Measurement of the photon structure function $F_2^\gamma (x,Q^2)$ with the LUMI detector at L3

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- Introduction
- Data and Monte Carlo
- Event selection
- Binning
- Unfolding
- Differential cross sections
- x and Q^2 dependence of F_2^γ
- Conclusion and outlook

Analysis goal

- Measure the photon structure function $F_2^{\gamma}(x,Q^2)$ from the measured differential cross section $\Delta\sigma(e^+e^- \rightarrow e^+e^-hadrons)$

- Centre-of-mass energies:
  $\sqrt{s} = 189 - 206\ GeV$

- Tagging detector: Luminosity Monitors (LUMI)

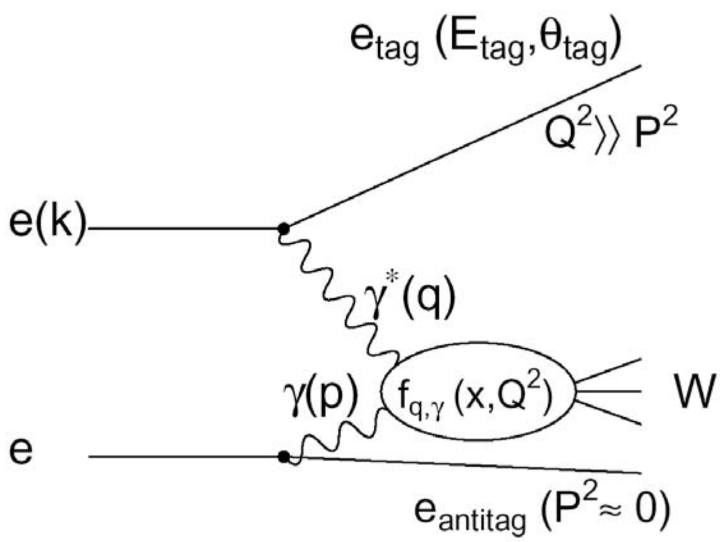
- LUMI Q^2 range

  1998 (189 GeV): 11-34 GeV^2
  1999 (194 GeV): 11-37 GeV^2
  (200 GeV): 11-38 GeV^2
  2000 (206 GeV): 11-40 GeV^2

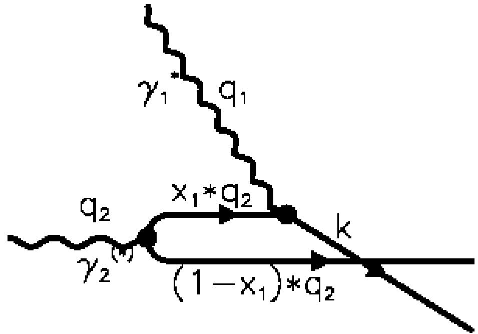
- Compare results with other experiments and theoretical predictions

Single-tag analysis of the $e^+e^- \to e^+e^-$hadrons deep inelastic scattering reaction:

- One of the scattered electrons detected (tagged) in LUMI; second electron undetected (scattering angle small, $P^2 \approx 0$)
- Quasy-real target photon probed by the highly virtual photon ($Q^2 >> 0$)



Variables



$$q_i = (E_{\gamma_i^*}, \vec{p}_{\gamma_i^*}), \ (i = 1,2)$$

$$q_i^{\,2} = E_{\gamma_i^*}^{\;2} - \vec{p}_{\gamma_i^*}^{\;2}$$

for single - tagged hadron production :

$$\boxed{\begin{aligned} -q_1^2 &= Q_1^2 \equiv Q^2 > 0 \\ -q_2^2 &= Q_2^2 \cong 0 = P^2 \end{aligned}}$$

mass squared of the outgoing interacting fermion :

$$\mathrm{k}^2 = (xq_2 + q_1)^2 = q_1^2 + 2xq_1 \cdot q_2 \cong 0$$

$$\Rightarrow \ x = -\frac{q_1^2}{2q_1 \cdot q_2} = \frac{Q^2}{2q_1 \cdot q_2}$$

x: Bjorken variable

Single-tag variables:

$$\boxed{Q^2 = -q^2 \approx 2E_{tag}E_{beam}(1 - \cos\theta_{tag})}$$

$$x = Q^2 / \left(Q^2 + W^2 + P^2\right) = Q^2 / 2(p \cdot q)$$

$$W \ = (q_1 + q_2)^2 = (E_{\gamma^*} + E_\gamma)^2 - (\vec{q} + \vec{p})^2$$

$$q_1 \quad (E_{\gamma^*}, q), \ q_2 = (E_\gamma, p)$$

For single tagged events: P ≅0

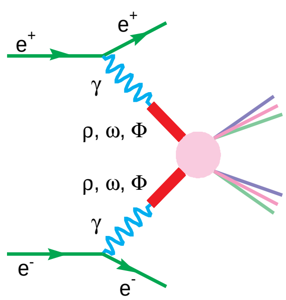
$$\boxed{x = \frac{Q^2}{Q^2 + W^2}}$$

Goal: measure the cross section for the single-tagged $\gamma^*\gamma$ process to extract the photon structure function $F_2^{\gamma}(x, Q^2)$

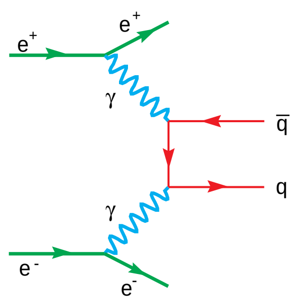
$$\frac{d\sigma_{e(k)\gamma^*(q)\to e_{tag}(k')X}(x,Q^2)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)\boxed{F_2^{\gamma}(x,Q^2)} - y^2 F_L^{\gamma}(x,Q^2)\right]$$

$$y = (p\cdot q)/(p\cdot K) \approx 1 - \left(E_{tag}/E_{beam}\right)\cdot \cos^2(\theta_{tag}),\ y \approx 0$$

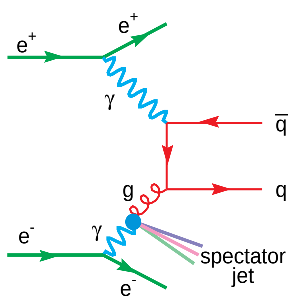
Main Processes contributing to the $e^+e^- \to e^+e^- \gamma^* \gamma \to e^+e^-$ + hadrons cross section



VDM



Direct process (QPM)



Single Resolved

Analysis Method

1. **Selection**
2. **Binning**
3. **Unfolding**

   Energy of the target photon is not known: correction with MC (PYTHIA, PHOJET, TWOGAM)
   BAYES unfolding method

4. **Calculate measured cross section**

$$\frac{N_{\text{unfolded}} - N_{\text{background}}}{L \cdot \text{acceptance} \cdot \text{trigger efficiency}}$$

5. **Divide measured cross section with analytically calculated cross section [Galuga] to obtain F_2^{γ}**

Error calculation

Statistical error (absolute)
Systematic error: difference between the results obtained with PHOJET, PYTHIA and TWOGAM (systematical error from data selection and unfolding is negligible compared to the systematical error obtained from the unfolding with MC's)
Total error: quadratic sum of the statistical and systematic error

Selections

1. LUMI tag

at least one cluster in LUMI with

- **Polar angle**

  $0.0325\ (\mathrm{rad}) \leq \theta \leq 0.0637\ (\mathrm{rad})$

- **Energy of the cluster reconstructed as an electromagnetic shower**

  $E_{clus} > 0.7\ E_{beam}$

- **Raw energy of the cluster**

  $E_{raw} > 0.8\ E_{clus}$

2. Hadrons in final state

number of tracks in TEC and photons in ECAL

$N_{tracks} + N_{\gamma} \geq 6$

3. Reject $e^{+}e^{-} \rightarrow q\bar{q}\gamma$ background

$E_{ECAL+HCAL} < 0.4\sqrt{s}$

4. Anti-tag

for clusters in LUMI opposite to the tag

$E^{opp}_{clus} < 0.45\ E_{beam}$

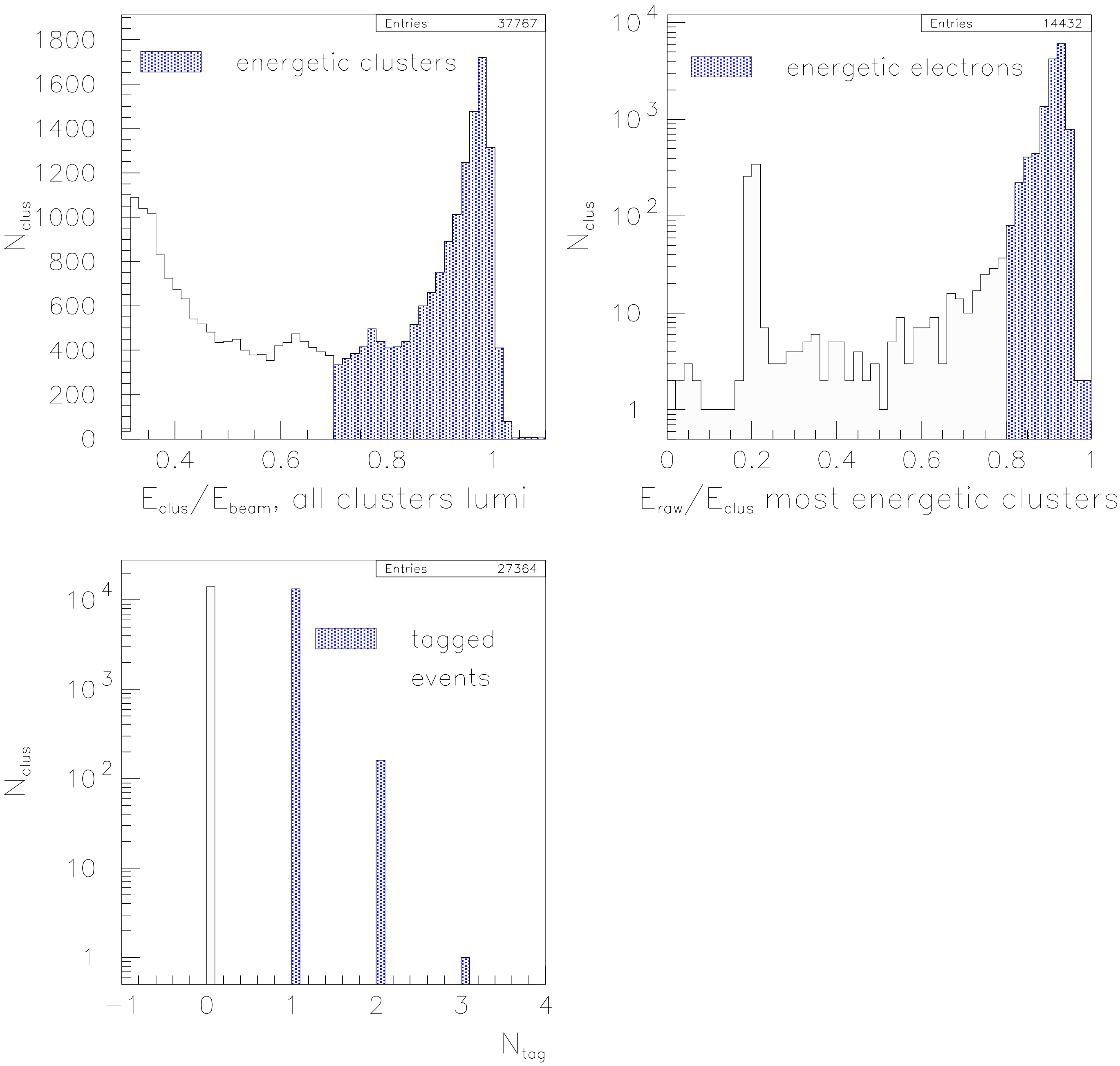
5. Exclude low masses

$W_{vis} \geq 5\ \mathrm{GeV}$

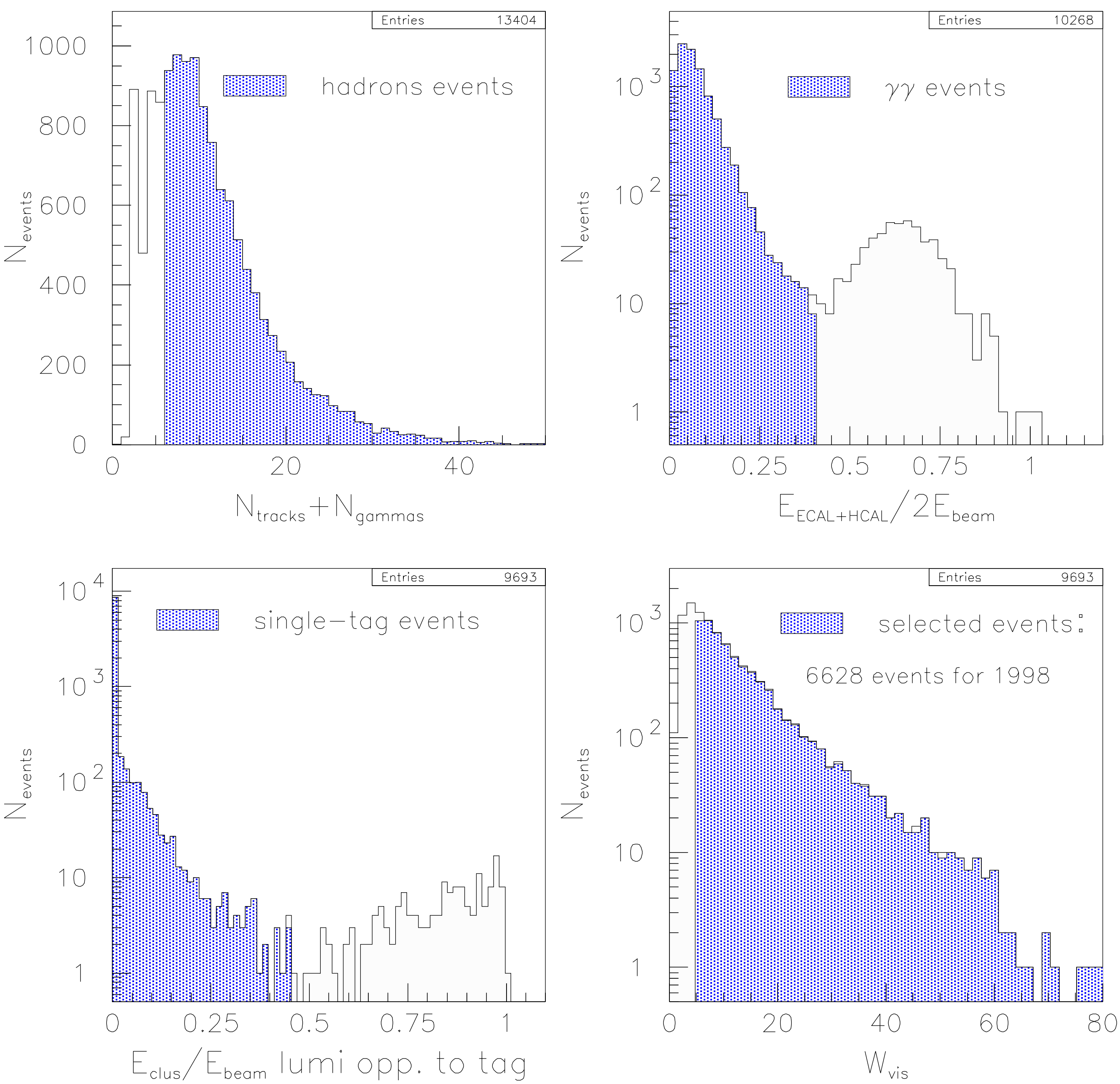
Data sets and Monte Carlo

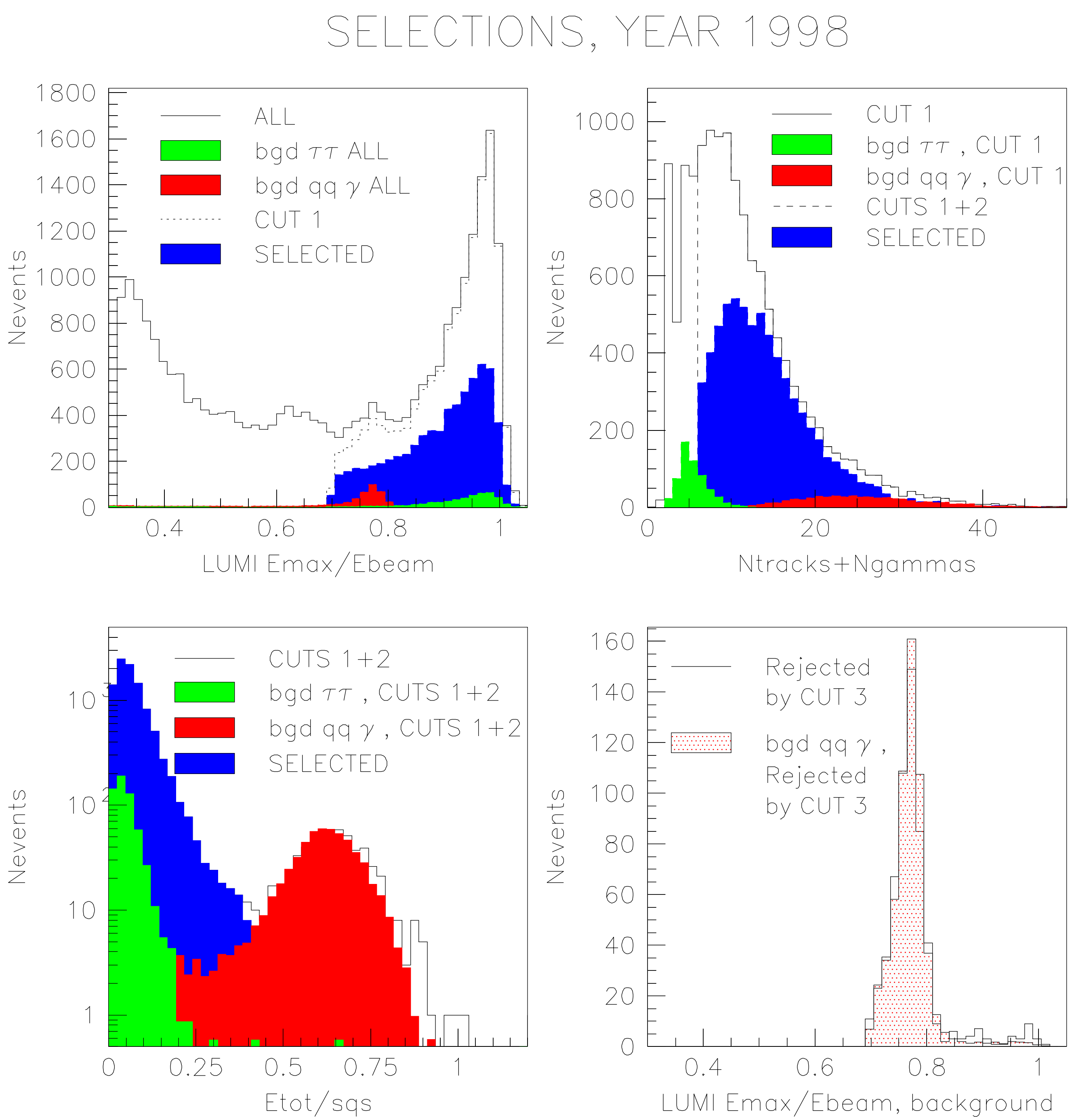
Data			
year	**E_{beam}(GeV)**	**L(pb^{-1})**	**$N_{selected}$**
1998	94.3	171.8	6628
1999a	97.3	111.4	4220
1999b	100.0	90.1	3095
2000	103.1	210.5	7990
Monte Carlo			
PHOJET	94.5	2807.4	54073
	97.8	1817.4	33603
	99.8	1818.1	33341
	102.0	1754.3	33380
PYTHIA	94.5	318.2	21223
	98.7	456.4	26169
	103	453.3	28570
TWOGAM (QCD+QPM+VDM)	94.5	5489.1	81127
	97.8	4264.4	61265
	99.8	4390.4	62067
	102.0	5298.5	73949
Background MC			
$\gamma^*\gamma^* \to \tau\bar{\tau}$	94.5	1022.7	1057
	98.0	224.7	211
	102	1100.0	1148
$Z\gamma \to q\bar{q}\gamma$	94.3	1960.7	381
	97.8	1123.5	200
	99.8	1141.5	210
	103.3	11318.4	396

SELECTIONS : CUT 1, LUMI tag for 1998

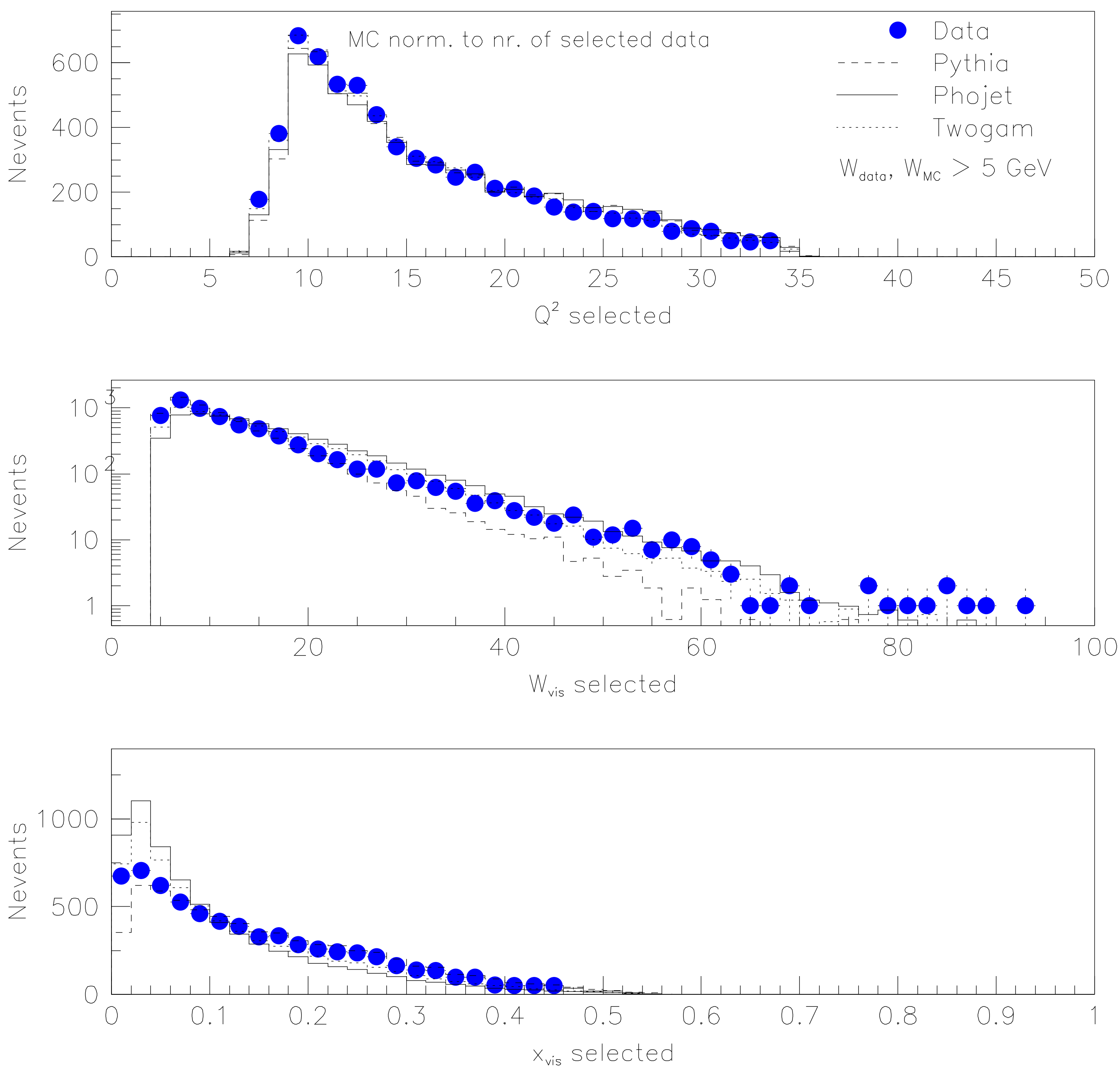


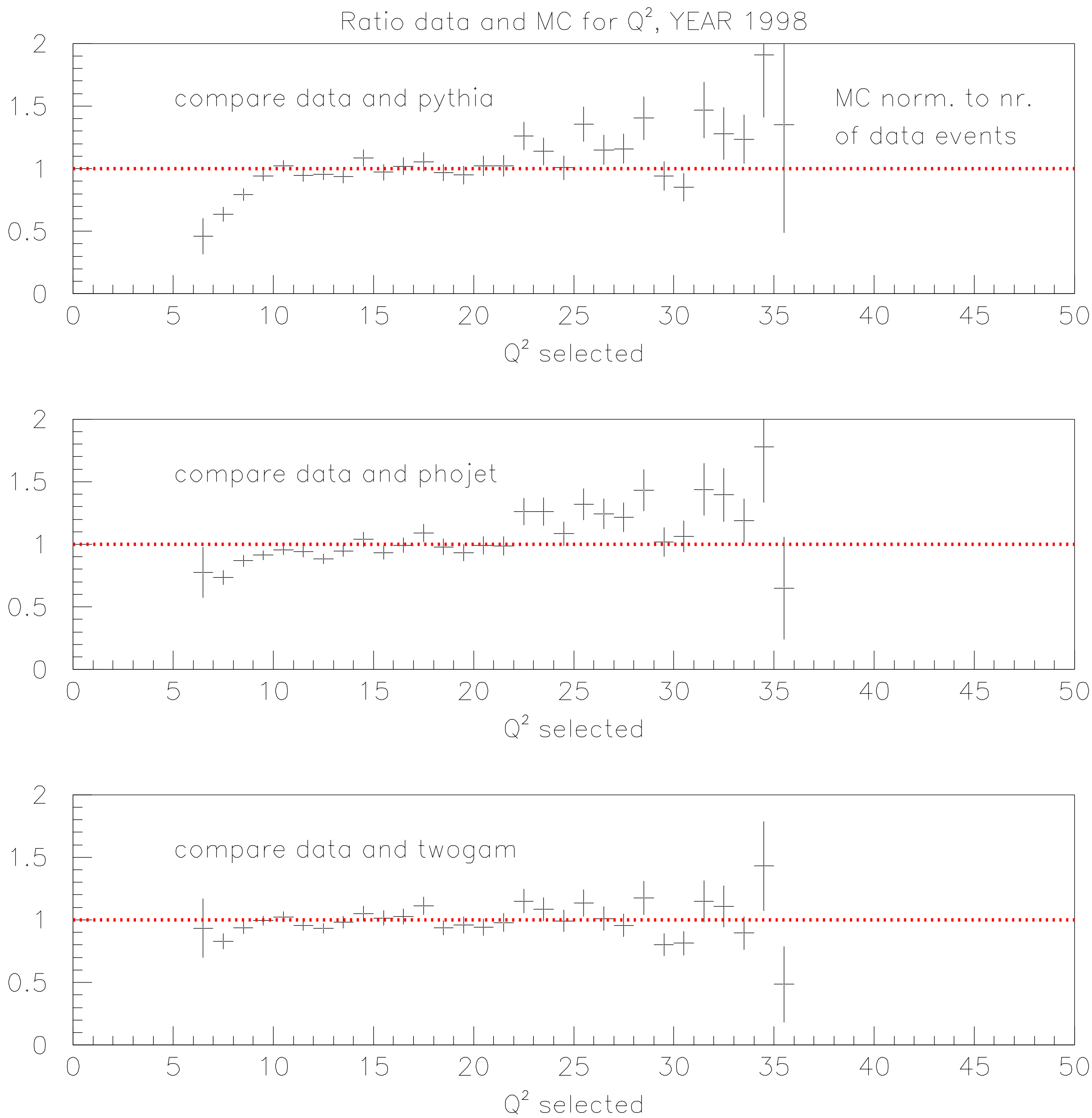
SELECTIONS: CUT 2−5 for 1998

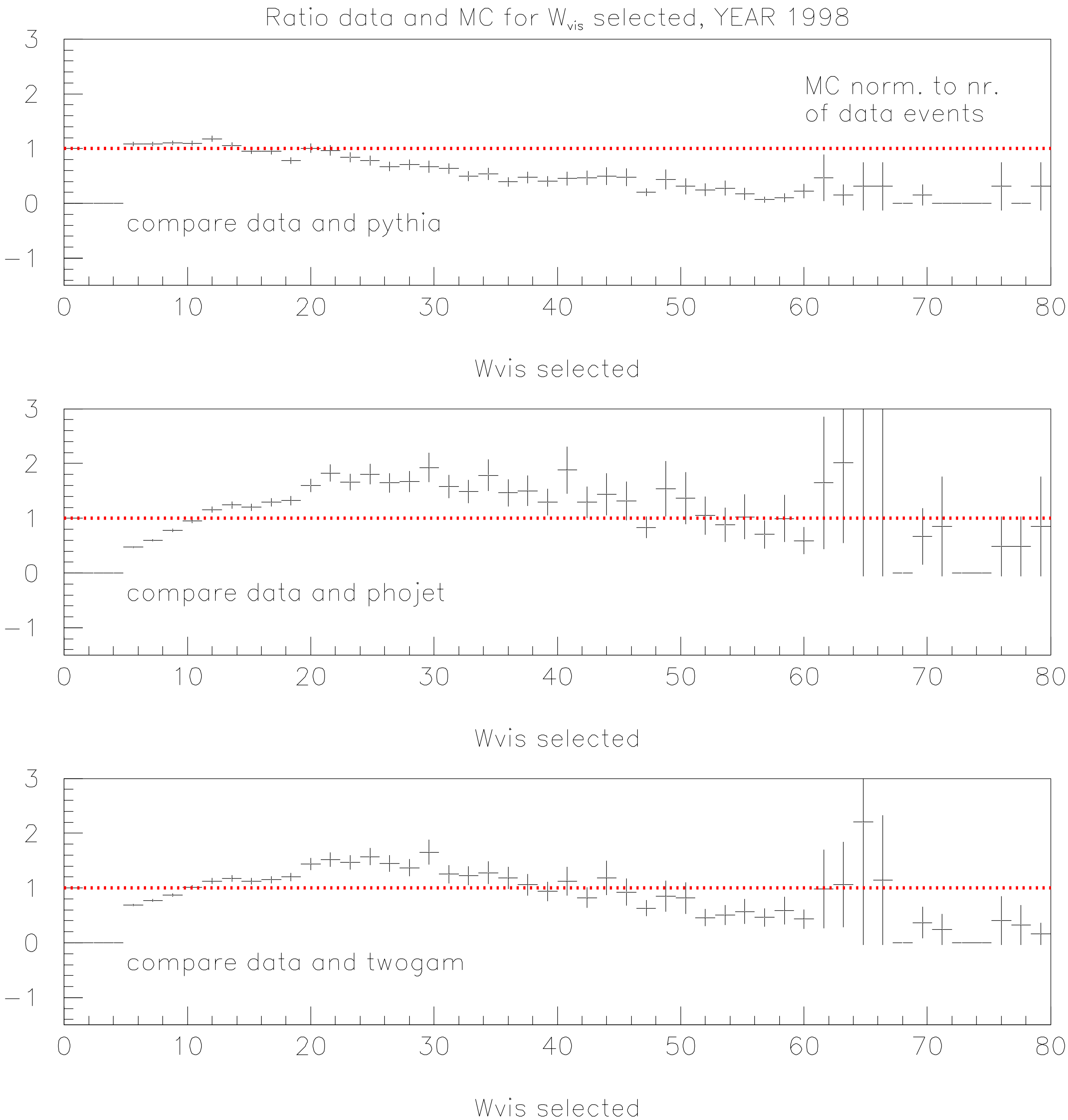



SELECTIONS, YEAR 1998
ALL
bgd ττ ALL
bgd qq γ ALL
CUT 1
SELECTED
Nevents
LUMI Emax/Ebeam
CUT 1
bgd ττ , CUT 1
bgd qq γ , CUT 1
CUTS 1+2
SELECTED
Nevents
Ntracks+Ngammas
CUTS 1+2
bgd ττ , CUTS 1+2
bgd qq γ , CUTS 1+2
SELECTED
Nevents
Etot/sqs
Rejected by CUT 3
bgd qq γ , Rejected by CUT 3
Nevents
LUMI Emax/Ebeam, background

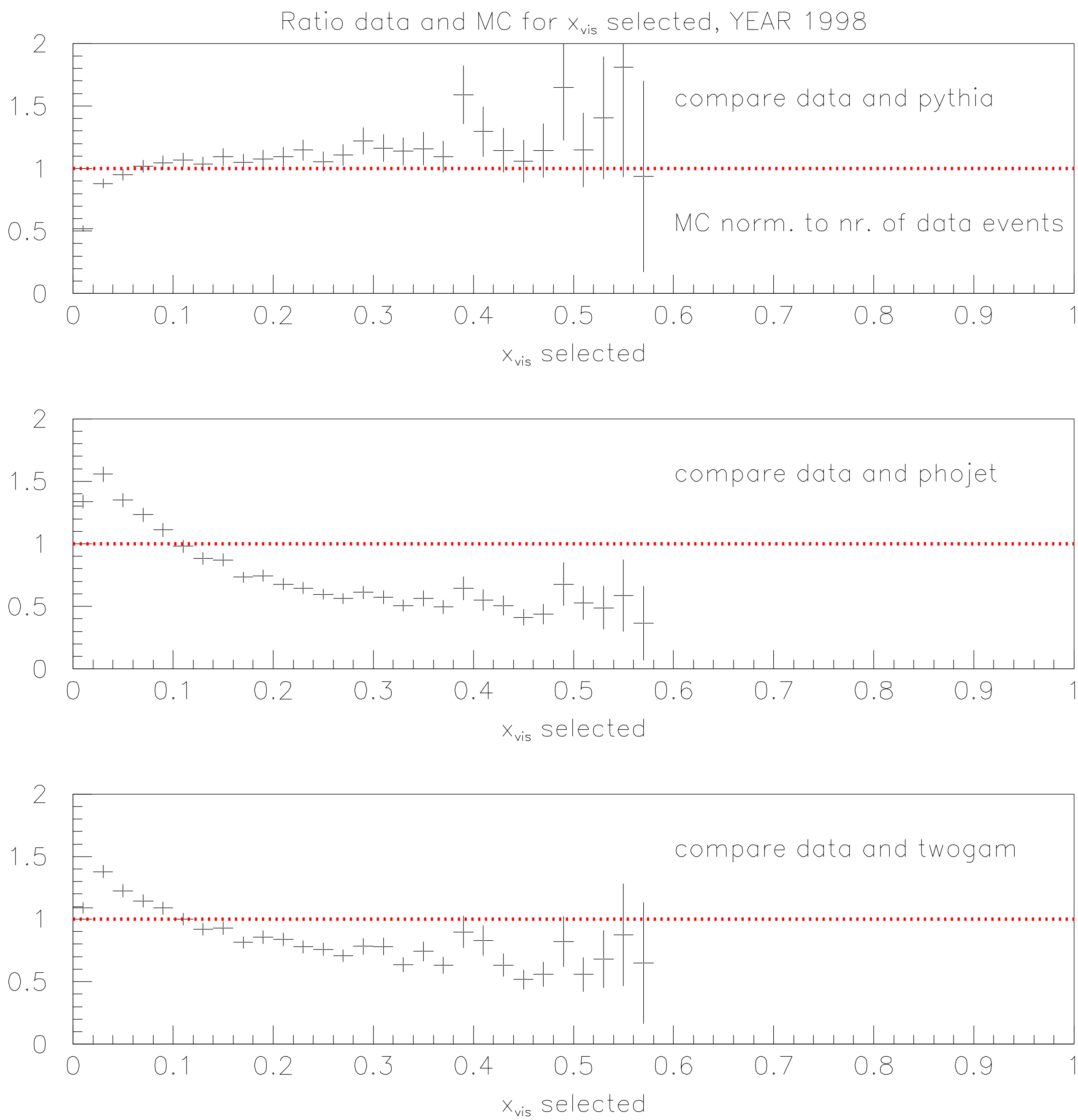
Superposed distributions of selected data (1998) and MC for Q^2, W_{vis}, X_{vis}




Ratio data and MC for Q², YEAR 1998
compare data and pythia
MC norm. to nr.
of data events
Q² selected
compare data and phojet
Q² selected
compare data and twogam
Q² selected



Ratio data and MC for W$_{vis}$ selected, YEAR 1998
MC norm. to nr.
of data events
compare data and pythia
Wvis selected
compare data and phojet
Wvis selected
compare data and twogam
Wvis selected


Ratio data and MC for x_{vis} selected, YEAR 1998
compare data and pythia
MC norm. to nr. of data events
compare data and phojet
compare data and twogam
x_{vis} selected
x_{vis} selected
x_{vis} selected

Binning

For the x dependence of $\Delta\sigma/\Delta x$, and F_2^{γ}/α:

Nr. x bins	Δx	$\langle x \rangle$
1	0.01 - 0.035	0.022
2	0.035 - 0.060	0.047
3	0.060 - 0.085	0.071
4	0.085 - 0.110	0.097
5	0.110 - 0.160	0.13
6	0.160 - 0.210	0.18
7	0.210 - 0.260	0.23
8	0.260 - 0.310	0.28
9	0.310 - 0.385	0.34
10	0.385 - 0.510	0.43

Nr. Q^2 bins	ΔQ^2 [GeV^2]	$\langle Q^2 \rangle$ [GeV^2]
1	11-14	12.4
2	14-20	16.6
3	20-28	23.6
4	28-34	30.8

ΔQ_2^2 [GeV^2]	$\langle Q_2^2 \rangle$ [GeV^2]
0-0.01	0.0007

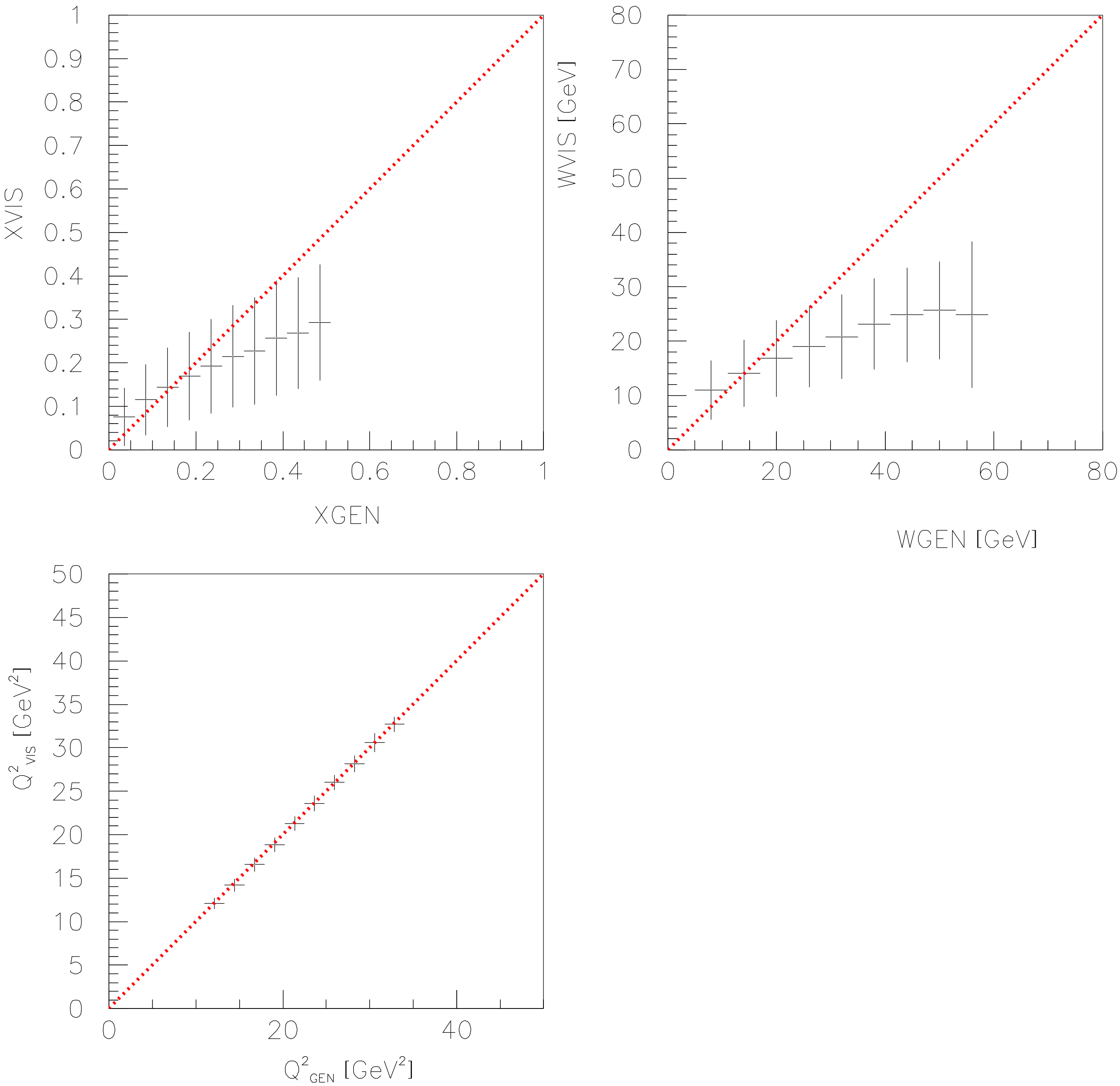
For the Q^2 dependence of $\Delta\sigma/\Delta Q^2$ (*), and F_2^{γ}/α:

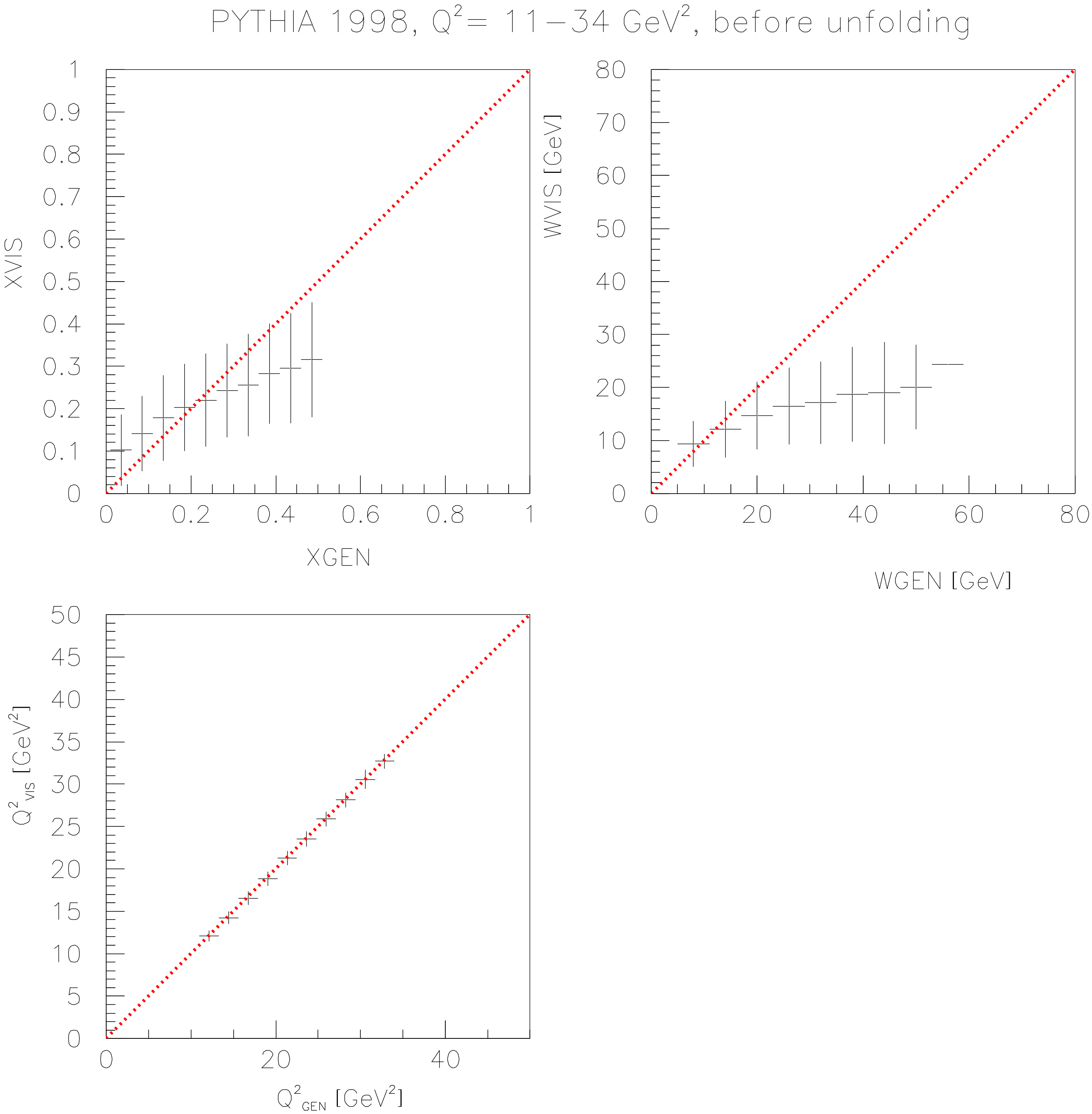
Nr. x Bins	Δx	$\langle x \rangle$
1	0.01-0.1	0.050
2	0.1-0.2	0.144
3	0.2-0.3	0.248
4	0.3-0.5	0.322

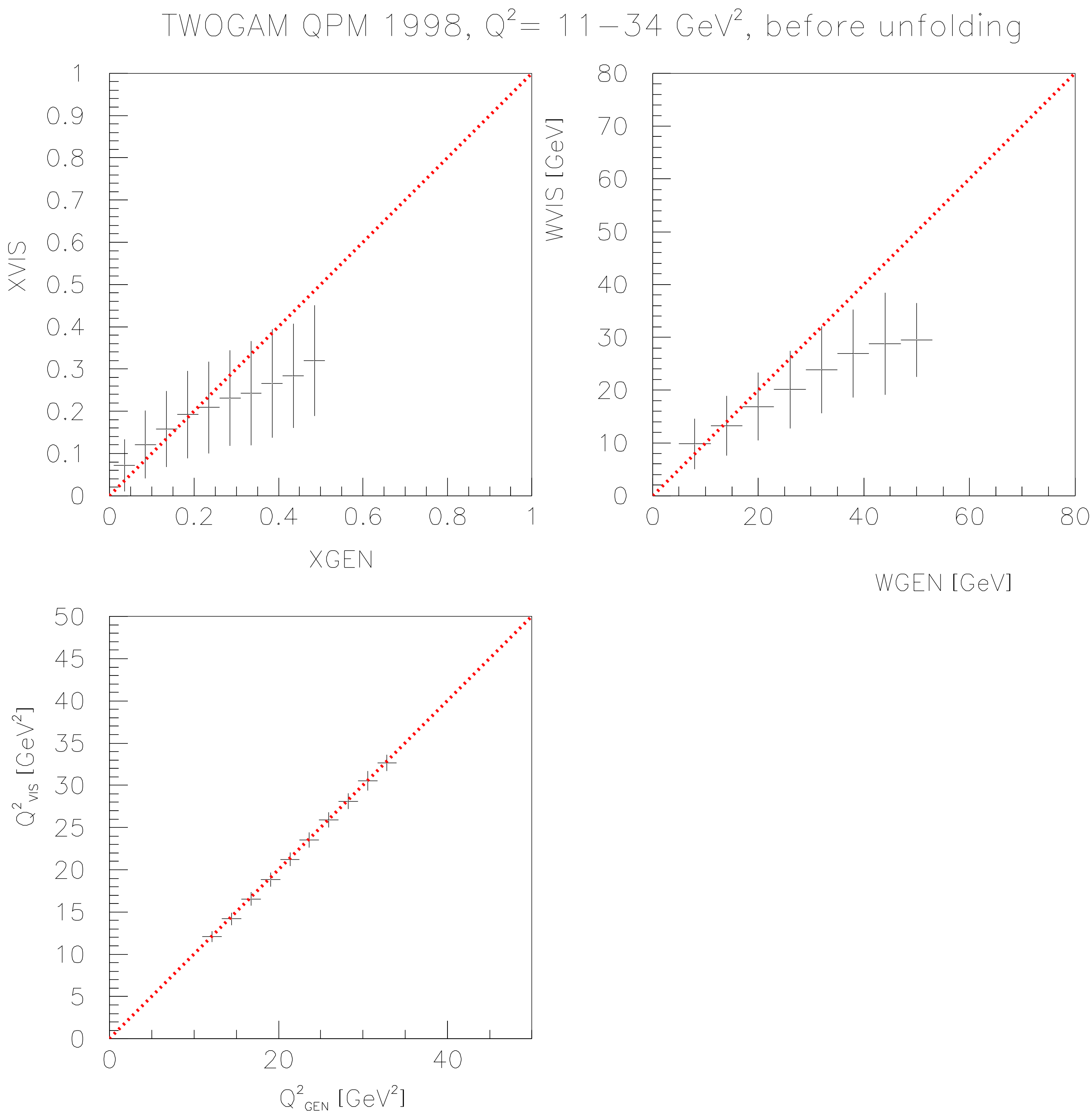
Nr. Q^2 bins	ΔQ^2 [GeV^2]	$\langle Q^2 \rangle$ [GeV^2]
1	11-14	12.4
2	14-20	16.6
3	20-34	23.6

* under investigation

PHOJET 1998, Q^2= 11−34 GeV^2, before unfolding

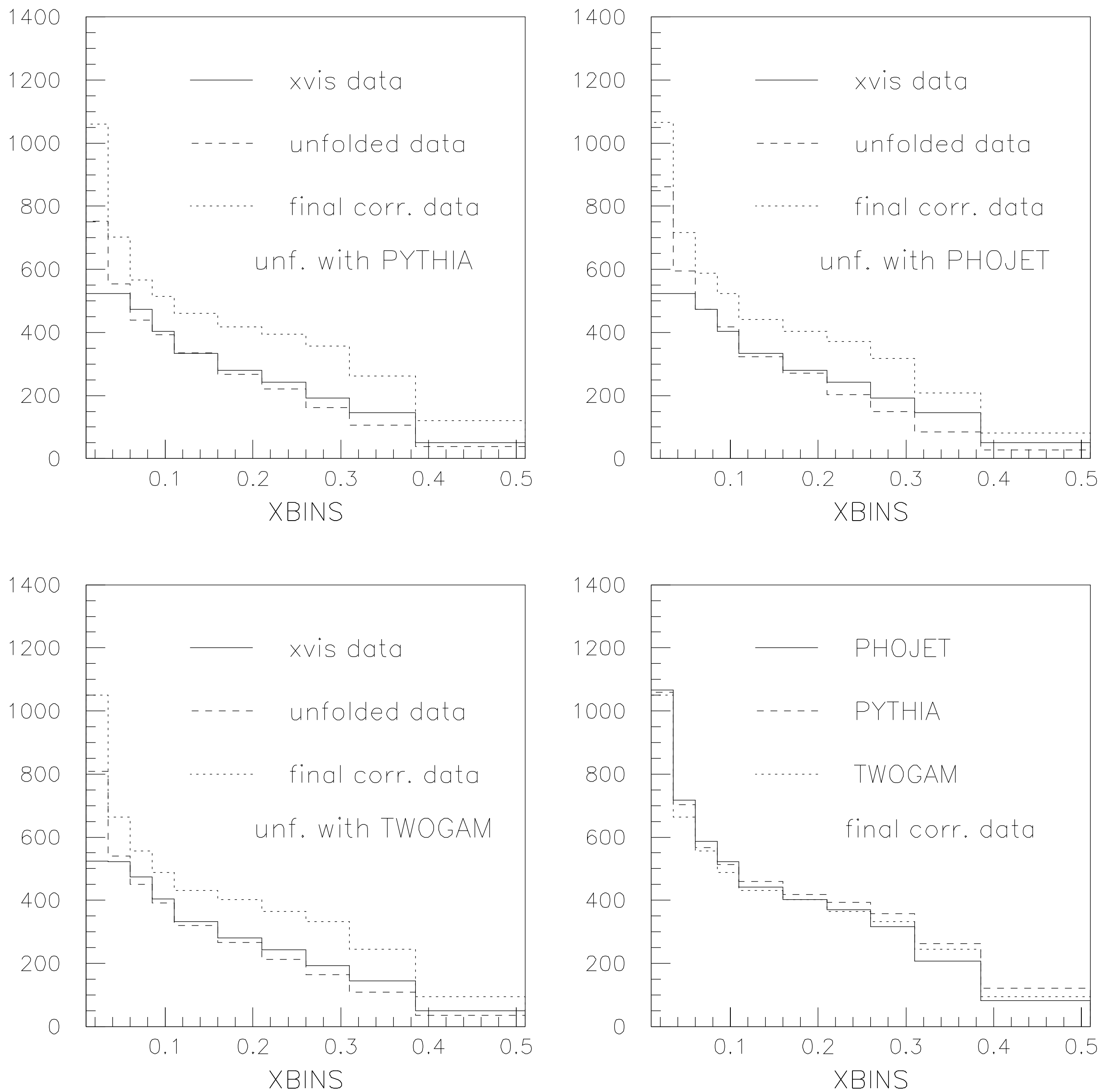



PYTHIA 1998, Q²= 11–34 GeV², before unfolding
XVIS
XGEN
WVIS [GeV]
WGEN [GeV]
Q² VIS [GeV²]
Q² GEN [GeV²]

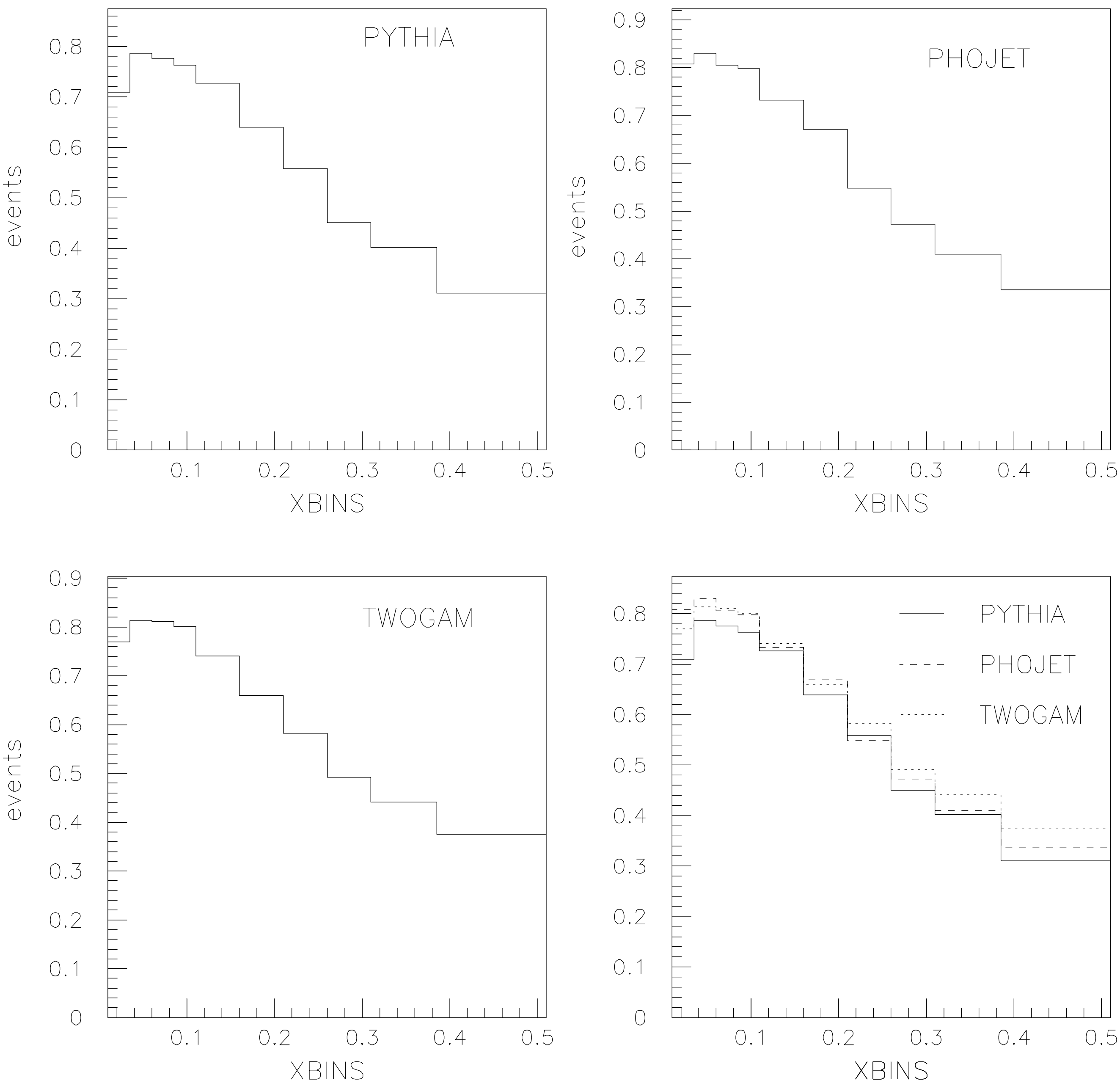


TWOGAM QPM 1998, Q²= 11−34 GeV², before unfolding
XVIS
XGEN
WVIS [GeV]
WGEN [GeV]
Q² VIS [GeV²]
Q² GEN [GeV²]

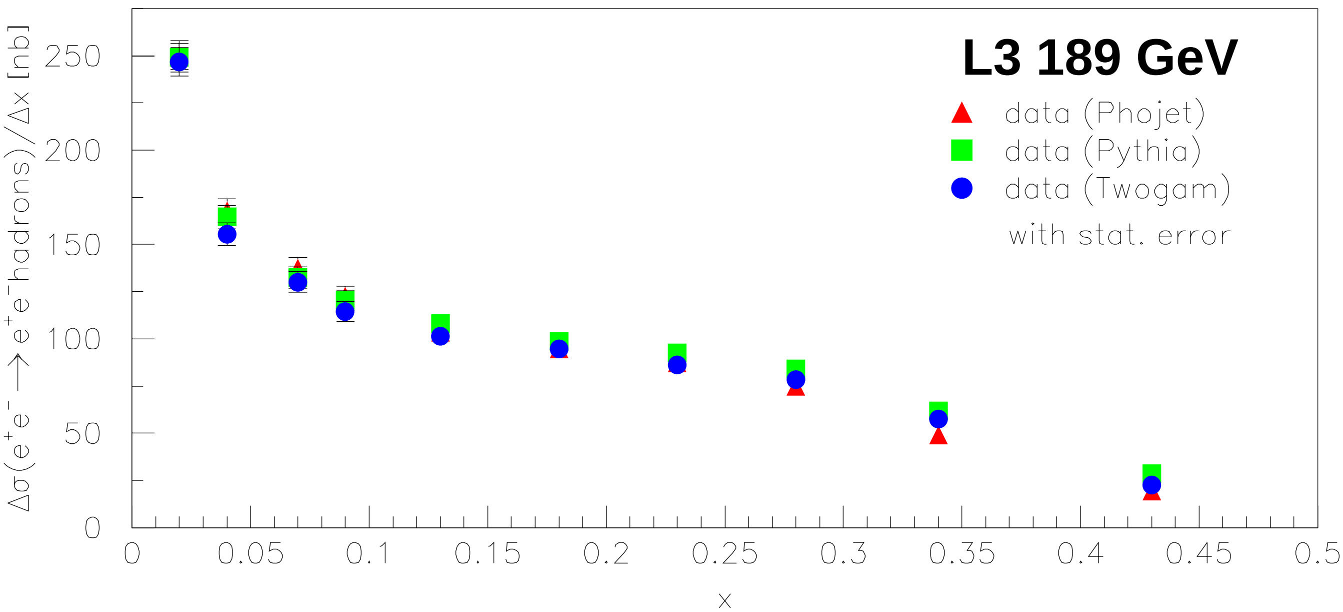
compare xvis, unfolded, and final corrected data, Wcut 5 GeV, 1998

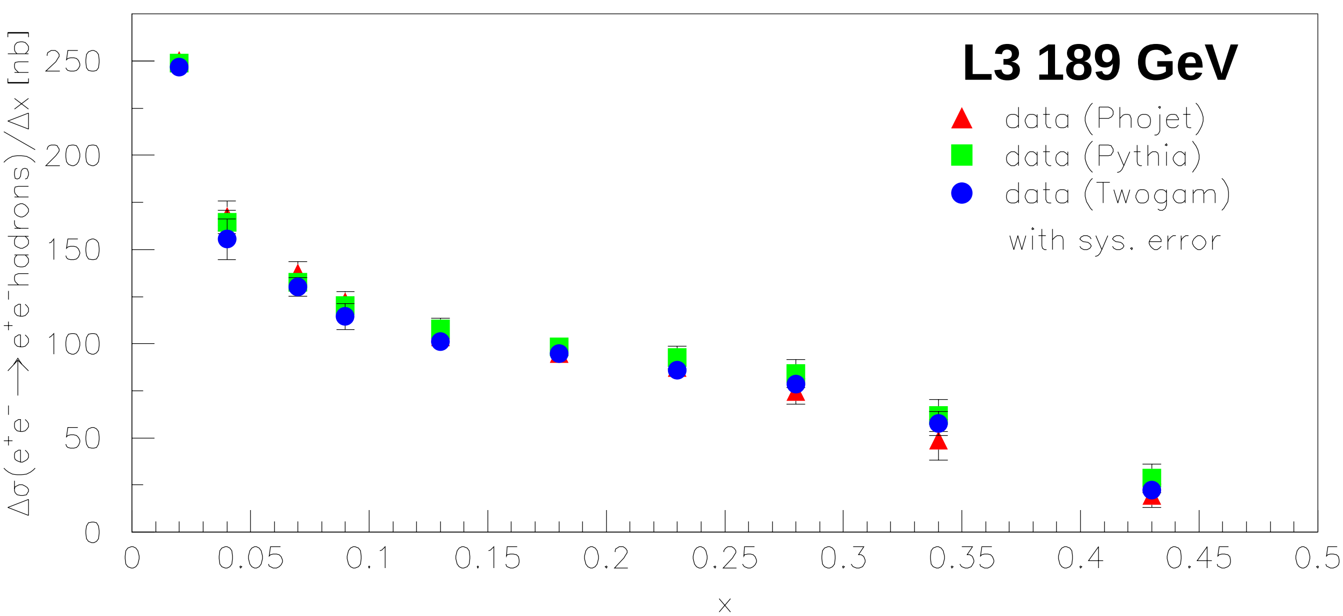


Acceptance = $N_{GEN\ accepted}/N_{GEN}$, Wcut 5 GeV, 1998

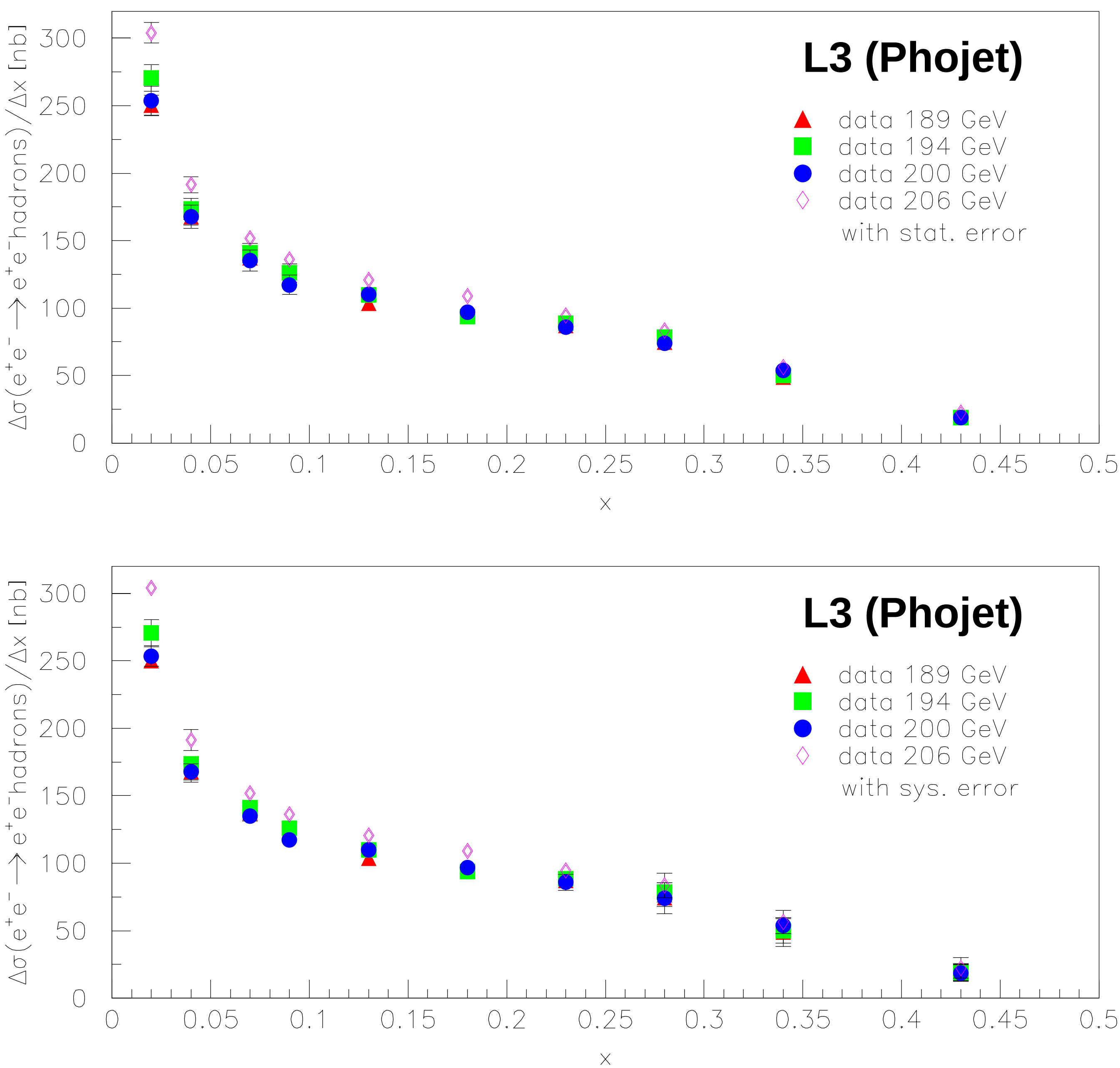


x dependence of Δσ/Δx, YEAR 1998





x dependence of Δσ/Δx, YEARS 1998–2000



Measurement of F_2^γ using GALUGA

(Version 2.0, Author: G.A. Schuler, CERN)

GALUGA calculates total e^+e^- cross section integrated over

$W_{min} < W < W_{max}$ and $Q^2_{min} < Q^2 < Q^2_{max}$

model: ρ-pole (Regge theory)

Reaction: $e^+(p_a) + e^-(p_b) \rightarrow e^+(p_1) + X(p_X) + e^-(p_2)$ The two photon process: $\gamma(q_1) + \gamma(q_2) \rightarrow X(p_X)$ The γγ c.m. energy: $W^2 = p_X{}^2$ The photon virtualities: $-Q_1^2 = t_1 = q_1^2 \equiv (p_a - p_1)^2$ $-Q_2^2 = t_2 = q_2^2 \equiv (p_b - p_2)^2$	Total cross section: $\sigma_{ab}(W^2, Q_i^2) = h_a(Q_1^2) h_b(Q_2^2) \sigma_{\gamma\gamma}(W^2)$ **for ρ-pole:** $\sigma_{\gamma\gamma} = 1$ for real photon: $h_T(Q^2) = \left(\frac{m_\rho^2}{m_\rho^2 + Q^2} \right)^2$ for virtual photon: $h_S(Q^2) = \frac{\xi Q^2}{m_{\rho^2}} \left(\frac{m_\rho^2}{m_\rho^2 + Q^2} \right)^2$

Obtain F_2^γ/α:

$$F_2^\gamma / \alpha = \frac{\Delta\sigma_{meas}(e^+e^- \rightarrow e^+e^- X)}{\Delta\sigma_{Galuga}(e^+e^- \rightarrow e^+e^- X)}$$

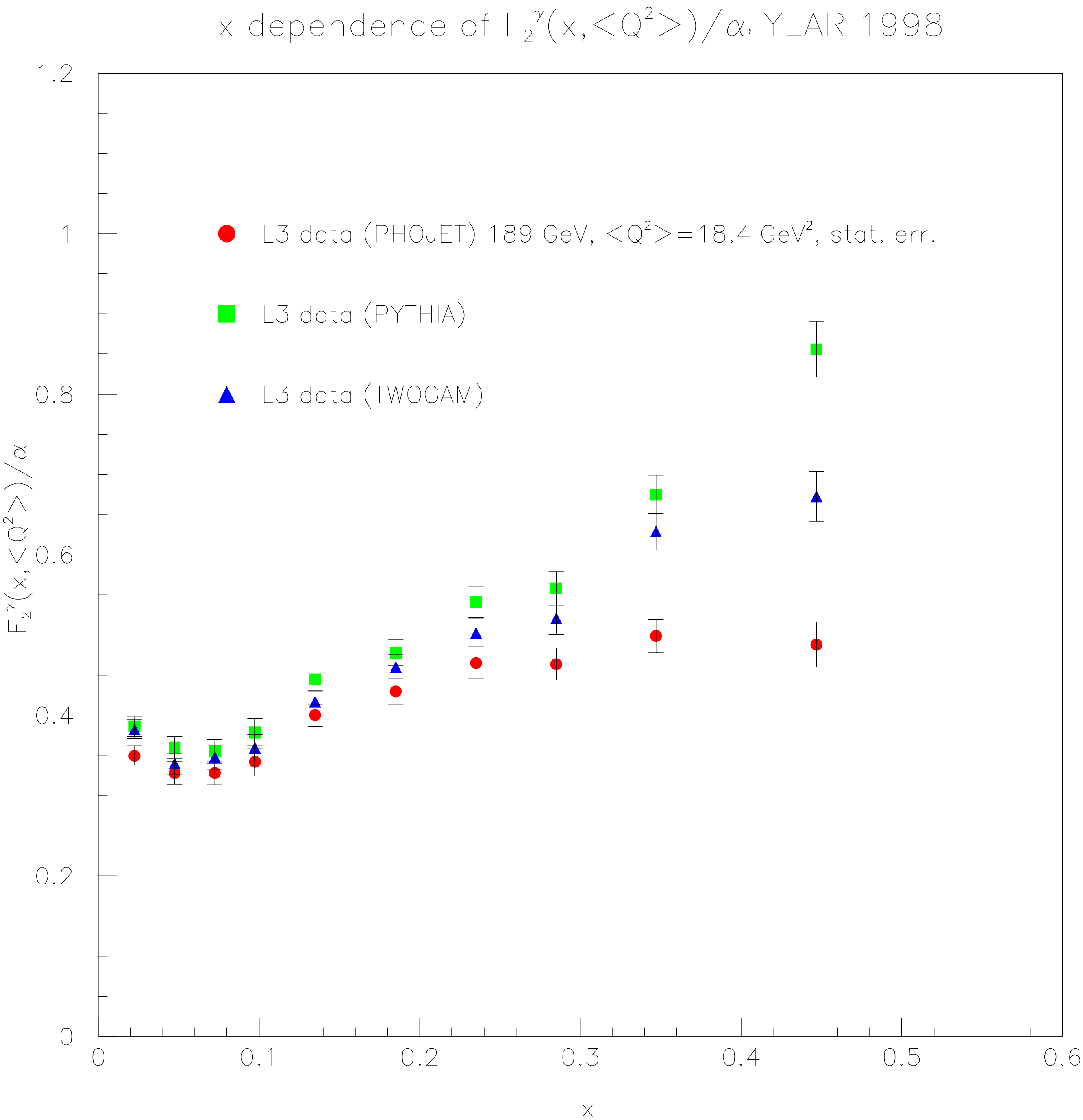
Integration limits (x dependence):

YEAR	W_{min} [GeV]	W_{max} [GeV]	Q^2_{min} [GeV^2]	Q^2_{max} [GeV^2]
1998	5	189	11	34
1999a	5	194	11	34
1999b	5	200	11	34
2000	5	206	11	34

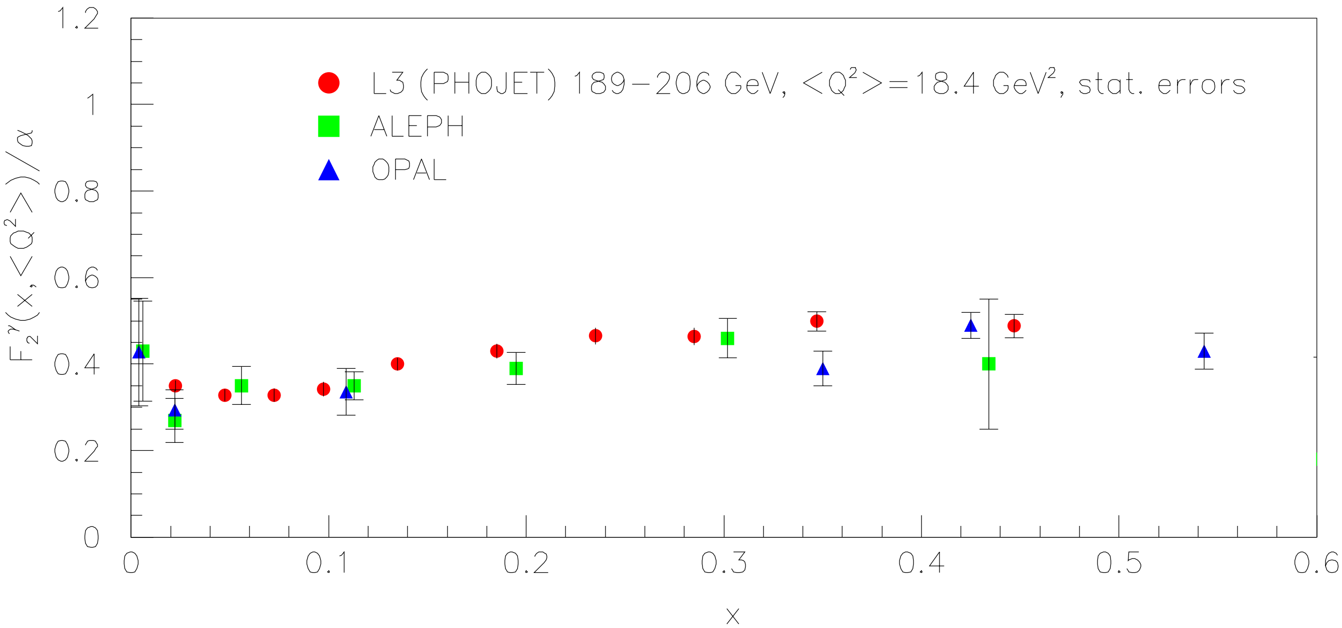
Integration limits (Q^2 dependence):

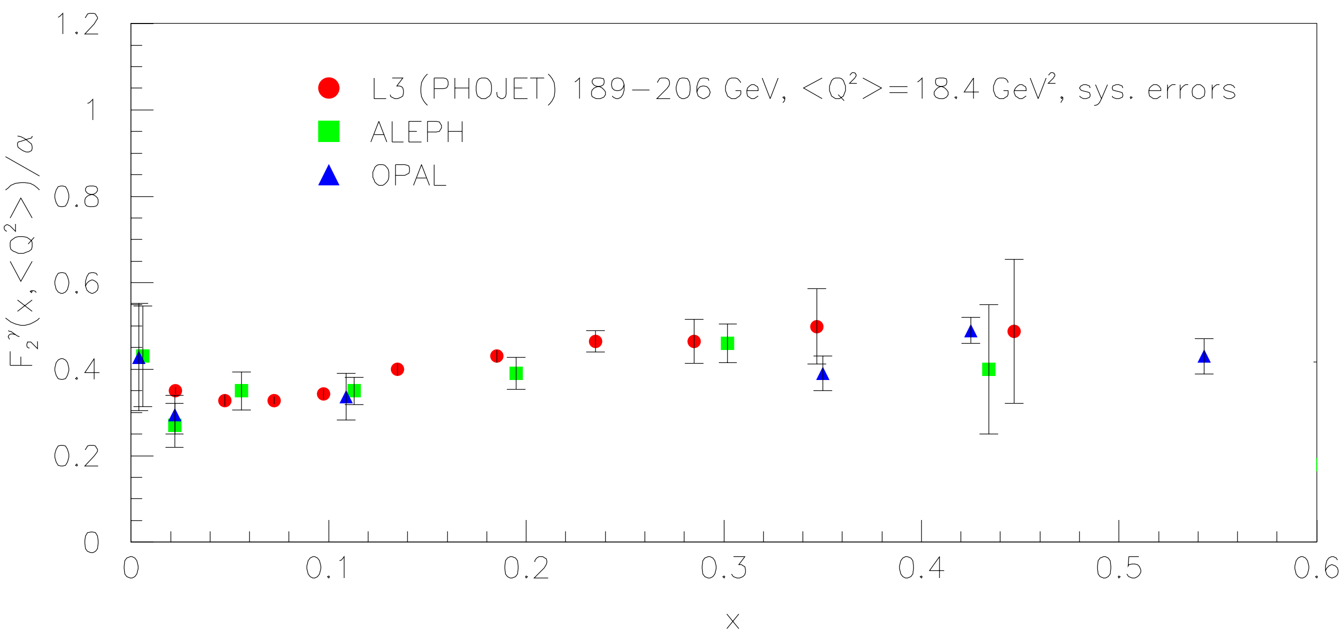
YEAR	W_{min} [GeV]	W_{max} [GeV]	Q^2_{min} [GeV^2]	Q^2_{max} [GeV^2]
1998	5	189	11 14 20	14 20 34
1999a	5	194	*	*
1999b	5	200	*	*
2000	5	206	*	*

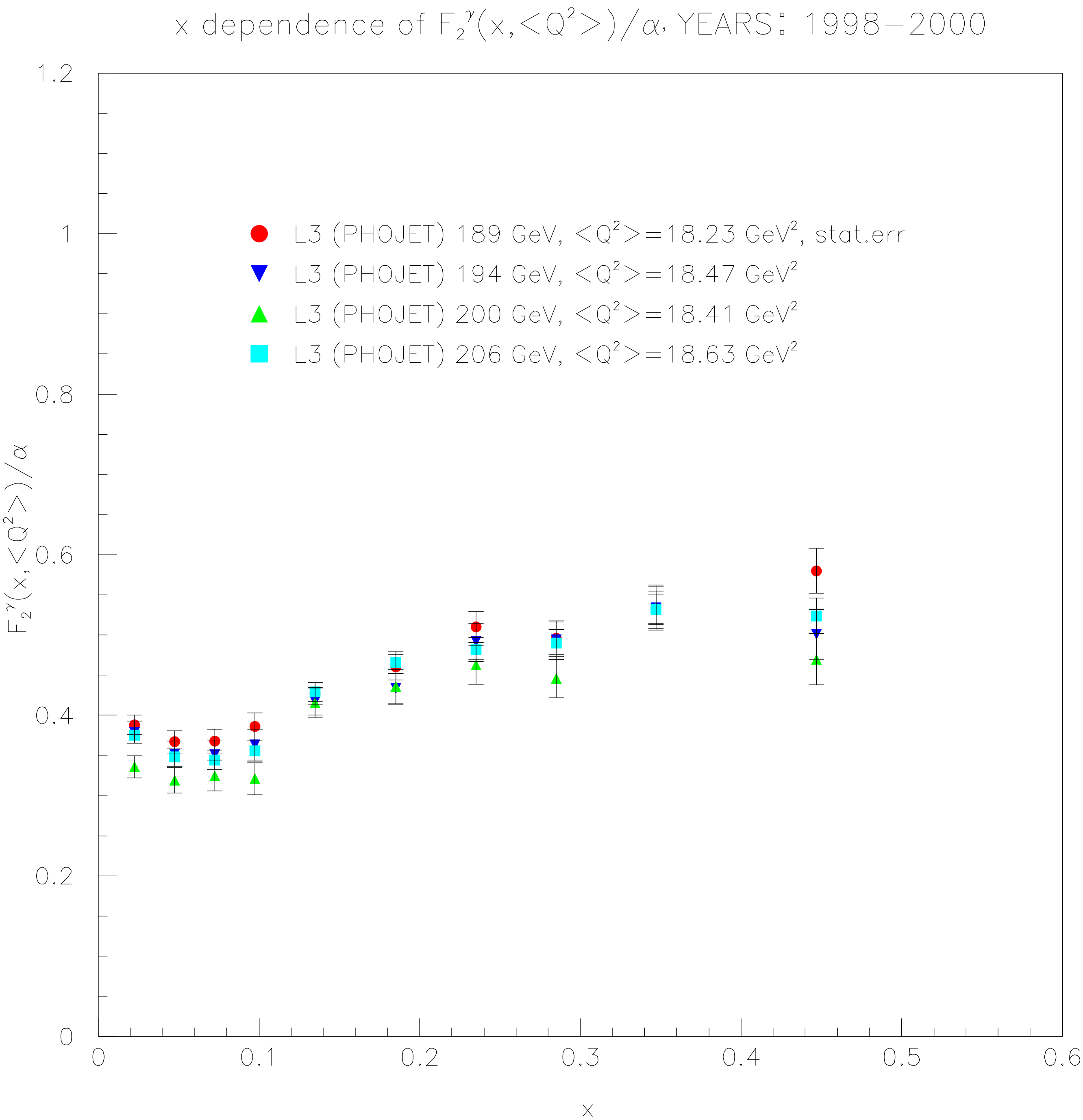
* to be analyzed

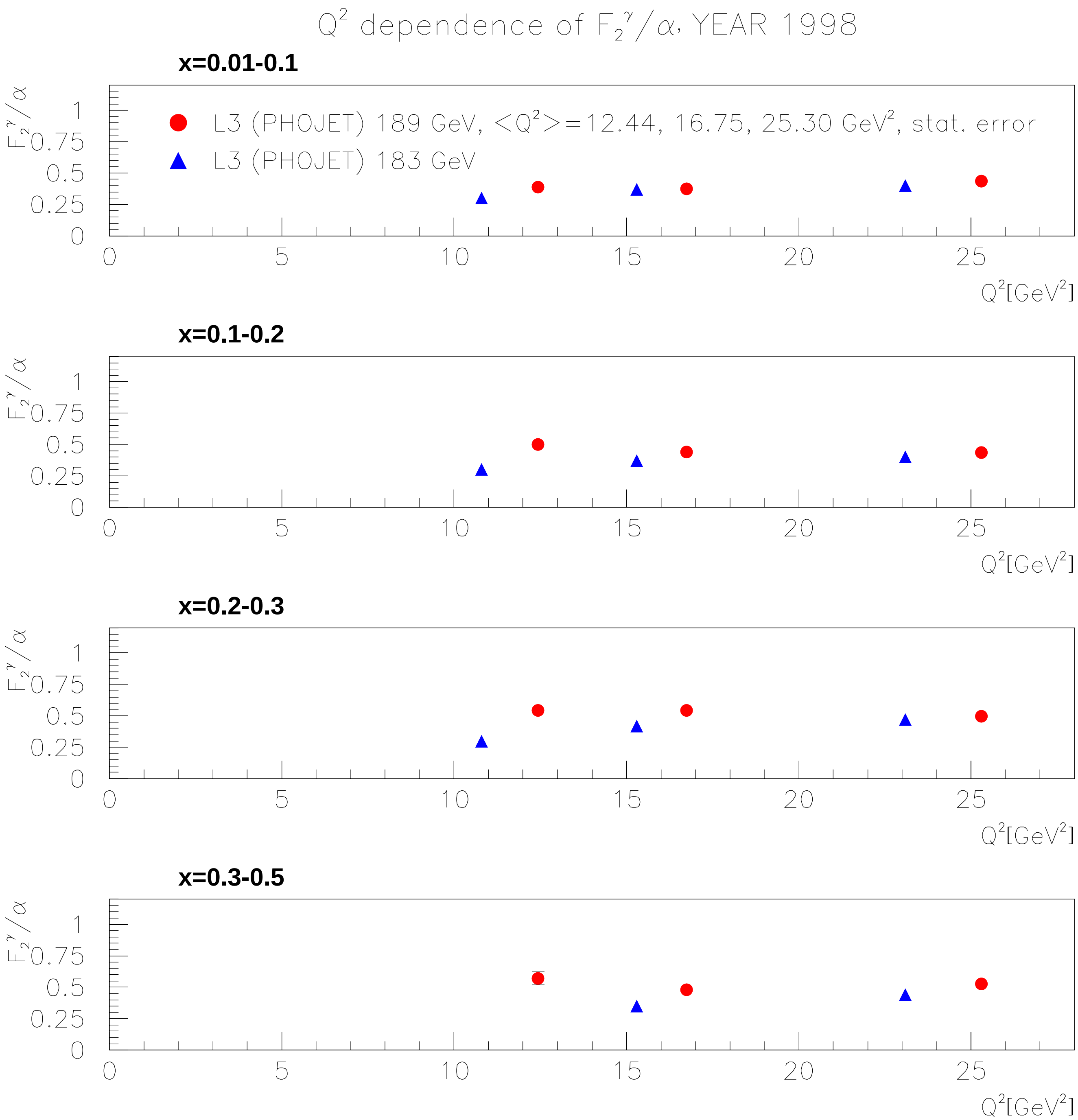


x dependence of $F_2^\gamma(x,<Q^2>)/\alpha$, YEAR 1998
L3 data (PHOJET) 189 GeV, $<Q^2>=18.4$ GeV^2, stat. err.
L3 data (PYTHIA)
L3 data (TWOGAM)
$F_2^\gamma(x,<Q^2>)/\alpha$
x
0
0.2
0.4
0.6
0.8
1
1.2
0.1
0.3
0.5

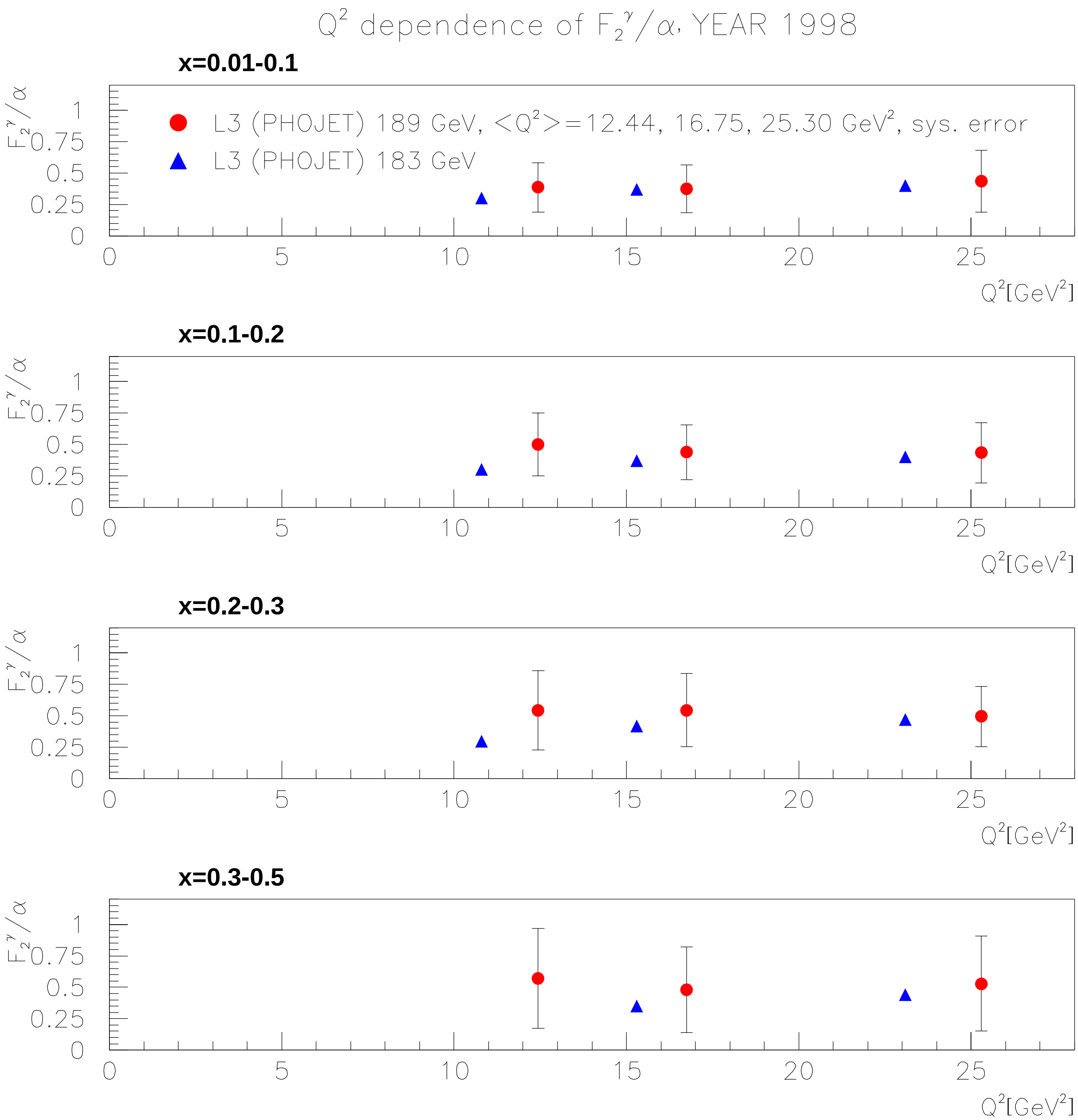

L3 (PHOJET) 189−206 GeV, <Q²>=18.4 GeV², stat. errors
ALEPH
OPAL
F₂^γ(x,<Q²>)/α
x


L3 (PHOJET) 189−206 GeV, <Q²>=18.4 GeV², sys. errors
ALEPH
OPAL
F₂^γ(x,<Q²>)/α
x


x dependence of $F_2^\gamma(x,<Q^2>)/\alpha$, YEARS: 1998−2000
L3 (PHOJET) 189 GeV, $<Q^2>=18.23$ GeV^2, stat.err
L3 (PHOJET) 194 GeV, $<Q^2>=18.47$ GeV^2
L3 (PHOJET) 200 GeV, $<Q^2>=18.41$ GeV^2
L3 (PHOJET) 206 GeV, $<Q^2>=18.63$ GeV^2
$F_2^\gamma(x,<Q^2>)/\alpha$
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1
1.2



Q^2 dependence of F_2^γ/α, YEAR 1998
x=0.01-0.1
x=0.1-0.2
x=0.2-0.3
x=0.3-0.5
L3 (PHOJET) 189 GeV, <Q^2>=12.44, 16.75, 25.30 GeV^2, stat. error
L3 (PHOJET) 183 GeV
F_2^γ/α
Q^2[GeV^2]



Q^2 dependence of F_2^γ/α, YEAR 1998
x=0.01-0.1
L3 (PHOJET) 189 GeV, <Q^2>=12.44, 16.75, 25.30 GeV^2, sys. error
L3 (PHOJET) 183 GeV
x=0.1-0.2
x=0.2-0.3
x=0.3-0.5
F_2^γ/α
Q^2[GeV^2]

Conclusions and outlook

- Single-tag events selection done for 189-206 GeV (1998, 1999, 2000 data)
  High enough statistics, low background
- Used Binning similar to other measurements by L3, OPAL, ALEPH experiments.
- Used unfolding to correct for detector effects and acceptance.
  Data unfolded with PYTHIA, PHOJET, and TWOGAM: good agreement.
- Calculated measured cross section and analyzed x dependence.
  Q^2 dependence: under investigation.
- Obtain F_2^γ/α using GALUGA.
  Evolution of F_2^γ/α with x analyzed and compared to ALEPH and OPAL: good agreement.
  Evolution of F_2^γ/α with Q^2 analyzed and compared to L3 (183 GeV) measurements: good agreement.
  The x range 0.1-0.6 should be included to be able to compare to other experiments: OPAL, ALEPH.

- Decide how to calculate systematic error (consider error from MODEL separately?)
- Comparison with different parameterizations not decided yet