Lessons from LEP

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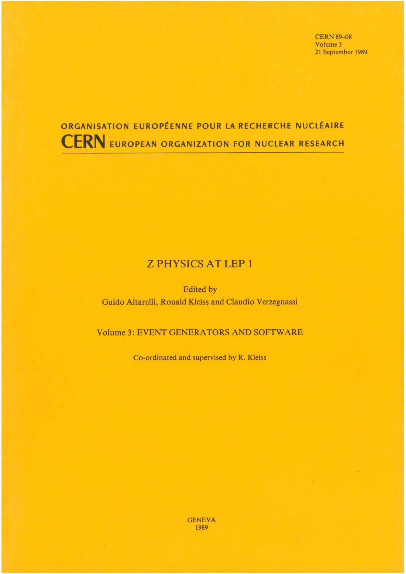
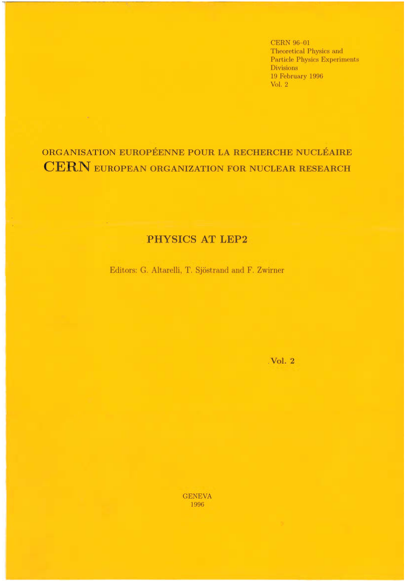
ECFA Higgs Factories: 2nd Topical Meeting on Generators, Brussels, 21 – 22 June 2023

LEP1-LEP2 Yellow Reports on generators





- Electroweak vs QCD
  - *“EW software can be required to give relatively unambiguous answers, with high implied accuracy”*
  - *“QCD software is still descriptive rather than predictive”*

Electroweak (EW)	strong (QCD)
‘new’ phenomena	‘old’ phenomena
‘new’ software	‘old’ software
rapid evolution	moderate evolution
theory ‘solved’	theory ‘unsolved’
high accuracy	low accuracy
agreement expected	no agreement expected

From LEP1 YR (1989)

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- given the available computational power: seminalytical vs MC

semianalytical	Monte Carlo
inclusive	exclusive
few cuts allowed	many cuts allowed
not good for experiment	good for experiment
no statistical error	statistical error
fast	not so fast
cross section arbitrary	cross sections positive

From LEP1 YR

- interesting final states
  - target exp precision expected at the % level
  - e.g. 20 MeV at best on M_Z, 0.0012 on $\sin^2\theta_W$

Pre. level	final state	accuracy (%)
High	$\mu^+\mu^-$ hadrons heavy quarks e^+e^- $\tau^+\tau^-$ $\nu\bar{\nu}\gamma$ Higgs + $f\bar{f}$	0.1-0.3
Medium	2,3 γ $e^+e^-f\bar{f}$ e^+e^-+hadrons	1-3
Low	New families Nonminimal Higgses New gauge bosons Supersymmetry Compositness etcetera...	10-30

Basic ingredients

- $\mathcal{O}(\alpha)$ weak corrections
- QED corrections exponentiated
  - with YFS (pioneering implementation in KORALZ and BHLUMI)
  - with Structure Functions (LL PDF's)

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- **Recognized, already at that time, the importance of comparisons of different predictions**

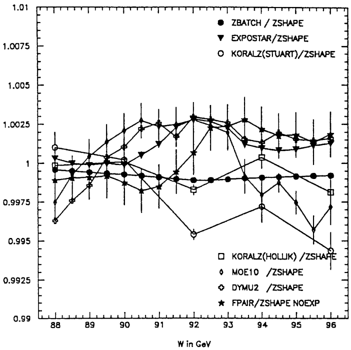
Program name	version number (if any)	last update
ZSHAPE	1.0	July 89
EXPOSTAR		June 89
CALASY	2.6	July 89
MOE	1.0	April 89
MMGE92		September 88
BREM5		October 88
MUONMC		September 88
DYMU2	2.2	June 89
KORALZ	3.6	July 89
FPAIR		August 89

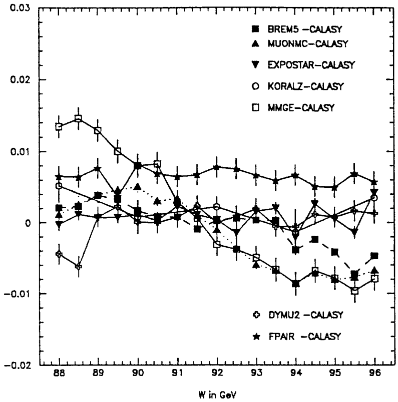
Table 21: Programs for $e^+e^- \to f\bar{f}$ considered in the comparison

program	88 GeV	92 GeV	96 GeV
EXPOSTAR	0.41	0.40	0.41
MOE	0.19	0.19	0.19
MMGE92	0.17	0.17	0.18
BREM5	0.30	0.29	0.30
MUONMC	0.09	0.10	0.11
DYMU2	1.3	0.28	0.75
KORALZ	49.	11.	30.
FPAIR	3.8	3.1	4.9

MC speed, msec/generated event (CRAY units)

Comparisons





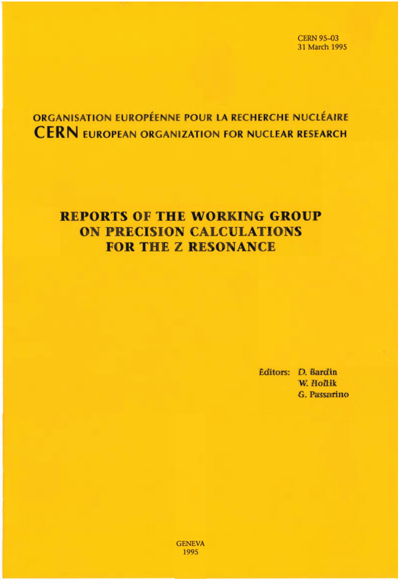
cross section

A_{FB}

Requirements for the "Ultimate Event Generator" (as of 1989)

- invariant mass cut
- Forward-Backward asymmetry
- Higher-Order QED effects
- Multiphoton kinematics
- Interference between initial- and final-state radiation, and box diagrams
- Implementation of weak effects
- Generation of fermion momenta
- Beam Polarization
- Implementation of quark and τ production
- Bhabha scattering mode
- Implementation of τ decay
- Support

Update on precision at the Z peak



CERN 95-03
31 March 1995

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

REPORTS OF THE WORKING GROUP
ON PRECISION CALCULATIONS
FOR THE Z RESONANCE

Editors: D. Bardin
W. Hollik
G. Passarino

GENEVA
1995

In 1994 the experimental accuracy reached a level much higher than originally expected: ~ 0.1 % at the Z-peak

$\Longrightarrow$ necessary a new update on the precision of th. predictions

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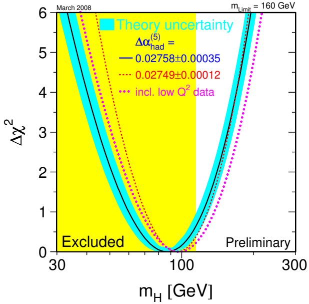
- Electroweak physics
- QCD at Z-resonance
- Small Angle Bhabha Scattering

Emphasis on theoretical uncertainties at Z-peak

- parametric and intrinsic
- different seminalytical codes (`BHM`, `WOH`, `TOPAZ0`, `ZFITTER`)
- introduction of "options" for the estimate of the th. uncertainty within each code



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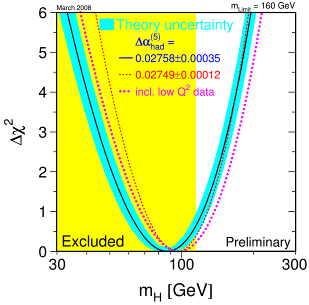

- still missing a common effort among different generator groups on Small Angle Bhabha

From LEP1 to LEP2: 1995

Emphasis on Monte Carlo EG

- Event generators for WW physics
- QCD event generators
- Gamma-Gamma event generators
- Event generators for Bhabha scattering

The new event generators for WW and ZZ thresholds

- With $\sqrt{s}$ at WW and ZZ thresholds, the new kind of process under study is $e^+e^- \to 4$ fermions
- challenging even if the precision requirement is one order of magnitude less than LEP1
- many more diagrams, the frontier was the calculation of complete tree-level matrix elements
    - helicity methods to calulate matrix elements

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  - first automated methods to generate amplitudes and MC code: `CompHEP and grc4f`
  - one new numerical method: the `ALPHA` algorithm (few years later extended to hadronic collisions $\to$ `ALPGEN`), able to calculate numerically the matrix element for aritrary number of external legs
- peaking structure in phase space more complicated, making the semianalytic approach not viable

Requirements for the “Ultimate Monte Carlo” (I)

- treat all possible four-fermion final states with all Feynman diagrams
- produce gauge-invariant results
  - e.g. restricting to double-resonant diagrams close to threshold breaks g.i.
  - correct treatment of bosonic widths
    - dramatic effects in $e^+e^- \to e\nu W(\to f\bar{f}')$
    - $\to$ fermion loop scheme and later the complex mass scheme $\Longrightarrow$ (later) RACOONWW and YFSWW
- fermion masses taken into account
- explicit $p_\perp$-carrying photons
- higher-order photonic radiation taken into account properly
- good control of non-QED radiative corrections, preferably in the form of complete $\mathcal{O}(\alpha)$ corrections and resummed higher-order effects where necessary

Requirements for the “Ultimate Monte Carlo” (II)

- have a good interface to hadronization packages
- have Higgs production and decay implemented
- have the possibility of anomalous couplings
- incorporate QCD effects, both in W self-energy and in the gluonic corrections to quark final states
  - also, interference between EW and QCD production channels in $4f$ final states

Detailed extensive comparisons among codes

- Tuned comparisons for selected processes (to check the technical precision)
  - for inclusive event selection
  - with ADLO/TH (Aleph, Delphi L3, Opal) canonical event selection
- "best you can do", to have an idea of the extent to which the predictions depend on the various physical ingredients
- "all you can do" comparisons an all four-fermion processes

Codes involved in the comparisons

Program	Type	Diagrams	ISR	FSR	NQCD	Coul.	AC	m_f	Hadr.
ALPHA	MC	all	BME	–	–	–	–	+	–
CompHEP	EG	all	SF	–	–	–	–	+	–
ERATO	MC	CC11/CC20	SF	–	+	–	+	–	+
EXCALIBUR	MC	all	SF	–	+	+	+	–	–
GENTLE	SA	CC11/NC32	SF/FF	–	+	+	–	±	–
grc4f	EG	all	SF/PS	PS	+	+	+	+	+
HIGGSPV	EG	NNC	SF(p_T)	–	+		–	±	–
KORALW	EG	CC11	YFS	PH	+	+	+	±	+
LEPWW	EG	CC03	REMT	PH	+	–	+	–	+
LPWW02	EG	CC03	SF	PH	+	+	–	±	+
PYTHIA	EG	CC03	SF+PS	PS	+	+	–	±	+
WOPPER	EG	CC03	PS	–	+	+	–	±	+
WPHACT	MC	all	SF	–	+	+	+	+	–
WTO	Int.	NCC	SF	–	+	+	–	–	–
WWF	EG	CC11	SF+ME	ME	+	+	+	+	+
WWGENPV	EG	CC11/CC20	SF(p_T)	SF(p_T)	+	+	–	±	+

Example of tuned comparisons

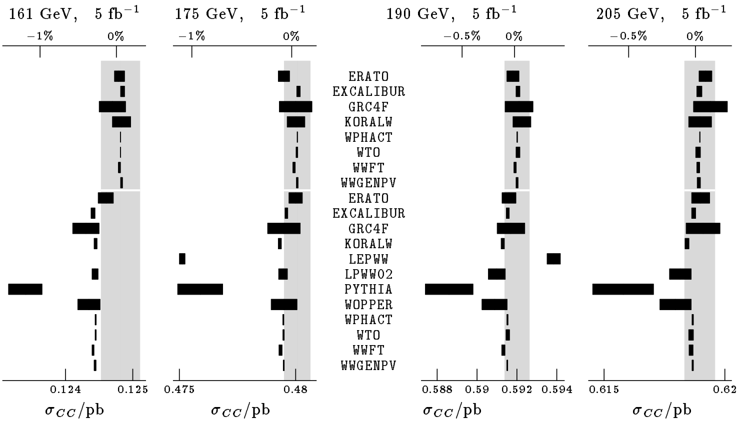


Figure 6: Tuned predictions for the total cross section for $e^+e^- \to \mu^-\bar{\nu}_\mu u\bar{d}$ after canonical (ADLO/TH) cuts.

Example of unleashed comparisons

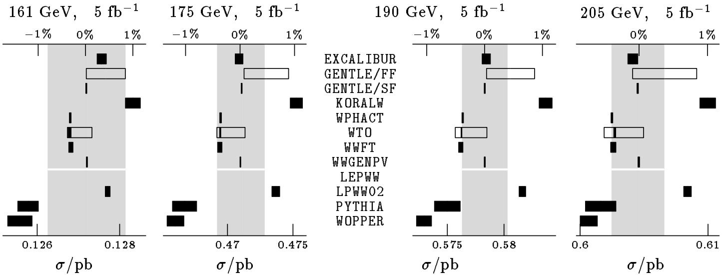


Figure 7: Unleashed predictions for the total cross section for $e^+e^- \to \mu^-\bar{\nu}_\mu u\bar{d}$ without cuts. The transparent, framed error bars are theoretical errors (cf. page 72).

- and similar ones for exclusive observables

Example of unleashed comparisons

final state	ALPHA	EXCALIB	GE/4fan	grc4f	HIGGSPV	WPHACT	WTO
Born, without gluon exchange diagrams							
$\mu^+\mu^-\tau^+\tau^-$	10.06(9)	10.08(0)	10.07(0)	10.07(0)	10.07(0)	10.07(0)	10.14(7)
$\nu_\tau\bar{\nu}_\tau\mu^+\mu^-$	9.894(10)	9.872(3)	9.871(0)	9.875(4)	9.872(3)	9.873(3)	9.884(10)
$\nu_\mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$	8.245(4)	8.242(3)	8.241(0)	8.240(4)	8.237(6)	8.241(1)	8.241(1)
$\mu^+\mu^-u\bar{u}$	23.99(2)	24.04(1)	24.03(0)	24.04(2)	24.03(1)	24.04(1)	—
$\mu^+\mu^-d\bar{d}$	23.46(2)	23.45(1)	23.45(0)	23.46(2)	23.45(1)	23.46(1)	—
$\nu_\mu\bar{\nu}_\mu u\bar{u}$	21.59(2)	21.59(1)	21.59(0)	21.58(1)	21.58(1)	21.59(1)	21.63(3)
$\nu_\mu\bar{\nu}_\mu d\bar{d}$	20.00(2)	19.99(1)	19.99(0)	20.00(1)	20.00(1)	19.99(1)	20.00(1)
$u\bar{u}c\bar{c}$	54.80(5)	54.75(2)	54.74(0)	54.73(4)	54.69(4)	54.74(2)	—
$u\bar{u}s\bar{s}$	51.83(5)	51.86(1)	51.86(0)	51.85(2)	51.85(5)	51.87(2)	—
$d\bar{d}s\bar{s}$	48.30(5)	48.33(2)	48.33(0)	48.34(1)	48.27(6)	48.34(1)	—
With ISR, with gluon exchange diagrams							
$\mu^+\mu^-\tau^+\tau^-$	—	10.29(0)	10.30(0)	10.29(1)	10.30(0)	10.30(0)	—
$\nu_\tau\bar{\nu}_\tau\mu^+\mu^-$	—	9.279(3)	9.284(1)	9.278(7)	9.283(3)	9.284(4)	—
$\nu_\mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$	—	6.379(3)	6.376(1)	6.373(4)	6.377(5)	6.377(1)	6.379(2)
$\mu^+\mu^-u\bar{u}$	—	23.74(1)	23.76(0)	23.77(2)	23.75(1)	23.75(1)	—
$\mu^+\mu^-d\bar{d}$	—	22.31(1)	22.34(0)	22.33(1)	22.33(1)	22.34(1)	—
$\nu_\mu\bar{\nu}_\mu u\bar{u}$	—	18.83(1)	18.84(0)	18.84(1)	18.85(1)	18.84(1)	—
$\nu_\mu\bar{\nu}_\mu d\bar{d}$	—	16.00(1)	15.99(0)	15.99(1)	16.00(1)	15.99(0)	—
$u\bar{u}c\bar{c}$	—	272.6(9)	272.3(0)	271.4(9)	272.1(1)	272.2(1)	—
$u\bar{u}s\bar{s}$	—	267.0(10)	266.8(0)	266.5(6)	266.8(1)	266.8(1)	—
$d\bar{d}s\bar{s}$	—	240.7(11)	240.8(0)	240.5(6)	240.6(4)	240.8(1)	—

Table 24: *NC32, NC24, NC10, NC06* family. Cross sections in fb.

Update on 4f physics (and generators) in 1999

CERN 2000–009
20 September 2000
Theoretical Physics and
Experimental Physics
Divisions

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

REPORTS OF THE WORKING GROUPS ON PRECISION CALCULATIONS FOR LEP2 PHYSICS

PROCEEDINGS

Editors: S. Jadach, G. Passarino and R. Pittau

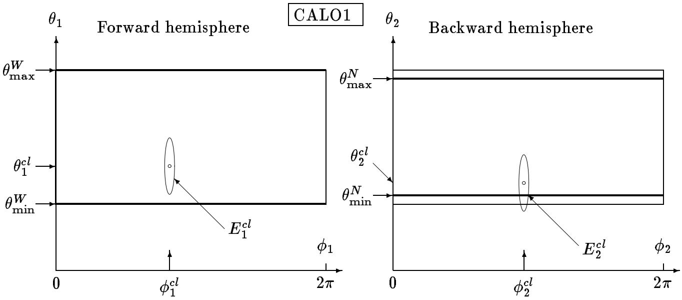
Standard interface and public accessible codes (1995)

"in order to avoid confusion among experimentalists required to run a moltitude of different codes"

- Interfaces to electroweak generators
  "it would therefore be advantageous if the event generator authors involved could agree on a common approach: EW authors provide the four-fermion configuration in a standards format and QCD authors provide a standard interface that converts this to a set of final hadrons... In this section we propose such a standard..."

- The World Wide Web offers new opportunities to make programs accessible
  - *A common practice of having a "home page" for each generator will allow the construction of useful generator directories*

SABS event selections: CALO1



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NW: $\theta^{cl}_1 \in (\theta^W_{\rm min}, \theta^W_{\rm max})$, $\theta^{cl}_2 \in (\theta^N_{\rm min}, \theta^N_{\rm max})$ $E^{cl}_1 E^{cl}_2 > z_{min} E^2_{beam}$

- fiducial θ range: $\theta^f_{\rm min} = 0.024$ rad, $\theta^f_{\rm max} = 0.058$ rad, $\theta^W_{\rm min} = \theta^f + \delta\theta$, $\theta^W_{\rm max} = \theta^f - \delta\theta$
- $\delta_\theta = (\theta^f_{\rm max} - \theta^f_{\rm min})/16$
- $\theta^N_{\rm min} = \theta^f + 2\delta\theta$, $\theta^N_{\rm max} = \theta^f - 2\delta\theta$
- cone with a radius of 0.010 rad

The case of Small Angle Bhabha Scattering

- The previously estimated 0.16% precision at Z-peak in SABS was becoming a limiting factor (notably on $\sigma^0_{\rm had}$ and N_ν)

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- four independent codes
  - `BHAGEN95`: MC integrator with $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha^2 L^2)$ and resummation with LL structure functions
  - `BHLUMI` (with `OLDBIS` and `LUMLOG`): MC event generator with $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha^2 L^2)$ matrix elements plus YFS exclusive exponentiation
  - `NLLBHA`: fixed order $\mathcal{O}(\alpha^2) + \mathcal{O}(\alpha^3 L^3)$ seminalytical code
  - `SABSPV`: MC integrator with $\mathcal{O}(\alpha)$ for t-channel matrix elements matched, in factorized form, to LL resummation with structure functions

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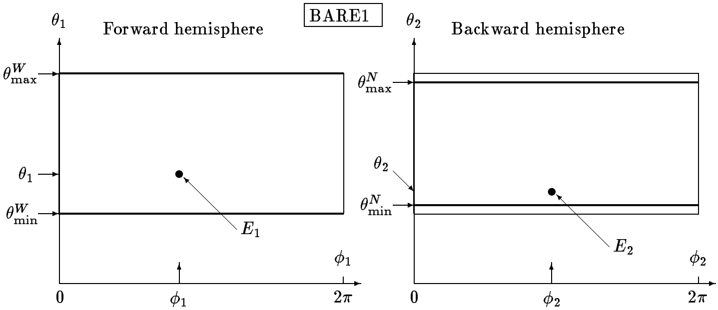
- Comparisons according to different event selections, with increasing complexity in order to match the real event selections of the experiments (QED corr. critically dependent on ev. selection)

SABS event selections: BARE1



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NW: $\theta_1 \in (\theta^W_{\min}, \theta^W_{\max})$, $\theta_2 \in (\theta^N_{\min}, \theta^N_{\max})$ $\quad s' > u_{min}\, s$

- fiducial θ range: $\theta^W_{\min} = 0.024$ rad, $\theta^W_{\max} = 0.058$ rad, $\theta^W_{\min} < \theta < \theta^W_{\max}$
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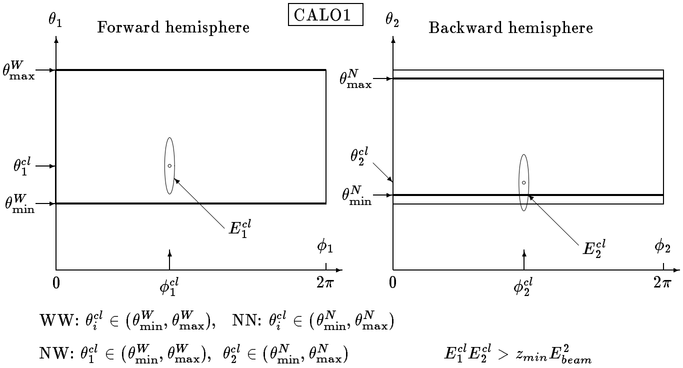

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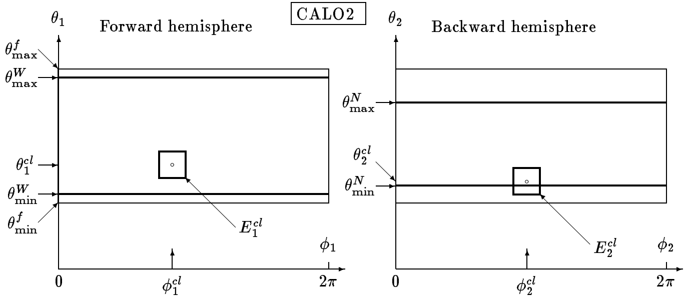
- cone with a radius of 0.010 rad

SABS event selections: CALO2



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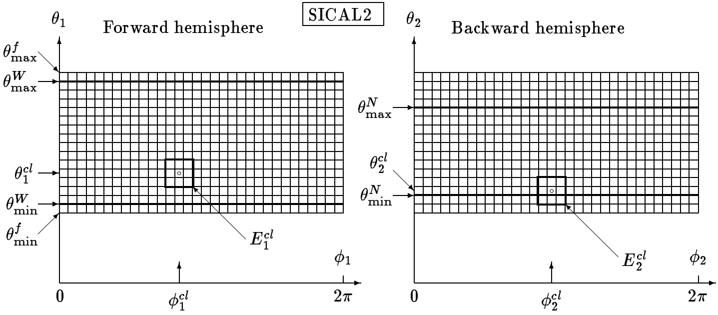
SABS event selections: SICAL2



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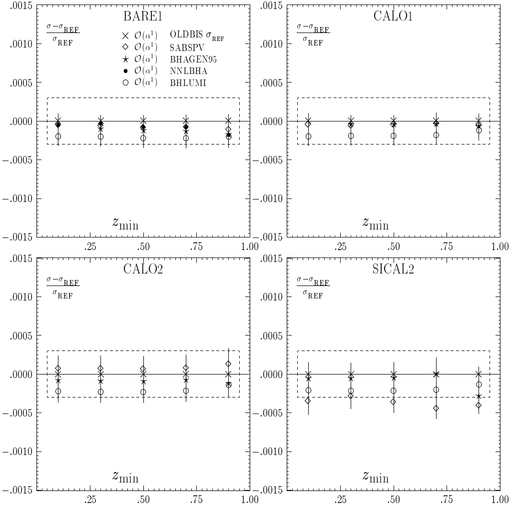
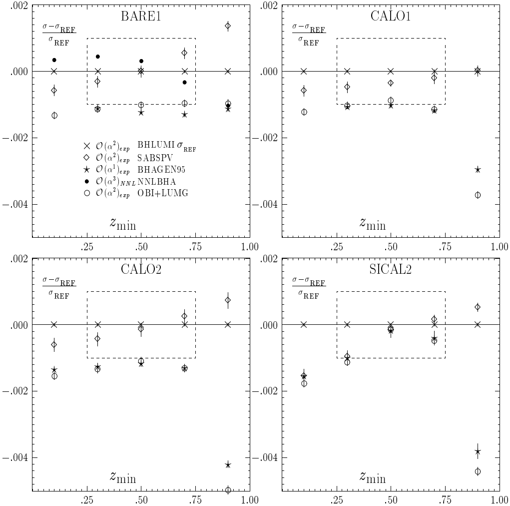
NW: $\theta_1^{cl} \in (\theta_{\min}^W, \theta_{\max}^W)$, $\theta_2^{cl} \in (\theta_{\min}^N, \theta_{\max}^N)$ $\qquad E_1^{cl} E_2^{cl} > z_{min} E_{beam}^2$

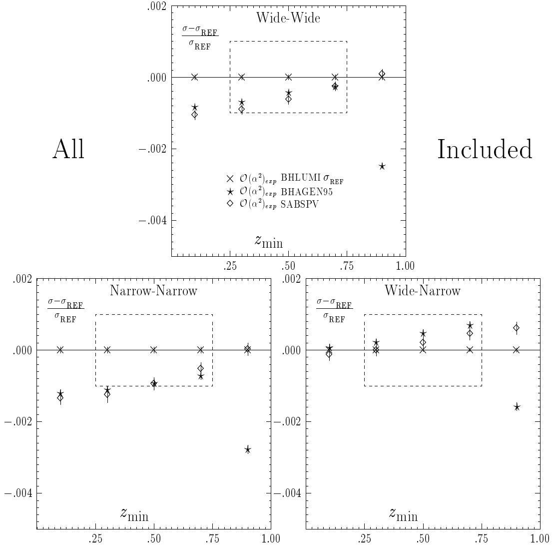
Results for Wide-Wide ES's with NLO matr. el.



Results for Wide-Wide ES's with complete matr. el.



Final results with complete matr. el.



Summary of th uncertainty on SABS (as of 1995)

	LEP1		LEP2
Type of correction/error	Ref. [6]	Present	Present
(a) Missing photonic $\mathcal{O}(\alpha^2 L)$	0.15%	0.10%	0.20%
(a) Missing photonic $\mathcal{O}(\alpha^3 L^3)$	0.008%	0.015%	0.03%
(c) Vacuum polarization	0.05%	0.04%	0.10%
(d) Light pairs	0.04%	0.03%	0.05%
(e) Z-exchange	0.03%	0.015%	0.0%
Total	0.16%	0.11%	0.25%

see talk by M. Skrzypek of yesterday for the present status

- Bhabha scattering is the example where the theoretical uncertainty has been a large source of systematics in the LEP physics analysis

SUMMARY

- it is never underestimated the importance of having predictions from different event generators, necessary for a robust assessment of the th. uncertanty

- even if several years ahead, it is never too early to start working on the next step in precision (see e.g. the case of SABS)

SUMMARY

- it is never underestimated the importance of having predictions from different event generators, necessary for a robust assessment of the th. uncertanty

- even if several years ahead, it is never too early to start working on the next step in precision (see e.g. the case of SABS)

- see next talk by Alan!