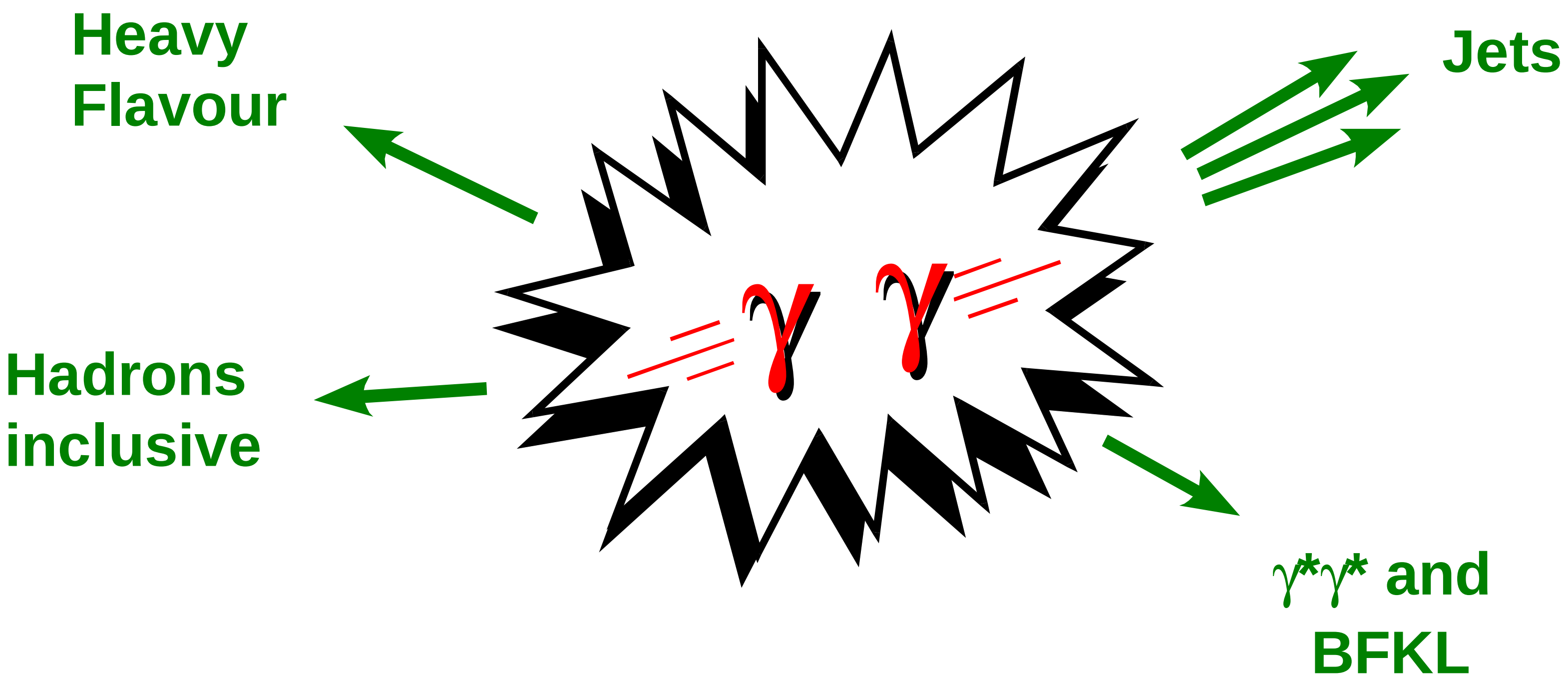
How well does QCD work for $\gamma\gamma$ – collisions ?

. . . News from the LEP experiments

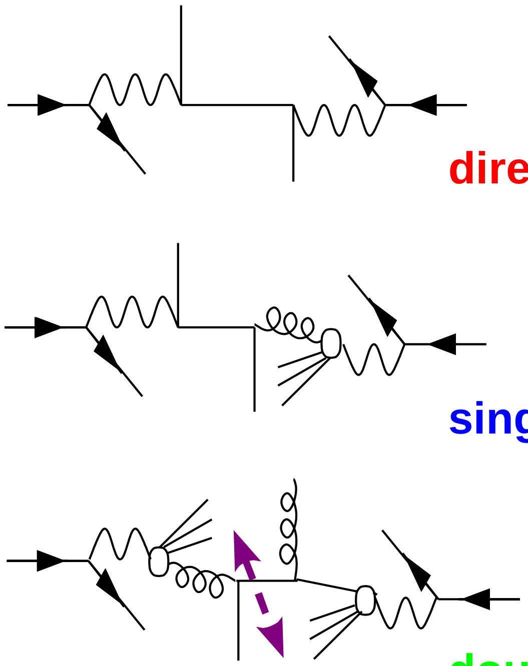


QCD/Photon Structure w/ di–jets

Jet Production Processes in $\gamma\gamma$ – collisions ...

estimate for fraction of photon mom. entering hard collision →

$$x_\gamma^\pm = \frac{\sum_{\text{jet1,2}} (E \pm Pz)}{\sum_{\text{hadrons}} (E \pm Pz)}$$

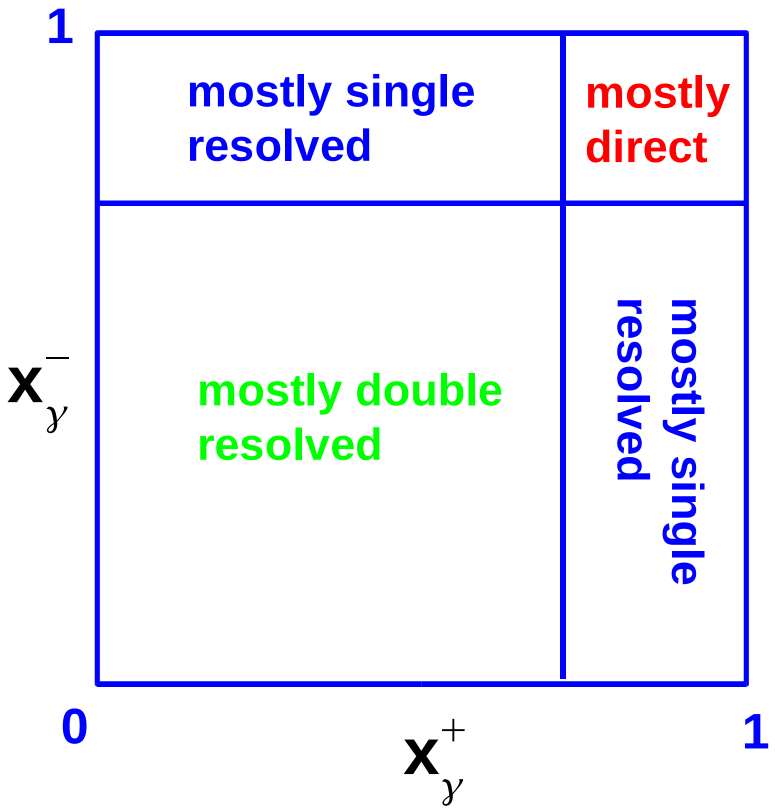


direct

single resolved

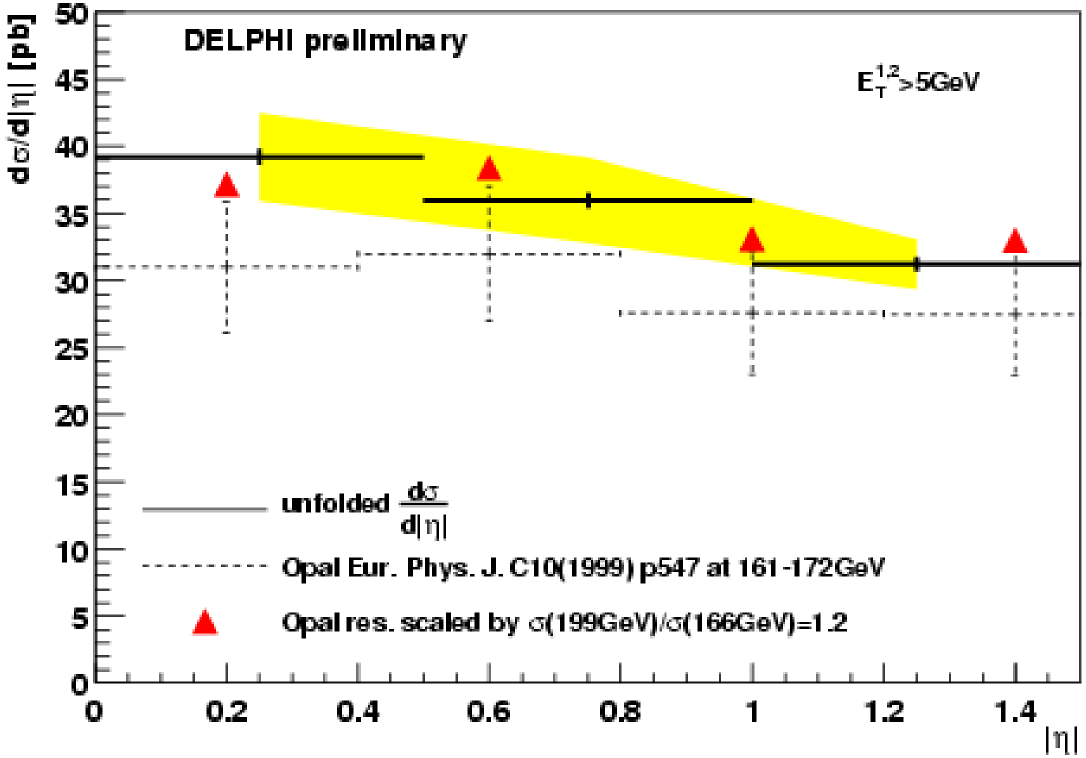
double resolved

multiple parton interactions (MIA)?



DELPHI: Differential di−jet x−section vs. |η|

$\sqrt{s}$=192−202GeV , $\mathscr{L}$ = 220 pb^{-1}, PXCONE w/ R=1



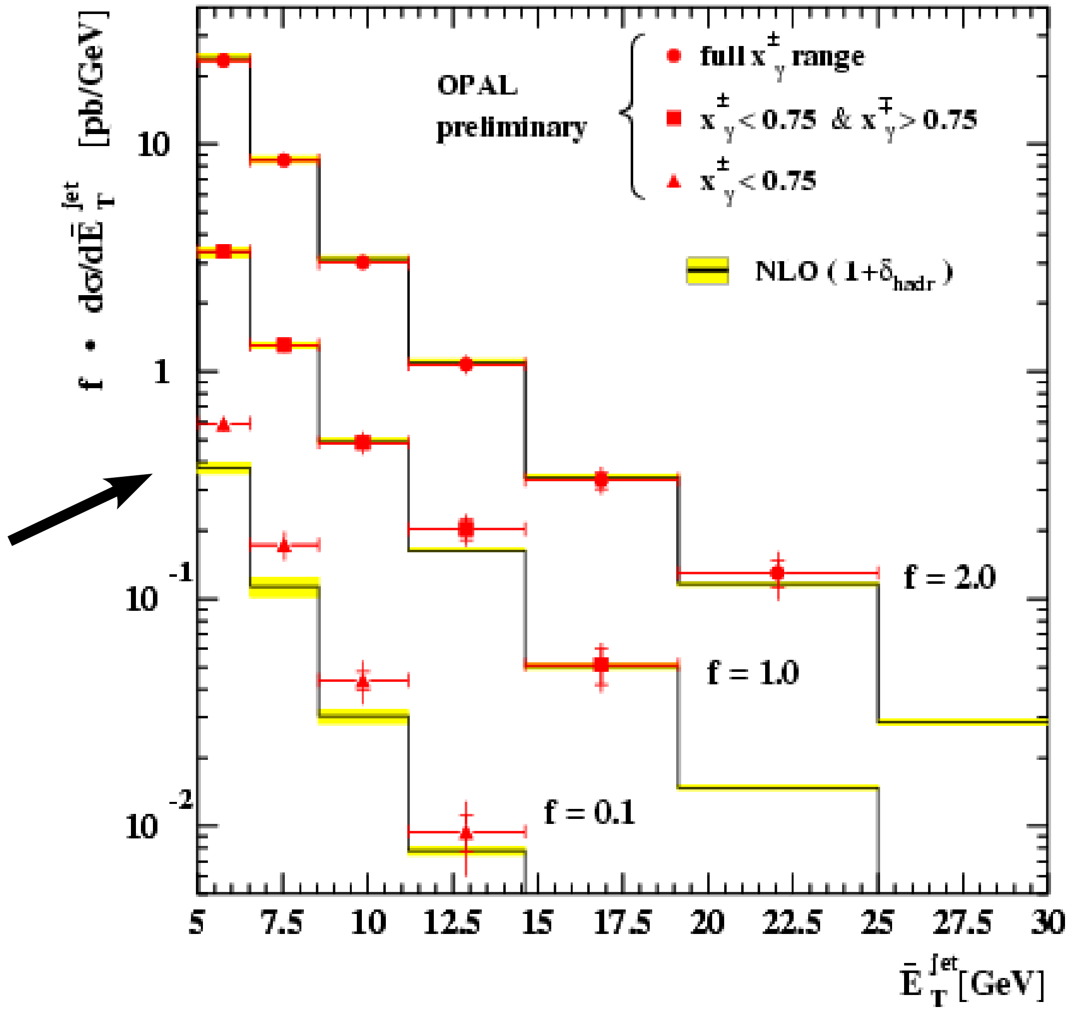
$d\sigma^{2j}/d|\eta|$ and $d\sigma^{2j}/dE_T$

⇨ **first DELPHI result, more detailed study in progress**

Good agreement between experiments

OPAL: Differential di−jet x−section vs. $E_{T,mean}$

$\langle\sqrt{s}\rangle = 198.5\,\text{GeV}$, $\mathscr{L}$ = 593 pb^{-1}, inclusive k_t jets, 25 diff. x−sections vs. $\mathbf{E_T}$, $\mathbf{x_\gamma}$, and η



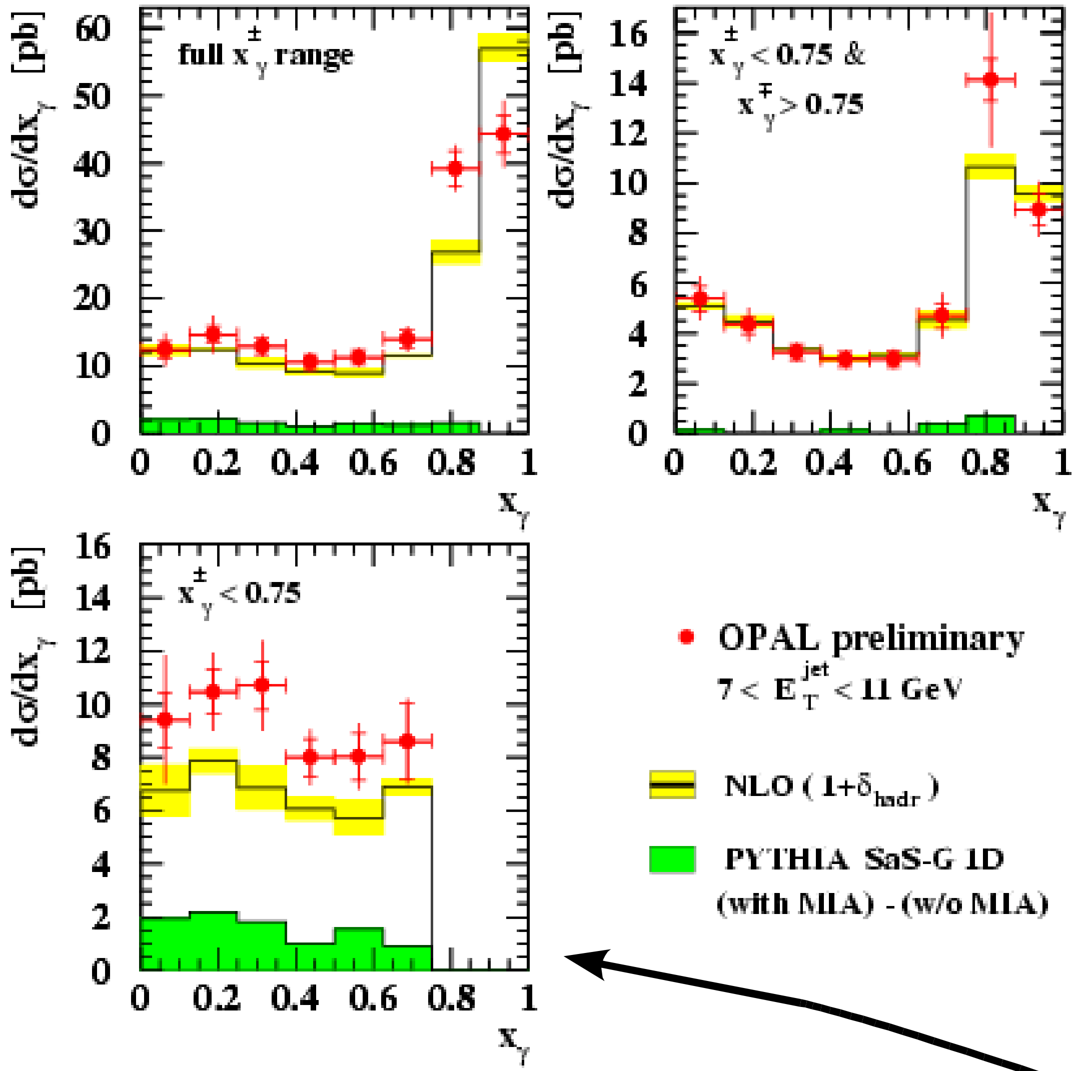
Well described by perturbative NLO QCD ...

... except for $x_\gamma^\pm < 0.75$

Here the MIA contribution is expected to be important

NLO: Klasen et al. w/ GRV−HO
5 flavours, $\Lambda_{QCD}(5)$=130 MeV
Yellow band: scale variation
[0.5 ... 2.0]

OPAL: Differential di–jet x–sections vs. x_γ



Low x_γ values reached, but no big dependence on MIA

This is a unique data sample, because ...

... we can "disentangle" the hard subprocess with purely experimental definitions from the underlying "mess"!

$x_\gamma \equiv$ two entries ⇨ at x_γ^+ and x_γ^-

Same process – different observable:

Inclusive hadron production

Studied by L3 in 189 – 202 GeV data, $\mathscr{L}$ = 414 pb^{-1}

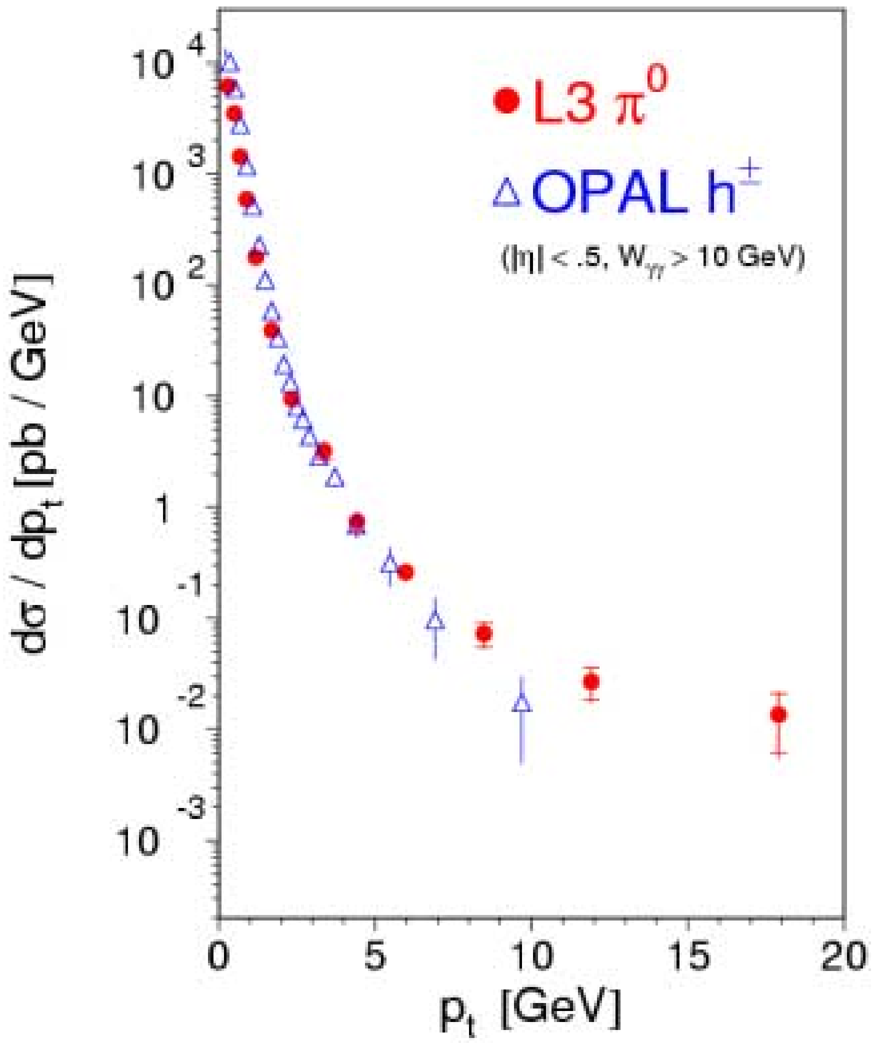
- $e^+e^- \Rightarrow e^+e^- \; K_s^0 \; X$ ⇨ $|\eta| < 1.5$, W > 5 GeV
- $e^+e^- \Rightarrow e^+e^- \; \pi^0 \; X$ ⇨ $|\eta| < 0.5$, W > 5 GeV
- $e^+e^- \Rightarrow e^+e^- \; \pi^\pm \; X$ ⇨ $|\eta| < 1.0$, W > 5 GeV

Studied by OPAL in 161 – 172 GeV data, $\mathscr{L}$ = 20 pb^{-1}

- $e^+e^- \Rightarrow e^+e^- \; h^\pm \; X$ ⇨ $|\eta| < 1.5$, W > 10 GeV (W bins)
- $e^+e^- \Rightarrow e^+e^- \; K_s^0 \; X$ ⇨ $|\eta| < 1.5$, W > 10 GeV (W bins)

Complimentary access to hard interactions and photon structure

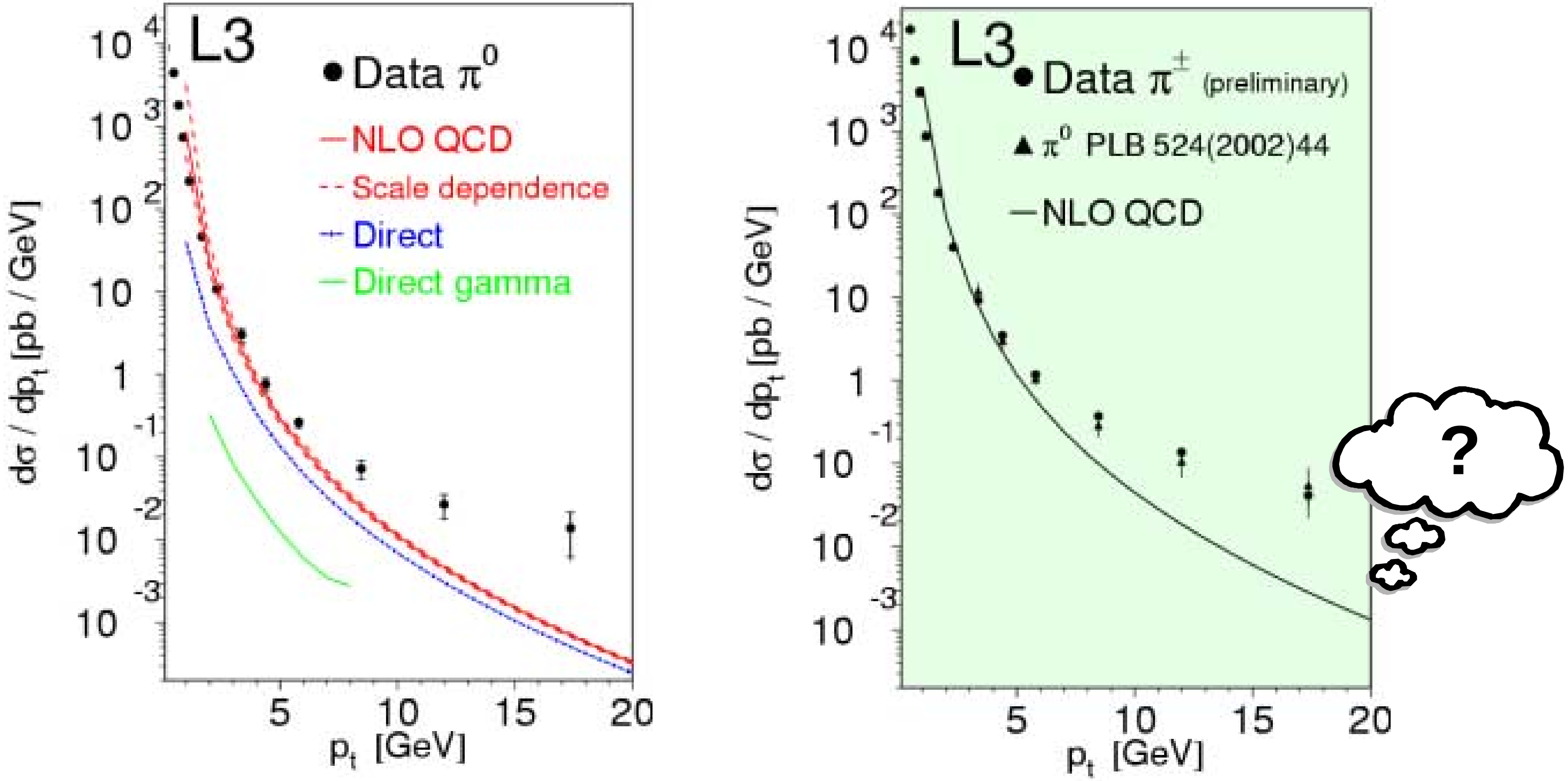
Are the experiments consistent?



L3 has used correction factors for $\mathscr{L}_{\gamma\gamma}$, |η| and $\pi^{\pm} \leftrightarrow \pi^0$ for the comparison

Good agreement between experiments
⇨ works also for K^0_s

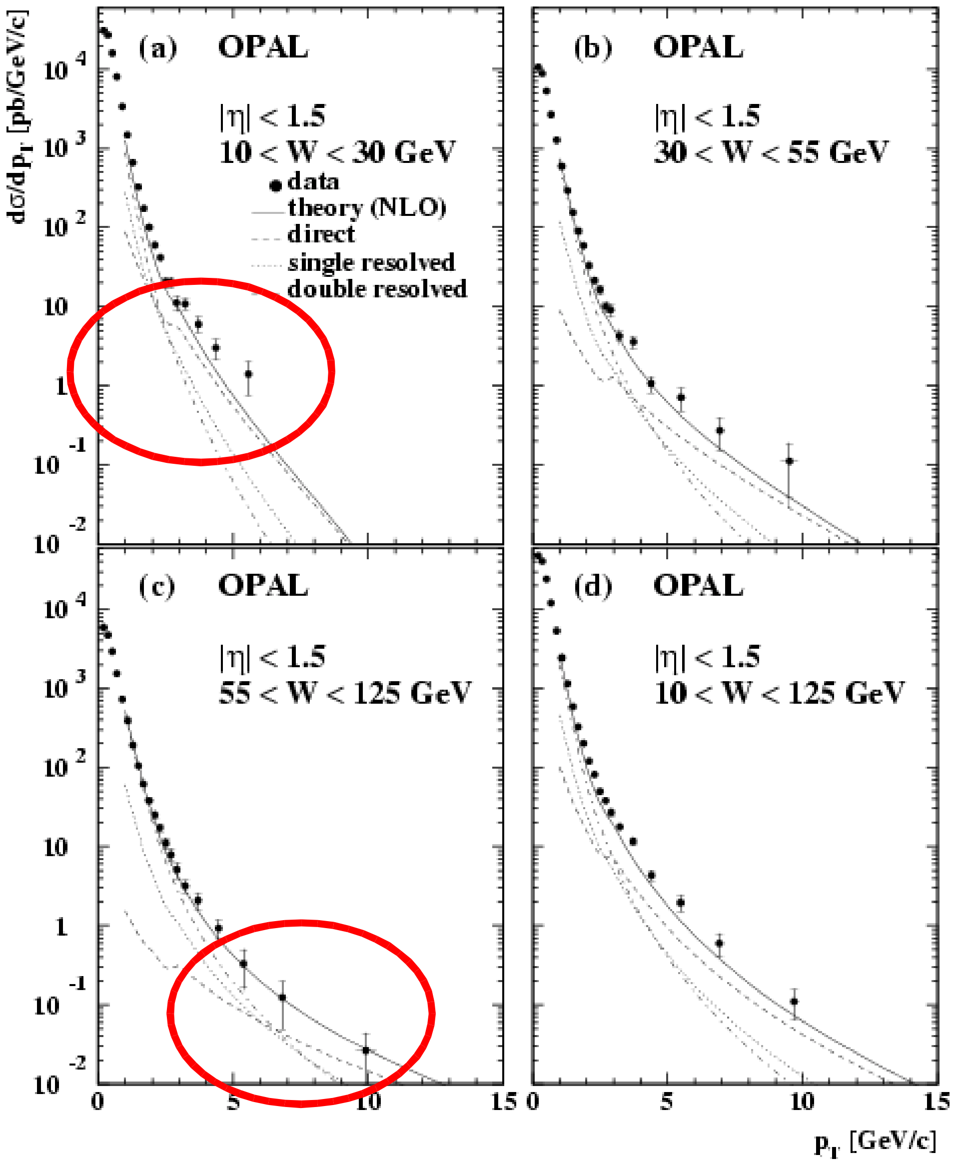
$d\sigma/dp_T$ for neutral and charged pions



NLO QCD is significantly too low for $\pi^{\pm}$ and π^0 for p_t > 8 GeV

NLO: Binnewies, Kniehl, Kramer

OPAL: $e^+e^- \Rightarrow e^+e^-\ h^\pm\ X$



OPAL data show the same tendency at low W

⇨ but seems o.k. at high W

It would be interesting to repeat / extend the measurments with high statistics in bins of W

NLO: Binnewies, Kniehl, Kramer

Moving from light to heavy quark production . . .

Latest results on Charm:

ALEPH: 183−189 GeV , $\mathscr{L}$ = 236.3 pb^{-1}

- **charm tagging via D^{*+}** ⇨ $|\eta_{D^*}| < 1.5$
- new data in preparation

DELPHI: 161−204 GeV, $\mathscr{L}$ = 458.4 pb^{-1}

- **charm tagging via D^{*+}** ⇨ $|\eta_{D^*}| < 1.4$

L3: 183−208 GeV , $\mathscr{L}$ = 683 pb^{-1}

- **charm tagging via D^{*+}** ⇨ $|\eta_{D^*}| < 1.4$

OPAL: 183−202 GeV , $\mathscr{L}$ = 428 pb^{-1}

- **charm tagging via D^{*+}** ⇨ $|\eta_{D^*}| < 1.5$

Latest results on Beauty:

L3: 189−202 GeV data, $\mathscr{L}$ = 410 pb^{-1}

- **beauty ID via $c \rightarrow [e^{\pm},\mu^{\pm}]$ X**

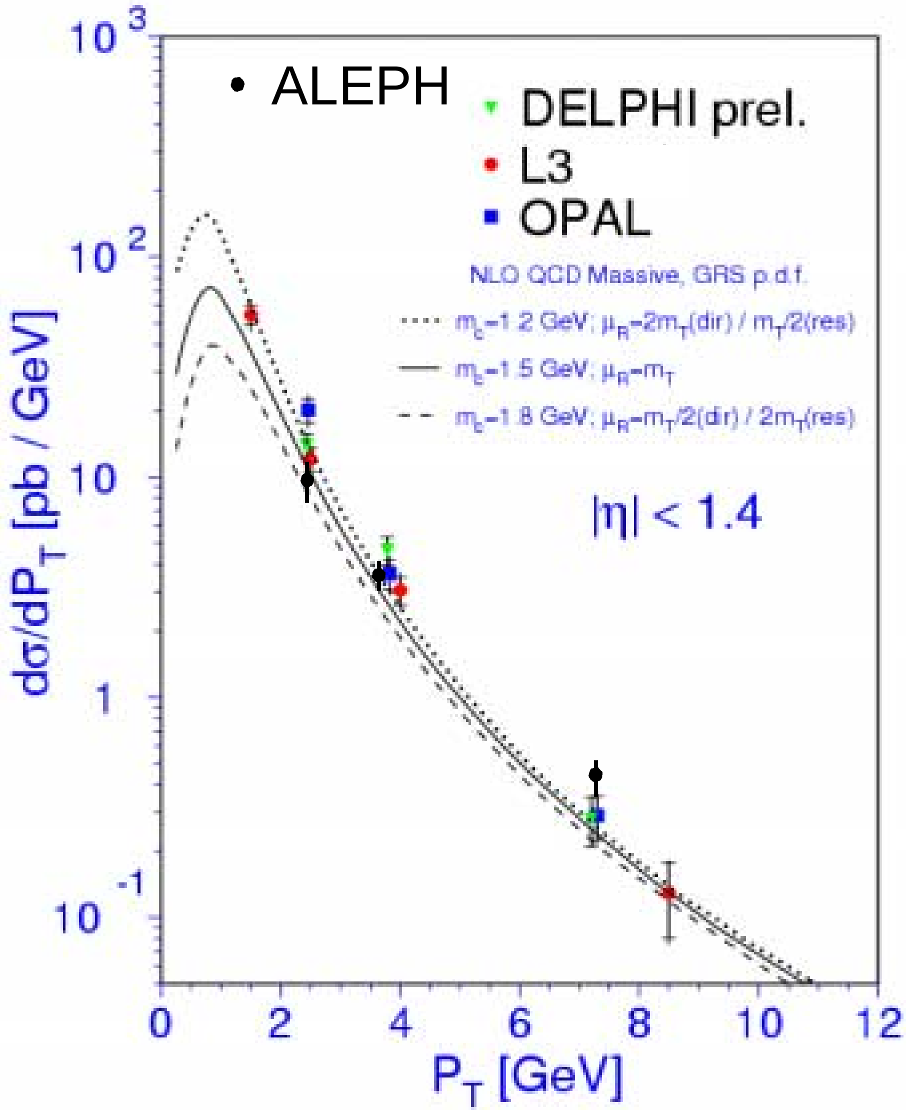
OPAL: 189−202 GeV data, $\mathscr{L}$ = 371 pb^{-1}

- **beauty ID via $c \rightarrow \mu^{\pm}$ X**

X−sections depend on quark masses and photon structure
+
Heavy Quark masses as appropriate scale for NLO QCD

dσ/dp$_T$ for D* mesons

There is some spread between the experiments at low P$_T$, but in general the data is ...

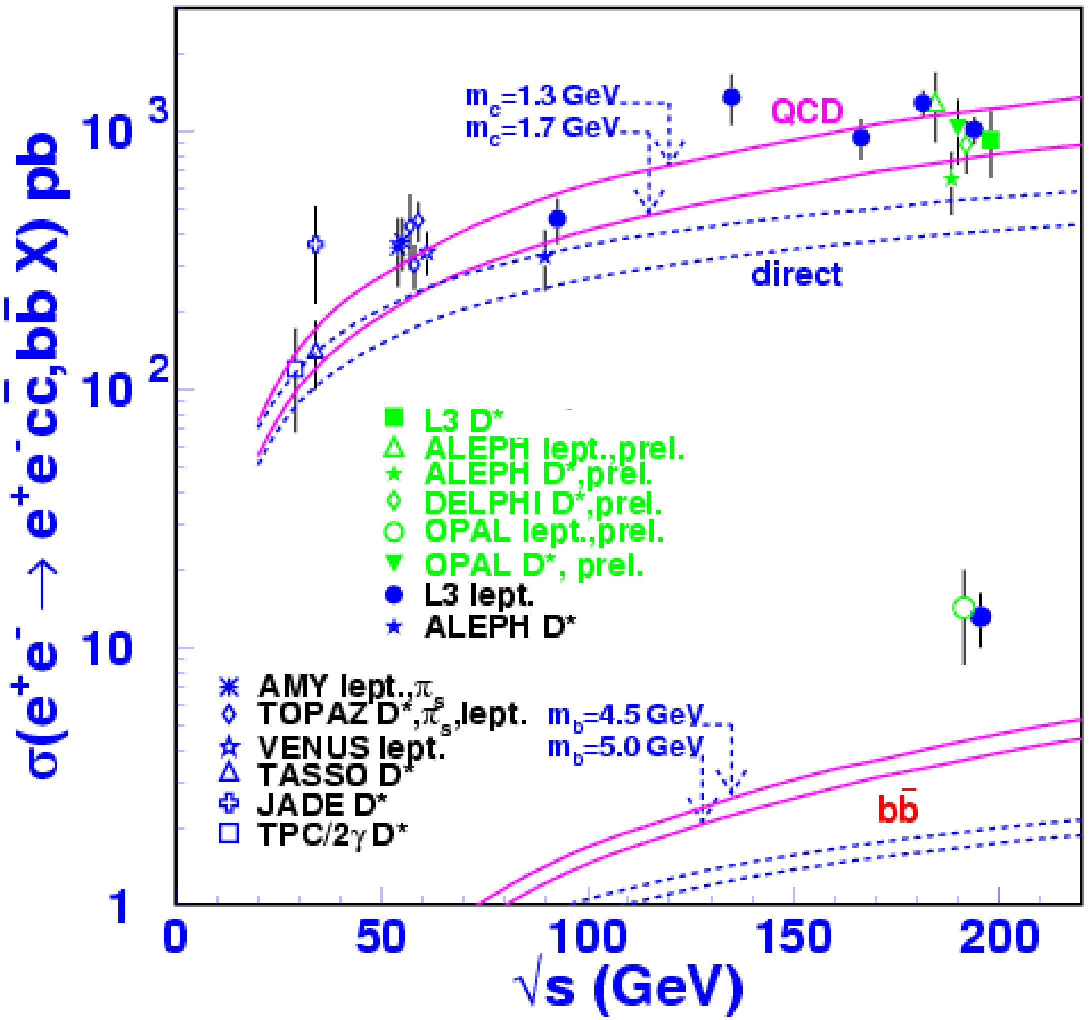


... in good agreement among the experiments

... well described by NLO QCD using massive quarks

NLO: Frixione, Krämer, Laenen

Charm and Beauty total x−section



cc: Exp. results are consistent
⇨ well described by NLO QCD.

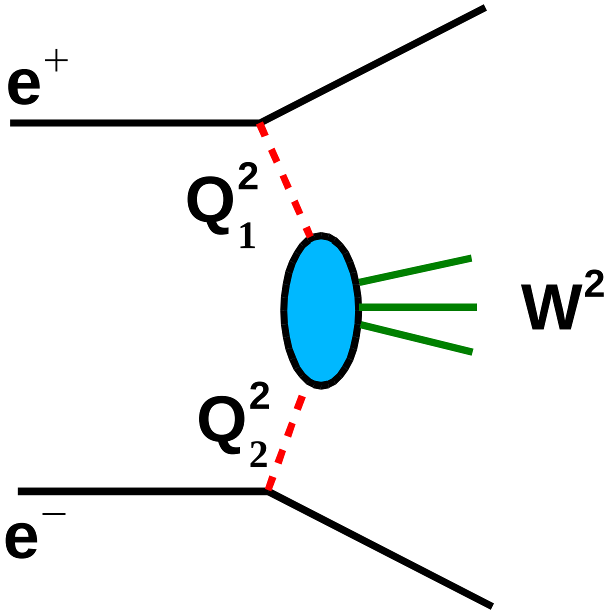
Clear evidence of gluonic contribution to the x−section.

?

bb: Exp. results consistent
⇨ but the theory prediction is too low.

NLO: Drees, Krämer, Zunft, Zerwas

The BFKL regime (?) : Scattering of two virtual photons



$Q^2_{1,2}$ Virtuality of the incident photons

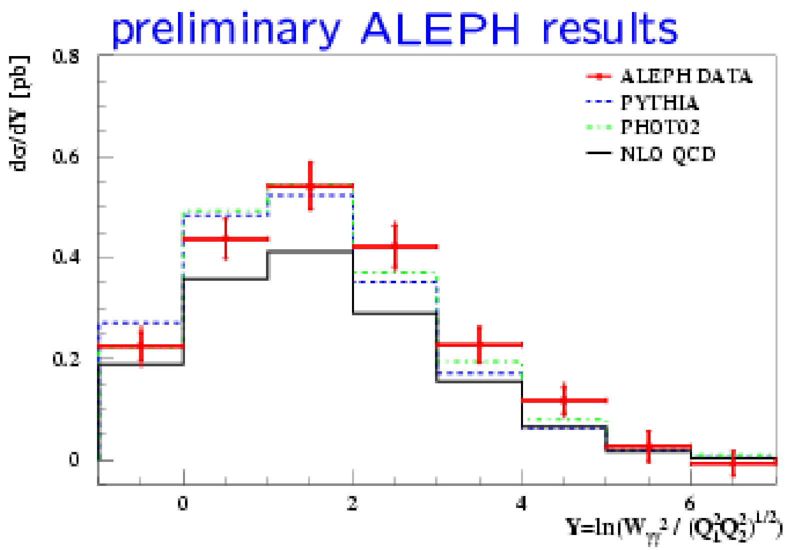
W^2 Invariant mass of hadronic system

$$Y = \ln\left(\frac{W^2}{\sqrt{Q_1^2 Q_2^2}}\right) \approx \bar{Y}$$

$Q_1^2 \sim Q_2^2$: little phase space for DGLAP evolution with strong ordering in Q^2

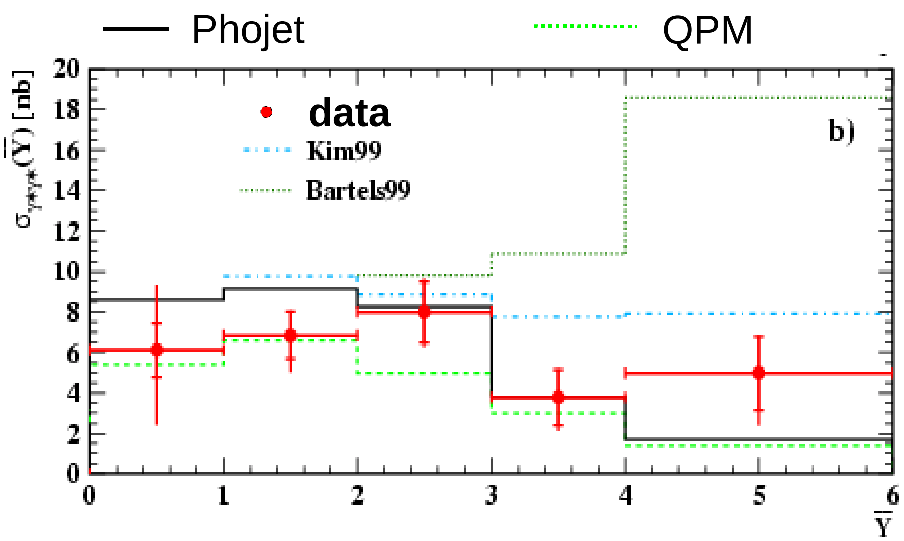
Good testing ground for onset of BFKL effects, which predict larger x−section at high Y

$\gamma^*\gamma^*$ cross–section vs. Y



189–208 GeV, $\mathscr{L}$ = 640 pb^{-1}
$E_{1,2} > 0.3E_{Beam}$, 35 < $\Theta_{1,2}$ < 155 mrad
W > 3 GeV

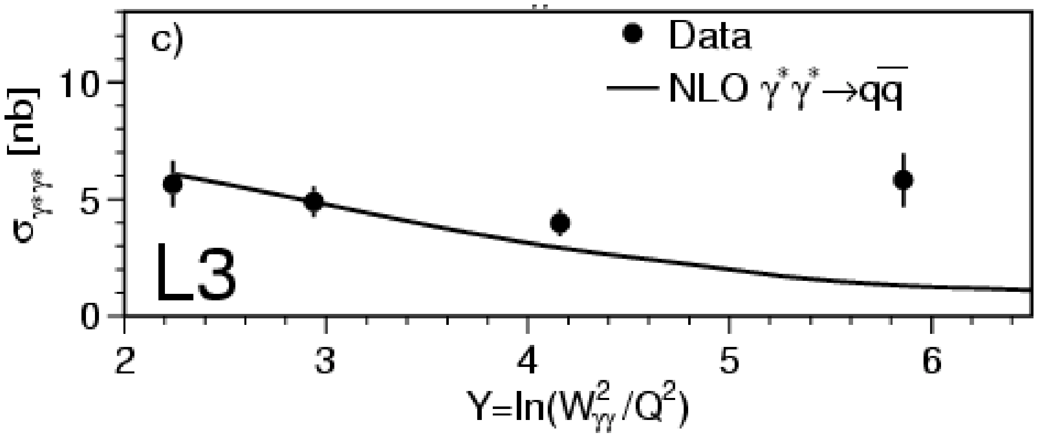
NLO: Frixione et al.



189–209 GeV, $\mathscr{L}$ = 593 pb^{-1}
$E_{1,2} > 0.4E_{Beam}$, 34 < $\Theta_{1,2}$ < 55 mrad
W > 5 GeV
(Data also described by NLO Cacciari et al. – not shown here)

There seems to be no "need" for BFKL type contributions here ...

$\gamma^*\gamma^*$ cross–section vs. Y



?

BKFL?
Resolved Photon?

189−209 GeV, $\mathscr{L}$ = 617 pb^{-1}
$E_{1,2}$ > 40 GeV, 30 < $\Theta_{1,2}$ < 66 mrad
W > 5 GeV

NLO: Cacciari et al.

L3 sees an excess over NLO QCD expectations for the highest Y point ...

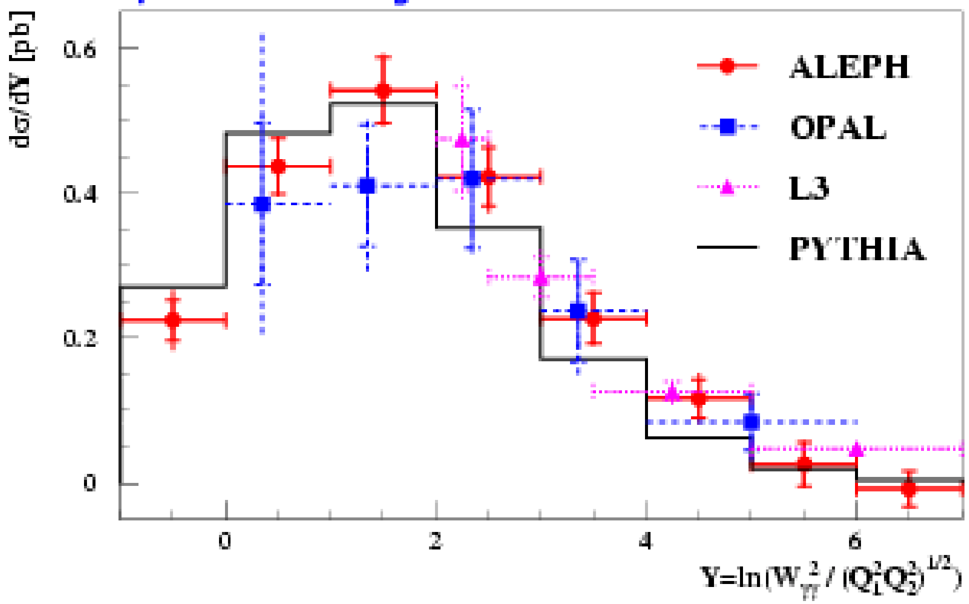
... are the experiments inconsistent?

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
$W_{\gamma\gamma\text{ min}}$	3 GeV	5 GeV	5 GeV

Phase space interpolation with GALUGA, PYTHIA or PHOT02

preliminary ALEPH results



After corrections for phase space differences the experiments agree

G.Prange at Photon 01

Conclusions: At this point NLO QCD works ...

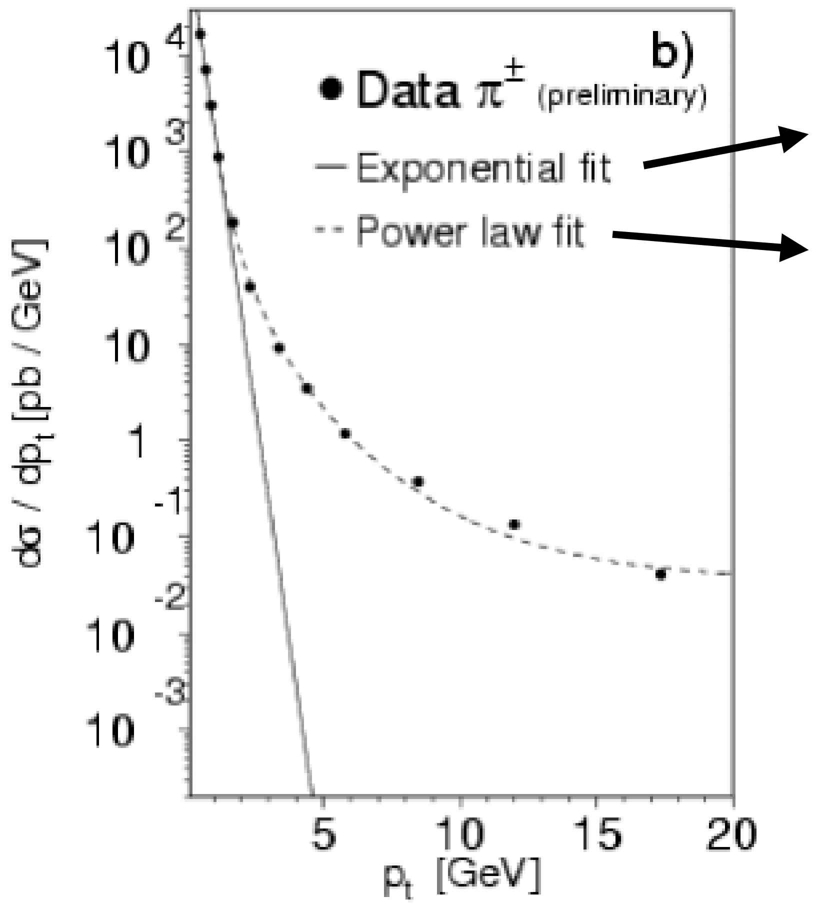
... well for :

- Di−jet production
- Charm production
- Virtual photon scattering (?)

... not so well for :

- inclusive hadron production (high p_T, low W)
- Beauty production

Appendix: inclusive hadron production



$$A e^{\frac{-p_T}{\langle p_T \rangle}}$$

$\langle pT \rangle \simeq 225$ MeV

$$A p_T^{-B}$$

$B \simeq 4$

Similar fits work for the π^0 case