Status $\mathcal{KK}$ MC-hh: Effects of ISR and IFI on Angular Distributions

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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.
- The latest version of $\mathcal{KK}$ MC supports quark initial states, and provides a natural starting point for incorporating EWK corrections to the parton-level process.
- $\mathcal{KK}$ 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.

$\mathcal{KK}$ MC

- $\mathcal{KK}$ MC is a precision event generator for $e^+e^- \to f\overline{f} + n\gamma$, $f = \mu, \tau, d, u, s, c, b$ for CMS energies from $2m_\tau$ to 1 TeV. The precision tag for LEP2 was 0.2%.
- ISR and FSR γ emission is calculated up to $\mathcal{O}(\alpha^2)$, including interference.
- The MC structure is based on an amplitude-level version of YFS exponentiation, called CEEX, including residuals calculated perturbatively to the relevant orders in $\alpha^k L^l$. ($L = \ln(s/m_e^2)$). CEEX mode: $\alpha, \alpha L, \alpha^2 L^2, \alpha^2 L$ with IFI.
- $\mathcal{O}(\alpha)$ EWK corrections and more are included via DIZET 6.21.
- τ decay is simulated using TAUOLA.

Coherent Exclusive Exponentiation

- CEEX was introduced for pragmatic reasons, the traditional exponentiation (EEX) of spin-summed cross sections suffered from a proliferation of interference terms, limiting its ability to reach the desired 0.2% precision tag for LEP2.
- CEEX works at the level of spinor helicity amplitudes, greatly facilitating the calculation of effects such as ISR-FSR interference, which are included in $\mathcal{KK}$ MC, and therefore $\mathcal{KK}$ MC-hh.
- CEEX is maximally exclusive: all real photons radiated are kept in the event record, no matter how soft or collinear. There is no need to “integrate out” a region of soft phase space because the exponentiated amplitudes are well-behaved at $k = 0$.

CEEX Formalism

CEEX refers to coherent exclusive exponentiation, in which the exponentiation is applied at the amplitude level. It was motivated partly by the need to include initial-final interference (IFI) in precision LEP studies.

In the presence of IFI, the separation of photons into ISR and FSR is ambiguous, so a sum over all possible partitions is performed. The partonic cross section for $q(p_1)\overline{q}(p_2) \to \ell(p_3)\overline{\ell}(p_4)$ has the form, as a function of $p^2 = (p_1 + p_2)^2$ and radiation cutoff v,

$$\sigma_{\rm CEEX}(p^2, v) \quad = \quad \sum_{N=0}^{\infty} \sum_{\mathcal{P}} \frac{1}{N!} \int Dp_1 Dp_2 \exp(Y(p_1, p_2, p_3, p_4)) \int \prod_{j=1}^{N} Dk_j$$

$$\delta\left(v - \frac{(2p - K_I(\mathcal{P})) \cdot K_I(\mathcal{P})}{p^2}\right) \delta\left(K_I(\mathcal{P}) - \sum_{j=1}^{n(\mathcal{P})} k_j\right) \rho_{\rm CEEX}^{(N,\mathcal{P})}(p_1, p_2; p_3, p_4; k_1, \ldots, k_N),$$

where $\mathcal{P}$ is a partition of the N into $n(\mathcal{P})$ ISR photons with total momentum $K_I(\mathcal{P})$ and $N - n$ FSR photons, with $\rho_{\rm CEEX}^{(N,\mathcal{P})}$ constructed from helicity amplitudes. The photon integrations include a soft region, and the Yennie-Frautschi-Suura Y is defined in a way that cancels the overall dependence on this region.

CEEX Formalism

The YFS form factor is a sum of terms depending on momentum pairs, each with implicit dependence on the soft-photon cutoff ($E_{\rm min}$):

$$Y(p_1,p_2,p_3,p_4) = Q_i^2 Y(p_1,p_2) + Q_f^2 Y(p_3,p_4) + Q_i Q_f Y(p_1,p_3)$$

$$+Q_i Q_f Y(p_2,p_4) - Q_i Q_f Y(p_1,p_4) - Q_i Q_f Y(p_2,p_3),$$

$$Y(p_i,p_j) = 2\alpha \widetilde{B}(p_i,p_j,E_{\rm min}) + 2\alpha {\rm Re}\ B(p_i,p_j),$$

with real and virtual formfactors

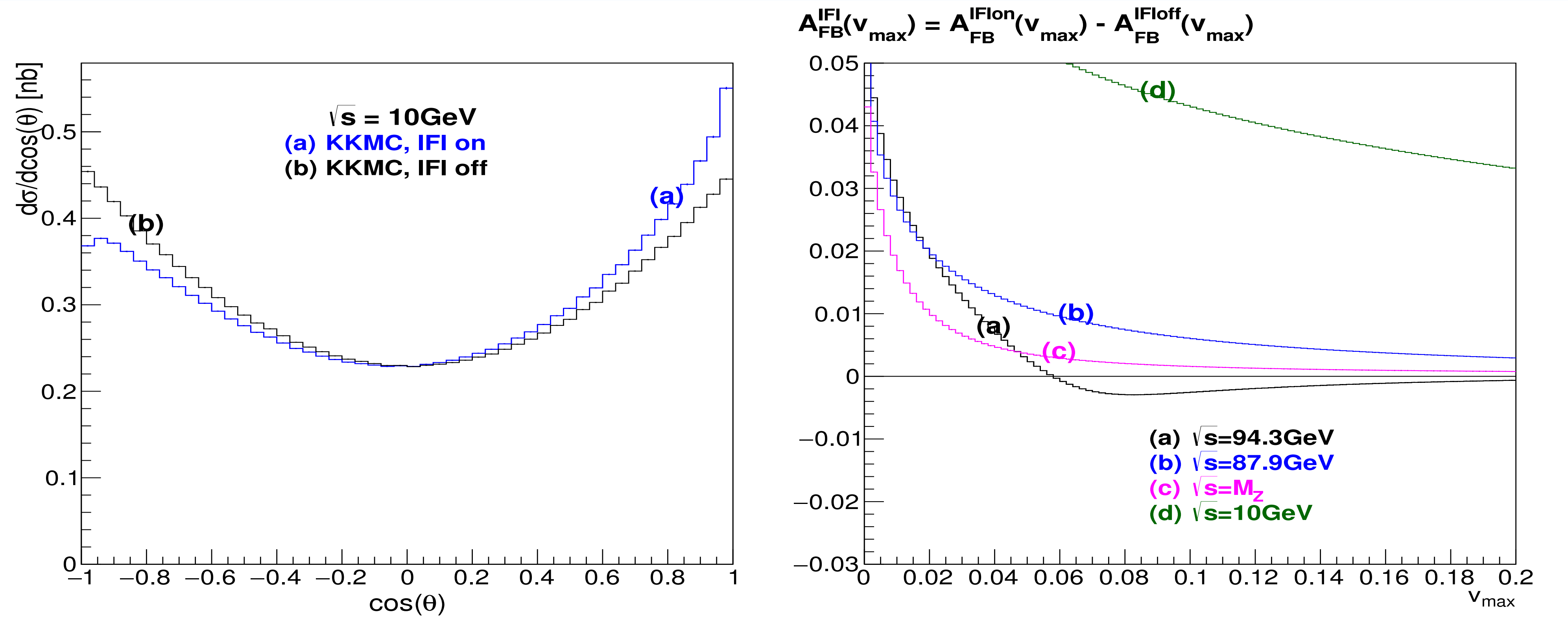
$$\widetilde{B}(p_i,p_j,E_{\rm min}) = -\int_{k^0<E_{\rm min}} \frac{d^3\vec{k}}{8\pi^2 k^0}\left(\frac{p_i}{p_i\cdot k} - \frac{p_j}{p_j\cdot k}\right)^2,$$

$$B(p,i,p_j) = \frac{i}{(2\pi)^3}\int \frac{d^4k}{k^2}\left(\frac{2p_i+k}{2p_i\cdot k+k^2} - \frac{2p_j-k}{2p_j\cdot k-k^2}\right).$$

IFI in $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$

IFI shifts angular distributions in a cutoff-dependent way. The figure on the right shows the effect on $A_{\rm FB}$ for various energies and cutoffs $v_{\rm max}$ on the fraction of the total CMS energy radiated to photons.

ref: S. Jadach & S. Yost, arXiv:1801.08611

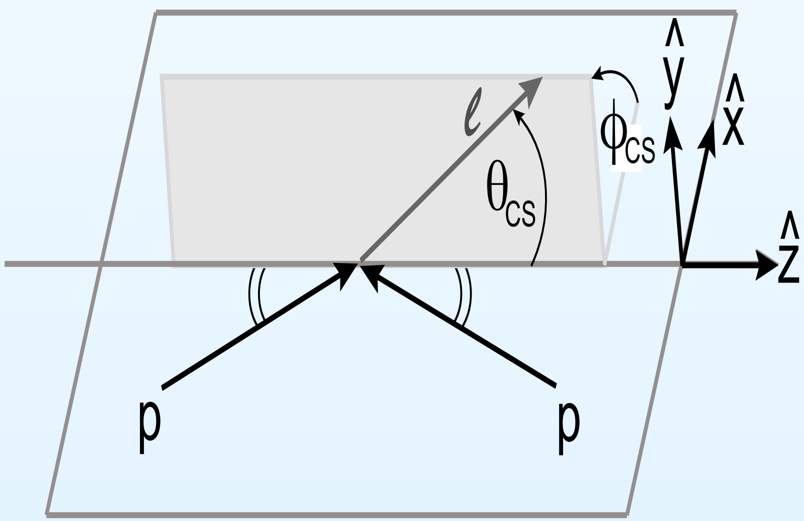


Angular Variables for $pp \to Z/\gamma^* \to \ell\bar{\ell}$

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 bisecting the momenta of the colliding protons.

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

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



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.
- Studies are under way to see the effect of this alternate definition.

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

- The following tests were run with the same 100M muon-event sample used in S. Jadach, B.F.L. Ward, Z. Was and S.A. Yost, arXiv:1707.06502.
- The events were generated at $7\mathrm{TeV}$ using MSTW-2008 PDFs and showered using the internal HERWIG6.5 parton shower.
- Results are included for the full $O(\alpha^2)$ CEEX radiative corrections, and compared to cases with IFI turned off and with ISR turned off.
- A_4 was calculated with only a cut $70 < M_{\mu\mu} < 110\ \mathrm{GeV}$.
- A_{FB} was calculated with an additional cut $p_T > 25\ \mathrm{GeV}, |\eta| < 2.5$ on both muons.
- The differential cross sections were calculated both with and without these additional muon cuts.
- Results for A_{FB} and A_4 are given in bins in $M_{\mu\mu}$ and $Y_{\mu\mu}$:

$$M_{\mu\mu} = 70-80, \quad 80-100, \quad 100-125, \quad 125-150, \quad 150-250 \quad \mathrm{GeV},$$
$$|Y_{\mu\mu}| = 0-1, \quad 1-2.5, \quad 2.5-3.5.$$

Numerical Results

	Full CEEX	no IFI	no ISR
Uncut σ (pb)	739.67 ± 0.12	739.40 ± 0.11	750.78 ± 0.05
Cut σ (pb)	342.72 ± 0.08	342.68 ± 0.08	345.09 ± 0.05
$A_{\rm FB}$ ($\times 10^{-3}$)	6.63 ± 0.10	6.59 ± 0.10	6.09 ± 0.10
A_4 ($\times 10^{-2}$)	1.677 ± 0.006	1.694 ± 0.006	1.664 ± 0.006

"Uncut" includes the $M_{\mu\mu}$ cut but no p_T or η cuts. In the following table, Δ_X is the fractional contribution of X to the full CEEX result, as inferred by turning off X. In particular, the IFI contribution to $A_{\rm FB}$ is consistent with zero, but cannot be ruled out at the % level without more statistics.

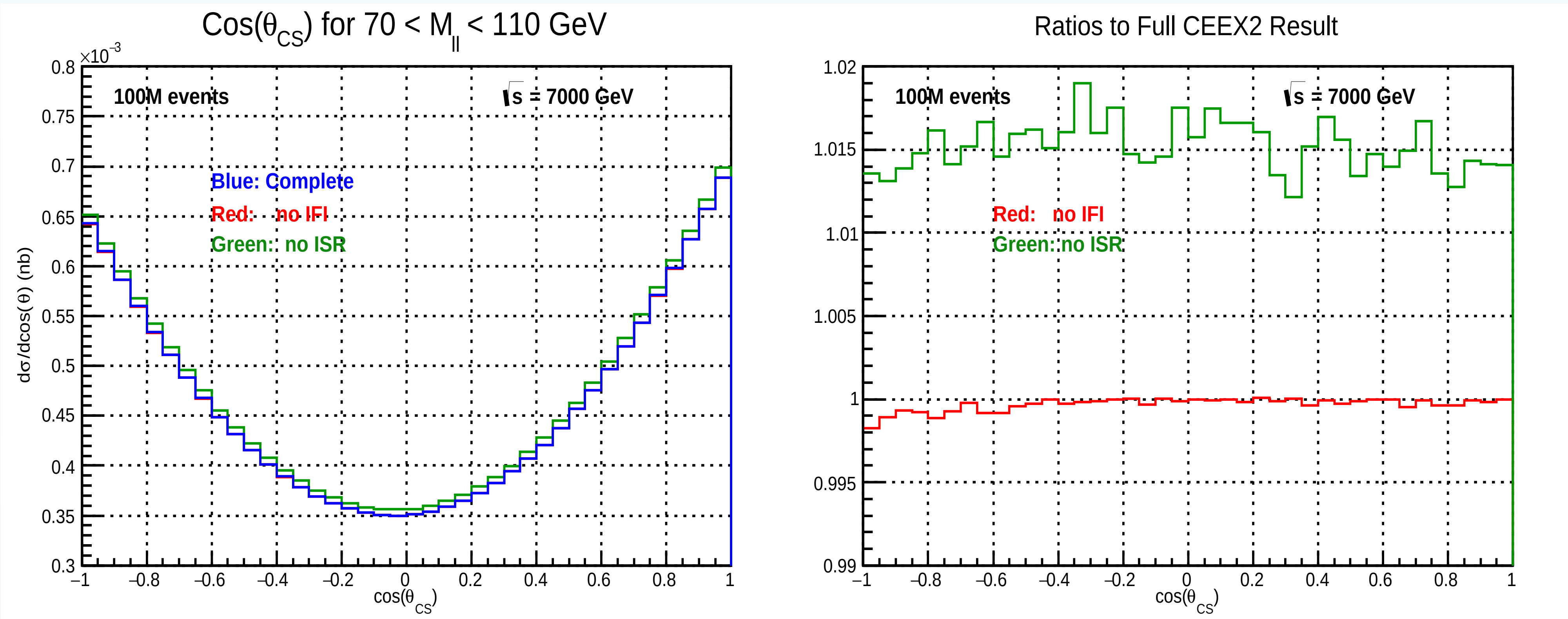
Fractional Contributions to CEEX Result

	$\Delta_{\rm IFI}$ (%)	$\Delta_{\rm ISR}(\%)$
Uncut σ	0.035 ± 0.022	-1.50 ± 0.02
Cut σ	0.013 ± 0.033	-0.69 ± 0.03
$A_{\rm FB}$	0.5 ± 2.1	8.2 ± 2.0
A_4	1.02 ± 0.53	0.77 ± 0.53

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

$70 < M_{\mu\mu} < 110$ GeV, no p_T, η cuts.

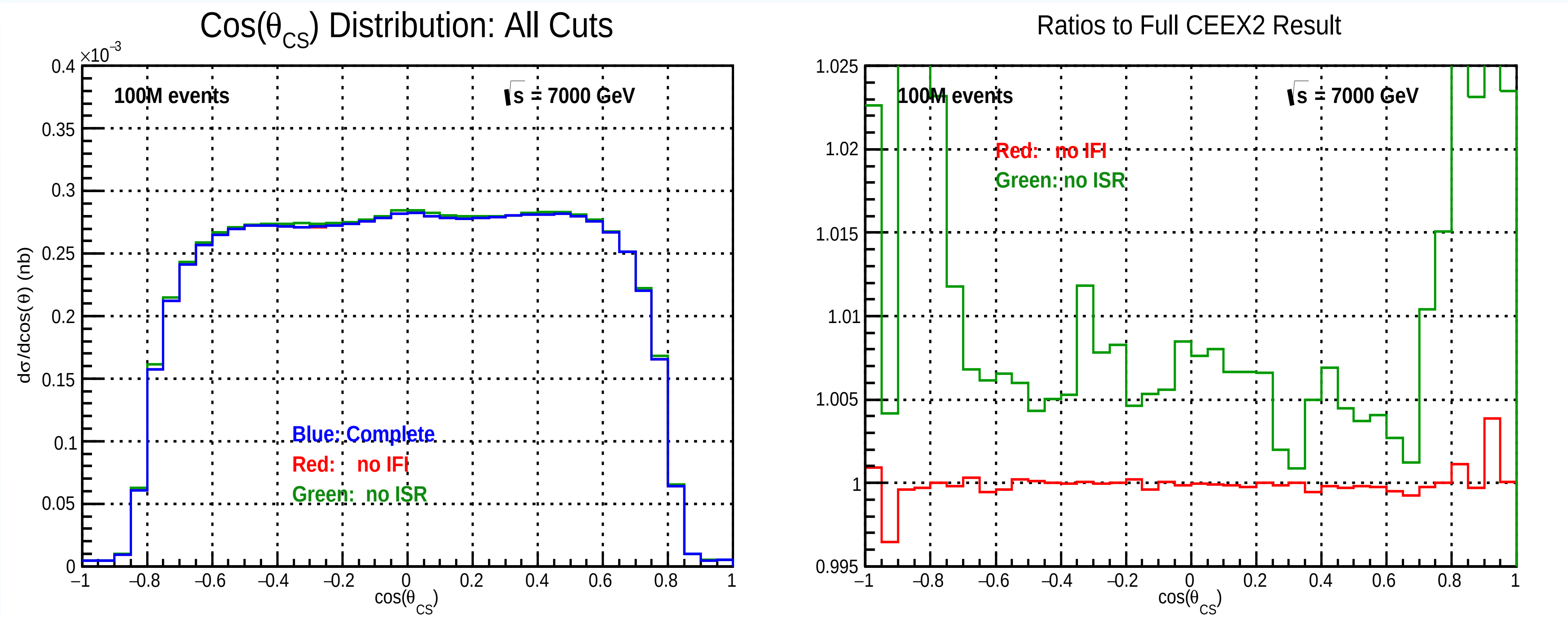
The IFI contribution is $<< 1\%$ but grows a bit in the backward direction. ISR is on the order of $1 - 2\%$, consistent with our previous papers.



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

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

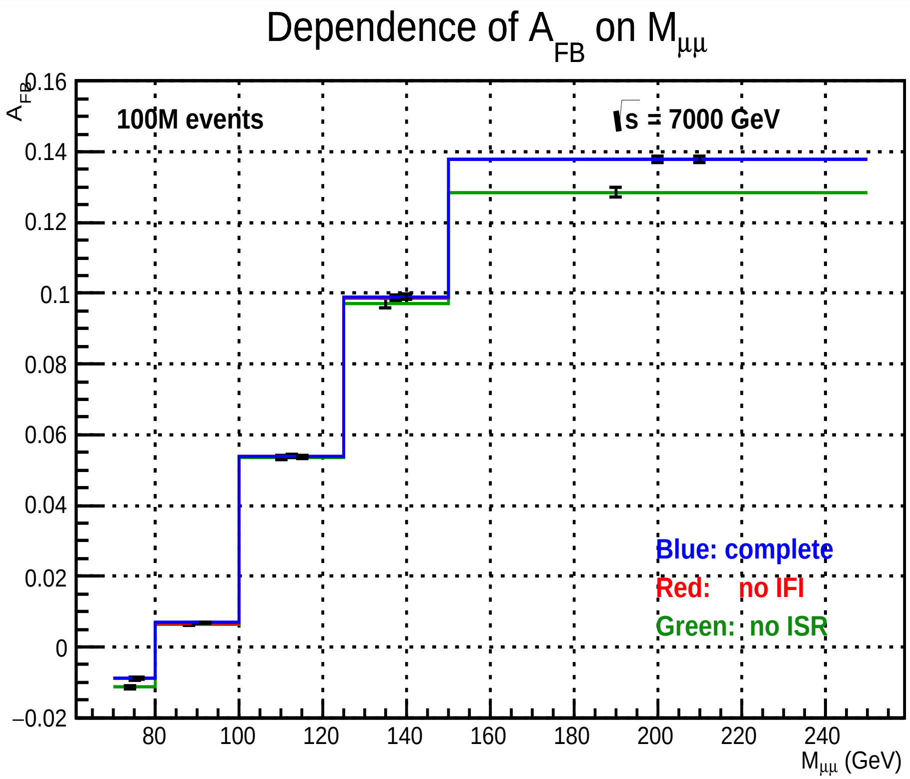
With the extra cuts, IFI is still very small, and ISR is comparable, away from the z axis where statistics are low.

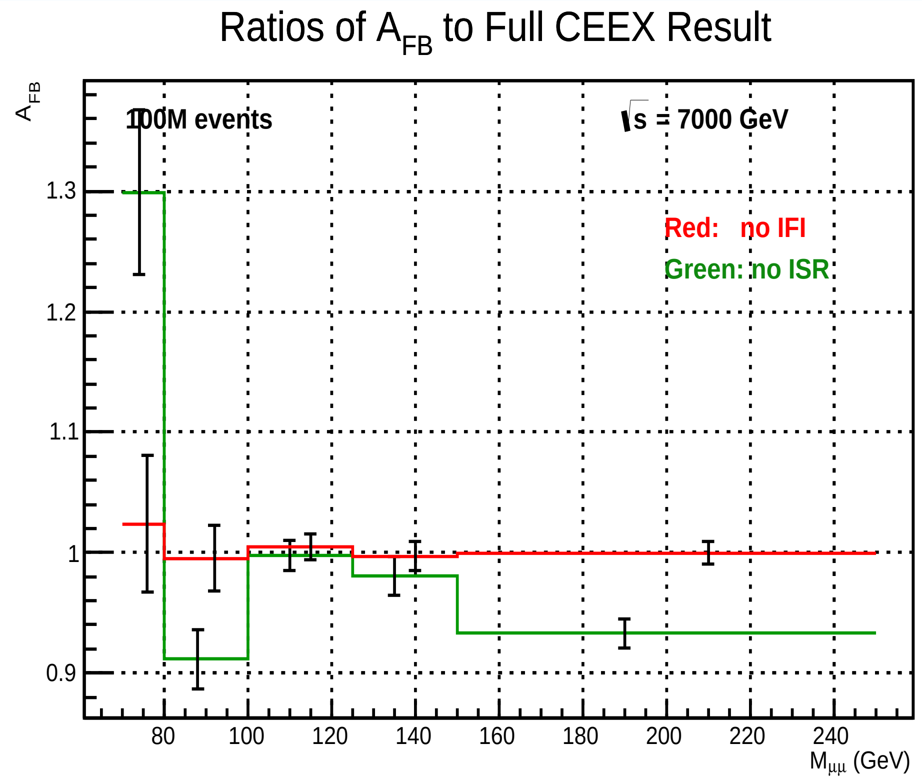


A_{FB} Binned in $M_{\mu\mu}$

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

$\Delta_{IFI} - 2.4 \pm 5.7\%$ in the lowest bin, partly because A_{FB} is so small there, and is less for the others.

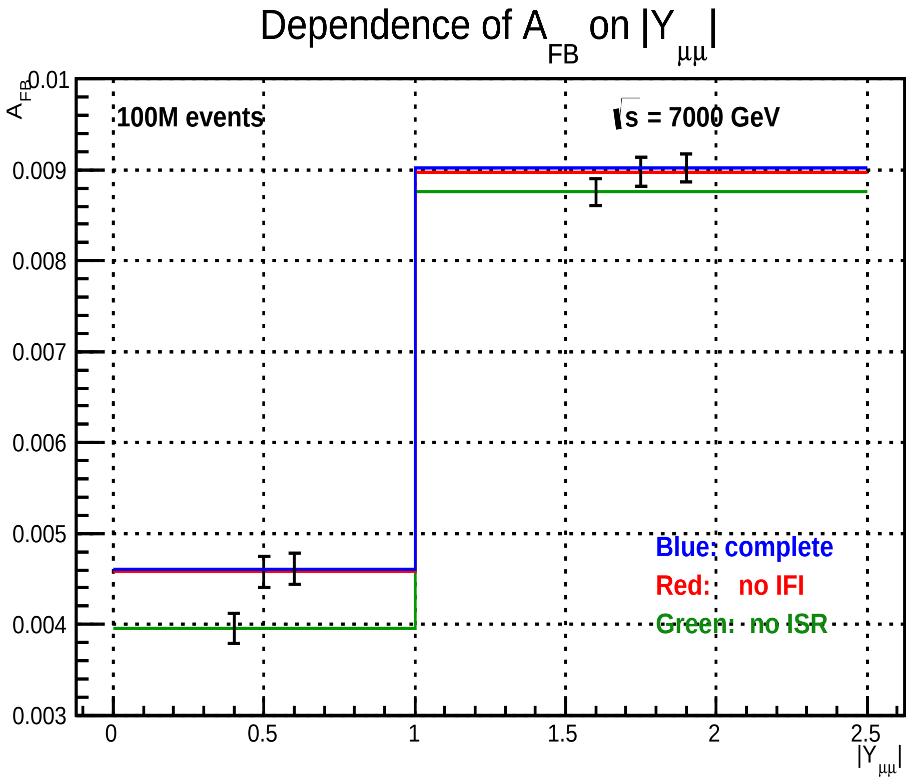


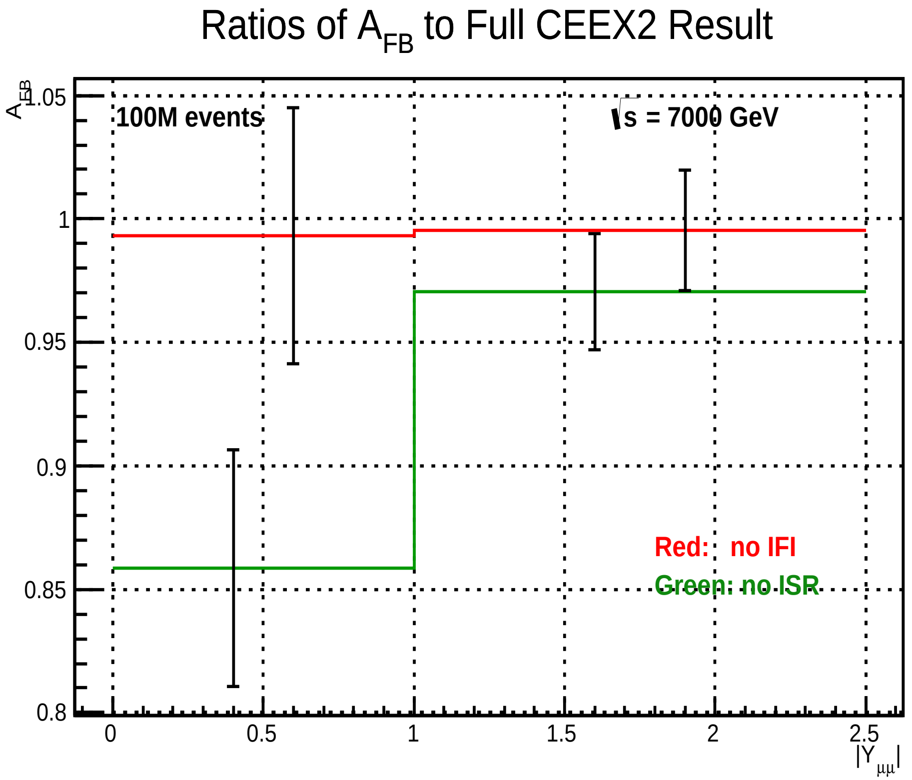


A_{FB} Binned in $Y_{\mu\mu}$

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

$$\Delta_{\mathrm{IFI}}(|Y| < 1) = 0.68 \pm 5.1\%, \qquad \Delta_{\mathrm{IFI}}(|Y| > 1) = 0.47 \pm 2.4\%$$

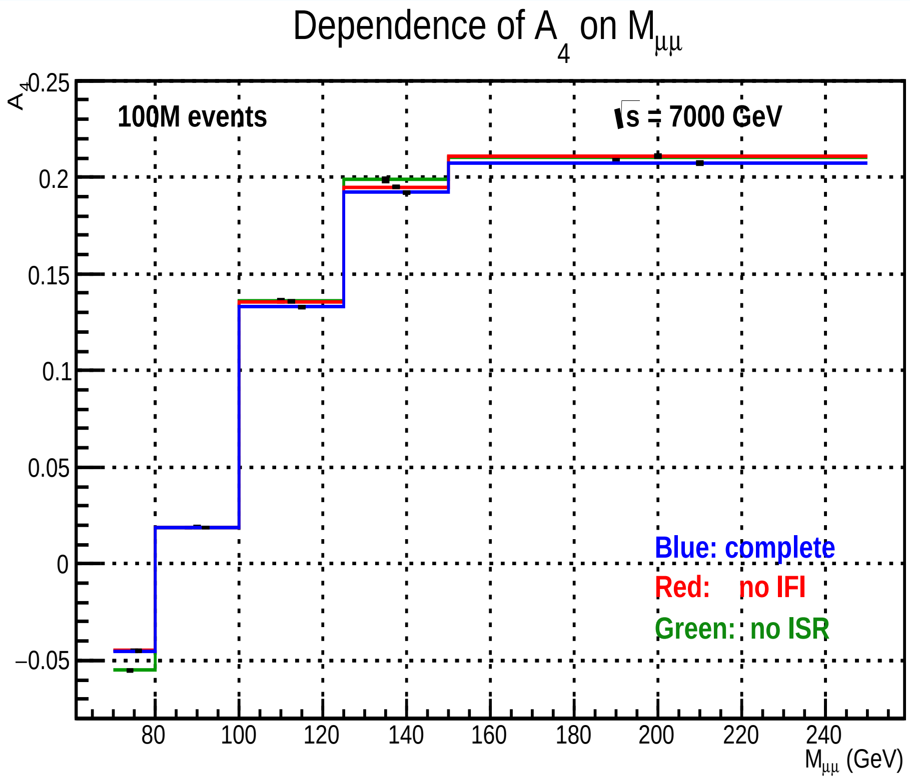


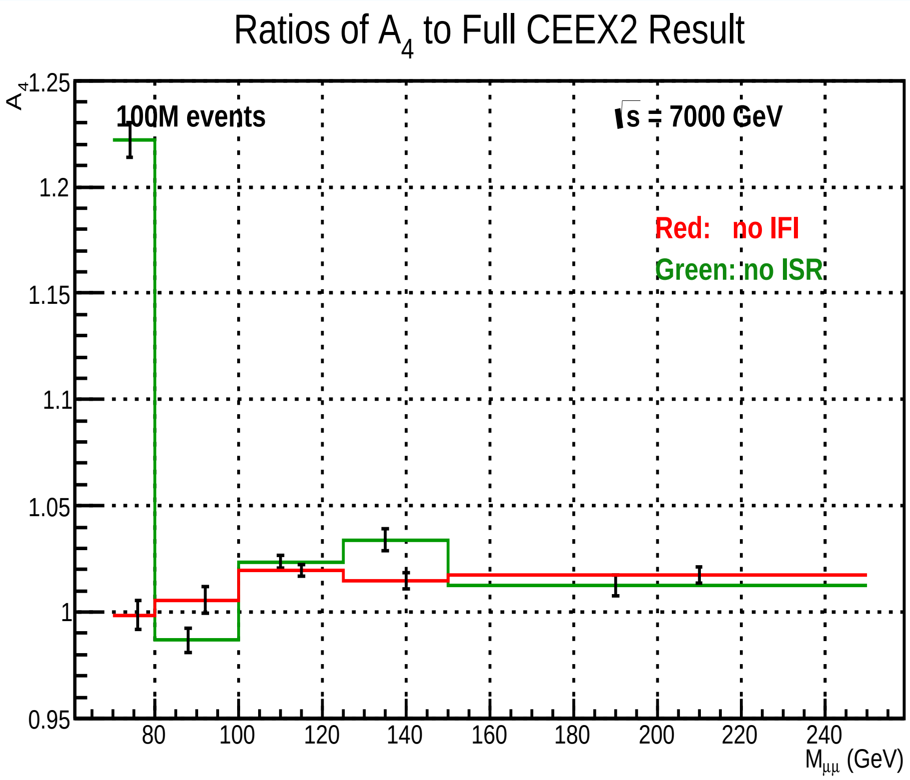


A_4 Binned in $M_{\mu\mu}$

No lepton cuts.

The IFI contribution can reach $\sim 2\%$ for large $M_{\mu\mu}$, but is consistent with zero near the Z resonance, where it is suppressed.

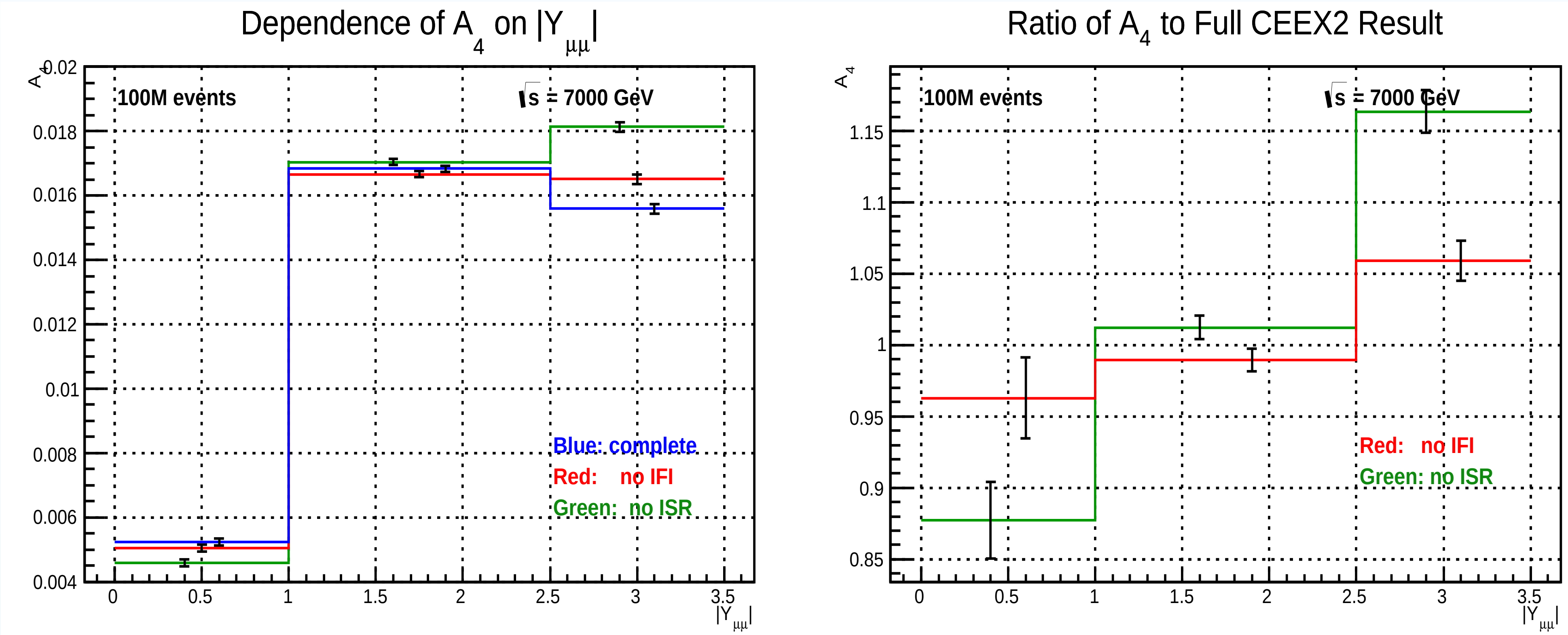




A_4 Binned in $Y_{\mu\mu}$

$$70 < M_{\mu\mu} < 110 \text{ GeV}$$

$$\Delta_{\rm IFI}(|Y| < 1) = 3.7 \pm 2.8\%, \qquad \Delta_{\rm IFI}(|Y| > 1) = 1.0 \pm 0.8\%$$



Summary

- For $70 < M_{ll} < 110\ \mathrm{GeV}$, the IFI contribution to A_{FB} is consistent with zero, but more statistics are needed to clarify this below the % level.
- The IFI contribution to A_4 appears to be at the fractional % level, but that estimate also would benefit from more statistics.
- 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.
- Some studies to find the effect of an alternative definition of the Z rest frame (adding back FSR according to proximity) are in progress, but not yet with adequate statistics to comment.
- 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)