KKMC-hh: Quark Mass Dependence in A_{FB} Calculation and Comparison of NNPDF to MMHT PDFs

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KKMC-hh is a collaboration with S. Jadach, B.F.L. Ward and Z. Wąs.

Computational resources provided by IFJ-PAN, Kraków.

New Results

We have run KKMC-hh using the MMHT PDF sets, comparing the MMHT2014nlo68cl to MMHT2015qed_nlo_inelastic.

We have also run KKMC-hh with different quark masses: 10 x the up and down quark mass, to see the size of the mass dependence.

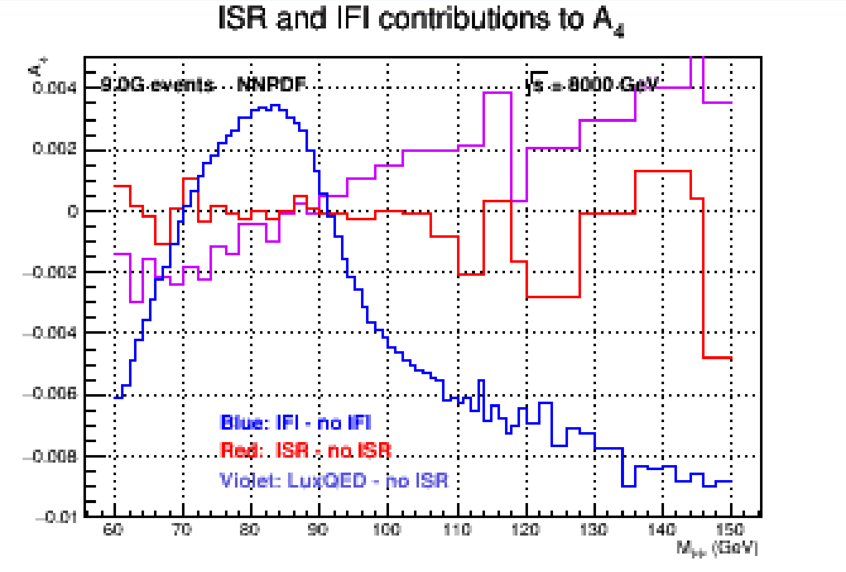
A separate set of studies is underway making detailed comparisons of KKMC-hh's ISR to the alternative of factoring ISR entirely into the PDFs, for NNPDF and MMHT, and possibly others.

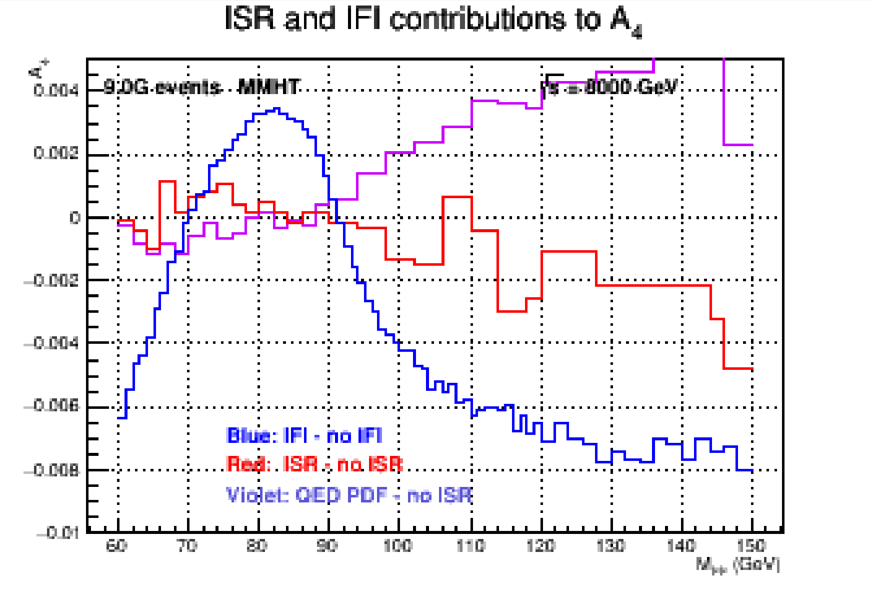
A new semianalytical tool is available: KKhhFoam. I will not present results from it, but we have found that it gives excellent agreement with KKMC-hh using a much simpler model with the photons integrated in a semi-soft limit.

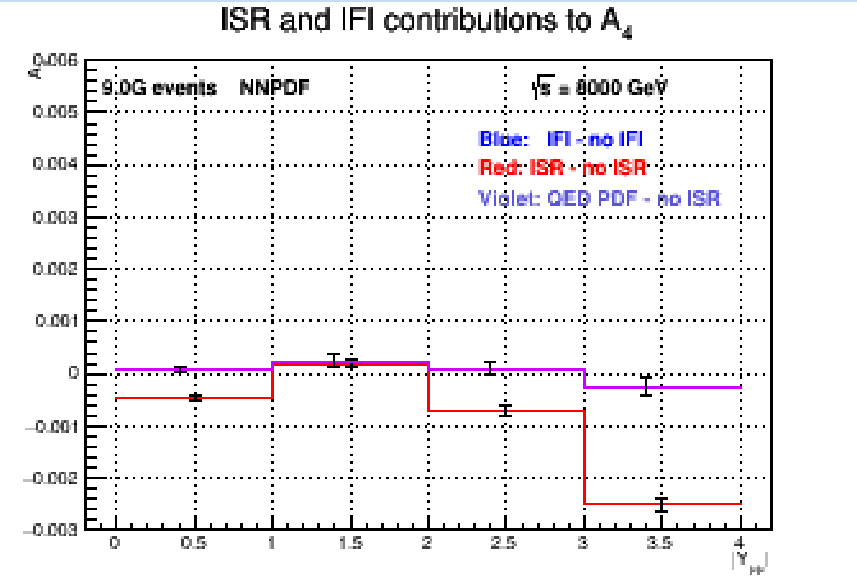
Results Presented

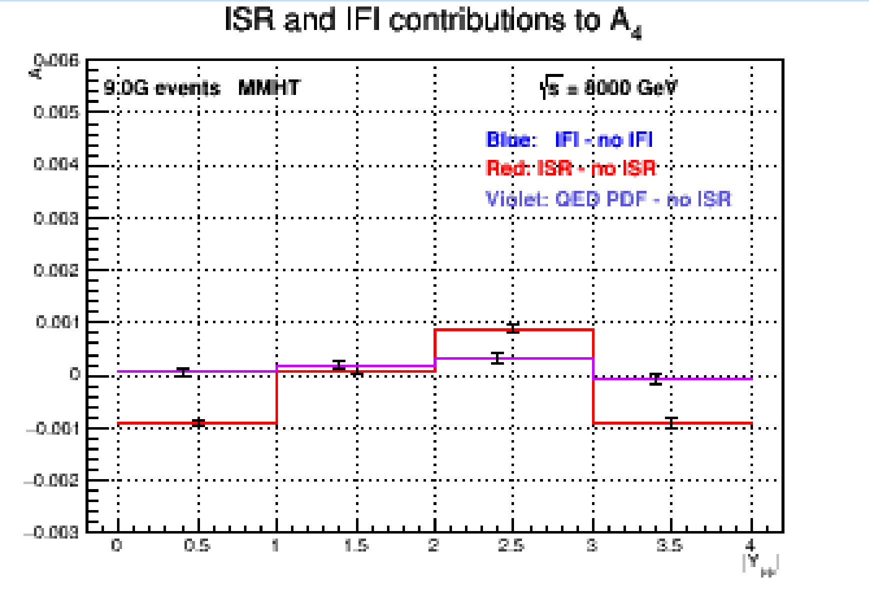
- All results are for muon pair final states with proton collisions with $\sqrt{s} = 8000\ \mathrm{GeV}$. Event samples are in the 7-10 billion event range.
- Our results all include a dilepton mass cut in all cases:
$$60\ \mathrm{GeV} < M_{ll} < 150\ \mathrm{GeV}.$$
- A_4 is calculated from $\frac{8}{3} A_{FB}$ in the full phase space.
- We also calculated A_{FB} with lepton cuts $P_T > 25\ \mathrm{GeV}, |\eta| < 2.5$ on both muons. The corresponding table is on the following page.
- All results include FSR corrections.

PDF Comparison for A_4 ($\frac{8}{3} A_{\mathrm{FB}}$, no lepton cuts)









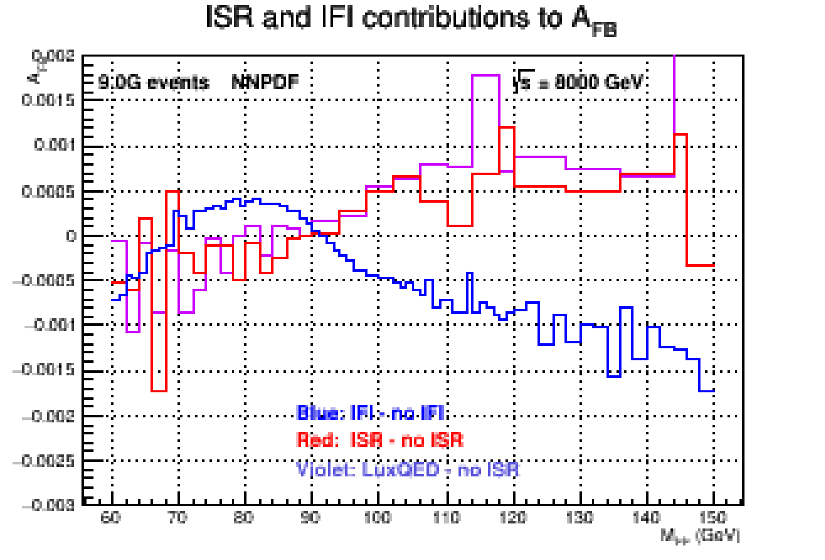
NNPDF is on the left,
MMHT is on the right.

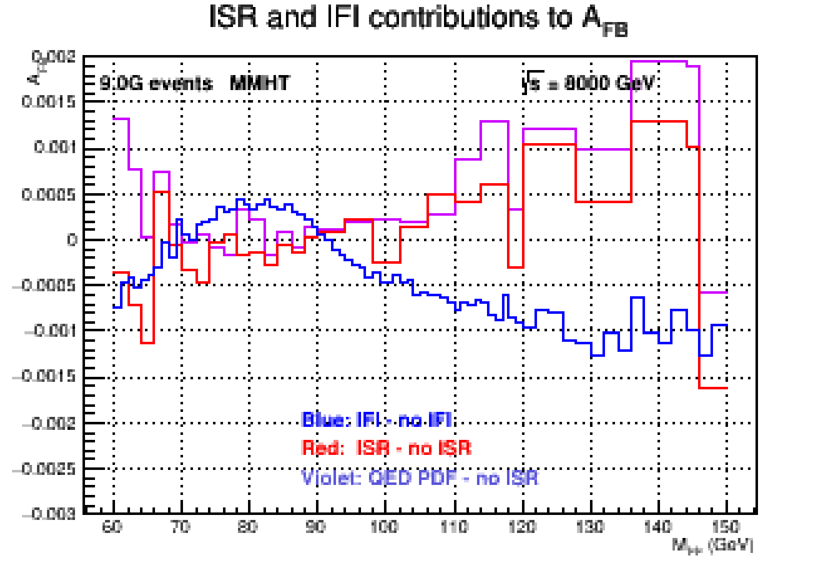
The KKMC-hh results are compatible in both versions.

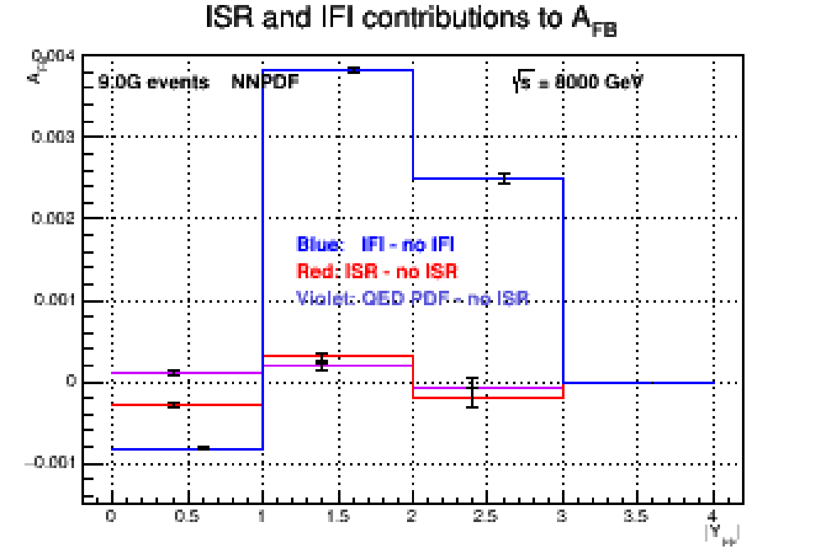
The violet line is the comparison of the QED-version of each PDF to the non-QED version.

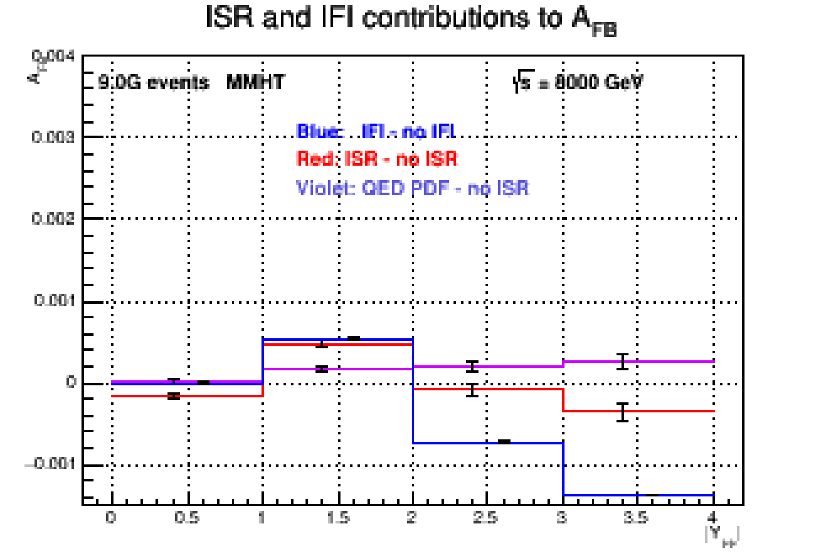
The shapes are similar in the M_{ll} histogram, but there is a shift.

PDF Comparison for A_{FB} (with lepton cuts)









NNPDF is on the left,

MMHT on the right.

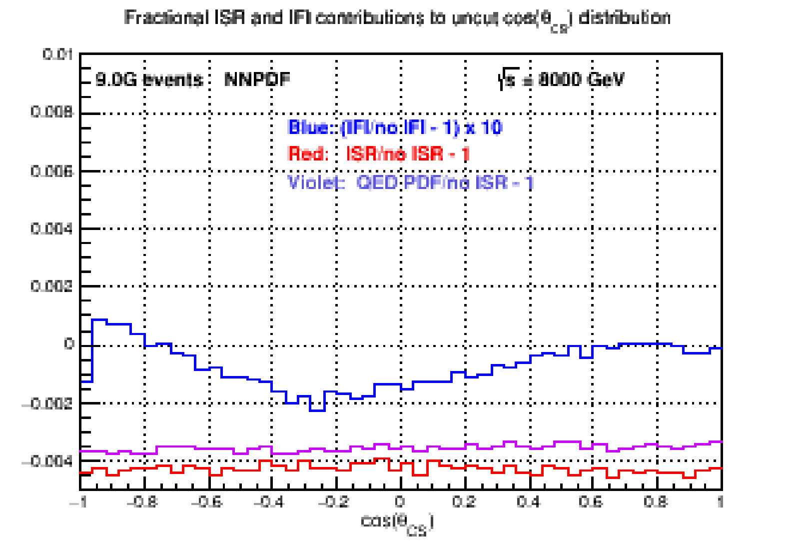
The M_{ll} dependence of IFI is very similar.

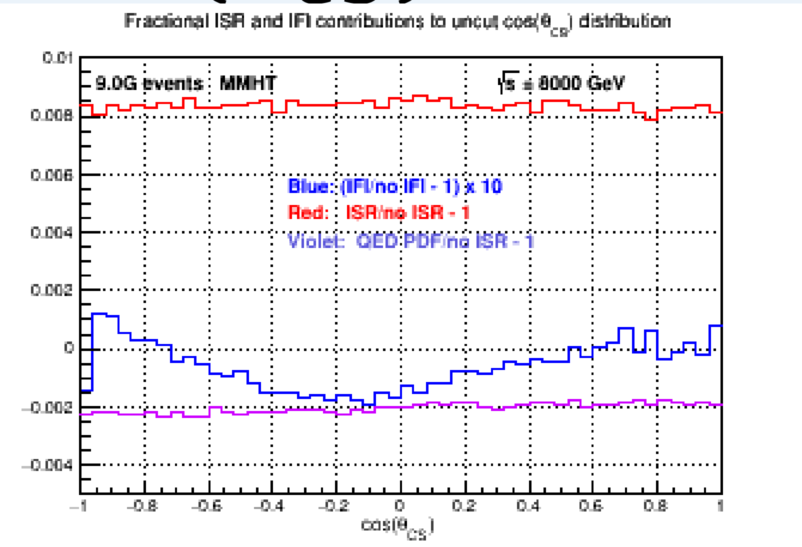
The M_{ll} dependence of ISR is more similar than it was without the lepton cuts.

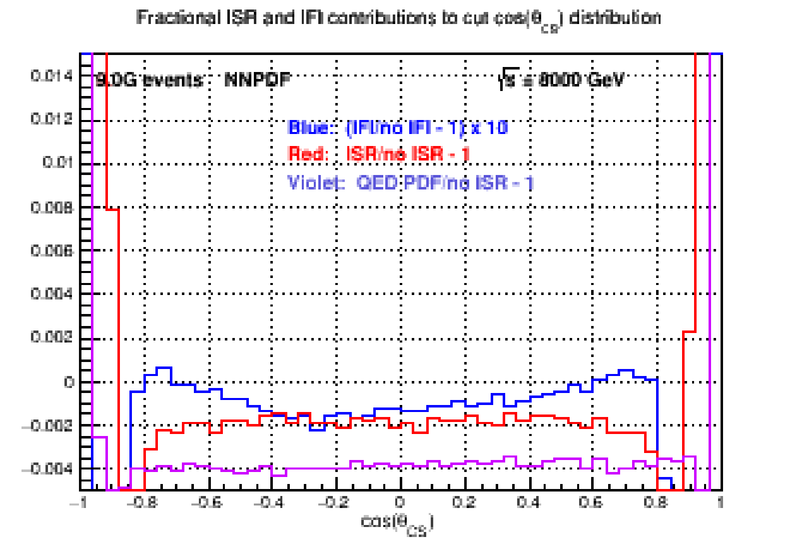
KKMC-hh ISR tracks the PDF ISR more closely.

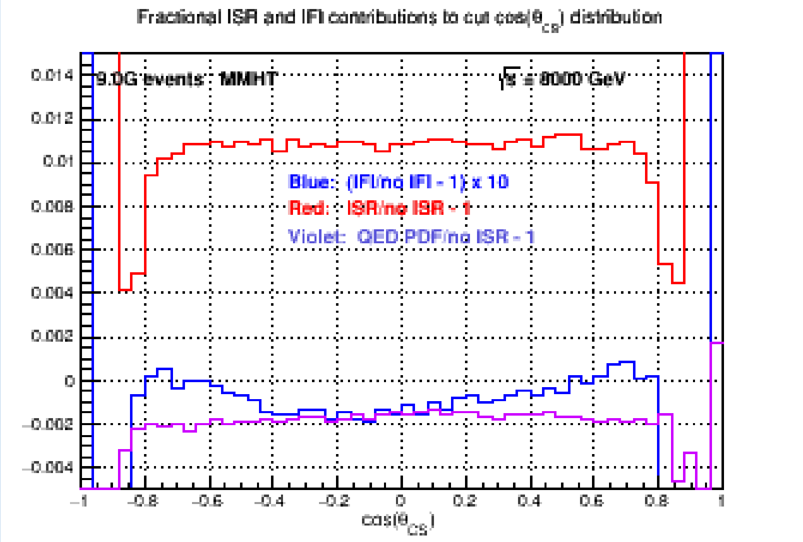
The rapidity dependence is less similar than it was without the lepton cuts.

PDF Comparison: $\cos(\theta_{CS})$ Distributions









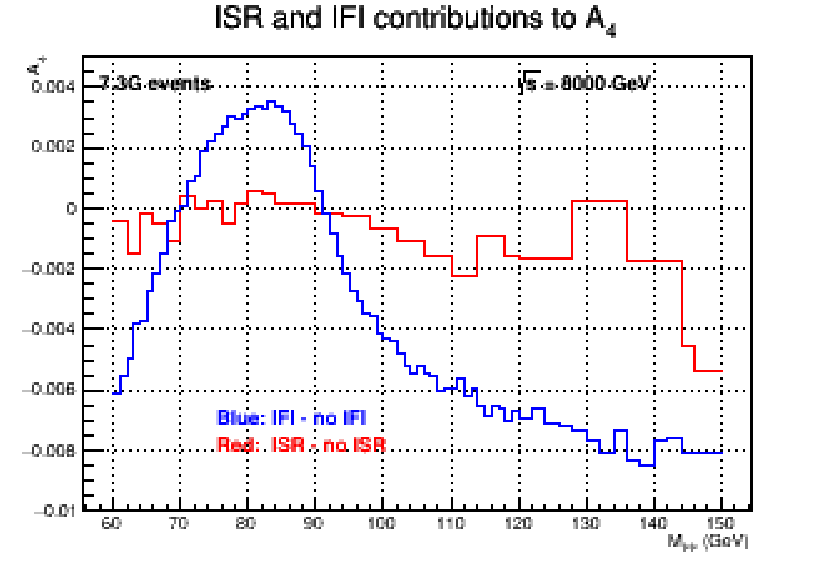
These plots compare the angular distributions for the two sets of PDFs.

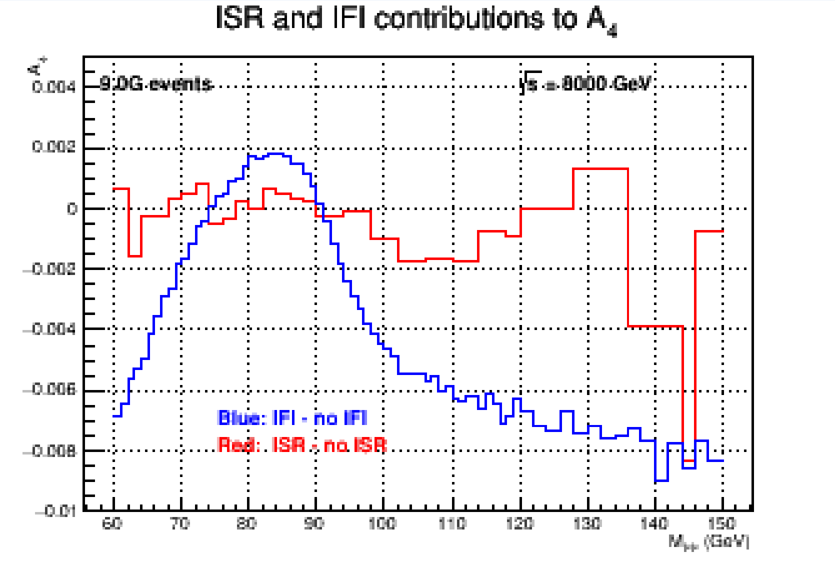
NNPDF is on the left, MMHT on the right.

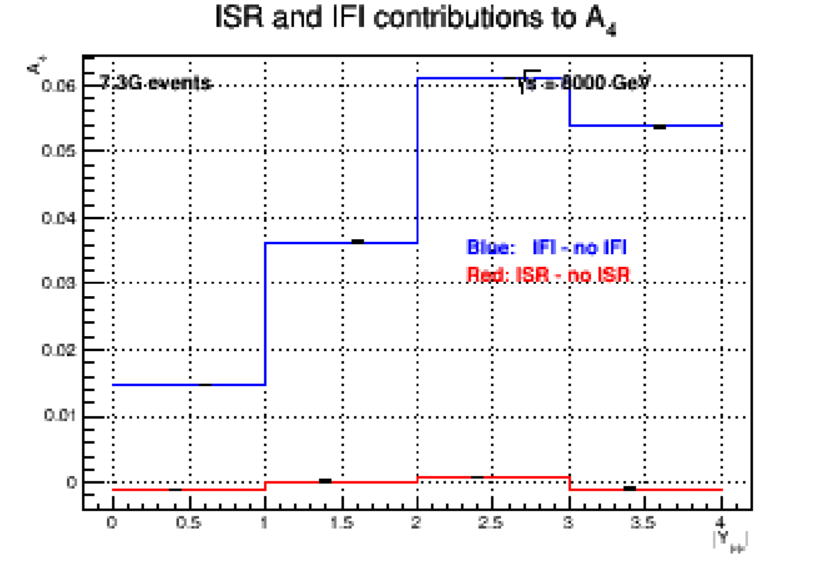
The IFI contributions are similar in shape.

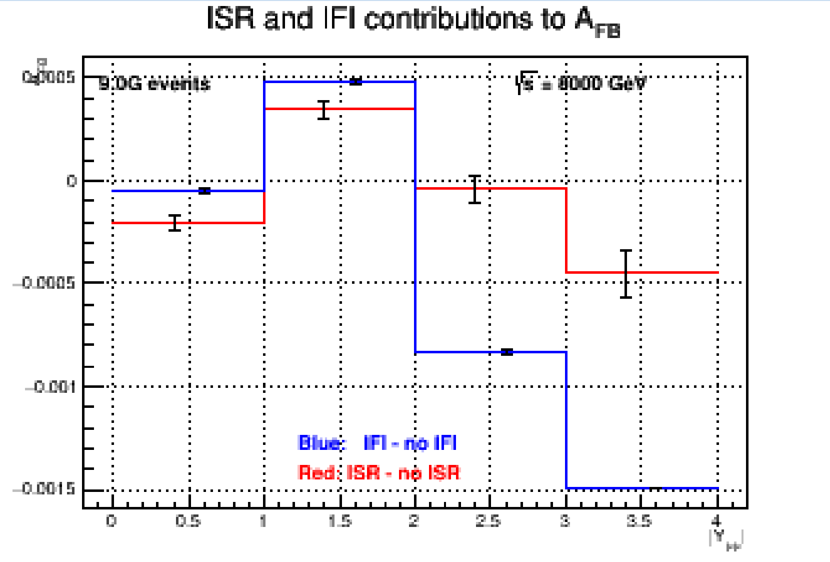
The ISR contributions are different, but flat or nearly flat,

Mass Comparison for A_4 ($\frac{8}{3}\,A_{FB}$, no lepton cuts)









These graphs use NNPDF.

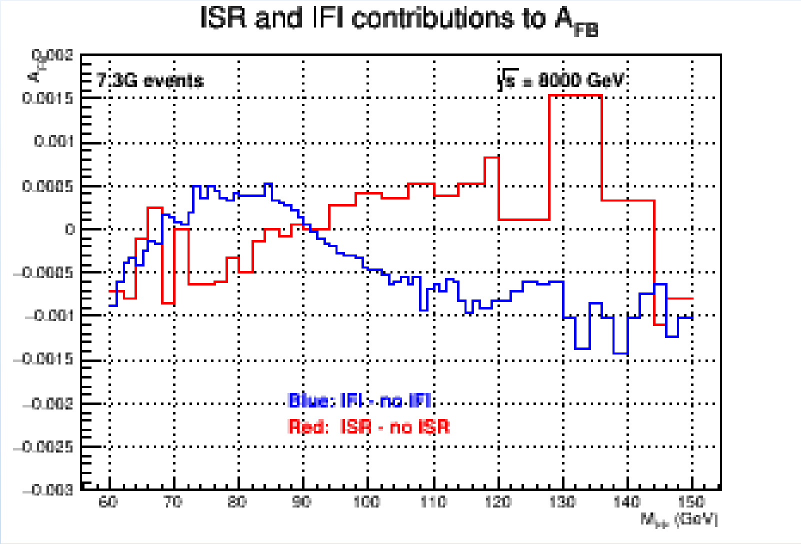
The graphs on the left have KKMC-hh default light quark masses:

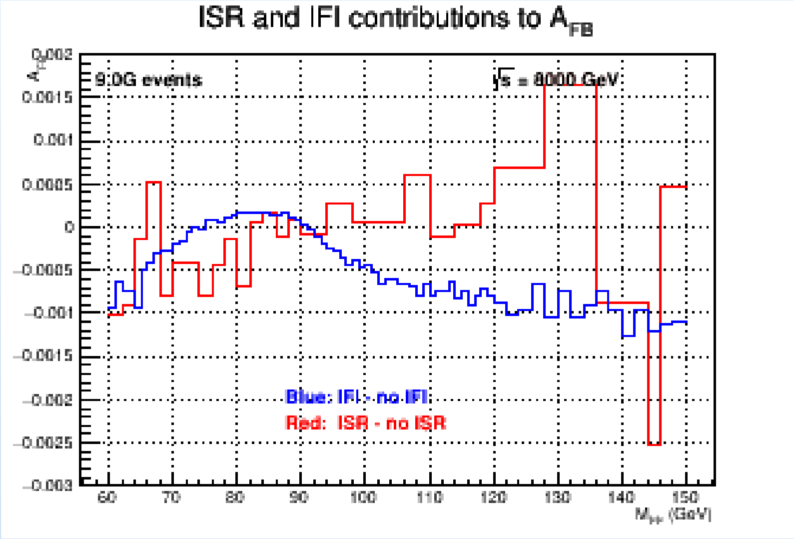
$$m_u = 2.2 \text{ MeV},$$
$$m_d = 4.7 \text{ MeV}.$$

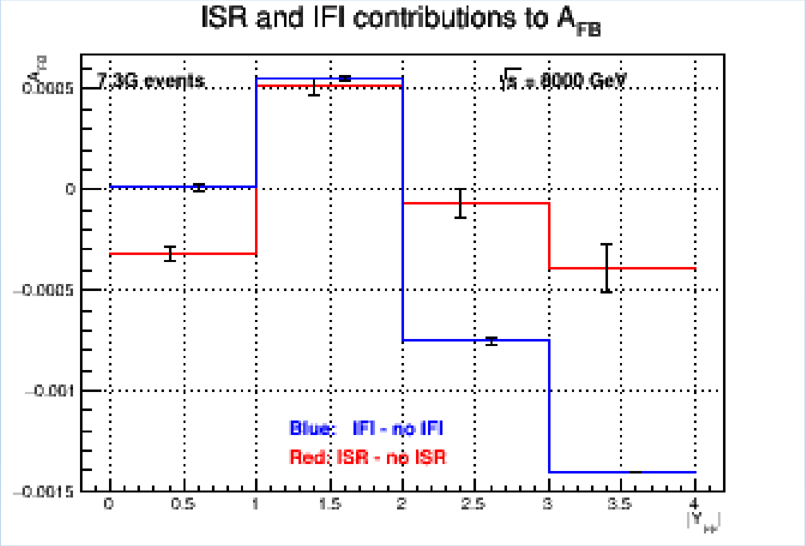
The light quark masses on the right are increased by a factor of 10.

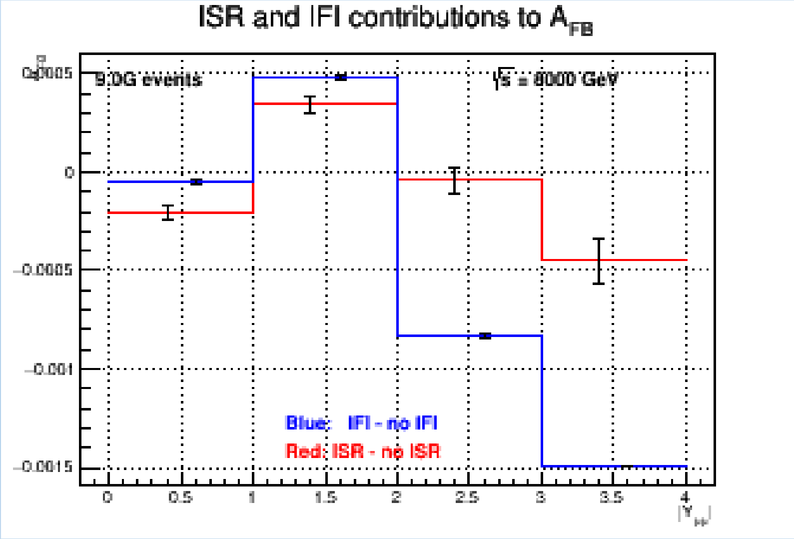
The M_{ll} histogram of the ISR dependence is not significantly changed, but the IFI dependence shifts.

Mass Comparison for A_{FB} (with lepton cuts)









These graphs use NNPDF.

The graphs on the left have KKMC-hh default light quark masses:

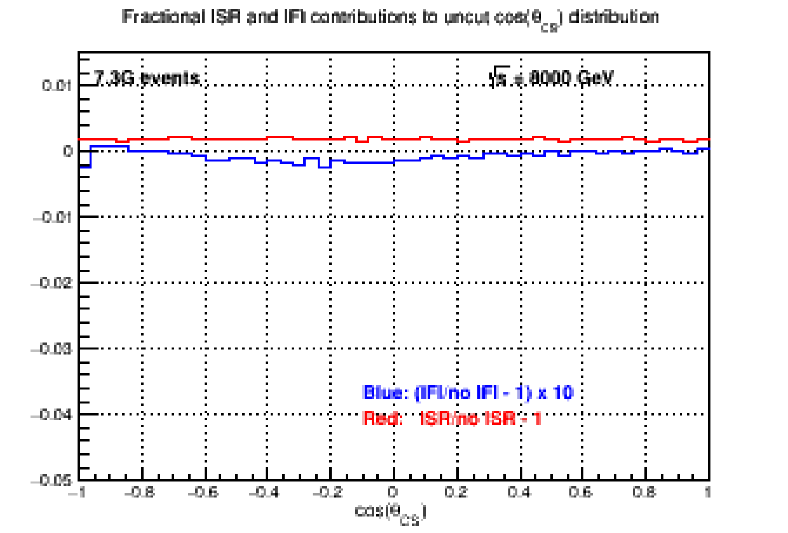
$$m_u = 2.2 \text{ MeV},$$
$$m_d = 4.7 \text{ MeV}.$$

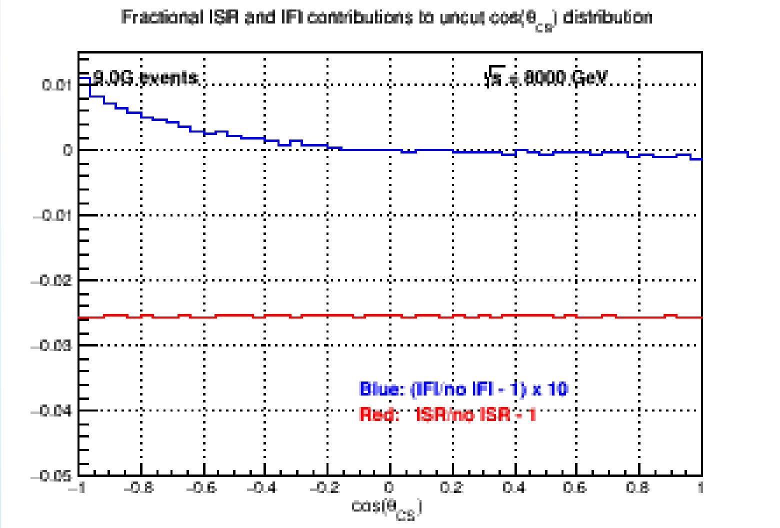
The light quark masses on the right are increased by a factor of 10.

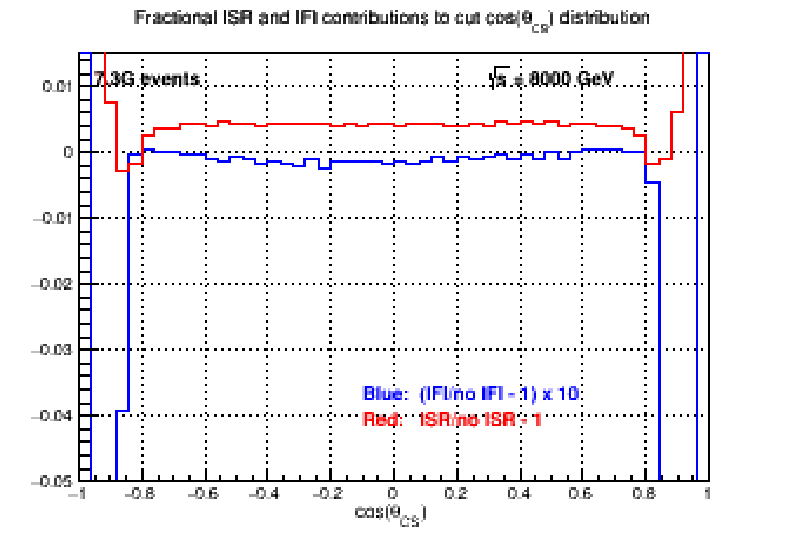
The M_{ll} histogram of the ISR dependence is not significantly changed, and the IFI shift is smaller.

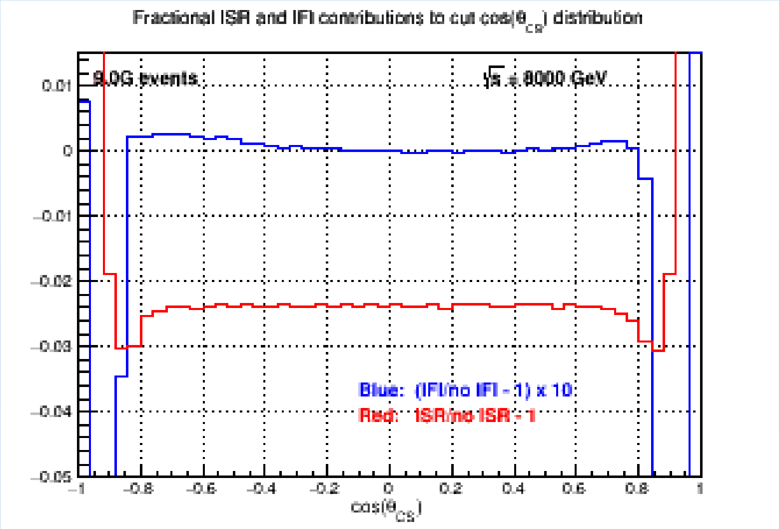
The Y_{ll} graphs are much more similar with the cuts.

Mass Comparison: $\cos(\theta_{CS})$ Distributions









These graphs use NNPDF.

The graphs on the left have KKMC-hh default light quark masses:

$$m_u = 2.2 \text{ MeV},$$
$$m_d = 4.7 \text{ MeV}.$$

The light quark masses on the right are increased by a factor of 10.

The ISR shift is fairly large when the quark masses are increased.

There is some effect on IFI, but more subtle: note the rescaling by 10.

KKhhFoam

KKhhFoam is derived from KKFoam* fpr e^+e^- scattering, which implements a semi-soft resummation and integration of multi-photon emission at the amplitude level.

KKFoam uses the adaptive MC Foam [S. Jadach] to integrate the lepton polar and azimuthal angles, the total photon energies for ISR and FSR, and if IFI is included, two energy evolution variables for that.

KKhhFoam adds the quark flavor and momentum fractions, for a 9-dimensional integral, which includes separate factors for ISR, FSR and IFI. Unlike in KKMC, IFI can be switched on independently of ISR and FSR.

The ISR, FSR and IFI can be studied at very high resolution in a relatively short time, and the relative simplicity of the expressions for each allow issues such as quark mass dependence to be studied in detail.

*S. Jadach, S. Yost, Phys. Rev. D100, 013002 [arXiv:1801.08611]

KKhhFoam

The KKhhFoam representation of the cross section is very compact: $c = \cos\theta$

$$\frac{d\sigma(s)}{dM_{ll}^2} = \frac{3}{4}\pi\sigma_0(s) \sum_{q=u,d,s,c,b} \int dx_q dx_{\bar{q}}\, f_q^{h_1}(x_q) f_{\bar{q}}^{h_2}(x_{\bar{q}}) \sum_{V,V'=\gamma,Z} \int dz dz' du du'$$
$$\times \int d\cos\theta\, \rho_I^{(2)}\left(\gamma_I(\hat{s}), z\right) \rho_F^{(2)}\left(\gamma_F(\hat{s}zz'), z'\right) \rho\left(\tilde{\gamma}(c), u\right) \rho\left(\tilde{\gamma}(c), u'\right) e^{Y(p_i,q_i)}$$
$$\times \frac{1}{4}\sum_{\{\lambda\}} \Re\left\{ e^{\alpha\Delta B_4^V(\hat{s}zu)} \mathfrak{M}_{\{\lambda\}}^V(\hat{s}zu, c) \left[e^{\alpha\Delta B_4^{V'}(\hat{s}zu')} \mathfrak{M}_{\{\lambda\}}^{V'}(\hat{s}zu', c)\right]^* \right\} \delta(M_{ll}^2 - \hat{s}zz'uu'),$$

$$\gamma_I = Q_q^2 \frac{\alpha}{\pi}\left(\ln\left(\frac{\hat{s}}{m_q^2}\right) - 1\right)$$

$$\gamma_F = Q_l^2 \frac{\alpha}{\pi}\left(\ln\left(\frac{\hat{s}zuu'}{m_l^2}\right) - 1\right)$$

$$\tilde{\gamma}(\cos\theta) = 2Q_q Q_l \frac{\alpha}{\pi} \ln\left(\frac{1-\cos\theta}{1+\cos\theta}\right),$$

$\hat{s}$ = scale of generated quarks, $z = 1 - v_I, z' = 1 - v_F$ where v_I, v_F are energy fractions for total ISR and FSR, and u, u' parametrize energies associated with IFI. The ρ factors all have the same form,

$$\rho(\gamma, z) = F(\gamma)\gamma(1-z)^{\gamma-1}, \qquad F(\gamma) = \frac{e^{-C_E\gamma}}{\Gamma(1+\gamma)} = \int_0^1 \rho(\gamma, z) dz$$

Quark Mass Dependence of ISR

To leading order, the quark mass enters IFI via

$$\rho(\gamma, z) = F(\gamma)\gamma(1-z)^{\gamma-1}, \qquad \gamma_I = Q_q^2 \frac{\alpha}{\pi}\left(\ln\left(\frac{\hat{s}}{m_q^2}\right) - 1\right)$$

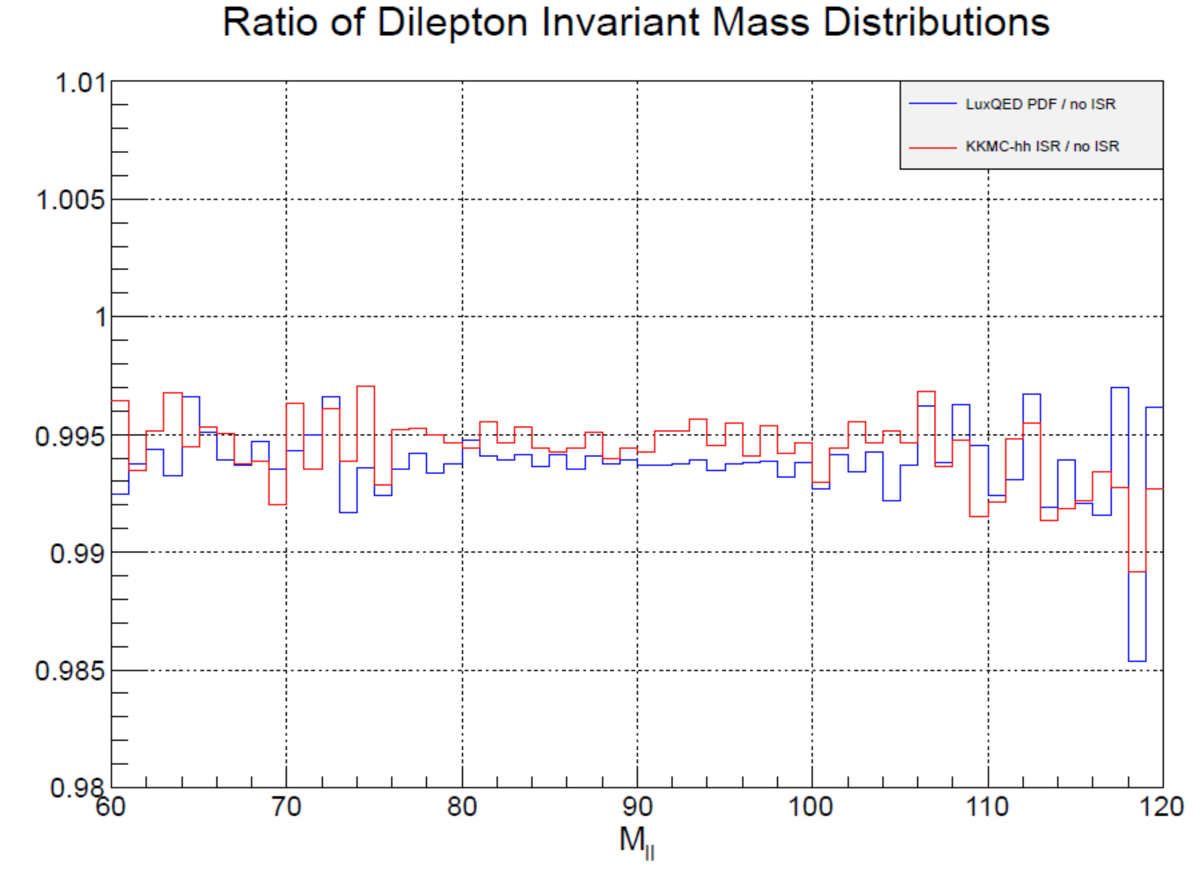
With IFI off, the hard process scale is $s' = \frac{M_{ll}^2}{z'} = z\hat{s}$, and $\sigma(s')$ is multiplied by a factor

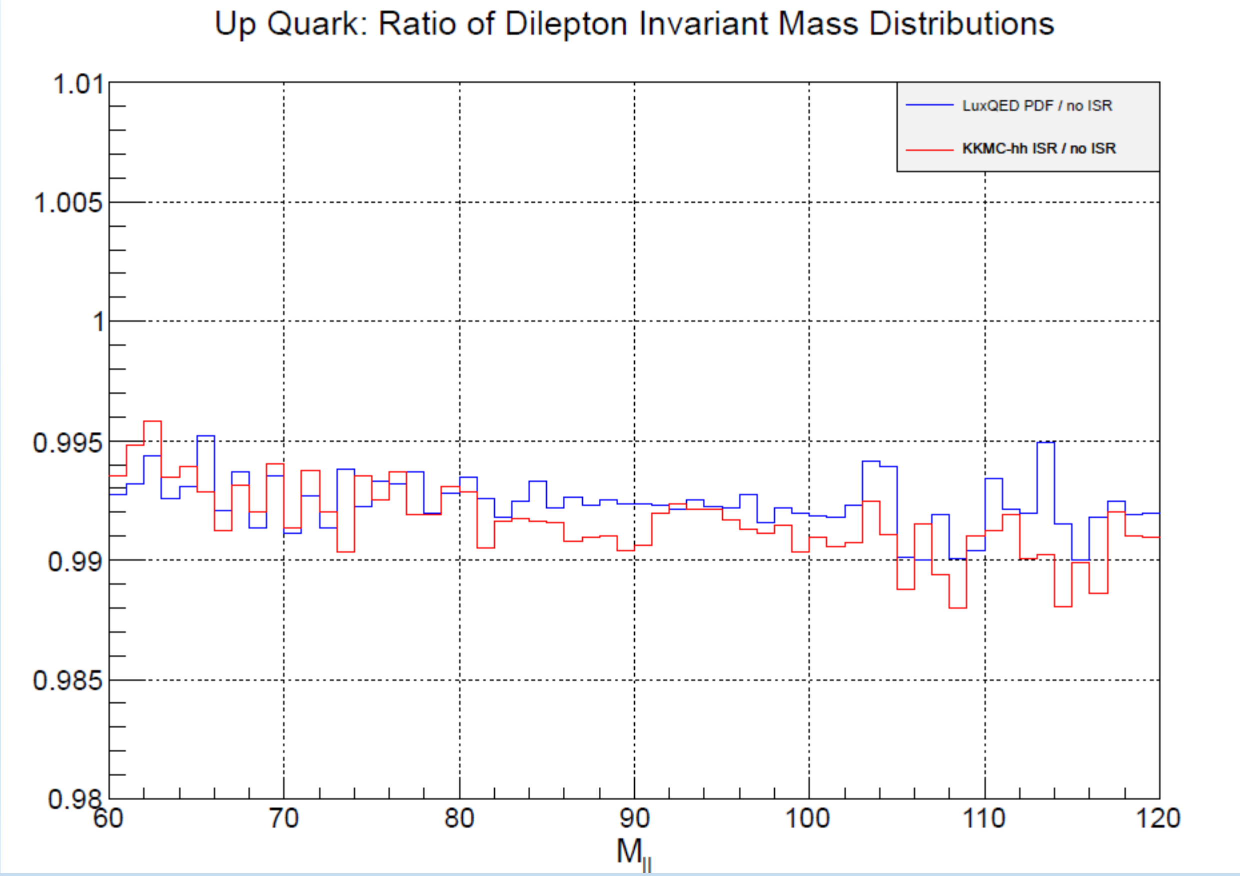
$$\int \frac{dz}{z} f_q^{h_1}(x_1) f_{\bar{q}}^{h_2}(x_2)\rho\left(\gamma_I\left(\frac{s'}{z}\right), z\right)$$

with $s' = s_h x_1 x_2\, z$. When we compare our results to QED-corrected PDFs, we are essentially comparing this factor to a product of PDFs, $\left[f_q^{h_1}(x_1) f_{\bar{q}}^{h_2}(x_2)\right]_{QED}$ that includes QED evolution together with QCD evolution. We would expect these to agree if the QED-corrected PDFs use a compatible definition of the quark masses, but this needs to be checked for any given PDF set. When we started KKMC-hh, MRST-QED was the only option, and it used current quark masses, which is compatible with our choice.

Comparison of ISR corrections to M_{ll} distribution

This is a comparison of the ISR contribution to M_{ll} calculated with KKMChh vs with LuxQED NNPDF. The results are very compatible. The left shows all quarks, the right the up alone.





Quark Mass Dependence of A_{FB}

Unlike ISR or FSR, IFI depends on a logarithm that does not contain a mass, but rather is angle dependent:

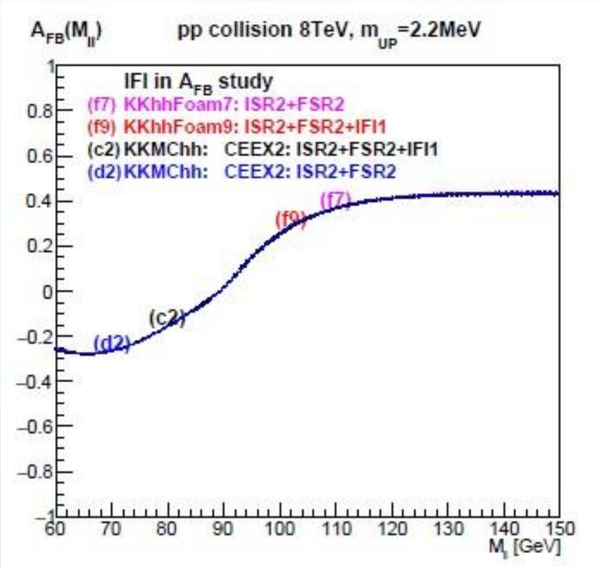
$$\tilde{\gamma}(\cos\theta) = 2Q_q Q_l \frac{\alpha}{\pi} \ln\left(\frac{1-\cos\theta}{1+\cos\theta}\right) ,$$

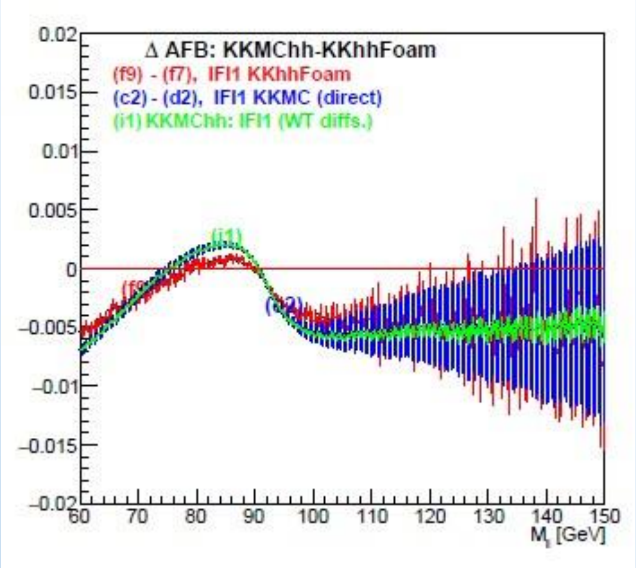
which allows it to have a significant influence on A_{FB}.

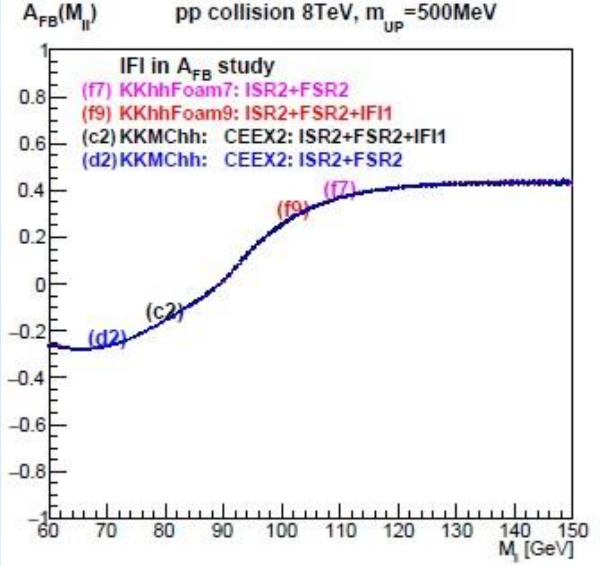
Although this factor does not contain a quark mass, IFI depends on the CM energy, which is linked via ISR to the PDFs, and ISR has a logarithmic dependence on the quark mass, so it is possible that it could affect A_{FB} through IFI, in principle.

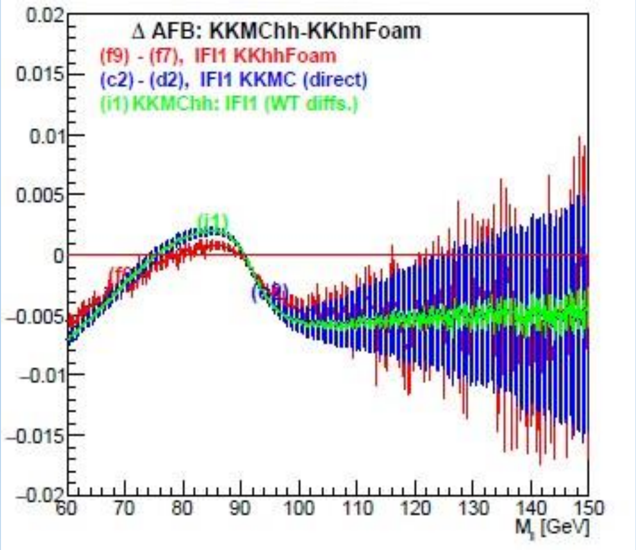
We checked this mass dependence for both up and down quarks – and it was found to be completely negligible, as shown on the following slide for the up quark alont.

A_{FB} for the Up Quark









As an example, the individual up quark contribution to A_{FB} has been compared for up-quark masses of $m_u =$ 2.2 MeV and 500 MeV.

Remarkably, there is no significant change – the mass dependence is completely negligible at this level.

Agreement between KKMC-hh and KKhhFoam is excellent.

Graphs by S. Jadach

A_{FB} for Multiple Quarks

For multiple quarks, it is possible for quark mass dependence to enter through a differential rescaling of each quark's contribution. Only valence quarks have an asymmetry for proton collisions, but all of the quarks enter into the denominator of A_{FB}, and the quark masses can influence these via ISR. This may be the origin of the shift seen in the previous slides.

$$A_{FB} = \frac{\sigma_u^F + \sigma_d^F - \sigma_u^B - \sigma_d^B}{\sigma_u + \sigma_d + \sigma_s + \sigma_c + \sigma_b}$$

If each of the terms in the numerator and denominator were rescaled by a factor depending only on the quark, the individual asymmetries would be independent of this scale, but the total would not have to be.

Summary

We have repeated the exercises with NNPDF using MMHT and found very similar results for the IFI and ISR contribution to A_4 and A_{FB}.

KKMC-hh gives compatible results for both of these, but their QED versions give somewhat different shifts in A_4, which are more significant than those seen from KKMC-hh's ISR.

With the fermion cuts, these differences become less significant (A_{FB}).

Changing the light quark masses by a factor of 10 has little influence on the ISR contribution to the asymmetries, but gives a noticeable shift in the IFI contribution.

KKhhFoam is a new tool which shows promise in providing a deeper understanding of the role of quark masses and the interaction of KKMC with parton distribution functions. We expect to have more results from it soon.

We are also beginning to integrate KKMC-hh with the current Herwig7, which will give a route to incorporating NLO QCD effects soon. KKMC-hh is now completely in C++, to facilitate this.