IFI and ISR effects for Z Drell-Yan Observables using $\mathcal{KK}$ MC-hh

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$\mathcal{KK}$ MC-hh

- $\mathcal{KK}$ MC-hh is an event-generator for Z production and decay in hadronic collisions, which grew from the e^+e^- event generator $\mathcal{KK}$ MC created by S. Jadach, B.F.L. Ward, and Z. Wąs and later adapted for $q\bar{q}$ collisions.
- $\mathcal{KK}$ MC-hh adds an LHAPDF interface and an interface to a shower generator, presently HERWIG6.5, but an external generator can be used.
- This talk will focus on the effect of QED radiative corrections in angular distributions, specifically A_{FB} and A_4.
- In particular, we will look at how angular distributions are affected by photon ISR (Initial-State Radiation) and IFI (Initial-Final Interference).

$\mathcal{KK}$ MC-hh Assumptions and Settings

- For the results in this talk, $\mathcal{KK}$ MC-hh was run at an 8 TeV CM energy using MRST 2008 PDFs and a HERWIG6.521 shower.
- Note: $\mathcal{KK}$ MC-hh should be used only with non-QED PDFs, since it includes collinear logarithms that are resummed in the PDFs. This is in contrast to the approach of programs such as WGRAD, ZGRAD and HORACE, in which the collinear logarithms are assumed to be in the PDFs, so running with QED PDFs would be appropriate.
- The most precise mode of $\mathcal{KK}$ MC-hh, denoted CEEX2, includes soft photon ISR and FSR radiation exponentiated to all orders, supplemented by $\mathcal{O}(\alpha^2)$ hard photon residuals calculated through NLL order. $\mathcal{O}(\alpha)$ hard matrix element corrections are included via DIZET6.21.
- In its default CEEX mode, KKMC-hh includes IFI with exponentiation of resonance effects.
- The HERWIG shower adds to this LO QCD with resummed LL radiation in the shower.

Standard Model Input Parameters

DIZET uses a modified G_μ Scheme with an over-complete set of inputs to take advantage of precision measurements to the extent possible. The following input parameters are used, taken from the 2014 EW Benchmark study, S. Alioli *et al.*, CERN-TH-2016-137 / arXiv:1606.02330

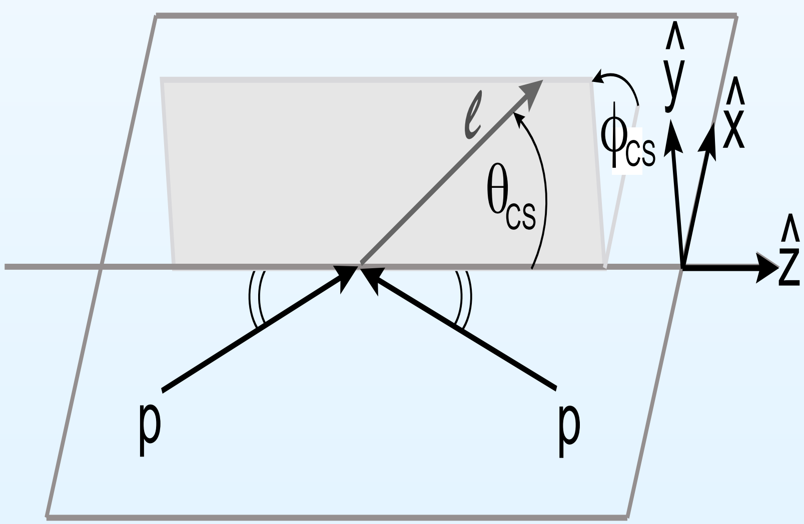
$1/\alpha(0)$	137.03599991	$1/\alpha(M_Z)$	128.952
G_F	1.1663787×10^{-5} GeV^{-2}	α_s	0.12018
$\sin^2(\theta_W)$	0.2232290158	M_Z	91.1876 GeV
Γ_Z	2.4952 GeV	M_W	80.385 GeV
Γ_W	2.085 GeV	M_H	125 GeV
m_d	4.7 MeV	m_u	2.2 MeV
m_s	0.15 GeV	m_c	1.2 GeV
m_b	4.6 GeV	m_t	173.5 GeV
m_e	510.999 keV	m_μ	105.6583 MeV
m_τ	1.777 GeV		

Angular Variables for $pp \to Z/\gamma^* \to \ell\bar{\ell}$

We will consider distributions of the angle $\theta_{\rm CS}$ of the negative ℓ defined in the Collins-Soper frame: the CM frame of $\ell^\pm$, relative to a $\hat{\mathbf{z}}$ axis oriented as shown relative to the proton beams.

If $P = p_\ell + p_{\bar{\ell}}$ and $p^\pm = p^0 \pm p^z$ in the lab,

$$\cos(\theta_{\rm CS}) = {\rm sgn}(P^z)\frac{p_\ell^+ p_{\bar{\ell}}^- - p_\ell^- p_{\bar{\ell}}^+}{\sqrt{P^2 P^+ P^-}}$$



Angular Variables

We will be primarily interested in the contribution of radiative corrections, in particular IFI, to the forward-backward asymmetry $A_{\rm FB}$ and angular coefficient A_4 as determined by $\theta_{\rm CS}$:

$$A_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \; , \qquad A_4 = \langle \cos(\theta_{\rm CS}) \rangle = \frac{\int \cos(\theta_{\rm CS}) d\sigma}{\sigma} \; .$$

- In the absence of radiated photons, the CM frames of the final leptons, the initial quarks, and the rest frame of the Z would be identical.
- There might be a better way to approximate the rest frame of the Z boson in the presence of radiation, although IFI makes the source of the photons, and hence the inferred Z momentum, ambiguous.
- For example, one might add back photons that appear to be FSR by a proximity measure. This is already done in $\mathcal{KK}$ MC-hh when defining the Z momentum passed to the QCD shower.
- I've included some slides in which FSR photons are identified as those closer (in the lab) to an outgoing fermion than to the beam.

Results from $\mathcal{KK}$ MC-hh

- The following tests were done using $\sim$ 100 M muon event samples, with MSTW2008 PDFs (LHAPDF index 21100).
- A_4 was calculated with only a cut $70 < M < 110$ GeV.
- $A_{\rm FB}$ was calculated with an additional cut $p_T > 25$ GeV, $|\eta| < 2.5$ on both muons.
- The differential cross sections were calculated both with and without these additional muon cuts.
- Results for $A_{\rm FB}$ and A_4 are given in bins in M and Y:

$$M = 70-80, \quad 80-100, \quad 100-125, \quad 125-150, \quad 150-250 \quad \text{GeV},$$
$$|Y| = 0-1, \quad 1-2, \quad 2-3, \quad 3-4.$$

Numerical Results at 8 TeV

	Full CEEX2	no IFI	no ISR
Uncut σ (pb)	864.62 ± 0.14	864.38 ± 0.13	877.17 ± 0.06
Cut σ (pb)	387.42 ± 0.09	387.41 ± 0.09	389.85 ± 0.53
$A_{\rm FB}$	$(1.330 \pm 0.017) \times 10^{-2}$	$(1.316 \pm 0.017) \times 10^{-2}$	$(1.259 \pm 0.015) \times 10^{-2}$
A_4	$(1.665 \pm 0.062) \times 10^{-2}$	$(1.665 \pm 0.062) \times 10^{-2}$	$(1.629 \pm 0.062) \times 10^{-2}$

"Uncut" includes the M cut but no p_T or η cuts.

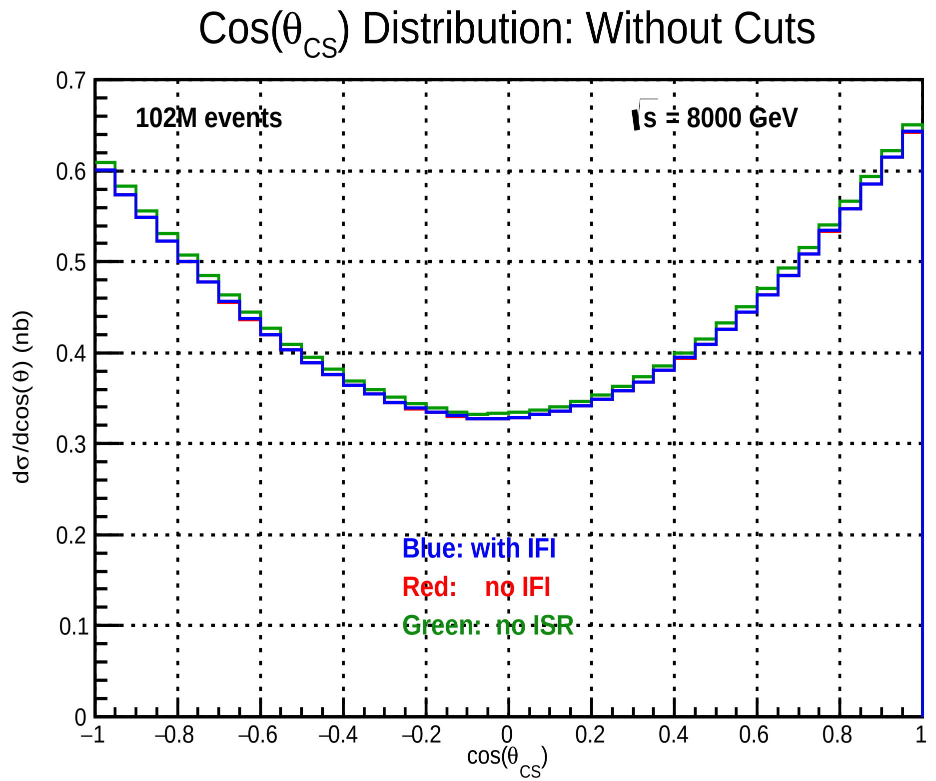
The following table shows the differences between the calculations of A_{FB} and A_4 without IFI or ISR and the full CEEX2 result:

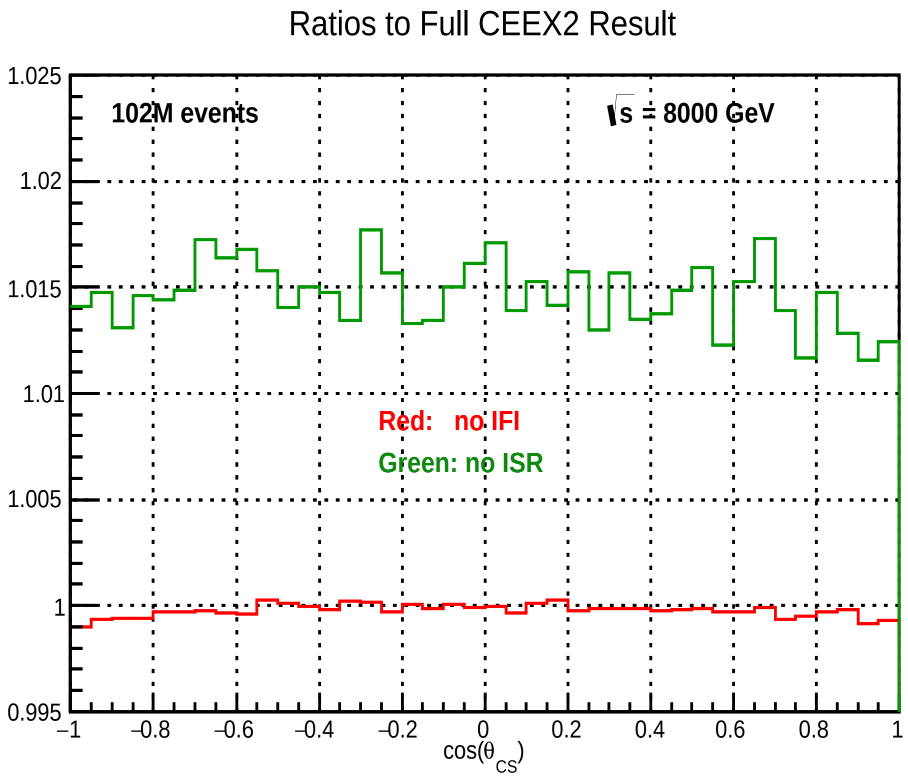
	no IFI - Full CEEX2	no ISR - Full CEEX2
$A_{\rm FB}$	$(-1.39 \pm 0.82) \times 10^{-4}$	$(-7.09 \pm 2.35) \times 10^{-4}$
A_4	$(-6.58 \pm 0.52) \times 10^{-4}$	$(-3.60 \pm 0.88) \times 10^{-4}$

Angular Distributions: Cos($\theta_{\rm CS}$)

$70 < M < 110$ GeV, no p_T, η cuts.

The IFI contribution is $< 0.1\%$ while ISR is $\sim 1.5\%$. This is similar to what I showed in my last talk at 7 TeV.

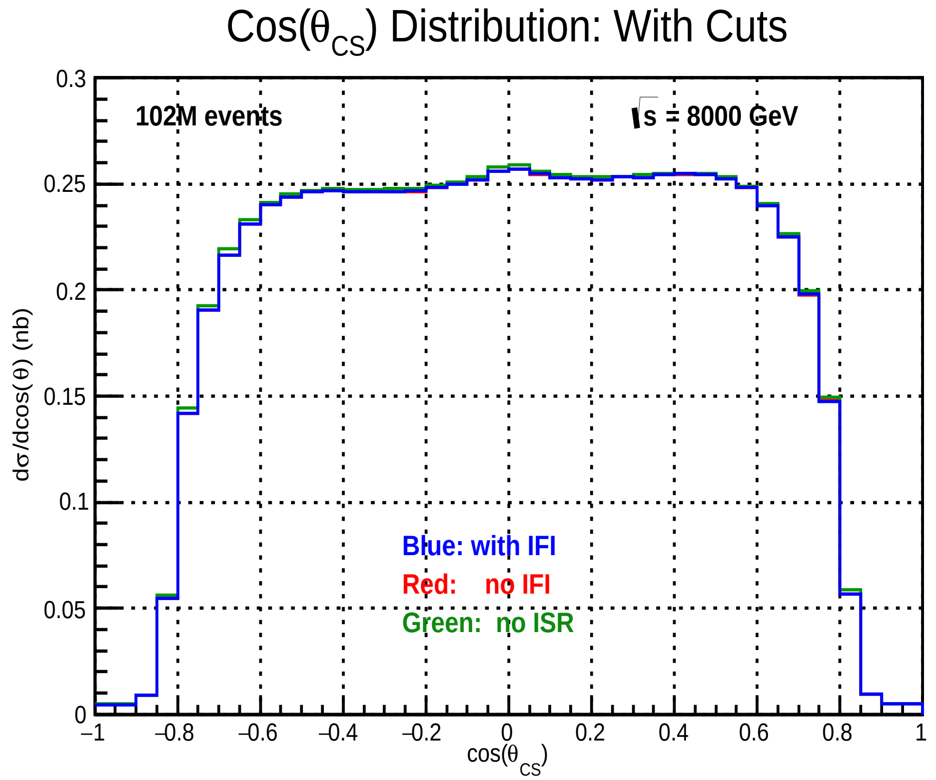


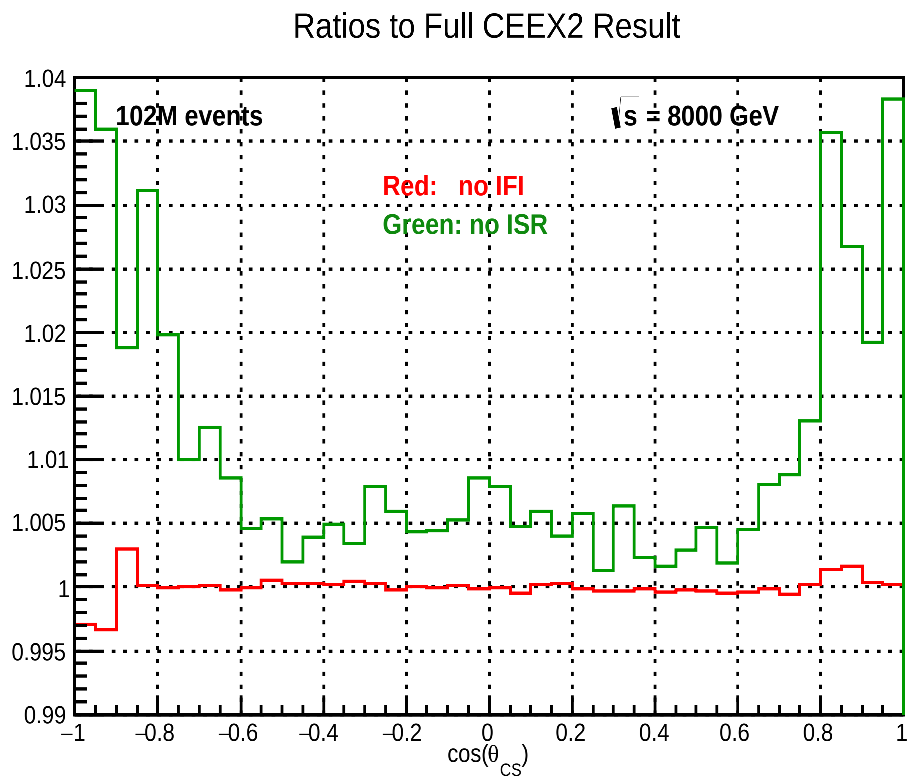


Angular Distributions: Cos($\theta_{\rm CS}$)

$$70 < M < 110 \text{ GeV}, \; p_T > 25 \text{ GeV}, \; |\eta| < 2.5$$

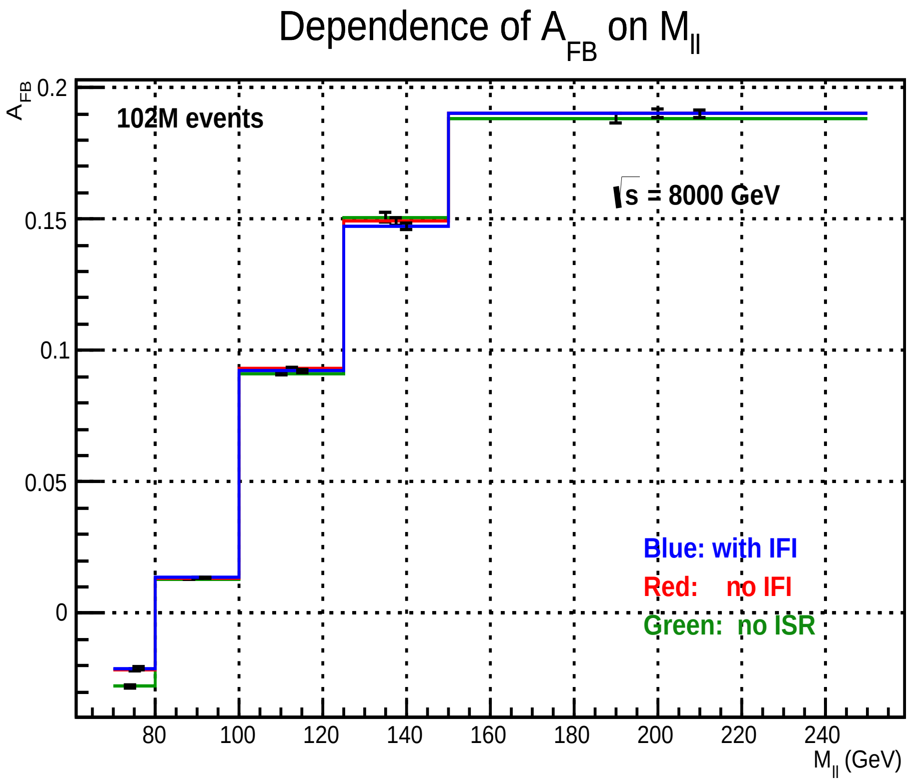
With the extra cuts, IFI $< 0.1\%$ again, and ISR $\sim 0.5\%$ was seen in the uncut case.

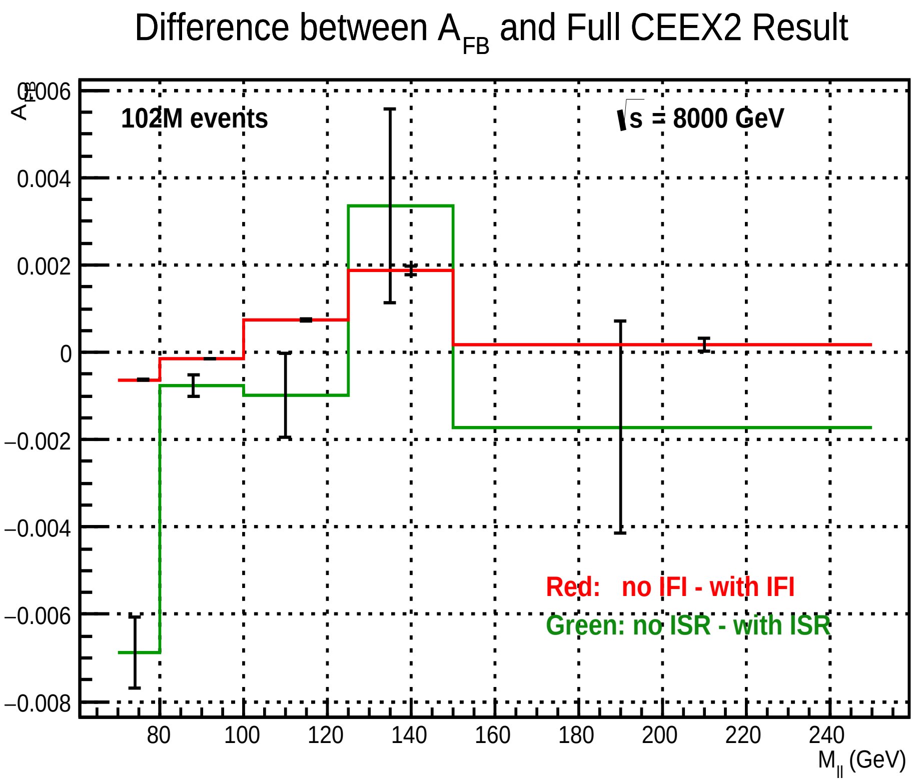




$A_{\rm FB}$ Binned in M_{ll}

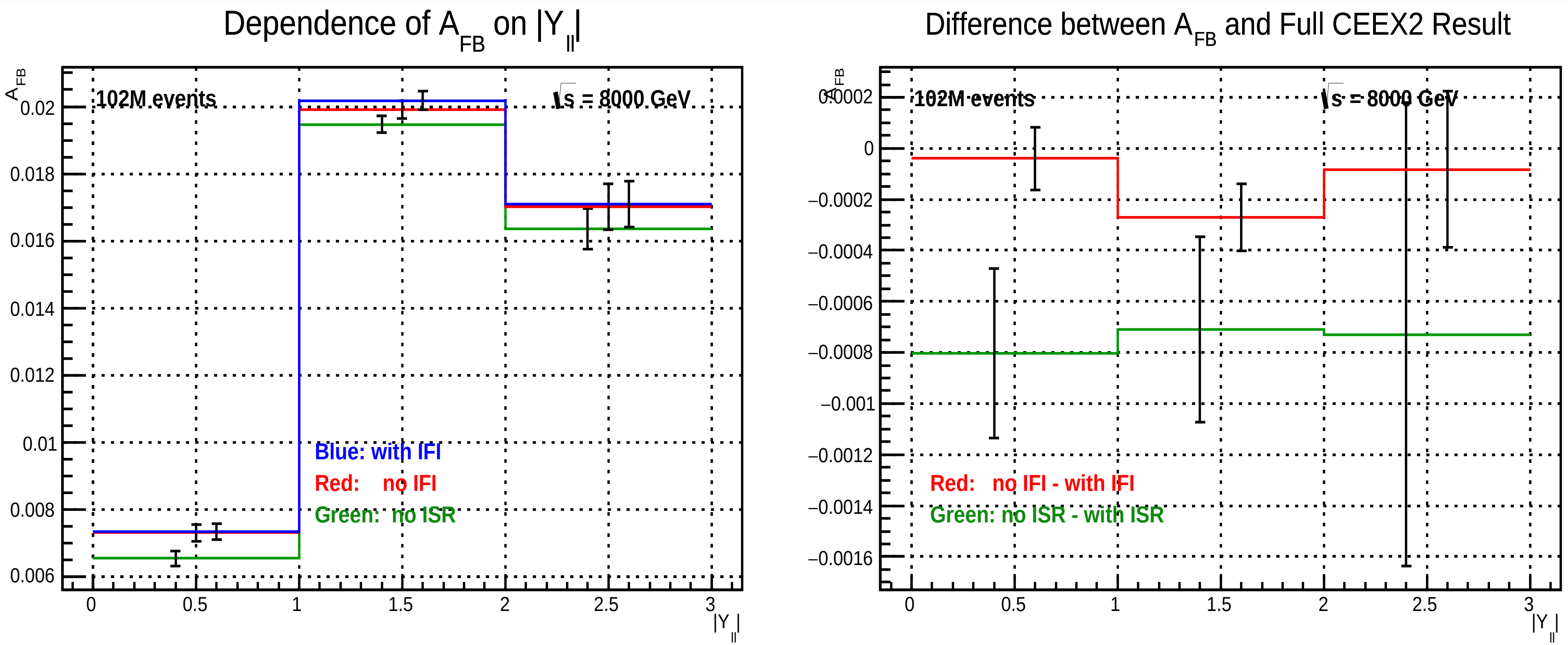
$$p_T > 25 \text{ GeV}, |\eta| < 2.5$$





A_{FB} Binned in Y_{ll}

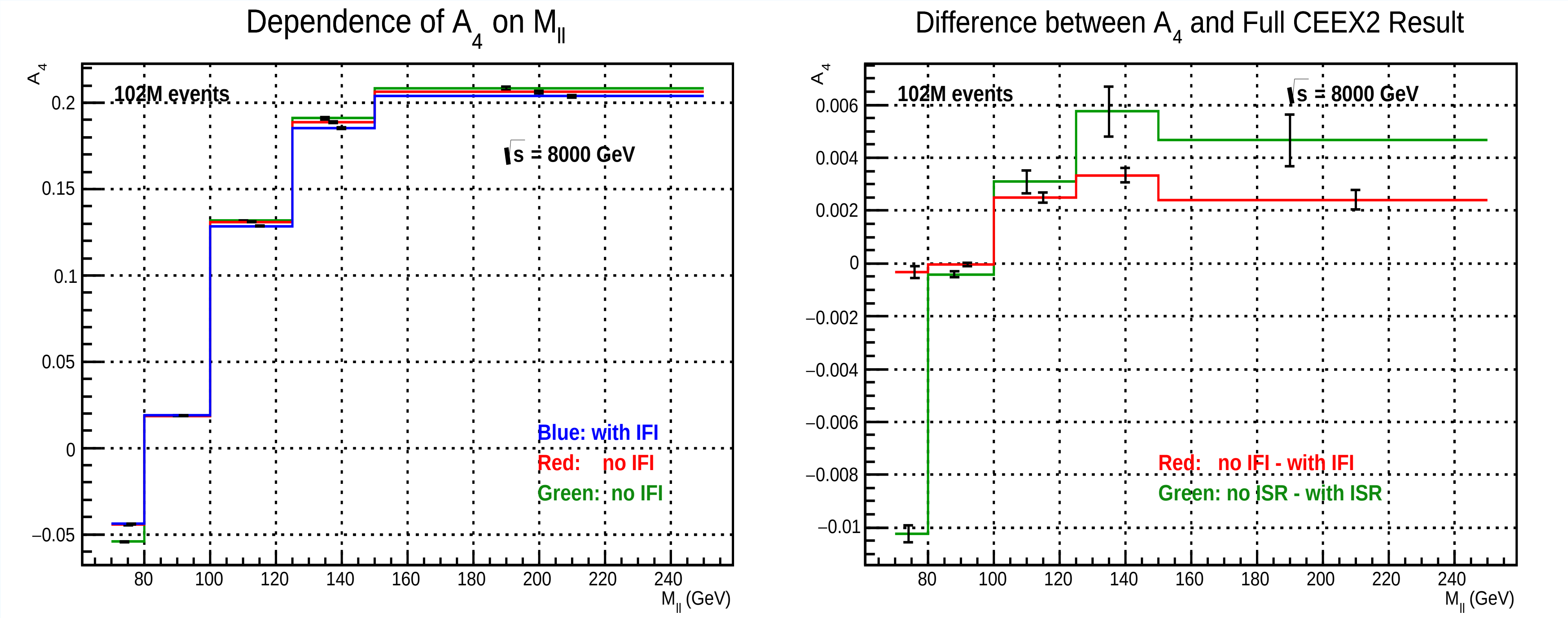
$$70 < M < 110 \text{ GeV}, \; p_T > 25 \text{ GeV}, \; |\eta| < 2.5$$



A_4 Binned in M_{ll}

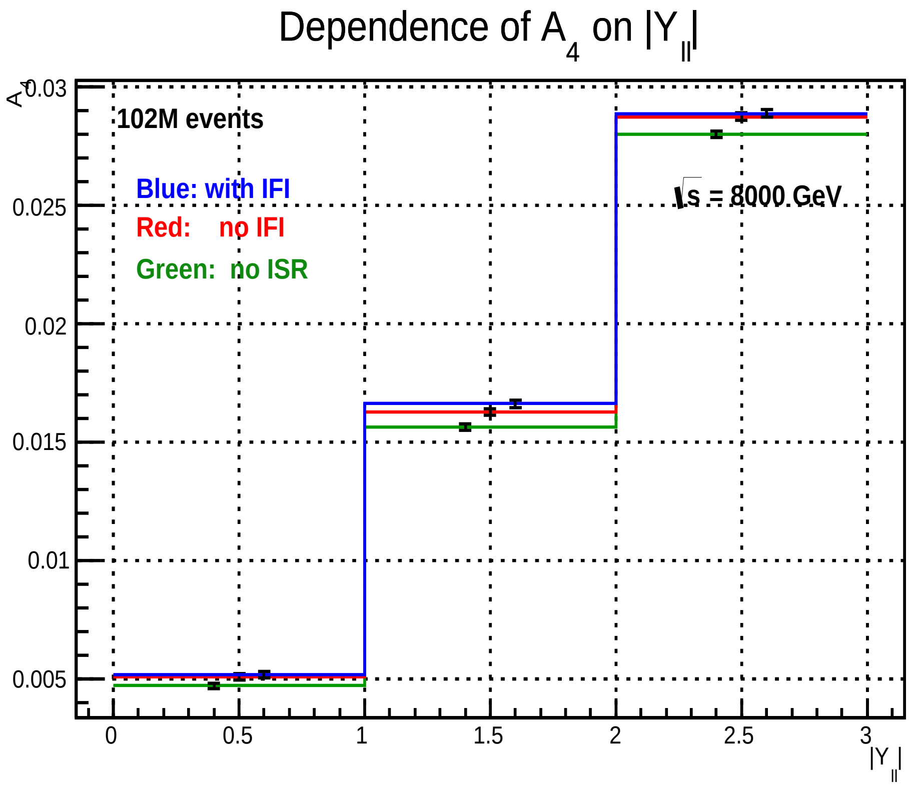
No lepton cuts.

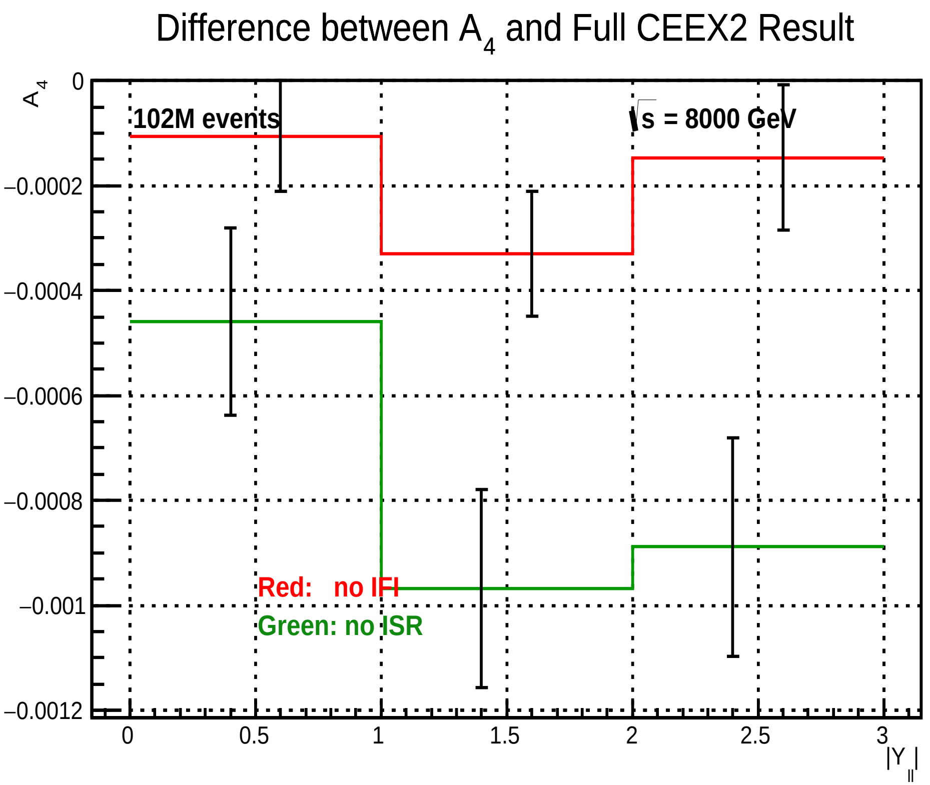
The IFI contribution is close to zero near the Z resonance, where it is suppressed.



A_4 Binned in Y_{ll}

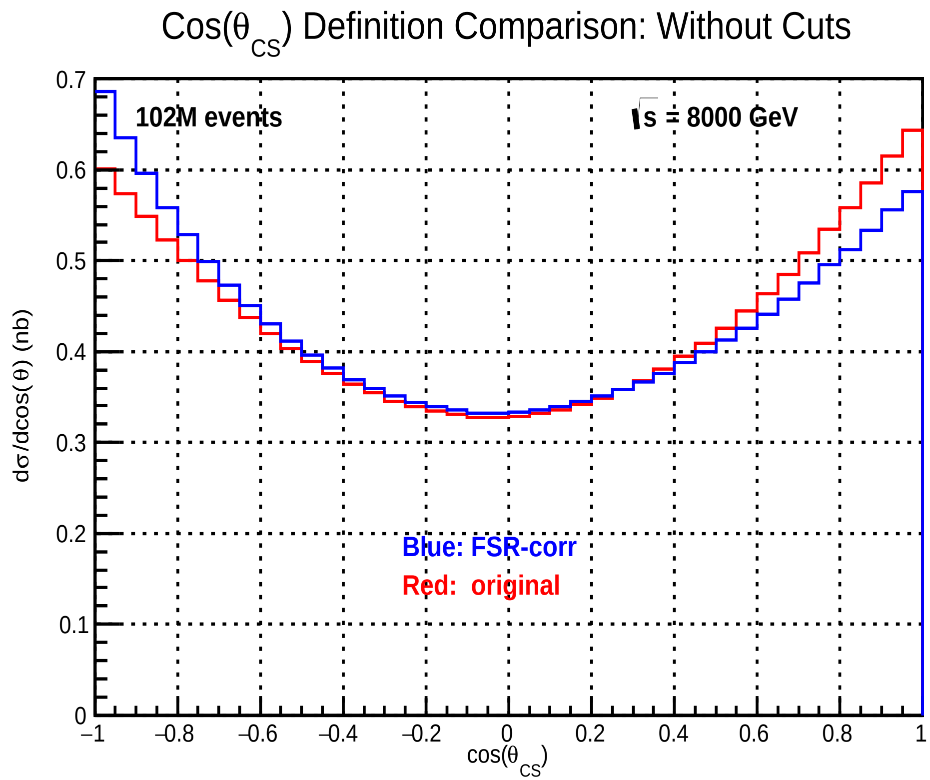
$70 < M < 110$ GeV

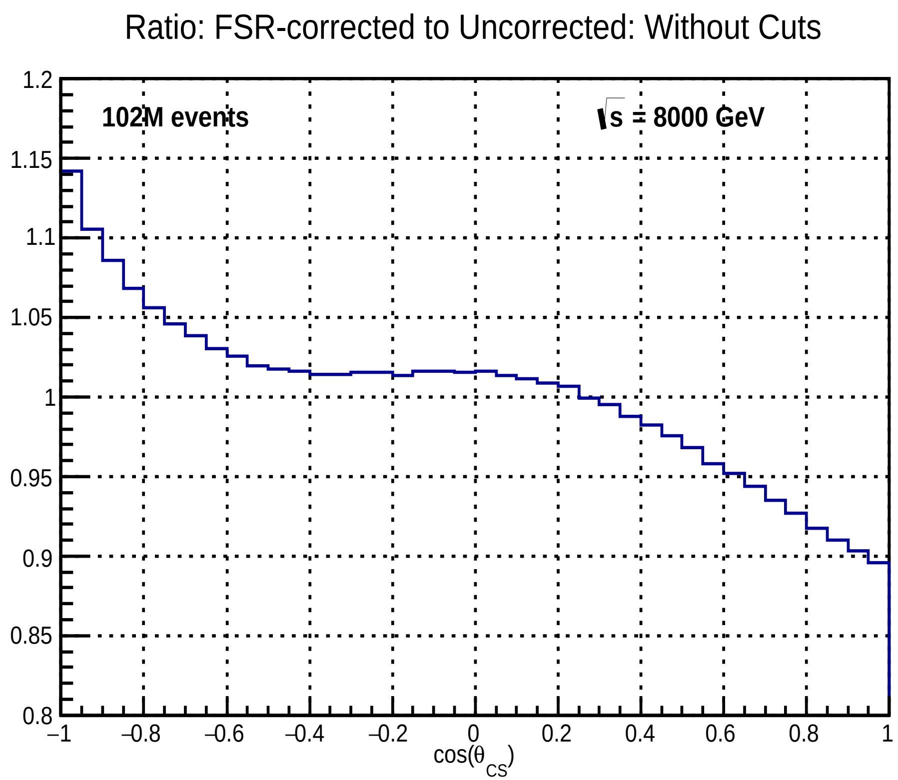




FSR Effect on $\cos(\theta_{CS})$

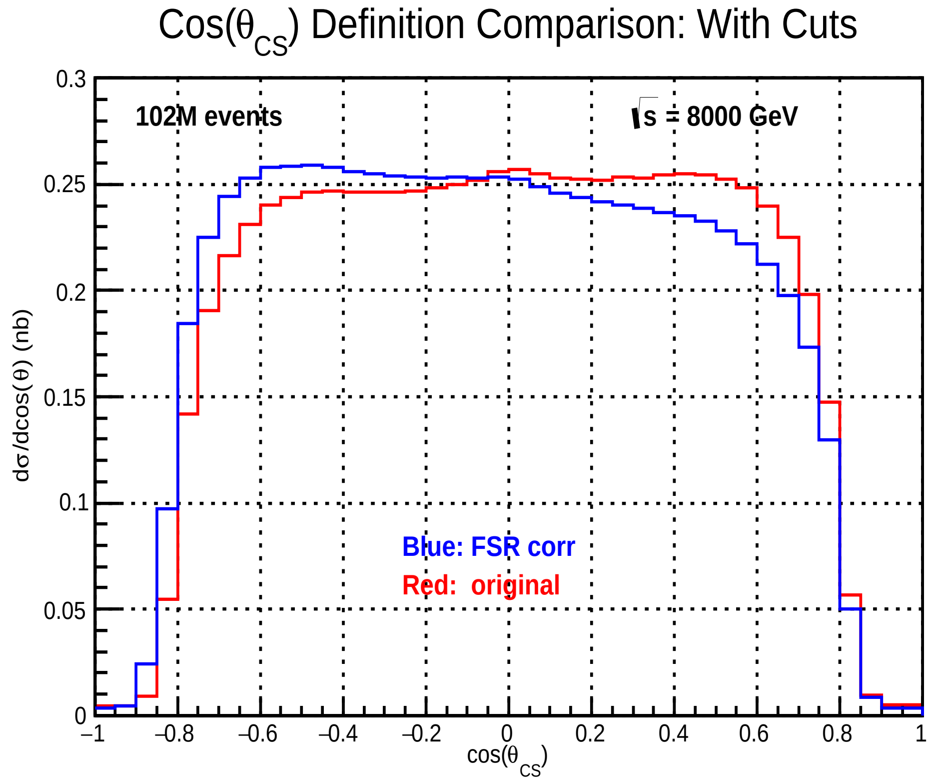
The CS angle is supposed to be in the frame of the Z, but was calculated with final leptons. Separating FSR from ISR is ambiguous due to IFI. Here, the photons that are closer to a muon than the quarks are taken to be FSR.

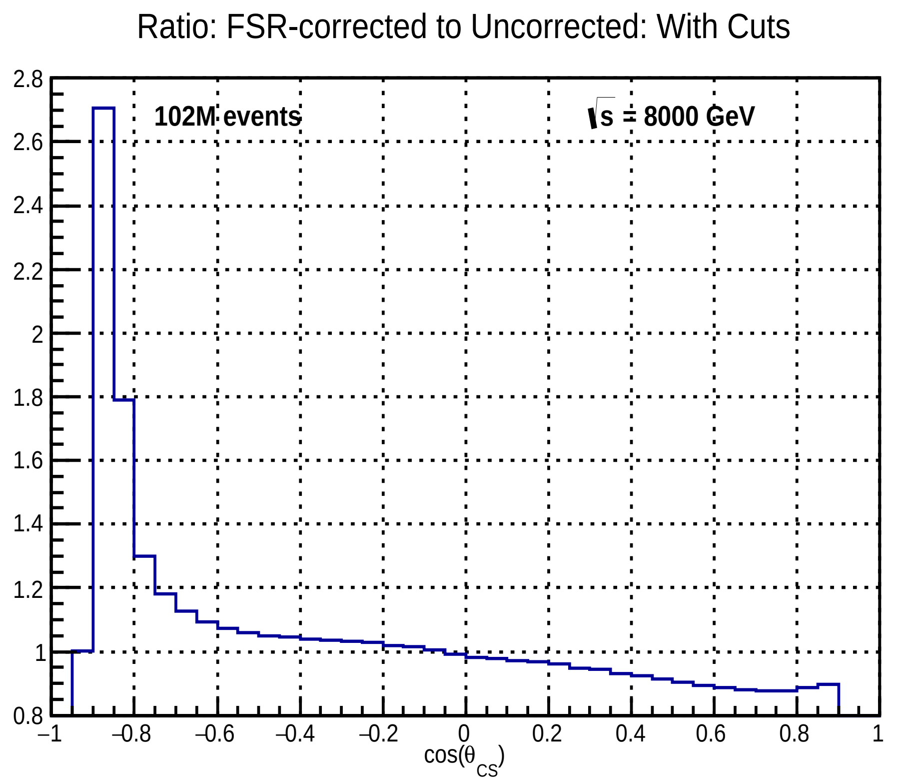




FSR Effect on Angular Distributions

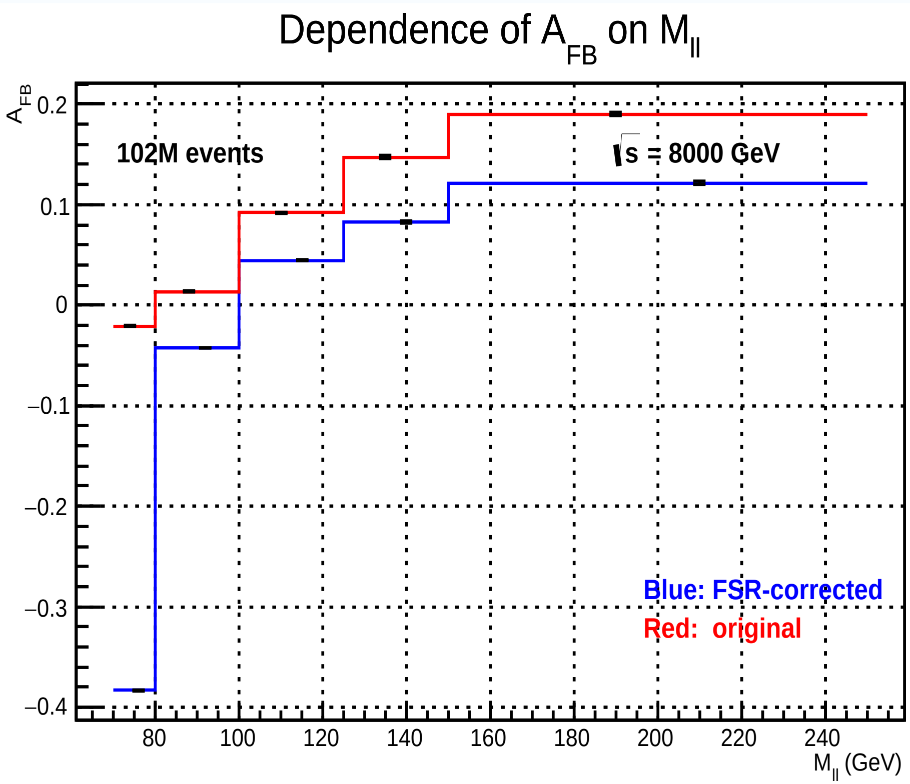
This is a similar plot with the lepton cuts applied.

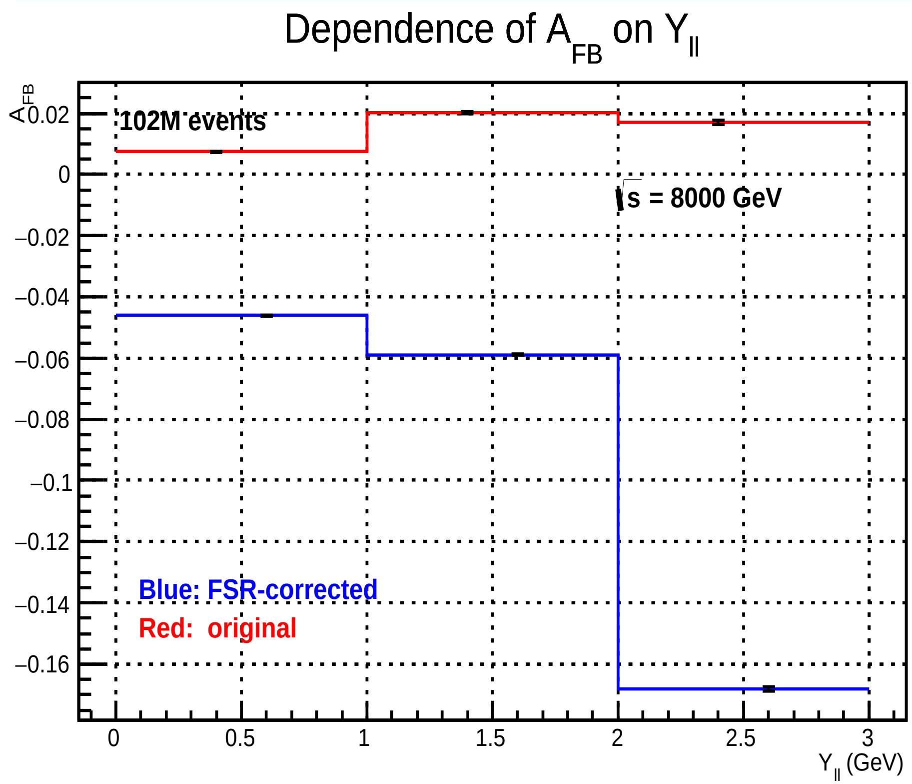




FSR Effect on $A_{\rm FB}$

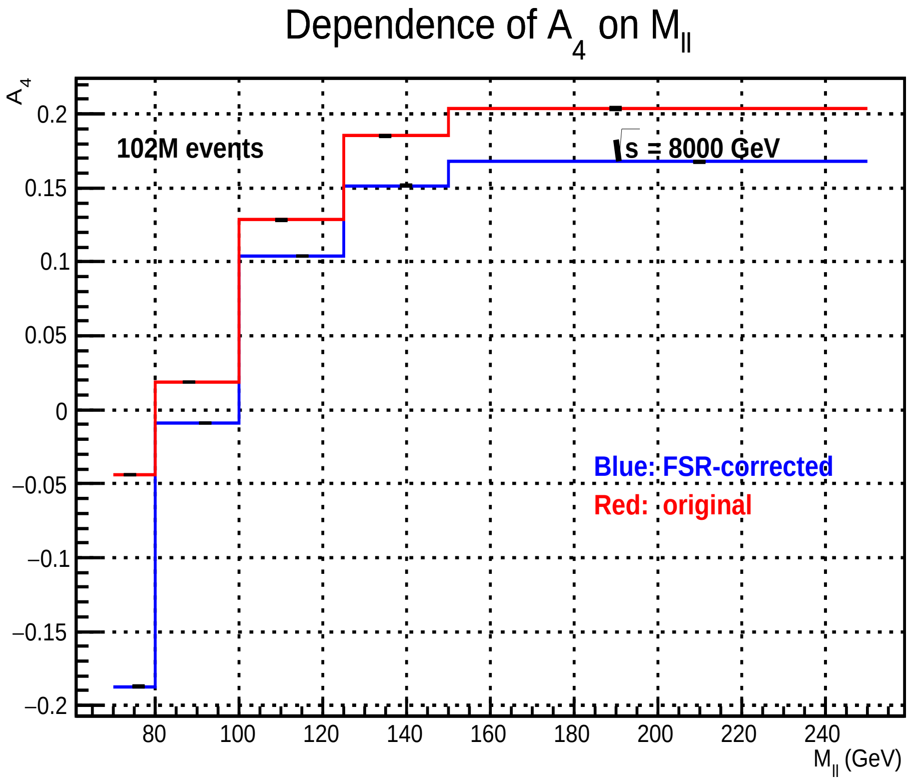
The effect of the same FSR correction is shown here on $A_{\rm FB}$.

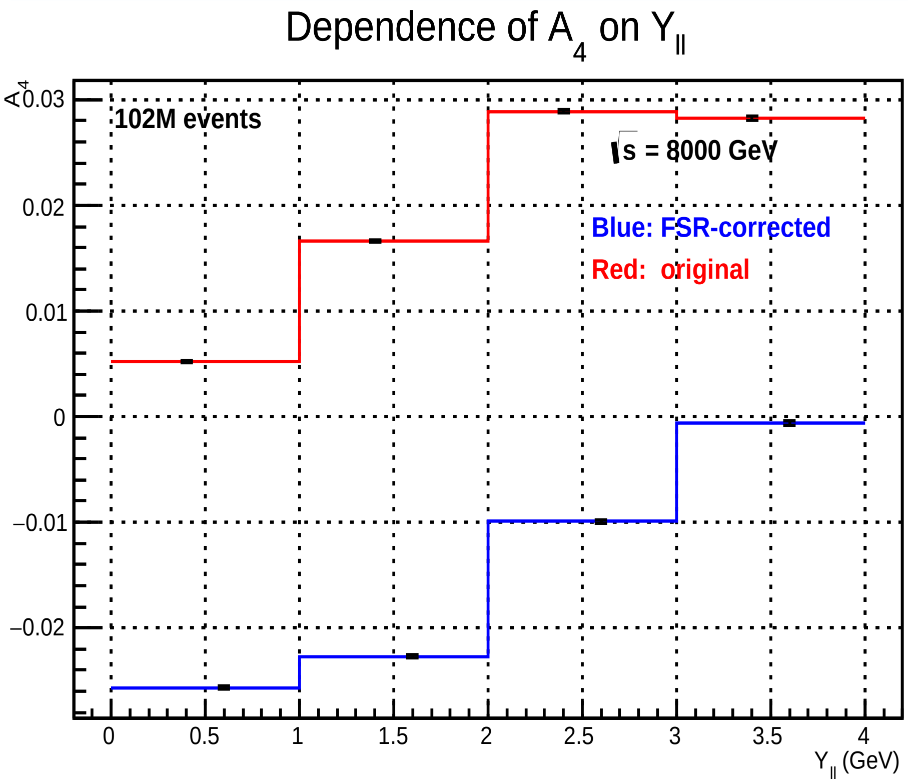




FSR Effect on A_4

The effect of the same FSR correction is shown here on A_4.





KKMC ISR vs PDF ISR

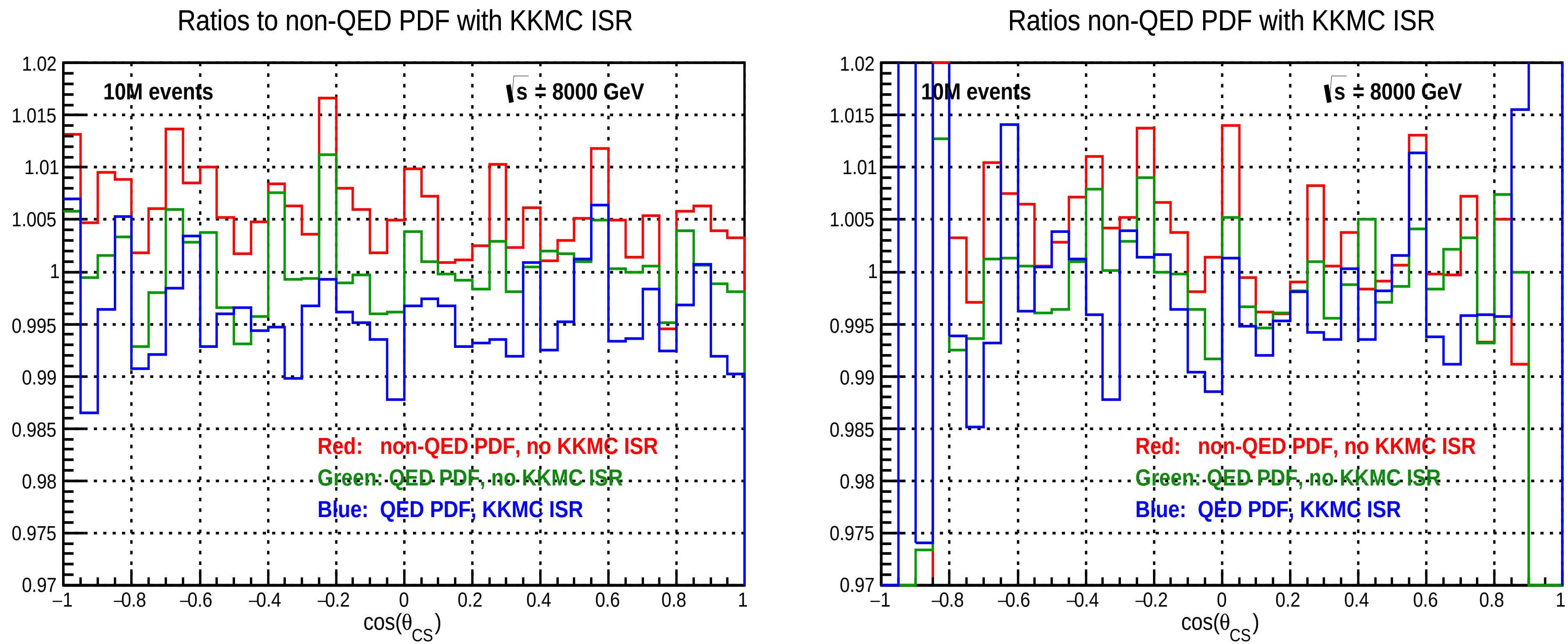
- KKMC-hh includes soft exponentiation of both ISR and FSR. This includes collinear emission. It must be used with a PDF which does not include such radiation.
- Some other calculations, such as WGRAD/ZGRAD and the POWHEG Box assume collinear radiation is accounted for in the PDF and set a QED factorization scale which renders the hard process insensitive to collinear emission, so that quark masses are merely regulators. These programs must be used with a QED PDF or they will miss effects from collinear ISR.
- KKMC-hh includes non-collinear ISR, but if all of ISR is left to the PDFs by setting a high QED factorization scale, non-collinear photon emission will be missed.
- The following slides compare the effect of using CT14 non-QED vs CT14 QED PDFs (LHAPDF index 13100 and 13300 respectively). The results are from an unshowered run at 8 TeV with 10M muon events, and the same cuts as before. IFI is not included. We compare:
  - KKMC-hh with ISR and a non-QED PDF (baseline case)
  - KKMC-hh without ISR and a non-QED PDF (no ISR)
  - KKMC-hh without ISR and a QED PDF (ISR from PDF)
  - KKMC-hh with ISR and a QED PDF (double-counting)

PDF Comparison: Cos(θ_{CS}) Distribution

This is an unshowered comparison with and without the cut

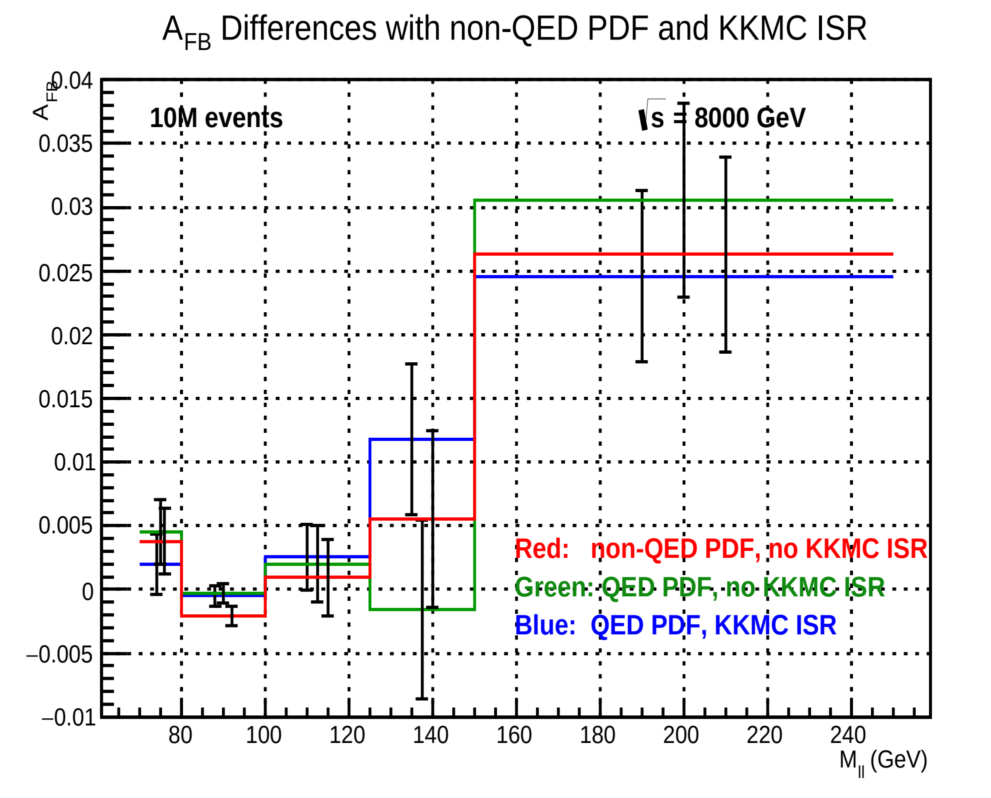
$$70 < M < 110 \text{ GeV}, \; p_T > 25 \text{ GeV}, \; |\eta| < 2.5.$$

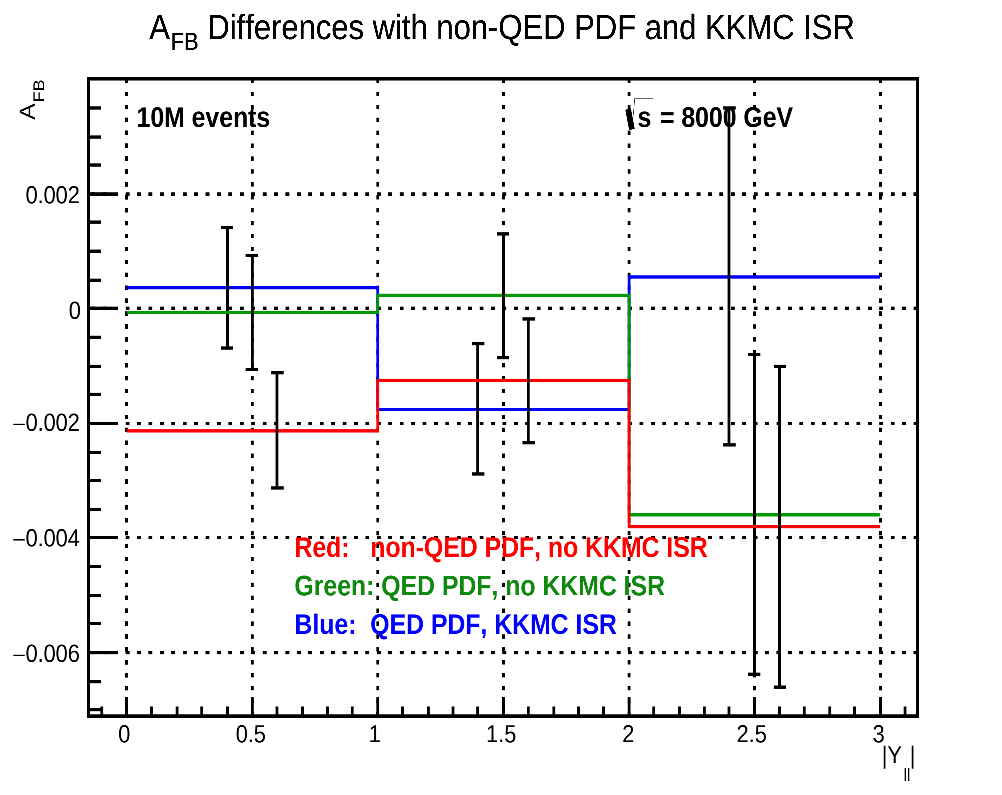
The figures show ratios with respect to the baseline case of KKMC-hh with ISR and a non-QED CT14 PDF.



PDF Comparison for $A_{\rm FB}$

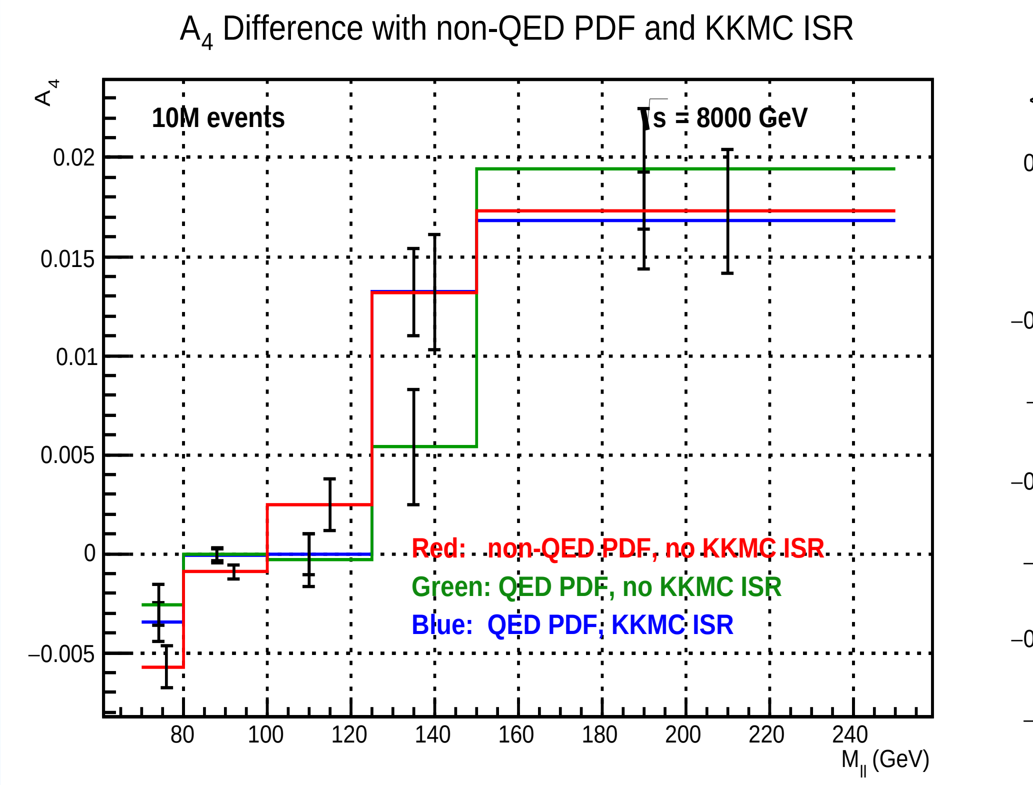
The same comparisons are shown here for $A_{\rm FB}$.

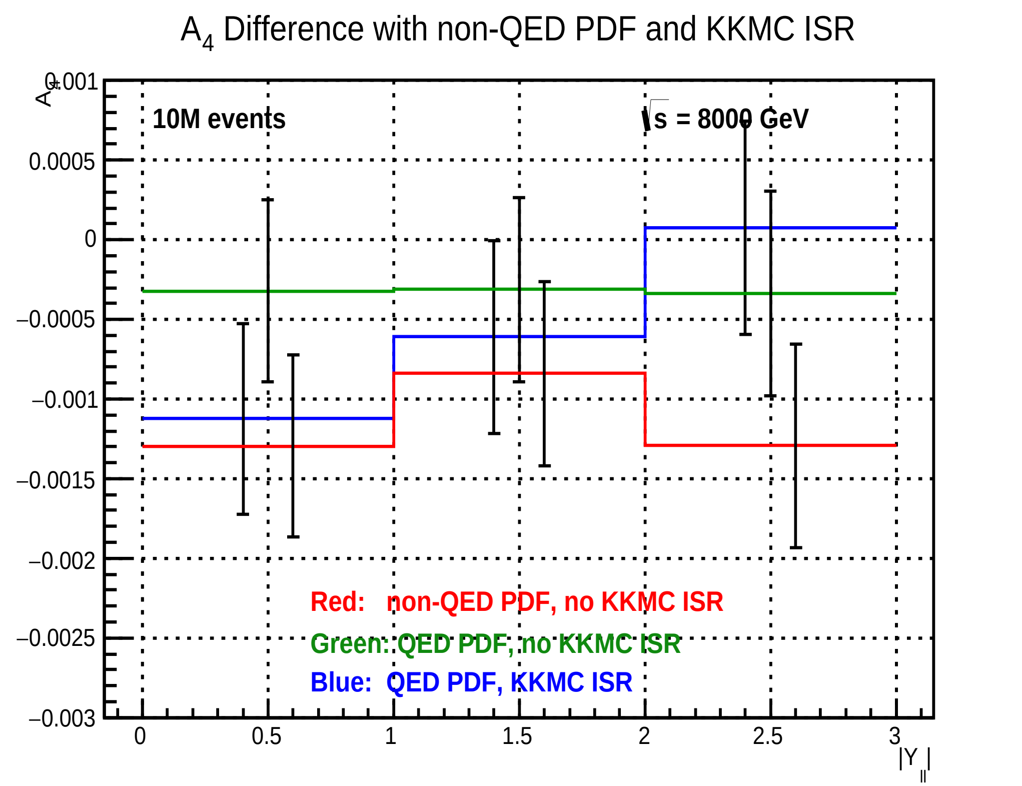




PDF Comparison for A_4

The same comparisons are shown here for A_4.



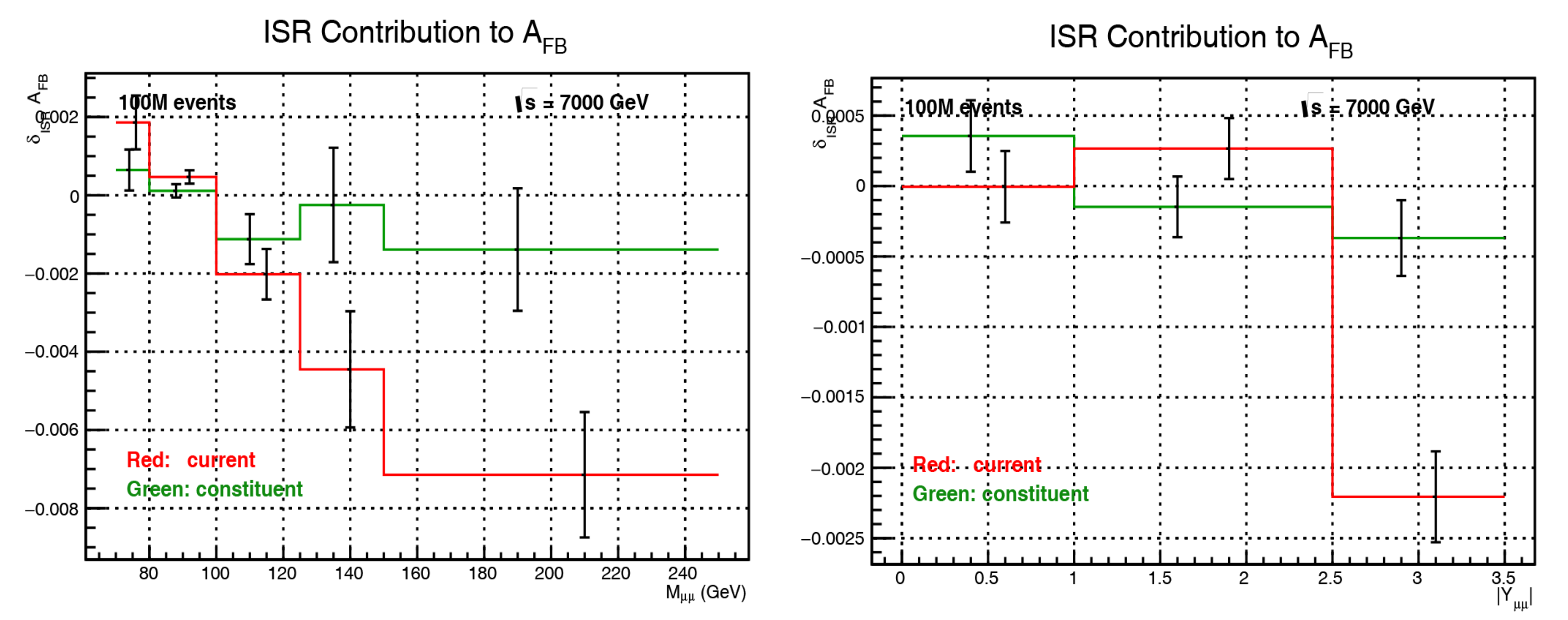


Quark Masses and Collinear ISR

- The presence of collinear logarithms in $\mathcal{KK}$ MC-hh ISR has raised the question of whether excessive ISR is being produced. In contrast to approaches where the logarithms are assumed to be factorized into the PDFs, the value of the quark masses has an influence on the results.
- We follow the MRST 2004 approach of using current masses for the light quarks. This is justified for energetic quarks by asymptotic freedom. which implies that perturbative calculations are applicable for both QED and QCD.
- Although the current mass appears to be preferred on general principles, I've included a few slides comparing the use of constituent and current quark sses, to show how much this affects the IFI and ISR contributions to $A_{\rm FB}$ amd A_4. These tests were run at 7 TeV and without a shower, but otherwise the same parameters, and MSTW 2008 PDFs.

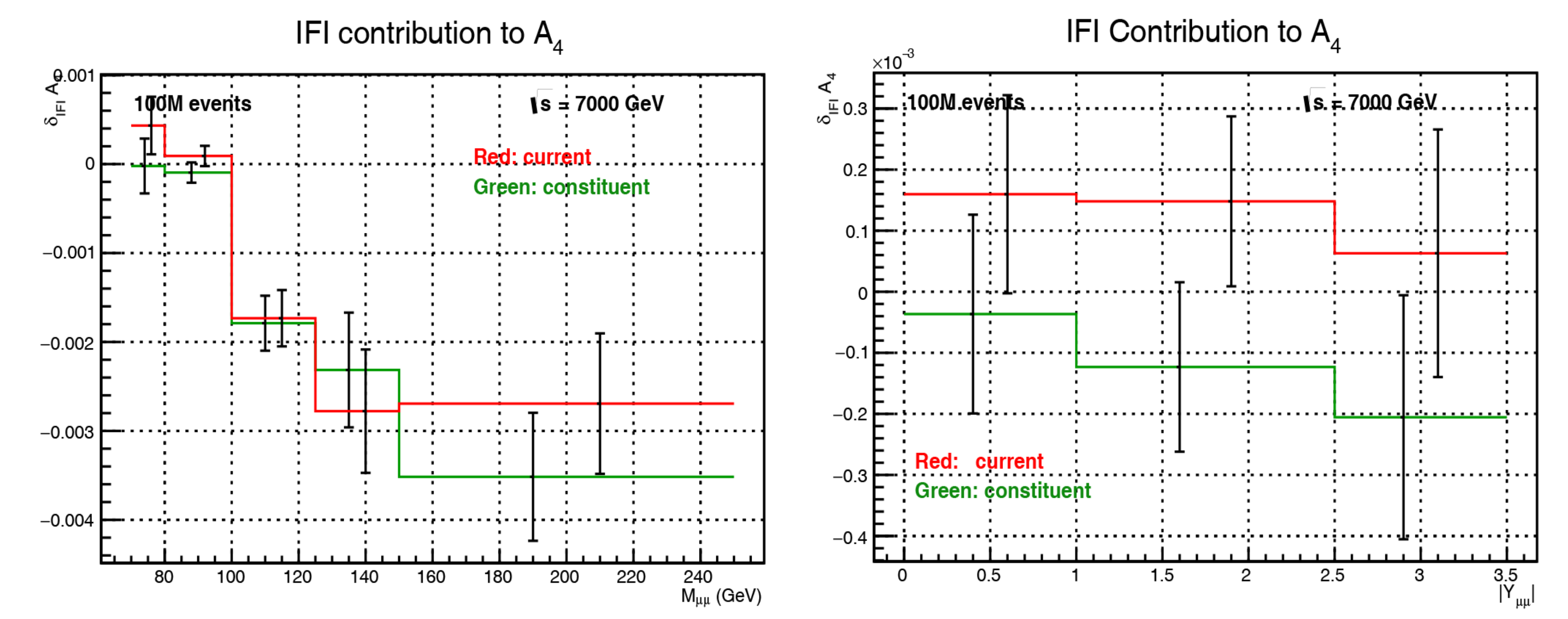
Quark Mass Comparison for $A_{\rm FB}$

The effect of using constituent versus current quark masses is shown here for $A_{\rm FB}$.



Quark Mass Comparison for A_4

The same comparisons are shown here for A_4.



QED-QCD Competition

- The issue has been brought up about whether competition between QED and QCD emission should suppress photon ISR.
- $\mathcal{KK}$ MC-hh treats QCD and QED radiation in a factorizable approximation, which is consistent with the negligible contribution of nonfactorizable terms in the $\mathcal{O}(\alpha_s \alpha)$ perturbative results of Dittmaier, Huss and Schwinn (arXiv:1403.3216).
- To the extent that QED and QCD corrections factorize, it should be a good approximation to treat them independently. This is rigorously true in the LL limit where the shower is constructed. At higher QCD precision, the issue may eventually need to be revisited. Presently, the competition manifests itself only through phase space constraints.
- This subject seems to be be worthy of futher discussion and clarification.

Summary

- For $70 < M_{ll} < 110\ \mathrm{GeV}$, the IFI contribution to A_{FB} is consistent with zero, but the statistics will improve as the current run progresses.
- The results seen here are generally consistent with what was seen at 7 TeV in my previous talk, although the ratio comparisons (rather than differences used here) in those slides can obscure this.
- Cuts can strongly affect the contribution of IFI, so it should always be checked for specific cuts of interest.
- ISR alone is a bigger effect than IFI, typically a few %, as seen in earlier studies with $\mathcal{KK}$ MC-hh. This is also cut dependent, and largely due to bin migration, since ISR reduces the CM energy.
- As expected, there is some sensitivity to how whether the FSR photons are removed before calculating the CS angle. There is an intrinsic ambiguity in how to do this in the presence of IFI.
- More details on $\mathcal{KK}$ MC-hh can be found in
  - Phys. Rev. D94 (2016) 074006 (arXiv:1608.01260)
  - arXiv:1707.06502 (submitted to Phys. Rev. D)