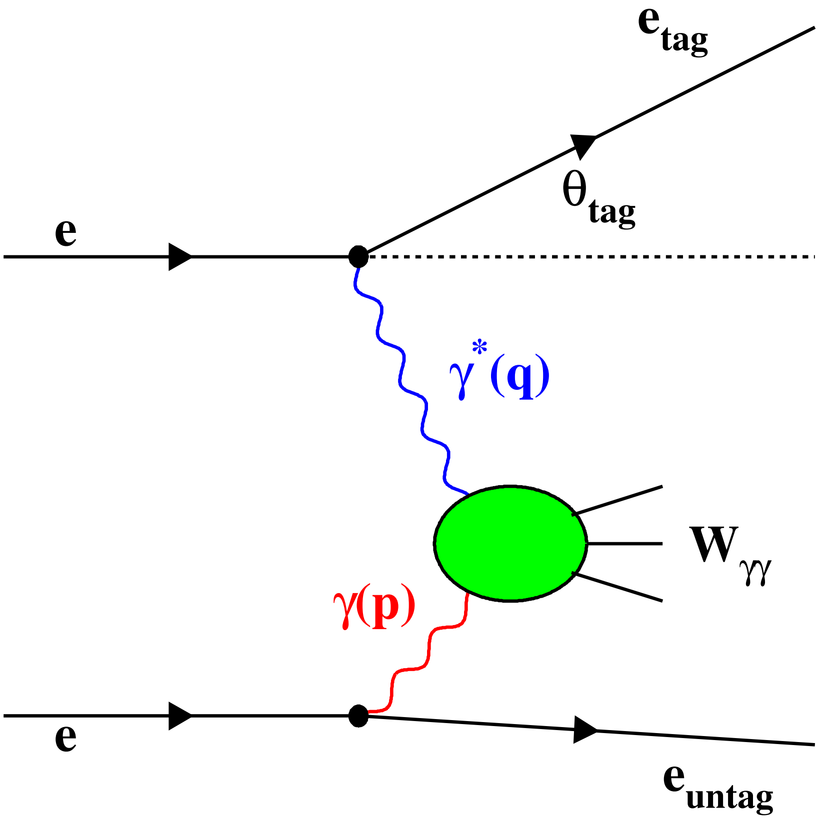
Photon Structure Function F_2^γ at L3

M.N.Kienzle-Focacci
Geneva University
representing the L3 Collaboration

- Introduction : x and Q^2 range of L3 data
- The leptonic structure functions
- The hadronic F_2^γ vs x
- Q^2 evolution of F_2^γ
- Conclusions

Sept. 12 1998

Kinematics



$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2^\gamma(x,Q^2) - y^2 F_L^\gamma(x,Q^2)]$$

$$Q^2 = -q^2 \ , \ P^2 = -p^2 \ , \ W_{\gamma\gamma}^2 = (q+p)^2$$

$$x = \frac{Q^2}{Q^2 + P^2 + W_{\gamma\gamma}^2} \ , \ y = 1 - \frac{E_{tag}}{E_{beam}} \cos^2 \frac{\theta_{tag}}{2} \ll 1$$

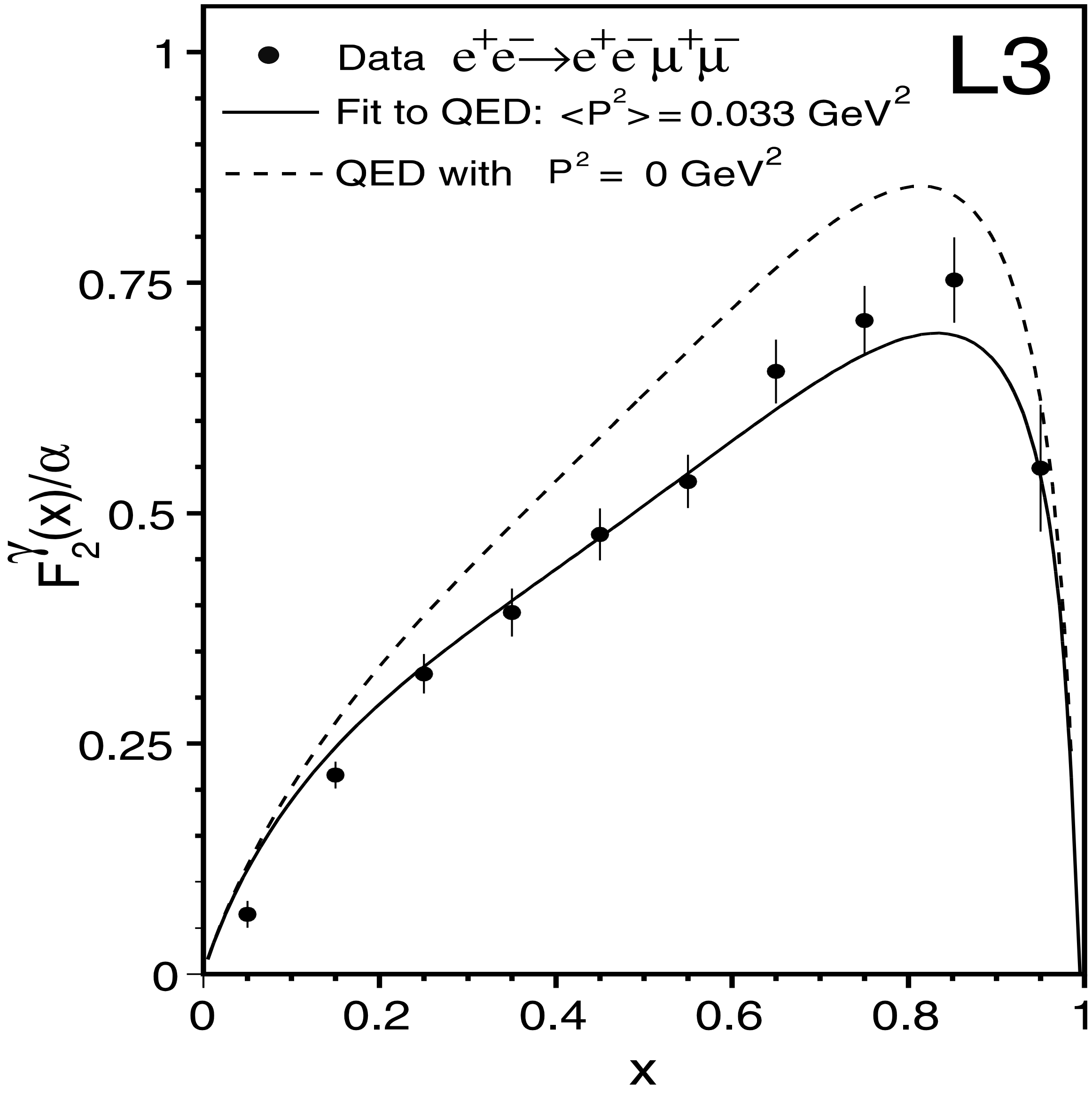
- ⇨ Only F_2^γ is measurable since y^2 is small.
- ⇨ We have access to F_L^γ by azimuthal correlations.
- ⇨ The integral flux of target photon is calculated analytically.

x and Q^2 ranges covered by L3

Channel	$\sqrt{s}$ (GeV)	Q^2 (GeV^2)	x	NeV	L$_{ee}$ (pb^{-1})	Ref.
Single Tag						
e^+e^-	91	1.4-7.6	0-1.	3802	93.7	1
$\mu^+\mu^-$	91	1.4-7.6	0-1.	7152	93.7	1
hadrons	91	1.2-3.	0.002-0.1	5772	140.	2
		3.-9.	0.005-0.2	4156		2
hadrons	91	40.-500.	0.05-0.98	500	140.	3
hadrons	183	9.-13.	0.01-0.3	632	51.9	4
		13.-18.	0.01-0.5	477		4
		18.-30.	0.01-0.5	540		4
Double Tag						
hadrons	91	1.2-9.		137	140.	5
	183	9.-30.		34	51.9	5

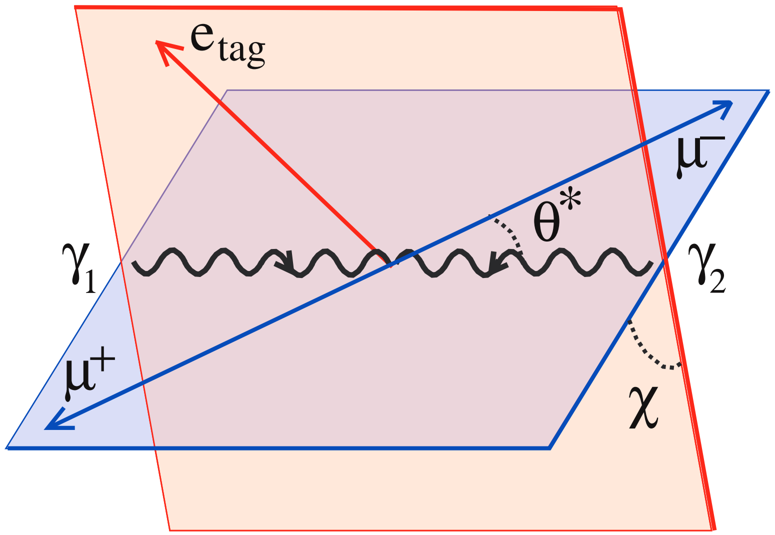
1) M.Acciari et al.,CERN-EP/98-060
2) M.Acciari et al., CERN-EP/98-098
3) F. Erne , Ascona L3 meeting (june 1998)
4) C.H.Lin, L3 Note 2298 (1998)
5) C.H.Lin, Ascona L3 meeting (june 1998)

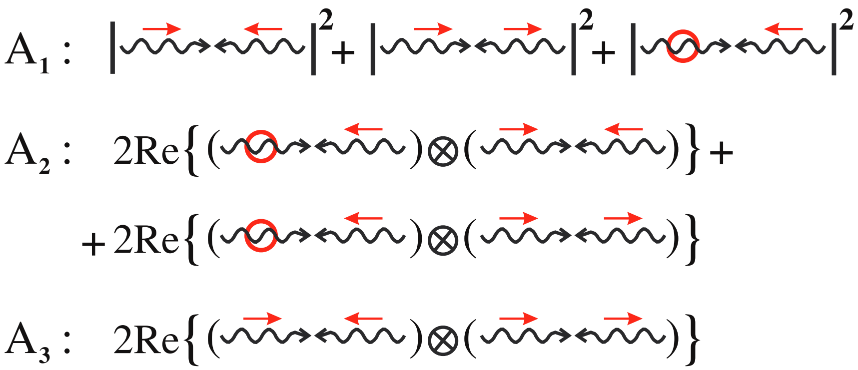
$F_{2,\mathrm{QED}}^{\gamma}(\mathrm{x})$ at $< Q^2 > = 1.7$ GeV^2



- non-zero target photon virtuality.
- $\langle P^2 \rangle = 0.033 \pm 0.005$ GeV^2 as for MC including Radiative Corrections.
- $\langle P^2 \rangle = 0.024$ GeV^2 for MC without R.C.

Azimuthal Correlations





$$\frac{d^4\sigma}{dx\,dy\,dz\,d\chi} = \frac{2\pi\alpha^2}{Q^2}\frac{1+(1-y)^2}{xy}\left[A_1(x,z) + A_2(x,z)\cos\chi + A_3(x,z)\cos 2\chi\right]$$

$$z = \cos\theta^*$$

$A_1 \propto F_2^\gamma \Rightarrow$ Sum of all photon helicity states

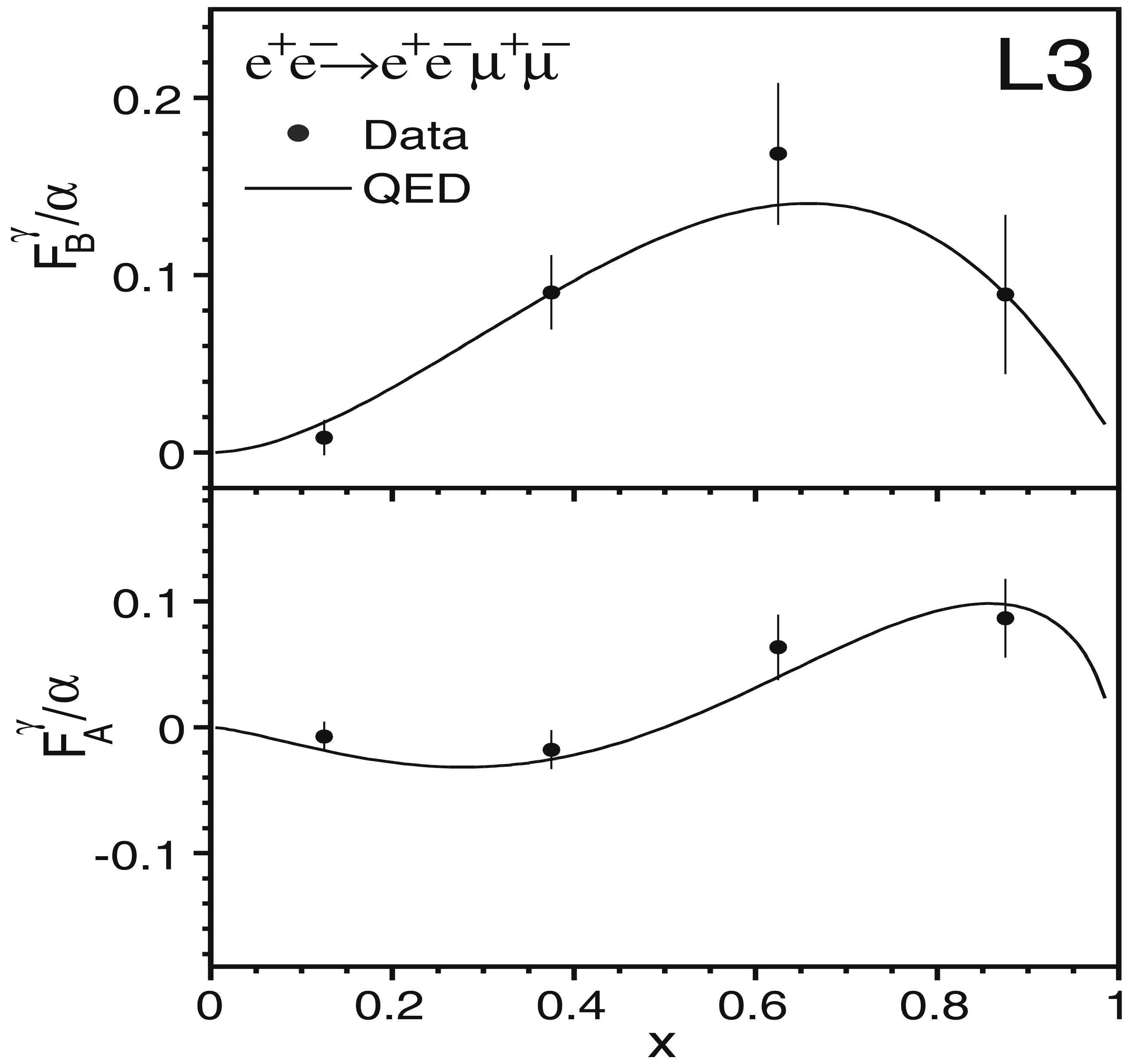
$A_2 \propto F_A^\gamma \Rightarrow$ Interference of longitudinal-transverse photons

$A_3 \propto F_B^\gamma \Rightarrow$ Interference of two transverse photons

N.B. 'transverse' photon : helicity ± 1,
'longitudinal' photon : helicity 0.

F_A^γ and F_B^γ

- F_A and F_B measurements, $< Q^2 > = 1.7$ GeV^2

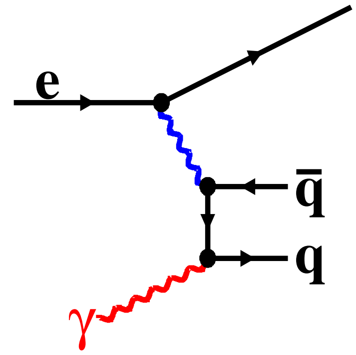


⇨ Non-zero F_A^γ is seen ➔ $F_L^\gamma \neq 0$

⇨ Consistent with QED prediction.

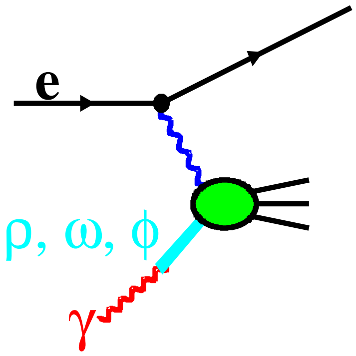
$$F_2^\gamma = F_2^{PL} + F_2^{hadr}$$

- F_2^{PL} : peaks at large x, must include $c\bar{c}$

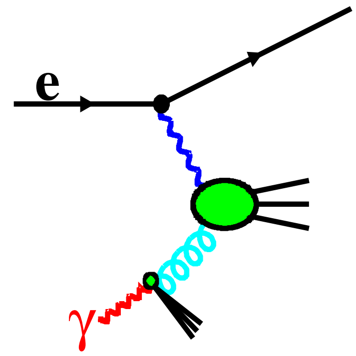


➜ QPM

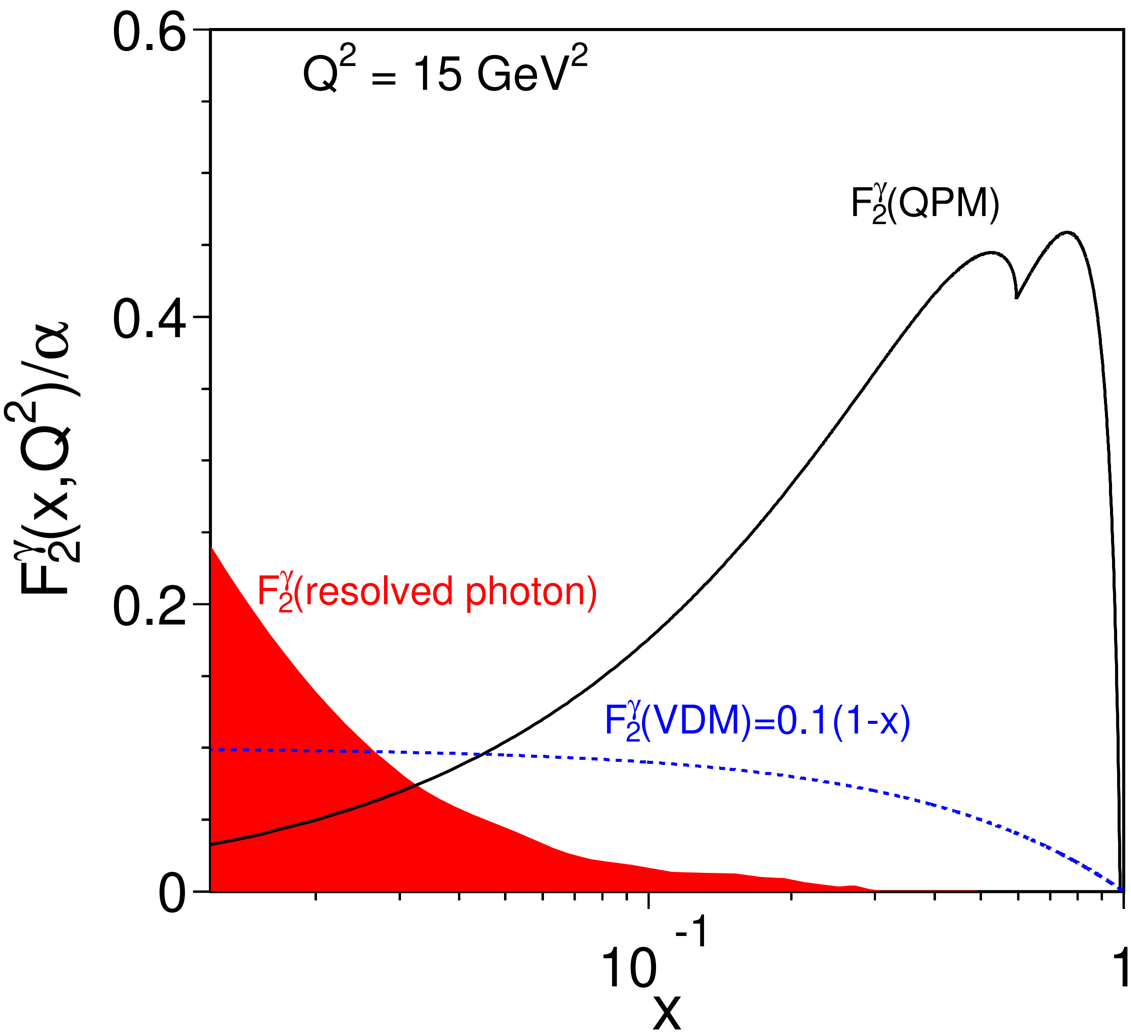
- F_2^{hadr} : main part at small x



➜ VDM, non-perturbative QCD



➜ Resolved γ, perturbative QCD



- **At high x ➜ Quark constituents are dominant.**
- **At low x ➜ Gluon constituents are dominant.**

➩ **The low x region is sensitive to the gluon density.**

Monte Carlo Programs :

- $F^\gamma_{2,\mathrm{QED}}$, $e^+e^- \to e^+e^-\mu^+\mu^-$, $q\bar{q}$:
  1. JAMVG, Vermaseren
  2. DIAG36, Berends, Daverveldt and Kleiss
  3. RADCOR, Berends, Daverveldt and Kleiss

- $F^\gamma_{2,\mathrm{QCD}}$, $e^+e^- \to e^+e^-$hadrons :
  1. TWOGAM (v1.71), Nova, Olshevski and Todorov
  2. PHOJET (v1.05c), Engel and Ranft
  3. HERWIG (v5.9), Marchesini et al.

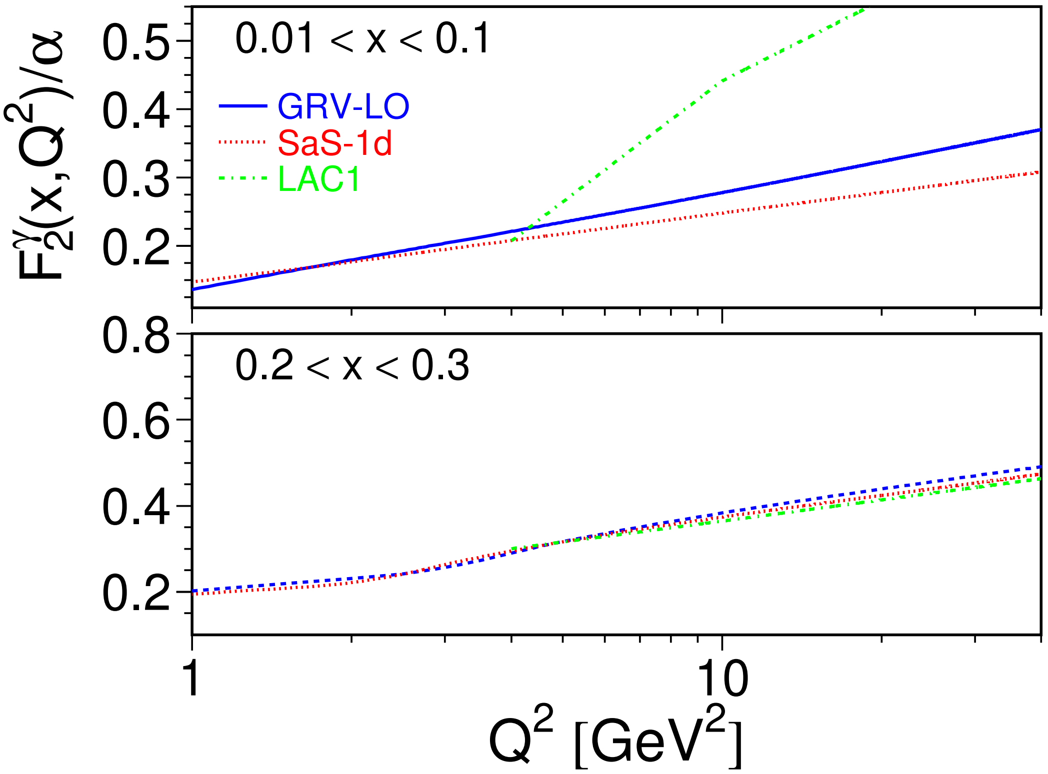
Note:

➯ No tuning of the hadronization on $\gamma\gamma$ events.

➯ for TWOGAM QCD we use
$p_t^{cut} = 2.3$ GeV at $\sqrt{s}$ =91 GeV
$p_t^{cut} = 3.5$ GeV at $\sqrt{s}$ =183 GeV

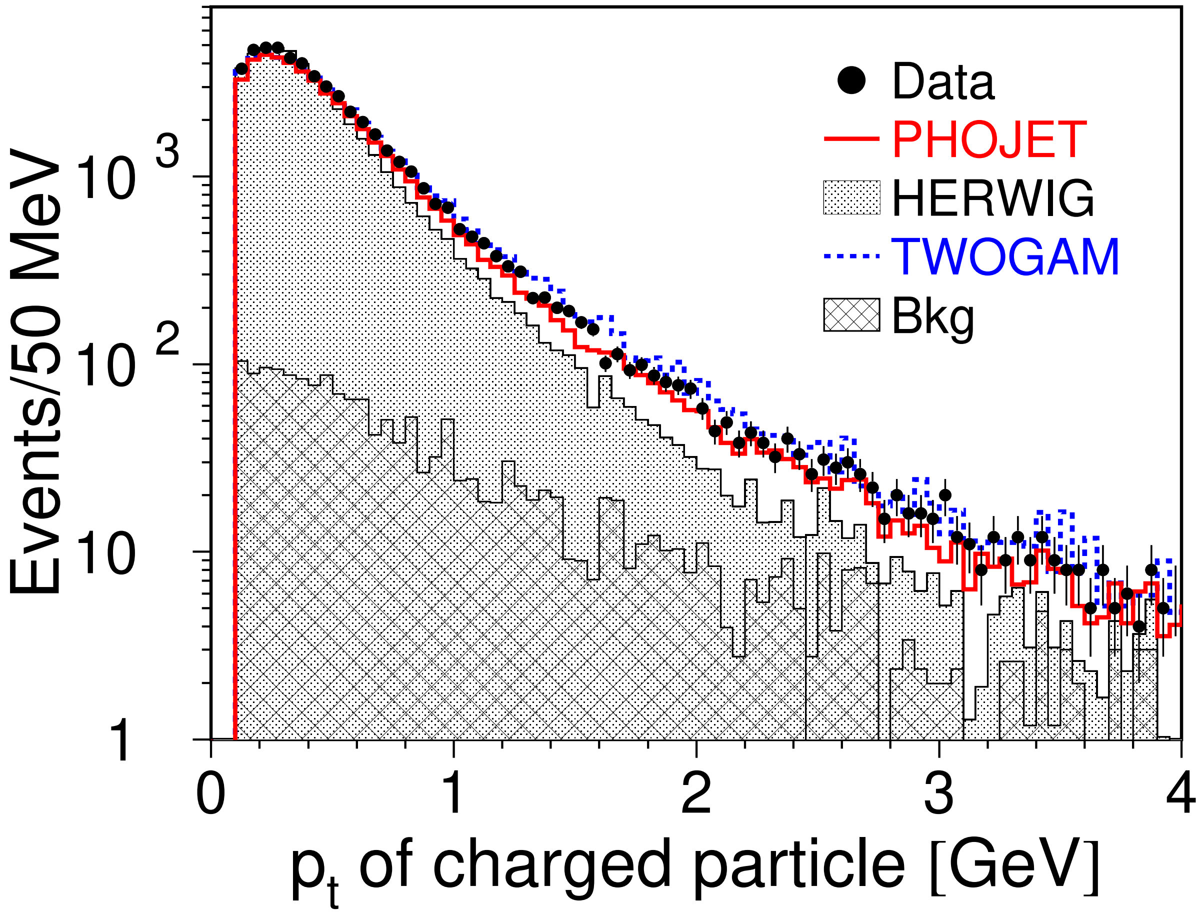
$F_{2,\mathrm{QCD}}^{\gamma}$ parametrisations

- GRV-LO/HO, Glück, Reya and Vogt (1992)
  evolution starts at a low value of Q_0^2 ($= 0.25$ GeV^2)
- SaS-1d, Schuler and Sjöstrand (1995, 1996)
  evolution starts at a low value of Q_0^2 ($= 0.36$ GeV^2)
- LAC, Abramovicz, Charchula and Levy (1991)
  evolution starts at a high value of Q_0^2 ($= 4$ GeV^2)



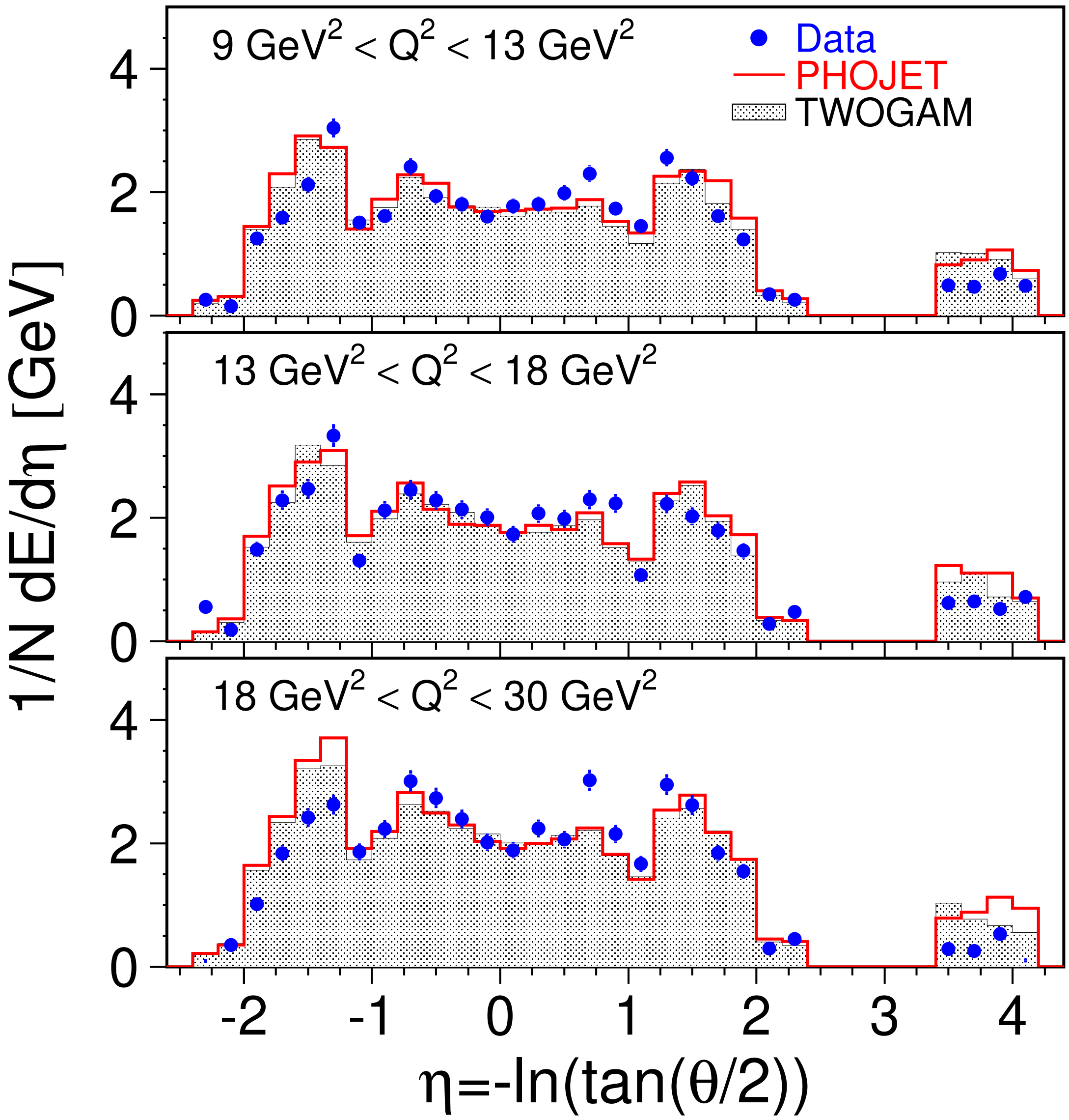
➩ The effect of $P^2 \neq 0$ is not taken into account,
it would reduce the predictions.

❑ **Compare the L3 data at $\sqrt{s}$= 183 GeV :**



⇨ **PHOJET and TWOGAM describe the data the spectrum of HERWIG is too soft.**

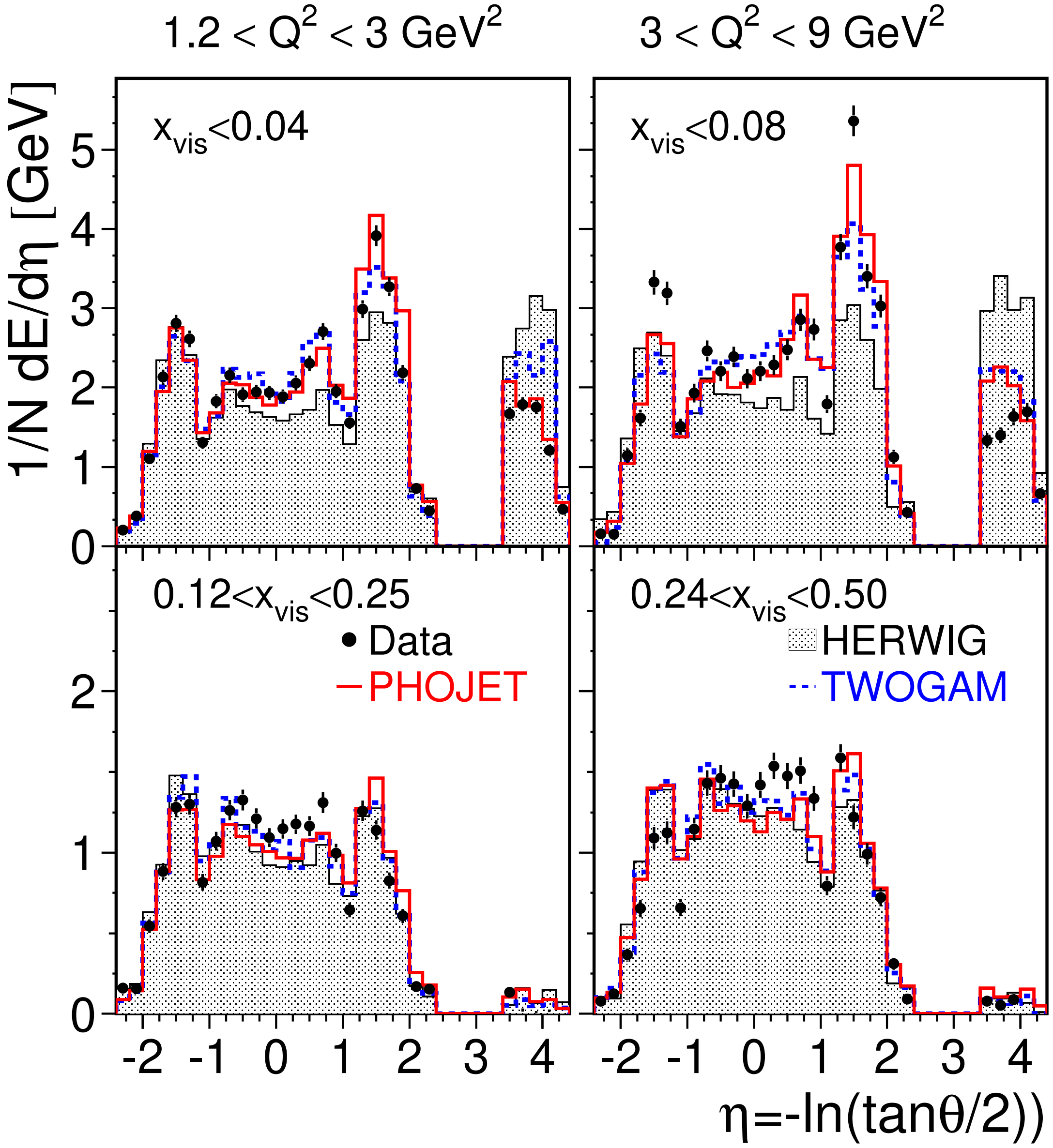
Energy Flow at $\sqrt{s}$= 183 GeV



η distribution of all particles : charged and γs

- ➩ The tag direction is always in negative side.
  The energy of tagged electron isn't shown.
- ➩ Reasonable description by PHOJET and TWOGAM.
- ➩ Use PHOJET for final result and TWOGAM to check the modelling dependence.

$F_{2,\mathrm{QCD}}^{\gamma}$: Energy Flow at $\sqrt{s}$= 91 GeV



- PHOJET and TWOGAM do better than HERWIG.
- HERWIG agreement improves at high x.

- Due to detector acceptance and efficiency

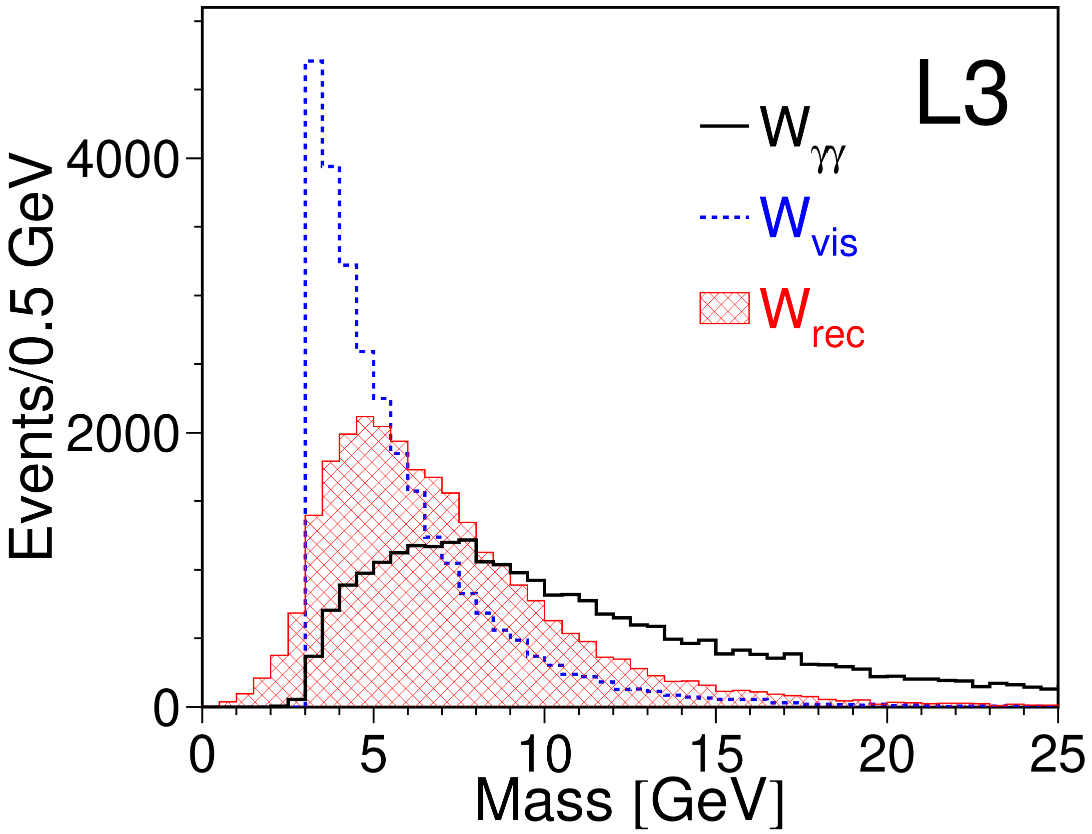
  ⇨ $W_{vis} < W_{\gamma\gamma}$ ➜ Unfolding

- Improve W_{vis} ➜ Use kinematics of e_{tag}

$$W^2_{rec} \equiv (p_+^{e_{in}} - p_+^{e_{tag}})(\sum_i p_-^i) - |p_t^{e_{tag}}|^2$$

$$p_\pm \equiv E \pm p_z$$

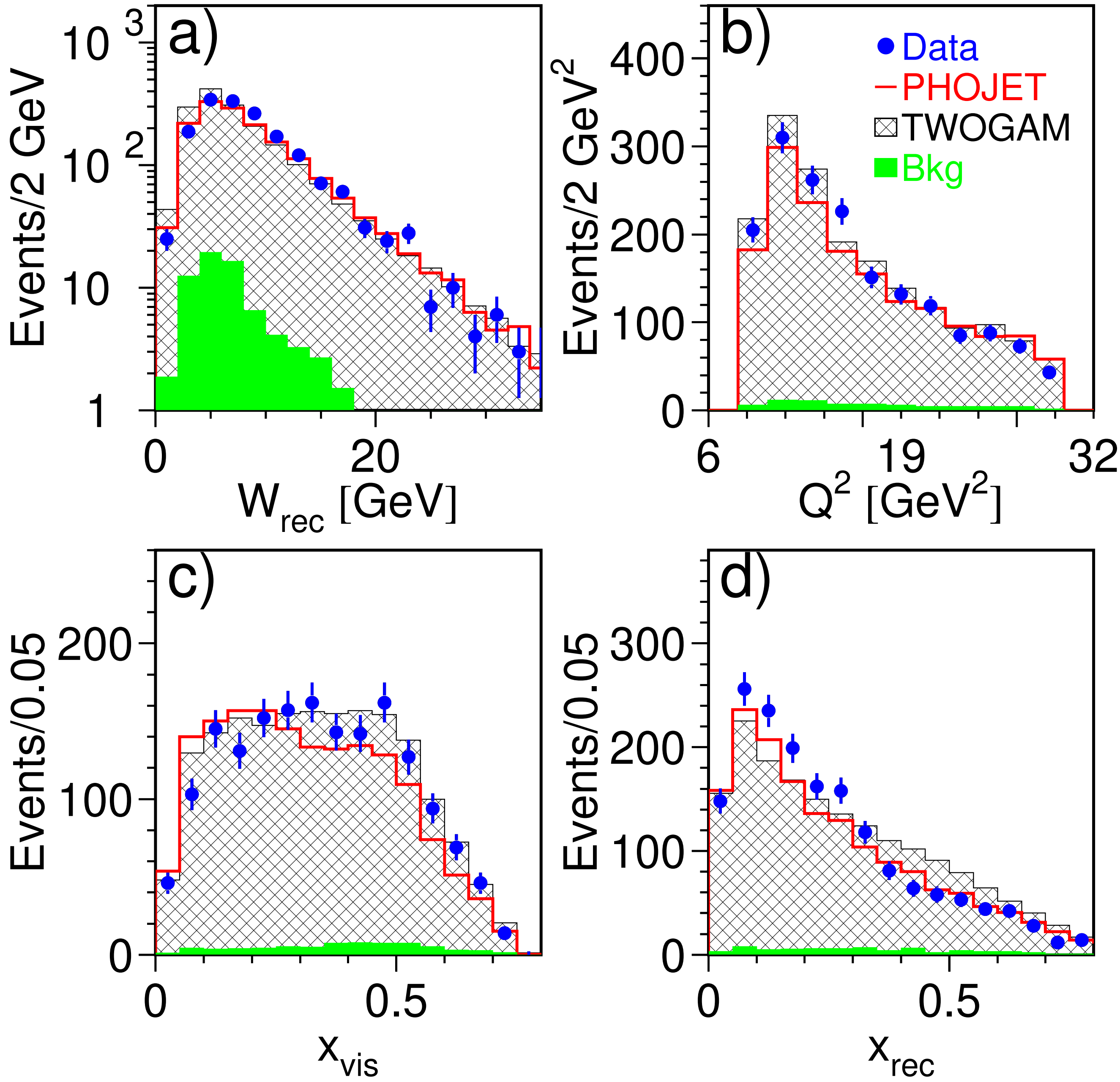
* Physics at LEP2, CERN 96-01, Vol.2, 201.



- Use Unfolding for x_{rec} ➜ x.

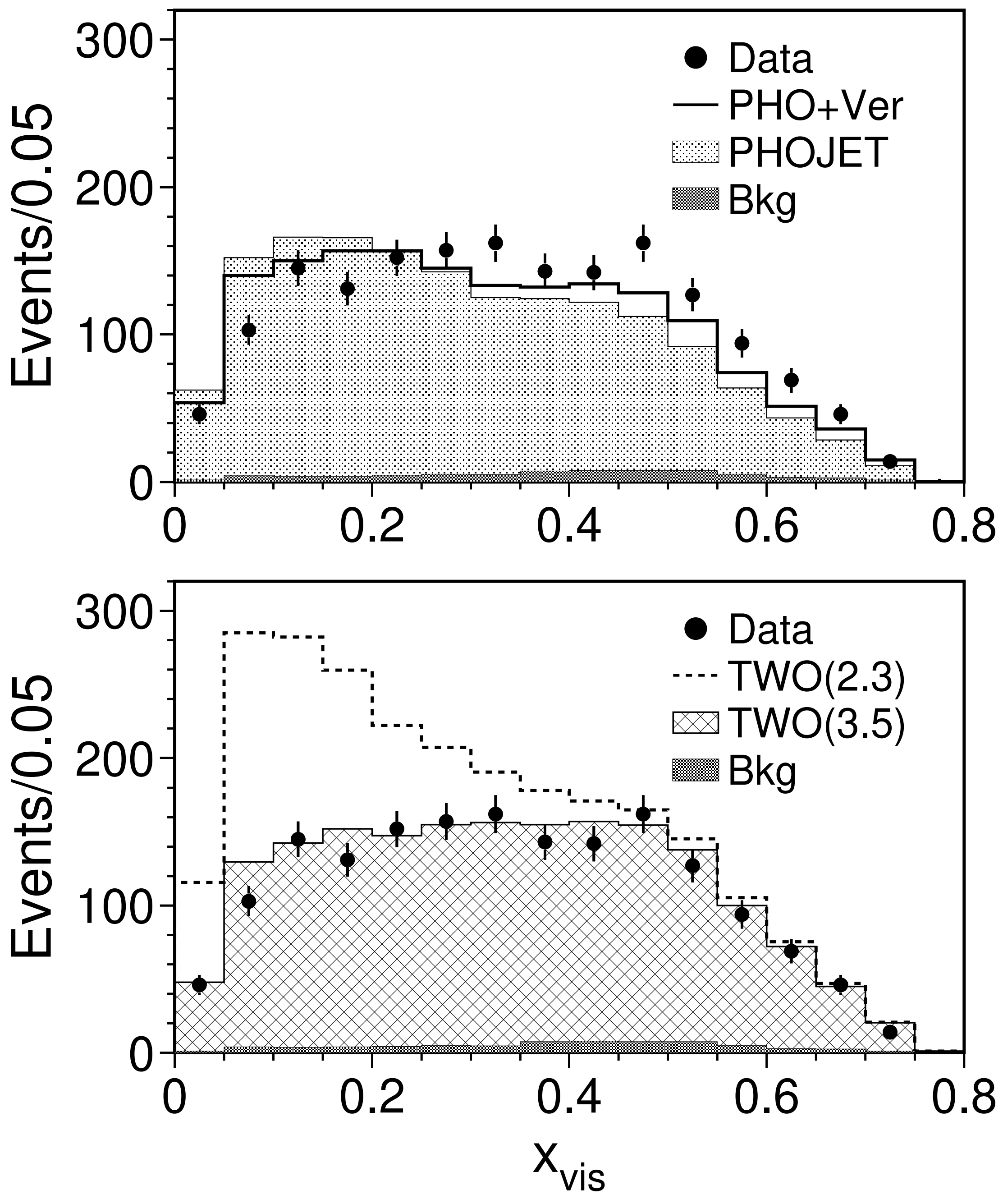
MC Comparison at $\sqrt{s}$= 183 GeV

❒ To unfold the data ➜ Good Monte Carlo Model



➩ Both PHOJET and TWOGAM describe the data reasonably well.

MC adjustement at $\sqrt{s}$= 183 GeV

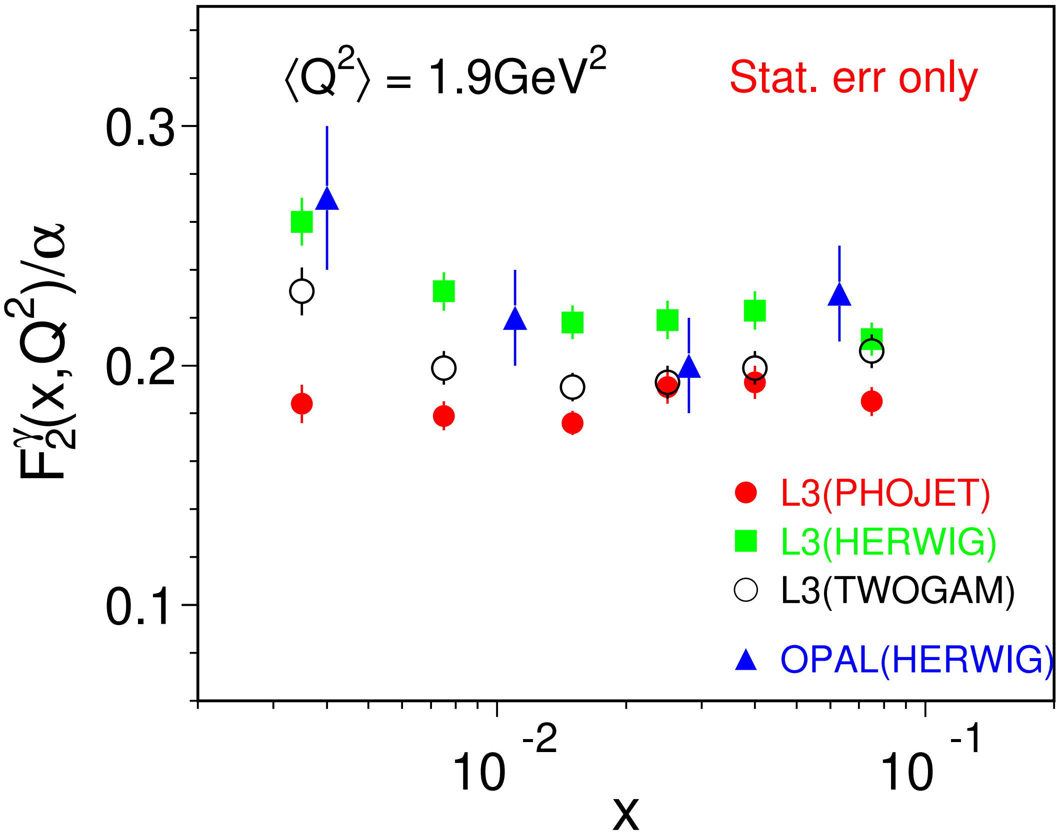


➩ The $c\bar{c}$ component must be added to PHOJET, it is given by JAMVG (Vermaseren).

➩ For TWOGAM a p_t^{cut} = 2.3 GeV gives a too big QCD component ➜ use p_t^{cut} = 3.5 GeV.

$F_{2,\mathrm{QCD}}^{\gamma}$: Modelling Dependence

- **Unfold the data with different Monte Carlos.** ($\sqrt{s} \simeq 91\mathrm{GeV}$)
- **The OPAL results are obtained with HERWIG.**

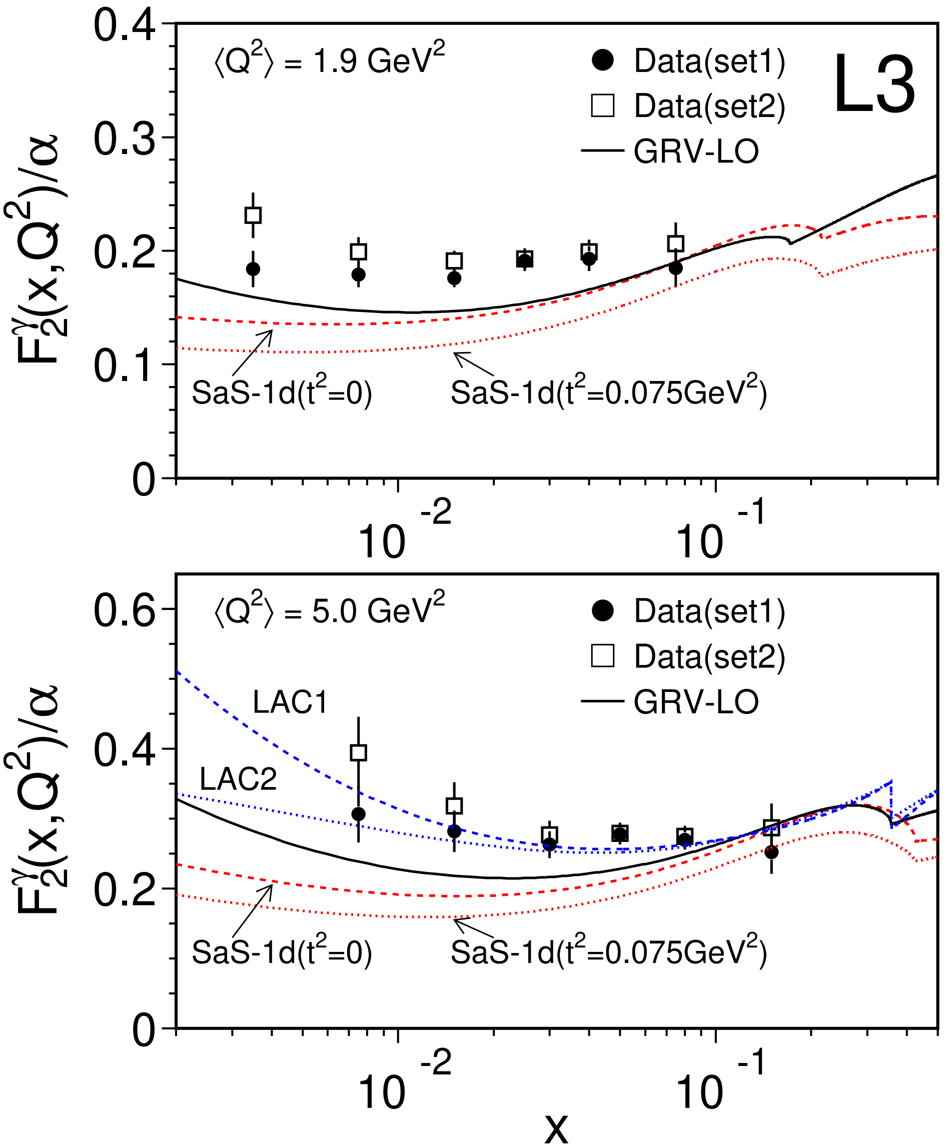


⇨ **L3 and OPAL agree if they use the same MC, but HERWIG doesn't describe the data as well as PHOJET.**

⇨ **The discrepancy is larger at low x and low Q^2.**

$F_{2,\mathrm{QCD}}^{\gamma}$: low Q^2 , $\sqrt{s} = 91$ GeV

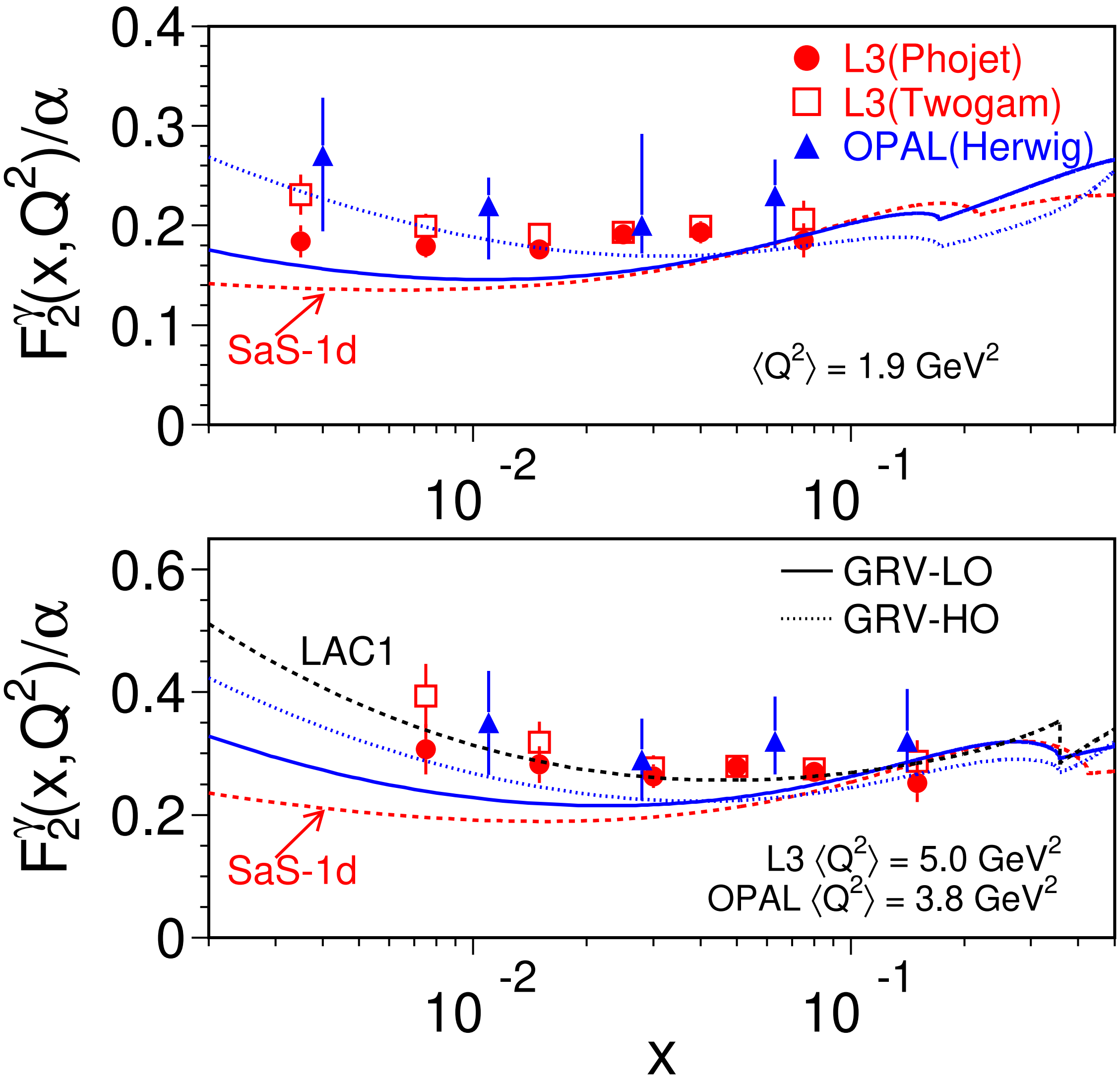
- $F_{2,\mathrm{QCD}}^{\gamma}$ at low Q^2 ➜ access to low x.



$t^2 \equiv P^2$ in these figures, set1 $\equiv$ PHOJET, set2 $\equiv$ TWOGAM

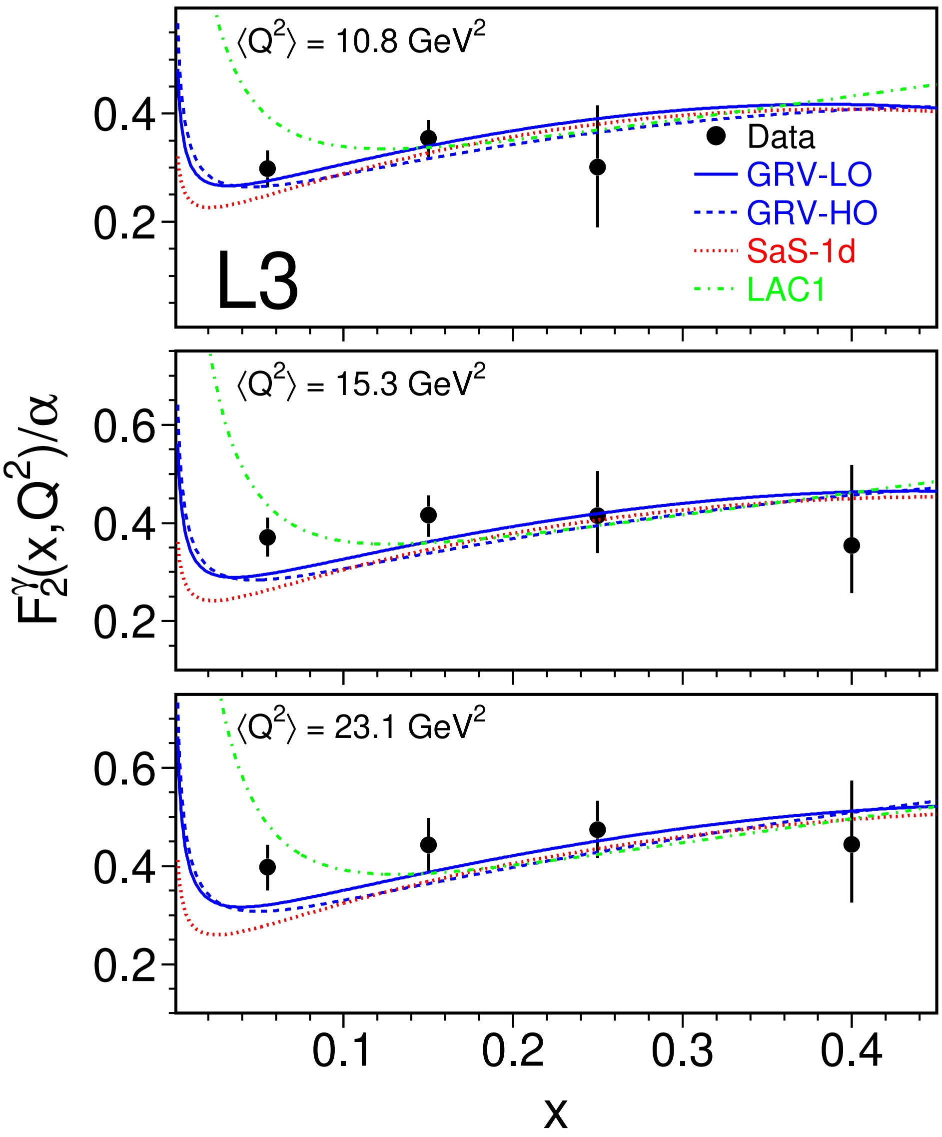
- ➩ GRV-LO and SaS-1d below the data
- ➩ LAC1 agrees with the data at $Q^2 = 5\mathrm{GeV}^2$ apparently!
  ➜ it disagrees with high Q^2 data and Q^2 evolution.

- The measured $F_{2,\mathrm{QCD}}^{\gamma}$ at low Q^2 ➜ access to low x.



⇨ **GRV-HO** describes the low x better than **GRV-LO**.

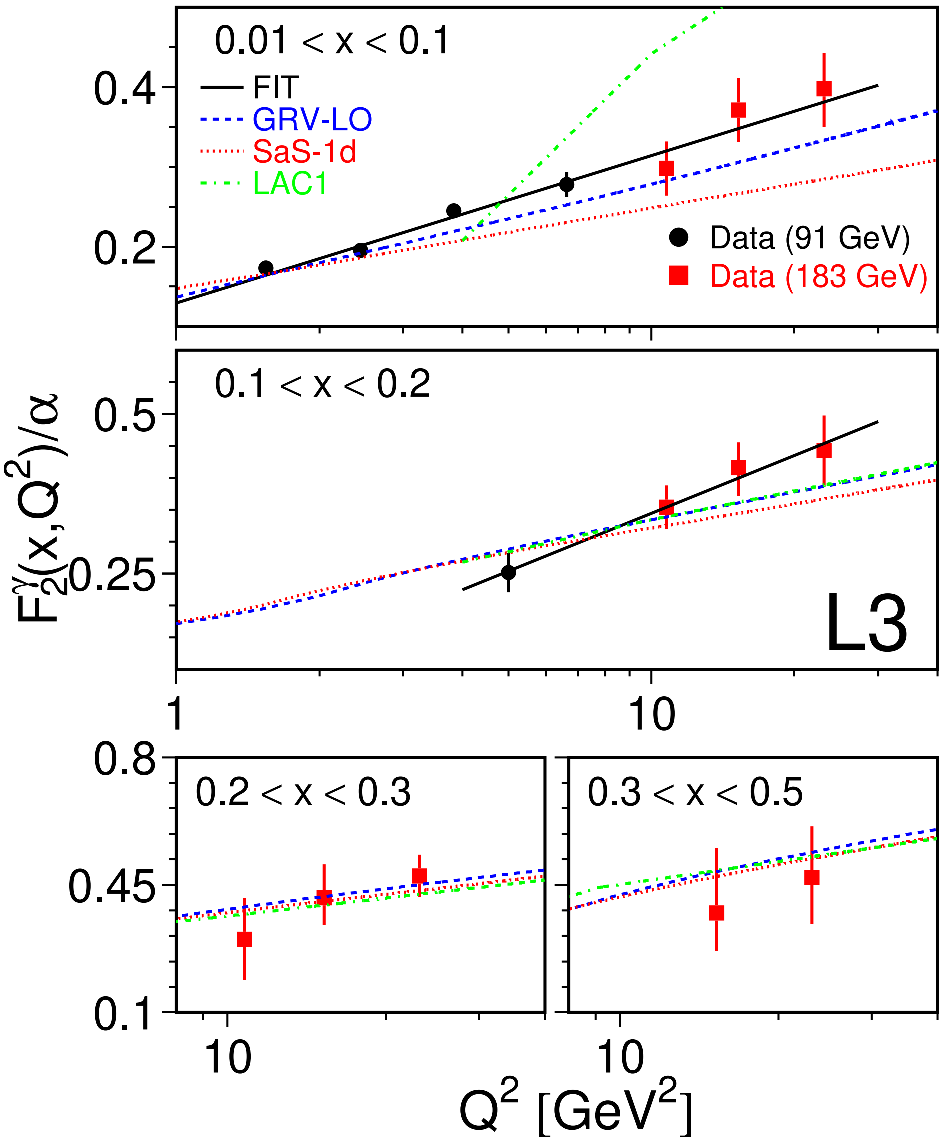
$F_{2,\mathrm{QCD}}^{\gamma}$: medium Q^2, $\sqrt{s}$= 183 GeV



➩ $x > 0.1$, good agreement with the parametrisations.

➩ $x < 0.1$, the data lie between **LAC1** and **GRV**.
➜ **Gluon density** is overestimated in **LAC1**.
➜ **Gluon density** is underestimated in **GRV** and **SaS-1d**.

- Use both measurements at $\sqrt{s} \simeq 91$ GeV and $\sqrt{s} \simeq 183$ GeV.
- The Q^2 ranges from 1.2 GeV^2 to 30 GeV^2.



➩ The measurements at 91 GeV and 183 GeV agree well.

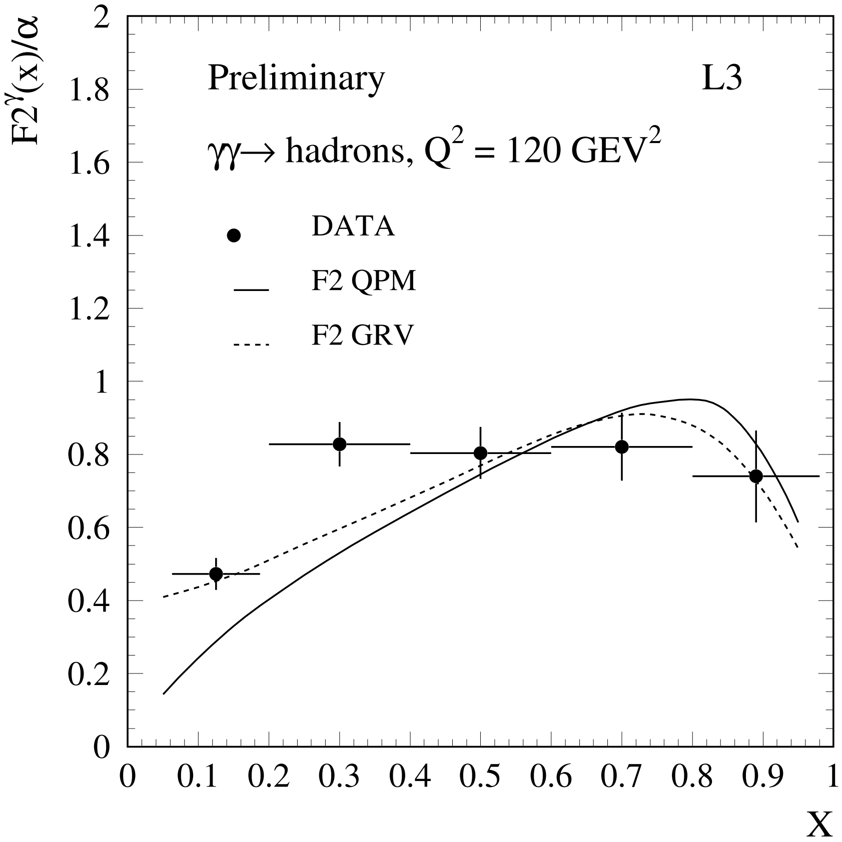
➩ LAC1 increases too fast and SaS-1d too slowly.

➩ Fit with $a + b \times \ln(Q^2/\mathrm{GeV}^2)$:

$b = 0.080 \pm 0.009 \pm 0.009$ in $0.01 < x < 0.1$

$b = 0.13 \pm 0.03 \pm 0.03$ in $0.1 < x < 0.2$

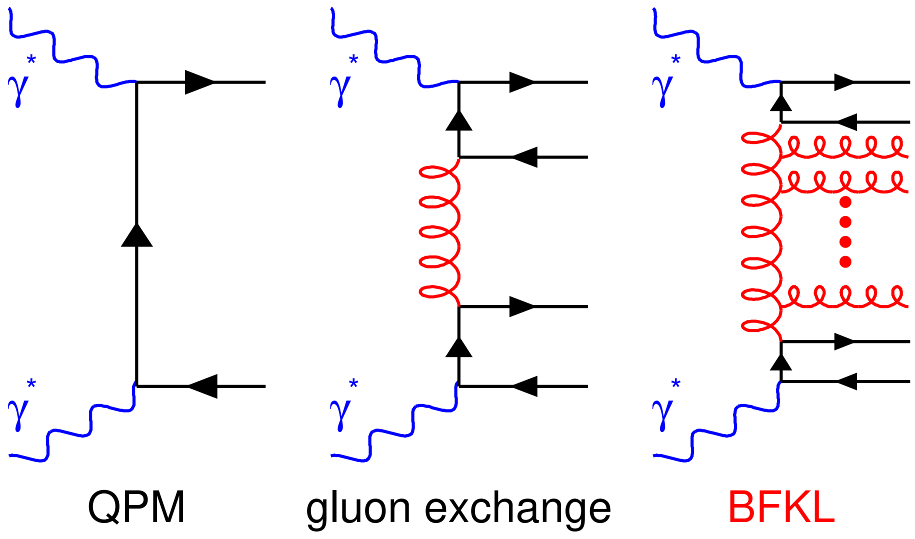
- **$F^\gamma_{2,\mathrm{QCD}}$ for $40 \leq Q^2 \leq 500$ GeV^2 and $\sqrt{s}$ =91 GeV**
  ➜ access to high x.



⇨ **QPM is insufficient to describe the data at low x**

⇨ **GRV is OK**

$\sigma_{\gamma^*\gamma^*}$ (Double-tagged events)



- **J. Bartels et al.** (Phys. lett. B389 742, 1996) and **S.J. Brodsky et al.** (Phys. Rev. D56 6957, 1997) point out the **BFKL Pomeron** can be investigated in $\gamma^*\gamma^*$ **collisions**.
  - ➪ BFKL diagram is dominant at high Q^2 and high $W_{\gamma^*\gamma^*}$.
  - ➪ two virtual photons ➜ double-tagged events
- In Leading order approximation :

$$\sigma_{\gamma^*\gamma^*} = \sigma_0\left(\frac{s}{s_0}\right)^{\alpha_P - 1} \simeq \sigma_0\left(\frac{W^2_{\gamma^*\gamma^*}}{\sqrt{Q_1^2 Q_2^2}}\right)^{\alpha_P - 1}$$

$$s_0 = \frac{\sqrt{Q_1^2 Q_2^2}}{y_1 y_2}\ ,\ y_i = 1 - (E_i/E_{beam})\cos^2\theta_i/2$$

$$\alpha_P - 1 = 4\ln 2\frac{N_c\alpha_s}{\pi}$$

- Using $N_c = 3$, $\alpha_s = 0.2$ ➜ $\alpha_P - 1 \simeq 0.53 > 0.079$
- The measurement of $\sigma(\mathrm{e^+e^-} \to \mathrm{e^+e^-}\gamma^*\gamma^* \to \mathrm{e^+e^-} + hadrons)$ is an excellent test for the BFKL Pomeron.

$\sigma_{\gamma^*\gamma^*}$: Analysis

- Data :
  L3 : 91 GeV, 140. pb^{-1}
  183 GeV, 51.9 pb^{-1}

- Monte Carlo :

  PHOJET: Engel and Ranft.
  (Phys. Rev. D54, 4246, 1995)

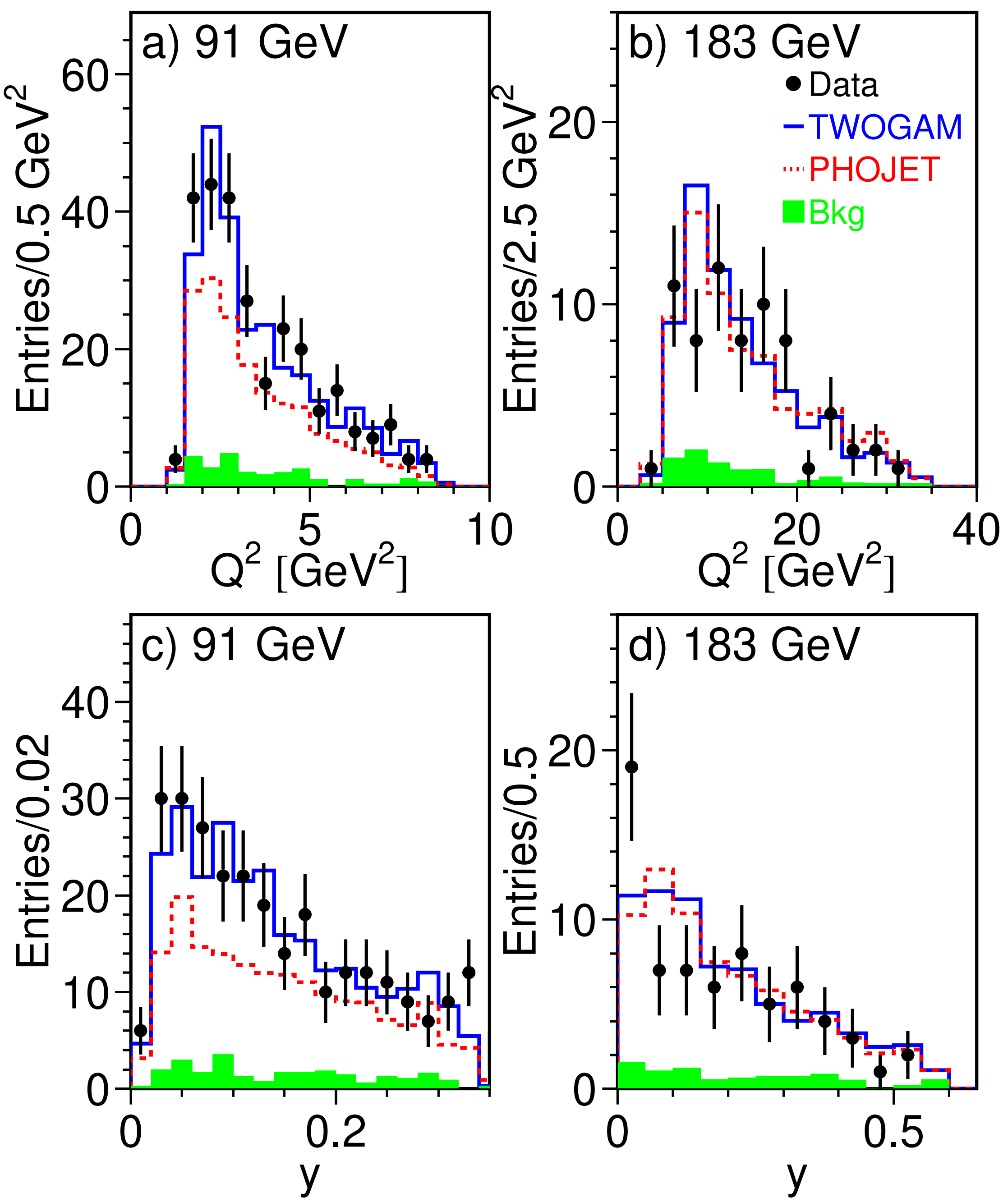
  TWOGAM: Nova, Olshevski and Todorov
  (Delphi Note 90-35)

  ➜ Good agreement with single-tagged events
  ➜ Neither of MCs use the assumption of BFKL Pomeron

- Event Selection :

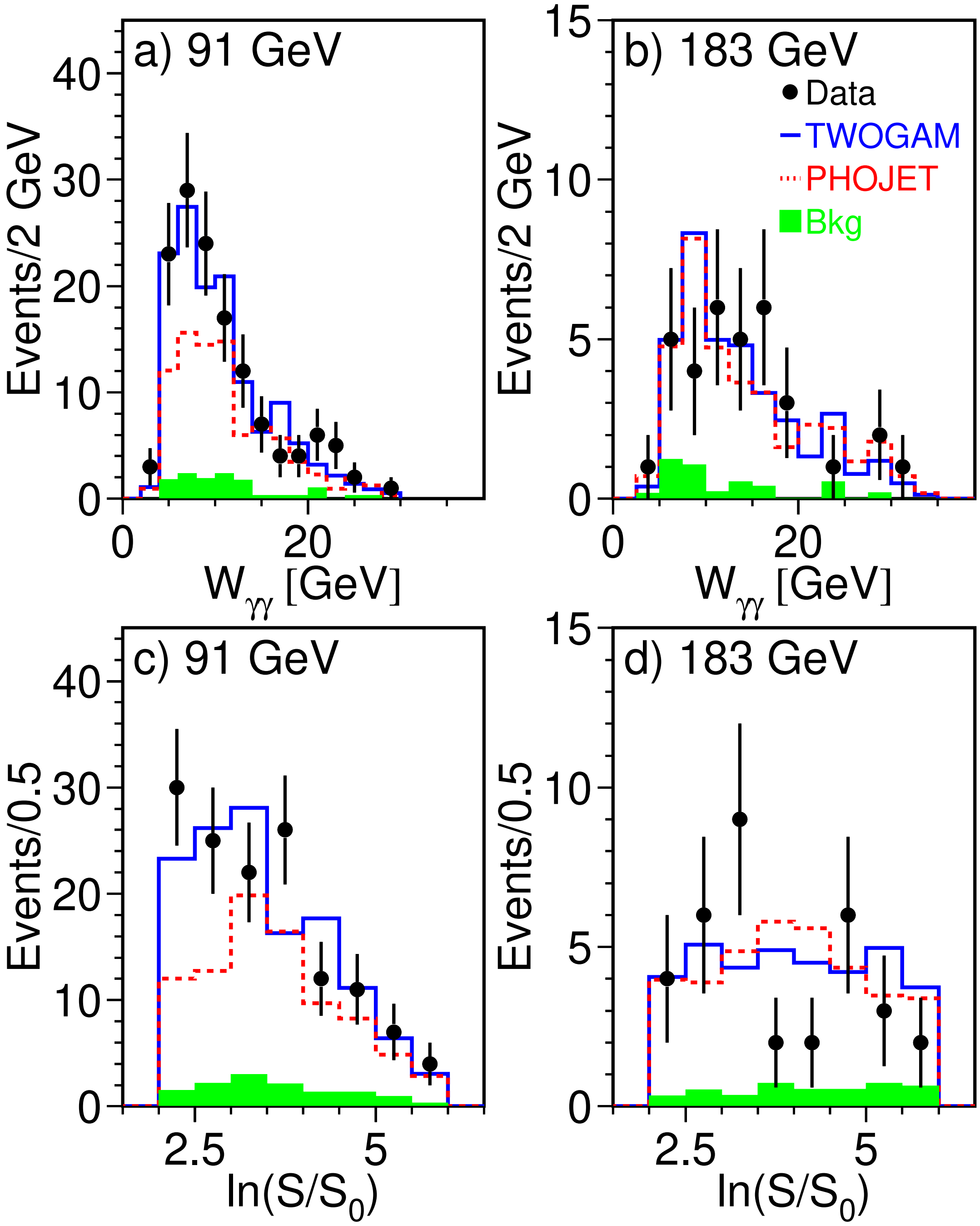
  - The tagged electron is identified by :
    $E_{tag} > 30\text{GeV}$ for $\sqrt{s} \simeq 91\text{GeV}$
    $E_{tag} > 40\text{GeV}$ for $\sqrt{s} \simeq 183\text{GeV}$
    30 mrad $< \theta_{tag} <$ 66 mrad
  - The number of tracks > 2
  - $W_{vis} > 2\text{GeV}$
  - $2 < \ln(s/s_0) < 6$

$\sigma_{\gamma^*\gamma^*}$: MC comparison



*Two entries per event

- **PHOJET is a factor of two lower than the data at 91 GeV.**
- **The backgrounds come from $e^+e^- \to e^+e^-\tau^+\tau^-$ and single tagged events.**



- **TWOGAM** describes the data well at both energies.
- **PHOJET** is lower than the data in the low mass region at 91 GeV.

- **BFKL** calculation is more reliable at high Q^2 and high $W_{\gamma\gamma}$.
- the kinematic region is limited by :
  - ➪ $E_{tag} > 30\text{GeV}$ and $30\ \text{mrad} < \theta_{tag} < 66\ \text{mrad}$
  - ➪ $Q^2 > 2.5\text{GeV}^2$ and $y \geq 0.1$
  - ➪ $2 < \ln(s/s_0) < 6$
- Number of events :

  91 GeV ➪ 12 events ($\varepsilon = 91\%$, $bkg = 5.9\%$)
  183 GeV ➪ 9 events ($\varepsilon = 86\%$, $bkg = 16\%$)

- $\sigma(e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- + hadrons)$:

	91 GeV	183 GeV
Data	$0.084 \pm 0.026 \pm 0.005$ pb	$0.17 \pm 0.07 \pm 0.01$ pb
BFKL	2.829 pb	2.135 pb
gluon exchange	0.200 pb	0.135 pb
QPM	0.032 pb	0.018 pb
TWOGAM	0.089 pb	0.28 pb
PHOJET	0.066 pb	0.25 pb

*QPM is estimated with Vermaseren M.C., $m_u = m_d = m_s = 0.325$ GeV and $m_c = 1.6$ GeV.
* Predictions of BFKL and gluon exchange are provided by A. De Roeck.

- PHOJET and TWOGAM agree with the data.
- The measured cross-section is much lower than the BFKL Pomeron prediction. ➜ the effect of NLO term ?!
- QPM is too low and the gluon exchange is compatible with the data at 183 GeV.

Conclusion

- Good data at LEP with L3:
  - high statistics, low experimental systematic error
  - Main uncertainty from MC models, at low x
- At low x, the data lie between LAC1 and GRV.
  - the gluon density is underestimated in GRV and SaS-1d and overestimated in LAC1.
- The Q^2 evolution is studied by using the data taken at 91 GeV and 183 GeV.
  - The value of F_2^γ shows a significant $\ln Q^2$ evolution.
  - For $x < 0.2$, the rise of F_2^γ is larger than GRV and SaS-1d models.
- Double tag events do not need BFKL diagrams

More data will come :

1998	$\sqrt{s} = 189$ GeV	$L_{ee} \geq 150\ pb^{-1}$
1999-2000	$\sqrt{s} \simeq 200$ GeV	$L_{ee} \simeq 300\ pb^{-1}$

we must and will understand better the processes involved in two-photon collisions.