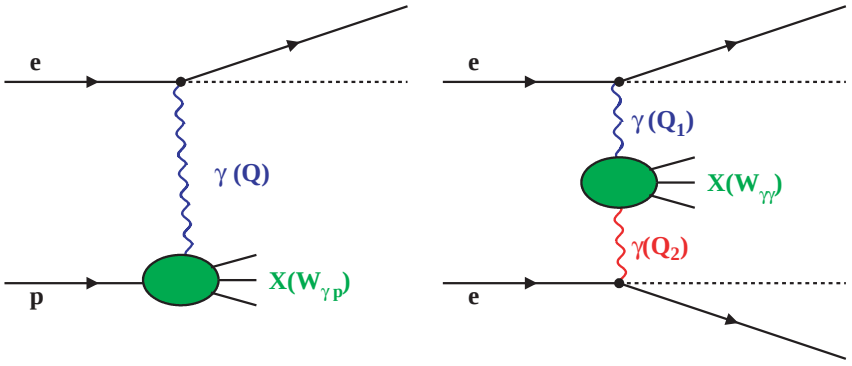
Virtual Photons



Photon virtuality:

$Q_1^2 = -q_1^2 = 2E_1E_1'(1-\cos\theta_1)$

$Q_2^2 = -q_2^2 = 2E_1E_2'(1-\cos\theta_2)$

$W_{\gamma\gamma}$: $\gamma\gamma$ center-of-mass energy

$W_{vis}^2 = (\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2 \leq W_{\gamma\gamma}^2$

h = particle measured in the detector

Hera

- $Q^2 >> 0$ DIS
- Composite target

LEP

- $Q_1^2 \equiv Q^2 > Q_2^2 \equiv P^2 \simeq 0$ Single-tag

➪ $\gamma \rightarrow q\bar{q}$ radiatively generated partons

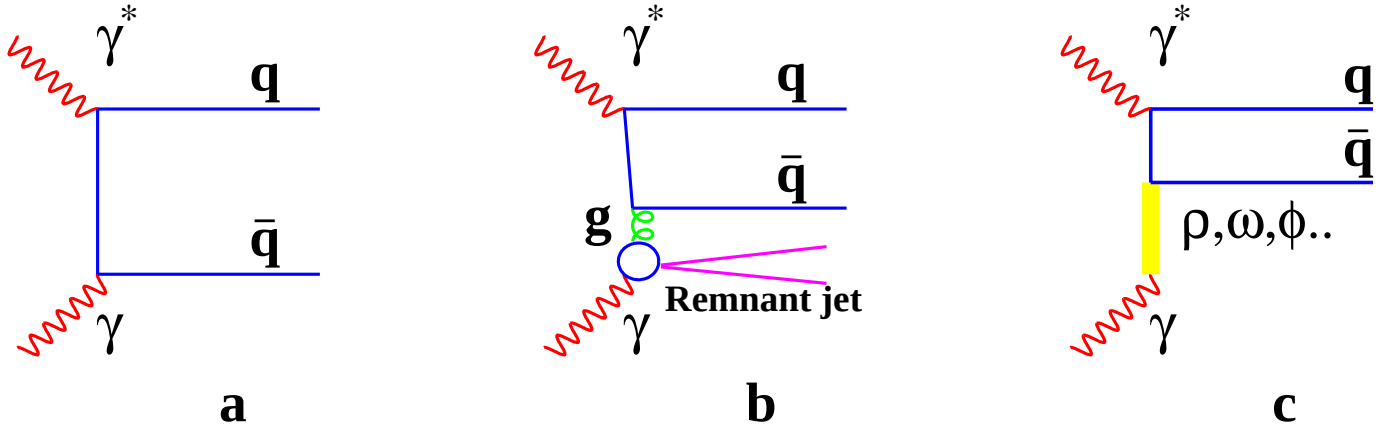
$$\frac{d\sigma_{e\gamma\rightarrow eX}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2^\gamma(x,Q^2) - y^2F_L^\gamma(x,Q^2)]$$

$x = Q^2/2(p\cdot q) = Q^2/(Q^2 + W_{\gamma\gamma}{}^2 + P^2)$

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

Photon structure function, F_2^γ , and parton density

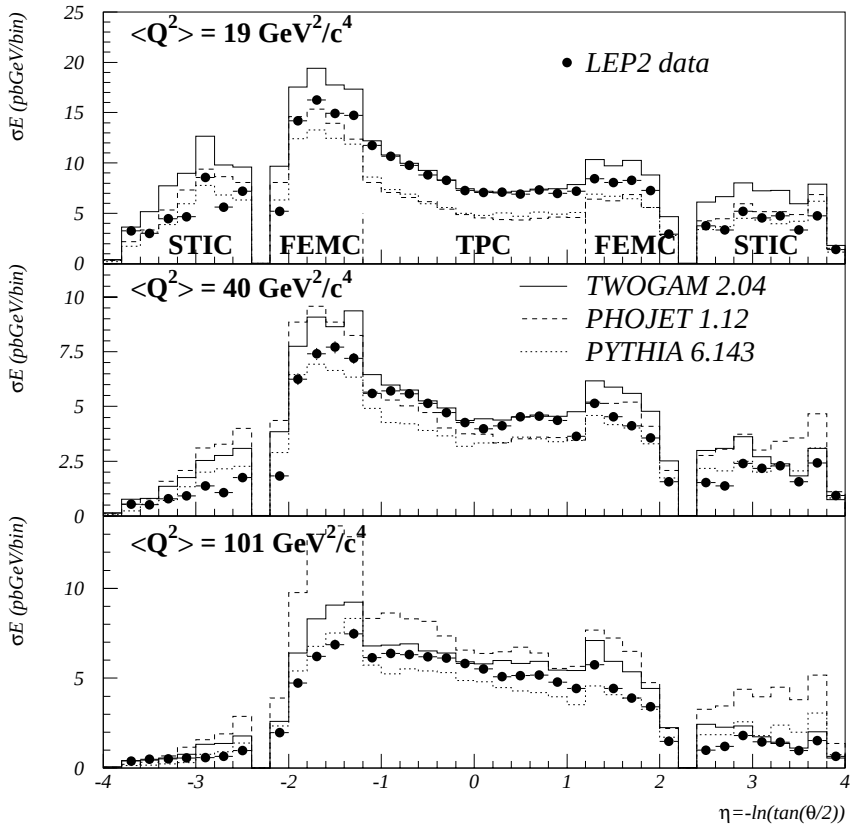
$$F_2^\gamma = x \sum_{i=1}^{N_f} e_i^2 (q_i^\gamma + \bar{q}_i^\gamma)(x, Q^2)$$



- **(a)** Pointlike coupling ⇒ fully calculable QED process:
  - ⇨ large quark density at large x and logarithmic rise with Q^2.
- **(b)** QCD corrections ⇒ DGLAP equation
  - ⇨ gluonic content of the photon.
  - ⇨ α_s measurement.
- **(c)** Initial conditions ⇒ non perturbative (VDM) contributions

Tagging scattered electron

DELPHI



Hadronic energy flow vs. rapidity

Electromagnetic calorimeters: luminosity monitor and endcap

Experiment	Detector	Acceptance (m
ALEPH	SICAL	24. – 58.
	LCAL	45. – 160.
DELPHI	STIC	35. – 174.5
	FEMC	174.5 – 637
L3	LUMI	33. – 64.
	EE	200. – 700
OPAL	SW	33. – 59.
	FD	60. – 140.
	EE	200. – 609

Kinematical range: LEP1

Experiment	$< Q^2 >$ GeV^2	x interval	points
ALEPH	9.9	0.005 - 0.8	4
	20.7	0.009 - 0.89	4
	284.	0.03 - 0.97	3
DELPHI	5.2	0.001 - 0.5	3
	12.7	0.01 - 0.39	5
	28.5	0.02 - 0.8	3
	101	0.001 - 0.8	4
L3	1.9	0.002 - 0.1	6
	5.	0.005 - 0.2	6
	120.	0.05 - 0.98	5
OPAL	1.9	0.0006 - 0.3679	4
	3.7	0.0015 - 0.6065	4
	8.9	0.0111 - 0.8187	3
	17.5	0.0235 - 0.9048	3

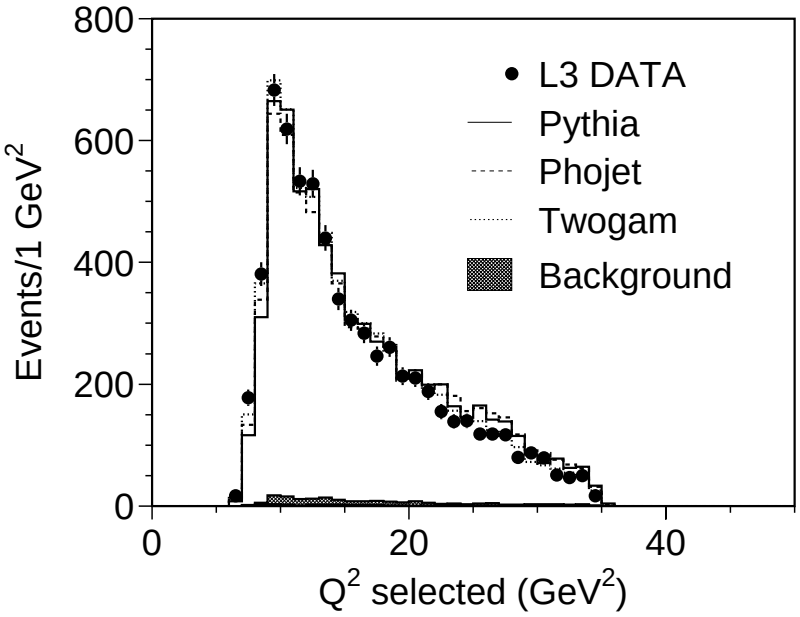
ALEPH Phys. Lett. B 458 (1999) 152

DELPHI This Conference (preliminary)

L3 Phys. Lett. B 436 (1998) 403; Phys. Lett. B 483 (2000) 373

OPAL Eur. Phys. J. C 18 (2000) 15

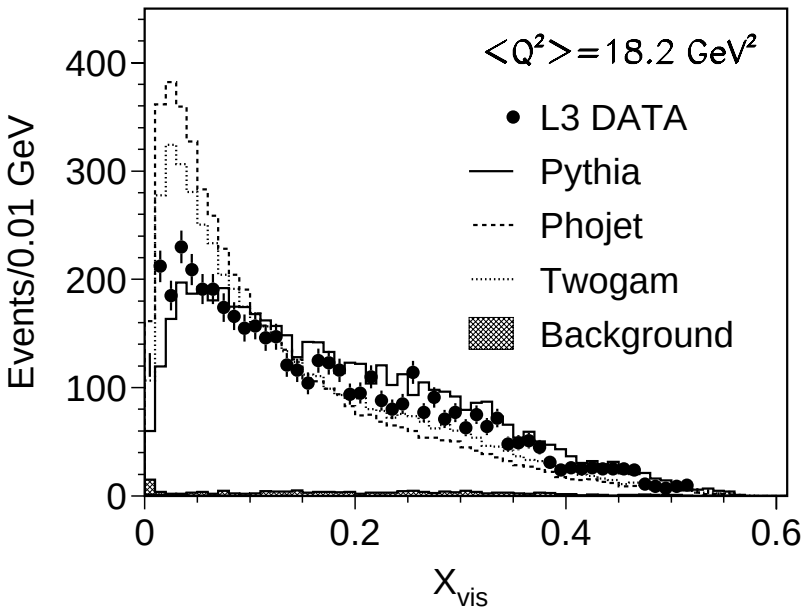
Kinematical range: LEP2



Experiment	$< Q^2 >$ GeV^2	x interval	points
ALEPH	17.3	0.002 - 0.7	8
	67.2	0.006 - 0.96	8
DELPHI	19.	0.001 - 0.8	4
	40	0.001 - 0.8	4
	700	0.01 - 0.8	2
L3	10.8	0.01 - 0.3	3
	15.3	0.01 - 0.5	4
	23.1	0.01 - 0.5	4
	18.4	0.001 - 0.51	11
OPAL	10.7	0.0009 - 0.8187	3
	17.8	0.0015 - 0.9048	4
	12.1	0.1 - 0.6	2
	19.9	0.1 - 0.6	2
	39.7	0.1 - 0.85	3
	76.4	0.1 - 0.85	3
	780.	0.15 - 0.98	3

ALEPH Eur. Phys. J. C 30 (2003) 145
DELPHI This Conference (preliminary)
L3 Phys. Lett. B 447 (1999) 147
and this Conference(preliminary)
OPAL Phys. Lett. B 533 (2002) 207

Monte Carlo modelling

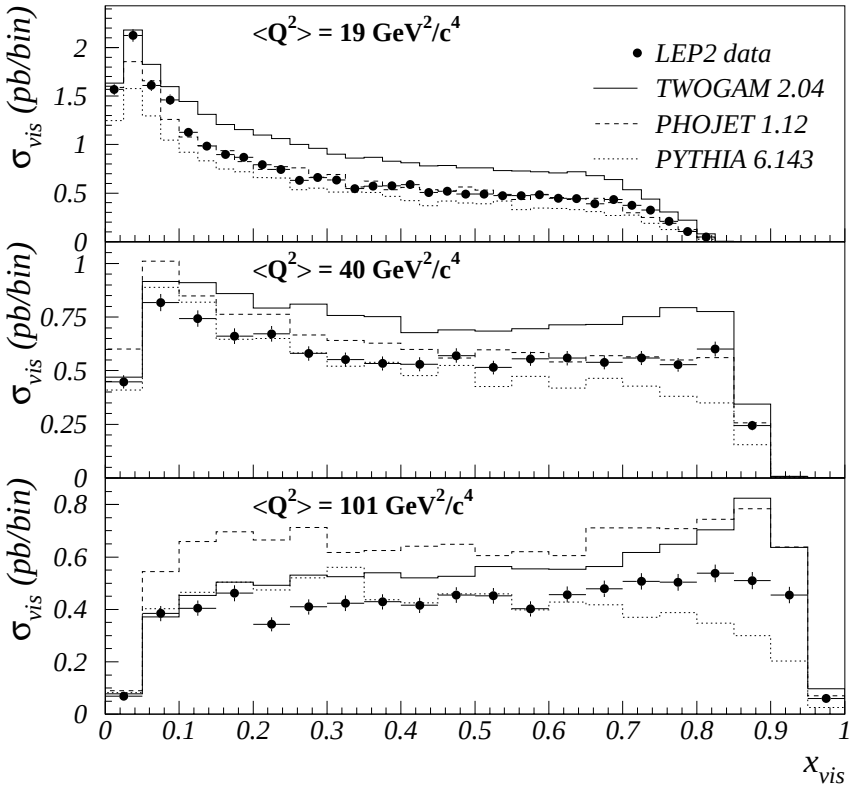


Experiment	Monte Carlo
ALEPH	Herwig 6.2
	Pythia 6.1
DELPHI	Twogam 2.04
	Phojet 1.12
	Pythia 6.143
L3	Phojet 1.05
	Twogam 1.71
	Pythia 6.2
OPAL	Herwig 5.9 + k_t
	Phojet 1.05

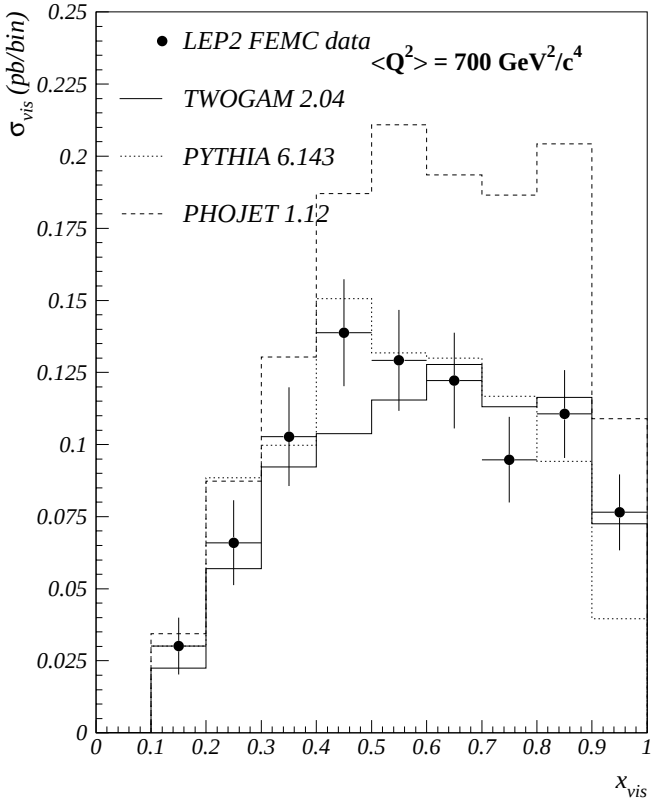
- The generators predict different shapes.
- Differences between Monte Carlo's larger than differences between the experiments (Lep $\gamma\gamma$ Working Group : Eur. Phys. J. C 23 (2002) 201)

Comparison with Monte Carlo: Delphi

STIC

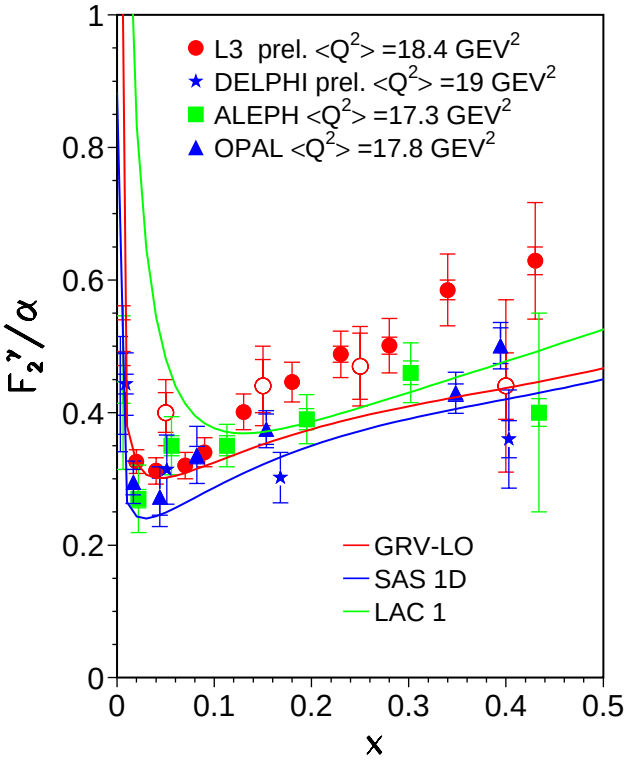


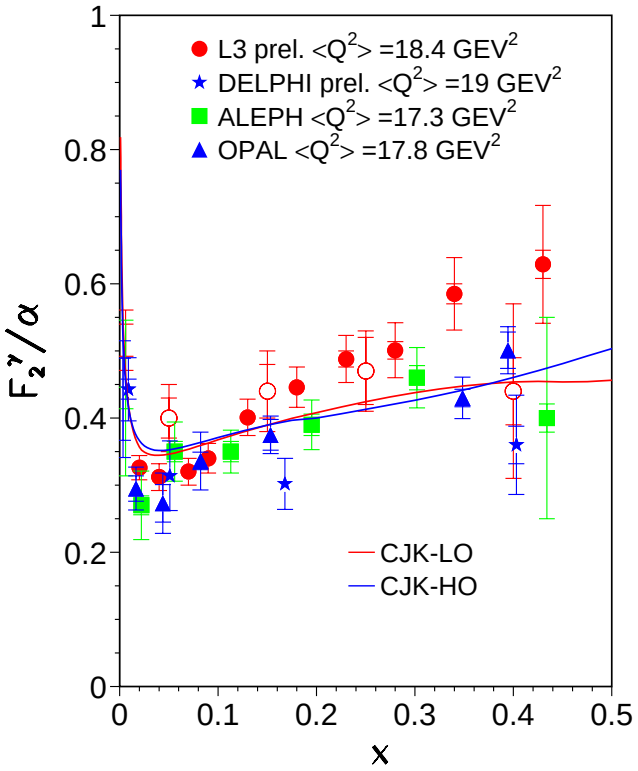
FEMC



- No Monte Carlo is able to reproduce all distributions for all Q^2.

F_2^γ vs x

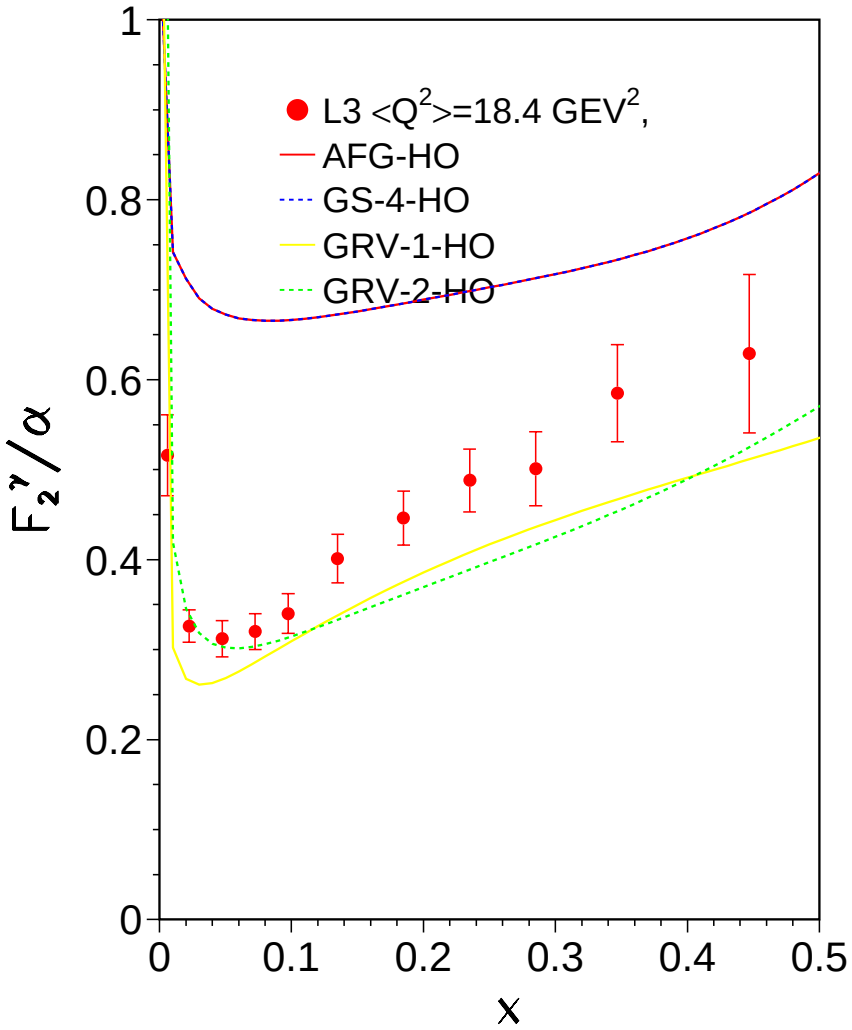




- Systematic larger than statistical uncertainty
- Large spread of p.d.f. predictions (fits on data before LEP, ~ 70 points)
- New fit CJK (208 points) F.Cornet *et al.*Phys. Rev. D 68 (2003) 014010

Note: Delphi gives 3 separate MC results, I averaged them for the LEP compilation.

Parton density functions



α_s measurement

S. Albino, M. Klasen and S. Söldner-Rembold, Phys.Rev.Lett.89:122004,2002

Fit F_2^γ data from PETRA, TRISTAN and LEP

1. Single-parameter fit of the pointlike photon structure function (NLO, $\overline{\text{MS}}$ scheme) for $Q^2 \geq 59$ GeV^2, $x \geq 0.45$ (20 points)
   $\alpha_s(M_Z) = 0.1183 \pm 0.0050(exp.) \pm 0.0029(theo.)$
2. Five-parameters fit (pointlike + hadronic):
   α_s, Q_0, $f_u^\gamma(x, Q_0^2) = Nx^\alpha(1-x)^\beta$; all Q^2 and all x (134 points)
   $\alpha_s(M_Z) = 0.1198 \pm 0.0028(exp.)^{+0.0034}_{-0.0046}(theo.)$
   $Q_0 = 0.83 \pm 0.09$ GeV $\simeq M(\rho), M(\omega)$

Comparable to other LEP measurements:

- $\alpha_s(M_Z) = 0.1240 \pm 0.0037(exp.) \pm 0.0026(theo.)$ from the ratio R_Z
- $\alpha_s(M_Z) = 0.1201 \pm 0.0013(exp.) \pm 0.0047(theo.)$ from event shape variables.