DESY Hamburg
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QCD and Two-Photon Physics at LEP

Armin Böhrer
(armin.boehrer@cern.ch)
Universität Siegen

Outline

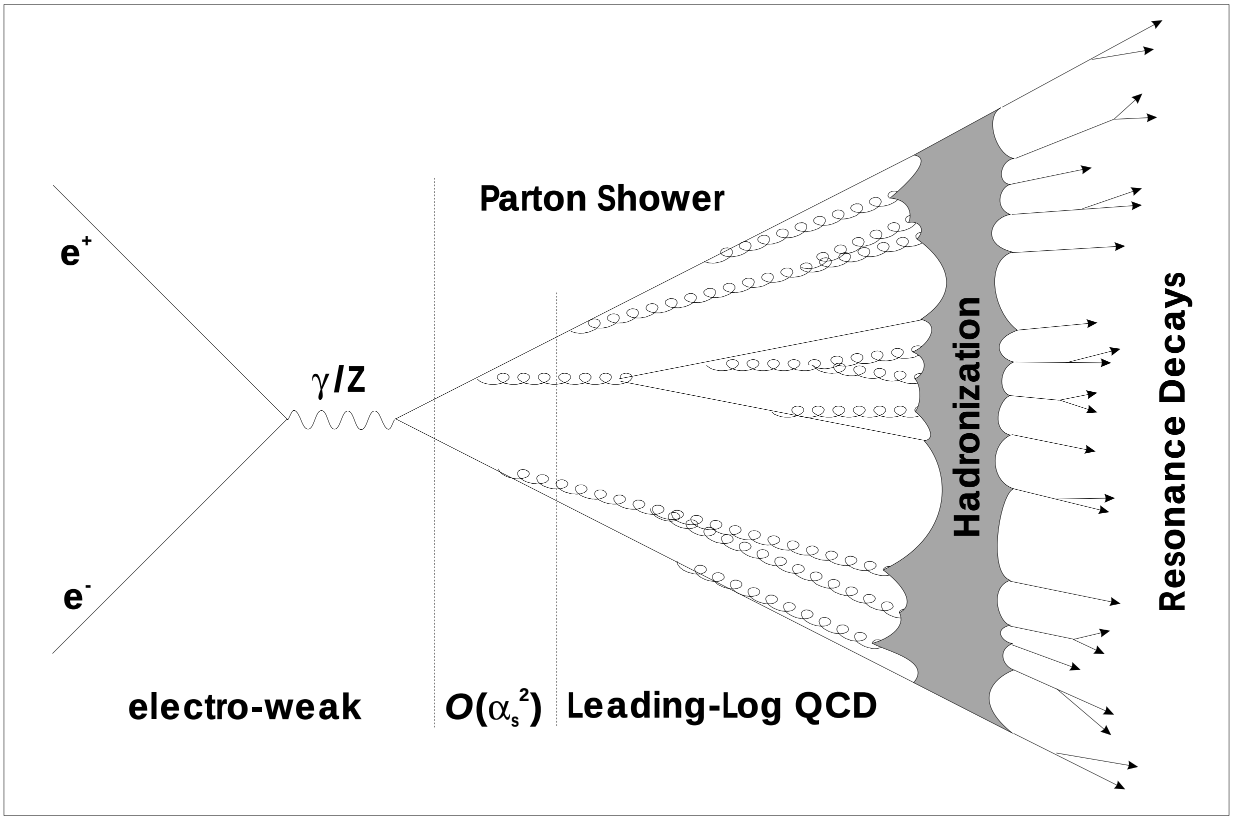
- QCD:
  - hard QCD: α_s, structure of QCD
  - soft QCD: jet structure, fragmentation
- $\gamma\gamma$:
  - structure functions
  - heavy flavour
  - exclusive particle production
- Summary

Introduction

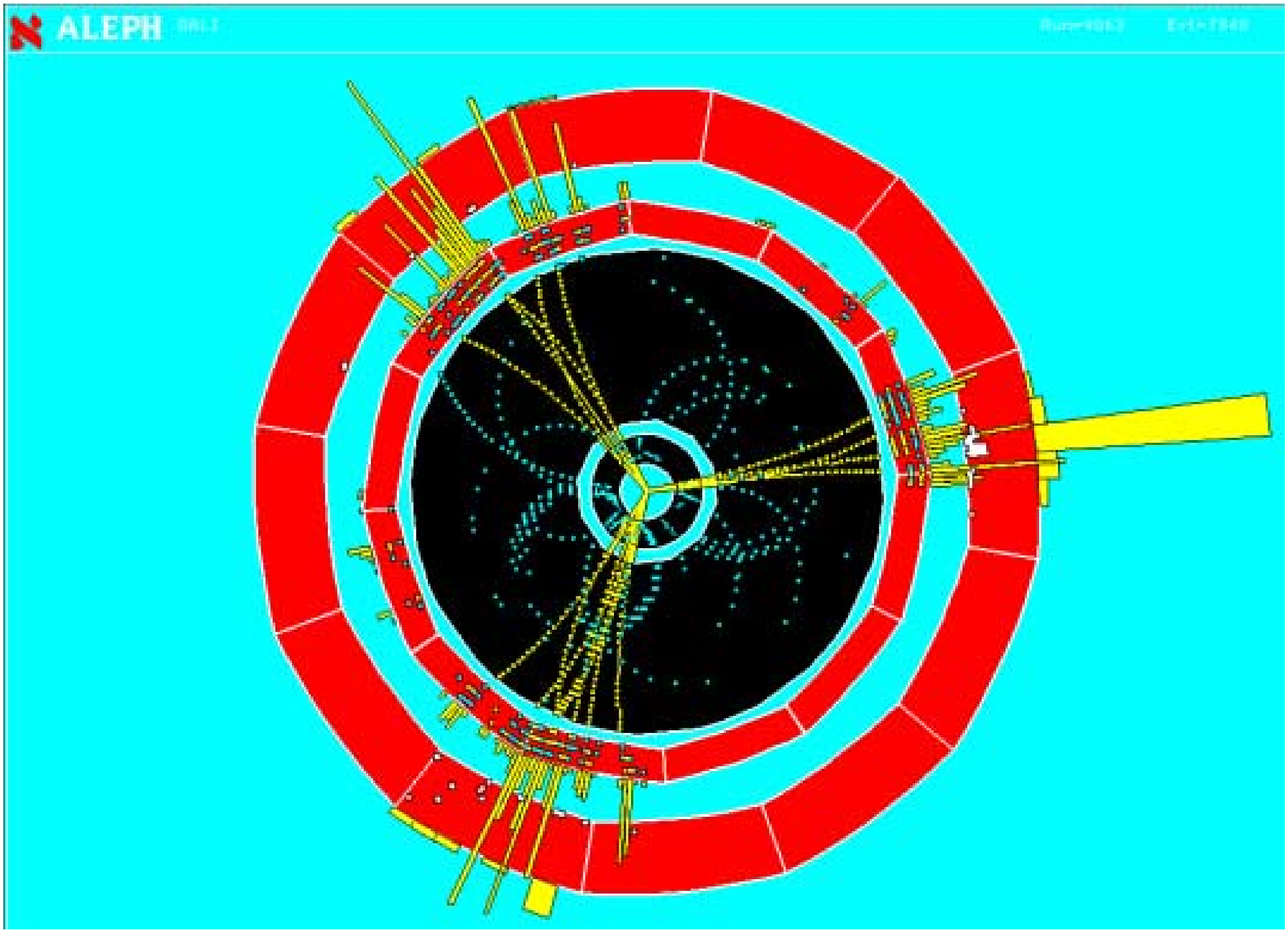
QCD: the theory of strong interactions

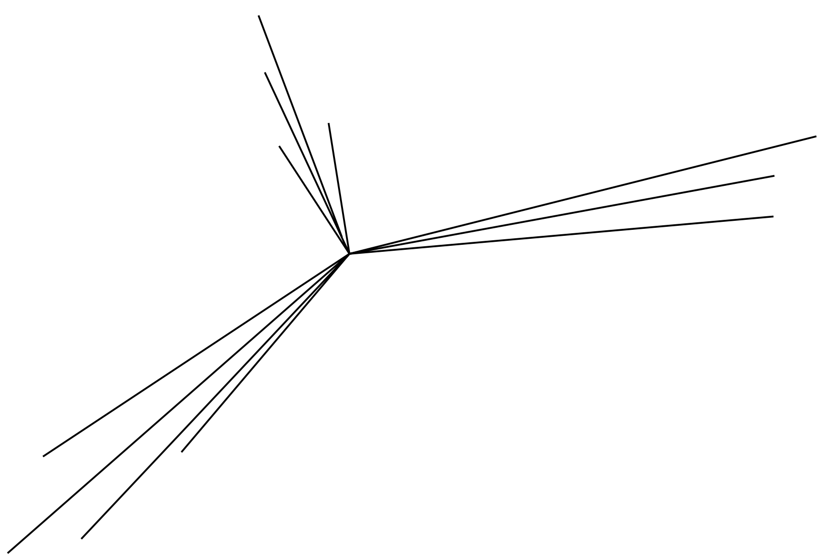
- Static quark model,
  hadrons build up of quarks
- DIS: charged partons in nucleon,
  but $\rightarrow$ fraction of momentum, scal. viol., Ω^-
- gluon, quarks have strong interaction $\rightarrow$ colour
- QCD theory: qg interaction, SU(3)
  spin-1/2 fermions, spin-1 gluon,
  $SU(3)_{colour}$, 3 quark colours, 8 gluon states,
  one coupling qq, qg
- e^+e^- (PETRA) $\rightarrow$ gluon is real
- LEP: high precision e^+e^- data and high statistics at $\sqrt{s}$ = 90-200 GeV

QCD in e^+e^- Annihilation



- **Electroweak process**
- **QCD (perturbative, small α_s)**
  - matrix element $O(\alpha_s^2)$
  - parton schauer in MC models (LL)
    (correspondance: partons $\leftrightarrow$ jets)
- **QCD (non-perturbative, large α_s)**
  - fragmentation/hadronisation
    (string model, cluster model)
- **particle decays**





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Jet Definition

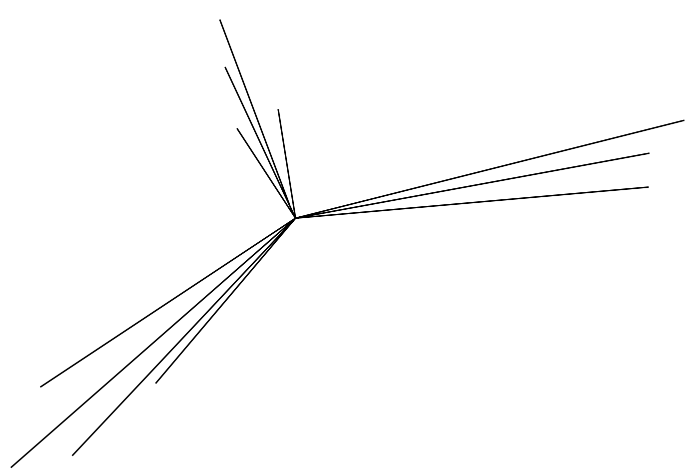
e.g., Durham-Jet-Algorithmus:

combination of particle pairs with smallest y_{ij}
as long as $y_{ij} < y_{cut}$ iterativly
until all $y_{ij} > y_{cut} \Rightarrow$ jet multiplicity $R_n(y_{cut})$ or
when 3 jets $\Rightarrow y_3 = \min(y_{ij})$, $\mathrm{d}n/\mathrm{d}y_3$

$$y_{ij} = \frac{2\left(1 - \cos\theta_{ij}\right)}{E_{vis}^2} \min\left(E_i^2, E_j^2\right)$$

with recombination scheme:

$$\begin{aligned} p_{ij} &= p_i + p_j \\ E_{ij} &= E_i + E_j \end{aligned}$$

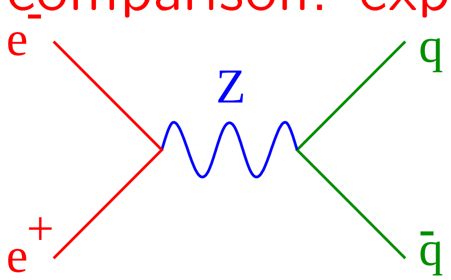


Jets → Partons

correspondance: jets → partons

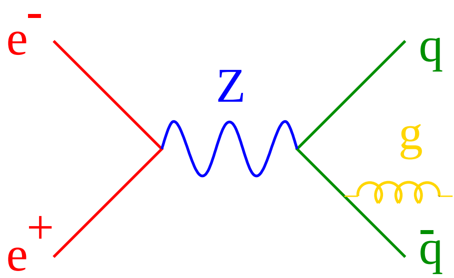
calculable in perturbative QCD

comparison: experiment → theory



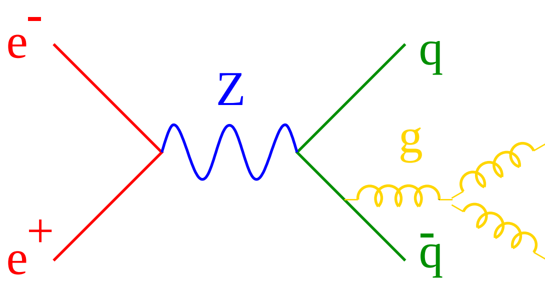
QPM: $O(\alpha_s^0)$

static quark model



QCD: $O(\alpha_s^1)$

dynamic quark model



QCD: $O(\alpha_s^2)$

dynamic quark model

group structure

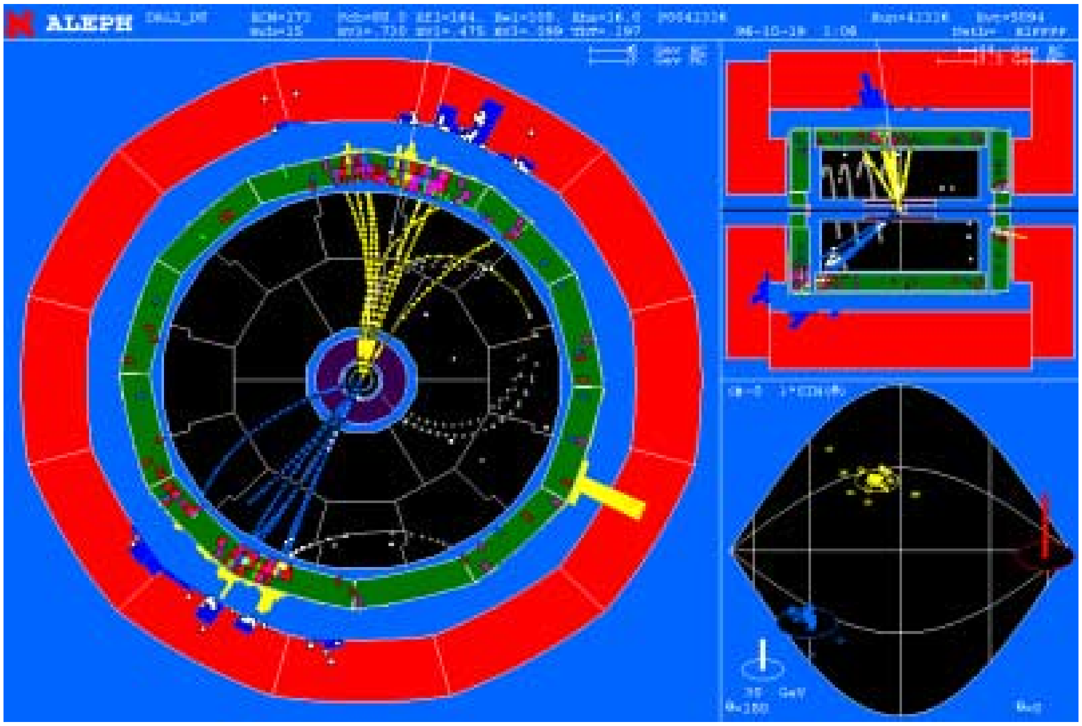
higher orders α_s,

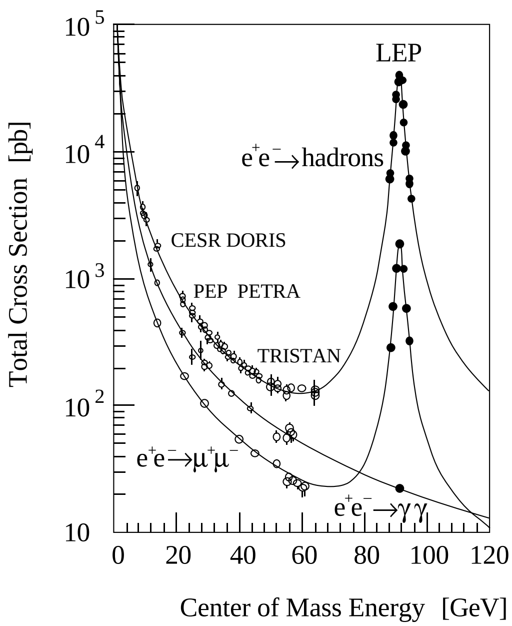
non-perturbative effects to be included

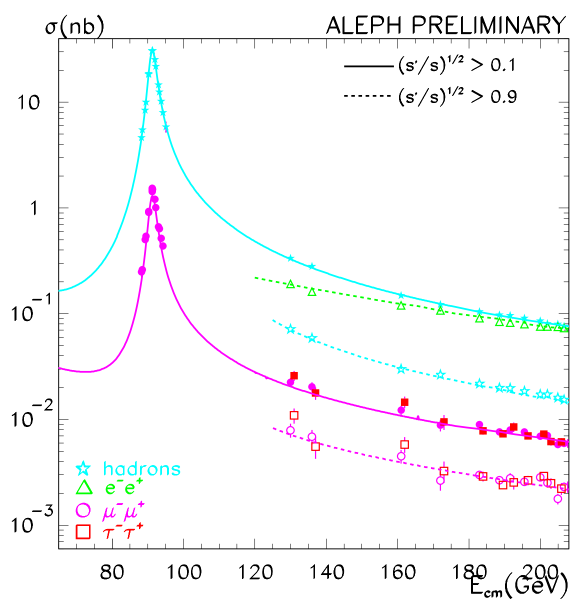
hadronisation

Properties of the e^+e^- Annihilation

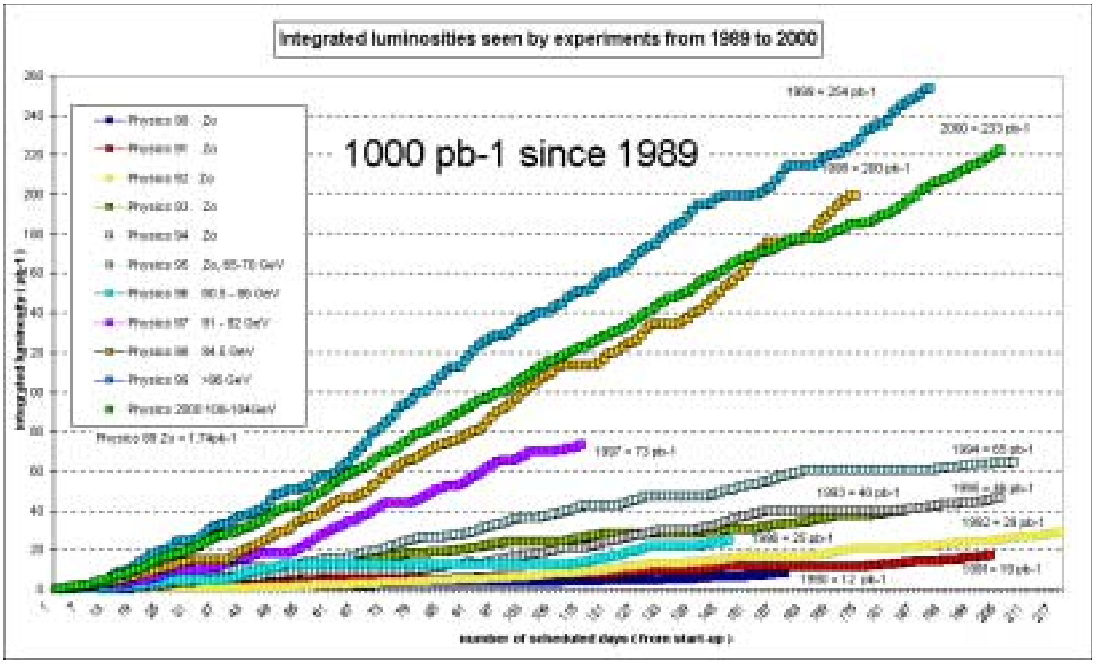
- **Known energy scale** $E_{\text{cm}} = 2 \cdot E_{\text{beam}}$
  but at LEP 2: "Radiative Return"

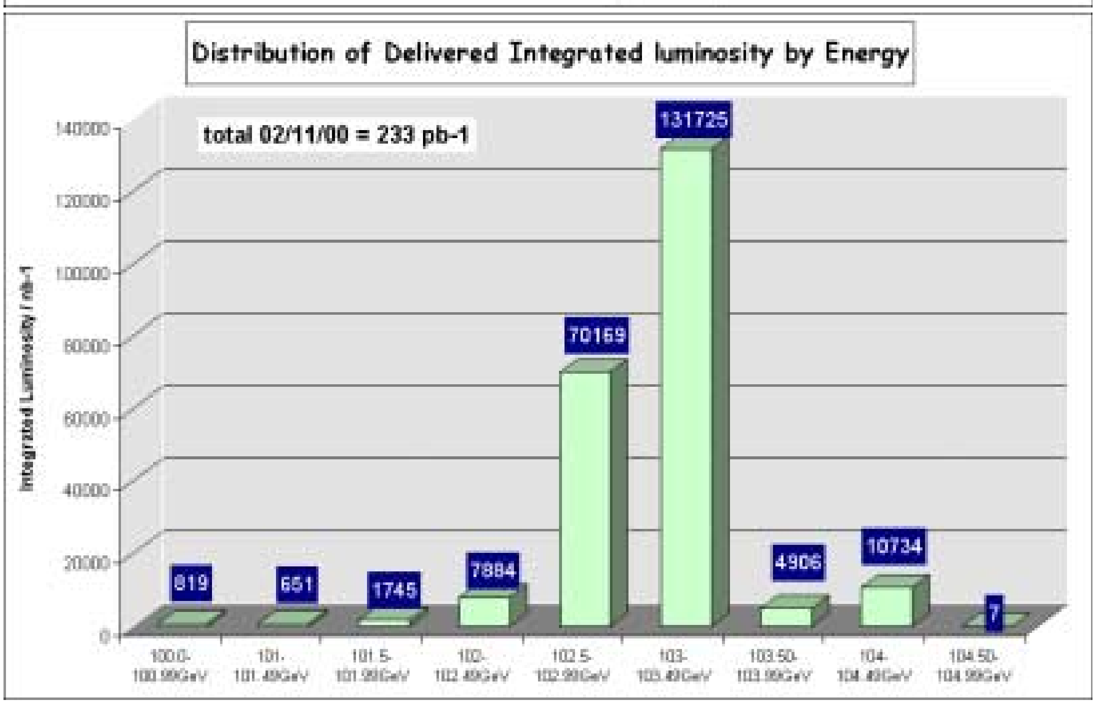






LEP Performance





- high statistics (and/or)
- high well known energy (and)
- high quality data

Measurement of the Strong Coupling Constant α_s

Needs good experimental observable
and calculable variable:

$\sim \alpha_s$ in leading order:

$\rightarrow$ low statistics sufficent

$\rightarrow$ applicable for all $\sqrt{s}$

calculable:

$\rightarrow$ infra-red and collinear safe for gluon strahlung

$\rightarrow O(\alpha_s^2)$

$\rightarrow O(\alpha_s^2)$ + NLLA $\Rightarrow$ event shape variables

Alternative (counting experiments):

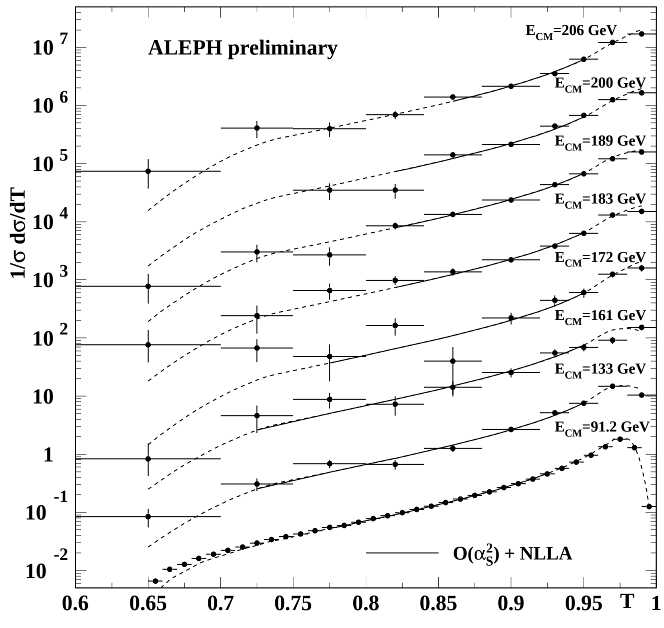
calculable:

$\rightarrow O(\alpha_s^3)$ $\Rightarrow$ inclusive cross sections

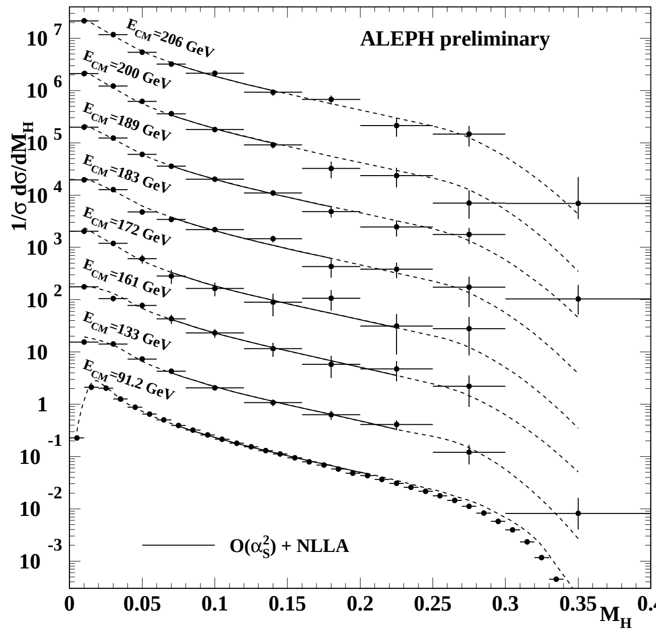
sensitivity to QCD from radiative corrections

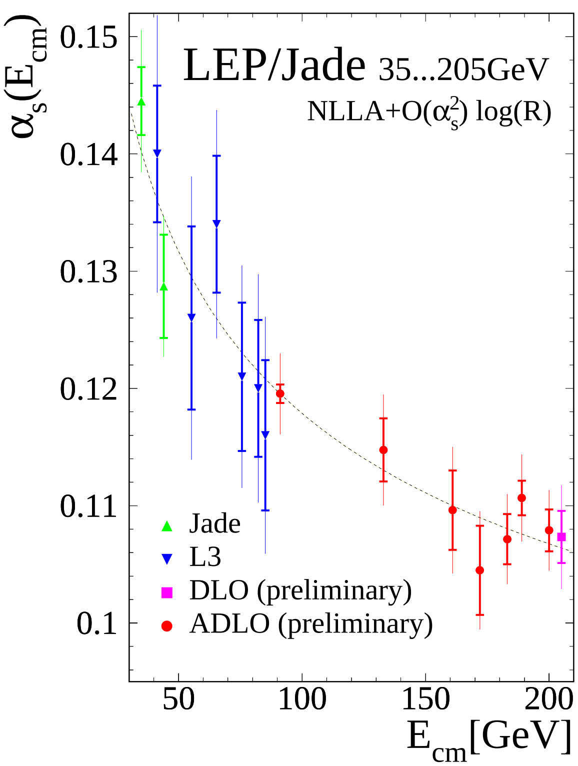
α_s^2 + NLLA: Fits for Various Energies

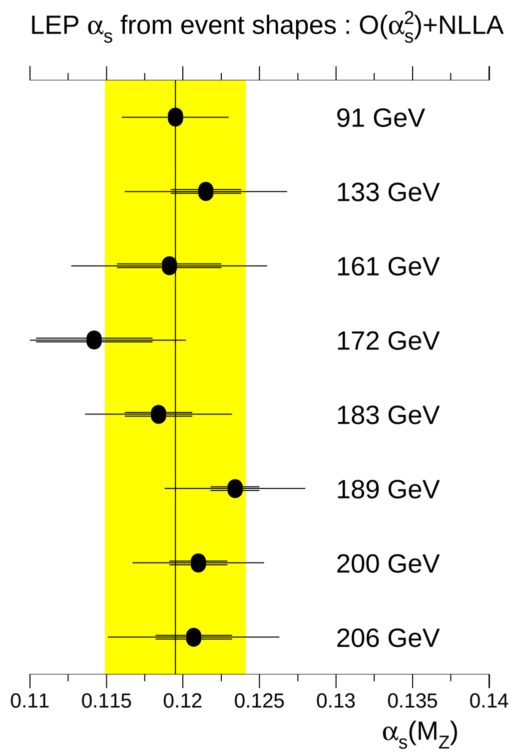
Thrust



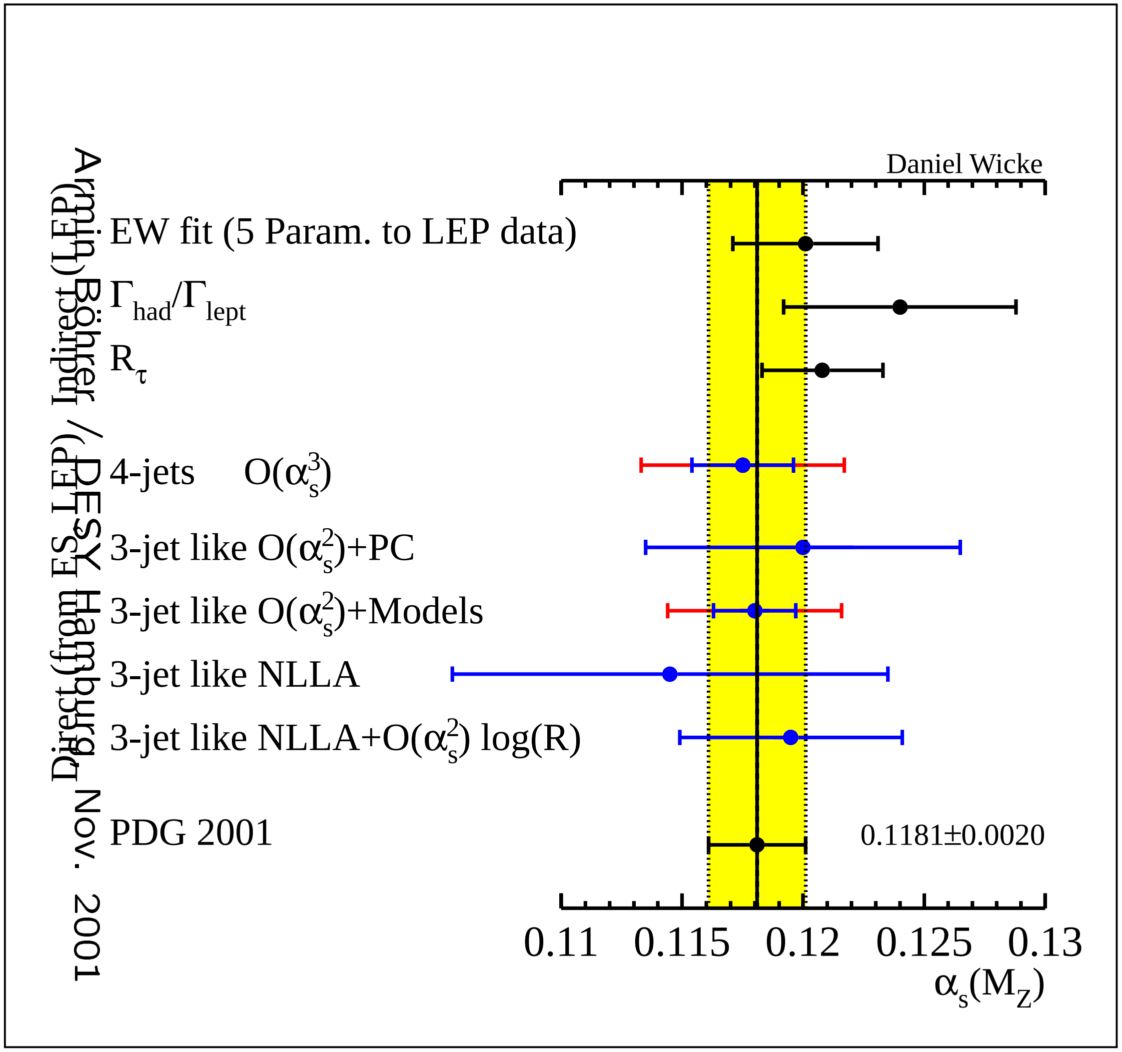
Heavy Jet Mass







All LEP α_s measurements



Studies of

- gauge structure of QCD,
- running b-quark mass,
- colour coherence,
- hadronisation models,
- power corrections as alternatives to hadronisation models,
- differences between quark and gluon jets,

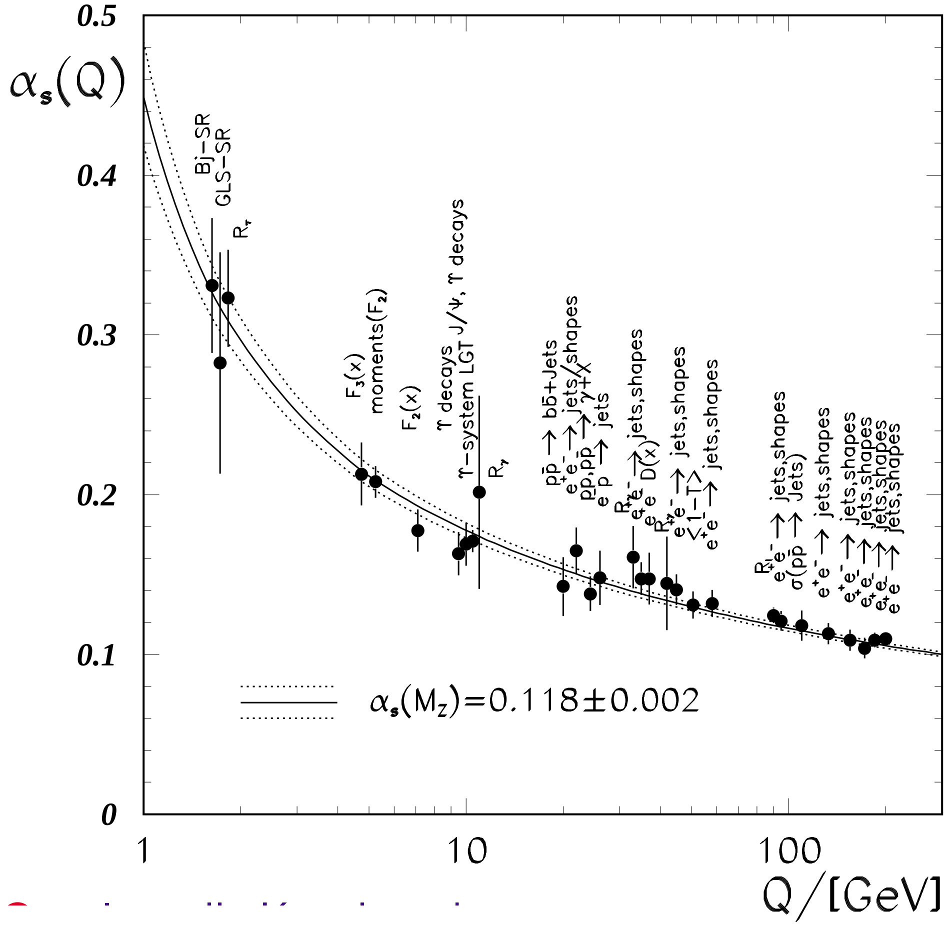
are all consistent with QCD predictions.

For this fig.: Theoretical uncertainties for all α_s from event shapes evaluated from change in renormalisation scale μ by factor 2.

Running Coupling Constant α_S

α_S measurement at different energies $\sqrt{s}$:

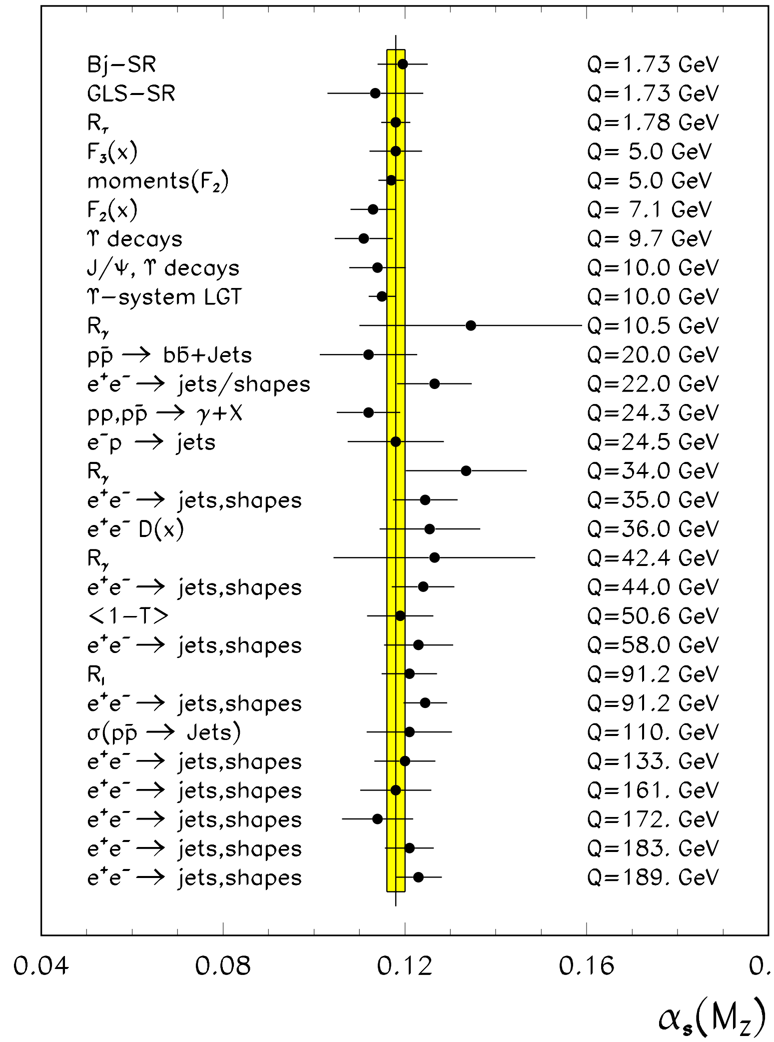
- LEP, SLC: $m_Z < \sqrt{s} < 200\,\mathrm{GeV}$
- CESR, LEP: $\alpha_S(m_\tau)$
- LEP: radiative events at the Z-pole: $\sqrt{s} < m_Z$
- PETRA/PEP: $\sqrt{s} < 40\,\mathrm{GeV}$



Summary of α_s Measurements

QCD Resultate von LEP

Vergleich verschiedener α_s-Messungen



➜ siehe auch S.Bethke hep-ex/0004021

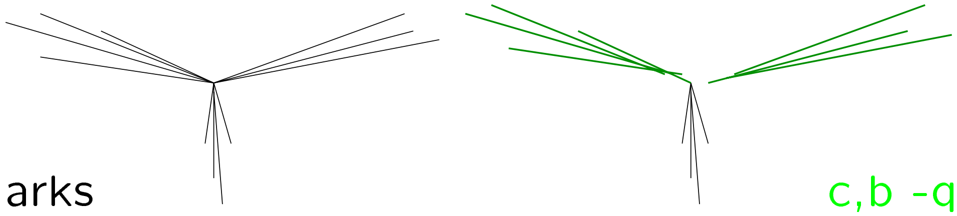
QCD-Kopplung

Michael Schmelling

$$\alpha_s = 0.118 \pm 0.002$$

Flavour Independence of α_s

Separation of different quark flavours:

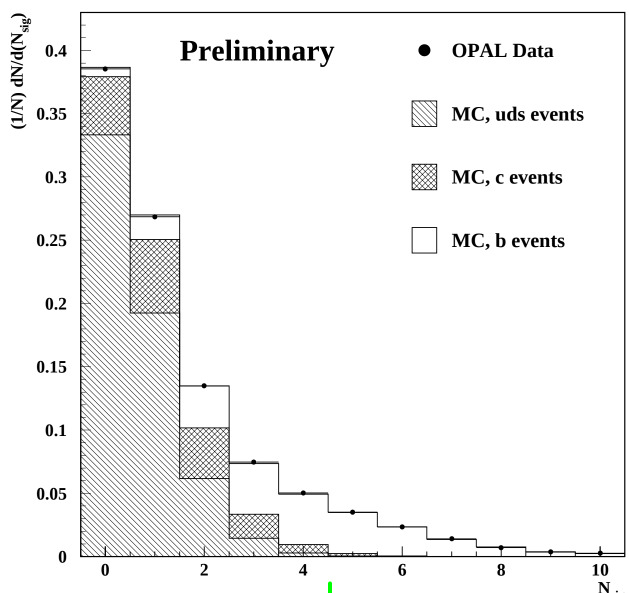


u,d,s -quarks

c,b -quarks

- vertex-tag:
  b- and c-hadronen have long life time
- lepton-tag:
  b- and c-hadrons decay semi-leptonically
- D*-tag:
  C-meson from direct c-quark oder b-hadron
- $\pi^{\pm}$-tag:
  leading $\pi^{\pm}$ indicates u,d
- γ-tag:
  a photon enriches u,c (2/3e) quarks

N_{sig}:
Number of tracks with large impact significance: $b/\sigma > 2.5$



uds: $N_{sig} = 0$, b: $N_{sig} \geq 5$ $\quad | \Rightarrow$

⇒ good separation of (heavy) flavoured events;

⇒ calculations for heavy quarks exist to $O(\alpha_s^2)$

Bernreuter et al., Nason et al., Rodrigo et al.

⇒ precise test of standard model

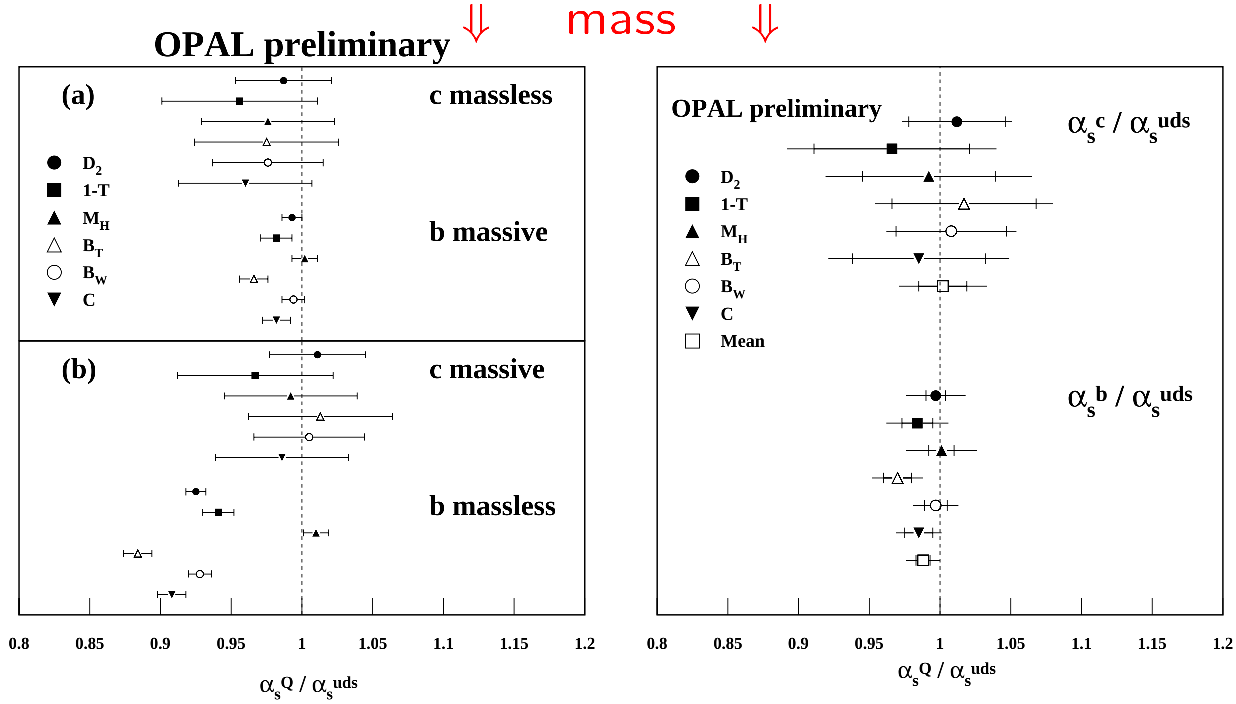
non-Abelian theory: qg coupling = gg coupling

$$\frac{\alpha_s^{c,b}}{\alpha_s^{uds}} \quad \text{or} \quad \frac{\alpha_s^{i}}{\alpha_s^{udscb}}$$

main uncertainties of α_s determination cancel in ratio $\alpha_s^{c,b}/\alpha_s^{uds}$ (scale dependance, fragmentation)

differences in α_s? → hint to new physics

without ⇓ mass ⇓ with



precision in measurements for all flavours

2% to 20% (per experiment)

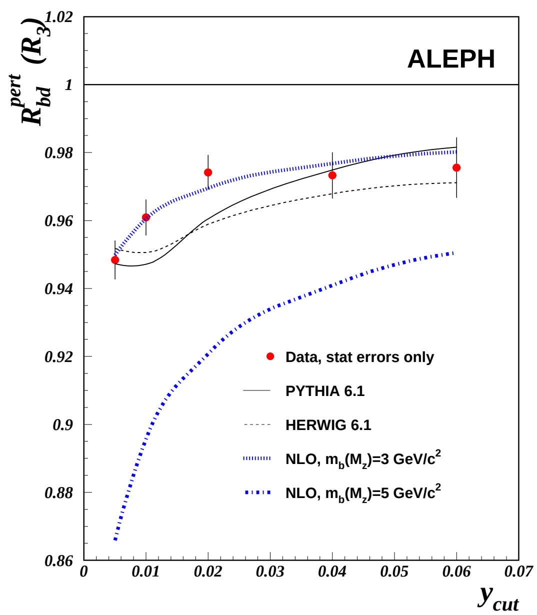
Determination of b-Quark Mass

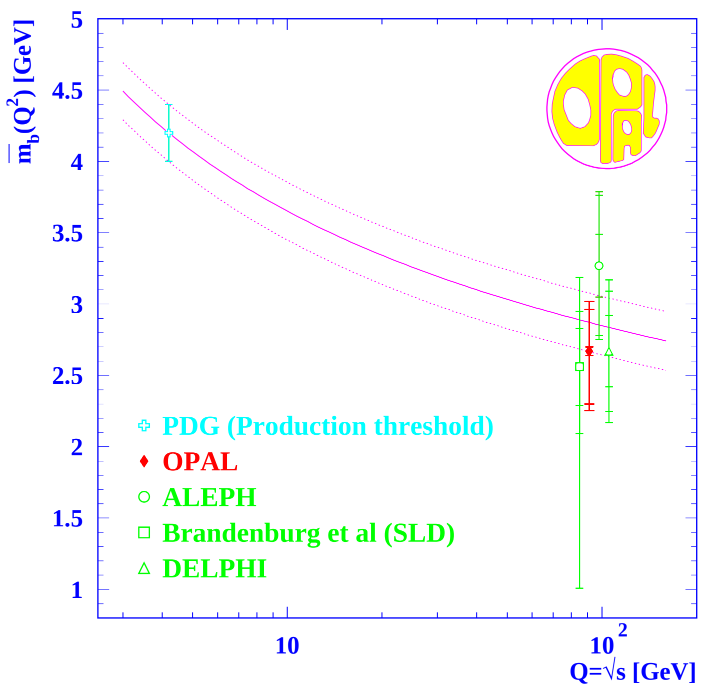
Reverse argument:

QCD is flavour blind

$\Rightarrow$ determine b-Quark mass!

renormalized mass runs $\sim \alpha_s$



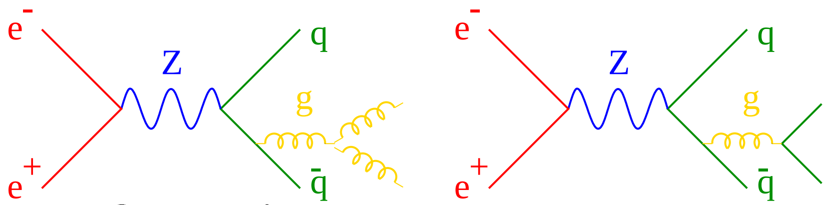


running b-quark mass m_b preferred

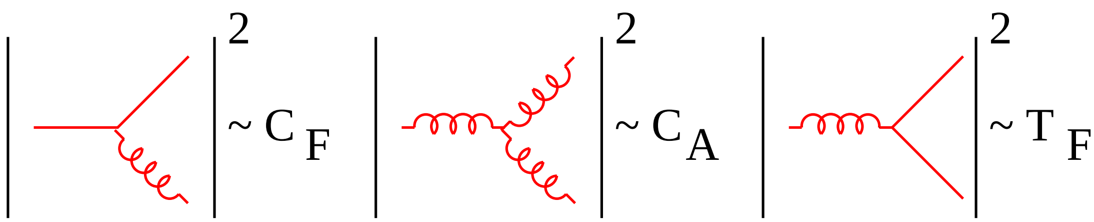
$$m_b(m_Z) = 3.27 \pm 0.22 \pm 0.22(exp) \pm 0.38(had) \pm 0.16(theo)\,\text{GeV(A)}$$
$$m_b(m_Z) = 2.67 \pm 0.25(stat) \pm 0.34(frag) \pm 0.27(theo)\,\text{GeV(D)}$$
$$m_b(m_Z) = 2.67 \pm 0.03(stat)^{+0.29}_{-0.39}(syst) \pm 0.19(theo)\,\text{GeV(O)}$$

$$m_b(m_\Upsilon/2) = 4.20 \pm 0.20\,\text{GeV}$$

Gluon Selfcoupling; Colour Factors



- prove gg self coupling
- measure colour factors = group structure
- QCD has 3 vertices in $O(\alpha_s)$
  $\rightarrow$ decomposition of coefficient functions: e.g.,
  $D_2 = \alpha_s C_F ... + \alpha_s^2 C_F (C_F ... + C_A + T_F n_f ...)$
  $R_4(y_{cut}) = \alpha_s^2 C_F (C_F ... + C_A + T_F n_f ...) + \alpha_s^3 ...$

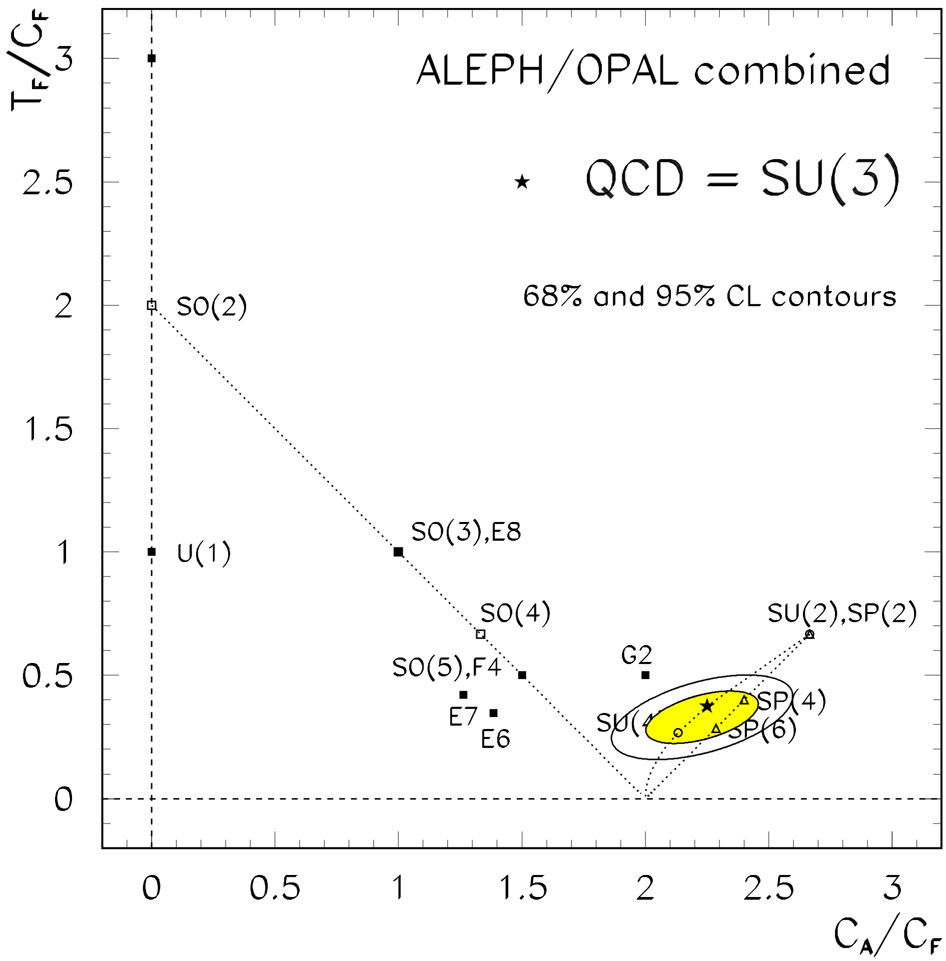


variable used:

- Differential 2-jet rate $D_2(y_{23}) = \frac{1}{\sigma tot} \frac{d\sigma}{dy_{23}}$
- 4-jet rate R_4, $y_{cut} = 0.008$, $E_1 > E_2 > E_3 > E_4$
  jet 1 and 2 = primary quarks,
  jet 3 and 4 = from gluon radiation: gg or $q\bar{q}$
  - $\chi_{BZ} = \angle[(\vec{p_1} \times \vec{p_2}), (\vec{p_3} \times \vec{p_4})]$
  - $\Theta_{NR} = \angle[(\vec{p_1} - \vec{p_2}), (\vec{p_3} - \vec{p_4})]$
  - $\Phi_{KSW} = \langle \angle[(\vec{p_1} \times \vec{p_4}), (\vec{p_2} \times \vec{p_3})] \rangle_{3 \rightarrow 4}$
  - $\cos(\alpha_{34}) = \cos(\angle(\vec{p_3}, \vec{p_4}))$

$\Rightarrow$ full analysis: fit to several observables

Colour Factors of QCD



4-jet data, Z-peak 1991-1995,
hadronization from MC models

	OPAL	ALEPH
C_A	$3.02 \pm 0.25 \pm 0.49$	$2.93 \pm 0.14 \pm 0.49$
C_F	$1.34 \pm 0.13 \pm 0.22$	$1.35 \pm 0.07 \pm 0.22$
$\alpha_s(m_Z)$	$0.120 \pm 0.011 \pm 0.020$	$0.119 \pm 0.006 \pm 0.022$

+ other experiments, + other methods

$C_A = 2.8 \pm 0.2$, $C_F = 1.3 \pm 0.2$ (S.Kluth)

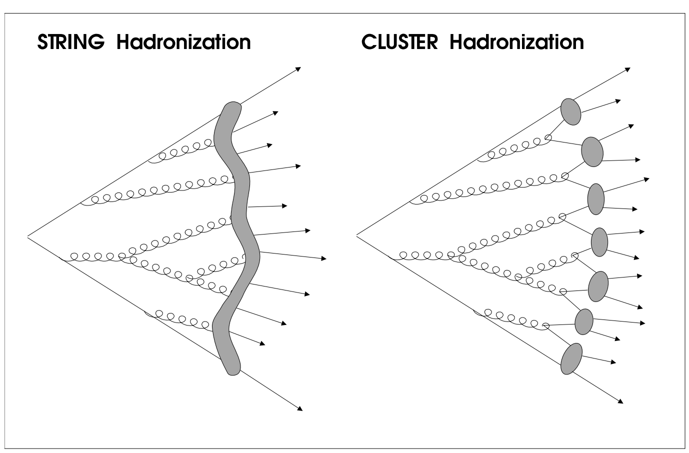
$C_A = 2.9 \pm 0.3$, $C_F = 1.5 \pm 0.3$, $n_f = 5.6$ (S.Kluth)

(SM: $C_A = 3$, $C_F = 1.33$, $T_F = 0.5$)

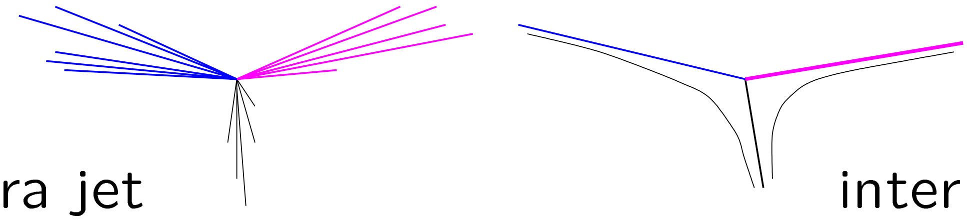
Jets, Subjets and all that

Data samples with high statistics
allow more detailed/driect studies:

1) MLLA+LPHD:
   predictions for particle multiplicity,
   momentum distributions
2) quark jet versus gluon jet:
   → more particles in gluon jets,
   from different colour charge?!
   → subjets, colour coherence and phase space
3) identified particles multiplicities, $\sim p$-spectra
   → model tuning
   → better α_s etc.



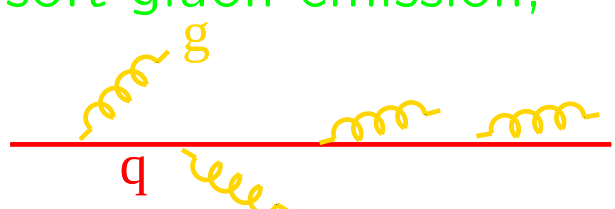
Colour Coherence and Local Parton Hadron Duality



intra jet
(e.g. subjets)

inter jet
(string effect)

reason: colour charge of quarks and gluons...
production of partons not independent:
colour coherence + MLLA:
$\Rightarrow$ suppression of soft gluon emission,

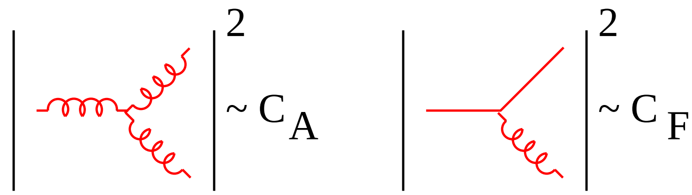


angular ordering
LPHD:
cross section (partons)
= cross section (hadrons)

$\Rightarrow$ suppression of soft hadrons
n_{cha}, $< n_{cha} >$ versus $\sqrt{s}$
ξ-spectra, $\xi = \ln(1/x)$, $x = p_{hadron}/p_{beam}$
Gaussian shape

Properties of Quark and Gluon Jets

- gluons have larger colour charge:



$C_A/C_F = 3/(4/3) = 2.25$

$\Rightarrow$ gluon-jets are wider, softer, n_{cha} is larger

- particle multiplicities: $r = n_{cha\,g}/n_{cha\,q} = ?$

naive expectation for $r = C_A/C_F$

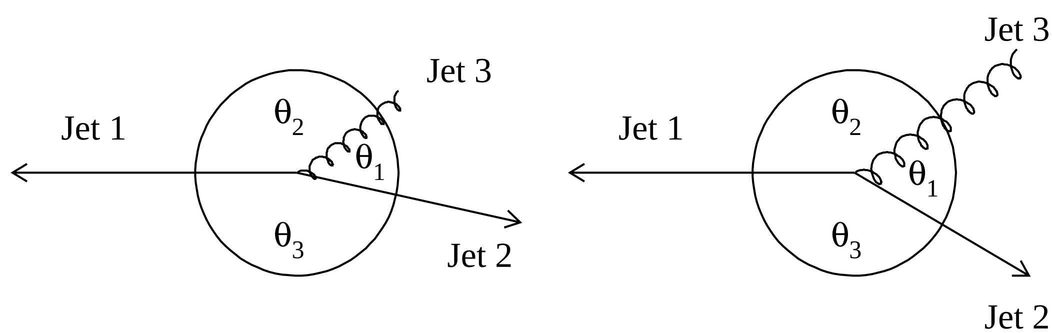
- measurement: $r = 1.0 - 1.2$ (PEP/PETRA/LEP)

gluon jet in 3-jet events (bias $\Rightarrow$ subjets)

- calculation (leading order)

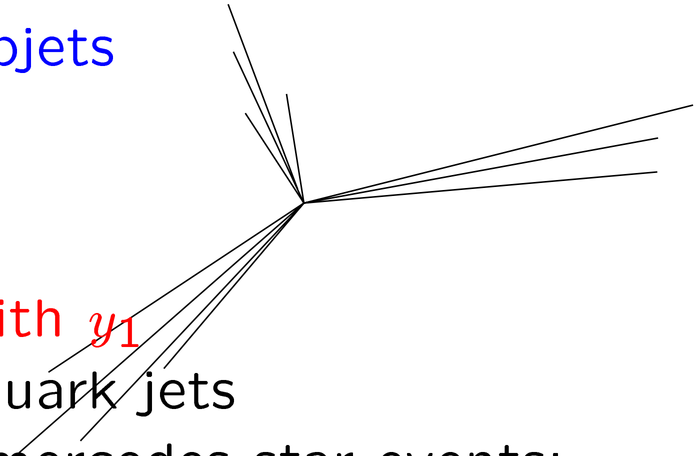
$\Rightarrow$ for q$\bar{\text{q}}$ and gg systems, resp.

- additional scale in addition to jet energy E_{jet}:



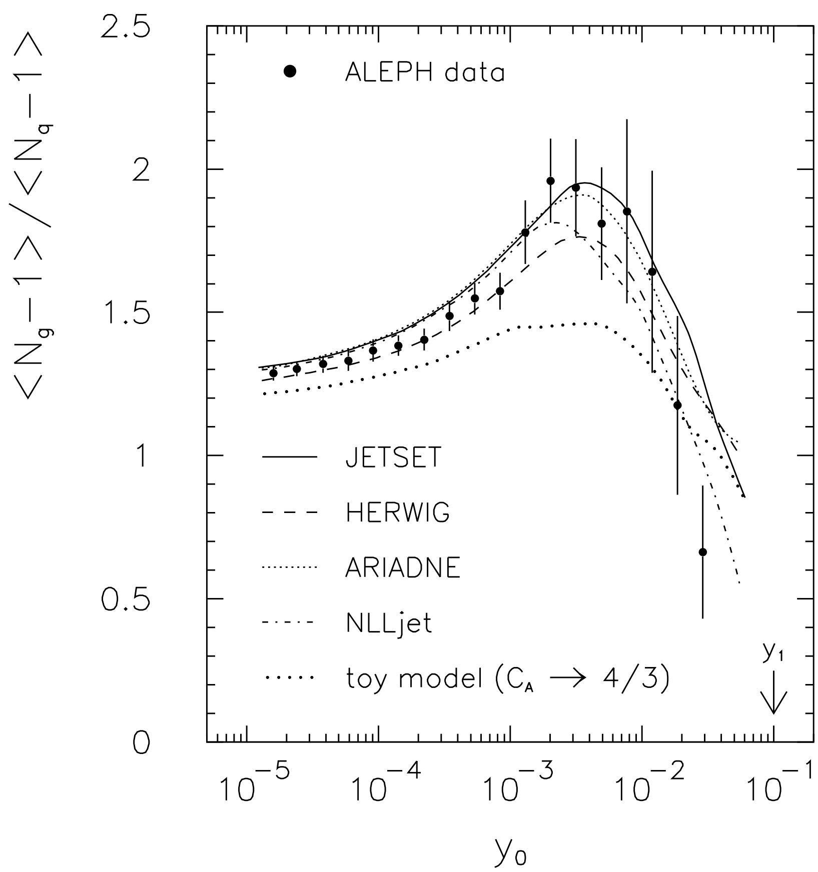
$\Rightarrow \kappa = E_{jet} \sin \frac{\theta_{min}}{2}$ $\qquad \theta_{min,3} = \min(\theta_1, \theta_2)$

Subjets



Basic idea:

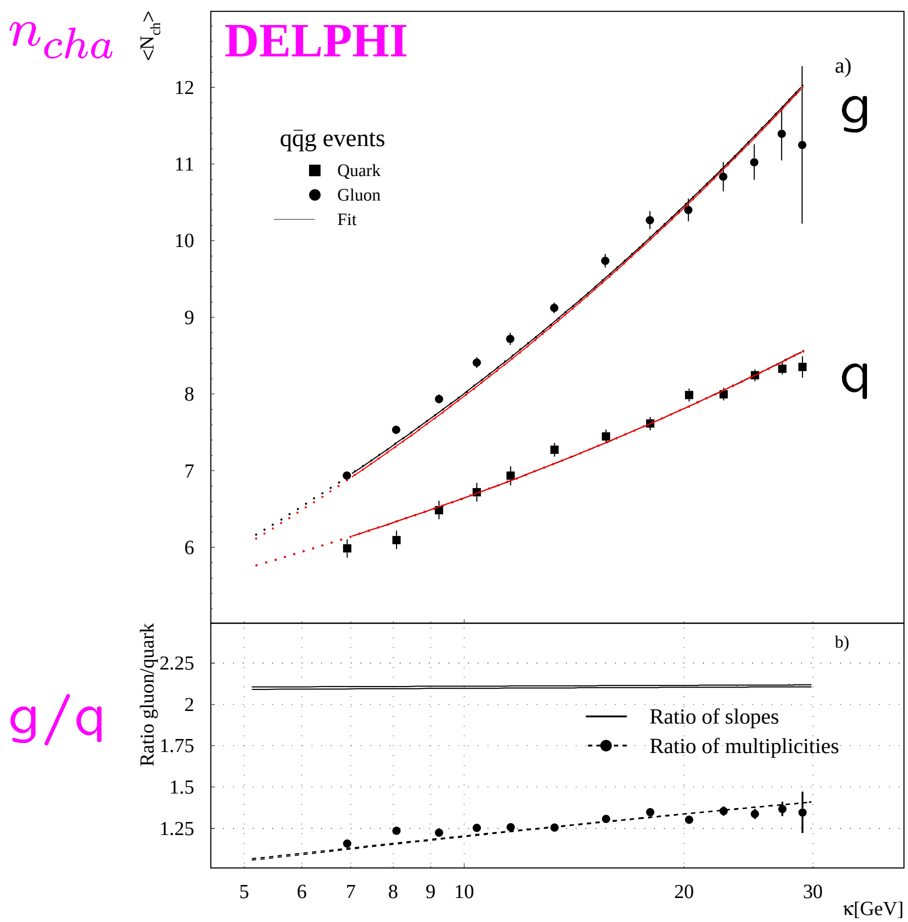
- select 3-jet events with y_1
  $\rightarrow$ study gluon and quark jets
  (well separated jet: mercedes star events; tagging via b-tag)
- study subjet multiplicity with $y_0 < y_1$



- gluon jets has higher multiplicity
- at small y_0: multiplicity ratio ≈ 1.25

Multiplicities in Quark and Gluon Jets

determination of dependency separately
for quark und gluon versus κ



$\rightarrow\ \kappa = E_{jet} \sin\frac{\theta_{min}}{2}$

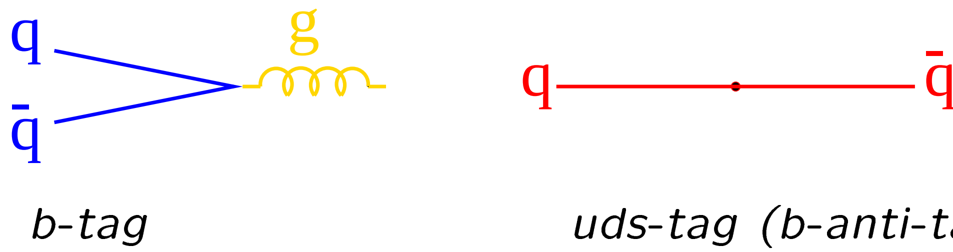
$\Rightarrow$ n_{cha} for gluons larger

$\Rightarrow$ slope with κ for gluons larger

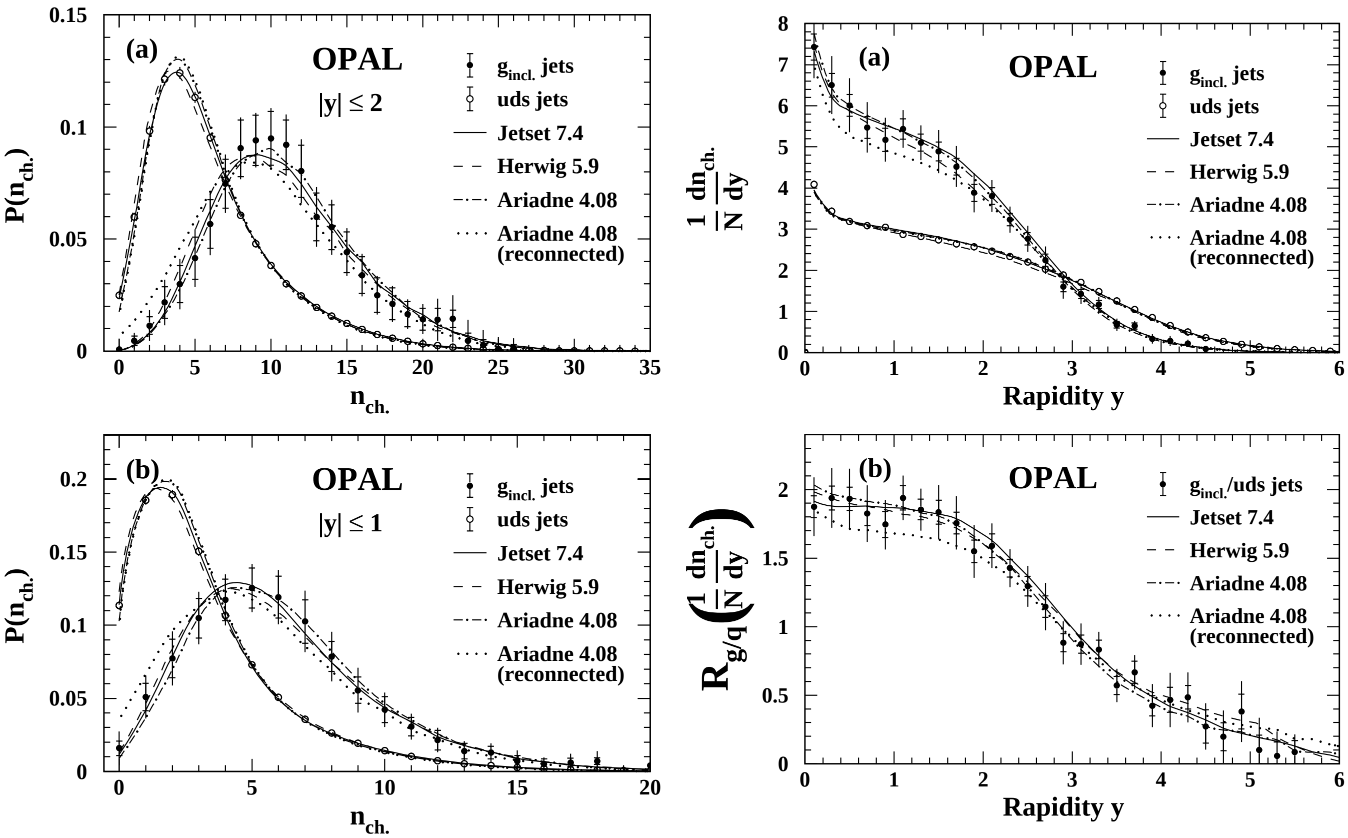
$$\frac{C_A}{C_F} = 2.266 \pm 0.053(stat) \pm 0.055(syst) \pm 0.096(theo)$$

$=$ test of group structure $SU(3)_{colour}$ in QCD alternative method: "isolation of gluons"

- $q\bar{q}$-pair opposite to gluon



- comp. gluon- with uds-quark jet (massless)
- calculation for massless jets, E-conservation
  $r \approx 1.5\ n_{cha}(g)/n_{cha}(q)$ Lupia, Ochs, Eden, Gustafson
- measurement (OPAL):
  $r = 1.51 \pm 0.02 \pm 0.04$ (phase space $\leftrightarrow$ E-cons.)
  $r = 1.92 \pm 0.05 \pm 0.10\ |y| < 1$

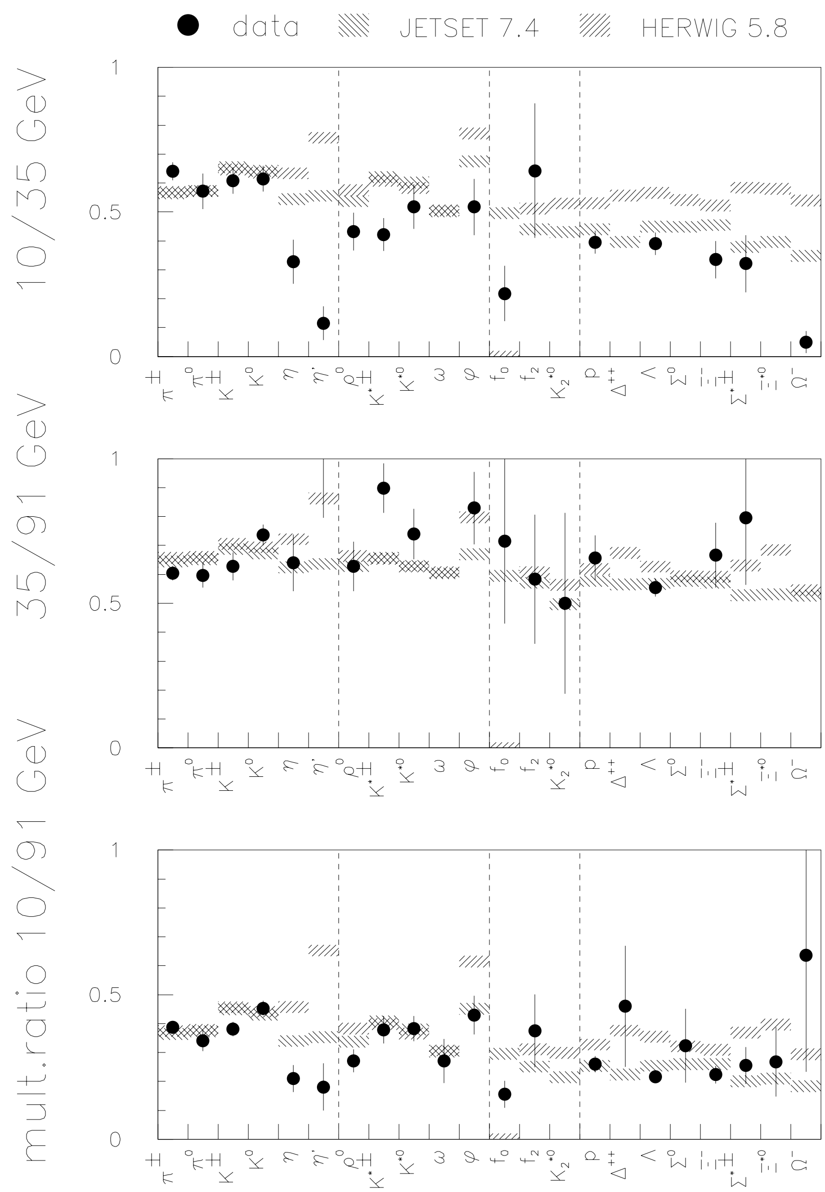


Multiplicities for Identified Particles

Particle	Averaged rate	Experiments	F	References
π^0	9.43±0.37	ADLO		[15,21,27,39]
$\pi^\pm$	17.06±0.24	ADO		[16,24,32]
K^0	2.041±0.029	ADLO	1.49	[17,19,29,34]
$K^\pm$	2.26 ±0.055	ADO	1.01	[16,24,32]
η	0.94±0.08	LO		[27,39]
η'	0.17±0.05	LO	2.36	[28,39]
ρ^0	1.23±0.10	AD	1.08	[15,25]
$\rho^\pm$	2.40±0.44	O		[39]
K^{*0}	0.754±0.034	ADO		[15,23,35]
$K^{*\pm}$	0.714±0.043	ADO		[15,19,31]
ω	1.084±0.086	ALO		[15,28,39]
ϕ	0.0966±0.0073	ADO	2.37	[15,23,38]
p	1.037±0.040	ADO	1.04	[16,24,32]
Λ	0.388±0.011	ADLO	2.04	[17,20,29,36]
Σ^-	0.082±0.007	DO		[26,37]
Σ^+	0.107±0.010	LO		[30,37]
Σ^0	0.078±0.008	ADLO		[15,22,30,37]
Ξ^-	0.0265±0.0011	ADO	1.23	[15,20,36]
Δ^{++}	0.088±0.035	DO	3.39	[18,33]
$\Sigma^{*\pm}$	0.0468±0.0043	ADO	1.74	[15,20,36]
Ξ^{*0}	0.0058±0.0010	ADO	2.65	[15,20,36]
Ω^-	0.0013 ±0.00024	ADO	1.14	[15,22,36]
$a_0^\pm(980)$	0.27±0.11	O		[39]
$f_0(980)$	0.147±0.011	DO		[25,38]
$K_2^{*0}(1430)$	0.084±0.040	DO	1.81	[25,35]
$f_2(1270)$	0.169±0.025	DO	1.36	[25,38]
$f_2'(1525)$	0.012±0.006	D		[25]
$\Lambda(1520)$	0.0225±0.0028	DO	1.09	[26,36]

$\sim$ momentum spectra/fragmentation functions

Multiplicities Ratios to Lower Energy Data



check of models, energy dependence, measurements, universality of fragmentation function

Measurement of BR($\omega \to \mu^+\mu^-$)

...or invert argument:

particle production rate and spectrum known:

e.g., ω from $\omega \to \pi^+\pi^-\pi^0$ decay

measure rare branching ratio: $\omega \to \mu^+\mu^-$

leptonic widths Γ of vector mesons V
depends on quark composition

$$\Gamma(\mathrm{V} \to \mathrm{l}^+\mathrm{l}^-) = \frac{16\pi\alpha^2 Q^2}{m_\mathrm{V}^2}|\psi(0)|^2 \ ,$$

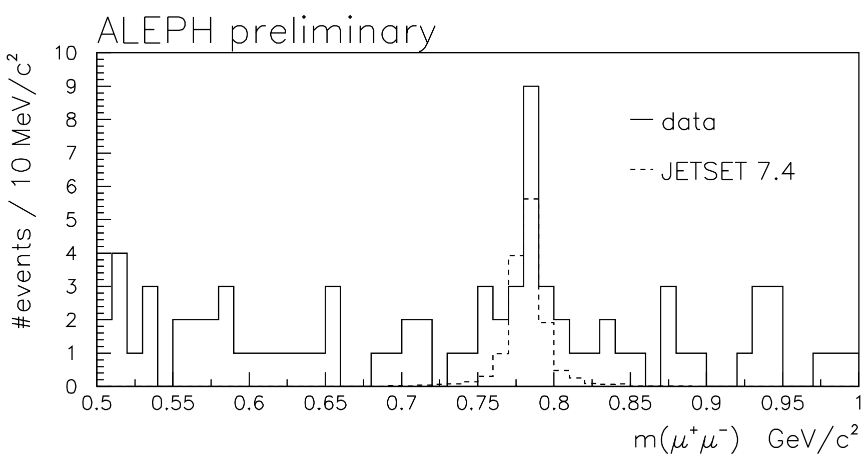
$Q^2 = |\sum a_i Q_i|^2$ superposition of quark amplitudes

$\rho^0 = 1/\sqrt{2}(\mathrm{u\bar{u}} - \mathrm{d\bar{d}})$

$\omega = 1/\sqrt{2}(\mathrm{u\bar{u}} + \mathrm{d\bar{d}})$

$\phi = \mathrm{s\bar{s}}$

PDG: BR($\omega \to \mu^+\mu^-$) $< 1.8 \times 10^{-4}$(CL=90%)

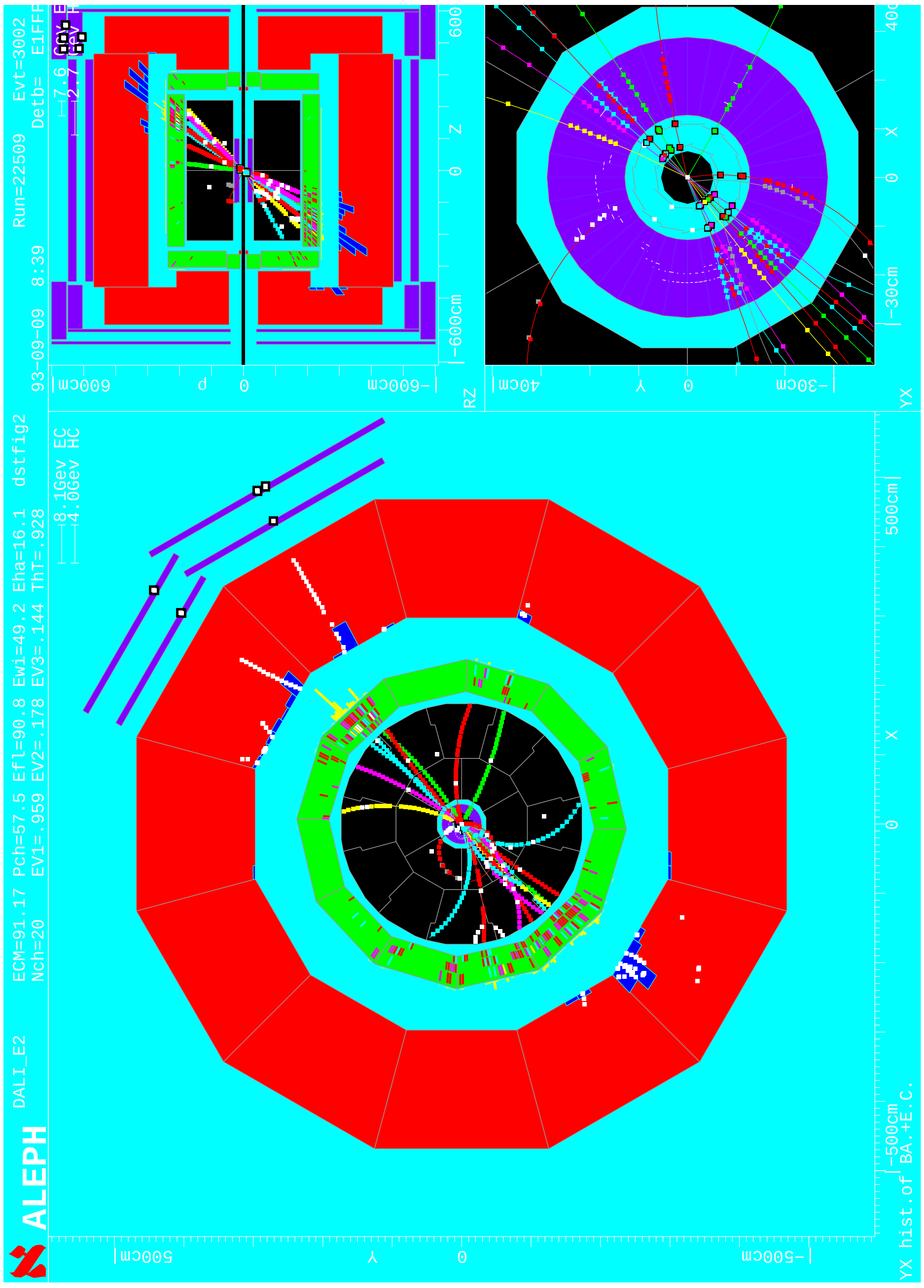


$$\mathrm{BR}(\omega \to \mu^+\mu^-) = (9.0 \pm 2.9 \pm 1.1) \times 10^{-5}$$

first measurement

agrees with BR($\omega \to \mathrm{e}^+\mathrm{e}^-$) $= (7.07 \pm 0.19) \times 10^{-5}$ (PDG)

Run 22509, Evt 3002: $m(\mu^+,\mu^-) = 782\,\mathrm{MeV}$



Two-Photon Physics at LEP

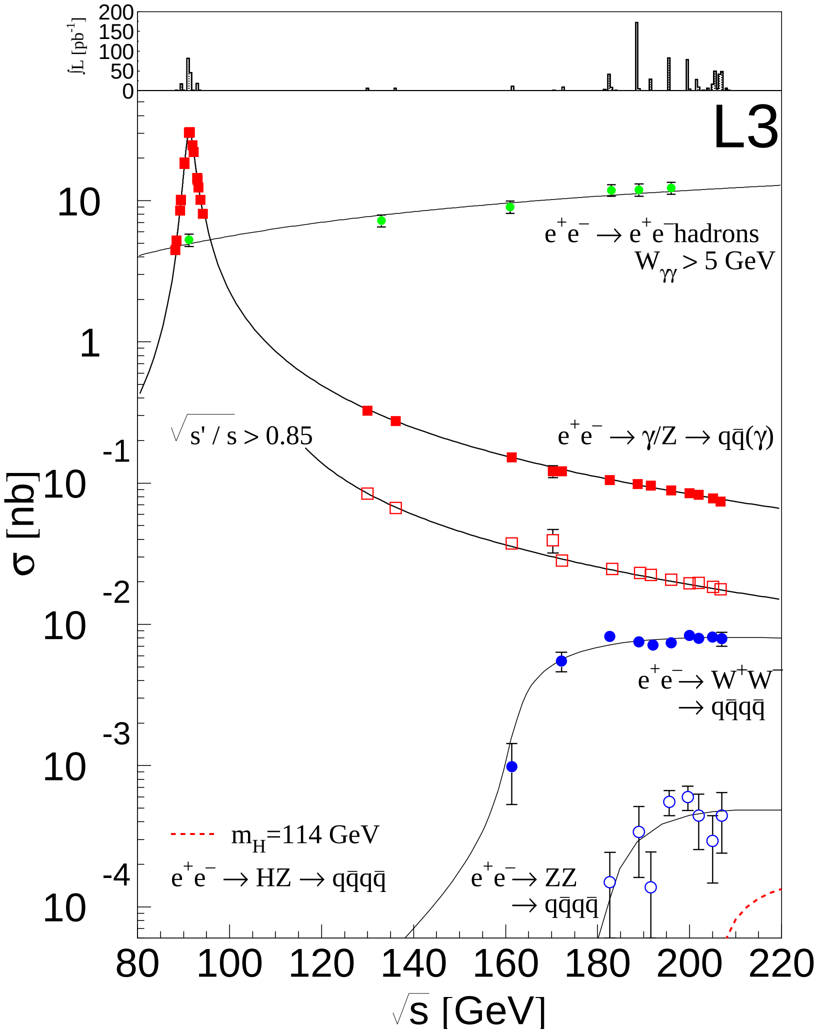
- Introduction
- Global event properties
- Structure functions
  Leptonic
  Hadronic single-tag
- Hadronic double-tag (BFKL)
- Total cross section
- Jets in $\gamma\gamma$
- Heavy flavour
  charm, bottom
- Inclusive particle production
- Exclusive particle production
- Conclusion

Armin Böhrer / DESY Hamburg, Nov. 2001

Cross Sections at LEP

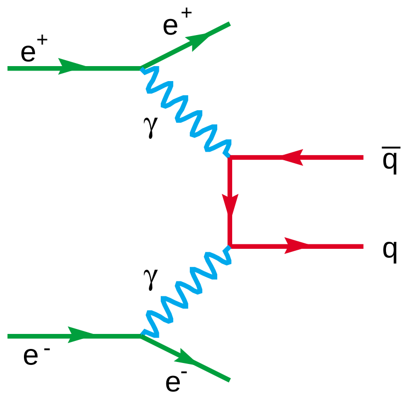
LEP has been build to study gauge bosons:

Z(LEP 1)	W(LEP 2)
g(LEP 1 +LEP 2)	γ(LEP 1+LEP 2)

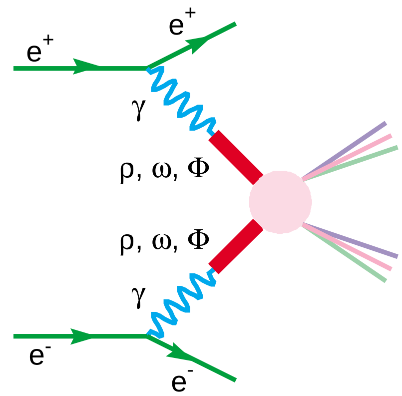


LEP2: majority of hadrons are from $\gamma\gamma$ collisions!

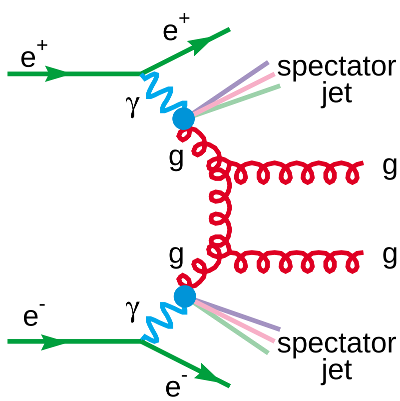
Commonly Used Classification



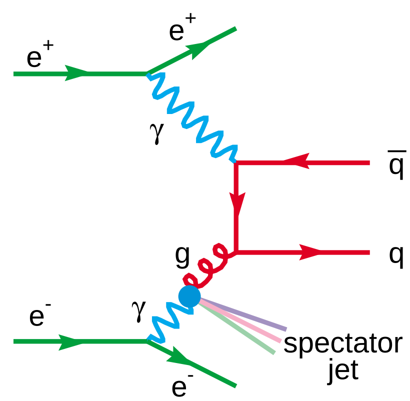
Direct



VDM



Double Resolved



Single Resolved

no-tag events (anti-tag events):

no scattered $e^{\pm}$ detected

single-tag events:

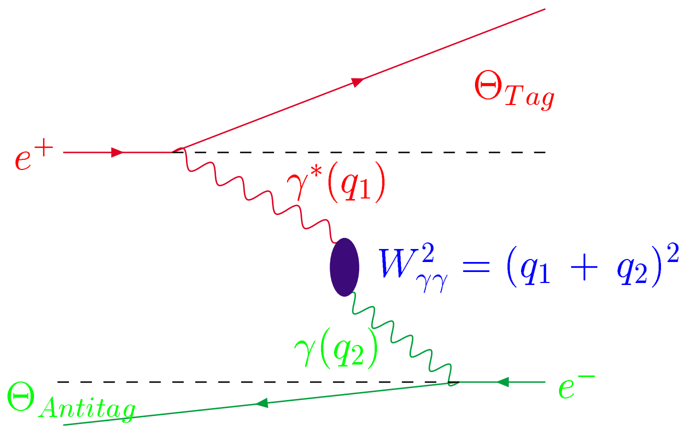
one scattered $e^{\pm}$ detected

double-tag events:

both scattered $e^{\pm}$ detected

$F_2^\gamma(x, Q^2)$

Measurement in single-tag events:
One electron (or positron) seen in detector



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

with

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

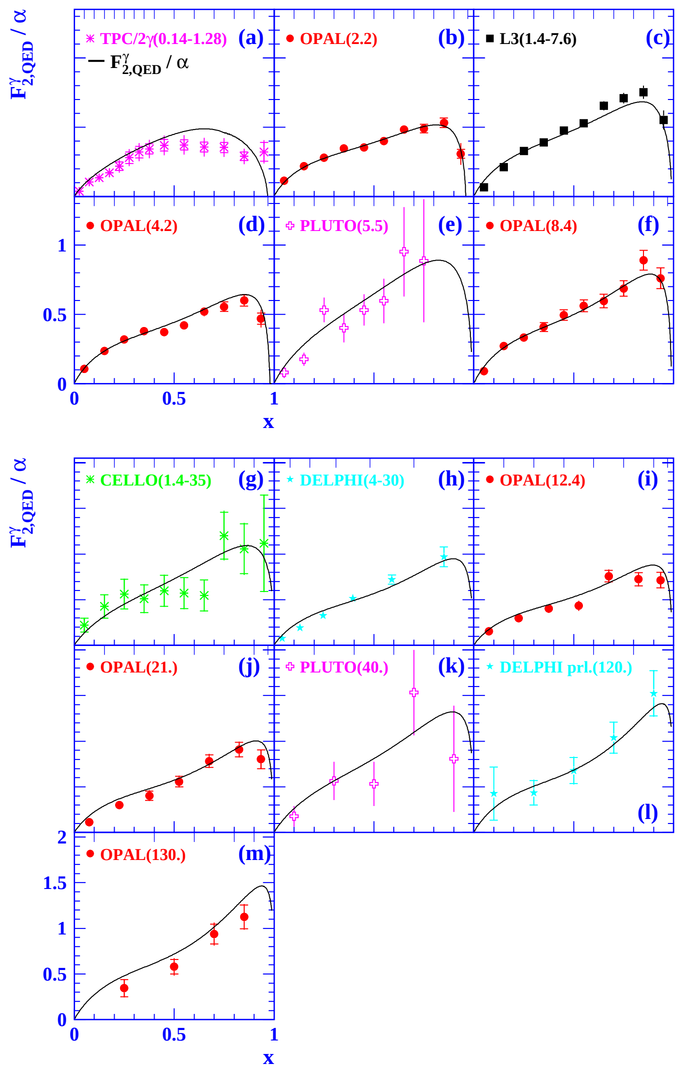
y small $\Rightarrow$ contribution from F_L^γ small

get F_2^γ from $\mathrm{d}\sigma/\mathrm{d}x$ after corrections
(background, acceptance; unfolding)

$F_{2,QED}^{\gamma}$

Increase at high $x \Rightarrow$ the point-like component

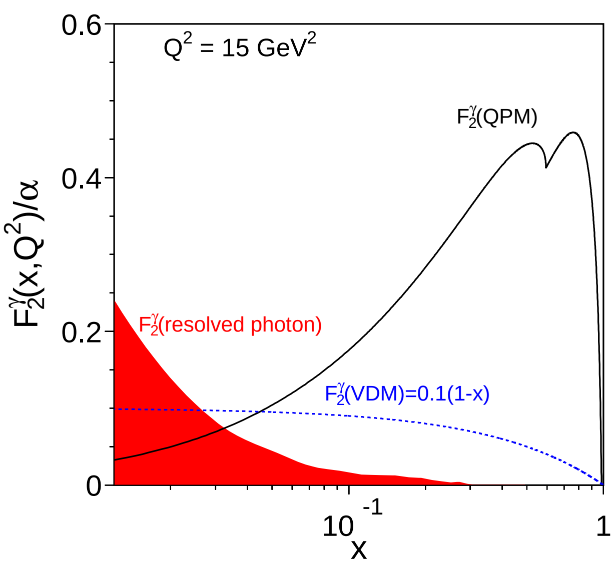
Dominated by real photon interaction

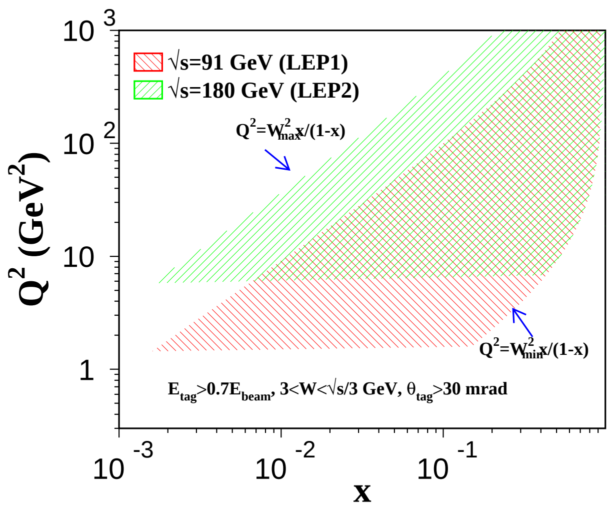


QED nicely describes data

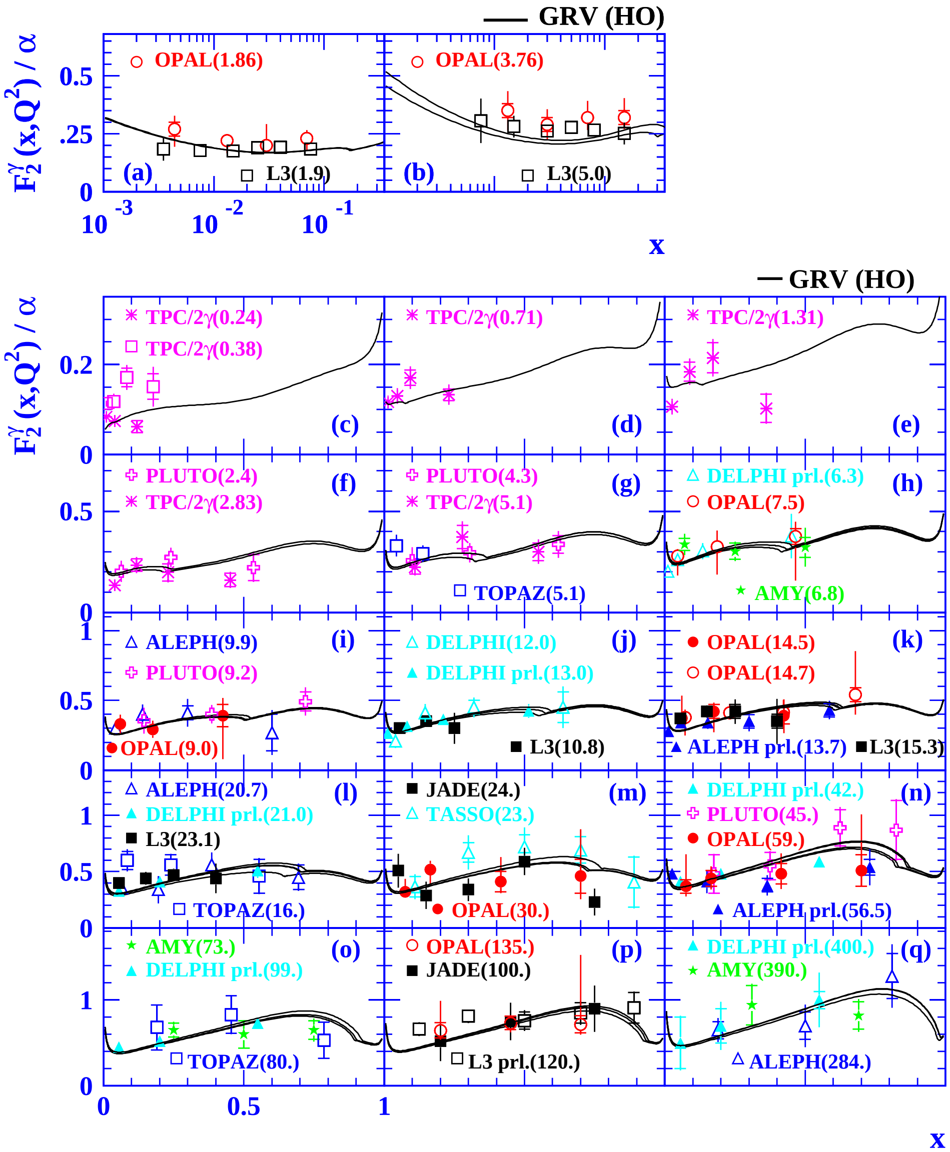
Hadronic Structure of the Photon: F_2^γ

- at high x point-like component dominates: $\sim$ QED
- various parameterizations of structure functions, however,
  QCD predicts evolution with Q^2
  increase as function of Q^2; steeper for small x
  data constrain in a wide x and Q^2 range
  - hadronic final state ($\neq$ leptonic f.s.)
    need good Monte Carlo simulation
    for detector correction (unfolding)





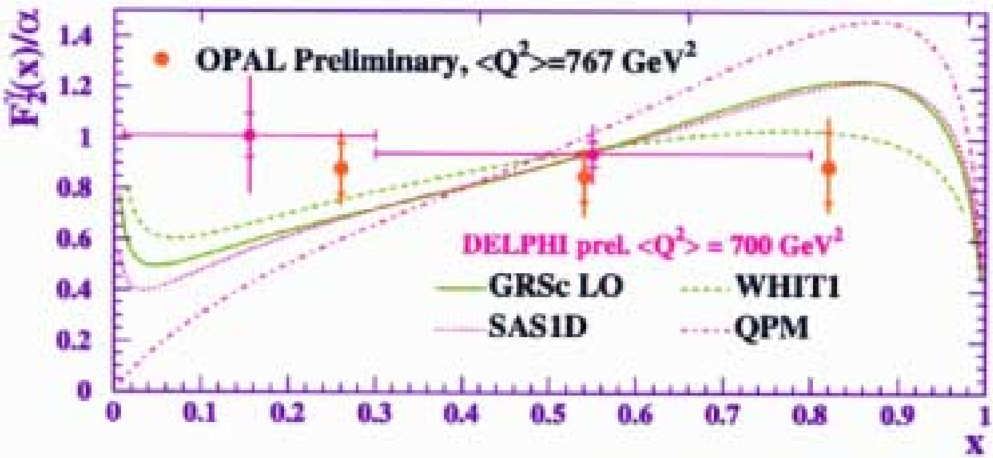
F_2^γ: Summary



- GRV and SaS parameterization describe data
- structure functions with large gluon content (e.g. LAC1) are disfavoured
- some scatter of data taken under similar conditions; consistency? systematic errors?
- TPC/2γ data at low x are disfavoured by GRV

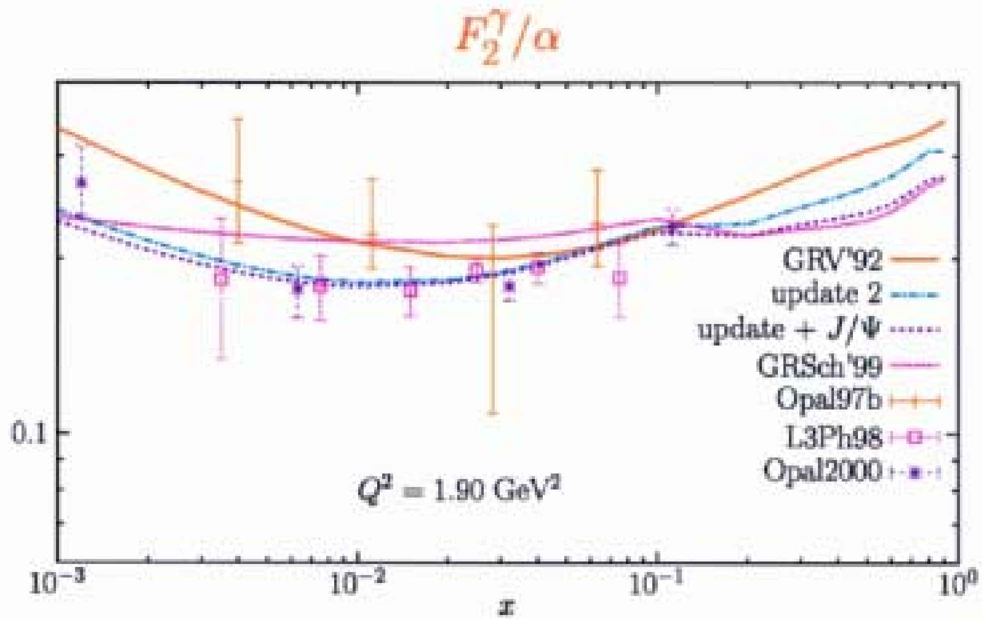
R.Taylor
I.Tiapkin

The high-Q^2 reach of F_2^γ



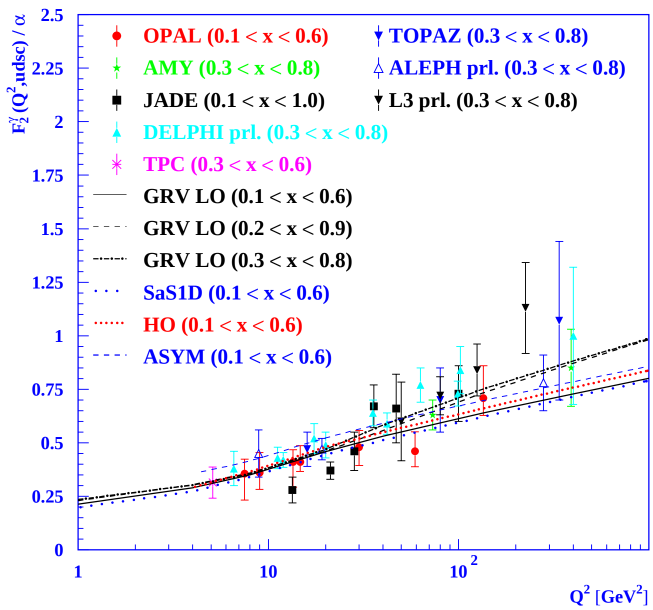
'Summary' of the theory contribution

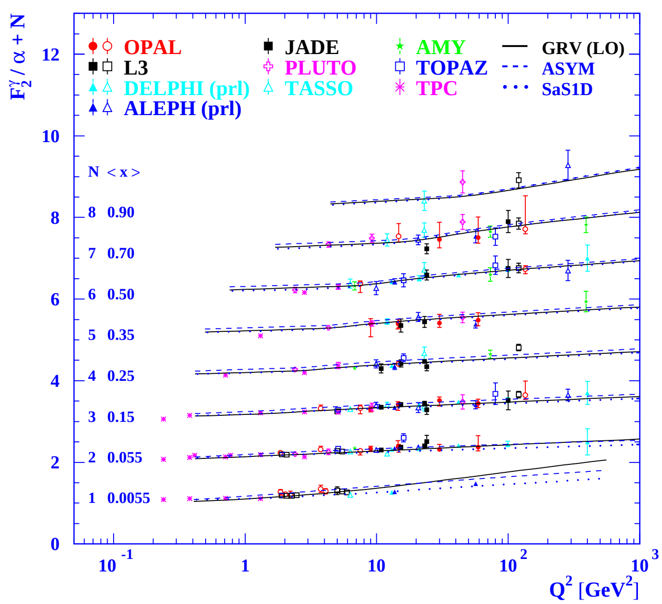
P. Jankowski



(R. Nisius)

F_2^γ: Evolution with Q^2; ..and for Different x





data show logarithmic rise with Q^2 as expected:

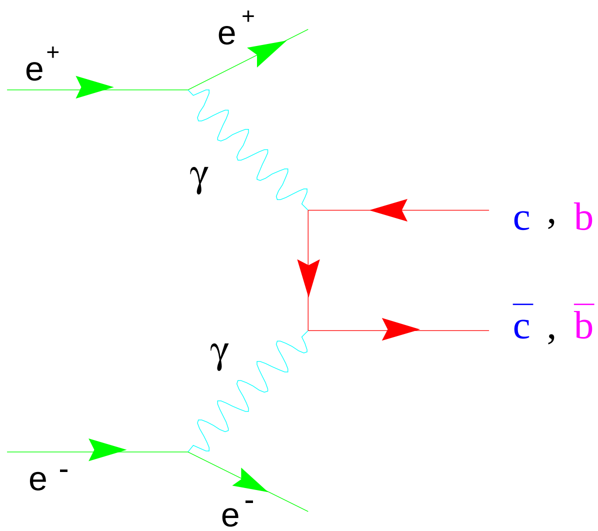
$$F_2^\gamma = a + b \ln \frac{Q^2}{\Lambda}$$

$\Lambda = 0.2$GeV is used

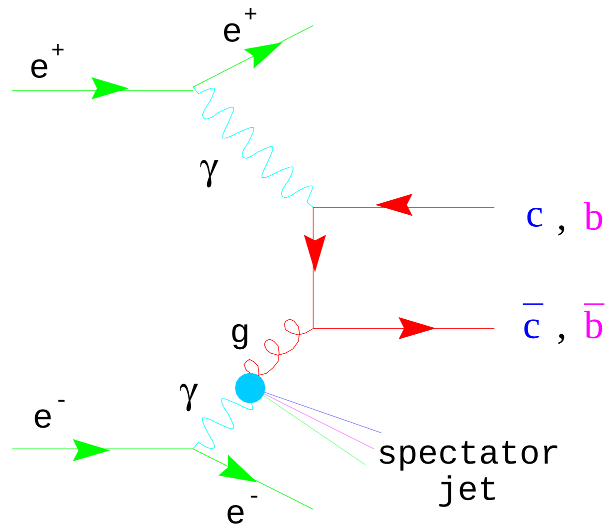
slope increases with increasing x as expected:

positive scaling violation ($\gamma \to q\bar{q}$; QED)

Heavy Flavour Production



Direct



Single Resolved

Test of perturbative QCD:

LEP II energies:

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

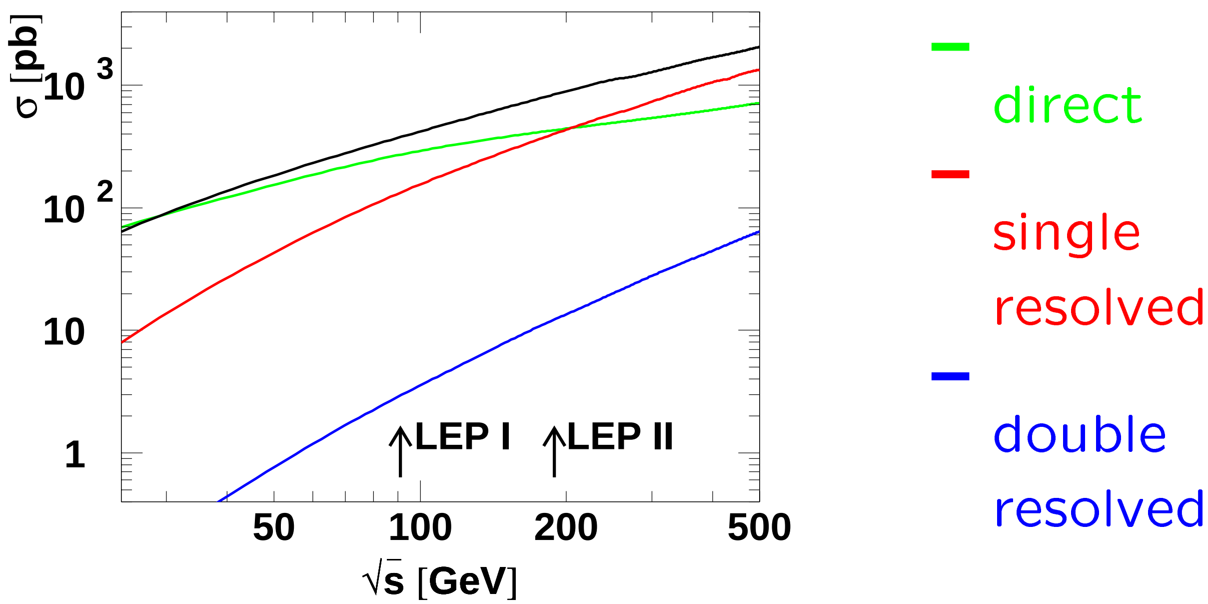
- direct process depends on quark mass (m_c, m_b) and α_s
- resolved process depends on gluon content of photon
- heavy quark production primarily charm $\sigma(\gamma\gamma \to c\bar{c}X) >> \sigma(\gamma\gamma \to b\bar{b}X)$

Total Cross Sections

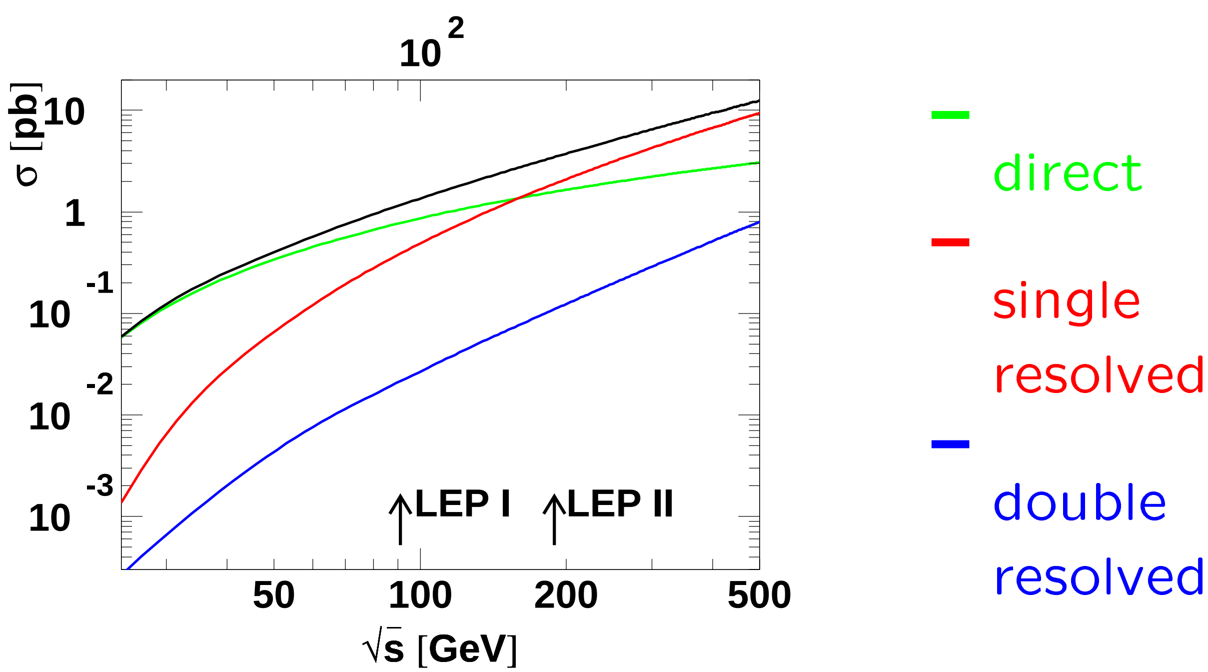
Theoretical Prediction

(Drees, Krämer, Zunft, Zerwas)

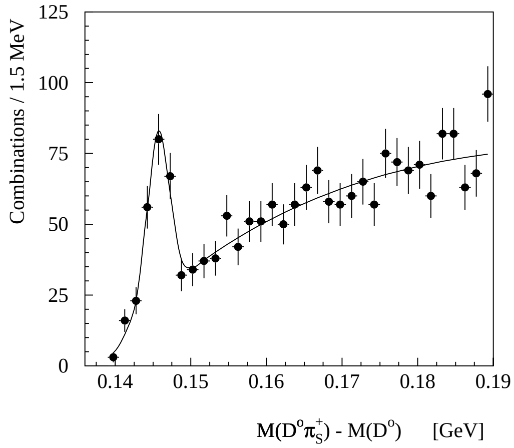
$\sigma(e^+e^- \to e^+e^- c\bar{c})$



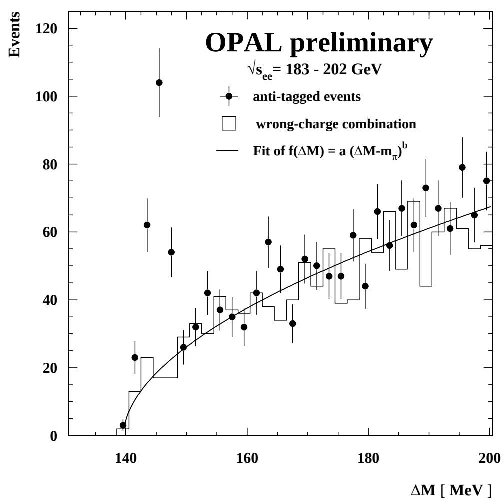
$\sigma(e^+e^- \to e^+e^- b\bar{b})$



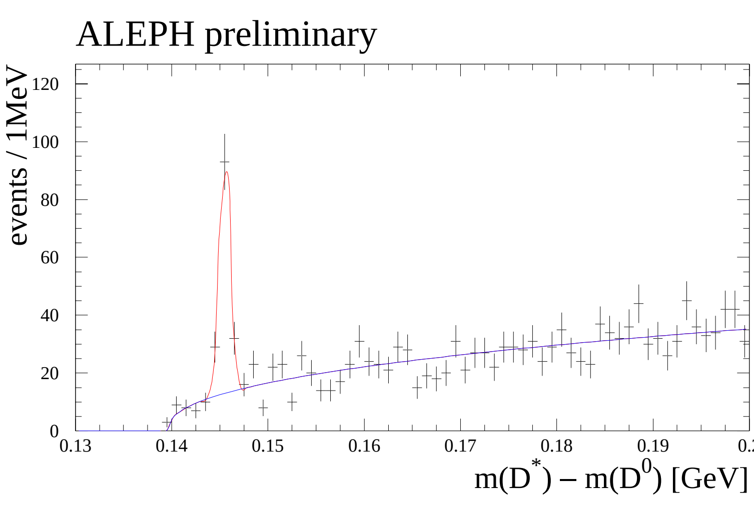
$D^{*\pm}$, Signals



L3: 144 now 544 events

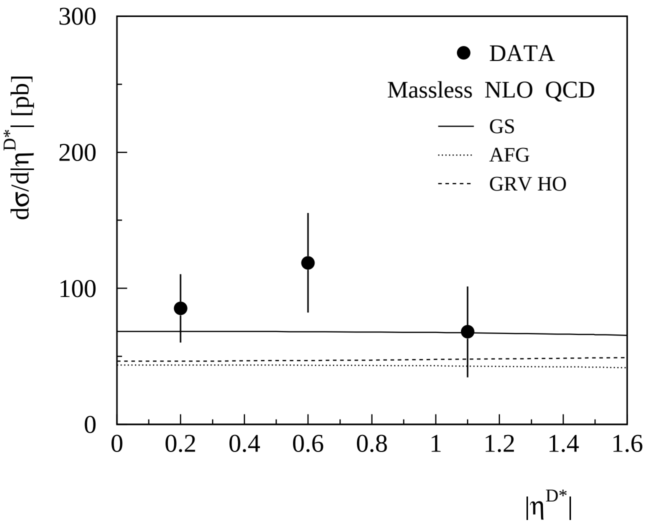


OPAL: 164 events



ALEPH: 113 events

$D^{*\pm}$, Pseudorapidity

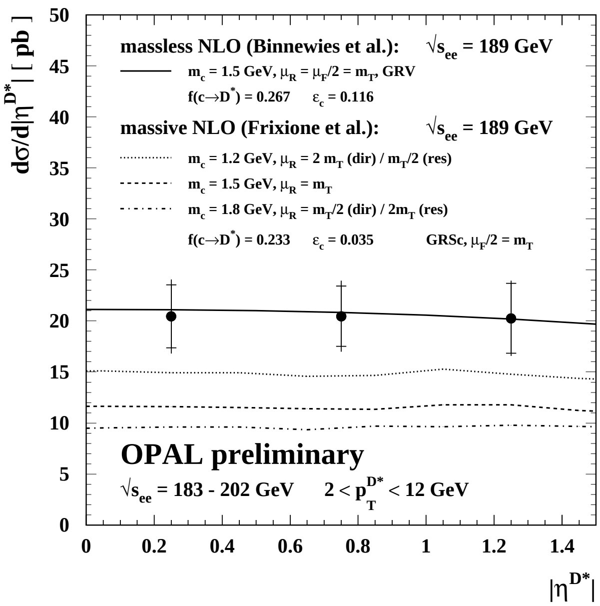


L3:

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

$|\eta| < 1.4$

reasonable agreement with NLO QCD (massless)

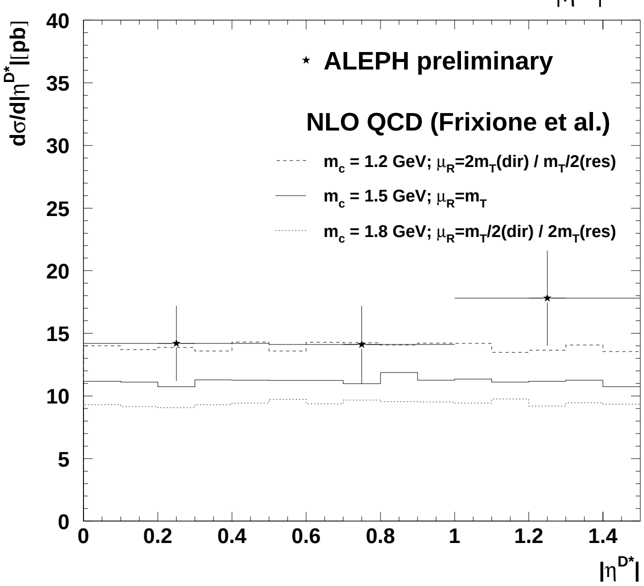


OPAL:

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

$|\eta| < 1.5$

good agreement with NLO QCD (massless)



ALEPH

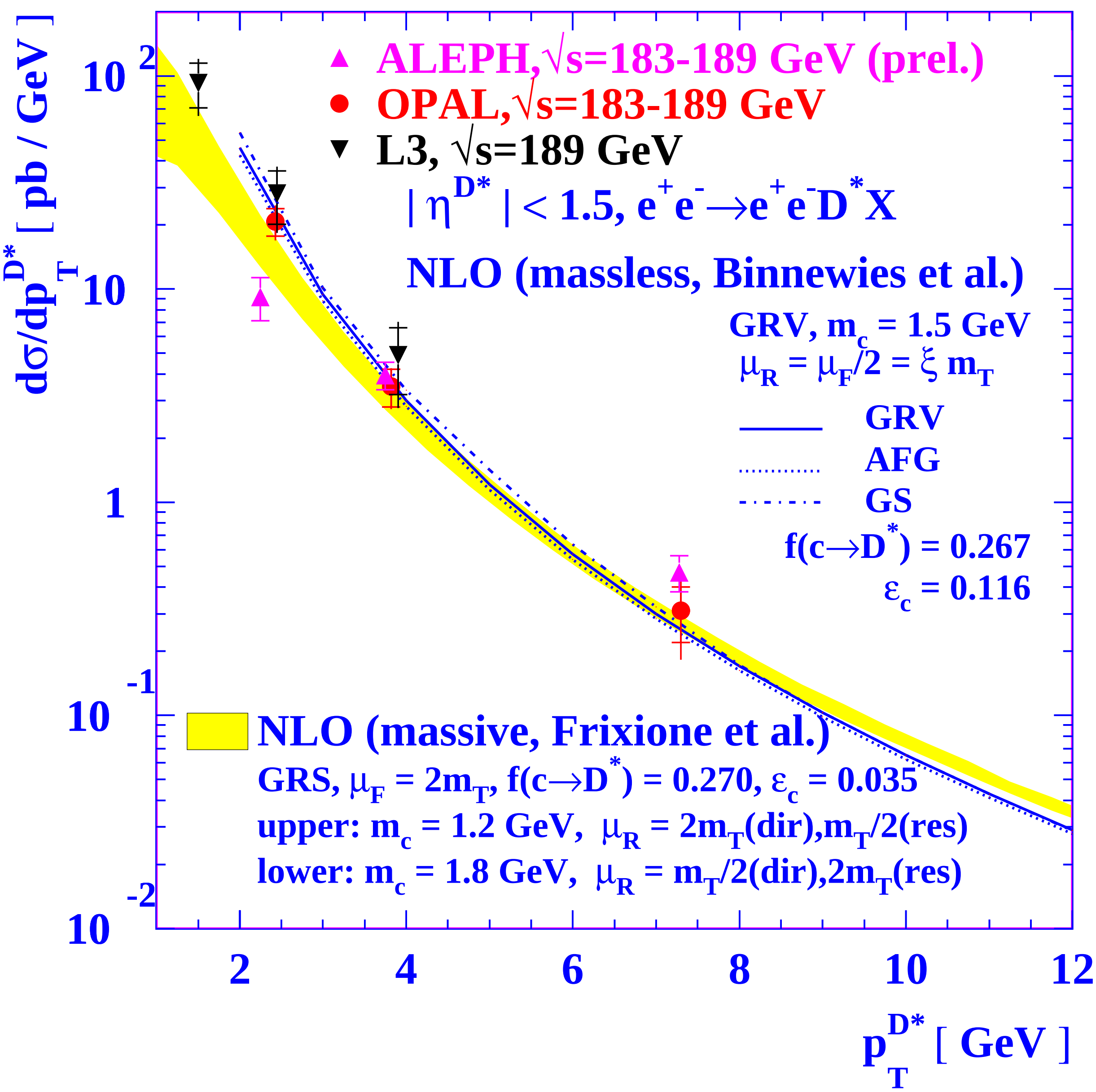
$2\ \text{GeV} < p_t(D^{*\pm}) < 12\ \text{GeV}$

$|\eta| < 1.5$

good agreement with NLO QCD (massive)

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

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



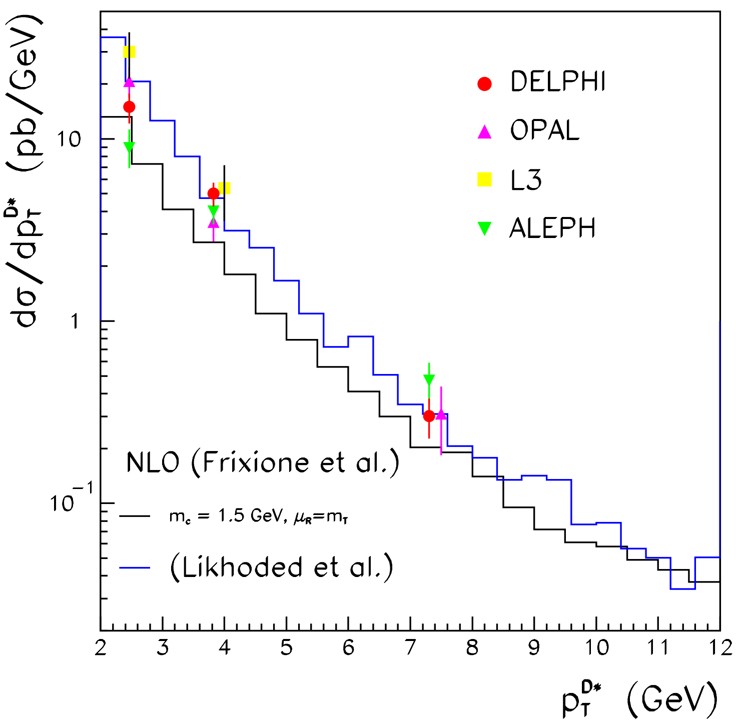
massless calculation in agreement with L3 and OPAL

massive calculation closer to ALEPH

ALEPH different slope to L3 and OPAL

$d\sigma/dp_T^{D^*}$ - comparision with other experiments

$\mid \eta^{D^*} \mid < 1 \rightarrow \mid \eta^{D^*} \mid < 1.5$



agreement with OPAL and L3;
different slope observed by ALEPH

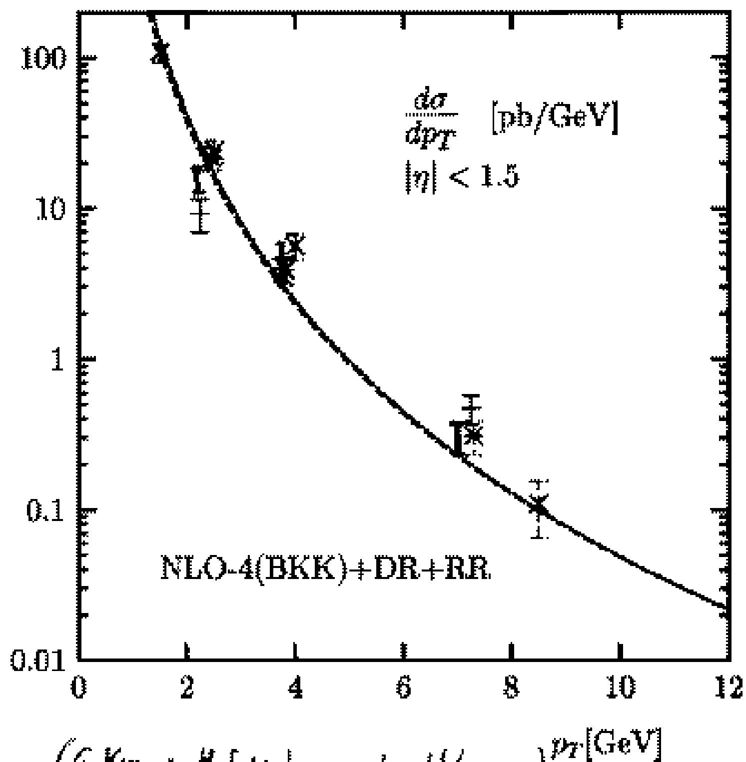


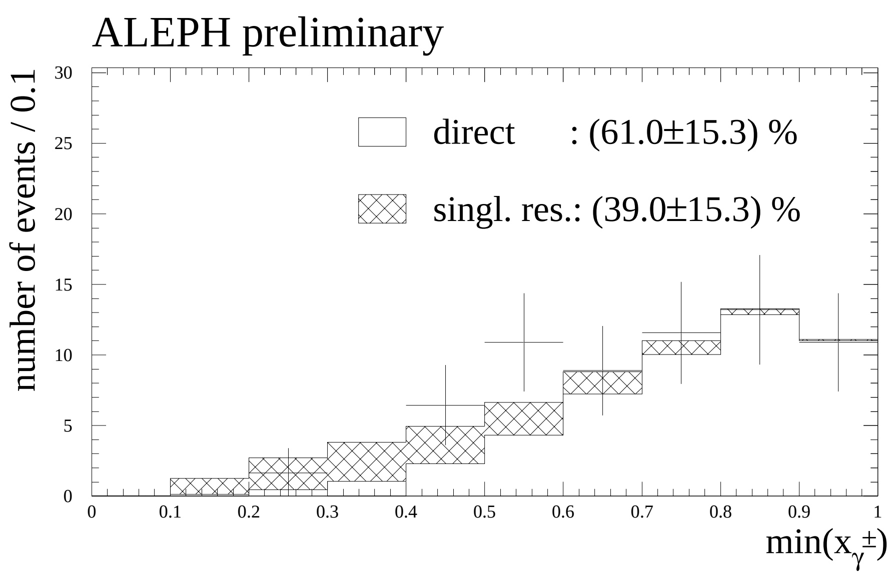
Figure 8: p_T distribution $d\sigma/dp_T$ after integration over $|\eta| < 1.5$ in the NLO 4-flavour scheme with $M_I = M_F = 2\sqrt{p_T^2 + m^2}$ including BKK-fragmentation compared to LEP data [1, 3, 23]. Full line: massless calculation, dashed line: massive calculation. Single- and double-resolved contributions are included using photon PDFs of Ref. [25].

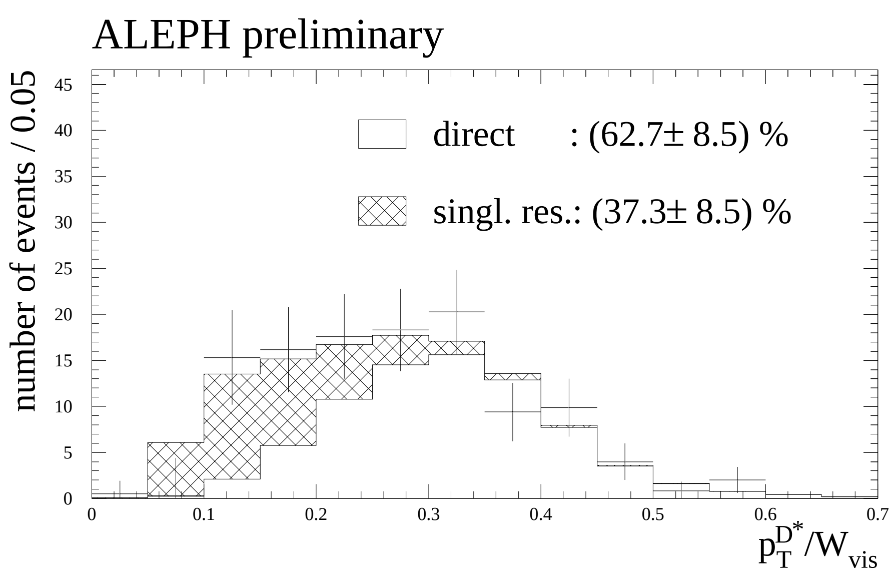
in Fig. 8. The full curve is the cross section in the massless approximation as in Fig. 7. In the dashed curve the direct massless cross section is replaced by the direct cross section with massive quarks, i.e. NLO-4(BKK) of the previous section, except for the change of factorization scales. The resolved components are as in Fig. 7. The experimental data points shown at p_T values between 1.5 GeV and 8.5 GeV are from ALEPH [1], L3 [23] and OPAL [3]. The overall agreement between the theoretical prediction (dashed curve) and the experimental data is quite good although the data points in the medium p_T range lie slightly above the theoretical curve. Even if a finite charm mass correction for the DR and RR contributions would be included, for which we expect a reduction of the theoretical prediction by approximately 15 % at $p_T = 2$ GeV and less at higher p_T, the overall agreement for $p_T \geq 2$ GeV would hardly change. The data from OPAL [3] and L3 [23] have been compared already with the predictions of the massless theory, which was

Direct and Resolved Contribution

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

$$x_T^{D*} = p_t^{D*}/W_{\text{vis}}$$





Fraction of Direct Contribution in Charm Events

Fraction of direct process

ALEPH :
$r_{\text{dir}} = (62.7 \pm 8.5)\%$

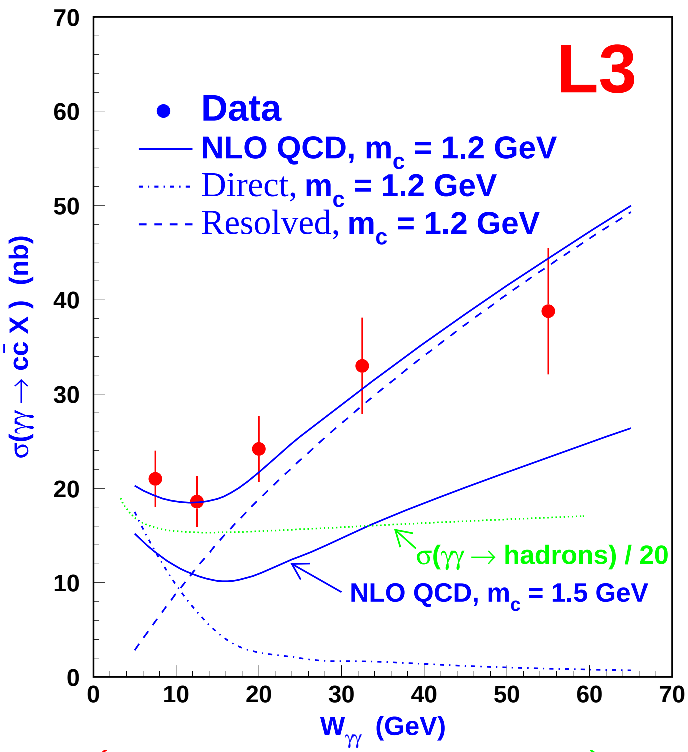
OPAL :
$r_{\text{dir}} = (44. \pm 6.)\%$

DELPHI :
$r_{\text{dir}} = (55. \pm 11.)\%$

NLO QCD (Frixione et al.):
$r_{\text{dir}} = (70.4\,^{+4.6}_{-7.2})\%$

Total Charm Cross Section

$\sigma(\gamma\gamma \rightarrow c\bar{c}X)$ vs $W_{\gamma\gamma}$



$\sigma_{\text{tot}} = As^{\varepsilon} + Bs^{-\eta}$ (Pomeron + Reggeon)

- Steeper rise with energy : $\varepsilon = 0.40 \pm 0.08$
- Data agree with NLO calculations $m_c = 1.2$ GeV
  S.Frixione et al. J.Phys.G 26(2000)723.
- Direct ($\gamma\gamma \rightarrow q\bar{q}$) decreases
  Resolved ($\gamma g \rightarrow q\bar{q}$) increases

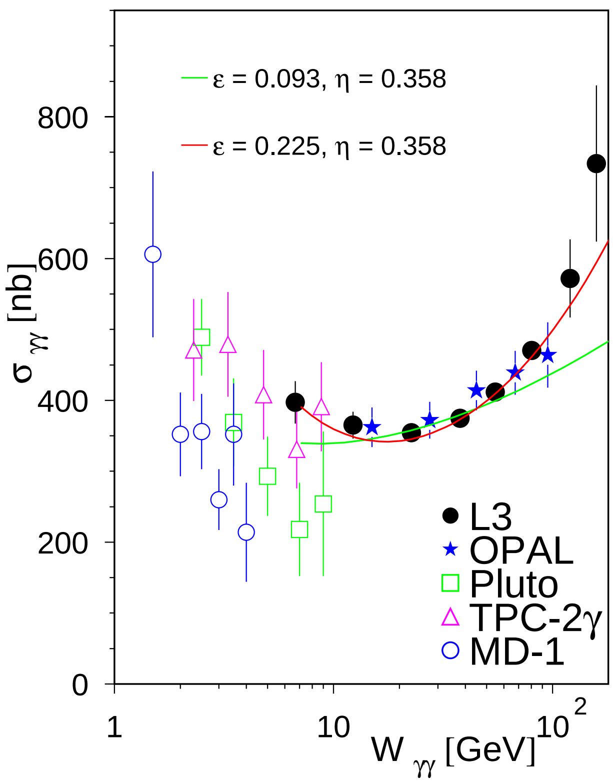
PYTHIA is only 66% of charm cross section

$\Rightarrow$ NLO corrections needed

Total Cross Section; All Flavours; LEP

$\sigma(\gamma\gamma \rightarrow hadrons)$ vs $W_{\gamma\gamma}$

Taking out $L_{\gamma\gamma}$ (QED) and exptrapolating to $Q^2 = 0$



Regge parameterization (Reggeon + Pomeron):

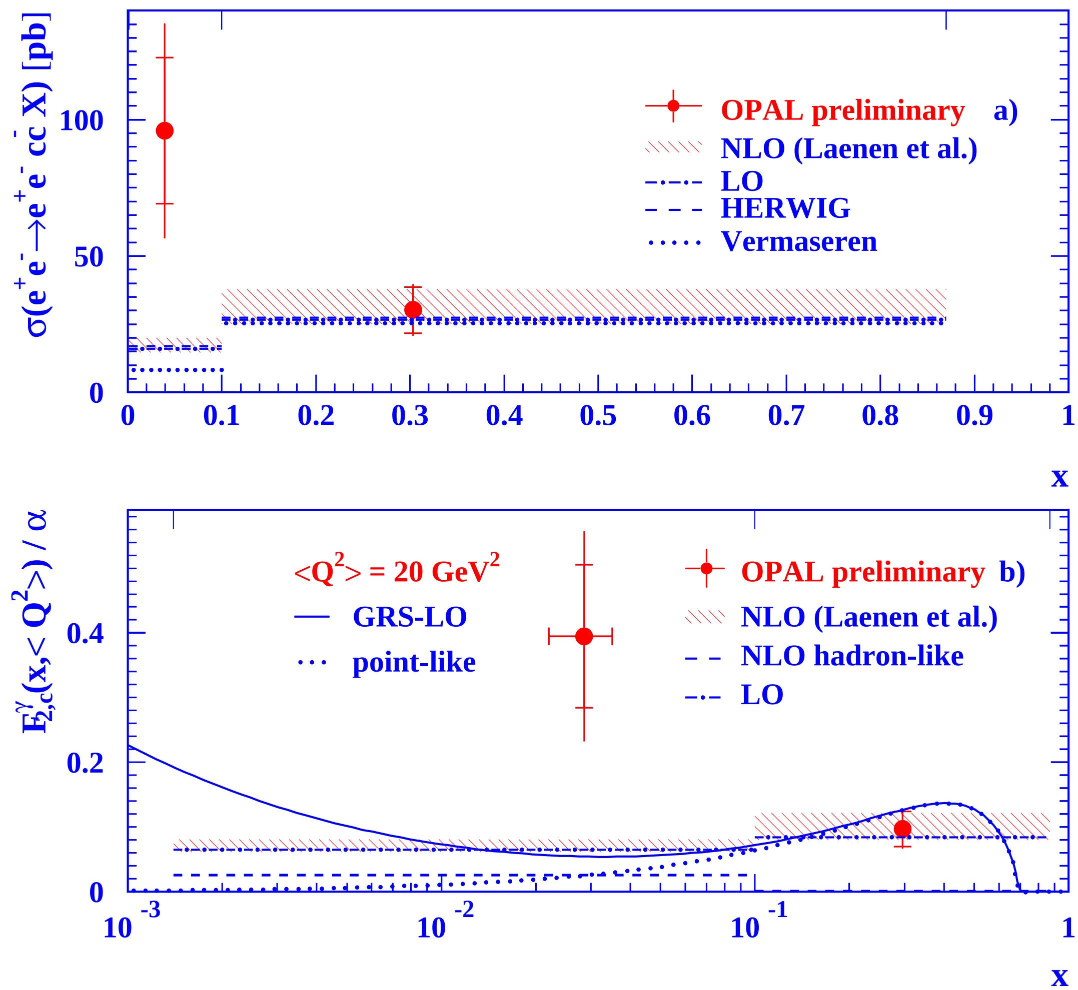
$$\sigma_{\gamma\gamma} = Bs^{-\eta} + As^{\varepsilon}, \ s = W^2_{\gamma\gamma}$$

If photons behave like hadrons, ε and η are *Universal* and constrained by hadron–hadron and γp data (PDG 2000):

$\varepsilon = 0.093 \pm 0.002$ soft Pomeron

Best fit $\varepsilon = 0.225 \pm 0.021$ ($\gamma \rightarrow q\bar{q}$ ⇨ hard Pomeron)

Charm Structure Function

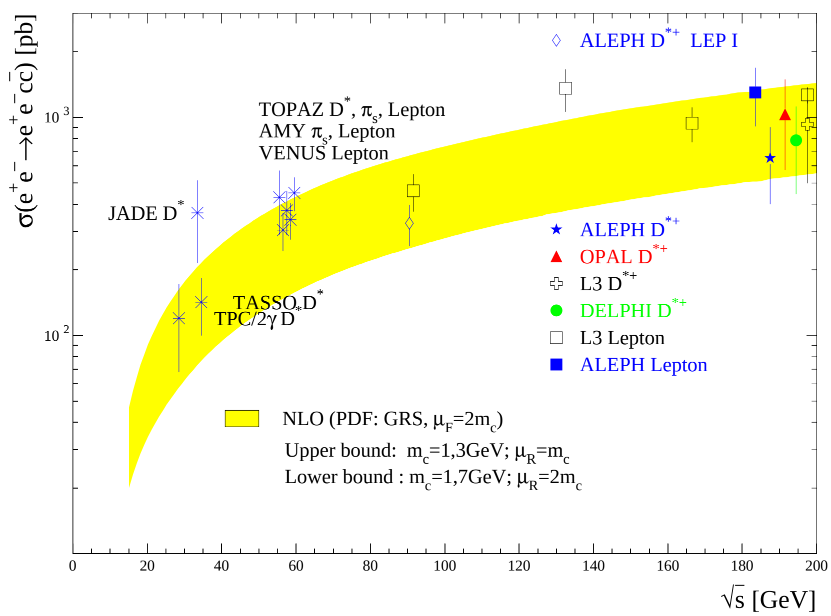


$x > 0.1$ agreement = pointlike part
(free parameters m_c, α_s)
calculable in perturbative QCD:
NLO Laenen = agreement

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

Inclusive Charm Cross Section

Total cross section $\sigma(e^+e^- \to e^+e^- D^* X)$



ALEPH ($\sqrt{s} = (183 - 189)$ GeV)
651 ± 75(stat.) ± 176(sys.) [pb]

OPAL ($\sqrt{s} = (183 - 202)$ GeV)
1033 ± 102(stat.) ± 111(sys.) ± 246(extr.)

L3 ($\sqrt{s} = (183 - 209)$ GeV)
929 ± 71(stat.) ± 136(sys.) ± 223(extr.)[pb]

DELPHI ($\sqrt{s} = (161 - 207)$ GeV)
783 ± 78(stat.) ± 70(sys.) ± 190(extr.)[pb]

good agreement of most measurements (σ_{tot}, η, p_t?)

clear evidence for direct and resolved fraction;

quantitative agreement

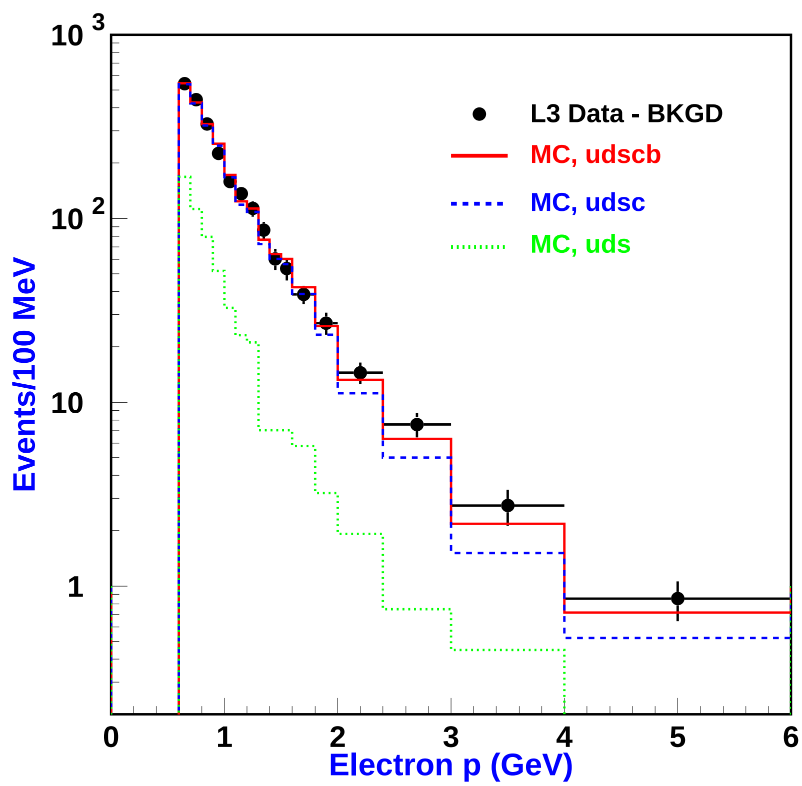
The Bottom Story

lepton(bottom) = large p

2 analysis strategies: cut- and fit analyses

2 lepton types: $e^{\pm}$ and $\mu^{\pm}$

((from 1999 conference note; old, but first+clear evidence for need of (more) bottom in $\gamma\gamma$))



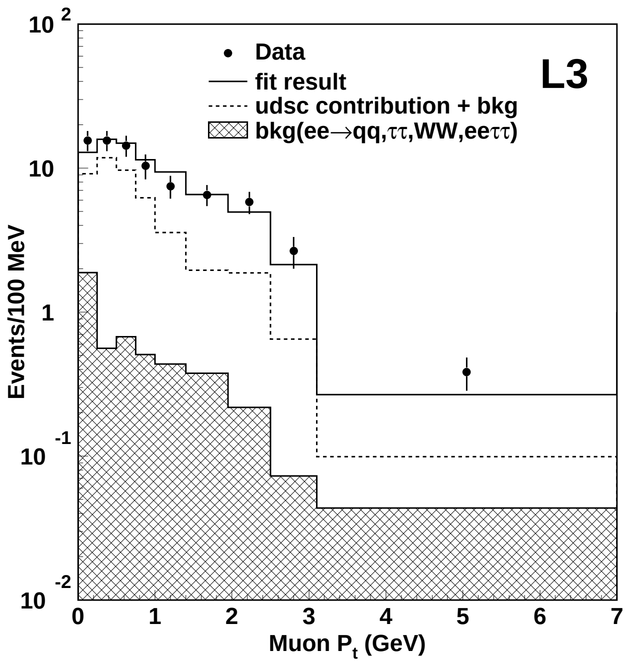
$b\bar{b}$ MC set to $\sigma(e^+e^- \to e^+e^-b\bar{b}X) = 5\,\mathrm{pb}$

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

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

b-sensitive variable:

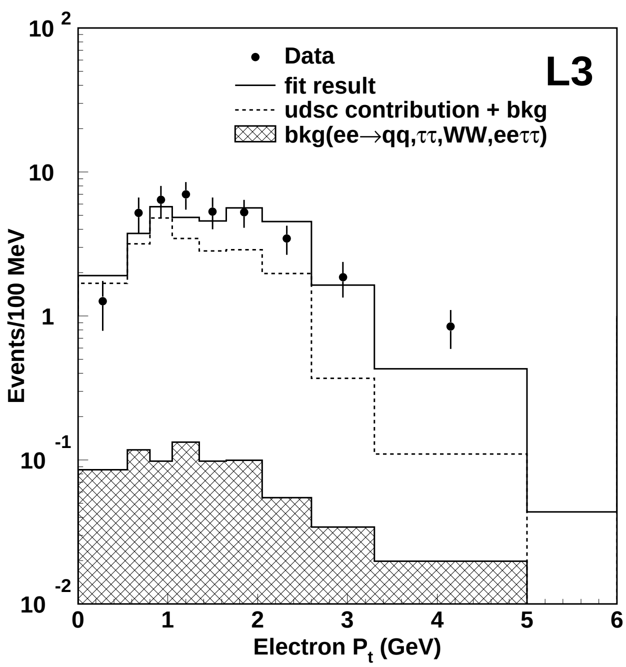
p_t(lepton) spectra to jet-direction



electrons

$p^e > 2$ GeV

b-purity 42%

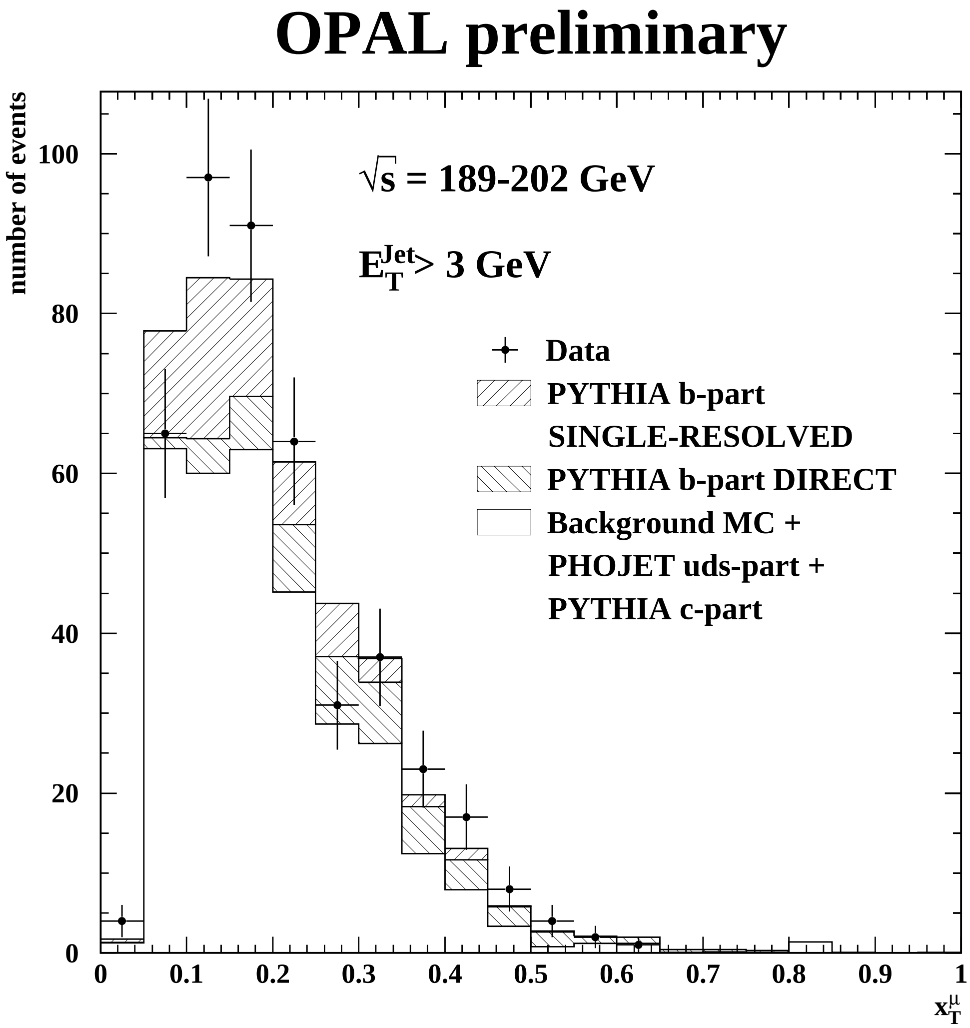


muons

$p^\mu > 2$ GeV

b-purity 51%

Bottom: Direct and Resolved Contributions



$x_{\mathrm{T}}^{\mu} = \frac{2p_{\mathrm{T}}^{\mu}}{W_{\mathrm{vis}}}$ — larger for direct than for resolved

direct plus resolved fraction of MC agree with data (about equal parts of direct and resolved)

OPAL:

$\sigma_{\rm fit} = 14.2 \pm 2.5^{+5.3}_{-4.8}\,{\rm pb}$

If $\sigma_{\rm b\bar{b}} = 0 \Rightarrow \sigma_{\rm c\bar{c}} > 2\,{\rm nb}$

L3

$\sigma_{\rm e^\pm} = 10.9 \pm 2.9 \pm 2.0\,{\rm pb}$

$\sigma_{\mu^\pm} = 14.9 \pm 2.8 \pm 2.6\,{\rm pb}$

average L3:

$\sigma_{\rm l^\pm} = 13.1 \pm 2.0 \pm 2.4\,{\rm pb}$

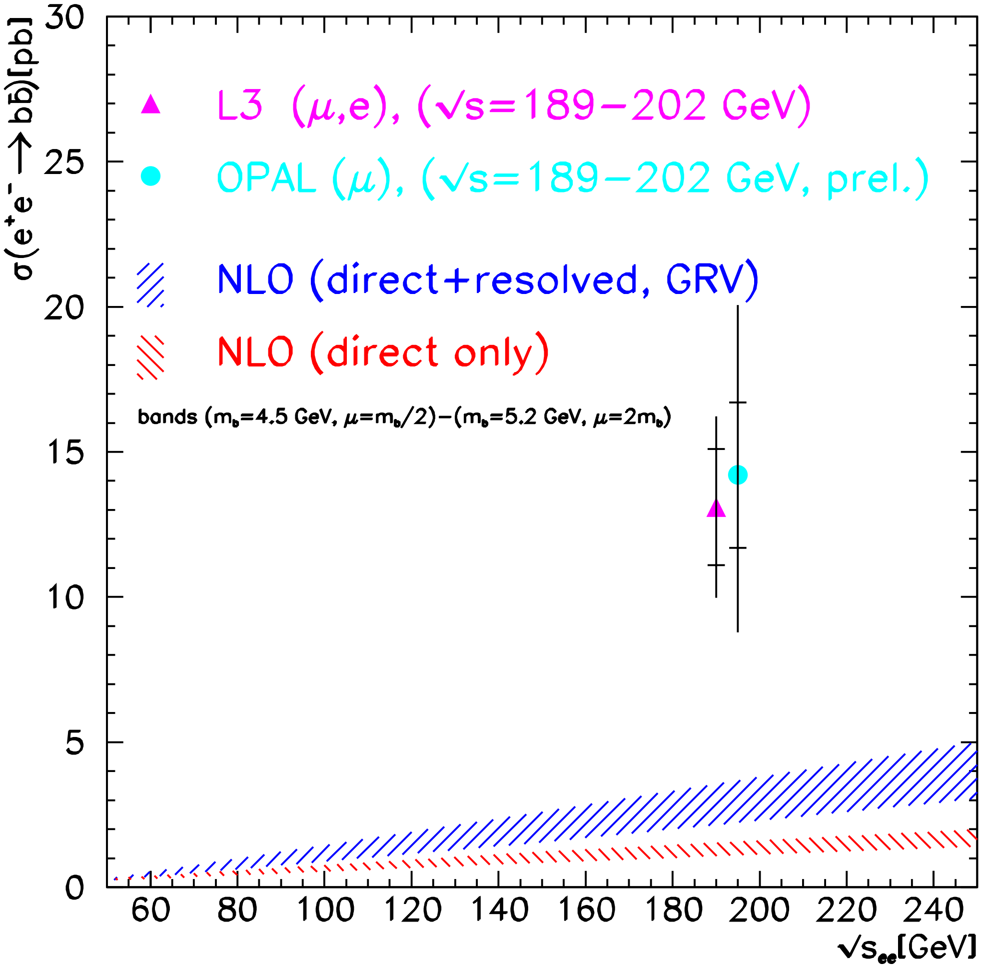
$\sigma_{\rm measured} >> \sigma_{\rm predicted}$

fitted charm cross sections

c/μ 814$\pm$164 pb

c/e 1092$\pm$226 pb

Inclusive Bottom Cross Section

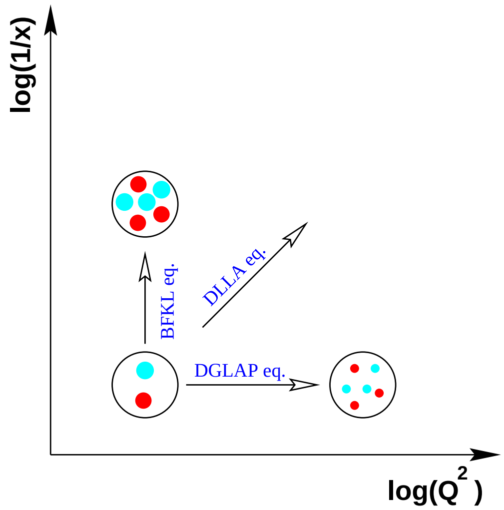


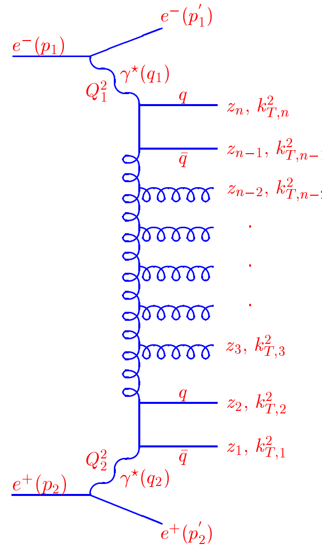
models to low: factors 3; $\approx 4\ \sigma$!

2 independent measurement;

though same methods (leptons)

Double-tag Cross Section
(Shown in the Discussion)





- DGLAP evolution scheme (leading $\ln(Q^2)$):
  - strong ordering in transverse momenta:
    $Q_1^2 \equiv k_{T,n}^2 \gg k_{T,n-1}^2 \gg ... \gg k_{T,1}^2 \equiv Q_2^2$
- BFKL evolution scheme (leading $\ln(1/x)$):
  - strong ordering in fractional longitudinal momenta:
    $x_1 \equiv z_n \ll z_{n-1} \ll ... \ll z_1 \equiv x_2$
- QPM process:
  - $\propto 1/W_{\gamma\gamma}^2$

$\Rightarrow$ double-tag events (with $Q_1^2 \approx Q_2^2$ and $W_{\gamma\gamma}^2 \gg Q_i^2$) in $\gamma\gamma$ nice place to test BFKL:

$$Y \equiv \ln\left(\frac{s_{ee}y_1y_2}{\sqrt{Q_1^2Q_2^2}}\right) \approx \ln\left(\frac{W_{\gamma\gamma}^2}{\sqrt{Q_1^2Q_2^2}}\right)$$

$\Rightarrow$ in leading order approximation

$$\sigma_{\gamma^*\gamma^*} \approx \sigma_0 \left(\frac{W_{\gamma\gamma}^2}{\sqrt{Q_1^2Q_2^2}}\right)^{\alpha_P-1}$$

$\alpha_P - 1 = 4\ln 2\frac{N_c\alpha_s}{\pi} \approx 0.53$ ($\alpha_s = 0.2$, $N_c = 3$)

Comparison: Data vs. MC and NLO

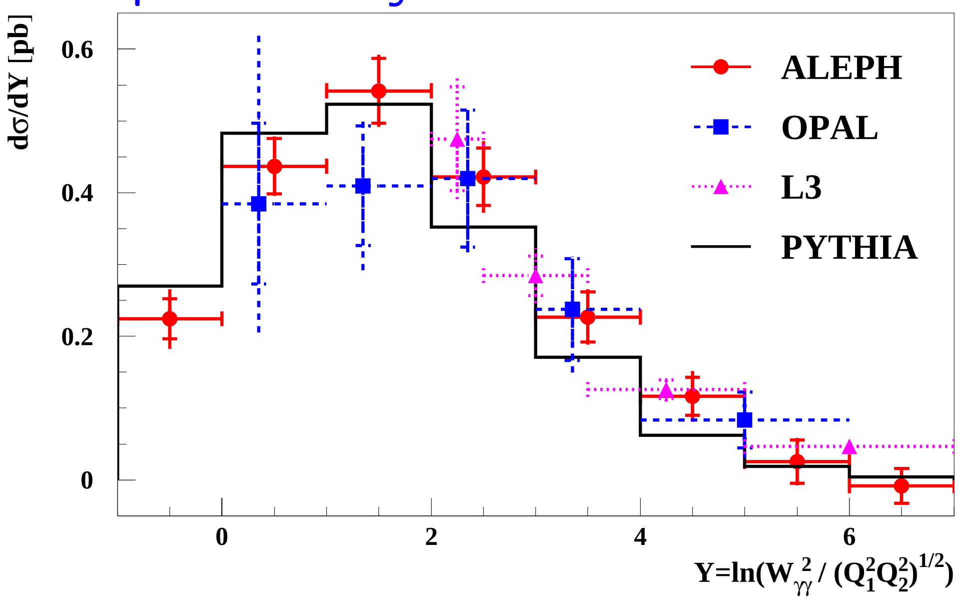
(Shown in the Discussion)

Kinematic range:

	ALEPH	OPAL	L3
$E_{\text{Tag min}}$	30% E_{beam}	40% E_{beam}	40 GeV
θ_{min}	35 mrad	34 mrad	30 mrad
θ_{max}	155 mrad	55 mrad	60 mrad
$W_{\gamma\gamma}$ min	3 GeV	5 GeV	5 GeV

Phase space interpolation with GALUGA, PYTHIA or PHOT02

preliminary ALEPH results



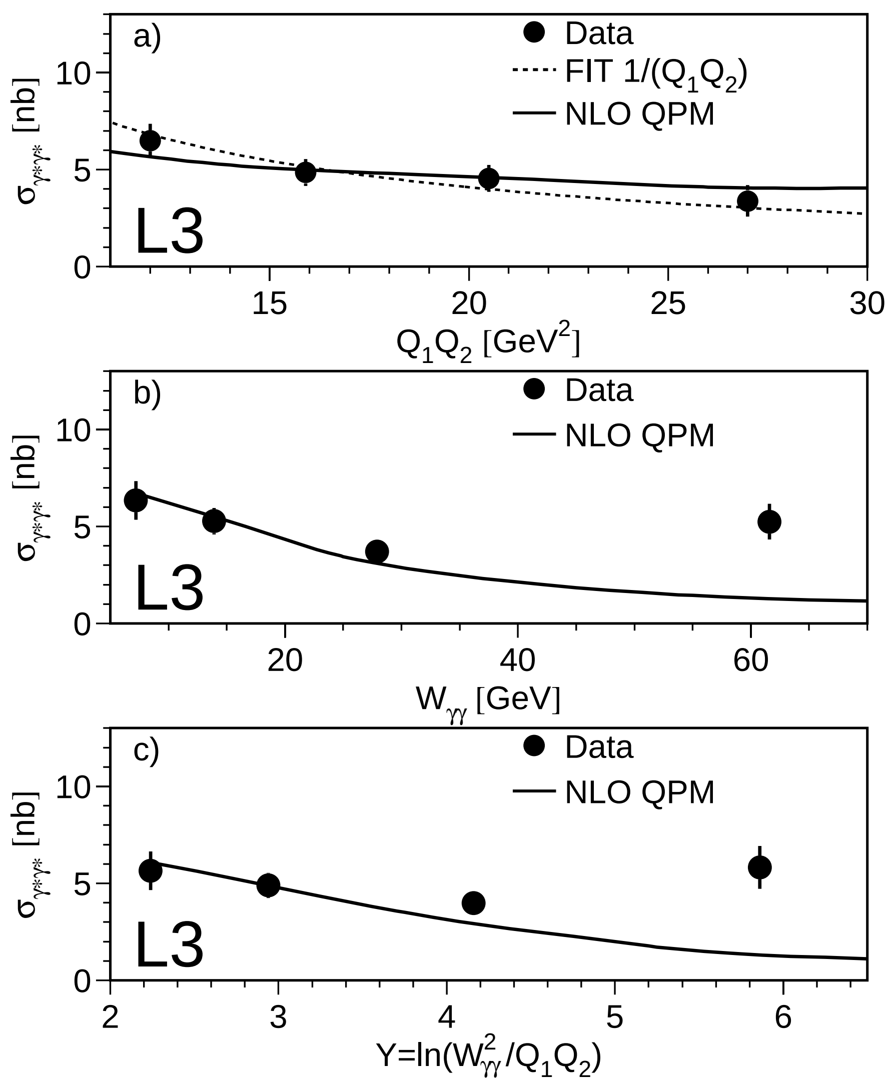
Remark:

$W_{\gamma\gamma}^2$ from hadrons (ALEPH, OPAL) or leptons (L3)

effect of initial state radiation important (L3)

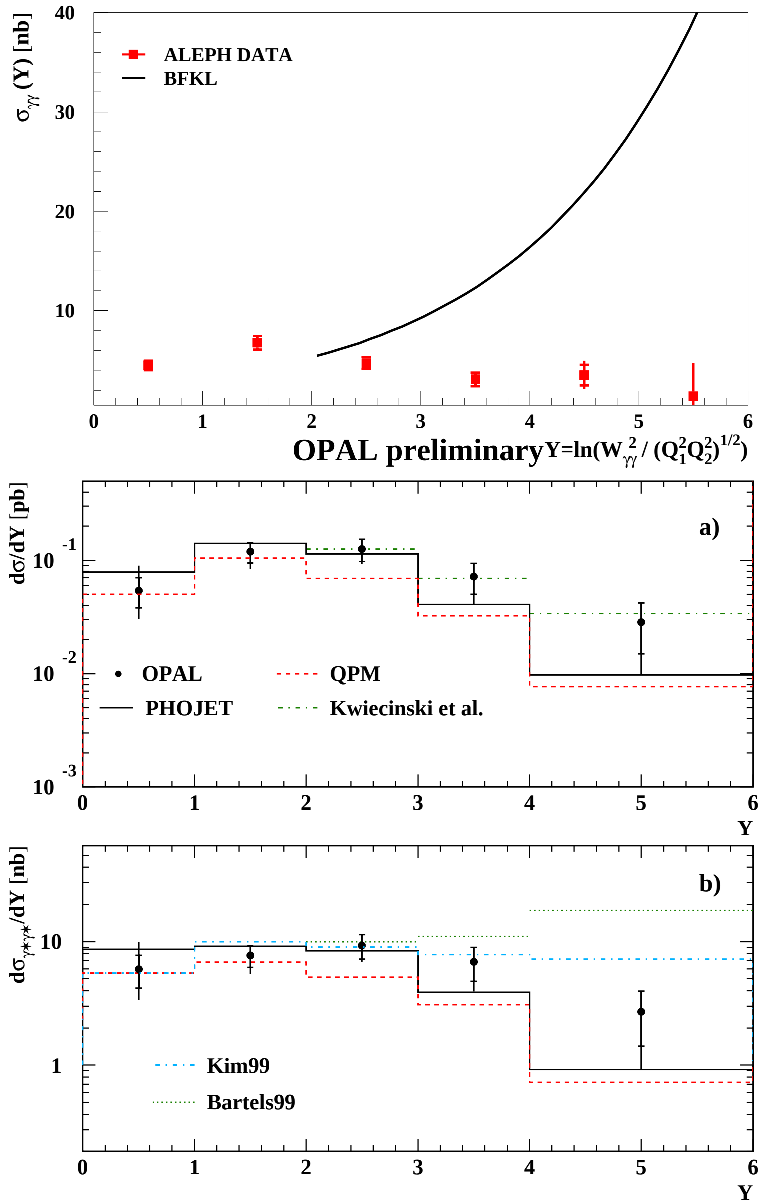
limited resolution of $W_{\gamma\gamma}^2$: some hadrons lost (AO)

Comparison: Data versus BFKL
(Shown in the Discussion)



QPM not sufficient!

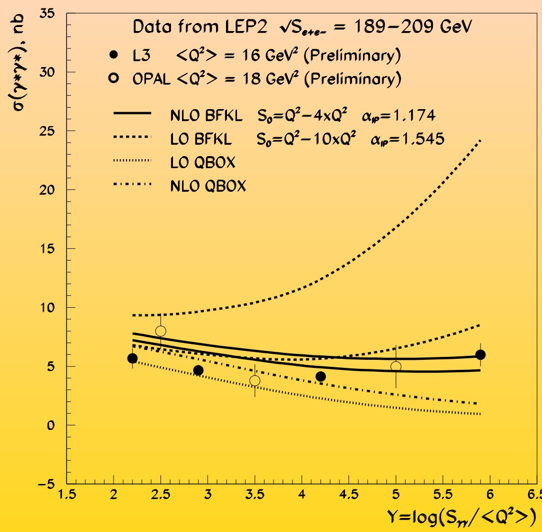
Comparison: Data versus BFKL
(Shown in the Discussion)



QPM, Phojet, NLO close to data:

BFKL needed? BFKL in excess?!

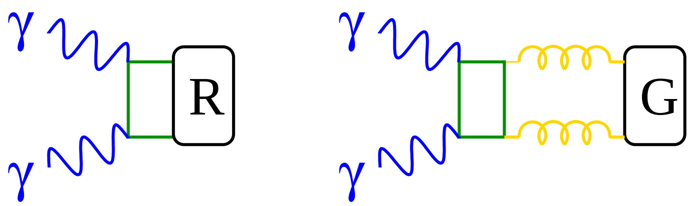
Comparison: Data versus BFKL
(Shown in the Discussion)



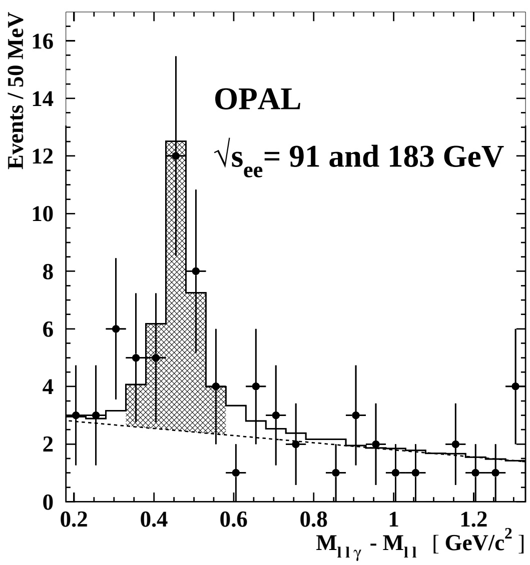
Exclusive Particle Production

Resonance production $(\gamma\gamma \to X)$

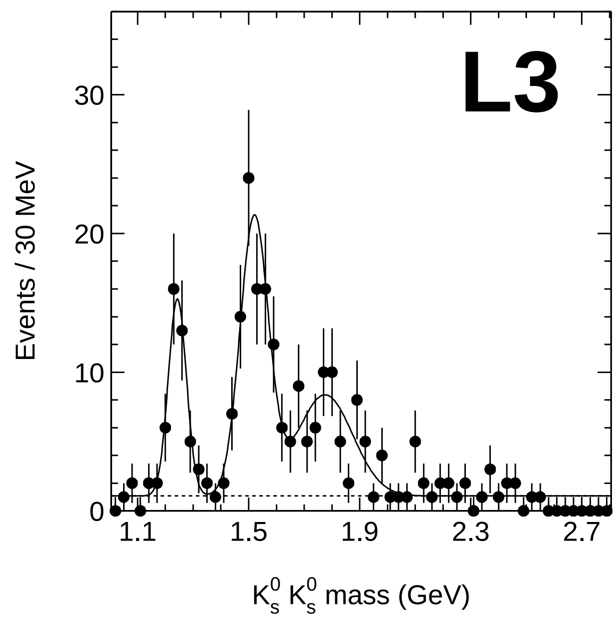
Measurement of partial width $\Gamma_{\gamma\gamma}$



z.B. $\chi_{c2} \to J/\psi\,\gamma$



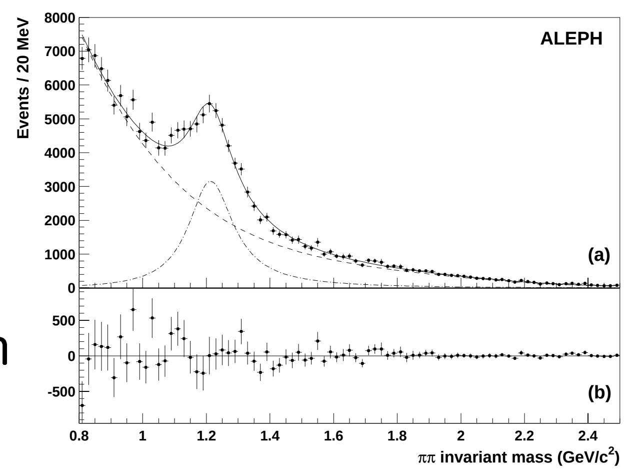
$f_2'(1525) \to K_s^0 K_s^0$



Sensitive to:

- Quark charge
- Form faktors
- (weak) coupling to photon (Glueballs!)
- Production mechanism (Dibaryon production)

$f_2(1270) \to \pi^+\pi^-$



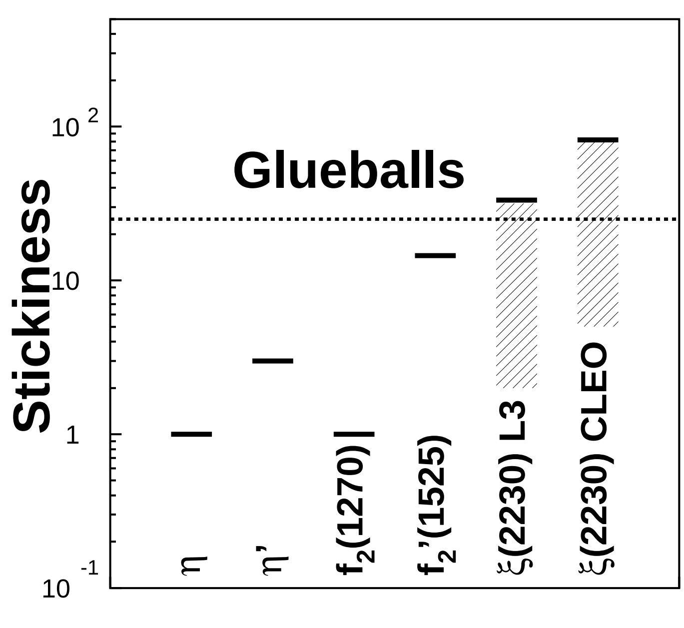
$\eta'(958)$	$\pi^+\pi^-\gamma$	0^{-+}	$4.17 \pm 0.10 \pm 0.27$	L
$a_2(1320)$	$\pi^+\pi^-\pi^0$	2^{++}	$0.98 \pm 0.05 \pm 0.09$	L
$a_2'(1752)$	$\pi^+\pi^-\pi^0$	2^{++}	$0.29 \pm 0.04 \pm 0.02*$	L
$f_2'(1525)$	$K_s^0K_s^0$	2^{++}	$0.093 \pm 0.018 \pm 0.022$	L
X(1770)	$K_s^0K_s^0$	0^{++}		L
$\xi(2230)$	$K_s^0K_s^0$	2^{++}	$\Gamma_{\gamma\gamma}\times$ BR $<$ 3eV	L
$\eta_c(2980)$	10 channels	0^{-+}	$6.9 \pm 1.7 \pm 2.2$	L
$\chi_{c2}(3555)$	$l^+l^-\gamma$	2^{++}	$1.07 \pm 0.39 \pm 0.24$	L
$\chi_{c2}(3555)$	$l^+l^-\gamma$	2^{++}	$1.76 \pm 0.47 \pm 0.40$	O
$\eta_c'(3590)/\eta_c$	5 channels	2^{++}	< 0.34	D
$f_0(1500)$	$\pi^+\pi^-$	0^{++}	< 0.31	A
$f_J(1710)$	$\pi^+\pi^-$	0^{++}	< 0.55	A
$\eta_b(9460)$	4 charged	0^{-+}	$\Gamma_{\gamma\gamma}\times$ BR $<$ 47eV	A
$\eta_b(9460)$	6 charged	0^{-+}	$\Gamma_{\gamma\gamma}\times$ BR $<$ 127eV	A
			* $\Gamma_{\gamma\gamma}\times$ BR	

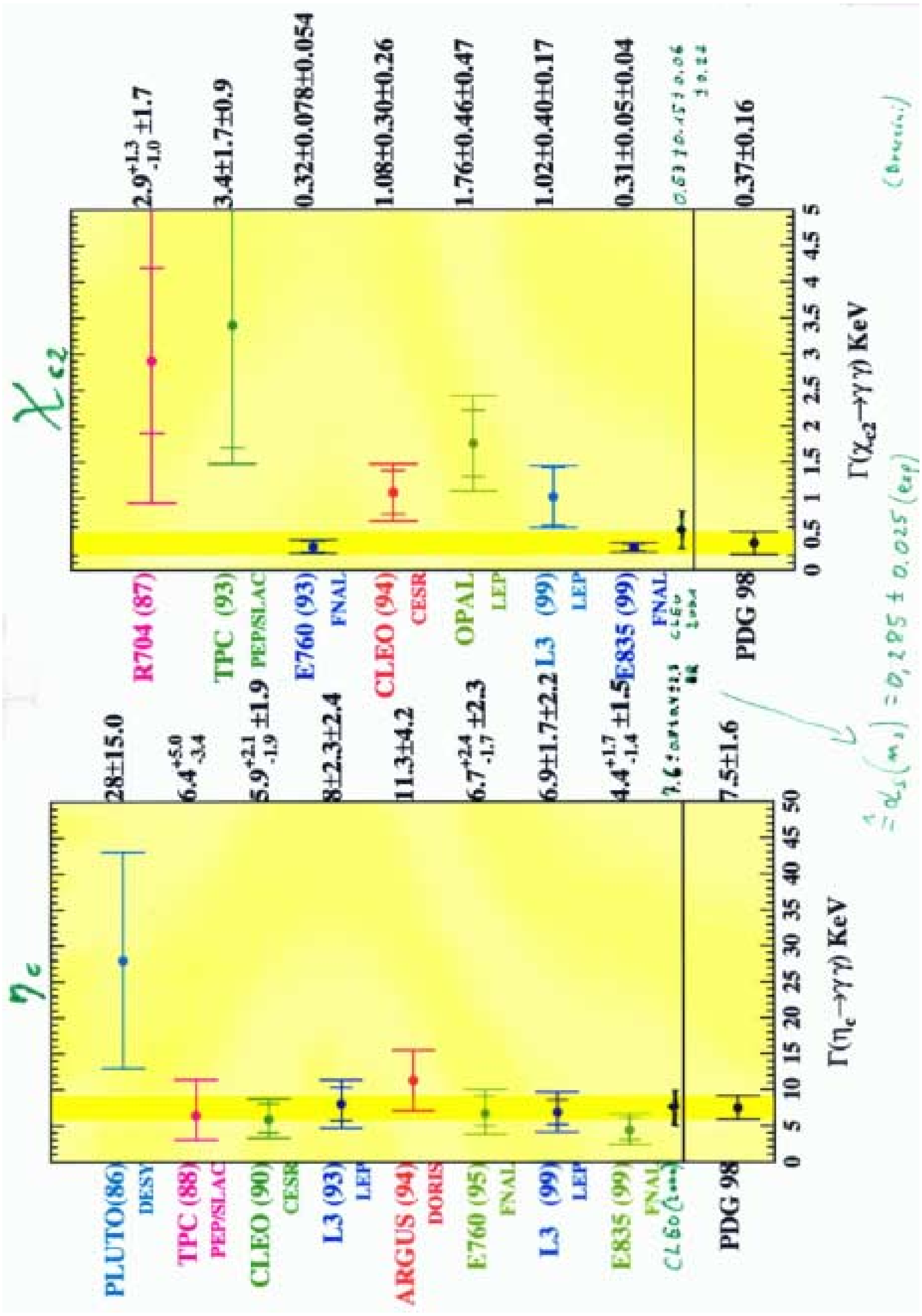
BES and MARK III: $\xi(2230)$ signal $J/\psi \to \xi\gamma$

$\Rightarrow$ Stickiness

(measure for gluon-photon coupling)

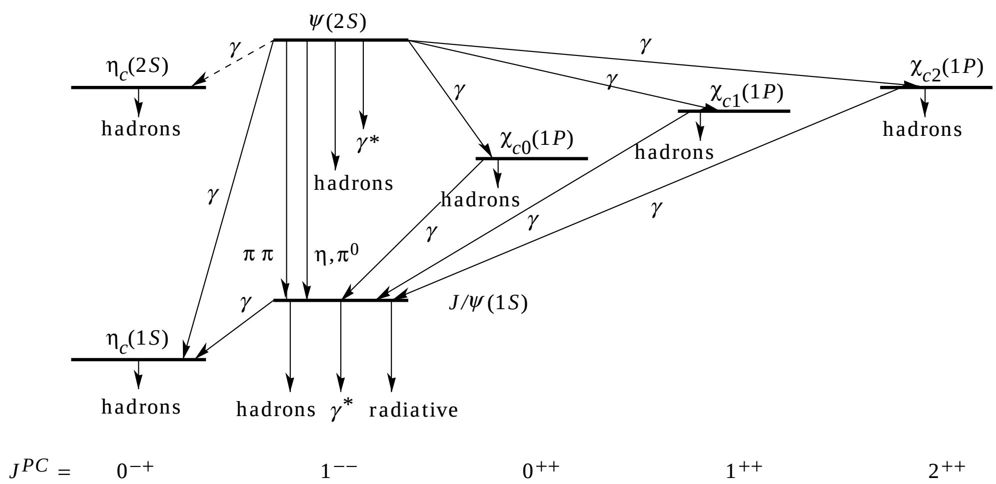
$$S_R = N_l \left(\frac{m_R}{k_{J/\psi\to\gamma R}}\right)^{2l+1} \frac{\Gamma(J/\psi \to \gamma R)}{\Gamma(R \to \gamma\gamma)} \sim \frac{|<R|gg>|^2}{|<R|\gamma\gamma>|^2}$$



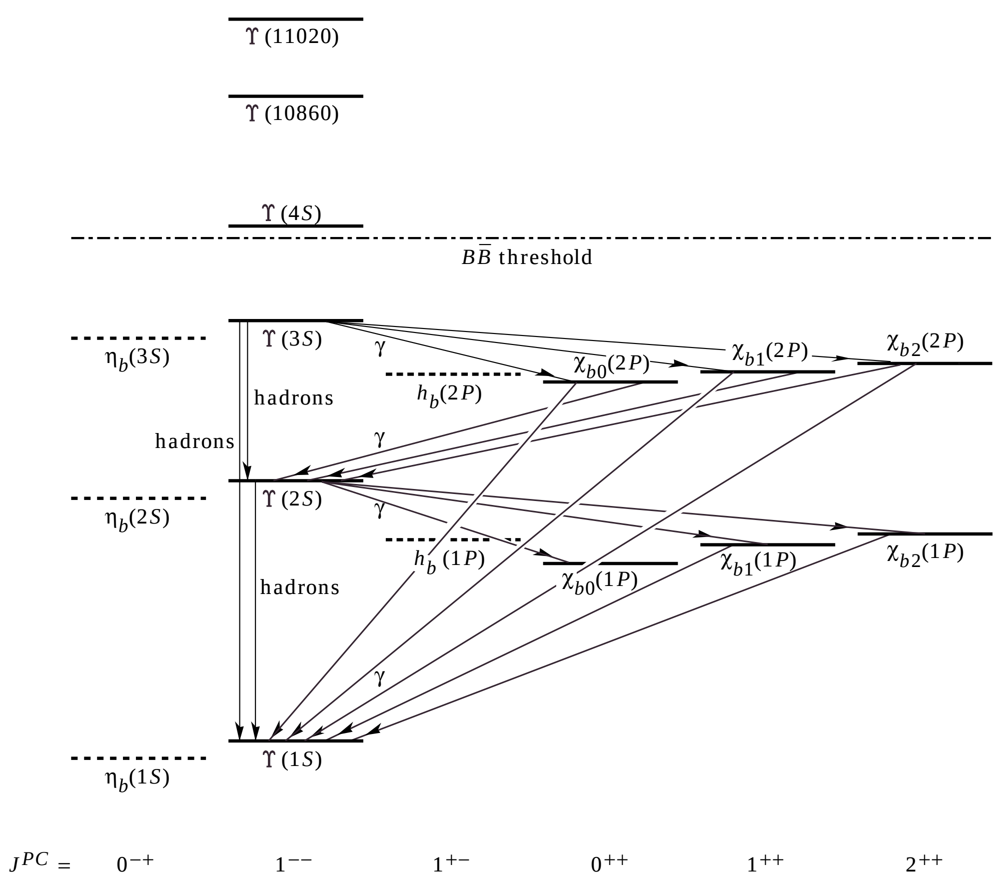


η_c
PLUTO(86) DESY 28±15.0
TPC (88) PEP/SLAC $6.4^{+5.0}_{-3.4}$
CLEO (90) CESR $5.9^{+2.1}_{-1.9}$ ±1.9
L3 (93) LEP 8±2.3±2.4
ARGUS (94) DORIS 11.3±4.2
E760 (95) FNAL $6.7^{+2.4}_{-1.7}$ ±2.3
L3 (99) LEP 6.9±1.7±2.2
E835 (99) FNAL $4.4^{+1.7}_{-1.4}$ ±1.5
PDG 98 7.5±1.6
$\Gamma(\eta_c \to \gamma\gamma)$ KeV
χ_{c2}
R704 (87) $2.9^{+1.3}_{-1.0}$ ±1.7
TPC (93) PEP/SLAC 3.4±1.7±0.9
E760 (93) FNAL 0.32±0.078±0.054
CLEO (94) CESR 1.08±0.30±0.26
OPAL LEP 1.76±0.46±0.47
L3 (99) LEP 1.02±0.40±0.17
E835 (99) FNAL 0.31±0.05±0.04
PDG 98 0.37±0.16
$\Gamma(\chi_{c2} \to \gamma\gamma)$ KeV

Charmonium States; ©RPP



Bottomonium States; ©RPP



Armin Böhrer / DESY Hamburg, Nov. 2001

Motivation

- $\eta_{\rm b}$ not yet seen!

  High $\gamma\gamma$ event statistics at LEP II
- Cross section can be calculated

  (Production: needs $\Gamma_{\gamma\gamma}$ $\Rightarrow$)

  (Decay: needs estimate of BR $\Rightarrow$)

  $\Rightarrow$ test of QCD (e.g., $\Gamma_{\gamma\gamma}$)
- $\eta_{\rm b}$ is massive, but $m(\eta_{\rm b})$ =???:

  mass should be close to Υ mass (9.46 GeV)

  $\Rightarrow$ test of NRQCD, $1/m$-expansion, lattice-QCD

hypothesis	$m(\eta_{\rm b})$	
naïve estimates		
hyperfine splitting	9.45 GeV	F.E. Close (book)
hyperfine (α_s, $r_{\rm eff}$)	9.42 GeV	H. Anlauf, T. Mannel
spin averaged masses	9.40 GeV	see G. Bali (review)
QCD calculations		
lattice NRQCD	9.38 GeV	A. El-Khadra, L. Marcantonio, Bali ...
lattice potential	9.37 GeV	G. Bali ...
$1/m$-expansion	9.40 GeV	S. Narison ...
potential model	9.36 GeV	T. Barnes, E.J. Eichten, D. Ebert ...
pQCD	9.41 GeV	N. Brambilla ...

$\Rightarrow$ $m(\eta_{\rm b}) \approx$ 9.32 to 9.43 GeV

Production Estimate of η_b

Production: $\gamma\gamma$ luminosity...

$$\sigma_{e^+e^-\to e^+e^-R}(s) = f(s,\ m(\eta_b),\ \Gamma_{\gamma\gamma})$$

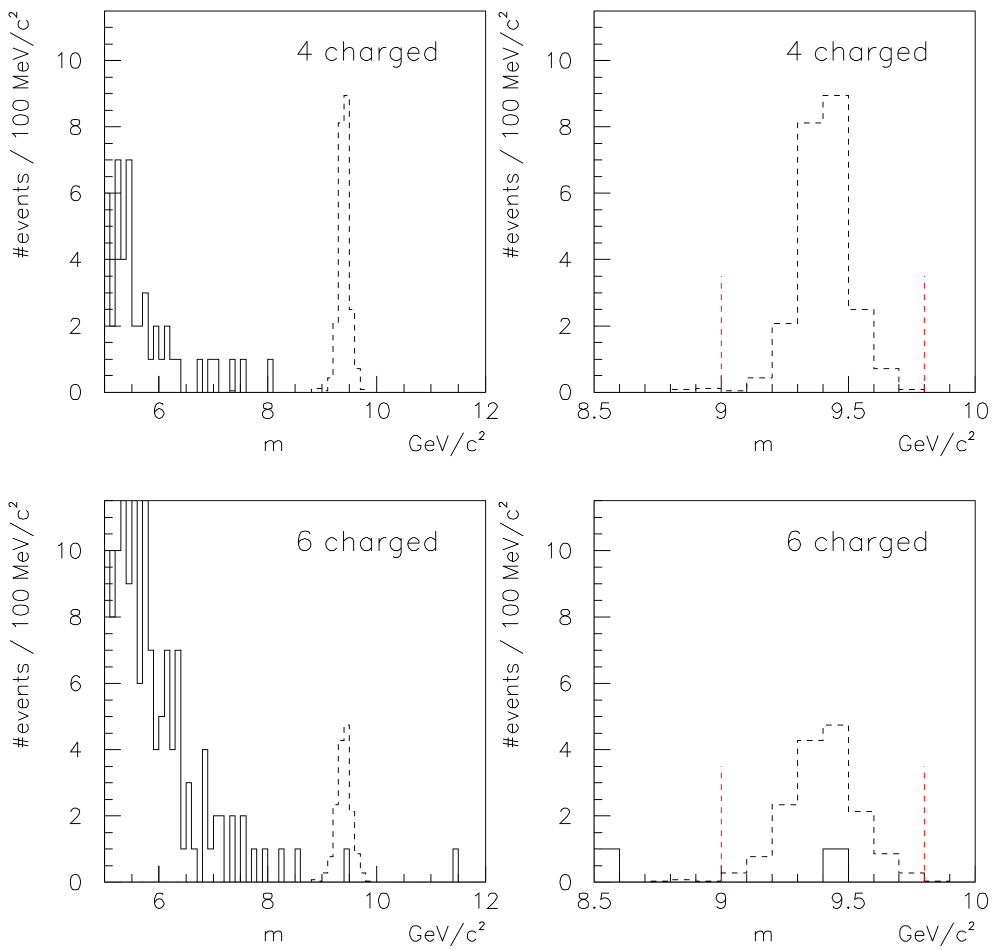
Partial width

hypothesis	$\Gamma_{\gamma\gamma}(\eta_b)$ [eV/c^2]	
estimates $\mathcal{O}(\alpha_s)$	(conservative)	
potential model	416 $\pm$ 25%	η_b, η_c Barger, ATLAS
potential model, $\Gamma_{e^+e^-}(\Upsilon)$	431 $\pm$ 25%	η_b, η_c Kwong
estimates $\mathcal{O}(\alpha_s)$	(new)	
potential model	500 $\pm$ 30	Fabiano
potential model, $\Gamma_{e^+e^-}(\Upsilon)$	490 $\pm$ 40	Fabiano
NRQCD	460	Schuler
NRQCD, $\Gamma_{e^+e^-}(\Upsilon)$	501	Czarnecki + Melnikov
estimates $\mathcal{O}(\alpha_s^2)$		
NRQCD, $\Gamma_{e^+e^-}(\Upsilon)$	570 $\pm$ 50	Czarnecki + Melnikov

(RPP2000: $\Gamma_{\gamma\gamma} = 7.4 \pm 1.4$ keV for η_c !!! (measured))

$\Gamma_{\gamma\gamma} = 416$ eV for η_b
(used by ALEPH; lowest = conservative prediction
Fabiano, Czarnecki + Melnikov from Sept.)
$\Gamma_{\gamma\gamma} = 557$ eV (from new $\mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2)$)

Invariant Mass Distribution
Data (——) and MC(BR=100%) (- - -)



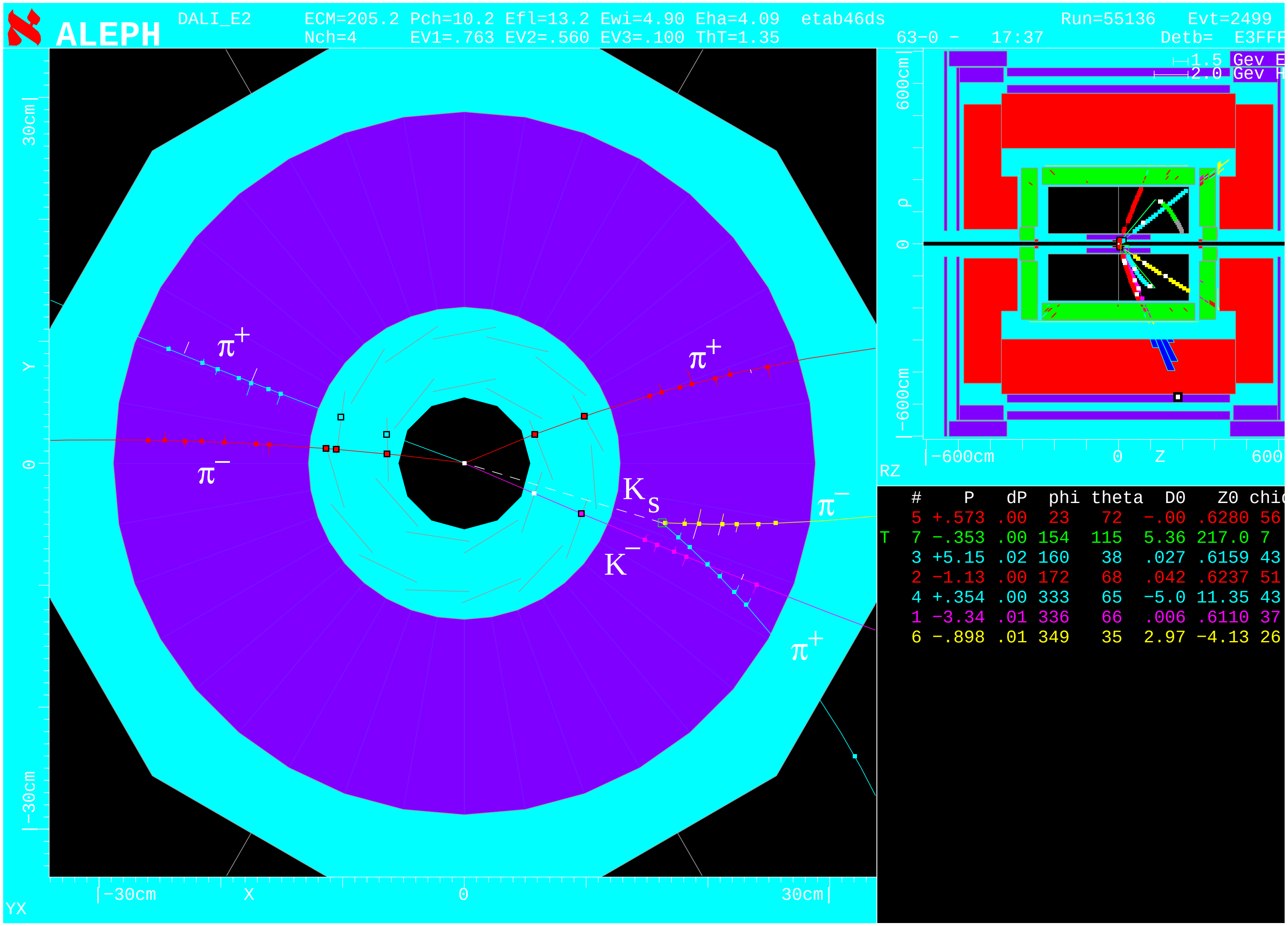
⇒ One candidate event in 6 charged mode!

$m = 9.30 \pm 0.04$ GeV

(for proper mass assignment of decay particles)

bgd $= 0.3 \pm 0.3$ (0.8 ± 0.4) events

Candidate Event



Armin Böhrer / DESY Hamburg, Nov. 2001

Limit for η_b Production

- expected η_b signal

  (BR from MLLA)

  4 charged mode: 0.65 events

  6 charged mode: 0.52 events

- expected background

  (mass region 9.00 GeV $<$ 9.80 GeV)

  4 charged mode: 0.3 ± 0.3 events

  6 charged mode: 0.8 ± 0.4 events

- observation

  4 charged mode: 0 events

  6 charged mode: 1 events

  ($m = 9.30 \pm 0.04$ GeV)

- $\alpha = 95\%$ upper limits:

  $\Gamma_{\gamma\gamma}(\eta_b) \times BR(4cha) < 57\,eV$

  $\Gamma_{\gamma\gamma}(\eta_b) \times BR(6cha) < 128\,eV$

  with $\Gamma_{\gamma\gamma}(\eta_b) = 416\,eV \pm 25\%$ (while new calc. $557\,eV \pm 15\%$):

  $BR(\eta_b \to 4\,charged) < 17\%$

  $BR(\eta_b \to 6\,charged) < 38\%$

4 LEP experiments have a chance to see it.

Conclusion

- A variaty of QCD test have been performed:
  - QCD now precision experiment
    (experimental and theoretical progress)
  - QCD successful for hard and soft:
    α_s, gauge structure,
    q$\leftrightarrow$g jets, fragmentation
- A lot of interesting physics studied in $\gamma\gamma$:
  - structure functions
  - jets, total cross section, inclusive p.p.
    good description (except for high p_t in ipp)
  - double-tag events: BFKL NLO important
  - heavy flavour:
    charm: fairly understood; problems in details
    bottom: cross section too low in QCD
  - exclusive particle production
    many good measurements

  ! only fraction of data analysed ($\gamma\gamma$):
  ... more to come
- Experimental and theoretical challenge