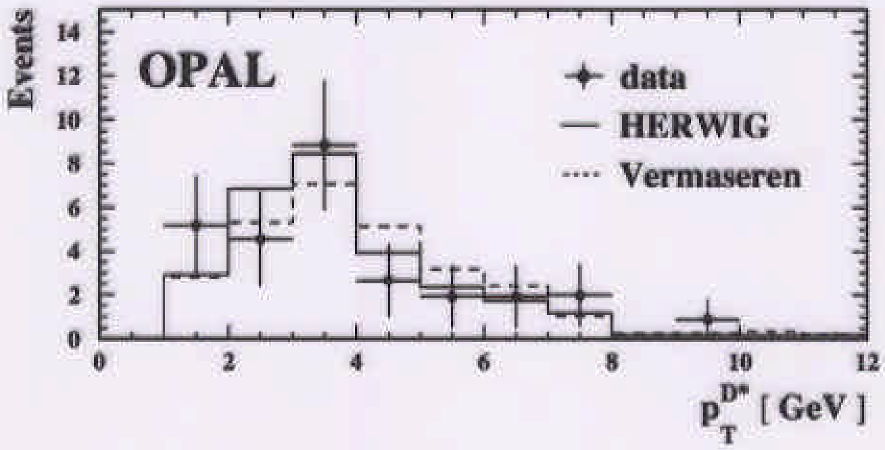
$0.0014 < x < 0.1$

$0.1 \quad < x < 0.87$

$\langle Q^2 \rangle \approx 20$ GeV^2

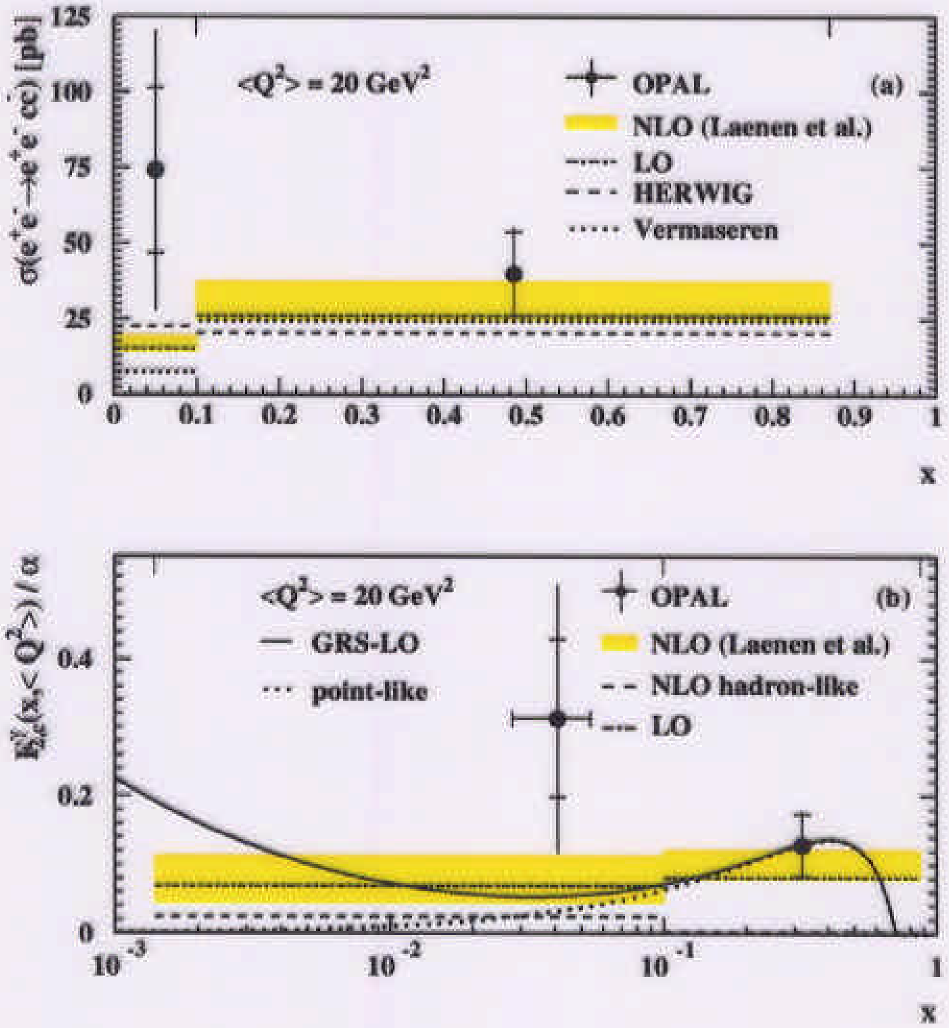
Charm Structure Function





Herwig and Vermaseren models describe data well

Charm Structure Function



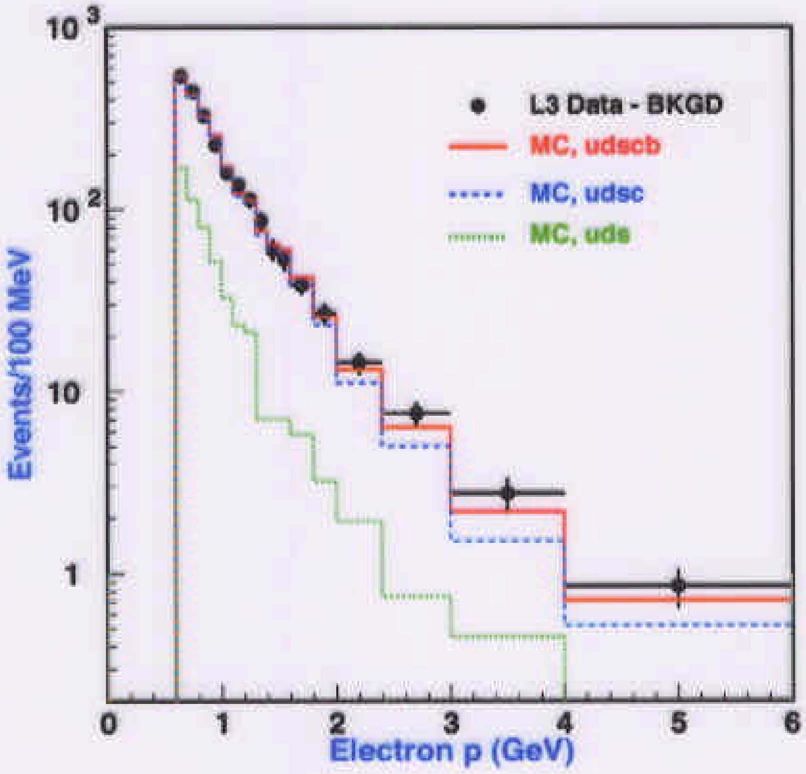
$x > 0.1$ agreement = pointlike part
(free parameters m_c, α_s)
calculable in perturbative QCD:
NLO Laenen = agreement

$x < 0.1$ data above MC, but not (yet) conclusive
suggests hadron like contribution

Need/Evidence for Bottom Production: L3

lepton(bottom) = large p; 2 analysis methods:

	$e^{\pm}$ events	$\mu^{\pm}$ events
cuts	103 ± 20	125 ± 23
fit	320	325



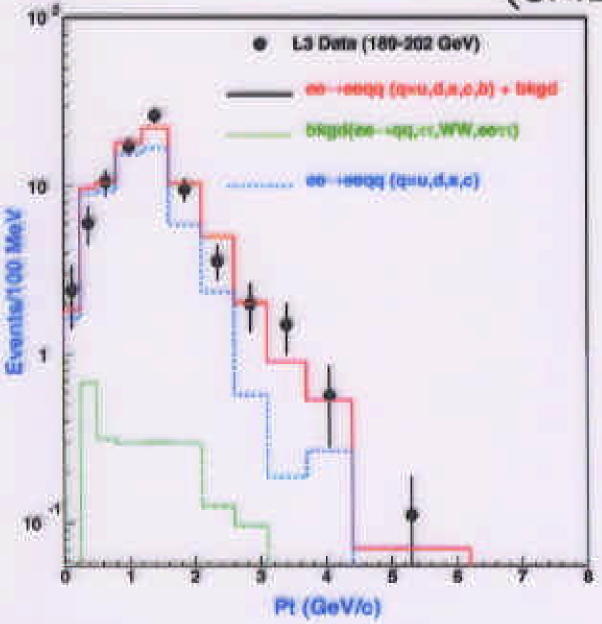
$b\bar{b}$ MC set to $\sigma(e^+e^- \to e^+e^- b\bar{b}X) = 5\,\text{pb}$

MC too low $\Rightarrow \sigma(e^+e^- \to e^+e^- b\bar{b}X) > 5\,\text{pb}$

Bottom: p_T of $e^{\pm}$ and $\mu^{\pm}$ to jet

lepton(bottom) = large p_T to jet direction

(JADE, $Y_{\text{cut}} = 0.1$; lepton excluded)



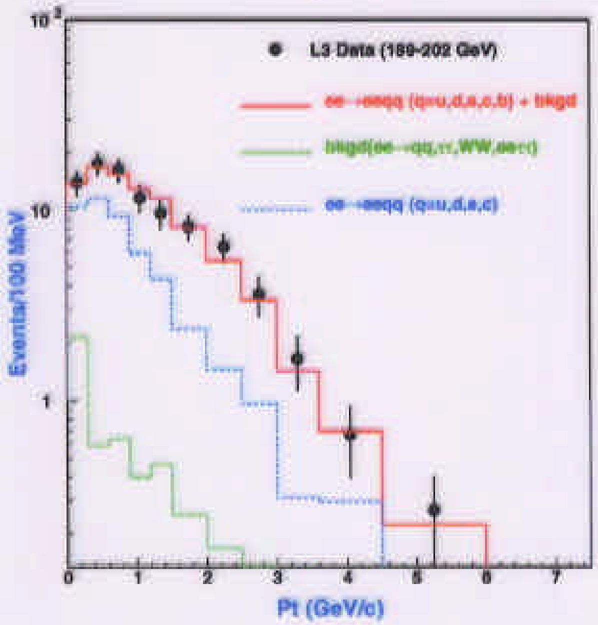
electrons

$p^{e} > 2\,\text{GeV}$

$p_t^{e} > 1\,\text{GeV}$

b-effi. = 1.0%

b-purity 51%



muons

$p^{\mu} > 2.5\,\text{GeV}$

$p_t^{\mu} > 1.5\,\text{GeV}$

b-effi. = 1.2%

b-purity 51%

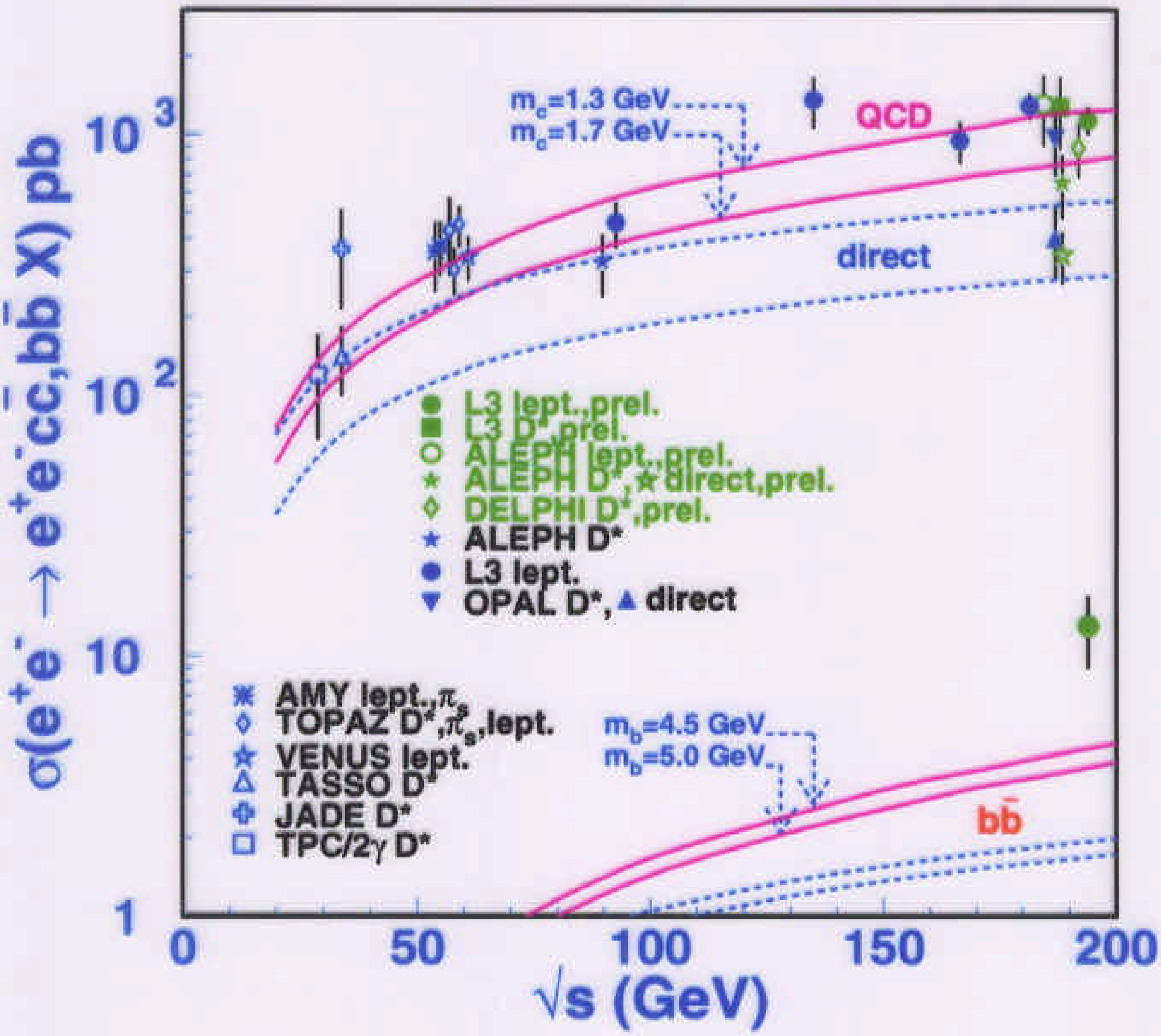
$\sigma_i(e^{\pm}) \approx \sigma_i(\mu\pm)$ consistent

$\sigma_{\text{cut}} = 13.04 \pm 1.79 \pm 3.59\,\text{pb}$

$\sigma_{\text{fit}} = 14.20 \pm 2.02 \pm 1.56\,\text{pb}$

$\sigma_{\text{measured}} >> \sigma_{\text{predicted}}$

Inclusive Charm and Bottom Cross Section



Conclusion

- Measurements of charm quark production:
  - agreement with QCD prediction
    $\Rightarrow \gamma\gamma \rightarrow c\bar{c}X$ needed
  - clear evidence for gluon content in photon
    $\Rightarrow \gamma g \rightarrow c\bar{c}X$ needed
  - NLO contribution seems important
  - fair agreement among 4 LEP experiments
    ALEPH, DELPHI, L3, OPAL , but...
  - fair agreement for various techniques
    (lepton, D^*)
  - $D^{\pm}$, D^0, Λ_c clear signals

  $\Rightarrow$ from evidence to precision = detailed studies
  e.g., direct/resolved, $\sigma(W_{\gamma\gamma})$, $F_{2,c}^{\gamma}$
- Measurements of bottom quark production:
  - $b\bar{b}$ production needed,
    predicted cross section too low