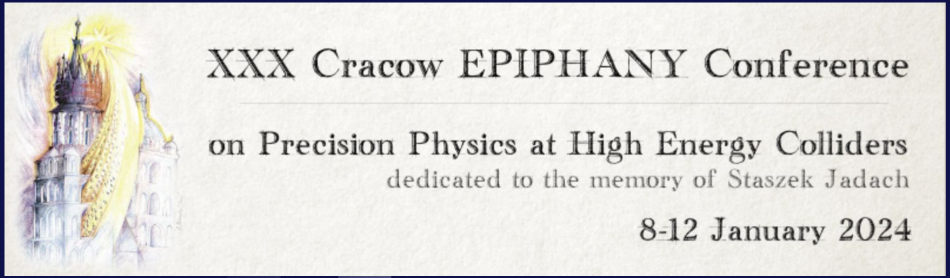
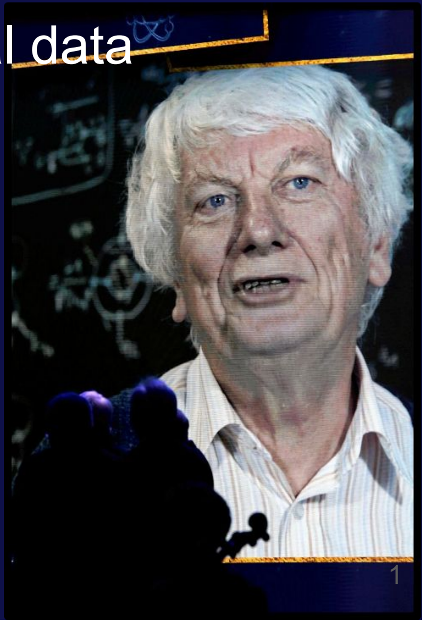


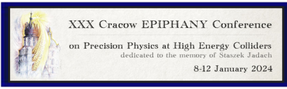
The number of light neutrino species

The first FCC-ee precision measurement with real data

By Staszek Jadach and some of his disciples/friends (*)

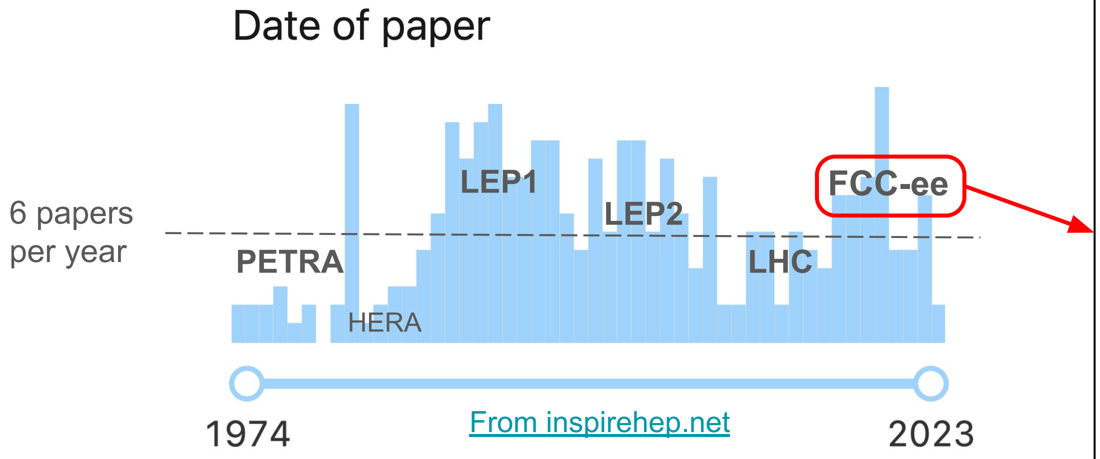
(*) Yorgos Voutsinas, Emmanuel Perez, Patrick Janot, Mogens Dam





Staszek Jadach: An inspiration for all of us

- Staszek published **313 papers in 50 years** of precision collider physics
  - A prolific source of new ideas and efficient tools
- **Always close to experiments and experimenters**
  - Addressing and solving concrete issues towards accurate physics results
- **Convinced that difficult questions can be solved by hard work**
  - Followed this motto (and dragged others into it) all the way from PETRA to FCC



Particularly productive on FCC-ee physics case

- Theory Yellow reports
- QED: ISR, FSR, IFI in KKMC
- A_{FB} and $\alpha_{QED}(m_Z)$ direct determination
- Z and Higgs coupling theory precision
- QCD corrections
- Γ_Z(invis) measurement above Z pole
- Bhabha scattering and Luminosity
- …

The approval of the FCC project will owe Staszek a lot

Today: A by-product from Staszek's work at FCC-ee

- Low-angle Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) cross section and BHLUMI : Factor 10 foreseen in the precision of the FCC-ee luminosity measurement

- These progress are back-propagated to the LEP Z pole data, leading to an improved measurement of the number of light neutrino species N_ν.

- Today's presentation is based on two publications
  - arXiv:1912.02067, P. Janot, **Staszek Jadach**
  - arXiv:1908.01704, G. Voutsinas, E. Perez, P. Janot, M. Dam

  I made this choice because this is my last work in real close collaboration with Staszek.

- Because of Covid'19, it is also the first public presentation of this work in a conference. It is just great that it takes place here in Cracow.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
STANFORD LINEAR ACCELERATOR CENTER

CERN-PH-EP/2005-041
SLAC-R-774
hep-ex/0509008
7 September 2005

arXiv:hep-ex/0509008v3 27 Feb 2006

Precision Electroweak Measurements on the Z Resonance

20-years-old measurement of N_ν

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1] the LEP Electroweak Working Group,[2] the SLD Electroweak and Heavy Flavour Groups

Phys. Rep. 427 (2006) 257

Accepted for publication in *Physics Reports*

Updated: 20 February 2006

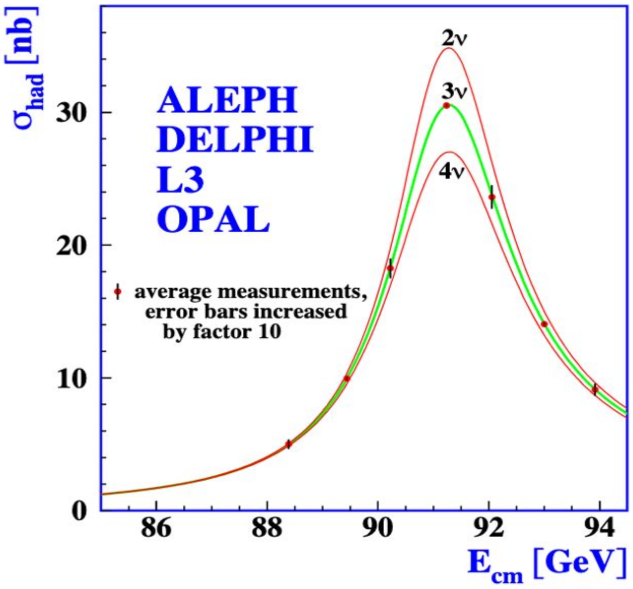
[1] See Appendix A for the lists of authors.
[2] Web access at http://www.cern.ch/LEPEWWG

1

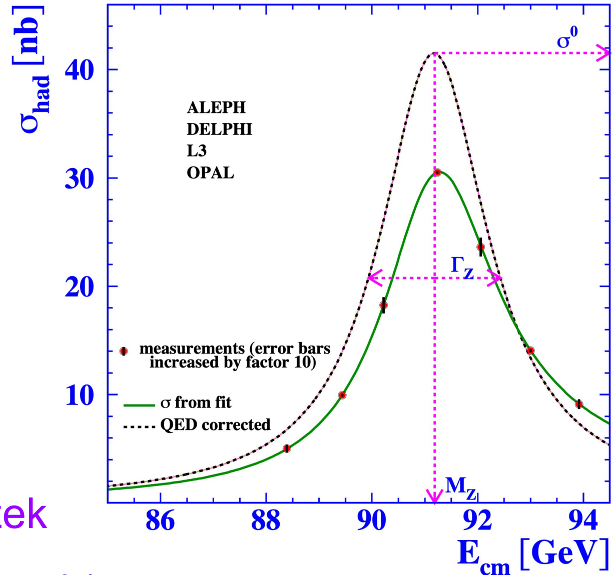
Reminder: Measuring N_ν at LEP

Phys. Rep. 427 (2006) 257

- **The Z lineshape determination**
  - Measure hadronic and leptonic cross sections (σ_{had} and $\sigma_{\ell\ell}$) as a function of E_{cm} ($\sqrt{s}$)



Fit to a Breit-Wigner shape
folded with QED ISR effects
Get m_Z, Γ_Z and σ^0
Get also $R^0_\ell = \sigma^0_{had} / \sigma^0_{\ell\ell}$
Staszek



- **The peak cross section σ^0 is very sensitive to N_ν**
  - The smaller the peak cross section, the larger the number of light neutrino active species

Reminder: Measuring N_ν at LEP

- **What was done in practice to extract N_ν :**
  - Total Z decay width : $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + N_\nu \Gamma_{\nu\nu}$
  - Divide by $\Gamma_{\ell\ell}$: $\Gamma_Z / \Gamma_{\ell\ell} = 3 + \delta_\tau + R^0_\ell + N_\nu (\Gamma_{\nu\nu} / \Gamma_{\ell\ell})$, with $R^0_l = \frac{\Gamma_{had}}{\Gamma_{ll}}$
    - δ_τ is a small phase-space correction due to the finite τ mass
    - $(\Gamma_{\nu\nu} / \Gamma_{\ell\ell})$ rather immune to SM parameters (m_{top}, m_H, …) : taken from SM
    - $\Gamma_Z / \Gamma_{\ell\ell}$ taken from Breit-Wigner peak expression $\sigma^0_{had} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$
  - Solve for N_ν :

$$N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM} = \left(\frac{12\pi}{m_Z^2}\frac{R^0_\ell}{\sigma^0_{had}}\right)^{\frac{1}{2}} - R^0_\ell - 3 - \delta_\tau$$

$\delta_\tau \approx -2.263 \cdot 10^{-3}$

R^0_ℓ: Measured

σ^0_{had}: Measured

$\left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM}$ – SM prediction:
= 1.99125 ± 0.00083 in 2005
= 1.99060 ± 0.00021 in 2019
Dubovik, Freitas, Gluza, Riemann, Usovitch
Phys. Lett. B 783 (2018) 86

Phys. Rep. 427 (2006) 257

Reminder: Measuring N_ν at LEP

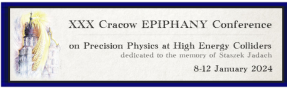
Phys. Rep. 427 (2006) 257

- **And the result was (in 2005) :** $N_\nu = 2.9840 \pm 0.0082$
  - Consistent within 2σ with the Standard Model (three light neutrino species)
  - But this long-standing 2σ deficit invited theoretical speculation
    - Neutrino mixing with right-handed neutrinos ? — *Phys. Lett. B* 241 (1990) 579
    - Neutrino mixing with heavy gauge singlet (e.g., in Technicolor) ? — *Phys. Rev. D* 67 (2003) 073012
    - Right-handed neutrinos propagating in extra dimensions ? — *Nucl. Phys. B* 623 (2002) 395
- **How is all this connected with Staszek ?**
  - The extraction of σ^0_{had} requires precise knowledge of the integrated luminosity $\mathscr{L}$

$$\sigma^0_{had} = N_{had} / \mathscr{L}$$

Dominant source of uncertainty on σ^0_{had} !

  - The uncertainty on $\mathscr{L}$ is the largest uncertainty on N_ν
    - Dominated by the theoretical uncertainty of the reference process cross section
    - ΔN_ν [theory] = 0.0046 (out of 0.0082)
    - Improved theoretical precision quickly pays off to either ascertain the deficit or reduce it

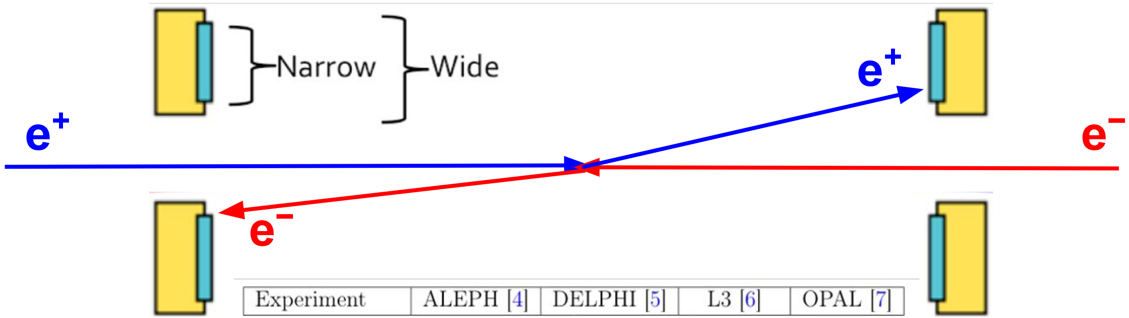


Integrated luminosity measurement at LEP

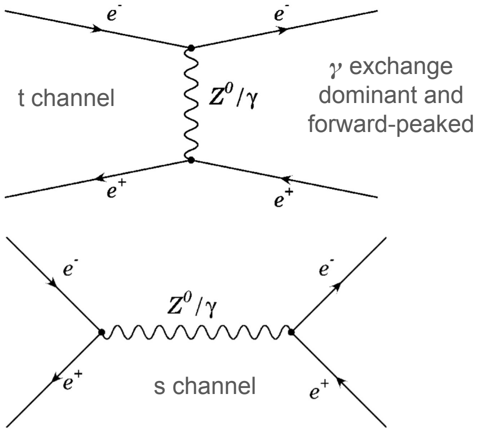
At LEP, the reference process was the low-angle Bhabha scattering $e^+e^- \rightarrow e^+e^-$

$$\mathcal{L} = N_{Bhabha} / \sigma_{Bhabha}$$

where the rate N_{Bhabha} was measured with low-angle calorimeters with an asymmetric acceptance (narrow on one side, wide on the other, changing sides for the next event)



Experiment	ALEPH [4]	DELPHI [5]	L3 [6]	OPAL [7]
Wide (mrad)	26.2–55.5	37.0–127.0	27.0–65.0	27.2–55.7
Narrow (mrad)	30.4–49.5	44.9–113.6	32.0–54.0	31.3–51.6



This well-known trick reduces the sensitivity to many experimental effects (position of the interaction point, misalignment, initial state radiation, etc.)

Published uncertainty of $\mathcal{L}$ measurement at LEP : 0.061% (theory) + 0.034% (exp - OPAL)

Integrated luminosity measurement at FCC-ee

With 5.10^{12} Z expected at FCC-ee (10^5 x LEP), a much better precision on $\mathcal{L}$ will be needed.

In 2019, Staszek was working on a way to reach 0.01% theoretical precision on σ_{Bhabha} :

Physics Letters B 790 (2019) 314–321

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

PHYSICS LETTERS B

The path to 0.01% theoretical luminosity precision for the FCC-ee ☆

Check for updates

S. Jadach [a,*], W. Płaczek [b], M. Skrzypek [a], B.F.L. Ward [c,d], S.A. Yost [e]

[a] Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[b] Marian Smoluchowski Institute of Physics, Jagiellonian University, ul. Łojasiewicza 11, 30-348 Kraków, Poland
[c] Baylor University, Waco, TX, USA
[d] Max Planck Institute für Physik, München, Germany
[e] The Citadel, Charleston, SC, USA

arXiv:1812.01004

ARTICLE INFO

Article history:
Received 29 November 2018
Accepted 7 January 2019
Available online 23 January 2019
Editor: L. Rolandi

ABSTRACT

The current status of the theoretical precision for the Bhabha luminometry is critically reviewed and pathways are outlined to the requirement targeted by the FCC-ee precision studies. Various components of the pertinent error budget are discussed in detail – starting from the context of the LEP experiments, through their current updates, up to prospects of their improvements for the sake of the FCC-ee. It is argued that, with an appropriate upgrade of the Monte Carlo event generator BHLUMI and/or other similar MC programs calculating QED effects in the low angle Bhabha process, the total theoretical error of 0.01% for the FCC-ee luminometry can be reached. A new study of the Z and s-channel γ exchanges within the angular range of the FCC-ee luminometer using the BHWIDE Monte Carlo was instrumental in obtaining the above result. Possible ways of BHLUMI upgrade are also discussed.

From an upgrade of BHLUMI MC gen

- Higher-order QED corrections
- Multi-photon distributions
- O(α) QED correction for Z exchange
- Vacuum polarization in t channel
- Light fermion pairs
  - e.g., $e^+e^- \rightarrow e^+e^-e^+e^-$

Some of these improvements were already available in 2019, and could be used for LEP.
Staszek was a great believer in picking the low-hanging fruits first, and go higher later.

Back-propagation of Staszek's FCC work to LEP

The effect of the improvements on σ_{Bhabha} precision are twofold for LEP

1) **The uncertainty of $\mathscr{L}$ will reduce**
   Precisions on σ^0_{had} and N_ν improves

2) **The value of σ_{Bhabha} may change**
   If, for example, σ_{Bhabha} decreases:
   Then $\mathscr{L}$ increases, σ^0_{had} decreases and N_ν increases

3) **The change may be $\sqrt{s}$ dependent**
   May affect Γ_Z and even m_Z in turn.

   Correlations between Z lineshape parameters will change as well

Everything is summarized here ⇒

Physics Letters B 803 (2020) 135319
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Improved Bhabha cross section at LEP and the number of light neutrino species ☆

Patrick Janot [a,*], Stanisław Jadach [b]

[a] CERN, EP Department, 1 Esplanade des Particules, CH-1217 Meyrin, Switzerland
[b] Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland

arXiv:1912.02067

A R T I C L E   I N F O

Article history:
Received 17 December 2019
Received in revised form 13 February 2020
Accepted 19 February 2020
Available online 25 February 2020
Editor: L. Rolandi

A B S T R A C T

In e^+e^- collisions, the integrated luminosity is generally measured from the rate of low-angle Bhabha interactions $e^+e^- \to e^+e^-$. In the published LEP results, the inferred theoretical uncertainty of ±0.061% on the predicted rate is significantly larger than the reported experimental uncertainties. We present an updated and more accurate prediction of the Bhabha cross section in this letter, which is found to reduce the Bhabha cross section by about 0.048%, and its uncertainty to ±0.037%. When accounted for, these changes modify the number of light neutrino species (and its accuracy), as determined from the LEP measurement of the hadronic cross section at the Z peak, to $N_\nu = 2.9963 \pm 0.0074$. The 20-years-old 2σ tension with the Standard Model is gone.

Strategy of the LEP integrated luminosity re-analysis

The goal was not to restart from scratch and derive an absolute value for $\mathscr{L}$ from the data of the four experiments at all centre-of-mass energies and for all LEP1 years !

The goal was instead to estimate the (small) relative correction factors due to the theory improvements, and easily reap the benefits from the better theoretical precision.

These relative correction factors are not expected to depend on a GEANT simulation of Bhabha events in the luminosity calorimeters. For this reason, the Bhabha event selection is emulated, in quasi-realistic, albeit imaginary detectors consisting of

- a pair of cylindrical calorimeters;
- symmetrically located around the beam axis and with respect to the IP;
- covering the physical polar angular ranges of the actual LEP LumiCals;
- divided in azimutal segments and radial pads (pad edges define wide/narrow cuts).

Electrons and photons deposit their full energy in the pad they hit. Other particles (μ, π ,ν, ...) escape undetected. No energy smearing is applied. Neighbouring pads are clustered. The most energetic two pads (E_1, E_2) are the final state electron and positron candidate.

Strategy of the LEP integrated luminosity re-analysis

The goal was not to restart from scratch and derive an absolute value for $\mathcal{L}$ ... e data of the four experiments at all centre-of-mass energies and for all LEP1 ...

The goal was instead to estimate the (small) relative correcti... the theory improvements, and easily reap the benefits from the be... ecision.

These relative correction factors are not exp... n a GEANT simulation of Bhabha events in the luminosity calorim... ason, the Bhabha event selection is emulated, in quasi-rea... nary detectors consisting of

- a pair of cylindrical calor...
- symmetrically locat... am axis and with respect to the IP;
- covering the ... gular ranges of the actual LEP LumiCals;
- divided i... ents and radial pads (pad edges define wide/narrow cuts).

Elect... ons deposit their full energy in the pad they hit. Other particles (μ, π ,ν, ...) esc... detected. No energy smearing is applied. Neighbouring pads are clustered. The mo... energetic two pads (E_1, E_2) are the final state electron and positron candidate.

Strategy inspired from Staszek et al, arXiv:hep -ph/9602393 (1996).
Re-coded in C++ and implemented in BHLUMI generator in 2019

Archeology: LEP LumiCal acceptance

Table 1
Wide and narrow acceptance for first- and second-generation LumiCals of the four LEP experiments. The periods where these devices were operated are also indicated. The ALEPH LCAL numbers are only indicative, as the fiducial acceptance followed the (square) detector cell boundaries, instead of specific polar angle values. The detector emulation used in this paper includes this subtlety.

Expt/LumiCal		Period	Narrow (mrad)	Wide (mrad)
ALEPH LCAL [5]		01/90 → 08/92	57–107	43–125
DELPHI SAT [6,7]	1st gen.	01/90 → 12/93	56.0–128.6	52.7–141.8
L3 BGO [8]		01/90 → 12/92	31.2–65.2	25.2–71.2
OPAL FD [9]		01/90 → 12/92	65.0–105.0	55.0–115.0
ALEPH SiCAL [10]		09/92 → 12/95	30.4–49.5	26.1–55.9
DELPHI STIC [11]	2nd gen.	01/94 → 12/95	43.6–113.2	37.2–126.8
L3 SLUM [12]		01/93 → 12/95	32.0–54.0	27.0–65.0
OPAL SiW [13]		01/93 → 12/95	31.3–51.6	27.2–55.7

Second generation LumiCals, closer to the beam axis (30 mrad), were installed in all four experiments to improve the theoretical and statistical precision on σ_{Bhabha}.

The acceptance of first generation LumiCals is similar to that of FCC-ee LumiCals

Archeology: LEP LumiCal acceptance

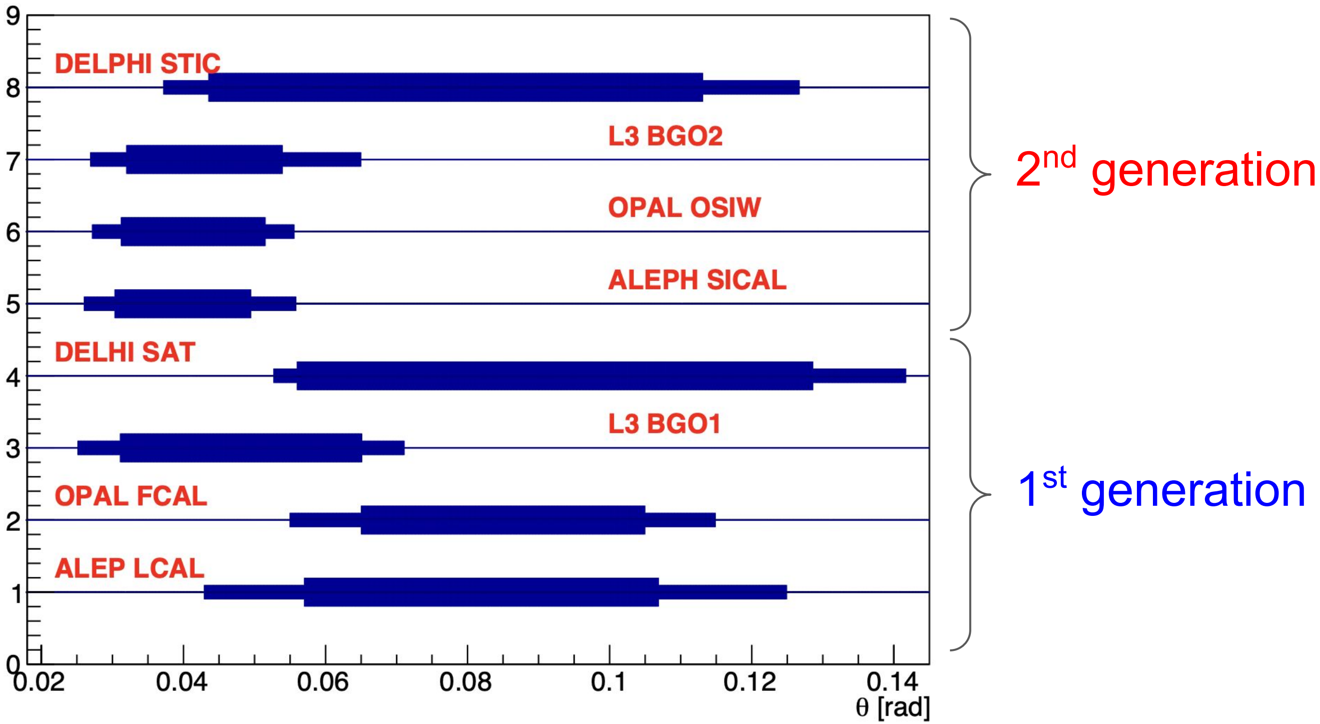


Figure 1: Graphical representation of the angular acceptance range of LEP luminosity detectors. Thick band denotes narrow range and thiner band denoted wide range in asymmetric event selection. Fiducial range not marked.

Archeology: Kinematic selection criteria

Table 4

Kinematic selection criteria applied to the clustered energies $E_{1,2}$ deposited in the two LumiCals, and on the acoplanarity and acollinearity angles between the two clusters, $\Delta\phi$ and $\Delta\theta$. The beam energy is denoted E_{beam}. Some of the selection criteria changed during the LEP 1 era. The periods of validity are also indicated. From 1993 onward in L3, the smaller cluster energy was allowed to be as small as 20% of the beam energy if the larger one energy exceeded 95% of the beam energy, in order to recover events with energy lost in the gaps between crystals. Also, in the first generation LumiCals (and in L3 over the whole LEP1 period), the clusters were required to be away from the vertical separation between the two halves of the calorimeters. Because the imaginary detectors considered here have no gaps and cracks, these last cuts are not emulated. This choice does not affect the relative cross-section changes studied in this letter.

Experiment	ALEPH [16]	DELPHI [17,18,35]	L3 [8,36]	OPAL [9,37,19]
$E_{1,2}^{\mathrm{min}}/E_{\mathrm{beam}}$ $E_{1,2}^{\mathrm{max}}/E_{\mathrm{beam}}$	> 0.44	> 0.65	> 0.40 > 0.80	> 0.45 ($\rightarrow$ 92) > 0.50 (93 $\rightarrow$)
$\dfrac{(E_1 + E_2)}{2E_{\mathrm{beam}}}$	> 0.60 ($\rightarrow$ 93) > 0.78 (in 94) > 0.84 (in 95)	–	–	> 0.67 ($\rightarrow$ 92) > 0.75 (93 $\rightarrow$)
$\Delta\phi$ (mrad)	< 175 ($\rightarrow$ 8/92) < 525 (9/92 $\rightarrow$)	< 350	< 175	< 350 ($\rightarrow$ 92) < 200 (93 $\rightarrow$)
$\Delta\theta$ (mrad)	–	–	–	– ($\rightarrow$ 92) < 10 (93 $\rightarrow$)

Archeology: BHLUMI version used for σ_{Bhabha} prediction

Table 2
Versions of BHLUMI used throughout the LEP 1 phase. In 1990, ALEPH [16] used the BABAMC generator [20] instead of BHLUMI. The corresponding uncertainty on the Bhabha cross section, as quoted by each experiment, is indicated in brackets.

	ALEPH	DELPHI	L3	OPAL
1990	BABAMC (0.320%)	2.01 (0.300%)	2.01 (0.250%)	2.01 (0.300%) later scaled to 4.04
1991–92	2.01 (0.210%)			
Fall 92	2.01 (0.160%)			
1993	4.04 (0.061%)	4.02 (0.170%)	4.04 (0.061%)	4.04 (0.054%)
1994–95		4.03 (0.061%)		

Available improvements

1. $O(\alpha)$ QED correction to Z exchange in t and s channels (BHLUMI 2.01 → BHLUMI 4.0x)
2. Vacuum polarization in the t channel (regular improvements in the past two decades)
3. Light-pair production (with a partial estimation already included in 1993-95 OPAL data)

For the purpose of the study, more than a billion Bhabha events were generated with BHLUMI 4.04, with various event-by-event reweighting to include improvements 1 & 2, and processed through the detector and event selection emulation.

Expected improved precision on σ_{Bhabha}

Table 3

Inspired from Refs. [28,29,25]: Summary of the theoretical uncertainties for a typical LEP luminosity detector covering the angular range from 58 to 110 mrad (first generation) or from 30 to 50 mrad (second generation). The total uncertainty is the quadratic sum of the individual components.

LEP Publication in:	1994		2000		2019	
LumiCal generation	1st	2nd	1st	2nd	1st	2nd
Photonic $\mathcal{O}(\alpha^2 L_e)$	0.15%	0.15%	0.027%	0.027%	0.027%	0.027%
Photonic $\mathcal{O}(\alpha^3 L_e^3)$	0.09%	0.09%	0.015%	0.015%	0.015%	0.015%
Z exchange	0.11%	0.03%	0.09%	0.015%	0.090%	0.015%
Vacuum polarization	0.10%	0.05%	0.08%	0.040%	0.015%	0.009%
Fermion pairs	0.05%	0.04%	0.05%	0.040%	0.010%	0.010%
Total	0.25%	0.16%	0.13%	0.061%	0.100%	0.037%

Table inspired from Staszek et al, Phys. Lett. B 790 (2019) 314.

To be improved to 0.010% for FCC-ee

Note: The detector & selection emulation reproduces the published Bhabha cross section values with a very reasonable accuracy. For example, ALEPH and OPAL published a ~84 nb and 78.71 nb cross section after selection, and the current emulation gives 84.48 nb and 78.74 nb, respectively.

These absolute cross-section values are, however, of little importance for this study, as only relative cross-section changes – expected to be very small (from a few 10^{-4} to 10^{-3}) – are evaluated here.

O(α) QED corrections on Z exchange

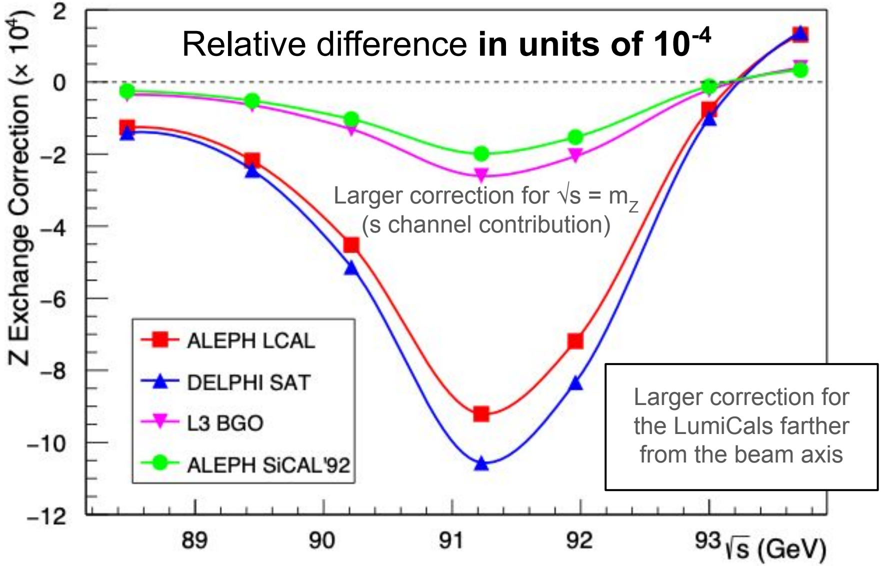
- Until the end of 1992, the LEP experiments were using BHLUMI 2.01, where the Z exchange contribution was implemented at tree-level only.
- The cross section was corrected with the BABAMC evaluation of the O(α) QED effects
- From 1993 onwards, everybody moved to BHLUMI 4.0x, with an improved evaluation of the QED correction + YFS exponentiation

Staszek et al, Phys. Lett. B 353 (1995) 349.

- Only OPAL reweighted their pre-1993 cross section with the improved evaluation
- Staszek performed the same reweighting with the other three experiments (by coding the BABAMC correction inside BHLUMI)

Comparison between BHLUMI 4.04 and BABAMC (used in ALEPH, L3, DELPHI published results)

Dots show the √s values at which LEP delivered collisions



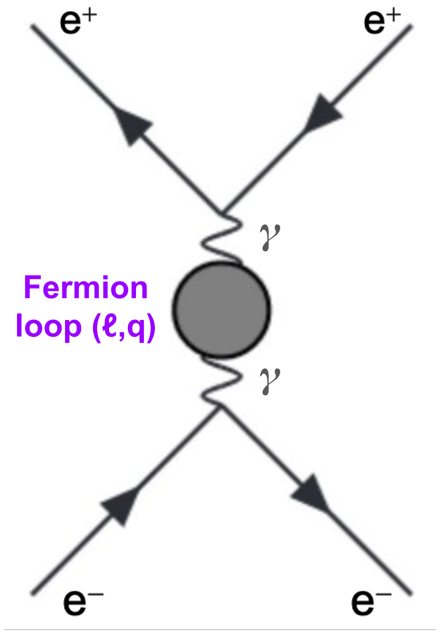
Cross-section correction up to −0.1%

Very small expected effect on N_ν (only 1990-92 data)

Vacuum polarization in the t channel

See talk of J. Gluza

- t-channel propagator dressed with a loop of charged fermions
  - Lepton contribution known to fourth order with virtually infinite precision
  - Hadronic contribution obtained from measurements of $\sigma(e^+e^- \rightarrow \text{hadrons})$ and perturbative QCD kernels, in the relevant t range from −1 to −10 GeV^2
- Progress on hadronic contribution with data from B and ϕ factories, implemented in
  - Code from Jegerlehner 2019 (hadr5x.f)
  - Private code from DHMZ 2020 (described in arXiv:1908.00921)
  - Private code from KNT 2018 (described in arXiv:1802 .02995)
- All versions give consistent cross-section reweighting in BHLUMI 4.04 (**Staszek**)
  - Jeg'19 used for the final results (cross checked w/ DHMZ'20 & KNT'18)
  - Compared with the different vacuum polarization codes used in LEP pubs
  - Uncertainty reduced by a factor 4, cross section reduced by a few 10^{-4}



Relative difference **in units of 10^{-4}**

Experiment	ALEPH	DELPHI	L3	OPAL
01/90 → 08/92	$-2.00^{-0.18}_{+0.21}$	$-1.02^{-0.18}_{+0.18}$	$+1.57^{-0.09}_{+0.10}$	$-4.60^{-0.03}_{+0.04}$
09/92 → 12/92	$+1.22^{-0.12}_{+0.12}$			
01/93 → 12/93	$-2.12^{-0.08}_{+0.09}$	$-4.62^{-0.06}_{+0.07}$	$-2.36^{-0.09}_{+0.11}$	$-2.24^{-0.09}_{+0.10}$
01/94 → 12/94		$-3.86^{-0.11}_{+0.12}$		
01/95 → 12/95				

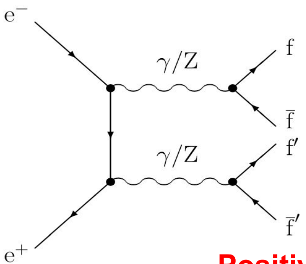
Jeg'19

Not an uncertainty but correction at $\sqrt{s}$ = $91.2^{+2.5}_{-2.7}$ GeV

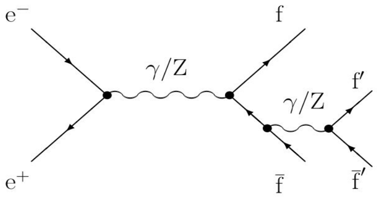
Light fermion pair production

Four-fermion final state (with at least one e^+e^- pair) may pass the event selection

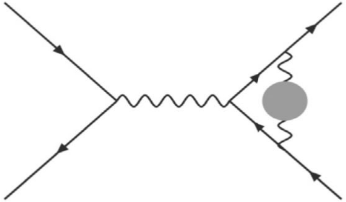
Conversion



Annihilation



Virtual correction at the same order
(interference with tree-level graph)



Specific four fermion MC generators

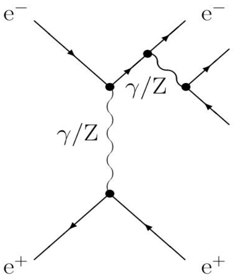
Positive correction

Negative correction

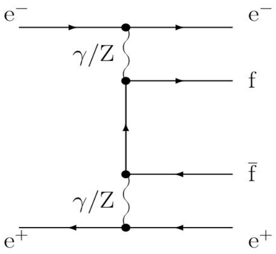
J. Gluza et al, arXiv:0807.4691
Phys. Rev. D 78 (2008) 085019

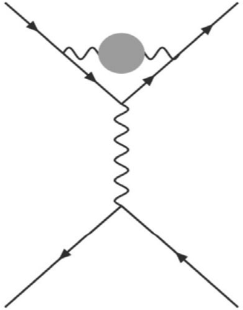
Dominant

Bremsstrahlung



Multiperipheral





Delicate cancelation w/o cuts, but **negative correction** when selection cuts are included

(smaller momentum and larger acoplanarity angle for the e^+e^- pair in the four-fermion final state)

Light fermion pair production (cont'd)

- $e^+e^- \to e^+e^- f\bar{f}$ final states generated by FERMISV for f = e, μ, τ, ν_e, ν_μ, ν_τ, u, d, s, c, b
  - FERMISV + ISR + FSR: J. Hilgart et al., Comput. Phys. Commun. 75 (1993) 191
  - Treatment of hadronic final states : ALEPH Coll., Z. Phys. C 66 (1994) 3
- $e^+e^- \to e^+e^- e^+e^-$ final state cross-checked with KORALW (better treatment at 0°)
  - KORALW: Staszek et al., Comput. Phys. Commun. 119 (1999) 272–311
- Cross checked and in agreement with earlier partial and partially analytical estimates
  - Staszek et al., Phys. Rev. D 55 (1996) 1206: only f = e, Bremsstrahlung graphs, ALEPH LCAL
  - G. Montagna et al., Phys. Lett. B 459 (1999) 649, only f = e, μ, τ, OPAL SiW
- Uncertainty reduced by a factor 4 with respect to previous estimates
  - Dominated by the (estimated) missing higher-order QED contribution to four-fermion production

Relative cross-section reduction
in units of 10^{-4}
(found to be independent of $\sqrt{s}$)

Experiment	ALEPH	DELPHI	L3	OPAL
01/90 → 08/92	-3.58 ± 0.06	-4.99 ± 0.06	-3.43 ± 0.04	-4.51 ± 0.09
09/92 → 12/92	-3.00 ± 0.06			
01/93 → 12/93			-3.77 ± 0.07	-4.72 ± 0.17 (-4.40 already applied in [13])
01/94 → 12/94	-3.52 ± 0.08	-3.91 ± 0.05		
01/95 → 12/95	-4.38 ± 0.08			

Combined fit of the Z lineshape

The reduction of σ_{Bhabha} corresponds to an increase of the integrated luminosity $\mathcal{L}$

Example: $\mathcal{L}$ effective increase at the Z peak ($\sqrt{s}$ = 91.227 GeV) **in units of 10^{-4}**

Similar values are obtained at Peak-2 ($\sqrt{s}$ = 89.443 GeV) and Peak+2 ($\sqrt{s}$ = 92.996 GeV)

Source/Experiment	ALEPH	DELPHI	L3	OPAL
Z exchange	0.52	0.35	0.06	0.00
Light fermion-pairs	3.35	4.07	3.76	0.40
Vacuum polarization	1.82	3.85	2.28	2.28
Total	+5.69	+8.27	+6.10	+2.68

For each LEP experiment:

- Take the Z lineshape parameters and covariance matrix from Phys. Rep. 427 (2006) 257
- Back propagate the errors of these parameters to the hadronic cross sections σ_{had} at Peak-2, Peak, and Peak+2 (assuming a Breit-Wigner resonance)
- Reduce the σ_{had} values & uncertainties according to the corrected integrated luminosity at each step
- Fit a new Breit-Wigner, with updated parameters and covariance matrix, at each step
- Optional: Get an updated (increased and more accurate) N_ν value per experiment, at each step

Combined fit of the Z lineshape (cont'd)

The combination of the four LEP experiments follows the exact same path (at each step) as that described in Phys. Rep. 427 (2006) 257.

The combination code written for this purpose was checked to give the exact same result as in Phys. Rep. 427 (2006) 257 when starting from the original individual experiment results, up to the last published digit.

Table 9
Combined peak hadronic cross section (σ^0_{had}) and the corresponding number of light neutrino species N_ν, at each step of the corrections considered in this letter.

Correction	σ^0_{had} [nb]	N_ν
Original value	41.540 ± 0.037	2.9846 ± 0.0082
New $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{\text{SM}}$	41.5400 ± 0.0372	2.9856 ± 0.0081
Z exchange	41.5390 ± 0.0369	2.9857 ± 0.0080
Light fermion-pairs	41.5292 ± 0.0353	2.9875 ± 0.0078
Vacuum polarization	41.5196 ± 0.0324	2.9893 ± 0.0074

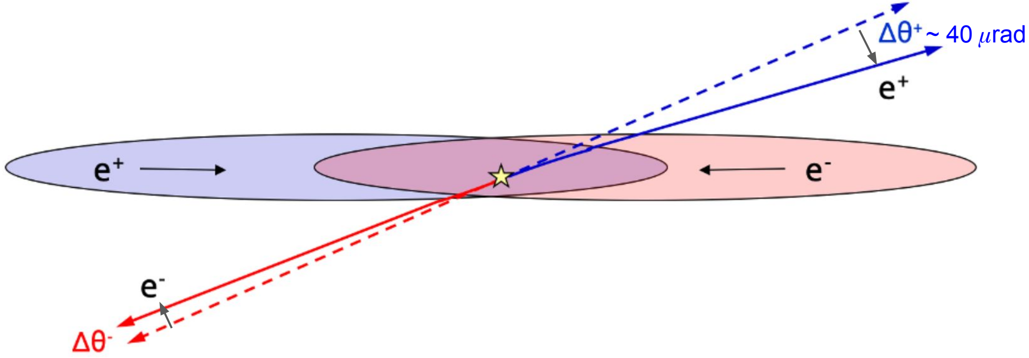
[Jeg'19]

It is remarkable that each correction tends to increase N_ν. Together with the improved precision from 0.0082 to 0.0074, the deficit with respect to the standard model is reduced from 2σ to 1.4σ

Meanwhile, on the FCC-ee experimenter's side …

Beam-induced effects on Bhabha events at FCC-ee

Large EM field caused by the density of the beam bunches affect the outgoing (charged) particles in Bhabha events



Positrons are attracted by the electron bunch they traverse, and electrons are attracted by the positron bunch they traverse, which result in a smaller polar angle than naively expected for both particles.

Effect already studied in ILC [*] and found to cause a bias on $\mathcal{L}$ 20 times larger than the desired precision of 0.01% at FCC-ee !

JHEP
Published for SISSA by Springer
Received: August 7, 2019
Revised: October 2, 2019
Accepted: October 13, 2019
Published: October 22, 2019

arXiv:1908.01704

Beam-beam effects on the luminosity measurement at FCC-ee

Georgios Voutsinas,[a] Emmanuel Perez,[a] Mogens Dam[b] and Patrick Janot[a]

[a] *CERN, EP Department, 1 Esplanade des Particules, CH-1217 Meyrin, Switzerland*
[b] *Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark*

E-mail: georgios.gerasimos.voutsinas@cern.ch, Emmanuel.Perez@cern.ch, dam@nbi.dk, Patrick.Janot@cern.ch

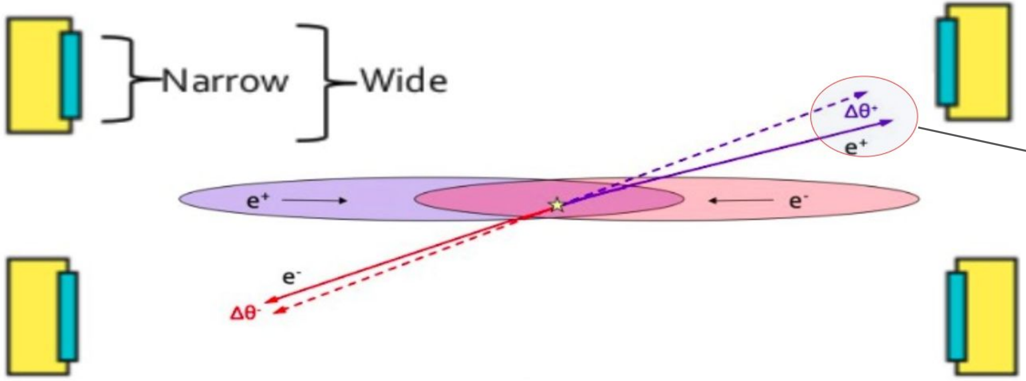
Abstract: The first part of the physics programme of the integrated FCC (Future Circular Colliders) proposal includes measurements of Standard Model processes in e^+e^- collisions (FCC-ee) with an unprecedented precision. In particular, the potential precision of the Z lineshape determination calls for a very precise measurement of the absolute luminosity, at the level of 10^{-4}, and the precision on the relative luminosity between energy scan points around the Z pole should be an order of magnitude better. The luminosity is principally determined from the rate of low-angle Bhabha interactions, $e^+e^- \to e^+e^-$, where the final state electrons and positrons are detected in dedicated calorimeters covering small angles from the outgoing beam directions. Electromagnetic effects caused by the very large charge density of the beam bunches affect the effective acceptance of these luminometers in a nontrivial way. If not corrected for, these effects would lead, at the Z pole, to a systematic bias of the measured luminosity that is more than one order of magnitude larger than the desired precision. In this note, these effects are studied in detail, and methods to measure and correct for them are proposed.

JHEP10(2019)225

[*] C. Rimbault et al., 2007 JINST 2 P09001

Qualitative effect on $\mathcal{L}$ and on N_ν

This focusing effect may deflect the particles in/out the LumiCal acceptance



This positron misses the narrow acceptance

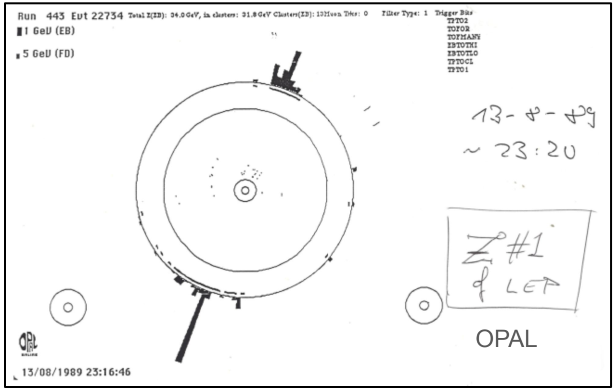
- The Bhabha process is strongly forward peaked, with a cross section that varies like ~1 / θ^3.
- The number of events that miss the acceptance from below is therefore much larger than the number of events that get into the acceptance from above.
- Consequently, the number of Bhabha events is smaller in the LumiCal acceptance than would have been expected without the focusing effect
- If ignored, this effect thus causes a negative bias in the integrated luminosity measurement (and on N_ν), which needs to be corrected a posteriori with a positive correction
- **Breaking news:** this effect was not considered at LEP, calling for a positive correction on $\mathcal{L}$ and on N_ν

And quantitively ?

Effect found to be not negligible at LEP, of the order of 0.1% ($\Delta\theta$ ~ 12 μrad @ 30 mrad) !

Led to this paper

Submitted to PLB on 13 Aug 2019
Exactly 30 years (to the day) after the detection of the first Z at LEP on 13 August 1989



OPAL

Physics Letters B 800 (2020) 135068
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Beam-beam effects on the luminosity measurement at LEP and the number of light neutrino species

Georgios Voutsinas [a], Emmanuel Perez [a], Mogens Dam [b], Patrick Janot [a,*]
[a] CERN, EP Department, 1 Esplanade des Particules, CH-1217 Meyrin, Switzerland
[b] Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark

arXiv:1908.01704

ARTICLE INFO

Article history:
Received 13 August 2019
Received in revised form 14 September 2019
Accepted 14 September 2019
Available online 31 October 2019
Editor: L. Rolandi

Marking the 30th anniversary of the first Z detected at LEP on 13 August 1989

ABSTRACT

In e^+e^- collisions, electromagnetic effects caused by large charge density bunches modify the effective acceptance of the luminometer system of the experiments. These effects consequently bias the luminosity measurement from the rate of low-angle Bhabha interactions $e^+e^- \to e^+e^-$. Surprisingly enough, the magnitude of this bias is found to yield an underestimation of the integrated luminosity measured by the LEP experiments by about 0.1%, significantly larger than the reported experimental uncertainties. When accounted for, this effect modifies the number of light neutrino species determined at LEP from the measurement of the hadronic cross section at the Z peak.

In practice …

The luminosity bias depends on many parameters

- The LumiCal acceptance (the closer to the beam, the larger the bias)
- The selection criteria for Bhabha events (the tighter, the larger the bias)

} See archeology in the previous slides

- The EM field created by the beam bunches (the stronger, the larger the bias)
  - Which itself depends on the bunch sizes σ_x, σ_y, σ_z, and the bunch population N
  - More archeology !

Average/year

Year	N (10^{11})	σ_x (μm)	σ_y (μm)	σ_z (mm)	β^*_x (m)	β^*_y (cm)
1991	1.07	148.	$\sim 6.$	10.0	1.25	5.
1992	1.27	148.	$\sim 6.$	10.0	1.25	5.
1993	1.207	213.	$\sim 4.$	10.3	2.5	5.
1994	1.280	171.	$\sim 4.$	10.0	2.0	5.
1995	1.155	206.	$\sim 4.$	10.5	2.5	5.

σ_x, σ_z :
Measured by experiments (continuously)

N : LEP database (per run)

σ_y :
Inferred by $\sigma_y \approx \sigma_x \beta^*_y / \beta^*_x$

Typically: Bias proportional to charge density, i.e., proportional to N and ~inversely proportional to σ_x

Numerically …

- Generate Bhabha events with BHLUMI 4.04
- Simulate final state particle deflection with GuineaPig [*] with the average beam parameters for each year ([*] D. Schulte, http://cds.cern.ch/record/382453)
- Apply each experiment's selection criteria in their LumiCal acceptance for each year
- And obtain the relative biases on the published $\mathscr{L}$ values at $\sqrt{s}$ = 91.227 GeV

Year	ALEPH	DELPHI	L3	OPAL
1993	-0.0877%	−0.0402%	−0.0816%	−0.0871%
1994	-0.1127%	−0.0622%	−0.1044%	−0.1113%
1995	−0.0859%	−0.0484%	−0.0799%	−0.0850%

  - The bias is almost proportional to N / σ_x, which explains the year-to-year variation
  - The ALEPH, L3, and OPAL LumiCals are closer to the beam than DELPHI's, which explains the smaller bias for the latter.
  - The DELPHI 1st generation LumiCal was still in use in 1993, which explains why the DELPHI bias in 1993 is smaller than that in 1995 (unlike the other three experiments)

Numerically …

- Error-weighted luminosity correction for each centre-of-mass energy √s (also including data from 1990 and 1992, though with small impact on the final result)

Correction on $\mathcal{L}$ **in units of 10^{-4}**

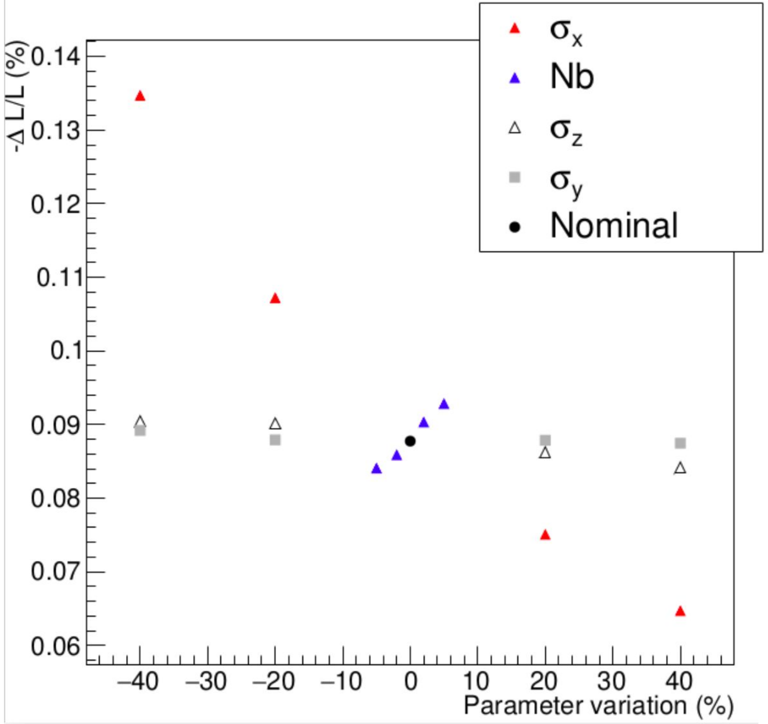
√s (GeV)	ALEPH	DELPHI	L3	OPAL
89.443	8.77	4.67	8.36	8.74
91.227	10.29	5.67	9.60	10.55
92.996	8.44	4.58	8.04	8.40

  - Data were taken off-peak in 1993 and 1995 (with a smaller bias) but not in 1994, so that off-peak data are corrected less than on-peak data – with a possible effect on the Z width
  - The luminosity bias is also inversely proportional to √s, because more energetic charged particles get less deflected by a given electromagnetic force

Possible systematic effects on the inferred $\mathcal{L}$ bias

Knowledge of the beam parameters

- **Beam currents** measured every 15 minutes with a ±2% precision, which translates directly to the luminosity bias (relative)
- **Bunch horizontal size** measured by the experiments with the even vertex position. All experiments agree within ±2%, which translates directly to the luminosity bias (relative)
- Much milder dependence of the luminosity bias on the **vertical and the longitudinal bunch sizes**
- The average bunch **currents of electrons and positrons** differed by 6 to 8%, causing a relative luminosity bias correction of (-0.6 ± 0.1)%



Time variation of the beam parameters (so far assumed to be constant over each year)

A time-dependent average of the bias, with exponential decay of the beam currents, is 0.7% smaller than the bias inferred from the luminosity-weighted averaged parameters

Possible systematic effects on the inferred $\mathcal{L}$ bias

Many other possible effects studied

Table 5: Summary of systematic corrections and uncertainties relative to the luminosity bias. Details can be found in the text.

Source	Systematic effect
Bunch currents	$\pm 2.0\%$
e^+/e^- imbalance	$-0.6\% \pm 0.1\%$
Horizontal bunch size	$\pm 2.0\%$
Bunch length	$\pm 0.4\%$
Vertical bunch size	$+0.8\% \pm 0.4\%$
Time dependence	$-0.7\% \pm 0.4\%$
Technical accuracy	$\pm 0.6\%$
β functions at IP	small
Bunch profiles	small
e^+/e^- bunch overlap	small
LumiCal acceptance	$\pm 0.2\%$
Averaging procedure	$\pm 0.5\%$
1990-1992 data	$-0.1\% \pm 0.0\%$
Other effects	$\pm 5.0\%$
Total	$-0.6\% \pm 5.8\%$

The “technical accuracy” of GuineaPig is estimated by comparing the GuineaPig prediction to an independent numerical integration of the average Lorentz force felt by the electrons and positrons.

This small relative correction on the luminosity bias of (-0.6 ± 5.8) % is to be added to the main correction from beam-induced effect shown two slides ago.

Overall integrated-luminosity increase

Correction on $\mathcal{L}$ **in units of 10^{-4}**

Table 8

Integrated-luminosity relative increase with respect to Ref. [1], determined for each of the four LEP experiments at the Peak−2, Peak, and Peak+2 centre-of-mass energies, due to the updated evaluations of the Z-exchange, the vacuum polarization, and the fermion-pair production contributions. The beam-induced luminosity increase [4], as well as the sum of all effects, are also indicated. All entries are in units of 10^{-4}.

Peak−2:

Source/Experiment	ALEPH	DELPHI	L3	OPAL
Z exchange	0.10	0.12	0.03	0.00
Light fermion-pairs	3.39	4.33	3.76	0.36
Vacuum polarization	2.05	3.90	2.13	2.20
Beam-induced [4]	8.77	4.67	8.36	8.74
Total	14.30	13.03	14.27	11.30

Peak :

Source/Experiment	ALEPH	DELPHI	L3	OPAL
Z exchange	0.52	0.35	0.06	0.00
Light fermion-pairs	3.35	4.07	3.76	0.40
Vacuum polarization	1.82	3.85	2.28	2.28
Beam-induced [4]	10.29	5.67	9.60	10.55
Total	15.98	13.94	15.69	13.24

Peak+2:

Source/Experiment	ALEPH	DELPHI	L3	OPAL
Z exchange	0.03	0.03	0.01	0.00
Light fermion-pairs	3.39	4.19	3.76	0.36
Vacuum polarization	2.18	4.01	2.27	2.33
Beam-induced [4]	8.44	4.58	8.04	8.40
Total	14.04	12.81	14.07	11.10

Updated combined fit of the Z lineshape

Table 9
Combined peak hadronic cross section (σ^0_{had}) and the corresponding number of light neutrino species N_ν, at each step of the corrections considered in this letter.

Correction	σ^0_{had} [nb]	N_ν	
Original value	41.540 ± 0.037	2.9846 ± 0.0082	
New $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{\text{SM}}$	41.5400 ± 0.0372	2.9856 ± 0.0081	
Z exchange	41.5390 ± 0.0369	2.9857 ± 0.0080	
Light fermion-pairs	41.5292 ± 0.0353	2.9875 ± 0.0078	
Vacuum polarization	41.5196 ± 0.0324	2.9893 ± 0.0074	Jeg'19
Beam-induced	41.4802 ± 0.0325	2.9963 ± 0.0074	

2.9958 ± 0.0074 DHMZ'20
2.9945 ± 0.0074 BMWc'20 (tbc)

The correction of the beam-induced effects again increases N_ν.

The long-standing 2σ deficit on the number of light neutrino species is gone.

The Z width is also very slightly increased by 0.3 MeV to 2.4955 ± 0.0023 GeV (because of the smaller beam induced effect in 1993 and 1995)

The new correlation matrices are available in the publication with Staszek

Our result made its way to the Hall of Fame in 2023

See https://pdglive.lbl.gov/
- Number of neutrino types
- Z properties (under Gauge and Higgs bosons)

Z HADRONIC POLE CROSS SECTION — 41.4802 ± 0.0325 nb

OUR EVALUATION is obtained using the fit procedure and correlations as determined by the LEP Electroweak Working Group (see the note "The Z boson" and ref. LEP-SLC 2006). Corrections as discussed in VOUTSINAS 2020 and JANOT 2020 are also included.

This quantity is defined as

$$\sigma_h^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma(e^+e^-)\,\Gamma(\text{hadrons})}{\Gamma_Z^2}$$

It is one of the parameters used in the Z lineshape fit.

VALUE (nb)	EVTS	DOCUMENT ID		TECN	
41.4802 ± 0.0325	**OUR EVALUATION**				
41.4802 ±0.0325		[1] JANOT	2020		
• • We do not use the following data for averages, fits, limits, etc. • •					
41.500 ±0.037		[2] VOUTSINAS	2020		
41.541 ±0.037		LEP-SLC	2006		E^{ee}_{cm} = 88 – 94 GeV
41.501 ±0.055	4.10M	[3] ABBIENDI	2001A	OPAL	E^{ee}_{cm} = 88 – 94 GeV
41.578 ±0.069	3.70M	ABREU	2000F	DLPH	
41.535 ±0.055	3.54M	ACCIARRI	2000C	L3	
41.559 ±0.058	4.07M	[4] BARATE	2000C	ALEP	
42 ±4	450	ABRAMS	1989B	MRK2	

[1] JANOT 2020 applies a correction to LEP-SLC 2006 using an updated Bhabha cross section calculation. ... account for correlated luminosity bias as presented in VOUTSINAS 2020 .

[2] VOUTSINAS 2020 applies a correction to LEP-SLC 2006 to account for correlated luminosity bias.

Number of Light ν Types — 2.996 ± 0.007

(already in the PDG in 2020)

VALUE	DOCUMENT ID		TECN
2.9963 ±0.0074	[1] JANOT	2020	
• • We do not use the following data for averages, fits, limits, etc. • •			
2.9918 ±0.0081	[2] VOUTSINAS	2020	
2.9840 ±0.0082	[3] LEP-SLC	2006	RVUE

Z WIDTH — 2.4955 ± 0.0023 GeV

OUR EVALUATION is obtained using the fit procedure and correlations as determined by the LEP Electroweak Working Group (see the note "The Z boson" and ref. LEP-SLC 2006). Corrections as discussed in VOUTSINAS 2020 and JANOT 2020 are also included.

VALUE (GeV)	EVTS	DOCUMENT ID		TECN	COMMENT
2.4955 ± 0.0023	**OUR EVALUATION**				
2.4955 ±0.0023		[1] JANOT	2020		
• • We do not use the following data for averages, fits, limits, etc. • •					
2.4955 ±0.0023		[2] VOUTSINAS	2020		
2.4952 ±0.0023		LEP-SLC	2006		E^{ee}_{cm} = 88 – 94 GeV

Why `JANOT' and not `JADACH' in the PDG quote ?

That was Staszek: a pleasure to work with and to learn from, also as a human being.

From: Staszek Jadach <Stanislaw.Jadach@cern.ch>
Subject: Re: 0.1 degrees correction
Date: 4 December 2019 at 10:44:01 CET
To: Patrick Janot <Patrick.Janot@cern.ch>

Dear Patrick,

[...]

I am just reading the paper.
It looks quite impressive thanks too your recent contributions!
Since your contribution is now bigger then mine you may swap the order of authors, if you wish. I dont mind:)

Since pairs and VP has improved a lot, pure QED in the total error budget now sticks out!
I have no choice but to think hard how to improve on that:)

best regards, Staszek

From: Patrick Janot <patrick.janot@cern.ch>
Subject: Re: 0.1 degrees correction
Date: 4 December 2019 at 12:23:24 CET
To: Staszek Jadach <Stanislaw.Jadach@cern.ch>

Regarding that:

> Since your contribution is now bigger then mine you may swap the order of authors, if you wish. I dont mind:)

I am not sure whose contribution is bigger - it seems instead that we had a very constructive and efficient collaboration :-)

Patrick.

From: Staszek Jadach <Stanislaw.Jadach@cern.ch>
Subject: Re: 0.1 degrees correction
Date: 4 December 2019 at 12:26:50 CET
To: Patrick Janot <Patrick.Janot@cern.ch>

Go ahead, you deserve credit for this work… st.

==
Phone: +48.12.6628.155
Address: IFJ PAN, ul. Radzikowskiego 152, 31-342 Krakow, Poland
http://nz42.ifj.edu.pl/user/jadach/main
==

TH Outlook: A lot of work to do for FCC-ee !

With 5.10^{12} Z expected at FCC-ee (10^5 x LEP), a much better precision on $\mathcal{L}$ will be needed.

- Coherent exponentiation of photonic corrections:
  Add terms of order $L^2\alpha^3$ and $L^4\alpha^4$ ($L = \ln(|t|/m_e^2)$)
  Photonic uncertainty becomes negligible (10^{-5})

- Continuous improvement of vacuum polarisation at $t \sim -10$ GeV^2 (improved measurements of σ ($e^+e^- \rightarrow$ hadrons at low energy)
  Factor 2 improvement (6.10^{-5})

- Add multiphoton correction to e^+e^- e^+e^- final state (other fermion pairs need not be known to better than 10 to 25%) within BHLUMI or in dedicated MC generators
  Factor 2 improvement (5.10^{-5})

- Include higher-order correction (QED and EW) to the interference between the Z exchange in the t-channel and the γ exchange in the s channel
  Factor 10 improvement or more ($< 10^{-4}$)

From arXiv:1812.01004

S. Jadach [a,*], W. Płaczek [b], M. Skrzypek [a], B.F.L. Ward [c,d], S.A. Yost [e]

Table 3
Anticipated total (physical+technical) theoretical uncertainty for a FCC-ee luminosity calorimetric detector with the angular range being 64–86 mrad (narrow), near the Z peak. Description of photonic corrections in square brackets is related to the 2nd column. The total error is summed in quadrature.

Type of correction/error	Update 2018	FCC-ee forecast
(a) Photonic $[\mathcal{O}(L_e\alpha^2)]$ $\mathcal{O}(L_e^2\alpha^3)$	0.027%	0.1×10^{-4}
(b) Photonic $[\mathcal{O}(L_e^3\alpha^3)]$ $\mathcal{O}(L_e^4\alpha^4)$	0.015%	0.6×10^{-5}
(c) Vacuum polariz.	0.014% [26]	0.6×10^{-4}
(d) Light pairs	0.010% [18,19]	0.5×10^{-4}
(e) Z and s-channel γ exchange	0.090% [11]	1.0×10^{-4}
(f) Up-down interference	0.009% [28]	0.1×10^{-4}
(f) Technical Precision	(0.027)%	0.1×10^{-4}
Total	0.097%	1.0×10^{-4}

And possibly (if feasible with the tight MDI layout)
Increase LumiCal acceptance at low angles to reduce the contribution of the Z exchange and the s channel

EXP Outlook: A lot of work to do for FCC-ee !

To achieve an experimental accuracy of 10^{-4} on the luminosity, one needs to

- Control the radial dimensions of the LumiCals to 1 μm (and the distance between the two LumiCals to 50 μm)
- Evaluate the beam-induced EM deflection (40 μm) to about 1 μm or better directly with the data
  - The large beam crossing angle (30 mrad) generates attractive Lorentz forces on all particles of one incoming bunch from the opposite bunch, of the same origin as the final-state beam-induced deflection
  - These forces further increase the crossing angle just prior to the collision, with an azimuthal modulation. Measuring the amplitude of this azimuthal modulation (e.g., with the final state e^+e^- acollinearity) would allow the determination of the final state e^+e^- EM deflection with an adequate precision
  - Note: Increasing the LumiCal acceptance to smaller angle would also strengthen the EM deflection …

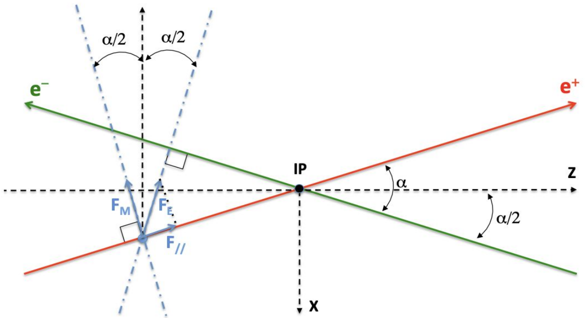
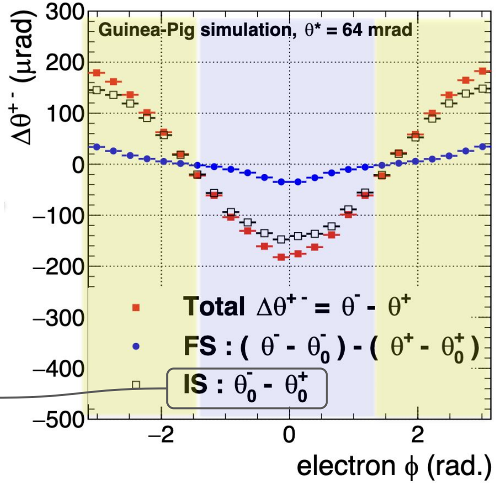


Figure 2. Schematic view of the electric and magnetic attractive Lorentz forces $\vec{F}_E$ and $\vec{F}_M$ acting on each positron from the opposite electron bunch, upon bunch crossing at the interaction point (IP). Similar forces from the positron bunch affect each electron. From ref. [15].

From arXiv:1908.01704

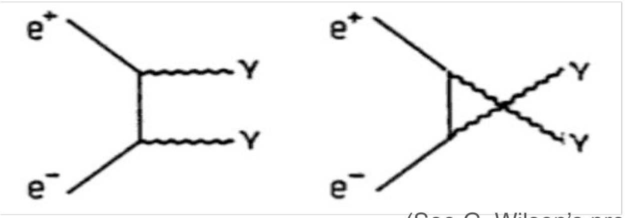
G. Voutsinas, E. Perez, M. Dam, P. Janot



Can be inferred with large-angle $\mu^+\mu^-$ events

Beyond $\Delta\mathscr{L} = 10^{-4}$ and $\Delta N_\nu = 0.001$ at FCC-ee ?

Measure the integrated luminosity with large angle diphoton events (> 10° from the beam)

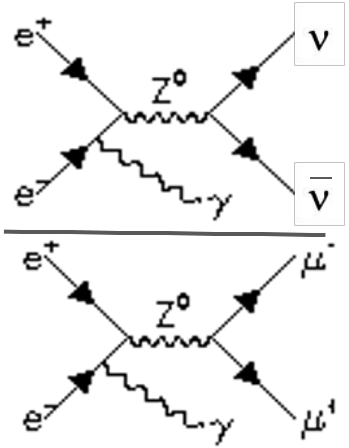


(See G. Wilson's presentation)

- Few 10^9 events at FCC-ee at √s = 91.2 GeV
  - **Statistical precision of 2.10^{-5}**
- **No EM deflection of final state photons**
- **Forecast theory precision as low as 2.10^{-5} ?**
  - Pure QED process (no Z exchange)
  - No hadronic contribution up to NNLO
  - NNLO QED corrections needed
  - Complete EW NNLO calculation needed ?

- Calorimeter radial dimensions controlled to 10 μm
  - Or measure acceptance directly from the data thanks to the large crossing angle ?
- Large background from Bhabha scattering (x1000)
  - Need excellent control of e/γ separation

Measure the number of neutrino species N_ν well above the Z peak, with radiative return events



$$= N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)_{SM}$$

At tree-level

(See G. Wilson's presentation)

- No integrated luminosity uncertainty
- QED corrections almost exactly cancel in the ratio
  - ΔN_ν(QED) ~ 0.0004 [KKMC, Staszek et al.]
- ΔN_ν(Stat) ~ 0.0008 for √s ~ 160 GeV
  - As low as 0.0004 at lower √s values

- Theory uncertainty due to t-channel W exchange in the $\nu_e \bar{\nu}_e \gamma$ final state may be dominant (tbc)

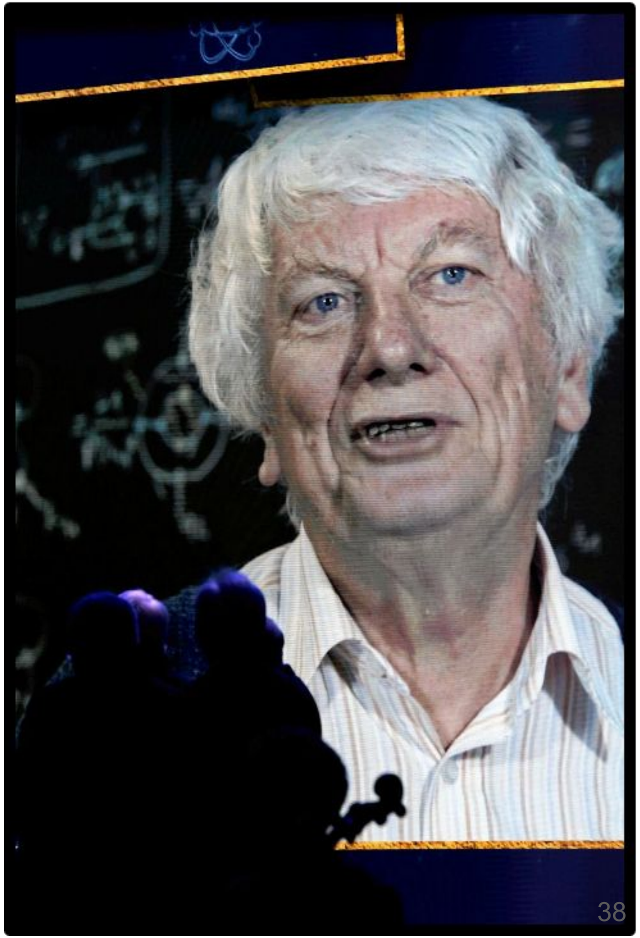
The show must go on

- Our credo for FCC-ee is to improve experimental and theoretical uncertainties down to the statistical precision offered by this collider: nobody wants to be responsible for missing a discovery (experiments and theory alike)

- With his prolific and hard work, Staszek paved the way with this perspective in mind, in many directions

- He still had a lot of ideas and enthusiasm to progress along this path, some of them already initiated until the very end of 2022

- We absolutely and collectively must continue developing Staszek's artwork on precision physics at colliders. Staszek expects no less from us.



Thank you for your attention.