QED Interference to muon asymmetry near Z peak

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INTRODUCTION

- In the SM overall fit to experimental data $M_Z, G_F, \alpha_{QED}(0)$ outweigh other data in the "testing power".
- However, $\alpha_{QED}(q^2 = 0)$ has to be ported to $\alpha_{QED}(q^2 = M_Z^2)$, and this limits its usefulness (testing power) beyond LEP precision.
- Patrick Janot has proposed (arxiv:1512.05544) another observable, $A_{FB}(e^+e^- \to \mu^+\mu^-)$ at $\sqrt{s_\pm} = M_Z \pm 3.5 GeV$, which has similar "testing profile" in the SM overall fit to data as $\alpha_{QED}(M_Z^2)$, but could be hopefully measured at high luminosity FCCee more precisely.
- This proposal is advertized as "measuring $\alpha_{QED}(M_Z^2)$" from $A_{FB}(\sqrt{s_\pm})$"
- However, A_{FB} near $\sqrt{s_\pm}$ is varying very strongly, hence is prone to large QED initial state radiation (ISR) corrections.
- A_{FB} away from Z peak gets also direct sizeable contributions from the QED initial-final state interference, nickname IFI.
- It is therefore necessary to re-discuss how efficiently these trivial QED effects can be controlled and/or eliminated,
  in particular do they cancel in $A_{FB}(s_+) - A_{FB}(s_-)$? etc.

Part I. State of art A.D. 2000

1. QED ISR spectrum is already under very good control, with all necessary leading and subleading corrections, exponentiation, fermionic pair production etc. – because it was needed for $\sigma(s)$ across Z resonance.
   - The most precise analytical result (used in Zfitter): by SJ, Skrzypek, Pietrzyk, Phys.Lett.B456(1999)77,
   - The best Monte Carlo implementation: **KKMC** by S.J, Ward, Wąs, Comput.Phys.Commun.130(2000)260 (contrib. from S.Yost).
2. Most likely the above knowledge of ISR is good enough for direct and indirect change of $A_{FB}(s_{\pm})$, see later on...
3. The present (as in 2000) state of art on IFI in $e^+e^- \to f\bar{f}$ to be found in:
   - Section 5.3 of "Two-Fermion..." part of "The LEP-2 MC Workshop 1999/2000" report, arxiv:0007180, pages 67-72
   - Section E in paper by SJ, Ward, Was, Phys.Rev. D63(2000)113009.
4. At LEP-1 on Z peak IFI was supressed by Γ/M_Z, its importance was realized at LEP-2 (where $A_{FB}(s)$ was mostly flat).

Dependence of IFI contrib. to δA_{FB}^{IFI} on max. phot. energy cut

Fig.10, Sect.5.3 “The LEP-2 MC Workshop 1999/2000”, arxiv:0007180

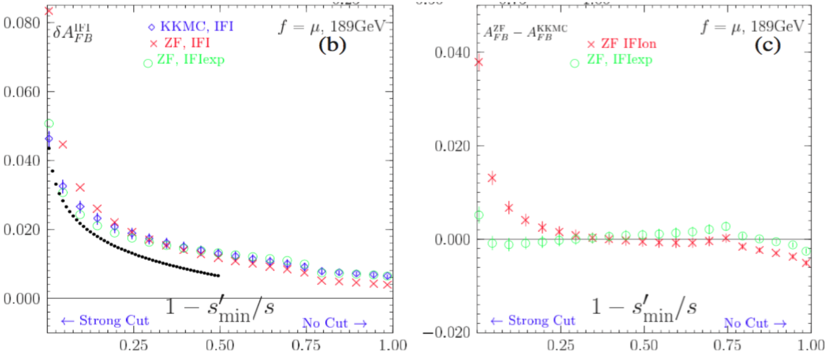


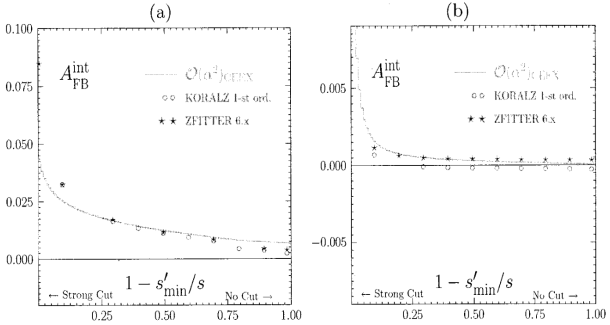
Fig. 10: The comparison of $\mathcal{KK}$MC and ZFITTER for A_{FB} at 189GeV. Black dots represent eq. (27).

- Total photon energy limited by $v = 1 - M_{\mu\mu}^2/s < v_{\max}$
- The agreement of KKMC vs. ZFitter $\sim$ 0.25% quoted as precision tag for LEP2.
- Cutof dependence of A_{FB} quite well reproduced (black dots) using:

$$\delta A_{FB}^{\rm IFI}(v_1) = -\kappa \ln v_{\max} \left(2\ln(2) + \frac{3}{4} + 2A_{FB}\right) + \mathcal{O}(\kappa^2 \ln^2 v_{\max}) + const.$$

The same δA_{FB}^{IFI} , including also KORALZ

Fig.28 in Phys.Rev. D63 (2000), (a) $\sqrt{s} = 189$GeV, (b) $\sqrt{s} = M_Z$



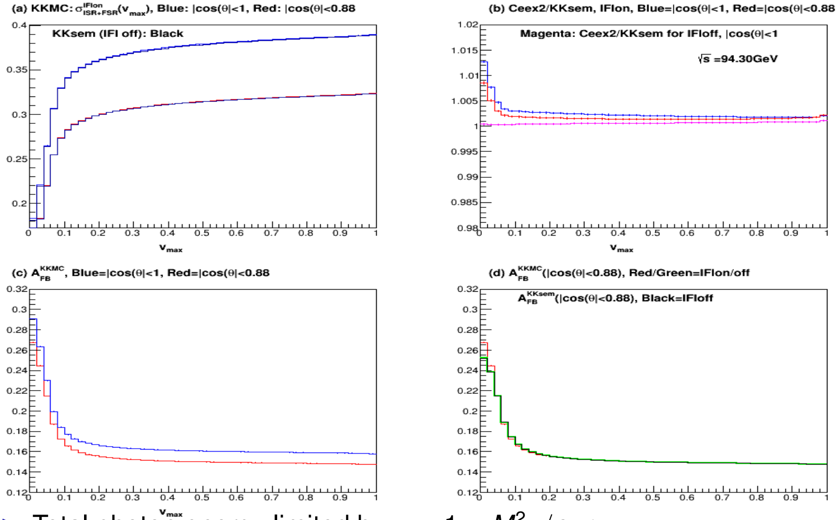
- IFI contrib. to A_{FB} from KKMC (YFS exponentiation) and KORALZ and ZFITTER (without exponentiation).
- They both diverge strongly with KKMC for strong cut-off on photon energy, hence exponentiation in IFI is mandatory!

Part II

Introductory callibration exercises using KKMC

1. Going to briefly verify whether KKMC results for σ and A_{FB} at $\sqrt{s_+} \simeq 95$GeV and $\sqrt{s_-} \simeq 88$GeV are as good as it was established at the end of LEP II.
2. The agreement with semianalytical crosscheck of KKsem will be done, whenewer such comparison is feasible (IFI off).
3. photon energy and $\cos\theta_\mu$ will be unrestricted or restricted mildly
4. In the following we are going plot $+A_{FB}$ at $\sqrt{s} > M_Z$ and $-A_{FB}$ at $\sqrt{s} < M_Z$, without any further notice!!!
5. All numerical results are preliminary!!!

The dependence of σ and A_{FB} on max. phot. energy cut



- Total photon energy limited by $v = 1 - M^2_{\mu\mu}/s < v_{\max}$
- Perfect agreement of KKMC and KKsem when IFI is off.

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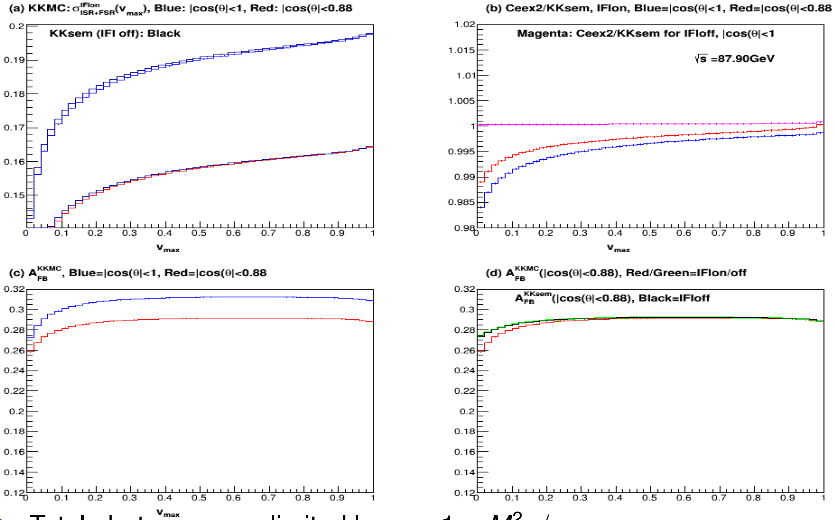

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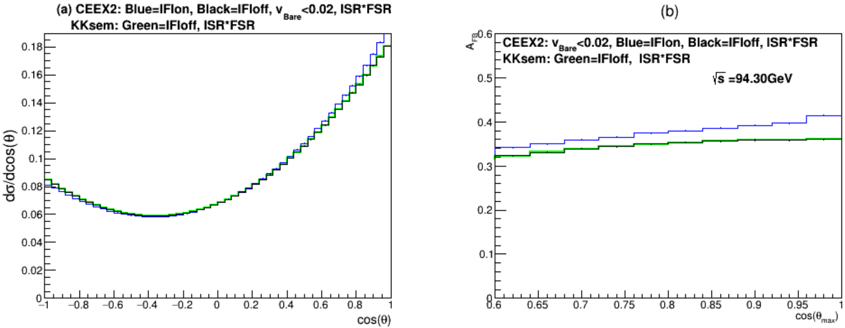
Angular distribution and $A_{FB}(\cos\theta_{\max}$ for $v < v_{\max} = 0.02$



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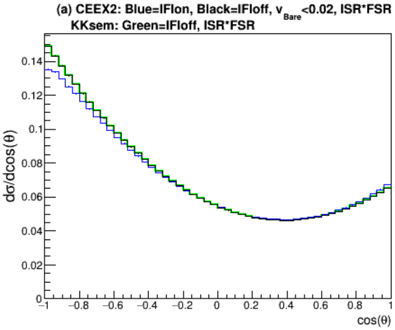
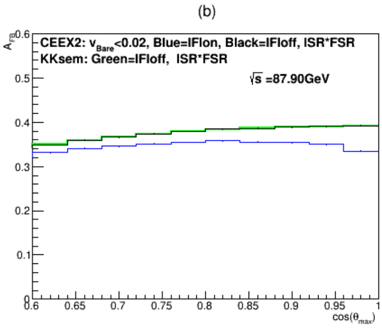


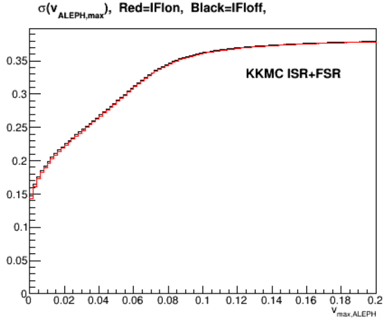


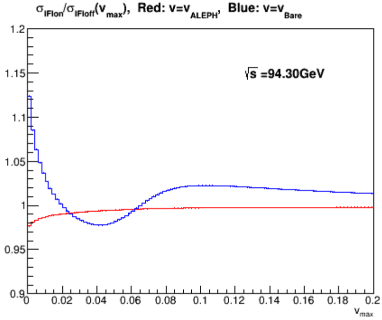
- Perfect agreement of KKMC and KKsem when IFI is off.

Part III

1. Next we shall restrict total emited photon energy below 20% of beam energy, keeping in mind that:
   - experiment will probably cut at 2% or stronger, in order to eliminate
   - Z radiative return, at $\sqrt{s} \simeq$ 95GeV located around 10%.
2. We shall start with σ but main focus will be on A_{FB}.
3. Main issues to be examined:
   - size and cut-off dependence of IFI in A_{FB}, $|\cos\theta| < 0.9$.
   - dependence on the type of kinematic variables used to cut photon energy (definition of θ_μ expected to be unimportant)
   - cancellations of QED effects between A_{FB} at $\sqrt{s_+} \simeq$ 95GeV and $\sqrt{s_-} \simeq$ 88GeV.
   - is effect of h.o. ISR affecting A_{FB} known/controlled precisely enough?
4. In the following we are going plot A_{FB} at $\sqrt{s} > M_Z$ and $-A_{FB}$ at $\sqrt{s} < M_Z$, without any further notice!!!
5. WARNING!!! All presented numerical results are preliminary!!!

How $\Delta_{\rm IFI}\sigma$ depends on type of variable used to cut photon energy?





- Surprisingly quite a lot! Especially above Z peak...

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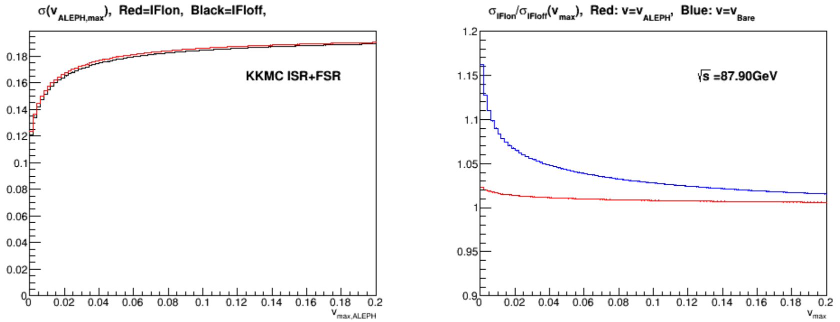

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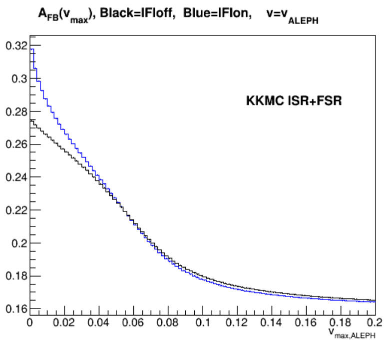
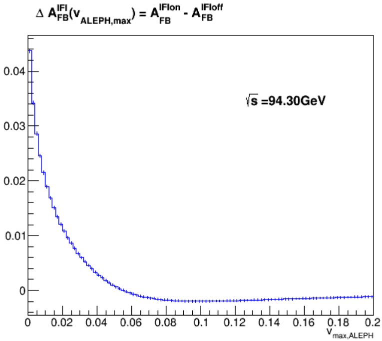
Is IFI contribution to A_{FB} smaller for strong cut on photons?





- NO! Quite opposite, it grows to $\sim 5\%$ for stronger cut on photos!
- Luckily it seems to cancel quite well between s_+ and s_-
- and is well predictable in the soft photon region...

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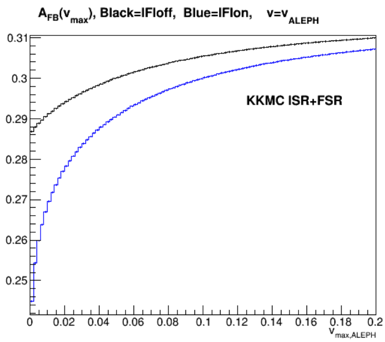

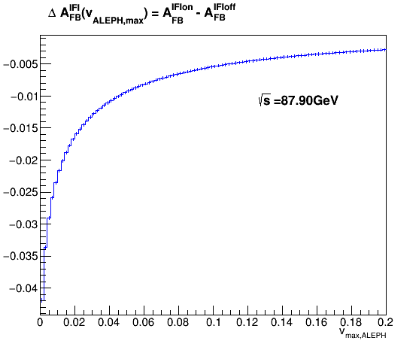

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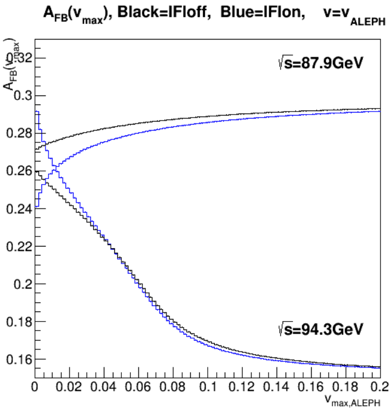
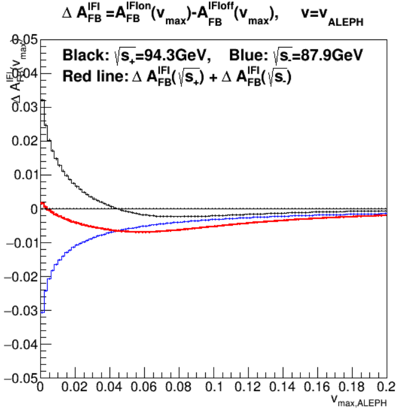
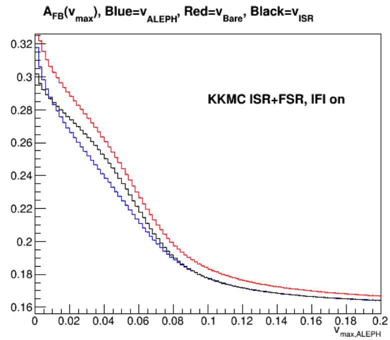
Does IFI cancel between $\sqrt{s_-}$ and $\sqrt{s_+}$?

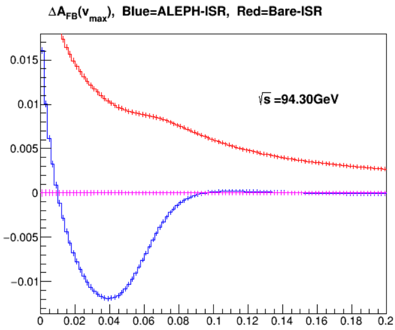




- YES, but finite part $\sim 1\%$ remains in the game.

How important is the type of kinematic cuts in A_{FB} ?





- It matters a lot, $\sim 1\%$, especially above Z! Similarly as for σ.
- Moreover, it does not seem to cancel between s_+ and s_-.
- However, QED ISR prediction is controlable very precisely in this soft photon region, in case we shall decide to eliminate it.
- Effect of changing definition of muon $\cos\theta$ is completely negligible!

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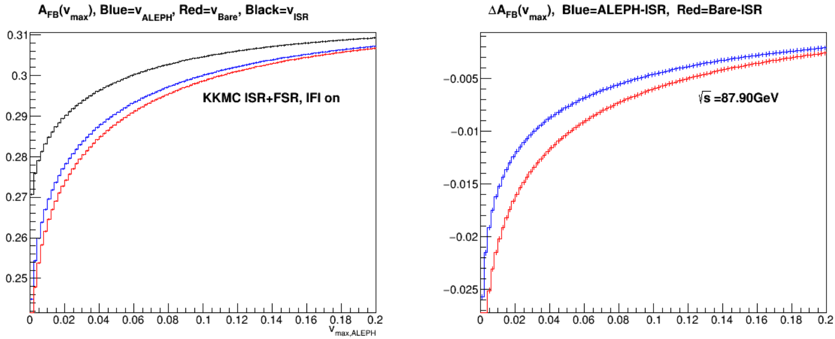

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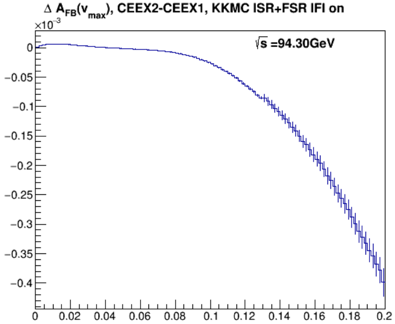
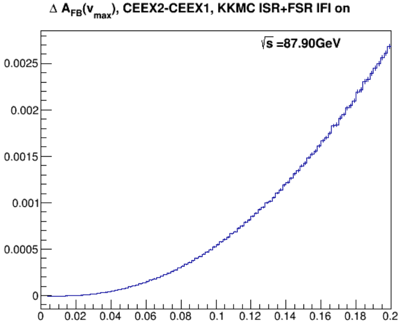
How big is (h.o.) uncertainty of ISR for A_{FB}?





- Examine downgrade of QED ME from CEEX2 to CEEX1
- IFI is the same, hence cancels. FSR should drop out.
  It is only change in ISR that matters.
- For strong cut on photon energy ISR uncertainty seems to be VERY small! Thanks to power of the soft photon approximation.

Summary

- Direct and indirect influence of IFR on A_{FB} is very big because of strong energy variation of A_{FB} near $\sqrt{s} = M_Z \pm 3.5 GeV$
- Moreover ISR effect is strongly depedent on the type of kinematical cuts. FSR also enters into the game.
- However, QED ISR (FSR) is under tight control, thanks to theoretical investments of the LEP era and because of the power of soft photon approximation (similarily as for Z lineshape).
- IFI contrubution grows high for strong cut-off on total photon energy. It will get under good control thanks to:
  1. cancellations between $\sqrt{s_\pm}$ energies
  2. power of soft photon approximation
  3. lack of mass logarithms in it (except of ISR, but see above).
- More work is needed to get better quantitative results.

Appendix

Definition of $v_{ALEPH} = 1 - z_{ALEPH}$ deduced from muon angles (acollinearity) according to 1996 ALEPH note:

$$z_{ALEPH} = \frac{\sin\theta_1 + \sin\theta_2 - |\sin\theta_1 + \theta_2|}{\sin\theta_1 + \sin\theta_2 + |\sin\theta_1 + \theta_2|}.$$

Definition of muon scattering angle according to Phys.Lett. B219, 103 (1989):

$$\cos\theta_{PL} = (E_1 \cos\theta_1 - E_2 \cos\theta_2)/(E_1 + E_2)$$

Definition of muon scattering angle according to Phys.Rev. D41, 1425 (1990):

$$y_1 = \sin\theta_2/(\sin\theta_1 + \sin\theta_2), \quad y_2 = \sin\theta_1/(\sin\theta_1 + \sin\theta_2),$$

$$\cos\Theta_{PRD} = y_1 \cos\theta_1 - y_2 \cos\theta_2.$$