Update on KKMC-hh Calculations

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

KKMC-hh: Introduction

- KKMC-hh is an event generator for $pp \to f\bar{f} + n\gamma, f = e, \mu, \tau$, based on KKMC, which was used at LEP with a precision tag of 0.2% (LEP2).
- ISR and FSR γ emission are included to $\mathcal{O}(\alpha^2 L)$ including interference (IFI)
- The MC structure is based on CEEX (Coherent Exclusive Exponentiation), which is similar to YFS exponentiation but implemented at the level of spinor amplitudes.
- CEEX was introduced because traditional YFS exponentiation ("EEX" in KKMC-hh) suffers from a proliferation of interference terms, and is wll suited to calculating IFI.
- $\mathcal{O}(\alpha)$ electroweak corrections are added via DIZET 6.21.
- τ decay is implemented using TAUOLA.
- Events can be showered with HERWIG6.521 internally, or externally with any LHA-compatible shower.

Standard Model Parameters

DIZET uses a scheme $(\alpha(0)v_0)$ with input parameters $G_\mu, \alpha(0), M_Z$. The other EW parameters are then calculated. M_W is calculated with EW corrections. DIZET uses quark masses depending on the hadronic vacuum polarization option selected. Those shown are for the default Jegerlehner fit (IHVP = 1). KKMC uses $\alpha(0)$ and quark current masses (in parentheses) for photonic ISR corrections. Input α_s values are shown also.

$1/\alpha(0)$	137.03599991	$1/\alpha(M_Z)$	128.885
G_F	1.16637×10^{-5} GeV^{-2}		
$\sin^2(\theta_\mathrm{W})$	0.22339867	$\sin^2(\theta_\mathrm{W})_\mathrm{eff}$	0.23171962
M_Z	91.1876 GeV	Γ_Z	2.4952 GeV
M_W	80.3591 GeV	Γ_W	2.085 GeV
M_H	125 GeV	m_d	83 MeV (4.7 MeV)
m_u	62 MeV (2.2 MeV)	m_s	215 MeV (150 MeV)
m_c	1.5 GeV (1.2 GeV)	m_b	4.7 GeV (4.6 GeV)
m_t	173.5 GeV (173.5 GeV)	m_e	510.999 keV
m_u	105.6583 MeV	m_τ	1.777 GeV
$\alpha_s(M_Z)$	0.012018	$\alpha_s(m_t)$	0.1094

ISR: QED PDFs vs KKMC-hh

QED ISR enters the angular distributions at the order of several per-mil, and cannot be neglected.

There are two options for handling the collinear singularities arising:

1. Use a calculation that factorizes collinear ISR effects and absorbs them into PDFs with a PDF that includes the collinear QED. Several are available. Current studies have focused on NNPDF3.1 NLO with LuxQED.
2. Use a complete ab-initio QED calculation, including collinear contributions regulated by quark masses, with a PDF that does not contain QED effects. The result will depend parametrically on quark masses. KKMC-hh follows this approach.

The two approaches should agree for variables which are not strongly sensitive to photon P_{T}.

The connection between these approaches should be studied in detail. KKMC-hh can be useful in such studies. Comparisons of quark momentum distributions could help determine the most appropriate values of the light quark masses.

Results from KKMC-hh

- The following tests are based on runs generating 5.7×10^9 muon events at 8 TeV, using NNPDF3.1 NLO PDFs ($\alpha_s(M_Z) = 0.12018$). **The QCD shower is off in these results.**
- All results include a dilepton mass cut $60 \text{ GeV} < M_{ll} < 116 \text{ GeV}$.
- **Uncut** / **Without cuts** means there are no additional cuts.
- **Cuts** / **With cuts** means there is a cut $P_T > 25 \text{ GeV}, |\eta| < 2.5$ on the individual muons.
- Levels of photonic corrections:
    1. FSR only using KKMC-hh with non-QED NNPDF3.1 NLO
    2. FSR + ISR using KKMC-hh with non-QED NNPDF3.1 NLO
    3. FSR + ISR + IFI using non-QED NNPDF3.1 NLO (KKMC-hh best result)
    4. FSR + LuxQED using KKMC-hh with NNPDF3.1 NLO + QED

All KKMC-hh photonic corrections are calculated using CEEX exponentiation with exact $\mathcal{O}(\alpha^2 L)$ residuals.

Numerical Results

Column 1 includes FSR only, with a non-QED PDF. Column 2 has FSR with LuxQED. Column 3 has KKMC-hh ISR + FSR with a non-QED PDF. Column 5 adds KKMC-hh IFI.

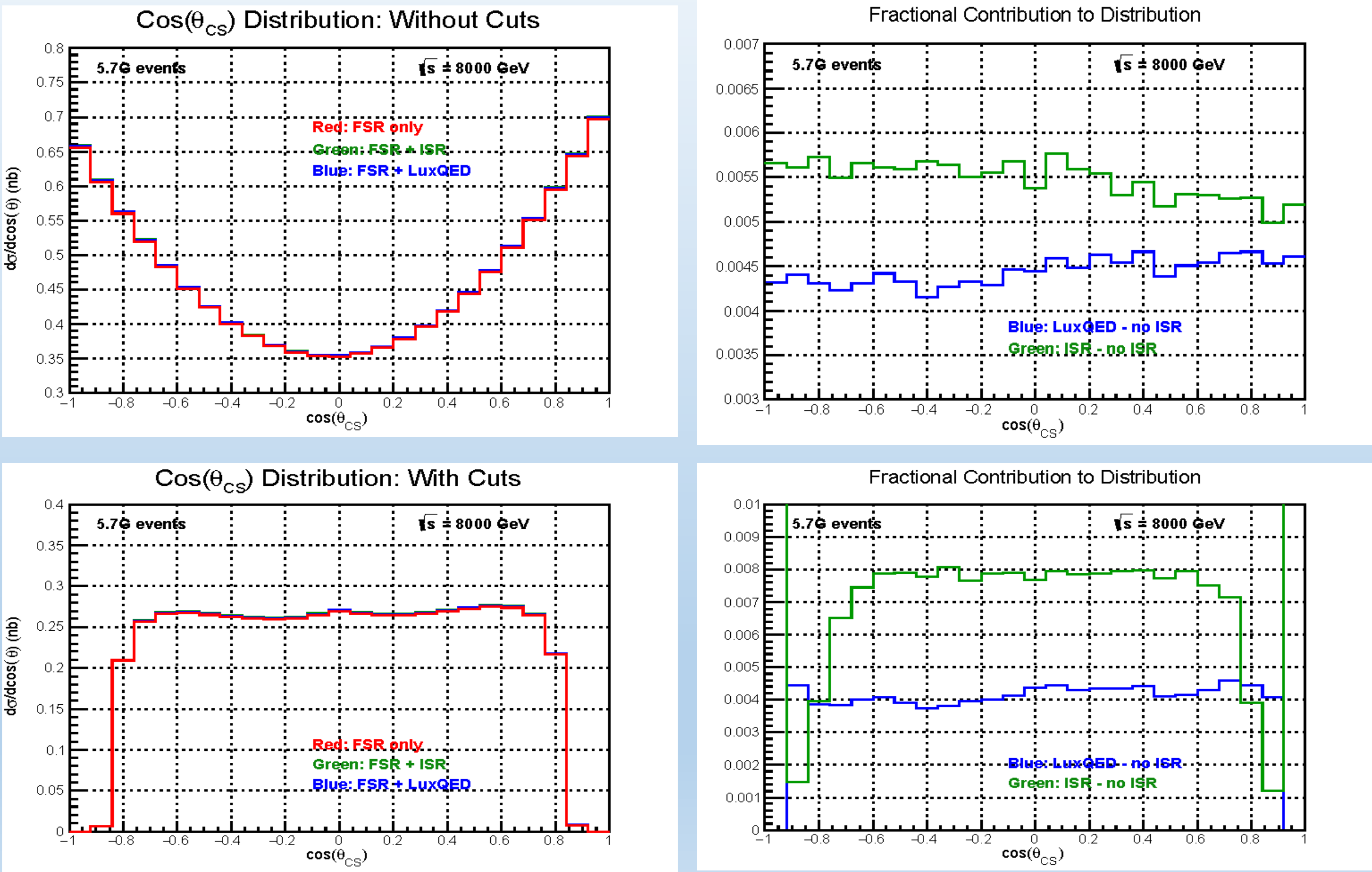
	1. No ISR	2. LuxQED	3. KKMC-hh ISR	4. %(ISR – no ISR)	5. With IFI	6. %(IFI – no IFI)
Uncut σ (pb)	939.858(7)	944.038(7)	944.99(2)	0.546 (2)%	944.91(2)	−0.0089(4)%
Cut σ (pb)	439.103(7)	440.926(7)	442.36(1)	0.742(3)%	442.33(1)	−0.0070(5)%

KKMC-hh shows an ISR effect of a fraction of a percent. LuxQED shows a slightly smaller effect, about 0.4% for each cross section. KKMC-hh shows an IFI effect below 0.1%.

	1. No ISR	2. LuxQED	3. KKMC-hh ISR	4. ISR – no ISR	5. With IFI	6. IFI – no IFI
$A_{\rm FB}$	0.01125(2)	0.01145(2)	0.01129(2)	$(3.9 \pm 2.8) \times 10^{-5}$	0.01132(2)	$(2.9 \pm 1.1) \times 10^{-5}$
A_4	0.06102(3)	0.06131(3)	0.06057(3)	$-(4.4 \pm 0.5) \times 10^{-4}$	0.06102(3)	$(4.5 \pm 0.3) \times 10^{-4}$

The ISR and IFI effects on $A_{\rm FB}$ is of order 10^{-5} while the effect on $A_4$is of order 10^{-5} in KKMC-hh. LuxQED gives a bigger ISR effect, on the order of 10^{-4} for both $A_{\rm FB}$ and A_4.

ISR contributions to CS angle distribution



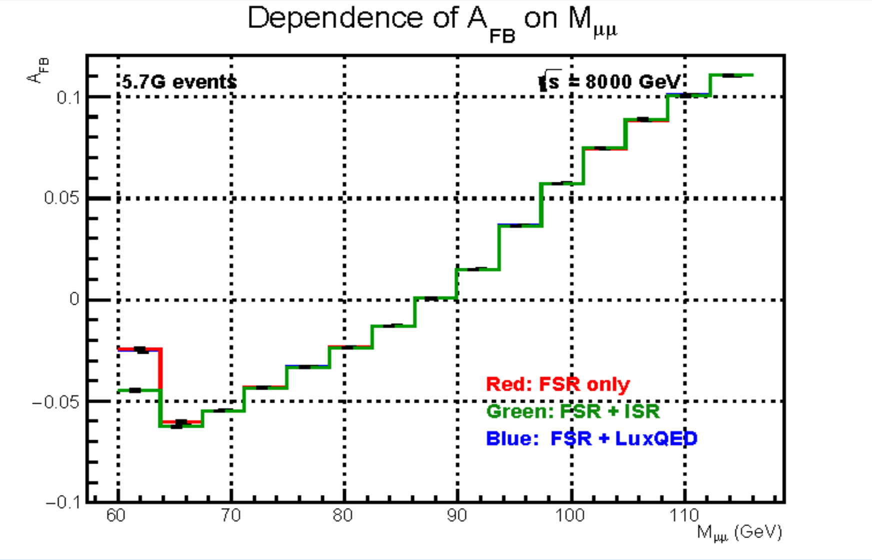
Without Lepton Cuts (used for A_4)

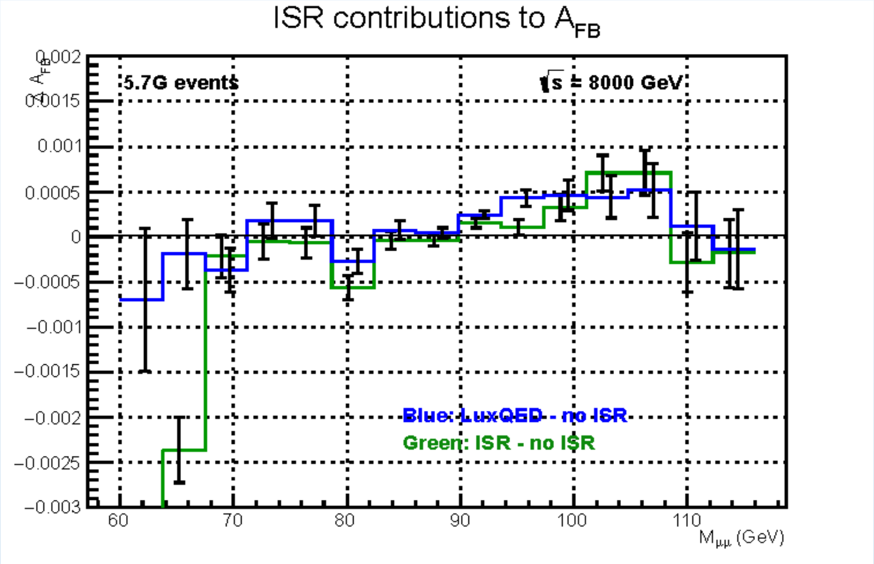
- **LuxQED** is in **blue**.
- **KKMC-hh ISR** in **green**.
- **Red** line has **FSR only** – the baseline here.

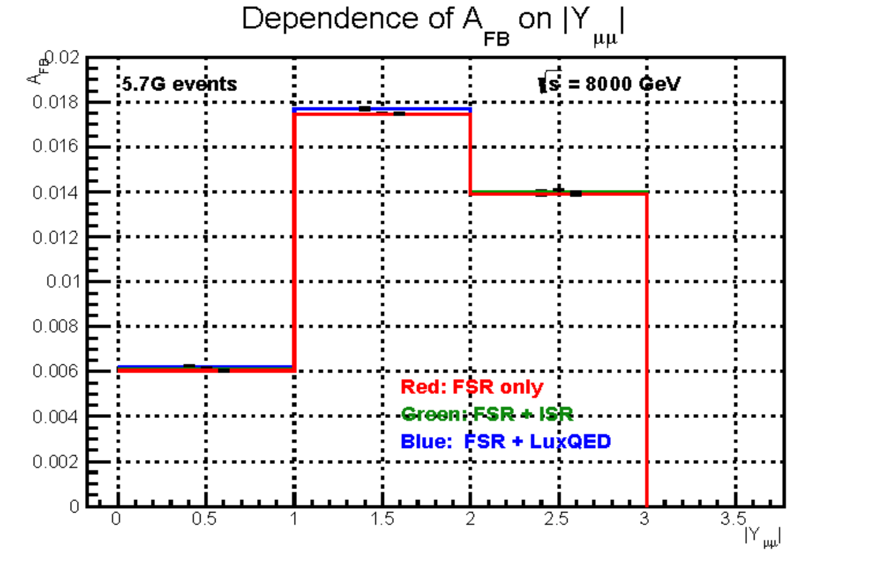
With Lepton Cuts (used for A_{FB})

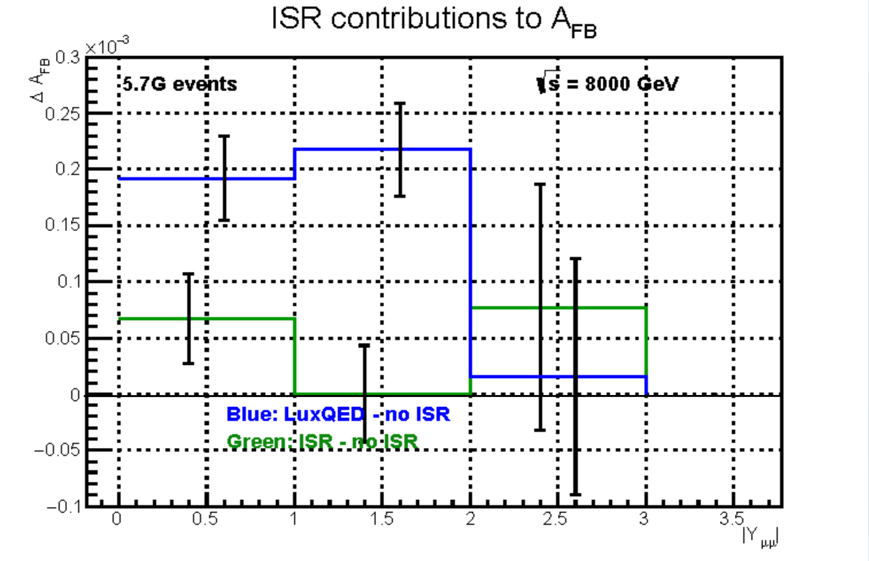
- ISR enters at the per-mil level.

ISR contributions to A_{FB} (with lepton cuts)







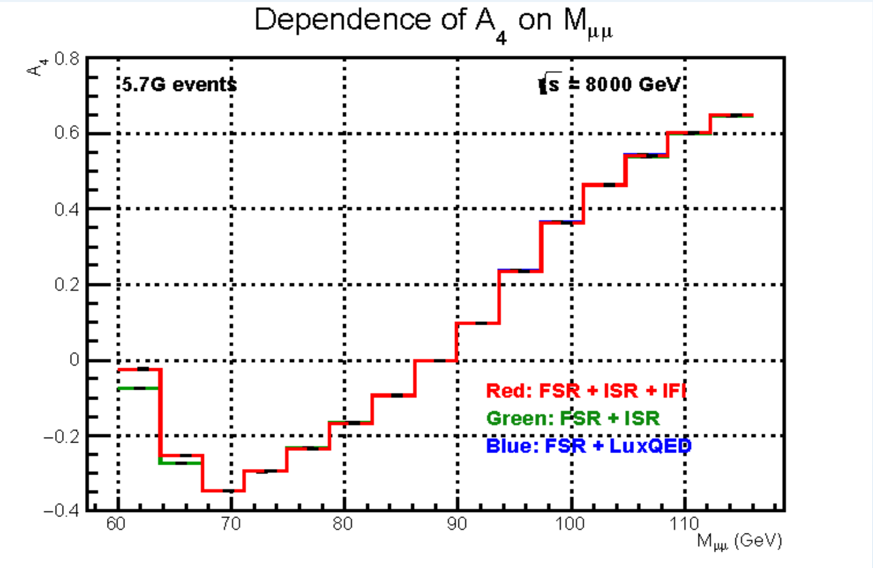


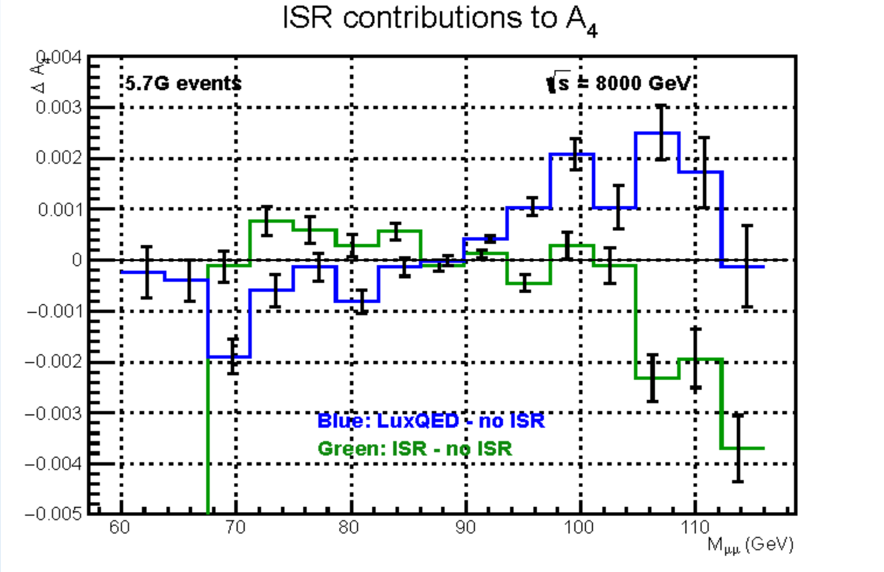
The ISR contribution to A_{FB} is typically on the per-mil level.

For most M_{ll} of interest, LuxQED and KKMC-hh produce very similar ISR effects.

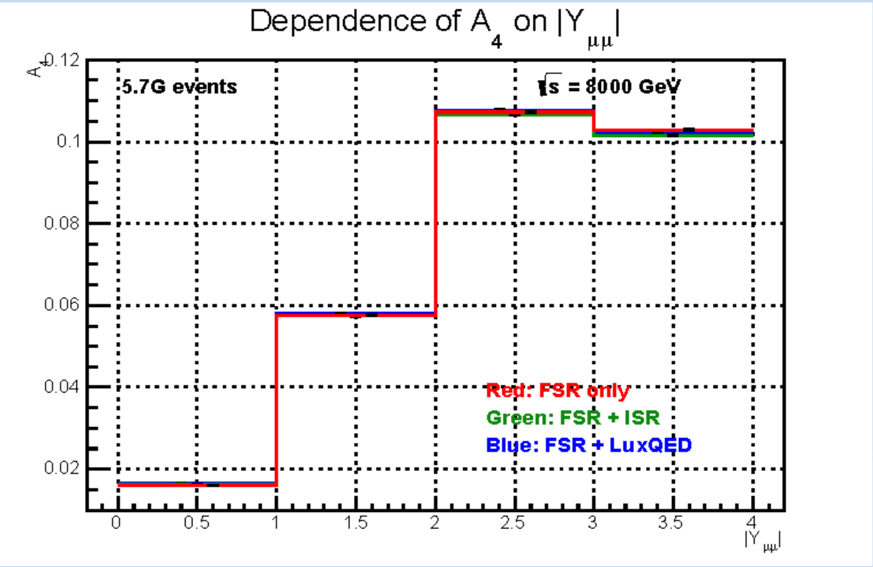
Integrating over M_{ll} and binning in $|Y_{ll}|$, both LuxQED and KKMC-hh give ISR contributions on the order of 10^{-4}, with the KKMC-hh correction smaller at low rapidities.

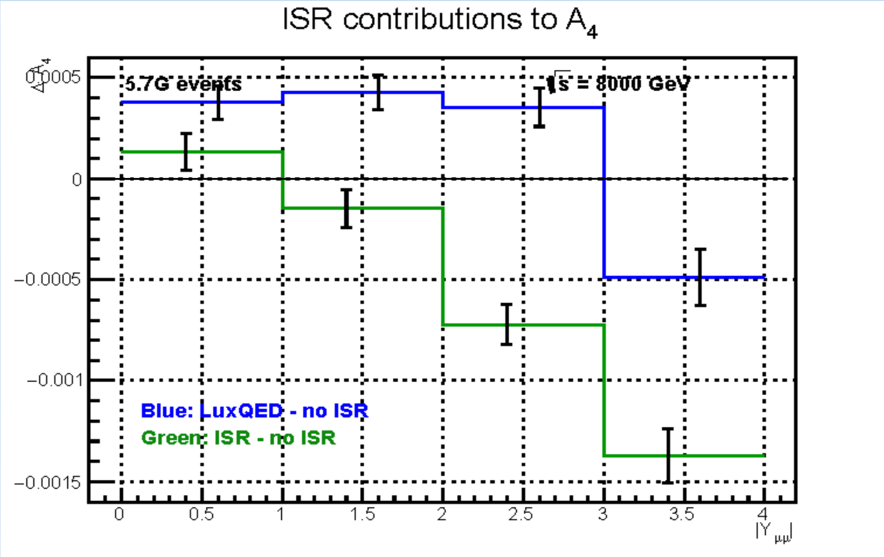
ISR contributions to A_4 (without lepton cuts)





The ISR contribution to A_4 is typically on the order of 10^{-3}, but differs in detail between LuxQED and KKMC-hh.



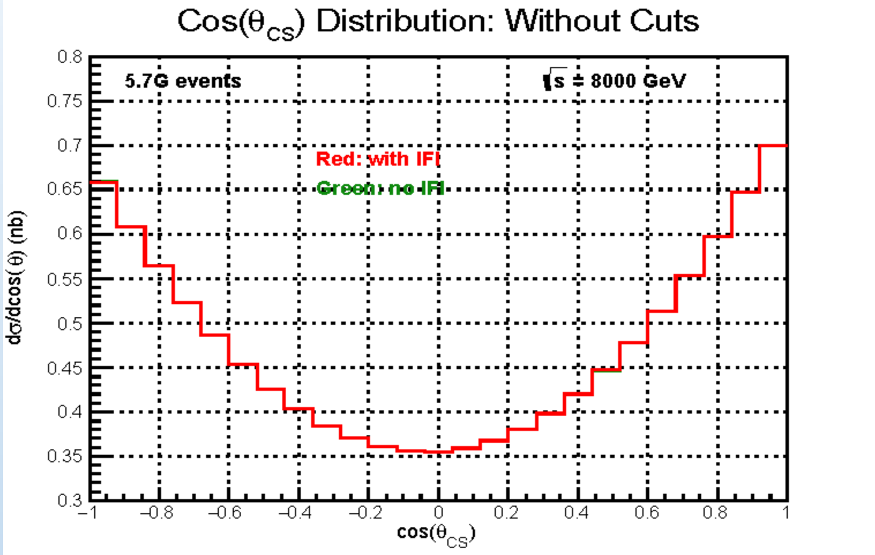


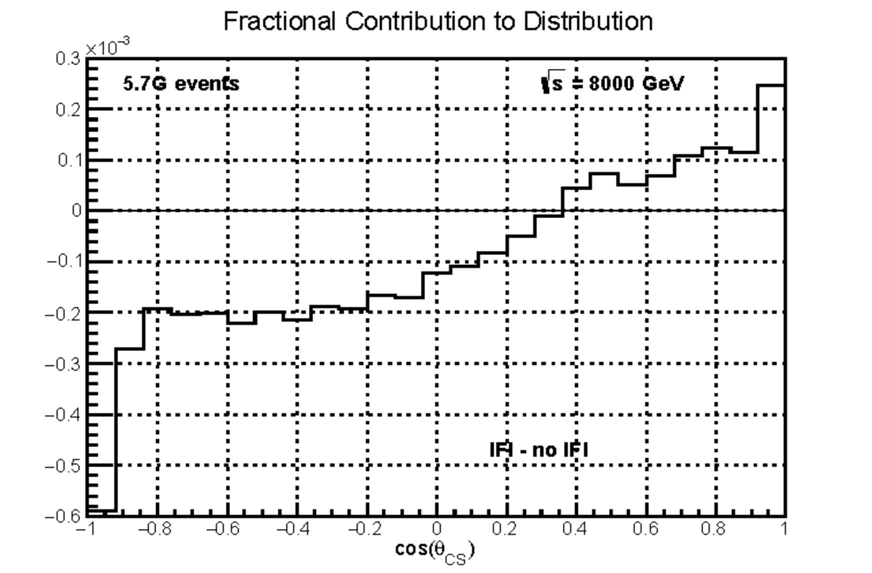
When integrated over M_{ll} and binned in $|Y_{ll}|$, the ISR contribution is a little smaller, and of order 10^{-4} for KKMC-hh at low rapidities.

Initial-Final Interference

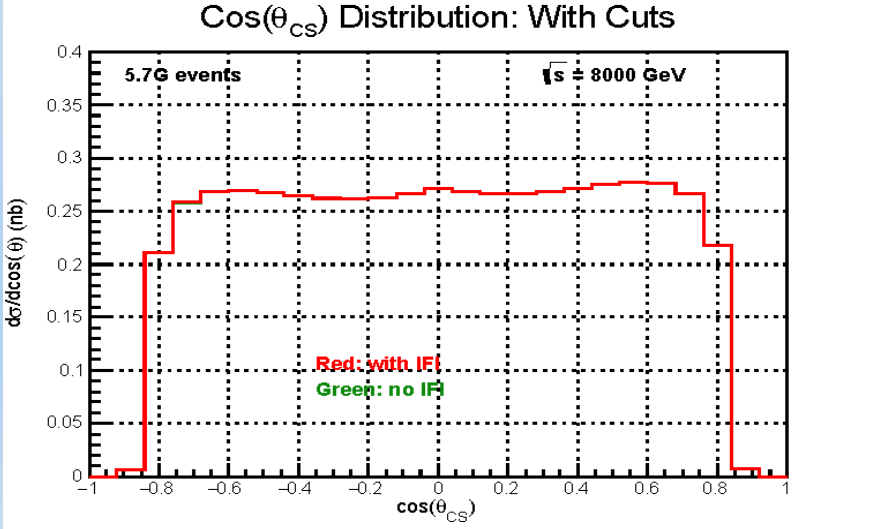
- Due to Initial-Final Interference (IFI), it is not possible to unambiguously separate photon radiation into ISR and FSR. This complicates the interpretation of A_{FB} and A_4 unless IFI can be shown to be sufficiently small.
- Exponentiation at the amplitude level (CEEX), in stead of the cross section level (YFS) facilitates the calculation of interference effects. This is one of the primary reasons CEEX was introduced, when effects at this level became relevant at LEP.
- IFI is implemented in CEEX by dividing the generated photons into partitions of ISR and FSR, and summing over all such partitions.
- The following slides compare KKMC-hh results with IFI turned on or off. The effect on angular variables is shown in terms of M_{ll} and Y_{ll} bins.

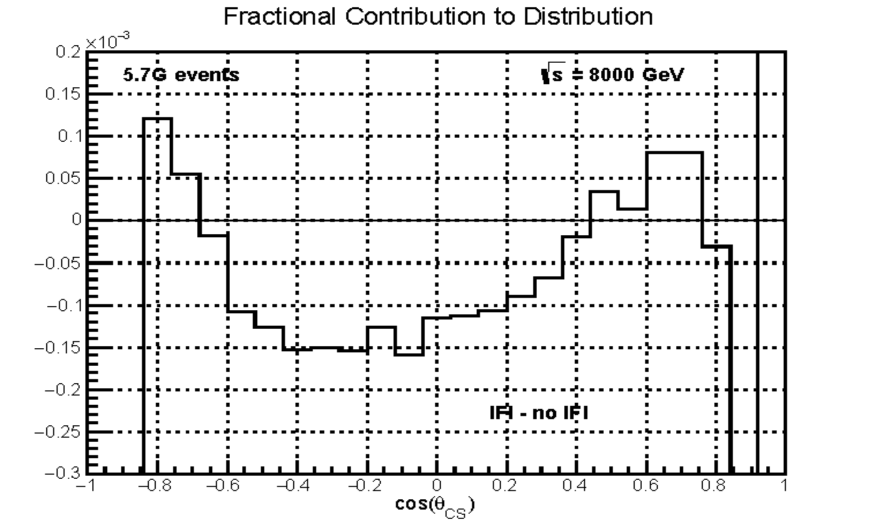
IFI contribution to CS angle distribution





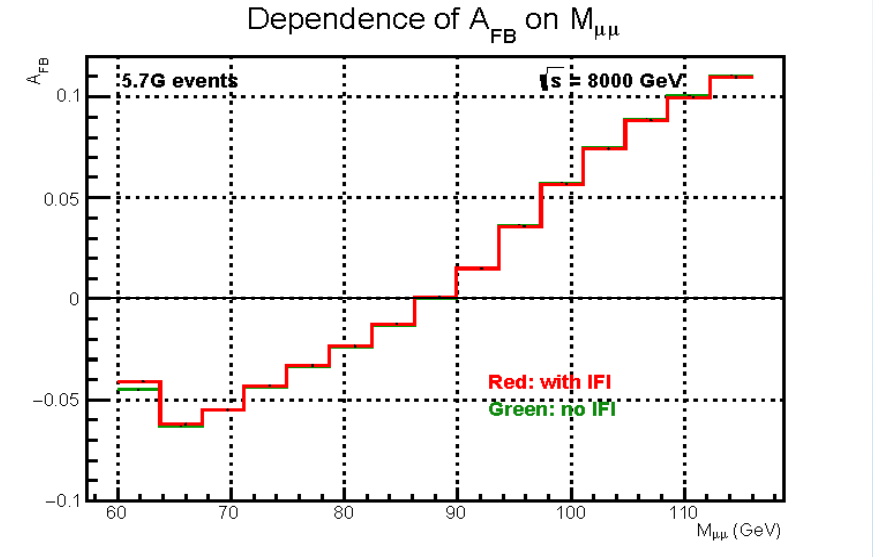
- Without Lepton Cuts (for A_4)

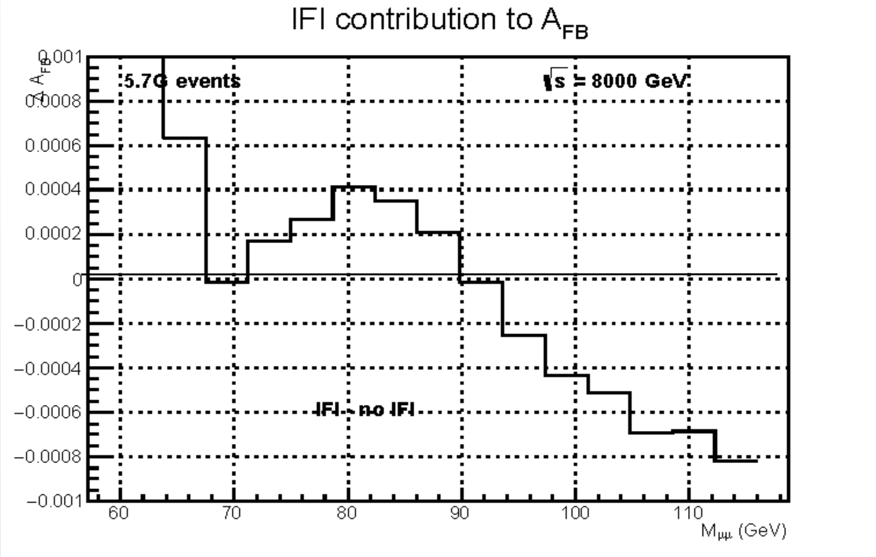


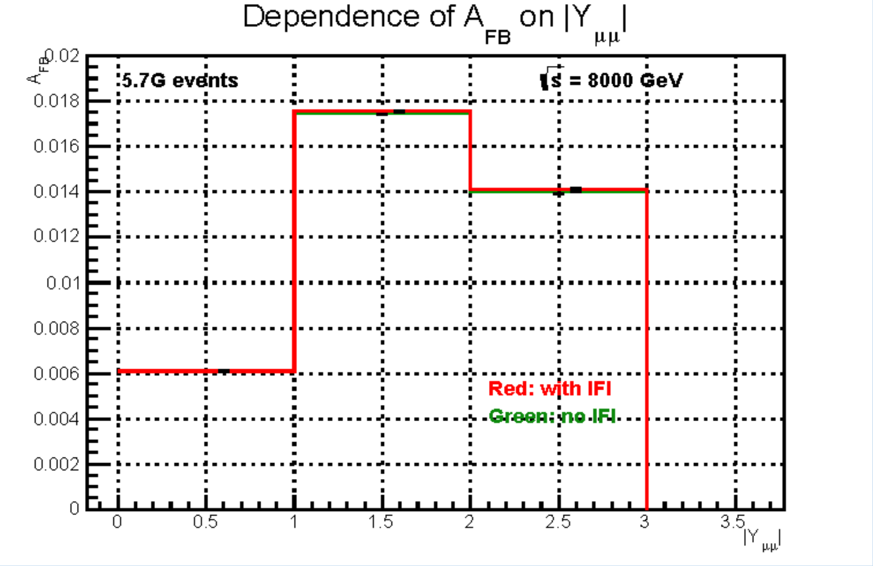


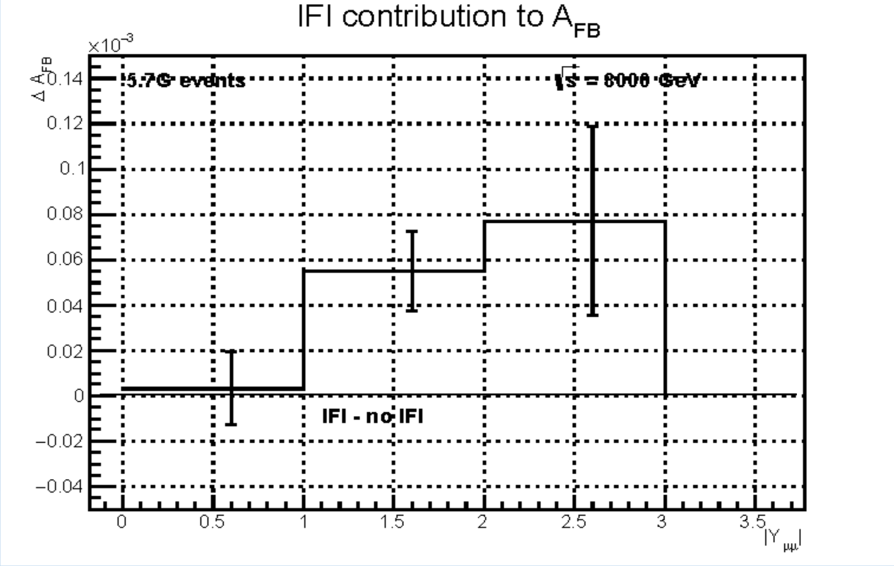
- With Lepton Cuts (for A_{FB})

IFI contribution to A_{FB} (with lepton cuts)



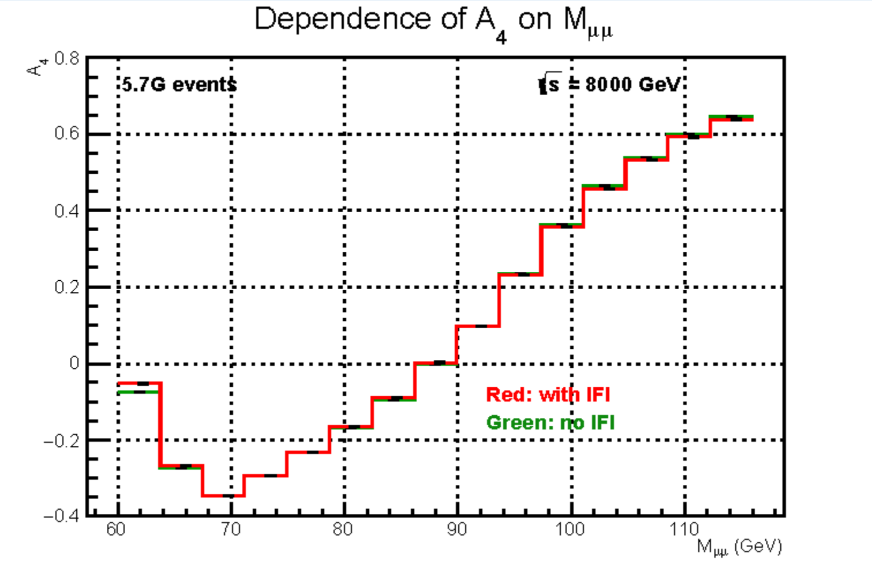


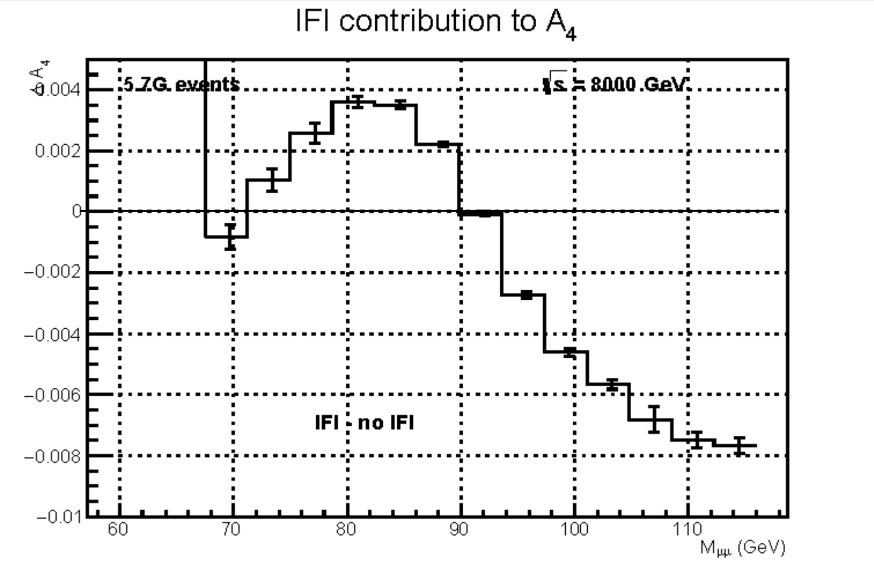




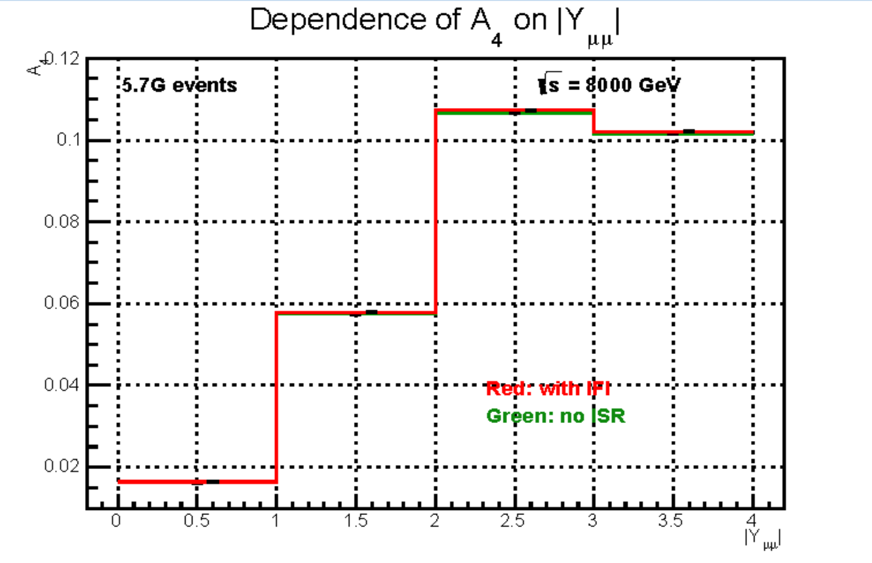
- The IFI contribution to A_{FB} is generally less than 10^{-3}.
- When integrated over M_{ll}, the IFI contribution is typically less than 10^{-4}, and much less for small rapidities.

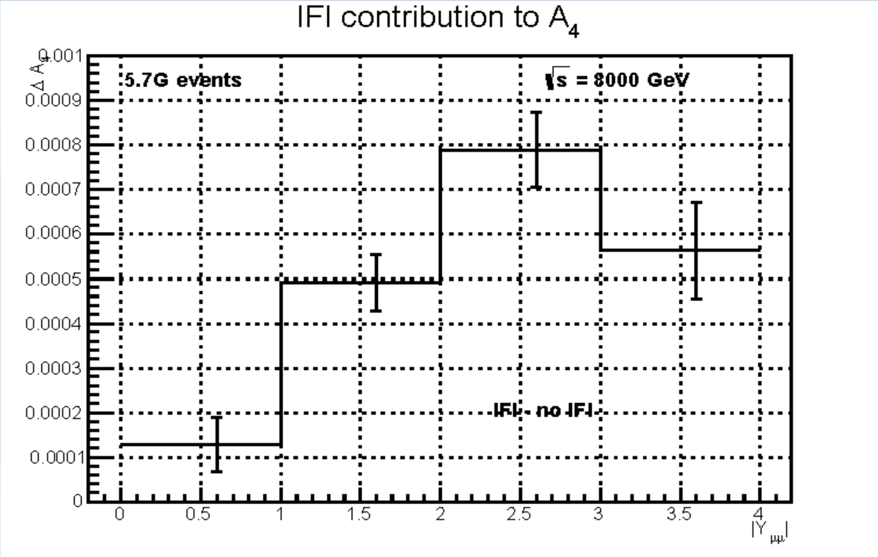
IFI contribution to A_4 (without lepton cuts)





- The IFI contribution to A_4 is generally less than 10^{-2} but depends on M_{ll}.





- When integrated over M_{ll}, the IFI contribution is generally less than 10^{-3}, and very small for some rapidities.

Showered Results

Due to available run-time, showered results are available only for a single 8 TeV run with 1.1×10^9 events, compared to 5.7×10^9 unshowered events used for the previous results.

The built-in HERWIG 6.21 LO shower is used here.

In this run, KKMC-hh ISR and IFI are on, and the non-QED NNPDF 3.1 NLO is used.

The numerical effect of the shower on the cross section and to A_{FB} and $A_4$is shown here:

	Without Shower	**With Shower**	**% Difference**
Uncut σ (pb)	$944.91(2)$	$938.44(4)$	$-0.684(7)\%$
Cut σ (pb)	$442.33(1)$	$412.54(3)$	$-6.730(7)\%$

	Without Shower	**With Shower**	**Difference**
A_{FB}	$0.01132(2)$	$0.01211(5)$	$0.00109(5)$
A_4	$0.06102(3)$	$0.06052(8)$	$-0.00050(8)$

Showered Results: IFI Contributions to σ

The following tables compare the IFI contributions to the cross section with and without fermion cuts.

Uncut σ	No IFI (pb)	With IFI (pb)	% Difference
No Shower	$944.99(2)$	$944.91(2)$	$-0.0089(4)$ %
Shower	$938.46(4)$	$938.44(4)$	$-0.002(1)$ %
% Difference	$-0.691(5)$ %	$-0.684(5)$ %	$0.007(1)$ %

Cut σ	No IFI (pb)	With IFI (pb)	% Difference
No Shower	$442.36(1)$	$442.33(1)$	$-0.0070(5)$ %
Shower	$412.54(3)$	$412.56(3)$	$-0.004(2)$ %
Difference	$-6.741(7)$ %	$-6.730(7)$ %	$0.011(2)$ %

In each case, the IFI contribution is significantly smaller with the shower on.

Showered Results: IFI Contributions to A_{FB}, A_4

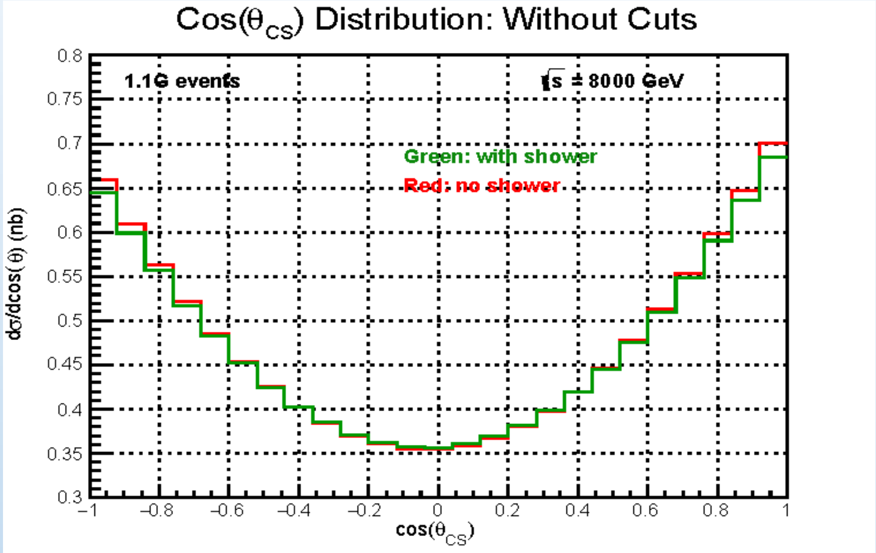
The following tables compare the IFI contributions to A_{FB} and A_4.

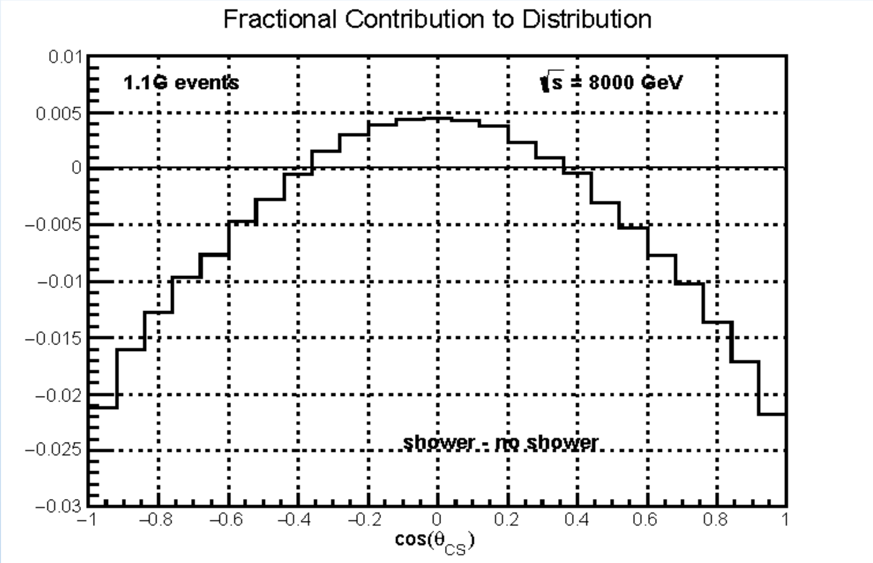
A_{FB}	No IFI (pb)	With IFI (pb)	Difference
No Shower	$0.01129(2)$	$0.01132(2)$	$(2.9 \pm 1.1) \times 10^{-5}$
Shower	$0.01235(5)$	$0.01241(5)$	$(5.8 \pm 2.6) \times 10^{-5}$
Difference	$0.00106(5)$	$0.00109(5)$	$(2.9 \pm 2.8) \times 10^{-5}$

A_4	No IFI (pb)	With IFI (pb)	Difference
No Shower	$0.06057(3)$	$0.06102(3)$	$(4.5 \pm 0.3) \times 10^{-4}$
Shower	$0.06003(8)$	$0.06052(8)$	$(4.9 \pm 0.8) \times 10^{-4}$
Difference	$-0.00055(8)$	$-0.00050(8)$	$(4.3 \pm 8.5) \times 10^{-5}$

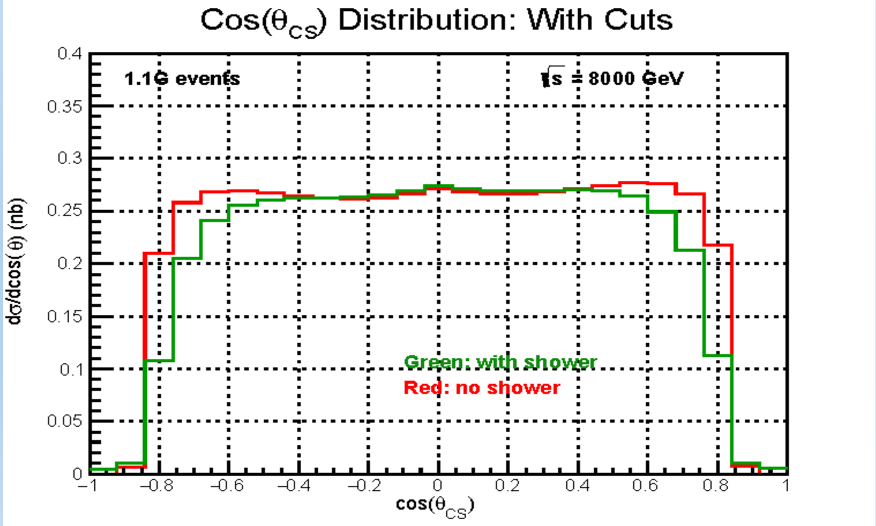
The effect of the shower on the IFI contribution is statistically insignificant for A_4 and barely significant, of order 10^{-5}, for A_{FB}.

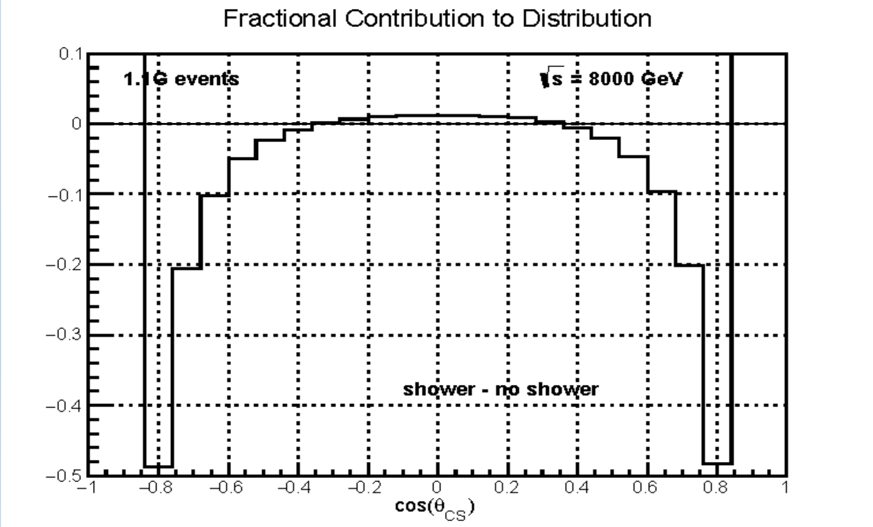
Showered contributions to angular distribution





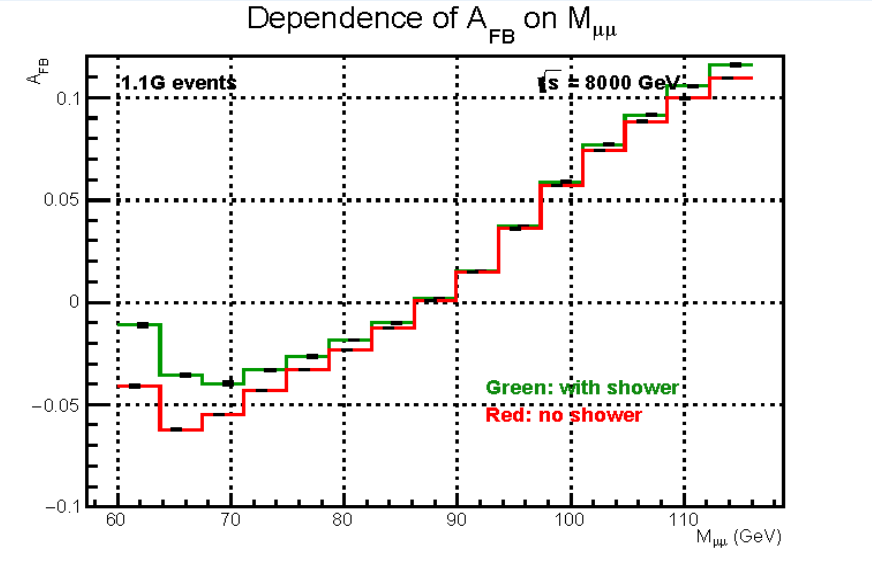
Without Lepton Cuts (for A_4)

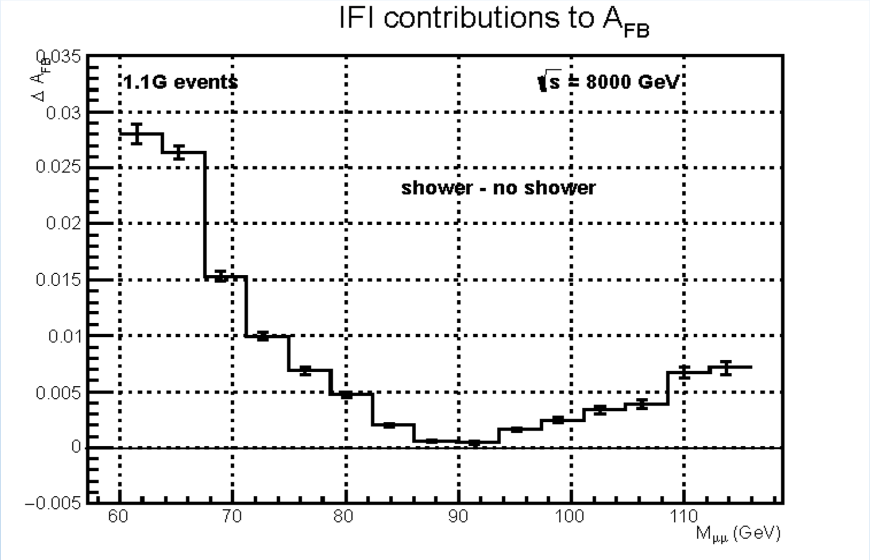




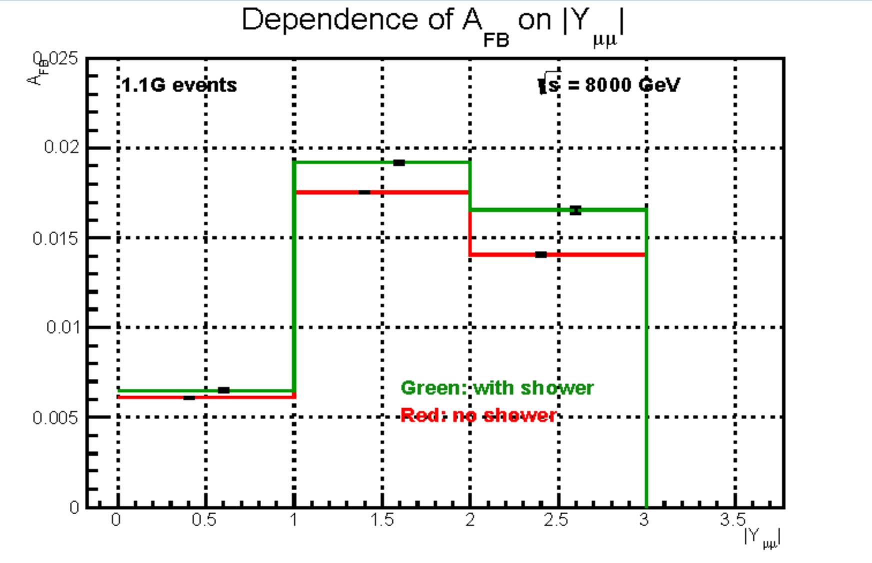
With Lepton Cuts (for A_{FB})

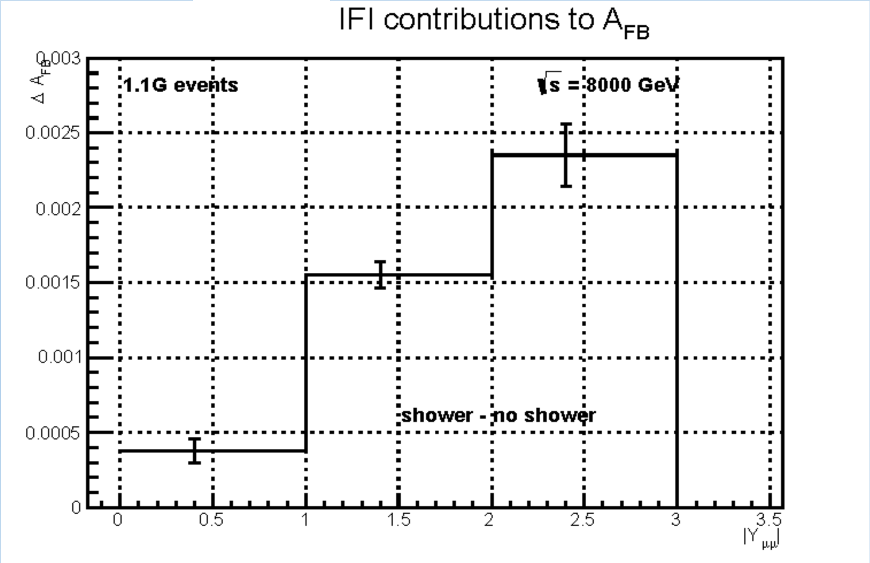
Showered contributions to A_{FB}





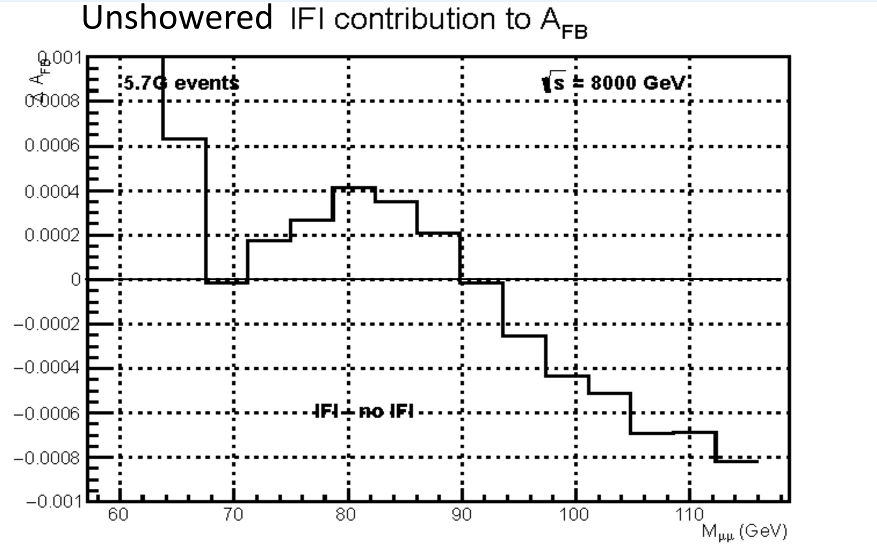
The effect of the shower on A_{FB} increases for M_{ll} away from M_Z where A_{FB} is suppressed.

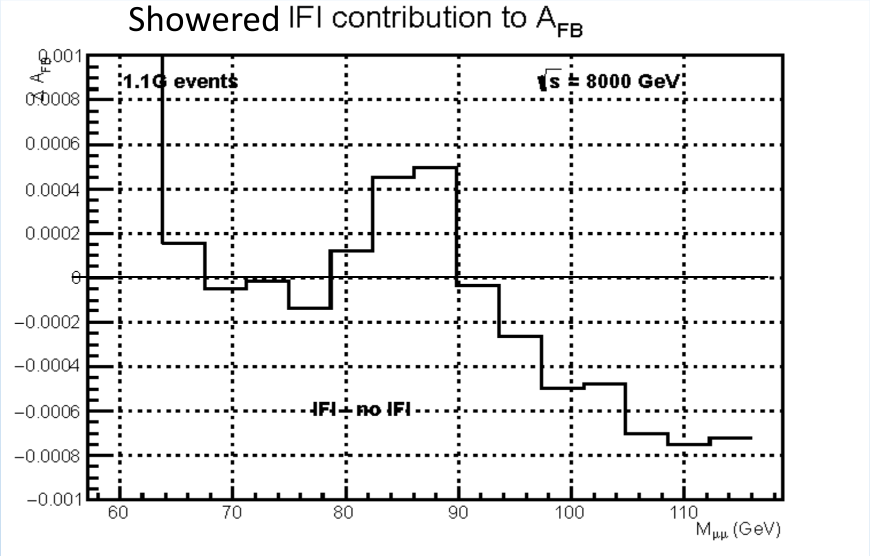




The effect of the shower on A_{FB} increases for larger rapidities Y_{ll}.

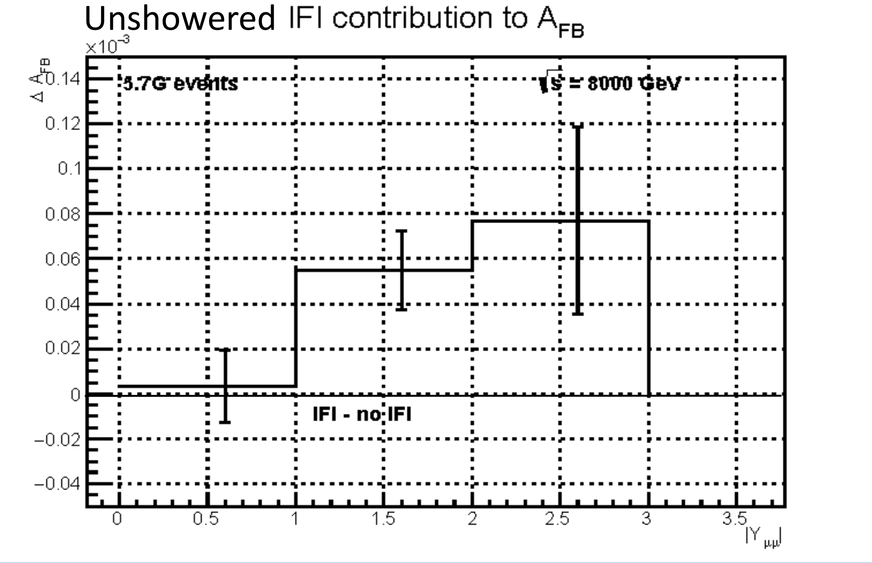
IFI contribution to A_{FB} with and without shower

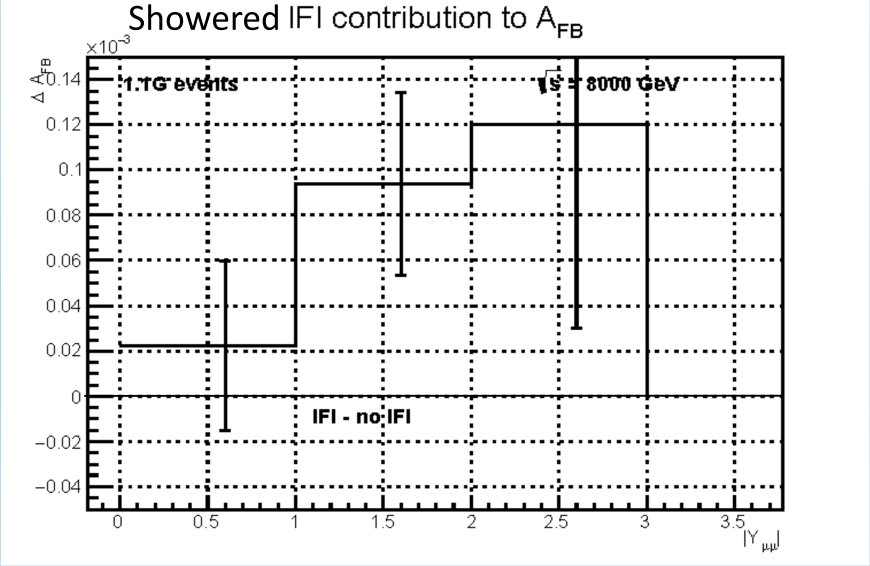




Dimuon M_{ll} bins

The differences between IFI and no-IFI results is shown

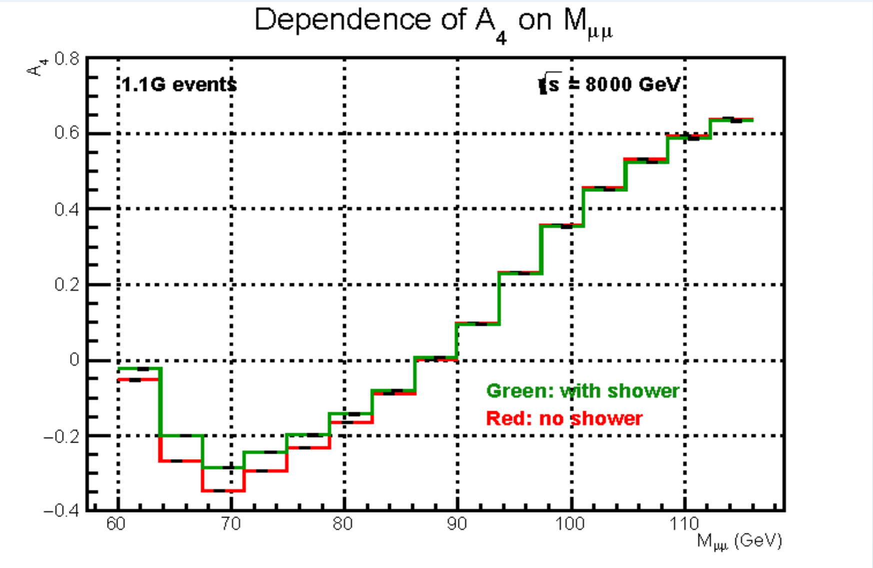


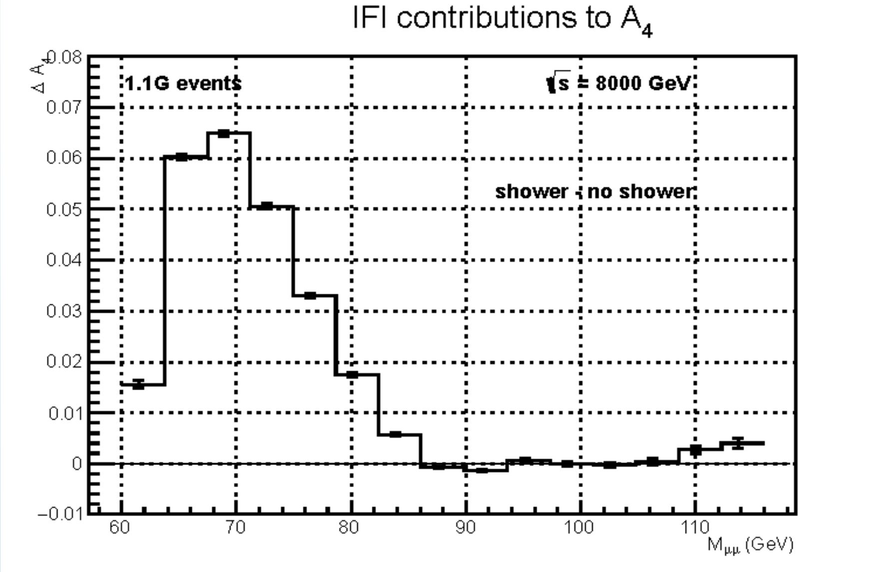


Dimuon $|Y_{ll}|$ bins

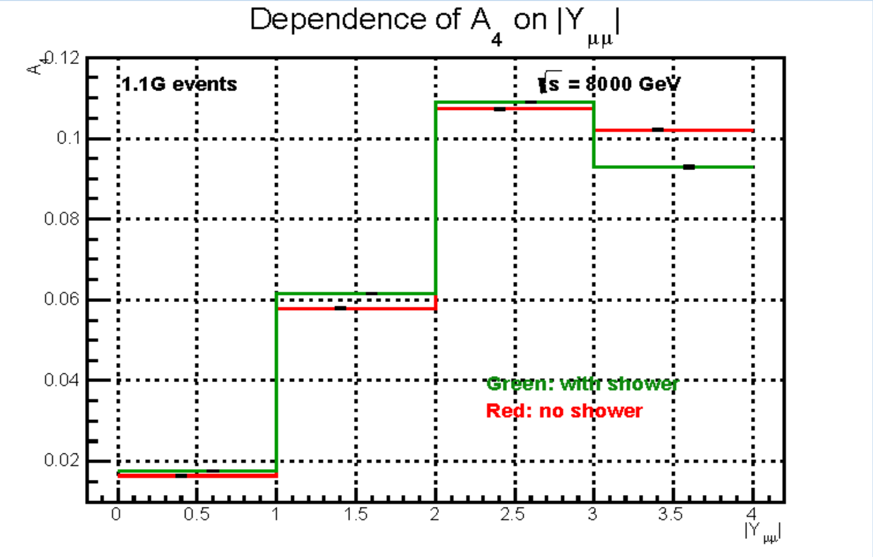
Unshowered results are on the left, showered on the right.

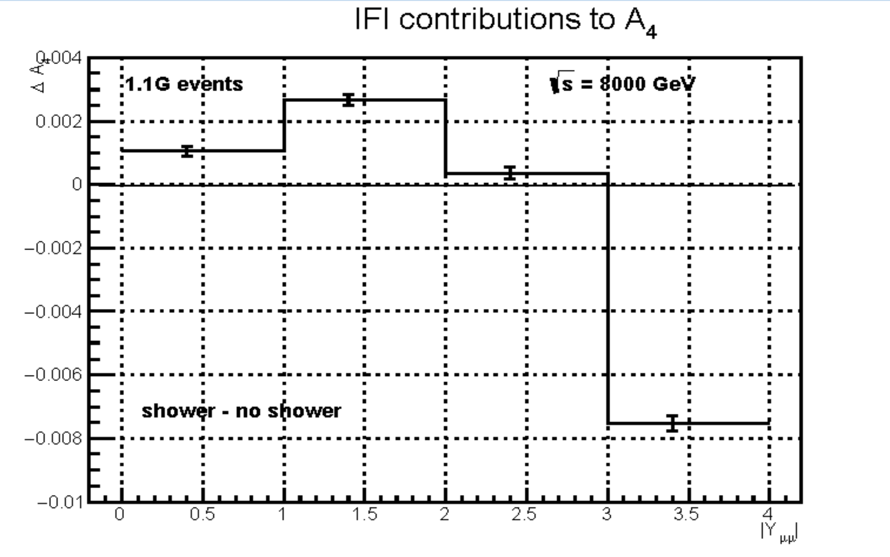
Showered contributions to A_4





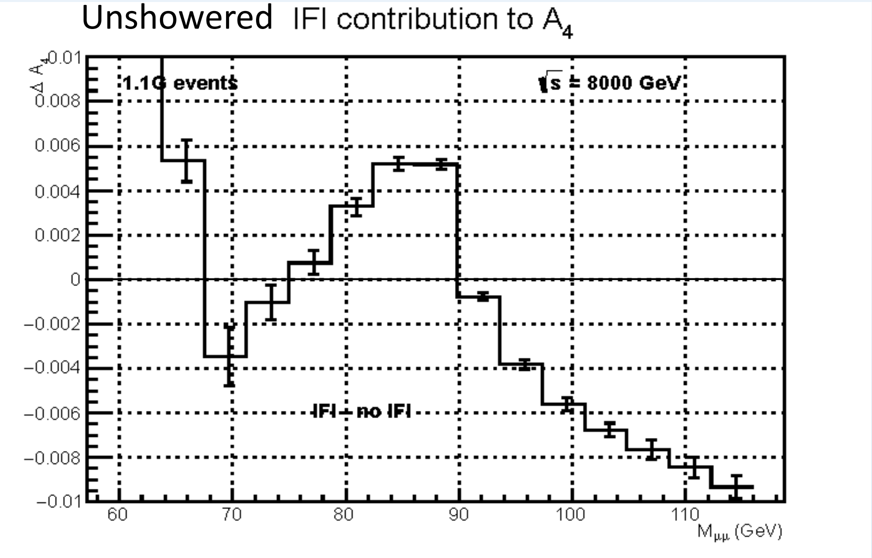
The effect of the shower on $A_4$is small for $M_{ll} \geq M_Z$.

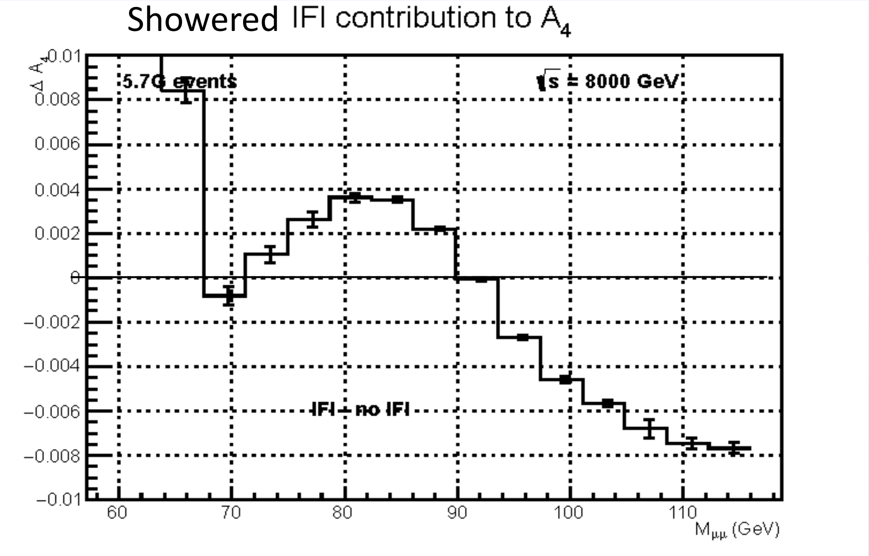




The effect of the shower on A_4 is fairly small except for large rapidity Y_{ll}.

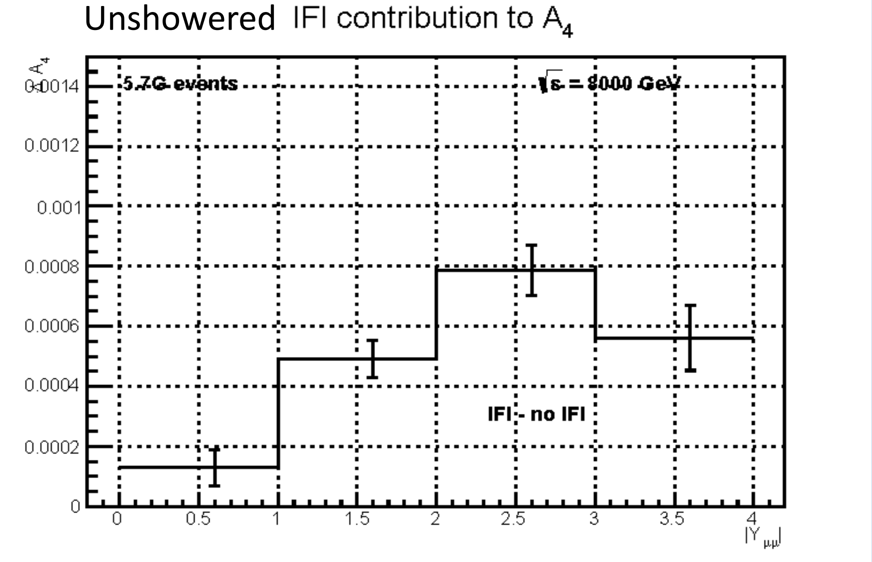
IFI contribution to A_4 with and without shower

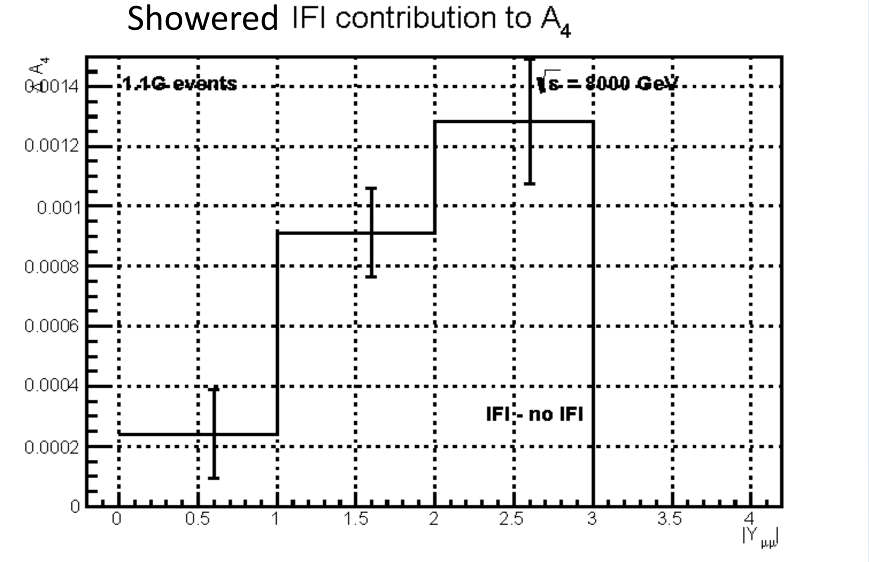




Dimuon M_{ll} bins

The differences between IFI and no-IFI results is shown





Dimuon $|Y_{ll}|$ bins

Unshowered results are on the left, showered on the right.

Summary

- ISR typically enters the angular results (A_{FB}, A_4) at the level of several per-mil. Both KKMC-hh and QED PDFs give a comparable ISR effect on angular results.
- The IFI effect is typically 1/10 the ISR effect or less, but this is sensitive to cuts.
- ISR in KKMC-hh is sensitive to the value of light quark masses. Uncertainties in these could be at the level of several per-mil. Further studies on the role of light quark masses are in progress.
- The parton shower changes the detailed results, but not the general size of the ISR and IFI corrections.
- Running KKMC-hh with an NLO shower is possible, and also a priority for these studies.

KKMC-hh and KKMC: References

Recent KKMC-hh and KKMC IFI papers:

- S. Jadach, B.F.L. Ward, Z. Wąs and S.A. Yost, KKMC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator, Phys. Rev. D94, 074006 (2016) [arXiv:1608.01260]
- Ibid., Systematic Studies of Exact $\mathcal{O}(\alpha^2 L)$ CEEX EW Corrections in a Hadronic MC for Precision Z/γ^* Physics at LHC Energies, Phys. Rev. D99, 076016 (2019) [arXiv:1707.06502]
- S. Jadach and S. Yost, QED Interference in Charge Asymmetry near the Z resonance at Future Electron-Positron Colliders, Phys. Rev. D 100, 013002 (2019) [arXiv:1801.08611]

Original KKMC and CEEX papers:

- S. Jadach, B.F.L. Ward and Z. Wąs, Comput. Phys. Commun. 130 (2000) 260 [hep-ph/9912214]
- Ibid., Phys. Rev. D63 (2001) 113009 [hep-ph/0006359]

Acknowledgments

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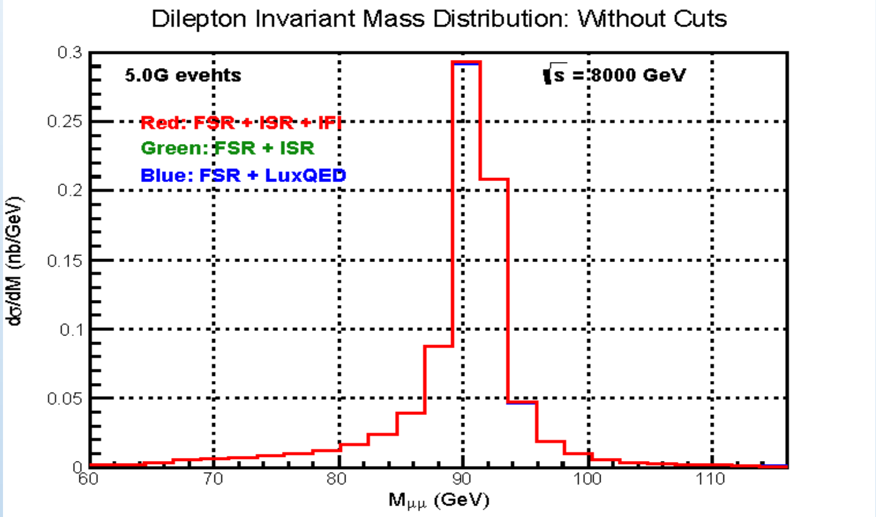
Appendix: Lepton and Dilepton Distributions

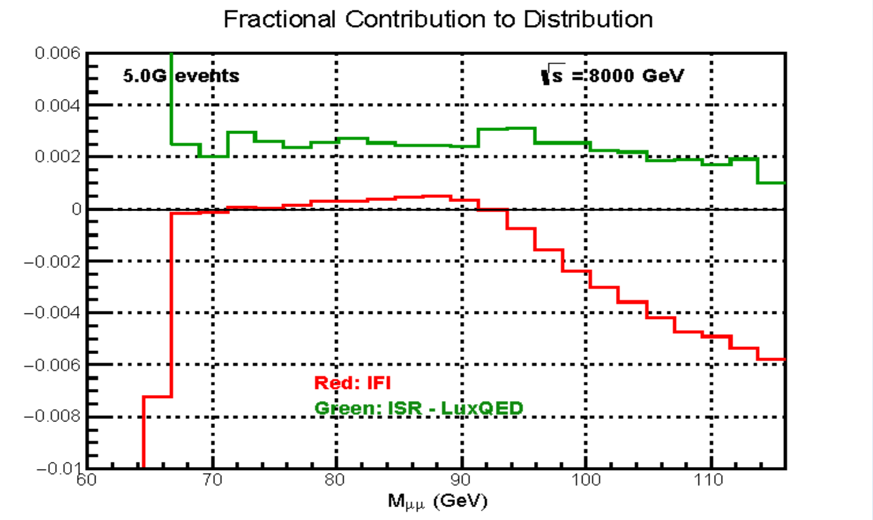
The following slides show various distributions with different levels of photonic corrections as shown.

The conventions follow the slides above.

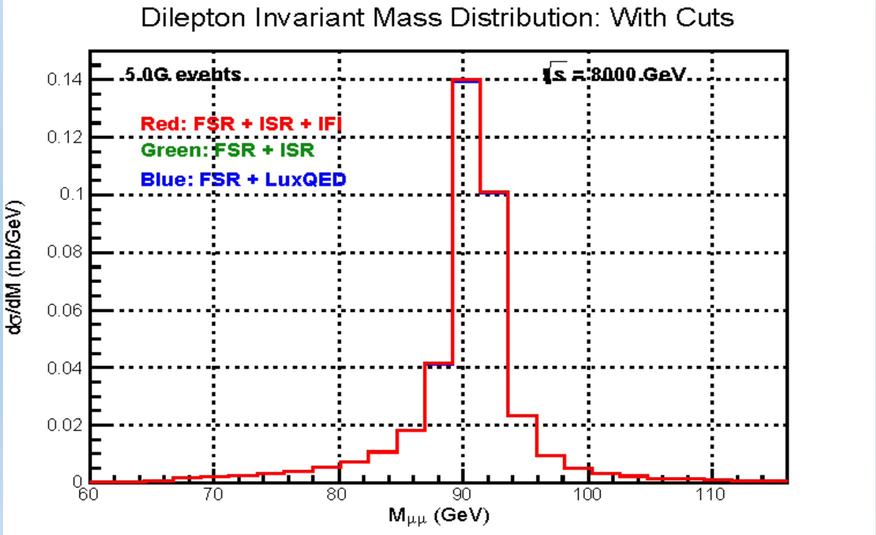
The results are all unshowered, from runs at a CM energy of 8 TeV.

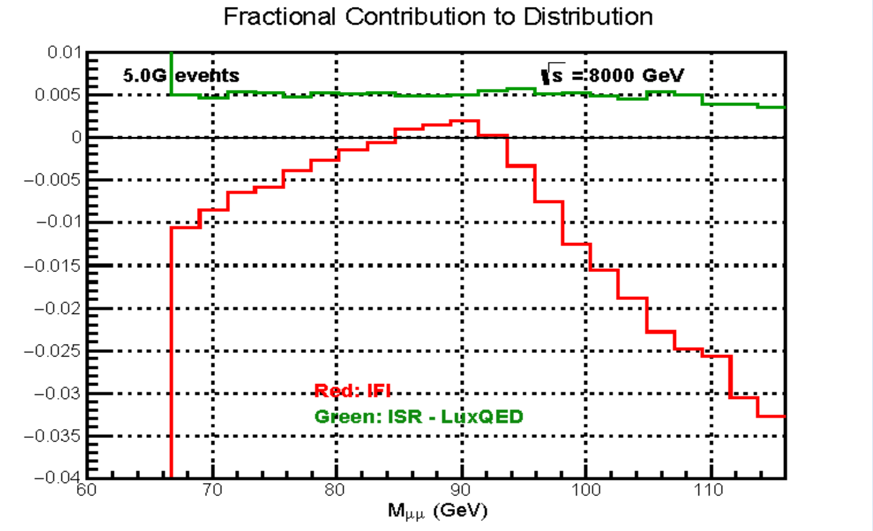
ISR and IFI contributions to M_{ll} distribution





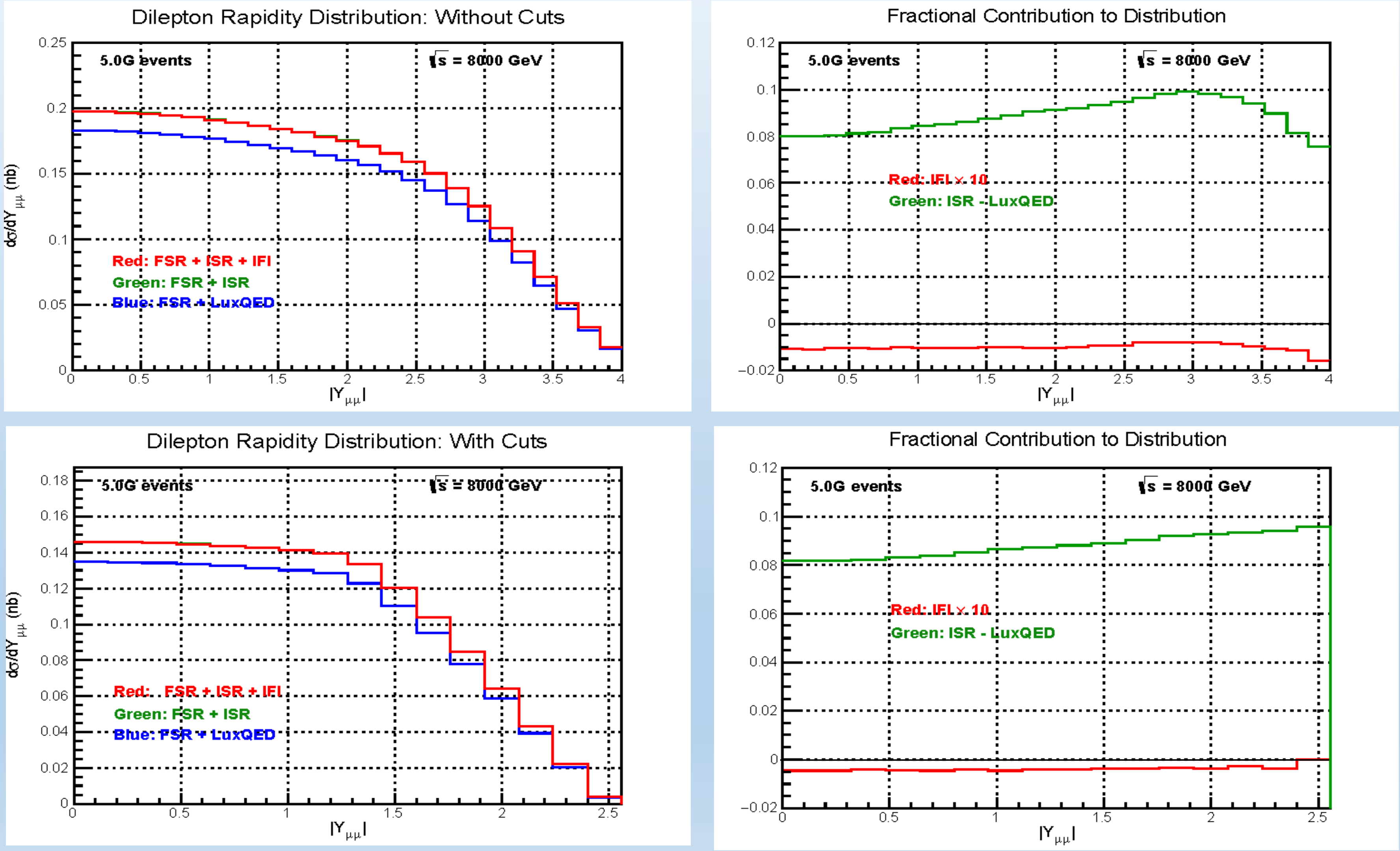
Without Lepton Cuts





With Lepton Cuts

ISR and IFI contributions to rapidity distribution

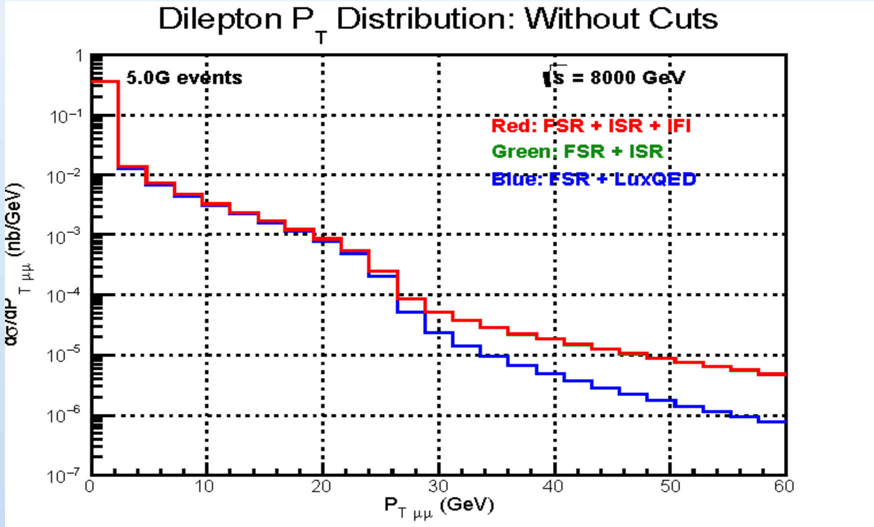


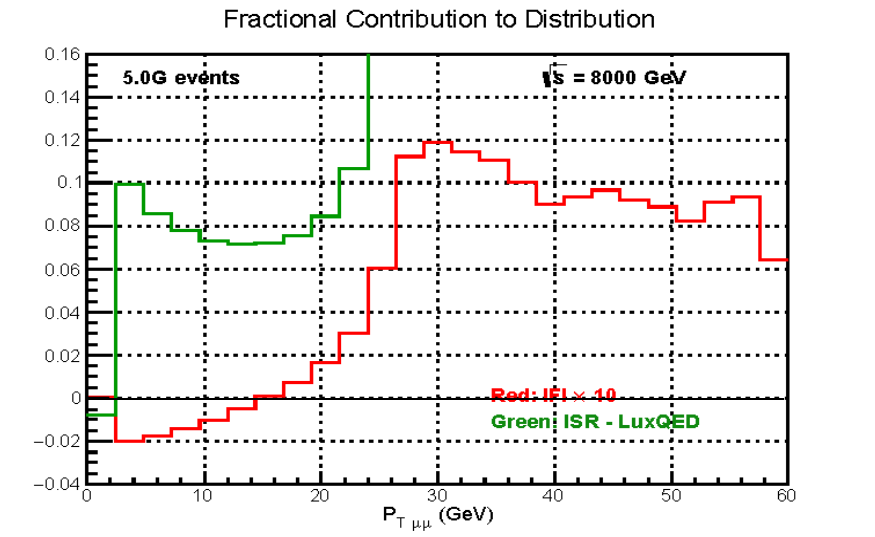
Without Lepton Cuts

With Lepton Cuts

ISR and IFI contributions to $P_{\mathrm{T}\,ll}$ distribution

Without Lepton Cuts





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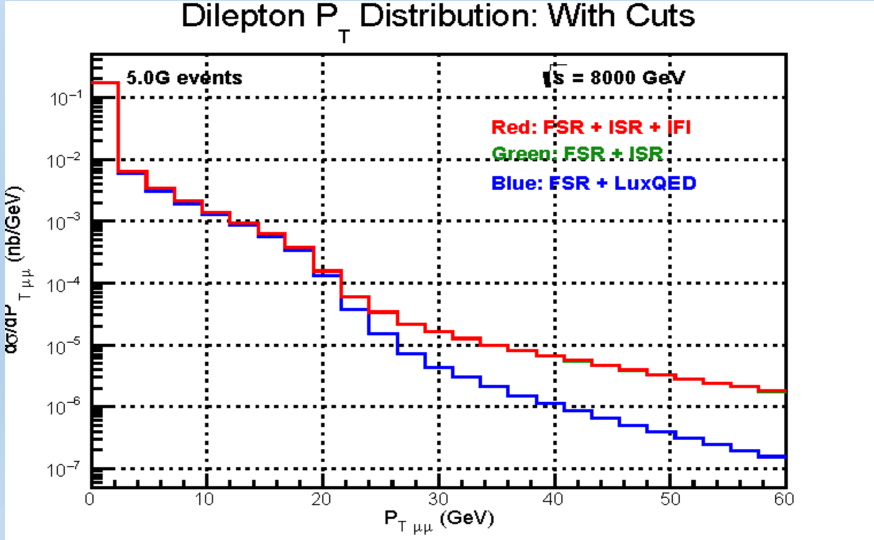
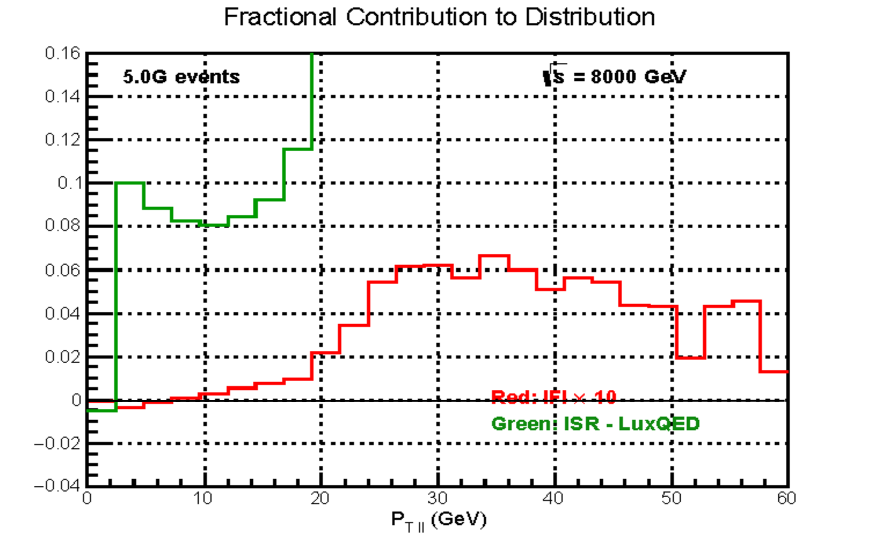
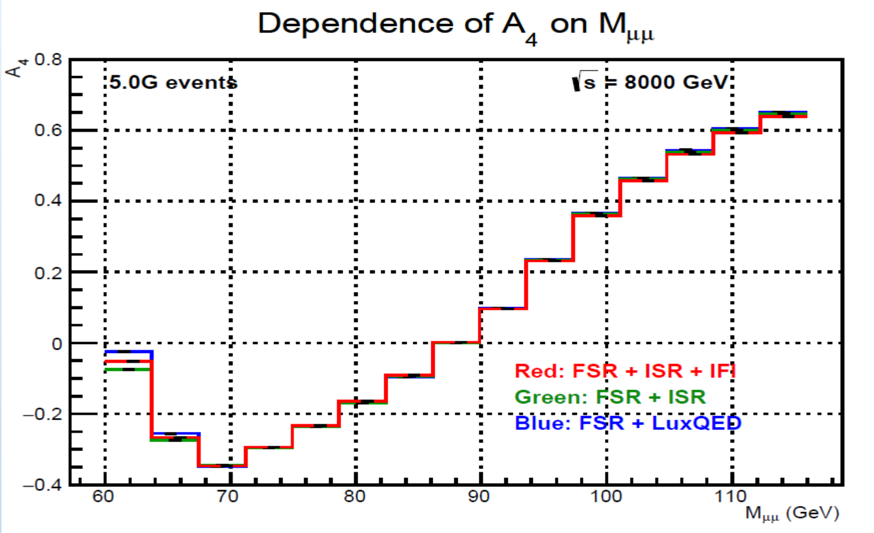
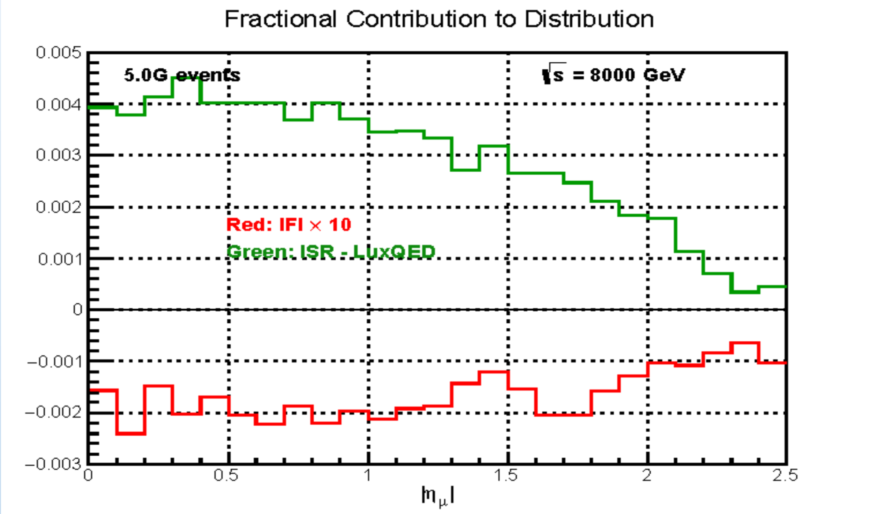


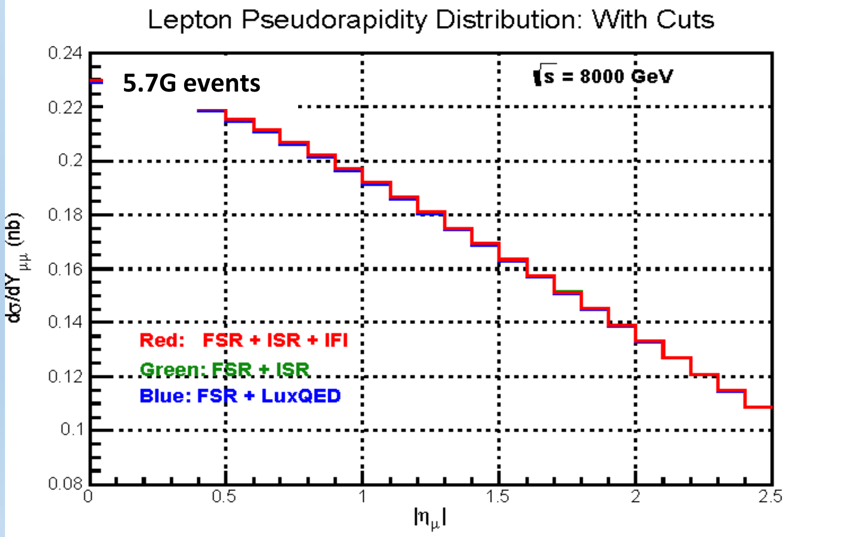


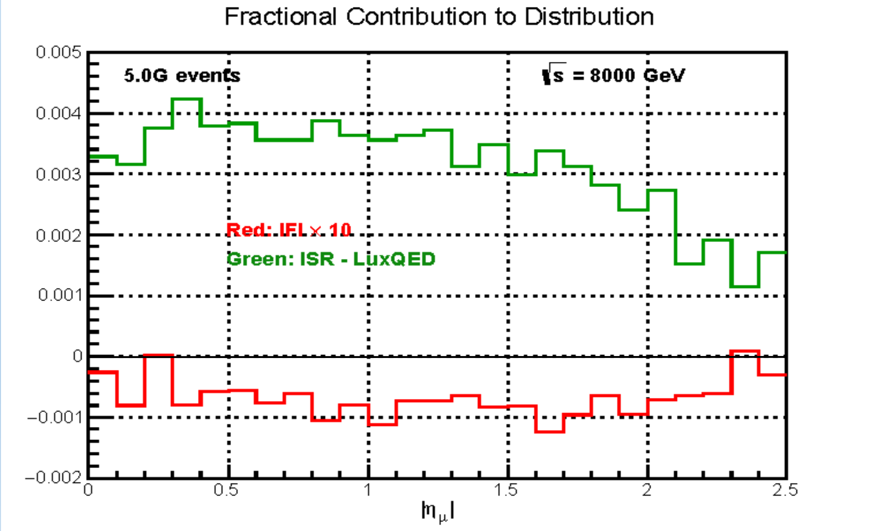
ISR and IFI contributions to lepton η distribution





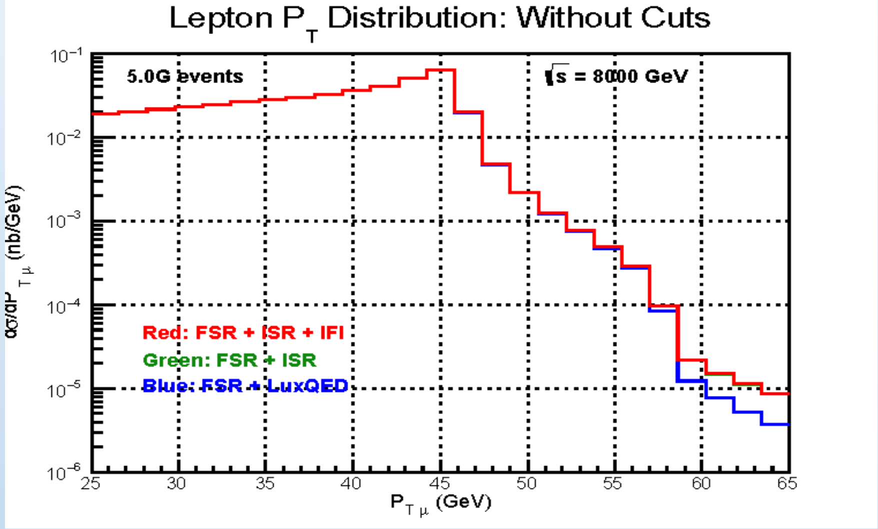
Without Lepton Cuts

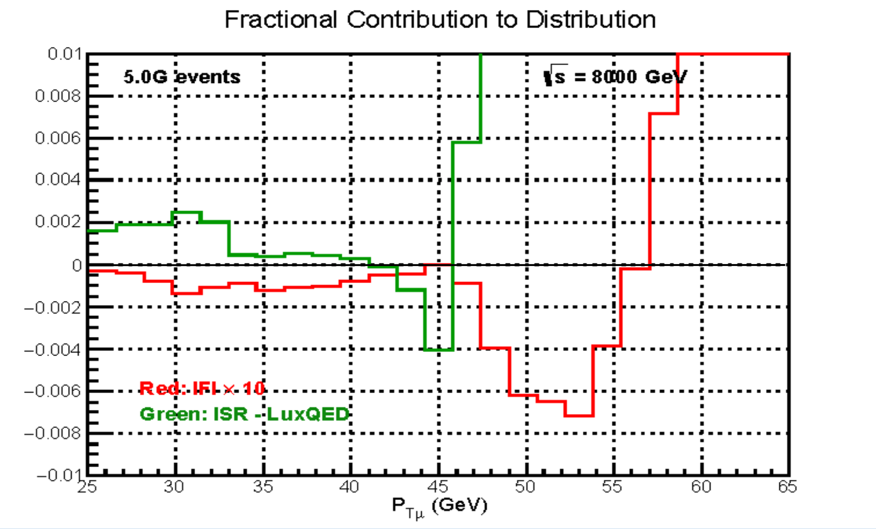




With Lepton Cuts

ISR and IFI contributions to lepton P_{T} distribution





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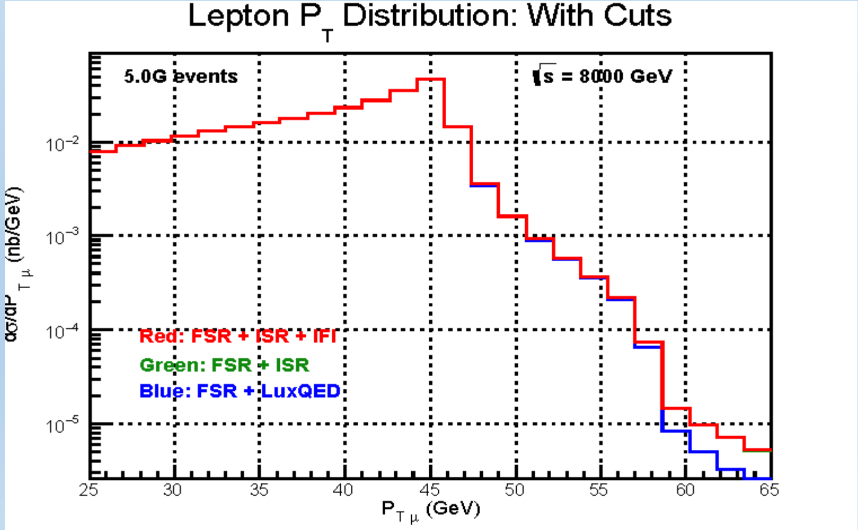

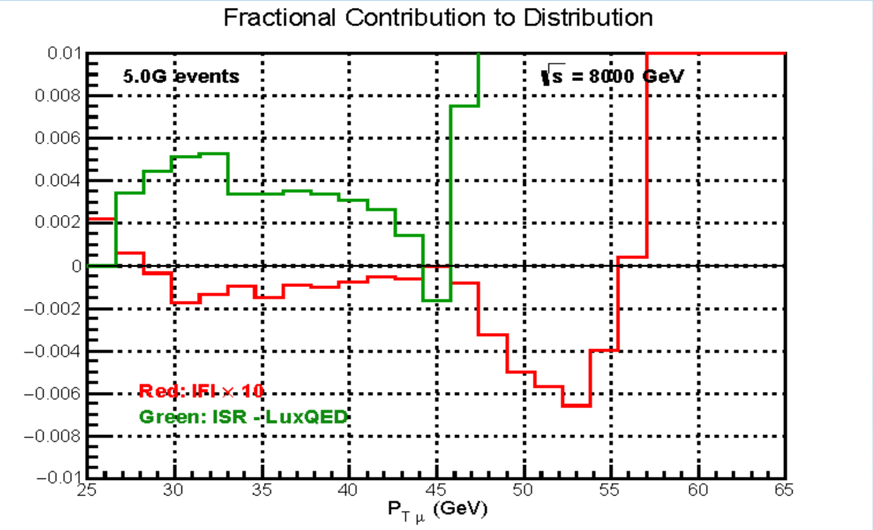

With Lepton Cuts