Precision luminosity measurement

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Istituto Nazionale di Fisica Nucleare

2nd ECFA Workshop on e^+e^- Higgs/EW/Top Factories

Paestum, October 11-13, 2023

Expert Team: A. Freitas;
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Meetings

- **MiniWorkshop: Luminosity (WG1-PREC), 16/12/2022**
  `https://indico.cern.ch/event/1218043/`

organised by A. Irles, A. Meyer, A. Freitas, P. Azzurri

- timetable:
  - Introduction
  - Theory uncertainties for e^+e^- luminosity measurements (S. Jadach)
  - Luminosity measurements at future circular colliders (Mogens Dam)
  - Luminosity Spectrum Reconstruction at Linear Colliders (Andre Sailer)
  - Discussion on open questions

- **ET Group meeting on 11 May 2023** `https://indico.cern.ch/event/1285690/`

Importance of precision measurements of luminosity

Luminosity is a key quantity for several absolute cross section measurements at an e^+e^- machine, e.g.

- σ_Z^0, the Z peak cross section
- light neutrino species from radiative return $(e^+e^- \to \nu\bar{\nu}\gamma)$
- Γ_Z from the line-shape of $e^+e^- \to f\bar{f}$
- M_W and Γ_W from line-shape of $e^+e^- \to W^+W^-$ close to threshold
- total cross section for $e^+e^- \to HZ \to HZZ$ coupling and total Γ_H

Reference processes for luminosity

- Instead of getting the luminosity from machine parameters, it's more effective to exploit the relation

$$\sigma = \frac{N}{L} \quad \rightarrow \quad L = \frac{N_{\rm ref}}{\sigma_{\rm theory}} \qquad \frac{\delta L}{L} = \frac{\delta N_{\rm ref}}{N_{\rm ref}} \oplus \frac{\delta \sigma_{\rm theory}}{\sigma_{\rm theory}}$$

- **Reference processes required to have**
  - **large rates** (so as not to be statistics limited)
  - **low backgrounds**
  - **good control of systematics**
    - particle ID, acceptance, . . .
    - theory: differential cross sections calculable with high theoretical precision, fully exclusive Monte Carlo generators required

Luminosity precision level

- In the past (LEP)
  - ⋆ Small-angle Bhabha scattering at LEP: ∼0.05%
- In the past/at present (flavour factories)
  - ⋆ Large-angle QED processes as $e^+e^- \to e^+e^-$ (Bhabha), $e^+e^- \to \gamma\gamma$, $e^+e^- \to \mu^+\mu^-$, to achieve a typical precision at the level of $1 \div 0.1\%$

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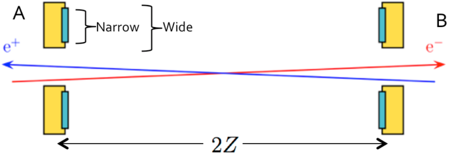
- **Realistic uncertainty target for future e^+e^- colliders?**
  - at Z pole 10^{-4} or better for the overall luminosity calibration
  - $\mathcal{O}(10^{-3})$ at $\sqrt{s} \geq 240$ GeV
  - 10^{-5} for point-to-point luminosity control (relative uncertainty between two close c.o.m. energies or two beam polarization settings)

SABS general features

- Bhabha scattering strongly peaked in the forward region $d\sigma/d\theta \sim 1/\theta^3$
  $\Longrightarrow$ special lumi detector (LumiCal) covering the region $\theta < 100$ mrad centered around the outgoing beams



M. Damm, talk at ECFA MiniWorkshop: Luminosity, 16/12/2022

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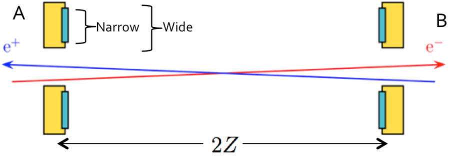

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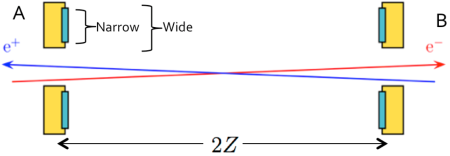

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  - uncertainties originating from physics and machine related interactions

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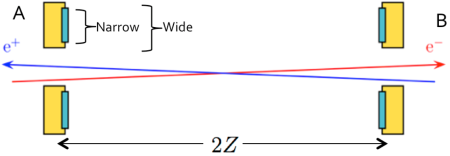

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- **Systematics (exp)**
  - detector related uncertainties
  - beam related uncertainties
  - uncertainties originating from physics and machine related interactions
- **Large statistics $\Longrightarrow$ ideal process for the point-to-point lumi control**

Luminosity: theoretical systematics on σ normalization

- **theoretical error in SABS at LEP1 by the end of operation**

Type of correction/error	(%)	(%)	updated (%)
missing photonic $O(\alpha^2 L)$	0.100	0.027	0.027
missing photonic $O(\alpha^3 L^3)$	0.015	0.015	0.015
vacuum polarization	0.040	0.040	0.040
light pairs	0.030	0.030	0.010
Z-exchange	0.015	0.015	0.015
total	0.110	0.061	0.054

I column: S. Jadach, O. Nicrosini et al. Physics at LEP2 YR 96-01, Vol. 2
A. Arbuzov et al., Phys. Lett. B389 (1996) 129
II column: B.F.L. Ward, S. Jadach, M. Melles, S.A. Yost, hep-ph/9811245
III column: G. Montagna et al., Nucl. Phys. B547 (1999) 39

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G. Abbiendi et al., (OPAL), Eur. Phys. J. C14 (2000) 373

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- progresses in hadronic contribution to vacuum polarization: new low energy data and determinations from different groups

Recent updates on th. predictions on luminosity (2019-2021)

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

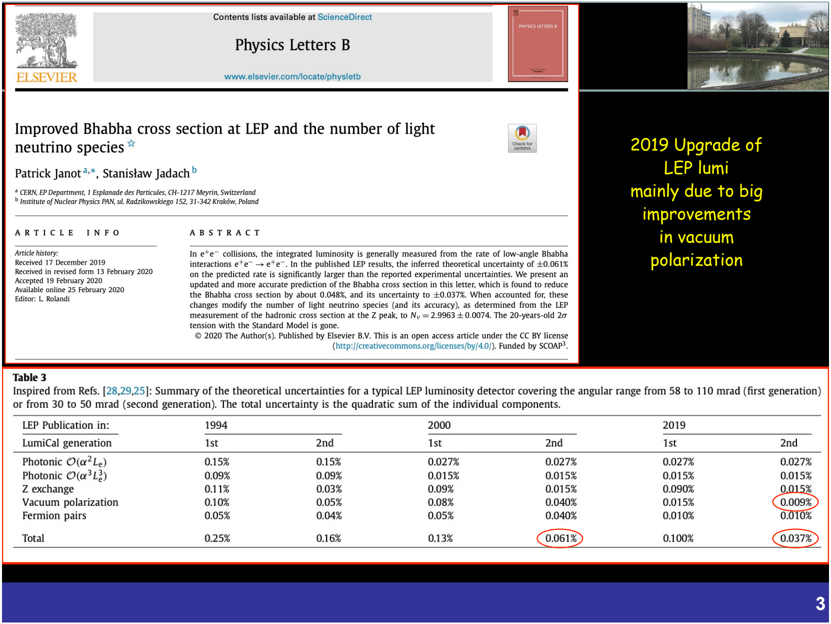
  S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and S.A. Yost, Phys Lett B790 (2019) 314

- “Improved Bhabha cross section at LEP and the number of light neutrino species”

  P. Janot and S. Jadach, Phys. Lett. B803 (2020) 135319

- “Study of theoretical luminosity precision for electron colliders at higher energies”

  S. Jadach, W. Placzek, M. Skrzypek and B.F.L. Ward, Eur. Phys. J. C81 (2021) 1047



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Physics Letters B

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

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ARTICLE INFO

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

ABSTRACT

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.

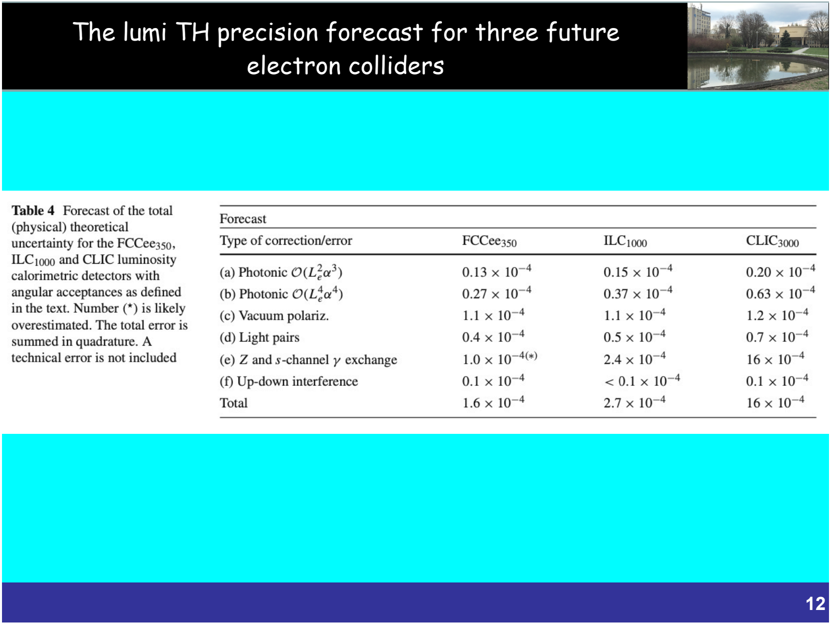
2019 Upgrade of LEP lumi mainly due to big improvements in vacuum polarization

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%

S. Jadach, talk@Lumi miniworkshop (2022)



The lumi TH precision forecast for three future electron colliders

Table 4 Forecast of the total (physical) theoretical uncertainty for the FCCee$_{350}$, ILC$_{1000}$ and CLIC luminosity calorimetric detectors with angular acceptances as defined in the text. Number (*) is likely overestimated. The total error is summed in quadrature. A technical error is not included

Forecast			
Type of correction/error	FCCee$_{350}$	ILC$_{1000}$	CLIC$_{3000}$
(a) Photonic $\mathcal{O}(L_e^2\alpha^3)$	0.13×10^{-4}	0.15×10^{-4}	0.20×10^{-4}
(b) Photonic $\mathcal{O}(L_e^4\alpha^4)$	0.27×10^{-4}	0.37×10^{-4}	0.63×10^{-4}
(c) Vacuum polariz.	1.1×10^{-4}	1.1×10^{-4}	1.2×10^{-4}
(d) Light pairs	0.4×10^{-4}	0.5×10^{-4}	0.7×10^{-4}
(e) Z and s-channel γ exchange	$1.0 \times 10^{-4(*)}$	2.4×10^{-4}	16×10^{-4}
(f) Up-down interference	0.1×10^{-4}	$< 0.1 \times 10^{-4}$	0.1×10^{-4}
Total	1.6×10^{-4}	2.7×10^{-4}	16×10^{-4}

12

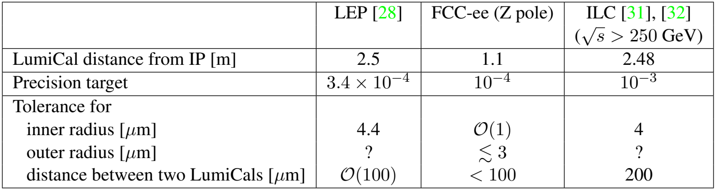
S. Jadach, talk@Lumi miniworkshop (2022)

Experimental challenges

- **detector aperture, position and alignment**
  - **important systematics from acceptance definition**

$$\frac{\delta\sigma^{\rm acc}}{\sigma^{\rm acc}} \sim \frac{2\delta\theta_{\rm min}}{\theta_{\rm min}} = 2\left(\frac{\delta R_{\rm min}}{R_{\rm min}} \oplus \frac{\delta z}{z}\right)$$

  - dicussed for ILC@500 GeV, should be revisited for latest proposed detector design and ILC operating scenarios
  - at FCC-ee, the design of the MDI region requires the lumi monitor to be placed closer to the IP compared to LEP or ILC, putting higher requirements on the position precision for the same angular acceptance uncertainty



	LEP [28]	FCC-ee (Z pole)	ILC [31], [32] ($\sqrt{s} > 250$ GeV)
LumiCal distance from IP [m]	2.5	1.1	2.48
Precision target	3.4×10^{-4}	10^{-4}	10^{-3}
Tolerance for			
inner radius [μm]	4.4	$\mathcal{O}(1)$	4
outer radius [μm]	?	$\lesssim 3$	?
distance between two LumiCals [μm]	$\mathcal{O}(100)$	< 100	200

Experimental challenges

- beam properties and its delivery to the IP
  - beam-energy asymmetry
  - energy calibration
    - selection of Bhabha events over background requires accurate calibration of the LumiCal energy scale
    - Bhabha scattering rate depends on the beam energy $\Longrightarrow$ beam energy uncertainty propagates to the lumi uncertainty
      discussed for CLIC @3 TeV in

      S. Lukic, I. Božović-Jelisavčić, M. Pandurović and I. Smiljanić, JINST 8 (2013) P05008
  - IP displacements due to finite transverse beam sizes and beam synchronization; beam spread effects
    to be quantified for linear colliders
    for circular colliders discussed in

    I. Smiljianic et al., JINST 17 (2022) P09014 (E12001 (2022))
- Impact of beam-beam interactions on Bhabha count
  - beamstrahlung modifies the differential rate of Bhabha scattering and electromagnetic deflection, in particular at lower c.o.m. energies ($Z-$pole)
    effect studied at linear colliders

    I. Božović Jelisavčić et al., JINST 8 (2013) P08012; S. Lukic and I. Božović-Jelisav, JINST 8 (2013) P05008

    and circular colliders in

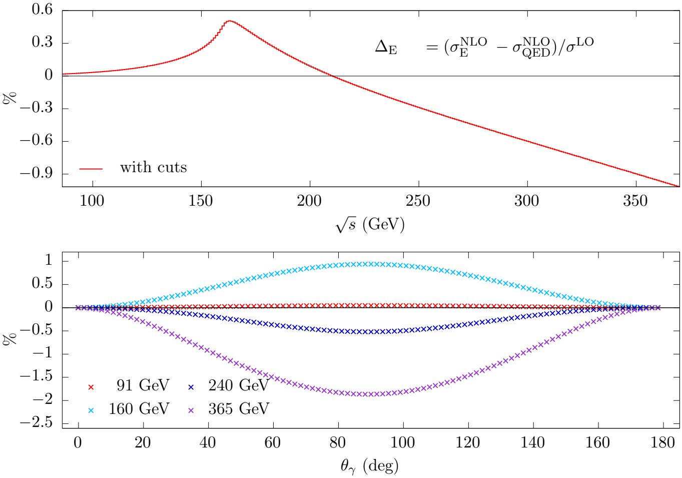
    G. Voutsinas, E. Perez, M. Dam and P. Janot, Phys. Lett. B800 (2020) 135068
  - Focusing of final state particles: $\mathcal{O}(10^{-3})$ correction due to scattered $e^{\pm}$ propagating through beam bunches
- Machine and physics background
  - photon conversion to e^+e^- pairs important at linear colliders, at high c.o.m. energies
  - two-photon process (Landau-Lifshitz) as a source of physics background should also be considered. discussed for linear colliders in H. Abramowicz, JINST 5 (2010) PI2002

$e^+e^- \to \gamma\gamma$: Pros and cons

- ✓ at LO, purely QED process, ***at any energy***
- ✓ at NLO, weak corrections (loops with Z & $W^\pm$), but not fermionic loops yet (in particular, ***no hadronic loops***)
- ✓ hadronic vacuum polarization (**and its uncertainty**) enters only at NNLO (2-loops, order α^2)
- ✓ $d\sigma/d\cos\theta \sim 1/\sin^2\theta$) $\Longrightarrow$ lowest angle acceptance less critical than for Bhabha

- ✗ Large Bhabha background, in particular at Z pole
- ✗ At NNLO also Ligh-by-Light contribution present, (**with its uncertainty**)
- ✗ Statistics lower than Bhabha for respective typical event selections
- ✗ Lack of independent MC codes for cross-checks/validation

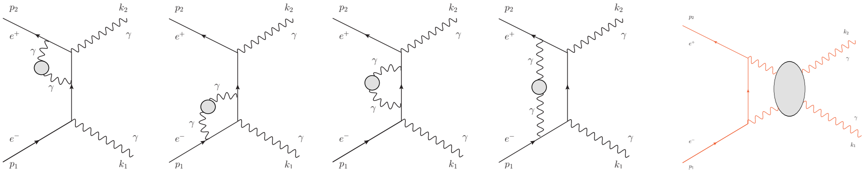
Pure weak corrections



C.M. Carloni Calame, M. Chiesa, G. Montagna, O. Nicrosini, FP, Phys. Lett. B798 (2019) 134976

- "small" at FCC-ee energies, larger for higher energies

Rough estimate of (NNLO) VP hadronic corrections (and uncertainties)



$$\sigma^{\mathrm{NNLO}}_{\Delta\alpha_{had}} \pm \delta\sigma \overset{\text{very naive!}}{\approx} \left(\sigma^{\mathrm{NLO}}_{\mathrm{QED}} - \sigma^{\mathrm{LO}}\right) \times \left[\Delta\alpha_{had}(s) \pm \delta\Delta\alpha_{had}\right]$$

$\sqrt{s}$ (GeV)	$\Delta\alpha_{had}(s)^*$	$\delta\sigma/\sigma_{LO}$ [1]	$\delta\sigma/\sigma_{LO}$ [2]
91	$(276.7 \pm 1.2) \cdot 10^{-4}$	$2.8 \cdot 10^{-5}$	$3.7 \cdot 10^{-6}$
160	$(309.1 \pm 1.2) \cdot 10^{-4}$	$3.0 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$
240	$(333.2 \pm 1.2) \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$	$3.9 \cdot 10^{-6}$
365	$(358.5 \pm 1.2) \cdot 10^{-4}$	$3.4 \cdot 10^{-5}$	$4.0 \cdot 10^{-6}$

- LbL contribution, with its uncertainty, should be quantified

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*from F. Jegerlehner's recent `hadr5n16.f`

Experimental challenges

- Statistical precision: event selection limits the analysis to the central tracker region, $|\cos\theta \leq 0.9| \Longrightarrow$ precision limited to
  - $\sim 5 \cdot 10^{-5}$ @Z-pole with 10 ab^{-1}
  - $\sim 4 \cdot 10^{-4}$ at $\sqrt{s} = 250$ GeV with 5 ab^{-1}
- Background: overall lumi precision of 10^{-4} requires the reduction of Bhabha events by a factor 10^{-6}, i.e. 10^{-3} per track
- Background from π^0 production expected to be small, $\mathcal{BR}(Z \to \pi^0\gamma) \sim 10^{-11}$

Y. Grossman et al., JHEP 04 (2015) 101

- Acceptance: 10^{-4} precision requires a precision on the angular acceptance of 50 μrad, looser w.r.t. SABS, but in the central detector region

Available dedicated tools/generators

- Bhabha scattering
  - BHLUMI 4.04
  - BHWIDE
  - BabaYaga
  - MCGPJ

- Di-photon
  - BabaYaga
  - BKQED

Summary and (some) open questions

- Further detailed investigating of di-photon production for precision determination of the integrated luminosity would be important
- Bhabha scattering preferred for the point-to-point luminosity control (leading systematics tend to cancel in the point-to-point comparison)
  Needed further studies on the correlations between lumi measurements at different c.o.m. energies
- Needed detailed studies of LumiCal detectors for different collider setups and detector concepts
- Radiation of additional fermion pairs currently not implemented in the dedicated MC codes
- Detailed quantitative analysis of beamstrahlung on lumi determination necessary
- Other potentially interesting processes for lumi measurements?